NATIONAL CENTRE FOR SCIENTIFIC RESEARCH "DEMOKRITOS"
INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

H.F.R.I.
Hellenic Foundation for Research & Innovation

Modelling uncertainties and prompt b-jet identification in $t\bar{t}b\bar{b}$ with dilepton signatures at the LHC

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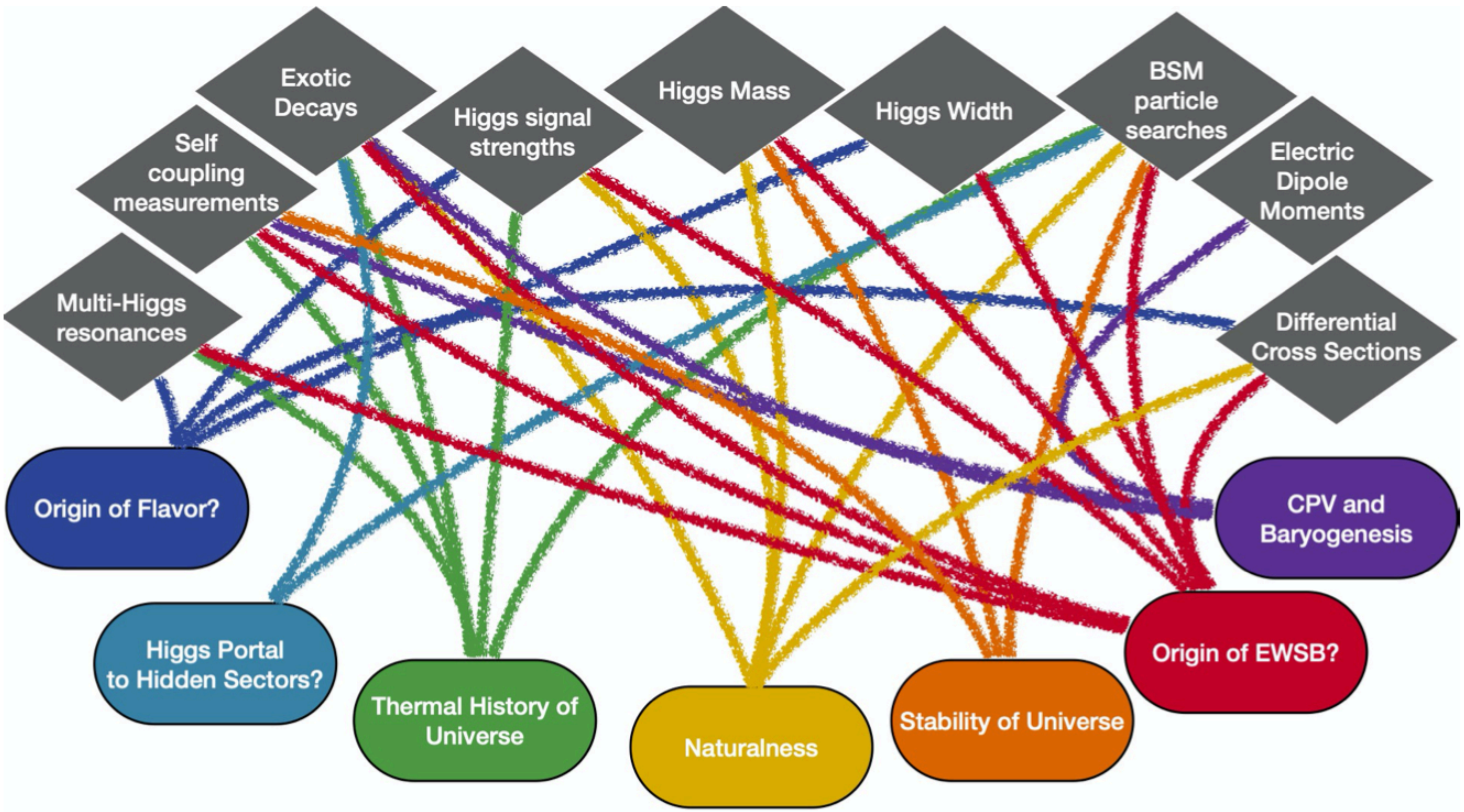
Work in collaboration with H.Y. Bi, H.B. Hartanto, M.Kraus, M.Lupattelli and M.Worek

Based on: *JHEP 08 (2021) 008* *Phys. Rev. D 107 (2023) 1*

Motivation

- Understanding the properties of the SM Higgs boson is central to the physics program of the LHC (and of future colliders as well)

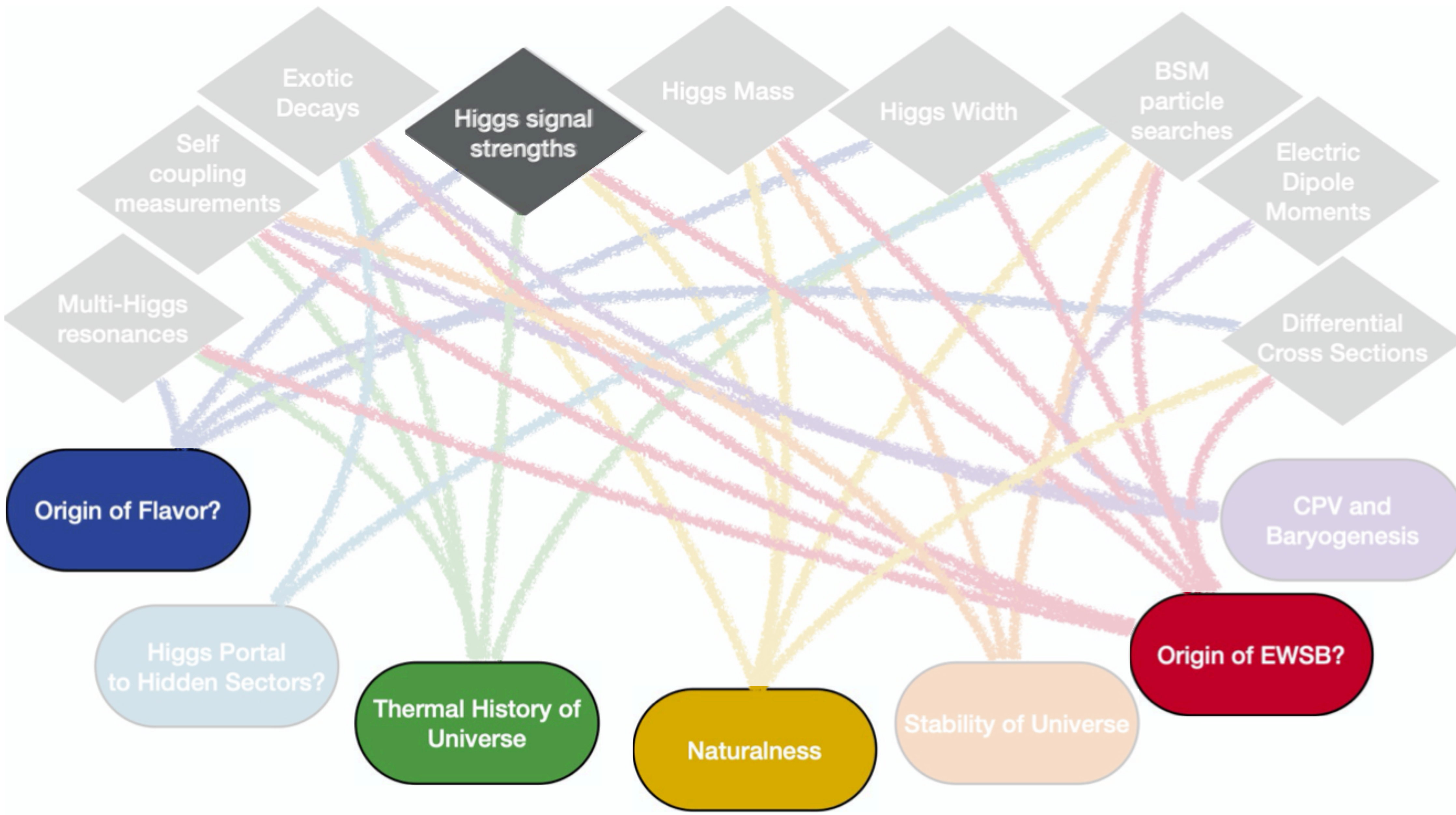


2209.07510 [hep-ph]

Motivation

- Measurements of Higgs signal strengths can provide stringent tests of the SM
- BSM physics can manifest through coupling modifiers (κ) with effects up to few %

↪ Talk by Sinead Farrington

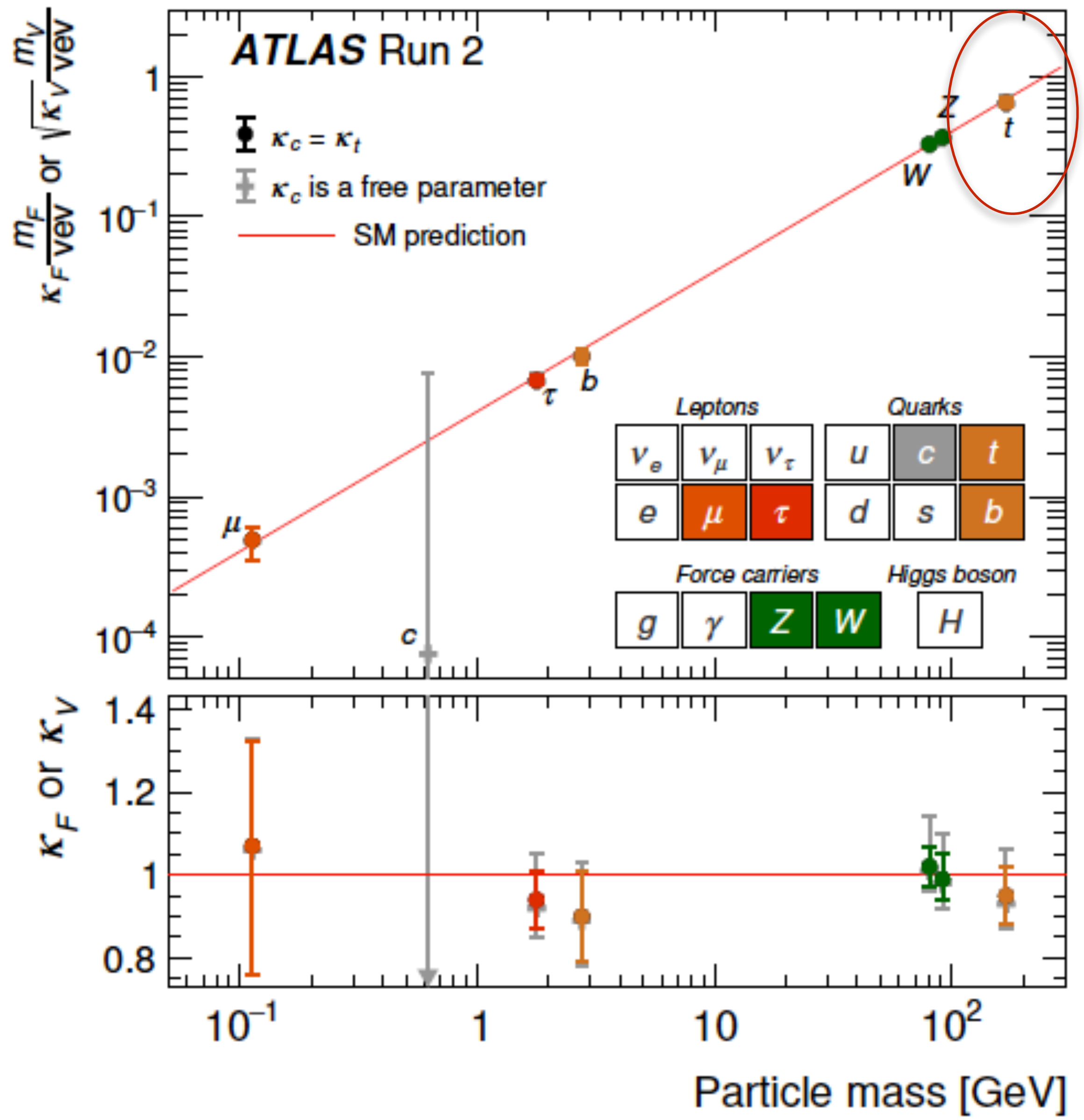


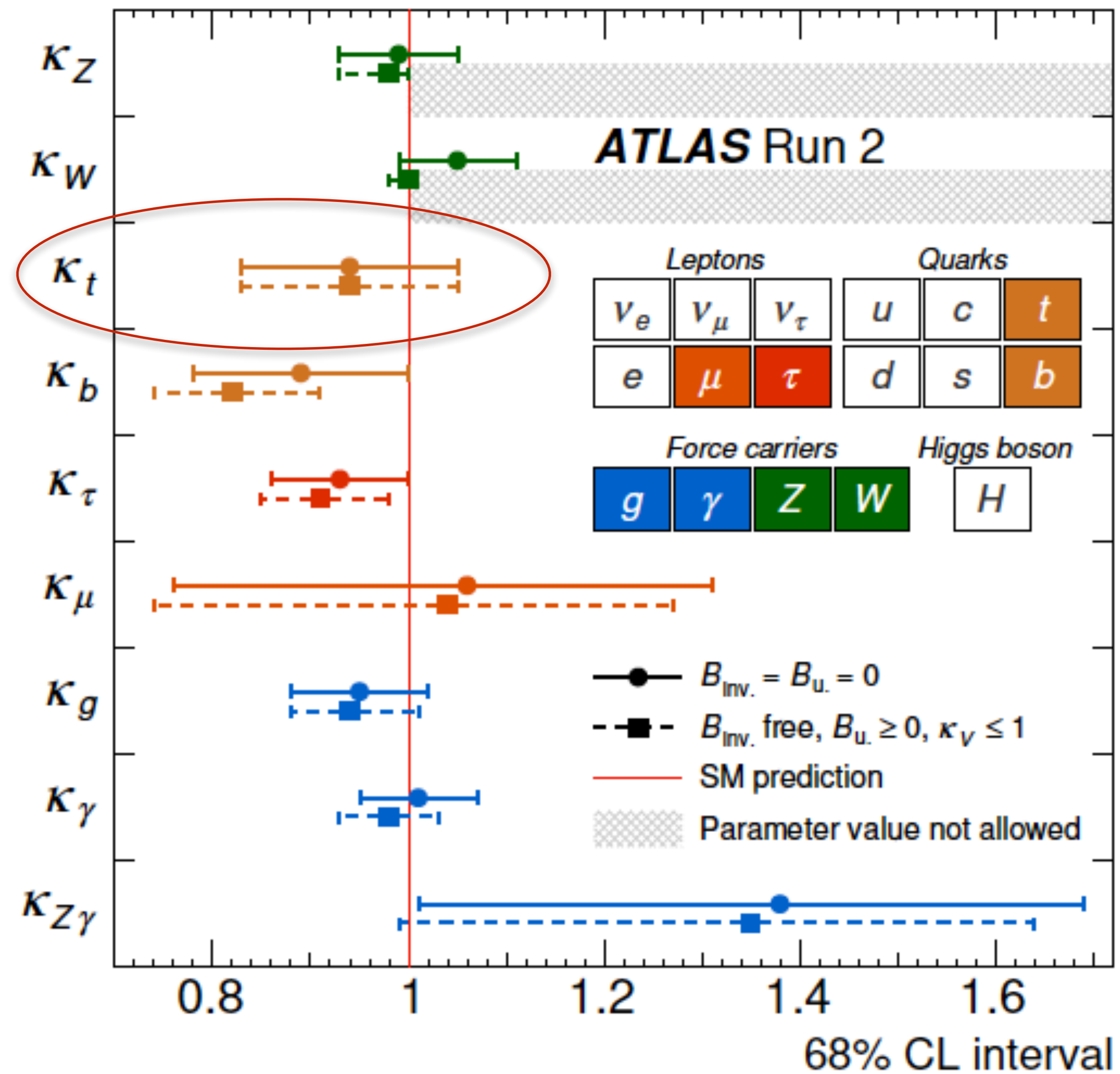
2209.07510 [hep-ph]

Higgs coupling measurements

- Legacy results from the LHC Run 2

[ATLAS, Nature 607 (2022) 7917, 52-59]



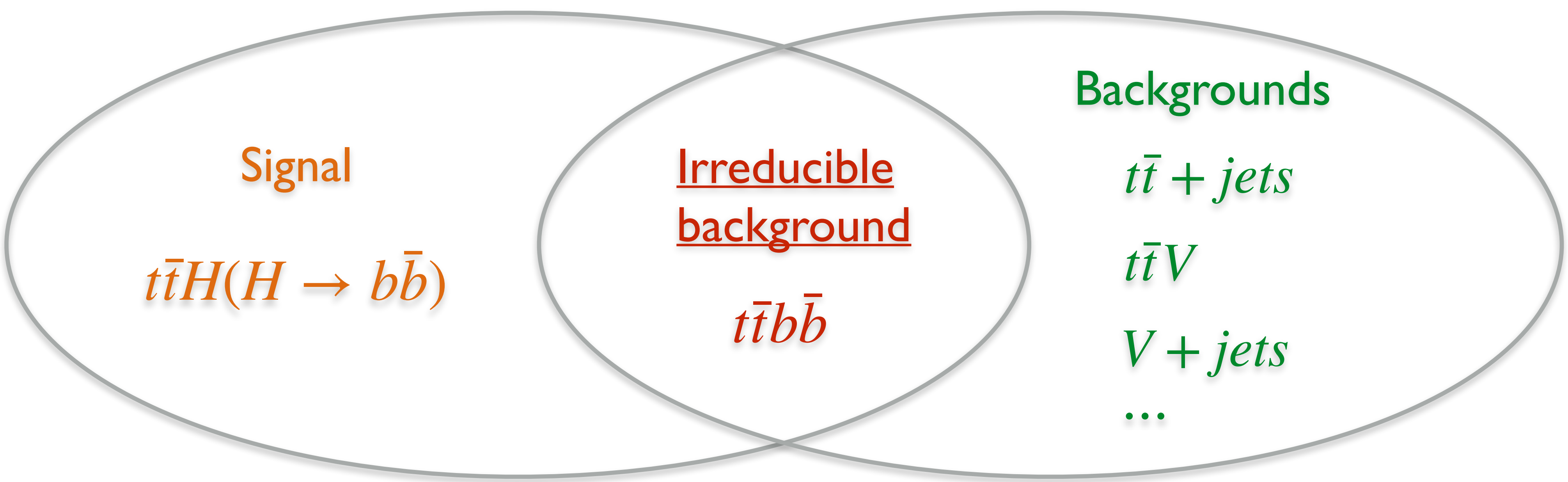


Why $ttH(H \to b\bar{b})$?

- Top-quark Yukawa coupling is the largest among SM particles
- $pp \to t\bar{t}H$ has direct sensitivity to top-quark Yukawa coupling at LHC

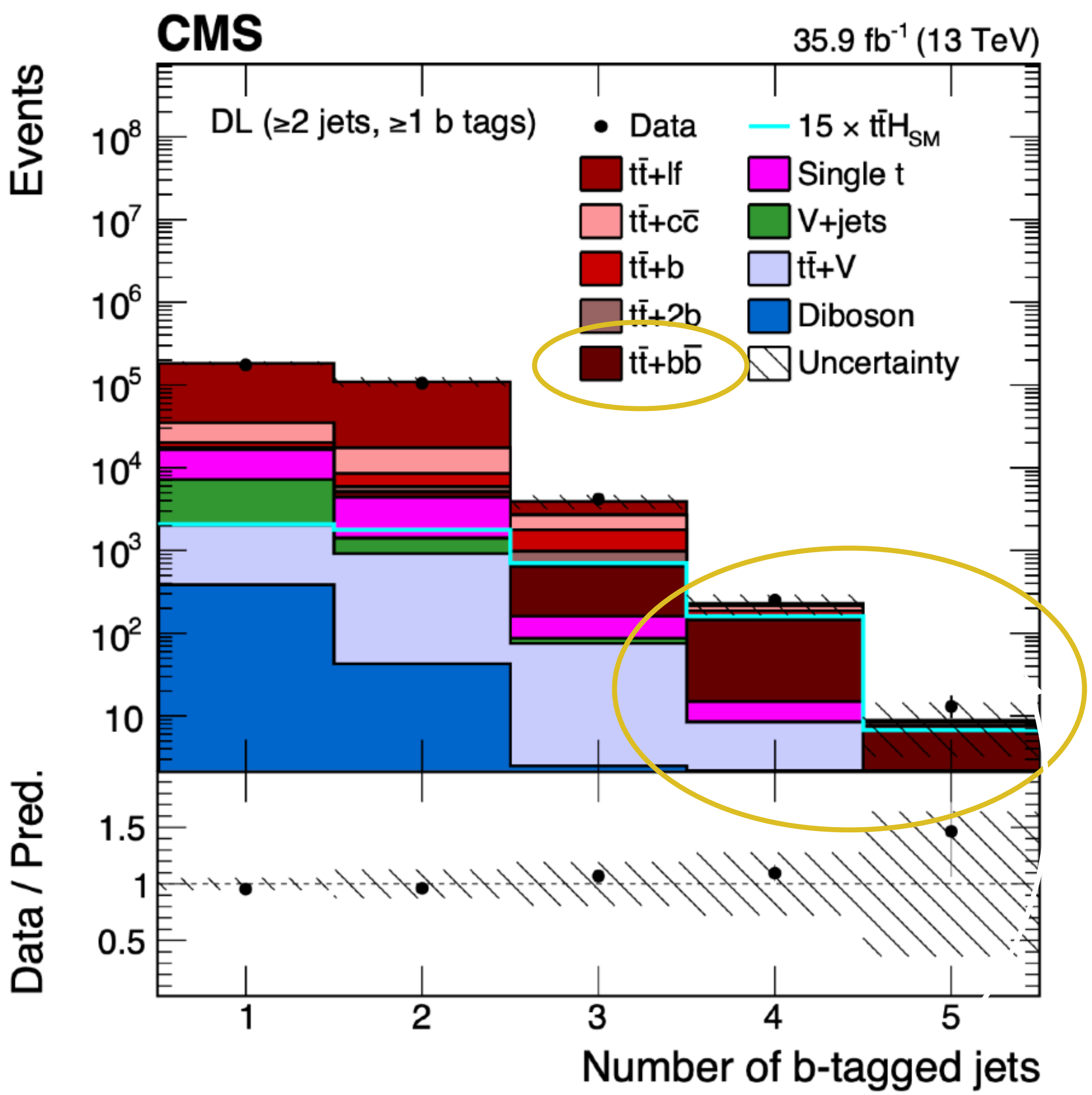
  ↪ Talk by Chiara Savoini
- $H \to b\bar{b}$ is the decay channel with the largest Branching Ratio ($\sim 58\%$)

However $pp \to t\bar{t}H(H \to b\bar{b})$ is a tiny signal in a huge QCD background



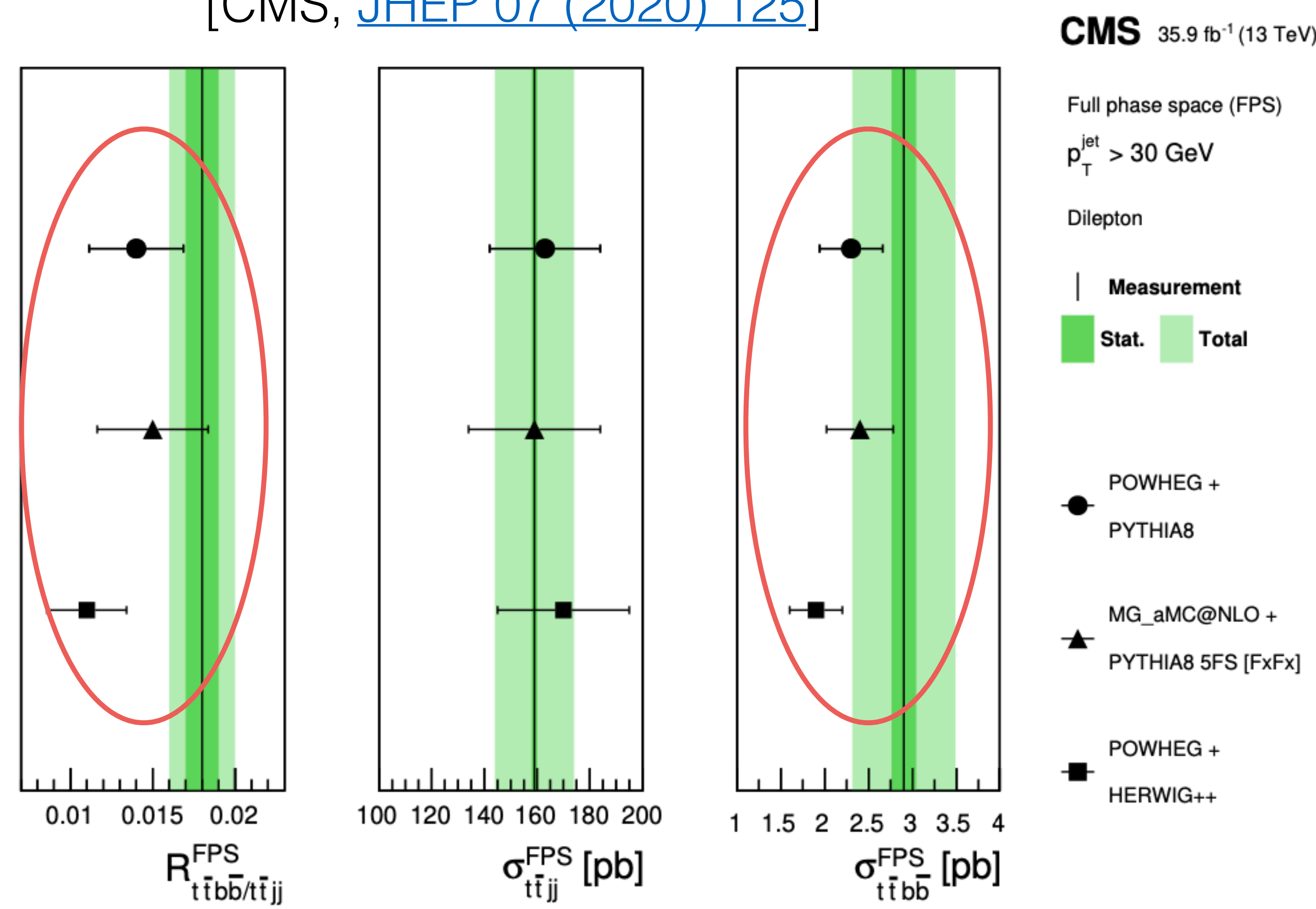
$t\bar{t}b\bar{b}$: theoretical challenges

[CMS, JHEP 03 (2019) 026]



- Slight tension with data reported in $\sigma(t\bar{t}b\bar{b})$ and in $\mathscr{R} = \dfrac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)}$

[CMS, JHEP 07 (2020) 125]



- $t\bar{t}b\bar{b}$: main background to $t\bar{t}H(H \to b\bar{b})$ for $N_{bjets} \geq 4$

$t\bar{t}b\bar{b}$: prompt b-jet identification

Signal

$t\bar{t}H(H \to b\bar{b})$

Irreducible background

$t\bar{t}b\bar{b}$

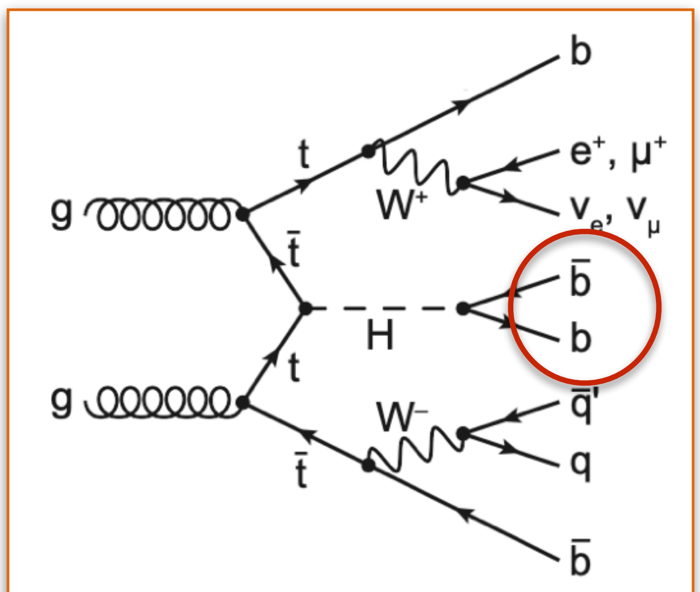
Backgrounds

$t\bar{t} + jets$

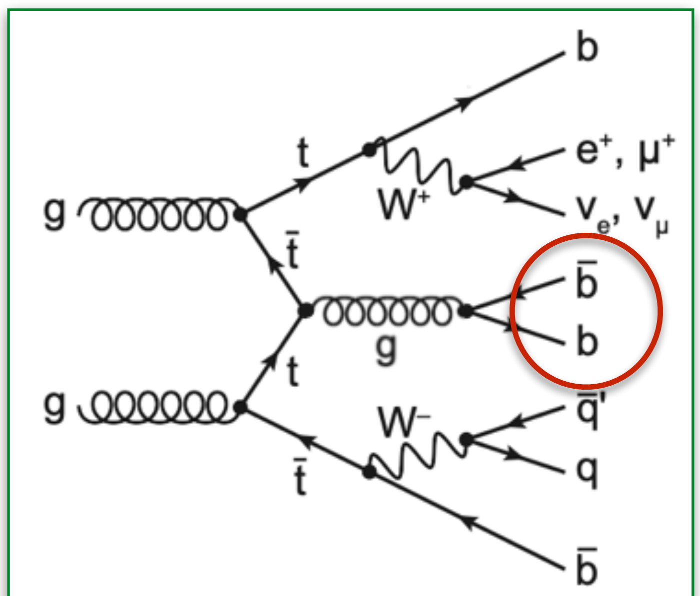
$t\bar{t}V$

$V + jets$

...



$t \to W^+ b \quad \bar{t} \to W^- \bar{b} \quad H \to b\bar{b}$

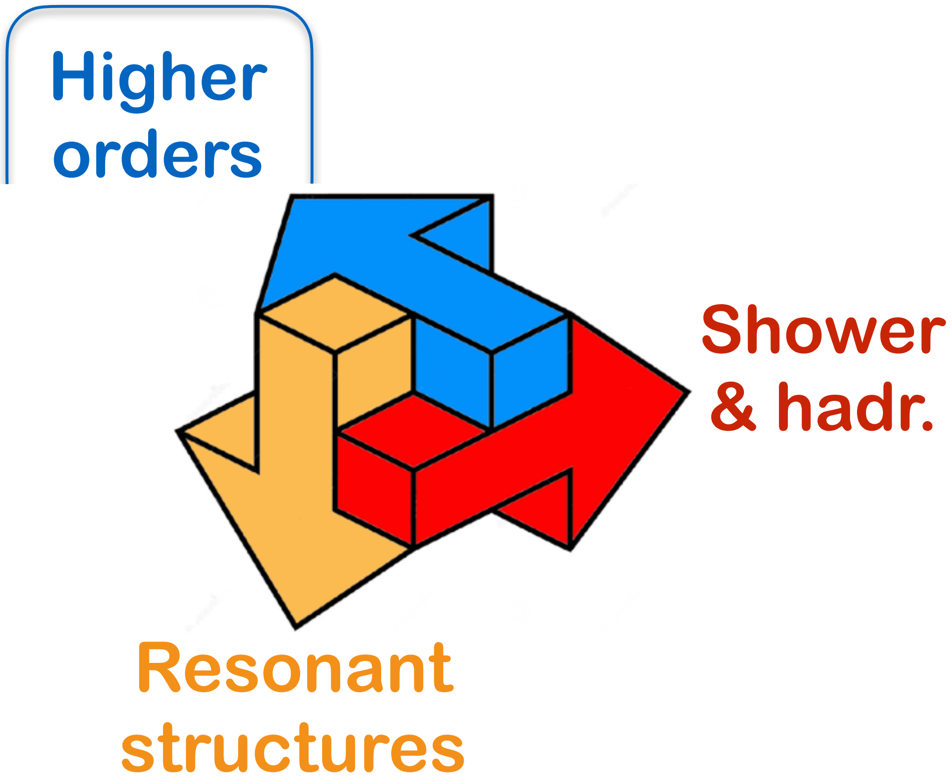


$t \to W^+ b \quad \bar{t} \to W^- \bar{b} \quad g \to b\bar{b}$

Combinatorial background:

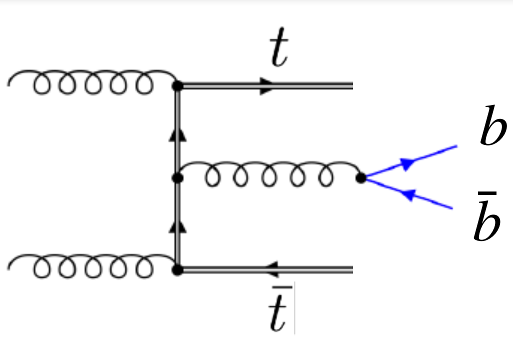
- challenges in top reconstruction & "prompt b-jet" identification
- smearing of Higgs peak in $M(b\bar{b})$ distribution

Avenues to precision



- Accurate predictions for *inclusive production rates*
- General idea on the impact of QCD corrections to $t\bar{t}b\bar{b}$ production
- Global view on the size of dominant theory uncertainties

State of the art: NLO QCD



Inclusive top production

$pp \to t\bar{t}b\bar{b}$

Bredenstein, Denner, Dittmaier, Pozzorini '08 '09

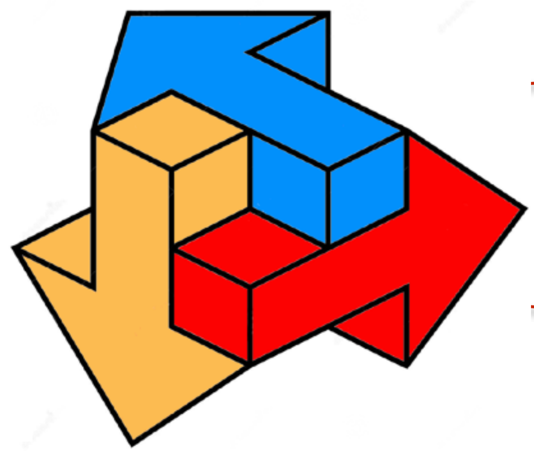
GB, Czakon, Papadopoulos, Pittau, Worek '09

Denner, Dittmaier, Kallweit, Pozzorini '10

Worek '12

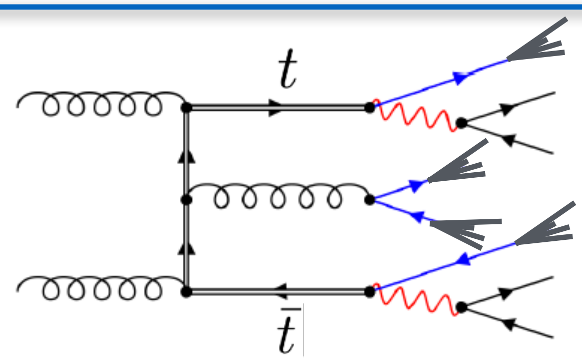
$pp \to t\bar{t}b\bar{b}j$

Buccioni, Kallweit, Pozzorini, Zoller '19



- Most realistic description of *hadronic observables*
- Based on Narrow Width Approximation for t and W decays (with spin correlations)
- Decay matrix elements computed with LO accuracy (radiative effects approximated by PS)

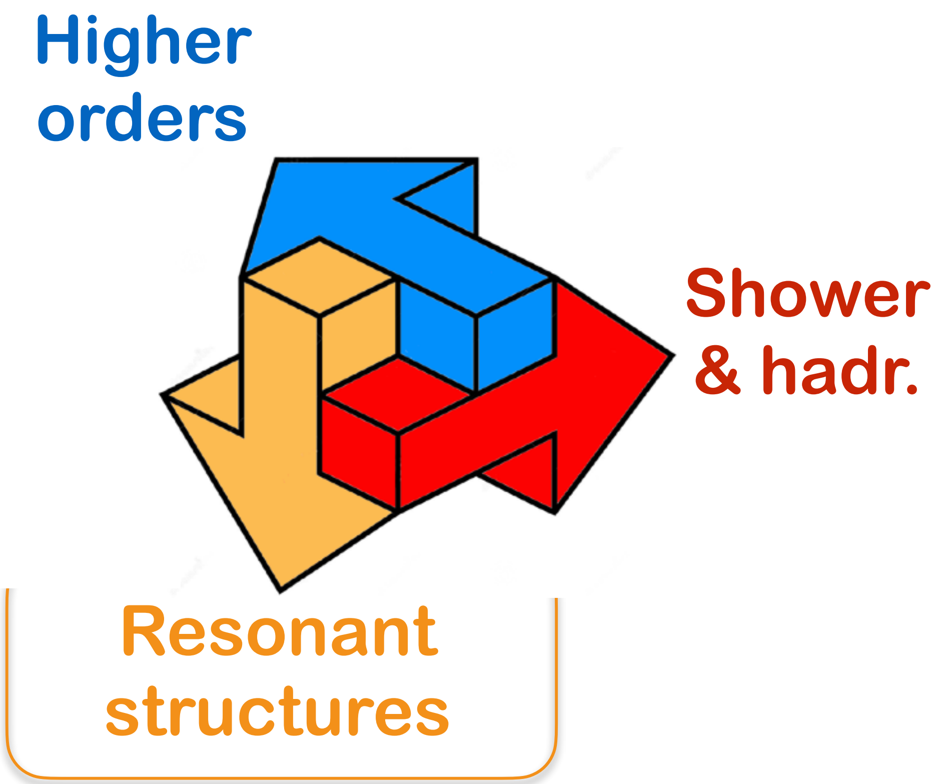
State of the art: NLO QCD



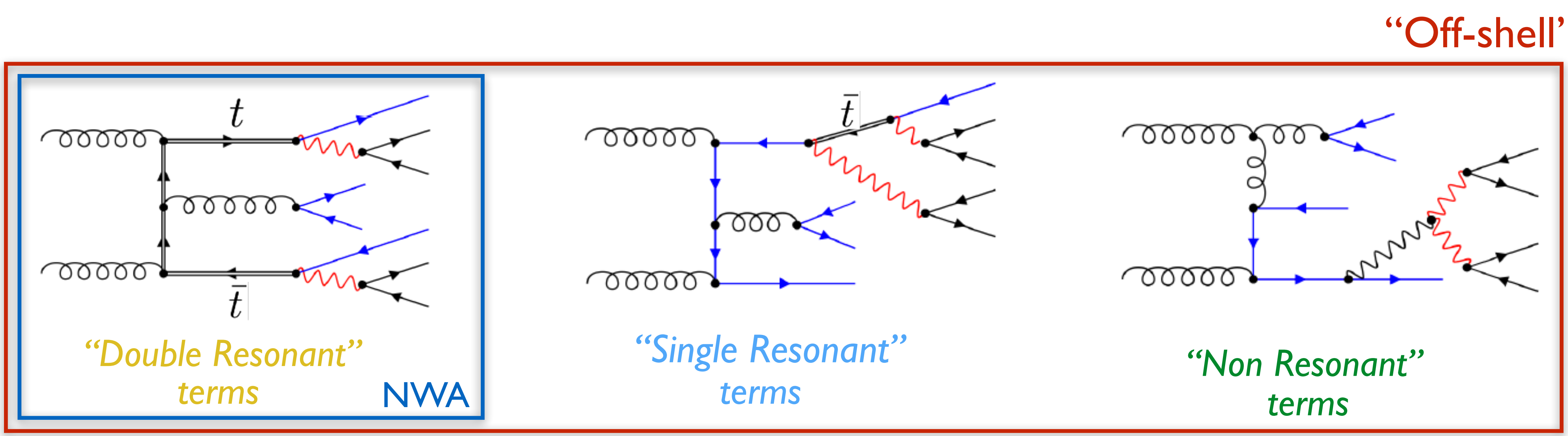
"Double Resonant" production x decay

- **POWHEG** matching
  - Garzelli, Kardos, Trocsanyi '14 '15 [5FS]
  - GB, Garzelli, Kardos '17 [4FS]
  - Jezo, Lindert, Moretti, Pozzorini '18 [4FS]
- **MC@NLO** matching
  - Cascioli, Maierhofer, Moretti, Pozzorini, Siegert '14 [4FS]
- Dedicated comparison of $t\bar{t}b\bar{b}$ MC's (**LHC HXSWG)**
  - Pozzorini, Buccioni, Siegert, Garzelli, GB, Jezo, Krause, Kardos, Lindert, Podskubka, Reuschle and Zaro '21 [4FS]

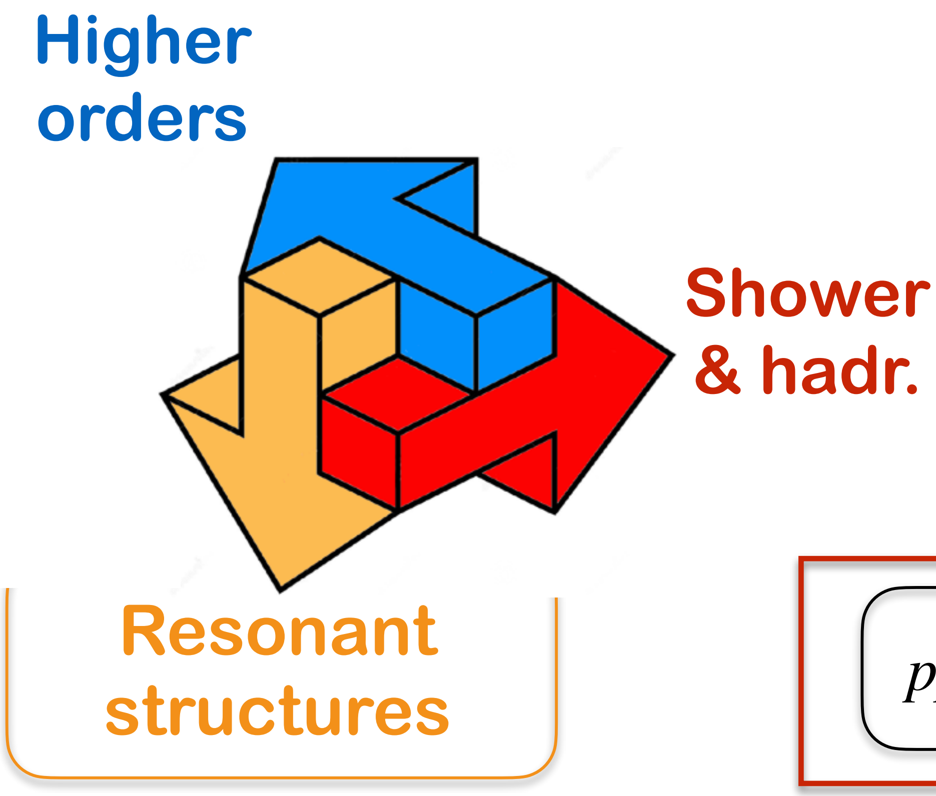
Avenues to precision



- Most realistic description of *resonant structures* over phase space
- Drops the limits $\Gamma_t/m_t \to 0,\ \Gamma_W/m_W \to 0$
- Complete calculation of fully decayed process at *fixed order*



"Off-shell" = DR + SR + NR + interferences



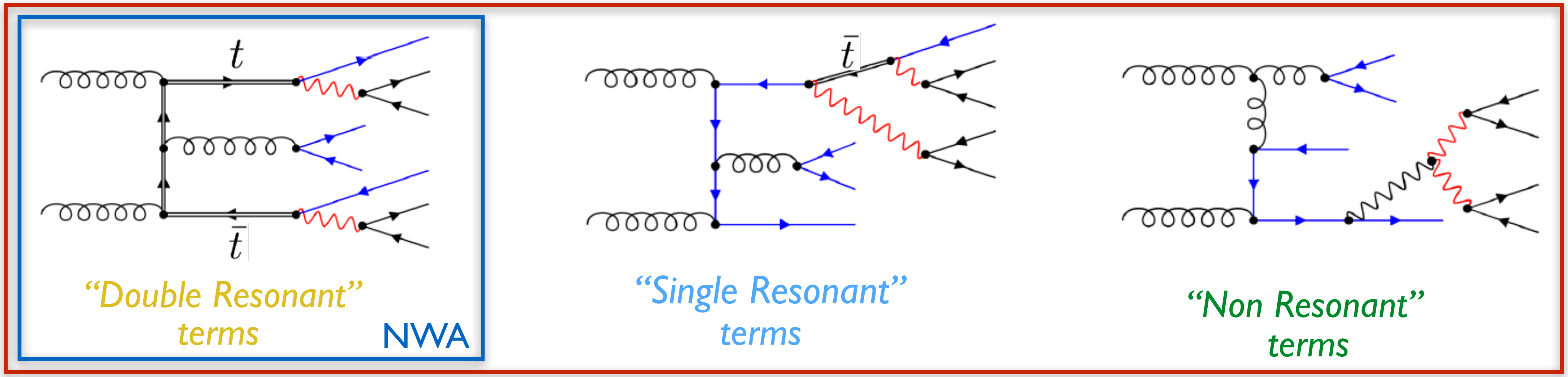
- Most realistic description of *resonant structures* over phase space
- Drops the limits $\Gamma_t/m_t \to 0,\ \Gamma_W/m_W \to 0$
- Complete calculation of fully decayed process at *fixed order*

Focus of this talk

$$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\, b\bar{b}b\bar{b}$$

Denner, Lang, Pellen '21
GB, Bi, Hartanto, Kraus, Lupattelli, Worek '21 '23

"Off-shell"

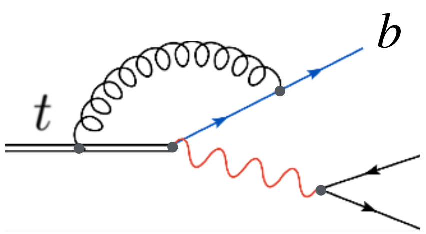


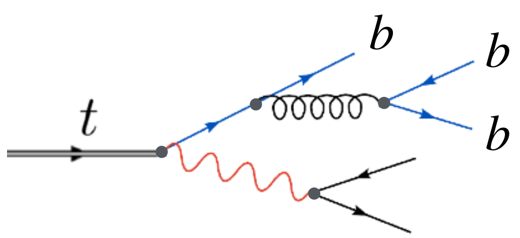
"Off-shell" = DR + SR + NR + interferences

Topics covered in this talk

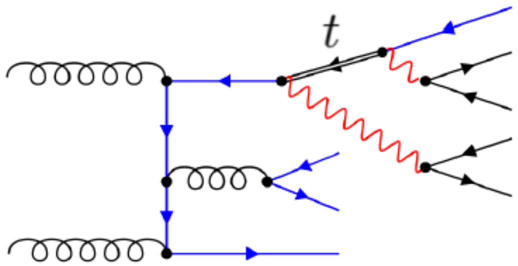
- Dominant theory uncertainties in $t\bar{t}b\bar{b}$ with *dilepton* signatures

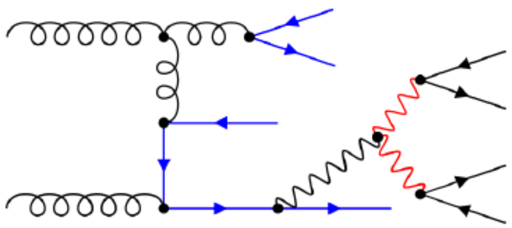
- Impact of top-quark decay modelling accuracy
  - QCD corrections to top decays
  - Multi b-jet top decays



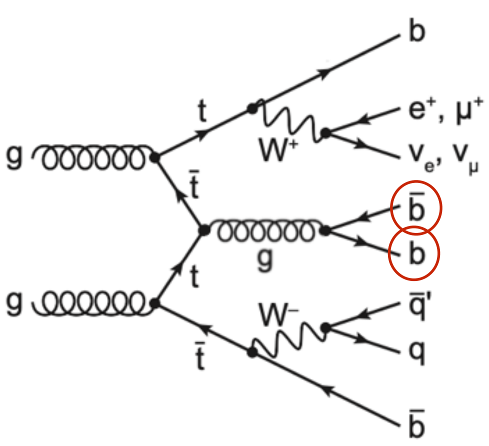


- Impact of full off-shell effects for t and W decays

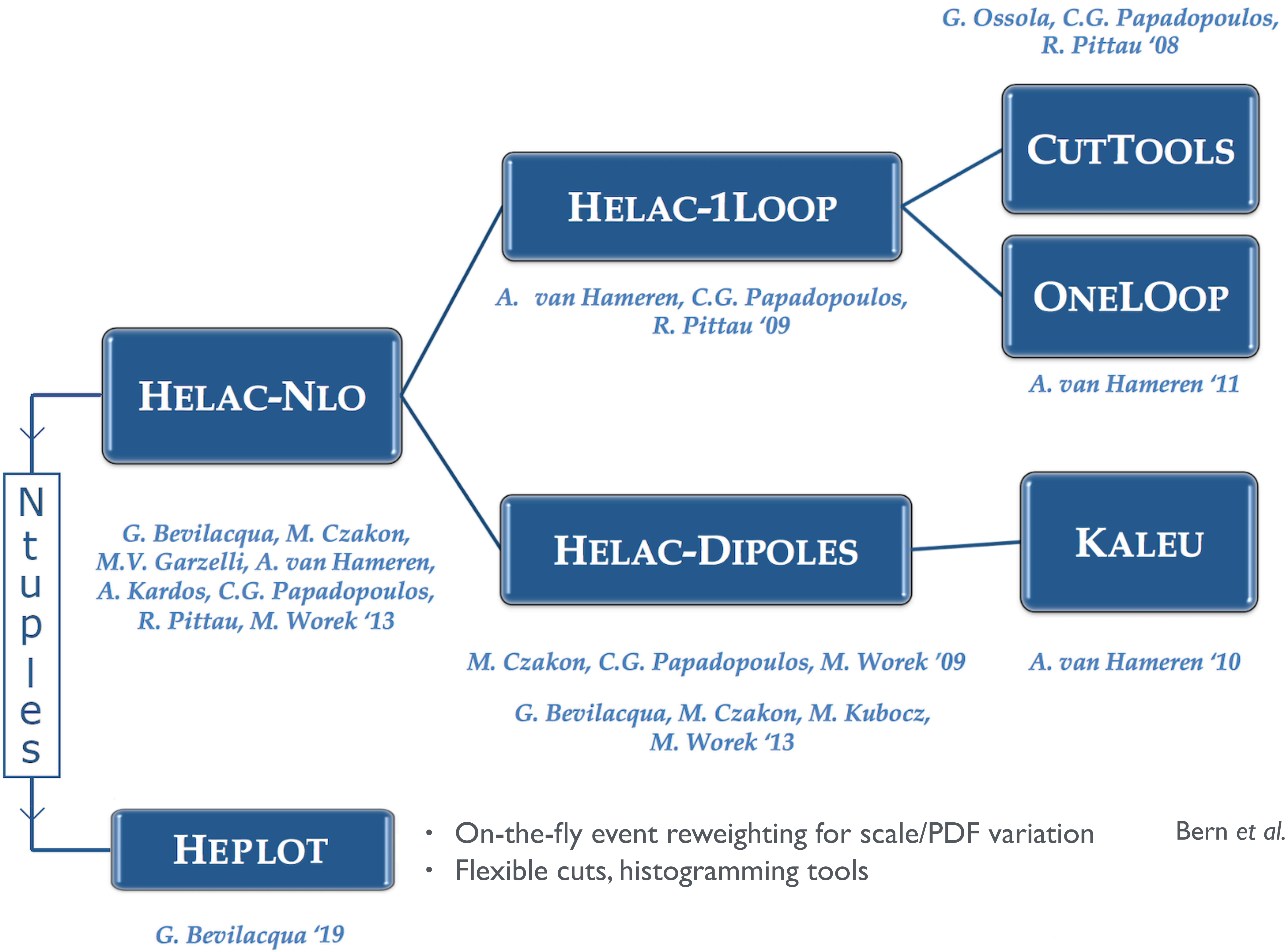




- b-jet labelling and identification of prompt b-jets



Computational framework



- On-the-fly event reweighting for scale/PDF variation
- Flexible cuts, histogramming tools

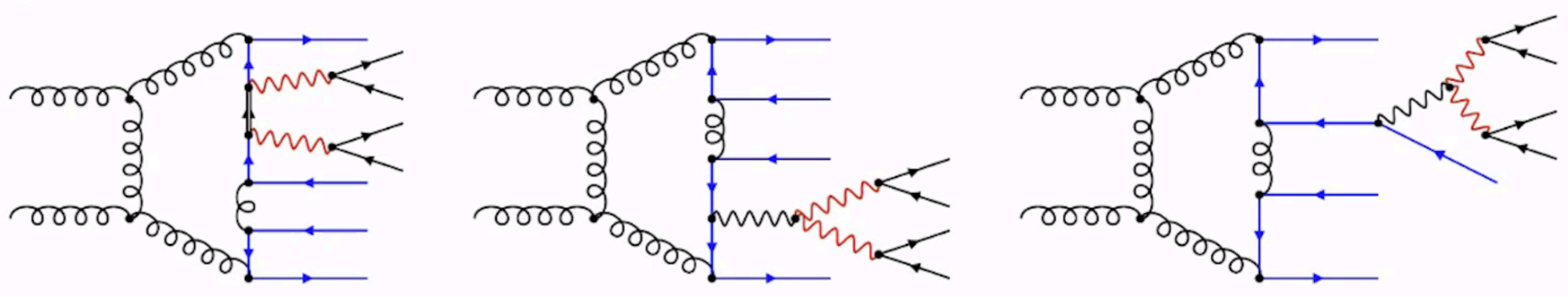
Bern *et al.* '14

Technical aspects of off-shell $t\bar{t}b\bar{b}$ at NLO

One-loop correction type	Number of Feynman diagrams
Self-energy	93452
Vertex	88164
Box-type	49000
Pentagon-type	25876
Hexagon-type	11372
Heptagon-type	3328
Octagon-type	336
Total number [gg channel]	271528

$$gg \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\,b\bar{b}$$

Partonic Subprocess	Number of Feynman diagrams	Number of CS Dipoles	Number of NS Subtractions
$gg \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}\,g$	41364	90	18
$q\bar{q} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}\,g$	9576	50	10
$gq \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}\,q$	9576	50	10
$g\bar{q} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}\,\bar{q}$	9576	50	10



I. Size of QCD corrections and dominant theory uncertainties at NLO

$t\bar{t}b\bar{b}$ with dilepton signatures: full off-shell predictions

- **Integrated fiducial cross sections**

$\sqrt{s} = 13$ TeV

Analysis cuts: $p_T(\ell) > 20$ GeV , $p_T(b) > 25$ GeV , $|y(\ell)| < 2.5$, $|y(b)| < 2.5$

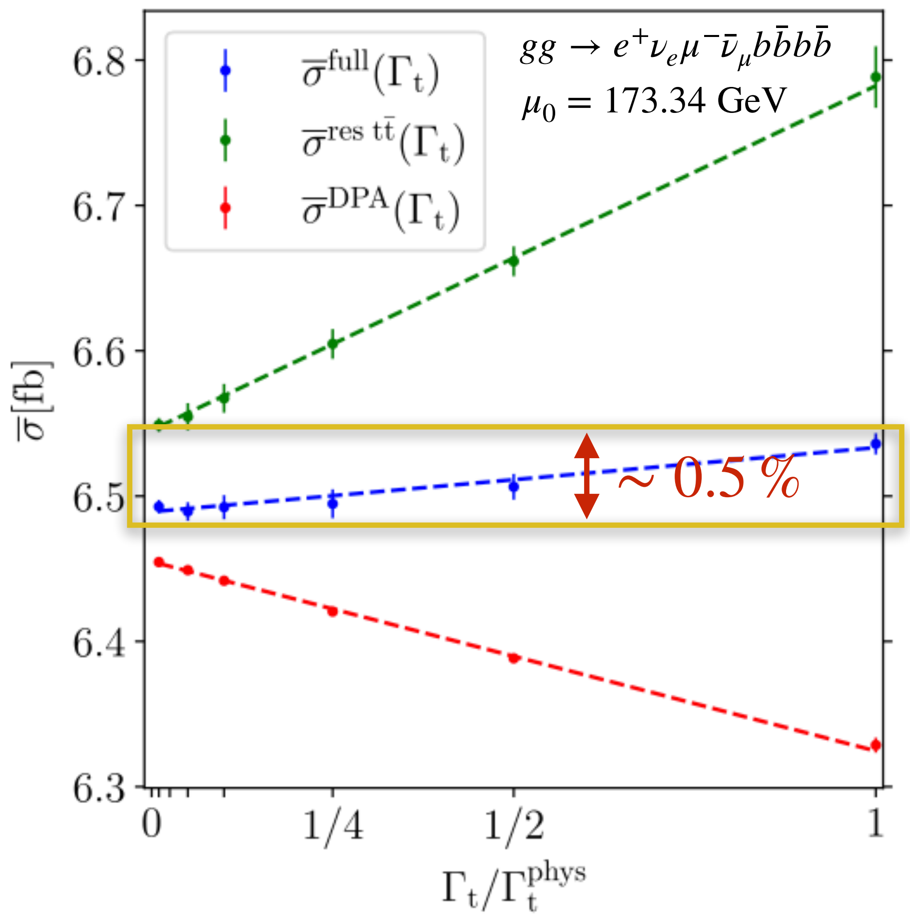
[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, JHEP 08 (2021) 008]

$p_T(b)$	$\sigma^{\rm LO}$ [fb]	$\delta_{\rm scale}$	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$	$\delta_{\rm PDF}$	$\mathcal{K} = \sigma^{\rm NLO}/\sigma^{\rm LO}$
		$\mu_R = \mu_F = \mu_0 = H_T/3$		[NNPDF 3.1]		
25	6.813	$+4.338$ (64%) -2.481 (36%)	13.22	$+2.66$ (20%) -2.95 (22%)	$+0.19$ (1%) -0.19 (1%)	1.94
30	4.809	$+3.062$ (64%) -1.756 (37%)	9.09	$+1.66$ (18%) -1.98 (22%)	$+0.16$ (2%) -0.16 (2%)	1.89
35	3.431	$+2.191$ (64%) -1.256 (37%)	6.37	$+1.07$ (17%) -1.36 (21%)	$+0.11$ (2%) -0.11 (2%)	1.86
40	2.464	$+1.582$ (64%) -0.901 (37%)	4.51	$+0.72$ (16%) -0.95 (21%)	$+0.09$ (2%) -0.09 (2%)	1.83

- QCD corrections are large
- Impact of jet veto:

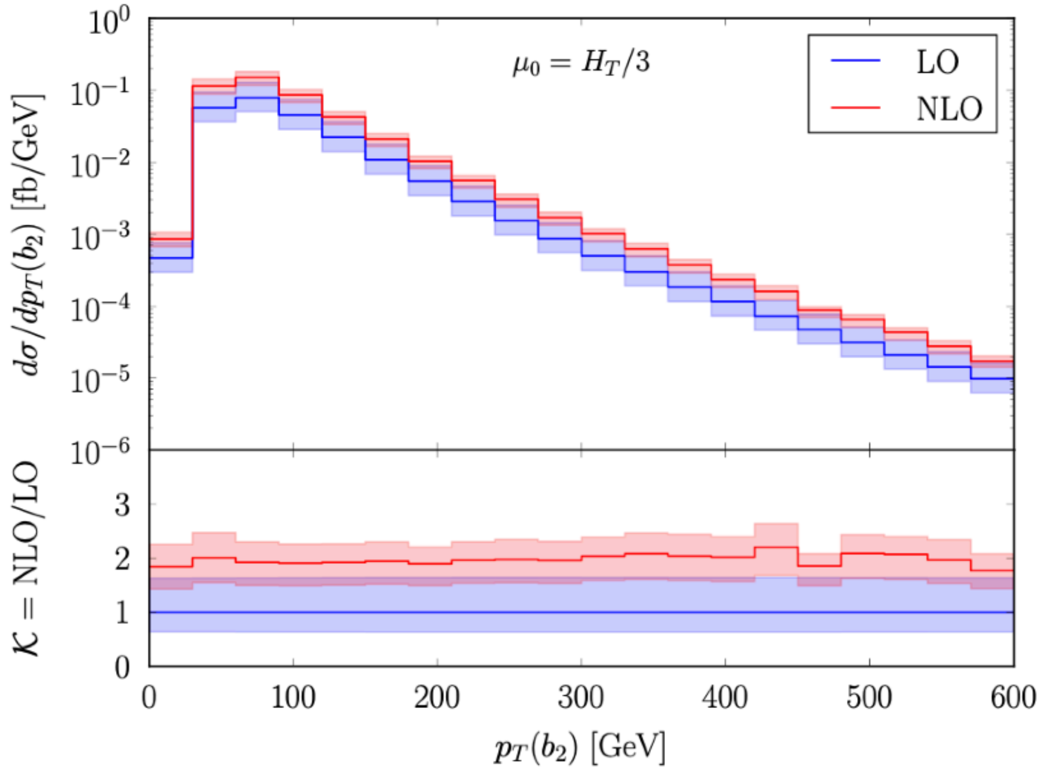
$$p_T^{\rm veto}(j) = 100 \text{ GeV} \rightarrow \sigma^{\rm NLO}/\sigma^{\rm LO} = 1.58$$
$$p_T^{\rm veto}(j) = 50 \text{ GeV} \rightarrow \sigma^{\rm NLO}/\sigma^{\rm LO} = 1.23$$

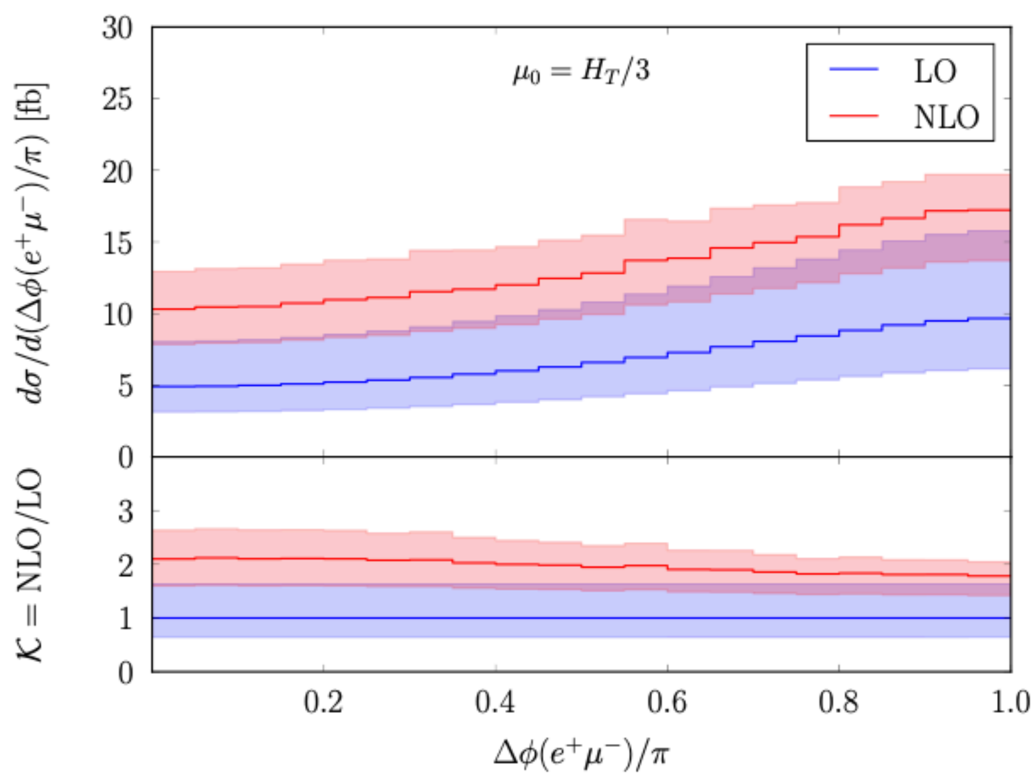
[Denner, Lang, Pellen, Phys. Rev. D 104 (2021), 056018]



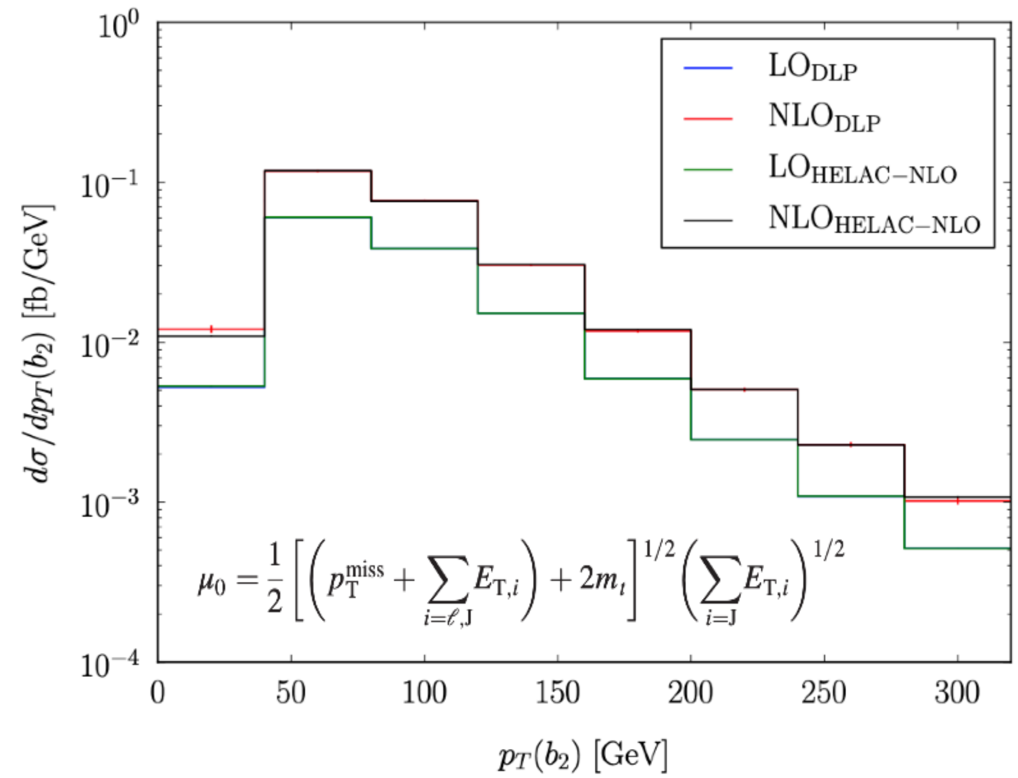
Off-shell $t\bar{t}b\bar{b}$: differential cross sections

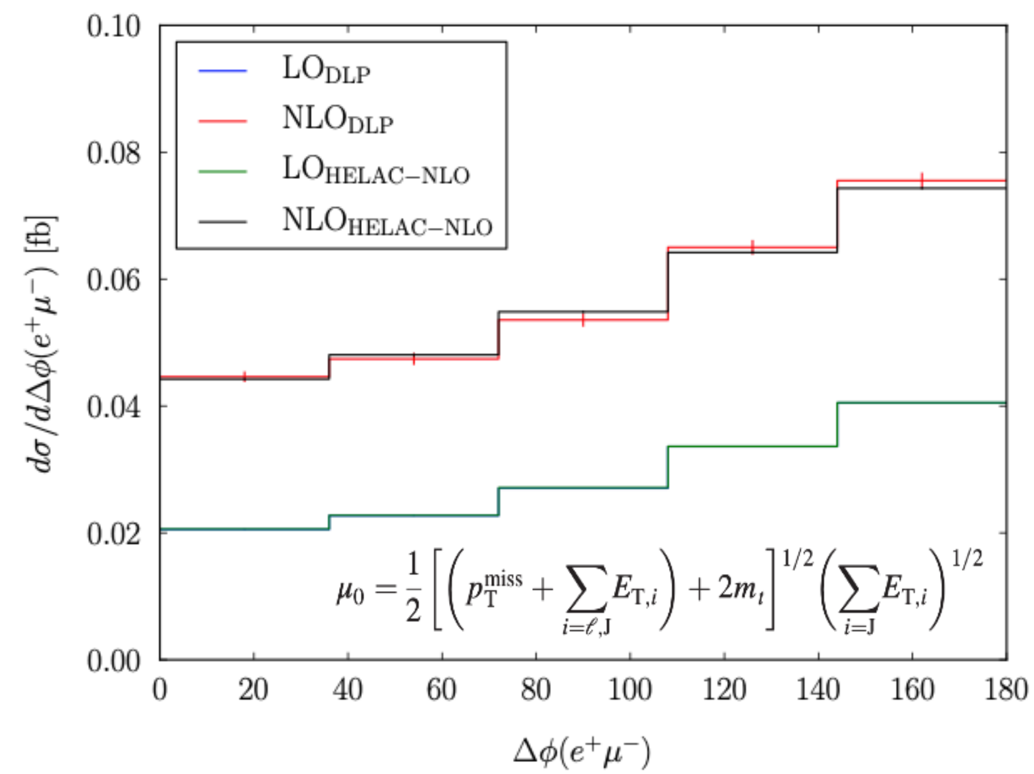
[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, JHEP 08 (2021) 008]





Comparison with Denner, Lang and Pellen, [Phys. Rev. D 104 (2021), 056018]





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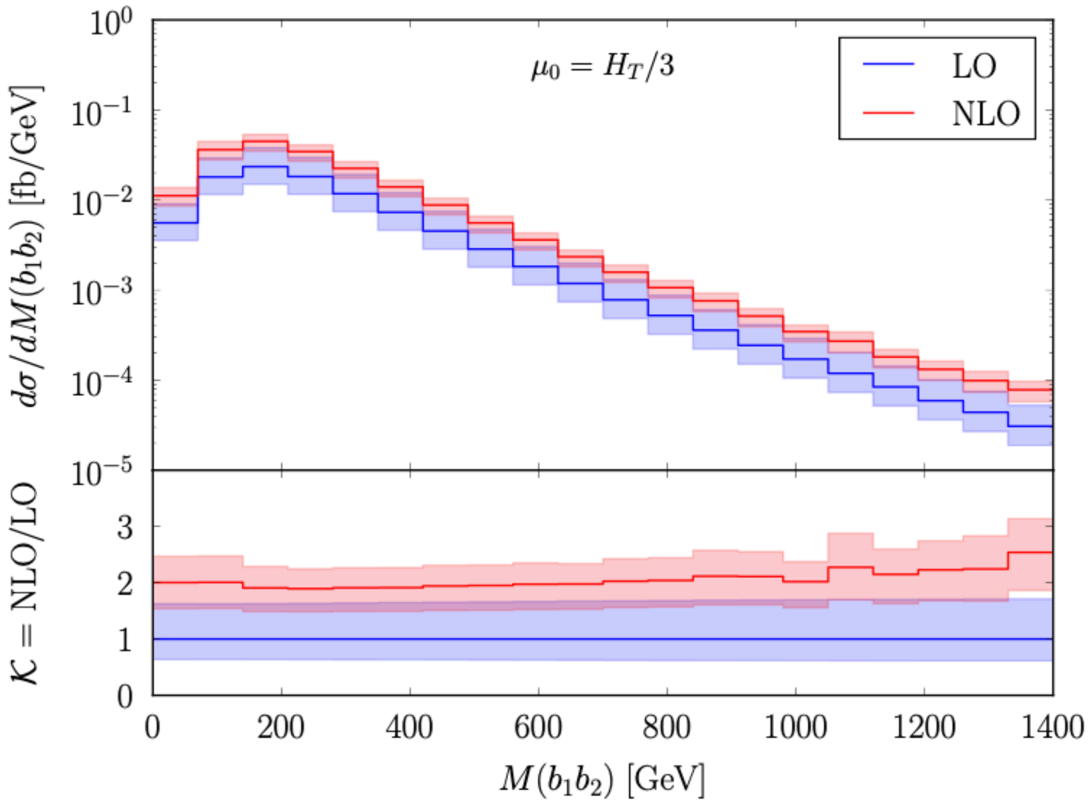
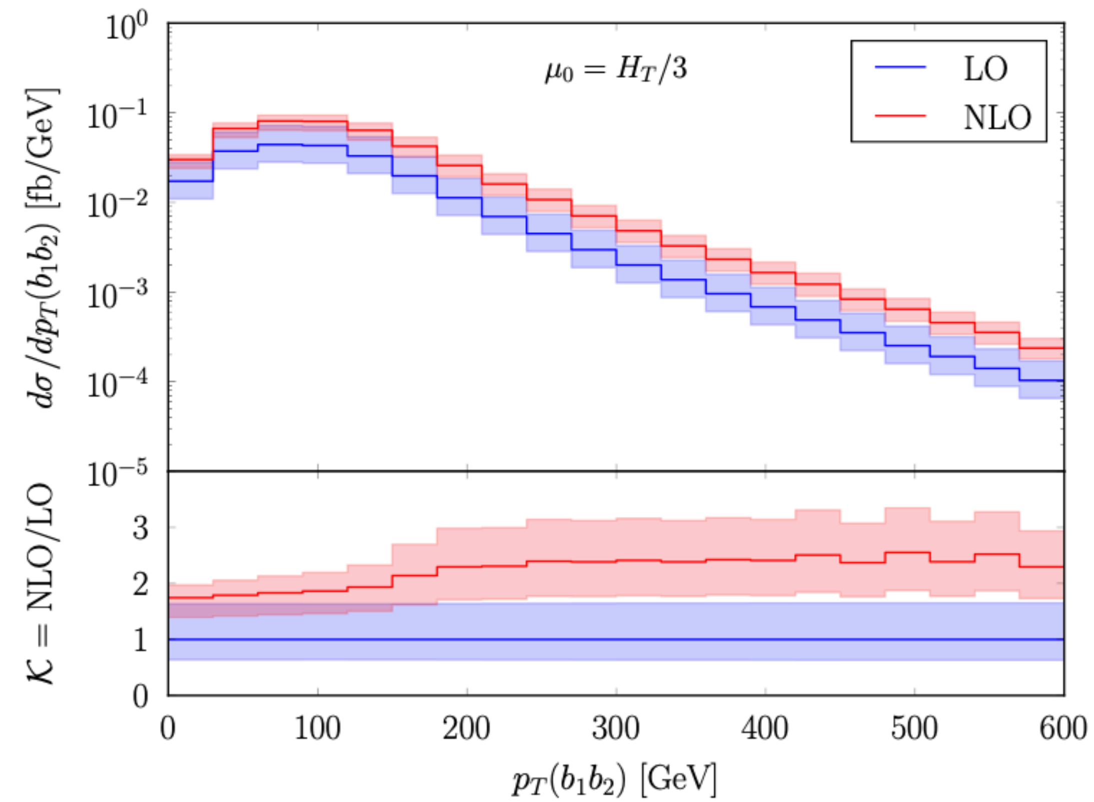
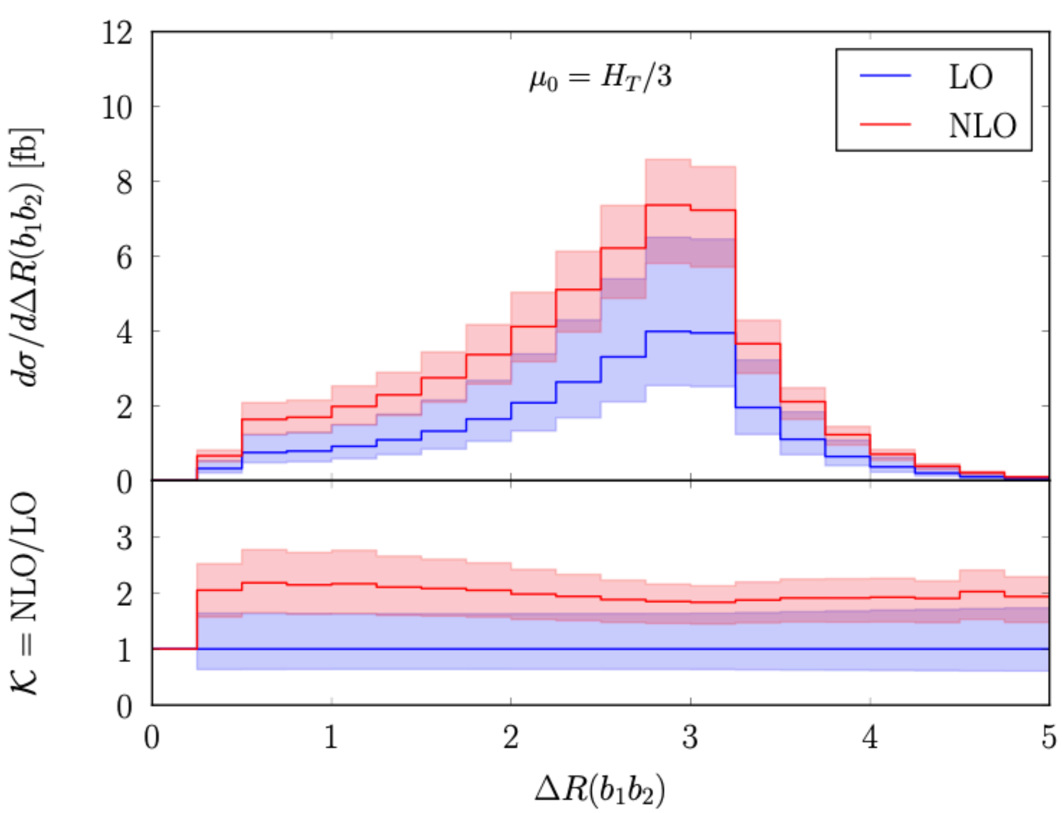
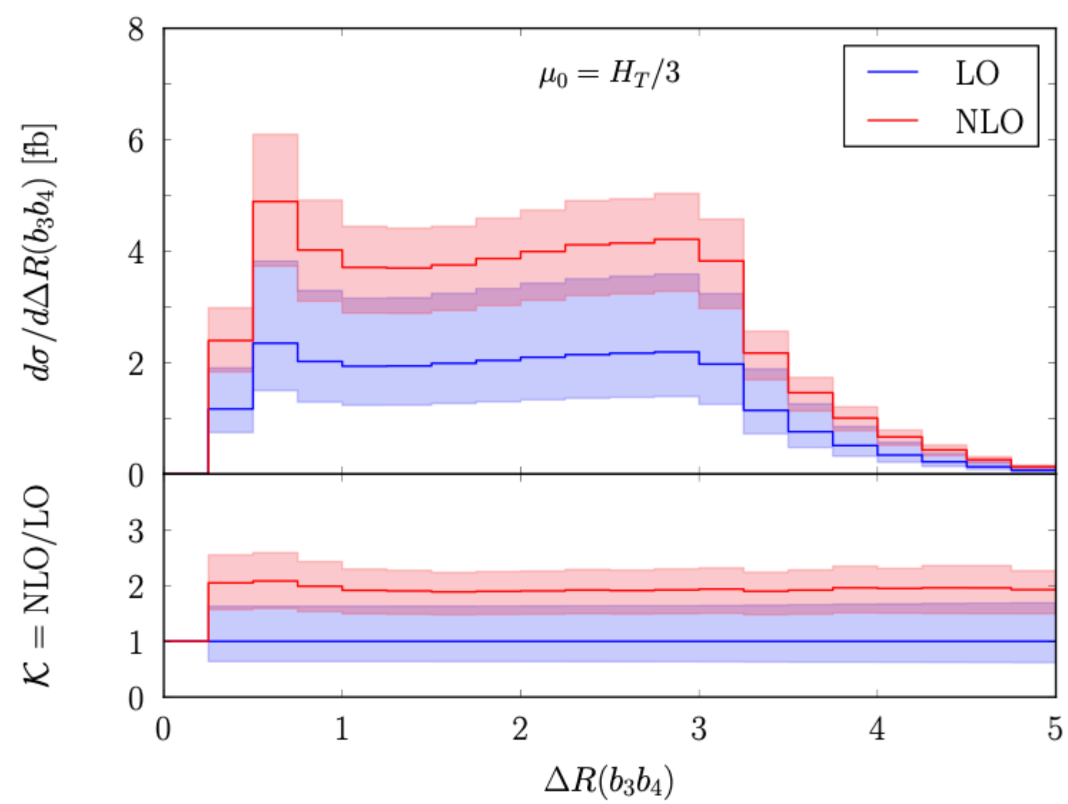


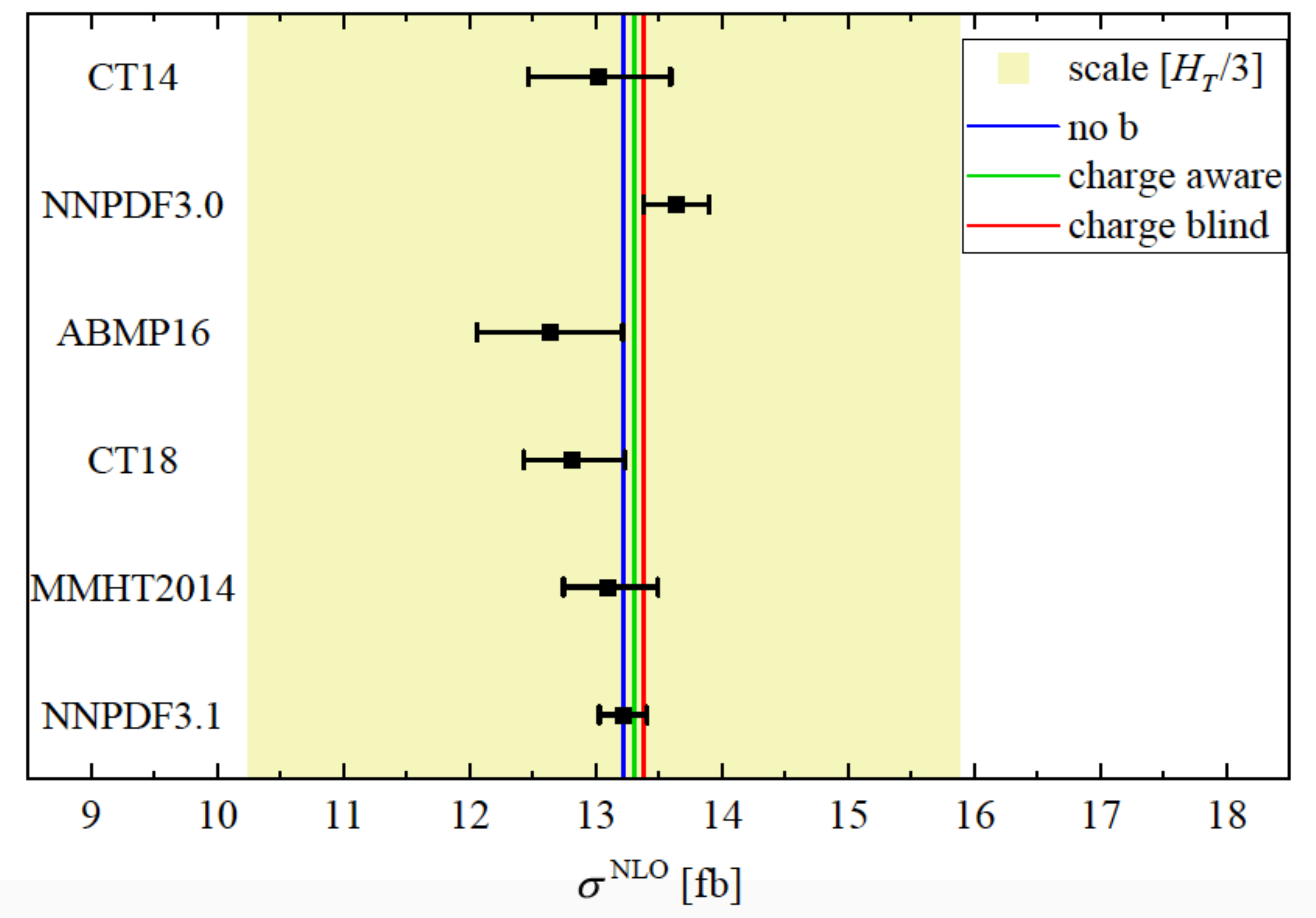


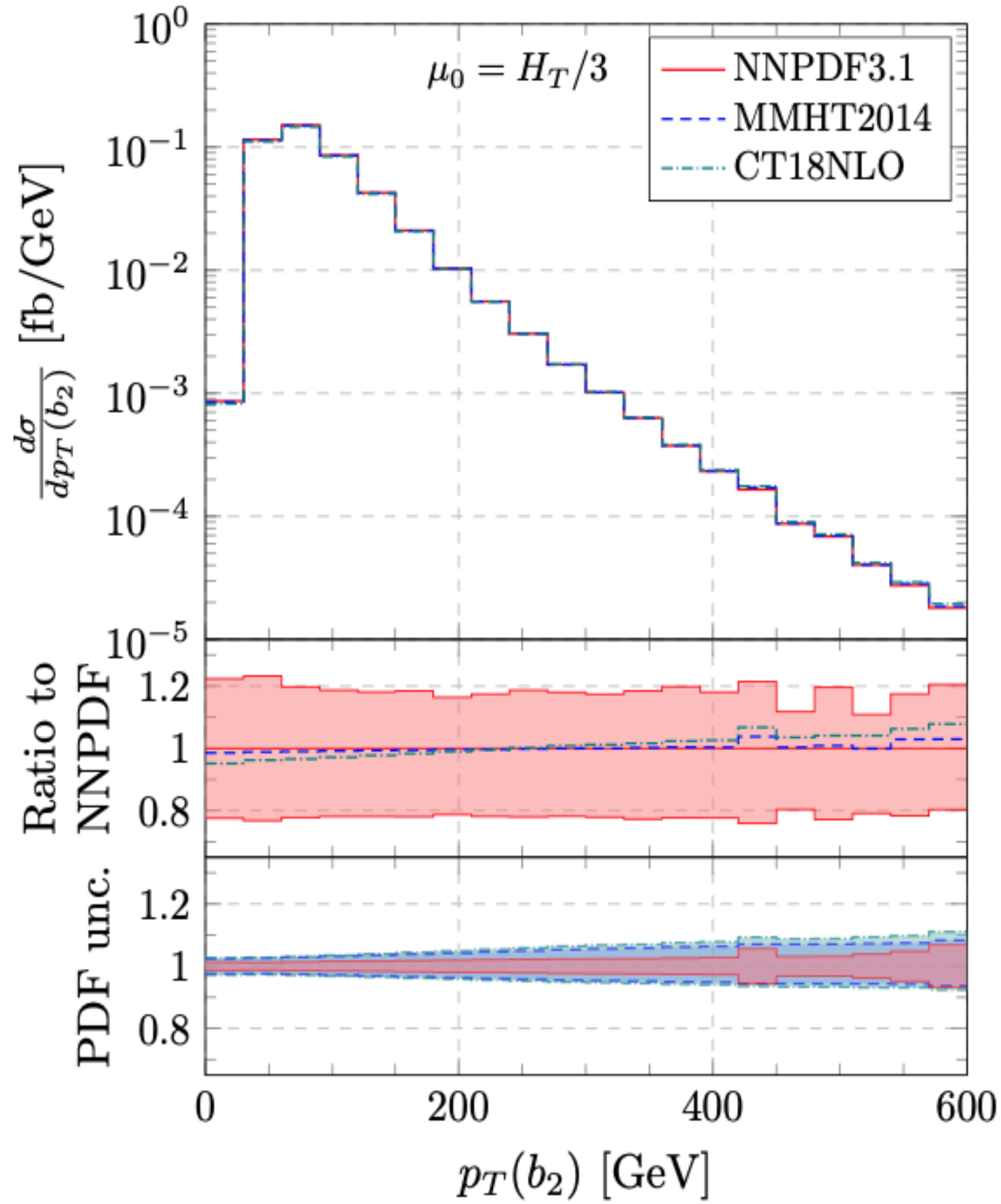




Off-shell $t\bar{t}b\bar{b}$: theoretical uncertainties at NLO

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, JHEP 08 (2021) 008]





NLO theory uncertainties

- Scale : $\mathcal{O}(20\%)$ - PDF : $\mathcal{O}(1\% - 3\%)$

↪ Relative sizes vary at high-energy tails

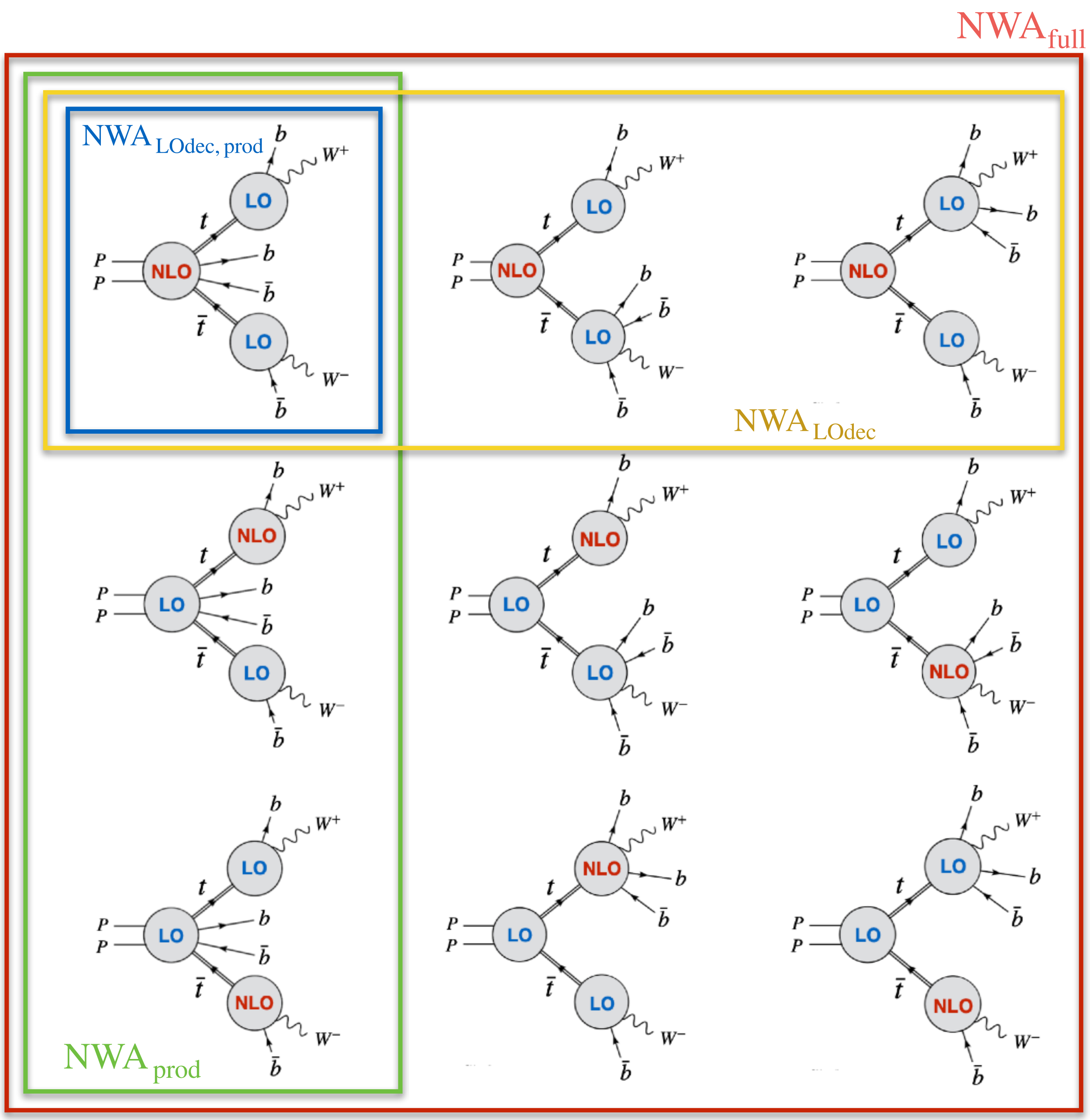
II. Accuracy of NWA and off-shell effects

$t\bar{t}b\bar{b}$: comparing modelling approaches

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]

- *Full off-shell* vs NWA

Modelling	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$ [fb]	$\frac{\sigma^{\rm NLO}}{\sigma^{\rm NLO}_{\rm NWA_{full}}} - 1$
Off-shell	13.22(2)	$^{+2.65\ (20\%)}_{-2.96\ (22\%)}$	+0.5%
$\rm NWA_{full}$	13.16(1)	$^{+2.61\ (20\%)}_{-2.93\ (22\%)}$	–
$\rm NWA_{LOdec}$	13.22(1)	$^{+3.77\ (29\%)}_{-3.31\ (25\%)}$	+0.5%
$\rm NWA_{prod}$	13.01(1)	$^{+2.58\ (20\%)}_{-2.89\ (22\%)}$	−1.1%
$\rm NWA_{prod,\,exp}$	12.25(1)	$^{+2.87\ (23\%)}_{-2.86\ (23\%)}$	−6.9%
$\rm NWA_{prod,\,LOdec}$	13.11(1)	$^{+3.74\ (29\%)}_{-3.28\ (25\%)}$	−0.4%



- NWA cross sections based on different levels of accuracy in top decay modelling

$t\bar{t}b\bar{b}$: comparing modelling approaches

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]

- *Full off-shell* vs NWA

Modelling	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$ [fb]	$\frac{\sigma^{\rm NLO}}{\sigma^{\rm NLO}_{\rm NWA_{full}}} - 1$
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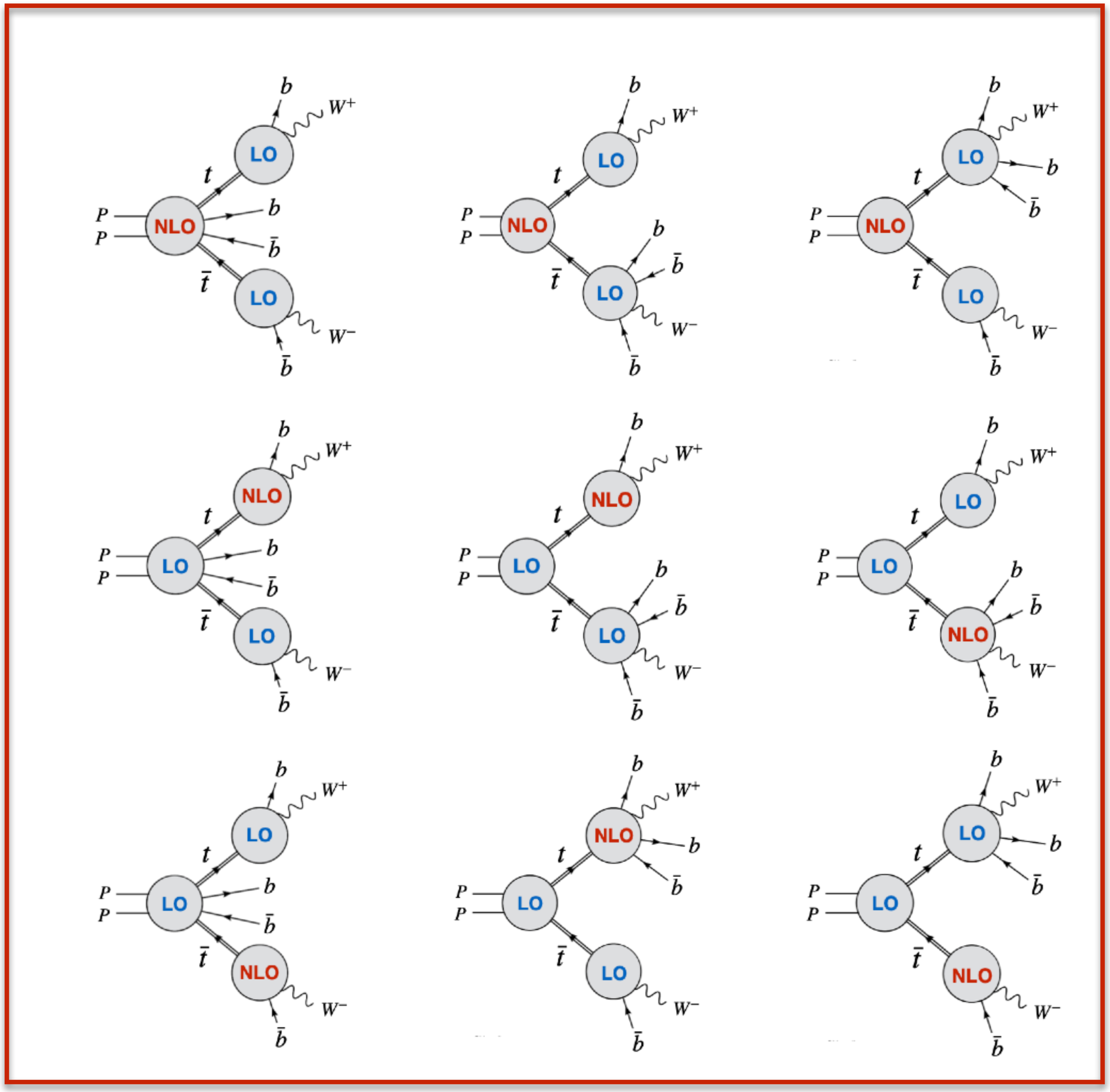
$\rm NWA_{full}$



- Off-shell vs $\rm NWA_{full}$:

↪ Off-shell effects: $+0.5\,\%$

$t\bar{t}b\bar{b}$: comparing modelling approaches

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]

- *Full off-shell* vs NWA

Modelling	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$ [fb]	$\frac{\sigma^{\rm NLO}}{\sigma^{\rm NLO}_{\rm NWA_{full}}} - 1$
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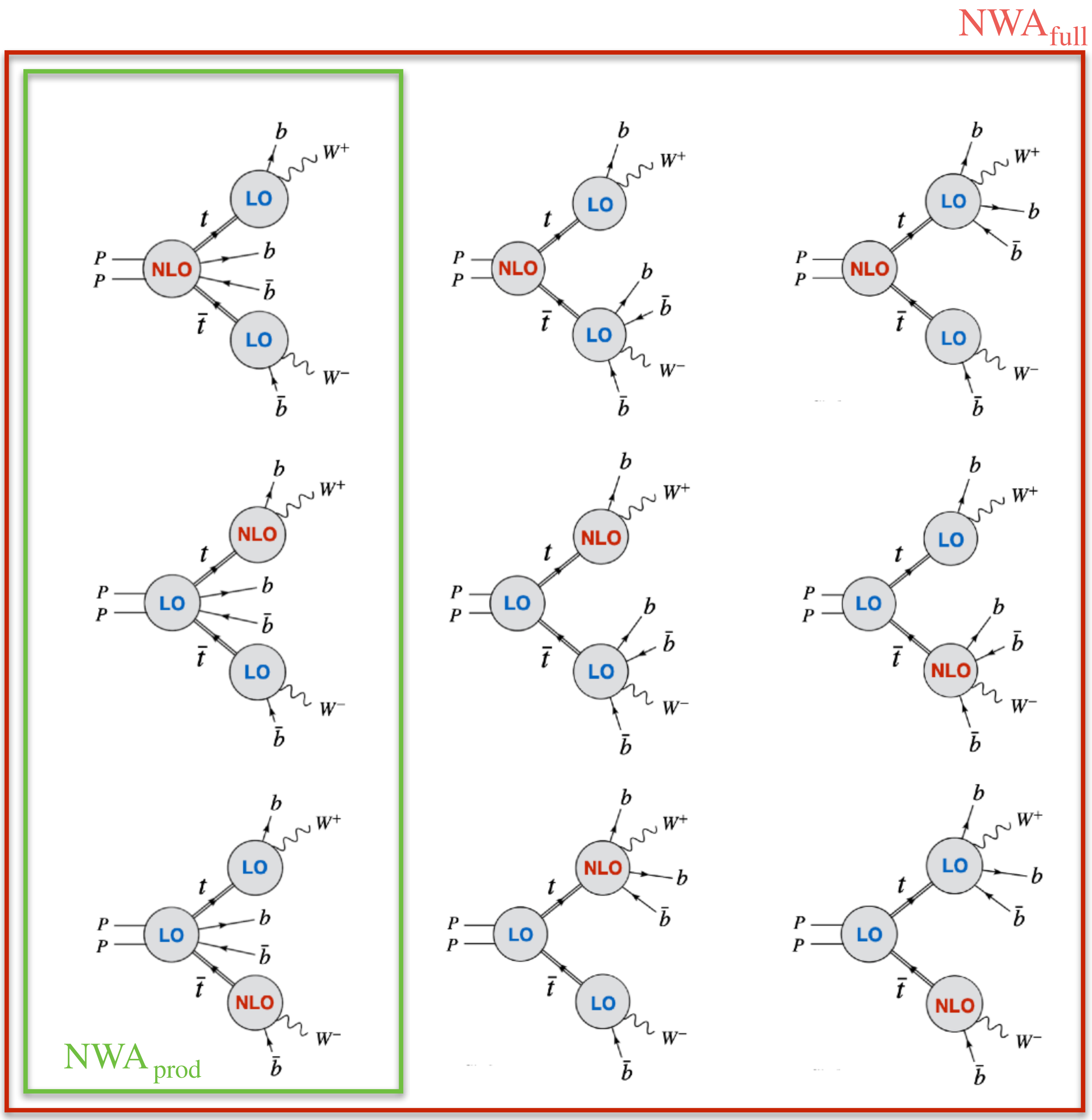
$\rm NWA_{prod,\,LOdec}$	13.11(1)	$^{+3.74\ (29\%)}_{-3.28\ (25\%)}$	−0.4%

- $\rm NWA_{full}$ vs $\rm NWA_{prod}$:

↪ Impact of $t \to Wbb\bar{b}$ decays: $+1\,\%$



[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]

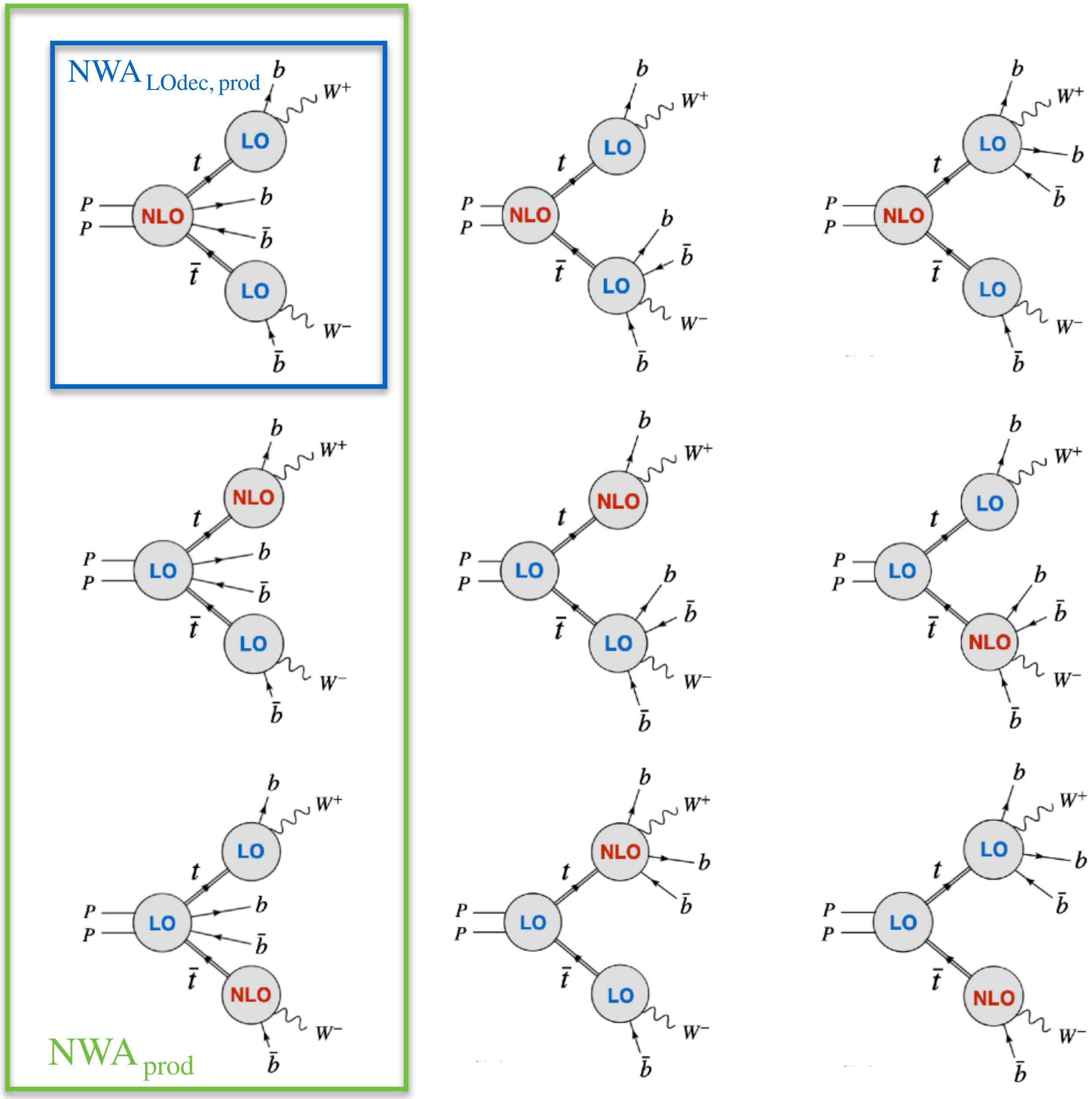
- *Full off-shell* vs NWA

Modelling	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$ [fb]	$\frac{\sigma^{\rm NLO}}{\sigma^{\rm NLO}_{\rm NWA_{full}}} - 1$
Off-shell	13.22(2)	$^{+2.65\ (20\%)}_{-2.96\ (22\%)}$	+0.5%
$\rm NWA_{full}$	13.16(1)	$^{+2.61\ (20\%)}_{-2.93\ (22\%)}$	–
$\rm NWA_{LOdec}$	13.22(1)	$^{+3.77\ (29\%)}_{-3.31\ (25\%)}$	+0.5%
$\rm NWA_{prod}$	13.01(1)	$^{+2.58\ (20\%)}_{-2.89\ (22\%)}$	−1.1%
$\rm NWA_{prod,\,exp}$	12.25(1)	$^{+2.87\ (23\%)}_{-2.86\ (23\%)}$	−6.9%
$\rm NWA_{prod,\,LOdec}$	13.11(1)	$^{+3.74\ (29\%)}_{-3.28\ (25\%)}$	−0.4%

- $\rm NWA_{prod}$ vs $\rm NWA_{prod,LOdec}$:

↪ Tiny difference: 0.8 %

How shall this be interpreted?



$t\bar{t}b\bar{b}$: comparing modelling approaches

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]

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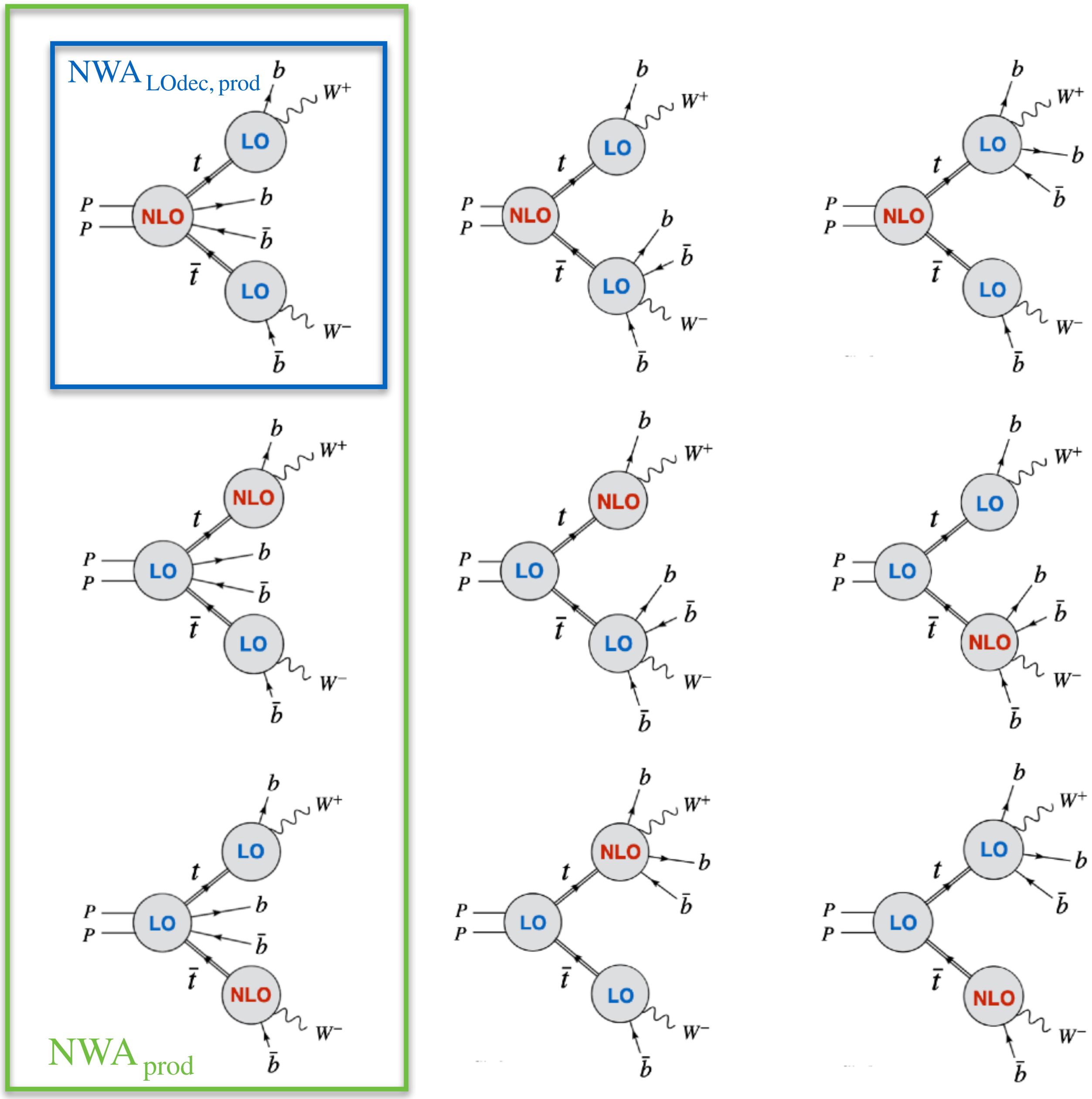
- $\rm NWA_{prod,exp}$ vs $\rm NWA_{prod,LOdec}$:

↪ Genuine QCD corrections to top decays: $-7\,\%$



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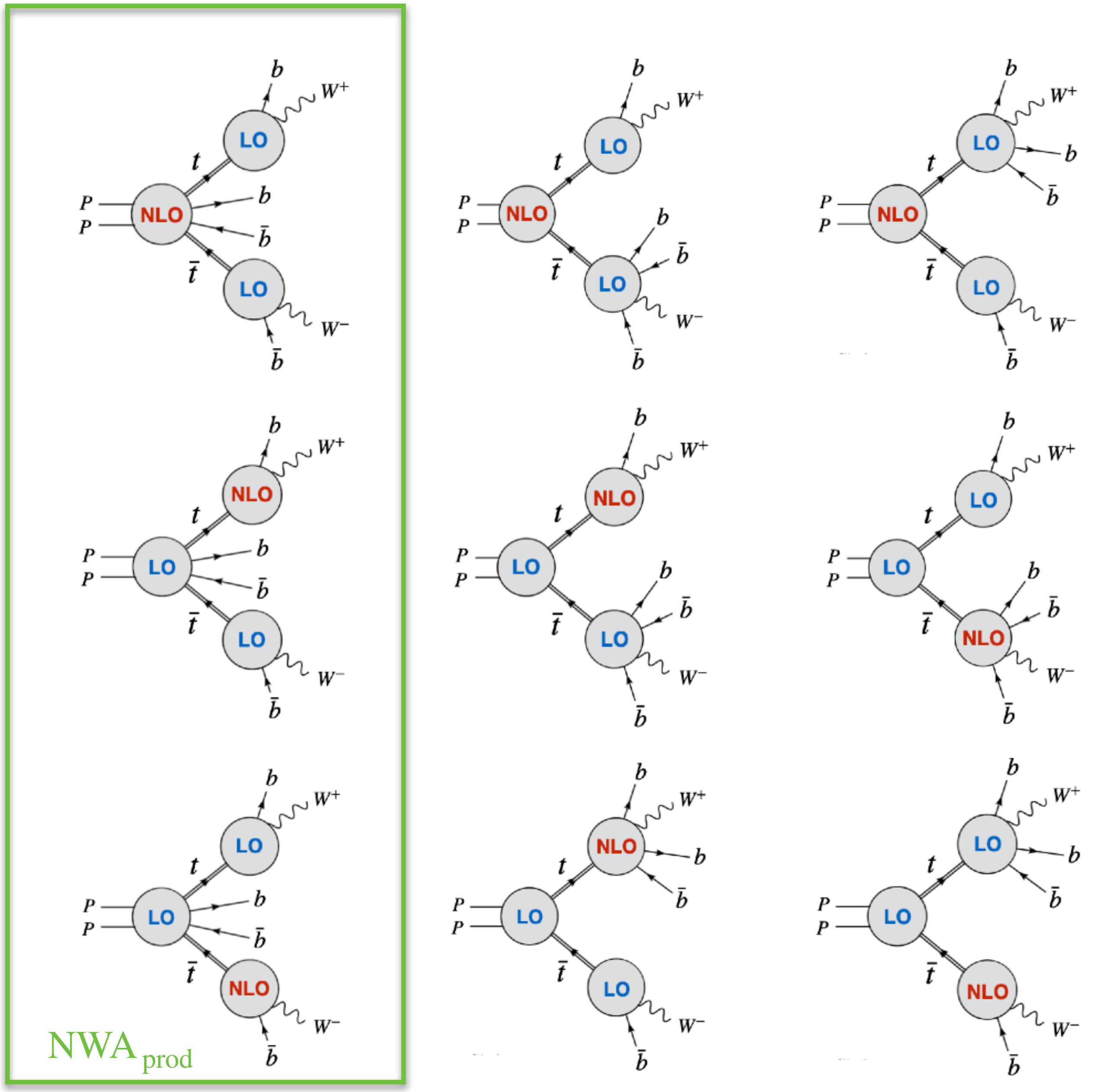
- $\rm NWA_{prod}$ vs $\rm NWA_{prod,exp}$:

↪ Impact of Γ_t^{NLO} expansion: $+6\,\%$

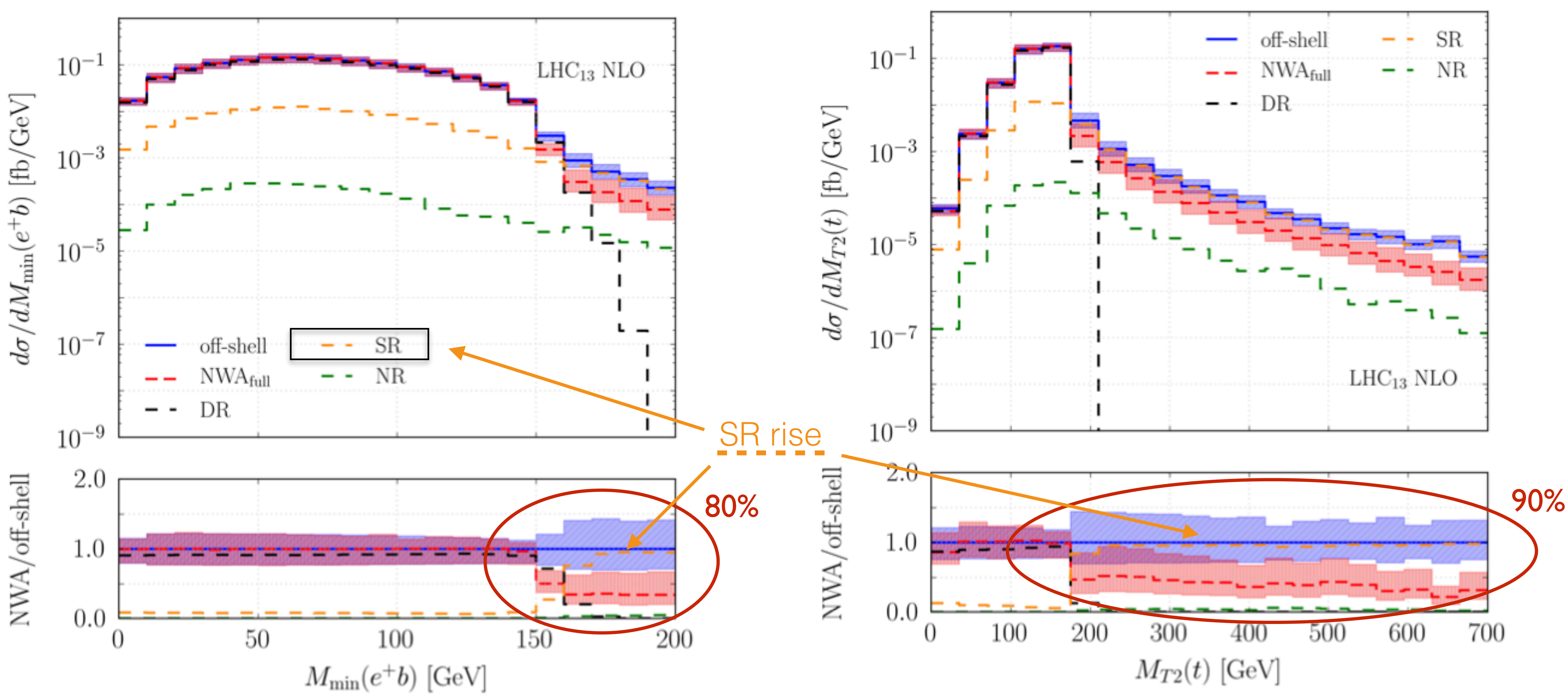
$\mathcal{O}(\alpha_s^2)$ effects (within NLO scale uncertainty)



$t\bar{t}b\bar{b}$: anatomy of full off-shell effects at differential level

- Off-shell effects amount to few permille for most observables used in SM analyses
- Threshold observables used in BSM studies are naturally more sensitive:

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]



$$\mathrm{LO_{NWA}} \rightarrow M_{min}(e^+b) < \sqrt{m_t^2 - m_W^2} \approx 153\ \mathrm{GeV}$$

$$M_{T2}(t) = \min_{\sum p_T^{\nu_i} = p_T^{miss}} \left[\max\{M_T^2(p_T(e^+X_t), p_T(\nu_1)),\; M_T^2(p_T(\mu^-X_{\bar{t}}), p_T(\nu_2))\}\right]$$

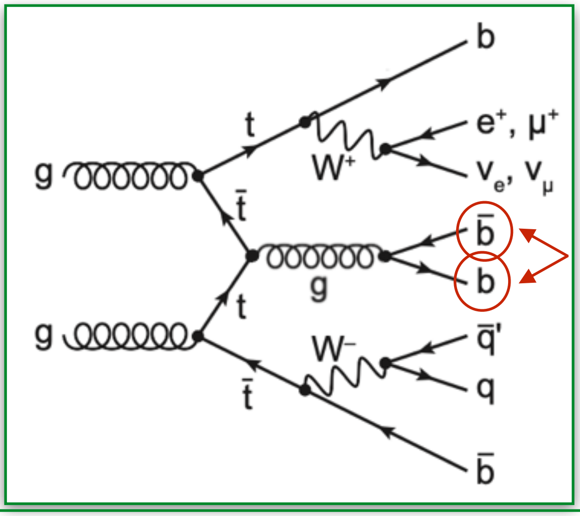
III. Identification of prompt b-jets

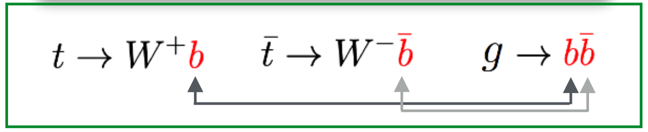
$t\bar{t}b\bar{b}$: prompt b-jet identification

- Labelling prompt b-jets in $t\bar{t}b\bar{b}$ is not free of ambiguities in a full calculation (due to combinatorial background and quantum interference)

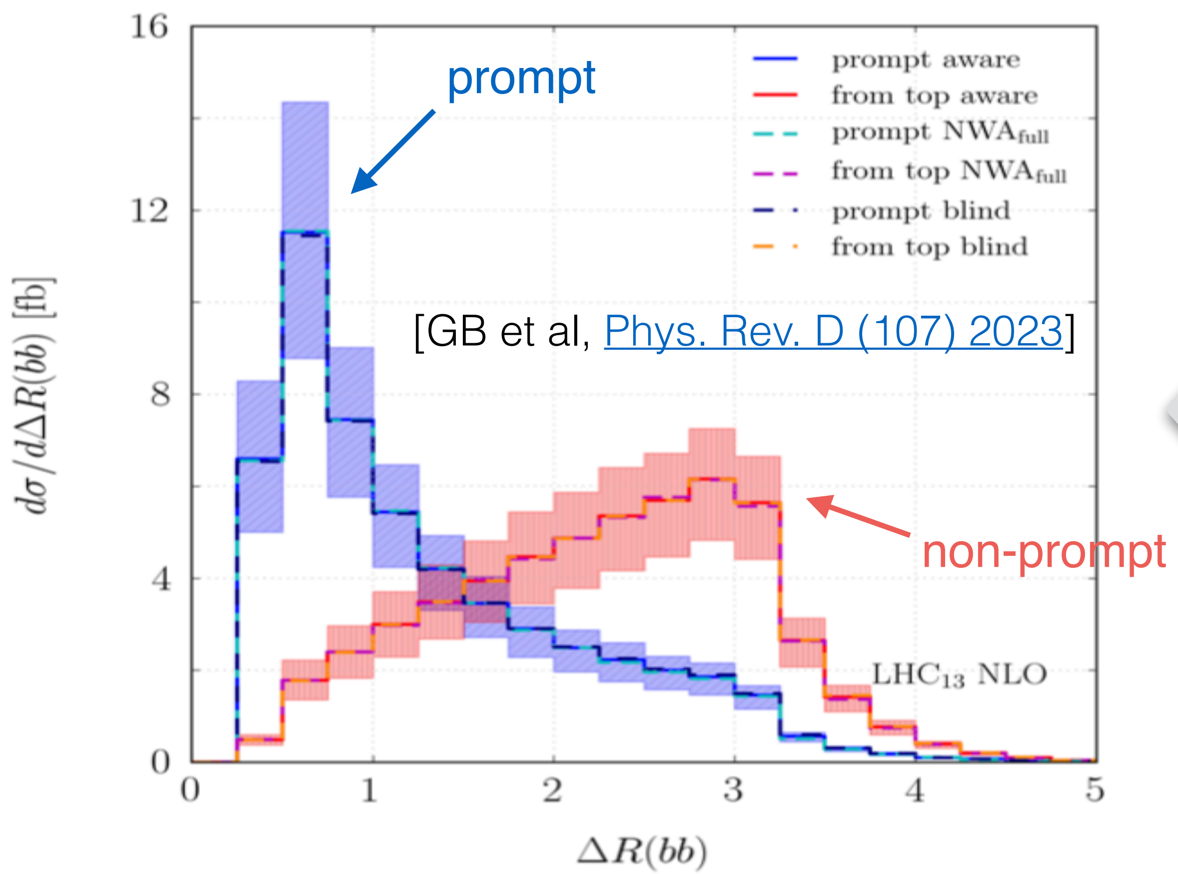
- Kinematic-based prescription: determine prompt b-jets according to a minimum principle for Q:

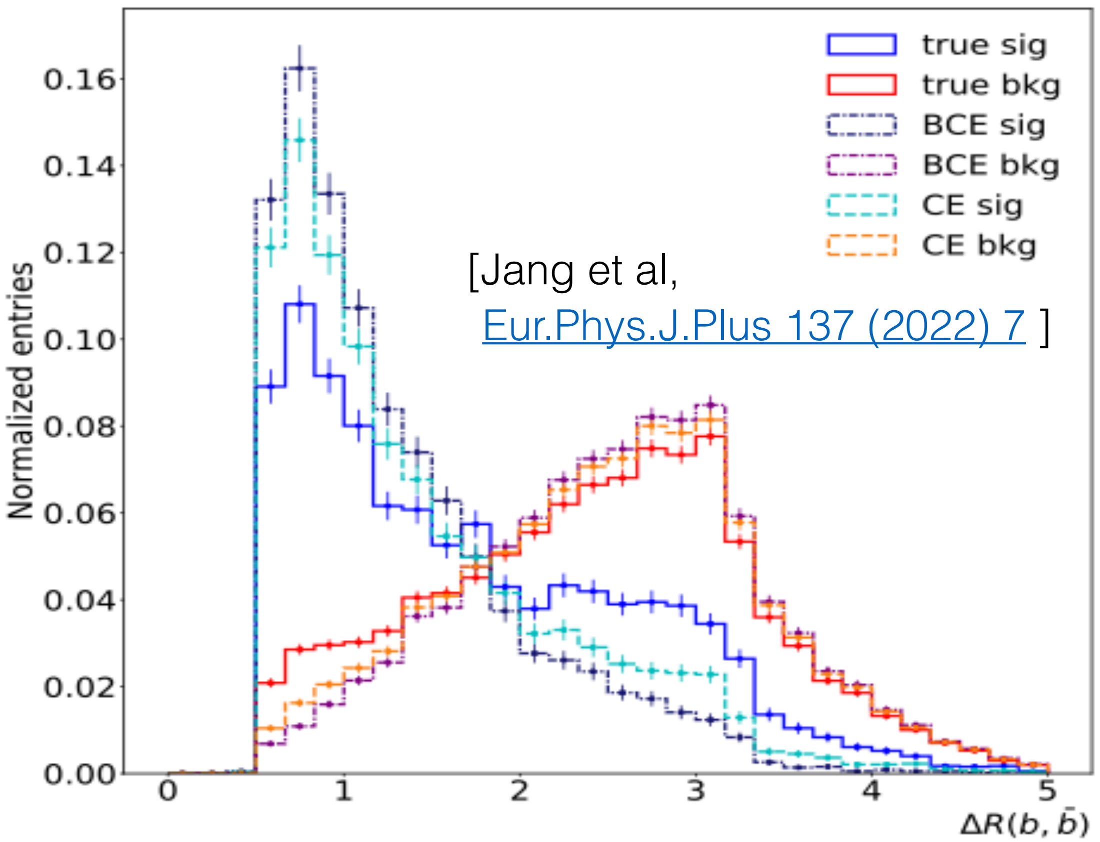
$$Q = |M(t) - m_t| \times |M(\bar{t}) - m_t| \times |M^{\text{prompt}}(bb)|$$





- Results consistent with DNN-based studies:

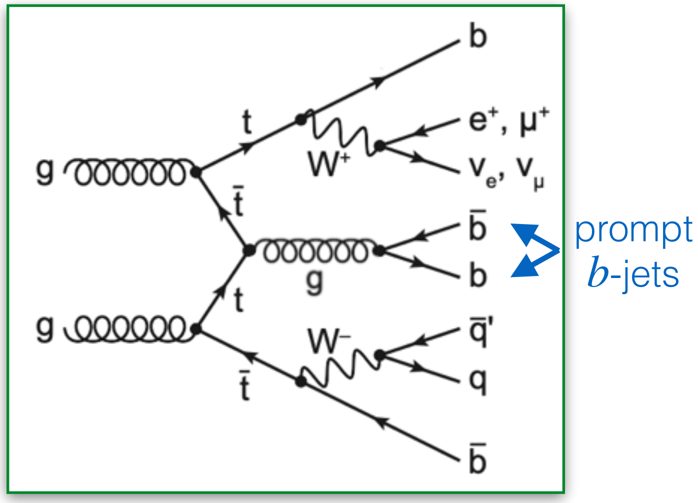


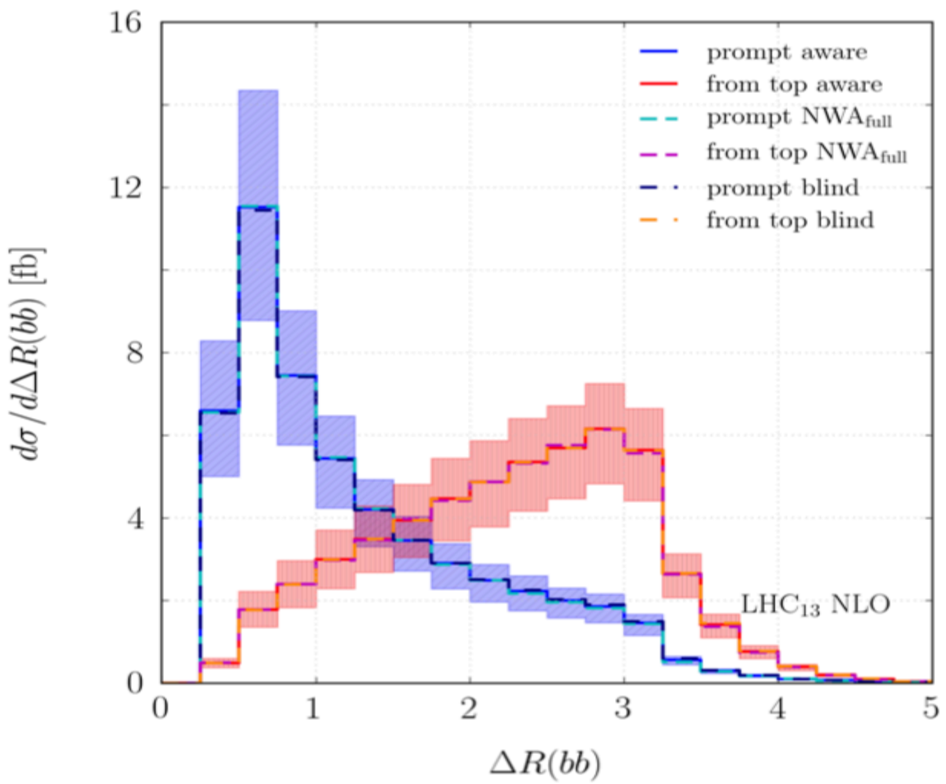


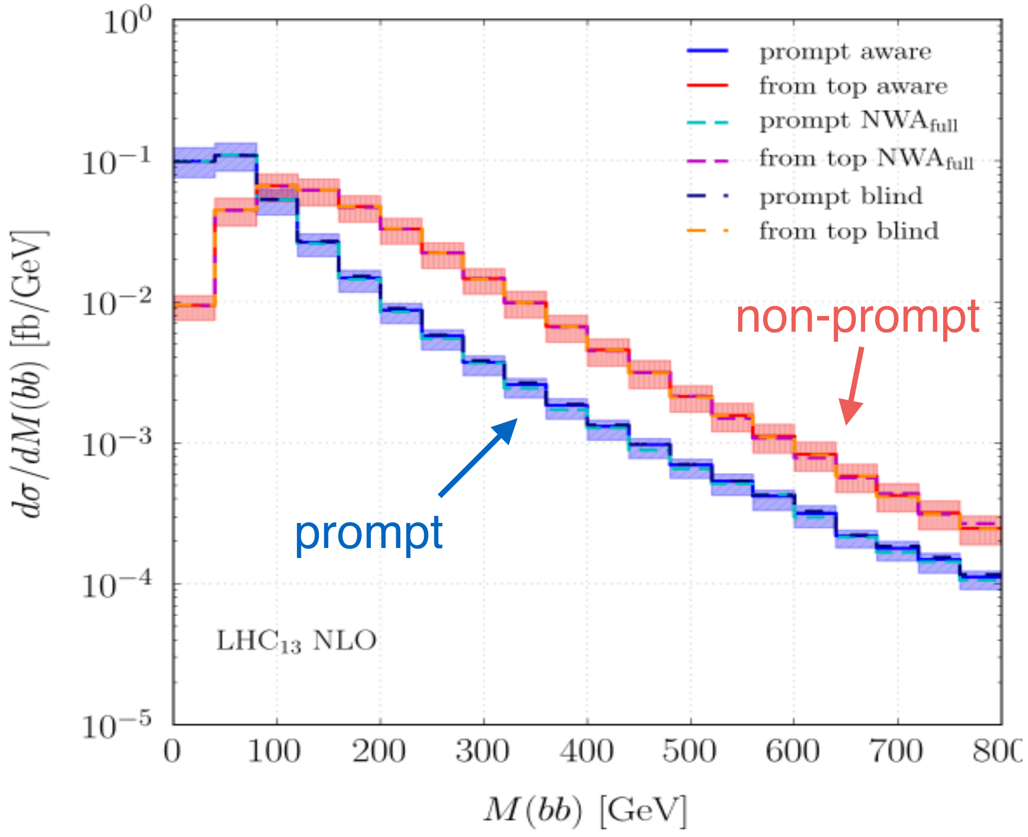
$t\bar{t}b\bar{b}$: prompt b-jet identification

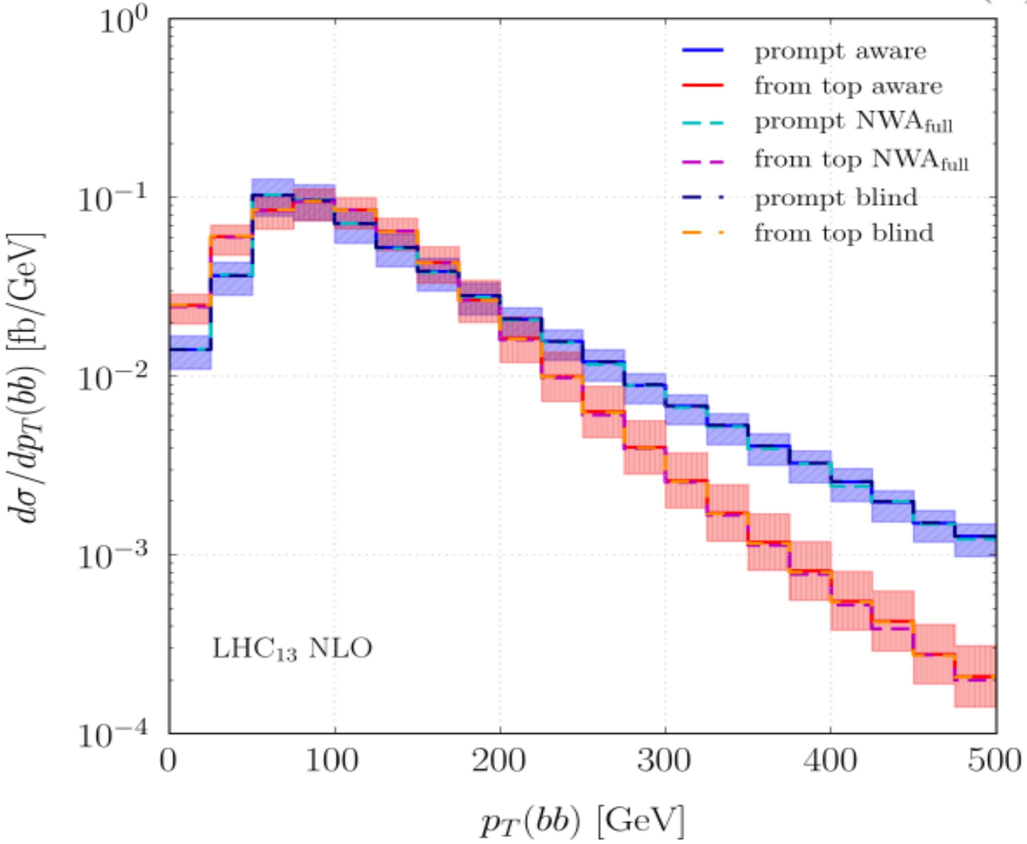
[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]

- Kinematical differences between $b\bar{b}$ pairs belonging to prompt and non-prompt categories









Conclusions

Summary

- Fixed-order analysis of based on *off-shell* $pp \to t\bar{t}b\bar{b}$ (dilepton signatures)
  - QCD corrections are large
  - Dominant uncertainties at NLO: $\mathcal{O}(20\%)$ [scale]
- Systematic comparison with NWA at different levels of accuracy
  - Off-shell effects small for most distributions used in SM analyses: $\mathcal{O}(0.5\%)$
  - Impact of QCD corrections to top quark decays: $-7\,\%$
  - Impact of $\mathcal{O}(\alpha_s^2)$ effects in $\sigma^{\rm NLO}_{\rm NWA}$ and $\sigma^{\rm NLO}_{\rm off-shell}$: $6\,\%$ (within the scale uncertainties)
- Kinematic-based method for prompt b-jet labelling and top-quark reconstruction

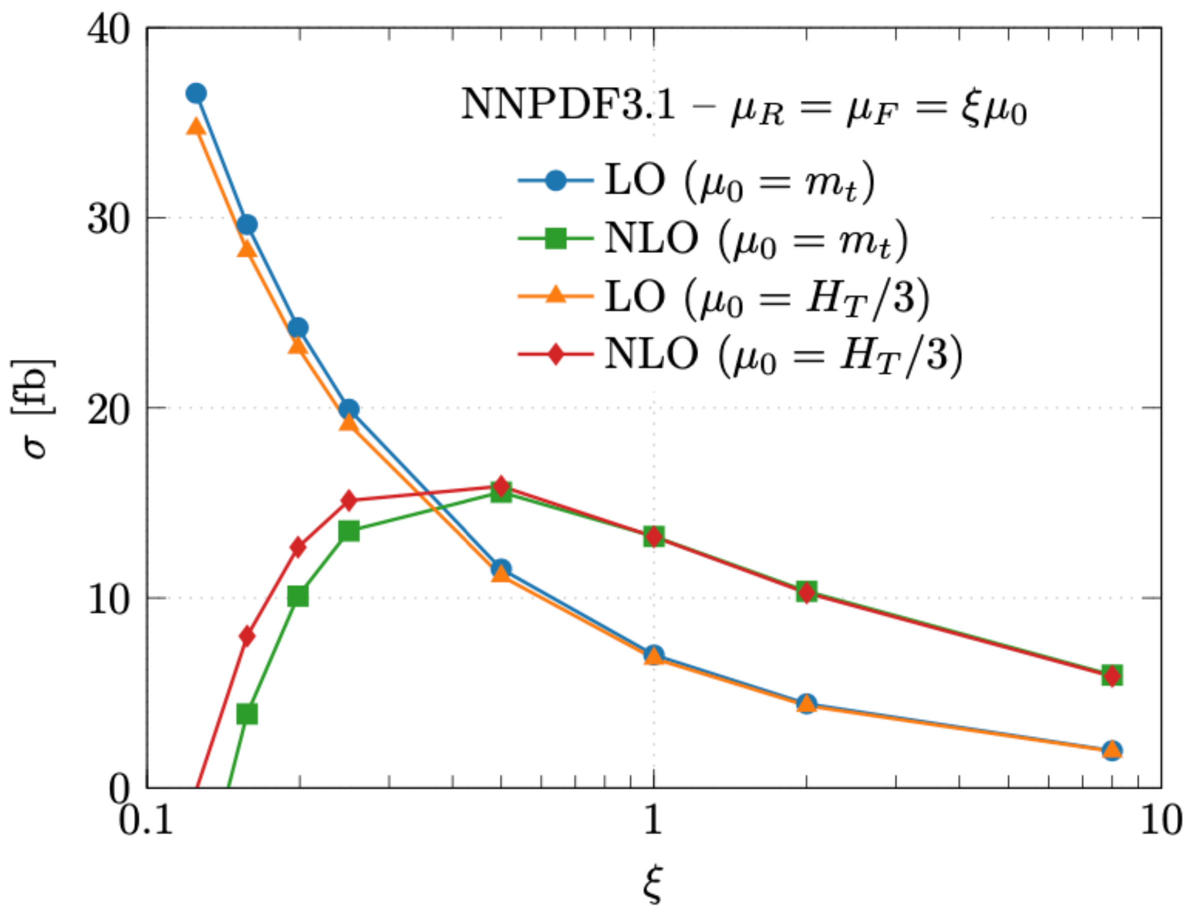
Outlook

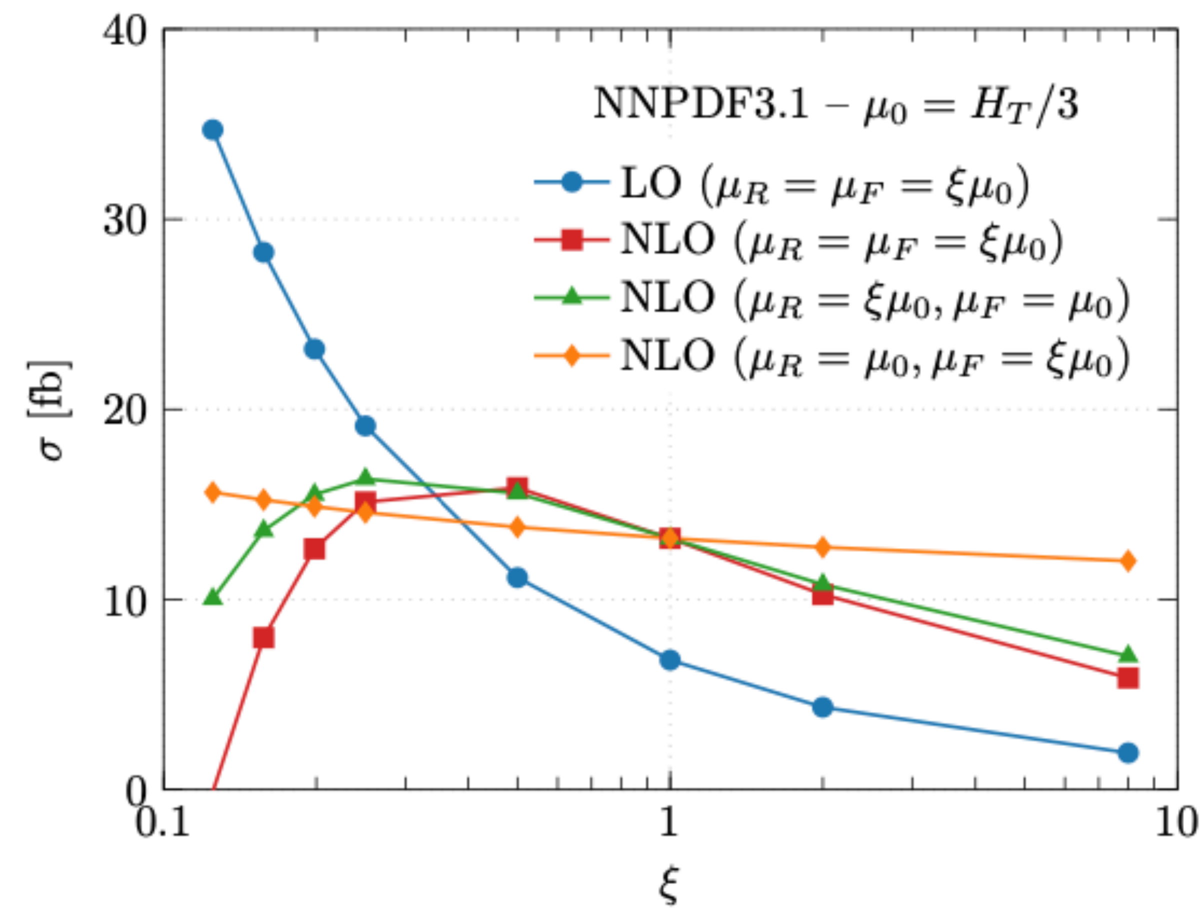
- Comparison with LHC data at differential level based on off-shell predictions

Backup slides

$t\bar{t}b\bar{b}$: scale dependence of the integrated cross section

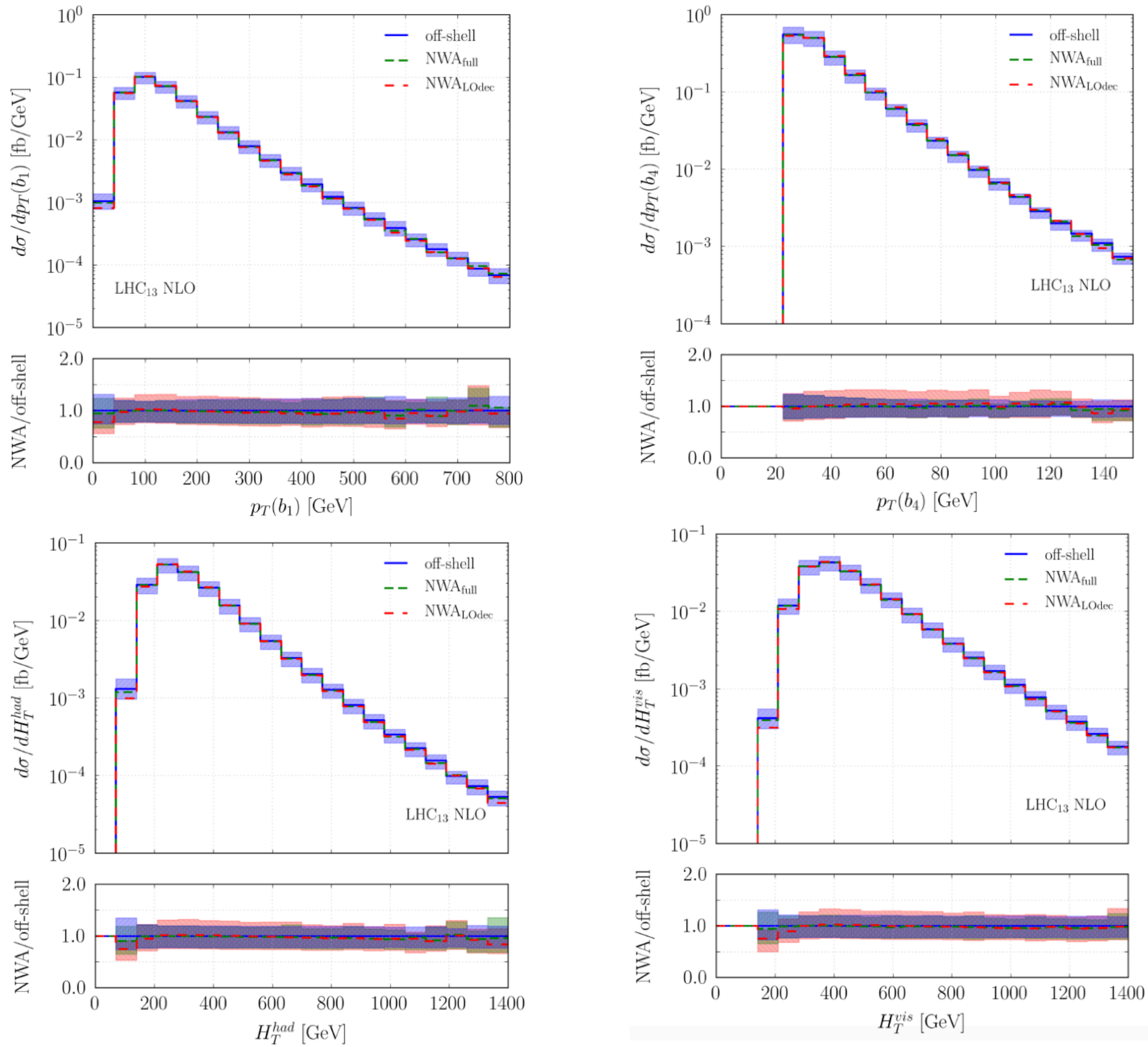
[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, JHEP 08 (2021) 008]





$t\bar{t}b\bar{b}$: impact of off-shell effects at differential level

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, Phys. Rev. D (107) 2023]



$$H_T^{had} = \sum_{i=1}^{4} p_T(b_i)$$

$$H_T^{vis} = H_T^{had} + \sum_{i=1}^{2} p_T(\ell_i)$$

$t\bar{t}b\bar{b}$: impact of initial-state b quark contributions

- Contributions induced by initial state b-quarks are suppressed by PDFs
- How good is the approximation of neglecting b-initiated contributions ?

Born

$$b\bar{b} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}$$
$$bb \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,bb$$
$$\bar{b}\bar{b} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,\bar{b}\bar{b}$$

Real

$$gb \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,b \qquad bb \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,bb\,g$$
$$g\bar{b} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,\bar{b} \qquad \bar{b}\bar{b} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,\bar{b}\bar{b}\,g$$
$$b\bar{b} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,g$$

- Comparing two different approaches of identifying b-jets:

"Charge blind" vs "Charge aware" [see *e.g.* ATLAS-CONF-2018-022]

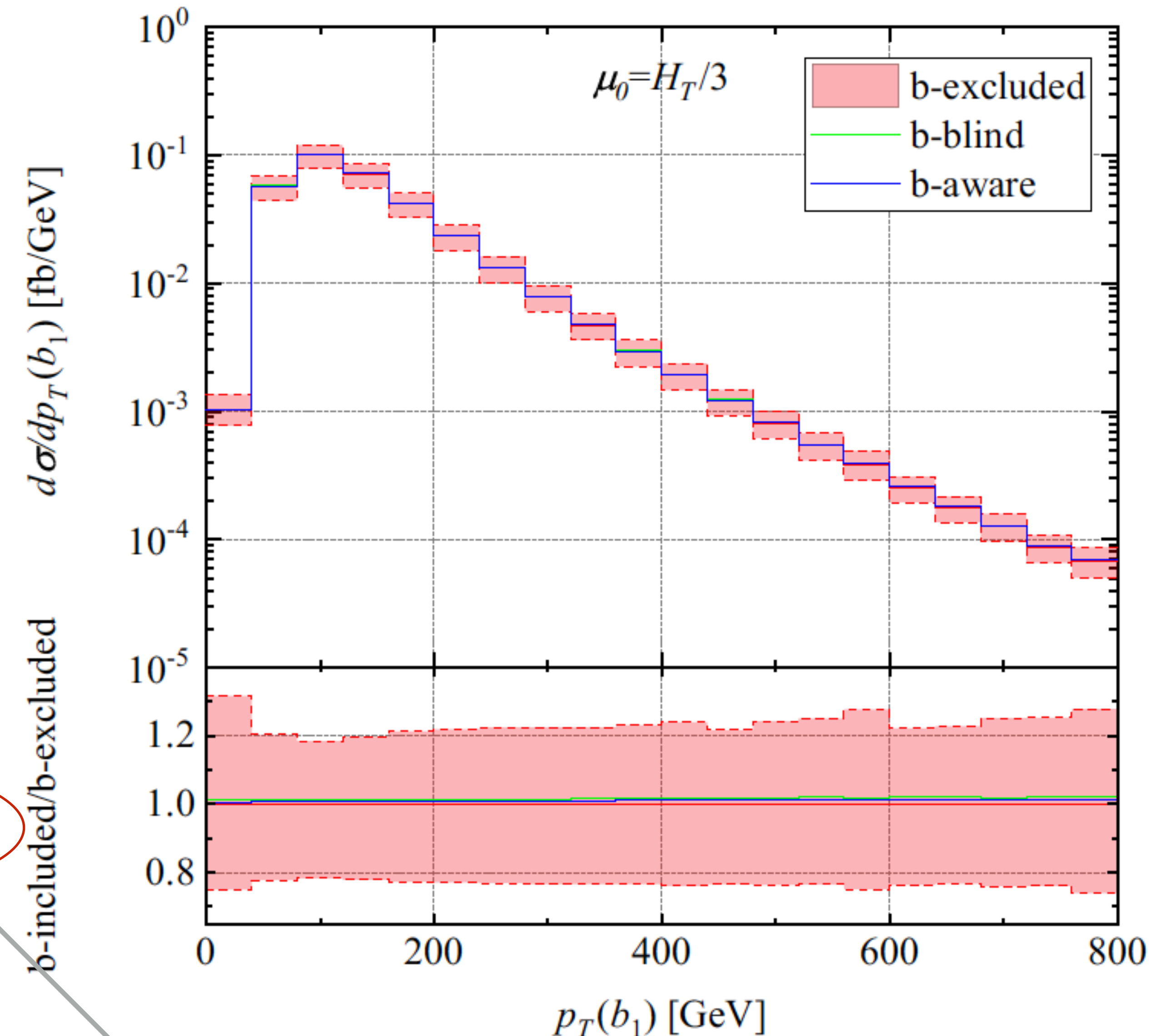
"Charge blind" → *Cannot* distinguish b- from $\bar{b}$-jets

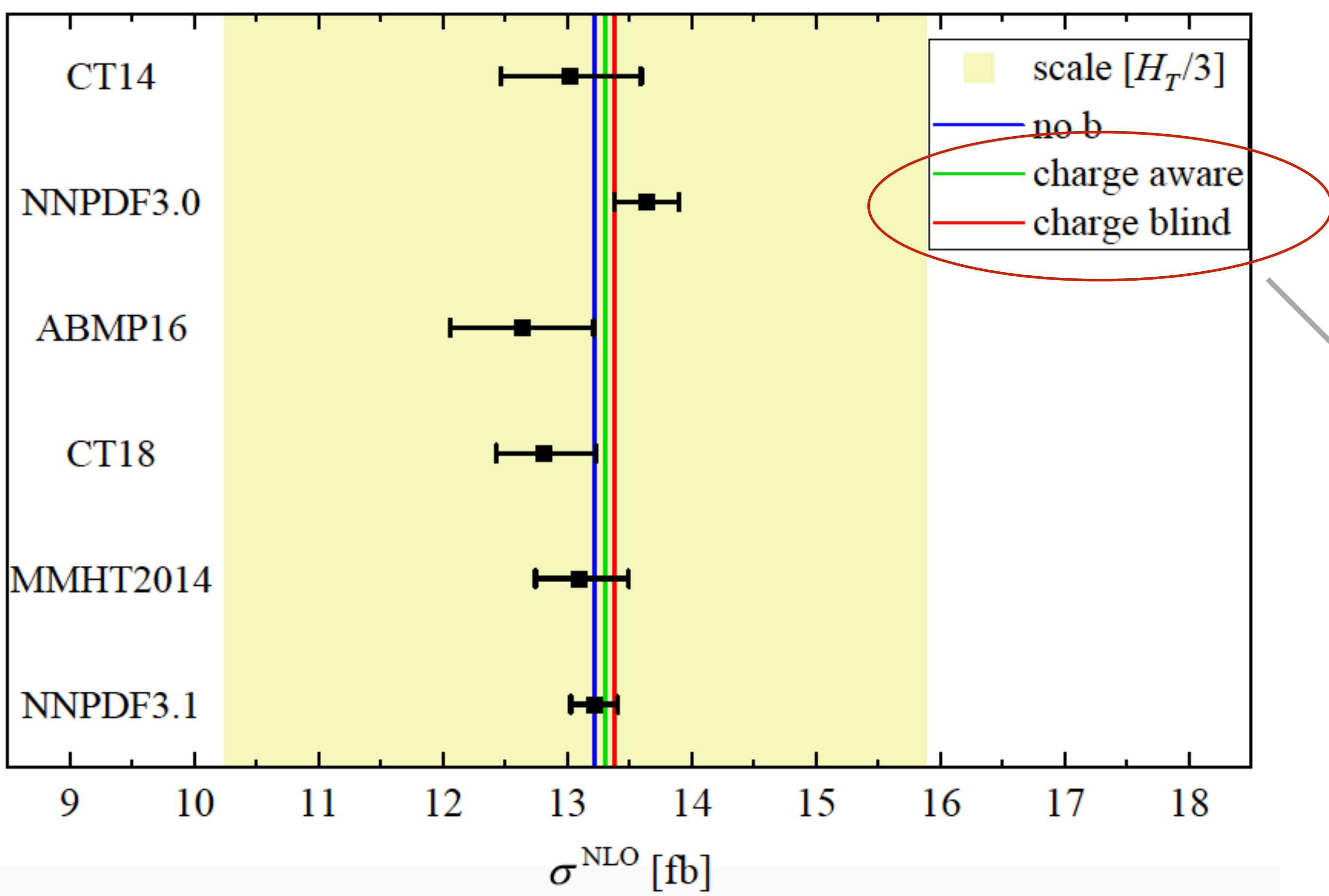
"Charge aware" → *Can* distinguish b- from $\bar{b}$-jets

$t\bar{t}b\bar{b}$: impact of initial-state b quark contributions

[GB, Bi, Hartanto, Kraus, Lupattelli and Worek, JHEP 08 (2021) 008]

LO	NLO
$\sigma^{\mathrm{LO}}_{\mathrm{no\,b}} = 6.813(3)$ fb	$\sigma^{\mathrm{NLO}}_{\mathrm{no\,b}} = 13.22(3)$ fb
$\sigma^{\mathrm{LO}}_{\mathrm{aware}} = 6.822(3)$ fb	$\sigma^{\mathrm{NLO}}_{\mathrm{aware}} = 13.31(3)$ fb
$\sigma^{\mathrm{LO}}_{\mathrm{blind}} = 6.828(3)$ fb	$\sigma^{\mathrm{NLO}}_{\mathrm{blind}} = 13.38(3)$ fb
impact: ~0.2%	**impact: ~1%**





"Charge blind" vs "Charge aware"

"Charge blind" → *Cannot* distinguish b- from $\bar{b}$-jets

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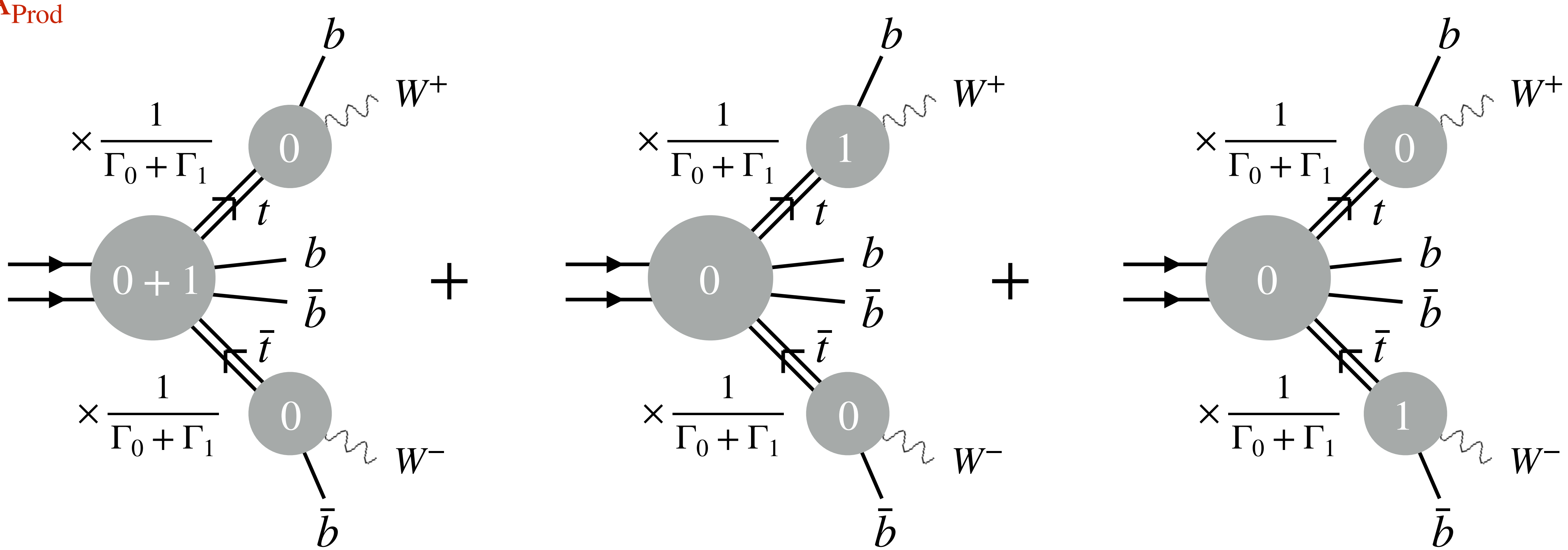
Effects of Γ_t expansion in NWA

- "Unexpanded" cross section in NWA:

$$\Gamma_t^{NLO} = \Gamma_0 + \Gamma_1$$

$\Gamma_0 \rightarrow \mathcal{O}(\alpha_s^0)$, $\Gamma_1 \rightarrow \mathcal{O}(\alpha_s)$

$d\sigma^{NLO}_{\mathrm{NWA_{Prod}}} \equiv$



- $d\sigma^{NLO}_{\mathrm{NWA_{Prod}}}$ yields the same Γ_t^{NLO} factors that are present in the full off-shell calculation
- Most suitable setup to assess the impact of genuine off-shell effects

Effects of Γ_t expansion in NWA

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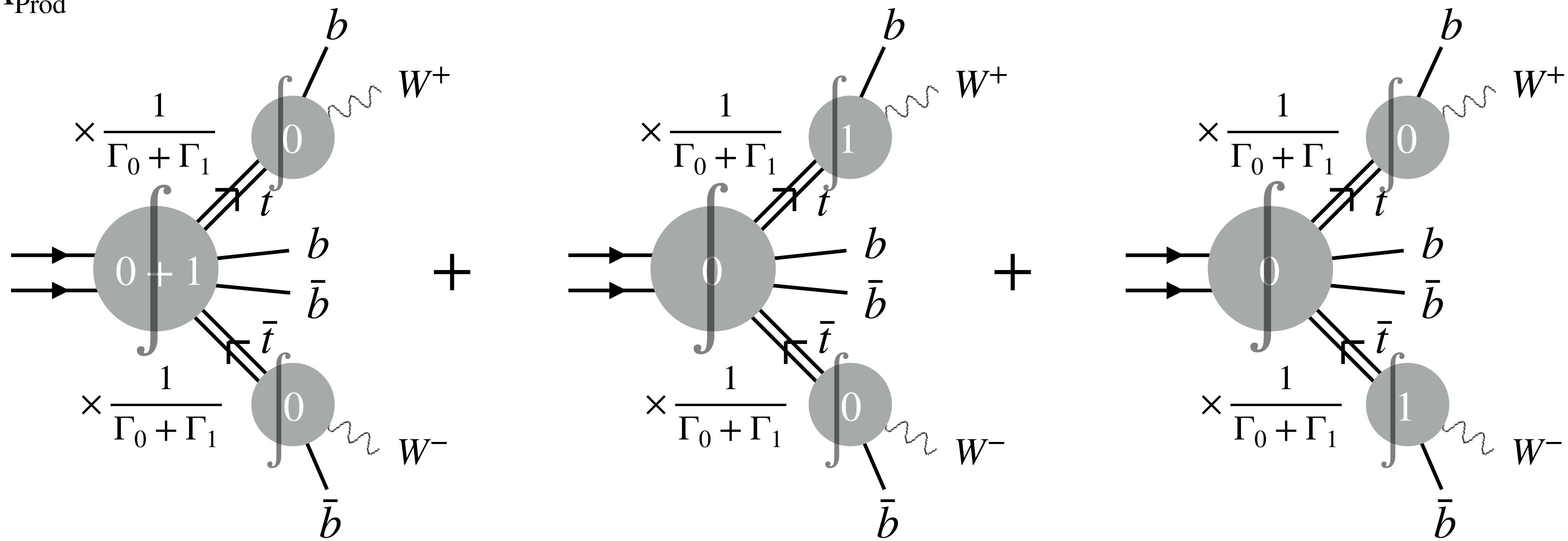
$$\Gamma_t^{NLO} = \Gamma_0 + \Gamma_1$$

Γ_0: $\mathcal{O}(\alpha_s^0)$ Γ_1: $\mathcal{O}(\alpha_s)$

$$\int d\sigma^{NLO}_{\mathrm{NWA_{Prod}}} =$$



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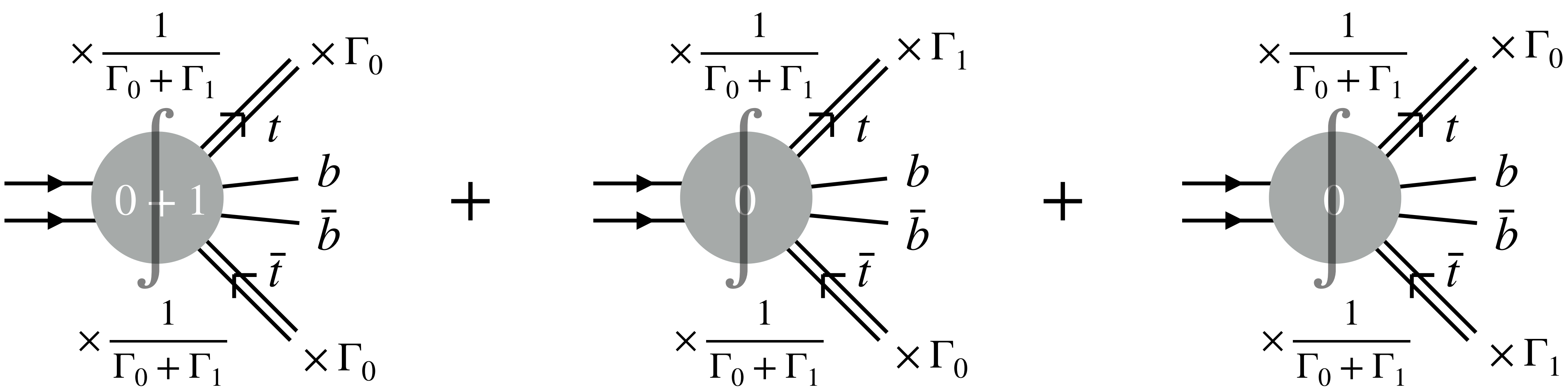

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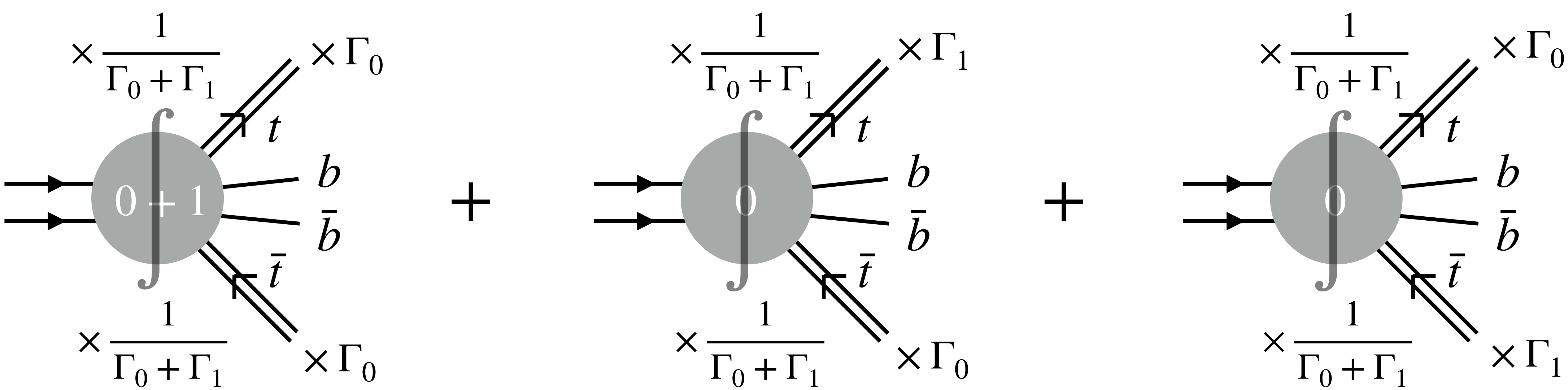

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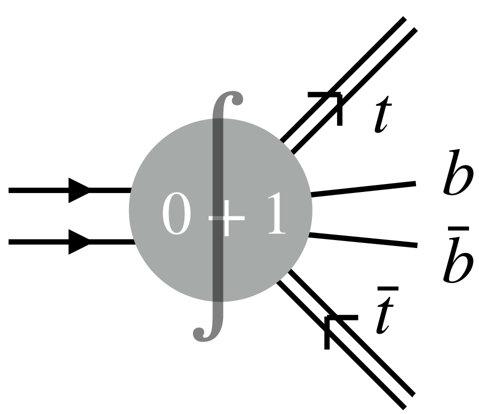


$$+ \ \mathcal{O}(\alpha_s^2) \quad = \quad \sigma^{NLO}_{t\bar{t}b\bar{b},\, incl.} + \ \mathcal{O}(\alpha_s^2)$$

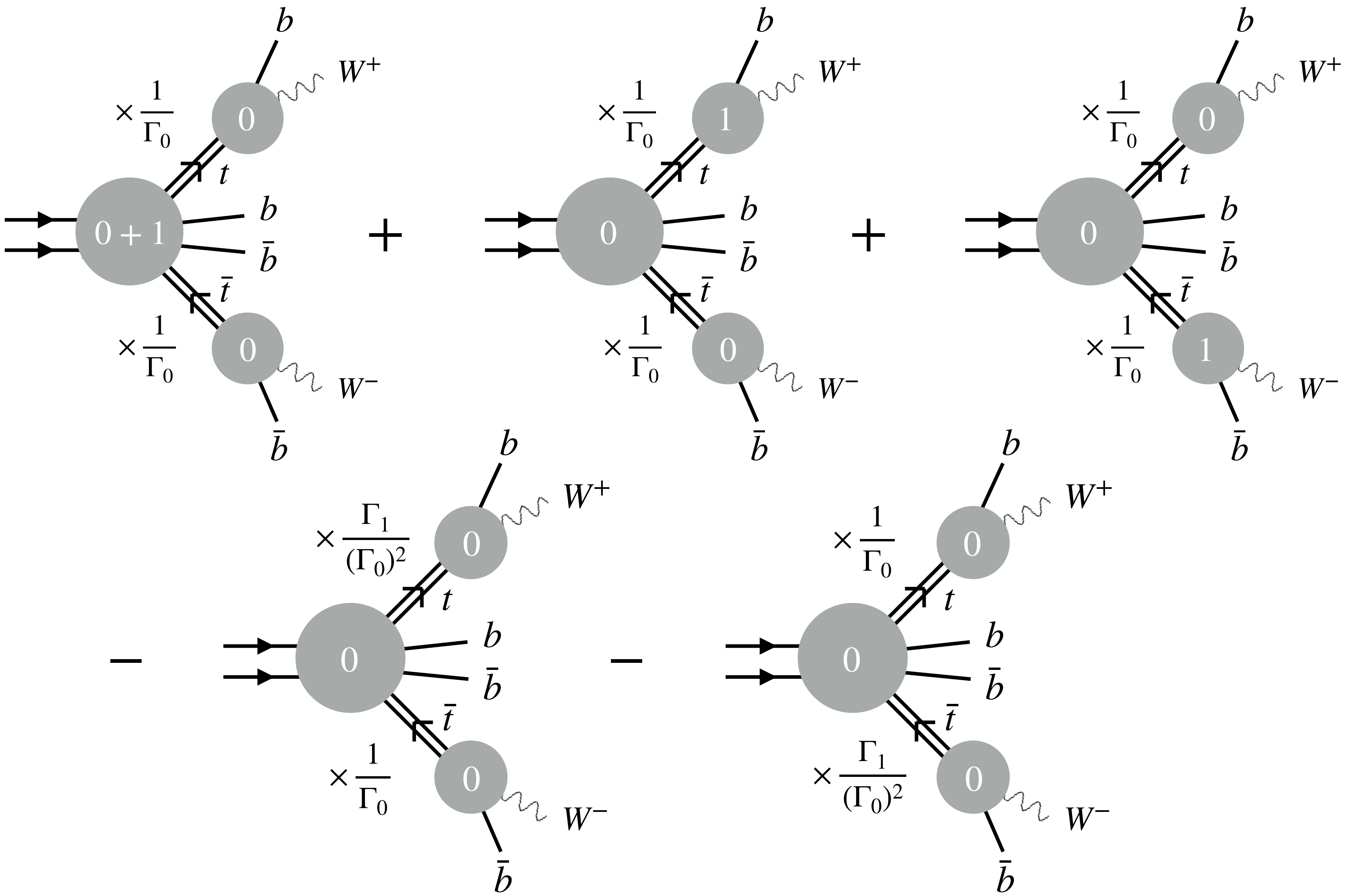
- Rigorous factorization at NLO spoiled by *formally suppressed $\mathcal{O}(\alpha_s^2)$ terms*.

Effects of Γ_t expansion in NWA

- "Expanded" cross section in NWA:

$$\frac{1}{\Gamma_0 + \Gamma_1} \sim \frac{1}{\Gamma_0} - \frac{\Gamma_1}{(\Gamma_0)^2} + \mathcal{O}(\alpha_s^2)$$

$d\sigma^{NLO}_{\text{NWA}_{\text{Prod, exp}}} \equiv$



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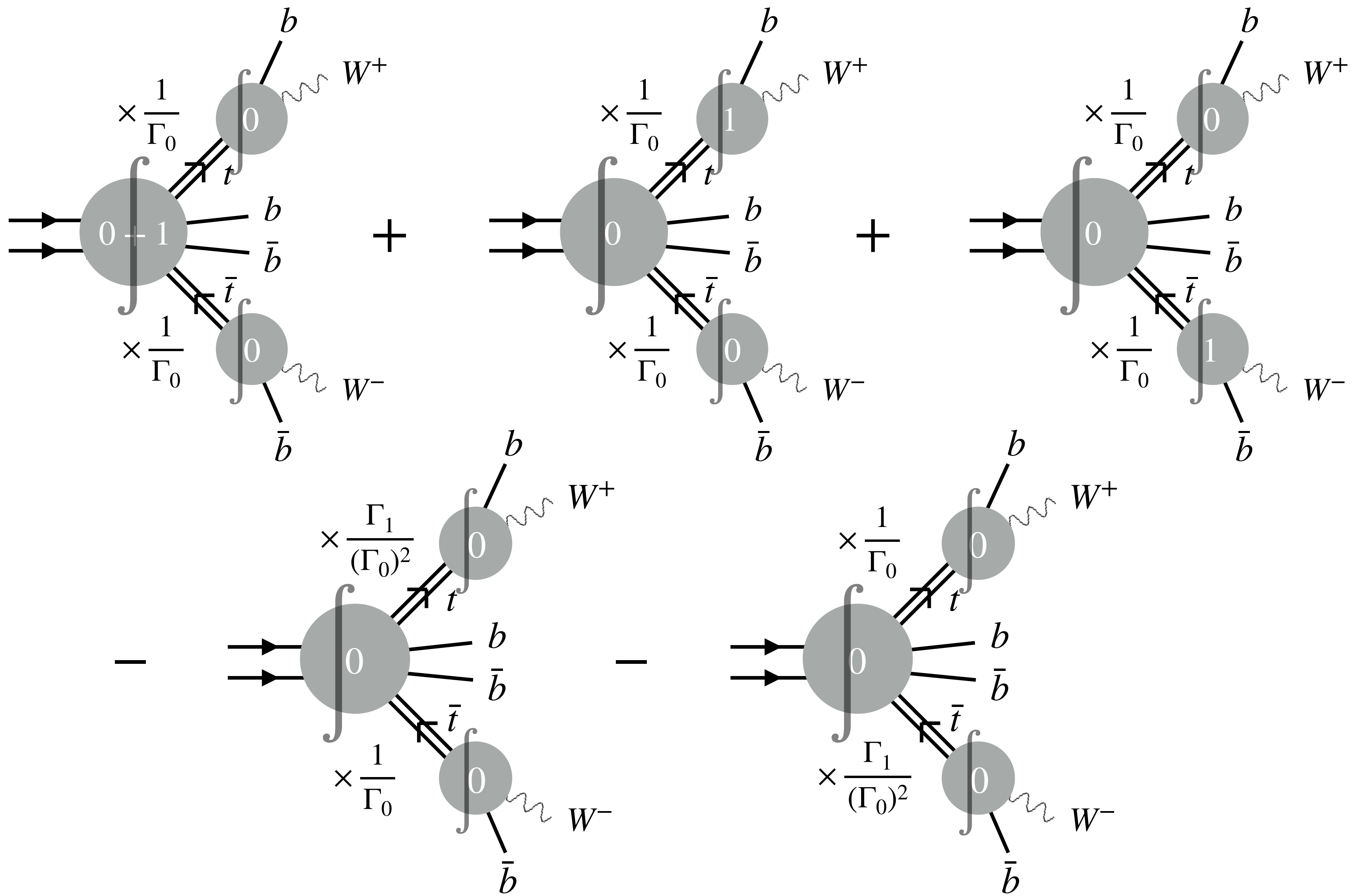
$$\int d\sigma^{NLO}_{\mathrm{NWA}_{\mathrm{Prod,exp}}} =$$



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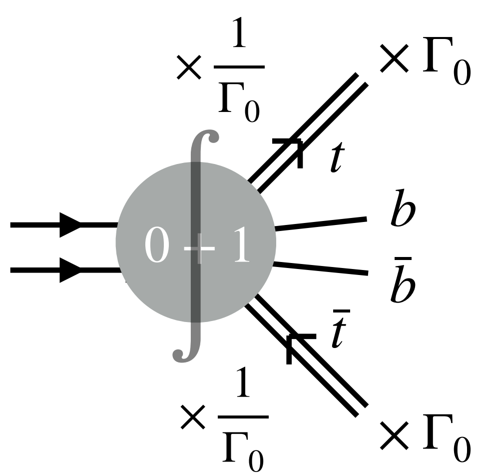

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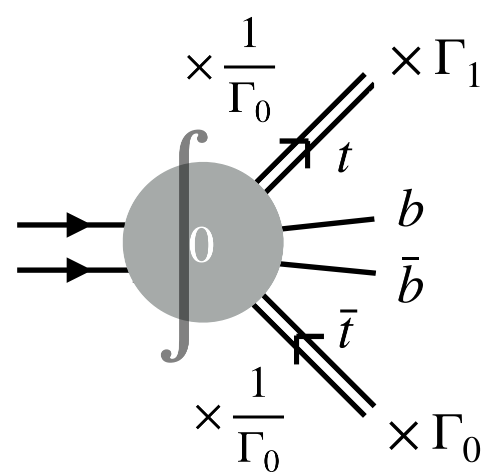

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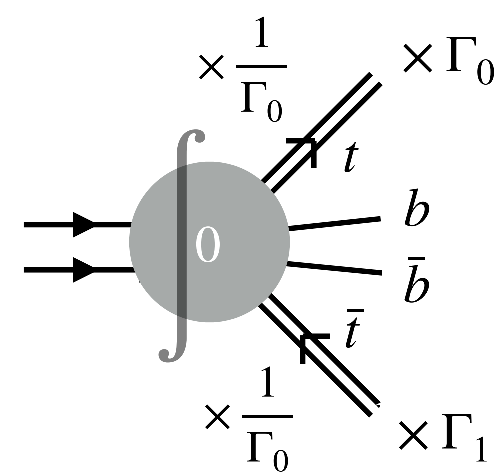

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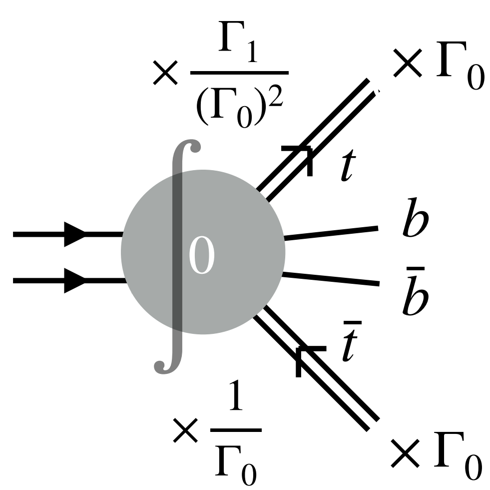

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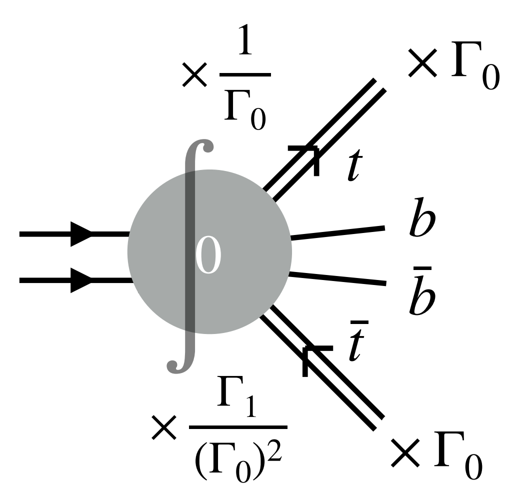
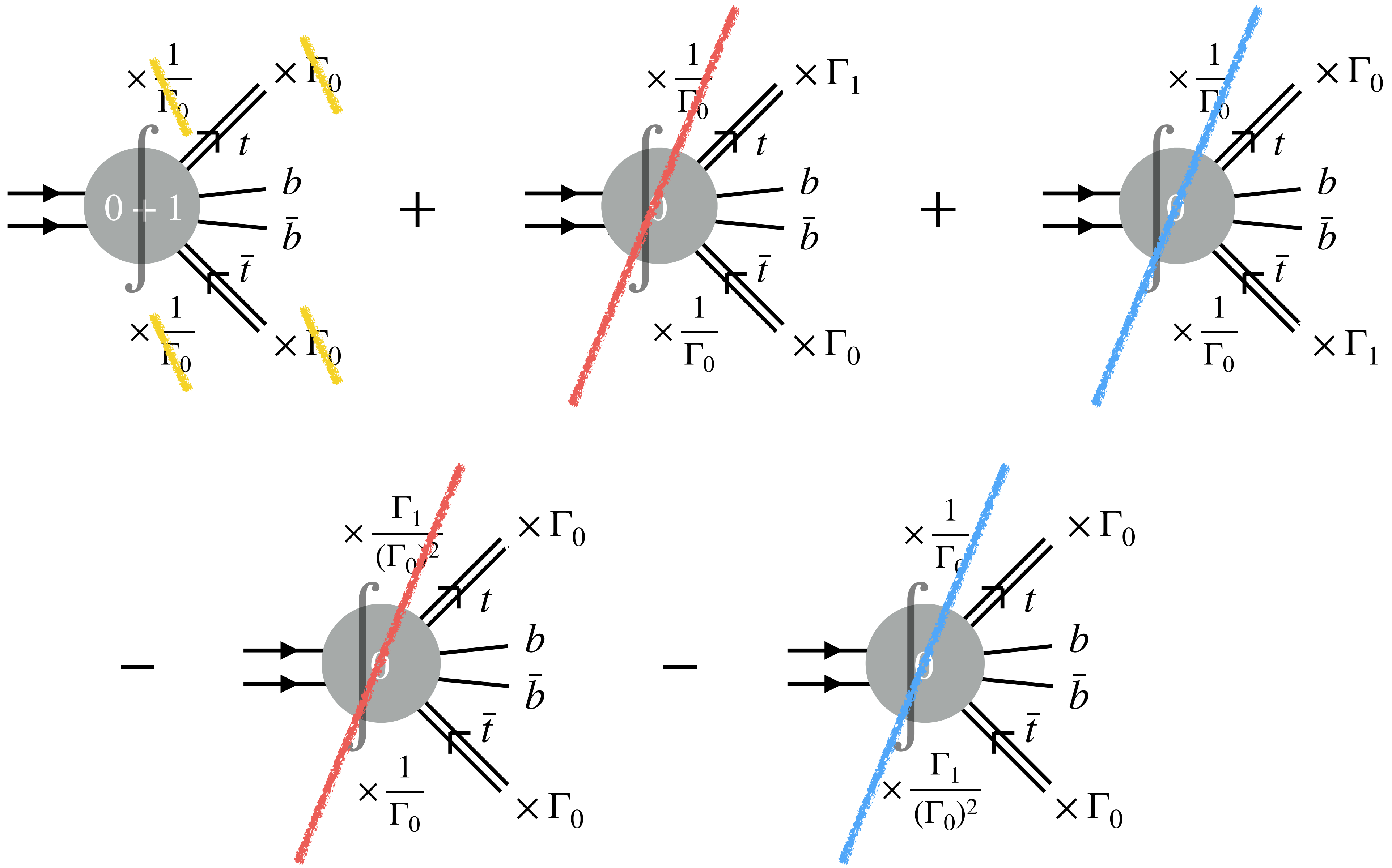


Effects of Γ_t expansion in NWA

- "Expanded" cross section in NWA:

$$\frac{1}{\Gamma_0+\Gamma_1} \sim \frac{1}{\Gamma_0} - \frac{\Gamma_1}{(\Gamma_0)^2} + \mathcal{O}(\alpha_s^2)$$

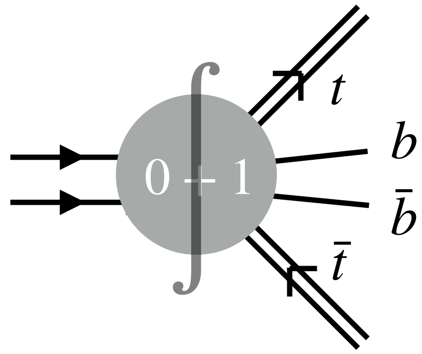
$$\int d\sigma^{NLO}_{\mathrm{NWA}_{\mathrm{Prod,exp}}} =$$



Effects of Γ_t expansion in NWA

- Rigorous expansion of Γ_t^{NLO} in NWA gets rid of "spurious" $\mathcal{O}(\alpha_s^2)$ contributions
- Note: the same procedure does not apply straightforwardly to the off-shell calculation

$$\int d\sigma^{NLO}_{\mathrm{NWA}_{\mathrm{Prod,exp}}} =$$



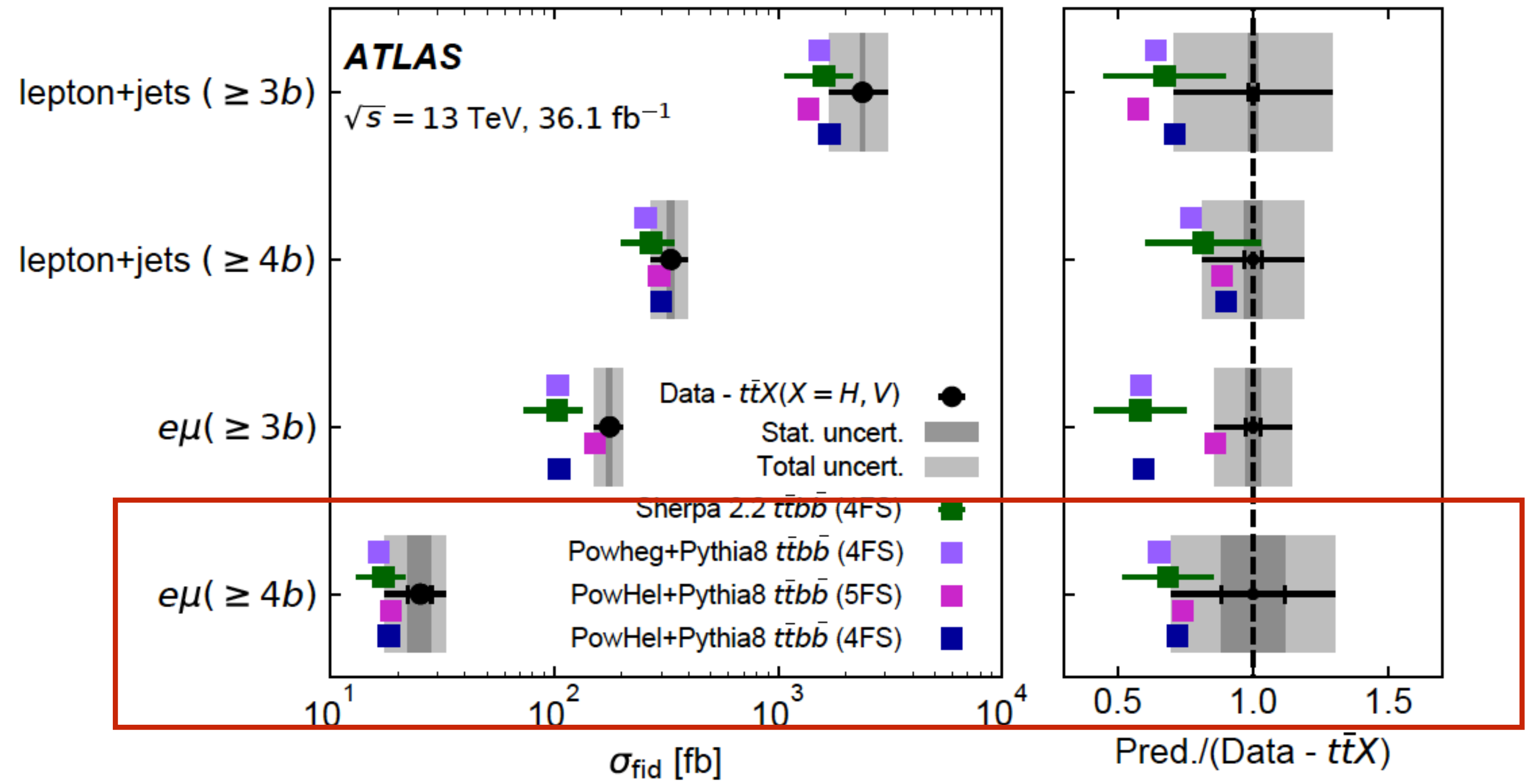
$$\equiv \quad \sigma^{\mathrm{NLO}}_{t\bar{t}b\bar{b},\ \mathrm{incl.}}$$

- The unusually large size of $\mathcal{O}(\alpha_s^2)$ effects, $\mathcal{O}(6\%)$, relates to the large size of QCD corrections to $t\bar{t}b\bar{b}$ production cross section

- These effects are well within the NLO scale uncertainties, $\mathcal{O}(20\%)$

ATLAS cuts:

$$p_T(\ell) > 25 \text{ GeV}, \quad p_T(b) > 25 \text{ GeV},$$
$$|y(\ell)| < 2.5, \quad |y(b)| < 2.5,$$
$$\Delta R(bb) > 0.4, \quad \Delta R(\ell b) > 0.4,$$



[ATLAS, JHEP 04 (2019) 046]

Theoretical predictions	$\sigma_{e\mu+4b}$ [fb]
Sherpa+OpenLoops (4FS)	17.2 ± 4.2
Powheg-Box+Pythia 8 (4FS)	16.5
PowHel+Pythia 8 (5FS)	18.7
PowHel+Pythia 8 (4FS)	18.2
Experimental result (Atlas)	25 ± 6.5

[GB et al, JHEP 08 (2021) 008]

HELAC-NLO (5FS): 20.0 ± 4.3 fb