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

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

Studying additional jet activity in top pair production at the LHC

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NCSR "Demokritos"

"Theory Challenges in the Precision Era of the Large Hadron Collider"

GGI, Florence
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In collaboration with M. Lupattelli, D. Stremmer and M. Worek

Phys.Rev.D 107 (2023) 11, 114027

$t\bar{t}$ + multijets at LHC: introduction and motivations

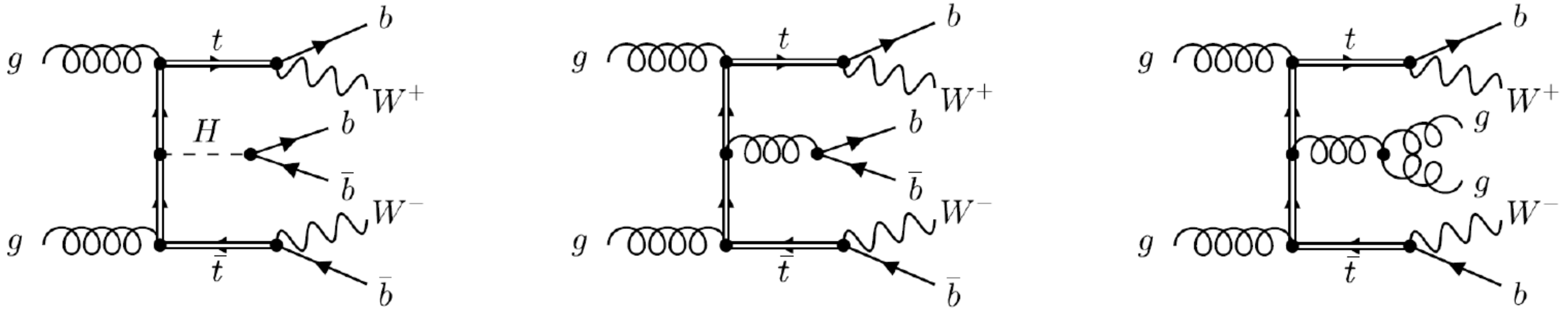
- About half of the inclusive $t\bar{t}$ sample is accompanied by additional hard jet(s) arising from QCD radiation

  Dittmaier, Uwer and Weinzierl '07, '09 …

- $t\bar{t}$ + jet provides a method to extract top quark mass at the LHC

  Alioli, Fuster, Irles, Moch and Uwer '13
  Alioli, Fuster, Garzelli, Gavardi, Irles, Melini, Moch, Uwer and Voss '22

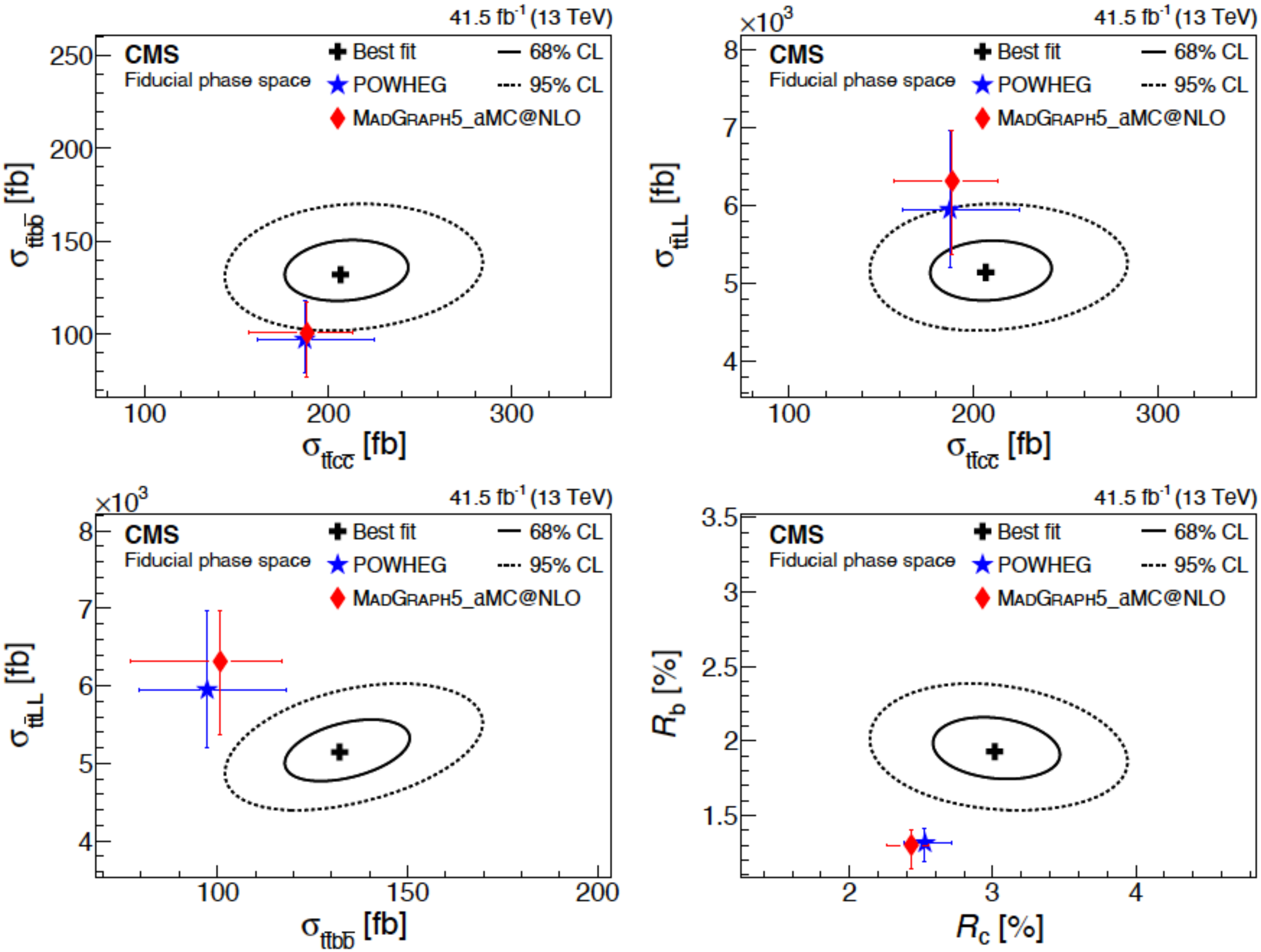
- $t\bar{t}$ + multijets is a background to $t\bar{t}H(H \to b\bar{b})$ production (and to many BSM searches as well)



- Genuine *multiscale* process, with characteristic scales typically separated by one order of magnitude → test of perturbative QCD

$t\bar{t}$ + multijets at LHC: introduction and motivations

Measuring flavour composition of $t\bar{t} + 2\,\text{jets}$



[CMS, Phys. Lett. B 820 (2021) 136565]

- Playground for testing novel b/c tagging algorithms
- Precise measurements of cross section ratios

$$R_b = \frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)}$$

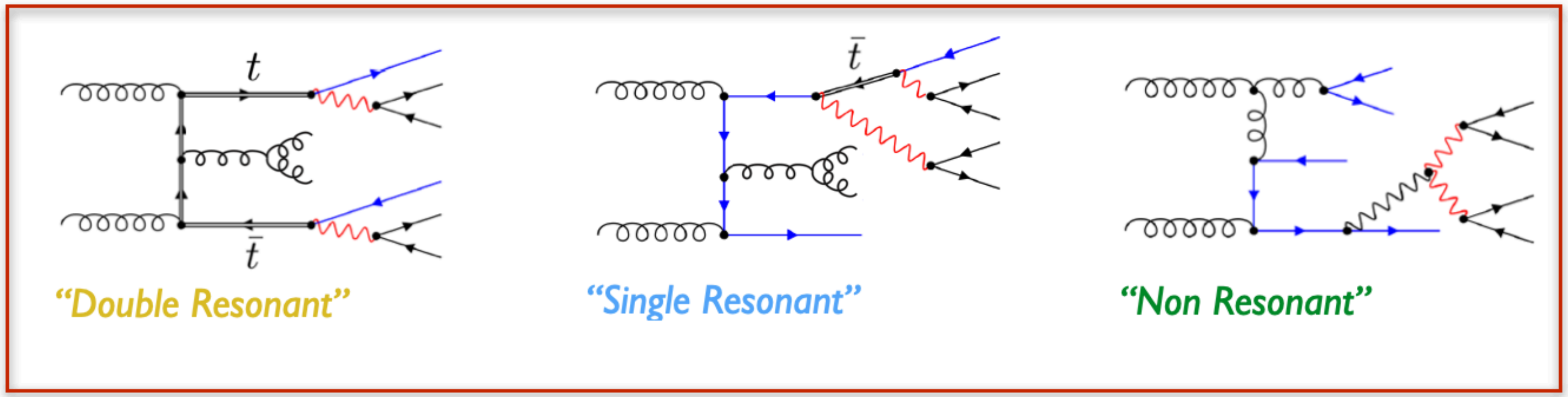
$$R_c = \frac{\sigma(t\bar{t}c\bar{c})}{\sigma(t\bar{t}jj)}$$

- 2.5σ tension in R_b

$t\bar{t}$ + multijets at LHC: theory challenges

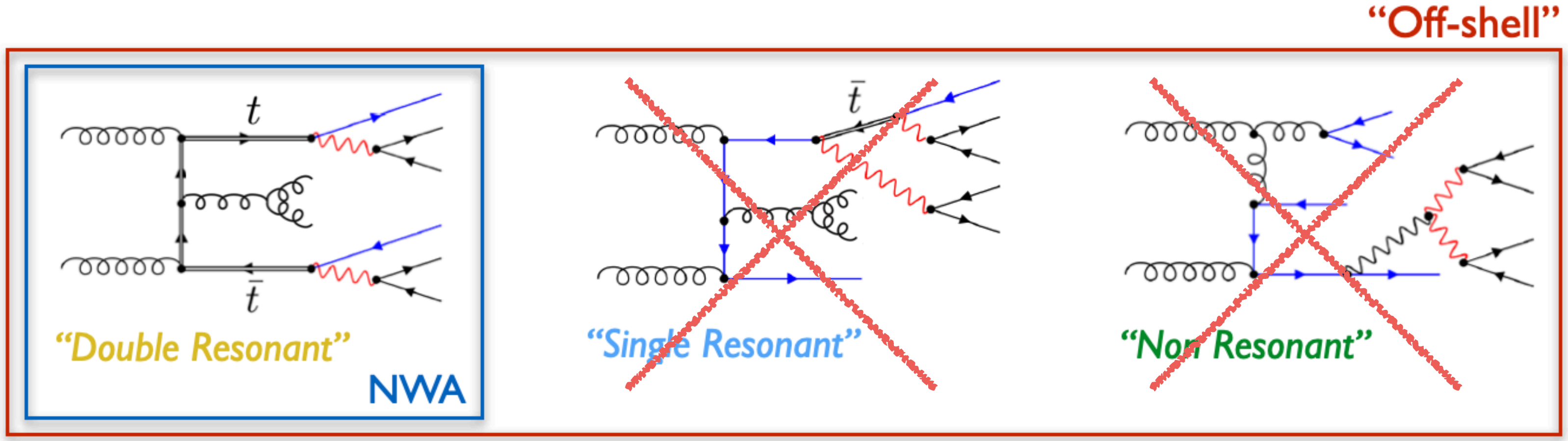
- ME calculations for fully decayed final states are often challenging

"Off-shell"



$t\bar{t}$ + multijets at LHC: theory challenges

- ME calculations for fully decayed final states are often challenging $\rightarrow$ use NWA



$\Gamma_t/m_t \rightarrow 0$

$\Gamma_W/m_W \rightarrow 0$

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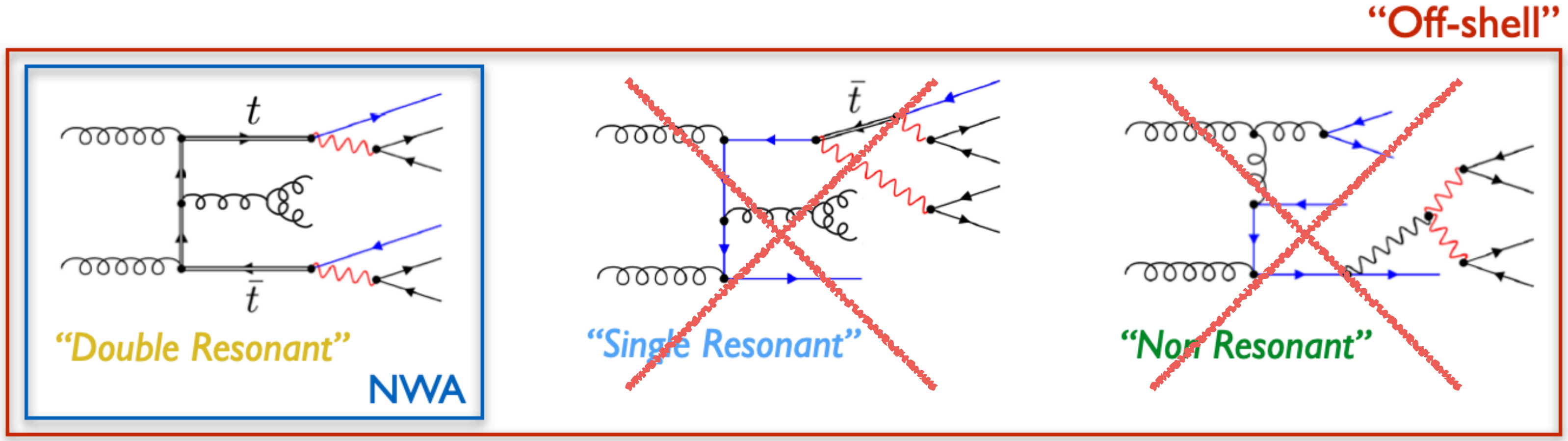
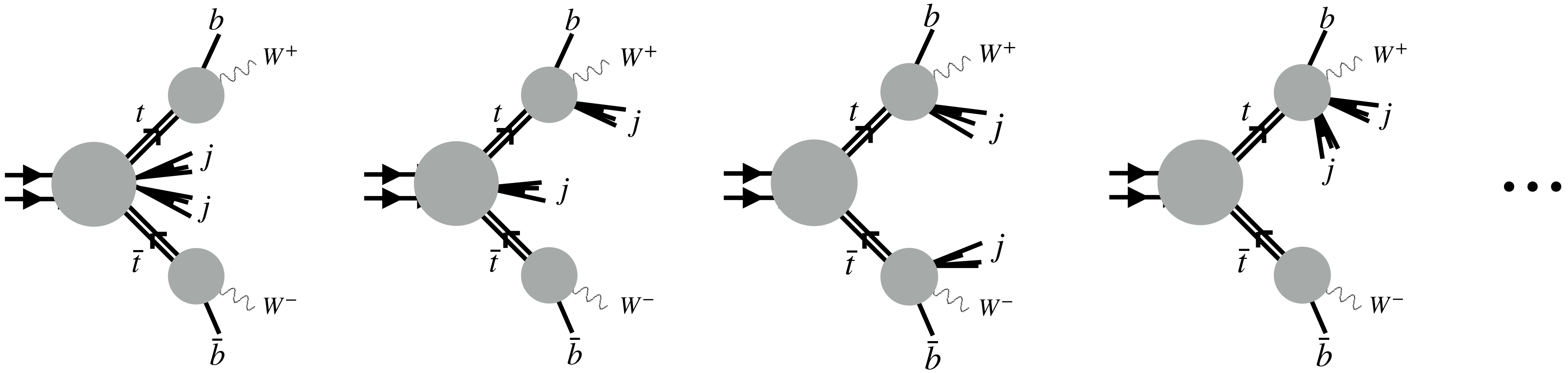


$\Gamma_t / m_t \rightarrow 0$

$\Gamma_W / m_W \rightarrow 0$

- The number of resonant structures entering the $t\bar{t} + n\,\mathrm{jets}$ cross section increases rapidly with n

e.g.: $n = 2$



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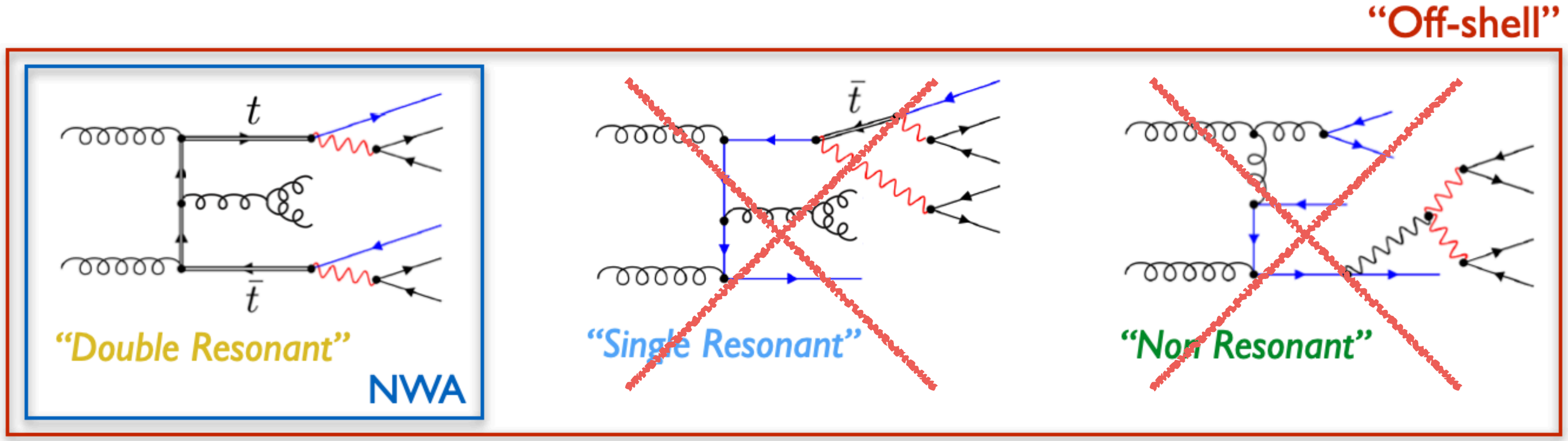

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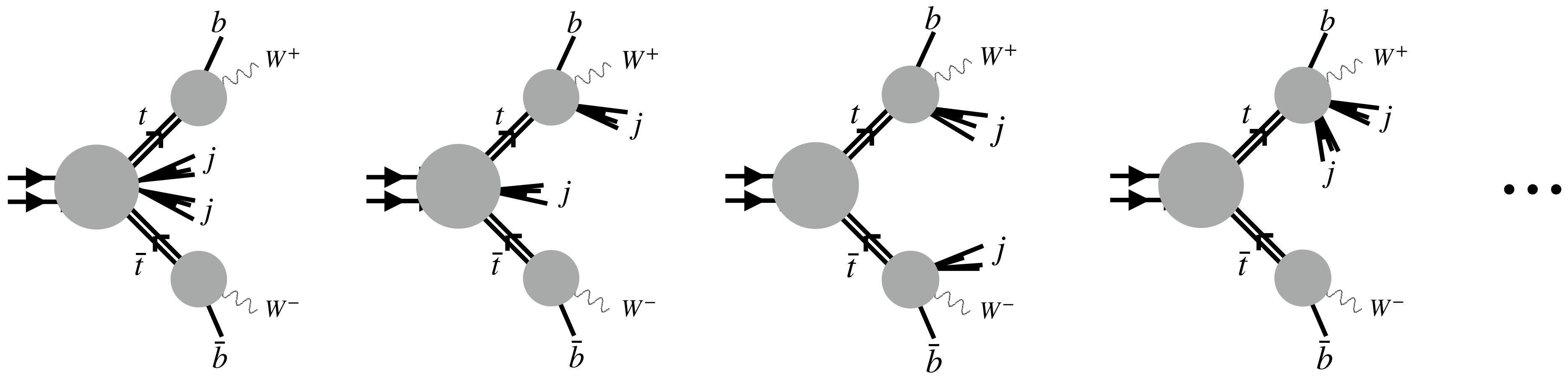

- QCD corrections to both *Production* and *Decay* ME's should be considered for accurate estimates of full NLO cross section

$t\bar{t}$ + multijets at LHC: theory challenges

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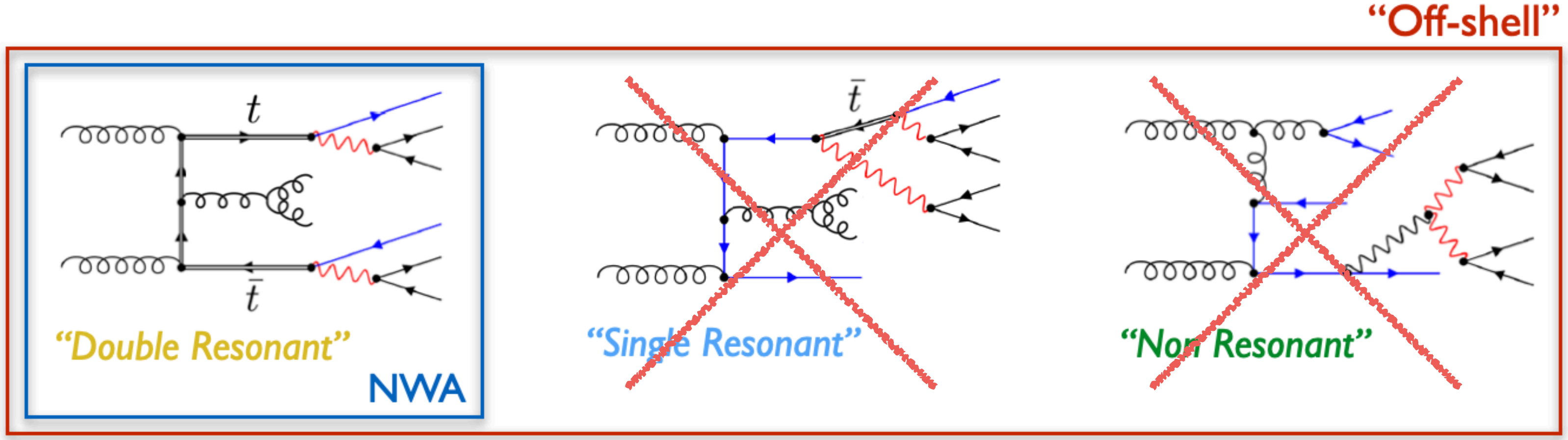

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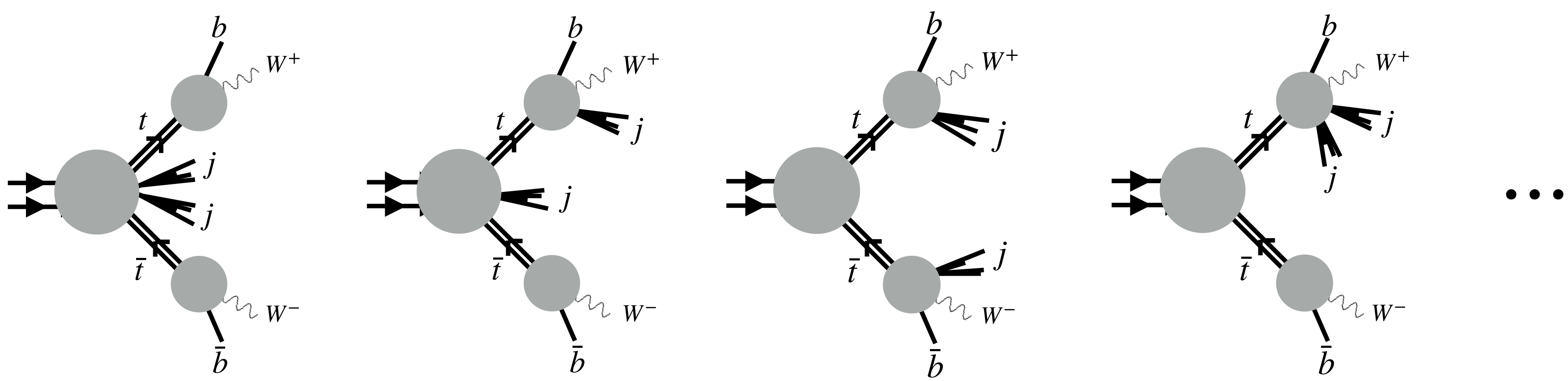


- QCD corrections to both *Production* and *Decay* ME's should be considered for accurate estimates of full NLO cross section

We'll focus on the case of $t\bar{t} + 2\,\mathrm{jets}$

$t\bar{t}jj$: theory status

Stable top quarks

- $pp \to t\bar{t} + 2\,\text{jets}$ [GB, Czakon, Papadopoulos and Worek '10,'11]

  ↪ NLO QCD: fixed-order

- $pp \to t\bar{t} + 0,1,2,3\,\text{jets}$ [Höche, Maierhöfer, Moretti, Pozzorini and Siegert '17]

  ↪ NLO QCD: NLO vs MiNLO

Exclusive final states

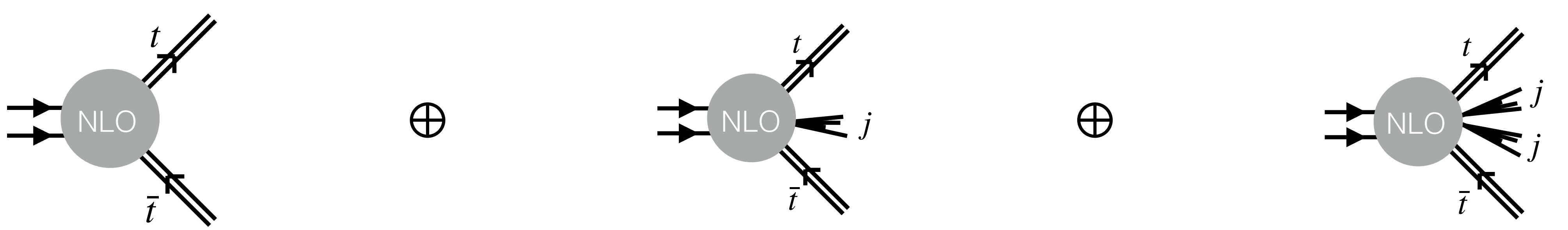
- $pp \to t\bar{t} + 0,1,2\,\text{jets}$ [Höche, Krauss, Maierhöfer, Pozzorini, Schönherr and Siegert '15]

  ↪ NLO QCD: MEPS@NLO multi-jet merging

- $pp \to t\bar{t} + 0,1,2,3,4\,\text{jets}$ [Gütschow, Lindert and Schönherr '18]

  ↪ NLO QCD+EW ($n \leq 1$ jet) & LO QCD+EW ($n > 1$): MEPS@NLO multi-jet merging

- State-of-the-art of $t\bar{t}jj$ MC simulations: NLO+PS (merging multijet samples)

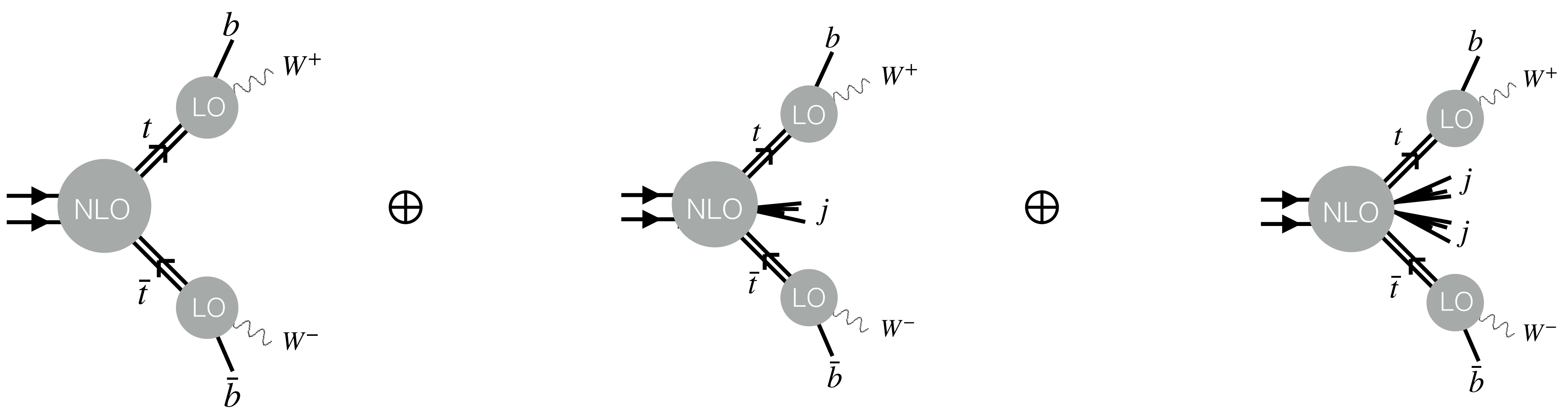


$pp \to t\bar{t} + 0\,\text{jet}$ $\quad$ $pp \to t\bar{t} + 1\,\text{jet}$ $\quad$ $pp \to t\bar{t} + 2\,\text{jets}$

$t\bar{t}jj$: state-of-the-art in a nutshell

- State-of-the-art of $t\bar{t}jj$ MC simulations: NLO+PS (merging multijet samples)

- Top quarks produced on-shell and decayed at LO with spin correlations

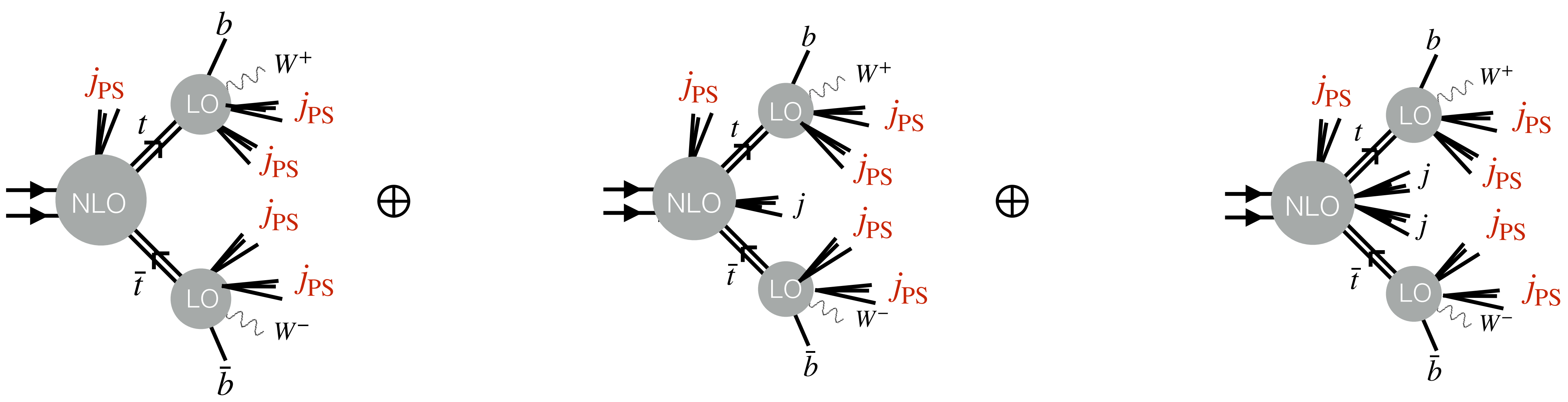


$t\bar{t}jj$: state-of-the-art in a nutshell

- State-of-the-art of $t\bar{t}jj$ MC simulations: NLO+PS (merging multijet samples)

- Top quarks produced on-shell and decayed at LO with spin correlations

- Parton Shower evolution (ISR/FSR) accounts for additional jet activity

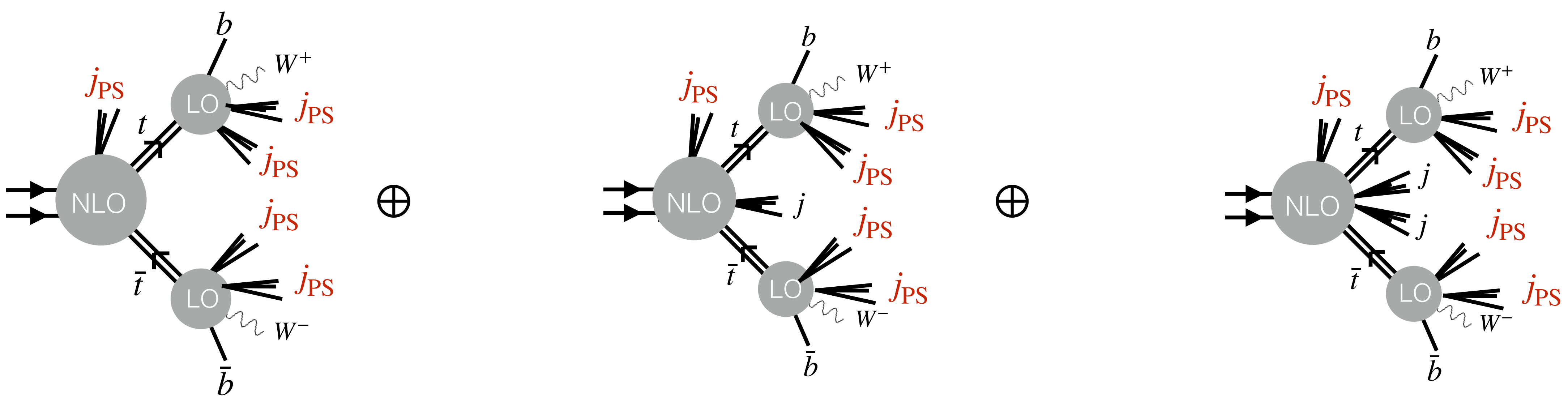


Interesting questions:

I. To what extent do QCD corrections to top decays impact fiducial NLO cross sections? → normalisation

II. Which phase space regions are more sensitive to hard jet radiation from top decays? → shapes

(III. What's the impact of full off-shell effects? → shapes, normalisation)



Goals of this study

- NLO QCD computation of $pp \to t\bar{t}jj \to \ell^+\nu_\ell \ell^-\bar{\nu}_\ell b\bar{b}jj$ in *full NWA*

- Anatomy of resonant contributions at NLO QCD
  ↪ Interplay under different kinematical cuts

- Effects of hard radiation off top quark decays
  ↪ Comparison with LO decay modelling (integrated and differential level)

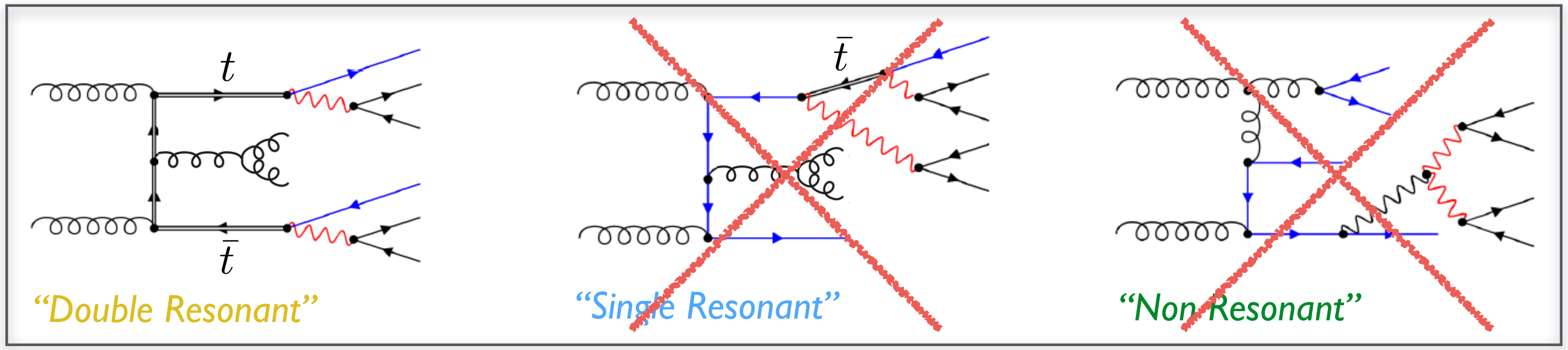
- Fiducial cross section ratios
  ↪ $R_1 = \sigma_{ttj}/\sigma_{tt} \quad R_2 = \sigma_{ttjj}/\sigma_{ttj}$

Technical details

- Using HELAC-NLO computational framework

GB, Czakon, Garzelli, van Hameren, Kardos, Papadopoulos, Pittau and Worek '13

- Narrow Width Approximation
  - $\Gamma_t/m_t \to 0 \qquad \Gamma_W/m_W \to 0$
  - spin correlated decays



- NLO in QCD
  - QCD corrections and jet radiation in *Production* and *Decay*
  - Results cross-checked with two different subtraction schemes:

Catani-Seymour subtraction

$$\mathcal{A}^D_{\mathrm{CS}}(\{p\}_{m+1}) = \sum_{i,j,k=1}^{m+1} \mathcal{A}^B(\{\tilde{p}\}^{(ijk)}_m) \otimes \mathcal{D}^{(ijk)}_{\mathrm{CS}}(\{\tilde{p}\}^{(ijk)}_m, \{p\}_{m+1})$$

Catani and Seymour '97, Catani, Dittmaier, Seymour and Trocsanyi '02

*extended to radiative decays : Campbell, Ellis and Tramontano '04
Melnikov, Sharf and Schulze '12

Nagy-Soper subtraction

$$\mathcal{A}^D_{\mathrm{NS}}(\{p\}_{m+1}) = \sum_{i,j} \mathcal{A}^B(\{\tilde{p}\}^{(ij)}_m) \otimes \left(\sum_k \mathcal{D}^{(ijk)}_{\mathrm{NS}}(\{\tilde{p}\}^{(ij)}_m, \{p\}_{m+1})\right)$$

GB, Czakon, Kubocz and Worek '13

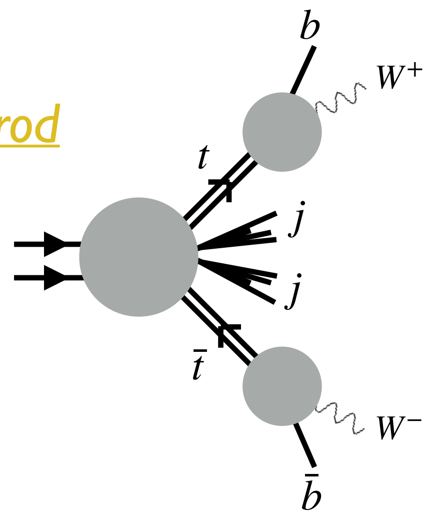
*extended to radiative decays : This work

Anatomy of resonant contributions

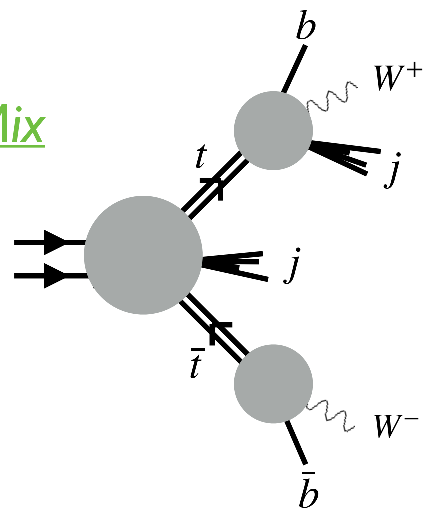
Resonant contributions to $t\bar{t}jj$ in NWA: **LO**

$$d\sigma^{\rm LO}_{t\bar{t}jj} = \Gamma_t^{-2}\Big(\underbrace{d\sigma^{\rm LO}_{t\bar{t}jj}\, d\Gamma^{\rm LO}_{t\bar{t}}}_{\text{Prod.}} + \underbrace{d\sigma^{\rm LO}_{t\bar{t}j}\, d\Gamma^{\rm LO}_{t\bar{t}j}}_{\text{Mix}} + \underbrace{d\sigma^{\rm LO}_{t\bar{t}}\, d\Gamma^{\rm LO}_{t\bar{t}jj}}_{\text{Decay}}\Big)$$

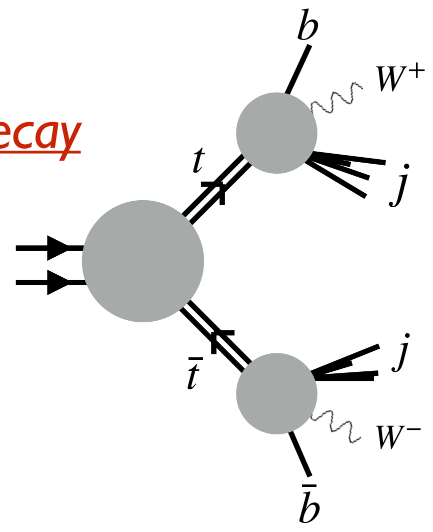
Prod



Mix

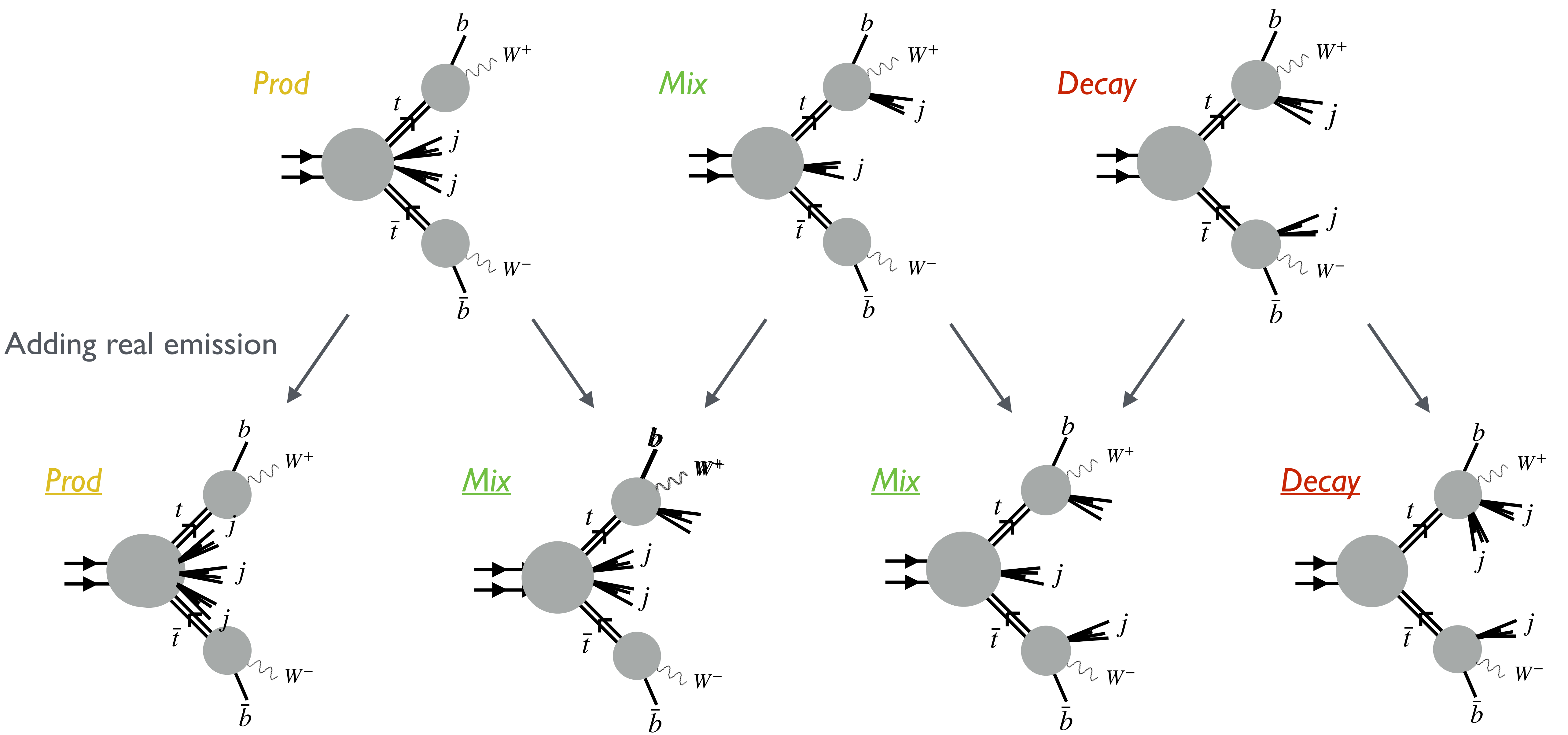


Decay



Resonant contributions to $t\bar{t}jj$ in NWA: **NLO**

$$
d\sigma^{\rm NLO}_{t\bar{t}jj} = \Gamma_t^{-2}\Big(\overbrace{\left(d\sigma^{\rm LO}_{t\bar{t}jj} + d\sigma^{\rm virt}_{t\bar{t}jj} + d\sigma^{\rm real}_{t\bar{t}jjj}\right) d\Gamma^{\rm LO}_{t\bar{t}}}^{\text{Prod.}} + \overbrace{d\sigma^{\rm LO}_{t\bar{t}} \left(d\Gamma^{\rm LO}_{t\bar{t}jj} + d\Gamma^{\rm virt}_{t\bar{t}jj} + d\Gamma^{\rm real}_{t\bar{t}jjj}\right)}^{\text{Decay}}
$$
$$
+ \underbrace{d\sigma^{\rm LO}_{t\bar{t}j}\, d\Gamma^{\rm LO}_{t\bar{t}j} + d\sigma^{\rm LO}_{t\bar{t}jj}\, d\Gamma^{\rm virt}_{t\bar{t}} + d\sigma^{\rm virt}_{t\bar{t}}\, d\Gamma^{\rm LO}_{t\bar{t}jj} + d\sigma^{\rm virt}_{t\bar{t}j}\, d\Gamma^{\rm LO}_{t\bar{t}j} + d\sigma^{\rm LO}_{t\bar{t}j}\, d\Gamma^{\rm virt}_{t\bar{t}j} + d\sigma^{\rm real}_{t\bar{t}jj}\, d\Gamma^{\rm real}_{t\bar{t}j} + d\sigma^{\rm real}_{t\bar{t}j}\, d\Gamma^{\rm real}_{t\bar{t}jj}}_{\text{Mix}} \Big)
$$



Phenomenological results

$t\bar{t}jj$: setup of the calculation

$$pp \to t\bar{t}jj \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,jj$$

$\sqrt{s} = 13\,\text{TeV}$

$(\ell = e, \mu)$

- **Event selection** → CMS-PAS-TOP-20-006

$$p_{T,\ell} > 20 \text{ GeV}, \quad |y_\ell| < 2.4, \quad \Delta R_{\ell\ell} > 0.4, \quad M_{\ell\ell} > 20 \text{ GeV},$$
$$p_{T,b} > 30 \text{ GeV}, \quad |y_b| < 2.4, \quad \Delta R_{bb} > 0.4,$$
$$p_{T,j} > 40 \text{ GeV}, \quad |y_j| < 2.4, \quad \Delta R_{jj} > 0.4,$$
$$\Delta R_{bl} > 0.4, \quad \Delta R_{jl} > 0.4, \quad \Delta R_{jb} > 0.8\ (0.4)$$

- **Scale**
  - $\mu_R = \mu_F = \frac{H_T}{2} \qquad H_T = \sum_{i=1}^{2} p_T(\ell_i) + p_T(b_i) + p_T(j_i) + p_{T,miss}$
  - uncertainty bands based on 7-point variation

- **Jet algorithm**
  - anti-k_T $(R = 0.4)$

- **PDF**
  - NNPDF3.1 PDF set with $\alpha_S = 0.118$

$t\bar{t}jj$: fiducial cross sections

Integrated fiducial cross sections

[GB, Lupattelli, Stremmer and Worek, Phys. Rev. D (107) 2023, 114027]

Modelling	$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}$ [fb]	$\frac{\sigma_i^{\rm LO}}{\sigma_{\rm NWA}^{\rm LO}}$	$\frac{\sigma_i^{\rm NLO}}{\sigma_{\rm NWA_{full}}^{\rm NLO}}$
$\rm NWA_{full}$	$868.8(2)^{+60\%}_{-35\%}$	$1225(1)^{+1\%}_{-14\%}$	1.00	1.00
Prod	$843.2(2)^{+60\%}_{-35\%}$	$1462(1)^{+12\%}_{-19\%}$	0.97	1.19
Mix	25.465(5)	−236(1)	0.029	−0.19
Decay	0.2099(1)	0.1840(8)	0.0002	0.0002
$\rm NWA_{full,exp}$	–	$1173(1)^{+7\%}_{-16\%}$	–	0.96
$\rm NWA_{LOdec}$	–	$1222(1)^{+12\%}_{-19\%}$	–	0.998

$\mu_0 = H_T/2$ NNPDF3.1 PDF

$\Delta R(jb) > 0.8$

- Moderate QCD corrections: $+41\ \%$
- NLO uncertainties — Scale: $\mathcal{O}(15\%)$ PDF: $\mathcal{O}(2\% - 3\%)$

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$\Delta R(jb) > 0.8$

- At LO: *Prod* is dominant, *Mix* and *Decay* are negligible (and all positive)
- At NLO: non-negligible and *negative* contribution from *Mix*: $-19\,\%$

$t\bar{t}jj$: fiducial cross sections

Integrated fiducial cross sections

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$\mu_0 = H_T/2$ NNPDF3.1 PDF

$\Delta R(jb) > 0.8$

- NWA_{full} vs $\text{NWA}_{\text{LOdec}}$: permille level difference

How stable are these conclusions under different kinematical cuts?

$t\bar{t}jj$: fiducial cross sections

[GB, Lupattelli, Stremmer and Worek, Phys. Rev. D (107) 2023, 114027]

$\Delta R(jb) > 0.8$

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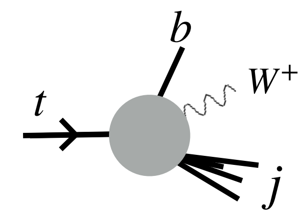
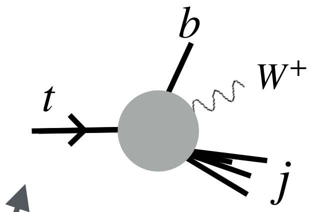
"more  suppressing"

"less  suppressing"

$\Delta R(jb) > 0.4$

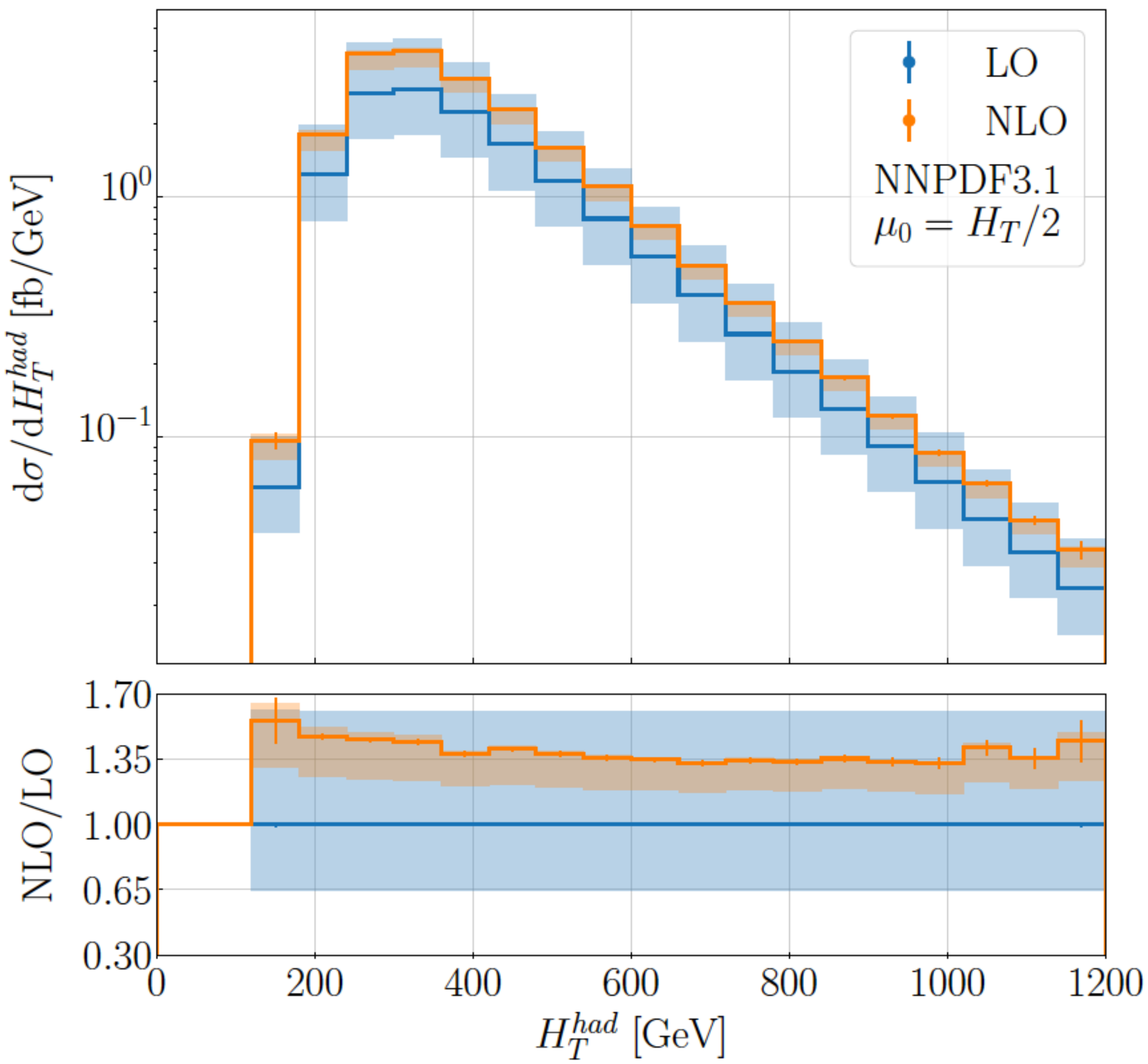
Modelling	$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}$ [fb]	$\frac{\sigma_i^{\rm LO}}{\sigma_{\rm NWA}^{\rm LO}}$	$\frac{\sigma_i^{\rm NLO}}{\sigma_{\rm NWA_{full}}^{\rm NLO}}$
$\rm NWA_{full}$	$1074.5(3)^{+60\%}_{-35\%}$	$1460(1)^{+1\%}_{-13\%}$	1.00	1.00
Prod	$983.1(3)^{+60\%}_{-35\%}$	$1662(1)^{+11\%}_{-18\%}$	0.91	1.14
Mix	89.42(3)	−205(1)	0.083	−0.14
Decay	1.909(1)	2.436(6)	0.002	0.002
$\rm NWA_{LOdec}$	–	$1390(2)^{+11\%}_{-18\%}$	–	0.95

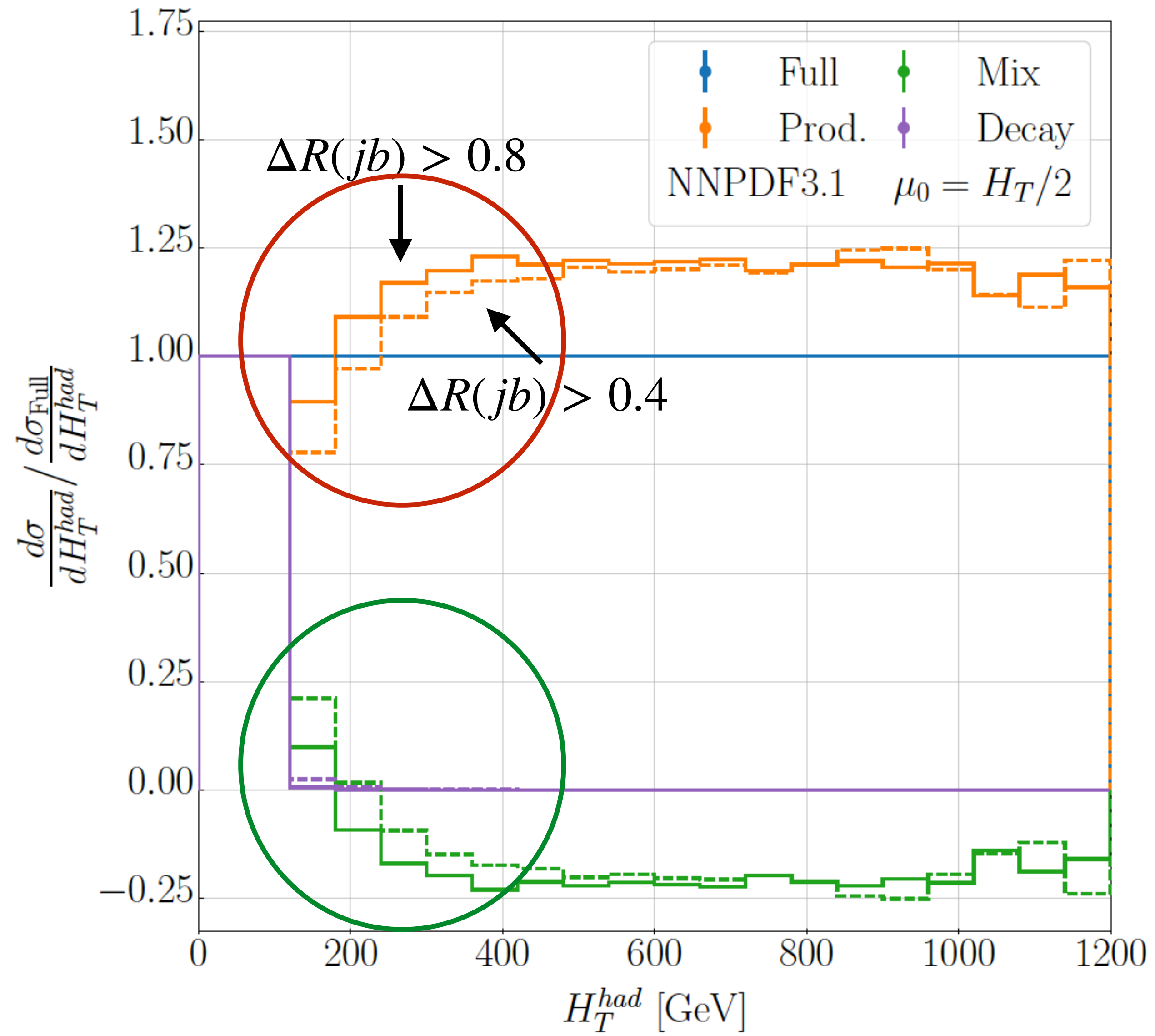
- *Prod-Mix* interplay varies when jet radiation off top quarks is less suppressed
- $|\rm NWA_{full} - NWA_{LOdec}| \sim 5\,\%$ for $\Delta R(jb) > 0.4$

$t\bar{t}jj$: differential cross sections

$$H_T^{had} = \sum_{i=1}^{2} p_{Tj_i} + \sum_{i=1}^{2} p_{Tb_i}$$

[GB, Lupattelli, Stremmer and Worek, Phys. Rev. D (107) 2023, 114027]



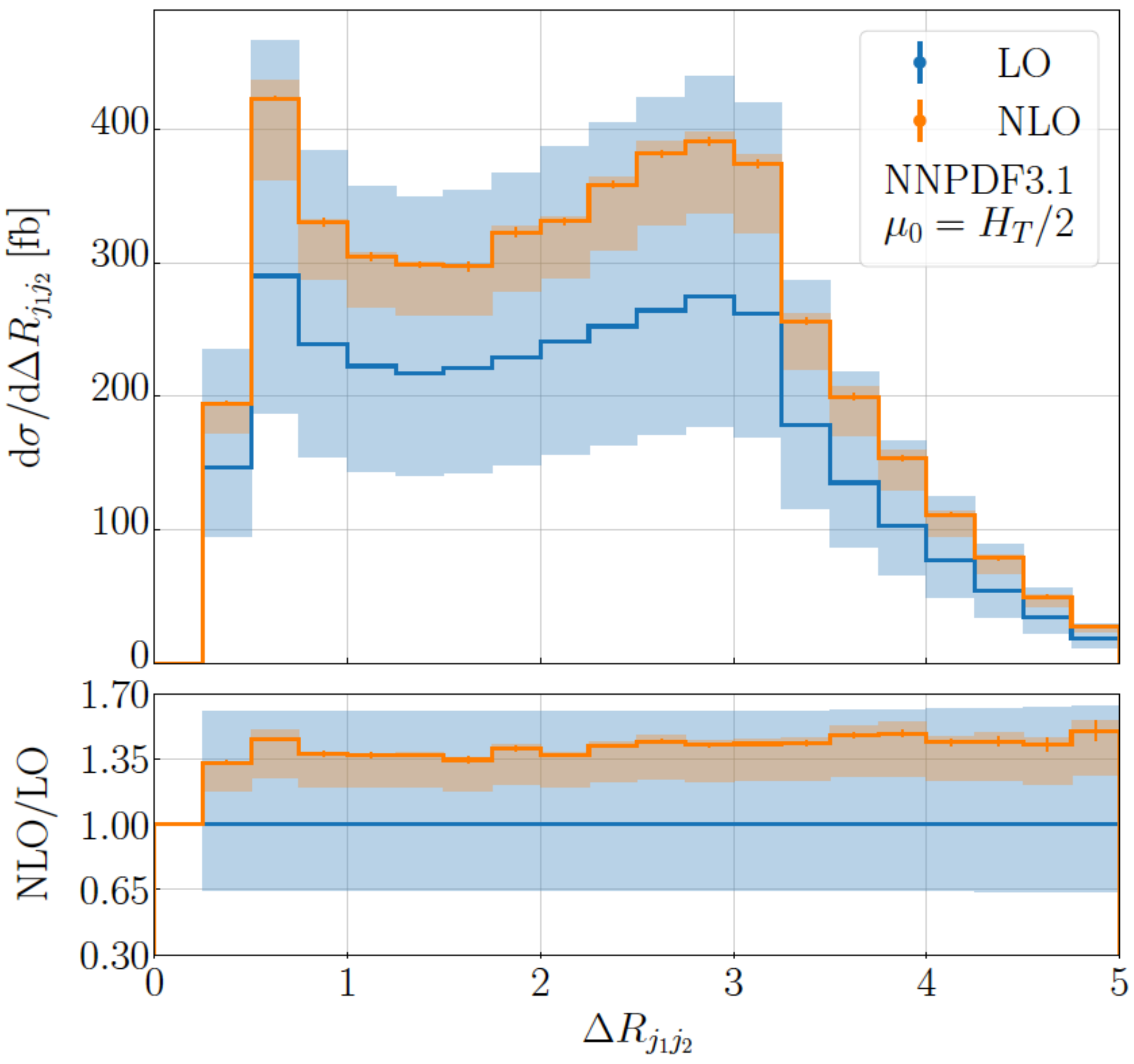


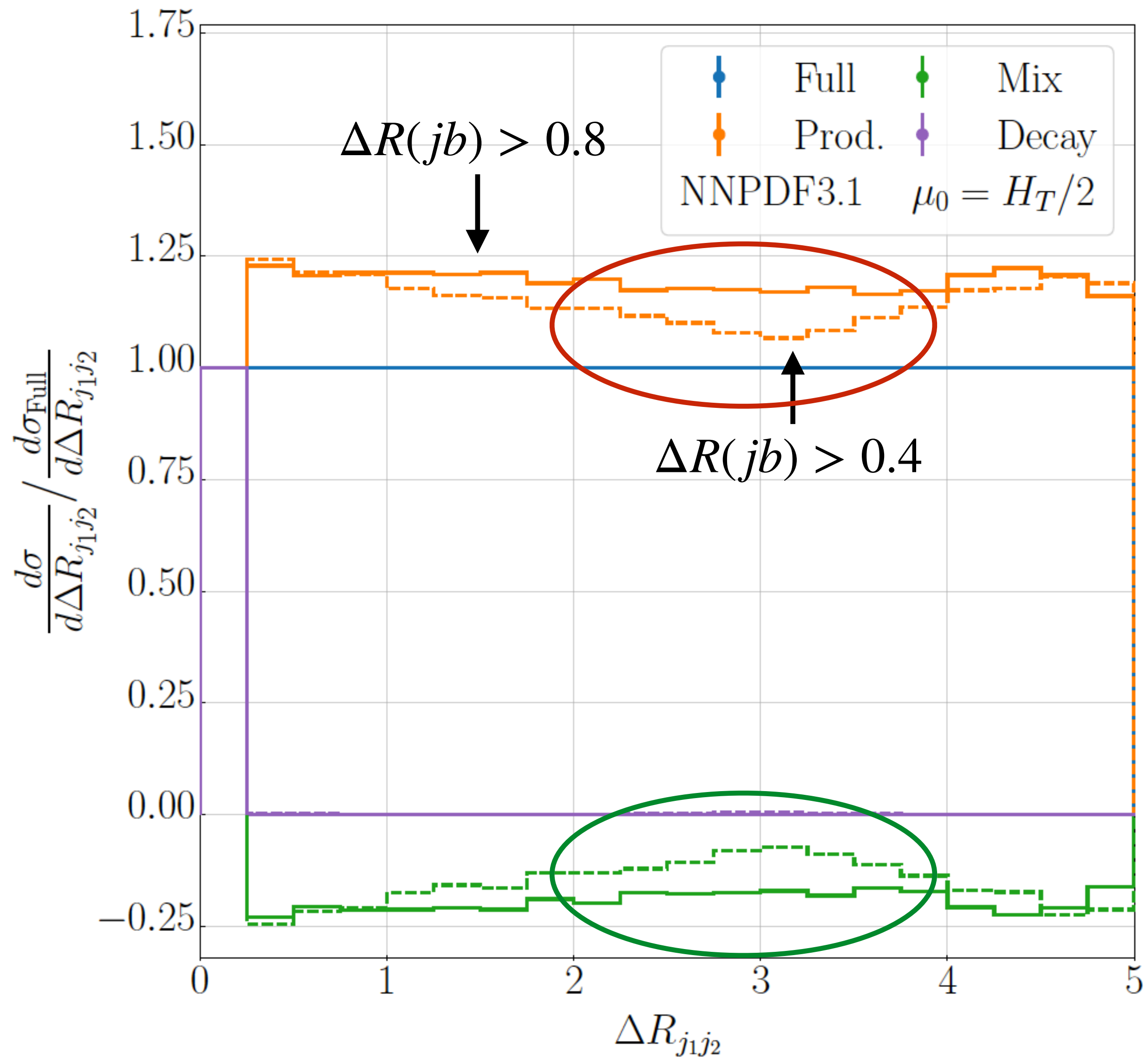
- Sensitivity to $\Delta R(jb)$ cut enhanced around the bulk

$t\bar{t}jj$: differential cross sections

$\Delta R_{j_1 j_2}$

[GB, Lupattelli, Stremmer and Worek, Phys. Rev. D (107) 2023, 114027]

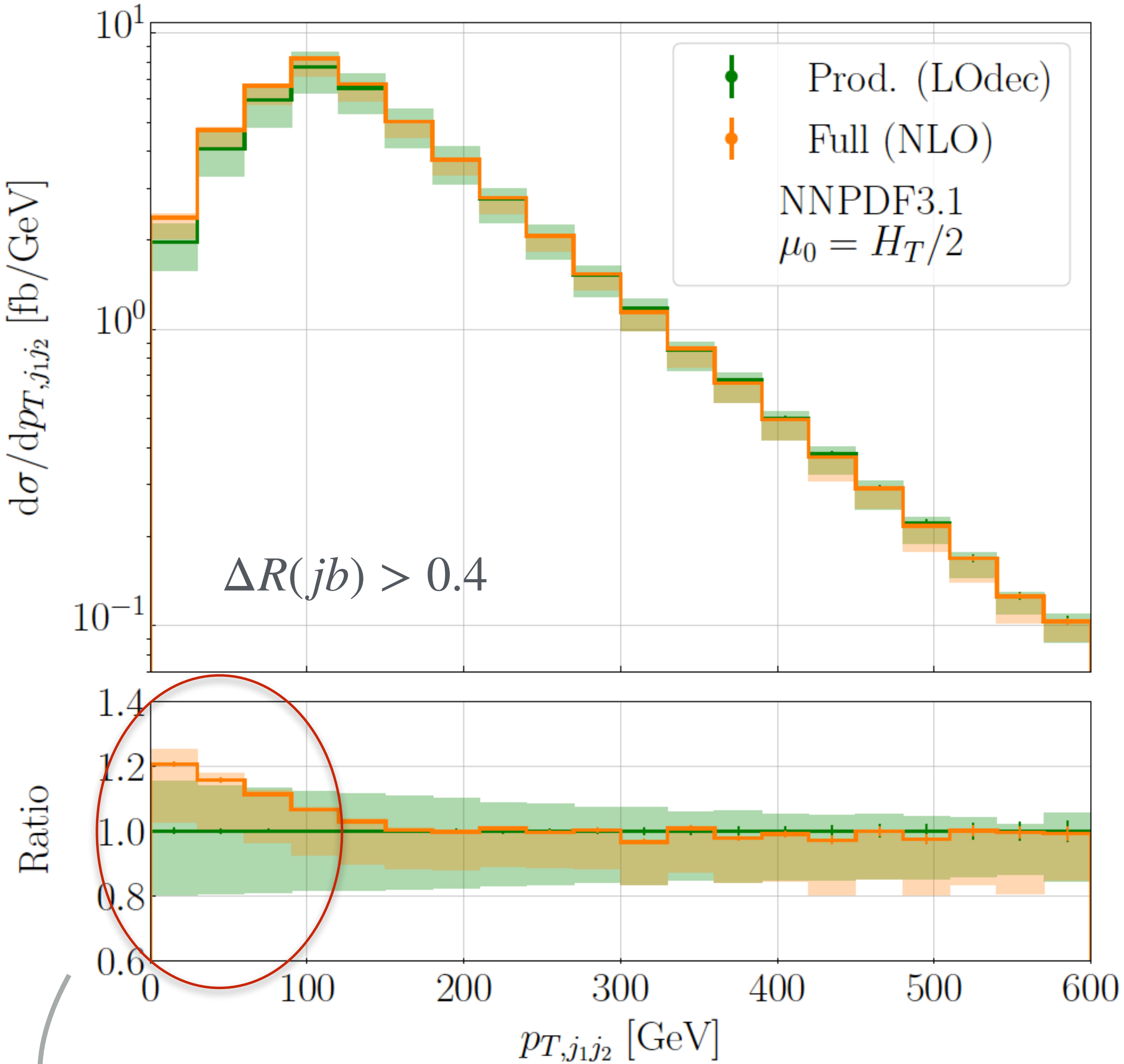


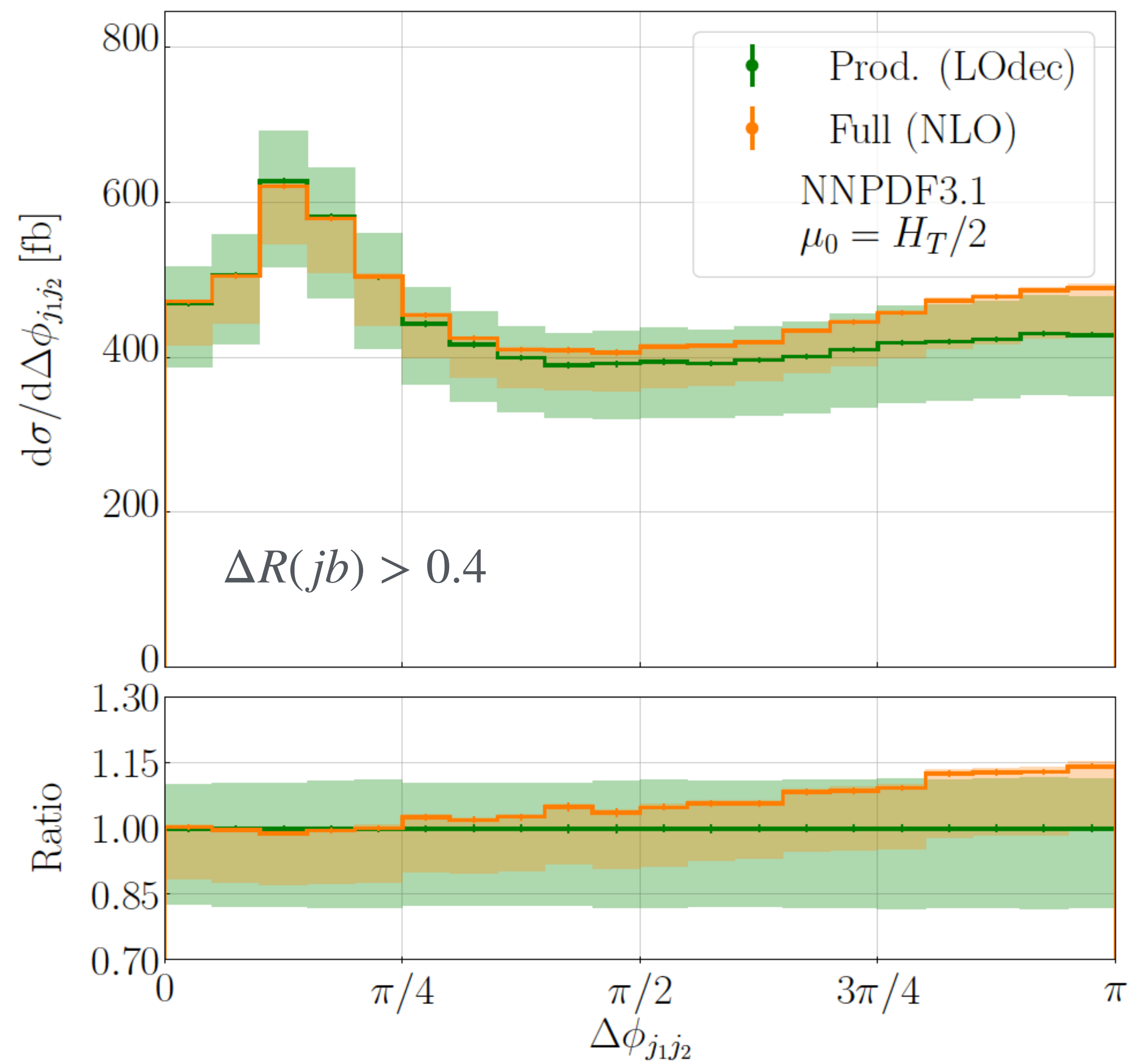


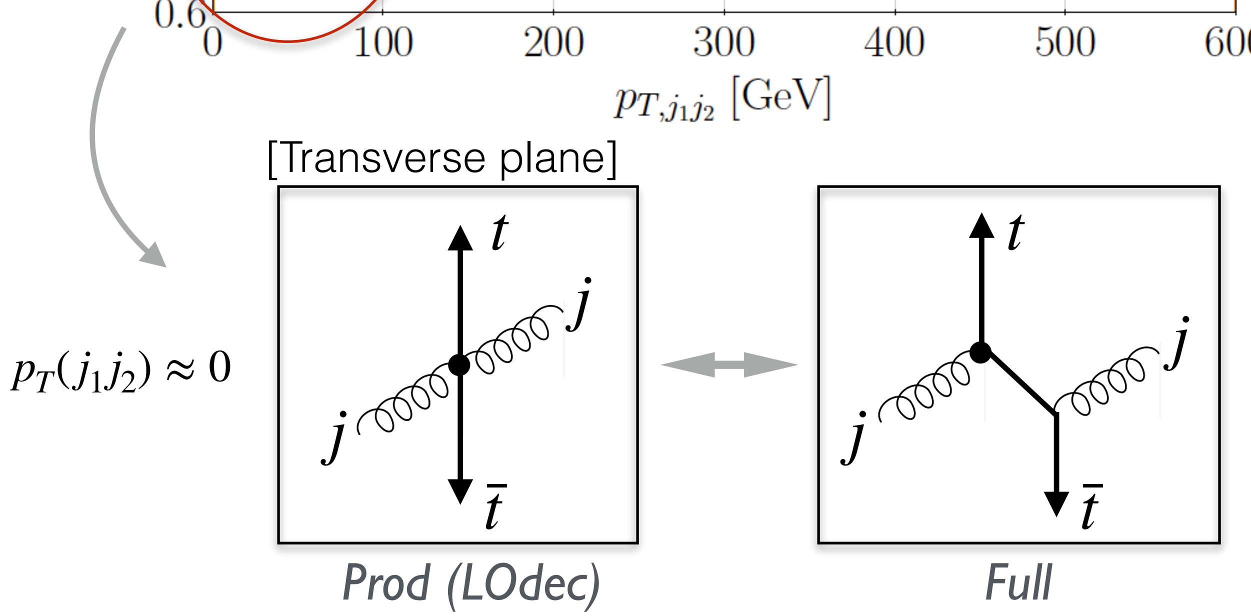
- Sensitivity to $\Delta R(jb)$ cuts enhanced around $\Delta R(j_1 j_2) = 3$

$t\bar{t}jj$: differential cross sections

[GB, Lupattelli, Stremmer and Worek, Phys. Rev. D (107) 2023, 114027]







- Shape distortions up to 15% - 20 % in both dimensionful and dimensionless observables

$t\bar{t}$ + jets: cross section ratios

[GB, Lupattelli, Stremmer and Worek, Phys. Rev. D (107) 2023, 114027]

Fiducial cross section ratios

$\Delta R(jb) > 0.8$

$\mathcal{R}_n$	$\mathcal{R}^{\rm LO}$	$\mathcal{R}^{\rm NLO}$	$\mathcal{R}^{\rm NLO}_{\rm exp}$
$\mathcal{R}_1 = \sigma_{t\bar{t}j}/\sigma_{t\bar{t}}$	$0.3686\,^{+12\%}_{-10\%}$	$0.3546\,^{+0\%}_{-5\%}$	$0.3522\,^{+0\%}_{-3\%}$
$\mathcal{R}_2 = \sigma_{t\bar{t}jj}/\sigma_{t\bar{t}j}$	$0.2539\,^{+11\%}_{-9\%}$	$0.2660\,^{+0\%}_{-5\%}$	$0.2675\,^{+0\%}_{-2\%}$

$$\mathcal{R}^{\rm NLO}_{\rm exp} = \frac{\sigma^0_{t\bar{t}j(j)}}{\sigma^0_{t\bar{t}(j)}}\left(1 + \frac{\sigma^1_{t\bar{t}j(j)}}{\sigma^0_{t\bar{t}j(j)}} - \frac{\sigma^1_{t\bar{t}(j)}}{\sigma^0_{t\bar{t}(j)}}\right)$$

- NLO QCD corrections: $\mathscr{R}_1 \rightarrow -4\,\%$ $\mathscr{R}_2 \rightarrow +4\,\%$
- NLO uncertainties: Scale $\rightarrow \mathcal{O}(5\%)$ PDF $\rightarrow \mathcal{O}(0.5\%)$

Conclusions

- First NLO QCD computation of $pp \to t\bar{t}jj \to \ell^+\nu_\ell \ell^-\bar{\nu}_\ell b\bar{b}jj$ in full NWA

  ↪ jet radiation consistently included in *Production* and *Decays*

- LO → *Prod* contribution is dominant, *Mix* and *Decays* negligible

  NLO → *Mix* contribution changes in magnitude and sign

- Interplay of resonant contributions to σ_{NLO} varies with kinematical cuts

$$\boxed{\Delta R(jb) > 0.8} \quad \to \quad \sigma_{\rm NLO} = 1462\,({\rm Prod}) - 236\,({\rm Mix}) + 0.2\,({\rm Dec}) = 1225 \text{ fb}$$

-19% of $\sigma_{\rm NLO}$

$$\boxed{\Delta R(jb) > 0.4} \quad \to \quad \sigma_{\rm NLO} = 1662\,({\rm Prod}) - 205\,({\rm Mix}) + 2.4\,({\rm Dec}) = 1460 \text{ fb}$$

-14% of $\sigma_{\rm NLO}$

Outlook: cross section ratios $\mathscr{R}_b = \dfrac{\sigma_{ttbb}}{\sigma_{ttjj}}$ and $\mathscr{R}_c = \dfrac{\sigma_{ttcc}}{\sigma_{ttjj}}$ in fiducial phase space regions

Backup slides

Lessons from $t\bar{t} + 1$ jet

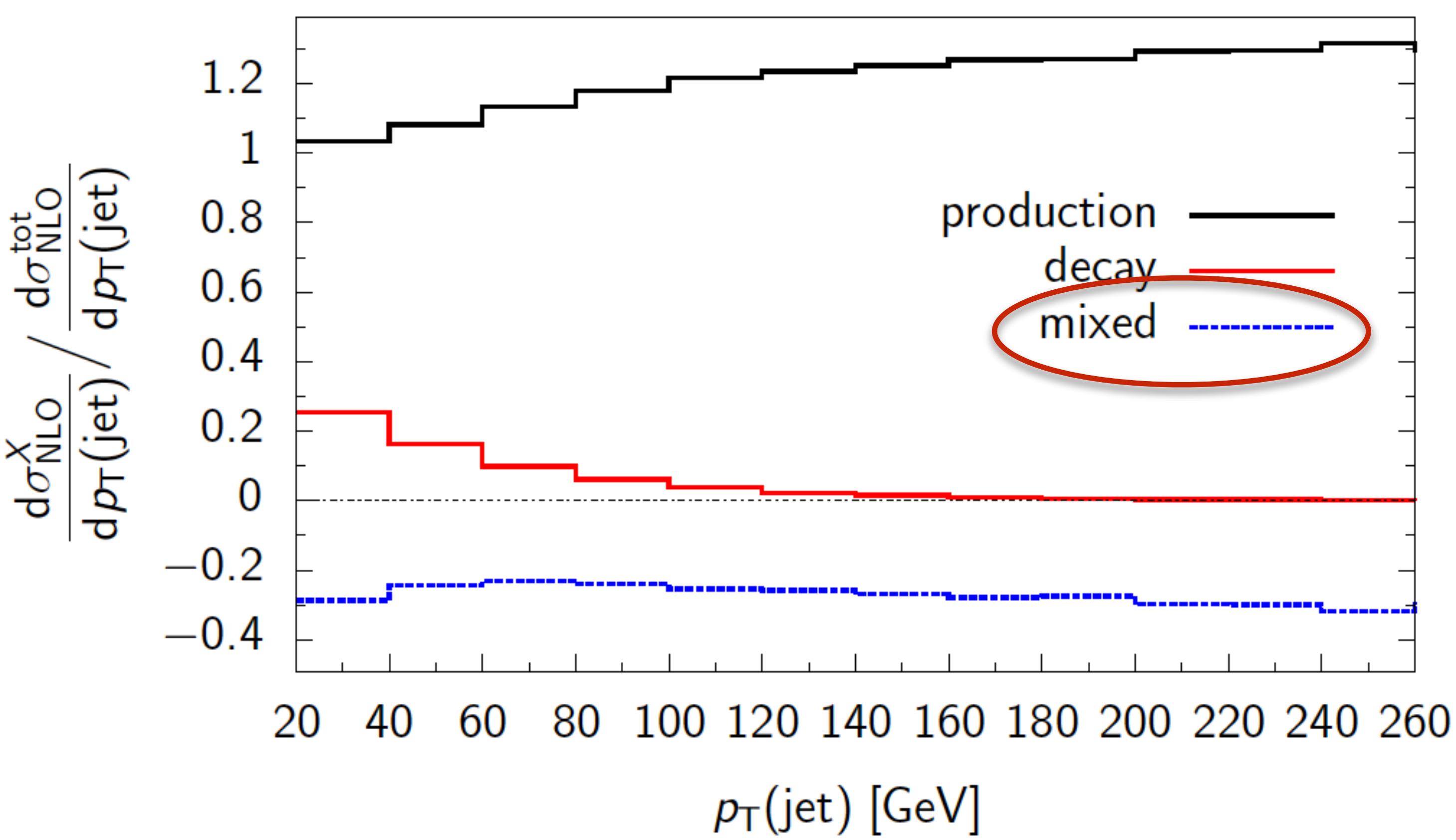
[Melnikov, Scharf and Schulze, Phys.Rev.D 85 (2012) 054002]

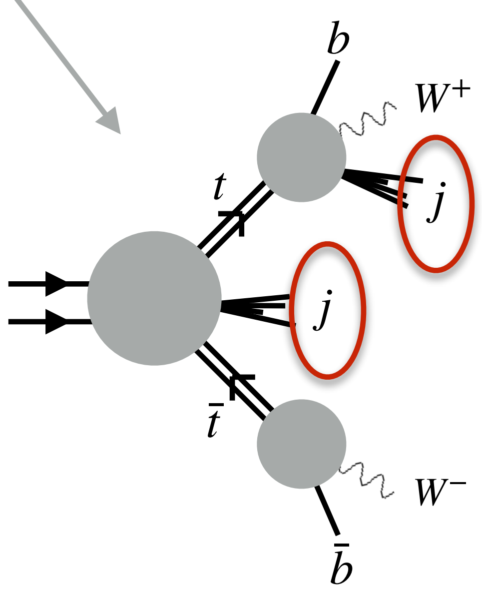
$$pp \to t\bar{t}j \to b\bar{b}\,\ell\nu_\ell\, jjj \qquad \sqrt{s} = 7\,\text{TeV}$$

$$\sigma_{\rm LO} = 316.9\ (\text{Pr}) + 33.4\ (\text{Dec}) = 350.3\ \text{fb},$$

$$\sigma_{\rm NLO} = 323\ (\text{Pr}) + 40.5\ (\text{Dec}) - 75.5\ (\text{Mix}) = 288\ \text{fb}.$$

-25% of $\sigma_{\rm NLO}$





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

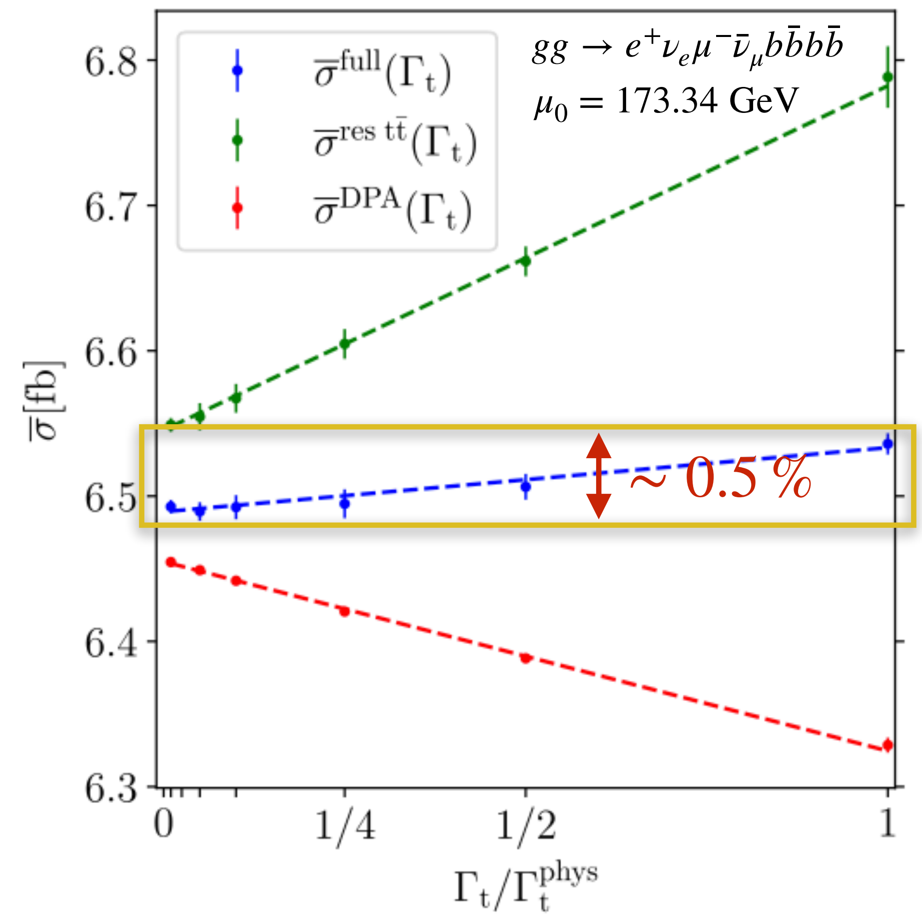
- **Integrated fiducial cross sections** $\sqrt{s} = 13$ TeV

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

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



- QCD corrections are large
- Impact of jet veto:

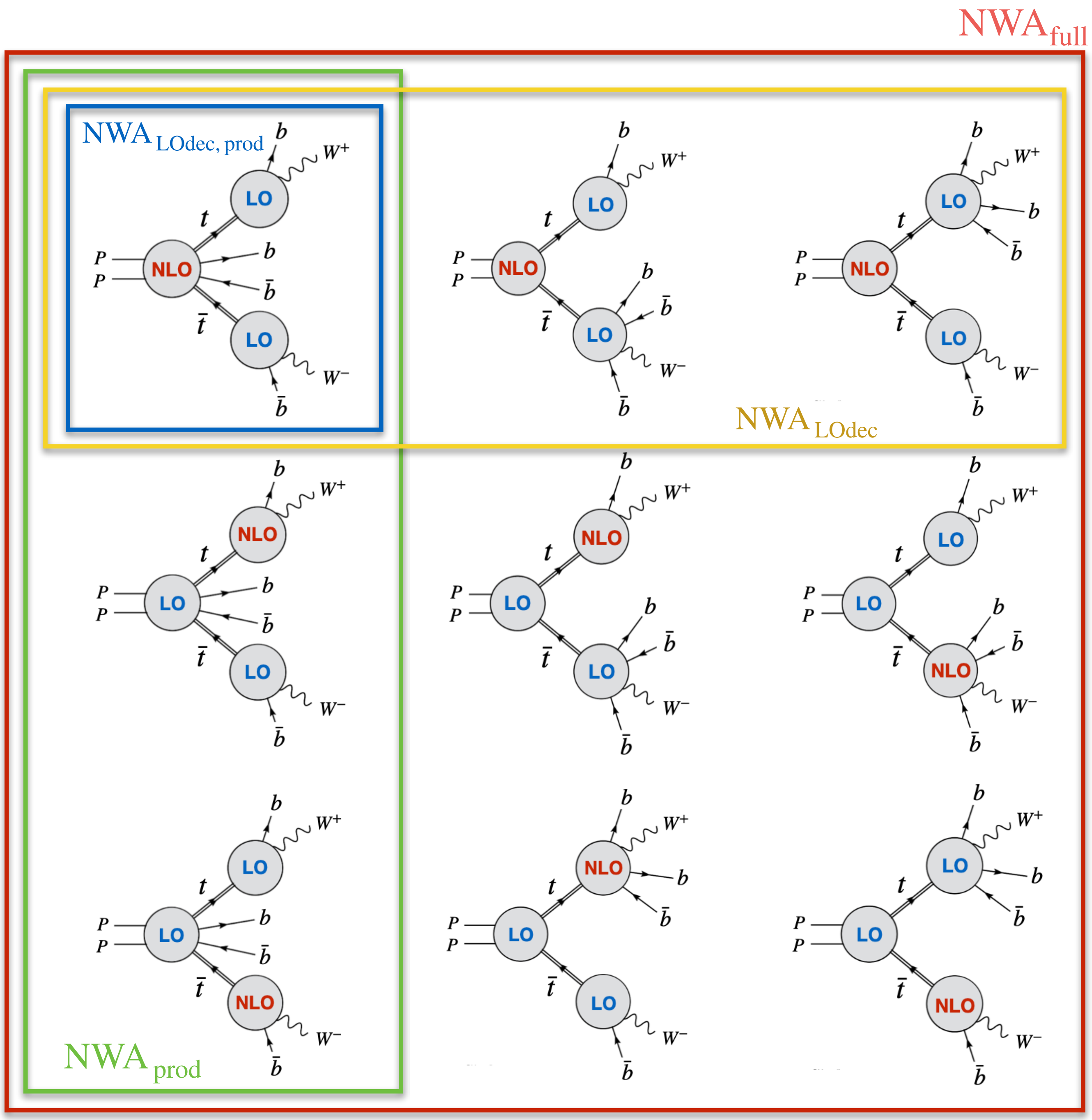
$$p_T^{\rm veto}(j) = 100 \text{ GeV} \rightarrow \sigma^{\rm NLO}/\sigma^{\rm LO} = 1.58$$
$$p_T^{\rm veto}(j) = 50 \text{ GeV} \rightarrow \sigma^{\rm NLO}/\sigma^{\rm LO} = 1.23$$

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

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

- *Full off-shell vs NWA*

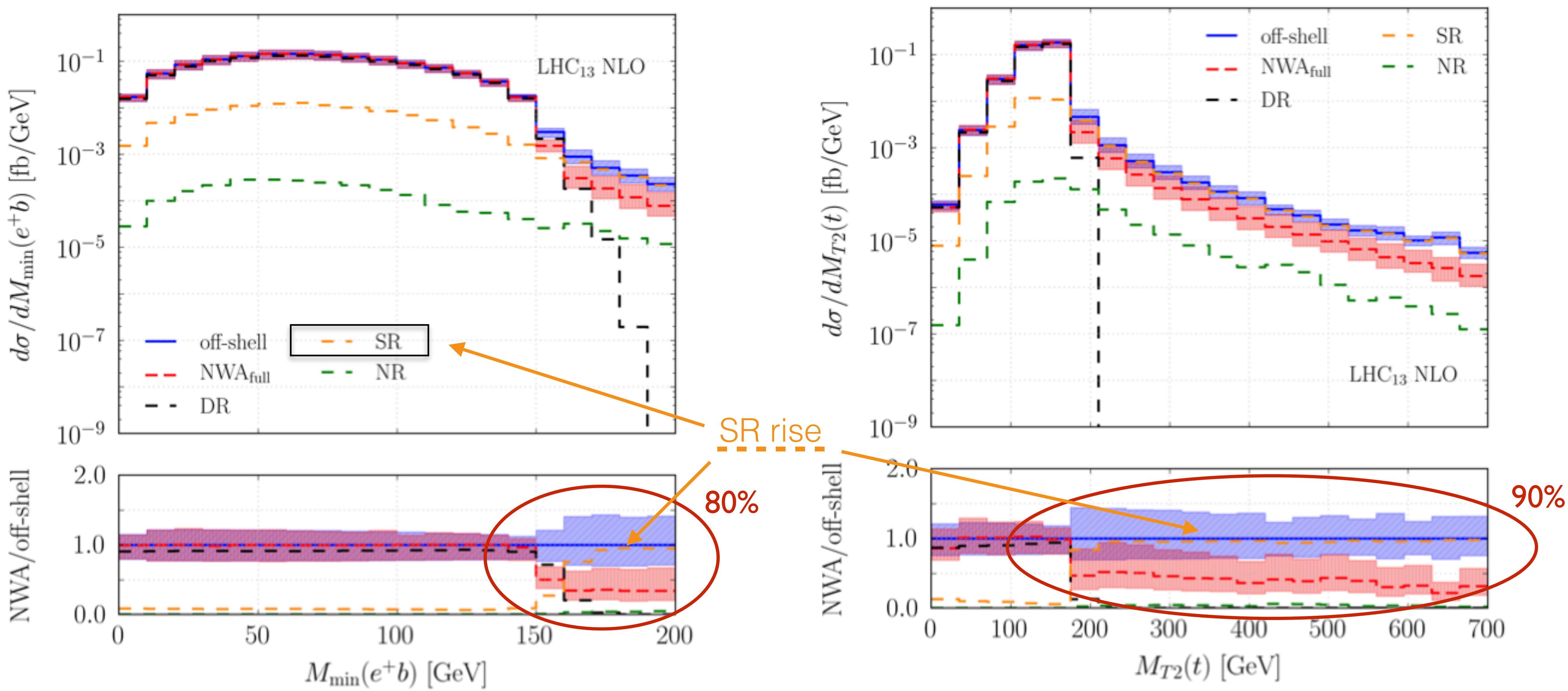
Modelling	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$ [fb]	$\frac{\sigma^{\rm NLO}}{\sigma^{\rm NLO}_{\rm NWA_{full}}} - 1$
Off-shell	13.22(2)	$^{+2.65\ (20\%)}_{-2.96\ (22\%)}$	+0.5%
$\mathrm{NWA_{full}}$	13.16(1)	$^{+2.61\ (20\%)}_{-2.93\ (22\%)}$	–
$\mathrm{NWA_{LOdec}}$	13.22(1)	$^{+3.77\ (29\%)}_{-3.31\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



- NWA cross sections based on different levels of accuracy in top decay modelling
- Genuine off-shell effects: 0.5 %

- 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]



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

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