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
August 29, 2023

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

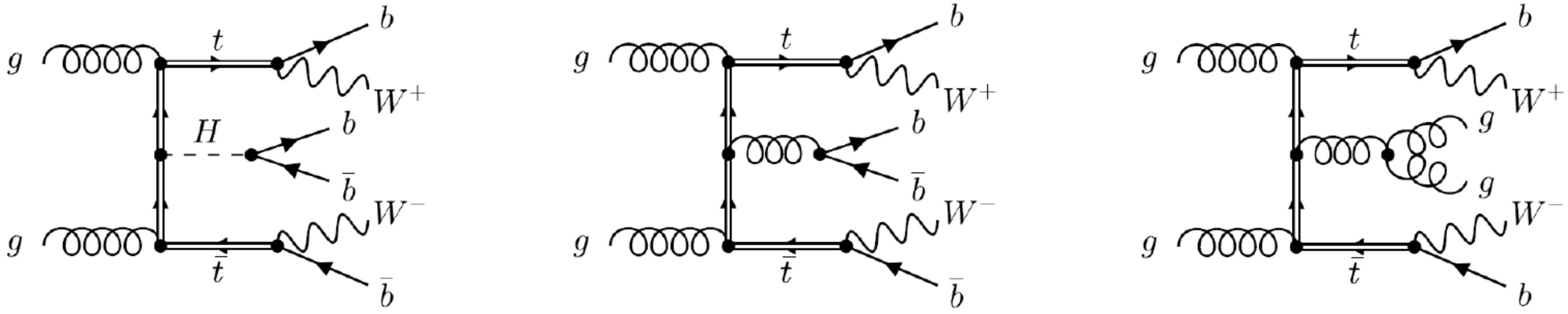
- About half of the inclusive $t\bar{t}$ sample is accompanied by additional hard jet(s) arising from QCD radiation

  Dittmaier, Uwer and Weinzierl '07, '09 …

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

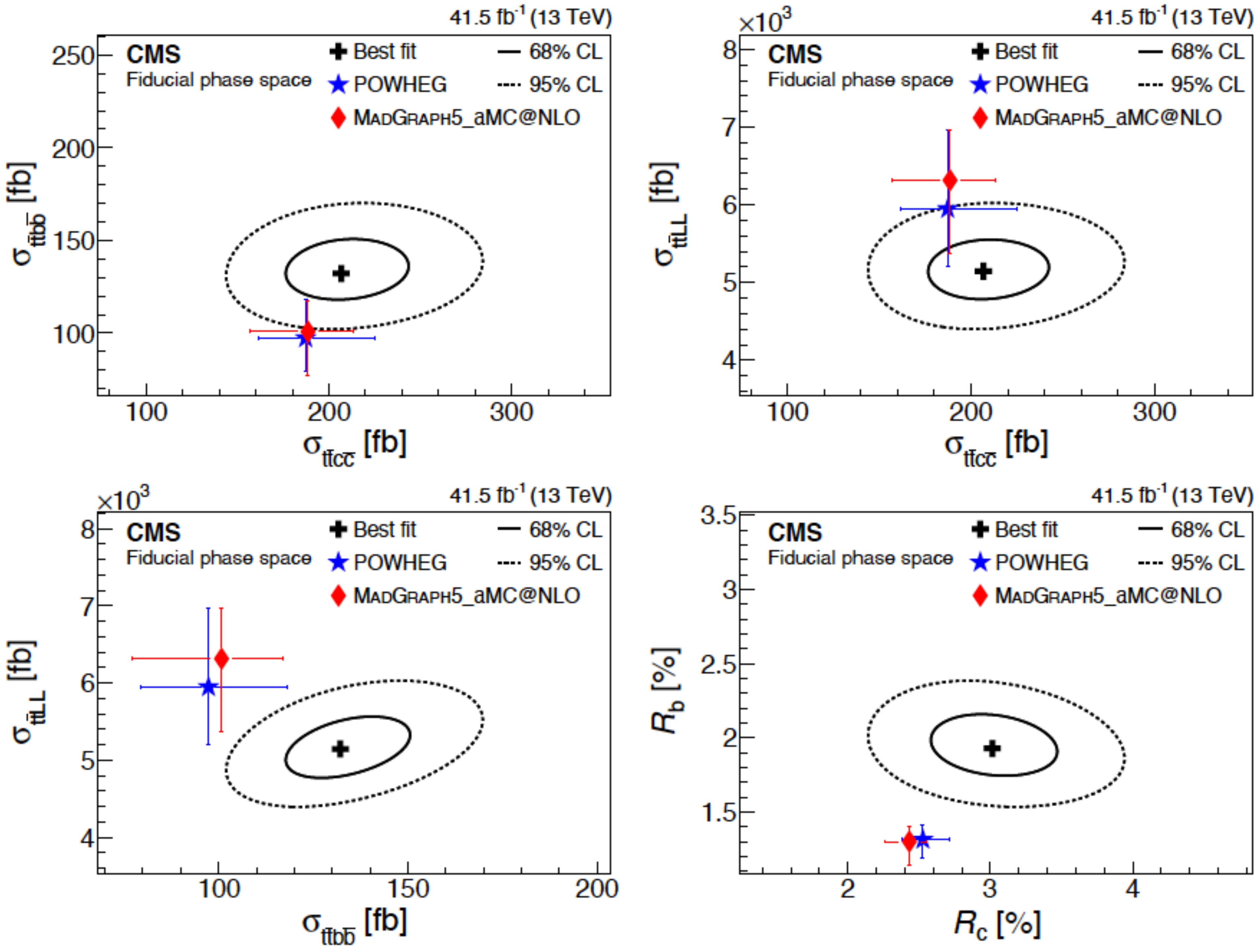
  Alioli, Fuster, Irles, Moch and Uwer '13
  Alioli, Fuster, Garzelli, Gavardi, Irles, Melini, Moch, Uwer and Voss '22

- $t\bar{t}$ + 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 $\quad \to \quad$ test of perturbative QCD

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

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

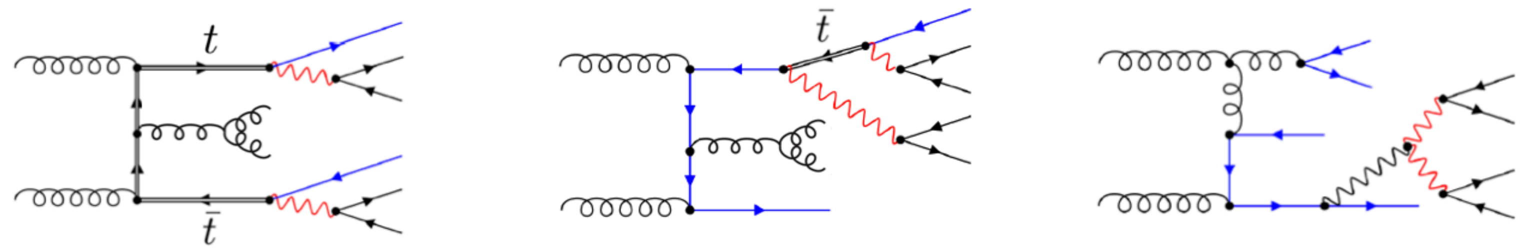
$$R_c = \frac{\sigma(t\bar{t}c\bar{c})}{\sigma(t\bar{t}jj)}$$

- 2.5σ tension in R_b

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

- ME calculations for fully decayed final states are often challenging

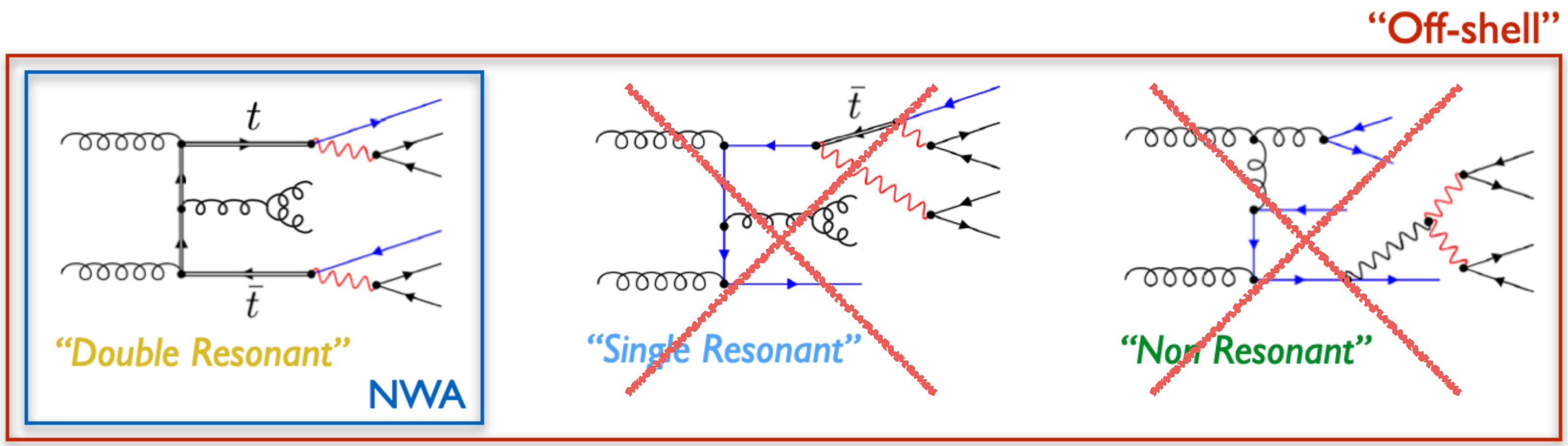
"Off-shell"



"Double Resonant" "Single Resonant" "Non Resonant"

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

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



$$\Gamma_t / m_t \rightarrow 0$$

$$\Gamma_W / m_W \rightarrow 0$$

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

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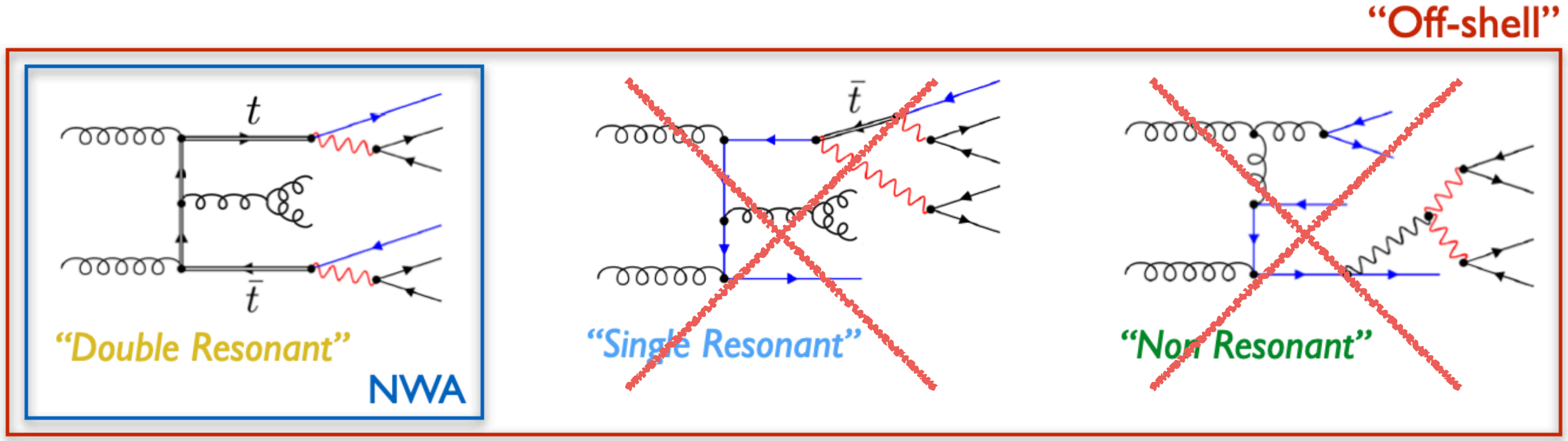
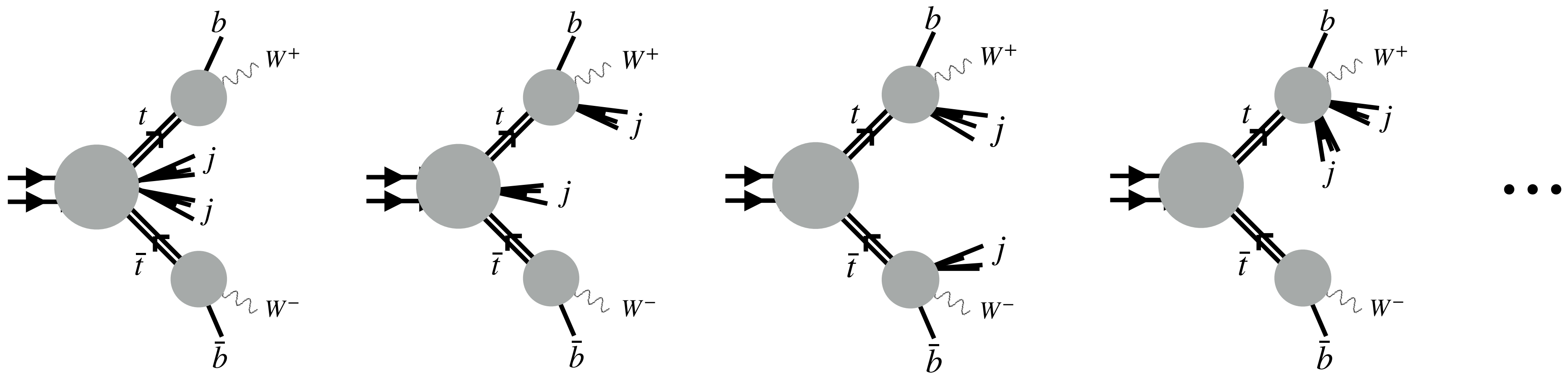


$\Gamma_t/m_t \to 0$

$\Gamma_W/m_W \to 0$

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

e.g. : $n = 2$



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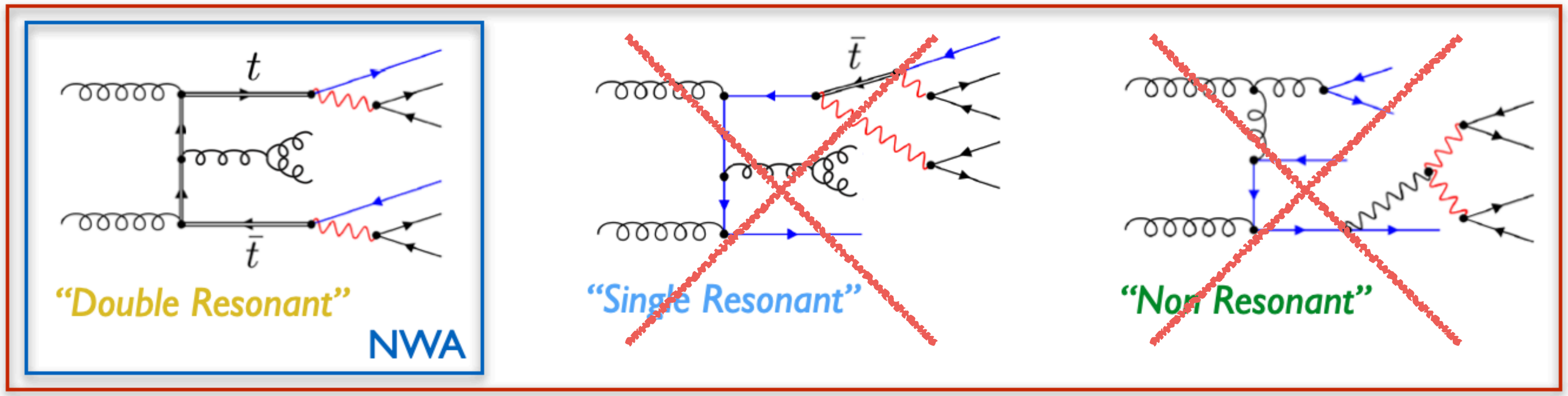

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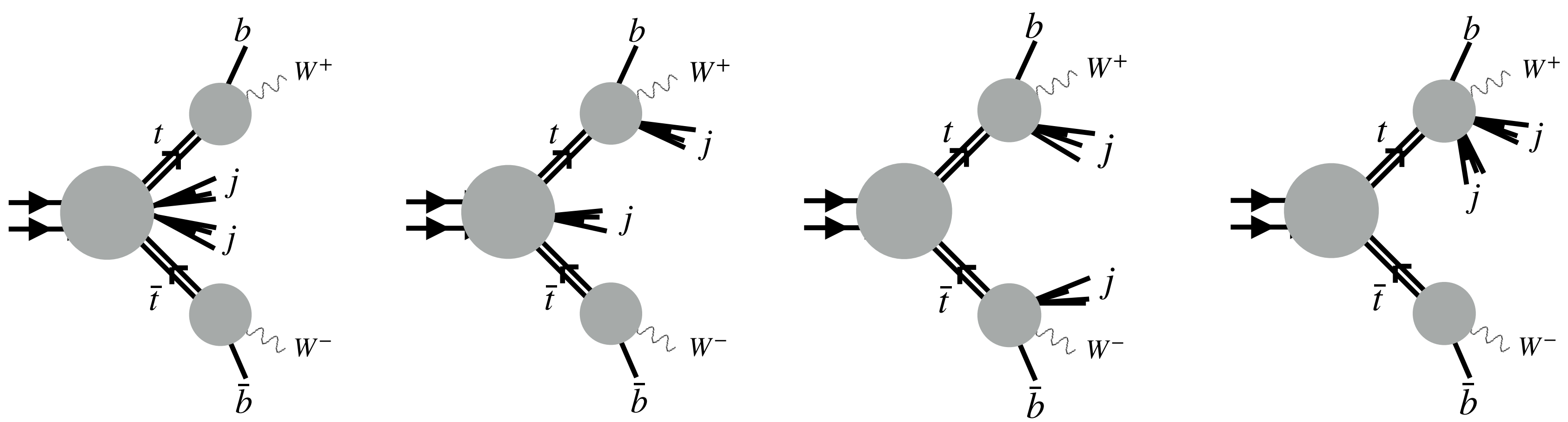
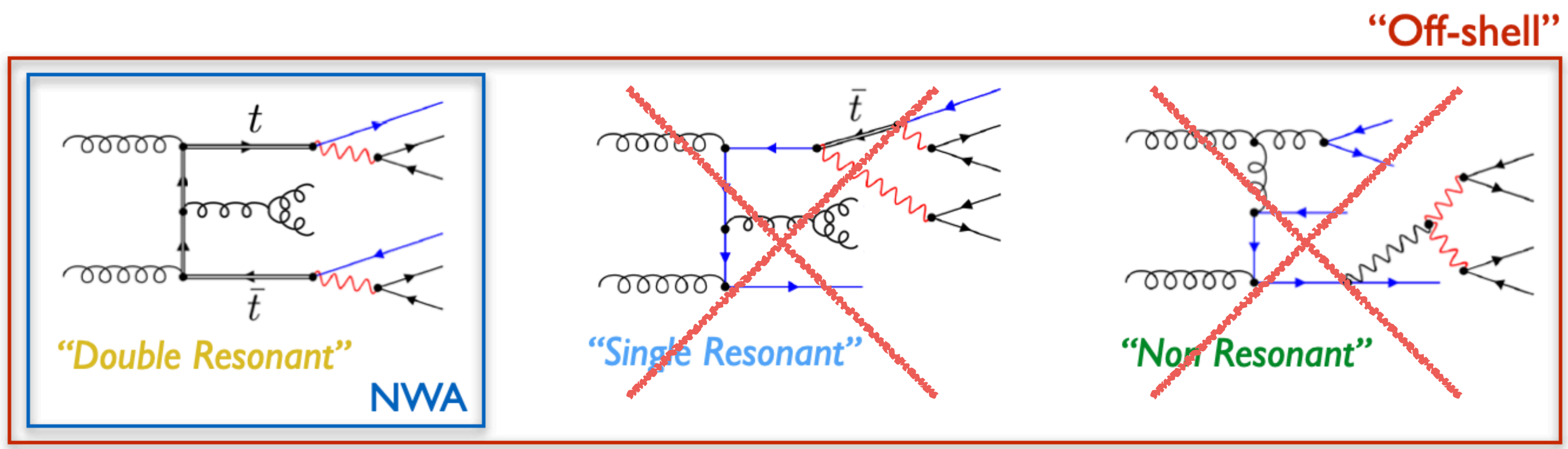


- QCD corrections to both *Production* and *Decay* ME's should be considered for accurate estimates of full NLO cross section

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

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



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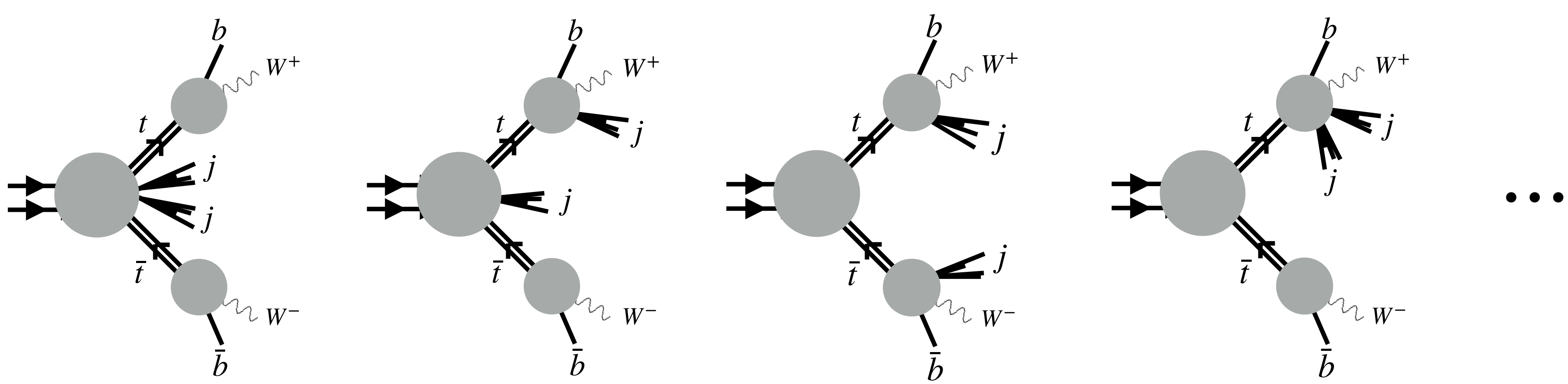


- QCD corrections to both *Production* and *Decay* ME's should be considered for accurate estimates of full NLO cross section

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

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

Stable top quarks

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

  ↪ NLO QCD: fixed-order

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

  ↪ NLO QCD: NLO vs MiNLO

Exclusive final states

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

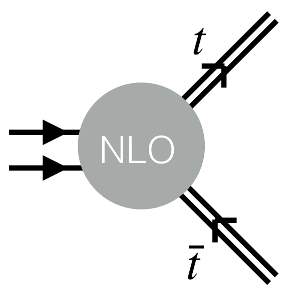
  ↪ NLO QCD: MEPS@NLO multi-jet merging

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

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

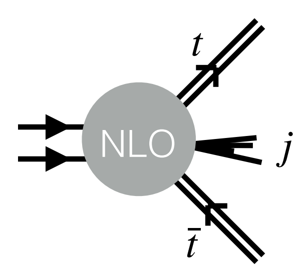
$t\bar{t}jj$: state-of-the-art in a nutshell

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



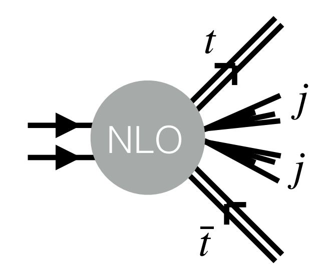
$pp \to t\bar{t} + 0\,\text{jet}$

$\oplus$



$pp \to t\bar{t} + 1\,\text{jet}$

$\oplus$

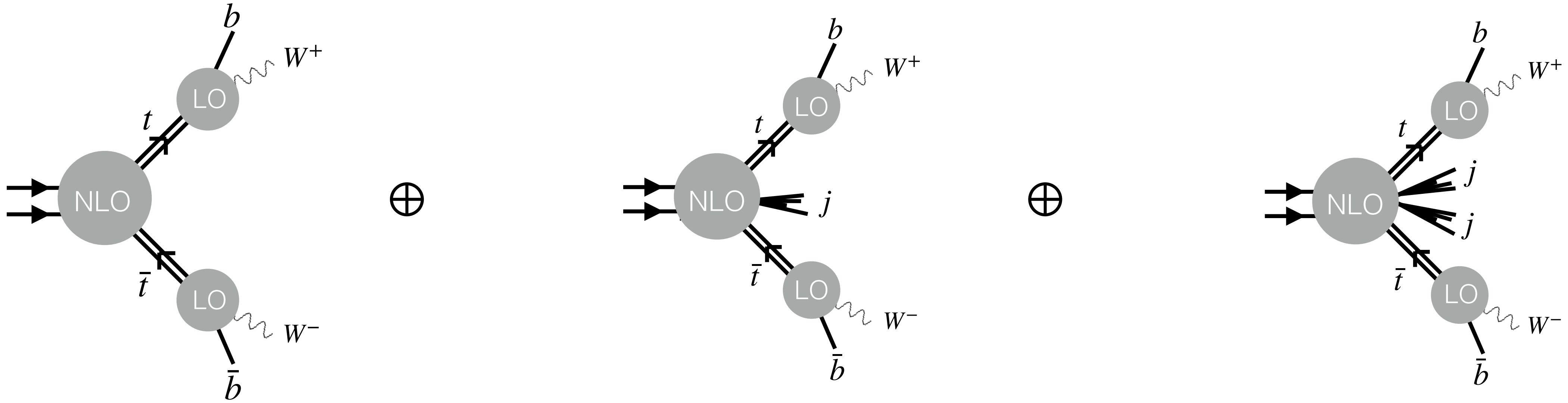


$pp \to t\bar{t} + 2\,\text{jets}$

$t\bar{t}jj$: 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

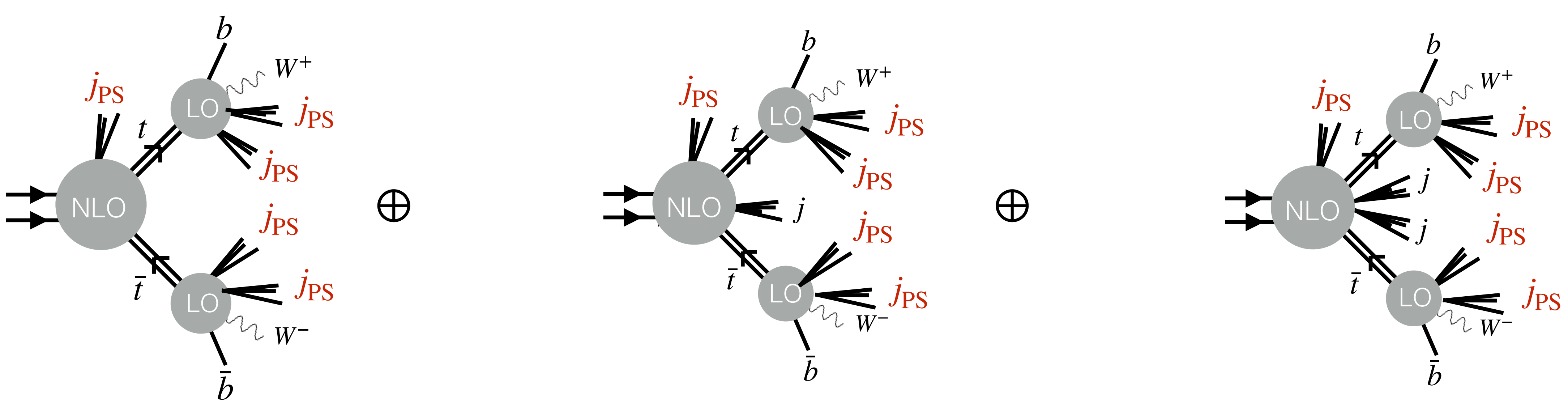


$t\bar{t}jj$: state-of-the-art in a nutshell

- 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



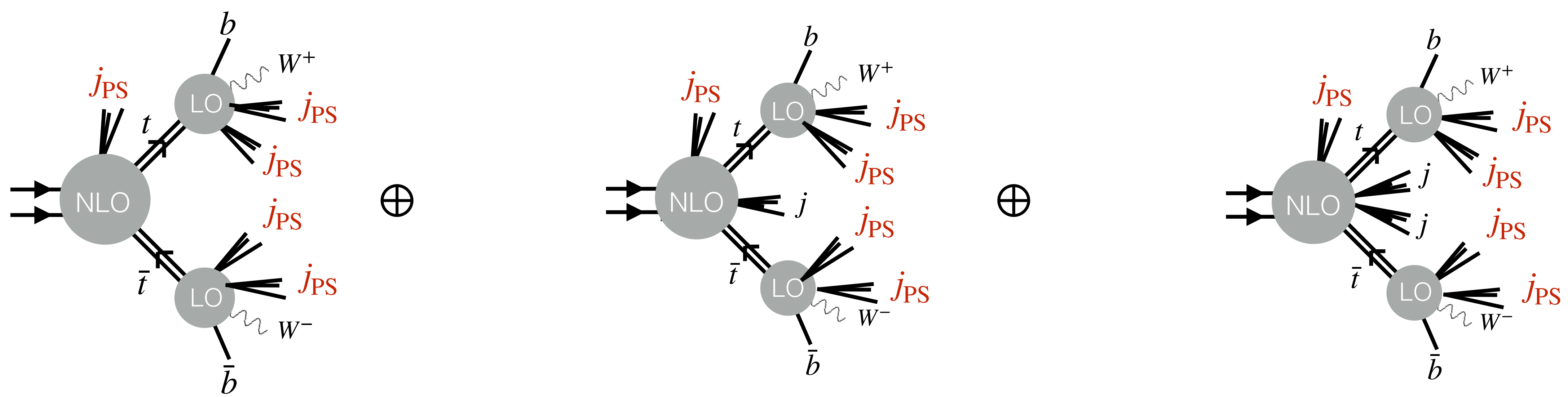
$t\bar{t}jj$: state-of-the-art in a nutshell

Interesting questions:

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

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

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



Goals of this study

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

- Anatomy of resonant contributions at NLO QCD
  - $\hookrightarrow$ Interplay under different kinematical cuts

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

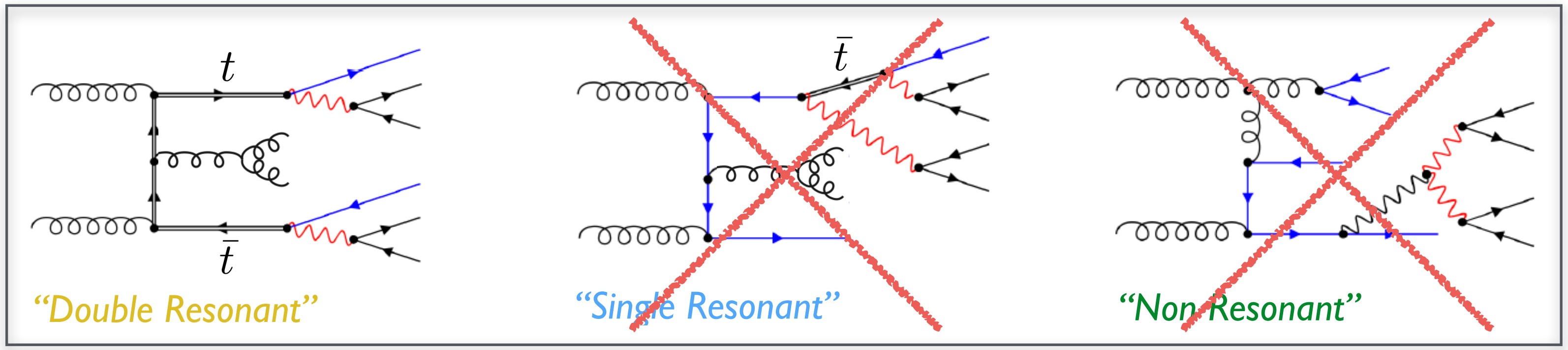
- Fiducial cross section ratios
  - $\hookrightarrow$ $R_1 = \sigma_{ttj}/\sigma_{tt} \quad R_2 = \sigma_{ttjj}/\sigma_{ttj}$

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

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

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

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

GB, Czakon, Kubocz and Worek ’13

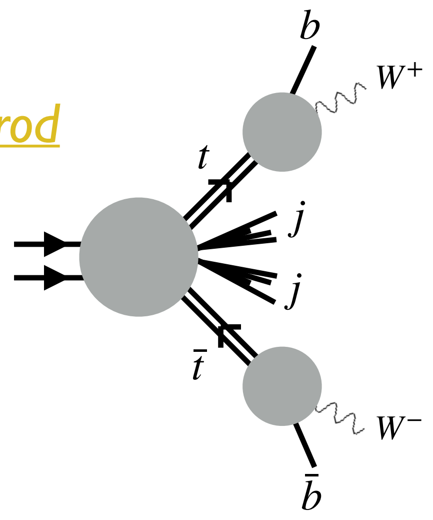
*extended to radiative decays : This work

Anatomy of resonant contributions

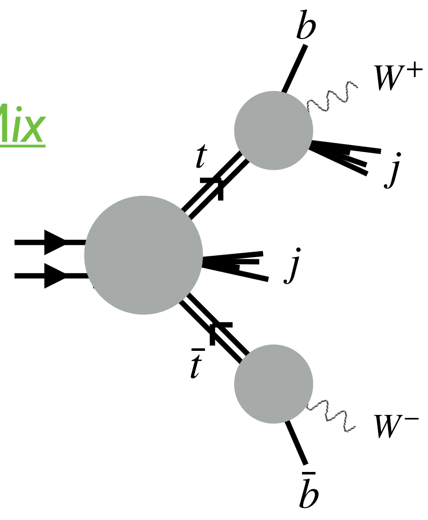
Resonant contributions to $t\bar{t}jj$ in NWA: **LO**

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

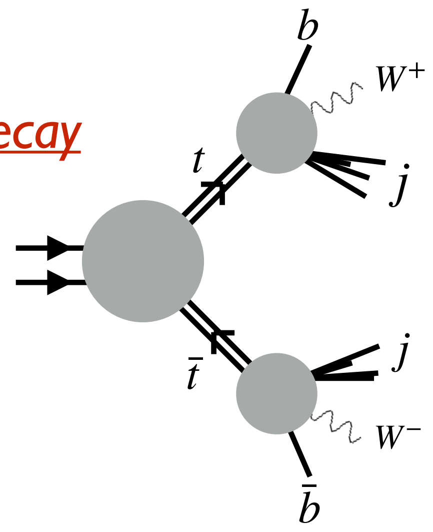
Prod



Mix

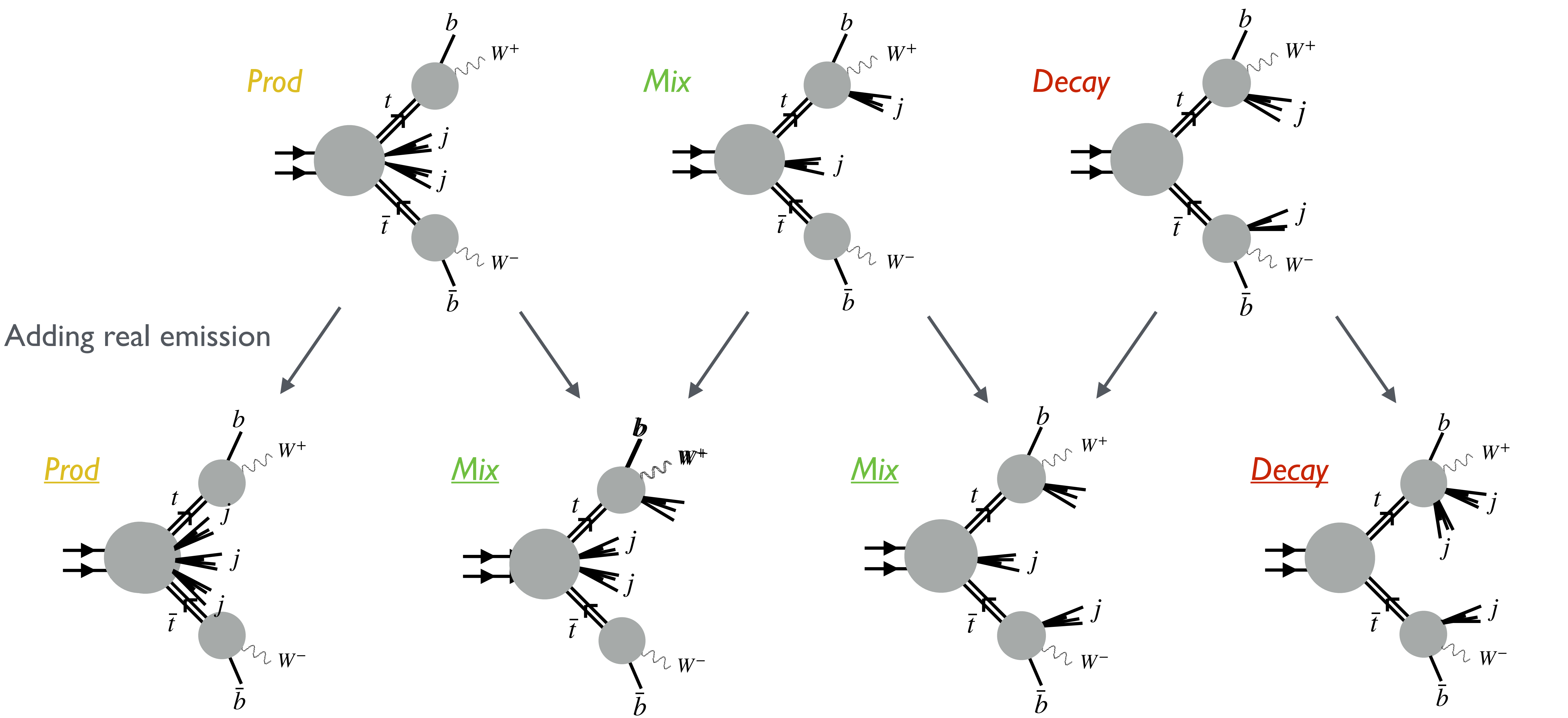


Decay



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

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



Phenomenological results

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

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

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

$(\ell = e, \mu)$

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

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

- **Scale**
  - $\mu_R = \mu_F = \dfrac{H_T}{2}$ $\qquad H_T = \sum_{i=1}^{2} p_T(\ell_i) + p_T(b_i) + p_T(j_i) + p_{T,miss}$
  - 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	σ^{LO} [fb]	σ^{NLO} [fb]	$\frac{\sigma_i^{\mathrm{LO}}}{\sigma_{\mathrm{NWA}}^{\mathrm{LO}}}$	$\frac{\sigma_i^{\mathrm{NLO}}}{\sigma_{\mathrm{NWA_{full}}}^{\mathrm{NLO}}}$
$\mathrm{NWA_{full}}$	$868.8(2)^{+60\%}_{-35\%}$	$1225(1)^{+1\%}_{-14\%}$	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
$\mathrm{NWA_{full,exp}}$	–	$1173(1)^{+7\%}_{-16\%}$	–	0.96
$\mathrm{NWA_{LOdec}}$	–	$1222(1)^{+12\%}_{-19\%}$	–	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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$\mu_0 = H_T/2$ NNPDF3.1 PDF

$\Delta R(jb) > 0.8$

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

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

$\Delta R(jb) > 0.8$

- $\mathrm{NWA_{full}}$ vs $\mathrm{NWA_{LOdec}}$: 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]

$\Delta R(jb) > 0.8$

Modelling	$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}$ [fb]	$\frac{\sigma_i^{\rm LO}}{\sigma_{\rm NWA}^{\rm LO}}$	$\frac{\sigma_i^{\rm NLO}}{\sigma_{\rm NWA_{full}}^{\rm NLO}}$
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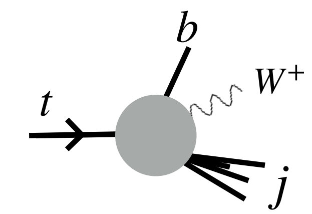
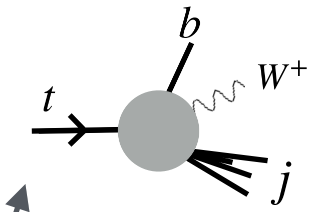
"more  suppressing"

"less  suppressing"

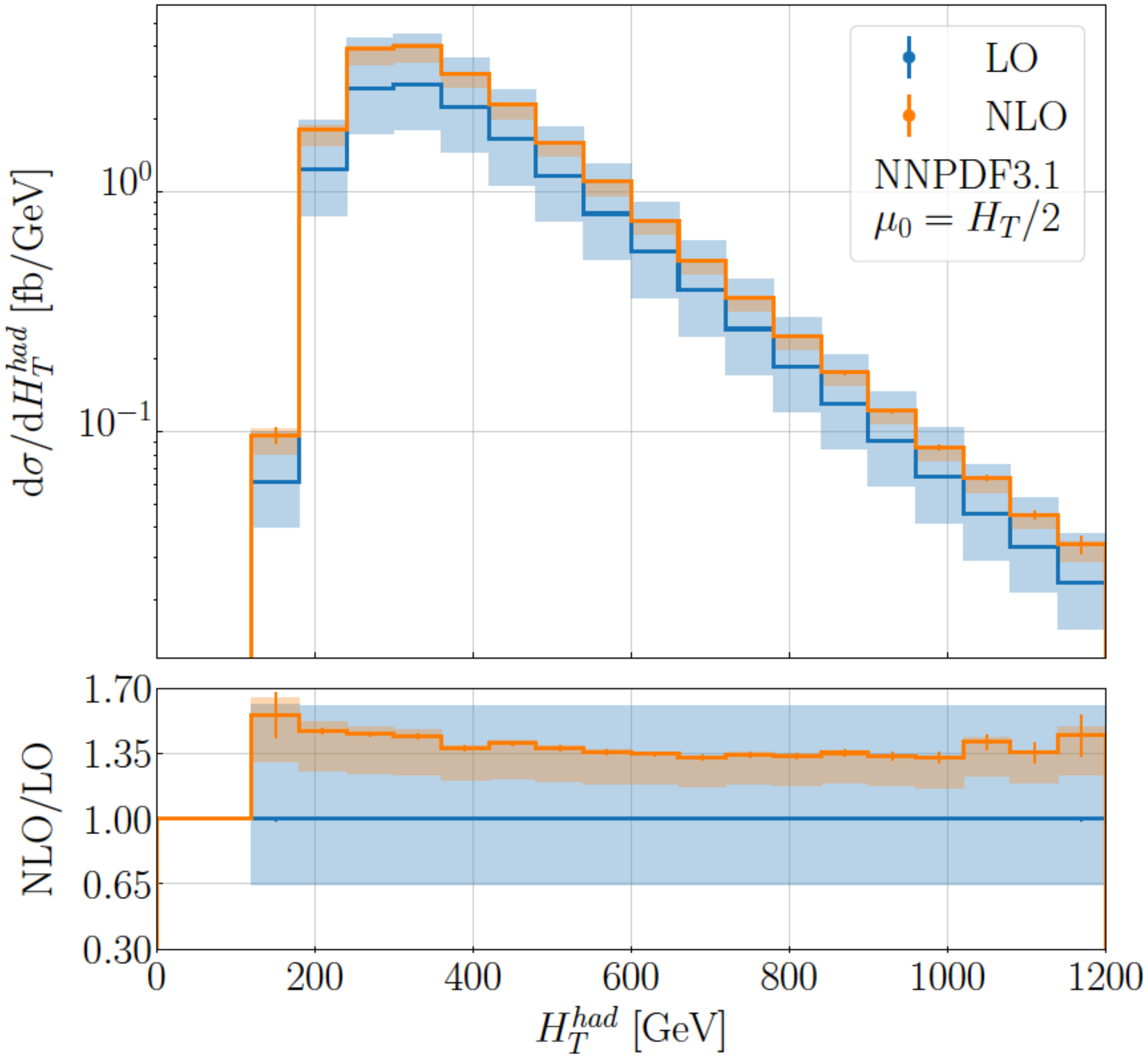
$\Delta R(jb) > 0.4$

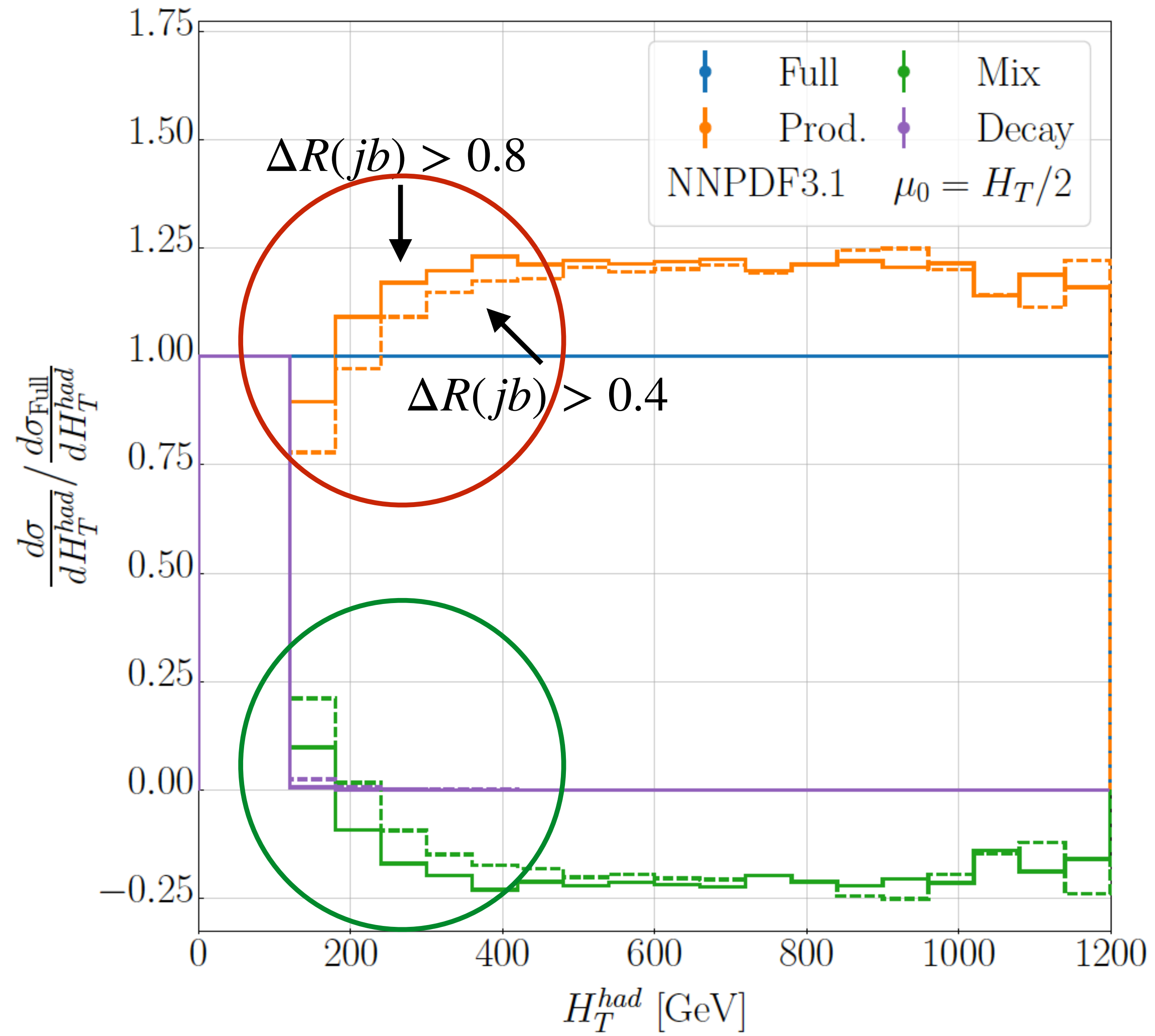
Modelling	$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}$ [fb]	$\frac{\sigma_i^{\rm LO}}{\sigma_{\rm NWA}^{\rm LO}}$	$\frac{\sigma_i^{\rm NLO}}{\sigma_{\rm NWA_{full}}^{\rm NLO}}$
$\rm NWA_{full}$	$1074.5(3)^{+60\%}_{-35\%}$	$1460(1)^{+1\%}_{-13\%}$	1.00	1.00
Prod	$983.1(3)^{+60\%}_{-35\%}$	$1662(1)^{+11\%}_{-18\%}$	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
- $|\mathrm{NWA_{full}} - \mathrm{NWA_{LOdec}}| \sim 5\,\%$ for $\Delta R(jb) > 0.4$

$$H_T^{had} = \sum_{i=1}^{2} p_{T j_i} + \sum_{i=1}^{2} p_{T b_i}$$

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

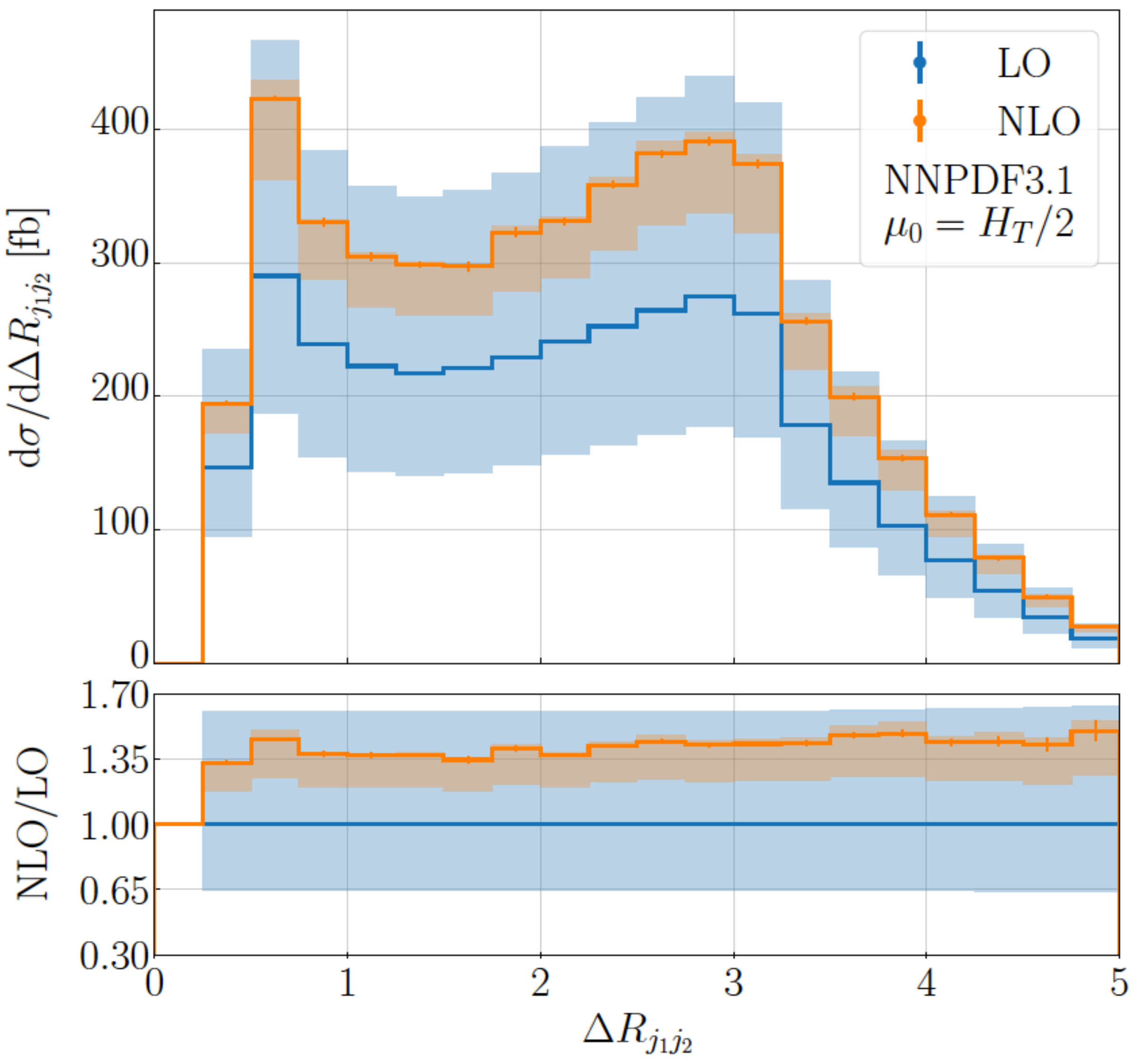


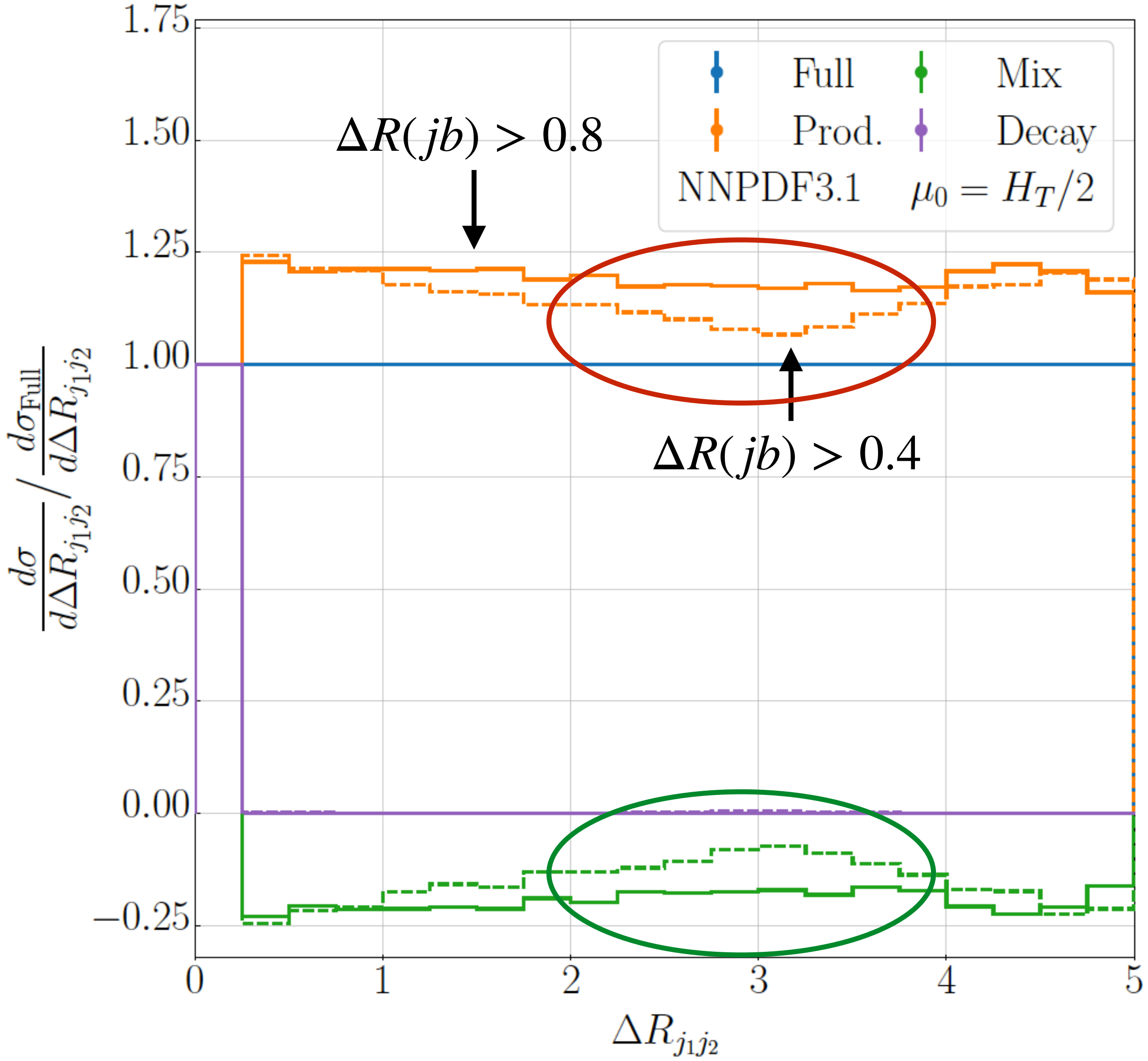


- Sensitivity to $\Delta R(jb)$ cut enhanced around the bulk

$\Delta R_{j_1 j_2}$

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

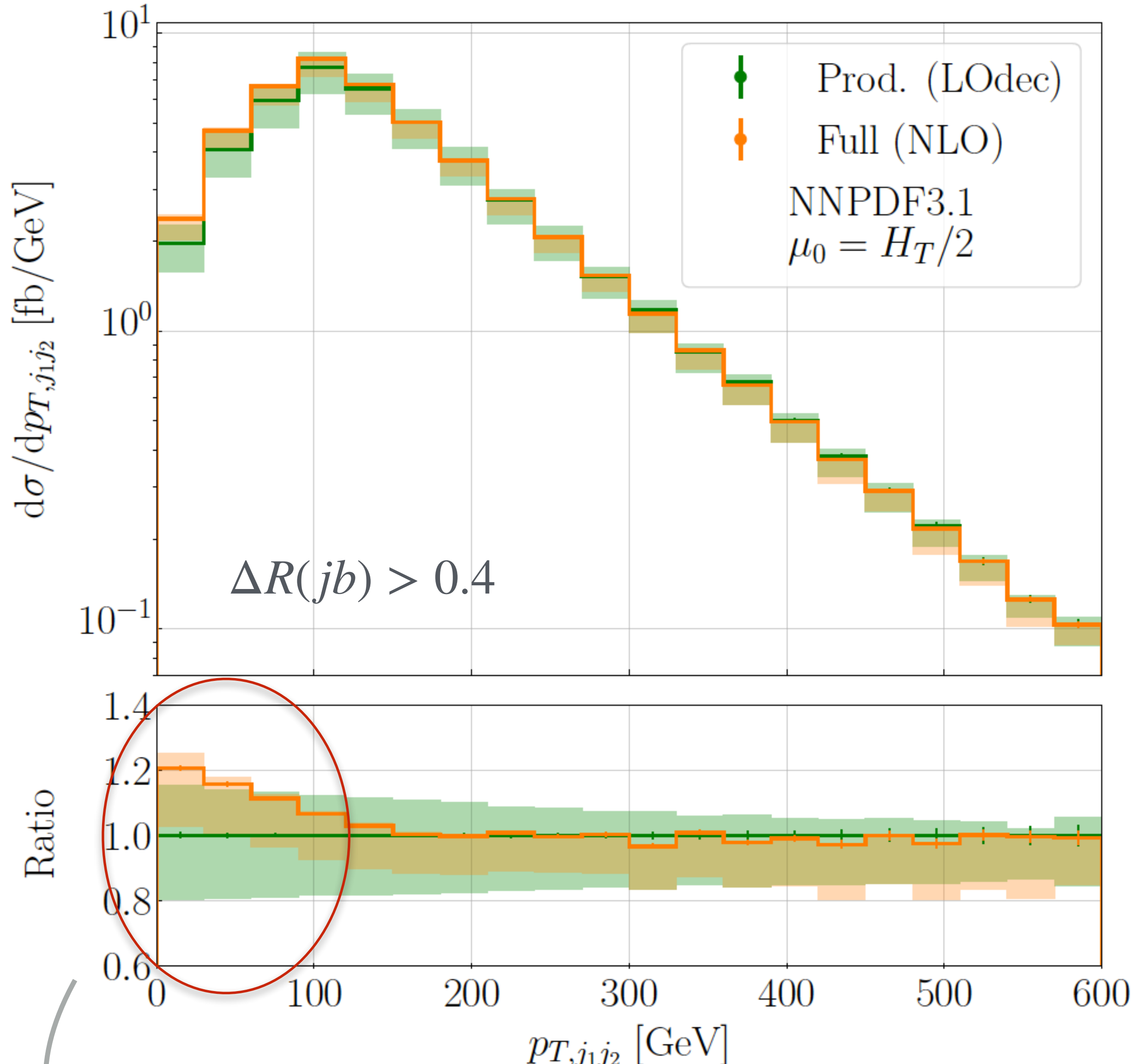


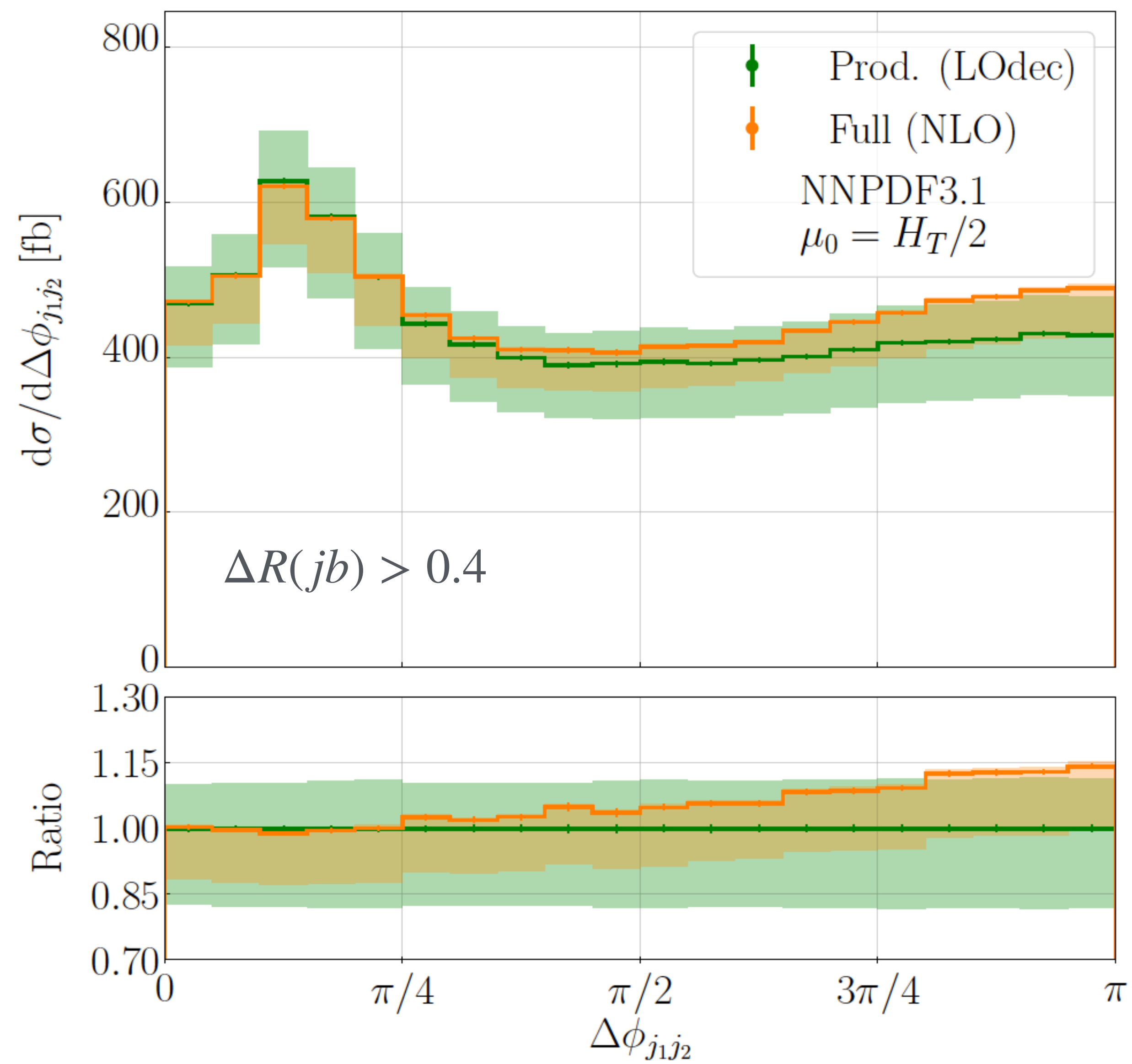


- Sensitivity to $\Delta R(jb)$ cuts enhanced around $\Delta R(j_1 j_2) = 3$

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

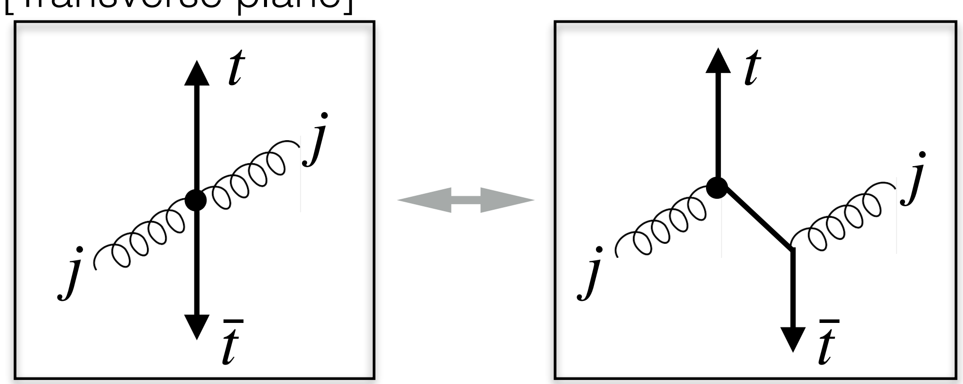
[GB, Lupattelli, Stremmer and Worek, Phys. Rev. D (107) 2023, 114027]





[Transverse plane]

$p_T(j_1j_2) \approx 0$



Prod (LOdec) *Full*

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

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

Fiducial cross section ratios

$\boxed{\Delta R(jb) > 0.8}$

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

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

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

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

$$\boxed{\Delta R(jb) > 0.8} \quad \to \quad \sigma_{\rm NLO} = 1462\,({\rm Prod}) \underbrace{-\,236\,({\rm Mix})}_{\textbf{-19\%}\text{ of } \sigma_{\rm NLO}} +\, 0.2\,({\rm Dec}) = 1225 \text{ fb}$$

$$\boxed{\Delta R(jb) > 0.4} \quad \to \quad \sigma_{\rm NLO} = 1662\,({\rm Prod}) \underbrace{-\,205\,({\rm Mix})}_{\textbf{-14\%}\text{ of } \sigma_{\rm NLO}} +\, 2.4\,({\rm Dec}) = 1460 \text{ fb}$$

<u>Outlook</u>: 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

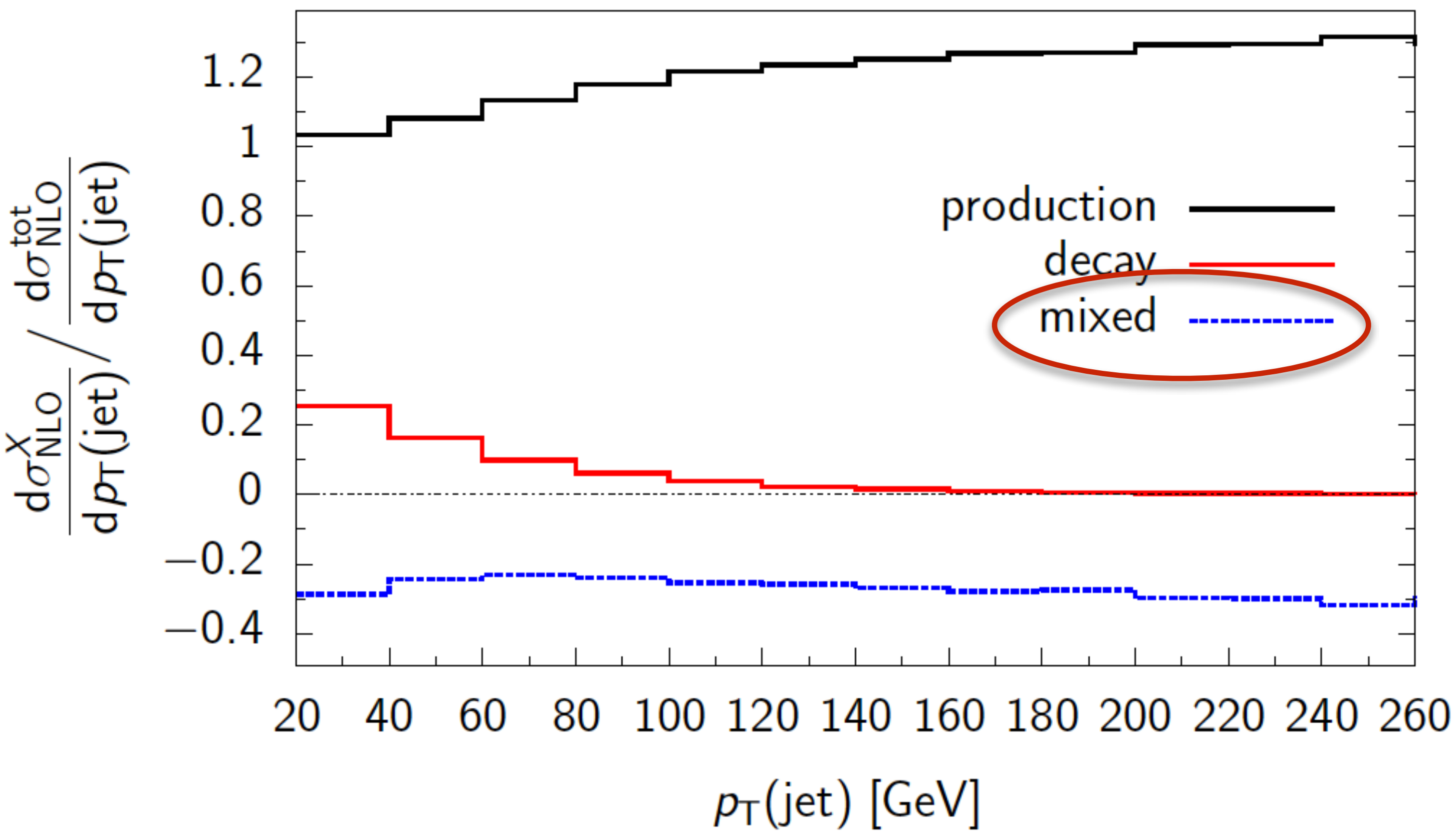
Lessons from $t\bar{t} + 1$ jet

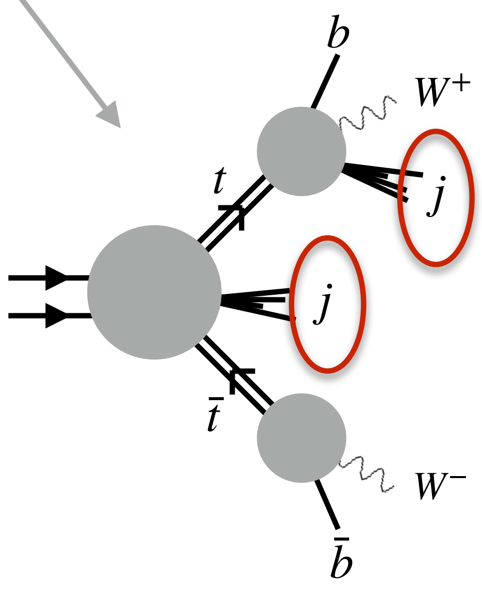
[Melnikov, Scharf and Schulze, Phys.Rev.D 85 (2012) 054002]

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

$$\sigma_{\mathrm{LO}} = 316.9\ (\mathrm{Pr}) + 33.4\ (\mathrm{Dec}) = 350.3\ \mathrm{fb},$$
$$\sigma_{\mathrm{NLO}} = 323\ (\mathrm{Pr}) + 40.5\ (\mathrm{Dec}) - 75.5\ (\mathrm{Mix}) = 288\ \mathrm{fb}.$$

-25% of σ_{NLO}





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

- **Integrated fiducial cross sections**

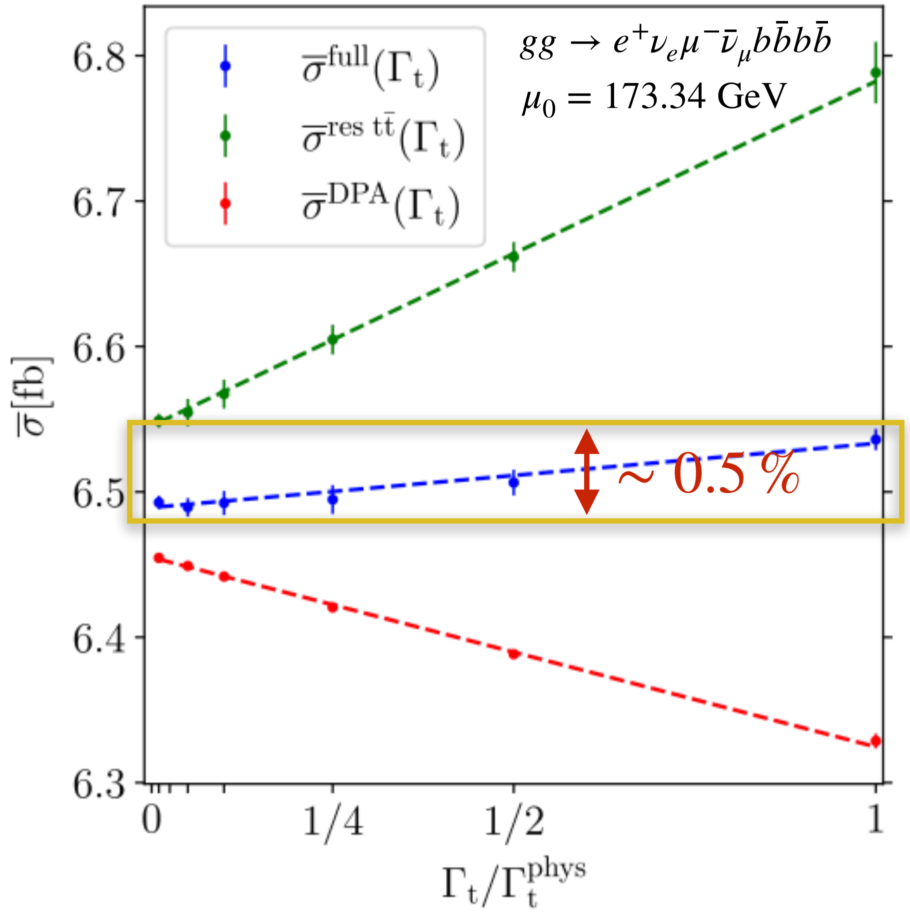
$\sqrt{s} = 13$ TeV

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:

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

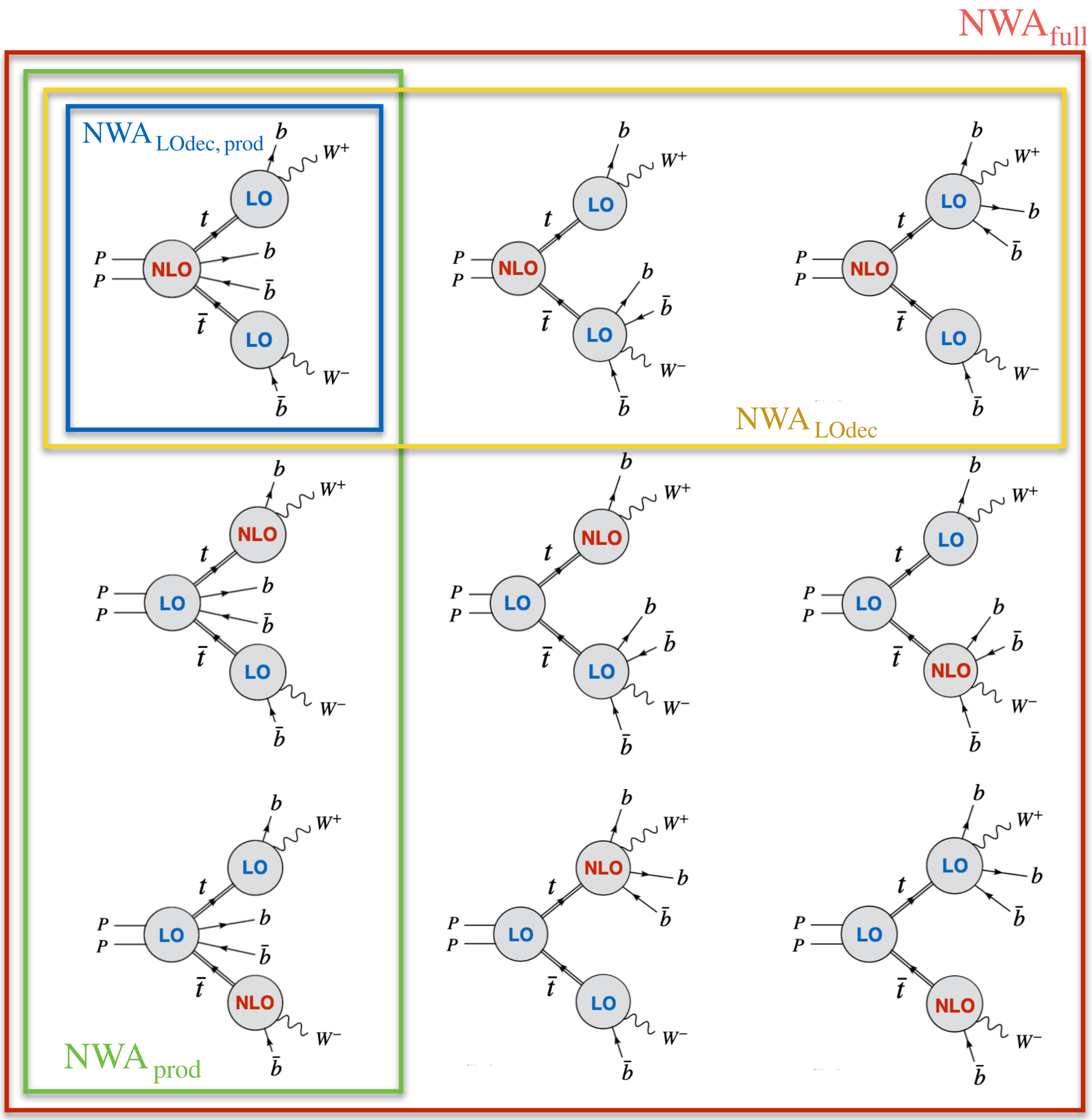
$$p_T^{\rm veto}(j) = 50 \text{ GeV} \quad \to \quad \sigma^{\rm NLO}/\sigma^{\rm LO} = 1.23$$

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

- *Full off-shell vs NWA*

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

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%

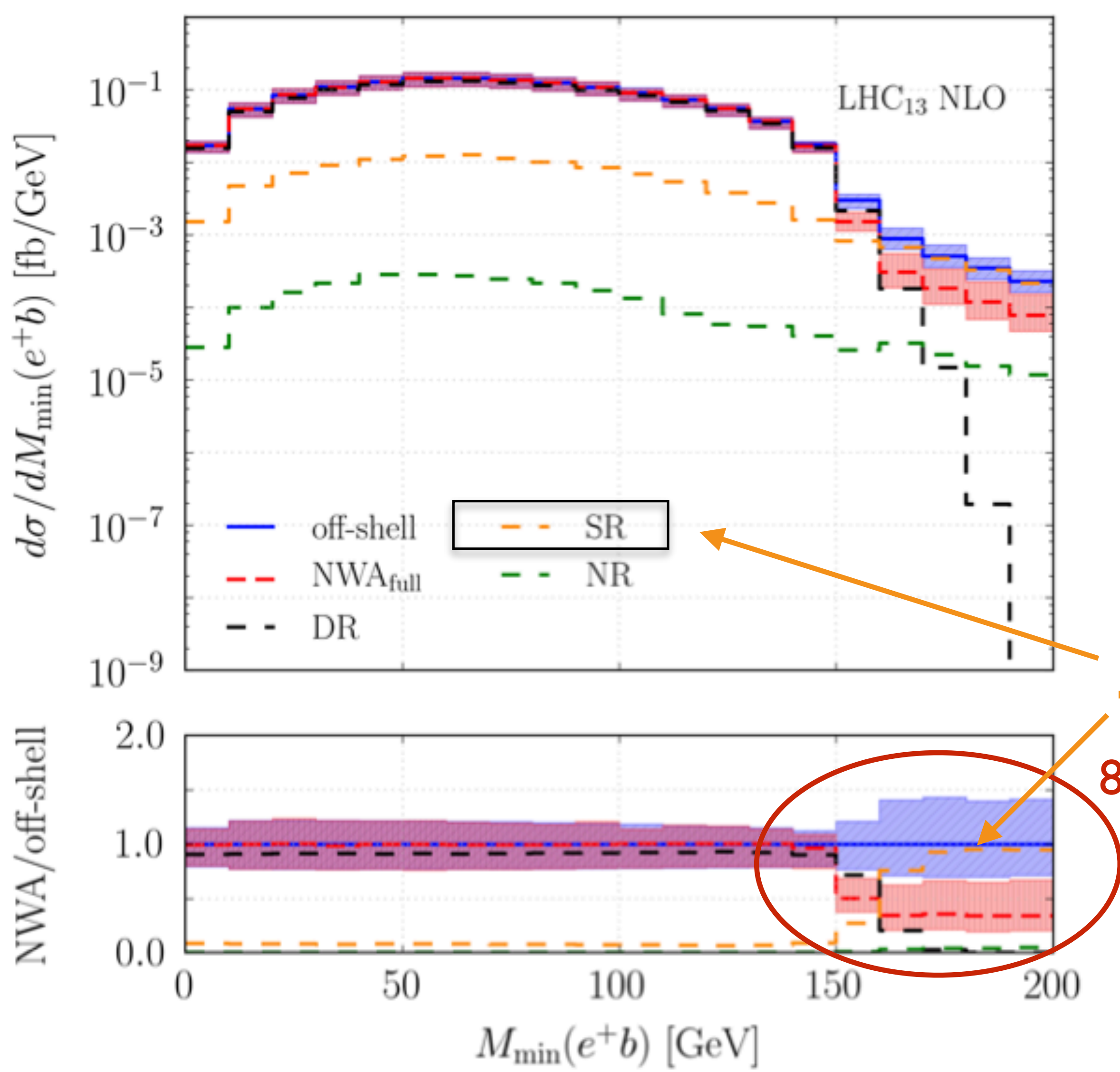


- NWA cross sections based on different levels of accuracy in top decay modelling
- Genuine off-shell effects: 0.5 %

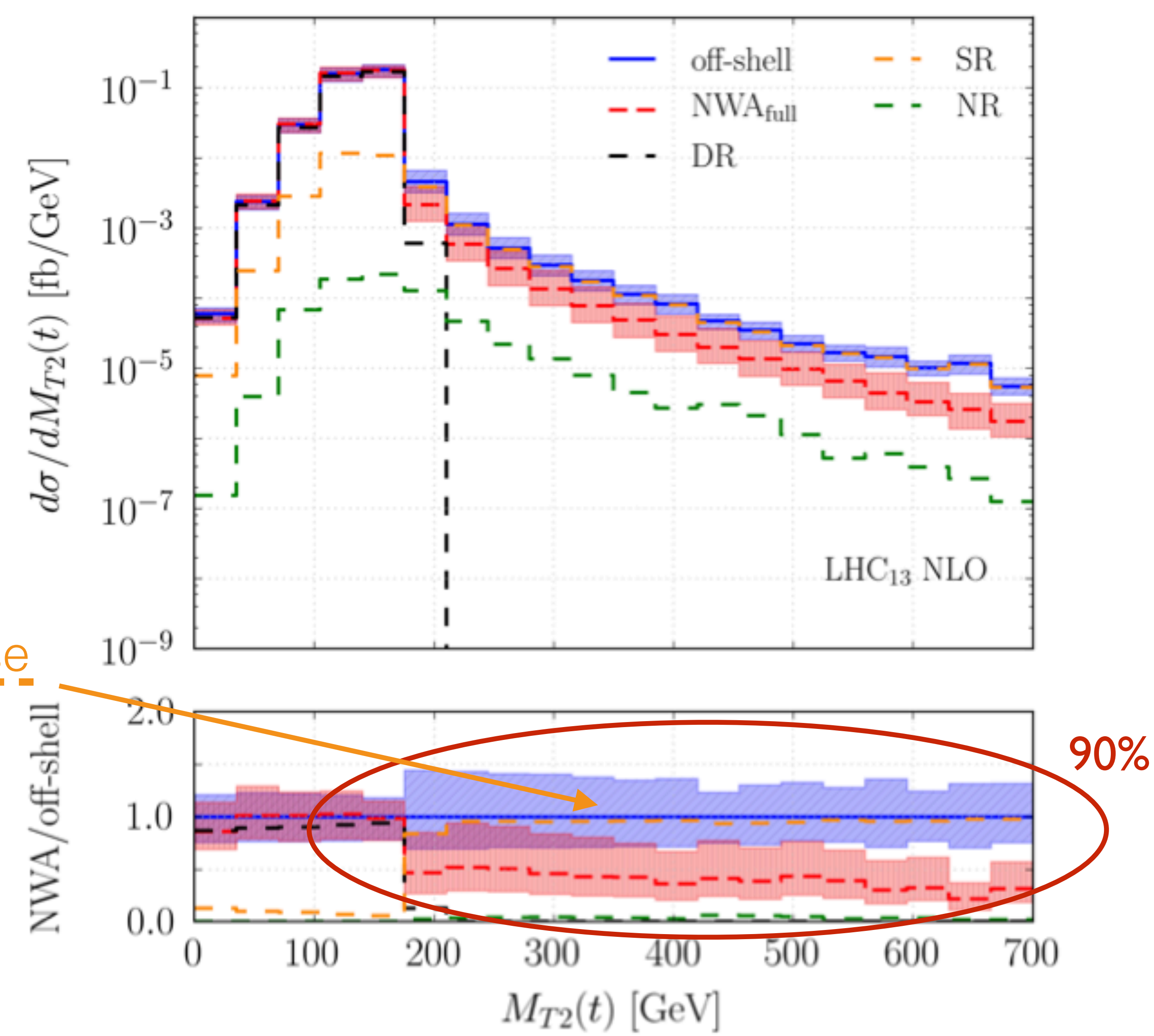
$t\bar{t}b\bar{b}$: full off-shell effects at differential level

- 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]



SR rise



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

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