NLO electroweak and QCD corrections to off-shell ttW production at the LHC

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Based on JHEP 11 (2020) 069 [2007.12089] and EPJC 81 (2021) 4, 354 [2102.03246].

Outline

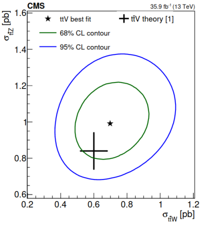
Introduction

Motivations

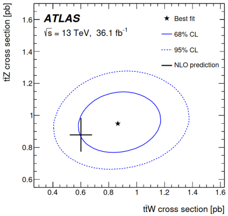
Hadro-production of $t\bar{t}W^{\pm}$ at the LHC, an optimal process for studying

- $t\bar{t}V$ coupling in or beyond the SM, new-physics effects (EFT, SUSY, ...) [Dror et al. 1511.03674, ...], particularly in the fully-leptonic channel
- charge asymmetries [Maltoni et al. 1406.3262, Bevilacqua et al. 2012.01363]: gg-channel opens up at NNLO QCD
- important background to $t\bar{t}H$ [Maltoni et al. 1507.05640]

Measured with Run-2 dataset [ATLAS 1609.01599 & 1901.03584, CMS 1711.02547].



[CMS 1711.02547]



[ATLAS 1901.03584]

Tension between data and SM predictions, in both direct [CMS 1711.02547, ATLAS 1901.03584] and $t\bar{t}H$ measurements [ATLAS 1806.00425, CMS 1804.02610].

Excess of $t\bar{t}W$ events over SM confirmed in improved analyses [ATLAS-CONF-2019-045, CMS-PAS-HIG-19-008].

Theory status

Improved theory modeling required → towards realistic final states.

NLO, on-shell:
NLO QCD [Maltoni et al. 1406.3262] and subleading NLO orders [Frixione et al. 1504.03446, Frederix et al. 1711.02116 & 1804.10017].

NLO, production × decay:
NLO QCD [Campbell Ellis 1204.5678].

NLO + PS, production × decay:
NLO QCD to LO QCD [Garzelli et al. 1208.2665] and NLO QCD to LO EW [Frederix Tsinikos 2004.09552, Cordero et al. 2101.11808] matched to parton-shower.

Resummation & merging, on-shell:
NLO QCD and EW + NNLL [Broggio et al. 1907.04343, Kulesza et al. 2001.03031], multi-jet merging at NLO [von Buddenbrock et al. 2009.00032].

NLO, off-shell:
NLO QCD [Bevilacqua et al. 2005.09427 & 2012.01363, Denner GP 2007.12089] and subleading NLO orders [Denner GP 2102.03246] in the 3ℓ channel.

NLO corrections to off-shell $t\bar{t}W$

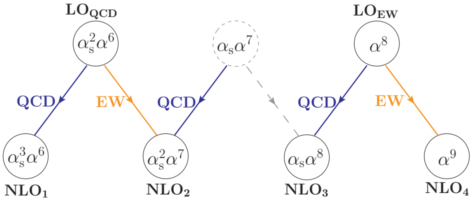
Details of the calculation: perturbative orders

LHC process:

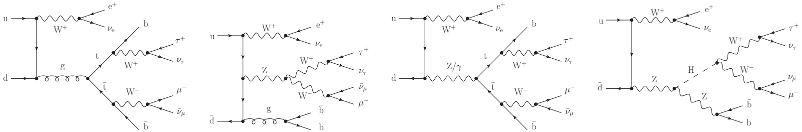
$\mathrm{p\,p} \to \mathrm{b\,\bar{b}\,e^+}\nu_\mathrm{e}\,\mu^-\bar{\nu}_\mu\,\tau^+\nu_\tau\ + X$

at NLO accuracy

$\to$ several contributions.



LO: double-resonant ($\mathrm{t\bar{t}}$), single-resonant (t or $\mathrm{\bar{t}}$), non-resonant diagrams. Interference of order $\mathcal{O}(\alpha_\mathrm{s}\alpha^7)$ vanishes (if CKM is unit matrix).

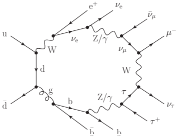


$\mathrm{NLO_1}$: genuine NLO QCD to LO QCD (expected to be dominant NLO contribution), up to 7-point functions in virtual corr., challenging real corr. (high-multiplicity). Real partonic channels with initial states $q\bar{q}$, gq.

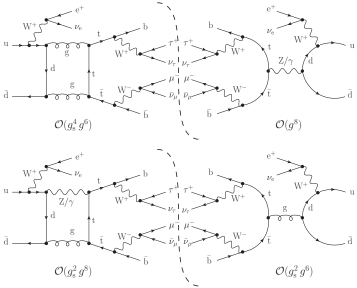
Details of the calculation: contributions

NLO$_2$: EW corrections to LO QCD plus QCD corrections to LO interference.

Up to 10-point functions in virtuals.



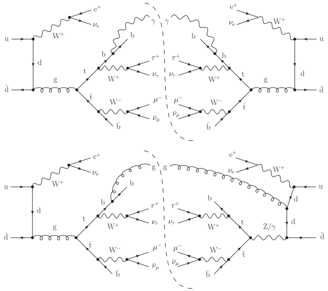
Two contributions:



High-multiplicity reals ($2 \to 9$) and large number of IR-singular configurations.

Channels: $q\bar{q}, \gamma q, gq$ (γq suppressed by PDFs).

QCD real corr. to LO interf. is non-zero if gluon is emitted by the initial state and absorbed by final state.



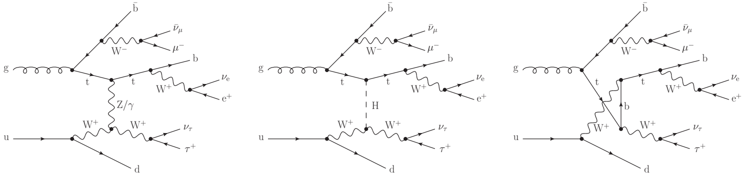
Virtual IR poles for $\mathcal{O}(g_s^2 g^8) \times \mathcal{O}(g_s^2 g^6)$ are cancelled by both classes of reals: only the sum of all contributions is IR safe!

Details of the calculation: contributions

NLO$_3$: pure QCD corrections to LO EW (EW corrections do not change color structure of LO interference) $\rightarrow$ enable simple matching to QCD PS (as NLO$_1$).

Expected to be subleading but larger than NLO$_2$ (already for on-shell production [Frederix et al. 1711.02116 & 1804.10017]).

Dominated by *gq*-channel contribution, that embeds $tW^+ \rightarrow tW^+$ scattering:



NLO$_4$: EW corrections to LO$_{EW}$, amount at 0.04% of LO$_{QCD}$ already at inclusive level [Frederix et al. 1711.02116]. Out of reach in a fiducial phase-space even at HL-LHC $\rightarrow$ neglected here.

Details of the calculation: setup

[Denner GP 2102.03246]

$\mathrm{pp} \to \mathrm{b}\,\bar{\mathrm{b}}\,\mathrm{e}^+\nu_\mathrm{e}\,\mu^-\bar{\nu}_\mu\,\tau^+\nu_\tau + \mathrm{X}$ at $\mathcal{O}(\alpha_\mathrm{s}^3\alpha^6)$, $\mathcal{O}(\alpha_\mathrm{s}^2\alpha^7)$, $\mathcal{O}(\alpha_\mathrm{s}\alpha^8)$

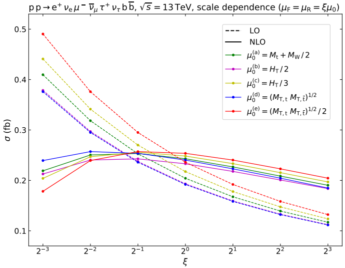
- full tree-level and one-loop amplitudes: RECOLA1 [Actis et al. 1605.01090]
- 1-loop tensor-integral reduction and evaluation: COLLIER [Denner et al. 1604.06792]
- multi-channel integration with MoCaNLO in-house Monte Carlo
- dipole subtraction of IR singularities both for EW and QCD real radiation [Catani Seymour 9605323, Dittmaier 9904440]
- complex-mass scheme [Denner et al. 9904472] for W, Z, top
- NNPDF3.1 NLO LUXQED PDFs (photon included, [Bertone et al. 1712.07053]) for both LO and NLO simulations; $N_F = 5$
- Both LO and NLO simulation: Γ_t computed including NLO QCD+EW corrections [Basso et al. 1507.04676]

Selections, mimic those of [ATLAS 1901.03584]:

2 b-jets (anti-k_t, $R = 0.4(0.1)$ for jet (photon) clustering, $p_{\mathrm{T,b}} > 25$ GeV, $|\eta_\mathrm{b}| < 2.5$),
3 ch. leptons ($p_{\mathrm{T},\ell} > 27$ GeV, $|\eta_\ell| < 2.5$, $\Delta R_{\ell\mathrm{b}} > 0.4$).

NLO QCD results: scale dependence

The inclusion of NLO QCD corrections reduces scale-uncertainties from 25% to 5%.



[Denner GP 2007.12089]

Comparison among different central scale choices:

- fixed $\mu_0 = M_\mathrm{W} + M_\mathrm{t}/2$;
- dynamical, resonance-blind $\mu_0 = H_\mathrm{T}/2$, or $\mu^0 = H_\mathrm{T}/3$ ($H_\mathrm{T} = p_\mathrm{T}^\mathrm{miss} + \sum_{i=b,\ell} p_{\mathrm{T,i}}$);
- dynamical, resonance-aware $\mu_0 = \sqrt{M_{T,\mathrm{t}} M_{\mathrm{T},\bar{\mathrm{t}}}}$ or $\mu_0 = \sqrt{M_{T,\mathrm{t}} M_{\mathrm{T},\bar{\mathrm{t}}}}/2$ ($M_{\mathrm{T,t}} = \sqrt{M_\mathrm{t}^2 + p_{\mathrm{T,t}}^2}$).

K-factors range between 1.07 to 1.25: QCD corrections are at the 10-20% level.

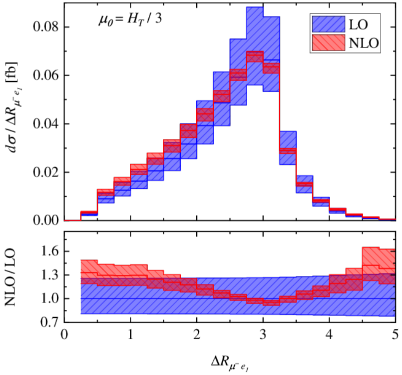
Note: (N)LO QCD understands $\Gamma_\mathrm{t}^{\mathrm{(N)LO\ QCD}}$ and (N)LO NNPDF3.1 PDFs.

central scale	LO	NLO QCD	K-factor	
$\mu_0^{(a)} = M_\mathrm{t} + M_\mathrm{W}/2$	$0.2042(1)^{+23.8\%}_{-18.0\%}$	$0.2452(7)^{+4.5\%}_{-6.8\%}$	1.20	
$\mu_0^{(b)} = H_\mathrm{T}/2$	$0.1931(1)^{+23.0\%}_{-17.5\%}$	$0.2330(9)^{+4.2\%}_{-6.5\%}$	1.21	
$\mu_0^{(c)} = H_\mathrm{T}/3$	$0.2175(1)^{+24.2\%}_{-18.2\%}$	$0.2462(8)^{+2.8\%}_{-5.8\%}$	1.13	
$\mu_0^{(d)} = \left(M_{\mathrm{T,t}} M_{\mathrm{T,\bar{t}}}\right)^{1/2}$	$0.1920(1)^{+23.0\%}_{-17.5\%}$	$0.2394(6)^{+5.4\%}_{-7.2\%}$	1.25	
$\mu_0^{(e)} = \left(M_{\mathrm{T,t}} M_{\mathrm{T,\bar{t}}}\right)^{1/2}/2$	$0.2360(1)^{+24.9\%}_{-18.7\%}$	$0.2535(8)^{+3.4\%}_{-5.2\%}$	1.07	$\leftarrow$ best

NLO QCD results: comparison with [Bevilacqua et al. 2005.09427]

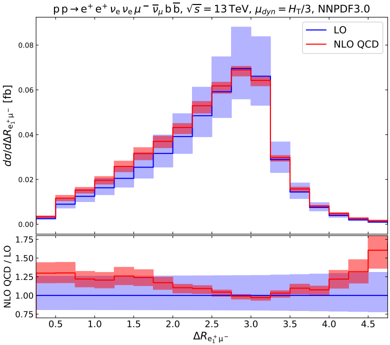
Good agreement using the setup of Ref. [Bevilacqua et al. 2005.09427], both at integrated and differential level (also for scale unc. and K-factors).

$$\sigma_{\text{LO}} = 0.1151^{+0.0305}_{-0.0225}\ \text{fb}$$
$$\sigma_{\text{NLO}} = 0.1244^{+0.0043}_{-0.0077}\ \text{fb}$$



[Bevilacqua et al. 2005.09427]

$$\sigma_{\text{LO}} = 0.1147(1)^{+0.0304}_{-0.0224}\ \text{fb}$$
$$\sigma_{\text{NLO}} = 0.1247(4)^{+0.0046}_{-0.0078}\ \text{fb}$$



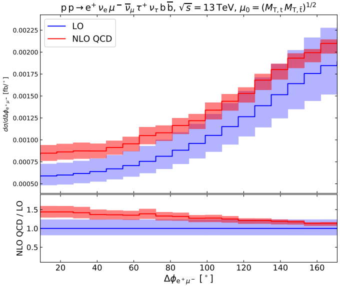
[Denner, GP 2007.12089]

NLO QCD results: selected distributions

Differential results for $\mu_0^{(\mathrm{d})}$ dynamical scale [Denner GP 2007.12089].

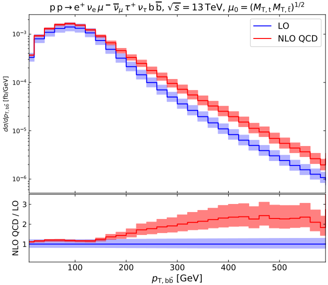
Observables which receive sizeable shape distortions:

Azimuthal separation between e^+ and μ^-



Moderate shape distortion due to NLO QCD corr. even with $\mu_0 = \left(M_{\mathrm{T,t}} M_{\mathrm{T,\bar{t}}}\right)^{1/2}$

Transverse momentum of the $\mathrm{b\bar{b}}$ system



Large K-factors ($\gtrsim 2$) in the tails of distributions for hadronic activity.

Combining NLO EW and QCD: integrated cross-sections

Total cross-sections in the fiducial setup [Denner GP 2102.03246]:

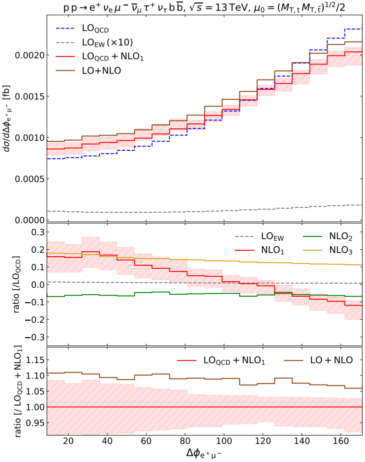
	$\mu_0^{(c)}$		$\mu_0^{(d)}$		$\mu_0^{(e)}$	
order	σ (fb)	ratio	σ (fb)	ratio	σ (fb)	ratio
$\mathrm{LO}_{\mathrm{QCD}}$ ($\alpha_s^2\alpha^6$)	$0.2218(1)^{+25.3\%}_{-18.8\%}$	1	$0.1948(1)^{+23.9\%}_{-18.1\%}$	1	$0.2414(1)^{+26.2\%}_{-19.3\%}$	1
$\mathrm{LO}_{\mathrm{EW}}$ (α^8)	$0.002164(1)^{+3.7\%}_{-3.6\%}$	0.010	$0.002122(1)^{+3.7\%}_{-3.6\%}$	0.011	$0.002201(1)^{+3.7\%}_{-3.6\%}$	0.009
NLO_1 ($\alpha_s^3\alpha^6$)	0.0147(6)	0.066	0.0349(6)	0.179	0.0009(7)	0.004
NLO_2 ($\alpha_s^2\alpha^7$)	−0.0122(3)	−0.055	−0.0106(3)	−0.054	−0.0134(4)	−0.056
NLO_3 ($\alpha_s\alpha^8$)	0.0293(1)	0.131	0.0263(1)	0.135	0.0320(1)	0.133
$\mathrm{LO}_{\mathrm{QCD}}+\mathrm{NLO}_1$	$0.2365(6)^{+2.9\%}_{-6.0\%}$	1.066	$0.2297(6)^{+5.5\%}_{-7.3\%}$	1.179	$0.2423(7)^{+3.5\%}_{-5.2\%}$	1.004
$\mathrm{LO}_{\mathrm{QCD}}+\mathrm{NLO}_2$	$0.2094(3)^{+25.0\%}_{-18.7\%}$	0.945	$0.1840(3)^{+23.8\%}_{-17.9\%}$	0.946	$0.2277(4)^{+25.9\%}_{-19.2\%}$	0.944
$\mathrm{LO}_{\mathrm{EW}}+\mathrm{NLO}_3$	$0.03142(4)^{+22.2\%}_{-16.8\%}$	0.141	$0.02843(6)^{+20.5\%}_{-15.6\%}$	0.146	$0.03425(7)^{+22.8\%}_{-17.0\%}$	0.142
LO+NLO	$0.2554(7)^{+4.0\%}_{-6.5\%}$	1.151	$0.2473(7)^{+6.3\%}_{-7.6\%}$	1.270	$0.2628(9)^{+4.3\%}_{-5.9\%}$	1.089

- NLO_1-corr. impact depends a lot on scale choice (from +0.5% to +18%)
- NLO_2 and NLO_3 relative corr. are scale-independent: −5% and +13% resp.
- $\mathrm{LO}_{\mathrm{EW}}$ is 1% of $\mathrm{LO}_{\mathrm{QCD}}$, NLO_3 corr. 10 times larger than its LO (tW scattering)
- scale-uncertainties dominated by NLO_1: $\approx \pm5\%$ for combined NLO result

In a very inclusive setup (only $M_{\mathrm{bb}} > 5$ GeV): similar NLO_2 corrections ($\approx -3\%$) as in on-shell calculation ($\approx -4\%$ in [Frederix et al. 1804.10017]).

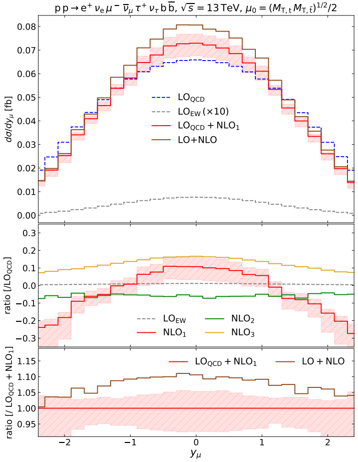
Combining NLO EW and QCD: angular & rapidity distributions

Azimuthal separation between e^+ and μ^-



- NLO_1 diminish with constant slope, NLO_2+NLO_3 give a rather flat correction to $LO+NLO_1$.

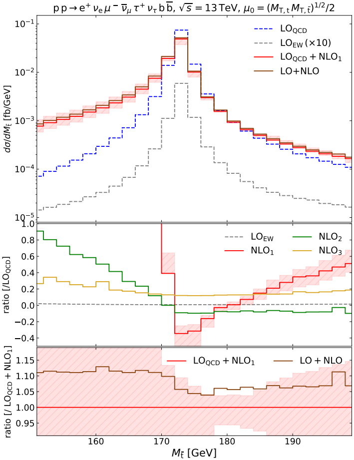
Rapidity of μ^-



- NLO_1 large variation (35%), NLO_2 rather flat, NLO_3 diminish from +16% (central) to +8% (forward)

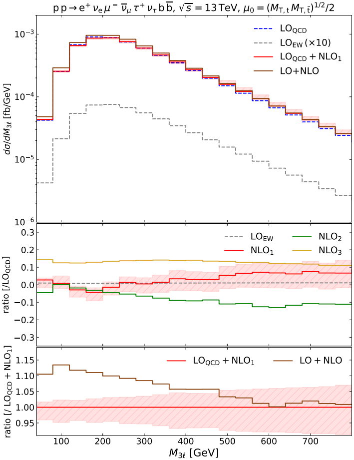
Combining NLO EW and QCD: invariant-mass distributions

Invariant mass of the $\bar{b}\mu^-\bar{\nu}_\mu$ system



- Large radiative tail at low mass both for NLO_2 and NLO_1. NLO_3 corrections are flatter.

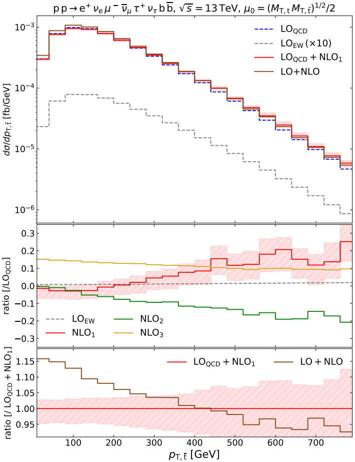
Invariant mass of the 3ℓ system



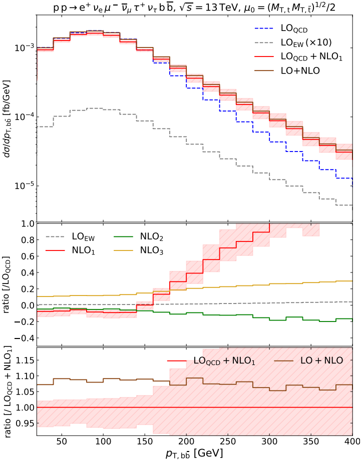
- Rather flat QCD corrections, NLO_2 corrections diminish down to -11% at 800 GeV.

Combining NLO EW and QCD: transverse-momentum distributions

Transverse momentum of $\bar{b}\mu^-\bar{\nu}_\mu$ system



Transverse momentum of $b\bar{b}$ system



- Negative growth of NLO_2 (-20% at 800 GeV): large EW Sudakov logs. NLO_3 flat, NLO_1 increases by 25%.
- Very large NLO_1 correction for $p_{\text{T,bb}} > 150$ GeV. Small NLO corrections in the soft region.

Conclusions & outlook

Conclusions & outlook

First calculations including complete off-shell effects at NLO QCD ($\alpha_s^3\alpha^6$) and subleading NLO orders ($\alpha_s^2\alpha^7$, $\alpha_s\alpha^8$) now available for $t\bar{t}W^{\pm}$ (in the 3ℓ channel).

Essential theory progress towards realistic final states modelling.

- NLO_1 corr. range between 0.5% and 18%, depending on central scale.
- Scale uncertainties reduced from 25% (LO) to 5% (NLO), mostly due to NLO_1.
- NLO_2 corr. are negative (−5%) and almost scale-independent and become large (down to −20%) in the tail of p_T and invariant-mass distributions.
- NLO_3 corr. are large (+10% to +25%) and also rather scale-independent, dominated by the qg channels that embed tW scattering.
- Combined NLO predictions exceed the scale-uncertainties of the NLO_{QCD} results: NLO_2 and NLO_3 necessary for a correct modelling of $t\bar{t}W$.
- Off-shell effects are important in the tails of several distributions. For inclusive variables, spin-correlated production×decay is a good approximation.
- All NLO corr. change distribution shapes (even angular ones).

Ultimate target: NLO+PS for off-shell $t\bar{t}W$ production.

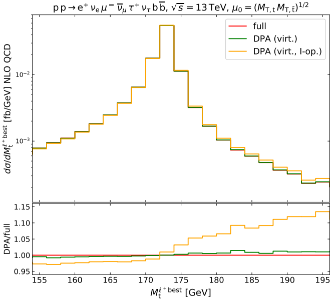
Backup

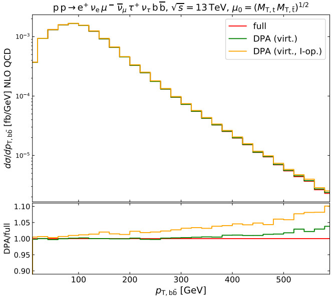
NLO QCD: full off-shell vs DPA

[Denner, GP 2007.12089]

Impact of off-shell effects: comparison with results in the double-pole approximation.

Either applied to the virtual only or also to the *I*-operators of the integrated dipoles





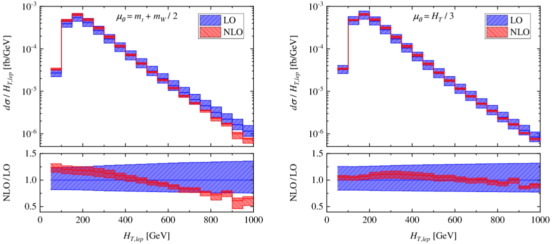
$$\sigma_{\mathrm{NLO}}^{\mathrm{full}} = 0.2394(6)\,\mathrm{fb}, \quad \sigma_{\mathrm{NLO}}^{\mathrm{DPA,\,V}} = 0.2395(7)\,\mathrm{fb}, \quad \sigma_{\mathrm{NLO}}^{\mathrm{DPA,\,V+I}} = 0.2422(7)\,\mathrm{fb}$$

Impressive agreement for DPA virtual only (small corr.). Larger discrepancies in off-shell regions if DPA applied to *I*-operators (up to 15%).

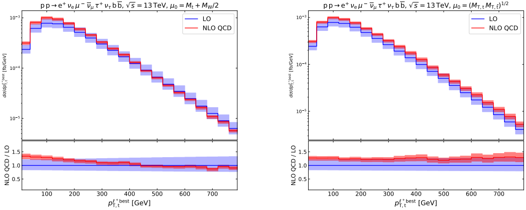
NLO QCD: fixed vs dynamical scale

Dynamical scale choices give flatter K-factors than the fixed ones.

[Bevilacqua et al. 2005.09427] : the $H_T/3$ choice sizeably improves perturbative convergence. Fig: scalar sum of lepton p_T's.

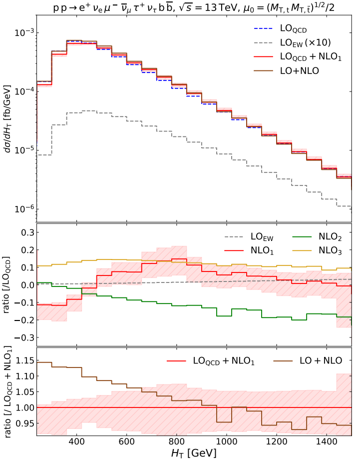


[Denner, GP 2007.12089] : the resonance-aware choice ($\sqrt{M_{T,t} M_{T,\bar{t}}}$) also performs well, similar results as $H_T/3$ (larger scale unc.). Fig: best-reco. top p_T.

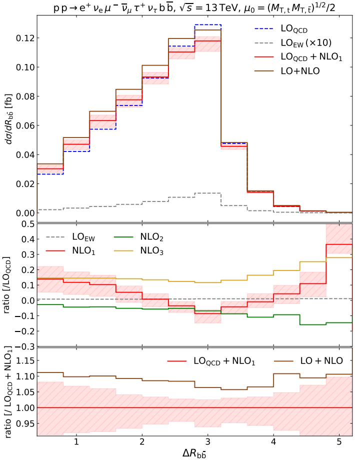


NLO EW and QCD: more distributions (1)

H_T variable

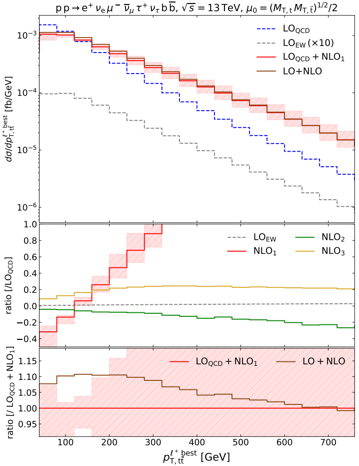


R-distance between the two b-jets



NLO EW and QCD: more distributions (2)

Transverse momentum of the $t\bar{t}$ system



Transverse momentum of the positron