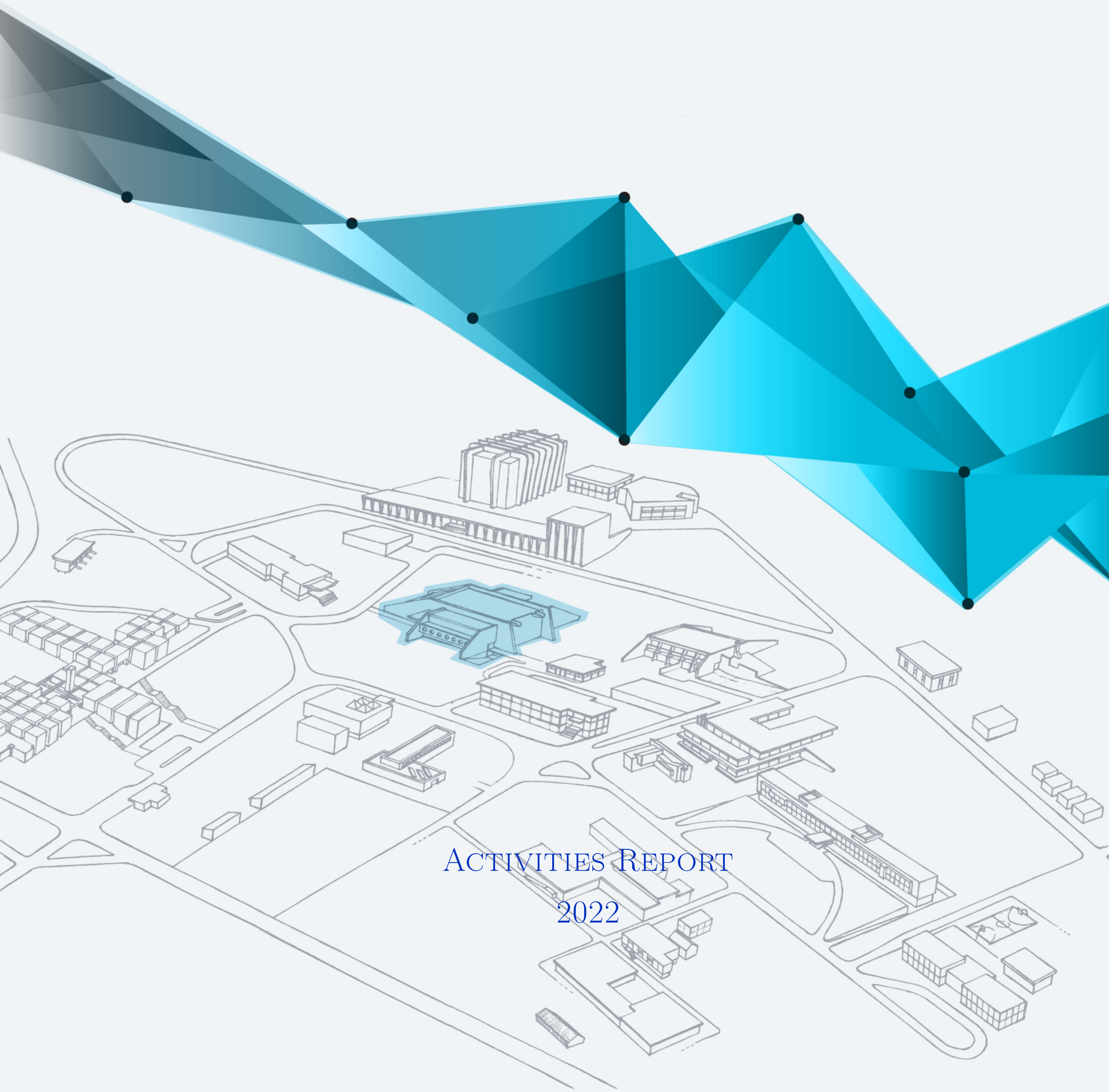
DEMOKRITOS

Institute Of Nuclear and Particle Physics



Activities Report

2022

Institute Of Nuclear and Particle Physics

National Center for Scientific Research "DEMOKRITOS"

Activities Report

2022

Editors:

C. Markou, G. Kareli

January 2022

Institute of Nuclear and Particle Physics,
NCSR "Demokritos"
Aghia Paraskevi, 15310, Athens, Greece

http://www.inp.demokritos.gr

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Institute of Nuclear and Particle Physics

Overview

The Institute of Nuclear and Particle Physics (INPP), at NCSR Demokritos, has as its mission the experimental and theoretical research, scientific excellence and innovation in High-Energy Physics, Nuclear Physics and Astro-Particle Physics as well as their applications in line with the National Research and Innovation Strategy for Smart Specialization.

The experimental and theoretical research in High Energy Physics focuses on the study of elementary particles and their interactions. INPP participates in the CMS and ATLAS experiments of the LHC at CERN. The Detector Instrumentation Laboratory (DIL) and the Data Acquisition, Monitoring and Analysis Laboratory (DAMA) of INPP, develop innovative detector technologies and instrumentation along with applications in science and innovation.

Nuclear Physics research focuses on Nuclear Structure, Nuclear Reactions, Nuclear Astrophysics and the study of interactions of X-rays with matter. The INPP hosts a 5.5. MV Tandem accelerator, a unique research infrastructure in Greece that is open to external users from Greece and abroad. The Tandem accelerator laboratory is an interdisciplinary open-access research infrastructure with innovative applications covering the fields of cultural heritage, environment, energy, human health and the development and testing of advanced materials and detectors. The XRF laboratory focuses on cultural heritage, environmental monitoring and biomedicine and offers technology transfer and on-site analytical services to museums, archaeological sites and other institutions.

The Astro-Particle Physics group participates in the development, deployment, data acquisition and data analysis of the kilometer cube underwater neutrino telescope in the Mediterranean, KM3NeT. The INPP hosts the Laboratory of Assembly, Testing and Calibration of the Digital Optical Modules, the basic units of the KM3NeT telescope. The INPP supports also the Deep-Sea Technology and Astro-Particle Physics Research Infrastructure in South-West Peloponnese (Kalamata, Pylos, Methoni).

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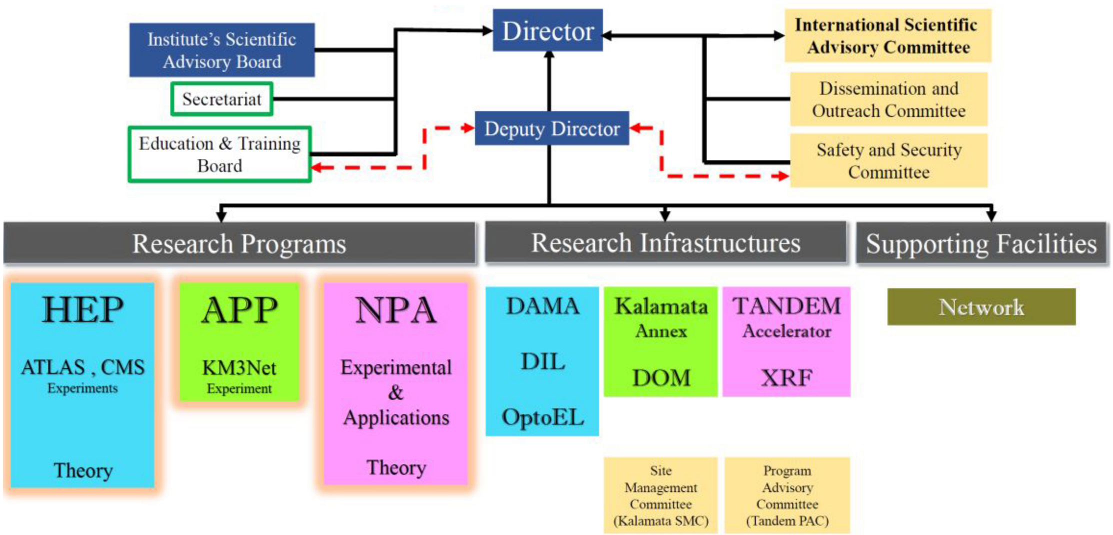
Organizational Chart



Director:	Dr. C. Markou
Deputy Director:	Dr. M. Axenides
Administration:	G. Kareli, Secretary M. Simantirakis, Administration
Institute Scientific Advisory Board:	M. Axenides (Chair) G. Anagnostou A. Karydas T. Geralis A. Lagoyannis
International Scientific Advisory Committee:	Prof. C. Bachas, Ecole Normale Superieure Prof. A. Bracco, University of Milan Prof. D. Charlton, University of Birmingham Prof. Y. Karyotakis, LAPP Annecy Prof. K. Kokkotas, University of Tübingen Prof. M. Lewitowicz, GANIL Prof. F. Linde, NIKHEF

Scientists in charge

High Energy Physics	Dr. T. Geralis: HEP-ATLAS & DAMA Dr. D. Loukas: HEP-CMS & DIL Dr. M. Axenides: HEP-Theory
Nuclear Physics & Applications	Dr. D. Bonatsos: Nuclear Structure Theory Dr. S. Harissopulos: Experimental Nuclear Physics & Applications – Tandem Dr. A. Karydas: XRF Laboratory & Applications
Astroparticle Physics	Dr. C. Markou: APP-KM3NeT

Personnel

The lists below reflect the INPP personnel as of the 31st of December 2022.

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Mobility

During 2022, Dr. S. Harissopoulos was on leave of absence in the International Atomic Energy Agency, Vienna.

Dr. A. Psallidas was hired as Researcher Gade C' joining the Experimental High Enrrgy Group.

Funding Programs in 2022

Research in INPP was mainly funded by the following programs with funding sources including National funding initiatives, the Horizon 2020 E.U. program, European research agencies as well as a limited number of contracts with the private sector.

Prog. ID	Title	Principal Investigator	Starting Date	Finishing Date	Budget
10231	Non destructive analyses with x-rays	Andreas Karydas	1/4/1998	31/5/2027	80,000.00 €
10461	Support for INPP	INPP Director	28/7/1998	31/12/2024	58,000.00 €
11041	Technologies for education and development	Theodoros Geralis	11/12/2002	21/12/2023	50.000,00 €
11458	Particle Phenomenology	Kostas Papadopoulos	1/3/2007	28/2/2025	90,000.00 €
11551	Fusion – Radiation studies	Anastasios Lagoyannis	1/12/2008	31/12/2022	30,000.00 €
11776	KM3NeT support activities	Christos Markou	1/1/2013	31/12/2024	59,000.00 €
11893	LIBRA	Sotirios Harissopulos	1/9/2014	31/8/2023	200,000.00 €
12209	ESSnuSB (H2020)	George Fanourakis	1/1/2018	31/3/2022	64,953.00 €
12217	ORASY	INPP Director	1/4/2018	31/12/2022	282,000.00 €
12239	CALIBRA	Sotirios Harissopulos	1/1/2017	31/3/2023	3,422,000.00 €
12312	Detector Development and Technologies for High Energy Physics (DeTANet)	Theodoros Geralis	11/2/2019	10/2/2023	125.962,67 €

12335	GEANT4-based particle simulation facility for future science mission support	Anastasios Lagoyannis	1/4/2019	30/10/2022	120.935,00 €
12356	Access to Ion and Neutron Beams at NCSR "Demokritos"	Anastasios Lagoyannis	13/6/2019	12/6/2024	15.000,00 €
12386	Chaotic dynamics and black holes in the BMN theory	Minos Axenides	10/4/2020	9/8/2021	45.545,50 €
12390	High order corrections in QCD and applications in the High energy LHC experiments	Constantinos Papadopoulos	1/4/2020	31/7/2021	37.037,00 €
12391	New generation of detectors and electronics for the upgrade of the CMS experiment at CERN	Dimitrios Loukas	17/3/2020	31/7/2021	41.041,00 €
12424	Nucleon separation energies	Dionysios Bonatsos	27/4/2020	27/8/2021	41.541,5 €
12429	Advanced System for collection and management of analytical data for documentation and conservation of large-scale paintings in an open laboratory	Andreas Karydas	28/7/2020	27/7/2023	155.311,00 €
12478	Intelligent, specialized, environmental observatory in Messinia	Christos Markou	1/5/2021	30/4/2023	400.000,00 €
12495	Development and Application of Ion Beam Techniques for Materials Irradiation and Characterization relevant to Fusion Technology	Michail Axiotis	1/5/2021	31/12/2025	15.000,00 €
12502	Silicon detectors and electronics	Dimitios Loukas	9/1/2021	31/12/2023	6.000,00 €

12532	KM3NeT CM	Christos Markou	4/4/2022	4/10/2022	25.000,00 €
12538	High Order Corrections and Tools for HighEnergy Colliders (HOCTOOLS-II)	Constantinos Papadopoulos	1/5/2022	30/4/2025	188.000,00 €
12540	ARENA - Accelerator based Research in Nuclear Astrophysics	Sotirios Harissopulos	1/4/2022	1/4/2025	188.000,00 €
12547	CMS/LHC tracker Week 2022	Aristotelis Kyriakis	3/5/2022	3/10/2022	60.000,00 €
12584	Mycenaean Vitreous Production A novel interdisciplinary approach towards resolving critical taxonomy issues	Artemios Oikonomou	26/9/2022	26/3/2024	96.878,00 €
12605	Software development in collaboration with IdeaSquare-Holodec at CERN	Christos Markou	1/12/2022	31/5/2024	16.600,00 €

High Energy Physics

High Energy Experimental Physics - ATLAS

Researchers:	Theodoros Geralis (Team Leader)
	Georgios Fanourakis (Researcher Emeritus)
	Andreas Psallidas
	Georgios Stavropoulos
PhD students:	Olga Zormpa
Master students:	Foteini Faidra Trantou
	Afroditi Machaira
Diploma students:	Kostas Spyrou
	Ilias Alexopoulos
Practical work students:	Three students
Technicians:	Ioannis Kiskiras

Introduction

In 2022, the INPP_ATLAS group concentrated mainly on the integration of the New Small Wheel (NSW) trigger, in Muon software developments and continued analysis in Z-mass precision measurement. The group was reinforced with a new researcher grade C, Andreas Psallidas, who started his qualification task on improvements of NSW track reconstruction. Software developments aimed at a realistic detector description, using as built parameters, performing alignment of the muon stations and taking into account deformations. The NSW Trigger group managed to provide triggers using the sTGC Pad Triger and partially the Micromegas trigger in the NSW monitoring stream. Even though the NSW trigger system did not arrive at the level to match the candidate muons with the outer detectors, it was a great success for the group.

The impact of the INPP_ATLAS team within the ATLAS collaboration is indicative from the responsibilities that are attributed to members of our group:

- **George Stavropoulos**: ATLAS Muon Software coordinator
- **Theodoros Geralis**: NSW Trigger Coordinator

In the activities subsections we describe the following items on which the ATLAS Demokritos group played leading role or had significant contribution during 2022:

1. sTGC Pad Trigger commissioning and integration
2. NSW autotriggering system
3. sTGC detector irradiation tests in Gif++
4. NSW Triggering in pp collisions
5. Muon and NSW software activities
6. Z-mass precision measurement analysis

Activities

sTGC Pad Trigger commissioning and integration

Both NSW wheels were integrated in ATLAS by January 2022. A repetition of all connectivity tests were performed in January 2022, validating all point to point connections: 1) pFEBs to Pad Trigger, 2) Pad Trigger to sFEB, 3) sFEB to Router and 4) Router to Trigger Processor as seen in Figure 1. More details on these tests are reported in last year's annual report that describes the connectivity tests on surface in building 191.

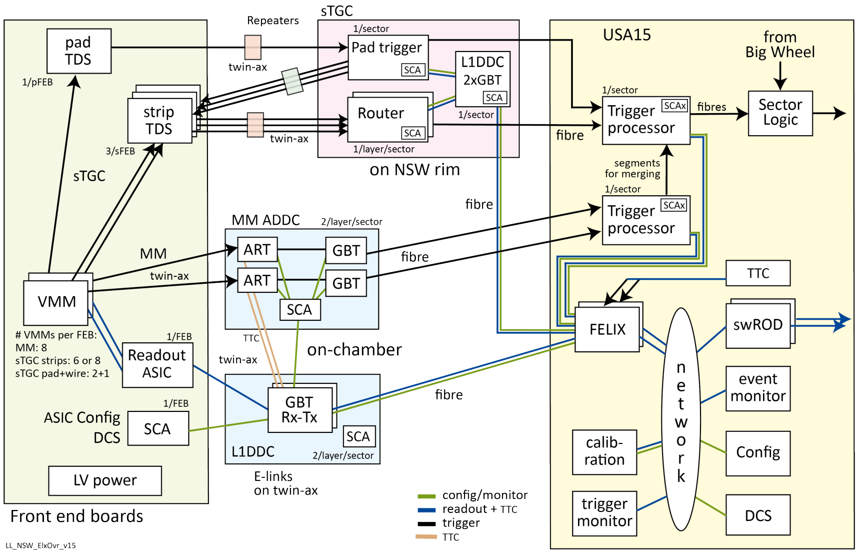

Figure 1: General Schematic of the NSW trigger electronics

Our group coordinated the effort of the NSW Trigger integration in ATLAS. The work consisted in completing the Pad Trigger (PT) and the Trigger Processor (TP) Firmware and performing system tests for their harmonic operation. A staged appoach was adopted that promoted first the advancement of the Pad Trigger part in combination with the Micromegas trigger part, leaving for a later stage the strips sTGC Trigger part. As it is seen in Figure 1 the muon candidates from the Micromegas TP are forwarded in the sTGC TP and merged with segments originating from the PT. Merging, duplicate removal, monitoring and finally forwarding of the data to the Sector Logic (SL) take place inside the sTGC TP FPGA. A lot of the functionalities but not all were implemented in the TP during 2022. By the end of 2022 all PTs of all sectors were included in ATLAS but only at the very end we managed to have the PT readout functional. The PT readout provided valuable data that were used for detailed studies on the Pad Trigger performance.

NSW Trigger latency. The group played leading role in estimating and measuring the latency of the Pad and the sTGC trigger. This was an important parameter as it had to be within the available budget of 44 Bunch Crossings (BC) i.e. 44 LHC clocks of 25 ns. Extensive calculations were performed including the particles (muons) Time of Flight (ToF), the propagation through all different

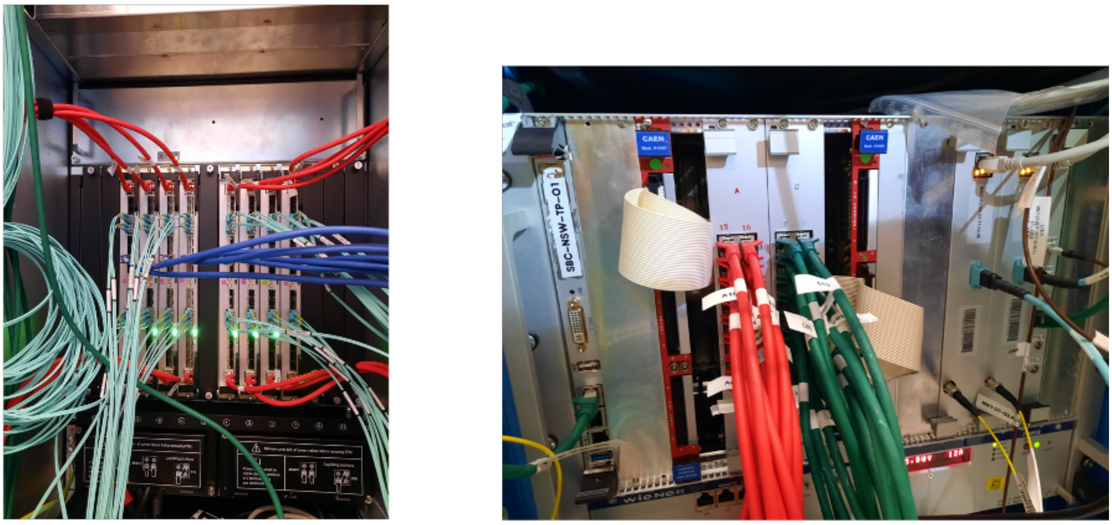

Figure 2: Left: Rear panel of the ATCA crate with the Trigger Processor connections for the L1A signals. This signal are fed in the front panel. Right: VME modules that collect the TP signals and forward it to the V1495 Caen module that provides the L1A signal to the Alti

transmission lines (twinax cables and fibers), the detector response, the electronics signal processing and finally the Pad Trigger and the Trigger Processor execution times. Estimations were compared with measurements and the final result was that the Pad Trigger was fully within budget but the MM, due to high noise and the use of long shaping time (200ns) in the FE electronics was on the limit to meet the budget.

NSW Autotrigger system. A VME based NSW Autotrigger system was built offering the capability to trigger on NSW detector signals, be it cosmics or real data without the availability of the ATLAS trigger and daq system (TDAQ). Special boards were built to collect the signals from every Trigger Processor and provide a trigger to the Alti TTC distribution system. The system was entirely designed and built by the INPP_ATLAS group and is hosted in USA15 electronics cavern near the ATLAS experiment (Figure 2). Special online software was developed to configure the Autotrigger e.g. select the sectors to include, specify the logic to implement etc.

Pad Trigger muon candidates. Even though the initial design was to use the sTGC strips and the MM triggers, Pad Trigger was the more advanced and thus was promoted to provide candidate muons to the Sector Logic (SL). Sector Logic is the system that combines NSW muon candidates and Outer Muons detector candidates to validate a real muon coming from the Interaction Point (IP) and reject fake triggers. Due to detector imperfections and lack of early optimization the coincidence of the Pad Trigger was loosened to mitigate for those effects. The Trigger Processor firmware was modified to merge only Pad muon candidates.

sTGC irradiation studies in Gif++

In order to understand the sTGC detector behavior in realistic conditions, a testbeam was performed in October 2021 at the Gamma Irradiation Facility (GIF++) at CERN. A layout of the building can be seen in Figure 3. A quadruplet of an sTGC detector was placed vertically to the SPS H4 beam and it was irradiated with photons from a $^{137}Cesium$ source. The full setup including the Micromegas quadruplet that was also participating in the testbeam is shown in the same Figure. The aim was to measure the muon detection performance at the presence of irradiation fluxes similar to the LHC ones during pp collisions at 14 TeV.

The INPP_ATLAS group studies the efficiency of the sTGC pads. To do so, events triggered by a 4 scintillator coincidence were analyzed. The 4 scintillator coincidence was carried out by adding 2 small scintillators together with the GIF++ large scintillators pair, covering the area of a 4-layer, trigger tower, on the sTGC quad.

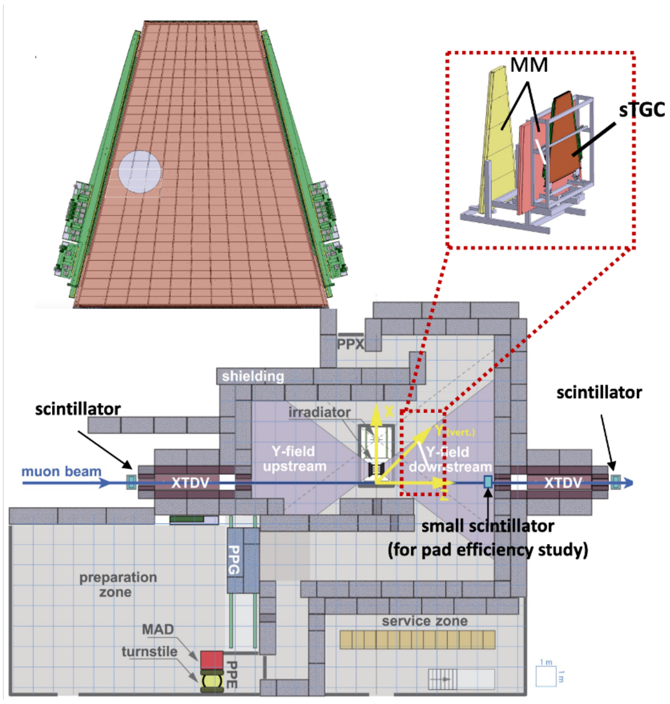

Figure 3: Arrangement of the GIF++ irradiation facility. The muon beam direction is indicated as well as the positions of the MM and the sTGC detector modules.

The sTGC sector was exposed to SPS muons of 100 GeV energy. Figure 4 on the left side shows the Landau distribution with no photon irradiation.On the right side the pad efficiency is evaluated, using three different selection criteria: 1) 4 strips + 4 wires, 2) 4 wires and 3) Three or more wires and as a function of the attenuation used on the Cesium source. This testbeam revealed the capability of the sTGC position determination. Figure 5 on the left side shows an excellent resolution based on the strips. The strips pitch is 3.2 mm and the precision comes from the charge distribution shape on the resistive coating. On the right side of the same Figure 5 the pad efficiency is shown as a function of the photon flux. It

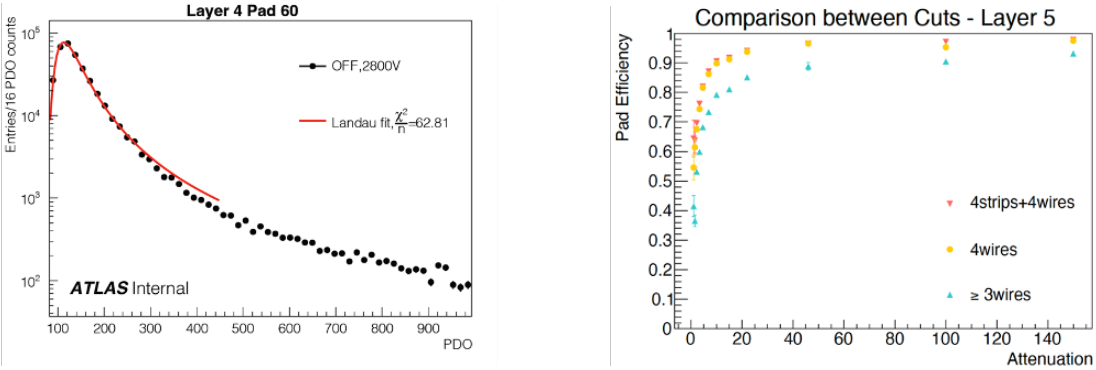

Figure 4: Left: Landau distribution from SPS muons recorded by the sTGC detectors. Right: Pad Efficiencies using different analysis cuts as a function of the attenuation

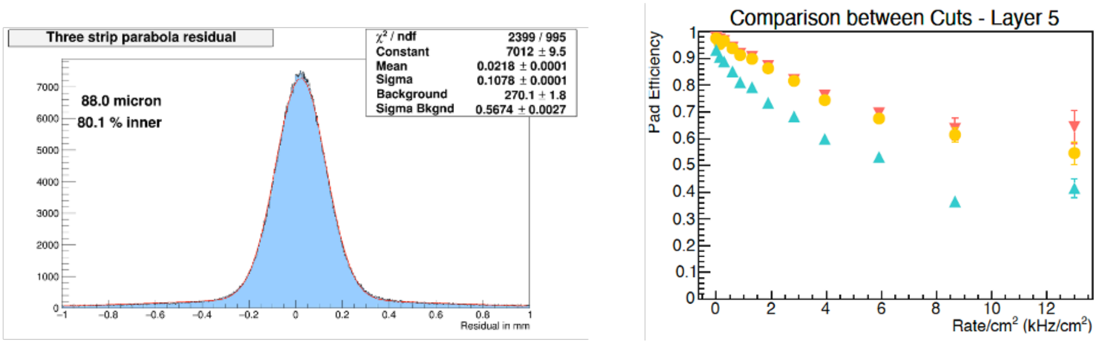

Figure 5: Left: Strips sTGC position resolution. Right: Pad Efficiencies using different analysis cuts as a function of the photon flux

is evident that at fluxes of the HL-LHC and in the innermost part the efficiency may drop as low as 50%, none the less this is only seen in the readout part, where long ADC conversion time is used in the VMM causing this inefficiency at high rates due to signal pileup and distortion. The pads are used on the trigger path and an ADC shaping time of 50 ns is used, thus not suffering from this kind of effect. An ATLAS internal Note is in preparation describing all these studies and results.

NSW Triggering in pp collisions

During 2022 the LHC started p-p collisions, after an extended shutdown period of maintenance and upgrades, for the so called Run3 period. The LHC accelerator ramped up in energy at 13.6 TeV offering the highest ever achieved energies in p-p collisions. As reported above our team coordinated the effort for the NSW Trigger integration in ATLAS and in particular, to start with, with the Pad Trigger and the Micromegas Trigger. One of the most important parameters in triggering is the latency, that is fixed in our case, and guarantees that all system buffers will sustain the readout rate without loss of events. The Pad Trigger offered very low latencies, while the Micromegas suffered from detector issues. All sectors are separate entities and forward their decision and data to the Sector Logic (SL). The SL combines the NSW muon candidates with the outer muon candidates in

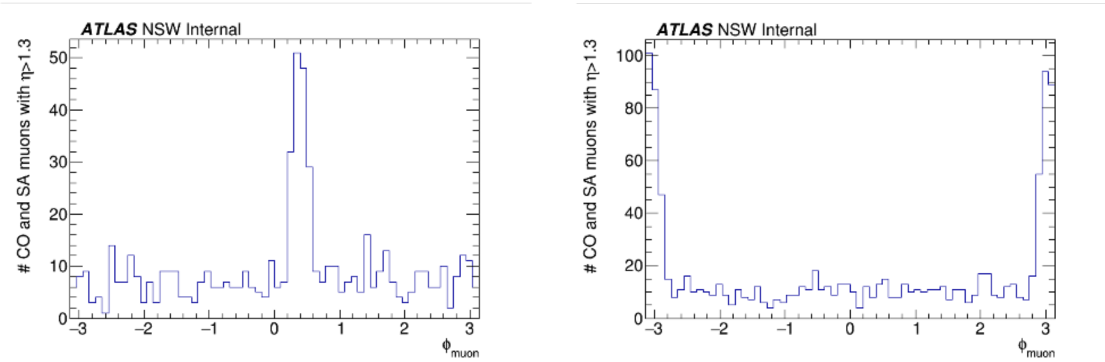

Figure 6: Left: Trigger on sector A02 with Pad only. The peak corresponds to the A02 width in ϕ. Right: Triggering on sector A09 with Pad and Micromegas trigger. The peak at the edge of the ϕ limits corresponds to the A09 ϕ width.

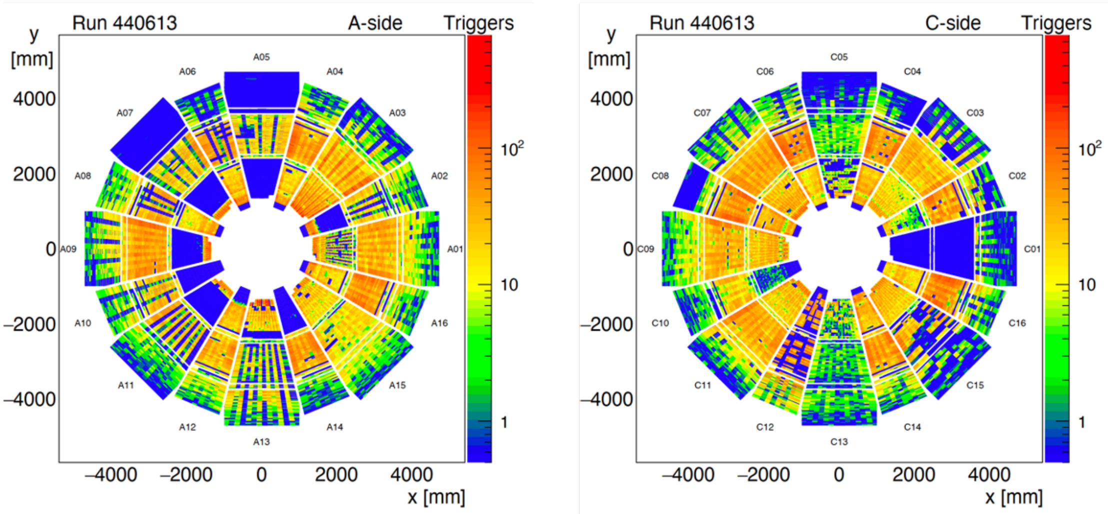

Figure 7: Hit map with valid muon candidates as found by the Pad Trigger in Wheel A (left) and in Wheel C (right).

order to provide valid muons coming from the IP and rejecting the fake ones.

NSW monitor decision. A first tool that was used for the NSW trigger validation was the NSWMON bit that is valid when at least on sector has provided a valid trigger. The NSWMON decision reaches the Central Trigger Processor (CTP), it can be used to write out data on which NSW had a valid trigger in the the so called NSWMON data stream. Figure 6 shows two case where only Pad Trigger is used (left) and Pad and Micromegas trigger is used (right).

Despite problems in the detectors performances, like missing HV in various layers, missing FE boards etc, we could get a first hit map with Pad decision as seen in Figure 7.

In 2022 the ATLAS Public note for the repeaters, went through the referee's process and was approved in November 2022:

Muon and NSW software activities

The muon spectrometer is made up of several thousand chambers and is the outermost layer of the ATLAS detector. It identifies and measures the momentum of muons that fly out of the collision point. The upgraded NSW of the ATLAS muon system consists of two types of gas detectors (sTGC and MicroMegas).

The responsibility of coordinating, by the ATLAS Demokritos group, the work of the ATLAS Muon Software Group, involving more than 40 scientists from more than 20 Institutes worldwide, continued during 2023. The ATLAS Muon software is developed in a multi-threaded C++/OO and Python environment and is organised in the following thematic areas

- Data Access (Byte-stream Conversion and Cabling).
- Detector Description and Alignment.
- Conditions Databases and DCS.
- Detector Specific calibration procedures.
- Simulation.
- Modelling of the Detector Response (Digitization and "local" Reconstruction).
- Track Reconstruction and Muon Identification.
- Trigger.
- Offline Data Quality.

The highest priority of the muon sw group during 2022 was the support of the Run 3 data and the proper integration of the new detectors (NSW, BIS78) in the ATLAS main software frame (Athena).

Andreas Psallidas on his qualification task studied the reconstruction of 'spoiled' clusters coming from high radiation background in the New Small Wheel detector. Specifically, muons with high transverse momentum undergo radiative energy losses, which may produce hits near the muon track and 'spoil' the shape of the cluster in the New Small Wheel. The goal was to identify these problematic clusters so that the hit positions of the muon track along the detector layers could be accurately calculated. A website was developed with detailed documentation of the study. Also, two sub-tasks independent of the main qualification task where studied, one related to alignment corrections from an ASCII file for Monte Carlo sample and the second on fixing a crash related to the reconstruction chain, which led to two merge requests (first,second) in the official offline reconstruction software of ATLAS (Athena). For the main qualification task a package has been developed in the official Athena framework using Boosted Decision Trees to classify the clusters as clean or spoiled.

Furthermore, Andreas Psallidas supervised Kostas Spyrou in his diploma thesis in cooperation with the Department of Physics of EKPA with subject: High Radiation background study in the muon clusters in the Micromegas detectors of the NSW of the ATLAS experiment.

Z-mass precision measurement analysis

The INPP_ATLAS group has started analysis on the Z-mass precision measurement. This is actually part of the PhD thesis work of Olga Zormpa. Recent

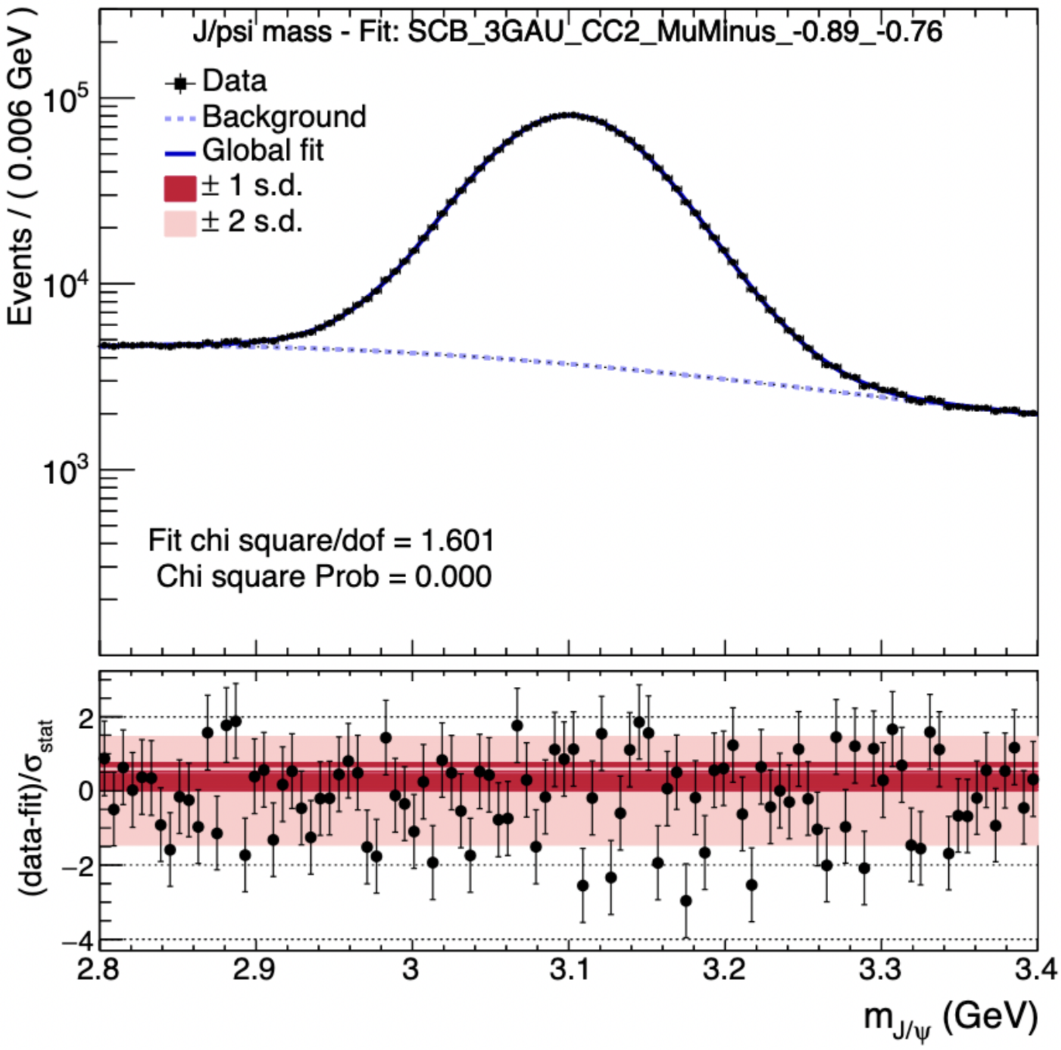

Figure 8: Example of Background fit in the Invariant Mass Distribution of J/psi. The data used were the ones from 2016 and the eta region is [-0.89,-0.76].

measurements from Fermilab on W-mass has revealed significant tension with the Standard Model EW fit of the order of 7σ. The current Z-mass measurement precision is dominated by the LEP result which has an impressive precision of 2.1 MeV. The combined result of all four LEP experiments is dominated by the LEP energy calibration and constitutes a common systematic error. Our group concentrates on the J/Ψ peak calibration using dimuon events. The analysis is based on low pile-up events as it was the W-mass measurement analysis in ATLAS.

Our group initially focused on estimating background contributions at the J/psi resonance, a critical component in the muon momentum calibration process. To achieve this, we explored a variety of Probability Density Functions (PDFs) to construct a model capable of accurately characterizing the J/psi invariant mass distribution. The chosen model combines a Crystal Ball function and three Gaussian distributions to represent the signal, while a second-degree Chebychev polynomial function effectively models the background. We obtained our results by segmenting eta into smaller regions. A representative fitting model for a specific region is illustrated in the following.Figure 8 .

Another study the group conducted, aimed to investigate the potential impact of geometric configurations on the invariant mass distribution of J/psi particle decays. Specifically, we analyzed whether swapping the detection eta regions for mu+ and mu- (changing mu+ from region B to region A and mu- from region A to region B) has any significant effect on the observed invariant mass distribution. This analysis provided valuable insights into whether the spatial configuration of the detectors plays a role in the observed mass distribution of the J/psi particle. Our findings contributed to a better understanding of the calibration and alignment of the muon detection system. This study commenced at the end of 2022, so results will be presented in next year's annual report.

ATLAS Publications and Internal Notes

The INPP_ATLAS members are included in 43 ATLAS papers that were published in peer review magazines in 2022. The citation index is 14.3. Full list of these papers is given in the Appendices.

It is worth to notice that three papers related to the NSW upgrade were under preparation during 2022, of which the one, related to the electronics, was submitted for publication. By the time of writing this paper is published in JINST. Also, we have published the repeaters work, initially in an internal note and finally - going through refereeing in ATLAS - as an ATLAS public Note:

- **ATLAS Public Note**: ATL-MUON-PUB-2022-003, T. Geralis et al. "The Serial and the LVDS signal repeaters for the ATLAS New Small Wheel sTGC Trigger".
- **Publication**: "The New Small Wheel electronics", 2023 JINST 18 P05012.

Funding

Some equipment and personnel (PhD) was funded by the DeTANet infrastructures program with an amount of about 50 kEuros for the ATLAS group for the period Feb. 2019 to Feb. 2023, Table 10. The main support came from the ATLAS NSW project which provided support for 2 FTEs for the whole of 2022.

Table 10: Funding through the infrastructures DeTANet program

Prog. ID	Title	Host Institution	Principal Investigator	Starting date	Finishing date	Budget (€)
12312	DeTANet	INPP	T. Geralis	10/02/2019	10/02/2023	125,962.67

Outreach

Researchers from our group provided guided tours to pupils from Greek schools and individuals at the CERN premises. We participated also in the 2nd Puzzle

Festival 2022 in Kastelorizo, Greece. We have organized an live connection from the Accelerator complex at CERN with Kastelorizo. The pupils had the chance to be guided through all Accelerators Control centers (PS, SPS, LHC) and the cryogenic systems.

Overview

In 2022 the ATLAS continued its strong presence and activities with high impact within the collaboration. The main activities are summarized below:

- Commissioning of the sTGC trigger in the ATLAS cavern. Validating all components before integration in ATLAS.
- Major contribution to the Muon and NSW activities
- NSW Trigger integration, with the inclusion of the Pad Trigger in a first approach NSW monitor trigger.
- Participation in the Z-mass precision measurement analysis.
- Completing the sTGC Gif++ irradiation studies.

Responsibilities

The members of the ATLAS Demokritos group have gradually undertaken important responsibilities, given the short time we participate as full members in the ATLAS Collaboration. Below we give a list of all responsibilities and participation in important bodies within ATLAS:

G. Stavropoulos: ATLAS Muon Software Coordinator, which is a major responsibility and achievement for our group.

G. Stavropoulos: Member of the Muon Steering group.

T. Geralis: NSW Trigger Coordinator

T. Geralis: Member of the NSW Steering Group

T. Geralis: Member of the Muon subdetector Institutes Board

T. Geralis: Member of the NSW Electronics Coordination Group

Presentations in the ATLAS internal meeting in 2022

Presentations: The members of the INPP ATLAS group have been organizing internal ATLAS meetings in the frame of their responsibilities, mainly within NSW but also the Muon community. Members of the group account for more than 120 presentations in 2022, in thematic meetings, in the Muon Weeks, in the parallel but also in plenary sessions.

High Energy Experimental Physics - CMS

Researchers:	G.Anagnostou
	G.Daskalakis
	A.Kyriakis
	D.Loukas
PhD students:	P.Assiouras
	A. Papadopoulos
	A.Stakia
Diploma students:	D.Papafilippou
Engineers:	I. Kazas (ELE)

Introduction

In 2022 the LHC started the Run-III by collecting physics collisions at $\sqrt{s} = 13.6$ TeV. During the 2022 physics run 42.0 fb^{-1} were delivered to CMS. The INPP CMS group continued the preparation of components and modules for the Phase II upgrade of the CMS in the HL-LHC, in parallel with the physics analysis program and maintenance of the CMS apparatus.

The physics program to the CMS-INPP during 2022 was mainly focused on the analysis of the full the Run-II dataset (2016, 2017, and 2018) that is now receiving the Ultra Legacy corrections for the various subsystems reaching the best possible understanding of the differences between MC and real data. These are the best possible data for physics searches and precision measurements of the Standard Model.

The INPP CMS group joint the CMS Tracker in 2015. The activities of the group were focused on the development of the Outer Tracker and especially on the silicon sensors. The group developed the necessary instrumentation and acquired the status of one among four international centers for the qualification of silicon sensor production provided by Hamamatsu Photonics in Japan. Associated with this activity is an under way program of irradiation studies with ^{60}Co-γ source. Gradually the group extended its activities to the Inner Tracker by assuming the responsibility for the development of firmware and middleware for the readout ASIC of the pixel detector.

Activities

Physics Analysis

The CMS-INPP data analysis group main goal is the deeper understanding of processes and mechanisms described by the Standard Model (SM) of particle physics and the quest for new symmetries and/or new matter in nature. To fulfill that goal the group has developed a twofold strategy: performs SM measurements and at the same time searches for specific topologies that might reveal the existence of supersymmetry or dark matter at LHC. Starting with the SM measurements, the objective is to enhance the experience of the team, gained over the past few years based on measurements in the electroweak sector of SM, by investing in studies in the field of top-quarks physics. The data from proton-proton (pp) collisions produced at the CERN LHC provide an excellent environment to investigate properties of the top quark, in the context of its production and decay, with unprecedented precision. Specifically, the measurements of the W boson helicity fractions in top quark decays, are very sensitive to the Wtb vertex structure. The comparison of the measured W helicity fractions with those estimated from the theory might reveal possible discrepancies from the SM predictions and contribute to a deeper understanding of the underlying physics processes. After the Higgs boson discovery, many theorists argue that a heavy top partner could explain the scale of the Higgs boson mass via loop cancellations. As such, an important extension of the measurements in the top-quark sector of the SM, will be a search for heavy top partners, exploring the $pp \rightarrow T^{'}T^{'} \rightarrow bbWW$ process. A new method was motivated/inspired from CMS-INPP analysis team as a new/different way to search for anything decaying like dilepton top-pairs.

CMS Analysis Note: CMS AN-2020/205

Top Physics, G. Daskalakis, A.Stakia

The study of the properties of the top quark is one of the major goals of the LHC proton-proton Collider program at CERN. The large data sample accumulated by the CMS experiment during Run II data taking, provides a unique opportunity to investigate many properties of the top quark, including the helicity of the Wbosons produced in the top-quark decays. The Wboson from the top decay can be produced with helicity 0, +1, -1, with corresponding partial widths Γ_0, Γ_{L} and Γ_{R}. The fractions of the three possible helicity states, are denoted as longitudinal (F_0), left-handed (F_{L}), and right-handed (F_{R}) and are defined as the partial width for a given helicity state divided by the total width ($\mathrm{F}_{0,\mathrm{L,R}} = \Gamma_{0,\mathrm{L,R}}/\Gamma$). The right-handed W^{+}bosons or left-handed W^{-}bosons are strongly suppressed by the V-A nature of the weak charged-current interaction of the top quark decays, as described by the standard model (SM).

For a value of top-quark mass m_{top}= 172.8±1.3 GeV and m_W= 80.399±0.023 GeV, the expected SM values are

$$\mathrm{F}_0 = 0.687 \pm 0.005 \qquad \mathrm{F}_{\mathrm{L}} = 0.311 \pm 0.005 \qquad \mathrm{F}_{\mathrm{R}} = 0.0017 \pm 0.0001 \tag{1}$$

at next-to-next-to-leading order (NNLO) in QCD, including electroweak effects. Possible deviations from the SM expectations would be an evidence of physics beyond the SM, indicating either violation of the expected V-A structure of the tWb vertex (anomalous couplings) or the presence of non-SM events in the $t\bar{t}$ candidate sample.

We perform the measurement of the W boson helicities using a sample of pp collisions which corresponds to an integrate luminosity of 138 fb^{-1}, collected at $\sqrt{s}$ = 13 TeV. Selected events contain only one lepton (electron or muon) and at least two reconstructed b-jets fulfilling the selection criteria. Three regions based on the jet/b-jet multiplicities were defined to improve the sensitivity. A binned maximum-likelihood fit is performed on the invariant mass of the lepton, b-jet pair in the defined regions, in order to extract simultaneously the $t\bar{t}$ production cross section and the F_0 and F_L helicity fractions. The full list of systematic uncertainties has been implemented for all data taking years (2016, 2017, and 2018). An example of the expected impact plot for the F_0parameter of interest using the 2017 dataset is shown in Fig. 9.

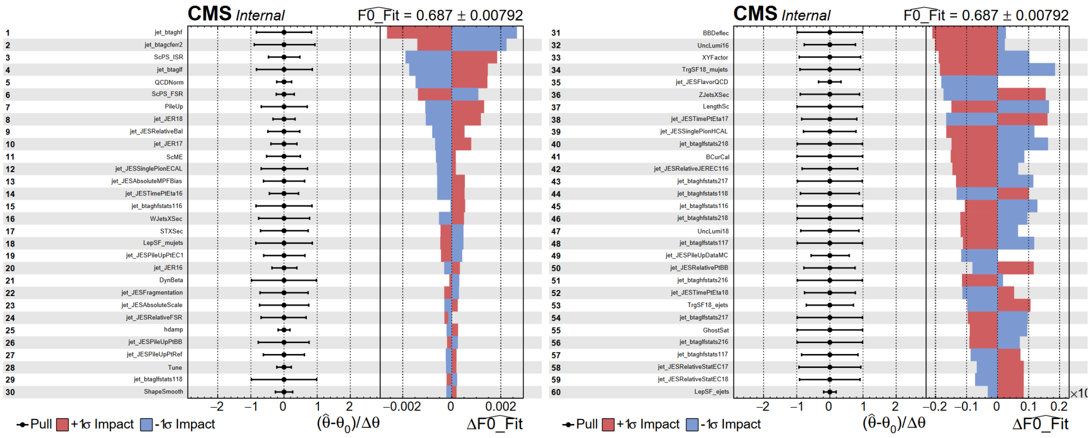

Figure 9: Expected impact plot for the F_0 parameter of interest using the 2017 dataset. The plot shows the 60 most important nuisance parameters out of 90 that have been included.

CMS Analysis Note: CMS AN-2017/343

Beyond Two Generations Physics, G. Anagnostou, A. Hadjiagapiou

The analysis of the Run2 data is continuing for the search $pp \to T'T' \to W'bW'b$ in the in the dilepton final state using pp collision data recorded by the CMS detector during 2016-17-18. The analysis is based on a two-dimensional mass reconstruction of the $T'T'$ system. The analytic solutions together with constraints from the parton distribution functions (PDFs) are used to reconstruct the masses of two unknown particles simultaneously. The two-dimensional mass reconstruction is then used to search for anything decaying like dilepton top pairs.

The analysis is now based on a new version of analysis software and its use has been tested the last period. The reconstruction of the system with two invisible particles is based on a generic method applicable to proton-proton colliders developed at INPP and applied for the first time in a running experiment such as CMS, at Run1 and currently at Run2. Other topologies have been considered, such as ttH, $H \to b\bar{b}$ in their dilepton top decays and this CMS analysis is currently using for its reconstruction the same method. The B2G (Beyond 2 Generations) physics group is interested in asymmetric topologies, a question that is currently under study.

Institutional Reviews, Committees

Analysis Review Committees (ARC):

Georgios Daskalakis was the chairman of the ARC for the publications:
EXO-19-017: ‘Search for new physics in lepton plus MET final state‘
EXO-21-009: ‘Search for new physics in the tau + MET final state (full Run 2)‘

Institutional Reviews:
"WW DPS with full Run2", CMS Collaboration, CMS Paper SMP-21-013

References for Published CMS Physics Papers in 2022

Process Quality Control(PQC) activities

P. Assiouras, I. Kazas, A. Kyriakis, D. Loukas

CMS Tracker collaboration follows a dedicated quality assurance plan in order to ensure that the characteristics of the new sensors that will be installed in the Outer Tracker of the HL-LHC meet the design specifications. The wafer layout for CMS tracker PS-s, 2S and PSp sensors includes test structures for measurements using manual probes and dedicated test structures that are arranged around an array of 20 contact pads that are equally spaced horizontally and vertically. This array of contact pads is called ”flute” and it allows automated measurements to be made, by using a 20-needle probe card and a switching matrix (Fig 10).

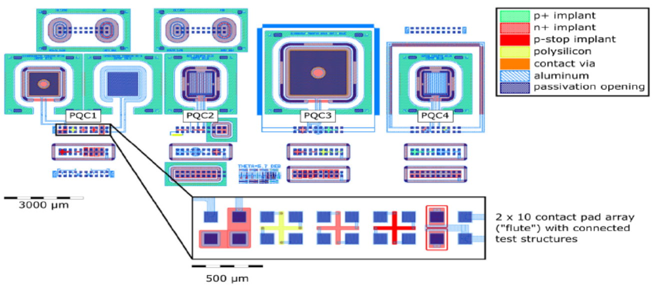

Figure 10: Schematic of the four different flutes that exist in each test structure set. They are separated in quick flutes allowing a fast evaluation of most important parameters and extended flutes that provide addition parameters for the quality control of the sensors. The color variation depicts the different materials and implantation with which the wafers are constructed

The test structures include among others a quarter-sized diode ($1.25mm \times 1.25mm$), from which the full depletion voltage and substrate resistivity are measured, a quarter-sized MOS capacitor ($1.29mm \times 1.29mm$) for flat band voltage and fixed oxide charge concentration measurements, capacitors to evaluate the thickness of the dielectric, Van der Pauw crosses [6] to measure the sheet resistances of polysilicon, n+ implant and p-stop, and a field-effect transistor to assess the inter-channel properties. Metal-oxide-semiconductor (MOS) capacitor is one of the most useful device in the study of the properties of the $Si - SiO_2$ interface. It consists of a SiO_2 layer sandwiched between a semiconductor bulk and a metal gate electrode.

An important parameter in the study of the MOS capacitor is the flat band voltage (V_{fb}). The flat band voltage corresponds to the voltage that when applied to the gate electrode the energy bands (E_c and E_v) of the substrate are flat at the Si/SiO_2 interface. If there is no charge present in the oxide or at the oxide-semiconductor interface, the V_{fb} simply equals the difference between the gate metal work function, ϕ_m and the semiconductor work function, ϕ_s (V_{fb} = ϕ_m - ϕ_s), which in an ideal case is zero (V_{fb} = 0). The presence of fixed oxide charges shifts the V_{fb} and this shift can be used to determine the fixed oxide charge concentration N_{ox}. Fig 11 shows the measured value of V_{fb} as a function of MOS the batch number from all the laboratories involved in the PQC activities. Our laboratory (*Demokritos*) measurement are shown with purple color.

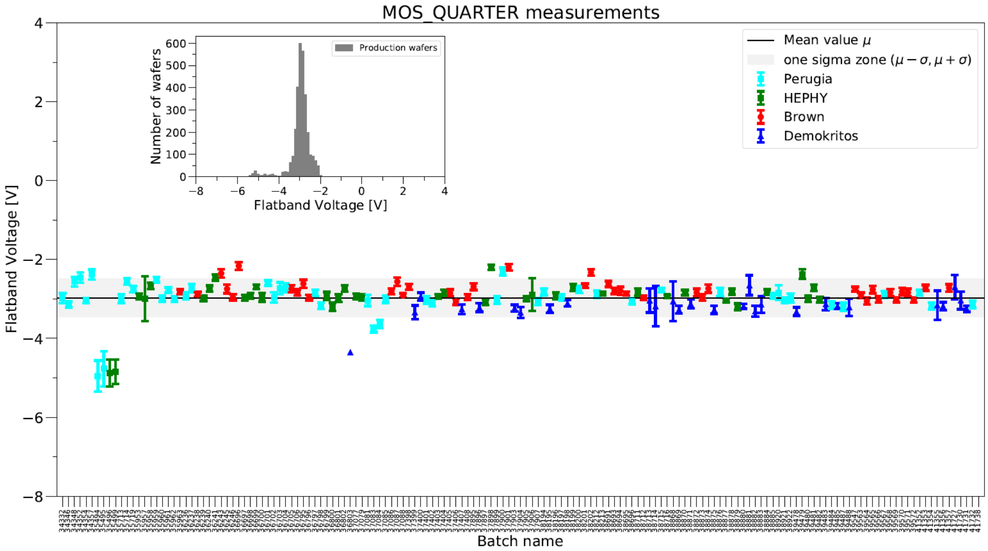

Figure 11: Average value of the flatland voltage for several batches. The color variation depicts measurements performed at different PQC centers: at *Demokritos* (depicted in purble), at *INFNPerugia* (depicted in cyan), at *Brown* (depicted in red) and at *HEPHY* (depicted in green). The black line is the mean value of all batches and the light gray shaded area is the one sigma deviation. Inside a histogram of the flat bland voltage is presented.

Irradiation studies on test structures

P. Assiouras, A. Kyriakis, I. Kazas, D. Loukas

During 2022, irradiation studies on test structures with gamma photons from a Co^{60} source were performed, complementary to already performed X-ray and particle irradiation studies. These test structures contain among others gate controlled diodes (GCD), field effect transistors (FET), metal oxide semiconductor capacitors (MOS) and Van der Pauw structures (VDP), that are fabricated in the same wafer as the main sensor. Finally TCAD simulations for the GCD structures are presented for comparison.

MOS, GCD, FET and VDP structures were irradiated with Co^{60} - γ photons from a 9.86 TBq source. The total absorbed dose obtained in several steps was of the order of 40kGy. The level of the radiation-induced charge in the test structures was determined from the shift of the flat band voltage in the MOS after irradiation. The flat-band voltage saturates at -35 V. In the GCD an increase to the surface current due to radiation induced defects in the interface was observed after about 40 kGy. In MOSFET a cancellation effect of the negative threshold voltage shift is observed which is caused from the accumulation of negative interface traps in the oxide. The threshold voltage is closely related to the strip isolation quality of the sensor and this indicates that the inter-strip isolation quality is not strongly affected by the exposure of γ photons of higher doses. The measurements were compared with the results of TCAD simulations based on a modified version of the Perugia surface model 2019, which takes into account ionizing radiation damage effects which result in the increase of both trapped oxide charge and interface traps. The model describes quiet well our experimental measurements of the GCD structures and reproduce the radiation-induced increase of the surface current Fig. 12.

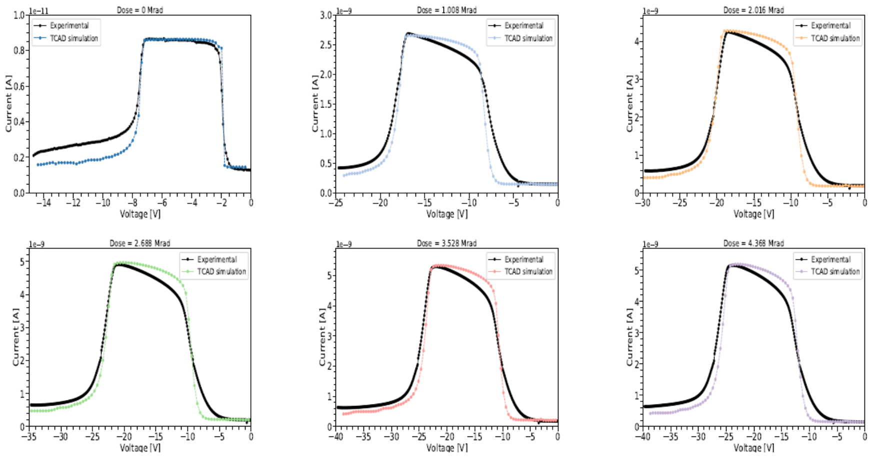

Figure 12: Experimental and TCAD simulated IV curves for a GCD structures for various Co^{60} irradiation doses. The model describes quiet well our experimental measurements of the GCD structures and reproduce the radiation-induced increase of the surface current

Funding

Outreach

The Institute of Nuclear and Particle physics has been promoting science to the public with several activities such as:

Summer School

The demokritos summer school is organized for more than fifty years, for students of all greek universities. Live lectures, invited researchers from universities abroad, laboratory visits, meetings with Demokritos researchers, but also special topics, round tables to introduce the participating students and graduates to positive and technological research.

The 58th summer school was organised by all five institutes demokritos institutes. The school took place from 15 to 22 July 2023 at the Demokritos campus. Each day was dedicated to the research topics of one of the institutes.

The first day (15 July) was dedicated to the INPP topics with presentations concerning neutrino, LHC, nuclear physics, cosmology as well as applied science such as cultural heritage research. There was also an invited talk by S.Trahanas concerning the foundations of quantum mechanics which was very popular among the hundred of attendant students.

Open Days

INPP researchers are involved in developing and delivering popularized science lectures to public or school audiences.

Also presentations and lectures and guiding tours are being given to schools visiting Demokritos and its facilities (among them INPP and the Tandem accelerator) with a few hundred visitors each year.

Physics Masterclass

The international particle physics masterclasses are workshops organized by the International Particle Physics Outreach Group (IPPOG). The Masterclasses take place in more than fifty countries all over the world. This year, the particle physics masterclass in Demokritos had 45 partcipant students from 10 high schools.

During the day, high school students have the opportunity to work together with researchers in high energy physics and analyze particle physics data from the Large Hadron Collider (LHC). Initially, the students attend presentations for particle physics theory, accelerators, detectors and cosmology. Then, in the second part of the masterclass, the students are trained to analyze events from CMS experiment and “discover” by themselves the Higgs Boson. Finally, a teleconference takes place with other high schools around the world participating in the masterclass at the same day. During the conference, the students present and discuss their results and familiarize themselves with the international/multicultural tradition of research in fundamental physics.

Theoretical High Energy Physics

Coordinator:	C .G. Papadopoulos
Researchers:	M. Axenides C. G. Papadopoulos G. Savvidy (Emeritus)
Adjunct Scientists:	E. Floratos S. Nicolis
Research Associates:	G. Bevilacqua K. Savvidy K. Filippas S. Konitopoulos, G. Pastras
PhD students:	N. Syrrakos D. Canko
Master students:	V. Karydis M. Ioannou
Diploma students:	V. Tzotzai
Practical work students:	V. Tzotzai

Introduction

The mission of the Theoretical High Energy Physics group is to conduct world-class research in the areas of Quantum Field Theory, Scattering Amplitudes and Particle Physics Phenomenology, String Theory and Quantum Gravity, Non-linear Chaotic Dynamics and Complex Systems and Cosmology. The group has a world-wide network of collaborating scientists and participates in individual and multi-partner projects funded by national and international research organizations. The training of young researchers from the undergraduate to the postdoctoral level is a significant and systematically pursued activity of the group.

Activities

High Energy Physics - Phenomenology

The research on High Energy Physics - Phenomenology aims to develop innovative methods and algorithms in order to establish an efficient framework for higher order corrections for multi-particle processes including

- amplitude reduction at the integrand level beyond one-loop,

- the evaluation of multi-loop Master Integrals and
- the application of the above-mentioned techniques to scattering processes at the LHC and beyond.

On the frontier of multi-loop calculations, the group achieved a major milestone, by completing the analytic representation of all mass-less hexabox (nonplanar) five-point amplitudes with one off-shell leg [1]. For the first of the three hexabox families, our result is unique world-wide. The methodology used is based upon the Simplified Differential Equations Approach (SDE) [2]. The SDE method has been also successfully applied to planar three-loop $2 \to 2$ scattering amplitudes [3]. On the frontier of two-loop scattering amplitudes, we have studied the reduction of two-loop amplitudes at the integrand level, as part of the newly developed software package HELAC-2LOOP [4]. All the above-mentioned work is essential to obtain high-precision predictions for scattering processes at the LHC, especially for the forthcoming high-luminosity Run as well as for future colliders [5]. G. Bevilacqua and collaborators studied the top quark pair production in association with two additional jets, $pp \to t\bar{t}j_1j_2$, based on HELAC-NLO [6]. They also contributed to the Snowmass report [7] with a study of modelling uncertainties of $t\bar{t}W^{\pm}$ production with multilepton signatures at the LHC. C. G. Papadopoulos participated with invited talk to Loops and Legs 2022, 25-30/4/2022, Ettal, Germany, and in Gearing up for High-Precision LHC Physics, 15-26/8/2022, MIAPbP, Munich, Germany and D. Canko in Hard Processes at the LHC (HP2 2022) 20th-22th September 2022 hosted by the IPPP, University of Durham, UK. C. G. Papadopoulos participated remotely to the workshop Precision calculations for future e^+e^- colliders: targets and tools, CERN, 7-17 June, 2022. C. G. Papadopoulos served as a member of the International Advisory Committee of the Workshop on the Standard Model and Beyond August 28 - September 8, 2022, Corfu Summer Institute, Corfu, Greece. During 2022, N. Syrrakos has successfully completed their PhD thesis [8].

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[2] Costas G. Papadopoulos. "Simplified differential equations approach for Master Integrals". In: *JHEP* 07 (2014), p. 088. DOI: 10.1007/JHEP07(2014)088. arXiv: 1401.6057 [hep-ph]

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[5] A. Blondel et al. "Standard model theory for the FCC-ee Tera-Z stage". In: *Mini Workshop on Precision EW and QCD Calculations for the FCC Studies : Methods and Techniques*. Vol. 3/2019. CERN Yellow Reports: Monographs. Geneva: CERN, Sept. 2018. DOI: 10.23731/CYRM-2019-003. arXiv: 1809.01830 [hep-ph]

[6] Giuseppe Bevilacqua et al. "Study of additional jet activity in top quark pair production and decay at the LHC". in: *Phys. Rev. D* 107.11 (2023), p. 114027. DOI: 10.1103/PhysRevD.107.114027. arXiv: 2212.04722 [hep-ph]

[7] K. Agashe et al. "Report of the Topical Group on Top quark physics and heavy flavor production for Snowmass 2021". In: (Sept. 2022). Ed. by Reinhard Schwienhorst and Doreen Wackeroth. arXiv: 2209.11267 [hep-ph]

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Small Scale Structure of Spacetime, Black Holes and Q.Entanglement

The Small Scale Structure of Spacetime (SSSS) project explores the possibility of a discrete spacetime structure in the presence of Strong Gravity. It is induced at the near horizon geometry of black holes and accounts for the finite Bekenstein-Hawking finite Entropy. In a series of papers We have proposed a specific modular finite quantum mechanical model for the Ads_2 near horizon geometry of extremal black holes [9]. The model is holographic and exhibits desirable properties at the Planck scale such as nonlocality and fast scrambling (chaotic mixing). More importantly we have shown that it exhibits a continuum limit [10].

Entanglement in Quantum Field Theory - EQFT-

The HFRI-funded project -HAPPEN-on Hollographic APPlications of ENtanglement http://happen.inp.demokritos.gr/ was successfully completed in the first half of 2022. The study of Quantum Entanglement in Field theories is important both in the physics of Quantum Information processing of Black Holes and in the early Universe cosmology where the work of Dr Pastras focussed his attention [11].

Fundamental Interactions, QCD Vacuum and Cosmology

The research in the field of Fundamental Interactions, QCD Vacuum and Cosmology aims to investigate the influence of quantum vacuum fluctuations of the gauge fields on the evolution history of the Universe and to uncover the internal mechanisms of the Inflation. We derive the quantum energy-momentum tensor and the corresponding quantum equation of state for gauge field theory using the effective Lagrangian approach. The vacuum energy-momentum tensor has a term proportional to the space-time metric and provides a finite non-diverging contribution o the effective cosmological term. This allows to investigate the influence of the gauge field theory vacuum polarisation on the evolution of Friedmann cosmology, inflation and primordial gravitational waves. The Type I-IV solutions of the Friedmann equations induced by the gauge field theory vacuum polarisation provide an alternative inflationary mechanism and a possibility for late-time acceleration. The Type II solution of the Friedmann equations generates the initial exponential expansion of the universe of finite duration and the Type IV solution demonstrates late-time acceleration. The solutions fulfil the necessary conditions

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[10] Minos Axenides, Emmanuel Floratos, and Stam Nicolis. "The arithmetic geometry of AdS_2 and its continuum limit". In: *SIGMA* 17 (2021), p. 004. DOI: 10.3842/SIGMA.2021.004. arXiv: 1908.06641 [hep-th]; Minos Axenides, Emmanuel G. Floratos, and Stam Nicolis. "The continuum limit of the modular discretization of AdS_2". In: *PoS* CORFU2021 (2022), p. 243. DOI: 10.22323/1.406.0243. arXiv: 2205.03637 [hep-th]

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for the amplification of primordial gravitational waves [12]. We give a general review on the application of Ergodic theory to the investigation of the dynamics of the Fundamental Interactions. We investigated the chaotic properties of the Yang-Mills gauge fields and of the self-gravitating N-body systems. As well as we developed the application of the maximally chaotic dynamics systems to the generation of high-quality random numbers, the so called MIXMAX random number generator for the advanced Monte Carlo simulations in High Energy Physics. We also investigated the stability of the fluid dynamics on a sphere that allows to estimate the time scale of the weather forecast [13]. In ergodic theory the maximally chaotic dynamical systems (MCDS) can be defined as dynamical systems that have nonzero Kolmogorov entropy. The hyperbolic dynamical systems that fulfil the Anosov C-condition belong to the MCDS insofar as they have exponential instability of their phase trajectories and positive Kolmogorov entropy. It follows that the C-condition defines a rich class of MCDS that span over an open set in the space of all dynamical systems. The large class of Anosov-Kolmogorov MCDS is realised on Riemannian manifolds of negative sectional curvatures and on high-dimensional tori. The interest in MCDS is rooted in the attempts to understand the relaxation phenomena, the foundations of the statistical mechanics, the appearance of turbulence in fluid dynamics, the non-linear dynamics of Yang-Mills field and gravitating N-body systems as well as black hole thermodynamics [14]. The results of the group were presented in the international conferences and workshops.

Funding

In Table 11 the ongoing funding of the group during 2022 is presented.

Outreach & Teaching

The group offers courses in quantum field theory for graduate and undergraduate students jointly from NTUA and NCSR-Demokritos, training of graduate students for advanced degrees. Seminars and lectures in summer schools organized by Demokritos for university undergraduate students. One such example is the National Network for the study of Complex Systems and Applications (COSA-Net), It was established on 2006 with a decision of the Demokritos Board of Directors as an inter-institute activity in Demokritos covering research and training on the

[12] George Savvidy. "Gauge field theory vacuum and cosmological inflation without scalar field". In: *Annals Phys.* 436 (2022), p. 168681. DOI: 10.1016/j.aop.2021.168681. arXiv: 2109.02162 [hep-th]; George Savvidy. "Gauge Field Theory Vacuum and Cosmological Inflation". In: *21st Hellenic School and Workshops on Elementary Particle Physics and Gravity*. Apr. 2022. arXiv: 2204.08933 [hep-th]; Georgios Savvidy. "Gauge Field Theory Vacuum and Cosmological Inflation". In: *PoS* CORFU2021 (2022), p. 123. DOI: 10.22323/1.406.0123

[13] George Savvidy. "Maximally chaotic dynamical systems of Anosov–Kolmogorov and fundamental interactions". In: *Int. J. Mod. Phys. A* 37.09 (2022), p. 2230001. DOI: 10.1142/S0217751X22300010. arXiv: 2202.09846 [hep-th]

[14] George Savvidy. "Maximally chaotic dynamical systems of Anosov–Kolmogorov and fundamental interactions". In: *Int. J. Mod. Phys. A* 37.09 (2022), p. 2230001. DOI: 10.1142/S0217751X22300010. arXiv: 2202.09846 [hep-th]

Table 11: Funding of the Theory Group

Prog. ID	Title	Host Institution	Principal Investigator	Starting date	Finishing date	Budget (€)
	HFRI: Two-loop Amplitude Calculations Based on Integrand Reduction	NKUA	C. G. Papadopoulos, D Canko	2019	2022	32,400
E-12390	Operational Program Human Resources Development, Education and Lifelong Learning 2014-2020 in the context of the project 'Higher order corrections in QCD with applications to High Energy experiments at LHC'	INPP	C. G. Papadopoulos	2020	2022	37,000
E-12386	Operational Program Human Resources Development, Education and Lifelong Learning 2014-2020 in the context of the project "Chaotic dynamics and black holes in BMN theory" (MIS 5047794)	INPP	E. Floratos, M. Axenides	2020	2022	45,500
E-12538	High Order Calculations and Tools for High Energy Colliders, HOCTools-II, 2nd Call for H.F.R.I. Research Projects to support Faculty Members and Researchers	INPP	C. G. Papadopoulos	2022	2025	188,000
318687	Chaotic Behavior of Closed Quantum Systems, 2nd Call for IEA-International Emerging Actions	INPP	M. Axenides	2021	2023	5,000

subject of Chaotic Dynamical Complex Systems. In addition to the research work of its members it offers seminars, a joint one semester graduate course with NTUA on the subject as well as it organizes annual summer schools on the subject area.

Overview

In 2022 the HEP-TH group continued successfully its well-recognized research program. For the coming years the plans are summarized below:

High Energy Physics Phenomenology and Computational Physics

1. Multi-loop frontier: Complete the computation of five-point two-loop Feynman Integrals with one off-shell leg. Extend the SDE method to Feynman Integrals with non-zero internal masses. Develop software package for efficient numerical evaluation of all two-loop Master Integrals with up to five external legs and up to two external masses.
2. Amplitude reduction: Study the integrand reduction at two loops, define

and optimize the integrand basis and compute the two-loop rational terms. Develop the HELAC-2LOOP package for arbitrary scattering process.

3. Physics applications: Integrate HELAC scattering amplitudes up to two-loops with available packages for radiative corrections (STRIPPER) to automate QCD NNLO corrections. Obtain theoretical predictions for $2 \to 2$ and $2 \to 3$ scattering processes. Study W, Z and Higgs production in association with jets at the LHC.

We plan to establish an efficient framework regarding common research projects with the ATLAS and CMS groups in INPP, considering the advance of LHC program in the coming years and the needs of the physics analysis of the forthcoming data.

Chaotic Lattice Field Theories

The activities of a part of our group (Axenides, Floratos and Nicolis) is following up their research on SSSS with the detailed study of coupled map Arnold cat map lattices [15], i.e. interacting manybody systems with chaotic constituents. Our scope is to obtain a deeper understanding of the conjecture that black holes are the fastest scramblers in nature by implementing nonlocality and quantum chaoticity in our specific construction and establish its quantum fast scrambling properties. We currently demonstrate its classical ergodic properties of strong and fast mixing.

Fundamental Interactions, QCD Vacuum and Cosmology

We intend to examine the phenomena of the chromomagnetic gluon condensation in the theory of strong interaction QCD and the problem of stability of the chromomagnetic vacuum fields. The apparent instability of the chromomagnetic vacuum fields is a result of quadratic approximation. The stability can be restored if the nonlinear interaction of negative/unstable modes will bee taken into account in the case of chromomagnetic vacuum fields and the interaction of the zero modes in the case of (anti)self-dual covariantly-constant vacuum fields. This approach will allow to prove the stability of the chromomagnetic vacuum condensate and will indicate that the Yang-Mills vacuum is highly degenerate quantum state.

Extended galaxy surveys revealed that at a large scale the Universe consists of matter concentrations in the form of galactic clusters, filaments and vast regions devoid of galaxies. We we are interested to investigate the generation of caustics in self-gravitating N-body system and the formation of cosmological large-scale structure due to the gravitational focusing. The gravitational caustics are space regions where the density of matter is higher than the average density in the surrounding Universe. The gravitational caustics can represent galaxies, galactic clusters and filaments and the regions between caustics, the voids.

We would like to develop a new approach to the dynamics of a self-gravitating N-body system formulating dynamics in terms of a geodesic flow on a curved Rie-

[15] Minos Axenides, Emmanuel Floratos, and Stam Nicolis. "Arnol'd cat map lattices". In: *Phys. Rev. E* 107.6 (2023), p. 064206. DOI: 10.1103/PhysRevE.107.064206. arXiv: 2208.03267 [hep-th]

mannian manifold of dimension 3N equipped by the Maupertuis's metric. The regions of negative sectional curvatures are responsible for the exponential instability of geodesic trajectories, while the regions of positive sectional curvatures are responsible for the gravitational focusing of geodesics and generation of caustics. The stability of geodesic trajectories can be analysed by means of the Jacobi equation and the gravitational focusing of geodesics by means of the Raychaundhuri equation. By solving these equations we will estimate the characteristic relaxation time scales and the time scale of generation of gravitational caustics of the cosmological large-scale structure.

HEP-TH

Considering the personnel situation, it is of paramount importance to have several new positions, at least for replacing retiring members of the group. We plan to formalize the association with INPP of scientists in our collaboration network and strengthen our links with groups from the Universities at the national level. We plan also to continue our networking activities (e.g., COST, Horizon Europe Doctoral Networks) and host individual applications for HFRI, IKY, MSCA-PF and ERC grants.

Astroparticle Physics

Astroparticle Physics

Coordinator:	Dr. Christos Markou
Researchers:	Dr. E. Tzamariudaki
	Dr. E. Drakopoulou
PhD students:	A. Sinopoulou
	D. Stavropoulos
	V. Tsourapis
	G. Zarpapis
Practical work students:	P. Broussali
	N. Plastiras
	K. Paschos
	G. Stavropoulou
	P-L. Sakkou
Employees:	C. Bagatelas
Technicians:	V. Tsagkli
	M. Axiotis

Introduction

The astroparticle physics group of the Institute of Nuclear and Particle Physics (INPP) is mainly focusing on the detection and subsequent study of neutrinos from cosmic accelerators. The study of cosmic neutrinos offers significant advantages towards answering basic questions about the origin and nature of cosmic rays. Neutrinos, being neutral, are not deflected by interstellar magnetic fields and, unlike protons, are not significantly absorbed by intervening matter. Thus, they point to their sources over all energy ranges and distance scales, and hence are uniquely valuable as cosmic messengers. In addition, the detection of astrophysical high energy neutrinos will shed light on the production mechanism of high energy gamma rays by understanding whether the sources of high energy gamma rays observed by the HESS telescope are due to electromagnetic or hadronic processes. The observation of neutrino emission from an astrophysical source, the blazar TXS 0506+056, by the IceCube Collaboration, marks the beginning of a new era in multi-messenger astronomy.

The INPP astroparticle physics group is a member of the KM3NeT collaboration. KM3NeT [16] is a distributed Research Infrastructure, member of the ESFRI Road Map that will consist of a network of neutrino telescopes in the Mediterranean Sea with user ports for Earth and Sea sciences. Once completed, the telescopes will have detector volumes between megaton and several cubic kilometers of clear sea water. Located in the depths of the Mediterranean Sea, KM3NeT will open a new window on our Universe and will contribute to the understanding of the properties of the elusive neutrino particles. The ARCA (*Astroparticle*

[16] **LOI**

Research with Cosmics in the Abyss) telescope, which is located offshore of Sicily, Italy, at a maximum depth of 3450 m, is devoted to the search for neutrinos from distant astrophysical sources, such as superenovae, gamma ray bursts or colliding stars. The ORCA (*Oscillation Research with Cosmics in the Abyss*) detector which is located 40 km offshore Toulon, France, at a depth of 2450 m, aims at studying neutrino properties through the precise measurement of neutrino oscillations exploiting neutrinos generated in the Earth's atmosphere. An artistic view of the KM3NeT detectors is shown if Figure 13.

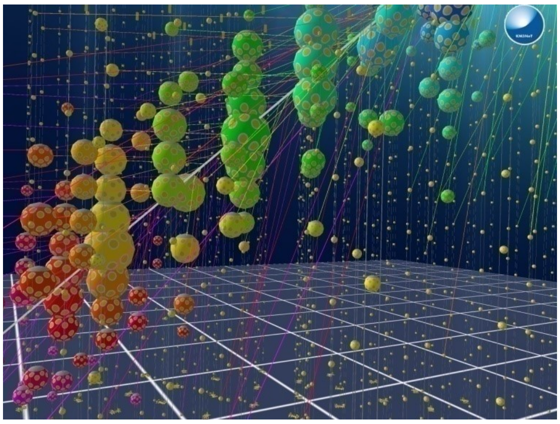


Figure 13: An artist's view of an event as it will be seen by the KM3NeT telescopes

Activities

In 2022 the group has been active in construction, testing and validation of the KM3NeT detectors and individual components, physics analyses and studies, governance and management.

KM3NeT management and governance

- Dr. C. Markou acts as the Greek-site manager and is a member of the Management Team of the experiment.
- Dr. C. Markou is also chairing the Conference committee of the experiment.
- Dr. C. Markou and Dr. E. Tzamariudaki are members of the KM3NeT Publication committee with Dr. E. Tzamariudaki co-chairing this committee.
- Dr. E. Tzamariudaki is a member of the Equality, Diversity and Inclusion committee (EDI) of KM3NeT.
- Dr. E. Drakopoulou is a member of the Open Science committee (OSC) of KM3NeT.

Physics analyses

Several group members have been active in physics analyses, focusing mainly to the analysis of the data from the first DUs of the ARCA and ORCA detectors.

The group has also made a significant contribution to the MC simulation efforts for the KM3NeT/ARCA detector and to MC simulation studies and comparisons with the data. In addition, Most of the physics analyses were carried out either in the context of Ph.D. and M.Sc. theses or refer to interim projects. These are briefly outlined below.

"Study of the Diffuse Astrophysical Neutrino Flux with the KM3NeT/ARCA Neutrino Telescope using data collected during the early stage of the construction phase"

Anna Sinopoulou, PhD Candidate

The aim of this work is to perform a study of the all-sky astrophysical diffuse neutrino flux with the data collected with 6 deployed Detection Units of the KM3NeT/ARCA detector configuration (ARCA6) corresponding to a livetime of ~101 days. The analysis initially focuses on optimizing requirements in order to isolate well reconstructed events and in addition, on finding suitable selection criteria for suppressing the background from atmospheric muons and identifying neutrino candidates. During 2022, Anna has finalised the analysis of the ARCA6 data and has extracted the sensitivity and discovery potential for a diffuse flux of astrophysical neutrinos. Anna has completed her thesis and has defended it successfully in November 2022.

The contribution from poorly reconstructed atmospheric muon events is the main source of background for this study. As neutrinos are the only particles able to penetrate the Earth, no atmospheric muons with $\cos_{\text{zenith}} < 0$ (referred to as upgoing) are expected. The number of atmospheric muon MC simulated events reconstructed as upgoing indicates the level of the remaining atmospheric muon contamination.

The requirements applied on events reconstructed as tracks aim at suppressing the atmospheric muon background, while keeping a high efficiency for neutrino induced events. Due to the small detector volume (6 DUs) loose requirements have been applied as first level selection conditions. The distributions of the cosine of the reconstructed zenith and the reconstructed energy are shown in Figures 14 and 15, respectively, for events surviving the loose selection requirements. From the MC simulation, after applying the loose selection requirements a reduction of the contribution of mis-reconstructed atmospheric muon tracks by 91% is achieved, keeping a high efficiency of well reconstructed neutrinos.

A study of the all-sky astrophysical diffuse neutrino flux, using the binned method, is attempted for the increased detector volume. For this study a blinded policy is followed using only a fraction of the available data for the analysis and the event selection. The optimization of the event selection to enhance the sensitivity and discovery potential for a diffuse astrophysical flux, is carried out entirely based on Monte Carlo simulation events. Once the analysis is completed, the full data sample is unblinded. Detailed data/MC comparisons were performed during all steps of the analysis.

In order to further reduce the atmospheric muon background, for events surviving the first level conditions, the event selection for the all-sky diffuse cosmic

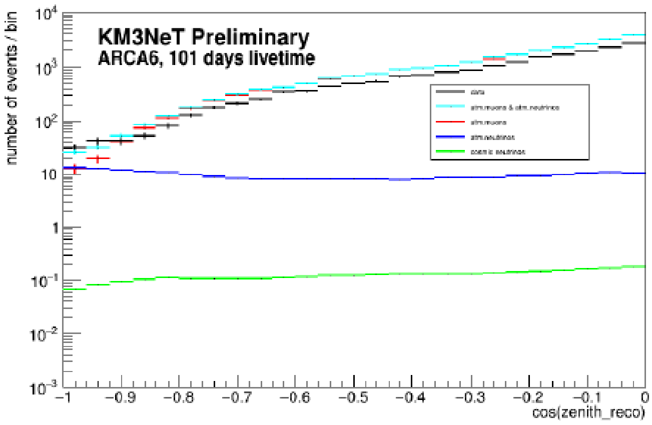


Figure 14: KM3NeT/ARCA6: Distribution of the cosine of the zenith angle for events surviving the loose selection requirements. The data (black) are compared with the MC simulation (cyan). The contribution of atmospheric muons (red), atmospheric neutrinos (blue) and astrophysical neutrinos (green) as expected by the MC simulation is also shown.

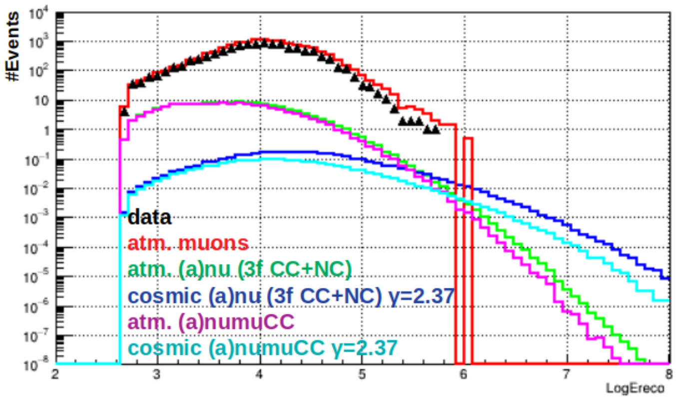
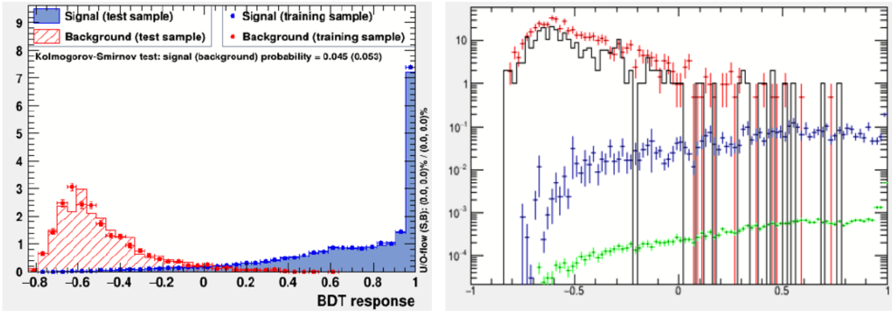


Figure 15: KM3NeT/ARCA6: Distribution of the reconstructed energy for events surviving the loose selection requirements. The data (black) are compared with the MC simulation. The contribution of atmospheric muons (red), atmospheric neutrinos (green) and astrophysical neutrinos (blue) as expected by the MC simulation is also shown.

neutrino flux was divided in two parts. The first part corresponds to the events reconstructed with energies E > 200 TeV which is referred to as "high-energy events/selection". These events are analysed with a cut and count method applying loose requirements due to the lack of statistics at high energy events while, events that do not survive the high-energy selection as well as events with a reconstructed energy E > 200 TeV (referred to as "low-energy events/selection"), are addressed using the Boosted Decision Trees (BDT) classification method. The division into high energy and low energy event samples makes it possible to keep more high energy events for which the background contribution is expected to be low. The distribution of the BDT response is shown in Figure 16 for the evaluation samples of data, atmospheric muons, atmospheric neutrinos and cosmic neutrinos. Events having BDT score ≥ 0.4 are selected. After applying this requirement, the final selection consists of $\sim$70% ($\sim$79%) cosmic (well reconstructed) neutrinos, $\sim$60% atmospheric neutrinos and $\sim$0.4% atmospheric muons comparing to the starting sample, with a corresponding improvement in the reconstruction quality after the selection.



(a) Training/Testing *(b) Evaluation*

Figure 16: Left: Distribution of the BDT score for upgoing atmospheric muon (red) and neutrino (blue) MC simulated events for the training and test samples. Right: Distribution of the BDT score for the evaluation samples for upgoing events in data (black) and MC simulated events. The contribution of atmospheric muons (red), atmospheric neutrinos (blue) and cosmic neutrinos (green) is indicated.

The sensitivity and the discovery potential was estimated for the all-sky cosmic neutrino diffuse flux as measured by the IceCube Collaboration [17] $1.44 \cdot 10^{-18} \cdot (E/100TeV)^{-2.28} GeV^{-1} cm^{-2} s^{-1} sr^{-1}$. For events surviving either the high energy selection criteria or the BDT score requirement, the value of the reconstructed energy is used to maximize the sensitivity for the cosmic neutrino flux, since due to the harder energy spectrum, cosmic neutrinos are expected to dominate at high energies. The model rejection factor (MRF) procedure based on the Feldman and Cousins upper limit estimation is applied. This method is used to select the requirement on the reconstructed energy to minimise the expected upper limit from the experiment, assuming there is no true signal present.

After unblinding the data a total yield of 284 events survived the selection conditions in data, while 118.25 atmospheric muons, 137.38 atmospheric neutrinos and 2.12 (1.21) cosmic (well-reconstructed) neutrinos were expected by MC simulations in the final sample. Comparing to the loose requirements at the first level of the event selection, a total reduction of 99.5% and 41% was achieved for the atmospheric muons and atmospheric neutrinos, respectively, with an efficiency of 80% for well reconstructed cosmic neutrinos. The reconstructed zenith is shown for tracks reconstructed as upgoing and fulfilling the final selection requirements, for the full data taking period of ARCA6 in Figure 17, for the data and for MC simulated atmospheric muons, atmospheric neutrinos and cosmic neutrinos.

The MRF is optimized for an energy cut at $\log E_{\mathrm{reco}} \geq 4.2$ yielding a sensitivity $\phi^{90\%}_{\mathrm{astro}} = 17.3 \cdot 10^{-18} GeV^{-1} cm^{-2} s^{-1} sr^{-1}$ and a discovery potential $\phi^{90\%}_{\mathrm{astro}} = 51.4 \cdot 10^{-18} GeV^{-1} cm^{-2} s^{-1} sr^{-1}$.

The results have been presented in a poster at XXX International Conference on Neutrino Physics and Astrophysics (NEUTRINO 2022) in Seoul, Korea.

[17] **ICdiffuse2019_10years**

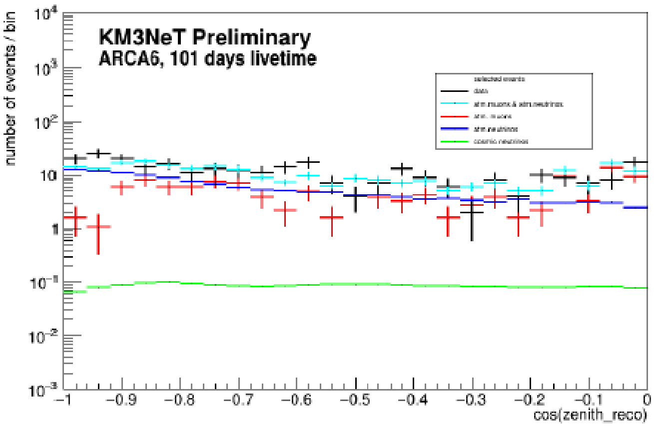
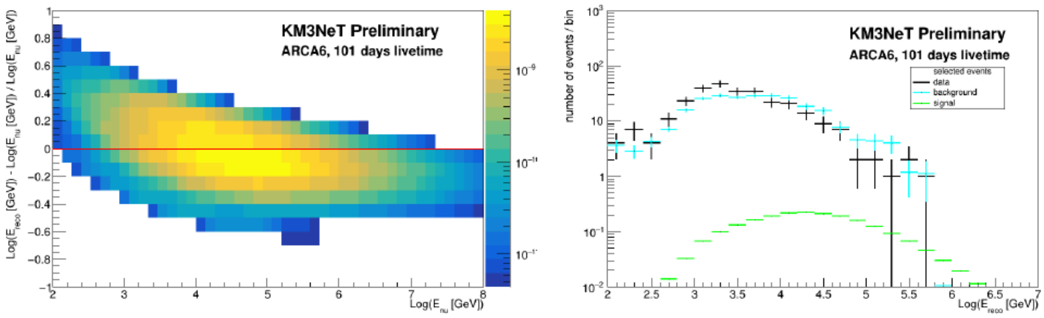


Figure 17: KM3NeT/ARCA6: Distribution of the cosine of the zenith angle for selected events. The data (black) are compared with the MC simulation (cyan). The contribution of atmospheric muons (red), atmospheric neutrinos (blue) and astrophysical neutrinos (green) as expected by the MC simulation is also shown.



(a) *(b)*

Figure 18: Difference of the reconstructed and the true neutrino energy over the true neutrino energy as a function of the neutrino energy for the final sample of cosmic neutrino MC simulation (a). Energy spectra for events surviving the final selection (b) for data (black) and MC simulated events for the background from atmospheric muons and atmospheric neutrinos (blue), and for the signal from cosmic neutrinos (green).

"Measurement of the atmospheric muon neutrino flux with the KM3NeT/ORCA6 detector"

D. Stavropoulos (Ph.D. candidate)

The goal of this work is to measure the flux of atmospheric muon neutrinos, using data collected with the 6 Detection Units of the ORCA detector, hereafter called KM3NeT/ORCA6. The measurement is performed in the energy range between 1-100 GeV. A data exposure equivalent to 555.7 days were used, collected between January 2020 and November 2021. The detector response was simulated with run-by-run MC simulated events for atmospheric muons (background) and atmospheric neutrinos (signal). The distribution of the cosine of reconstructed zenith is shown in Fig. 19, for all reconstructed events as well as for the events that survive the *anti-noise cuts*, selection criteria to reject random noise events. An additional requirement on the cosine of reconstructed zenith, accepting only events with an upward-going direction (i.e. between -1 and 0), is applied in order to reject the majority of the remaining background. The application of the anti-noise cuts along with the requirement for an upward-going reconstructed direction lead to an event pre-selection.

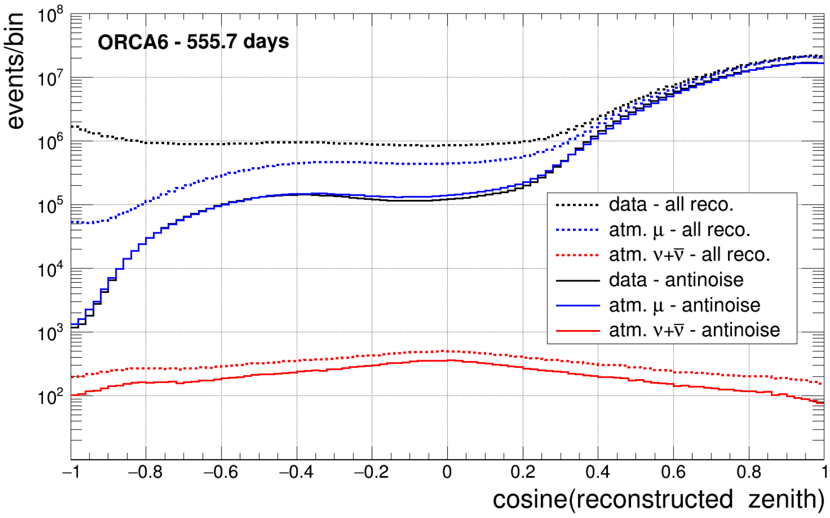


Figure 19: Distribution of reconstructed cosine zenith for data and MC simulated events before and after the application of anti-noise cuts.

Events reconstructed as upward-going that survive these anti-noise cuts are further selected using a Boosted Decision Tree (BDT) algorithm. For this, the *TMVA* software was used. Atmospheric $\nu_\mu + \bar{\nu}_\mu$ CC events are considered as signal, and atmospheric muons as background. 20 features are used for the BDT, which are related to the reconstructed event position and direction, the reconstruction quality, and the event topology considering signal-like hits and charge distributions. Indicative event variables used as BDT features are shown in Fig. 20. Dedicated MC event samples were produced to train and test the BDT algorithm.

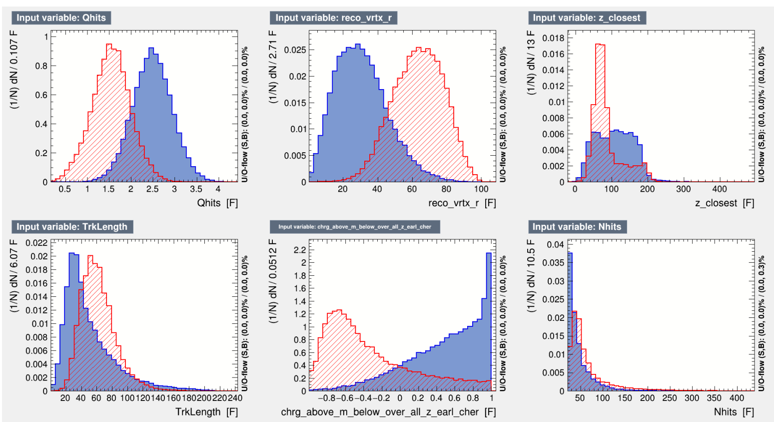


Figure 20: Indicative event variables used as BDT features. Distributions for signal are drawn with blue, while for background are drawn with red.

The phase space of the BDT parameters has been scanned in order to find an optimal parameter set. For each set of parameters, the efficiency at indicative BDT score values as well as an overtraining check were performed, using an amount of $\sim 10\%$ of the data livetime. The optimal values of the chosen set of parameters, include the number of trees set to 400, the tree maximum depth to 6, and the adaptive boost parameter set to 0.3. The BDT score distributions for data and MC simulated events satisfying the anti-noise selection criteria and reconstructed as upgoing, are shown in Fig. 21.

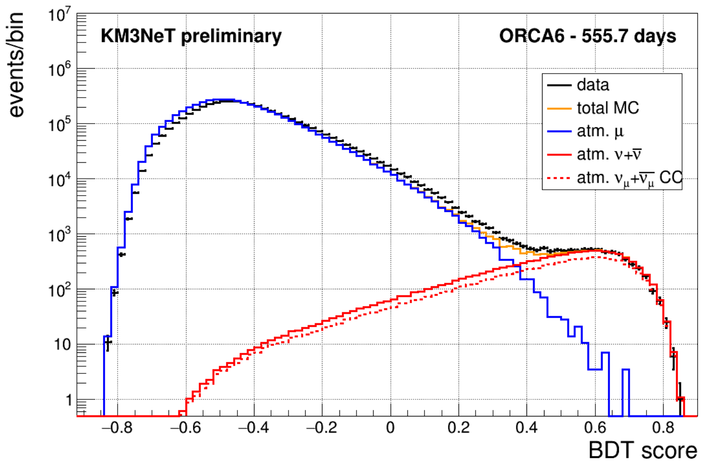


Figure 21: BDT score distributions for the upward-going ORCA6 events that survive the anti-noise criteria.

Good discrimination between the signal and background is achieved, as the former dominates at the higher score values, while the latter at the lower values. The requirement for an event to be included in the final selection is to have a BDT score greater or equal than 0.56. That leads to 4197 data events, while 4196.1 atmospheric $\nu + \bar{\nu}$ events are expected from MC simulation, from which 3214.8 are $\nu_\mu + \bar{\nu}_\mu$ CC events. The resulting contamination of atmospheric muon in the MC sample is estimated to be 28.1 events, which corresponds to 0.6% of the sample. A good agreement between data and MC simulation is obtained. The reconstructed cosine zenith distribution is presented in Fig.22, for the BDT selected events. The distribution of the radial distance between the reconstructed vertex and the barycenter of the detector is also shown in Fig.23.

A study concerning the unfolding of the energy spectrum of $\nu_\mu + \bar{\nu}_\mu$ CC events from the experimentally measured one, is ongoing using the event selection presented here.

"Development of methods and study of the neutrino flux with the KM3NeT neutrino telescope"

V. Tsourapis, Ph.D. student.

The goal of this analysis is to study the high and ultra-high energy neutrinos originating from astrophysical sources. The first goal is reached by studying the optical data that are being collected by the KM3NeTARCA telescope and the second through exploiting the method of acoustic detection.

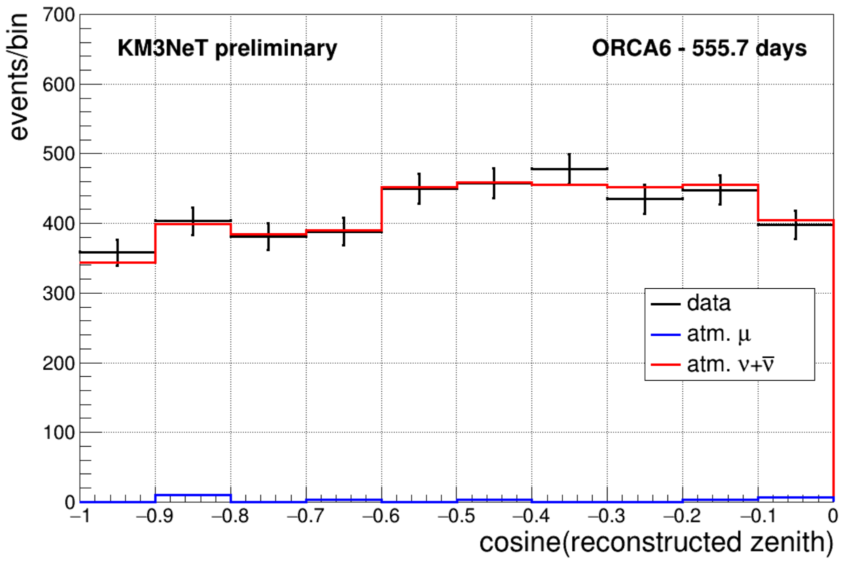


Figure 22: Distribution of reconstructed cosine zenith.

In order to ensure a good description by the Monte Carlo (MC) simulations of the variables used to select neutrino events, detailed data-MC comparisons need to be performed for all detector configurations of KM3NeTARCA under study. Vasilis carried on the work of Anna Sinopoulou and continued by making comparisons for the ARCA6 period (6 deployed Detection Units at the time). Vasilis updated the software and carried out the data-MC comparisons for the newest running period with 8 detection units (ARCA8) as shown indicatively in Figure 24 for the the number of hit DOMs and the number of trigger hits. The results of this first evaluation were presented at the Data Processing and Data Quality (DPDQ) working group meetings of KM3NeT. The quality of this data taking period was further inspected by checking the specific periods for which the quality parameters were out of bounds.

Along with the data-MC comparisons, requirements were determined in order to reject the noise coming from ^{40}K decays in the water. After the data quality was ensured, Vasilis began working on the next step of his analysis. When searching for astrophysical neutrinos, a common strategy in order to reject the atmospheric muon background is to consider only upgoing events (zenith $> 90^{\circ}$), since atmospheric muons cannot pass through the Earth. However, atmospheric muon events are present also in the sample of events selected as upgoing, as a small fraction is mis-reconstructed as upgoing. The contribution of the atmospheric muon background is illustrated in Figure 25 the cosine of the reconstructed zentith and the reconstructed energy is shown for events satisfying the loose selection criteria.

For this reason, machine learning techniques were employed in order to discriminate between badly reconstructed atm. muons and well reconstructed neutrinos. Based on the work that has already been done in the INPP Demokritos' APP group, Vasilis trained a Boosted Decision Tree (BDT) classifier. The input variables to the algorithm and the hyper-parameters were changed to be suitable for ARCA8. The results were presented at the face-to-face meeting of the Astronomy

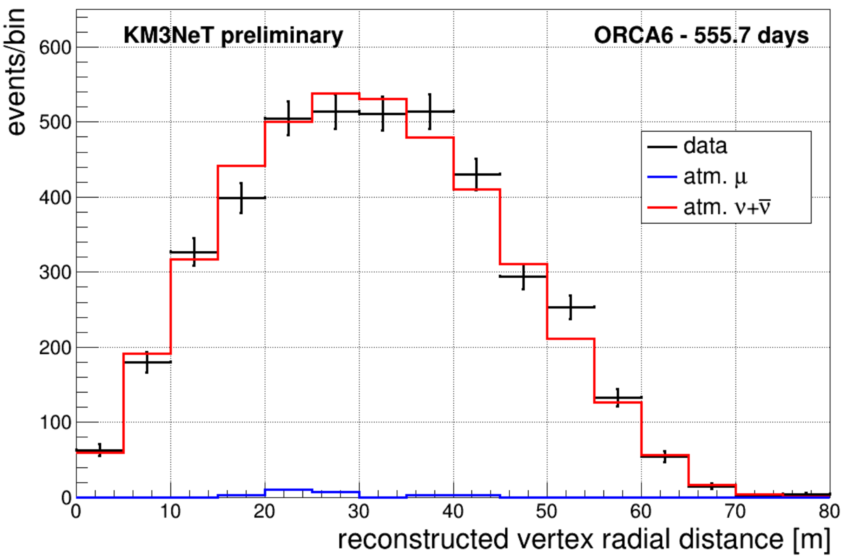


Figure 23: Distribution of the reconstructed vertex radial distance.

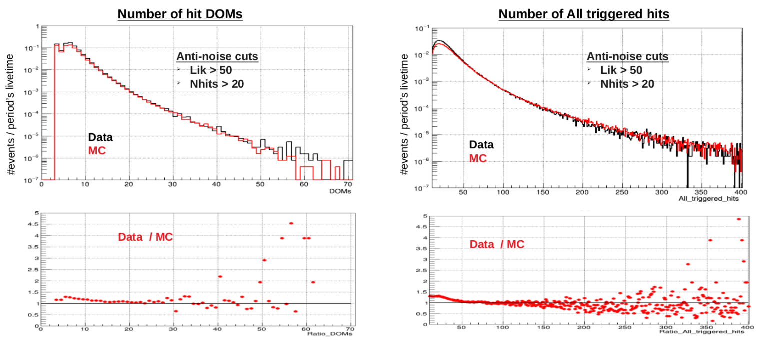


Figure 24: Distribution of the number of hit DOMs and the number of trigger hits in data (black) and atmospheric muon MC simulation for the ARCA8 data taking period.

working group of KM3NeT.

During the early phase of the detector construction, as more data are collected, there are often further developments on the reconstruction software algorithms aiming at an improvement of the description of the data by the MC simulation. For this reason, different tunings on the parameters of the atm. muon simulation (MUPAGE) have been investigated. Vasilis performed comparisons of the data and the MC simulation for the different versions and tunings, providing important input for the tunings to be used for the MC /it mass production. The production of these MC simulation samples was also performed by the APP group of the INPP. The group was also very active in the /it mass production of the MC simulation for all the KM3NeT/ARCA detector configurations.

Using the new version of the MC, Vasilis retrained the BDT. The Grid Search technique (based on a framework developed by Dimitris Stavropoulos for KM3NeTORCA) was used to select the best combination of hyper parameters. The models were sorted by considering the highest F1-score and the lowest Model Rejection Factor (MRF). Moreover, models with even or uneven number of events between the

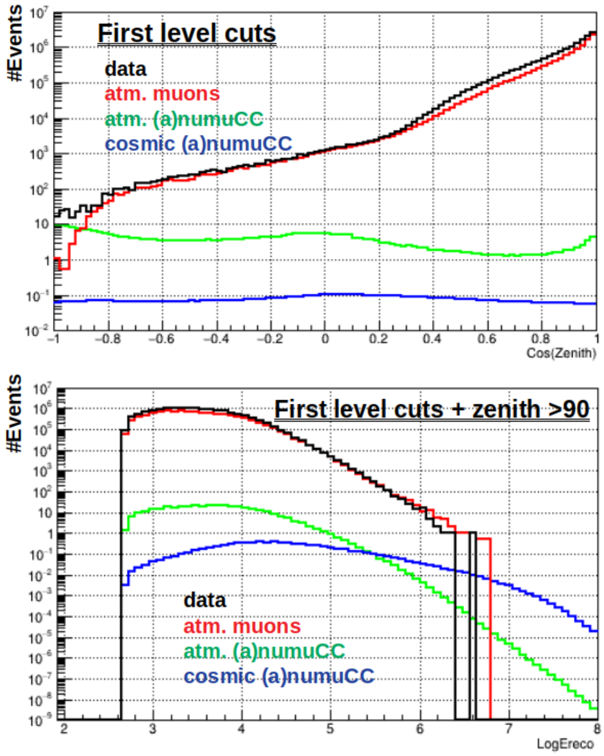


Figure 25: KM3NeT/ARCA8: Distribution of the cosine of the zenith angle (left) and reconstructed energy (right) for events surviving the loose selection requirements. The data (black) are compared with the MC simulation. The contribution of atmospheric muons (red), atmospheric neutrinos (green) and astrophysical neutrinos (blue) as expected by the MC simulation is also shown.

signal and background class were considered.

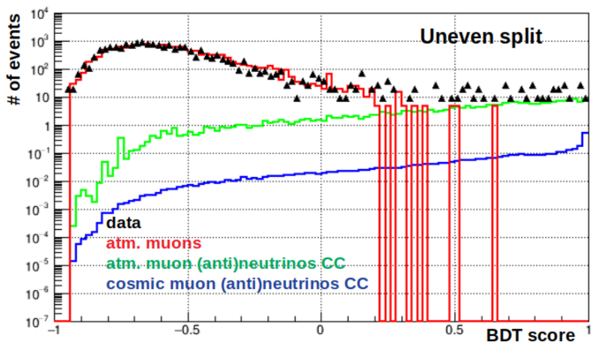


Figure 26: BDT score distribution for the ARCA8 period for uneven split of signal and background class.

Finally, Vasilis calculated the ARCA8 detector's sensitivity to a diffuse flux of astrophysical neutrinos for the ARCA8 data taking period.

"Acoustic neutrino detection"

D. Stavropoulos, V. Tsourapis, K. Paschos, G. Zarpapis. Supervisor: C. Markou

Acoustic neutrino detection is based on the thermo-acoustic model, introduced by Askaryan, where the instantaneous energy deposition of a particle's shower in a medium produces a sound wave. When an Ultra High Energy (UHE) neutrino interacts with seawater, a sufficient amount of energy is deposited heating the medium and producing a pressure field which, in turn, is enough to create a detectable bipolar acoustic pulse. The characteristic shape of the pulse as well as its spectrum at the frequency domain are shown in Fig. 27

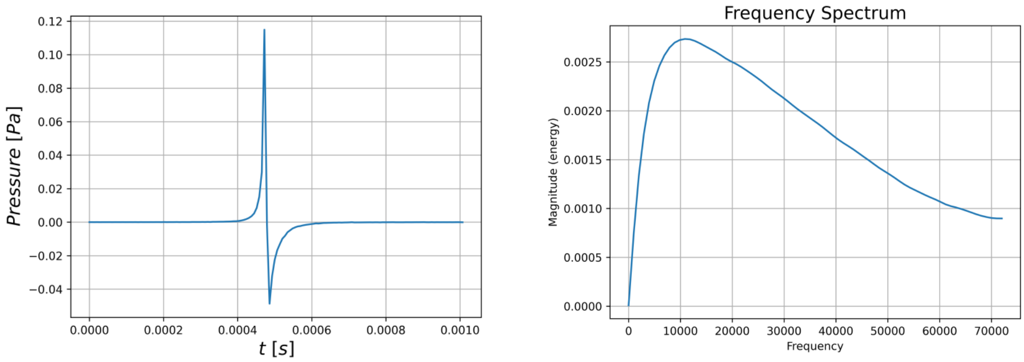


Figure 27: The characteristic acoustic neutrino pulse *(left)*, and its spectrum at the frequency domain *(right)*.

A study was performed with the aim to examine the possibility of discriminating UHE neutrino induced acoustic pulses in underwater recordings. People involved in this study focused on creating a full software pipeline concerning the simulation of acoustic neutrino pulses. Acoustic neutrino pulses were produced from showers generated with energies between 10-100 EeV, following an E^{-2} energy spectrum. This software pipeline consists of two parts. The first one concerns the hadronic shower generation (CORSIKA-IW), while the second part concerns the integration over the deposited shower energy and the pulse calculation, accounting for the attenuation of the pulse's propagation in the seawater (based on the work that had been done by the ACORNE collaboration). The initial software developed by ACORNE was translated from MATLAB to Python to benefit from this language's versatility and community support. The translated code is publicly available (https://github.com/DimiStav/acoustic_nu_pulse). Continuous audio recordings collected offshore Pylos at a depth of 1600m were separated into 5 ms chunks, and simulated neutrino acoustic pulses were added to a portion of them. The goal was to discriminate between the chunks with pulse added and chunks with pure background.

Dolphins produce sounds with a specific waveform and frequency. The so called dolphin clicks had to be identified and removed from the analysis. For the identification of the chunks that contain dolphin clicks, a Butterworth/bandstop filter was applied. A high-pass filter at 5 kHz was additionally applied in order to reject the contribution from low frequency sources.

The wavelet transformation was used, in order to discriminate audio chunks containing signal from chunks with pure background. It is noticed that the sum of the wavelet coefficients is much higher at the position the pulse was added. In Fig. 28, a background chunk is shown with and without an additional acoustic neutrino pulse added on top. The several steps of processing are also illustrated.

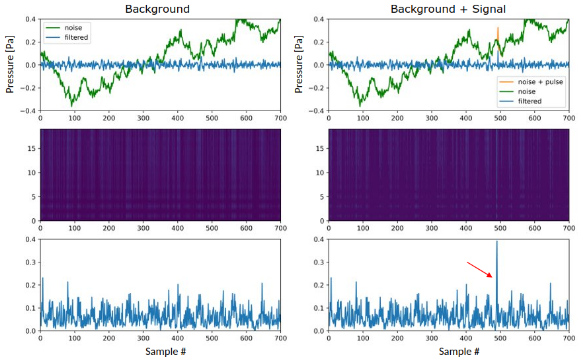


Figure 28: Left: The waveform of a chunk before and after the filtering *(top)* along with the wavelet transform coefficients *(middle)* and their sum along the y axis *(bottom)*. *Right: The same as in the left plots with a neutrino acoustic pulse added in the chunk waveform.*

By summing over the columns of the matrix of the wavelet transform coefficients, a variable is considered for the discrimination between background and signal chunks. This variable is extracted as the fraction of the maximum sum in a chunk divided by the mean of the sums in the same chunk. The distribution of this variable for signal and background chunks is shown in Fig. 29.

By summing over the columns of the matrix of the wavelet transform coefficients, a variable is considered for the discrimination between background and signal chunks. This variable is extracted as the fraction of the maximum sum in a chunk divided by the mean of the sums in the same chunk. The distribution of this variable for signal and background chunks is shown in Fig. 29.

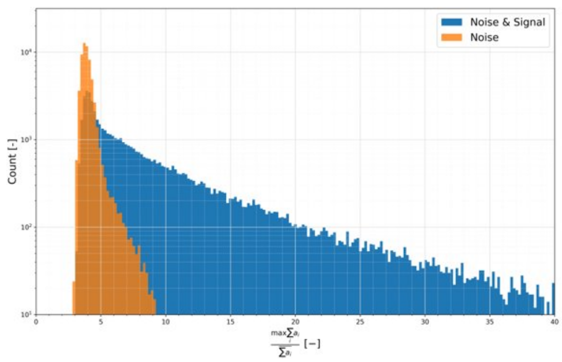


Figure 29: Distribution of the maximum sum in a chunk over the mean of the sums in the same chunk.

In Fig. 30, the signal efficiency that is achieved with a cut at a given max/mean value is presented, along with the signal purity. For an indicative cut at the maximum significance value, a $\sim$ 70 % efficiency is achieved, with a $\sim$ 85 % background rejection.

This analysis was presented at the KM3NeT collaboration meeting that took place in Rome, on October 2022.

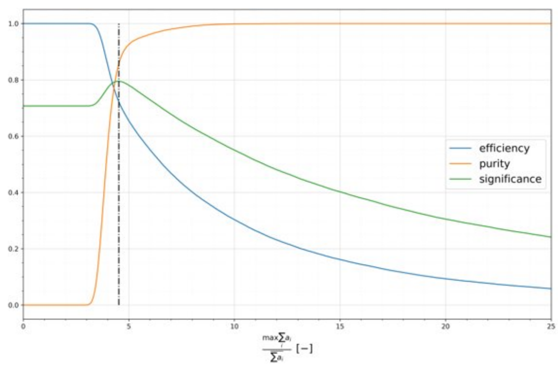


Figure 30: The signal efficiency and purity.

ANNIE

The Accelerator Neutrino Neutron Interaction Experiment (ANNIE) is a 26-ton Gd-doped water Cherenkov detector installed in the Booster Neutrino Beam (BNB) at Fermilab. Its main goals are the measurement of the neutron multiplicity in neutrino-nucleus interactions as well as the cross-section of Charged Current Quasi-Elastic (CCQE) neutrino interactions in water. Besides the physics goals, the experiment also aims to be a testbed for new technologies such as Large Area Picosecond Photodetectors (LAPPDs) and Water-based Liquid Scintillators (WbLS). We joined ANNIE in late 2021 and work on the event reconstruction and data analysis.

A schematic representation of the detector components is shown in Figure 31. The detector is composed of multiple subsystems. The water tank filled with Gadolinium-doped water and instrumented with 132 PMTs and 5 LAPPDs. Interactions of neutrinos are detected within this volume using the Cherenkov light emitted by the corresponding charged lepton in Charged Current interactions. Since the BNB is mainly composed of muon neutrinos, we will predominantly detect muons that are produced in the neutrino interactions. Due to their minimal ionizing nature, they can travel a large distance before being stopped. As such, most of the neutrino-induced muons in ANNIE will leave the water tank and hence not deposit their full kinetic energy into the tank. To get an energy estimate for those particles, the scintillator-steel sandwich detector Muon Range Detector (MRD) is placed downstream of the tank. Interactions of neutrinos in the rocks upstream of the water tank can also generate muons that are able to reach the water tank. Such "dirt" muons need to be singled out to avoid backgrounds. They are spotted by the scintillator veto system of ANNIE that is located directly upstream of the water tank, the Front Muon Veto (FMV).

The physics analyses carried out by group members were either in the context of B.Sc. theses or refer to interim projects. These are briefly outlined below.

"Removing background noise from data using Deep Learning methods"

I. Vitsikanos, G. Stavropoulou, P. - L. Sakkou, Internships, Supervisor: E. Drakopoulou

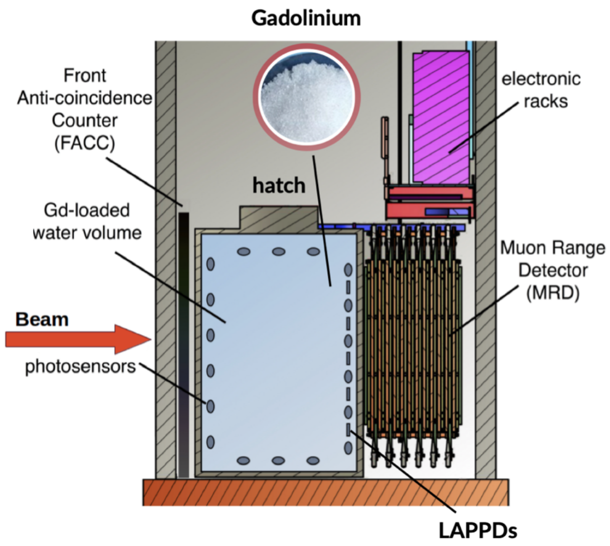


Figure 31: Schematic view of the ANNIE detector hall with the different components. From left to right, the Front Muon Veto (FMV), water tank, and Muon Range Detector (MRD) are visible. The second floor contains all the electronics racks, while the third floor on the very top stores the DAQ and monitoring computers.

During these internships a Deep Learning Neural Network (DNN) was employed to discriminate signal (neutron captures in Gd) from background (instrumental noise and background from cosmic rays) in ANNIE experiment. During the first part of his internship, Ioannis Vitsikanos improved the existing DNN and successfully trained, tested the algorithm using the most recent calibration (with AmBe source) data. He presented his work in ANNIE analysis meetings. Grigoria Stavropoulou continued Ioannis studies and applied the algorithm to calibration (with AmBe source) data from the second calibration campaign. Completing this work Paraskevi-Lydia Sakkou optimised the DNN parameters. The results of this algorithm are summarised in Figure 32. The background is correctly identified while keeping 62% of signal events.

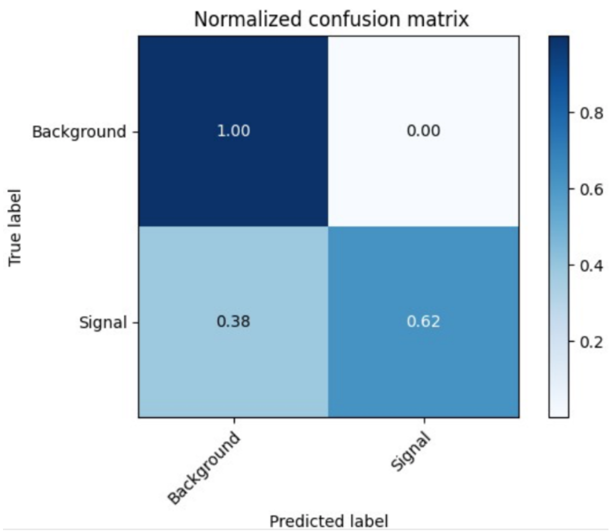


Figure 32: Confusion matrix for DNN classifier showing the percentage of events belonging to each class.

"Muon Energy reconstruction in ANNIE"

I. Vitsikanos, C. Karagiannis, Internships, Supervisor: E. Drakopoulou

I. Vitsikanos started the effort to incorporate the python-based machine learning algorithms for track length and energy reconstruction in the official ANNIE analysis software package (written in C++). For this, he used docker and debugged several scripts. This challenging work was continued by Chrysovalantis Karagiannis. Chrysovalantis Karagiannis first updated the muon track length and energy reconstruction algorithms to the recent simulated data from ANNIE. These algorithms employ a DNN using PMT hits information for the track length reconstruction and a Boosted Decision Tree (BDT) using input variables based on the event topology information for the energy reconstruction. Then he optimised the machine learning algorithms hyper-parameters in ANNIE. Figure 33 shows the muon energy resolution ($\Delta E/E_{muon}$, where $\Delta E = E_{muon} - E_{reco}$) achieved with this method.

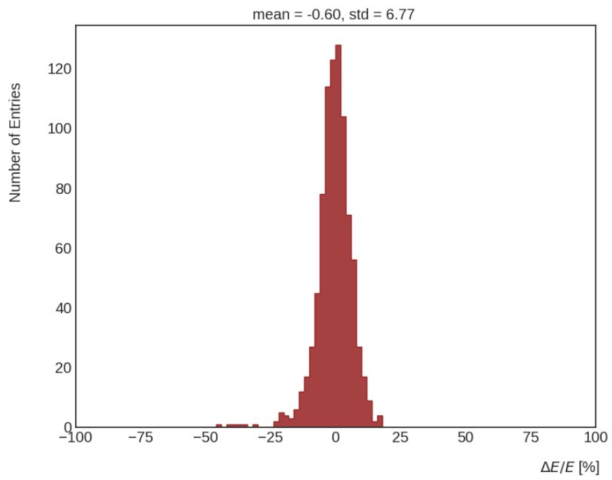


Figure 33: Energy resolution ($\Delta E/E$) for muons crossing the ANNIE detector.

The results of this work have been presented in a poster at XXX International Conference on Neutrino Physics and Astrophysics (NEUTRINO 2022) in Seoul, Korea.

"Vertex Reconstruction using Deep Learning Techniques in ANNIE."

P. - L. Sakkou, BSc thesis, Supervisor: E. Drakopoulou

In October 2022 Paraskevi-Lydia Sakkou started her BSc thesis analysing simulated events from the ANNIE experiment.

Funding

Outreach

In July 2022 the group organised the first Python and Machine Learning Bootcamp to provide basic training in programming with Python for data analysis and Machine Learning.

Overview

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Nuclear Physics and Applications

Theoretical Nuclear Physics

Researchers:	Dennis Bonatsos
Adjunct Scientists:	Mohamed Hammad
Research Associates:	Andriana Martinou
PhD students:	Smaragda Sarantopoulou
	Spiridon Peroulis

Introduction

The most well-established theoretical model for the study of Nuclear Structure is the Nuclear Shell Model. Computer codes, based on the Nuclear Shell Model, have been developed by various researchers worldwide, to deliver theoretical predictions for the nuclear structure observables. But since the nucleus is a many-body system consisting of protons and neutrons, which interact through a yet unknown force, the so called "strong force", even super-computers fail to run these codes for medium mass and heavy nuclei.

Therefore the nuclear physics society is developing the Algebraic Nuclear Models, in its effort to cut back the computational work. The algebraic version of the Nuclear Shell Model, namely the Shell Model SU(3) symmetry, was introduced by J. P. Elliott in 1958 [18], but unfortunately it was meant to be applied only in light nuclei. Efforts to extent the theory to massive nuclei started in 1972 by the research group of J. P. Draayer [19].

The Nuclear Theory group of the INPP at NCSR Demokritos undertook this task by inventing the proxy-SU(3) symmetry in 2017 [20], which is an algebraic Shell Model theory applicable in medium mass and heavy nuclei. Since then the group has intensively worked to set the foundations [21] of this model and to use it so as to solve major problems in the theory of nuclear structure.

Currently the proxy-SU(3) symmetry can be used to predict almost every nuclear observable with satisfactory agreement to the data. But the complexity of

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[20] Dennis Bonatsos et al. "Proxy-SU(3) symmetry in heavy deformed nuclei". In: *Physical Review C* 95.6 (June 2017). DOI: 10.1103/physrevc.95.064325; Dennis Bonatsos et al. "Analytic predictions for nuclear shapes, prolate dominance, and the prolate-oblate shape transition in the proxy-SU(3) model". In: *Physical Review C* 95.6 (June 2017). DOI: 10.1103/physrevc.95.064326

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the calculations can be raised significantly, if one includes the proton or neutron excitations in the full Shell Model space or if one adds the non-SU(3), realistic nucleon-nucleon interactions. Thus the future of the proxy-SU(3) symmetry is to use machine learning [22] techniques or even run its codes in supercomputers in order to deliver yet unreachable predictions.

Activities

The most ground breaking application of the proxy-SU(3) symmetry is in the phenomenon of shape coexistence in nuclei. Shape coexistence emerges when the nucleus manifests two different nuclear shapes in low-lying energies. The nuclear physics community believed that shape coexistence can occur in every nucleus [23], while in 2018 Andriana Martinou in her PhD thesis [24] suggested that it can occur in certain nuclei, which form islands on the nuclear chart. Several publications towards this direction emerged since then, as for example the Ref. [25]. During 2022, the group further justified the occurrence of the islands of shape coexistence through the Covariant Energy Density Functional theory along with K. E. Karakatsanis [26] (a postdoctoral researcher).

The proxy-SU(3) symmetry describes best the deformed nuclei with prolate or oblate shape. Nevertheless other than deformed nuclear shapes exist, such as the spherical and the unstable ones. These nuclear shapes have been studied through a well-known nuclear model, the Interacting Boson Model, which was proposed in 1975 [31]. Unfortunately this model is not properly connected with the nuclear Shell Model and this has been outlined by many authors.

The innovation introduced in 2022 by Andriana Martinou, currently a Research Associate in the INPP of Demokritos and member of the Nuclear Theory group, was to suggest an alternative model, called the U(6) Boson Model, which is similar in spirit with the Interacting Boson Model, but properly connected with the proxy-SU(3) symmetry and with the nuclear Shell Model [32]. Within this model the

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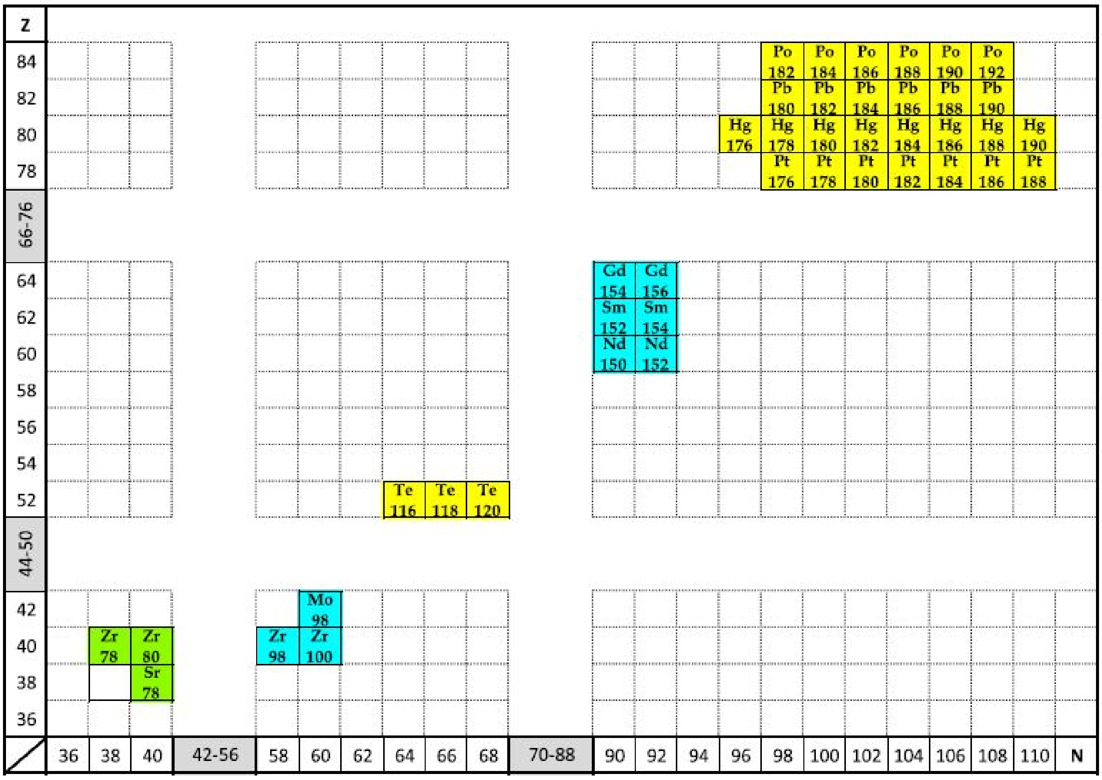

Figure 34: Picture taken from Ref. [29]. The map shows which nuclei are predicted to have shape coexistence, within the dual-shell mechanism [30].

Nuclear Theory group can study various shapes of medium mass and heavy nuclei and furthermore the nuclear metastable (or isomeric) states can be investigated.

The nuclear isomers are the most prominent nuclei, which can have vast technological applications with important societal impact. Such nuclei, have long-living excited nuclear states and so they can be used into the a) radio-medicines, b) nuclear clock [33], c) future nuclear batteries [34], d) the nuclear waste management [35] and e) the astromers [36]. All of them will have exciting scientific and societal impact in the future. Thus Andriana Martinou started working along with a collaborator, Nikolay Minkov, on the Thorium Nuclear Clock; the outcome of this collaboration is in the future to come.

During 2022 Smaragda Sarantopoulou completed her PhD Thesis [37]. Saran-

2023), p. 455. DOI: 10.3390/sym15020455

[33] P G Thirolf, B Seiferle, and L von der Wense. "The 229-thorium isomer: doorway to the road from the atomic clock to the nuclear clock". In: *Journal of Physics B: Atomic, Molecular and Optical Physics* 52.20 (Sept. 2019), p. 203001. DOI: 10.1088/1361-6455/ab29b8

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topoulou worked on the highest weight SU(3) irreps, which are used to predict without any parameter the prolate to oblate shape/phase transition of the nuclear shape, and furthermore she calculated within the proxy-SU(3) symmetry the nuclear binding energies and the two-nucleon separation energies [38]. The method introduced in Sarantopoulou's PhD Thesis can be used for predicting the neutron capture cross sections [39] from a nuclear structure model, namely from the proxy-SU(3) symmetry.

The youngest PhD candidate of the Nuclear Theory group is Spiridon Peroulis. He is working on the prediction of the electric quadrupole nuclear transition probabilities (B(E2)s) through the proxy-SU(3) symmetry [40]. Peroulis aspires to calculate the B(E2)s without the use of effective electric charges for the first time and to create an on-line and user-friendly tool, which shall output his predictions.

During 2022 the Nuclear Theory group participated in the official evaluation of the INPP by the General Secretariat for Research and Innovation. The work of the group was presented in the committee by Andriana Martinou and received excellent remarks for their scientific work and direction.

In the framework of international theoretical collaborations in 2022, shape/phase transitions and critical point symmetries in atomic nuclei have been considered within several different frameworks. The shape/phase transitions in the Ce isotopes have been studied using the macroscopic Algebraic Collective Model, as well as two microscopic models, the Skyrme-Hartree-Fock + Bardeen-Cooper-Schrieffer (BCS) approach and the symmetry-conserving configuration-mixing method with Gogny energy density functionals [41]. In addition, nuclei near the X(5) critical point symmetry have been considered within a quasi-exactly soluble Bohr collective Hamiltonian with a decatic model [42].

The Nuclear Theory group hosted in the INPP Mohamed Hammad, an Associate Professor in Damanhour University of Egypt. Prof. Hammad has a strong background in mathematics. During his 7 months stay in the INPP he studied the U(6) algebra of the Interacting Boson Model in the presence of both proton and neutron states. The outcome of this collaboration was Ref. [43].

The Nuclear Theory group has a close collaboration with the experimental

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group of T. J. Mertzimekis from the University of Athens. The collaboration studied the features of the Yb isotopes in Ref. [44]. Additionally, during 2022, the collaboration submitted the following proposal for experiment:
• "Lifetime measurements on 178Yb", P. Koseoglou et al., IFIN-HH Tandem accelerator (submitted 10/2022). The proposal was successful and the group was given a two weeks run in the IFIN-HH in July 2023.
The collaboration during 2022 performed the following experiment:
• "Exploring collectivity and shape coexistence in neutron-deficient Te nuclei", T.J. Mertzimekis et al., IFIN-HH Tandem accelerator, July 2022.

Alongside Andriana Martinou collaborated with Jerry Draayer (a Professor of the Louisiana State University and former CEO of the Southeastern Universities Research Association), and with Feng Pan (a Professor in the Liaoning Normal University in China) as co-editors to form the Special Issue "Symmetry in Nuclear Physics: Model Calculations, Advances and Applications" in the journal "Symmetry".

Figure 35: Andriana Martinou has been a co-editor, along with Jerry Draayer and Feng Pan, in the Special Issue "Symmetry in Nuclear Physics: Model Calculations, Advances and Applications" in the journal "Symmetry".

In the year 2021 the Hellenic Nuclear Physics Society held its annual Symposium in the NCSR "Demokritos". Andriana Martinou was a member of the organization committee. Subsequently, in 2022 Andriana Martinou was a co-editor of the peer review proceedings of the symposium (see Refs. [45]).

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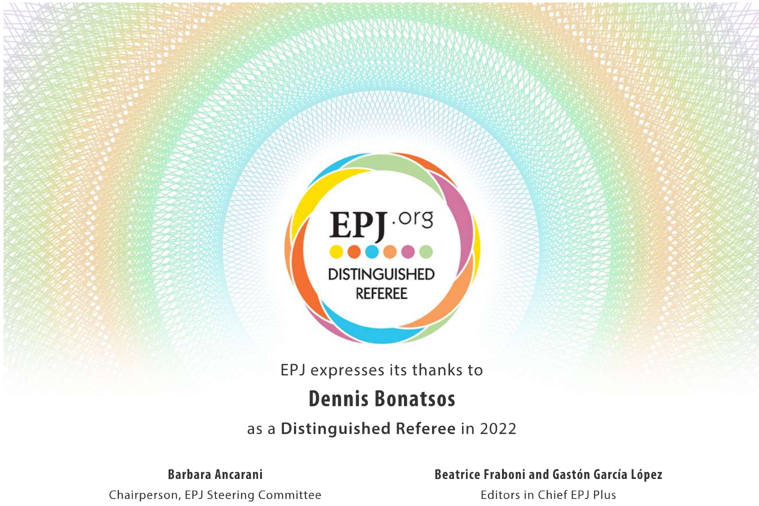
Furthermore Dennis Bonatsos has been named a Distinguished Referee in the European Physical Journal in 2022.



List of the international collaborators:

- **Jerry P. Draayer**[5], **Feng Pan**[6],

[5] *Louisiana State University, Baton Rouge, USA*,
[6] *Liaoning Normal University, Dalian, P.R. China*
Collaboration on microscopic fermionic nuclear models taking advantage of symmetries, as well as on quasi-exactly soluble collective models related to critical point symmetries of nuclear shape/phase transitions.

- **Hassan Hassanabadi**[7], **Hadi Sobhani**[7]

[7] *Shahrood University of Technology, Iran*
Collaboration on quasi-exactly soluble collective models related to critical point symmetries of nuclear shape/phase transitions [46].

- **Nikolay Minkov**[8]

[8] *INRNE, Bulgarian Academy of Sciences, Sofia, Bulgaria*
Close collaboration on all group theoretical and numerical aspects of the development of the proxy-SU(3) model from its very beginning, as part of a long term collaboration going on for 30 years.

- **T. J. Mertzimekis**[9], **K. Zyriliou**[9], **P. Vasileiou**[9], **S. Pelonis**[9], **V. Lagaki**[9],

of the Nuclear Structure of 180Hf. Preliminary results". In: *Proceedings of the 29th Annual Symposium of the Hellenic Nuclear Physics Society*. Ed. by G. Anagnostopoulos et al. Vol. 28. HNPS Advances in Nuclear Physics. 2022, p. 112. DOI: 10.12681/hnps.3538

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I. Madesis [9], A. Karadimas[9],E. Marommatis[9], A. Chalil[10], P. Koseoglou[11]
[9] *Physics Department, National Kapodistrian University of Athens, Athens, Greece*
[10] *Institute of Research into the Fundamental Laws of the Universe, CEA, Saclay, France,*
[11] *Technische Universität Darmstadt, Darmstadt, Germany*
Collaboration in experimental proposals approved at the Horia Hulubei National Institute for R & D in Physics and Nuclear Engineering, Bucharest, Romania. The experiments aim to measure the spectrum and the lifetimes of the ^{178}Yb and the neutron deficient Te isotopes. The Nuclear Theory theory group of the INPP in Demokritos contributed with theoretical predictions of spectra, lifetimes and electric transition probabilities among nuclear states.

• **P. Alexa**[12], **M. Abolghasem** [12], **G. Thiamova** [13], **T. R. Rodríguez** [14], **P.-G. Reinhard** [15]
[12] *Technical University Ostrava, Ostrava, Czech Republic*
[13] *Universite Grenoble 1, CNRS, LPSC, Institut Polytechnique de Grenoble, Grenoble, France*
[14] *Universidad Autónoma de Madrid, Madrid, Spain*
[15] *University of Erlangen, Erlangen, Germany*
Collaboration on the macroscopic and microscopic description of shape/phase transition in the Ce isotopes[47].

Funding

During 2022 the Nuclear Theory group has been funded by one grant with MIS number KP-06-PN48/3, which had been awarded by the National Science Fund of Bulgaria to N. Minkov in the I.N.R.N.E. in Sofia, Bulgaria. Three members (D. Bonatsos, A. Martinou and S. Sarantopoulou) of the Nuclear Theory group of the INPP in Demokritos have participated in the proposal. The research aims to investigate the " Evolution of nuclear structure, shapes and symmetries in the standard and extreme regions of nuclear masses and energy". The three members of the Nuclear Theory group in the INPP use the fund to cover travel expenses and fees for conferences.

Table 12: Grants used by the Nuclear Theory group of the INPP Demokritos in 2022.

Prog. ID	Title	Host Institution	Principal Investigator	Starting date	Finishing date	Budget (€)
KP-06-N48/1	Evolution of nuclear structure, shapes and symmetries in the standard and extreme regions of nuclear masses and energy	INRNE-BAS	N. Minkov	26/11/2020	26/11/2023	86,920.00

[47] P. Alexa et al. "Macroscopic and microscopic description of phase transition in cerium isotopes". In: *Physical Review C* 106.5 (Nov. 2022). DOI: 10.1103/physrevc.106.054304

Outreach

The group participated in the following conferences:

1. "100 years of nuclear isomers", May 2022, Berlin, Germany. Andriana Martinou presented a poster on the "B(E2) transition rates within the proxy-SU(3) symmetry."

2. "Shapes and Symmetries in Nuclei: From Experiment to Theory (SSNET'22 Conference)", 30 May-3 June 2022, Orsay, France. Online participation. Dennis Bonatsos gave an invited lecture on "Islands of shape coexistence in covariant density functional theory" and Andriana Martinou gave an invited lecture on the "Islands of shape coexistence within the proxy-SU(3) symmetry", see Ref. [48].

3. "XV International Conference on Nuclear Structure Properties", June 2022, Kirikkale, Türkiye. Online participation. Dennis Bonatsos gave an invited lecture on "Islands of shape coexistence."

4. "10^{th} International Workshop on Quantum Phase Transitions in Nuclei and Many-Body Systems", July 2022, Dubrovnik, Croatia. Dennis Bonatsos presented two lectures on "Islands of shape coexistence within covariant density functional theory and the proxy-SU(3) symmetry" and on the "Prolate to oblate transition within the proxy-SU(3) symmetry." Andriana Martinou presented her work on the "U(6) Boson Model".

5. Dennis Bonatsos participated in the "39^{th} International Workshop on Nuclear Theory", July 2022, Rila Mountains, Bulgaria. Dennis Bonatsos opened the workshop with his lecture on "Islands of shape coexistence in proxy-SU(3) symmetry and in covariant density functional theory", and he was a session chairman (see Ref. [49]).

Dennis Bonatsos participated in the organization of the following international conferences:

1. "38^{th} International Physics Congress of the Turkish Physical Society" (TPS-38), September 2022, Bodrum, Turkey. Member of the Advisory Board.

2. "39^{th} International Workshop on Nuclear Theory", July 2022, Rila Mountains, Bulgaria. Member of the International Advisory Committee.

Dennis Bonatsos participated online in the following one-day meetings:

1. "Event for Joe Hamilton" of Vanderbilt University, June 2022.

[48] Andriana Martinou et al. "Islands of Shape Coexistence: Theoretical Predictions and Experimental Evidence". In: *Symmetry* 15.1 (Dec. 2022), p. 29. DOI: 10.3390/sym15010029

[49] D. Bonatsos et al. "Islands of shape coexistence in proxy-SU(3) symmetry and in covariant density functional theory". In: *Proceedings of the 39th International Workshop on Nuclear Theory*. Ed. by M. Gaidarov and N. Minkov. Vol. 39. Nuclear Theory. 2022

2. “Symposium celebrating the life and work of Prof. David Rowe”, Toronto, Canada, June 2022.

Overview

The Nuclear Theory group during 2022 has expanded its international reputation by the further justification of the dual-shell mechanism for shape coexistence and by the broadening and strengthening of its international collaborations.

The close collaboration of Andriana Martinou with Nikolay Minkov in the subject of the nuclear isomers within the newly introduced U(6) Boson Model opens a new and fruitful direction of research for the INPP, since the international interest on the topic is expected to raise, due to the numerous applications of the nuclear isomers with vast scientific and societal impact.

The upcoming work of S. Peroulis on the online tool for the B(E2)s within the proxy-SU(3) symmetry will be an innovation, which will capture the interest of the international nuclear physics community.

The close collaboration of Andriana Martinou with the Louisiana group of J.P. Draayer will open new applications of the proxy-SU(3) symmetry into challenging computing and in machine learning techniques.

Experimental Nuclear Physics

Researchers:	M. Axiotis
	S. Harissopulos
	A. Lagoyannis
Research Associates:	E. Vagena
PhD students:	A. Laoutaris
	S. Nanos
	M. Peoviti
	E. Taimpiri
	A. Ziagkova
Master students:	K. Kaperoni
	A. Kotsovolou
Employees:	M. Andrianis
Engineers:	V. Andreopoulos
Technicians:	M. Tsopanakis

Introduction

The activities of the Experimental Nuclear Physics group of I.N.P.P. are mainly implemented in the TANDEM Accelerator of the Institute. During 2022, the Accelerator underwent a major upgrade as described in the appropriate Research Infrastructure section.

Moreover, additionally to its main research activities, the group supports external users for the preparation and the running of their experiments at the accelerator.

Activities

Here under, brief information on the group's scientific output for 2022 is provided.

Nuclear Astrophysics

In this line of research, the group is mainly involved in testing and trying to improve the nuclear inputs entering the Hauser-Feshbach (HF) theory. Through this theory, reactions' cross-sections and reaction rates are subsequently calculated in order serve as input to network calculations for the determination of nuclear abundances of the elements observed in our solar system. On this front, new measurements were performed at the Bochum University, Germany, in order to evaluate the alpha Optical Model Potential for the (α,γ) reaction on ^{63}Cu.

IBA

In order to investigate theoretically the elastic scattering of deutrons on ^{16}O and therefore validate and extend the pre-existing evaluation (SigmaCalc 2012), the cross-sections of the (d,d_0) reaction on ^{nat}O were measured in the energy range 1980 to 2500 keV for five scattering angles (130°, 140°, 150°, 160° and 170°). The resulting data was compared with R-matrix theory calculations, yielding good results for the parameters used and taking into account that the incident ions are deuterons, where several characteristics were not taken into account (polarization of deuterons, charge asymmetry, ...).

Furthermore, in collaboration with the EuroFusion community, different Beryllium (Be) marker tiles of the main JET tokamak chamber after different campaigns were investigated for carbon impurity deposition and deuterium fuel retention. The studies were carried out with ^2H and ^3He beams and yielded significant insights on the Plasma Facing Surfaces and their role of the reactor's operation for the different experimental campaigns.

Nuclear Structure

In the field of nuclear structure, the group has assisted at the study of high spin states of ^{167}Tm, produced via fusion-evaporation reaction of ^7Li on ^{164}Dy at the XTU Tandem accelerator of the INFN Legnaro National Laboratory, Italy. The present data have allowed to extend the level scheme of ^{167}Tm. The experimental data have been compared with theoretical calculations of cranked shell-model; crossing frequencies are in agreement with those of the neighboring even-even isotones, within experimental errors, and there is no evidence of a configuration-dependence of band crossing frequencies. Experimental B(M1)/B(E2) values were extracted and compared with the results of theoretical calculations which are based on a semiclassical cranking model. Finally, the experimental high-spin decay sequences have been compared with the results of projected shell-model (PSM) calculations; agreement between experiment and theory is excellent over the complete range of spins. The calculated energy levels of the one-quasiparticle bands in ^{167}Tm depend sensitively on the deformation parameters used in the PSM calculation.

Applications/Irradiations

Within the Eurofusion project in 2022 the defects creation during irradiation at cryogenic temperatures were studied for Tungsten (W) and Iron (Fe). The irradiations were performed at 7 MeV for the W case, at 5 MeV for the Fe case and for different dose levels. The creation of defects was studied through in-situ resistivity measurements, and after the irradiation the recombination of the defects was studied through an annealing process. For the case of Fe, an additional integrated theoretical study was performed for the interactions between radiation defects and Nitrogen (N) solute atoms in α-Fe, in order to determine their impact on the microstructure, mechanical properties and performance of steel; N along with Carbon (C) are the most common foreign interstitial atoms in Fe and have a strong effect on it's properties.

G4G

During 2022 the GRAS code, developed by the group, was submitted to ESA, and a candidate of GRAS version 6.0 was released.

Funding

Table 13: Funding of the Nuclear Physics Experimental group of the I.N.P.P. Demokritos in 2022.

Prog. ID	Title	Host Institution	Principal Investigator	Starting date	Finishing date	Budget (€)
11893	LIBRA	I.N.P.P.	S. Harissopulos	1/9/2014	31/8/2023	200,000.00
12239	CALIBRA	I.N.P.P.	S. Harissopulos	1/1/2017	30/9/2022	3,422,000.00
12335	GEANT4-based particle simulation facility for future science mission support	I.N.P.P.	A. Lagoyannis	1/4/2019	30/4/2022	120.935,00
12356	Access to Ion and Neutron Beams at NCSR "Demokritos"	I.N.P.P.	A. Lagoyannis	13/6/2019	12/6/2024	15.000,00
12495	Development and Application of Ion Beam Techniques for Materials Irradiation and Characterization relevant to Fusion Technology	I.N.P.P.	M. Axiotis	1/5/2021	31/12/2025	16.000,00
12540	Accelerator-based Research in Nuclear Astrophysics(ARENA)	I.N.P.P.	S. Harissopulos	19/4/2022	18/4/2025	188.000,00

Outreach

PhD Thesis - Ongoing

1. **S. Chasapoglou:** Lagoyannis, NTUA
2. **A. Laoutaris:** Lagoyannis, UoC
3. **S. Nanos:** Axiotis, UoI
4. **M. Peoviti:** Axiotis and Lagoyannis, UoI
5. **K. Preketes - Sigalas:** Lagoyannis, NTUA
6. **P. Tsavalas:** Lagoyannis, NTUA
7. **A. Zyriliou:** Lagoyannis, NKUA

MSc Thesis

1. **E. Taimpiri:** "Differential cross section measurements of light elements for d-PIGE purposes", Lagoyannis, NTUA, 2021
2. **A. Ziagova:** "Study of the parsitic neutron beam at NCSR Demokritos using the GEANT4 Monte Carlo Code", Axiotis, NTUA, 2022

MSc Thesis - Ongoing

1. **A. Kotsovolou:** "Differential Cross-Section Measurements of the $^{18}O(p,\alpha_0)$ Reaction at 170°, in the Energy Range Ep=1-2 MeV, for NRA Purposes"; Lagoyannis, NTUA, 2021

X-ray Spectrometry

Researchers:	Dr. Andreas-Germanos Karydas
Research Associates:	Dr. Maria Kaparou (since 2021)
	Dr. Artemios Oikonomou (since September 2022)
	Dr. Efrossyni Androulaki (since September 2022)
	Dr. Panagiotis Assiouras (since October 2022)
PhD students:	Kalliopi Tsampa, NTUA
	Nikoletta-Kanela Kladouri, UoP
	Stefanos Papagiannis, UoI, ENRACT Lab
	Ermioni Vassiou, UNIWA
Master students:	Elena Konstantakopoulou
	Theofanis Tsakiris
	Michail Chrysovalantis Papadakis
	Evangelia Eleftheriou
	Dimitra Tsakou
Practical work students:	Eirini Stylianou, Chemistry Dpt., UoPatras
	Anastasios Gkikas, Physics Dpt., NKUA
	Theotokis-Konstantinos Floudas, Dpt. of Mechanical Engineering, NTUA
	Konstantinos Stergiou, Dpt. of Chemical Engineering, NTUA
	Petros Tsatsos, Dpt. of Chemical Engineering, NTUA
	Maria-Fanouria Flokou, SEMFE, NTUA

Introduction

The research interests of the x-ray spectrometry group (INPP-XRS), include three basic directions:

1. the use of synchrotron radiation for basic and applied research. The basic research activities refer to the measurement of fundamental x-ray and atomic parameters related to the interaction of X-rays with matter and atom de-excitation processes, whereas applications involve the characterization of advanced nanostructured and Cultural Heritage materials.
2. the development of laboratory or/and portable x-ray fluorescence methodologies and applications in the fields of cultural heritage and environmental monitoring, including the design, realization, and characterization of novel prototype spectrometers.
3. the development of cultural heritage and environment- related applications using x-rays induced through the inner shell atoms ionization by energetic proton beams with micrometer or millimeter size (micro-PIXE and external beam PIXE).

During 2022, the INPP-XRS intensified further its research program related to the multi-thematic areas, succeeded in generating substantial results and scientific contributions. International collaborations include colleagues from the Istituto di Scienze per il Patrimonio Culturale, Consiglio Nazionale delle Ricerche

(ISPC-CNR), the Nuclear Engineering and Techniques Group, Center for Nuclear Sciences and Technologies Dept. of Nuclear Sciences and Engineering Instituto Superior Técnico, Universidade de Lisboa, Portugal, Elettra Sincrotrone Trieste in Italy and the Physics Department of Panjab University, India. With respect to National Collaborations the INPP-XRS group continued its fruitful collaboration with the Department of History, Archaeology & Cultural Resources Management University of Peloponnese, the Department of Materials Science and Engineering at the University of Ioannina and within N.C.S.R. "Demokritos" the long-standing collaboration with the Environmental Radioactivity Laboratory (ERL) of the Institute of Nuclear and Radiological Sciences and Technology, Energy and Safety (INRASTES). A scientific highlight of the collaboration with colleagues form Elettra Sincrotorne Trieste is a paper published in a Nature journal (Scientific Reports) with the subject: "Reconstruction of 3D topographic landscape in soft X-ray fluorescence microscopy through an inverse X-ray-tracing approach based on multiple detectors", https://doi.org/10.1038/s41598-022-24059-y. This work deals with the self-attenuation problem of light elements X-rays that prevents their accurate quantification in soft X-ray synchrotron beamlines. Since self- attenuation depends on the amount of sample mass present between the radiation source and detection system, it allows then for the exploitation of this effect to recover the sample topography. In this work, an X-ray-tracing application based on the use of multiple silicon drift detectors, is introduced to inversely reconstruct the geometrical features of a 3D sample with correct topographical landscape. The reconstruction was based on the 2D XRF count rates maps obtained from a simulated sample composed of three cells with different sizes but similar composition.

Activities

Synchrotron Measurement of Fundamental X-ray Parameters

The fostering of XRF applications in various disciplines, presenting high relevance with technological, societal, cultural and policy making needs, calls for further advances not only with respect to improved equipment performance and capabilities, but also to our basic knowledge regarding X-ray fundamental processes with matter. In this respect, the availability of different databases with X-ray Fundamental Parameters (FPs), being important for XRF quantification, helps to cope with analytes for which certified reference materials cannot be manufactured efficiently. However, even though many compilations exhibit internal consistencies, because are based on specific atomic model calculations or/and of careful evaluations, there is in fact a lack of systematic and consistent FP experimental data associated with low relative uncertainties ($\leq$5%).

The experimental method of choice for the determination of many different X-ray FPs is the selective photoionization method using tunable synchrotron radiation of highly spectral quality delivered by appropriate double crystal monochromators and high order suppressor optics. The need for systematic measurements and consistency requires the availability of different crystals to extend the range of investigated atomic numbers allowing scanning through K, L- or even M-subshells. Moreover, apart from the optimum target related requirements (ultra-thin targets of certified areal density and homogeneity, deposited ideally on ultra-thin substrates of high purity), there are further specific key instrumental needs to minimize associated experimental uncertainties, such as high precision and accuracy beam intensity monitoring before/after the sample and energy dispersive detector with known intrinsic characteristics, energy response and reliable dead time correction. The above requirements for systematic FP studies are fulfilled at the XRF beamline of Elettra Sincrotrone Trieste and series of data for Sn, Sb, Dy, W and Re elements have been already published since 2017 within an international collaborative effort. During 2022 two more papers were published reporting experimental production cross sections (XRPCS) for synchrotron radiation induced L-series of Sn and Sb X-rays, at energies across their respective Li absorption edges and above their L1 edges up to 14 keV (http://dx.doi.org/10.1016/j.nimb.2022.04.010; http://dx.doi.org/10.1002/xrs.3247). The measured Lk XRPCS have been compared with different sets of theoretical cross sections calculated using the Dirac-Fock (DF) model-based X-ray emission rates, the non-relativistic Hartree-Fock-Slater (HFS) model-based photoionization cross-sections and three sets of fluorescence and Coster-Kronig (CK) yields based on the Dirac-Hartree-Slater (DHS) model, the semi-empirical values tabulated by Krause, and the recently reported experimental values. The present measured Lk XRP cross sections above their respective Sn and Sb L1 absorption edges were found to differ by up to 25% from different sets of presently calculated values. On the contrary, the present measured Lp XRPCS across the Sn and Sb Li absorption edges were found to be in good agreement with those calculated using the experimental photoionization cross sections, fluorescence and CK yields. Further, a good agreement observed between the present measured and calculated branching ratios for both Sn and Sb indicates the reliability of the Dirac-Fock model based X-ray emission rates. The Lp XRPCS and intensity ratios for Sn and Sb calculated using the experimental photoionization cross sections, the DF model based X-ray emission rates and the experimental fluorescence and CK yields are recommended for use in different applications.

Cultural Heritage (CH)

In this thematic the XRF laboratory efforts were focused on the design, development and commissioning of a prototype, modular and portable macro XRF (MA-XRF) spectrometer. The spectrometer consists of a transmission 12W Rh anode X-ray tube, a silicon drift detector (SSD) of a 150mm^2 active area and a laser proximity sensor integrated on a three-axis motorized platform (75cm x 50cm x 25cm). The proximity sensor allows reproducible alignment of the spectrometer head and control of the measurement geometry. The setup is controlled by an in-house developed LabView program. Modular optics, including a polycapillary X-ray lens and diaphragms of variable diameters provide a tunable sized exciting beam from ~0.1mm to several mm's, optimized for different applications. Moreover, the possibility to precisely adjust the position of the tube and optics versus the analyzed surface allows to keep a constant and reproducible detection geometry. This work was carried out in the framework of the National funded program called PROTEUS "Advanced System for collection and management of analytical data for documentation and conservation of large-scale paintings in an open laboratory" T2EΔK-02428, MIS(5069984) in collaboration with ISL-CCI: Information Systems Laboratory, Centre for Cultural Informatics & CVRL: Computer Vision and Robotics Laboratory, ICS FORTH, Greece, PRINTEC, U2M – up2metric P.C., Photonics for Heritage Science, IESL FORTH, Greece and the National Gallery of Athens, Alexandros Soutsos Museum, Evripidis Koutlidis Foundation, Greece. The underlying idea of the PROTEUS project is to introduce the public to the work of the art conservator and, through this, in the materials and techniques employed, the historical context of a work of art as well as the message and the expression of the creator. The main objective is the development of an Open-Access Workshop (OAW) within the premises of the National Gallery at Athens (NGA), where researchers from IESL-FORTH and INPP-NCSR Demokritos will install innovative analytical systems based on imaging (MA-XRF, HIS, SWIR) and spectroscopic techniques (FORS, LED-LIF) which, via combined protocols for in-situ application, will integrate and upgrade the current documentation and conservation methodology used by NGA for the integrated study of paintings. The concept becomes particularly important in the case of very large paintings, which, to date, could not be studied with conventional protocols. Overall, the PROTEUS project will produce a unified platform for the acquisition and management of analytical data and documentation of conservation interventions, interpretation, and presentation of results. In a collaborative activity with the University of the Peloponnese, Department of History, Archaeology & Cultural Resources Management, μ-XRF analysis was applied for the characterization of black crust on archaeological marble from the Library of Hadrian in Athens and provided useful insights related to the inferences of contributing pollution sources. In this work (https://doi.org/10.1016/j.culher.2021.12.003), samples of black crust from the Roman-era monument of the Library of Hadrian (Athens) have been collected to perform chemical and mineralogical characterization of the degradation products on built heritage, utilizing a synergy of analytical techniques. The decay features consist of typical black crusts and a Fe-rich aluminosilicate patina. The chemical composition of the crusts, the element distribution along the crust and the characterization of individual embedded particles were combined to determine groups of elements related to specific sources and investigate how they are related to each other. Traffic was found to pose a clear fingerprint on the type and chronological development of anthropogenic pollutant deposition in the black crusts formed in this urban environment.

Environmental monitoring

In this activity the XRF laboratory designed and coordinated a collaborative effort with the school of Chemical and Environmental Engineering, Technical University of Crete, the Department of Materials Science and Engineering, University of Ioannina and with the Environmental Radioactivity Laboratory, INRASTES, NCSR Demokritos, aimed to evaluate the application of a handheld X-ray fluorescence analyzer (HHXRF) for the quantification of air particulate matter on Teflon filters. This effort is of particular interest in view of the widespread use of HHXRF analyzers in various disciplines and the emerging need to acquire concentrations of inorganic pollutants in air to support identification of pollution sources. In more specific, in a paper published in Spectrochimica Acta

B' (https://doi.org/10.1016/j.sab.2022.106517), the optimization and calibration methodology of a handheld XRF spectrometer and its subsequent application in elemental quantification of unknown particulate matter samples was presented. The optimization of the HHXRF analyzer was conducted through investigation of the elemental sensitivities and Limits of Detection (LoD) at variable excitation conditions (voltage, filter). Accordingly, five optimum operating conditions were obtained each one targeted in different elemental range: 1) $Z = 11–12$, 2) $12 < Z < 17$, 3) $16 < Z < 23$, 4) $22 < Z < 31$ and 5) $30 < Z < 92$. Subsequently, a number of reference (5 multi-element and 42 compound/single element) materials were used to obtain calibration curves for 24 elements (Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Br, Rb, Sr, Pb). Weighted least-square regression analysis was implemented to best fit the experimentally measured intensities with mass loadings resulting for most of the elements to high correlations (Pearson $r > 0.98$) and low statistical error. In addition, intercomparison of the elemental concentrations from 28 unknown particulate matter samples between the handheld and a benchtop XRF spectrometer showed good agreement.

Analytical Services

In 2022 the XRF laboratory provided in-situ analytical services to:

- Benaki museum in the framework of ERC Ricontrans: Russian Icons Transfer, Visual Culture, Piety and Propaganda: Transfer and Perception of Russian Religious Art in the Balkans and the Eastern Mediterranean (16th-early 20th century).
- University of Missouri-St Louis (Prof. M. Cosmopoulos) on the scientific analyses of the Iklaina frescoes using X-ray Fluorescence (XRF) spectroscopy, to identify the composition of the pigments and technology used for the execution of the paintings.
- Swiss Archaeological School in Greece on the micro-XRF analysis of polychromy on a Gorgoneion clay at the Eretria Archaeological Museum.

Outreach

Presentations at Conferences/Meetings/Symposia contributions

The International Congress on Archaeological Sciences in the Eastern Mediterranean and the Middle East, ICAS-EMME3, 14-18 March 2022, Nicosia, Cyprus

- Exploring Mycenaean Glass world via traditional and newly- applied techniques, Kaparou, M., Tsampa, K., Zacharias, N., Karydas, A. G., Oral presentation by M. Kaparou

International Symposium on Archaeometry, Lisbon, 16th – 20th May 2022

- Bronze votive objects from the sanctuaries of Tegea, Arcadia, Greece, 9th-7th c. BCE: A technological study using optical microscopy (OM), portable micro- X-ray fluorescence spectrometry (micro-XRF) and micro particle induced X-ray emission analysis (micro-PIXE), Kladouri, N.K., Karydas, A.G., Orfanou, V., Tsampa, K., Kantarelou, V., Karapanagiotou, A.V., Zacharias, N., Oral presentation by N. K. Kladouri

- XRF application on faience cylinder seals towards unveiling the flow of materials and ideas, Karydas, A. G., Kaparou, M., Asvestas, A., Tsampa, K., Kladouri, N. K., Anagnostopoulos, D., Tsouparopoulou, Chr., Oral presentation by M. Kaparou

International Conference on Accelerators for Research and Sustainable Development: From Good practices towards Socioeconomic Impact, 23-27 May 2022, IAEA, Vienna, Austria

- Applications if Proton Induced X-rays at the Tandem accelerator Laboratory of NCSR "Demokritos", A.G.Karydas, M. Axiotis, A. Lagoyannis and S. Harissopulos, Oral presentation by A.G. Karydas

European X-ray Spectrometry Conference, June 27-July 1, Antwerp, Belgium

- A comparative study of scanning μ-PIXE and μ-XRF in Cultural Heritage studies, K. Tsampa, M. Kaparou, N.K. Kladouri, E. Eleftheriou, C. Pacheco, Q. Lemmason, L. Pichon, G. Spyropoulos, C. Caliri, F.P. Romano and A.G. Karydas, Poster presentation by K. Tsampa
- Experimentally Revisited X-ray Fundamental Parameters at the XRF beamline of Elettra Sincrotrone Trieste, A. G. Karydas, V. Ayri, S. Kaur, M. Czyzycki), G. Aquilanti, A. Migliori and S. Puri., Oral presentation by A.G. Karydas
- Influence of cascade vacancy decay on the average M-shell Fluorescence Yield for Rhenium, Vibha Ayri, Anil Kumar, Mateusz Czyzycki, Andreas G. Karydas and Sanjiv Puri, Poster presentation by A.G. Karydas
- Depth profiling of implanted Fe and Xe ions in silicon using synchrotron induced GI XRF spectrometry, Th. Tsakiris, M. Kokkoris, M. Czyzycki, M.K. Tiwari, E. Ntemou and A. G. Karydas, Poster presentation by A.G. Karydas

MA-XRF 2022: MA-XRF scanning in Conservation, Art and Archaeology, 26 - 27 September 2022, Delft, The Netherlands

- Revisualization of Vanished Ancient Polychrome on Early Cycladic II (2600-2300 BC) Figurines, E.Eleftheriou, C.Caliri, P.Romano, K.Tsampa, S.Sotiropoulou and A. G. Karydas, Oral presentation by E. Eleftheriou

Eighth Balkan Symposium on Archaeometry, 3rd—6th October 2022, Belgrade, Serbia

- MA-XRF imaging of Greek Antiquities A. G. Karydas, C. Caliri, E. Eleftheriou, K. Tsampa, Th. Gerodimos, D. F. Anagnostopoulos and F.P. Romano, Invited talk by A.G. Karydas
- HHXRF characterization of pigments on funerary paintings from the Royal Tombs at Aigai, ancient Macedonia H. Brecoulaki, K. Tsampa, E. Eleftheriou and A. G. Karydas, Oral presentation by K. Tsampa

- A multidisciplinary study of Iron Age glass beads from the Cave Coroneia, Boeotia, Greece A. Oikonomou, S. Oikonomidis, K. Bataoula, N. Skoumi and A. G. Karydas, Oral presentation by A. Oikonomou
- Angular resolved XRF and XANES analysis of Attic Black Gloss ceramics, C. Caliri, A. G. Karydas, A. Migliori, and F. P. Romano, Poster presentation by A.G. Karydas
- ICP-LA-MS analysis of Archaic to Hellenistic glass from Thebes, Greece: a contribution to glass studies M. Kaparou, A. Oikonomou, V. S. Šelih, J. T. van Elteren and N. Zacharias, Oral presentation by M. Kaparou

Invited Seminar (by Andreas Karydas)

MA-XRF imaging of Greek Antiquities, Seminar given by Andreas G. Karyda in the context of the bilateral collaboration between the Institute of Electronic Structure and Laser (IESL) of FORTH and the Palace Museum in Beijing within the Chinese National Key R&D Program Project "One Belt One Road: China-Greek Cultural Relics Protection Technology Joint Research".

Participation at Elettra Sincrotrone Trieste Beamtimes

December 2022, 15 shifts Collaboration with IAEA and Elettra Sincrotrone Trieste using internal beamtime allocation at the XRF beamline.

Chapter in Book

Jack L. Davis, Sharon R. Stocker, Hariclia Brecoulaki, Maria Perla Colombini, Myrto Georgakopoulou, Shpresa Gjoncecaj, Andreas Karydas, Noémi Müller, Erika Ribechini, and Allison Sterrett-Krause, The small finds 403-445, in the book A Sanctuary in the Hora of Illyrian Apollonia Excavations at the Bonjakët Site (2004–2006), Edited by Jack L. Davis, Sharon R. Stocker, Iris Pojani, and Vangjel Dimo

MSc theses submitted in 2022

1. “Study of transmission target, end-window tube X-ray emission spectrum” **Dimitra Tsakou**, National Technical University of Athens, School of Applied Mathematical and Physical Sciences
2. “Advanced XRF Tools and Methodologies for the Revisualization of Vanished Ancient Polychrome” **Evangelia Eleftheriou**, National Technical University of Athens, School of Applied Mathematical and Physical Sciences

DOM

Since 2016 a Digital Optical Module integration, validation and testing facility has been established in the premises of INPP (see Figure 36). The DOM lab has been funded exclusively through internal funds. It was completed in record time (compared to other similar labs in KM3NeT) and has been operational in late 2016. Ever since, the lab continues with the integration of DOMs.

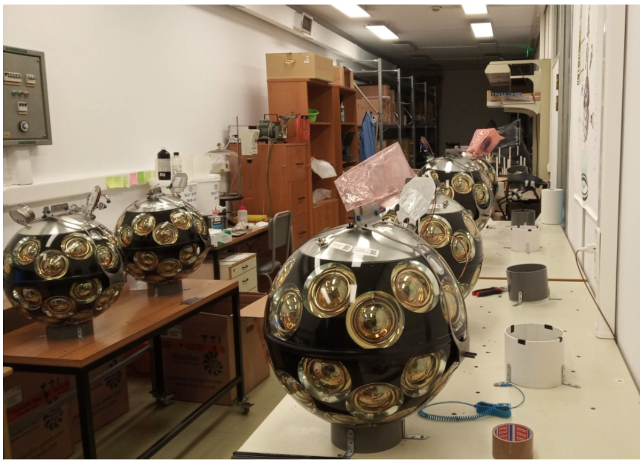

Figure 36: The DOM Lab at INPP.

Currently the lab employs 2 FTEs of skilled personnel, with additional help from other group members as the need arises. The 2022 was a very fruitful year concerning the DOM integration, since 36 DOMs (2 Detection Units) were integrated, calibrated, and tested successfully. An additional contribution to the KM3NeT collaboration is testing and validation effort concerning the high-pressure testing of the DOM penetrators which are used for powering the DOMs and for data transfer from the DOMs to the shore station via an electro optical cable. As the penetrators can be a single point of failure for the DOMs, acceptance testing is extremely important. These tests are done using a high-pressure testing chamber, capable of sustaining pressure up to 600bars (see Figure 37). These tests are done for all the KM3NeT DOM penetrators.

Figure 37: Pressure testing of the penetrators.

TANDEM Accelerator Laboratory

During 2022 the in house Tandem Accelerator underwent a major upgrade within the CALIBRA project. At the beginning of the year all experimental activities of the accelerator were ceased and the deconstruction begun.

Low Energy Part

The old ion sources were dismantled and the whole Low Energy part of the accelerating beam line was shortened. This means that the inflection magnet was moved closer to the tank and the optical elements (focusing and steering elements) were also relocated to new positions. The new positions of the elements were determined through ion beam optics calculations and their placement had to be made with accurate alignment. During the construction phase, two new ion sources were installed (a TORVIS and a SNICS) with their respective power supplies and controls.

Tank

The main upgrade was done in the heart of the accelerator, in the tank. The complete canal in the terminal, with the High Voltage electronics and the foil changer system was removed. Additionally, the old belt charging system was removed. The charging system was replaced by a new of pelletron type, consisting of three motors moving three charging chains. The upgrade of the charging system, apart from giving more "stable" voltage, it renders the accelerator easier to maintain, since for the old one it was hard to find and replace the charging belt. The stripper

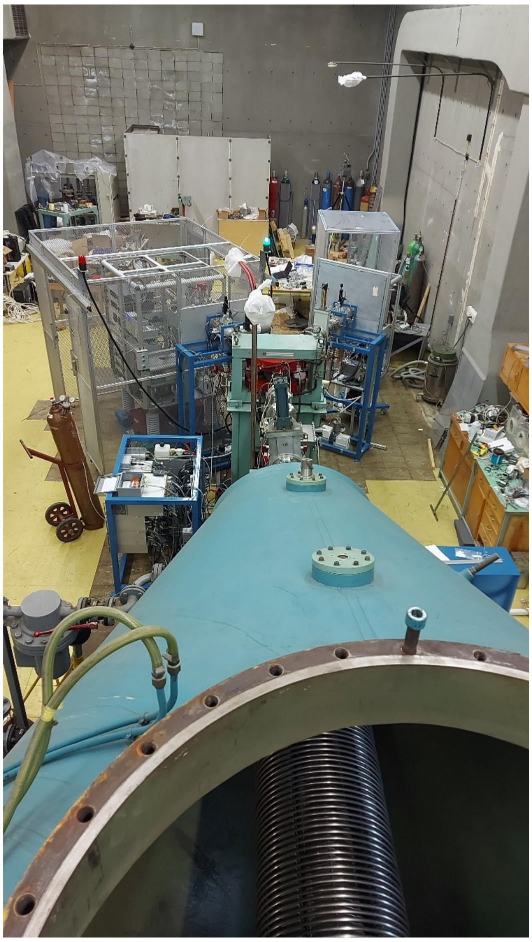

Figure 38: General view of the two new sources

canal was also replaced with it's associated foil and gas stripping system and it's respective electronics, that now communicate with the "outer" world via optical links.

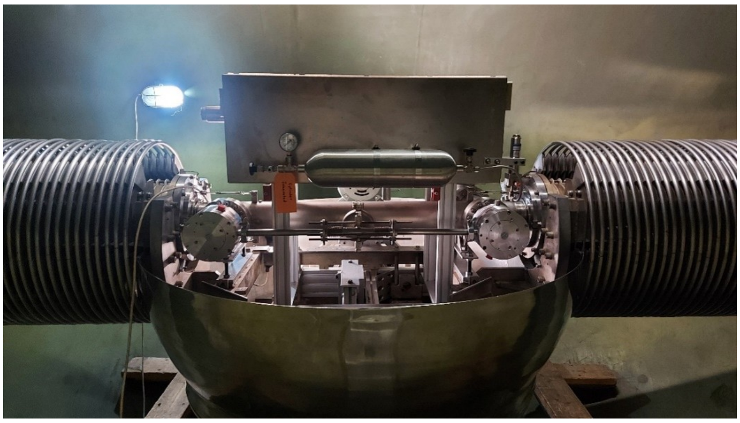

Figure 39: The new terminal inside the tank

Control

Before the upgrade, the most part of the control of the accelerator was done with analog electronics. During the upgrade many of the power supplies were updated and a new control system was installed. After the upgrade the whole control is computerized, facilitating the reproducibility of the beams provided. Moreover, since the control is done via a PC, it gives the possibility of remote connection and troubleshooting probable problems by an on-call operator.

Commissioning

After the upgrade some time was allocated in order to get accustomed with the new control system, along with the testing of the upgrades. The outcome demonstrates that the upgrade was carried out successfully. The provided beams have greater intensity and the operation of the accelerator is easier and more stable. It is planed that now an accelerator operation course can be provided, in order to train post-graduate students to maintain/operate the beam during their experiments.

Figure 40: The new computerized control

High Energy Physics - ATLAS

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