Study of additional jet activity in top quark pair production and decay at the LHC

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Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Based on:

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

G. Bevilacqua, M. Lupattelli, D. Stremmer, M. Worek

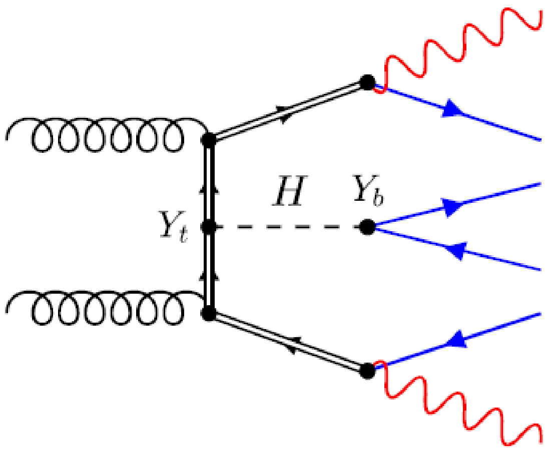
TOP2023 – Traverse City – 26 September 2023

Funded by DFG Deutsche Forschungsgemeinschaft German Research Foundation

Research Training Group Physics of the Heaviest Particles at the LHC

Motivations

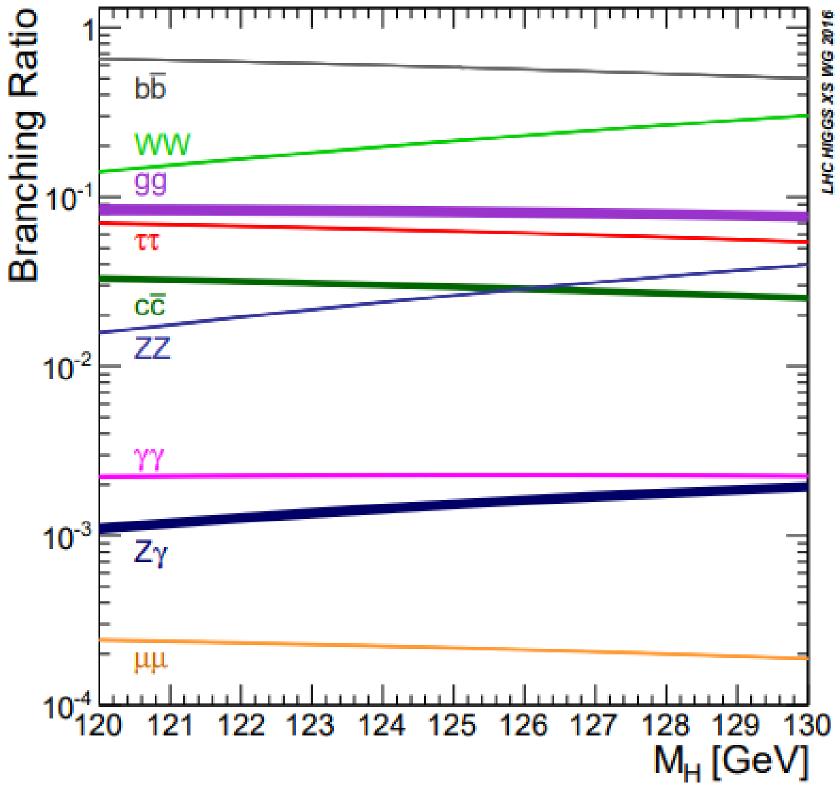
- $t\bar{t}jj$ background to $t\bar{t}H(H \rightarrow b\bar{b})$.



$t\bar{t}H$ provides direct access to Y_t.

- $\frac{\sigma(pp \rightarrow t\bar{t}H)}{\sigma(pp \rightarrow H+X)} \approx 1\%$.
- $\mathcal{BR}(H \rightarrow b\bar{b}) = 58\%$.

LHC Higgs Cross Section Working Group Collaboration '16



All Feynman diagrams generated with FeynGame - *Harlander, Klein, Lipp, Comput.Phys.Commun. 256 (2020) 107465*

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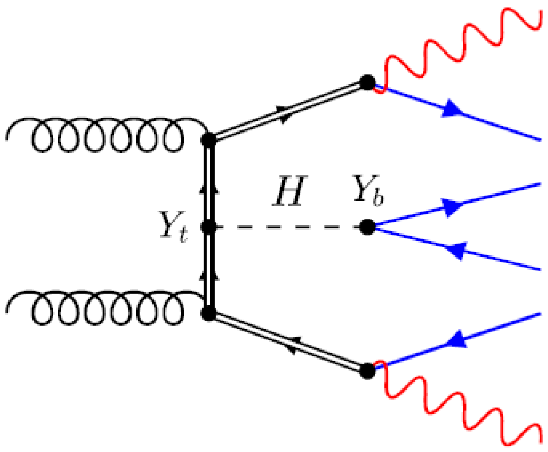

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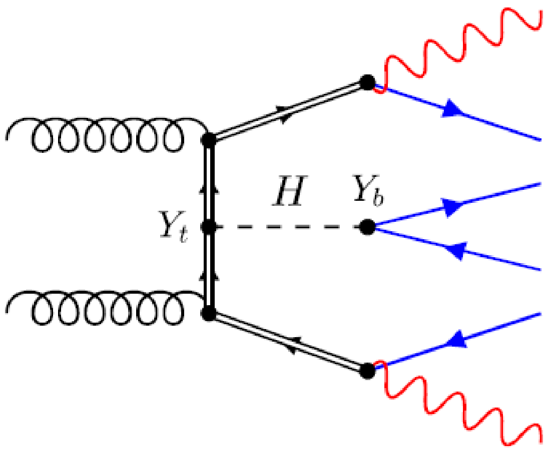
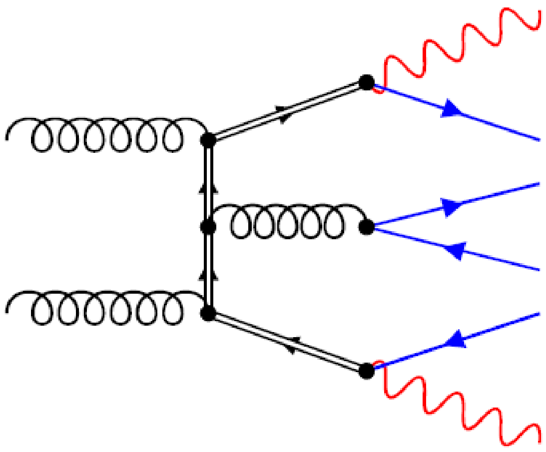
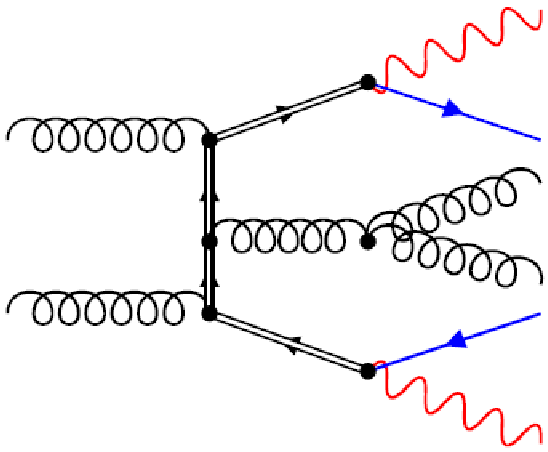


Signal
(Combinatorial Background)



$t\bar{t}b\bar{b}$
Irreducible Background



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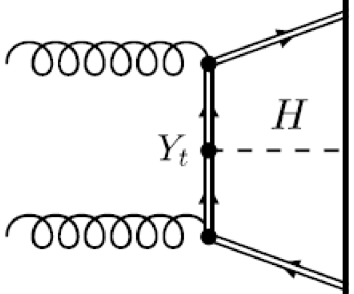
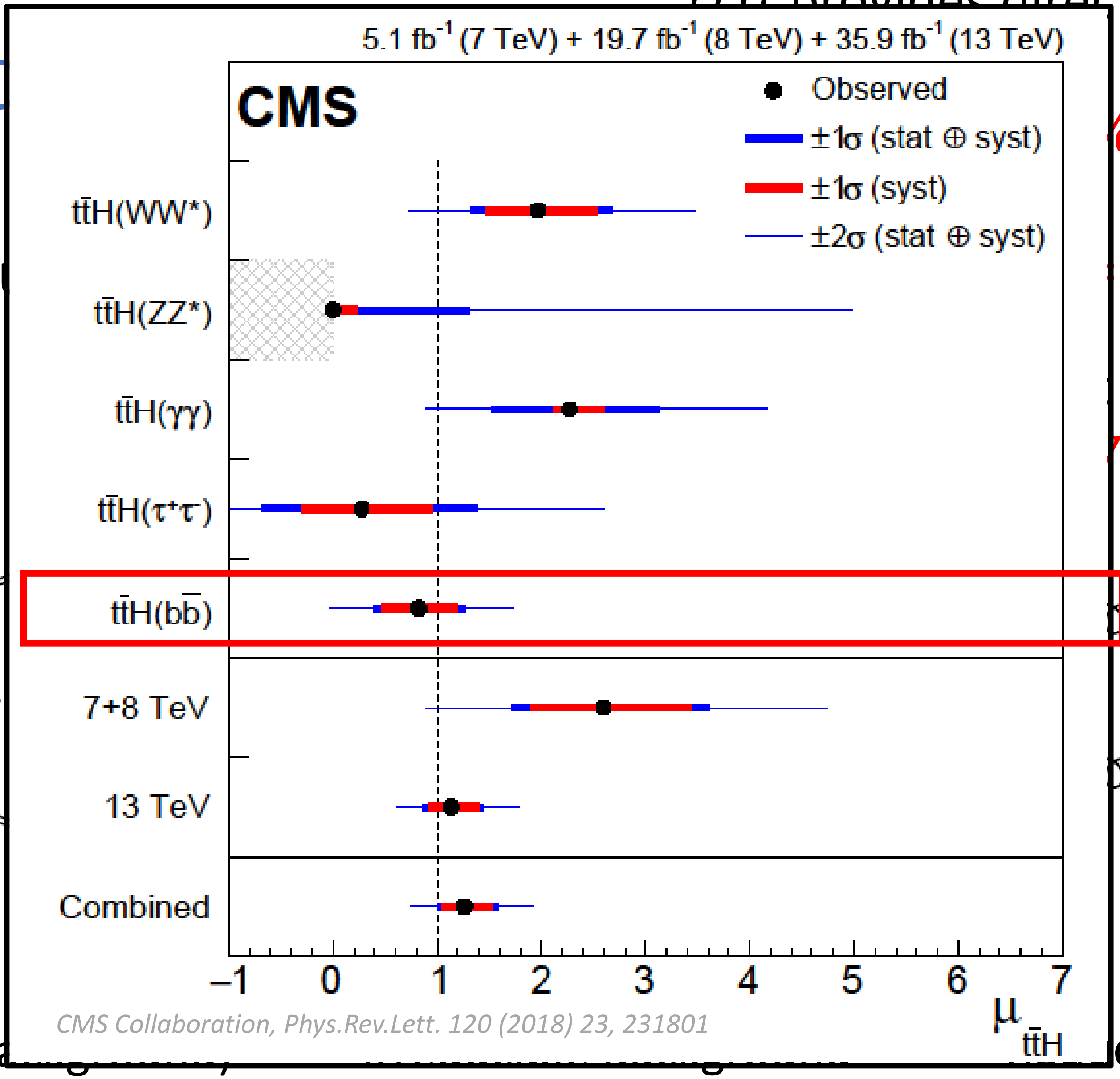
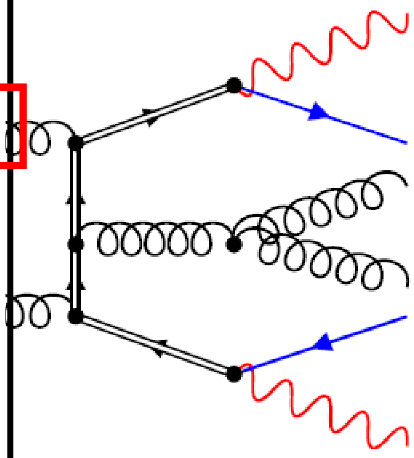




CMS Collaboration, Phys.Rev.Lett. 120 (2018) 23, 231801



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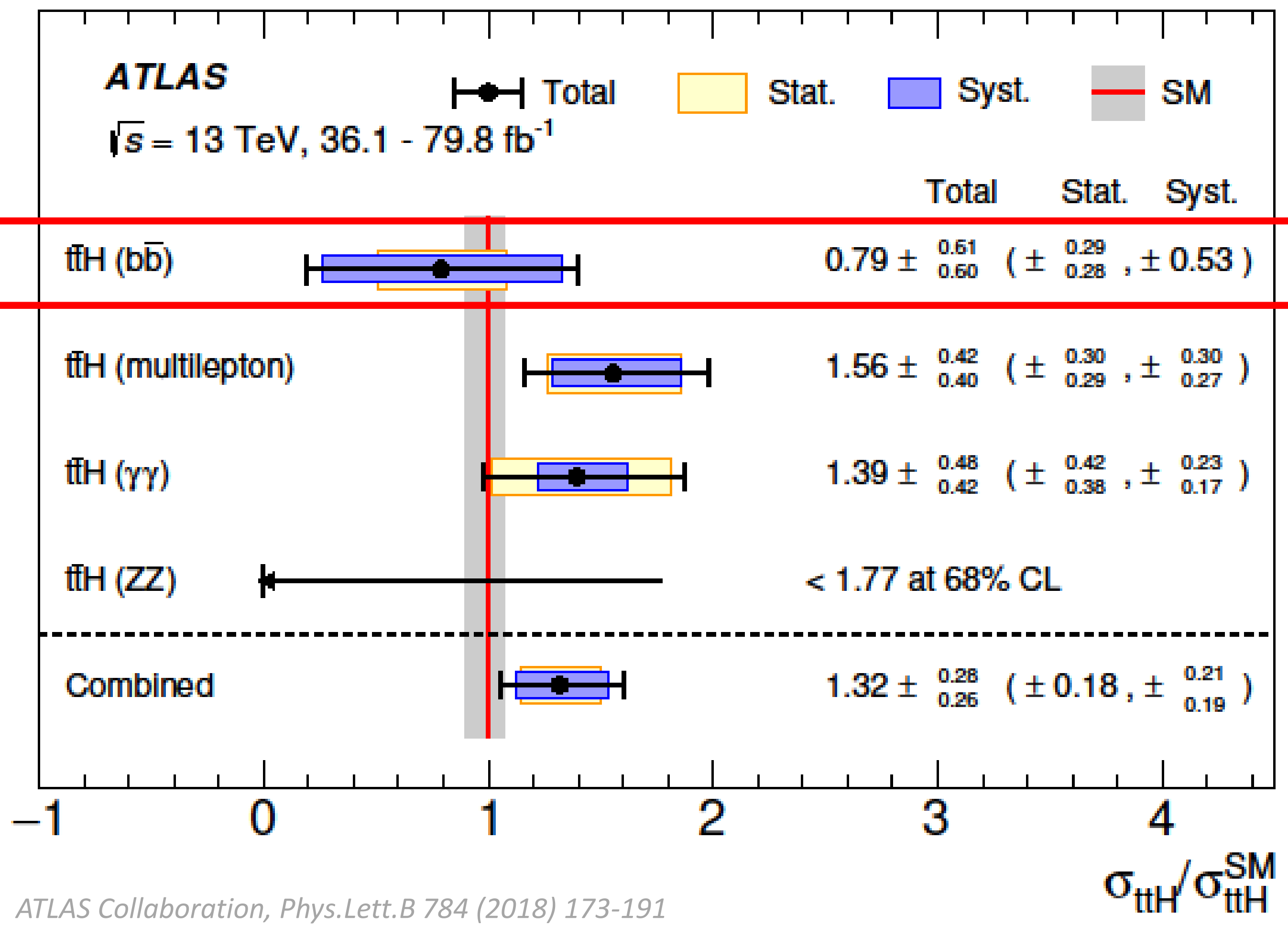

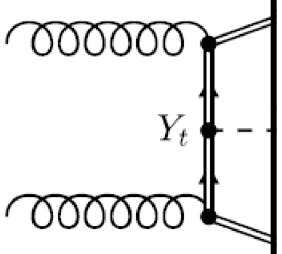

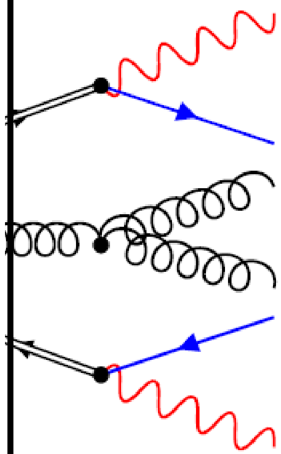

ATLAS Collaboration, Phys.Lett.B 784 (2018) 173-191

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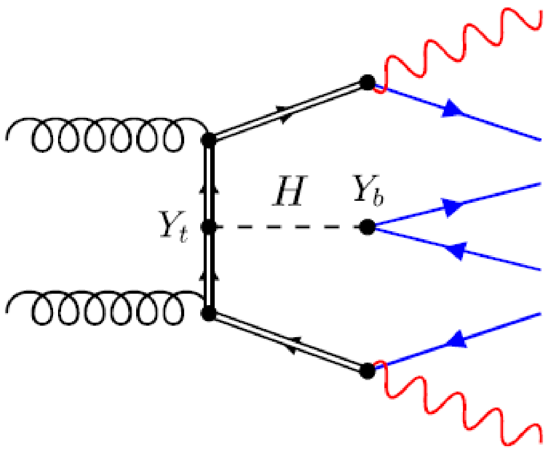

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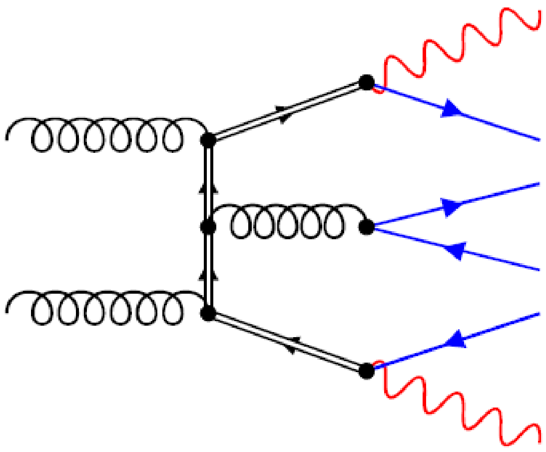

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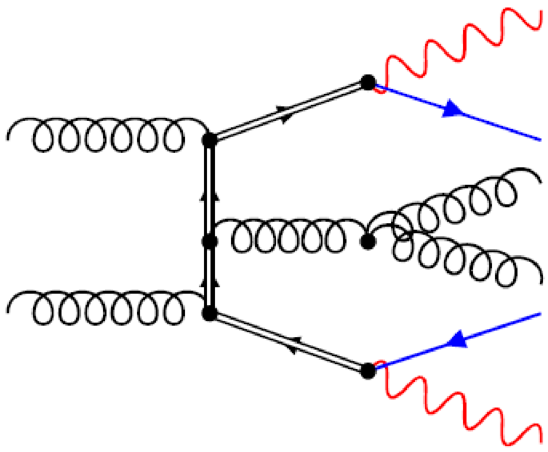

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Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek, JHEP 08 (2021) 008

Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek, Phys.Rev.D 107 (2023) 1, 014028

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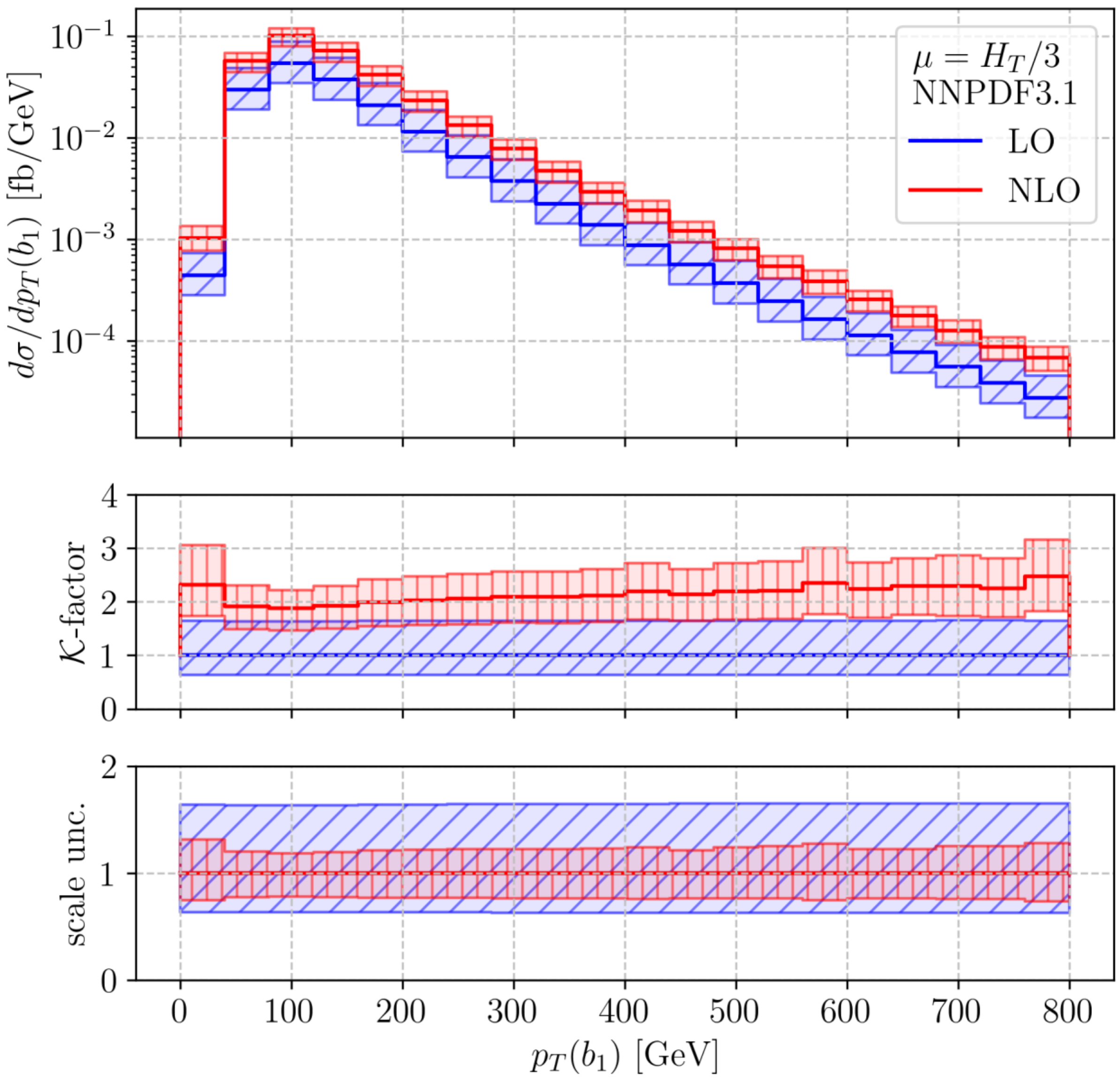
- Full off-shell effects important for observables with kinematic edges.
- Study of b-jet activity.
- Found agreement with experimental results from ATLAS.



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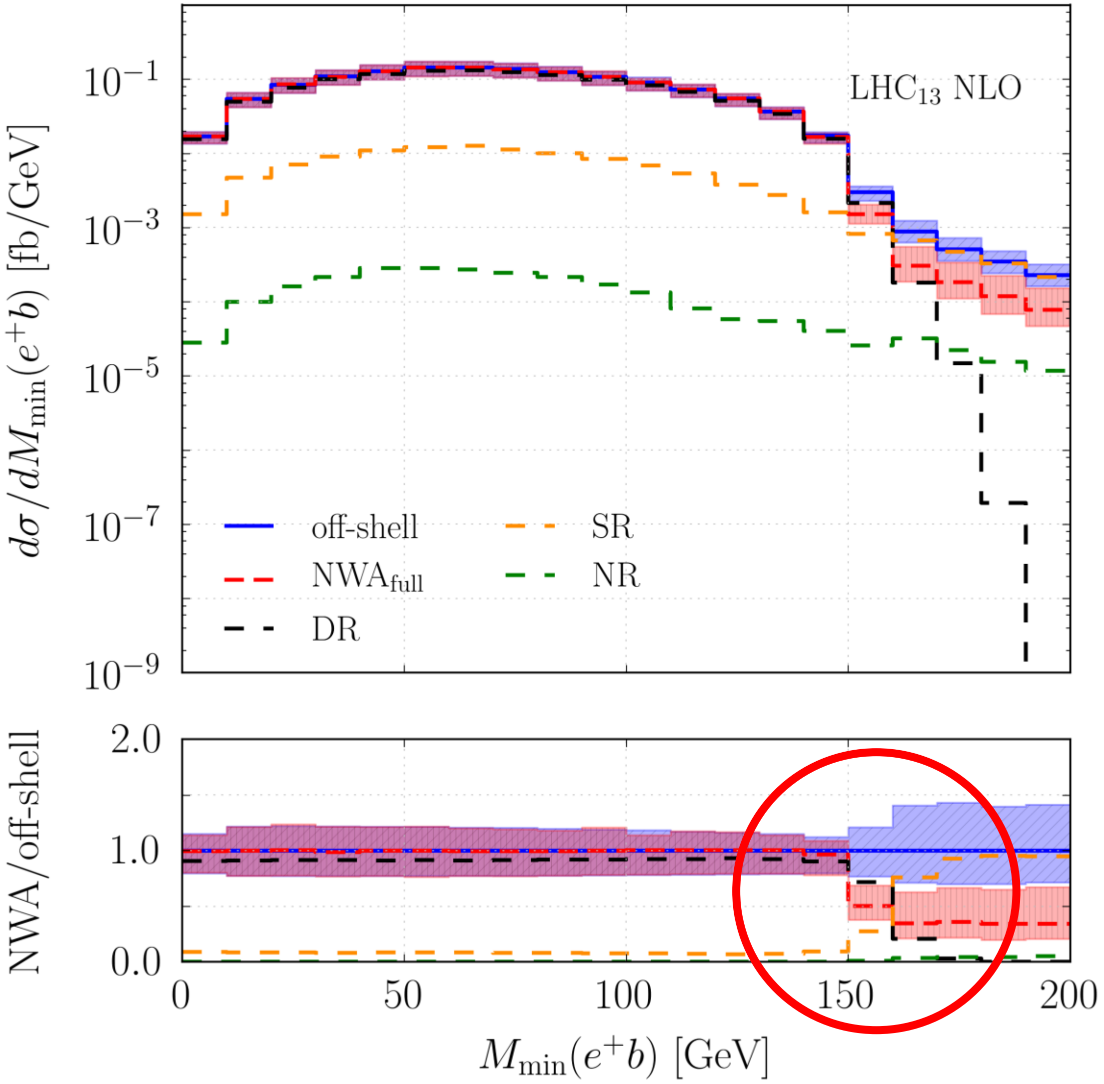

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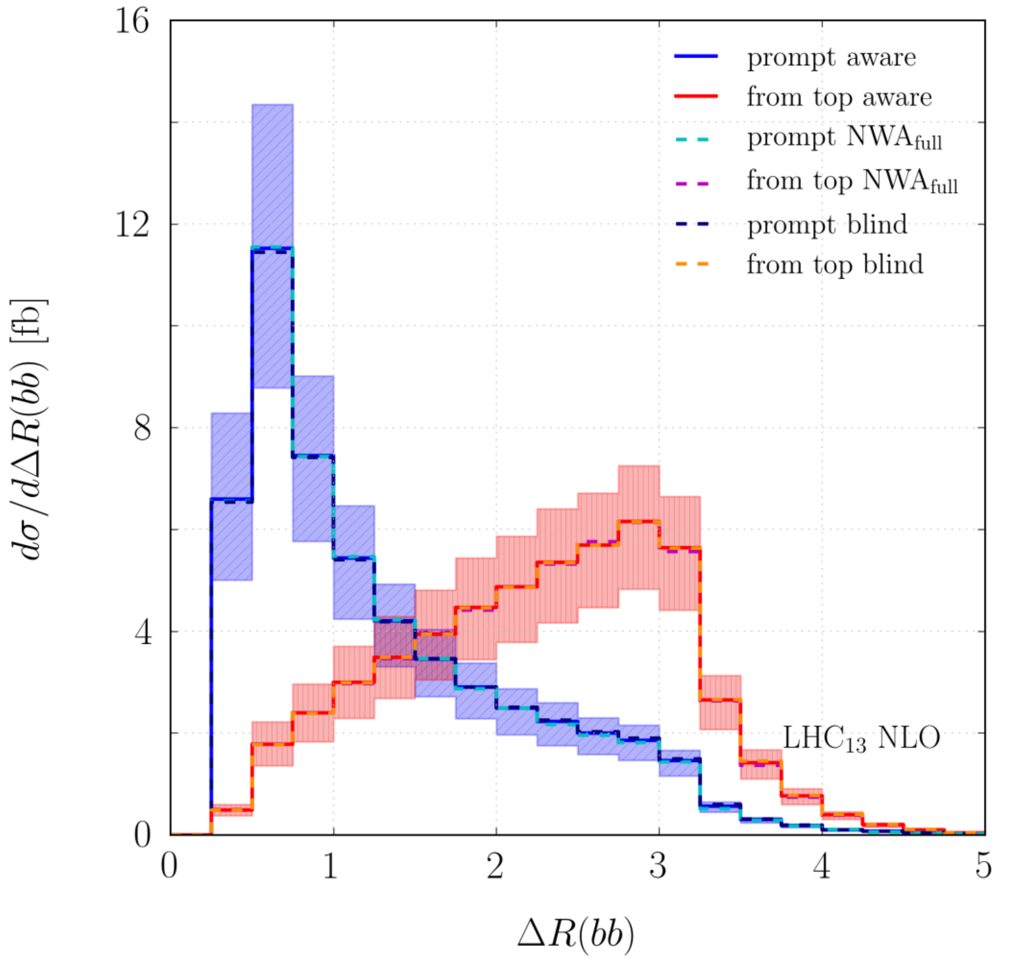

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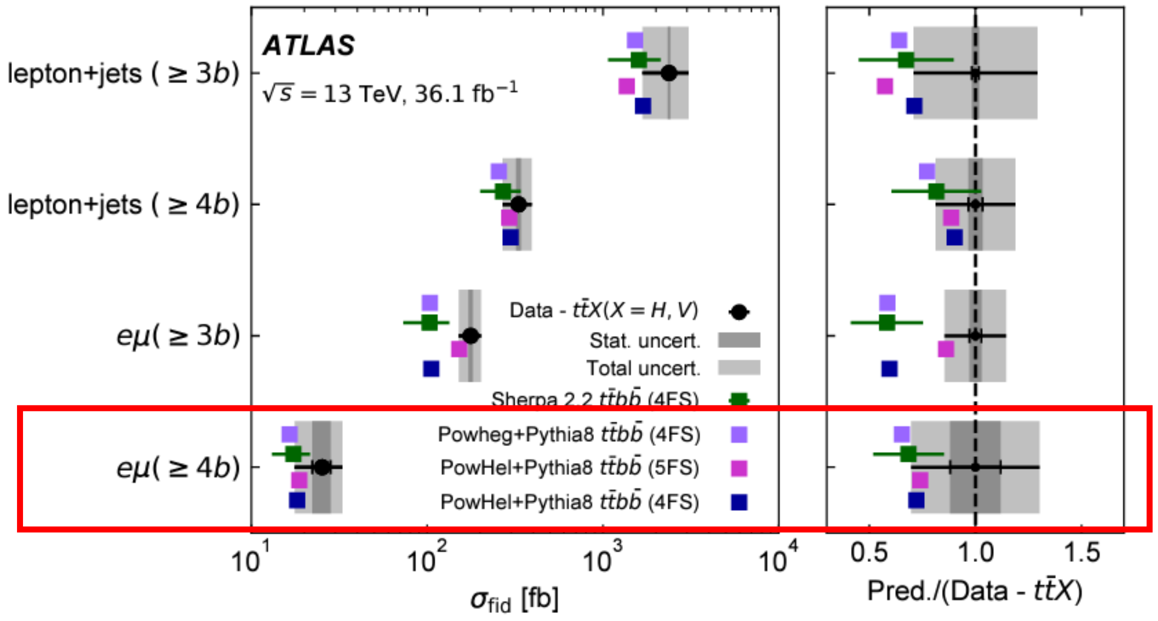
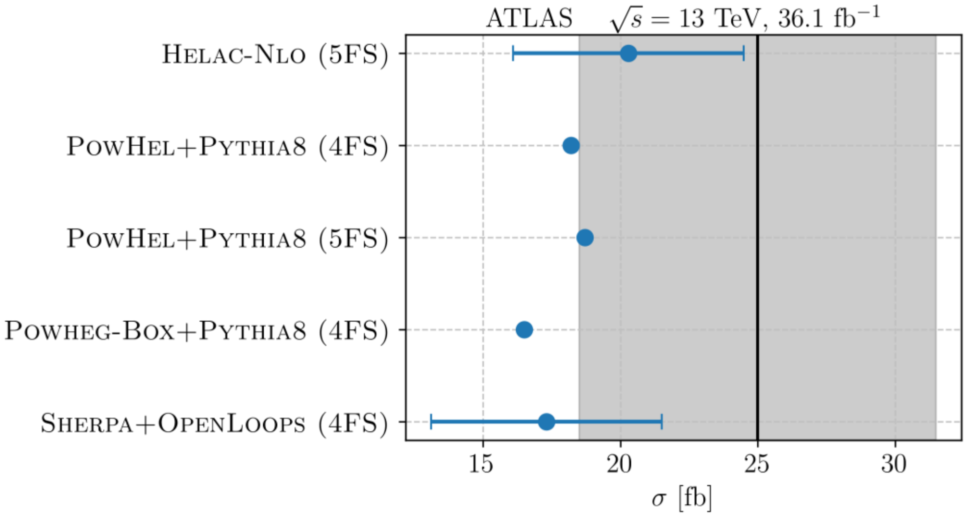
ATLAS Collaboration, JHEP 04 (2019) 046





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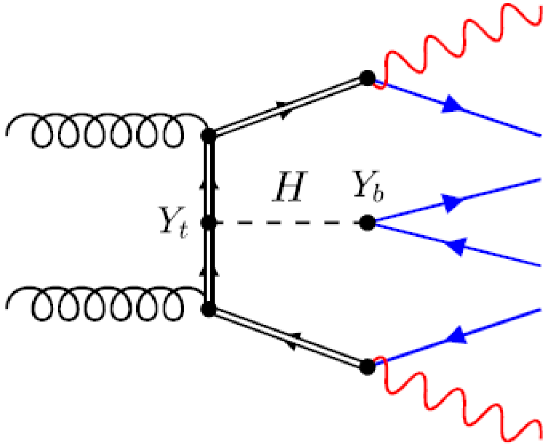

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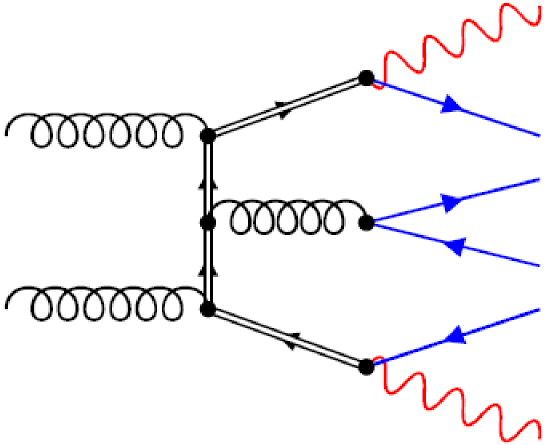

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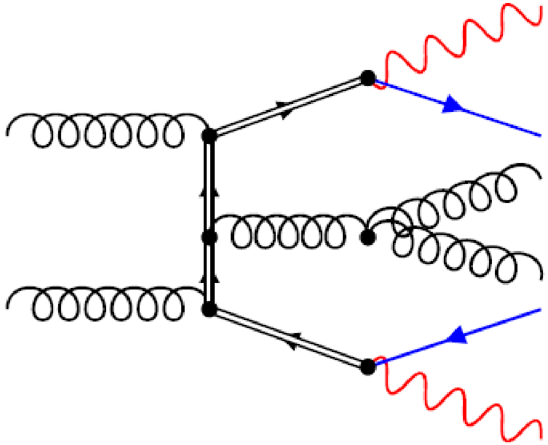
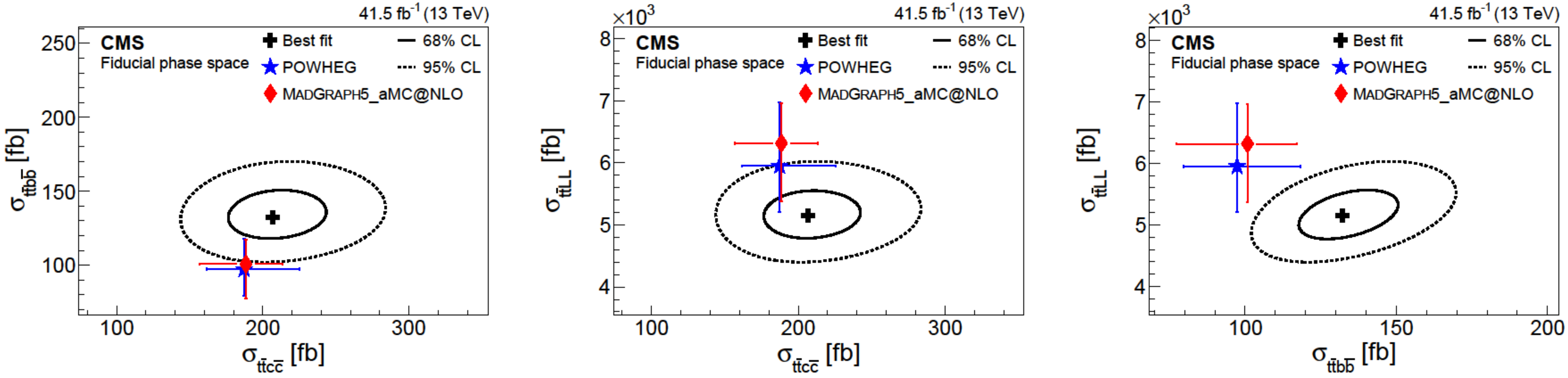


$t\bar{t}jj$
Reducible Background

Motivations

- Along with $t\bar{t}b\bar{b}$ and $t\bar{t}c\bar{c}$ playground for b- and c-jet tagging.



CMS Collaboration, Phys.Lett.B 820 (2021) 136565

$t\bar{t}jj$ theory state-of-the-art

- NLO QCD predictions with stable top quarks:

(Bevilacqua, Czakon, Papadopoulos, Worek '10, '11)

- NLO QCD predictions matched to parton shower:

(Hoeche, Krauss, Maierhoefer, Pozzorini, Schonherr, Siegert '15 | Höche, Maierhöfer, Moretti, Pozzorini, Siegert '17 | Gütschow, Lindert, Schönherr '18)

- NLO QCD predictions in the NWA including additional radiation and NLO QCD corrections in top-quark decays:

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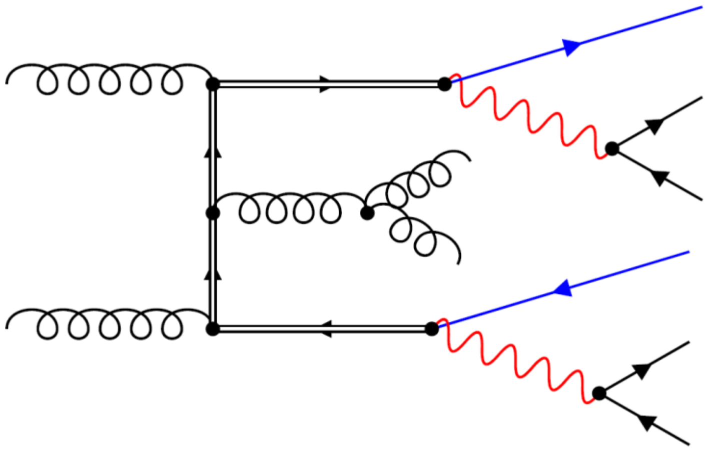
Latest theoretical predictions for $t\bar{t}jj$

- Dilepton channel: $pp \to l^+ \nu_l l^- \bar{\nu}_l b\bar{b}jj + X$.
- NLO in QCD → α_s corrections to $\mathcal{O}(\alpha_s^4 \alpha^4)$ Born level (both in production and decay).
- Narrow Width Approximation.
- 5-flavour scheme.
- LHC $\sqrt{s} = 13$ TeV.



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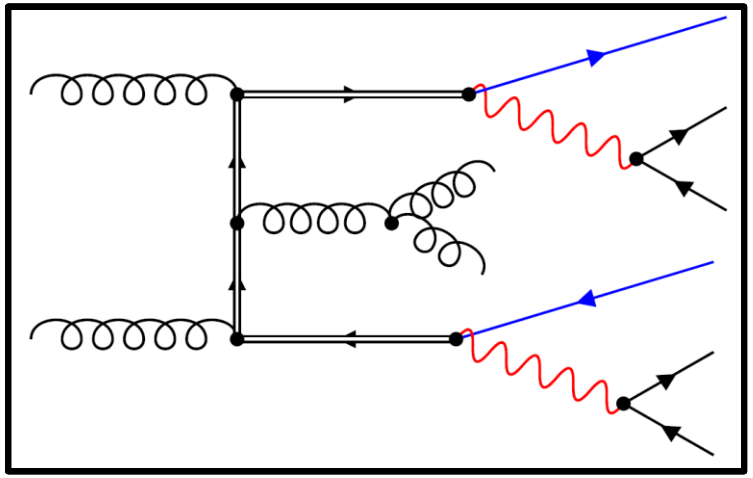
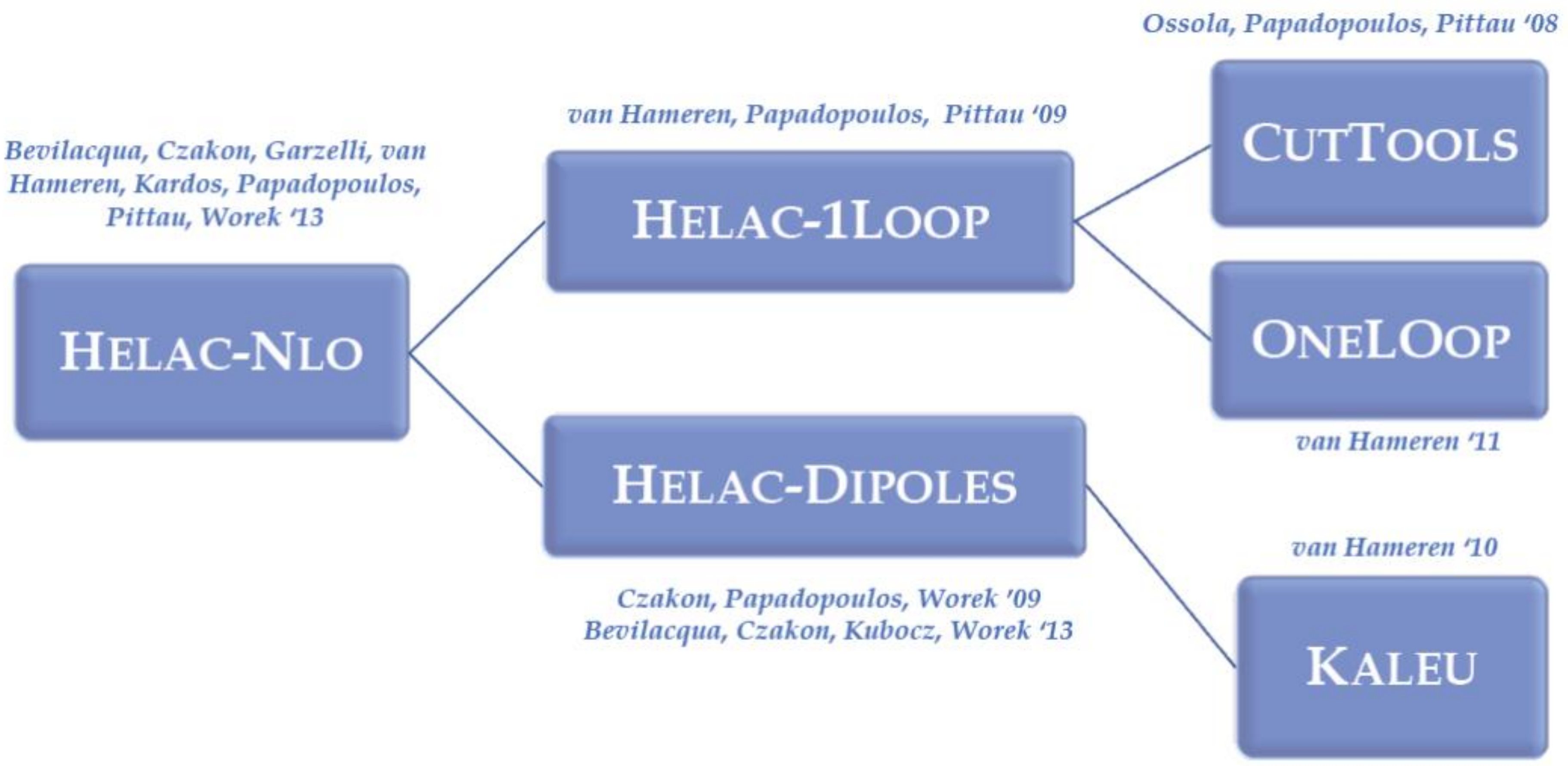
Narrow-width approximation



Double resonant

$$\frac{1}{(p^2-m^2)^2+m^2\Gamma^2} \to \frac{\pi}{m\Gamma}\delta(p^2-m^2)$$

- Forces on-shell production of the unstable particle.
- Neglects $\mathcal{O}(\Gamma/m)$ effects → $\approx$ 0.8% for top quark.
- Preserves top-quark spin correlations.
- Allows for treatment of top-quark decays beyond LO.
- Induces a factorization of the cross section into production × decays $\Longrightarrow$ only DR contributions.



Theoretical predictions stored in the form of modified Les Houches Event Files[1] and ROOT Ntuples[2]. They allow to:

- change kinematic cuts;
- change μ_R, μ_F and PDF set;
- define new observables.

[1]Alwall et al., Comput.Phys.Commun. 176 (2007) 300-304

[2]Bern et al., Comput.Phys.Commun. 185 (2014) 1443-1460
Antcheva et al., Comput.Phys.Commun. 180 (2009) 2499-2512

$t\bar{t}jj$ in the NWA (LO)

$$d\sigma^{\rm LO}_{\rm Full} = \left(\Gamma^{\rm LO}_{t,\rm NWA}\right)^{-2}\Big(\overbrace{d\sigma^{\rm LO}_{t\bar{t}jj}\,d\Gamma^{\rm LO}_{t\bar{t}}}^{\rm Prod.} + \overbrace{d\sigma^{\rm LO}_{t\bar{t}}\,d\Gamma^{\rm LO}_{t\bar{t}jj}}^{\rm Decay} + \overbrace{d\sigma^{\rm LO}_{t\bar{t}j}\,d\Gamma^{\rm LO}_{t\bar{t}j}}^{\rm Mix}\Big)$$

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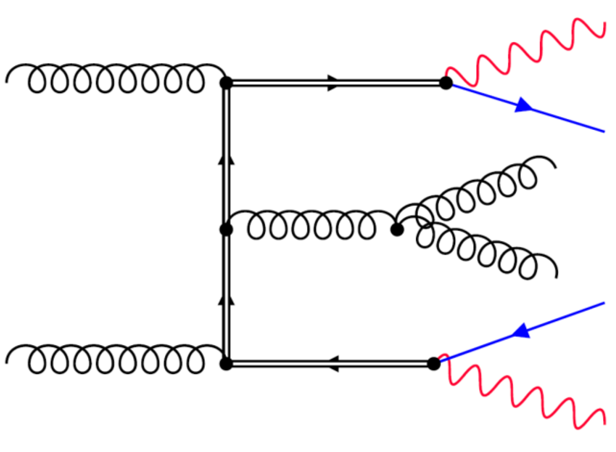

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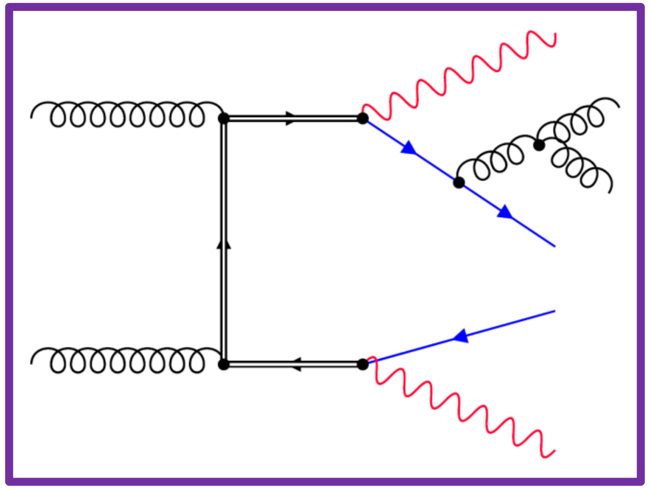

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- Decay contribution included for the first time at the matrix-element level.

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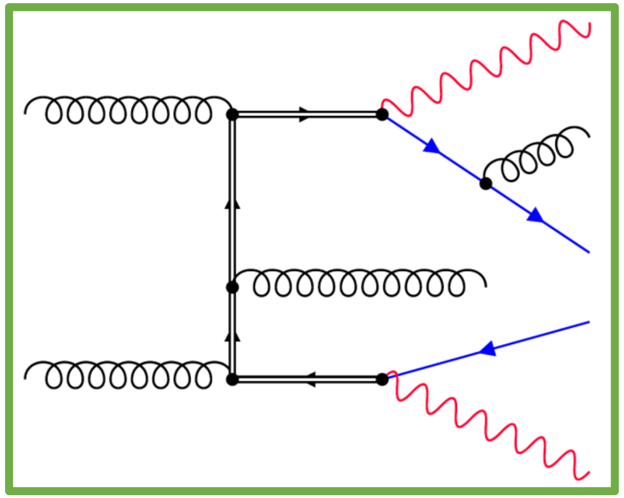

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$t\bar{t}jj$ in the NWA (NLO)

$$
\begin{aligned}
d\sigma^{\rm NLO}_{\rm Full} = {} & (\Gamma^{\rm NLO}_{t,\rm NWA})^{-2} \times \\
& \Big[\overbrace{(d\sigma^{\rm LO}_{t\bar{t}jj} + d\sigma^{\rm virt}_{t\bar{t}jj} + d\sigma^{\rm real}_{t\bar{t}jjj})\, d\Gamma^{\rm LO}_{t\bar{t}}}^{\rm Prod.} + \overbrace{d\sigma^{\rm LO}_{t\bar{t}}\,(d\Gamma^{\rm LO}_{t\bar{t}jj} + d\Gamma^{\rm virt}_{t\bar{t}jj} + d\Gamma^{\rm real}_{t\bar{t}jjj})}^{\rm Decay} + \\
& \left.\begin{aligned}
& d\sigma^{\rm LO}_{t\bar{t}j}\, d\Gamma^{\rm LO}_{t\bar{t}j} + d\sigma^{\rm LO}_{t\bar{t}jj}\, d\Gamma^{\rm virt}_{t\bar{t}} + d\sigma^{\rm virt}_{t\bar{t}}\, d\Gamma^{\rm LO}_{t\bar{t}jj} + d\sigma^{\rm virt}_{t\bar{t}j}\, d\Gamma^{\rm LO}_{t\bar{t}j} + \\
& \quad d\sigma^{\rm LO}_{t\bar{t}j}\, d\Gamma^{\rm virt}_{t\bar{t}j} + d\sigma^{\rm real}_{t\bar{t}jj}\, d\Gamma^{\rm real}_{t\bar{t}j} + d\sigma^{\rm real}_{t\bar{t}j}\, d\Gamma^{\rm real}_{t\bar{t}jj} \Big]
\end{aligned}\right\} \text{Mix}
\end{aligned}
$$

Predictions for default set of cuts +

- $\Delta R(jb) > 0.8$: suppresses jet activity in top-quark decays (setup of *CMS-PAS-TOP-20-006*).
- $\Delta R(jb) > 0.4$: more inclusive towards jet activity in top-quark decays.

Integrated fiducial cross section

$\Delta R(jb) > 0.8$

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	$\sigma_i^{\rm LO}$ [fb]	$\sigma_i/\sigma_{\rm Full}$	$\sigma_i^{\rm NLO}$ [fb]	$\sigma_i/\sigma_{\rm Full}$	$\mathcal{K} = \sigma^{\rm NLO}/\sigma^{\rm LO}$
Full	$868.8(2)^{+60\%}_{-35\%}$	-	$1225(1)^{+1\%}_{-14\%}$	-	1.41
Prod.	$843.2(2)^{+60\%}_{-35\%}$	0.97	$1462(1)^{+12\%}_{-19\%}$	1.19	1.73
Mix	25.465(5)	0.029	$-236(1)$	-0.19	-9.27
Decay	0.2099(1)	0.0002	0.1840(8)	0.0002	0.88

$$\mu_0 = H_T/2$$

$$H_T = \sum_{i=1}^{2} p_T(\ell_i) + \sum_{i=1}^{2} p_T(j_i) + \sum_{i=1}^{2} p_T(b_i) + p_T^{\rm miss}$$

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- NLO QCD corrections of medium size (41%).
- LO→NLO: reduction of theoretical uncertainty.
- Full calculation slightly more accurate (14% uncertainty against 19%)

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Cross-section decomposition at **LO**:

- Prod. contribution dominant (97%).
- Mix contribution (3%) negligible compared to theoretical uncertainty (60%).
- Decay contribution imperceptible.

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$\Delta R(jb) > 0.8$

Bevilacqua, Lupattelli, Stremmer, Worek, Phys.Rev.D 107 (2023) 11, 114027

	$\sigma_i^{\rm LO}$ [fb]	$\sigma_i/\sigma_{\rm Full}$	$\sigma_i^{\rm NLO}$ [fb]	$\sigma_i/\sigma_{\rm Full}$	$\mathcal{K} = \sigma^{\rm NLO}/\sigma^{\rm LO}$
Full	$868.8(2)^{+60\%}_{-35\%}$	-	$1225(1)^{+1\%}_{-14\%}$	-	1.41
Prod.	$843.2(2)^{+60\%}_{-35\%}$	0.97	$1462(1)^{+12\%}_{-19\%}$	1.19	1.73
Mix	25.465(5)	0.029	$-236(1)$	-0.19	-9.27
Decay	0.2099(1)	0.0002	0.1840(8)	0.0002	0.88

Cross-section decomposition at **NLO**:

- Mix contribution negative and enhanced in absolute value (-19%) → now comparable to theoretical uncertainty (14%).

Integrated fiducial cross section

$\Delta R(jb) > 0.4$

Bevilacqua, Lupattelli, Stremmer, Worek, Phys.Rev.D 107 (2023) 11, 114027

	$\sigma_i^{\rm LO}$ [fb]	$\sigma_i/\sigma_{\rm Full}$	$\sigma_i^{\rm NLO}$ [fb]	$\sigma_i/\sigma_{\rm Full}$	$\mathcal{K} = \sigma^{\rm NLO}/\sigma^{\rm LO}$
Full	$1074.5(3)^{+60\%}_{-35\%}$	-	$1460(1)^{+1\%}_{-13\%}$	-	1.36
Prod.	$983.1(3)^{+60\%}_{-35\%}$	0.91	$1662(1)^{+11\%}_{-18\%}$	1.14	1.69
Mix	89.42(3)	0.083	$-205(1)$	-0.14	-2.30
Decay	1.909(1)	0.002	2.436(6)	0.002	1.28

Integrated fiducial cross section

$\Delta R(jb) > 0.4$

Bevilacqua, Lupattelli, Stremmer, Worek, Phys.Rev.D 107 (2023) 11, 114027

	$\sigma_i^{\rm LO}$ [fb]	$\sigma_i/\sigma_{\rm Full}$	$\sigma_i^{\rm NLO}$ [fb]	$\sigma_i/\sigma_{\rm Full}$	$\mathcal{K} = \sigma^{\rm NLO}/\sigma^{\rm LO}$
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Mix	89.42(3)	0.083	$-205(1)$	-0.14	-2.30
Decay	1.909(1)	0.002	2.436(6)	0.002	1.28

Cross-section decomposition at **LO**:

- Prod. contribution still dominant (91%).
- Mix contribution slightly larger (8%) but still negligible compared to theoretical uncertainty (60%).

Integrated fiducial cross section

$\Delta R(jb) > 0.4$

Bevilacqua, Lupattelli, Stremmer, Worek, Phys.Rev.D 107 (2023) 11, 114027

	$\sigma_i^{\rm LO}$ [fb]	$\sigma_i/\sigma_{\rm Full}$	$\sigma_i^{\rm NLO}$ [fb]	$\sigma_i/\sigma_{\rm Full}$	$\mathcal{K} = \sigma^{\rm NLO}/\sigma^{\rm LO}$
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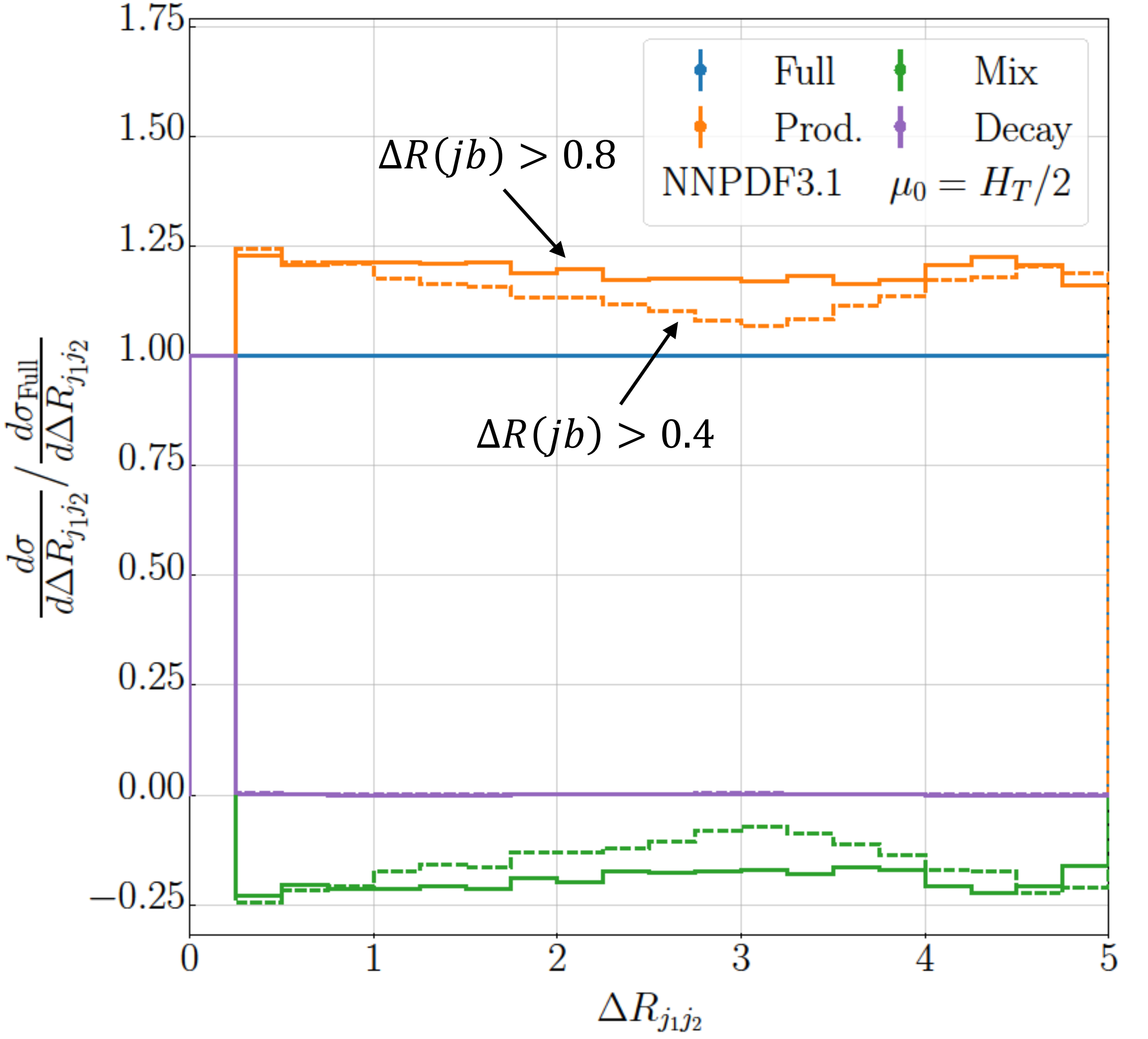
Mix	89.42(3)	0.083	$-205(1)$	-0.14	-2.30
Decay	1.909(1)	0.002	2.436(6)	0.002	1.28

Cross-section decomposition at **NLO**:

- Mix contribution slightly smaller absolute value (-14%) compared to the $\Delta R(jb) > 0.8$ cut case → still non negligible.

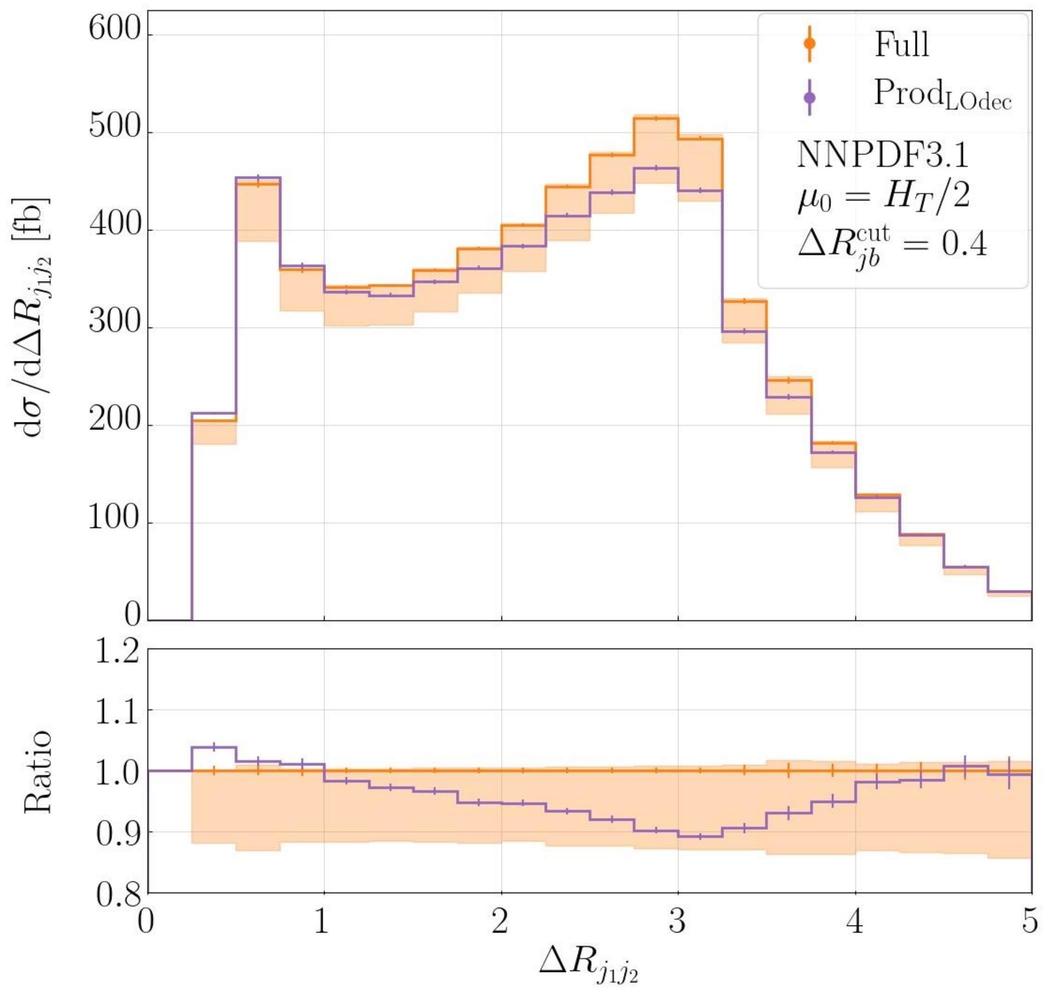
The Mix contribution at the differential level



Bevilacqua, Lupattelli, Stremmer, Worek, Phys.Rev.D 107 (2023) 11, 114027

- Solid line: $\Delta R(jb) > 0.8$ cut.
- Dashed line: $\Delta R(jb) > 0.4$ cut.
- Mix contribution negative: can reach -25%.
- Non-trivial kinematic dependence of Prod. and Mix for $\Delta R(jb) > 0.4$ cut.

The Mix contribution at the differential level

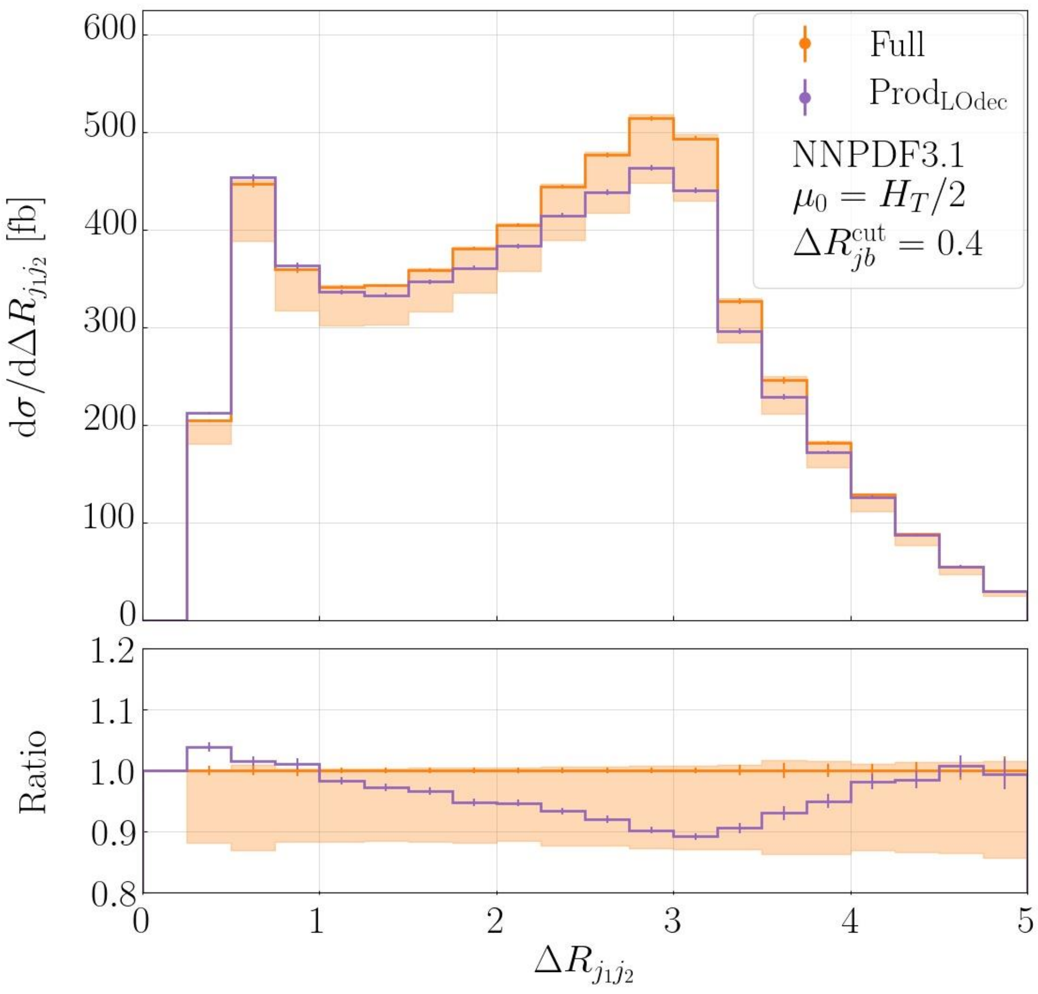


- Prod. with LO decays prediction is a mere rescaling of Prod. by a factor

$$\left(\frac{\Gamma_{t,\mathrm{NWA}}^{\mathrm{NLO}}}{\Gamma_{t,\mathrm{NWA}}^{\mathrm{LO}}}\right)^2$$

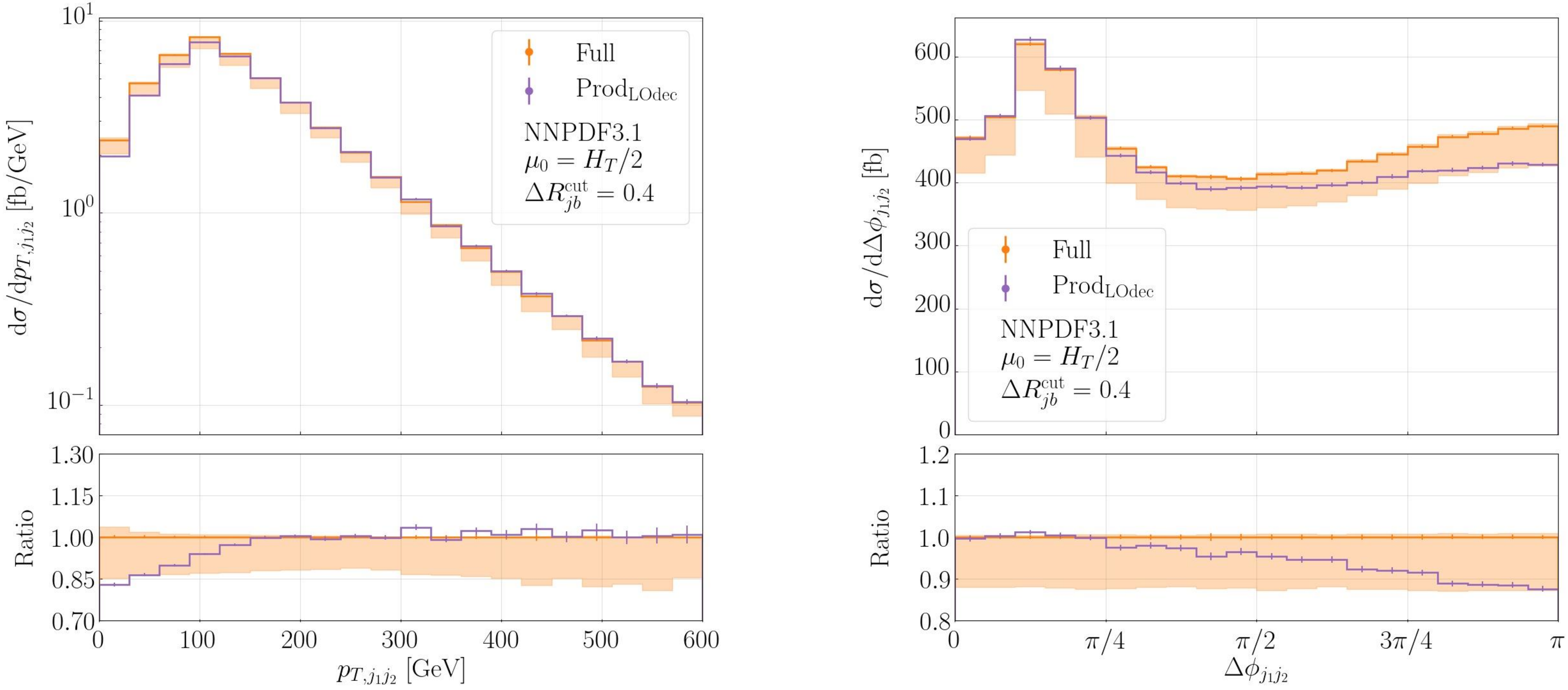
- Prod. with LO decays is the fixed-order part of matched to parton shower predictions.

The Mix contribution at the differential level



- Mix contribution affects shape of observables for $\Delta R(jb) > 0.4$ cut.
- Differences in the range [-11%,+4%] → shape distortion of 15%.
- Prod. with LO decays lies outside the uncertainty band of the full calculation in few bins.
- Slight reduction of theoretical uncertainty:
  - Full uncertainty in range [12%,14%],
  - Prod. (LOdec) in range [17%,19%].

The Mix contribution at the differential level



Bevilacqua, Lupattelli, Stremmer, Worek, Phys.Rev.D 107 (2023) 11, 114027

Summary

- $pp \to l^+ \nu_l l^- \bar{\nu}_l b\bar{b}jj + X$ at NLO in QCD with light jets consistently included in production and decay of top-quark pair.

- NLO QCD corrections of **41%** ($\Delta R(jb) > 0.8$), **36%** ($\Delta R(jb) > 0.4$).

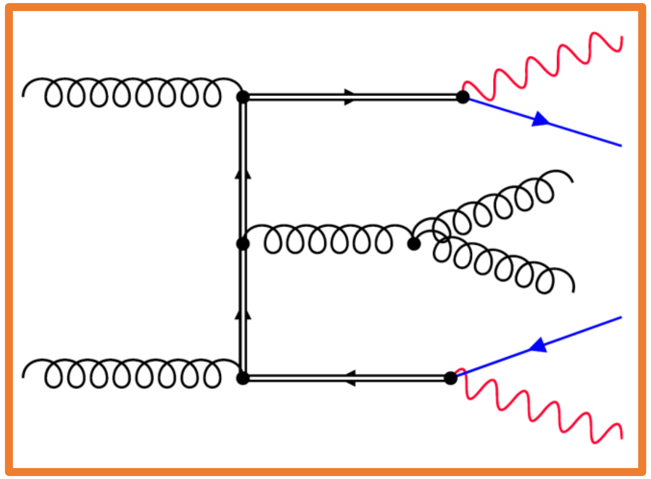
- Mix contribution **-19%** ($\Delta R(jb) > 0.8$), **-14%** ($\Delta R(jb) > 0.4$) comparable with theoretical uncertainty (**14%** and **13%** respectively).

- For more inclusive $\Delta R(jb) > 0.4$ cut, Mix affects the shape of differential distributions.

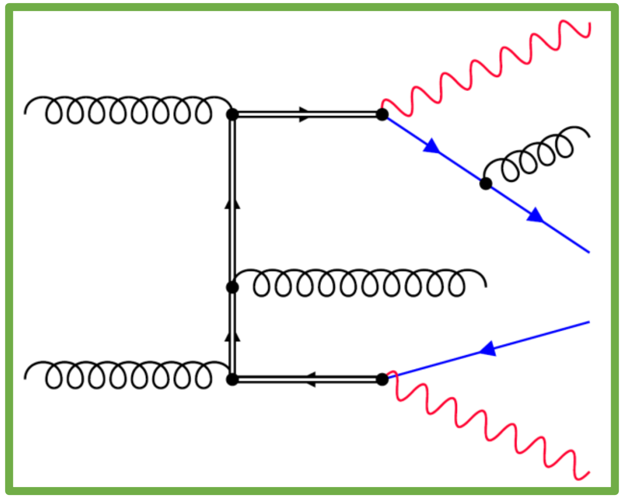
- At fixed order, inclusion of the Mix contribution is imperative.

Outlook

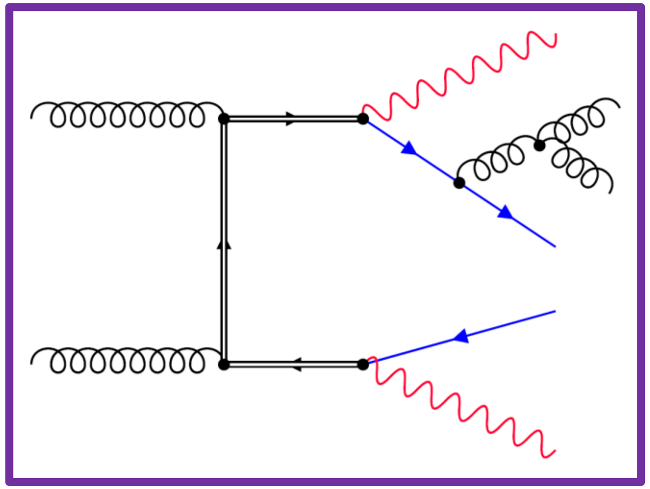
Comparison to parton shower:



Prod.



Mix



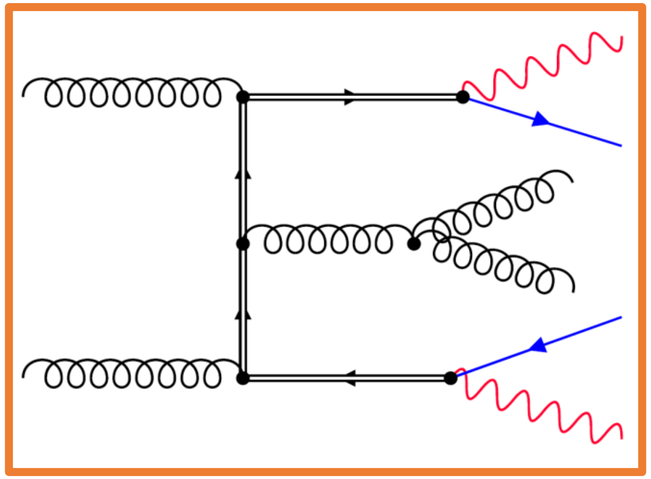
Decay.

- Parton shower includes all order effects.
- Includes emissions in top-quark decays in the soft/collinear approximation.

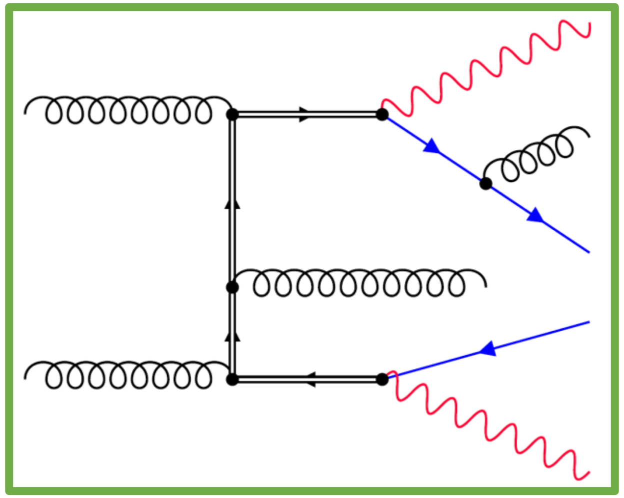
Outlook

Thank you!

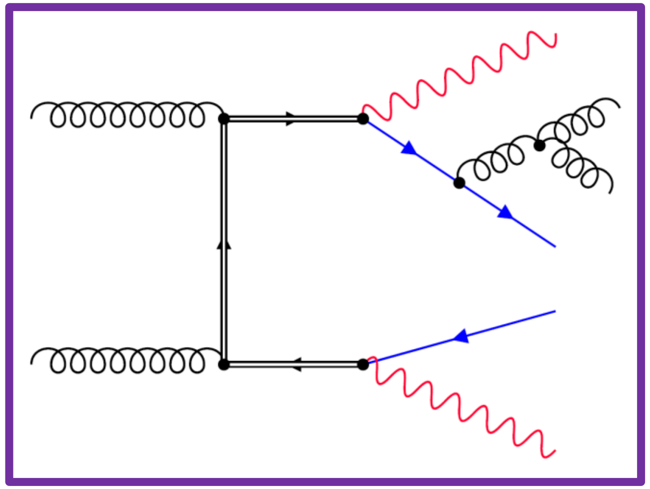
Comparison to parton shower:



Prod.



Mix

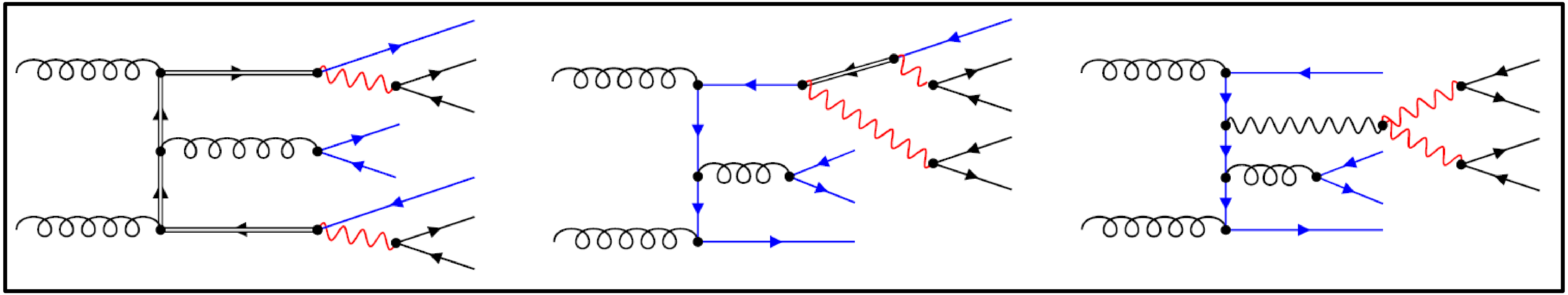


Decay.

- Parton shower includes all order effects.
- Includes emissions in top-quark decays in the soft/collinear approximation.

Backup

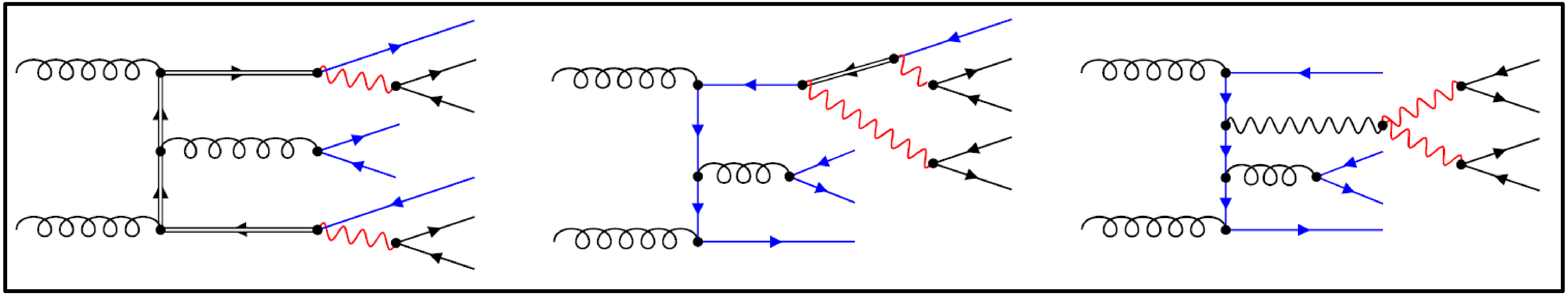
Full off-shell calculation



Double resonant | Single resonant | Non-resonant

- Unstable particles described by Breit-Wigner propagators. $\frac{1}{p^2 - m^2 + im\Gamma}$
- Every possible double-, single- and non-resonant contribution included.
- Interferences consistently incorporated at the matrix-element level.

Full off-shell calculation



Double resonant   Single resonant   Non-resonant

- Preserves top-quark spin correlations.
- Allows for treatment of top-quark decays beyond LO.

Integrated fiducial cross section $t\bar{t}b\bar{b}$

$p_T(b)$ [GeV]	σ^{LO} [fb]	σ^{NLO} [fb]	δ^{NLO}_{scale}	δ^{NLO}_{PDF}	$\mathcal{K} = \sigma^{NLO}/\sigma^{LO}$
$\mu_R = \mu_F = \mu_0 = m_t$					
25	6.998	13.24	$^{+18\%}_{-22\%}$	$^{+1\%}_{-1\%}$	1.89
30	5.113	9.25	$^{+14\%}_{-21\%}$	$^{+2\%}_{-2\%}$	1.81
35	3.775	6.57	$^{+12\%}_{-20\%}$	$^{+2\%}_{-2\%}$	1.74
40	2.805	4.70	$^{+10\%}_{-19\%}$	$^{+2\%}_{-2\%}$	1.68
$\mu_R = \mu_F = \mu_0 = H_T/3$					
25	6.813	13.22	$^{+20\%}_{-22\%}$	$^{+1\%}_{-1\%}$	1.94
30	4.809	9.09	$^{+18\%}_{-22\%}$	$^{+2\%}_{-2\%}$	1.89
35	3.431	6.37	$^{+17\%}_{-21\%}$	$^{+2\%}_{-2\%}$	1.86
40	2.464	4.51	$^{+16\%}_{-21\%}$	$^{+2\%}_{-2\%}$	1.83

Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek, JHEP 08 (2021) 008

- Very large NLO QCD corrections.
- Large theoretical uncertainty.
- Scales μ_R and μ_F main source of theoretical uncertainty.
- Predictions are stable under variation of the cut on $p_T(b)$.

$$H_T = \sum_{i=1}^{4} p_T(b_i) + \sum_{\ell_i = e^+,\mu^-} p_T(\ell_i) + p_T^{miss}$$

Various predictions for $t\bar{t}b\bar{b}$

$$d\sigma^{\rm NLO}_{\rm NWA_{full}} = (\Gamma^{\rm NLO}_{t,\rm NWA})^{-2} \times$$
$$\Big[\overbrace{(d\sigma^{\rm LO}_{t\bar{t}b\bar{b}} + d\sigma^{\rm virt}_{t\bar{t}b\bar{b}} + d\sigma^{\rm real}_{t\bar{t}b\bar{b}j})d\Gamma^{\rm LO}_{t\bar{t}}}^{\rm I} + \overbrace{d\sigma^{\rm LO}_{t\bar{t}b\bar{b}}(d\Gamma^{\rm virt}_{t\bar{t}} + d\Gamma^{\rm real}_{t\bar{t}j})}^{\rm II} +$$
$$\underbrace{d\sigma^{\rm LO}_{t\bar{t}}(d\Gamma^{\rm virt}_{t\bar{t}b\bar{b}} + d\Gamma^{\rm real}_{t\bar{t}b\bar{b}j})}_{\rm III} + \underbrace{(d\sigma^{\rm LO}_{t\bar{t}} + d\sigma^{\rm virt}_{t\bar{t}} + d\sigma^{\rm real}_{t\bar{t}j})d\Gamma^{\rm LO}_{t\bar{t}b\bar{b}}}_{\rm IV}\Big],$$

$$d\sigma^{\rm NLO}_{\rm NWA_{exp}} = d\sigma^{\rm NLO}_{\rm NWA_{full}} \left(\frac{\Gamma^{\rm NLO}_{t,\rm NWA}}{\Gamma^{\rm LO}_{t,\rm NWA}}\right)^2 - d\sigma^{\rm LO}_{\rm NWA_{full}} \frac{2(\Gamma^{\rm NLO}_{t,\rm NWA} - \Gamma^{\rm LO}_{t,\rm NWA})}{\Gamma^{\rm LO}_{t,\rm NWA}}$$

- All the predictions are equally valid.

$\mu_R = \mu_F = \mu_0 = H_T/3$			
Approach	$\sigma_i^{\rm NLO}$ [fb]	$\delta^{\rm NLO}_{\rm scale}$	$\sigma_i^{\rm NLO}/\sigma^{\rm NLO}_{\rm NWA_{full}} - 1$
Off-shell	13.22(2)	$^{+20\%}_{-22\%}$	+0.5%
$\rm NWA_{full}$	13.16(1)	$^{+20\%}_{-22\%}$	-
$\rm NWA_{exp}$	12.38(1)	$^{+24\%}_{-23\%}$	−5.9%
$\rm NWA_{LOdec}$	13.22(1)	$^{+29\%}_{-25\%}$	+0.5%
$\rm NWA_{prod}$	13.01(1)	$^{+20\%}_{-22\%}$	−1.1%
$\rm NWA_{exp,prod}$	12.25(1)	$^{+23\%}_{-23\%}$	−6.9%
$\rm NWA_{LOdec,prod}$	13.11(1)	$^{+29\%}_{-25\%}$	−0.4%

Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek, Phys.Rev.D 107 (2023) 1, 014028

b-jet identification

Theoretical approach

Charge aware labelling: the reconstruction is sensitive to the electric charge of the b jets.

Charge blind labelling: the reconstruction is not sensitive to the electric charge of the b jets.

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

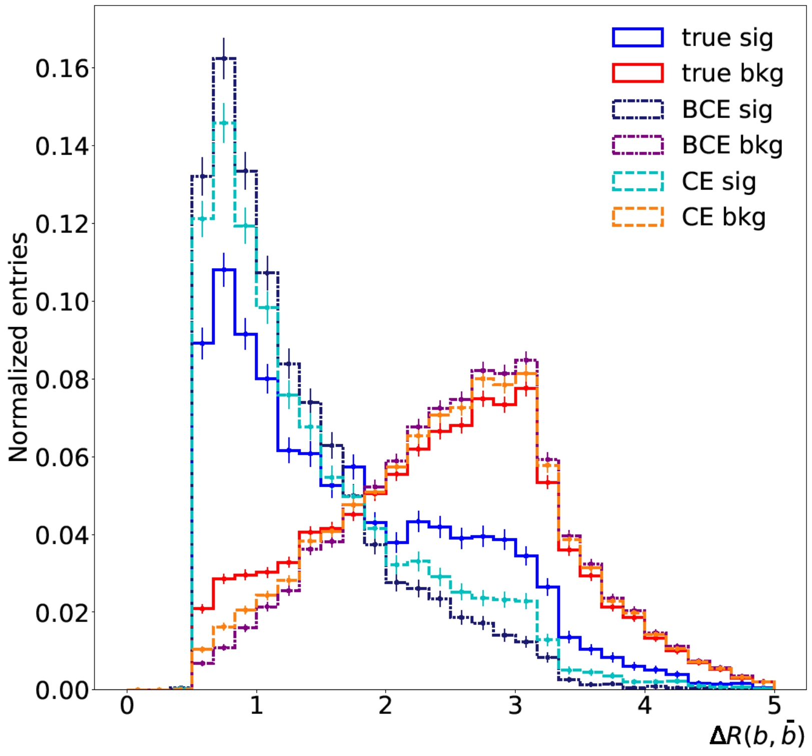
Resonant Histories to reconstruct t and $\bar{t}$ decay products (**charge blind labelling**):

$$\begin{array}{lll} t \to W^+ b_i & \bar{t} \to W^- b_j & (i \neq j = 1,2,3,4) \\ t \to W^+ b_1 & \bar{t} \to W^- b_2 b_3 b_4 & \text{and permutations} \\ t \to W^+ b_2 b_3 b_4 & \bar{t} \to W^- b_1 & \text{and permutations} \end{array}$$

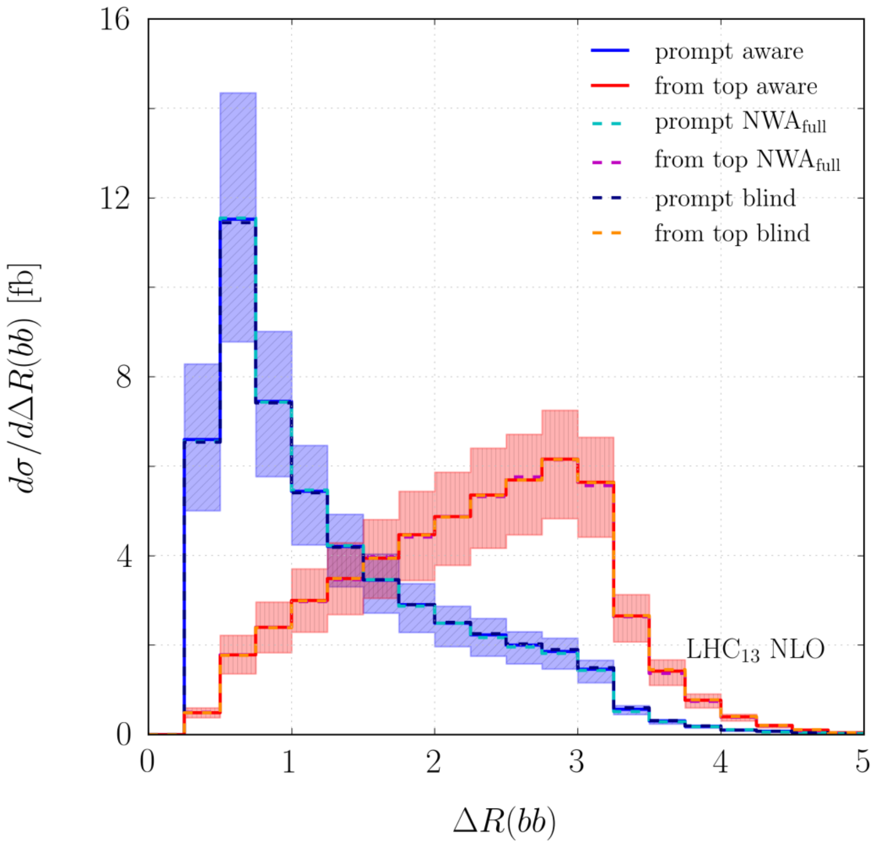
Similar for **charge aware labelling**.

Comparison to Machine Learning ($t\bar{t}b\bar{b}$)

Jang, Ko, Noh, Choi, Lim, Kim, Eur.Phys.J.Plus 137 (2022) 7, 870



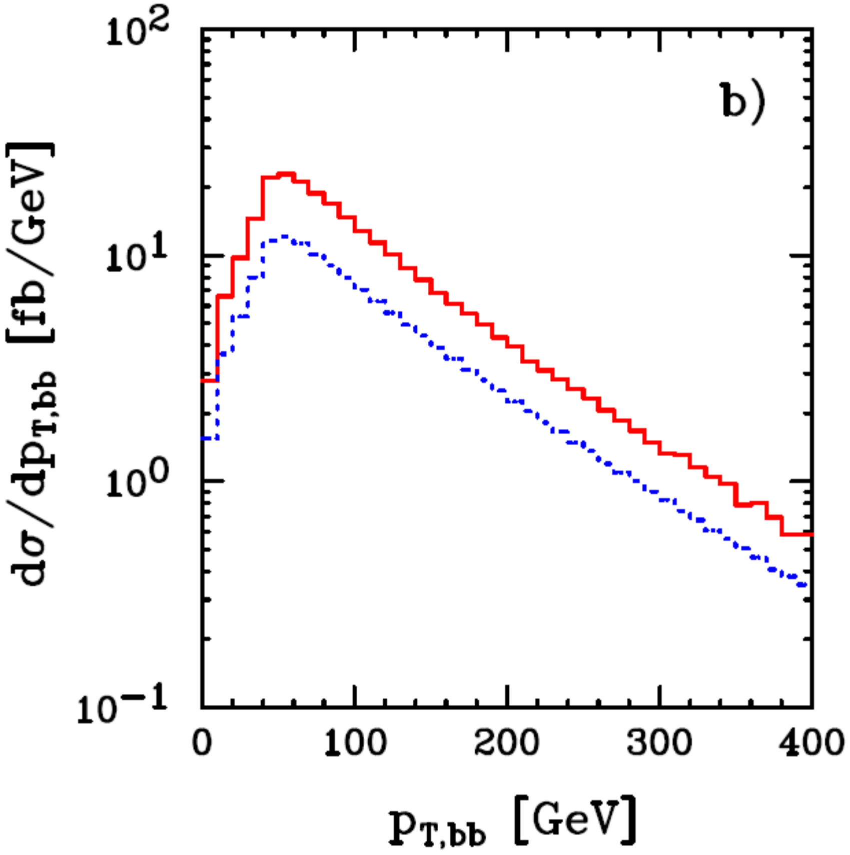
Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek, Phys.Rev.D 107 (2023) 1, 014028

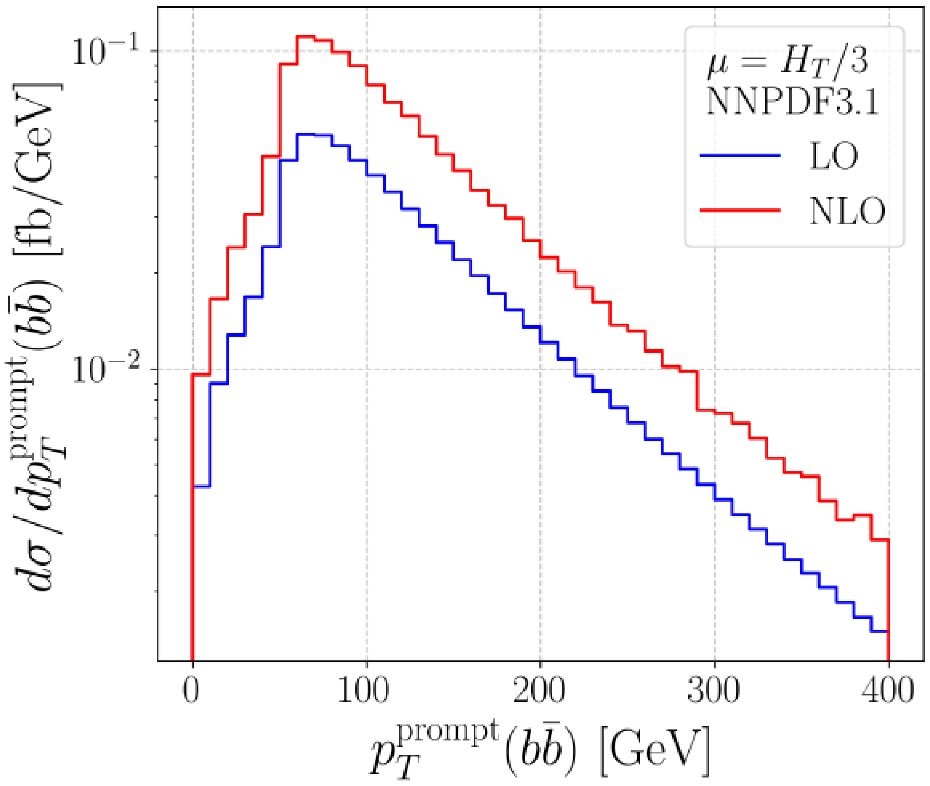


Very good agreement in shape and location of the peaks.

Comparison to stable-top predictions ($t\bar{t}b\bar{b}$)

Bevilacqua, Czakon, Papadopoulos, Pittau, Worek, JHEP 09 (2009) 109





Very good agreement in shape and location of the peaks.

$t\bar{t}b\bar{b}$ summary plot

Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek, JHEP 08 (2021) 008