Off-shell $t\bar{t}b\bar{b}$ Production at the LHC

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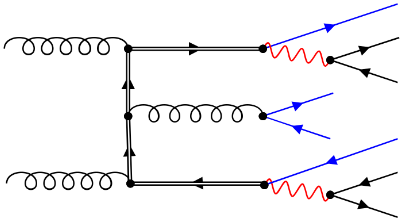
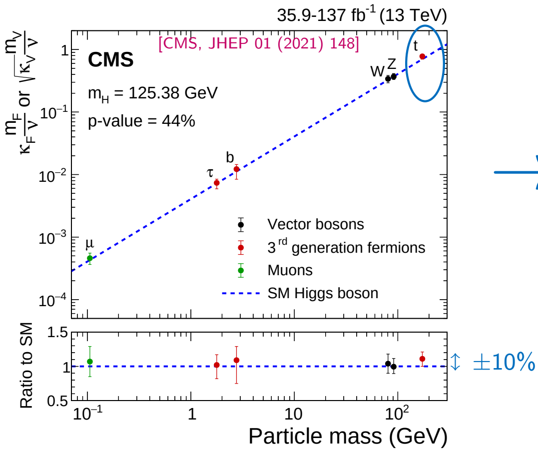
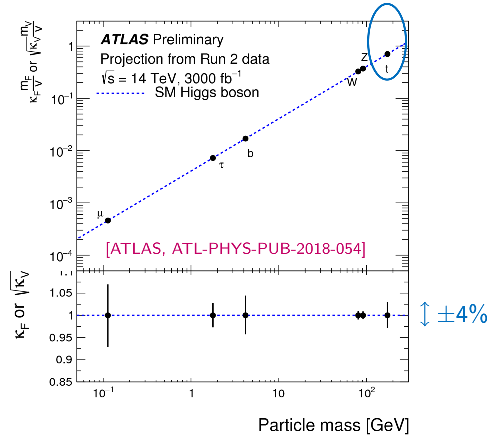


Motivations

Higgs Boson measurements are stringent tests of the Standard Model

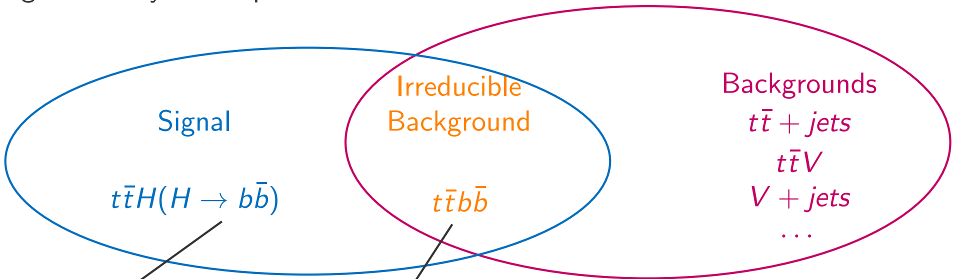


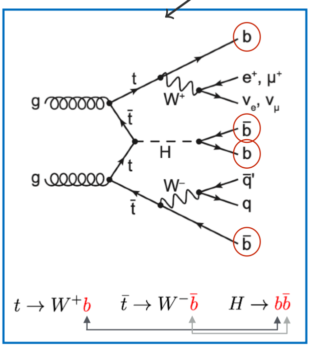


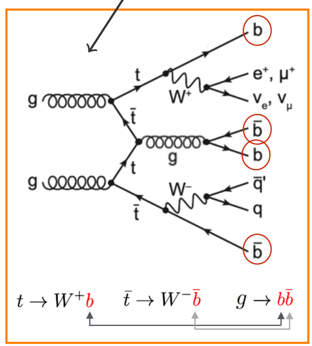
- BSM physics can manifest through Higgs couplings modifications

[Peskin, arXiv:1207.02516]

- $pp \to t\bar{t}H$ probes top Yukawa at tree-level & $H \to b\bar{b}$ has largest BR ($\sim$ 58%)
- Challengeing for theory and experiment



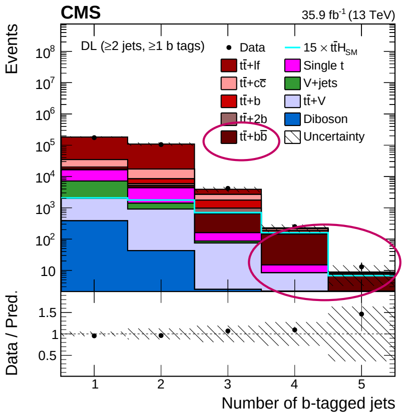




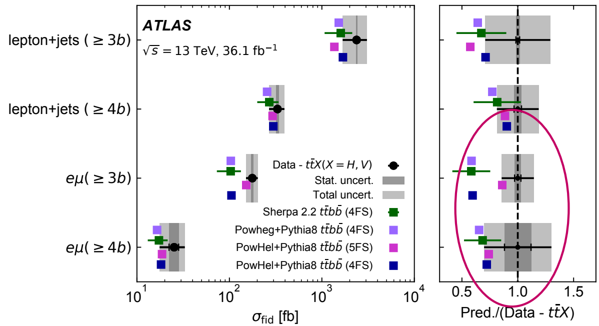
Combinatorical background

Top, Higgs reconstruction
$\to$ prompt b jet identification

[CMS, JHEP 03 (2019) 026]



[ATLAS, JHEP 04 (2019) 046]



- $t\bar{t}b\bar{b}$ is main background to $t\bar{t}H(H \to b\bar{b})$ for $N_{bjets} \geq 4$
- Tension with $t\bar{t}b\bar{b}$ measurements
  $\to$ Improve modelling

Theory Status

NLO QCD fixed order

$pp \to t\bar{t}b\bar{b}$ [Bredenstein, Denner, Dittmaier, Pozzorini '08,'09,'10]

[Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09]

[Worek '12] [Bevilacqua, Worek '14]

$pp \to t\bar{t}b\bar{b}j$ [Buccioni, Kallweit, Pozzorini, Zoller '19]

$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}$ [Denner, Lang, Pellen '20]

[Bevilacqua, Bi, Hartanto, MK, Lupattelli, Worek '21,'22]

NLO + PS

- POWHEG matching [Kardos, Trócsányi '14]

[Garzelli, Kardos, Trócsányi '15]

[Bevilacqua, Garzelli, Kardos '17]

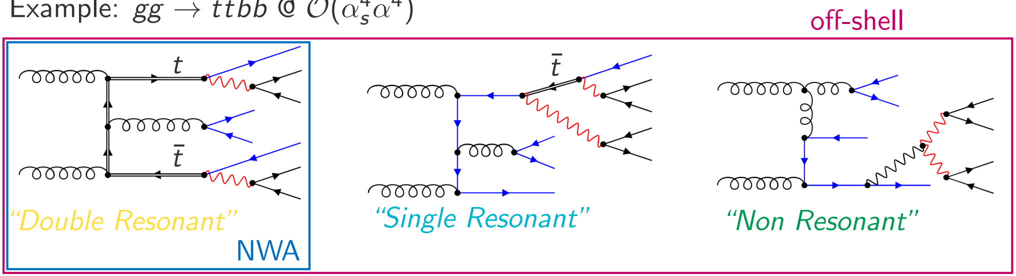
[Ježo, Lindert, Moretti, Pozzorini '18]

- MC@NLO matching [Cascioli, Maierhöfer, Moretti, Pozzorini, Siegert '14]

Beyond Stable Top Quarks

- **Complete matrix elements at fixed perturbative order:**
  - release limit $\Gamma_t / m_t \to 0$ (Narrow Width Approximation)
  - include non-factorizable contributions

- Example: $gg \to t\bar{t}b\bar{b}$ @ $\mathcal{O}(\alpha_s^4 \alpha^4)$



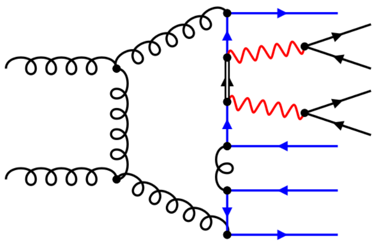
"off-shell" = DR + SR + NR + interferences + Breit-Wigner effects

- Genuine *multi-scale* process!

A very challenging Calculation!

A glimpse at the complexity of $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}$

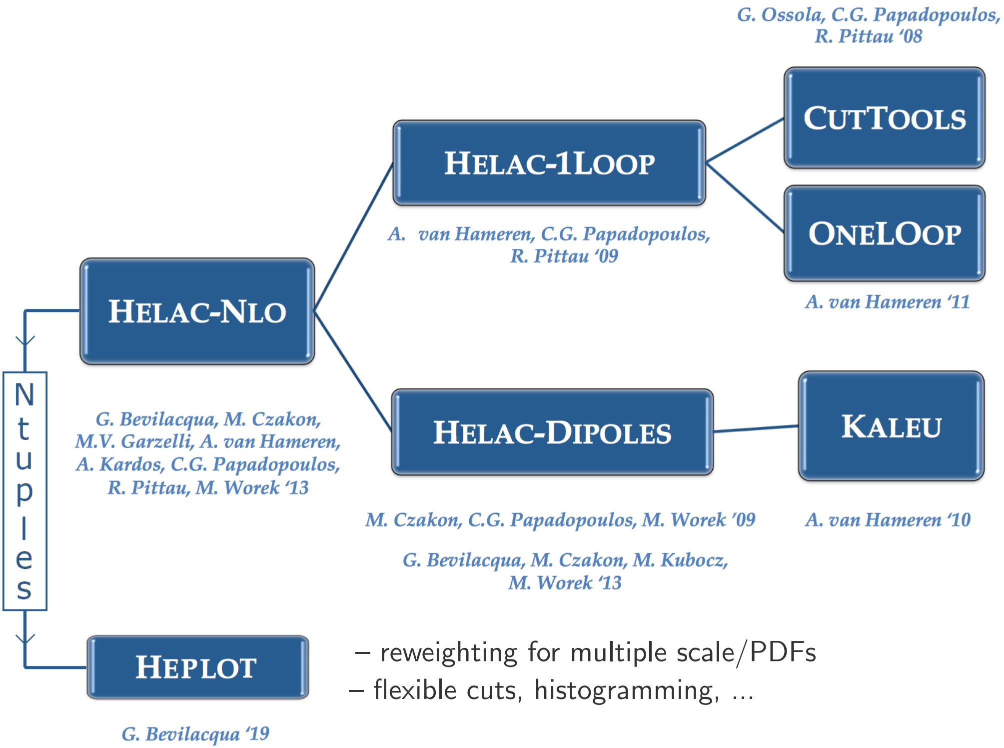
One-loop correction type	Number of Feynman diagrams
Self-energy	93452
Vertex	88164
Box-type	49000
Pentagon-type	25876
Hexagon-type	11372
Heptagon-type	3328
Octagon-type	336
Total number	271528



Partonic Subprocess	Number of Feynman diagrams	Number of CS Dipoles	Number of NS Subtractions
$gg \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,g$	41364	90	18
$q\bar{q} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,g$	9576	50	10
$gq \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,q$	9576	50	10
$g\bar{q} \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,b\bar{b}\,\bar{q}$	9576	50	10

$\Rightarrow$ Computation performed with HELAC-NLO

The HELAC-NLO framework



– reweighting for multiple scale/PDFs
– flexible cuts, histogramming, ...

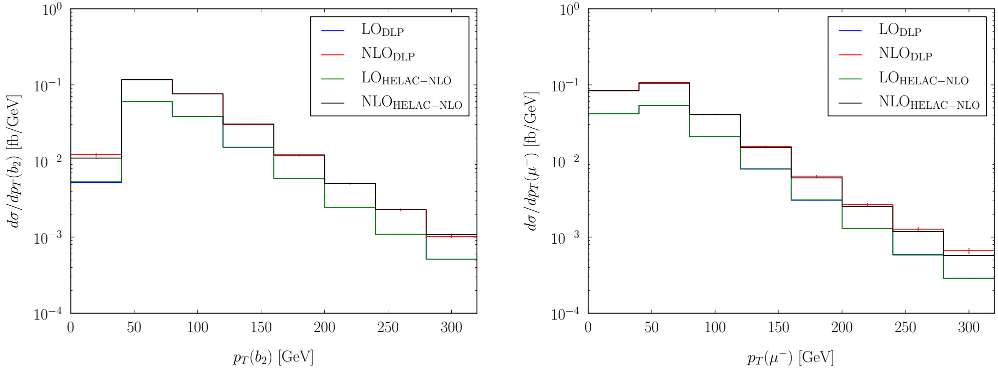
Validation

Comparison with results from Denner, Lang, Pellen '20

Integrated cross section

$$\sigma^{\mathrm{NLO}}_{\mathrm{HELAC}} = 10.28(1)^{+18\%}_{-21\%}\ \mathrm{fb} \qquad \sigma^{\mathrm{NLO}}_{\mathrm{DLP}} = 10.28(8)^{+18\%}_{-21\%}\ \mathrm{fb}$$

Differential distributions



Excellent agreement!

[Bevilacqua, Bi, Hartanto, MK, Lupattelli, Worek '21]

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

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

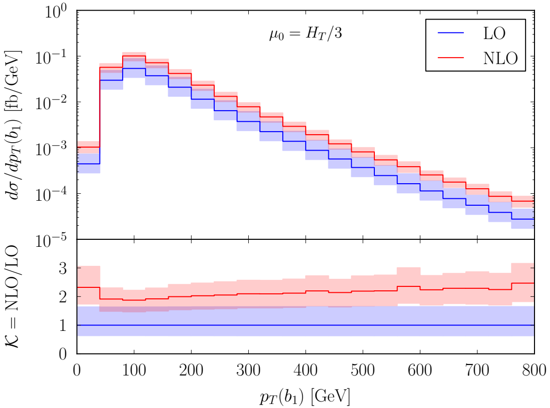
$$p_T(\ell) > 20 \text{ GeV}\,, \quad p_T(b) > 25 \text{ GeV}\,, \quad |y(\ell)| < 2.5\,, \quad |y(b)| < 2.5$$

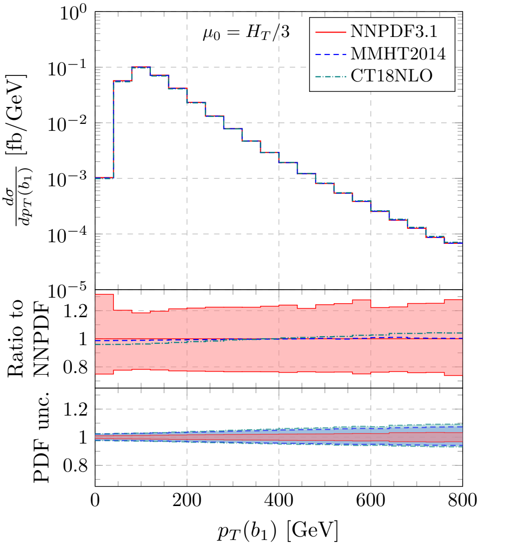
$p_T(b)$	$\sigma^{\rm LO}$ [fb]	$\delta_{\rm scale}$	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$	$\delta_{\rm PDF}$	$\mathcal{K} = \sigma^{\rm NLO}/\sigma^{\rm LO}$
$\mu_R = \mu_F = \mu_0 = m_t$ [NNPDF 3.1]						
25	6.998	+4.525 (65%) −2.569 (37%)	13.24	+2.33 (18%) −2.89 (22%)	+0.19 (1%) −0.19 (1%)	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
$\mu_R = \mu_F = \mu_0 = H_T/3$ [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

- Large NLO corrections
- 20% scale uncertainty
- mild $p_T(b)$ dependence for $\mu_0 = H_T/3$
- dominanted by real radiation
- $p_T^{\rm veto}(j) = 50$ GeV
  $K = 1.11$ & $K = 1.23$

[Bevilacqua, Bi, Hartanto, MK, Lupattelli, Worek '21]

$t\bar{t}b\bar{b}$: Differential distributions





- Large shape distortions $(+90\% - 135\%)$
- Scale dependence: $\pm 20 - 30\%$

- PDF uncertainties small-ish ($\leq 10\%$)

[Bevilacqua, Bi, Hartanto, MK, Lupattelli, Worek '21]

[Bevilacqua, Bi, Hartanto, MK, Lupattelli, Worek '21]

LO

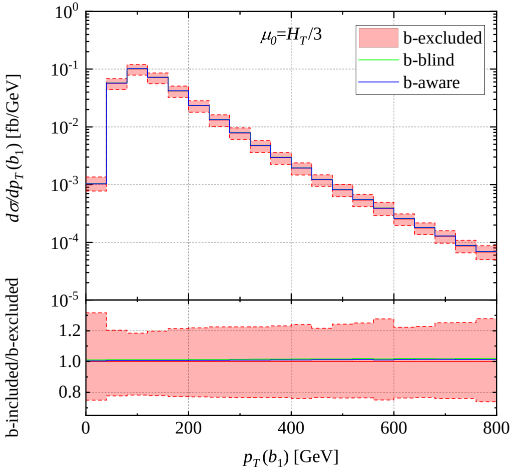
$$\sigma^{LO}_{\text{no b}} = 6.813(3) \text{ fb}$$
$$\sigma^{LO}_{\text{aware}} = 6.822(3) \text{ fb}$$
$$\sigma^{LO}_{\text{blind}} = 6.828(3) \text{ fb}$$

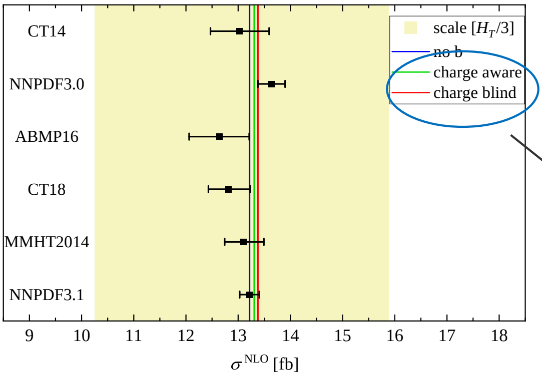
impact: ~0.2%

NLO

$$\sigma^{NLO}_{\text{no b}} = 13.22(3) \text{ fb}$$
$$\sigma^{NLO}_{\text{aware}} = 13.31(3) \text{ fb}$$
$$\sigma^{NLO}_{\text{blind}} = 13.38(3) \text{ fb}$$

impact: ~1%





Charge blind vs **Charge aware**

Charge blind → *Cannot* distinguish b from $\bar{b}$

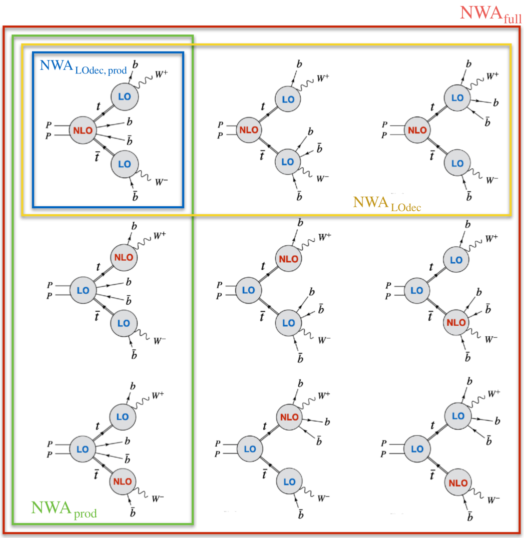
Charge aware → *Can* distinguish b from $\bar{b}$

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

[Bevilacqua, Bi, Hartanto, MK, Lupattelli, Worek arXiv:2202.11186]

- Impact of off-shell effects and decay modelling accuracy

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%
$\rm NWA_{LOdec,prod}$	13.11(1)	$+3.74$ (29%) -3.28 (25%)	-0.4%



- Complete off-shell effects: $+0.5\ \%$
- $\rm NWA_{LOdec}$ agrees well with Off-shell [but scale uncertainties are larger]

↪ Interplay among different resonant contributions to $\rm NWA_{full}$

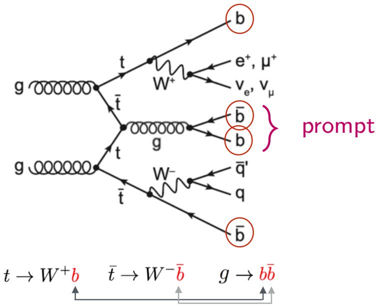
[Slide by Giuseppe Bevilacqua]

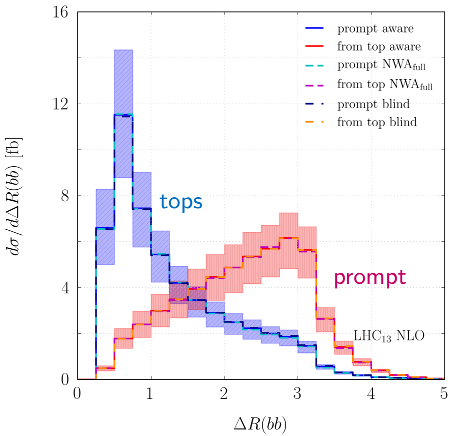
$t\bar{t}b\bar{b}$: prompt b jet identification

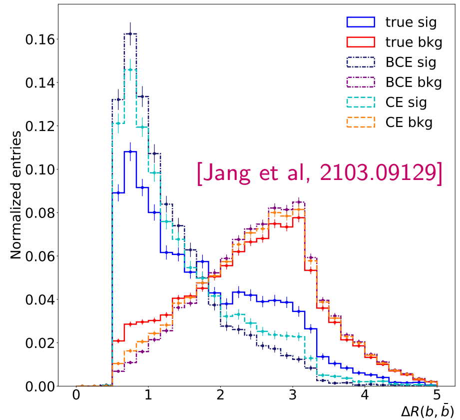
- Labelling prompt b jets in $t\bar{t}b\bar{b}$ is not free of ambiguities! (interferences, decays,...)
- Kinematical prescription: reconstruct top quarks and prompt b jets by minimizing

$$Q = |M(t) - m_t| \times |M(\bar{t}) - m_t| \times \left|M^{\text{prompt}}(bb)\right|$$

- Results consistent with Neural Network studies

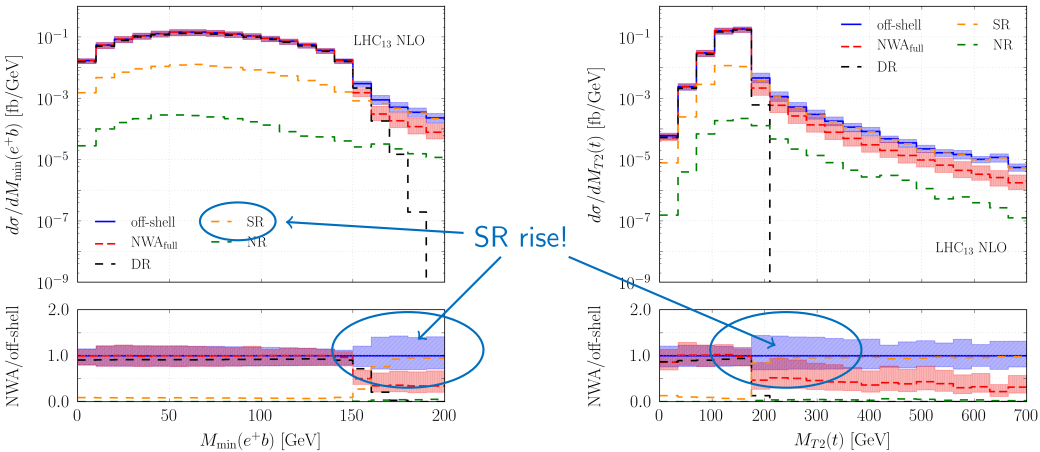






$t\bar{t}b\bar{b}$: Impact of off-shell Effects

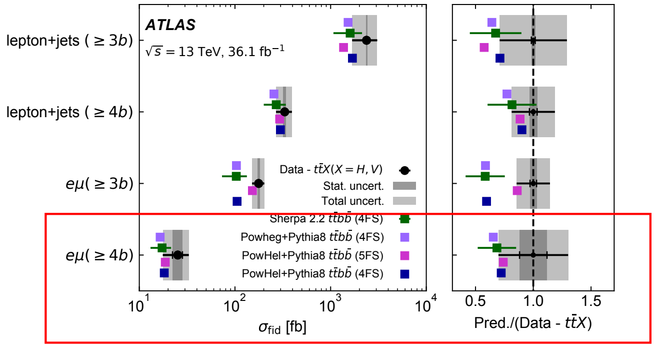
- For most observables: off-shell effects are few permille effects
- Threshold observables are naturally more sensistive



$$\mathrm{LO_{NWA}} \to M_{\min} \leq \sqrt{m_t^2 - m_W^2} \approx 153 \text{ GeV}$$

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

Comparison to ATLAS measurement



[ATLAS, JHEP 04 (2019) 046]

Theoretical predictions	$\sigma_{e\mu+4b}$ [fb]
Sherpa + OpenLoops (4FS)	17.2 ± 4.2
Powheg-Box + Pythia 8 (4FS)	16.5
PowHel + Pythia 8 (5FS)	18.7
PowHel + Pythia 8 (4FS)	18.2
Experimental result (ATLAS)	25 ± 6.5

[MK et al, JHEP 08 (2021) 008]

HELAC-NLO (5FS): 20.0 ± 4.3 fb

- Very good agreement with experimental result!
- All predictions are compatible within theoretical uncertainties

Summary

Summary:

- NLO QCD corrections for full off-shell $pp \to t\bar{b}b\bar{b}$
  - Large NLO corrections $\sim 89\%$
  - Scale uncertainties $\sim 20 - 30\%$
- Full agreement with [Denner, Lang, Pellen '20]
- Good agreement with ATLAS results
- NWA is doing great for most distributions of interest
- Kinematical prescription can help to categorise prompt b jets

Outlook:

- combine $t\bar{t}b\bar{b}$ with $t\bar{t}H(H \to b\bar{b})$ for state-of-the-art pheno study