ttbb predictions at NLO in QCD and b-jet modelling

Michele Lupattelli

Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

In collaboration with:

Giuseppe Bevilacqua, Huan-Yu Bi, Heribertus Bayu Hartanto, Manfred Kraus, Malgorzata Worek

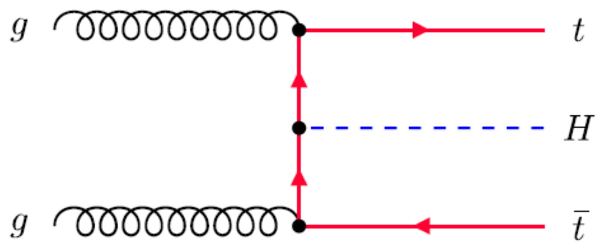
Based on *JHEP 08 (2021) 008* and *arXiv:2202.11186*

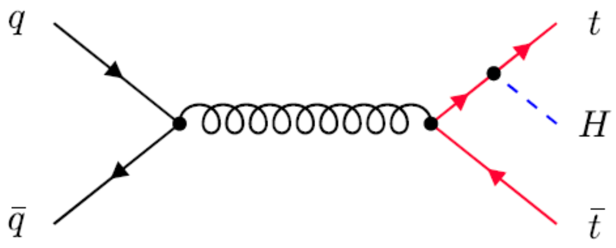
ICHEP 2022

Bologna – 8 July 2022

Funded by
DFG Deutsche Forschungsgemeinschaft
German Research Foundation

ttH and ttbb





PROS

Direct coupling top-Higgs already at tree level

CONS

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

Discovery in 2018

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

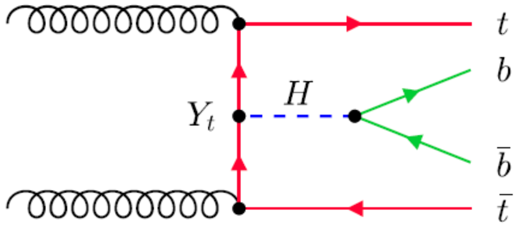
Feynman diagrams generated with FeynGame
[Harlander, Klein, Lipp, Comput. Phys. Commun. 256 (2020) 107465]

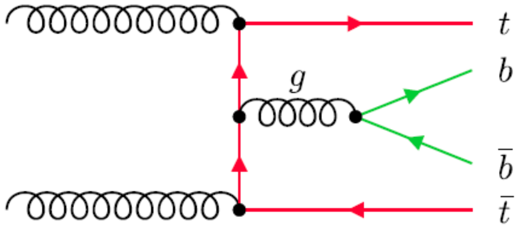
$$H \to b\bar{b}$$

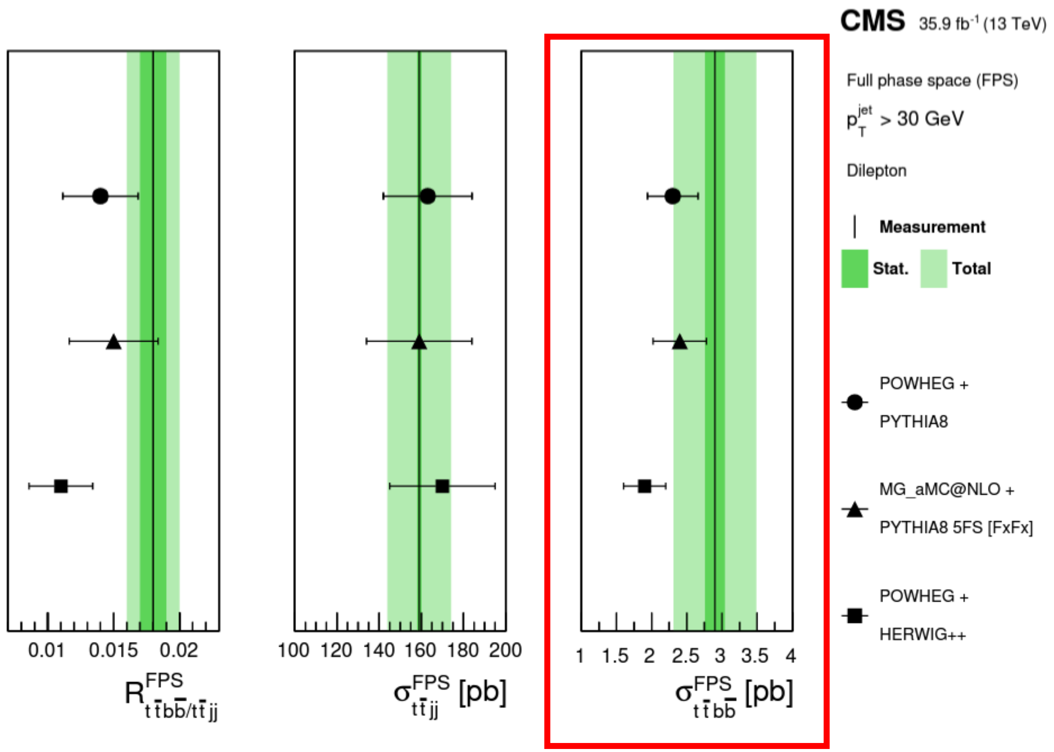
PROS $\mathcal{BR} = 58\%$

CONS «Combinatorial Background»

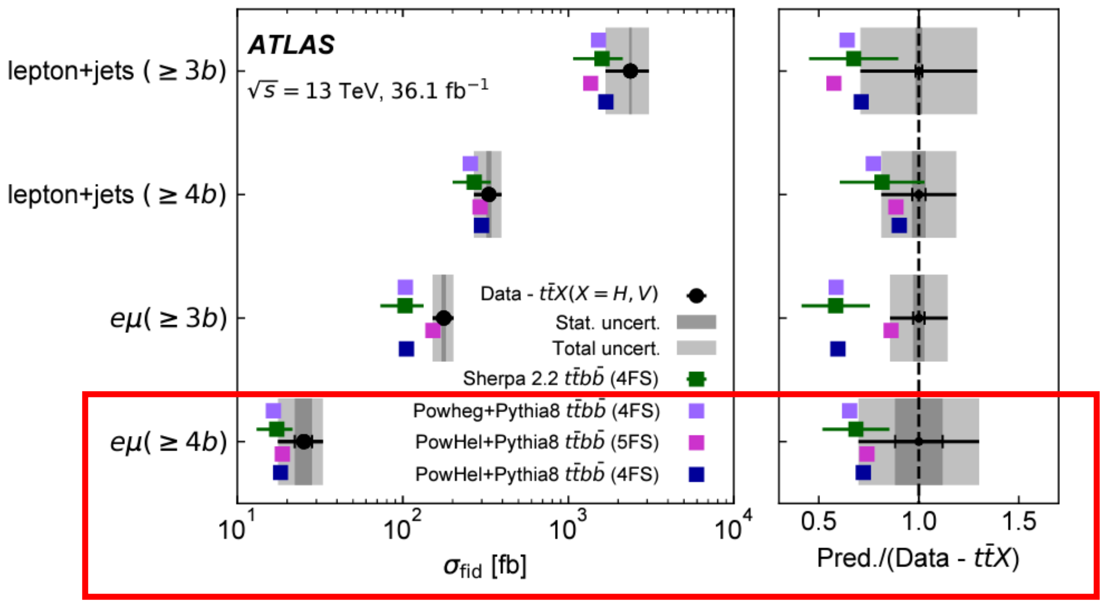
ttbb is irreducible background







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)

- 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)

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)

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

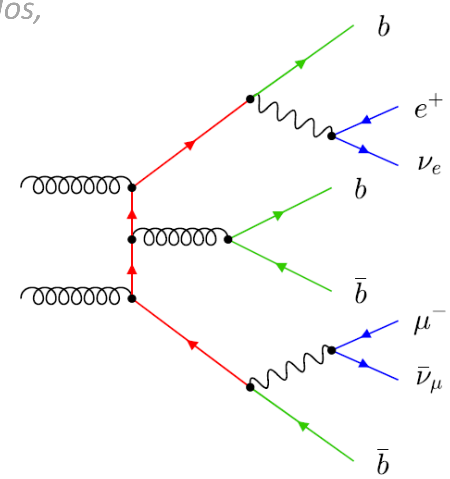
  (Kardos, Trócsányi '14 | Cascioli, Maierhöfer, Moretti, Pozzorini, Siegert '14 |Garzelli, Kardos, Trócsányi '15 | Bevilacqua, Garzelli, Kardos '17)

  - NLO QCD in NWA

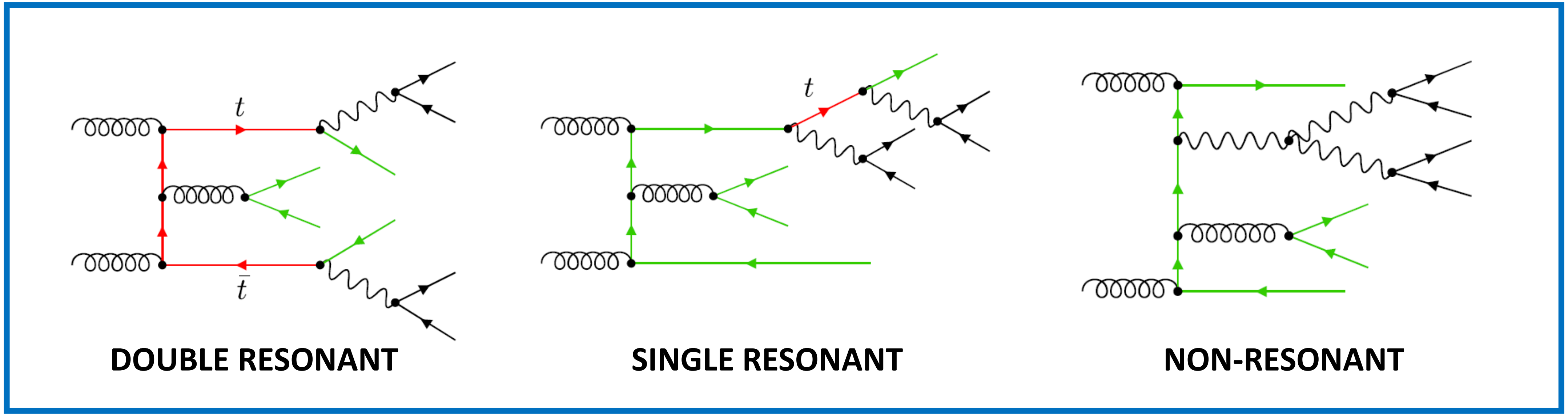
  (Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek '22)

  - NLO QCD with full off-shell effects

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

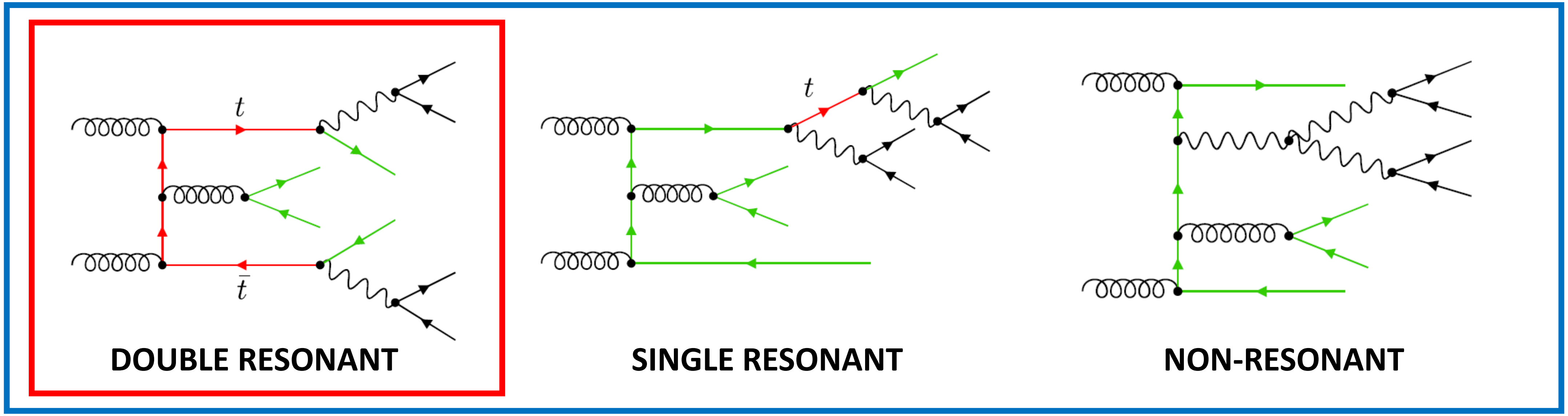


SETUP:
- NLO QCD
- 5 flavour scheme
- LHC 13 TeV



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



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

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

Results – LO vs NLO

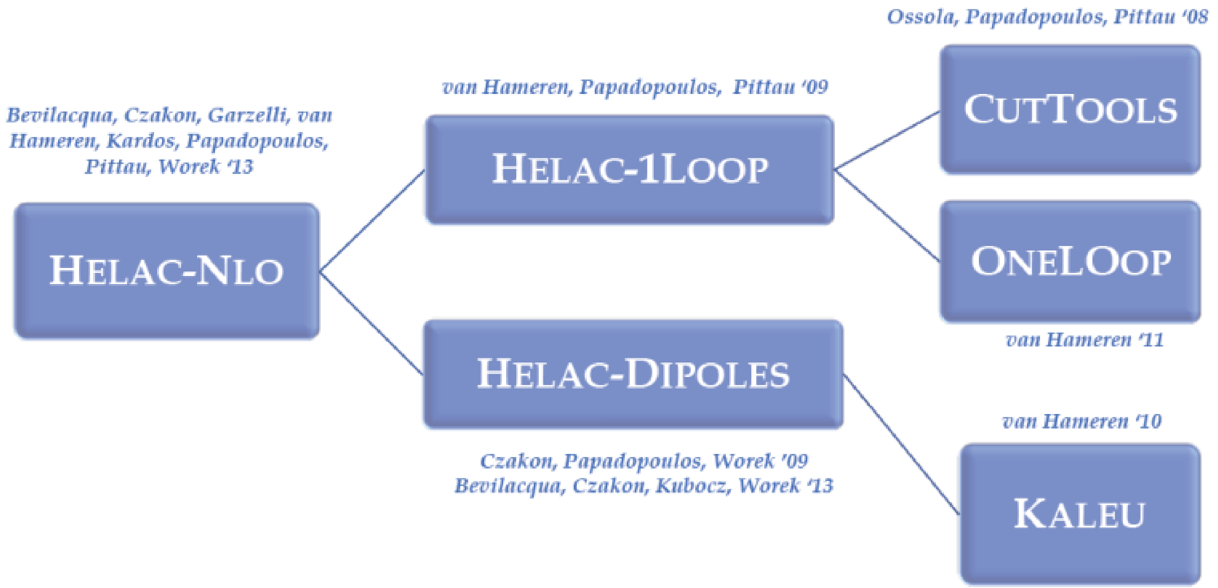
Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek, JHEP 08 (2021) 008

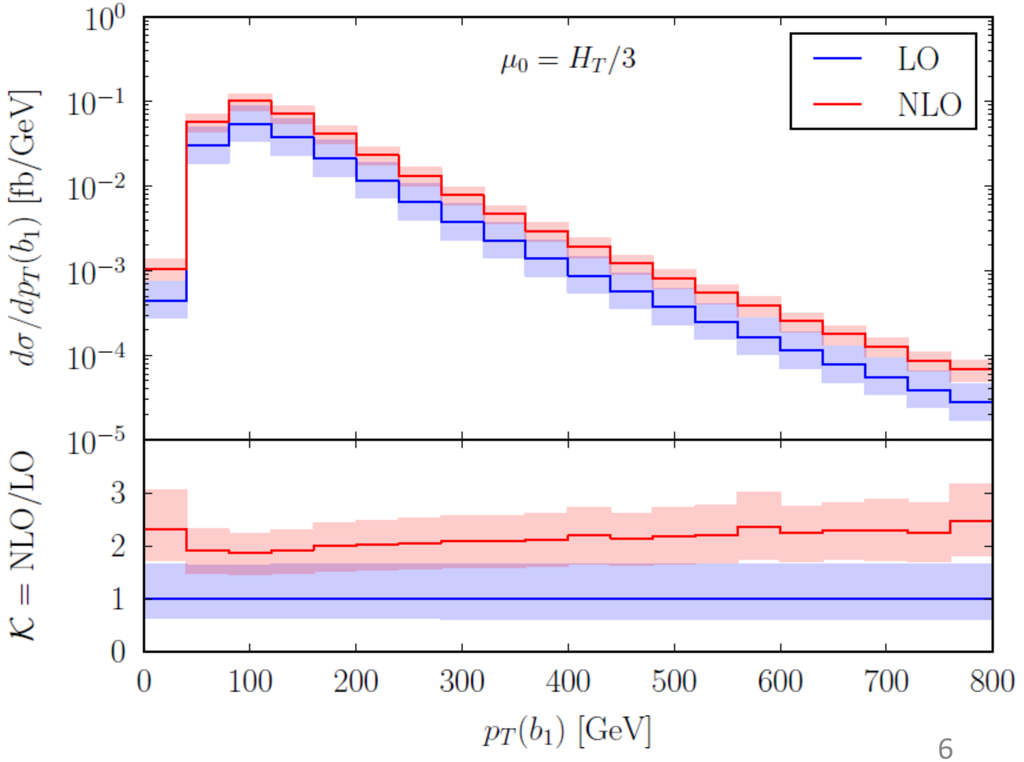
	σ [fb]	$+\delta_{\text{scale}}$ [fb]	$-\delta_{\text{scale}}$ [fb]
LO	6.813	+4.338(64%)	−2.481(36%)
NLO	13.22	+2.65(20%)	−2.96(22%)

- Huge NLO QCD corrections (~94%)
- Reduction of theoretical uncertainty
- Scale dependence main source of theoretical uncertainty (PDF ~1%)

$$\mu = H_T/3$$

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

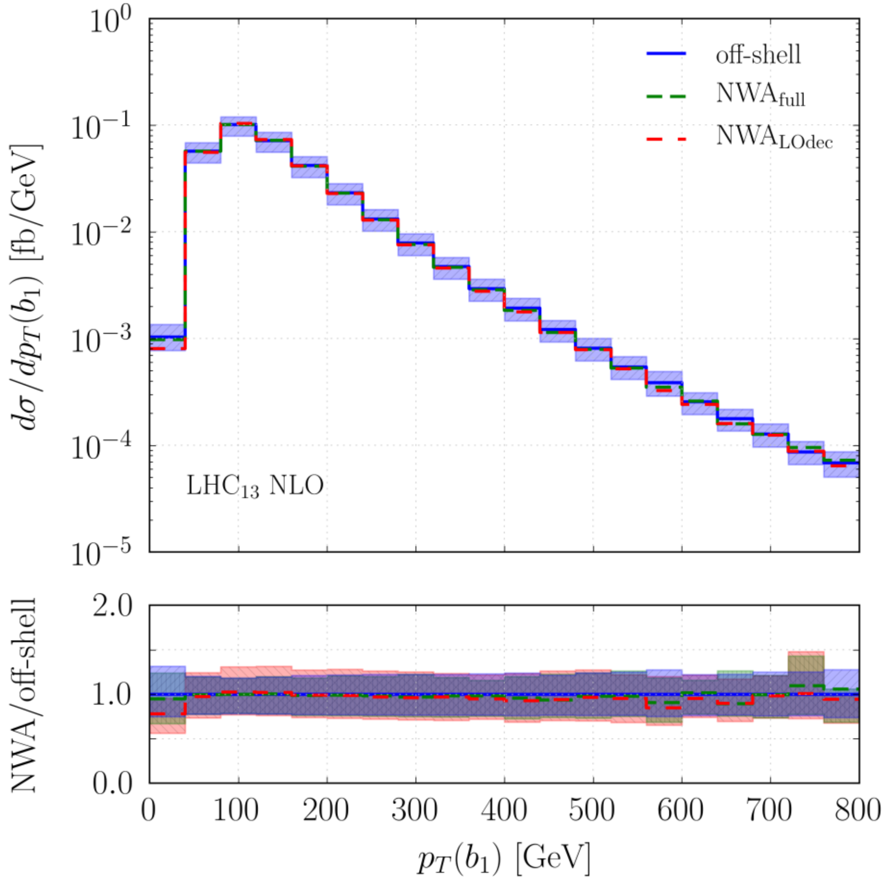




Results – Off-shell effects

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

	$\sigma^{\rm NLO}$ [fb]	$+\delta_{\rm scale}$ [fb]	$-\delta_{\rm scale}$ [fb]
Off-shell	13.22	+2.65(20%)	−2.96(22%)
$\rm NWA_{full}$	13.16	+2.61(20%)	−2.93(22%)



Integrated level:

- Negligible off-shell effects (~0.5%)
- Same theoretical accuracy

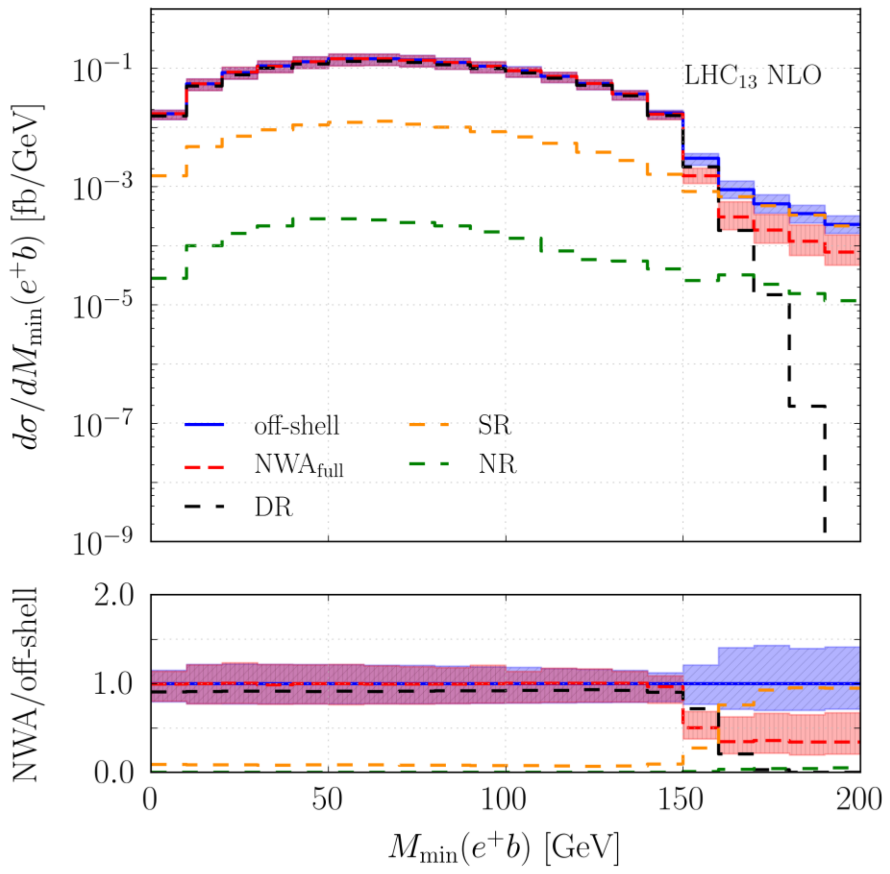
Differential level

- Negligible off-shell effects for standard observables

Results – Off-shell effects

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

	$\sigma^{\rm NLO}$ [fb]	$+\delta_{\rm scale}$ [fb]	$-\delta_{\rm scale}$ [fb]
Off-shell	13.22	+2.65(20%)	−2.96(22%)
$\rm NWA_{full}$	13.16	+2.61(20%)	−2.93(22%)



Integrated level:

- Negligible off-shell effects (~0.5%)
- Same theoretical accuracy

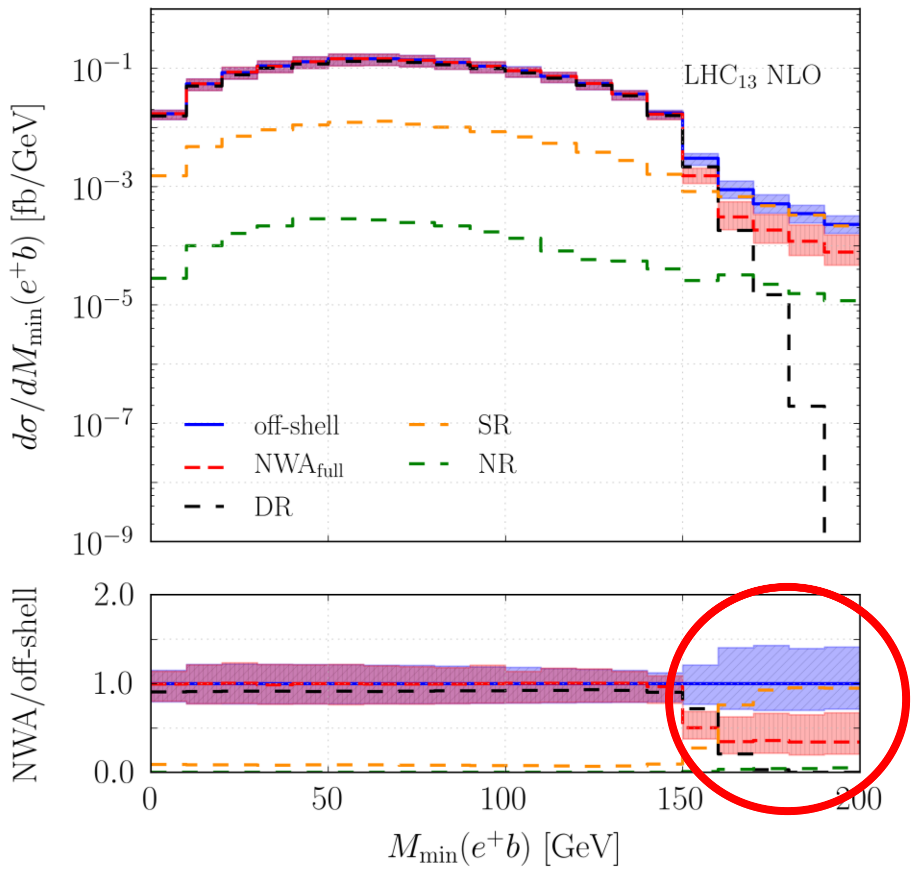
Differential level

- Negligible off-shell effects for standard observables
- Significant off-shell effects in observables with kinematic edges
- Large differences between full off-shell and NWA (~66%)
- Single resonant contribution dominant after kinematic edge

Results – Off-shell effects

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

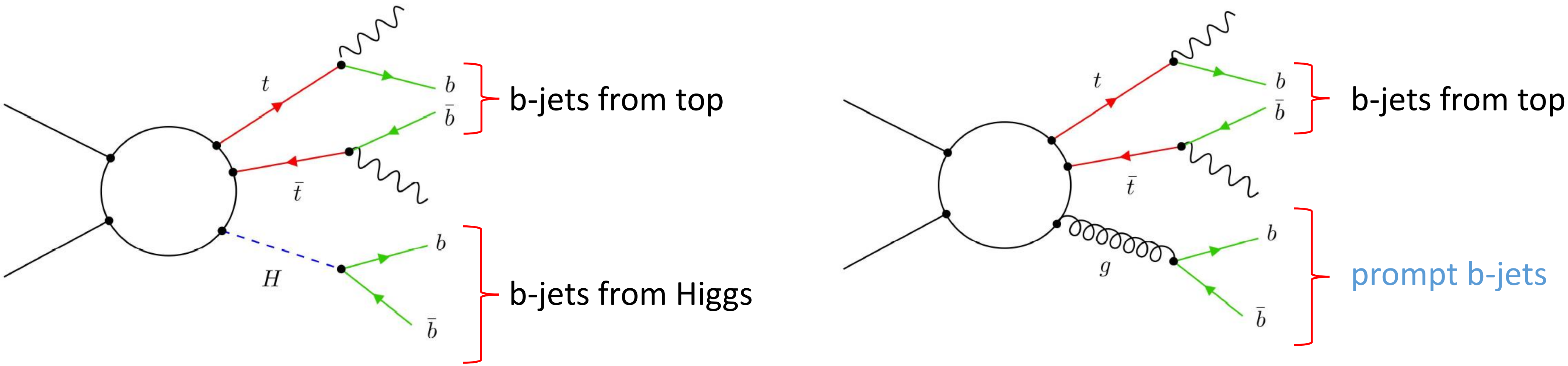
	σ^{NLO} [fb]	$+\delta_{\mathrm{scale}}$ [fb]	$-\delta_{\mathrm{scale}}$ [fb]
Off-shell	13.22	+2.65(20%)	−2.96(22%)
$\mathrm{NWA}_{\mathrm{full}}$	13.16	+2.61(20%)	−2.93(22%)



Integrated level:
- Negligible off-shell effects (~0.5%)
- Same theoretical accuracy

Differential level
- Negligible off-shell effects for standard observables
- Significant off-shell effects in observables with kinematic edges
- Large differences between full off-shell and NWA (~66%)
- Single resonant contribution dominant after kinematic edge

b-jet labelling

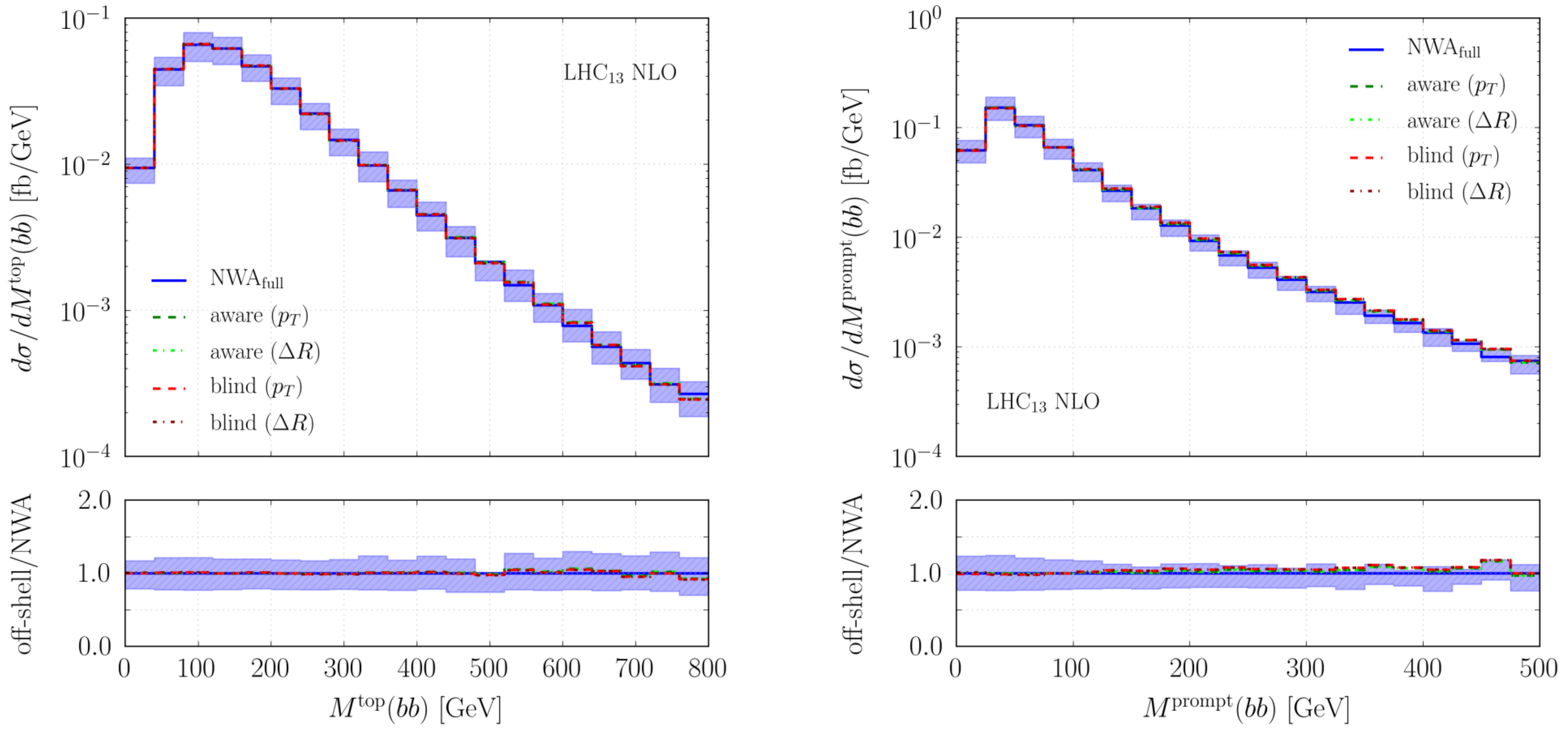


Prompt b-jets represent background to Higgs boson in ttH(bb) → Prescription to distinguish between b-jets from top and prompt b-jets needed

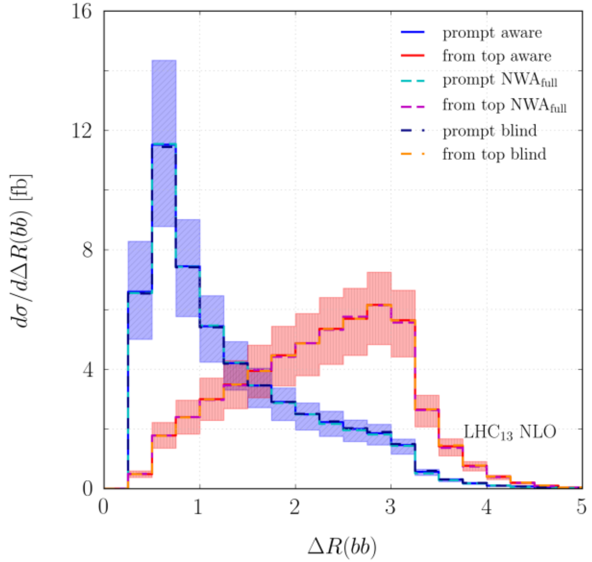
b-jet labelling

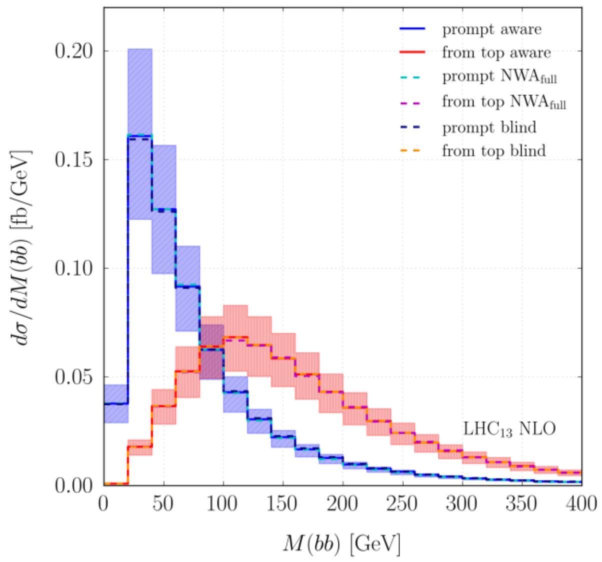
$$Q = |M(t) - m_t| \times |M(\bar{t}) - m_t| \times M(bb)$$

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



Theoretical approach

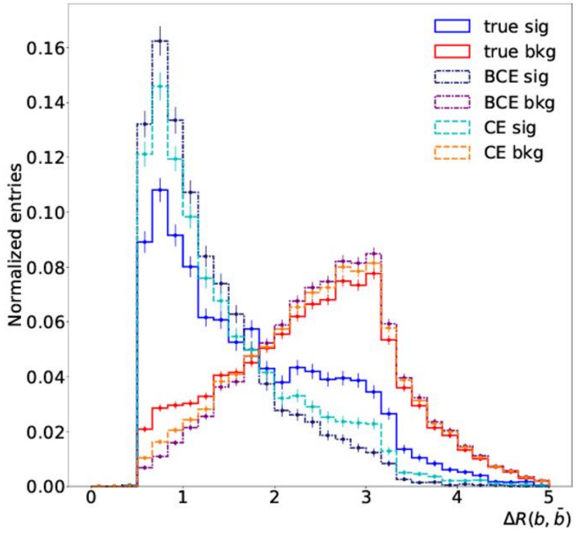


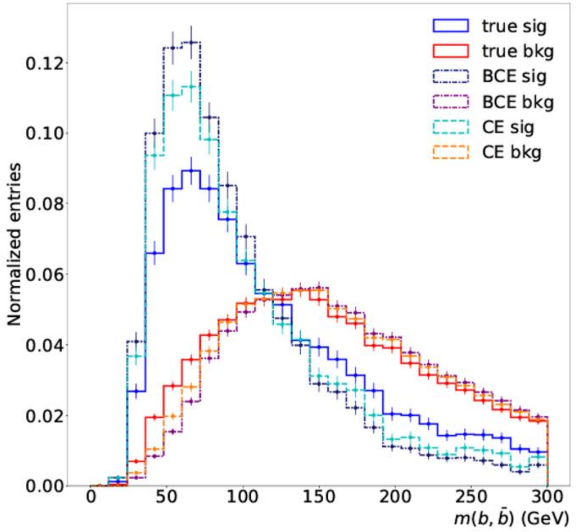


Bevilacqua, Bi, Hartanto, Kraus,

Lupattelli, Worek, arXiv:2202.11186

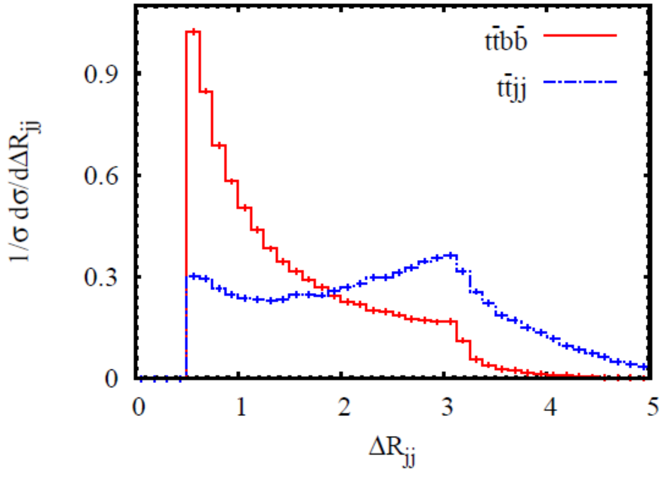
Machine learning

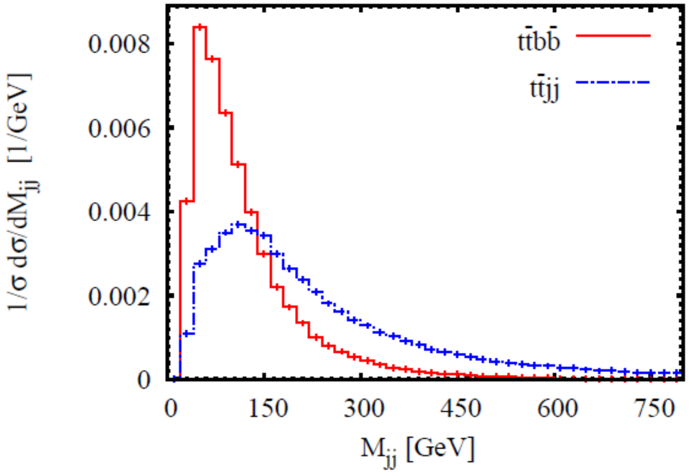




Jang, Ko, Noh, Choi, Lim, Kim, arXiv 2103.09129

Stable tops





Bevilacqua, Worek, JHEP 07 (2014) 135

Summary ttbb

- Huge NLO QCD corrections ≈ 94%
- Theoretical Uncertainties ≈ 20%
- Significant off-shell effects observed for observables with kinematic edges
- 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

Thank you!

Backup slides

LHC Setup

Input parameters

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

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

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

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

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

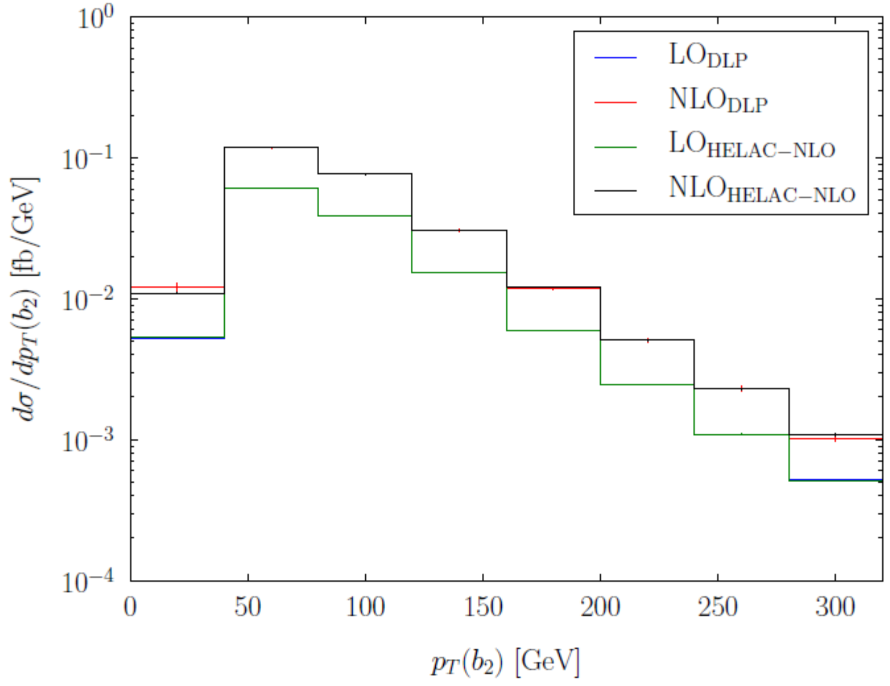
Cuts

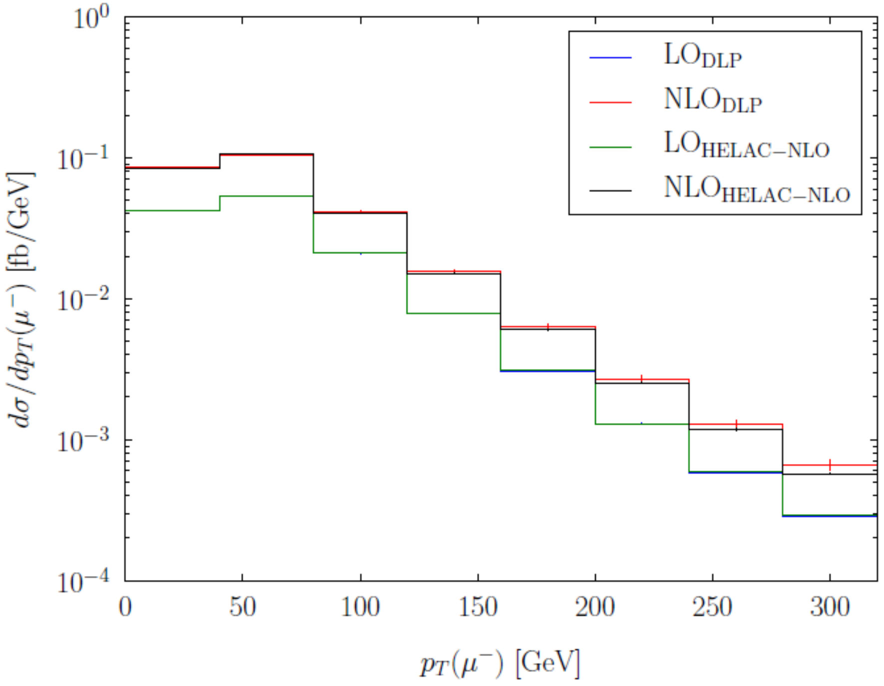
$$p_T(\ell) > 20\ \text{GeV}\,, \qquad |y(\ell)| < 2.5\,, \qquad p_T(b) > 25\ \text{GeV}\,, \qquad |y(b)| < 2.5\,,$$

Comparison theoretical predictions full off-shell ttbb

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

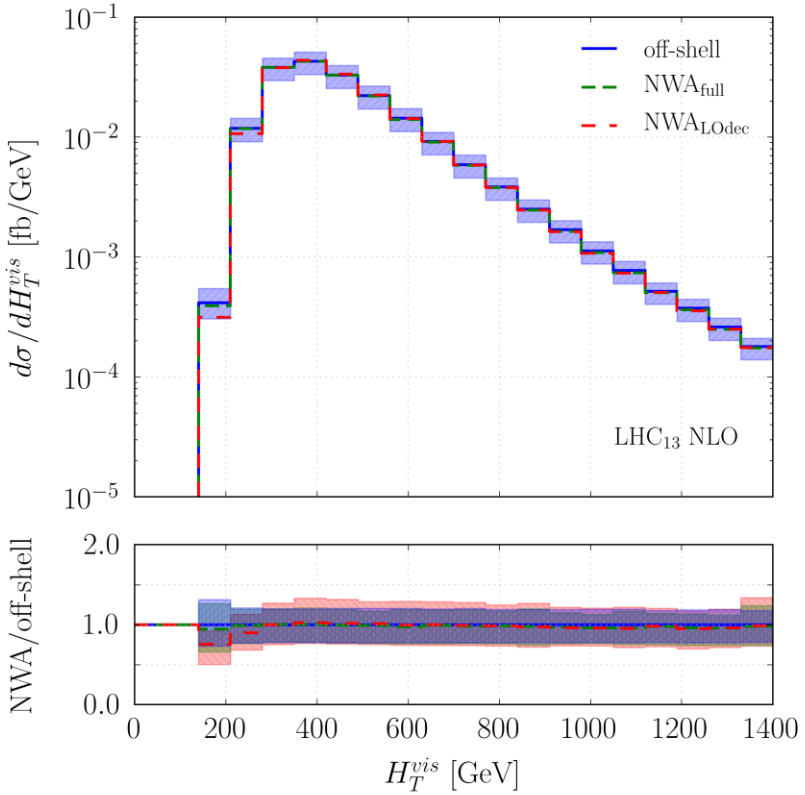
$$\sigma^{\rm NLO}_{\rm DLP}(\text{NNPDF3.1}, \mu_0 = \mu_{\rm DLP}) = 10.28(8)^{+18\%}_{-21\%}\,\text{fb}\,.$$





Predictions for ttbb at NLO

Modelling	σ_i^{NLO} [fb]	$+\delta_{\text{scale}}$ [fb]	$-\delta_{\text{scale}}$ [fb]	$\sigma_i^{\text{NLO}}/\sigma_{\text{NWA}_{\text{full}}}^{\text{NLO}} - 1$
Off-shell	13.22 (2)	+2.65 (20%)	−2.96 (22%)	+0.5%
DR	12.08 (2)	–	–	–
SR	1.112 (5)	–	–	–
NR	0.0249 (4)	–	–	–
NWA_{full}	13.16 (1)	+2.61 (20%)	−2.93 (22%)	–
$\text{NWA}_{\text{LOdec}}$	13.22 (1)	+3.77 (29%)	−3.31 (25%)	+0.5%
NWA_{exp}	12.38 (1)	+2.91 (24%)	−2.89 (23%)	−5.9%
NWA_{prod}	13.01 (1)	+2.58 (20%)	−2.89 (22%)	−1.1%
$\text{NWA}_{\text{LOdec,prod}}$	13.11 (1)	+3.74 (29%)	−3.28 (25%)	−0.4%

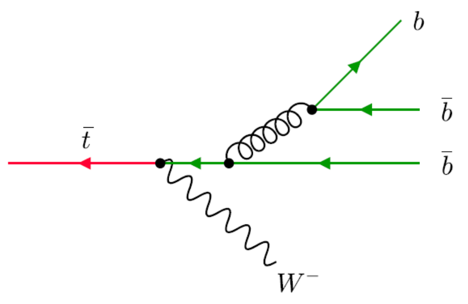


b-jet labelling

Theoretical approach

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

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



DISCRIMINATORS

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

Identifies the b from antitop

Identifies the prompt b-pair