Phenomenology of ttbb at the LHC

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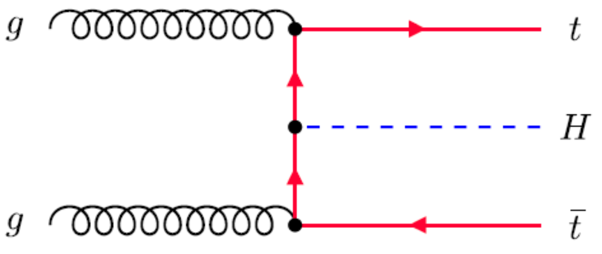
Based on *JHEP 08 (2021) 008* and *arXiv:2202.11186*

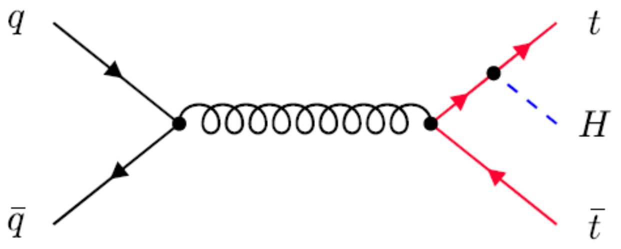
Young Scientists Meeting of the CRC TRR 257

Karlsruher Institut für Technologie – 10 June 2022

Funded by Deutsche Forschungsgemeinschaft German Research Foundation

Motivations

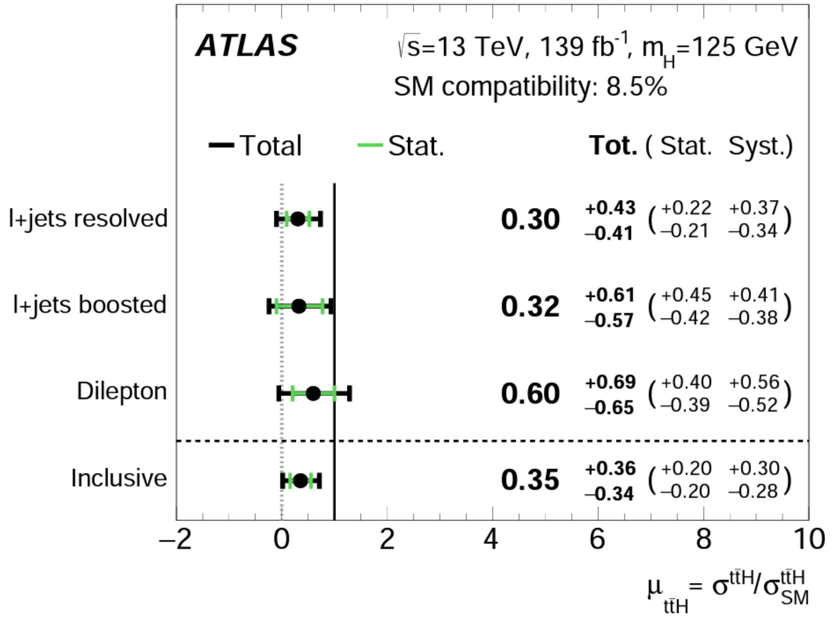




Feynman diagrams generated with FeynGame
[Harlander, Klein, Lipp, Comput. Phys. Commun. 256 (2020) 107465]

Discovery in 2018

ATLAS collaboration, Phys. Lett. B 784 (2018) 173
CMS collaboration, Phys. Rev. Lett. 120 (2018) 231801



ATLAS Collaboration, arXiv 2111.06712

$$Y_t = \frac{\sqrt{2}m_t}{v} \approx 1$$

PROS

Direct coupling top-Higgs already at tree level

No BSM contributions present

CONS

$$\frac{\sigma(pp \to t\bar{t}H)}{\sigma(pp \to H)} \approx 1\%$$

Motivations

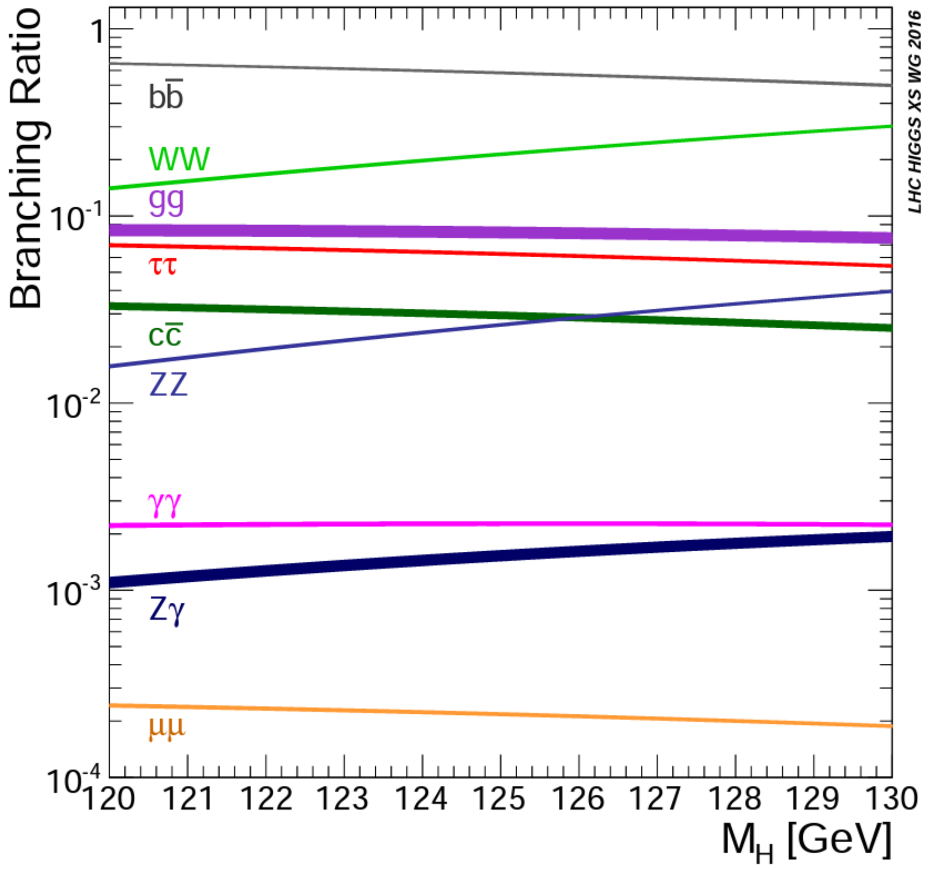
PROS

$$H \to b\bar{b} \qquad \mathcal{BR} = 58\%$$

It is the dominant decay channel of the Higgs boson

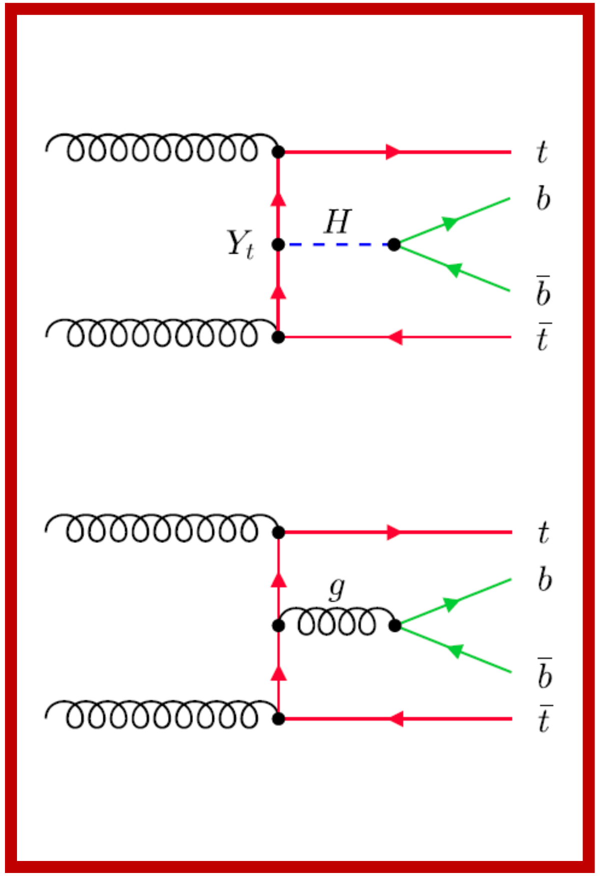
CONS

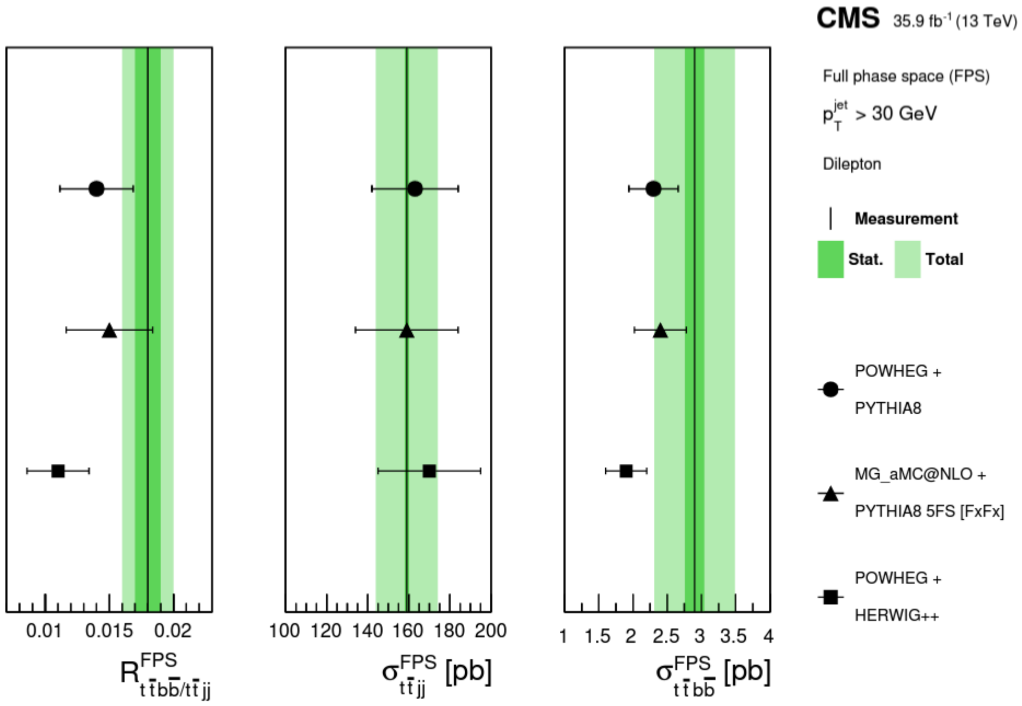
Challenging channel because of «Combinatorial Background»



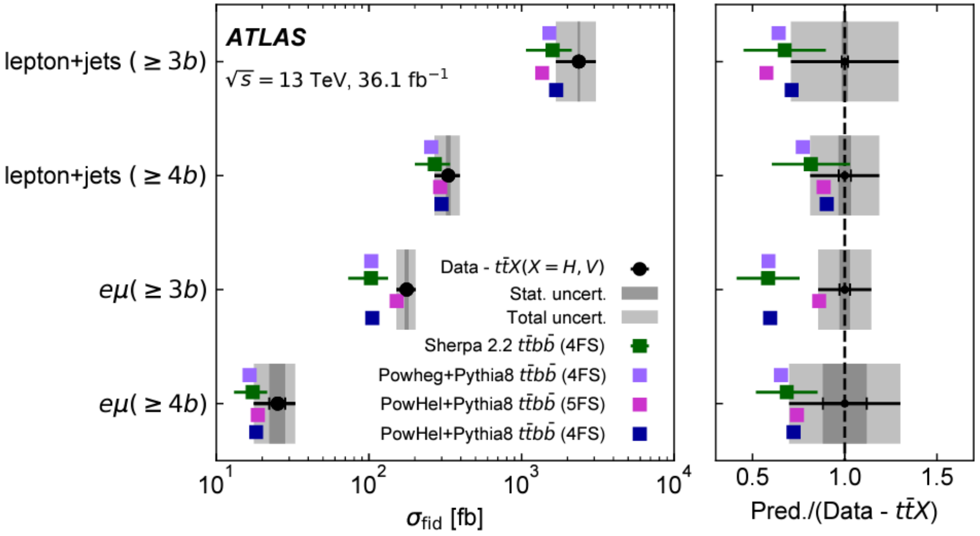
LHC Higgs Cross Section Working Group Collaboration '16

Motivations





CMS Collaboration, JHEP 07 (2020) 125



ATLAS Collaboration, JHEP 04 (2019) 046

Theoretical predictions for ttbb

- NLO QCD calculations with stable top quarks:

(Bredenstein, Denner, Dittmaier, Pozzorini '08,'09,'10 |Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09 | Worek '12 | Bevilacqua, Worek ’14|Buccioni, Kallweit, Pozzorini, Zoller '19)

  - General idea of size of NLO corrections
  - No reliable description of top decay products and radiation pattern

- More realistic studies:
  - NLO QCD matched to Parton Shower

    (Kardos, Trócsányi '14 | Cascioli, Maierhöfer, Moretti, Pozzorini, Siegert '14 |Garzelli, Kardos, Trócsányi '15 | Bevilacqua, Garzelli, Kardos ‘17)
  - NLO QCD in NWA

    (Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek ’22)
  - NLO QCD with full off-shell effects

    (Denner, Lang, Pellen ’20 | Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek '21)

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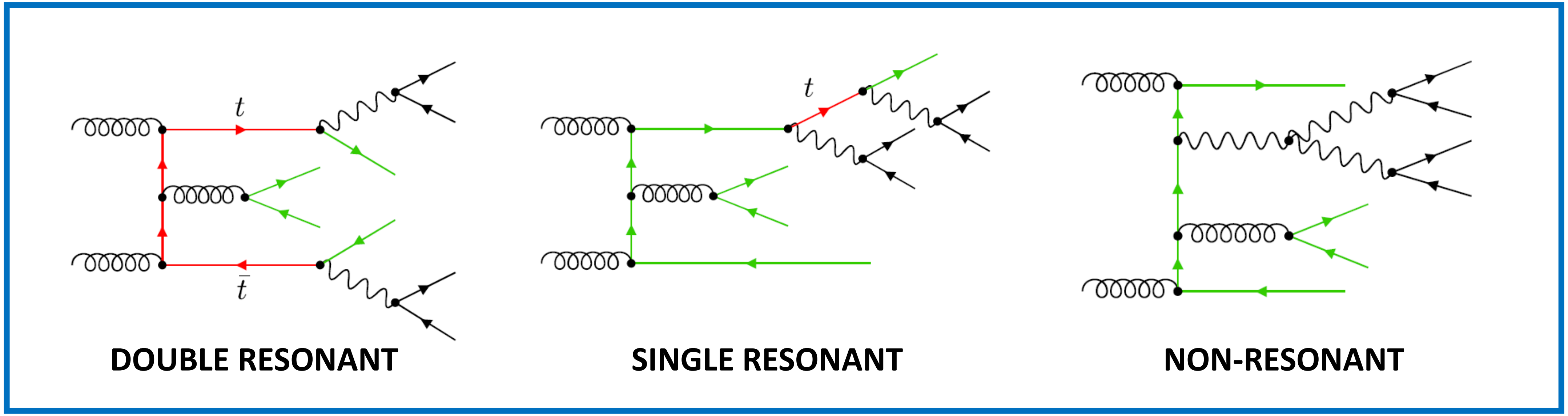
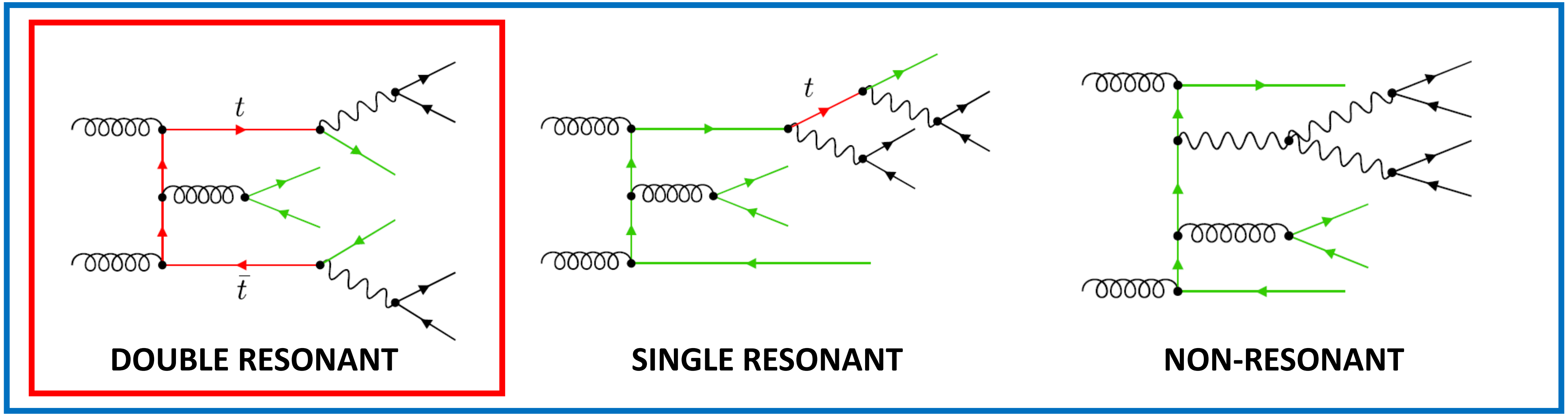


Full Off-Shell calculation:

- Off-shell t and W described by Breit-Wigner propagators
- Double-, single- and non-resonant top contributions included
- All interference effects consistently incorporated at the matrix element level



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Narrow Width Approximation:

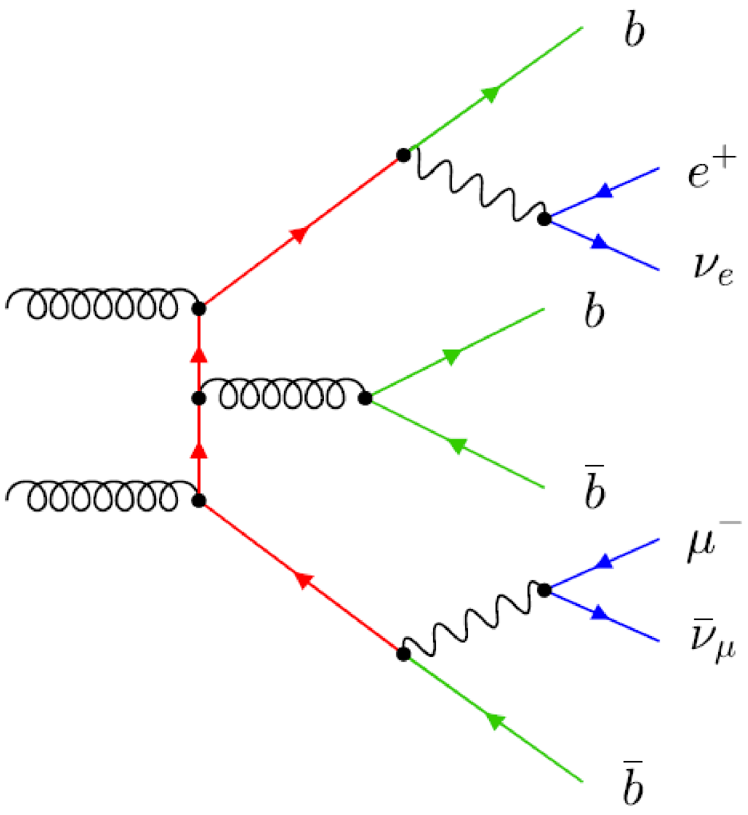
- t and W produced on-shell
- Factorization of the cross-section in production × decay
- NLO QCD corrections to both production and decay

$$\lim_{\Gamma/m \to 0} \frac{1}{(p^2 - m^2)^2 + m^2\Gamma^2} \sim \frac{\pi}{m\Gamma}\delta(p^2 - m^2)$$

$$\frac{\Gamma_t}{m_t} \approx 0.008 = 0.8\%$$

forces on-shell production

State of the art ttbb theoretical results



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

SETUP:

- NLO QCD
- Full off-shell
- Dileptonic decay channel of tops
- 5 flavour scheme
- LHC 13 TeV

- *Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek, JHEP 08 (2021) 008*
- *Denner, Lang, Pellen, Phys.Rev.D 104 (2021) 5, 056018*

Integrated fiducial cross-sections

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

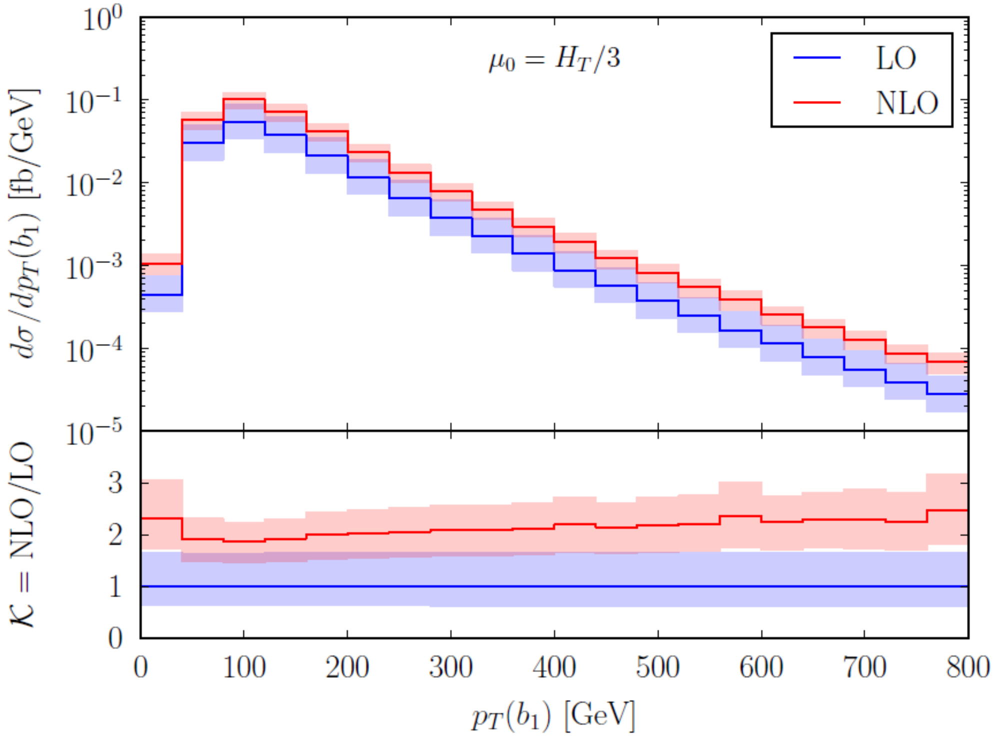
$p_T(b)$	$\sigma^{\rm LO}$ [fb]	$\delta_{\rm scale}$	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$	$\delta_{\rm PDF}$	$\mathcal{K} = \sigma^{\rm NLO}/\sigma^{\rm LO}$
			$\mu_R = \mu_F = \mu_0 = m_t$			
25	6.998	$+4.525$ (65%) -2.569 (37%)	13.24	$+2.33$ (18%) -2.89 (22%)	$+0.19$ (1%) -0.19 (1%)	1.89
30	5.113	$+3.343$ (65%) -1.889 (37%)	9.25	$+1.32$ (14%) -1.93 (21%)	$+0.14$ (2%) -0.14 (2%)	1.81
35	3.775	$+2.498$ (66%) -1.401 (37%)	6.57	$+0.79$ (12%) -1.32 (20%)	$+0.10$ (2%) -0.10 (2%)	1.74
40	2.805	$+1.867$ (67%) -1.051 (37%)	4.70	$+0.46$ (10%) -0.91 (19%)	$+0.08$ (2%) -0.08 (2%)	1.68
			$\mu_R = \mu_F = \mu_0 = H_T/3$			
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

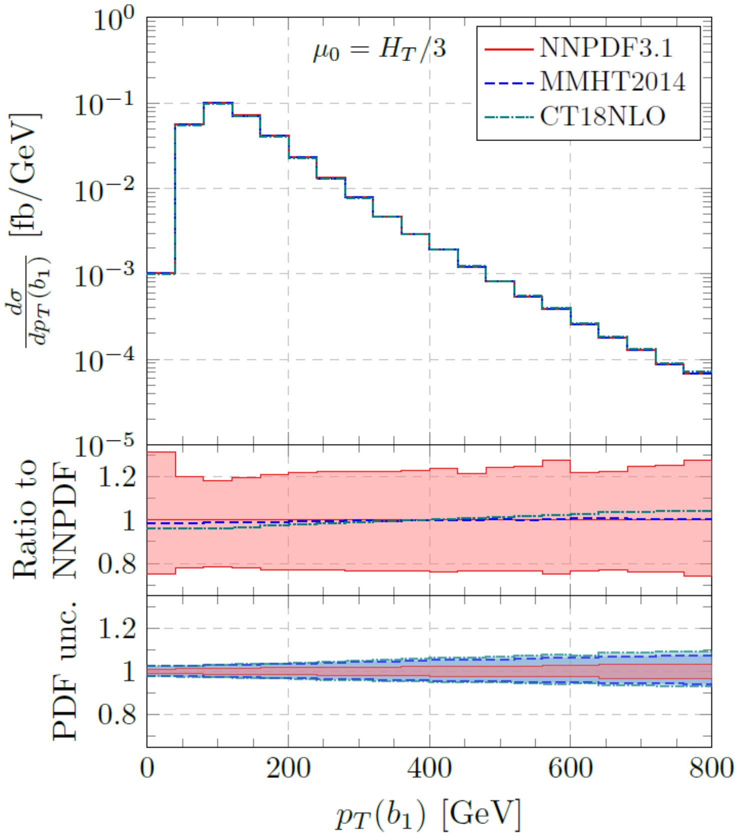
$$H_T = p_T(b_1) + p_T(b_2) + p_T(b_3) + p_T(b_4) + p_T(e^+) + p_T(\mu^-) + p_T^{\rm miss}$$

- Big NLO QCD corrections
- Significant reduction of theoretical uncertainties going from LO to NLO
- Scale dependence main source of theoretical uncertainty
- With jet veto of 50 GeV:

  $\mathcal{K} = 1.11$ $\mathcal{K} = 1.23$

Differential distributions - uncertainties





- NLO QCD corrections [90%, 135%]
- Scale dependence 20% - 30%
- PDF uncertainties small

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

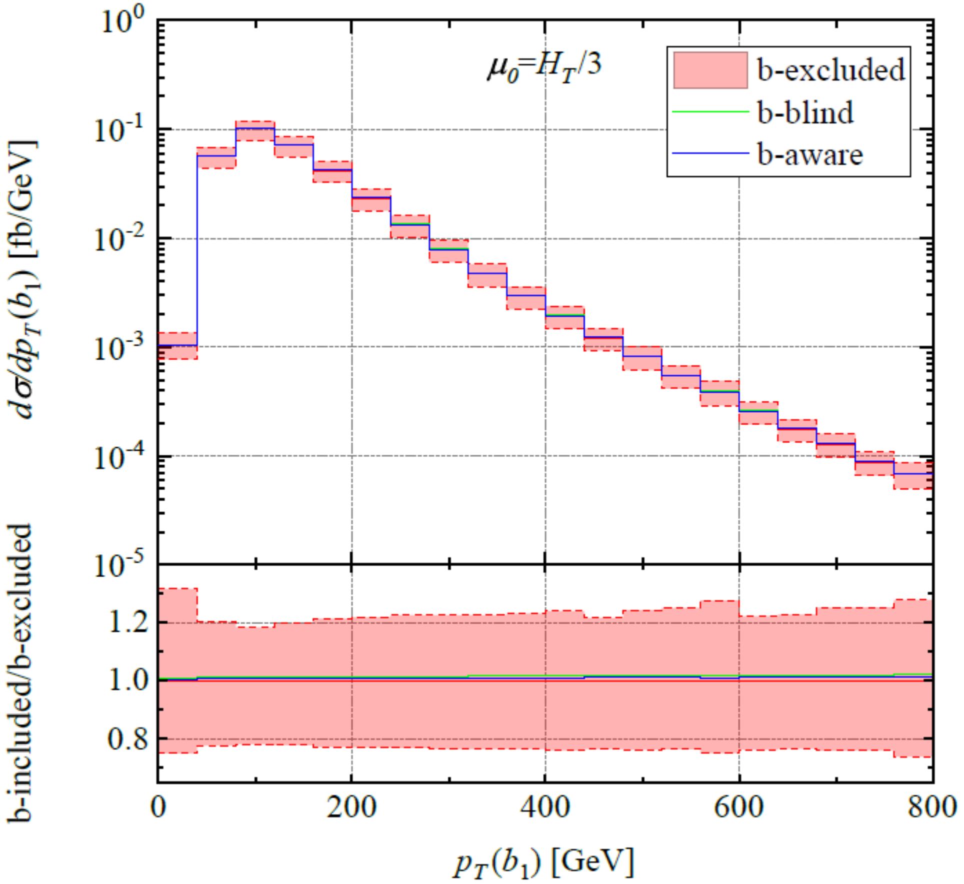
Contribution of initial states involving b-quarks

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

$\mu = H_T/3$	LO (fb)	$\sigma_b/\sigma_{\text{no } b}$	NLO (fb)	$\sigma_b/\sigma_{\text{no } b}$
no b	6.813(3)	-	13.22(3)	-
aware	6.822(3)	0.1%	13.31(3)	0.7%
blind	6.828(3)	0.2%	13.38(3)	1.2%

$\mu = H_T/3$	σ (fb)	$+\delta_{\text{scale}}$	$-\delta_{\text{scale}}$
LO	6.813	+64%	-36%
NLO	13.22	+20%	-22%

We can safely neglect these contributions!



Off-shell effects and corrections to decays

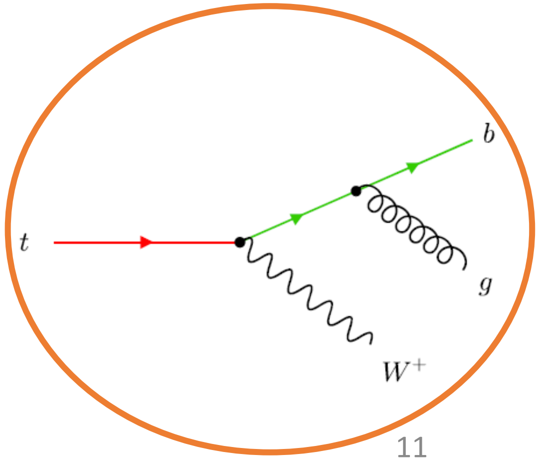
Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek, arXiv:2202.11186

$H_T/3$	σ [fb]	$+\delta_{\text{scale}}$	$-\delta_{\text{scale}}$
Off-shell	13.22	+20%	-22%
NWA_{full}	13.16	+20%	-22%
NWA_{exp}	12.38	+24%	-23%
$\text{NWA}_{\text{LOdec}}$	13.22	+29%	-25%

Several NWA predictions:

- **NWA full:** used for comparison to full off-shell predictions.
- **NWA full expanded:** NWA full presents $1/\Gamma_t$ factors. We expand NWA full in α_s to recover $O(\alpha^4\alpha_s^5)$. This expansion is not possible in the full off-shell case.
- **NWA LO decays:** the NLO QCD corrections to the top-quark decays are not considered.

- **+0.5%** off-shell effects → negligible at the integrated level
- **NWA full** and **NWA LO decays** **0.5%** relative difference
- **NWA full expanded** and **NWA LO decays** **6.8%** relative difference
- No NLO QCD corrections to top-quark decays → worse theoretical accuracy
- All the results are compatible within theoretical uncertainties



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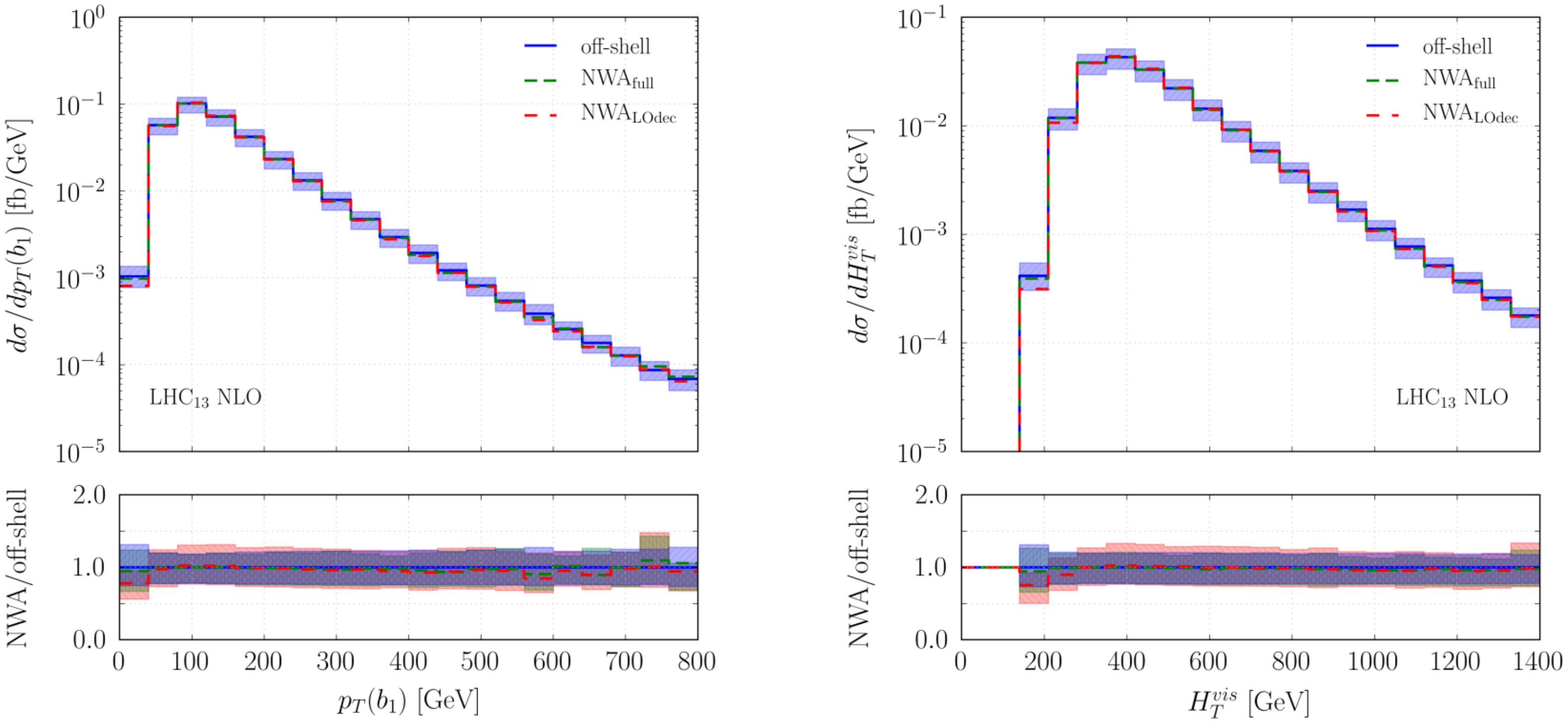


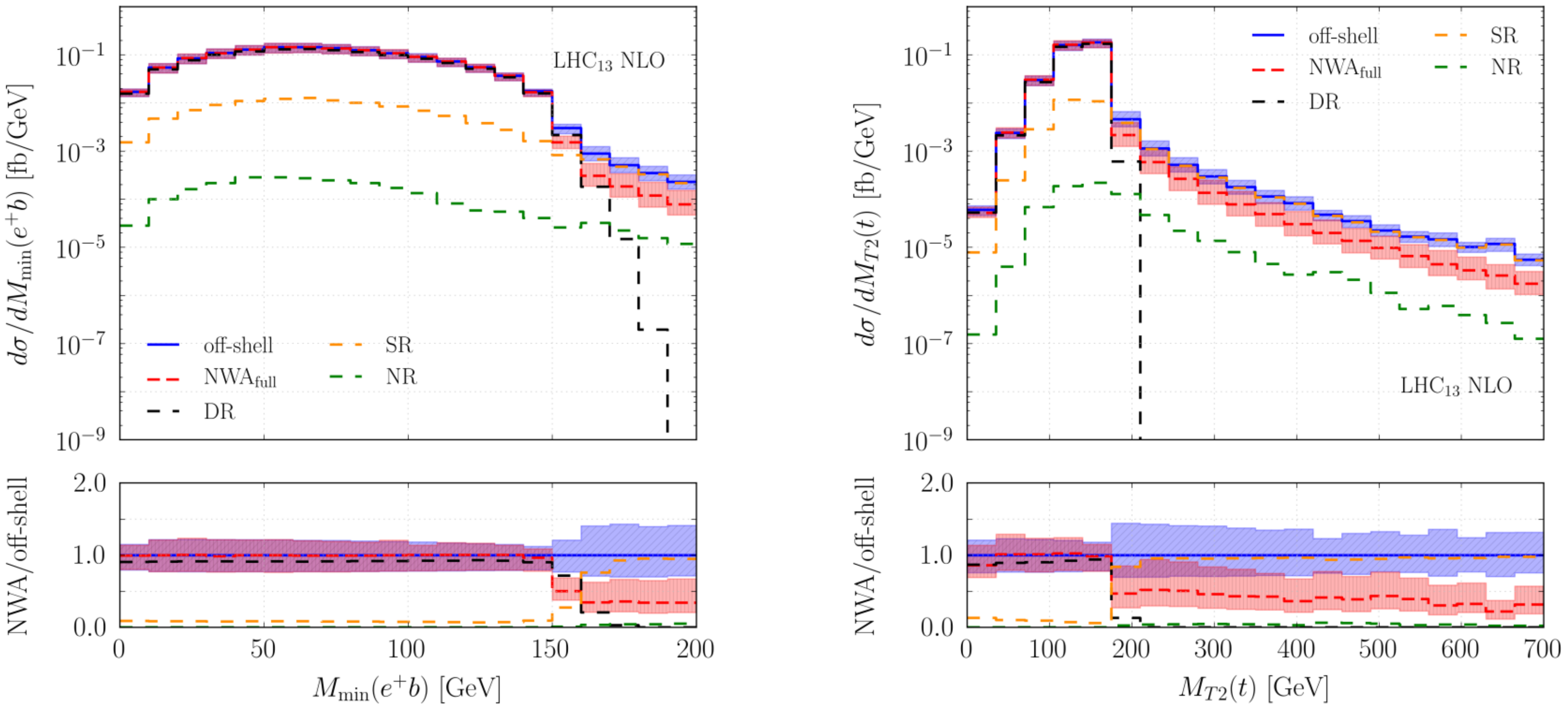
- Negligible off-shell effects predicted for most of the observables, e.g.

$$p_T(b_i), \quad M(b_i, b_j), \quad H_T,$$

- NWA very good approximation for these observables.
- Neglecting NLO QCD corrections to top-quark decays worsen theoretical precision.

Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek, arXiv:2202.11186

Off-shell effects



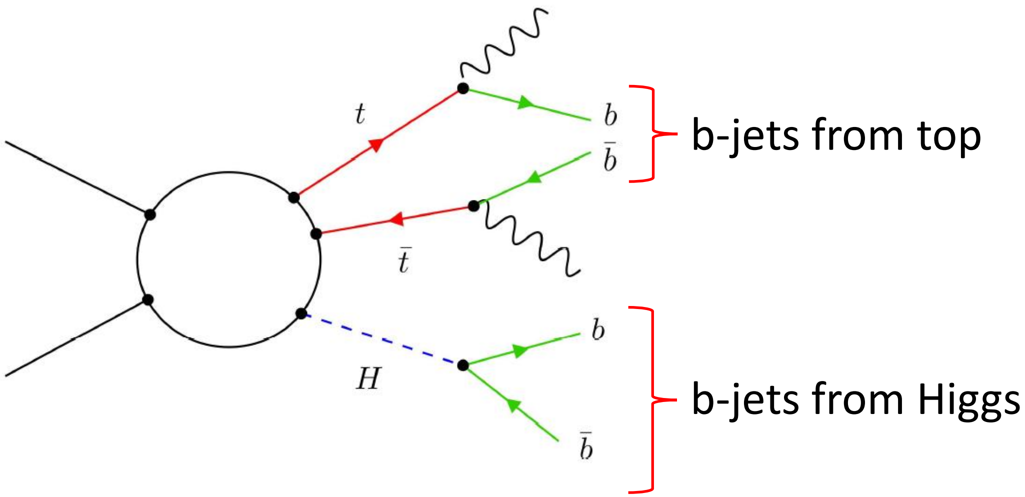
Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek, arXiv:2202.11186

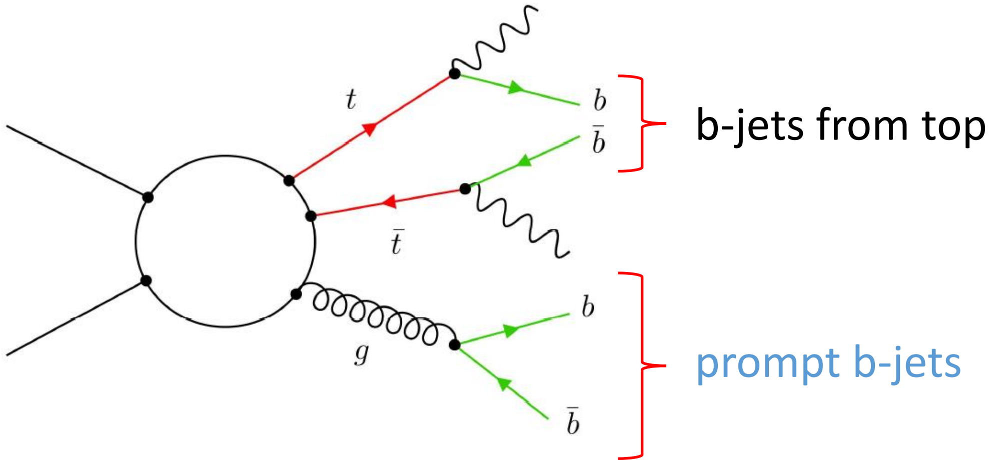
Significant off-shell effects in observables with kinematic edges.

These observables are used for BSM searches.

- Large differences between full off-shell and NWA (up to **66%** and **80%** respectively)
- Single resonant contribution dominant after kinematic edge

b-jet labelling





Prompt b-jets represent background to Higgs boson in ttH(bb) → Prescription to distinguish between b-jets from top and prompt b-jets needed

b-jet labelling

Theoretical approach

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

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

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

Resonant Histories to reconstruct top and antitop decay products (**charge blind labelling**):

$$t \to W^+ b_i \qquad \bar{t} \to W^- b_j \qquad (i \neq j = 1, 2, 3, 4)$$

$$t \to W^+ b_1 \qquad \bar{t} \to W^- b_2 b_3 b_4 \qquad \text{and permutations}$$

$$t \to W^+ b_2 b_3 b_4 \qquad \bar{t} \to W^- b_1 \qquad \text{and permutations}$$

Similar for **charge aware labelling**

b-jet labelling

Theoretical approach

Selected history: $t \to W^+ b_1\,,\ \bar{t} \to W^- b_2$ ⟶ $(bb)^{\text{top}} = b_1 b_2$ $(bb)^{\text{prompt}} = b_3 b_4$

b-jet labelling

Theoretical approach

Selected history: $t \to W^+ b_1,\ \bar{t} \to W^- b_2$ → $(bb)^{\text{top}} = b_1 b_2$ $(bb)^{\text{prompt}} = b_3 b_4$

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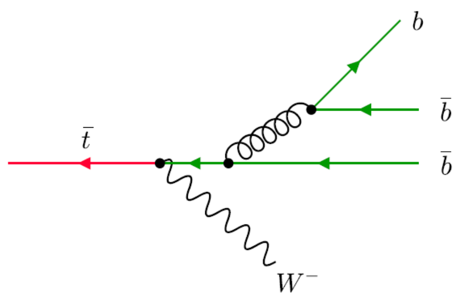

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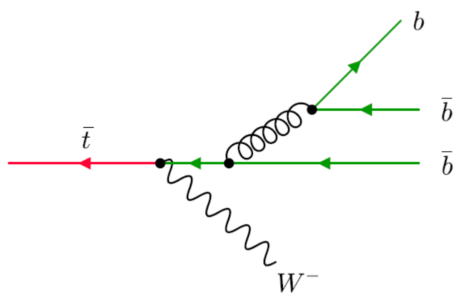
Selected history: $t \to W^+ b_1,\ \bar{t} \to W^- b_2 b_3 b_4$ → $(bb)^{\text{top}} = b_1 b_?$ $(bb)^{\text{prompt}} = b_? b_?$



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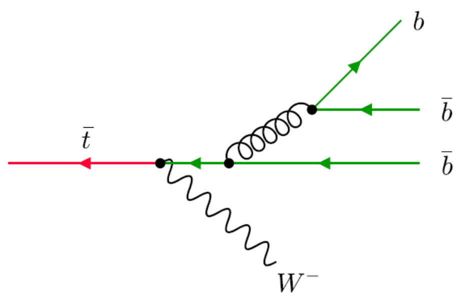


DISCRIMINATORS

$p_{T,\max}(b_i)$ V $\Delta R_{\min}(b_i b_j)$

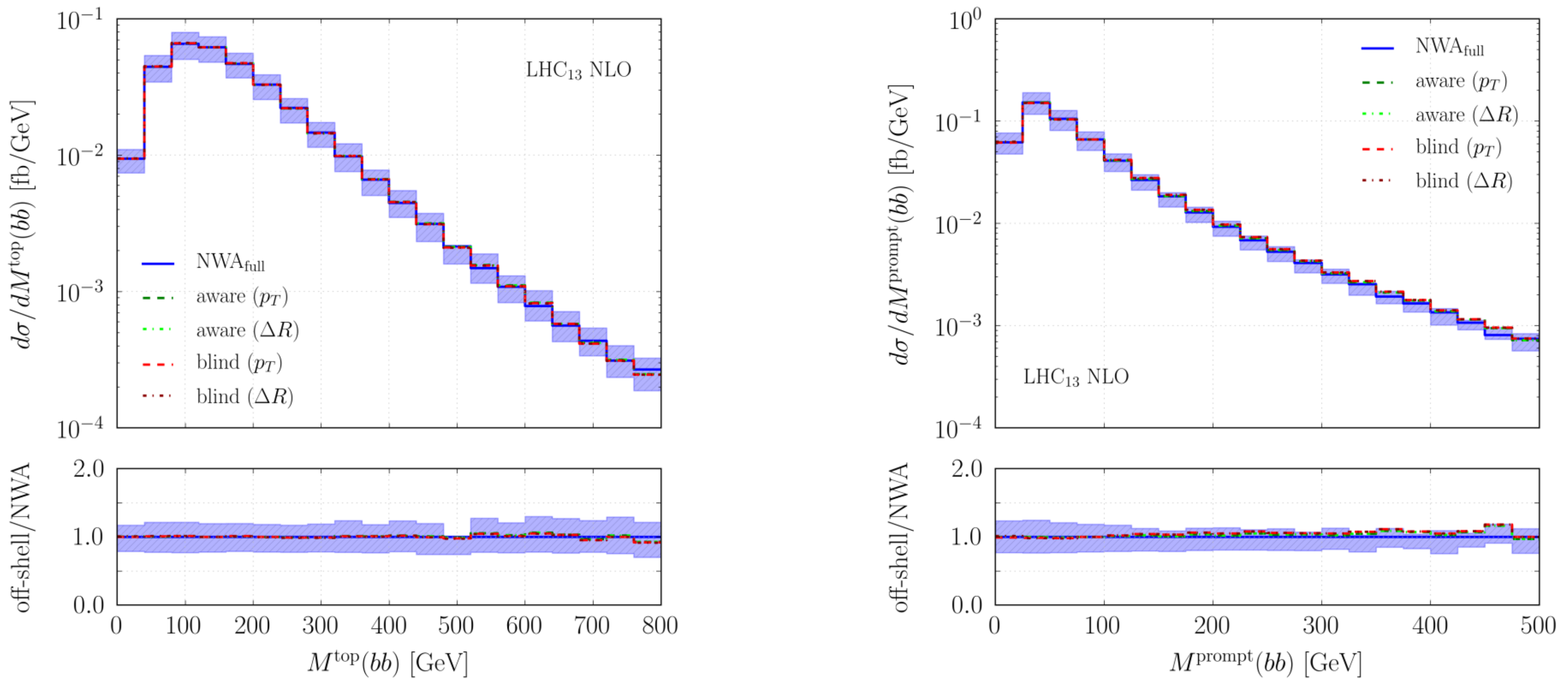
Identifies the b from antitop

Identifies the prompt b-pair

b-jet labelling

NWA is reference: knowledge of the decay chain → we can distinguish prompt b-jets and b-jets from top decays without any reconstruction.

Theoretical results

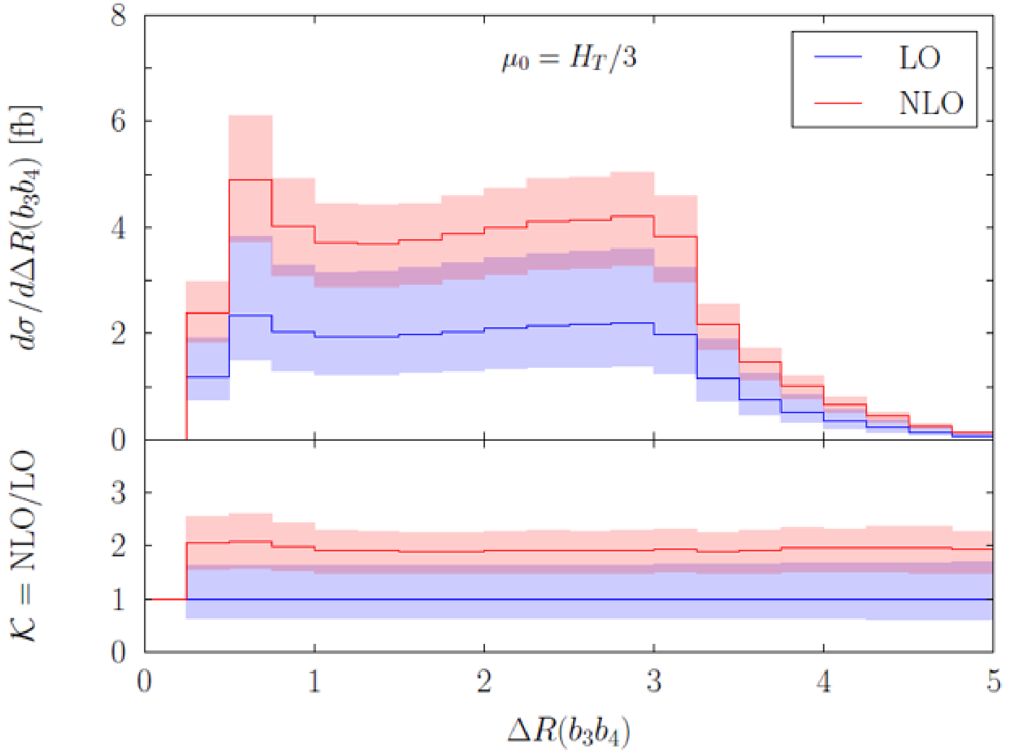


Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek, arXiv:2202.11186

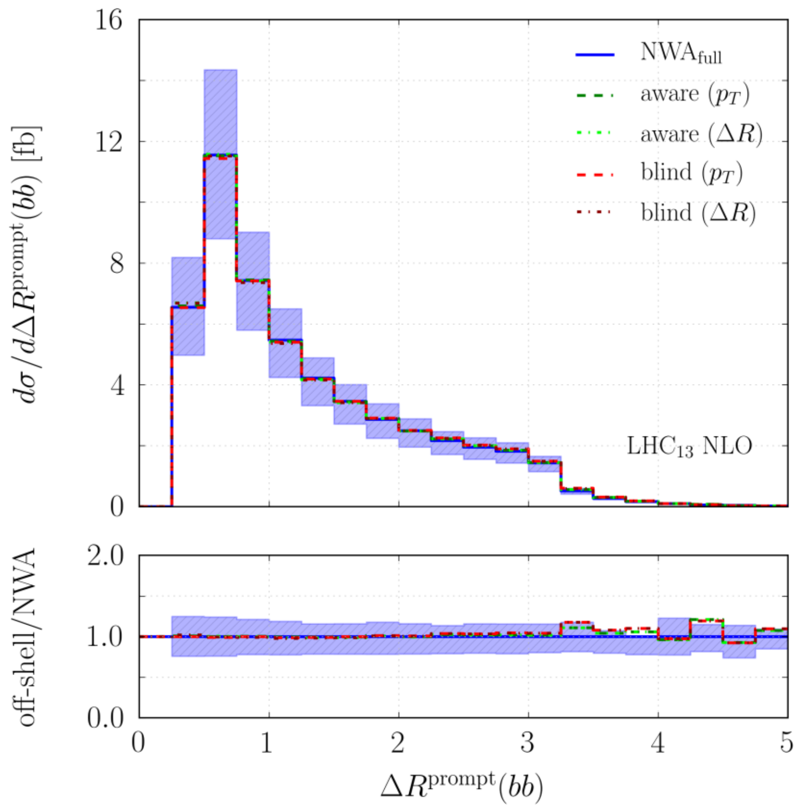
b-jet labelling

Theoretical results

The prompt b-jets are very often produced close in angular separation



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



Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek, arXiv:2202.11186

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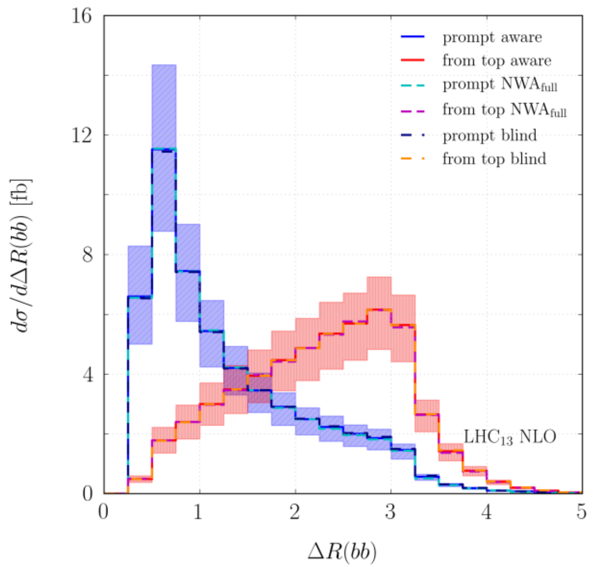
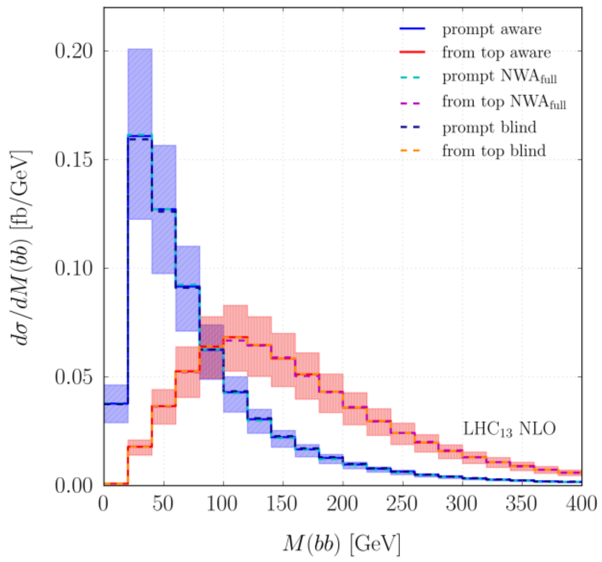
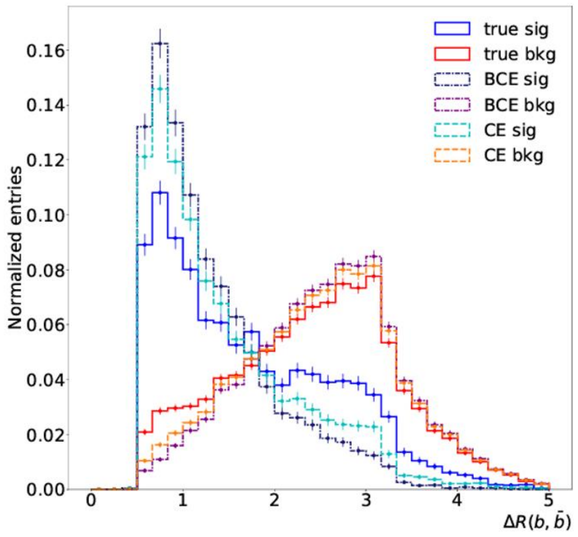
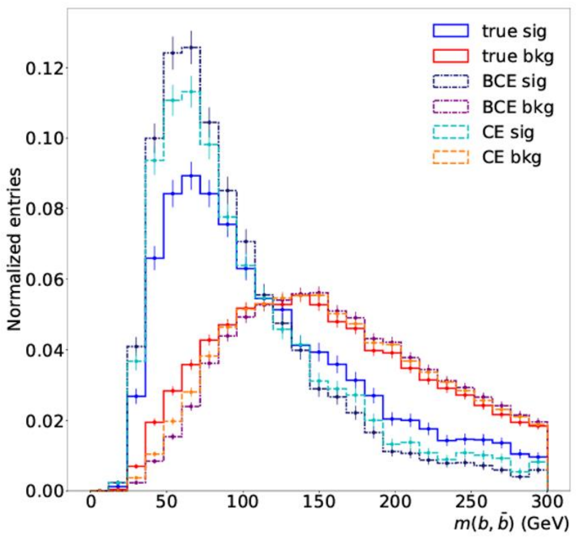




Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek, arXiv:2202.11186

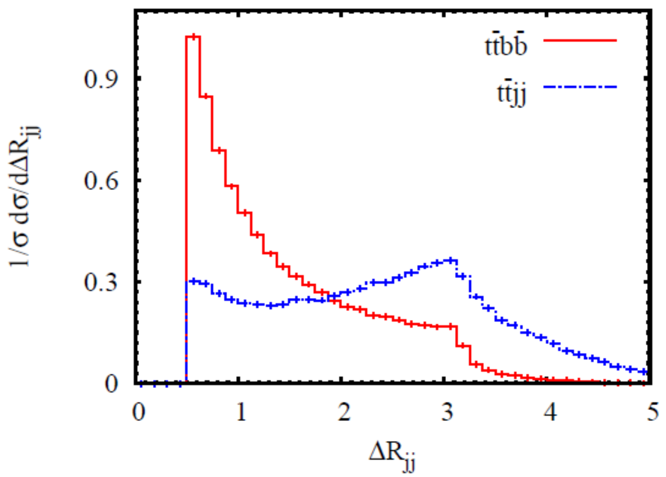
Machine learning

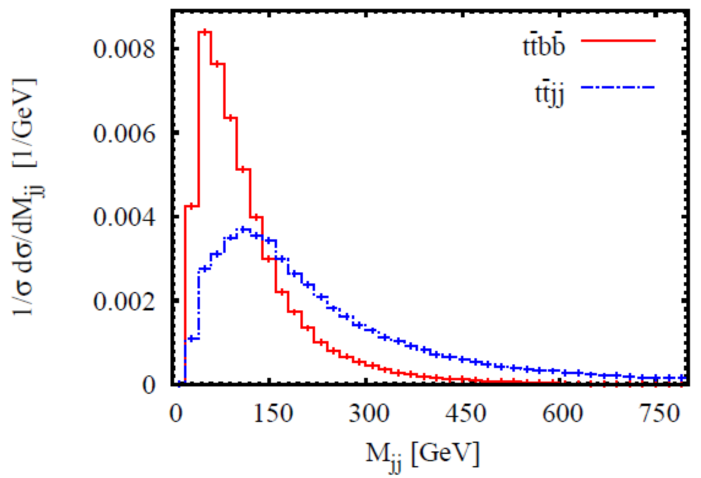




Jang, Ko, Noh, Choi, Lim, Kim, arXiv 2103.09129

Stable tops





Bevilacqua, Worek, JHEP 07 (2014) 135

Summary ttbb

- Huge NLO QCD corrections ≈ 89%
- Theoretical Uncertainties ≈ 20%
- Contribution of initial state b-quarks negligible
- b-jet labelling
  - Prompt b-jets as a background to Higgs boson in ttH
  - Simple prescription to label b-jets as effective as machine learning techniques
- Significant off-shell effects observed for observables with kinematic edges
- NLO QCD Corrections to decays improve precision

Backup slides

LHC Setup

Input parameters

$$G_F = 1.16638 \cdot 10^{-5}\ \text{GeV}^{-2}\,, \qquad m_t = 173\ \text{GeV}\,,$$

$$m_W = 80.351972\ \text{GeV}\,, \qquad \Gamma_W^{\text{NLO}} = 2.0842989\ \text{GeV}\,,$$

$$m_Z = 91.153481\ \text{GeV}\,, \qquad \Gamma_Z^{\text{NLO}} = 2.4942664\ \text{GeV}\,.$$

$$\Gamma_{t,\text{off-shell}}^{\text{LO}} = 1.443303\ \text{GeV}\,, \qquad \Gamma_{t,\text{off-shell}}^{\text{NLO}} = 1.3444367445\ \text{GeV}\,.$$

$$\Gamma_{t,\text{NWA}}^{\text{LO}} = 1.466332\ \text{GeV}\,, \qquad \Gamma_{t,\text{NWA}}^{\text{NLO}} = 1.365888\ \text{GeV}.$$

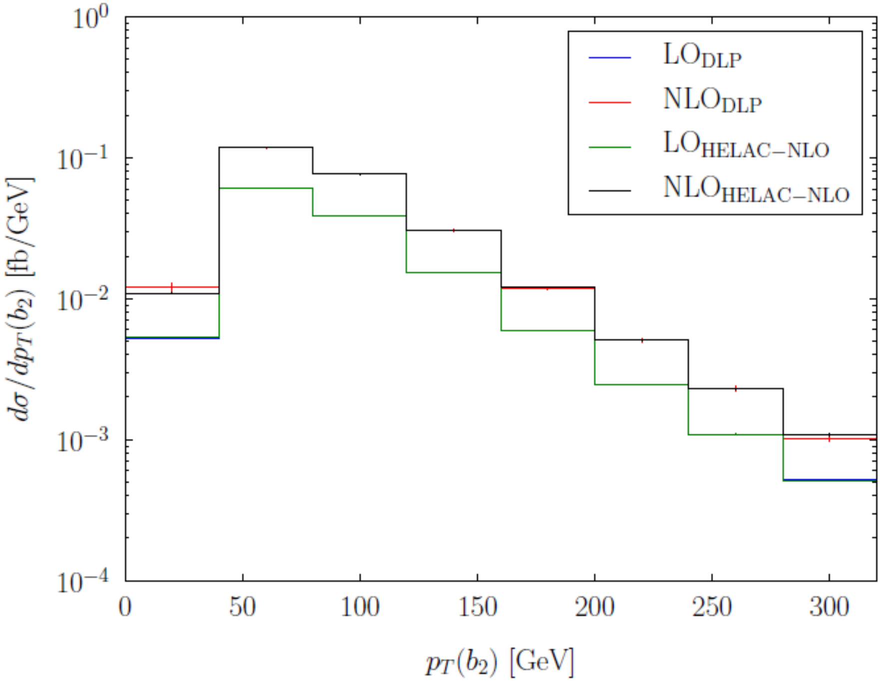
Cuts

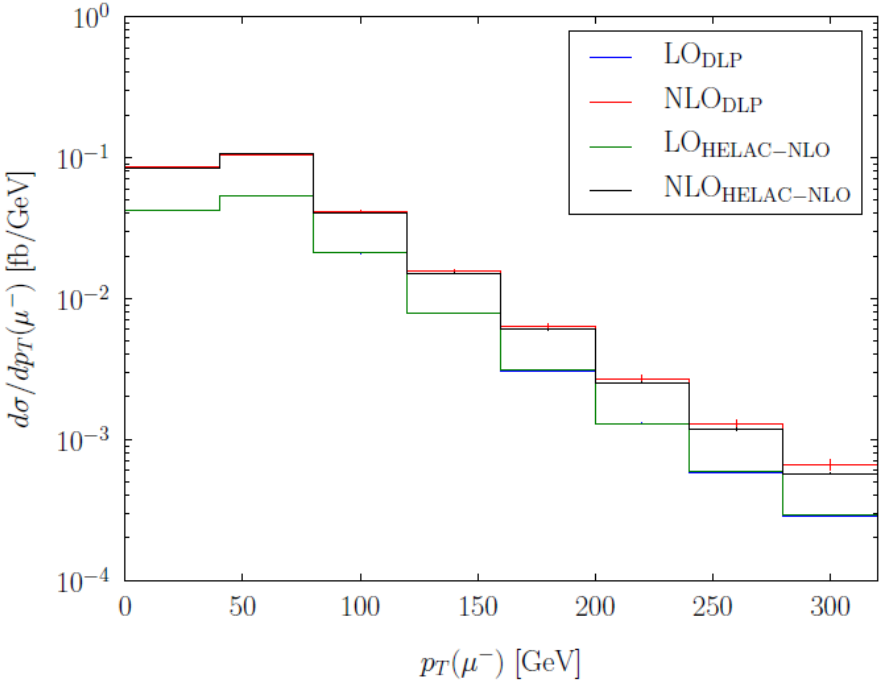
$$p_T(\ell) > 20\ \text{GeV}\,, \qquad |y(\ell)| < 2.5\,, \qquad p_T(b) > 25\ \text{GeV}\,, \qquad |y(b)| < 2.5\,,$$

Comparison theoretical predictions full off-shell ttbb

$$\sigma^{\rm NLO}_{\rm HELAC-NLO}({\rm NNPDF3.1}, \mu_0 = \mu_{\rm DLP}) = 10.28(1)^{+18\%}_{-21\%}\,{\rm fb}\,,$$

$$\sigma^{\rm NLO}_{\rm DLP}({\rm NNPDF3.1}, \mu_0 = \mu_{\rm DLP}) = 10.28(8)^{+18\%}_{-21\%}\,{\rm fb}\,.$$





Expansion of NWA full

NWA full

$$
\begin{aligned}
d\sigma^{\rm NLO}_{\rm NWA_{full}} = {} & d\sigma^{\rm NLO}_{t\bar{t}b\bar{b}} \frac{d\Gamma^0_{t\to W^+b} d\Gamma^0_{\bar{t}\to W^-\bar{b}}}{(\Gamma^{\rm NLO}_{t,\rm NWA})^2} \\
& + d\sigma^{\rm NLO}_{t\bar{t}} \left(\frac{d\Gamma^0_{t\to W^+b b\bar{b}} d\Gamma^0_{\bar{t}\to W^-\bar{b}}}{(\Gamma^{\rm NLO}_{t,\rm NWA})^2} + \frac{d\Gamma^0_{t\to W^+b} d\Gamma^0_{\bar{t}\to W^-\bar{b}b\bar{b}}}{(\Gamma^{\rm NLO}_{t,\rm NWA})^2} \right) \\
& + d\sigma^{\rm LO}_{t\bar{t}b\bar{b}} \left(\frac{d\Gamma^1_{t\to W^+b} d\Gamma^0_{\bar{t}\to W^-\bar{b}}}{(\Gamma^{\rm NLO}_{t,\rm NWA})^2} + \frac{d\Gamma^0_{t\to W^+b} d\Gamma^1_{\bar{t}\to W^-\bar{b}}}{(\Gamma^{\rm NLO}_{t,\rm NWA})^2} \right) \\
& + d\sigma^{\rm LO}_{t\bar{t}} \left(\frac{d\Gamma^1_{t\to W^+b b\bar{b}} d\Gamma^0_{\bar{t}\to W^-\bar{b}}}{(\Gamma^{\rm NLO}_{t,\rm NWA})^2} + \frac{d\Gamma^1_{t\to W^+b} d\Gamma^0_{\bar{t}\to W^-\bar{b}b\bar{b}}}{(\Gamma^{\rm NLO}_{t,\rm NWA})^2} \right. \\
& \left. + \frac{d\Gamma^0_{t\to W^+b b\bar{b}} d\Gamma^1_{\bar{t}\to W^-\bar{b}}}{(\Gamma^{\rm NLO}_{t,\rm NWA})^2} + \frac{d\Gamma^0_{t\to W^+b} d\Gamma^1_{\bar{t}\to W^-\bar{b}b\bar{b}}}{(\Gamma^{\rm NLO}_{t,\rm NWA})^2} \right)
\end{aligned}
$$

NWA full expanded

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