Higher-order and off-shell effects in top-quark processes at high-energy colliders

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Introduction

Improving the perturbative description of full off-shell top-quark processes at colliders is a mandatory step for realistic predictions, though not the only one (parton-shower matching, hadronisation, . . .).

Computing NLO QCD and EW corrections is not straightforward:

1. high-multiplicity final states,
2. complicated resonant structures,
3. non-resonant effects and spin-correlations must be included,
4. mixing of EW and QCD corrections at a given order.

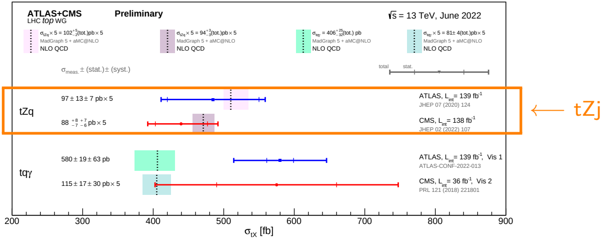
In this talk I introduce such complications using as illustrative processes:

$\rightarrow$ tZj at the LHC

$\rightarrow$ $t\bar{t}$ at lepton colliders

Off-shell effects at the LHC: the tZj process

A rare process at the LHC: weak boson Z in association with a single (anti)top quark
$\rightarrow$ electroweak induced



Run-2: observed [CMS 1812.05900, ATLAS 2002.07546], differential meas. [CMS 2111.02860].

Gives access to top-quark-to-Z-boson (more directly than $t\bar{t}Z$), triple-gauge (WWZ) and Wtb couplings to constrain new physics [Li et al. 1103.5122, Kidonakis 1712.01144, Degrande et al. 1804.07773, Liu Moretti 2010.05148].

EW-induced process: top quark is polarised [Mahlon Parke 9912458].

tZj: SM predictions

NLO QCD: narrow-with approximation (NWA) [Campbell Ellis Röntsch 1302.3856].

NLO QCD+EW: on-shell top , off-shell Z [Pagani Tsinikos Vryonidou 2006.10086].

PS matching: NLO QCD + QCD shower, LO decays [Pagani Tsinikos Vryonidou 2006.10086]

NLO, full off-shell: NLO EW + QCD [Denner GP Schwan 2207.11264] in the 3ℓ channel.

Soft-gluon resummation: exact NLO + soft-gluon corr. [Kidonakis Yamanaka 2210.09542].

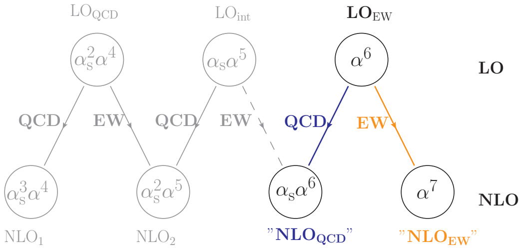
Broad SMEFT interpretation also available [Degrande et al. 1804.07773]

$\mathrm{p\,p} \to \mathrm{e^+e^-}\,\mu^+\nu_\mu\,\mathrm{j_b}\,\mathrm{J} + X$

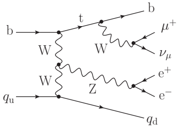
$\mathrm{j_b}$ = b-tagged jet

J = any jet

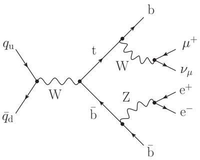
in the 5-flavour scheme



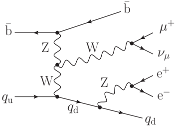
LO: $\mathrm{LO_{QCD}}$ non-resonant, $\mathrm{LO_{int}}$ vanishes (CKM unit matrix), single-top in $\mathrm{LO_{EW}}$. Channels with initial states $q\bar{q}$, qb



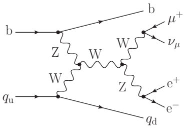
t-channel resonant



s-channel resonant



non-resonant

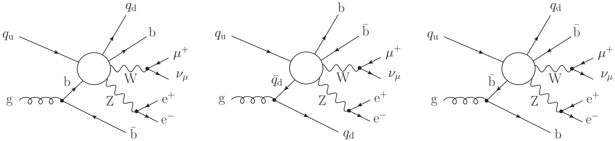


VBS-like

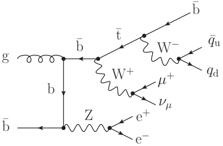
tZj: NLO contributions

NLO QCD and **EW**: genuine corrections to LO EW (no interference).
Real channels with initial states $q\bar{q}$, qb, gq, γq, gb, γb.

Not possible to distinguish between *t*-channel and *s*-channel contributions at NLO:



Fiducial-volume for top quark contaminated by hadronically decaying antitop ($\gamma\bar{b}$, g$\bar{b}$):



The same holds for the charged-conjugated process: very large correction ($\approx +10\%$).
Irreducible bkg that can only be treated with jet vetoes/ special cuts.

tZj: integrated cross-sections and off-shell effects

Fiducial cross-sections [Denner GP Schwan 2207.11264] in the setup of [ATLAS 2002.07546].

- Sizeable QCD and EW corrections.
- QCD-scale (downward) uncertainty diminished from LO to NLO QCD.

order	σ [fb]	ratio [/LO]
LO [$\mathcal{O}(\alpha^6)$]	$0.6416(0)\ ^{+8.9\%}_{-13.5\%}$	100.0%
δ_{QCD} [$\mathcal{O}(\alpha_s\alpha^6)$]	0.1987(5)	31.0%
δ_{EW} [$\mathcal{O}(\alpha^7)$]	-0.0416(6)	-6.5%
NLO QCD	$0.8402(5)\ ^{+8.6\%}_{-3.9\%}$	131.0%
NLO EW	$0.5999(6)\ ^{+9.4\%}_{-13.9\%}$	93.5%
NLO QCD+EW	$0.7986(8)\ ^{+9.4\%}_{-4.2\%}$	124.5%

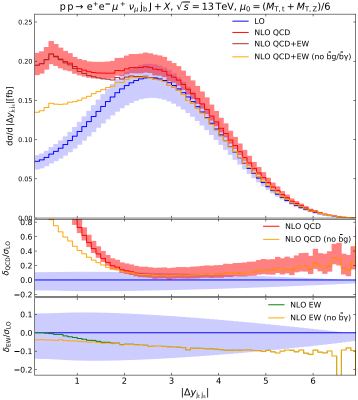
Off-shell [Denner GP Schwan 2207.11264] vs on-shell [Pagani et al. 2006.10086] in Z-peak setup: same EW correction (relative to NLO QCD), differences at NLO QCD.

	on-shell	off-shell* (w/o decay corr.)	off-shell*
NLO QCD/LO	1.24	1.289	1.195
(NLO QCD+EW)/NLO QCD	0.93	0.919	0.924

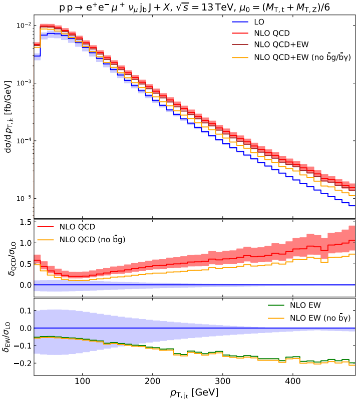
* excluded $\bar{\text{b}}\gamma$, $\bar{\text{b}}\text{g}$ channels

tZj: differential results

Rapidity separation between top-decay jet and spectator jet, $|\Delta y_{\mathrm{j_t j_s}}|$.



Transverse momentum of the top-decay jet, $p_{\mathrm{T,j_t}}$.

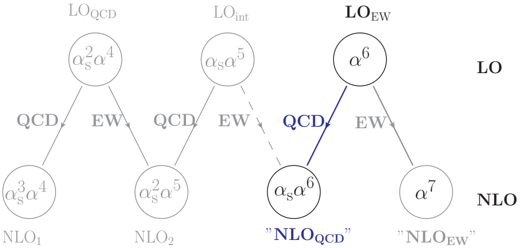


- Dominant tZ topology gives peak at $|\Delta y_{\mathrm{j_t j_s}}| \approx 2.5$.
- Large hadronic-antitop contribution at small values ($\approx 100\%$ of LO for $|\Delta y_{\mathrm{j_t j_s}}| < 1$)
- Increasing positive QCD corrections (up to 100%), at variance with spectator jet ($\to 0$, at large p_{T}).
- EW-Sudakov enhancements in the tails (negative EW corr., up to -20%)

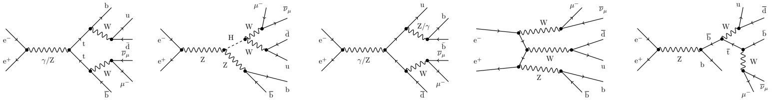
Off-shell effects at lepton colliders: $t\bar{t}$

$t\bar{t}$ production at lepton colliders is EW induced: cleaner environment (than LHC), similar issues arise with off-shell effects, especially in semi-leptonic decay channel.

$e^+e^- \to j_b j_b j\, j\, \mu^+ \nu_\mu$
at NLO accuracy:
(mostly) annihilation process



Full off-shell description: resonant ($t\bar{t}$) and non-resonant (single-top, triboson ...)



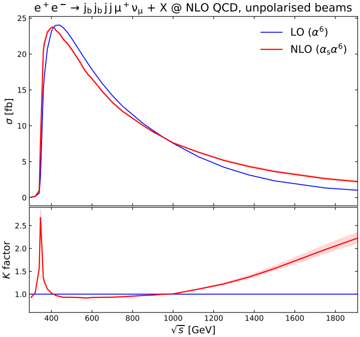
$t\bar{t}$ at lepton colliders: cross-section scan

Higher-order and non-resonant effects strongly depend on the decay channel, *e.g*

$e^+e^- \rightarrow j_b j_b j\, j\, e^+\nu_e$: t-channel contributions (not only annihilation),

$e^+e^- \rightarrow j_b j_b\, e^+\nu_e\mu^-\bar{\nu}_\mu$: different QCD corrections (two jets only),

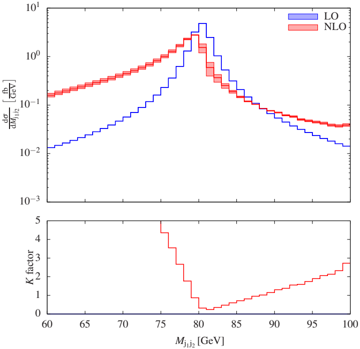
and on the collider energy,



- below and about threshold ($2\,m_{\text{top}}$) similar QCD corrections as in fully leptonic channel
- positive and increasing QCD effects for $\sqrt{s} \gtrsim 1$TeV
- irreducible-bkg larger with increasing $\sqrt{s}$
- huge QCD corrections at high energy due to event selection (2 light jets with $R = 0.4$) cutting boosted-W topolgies at LO

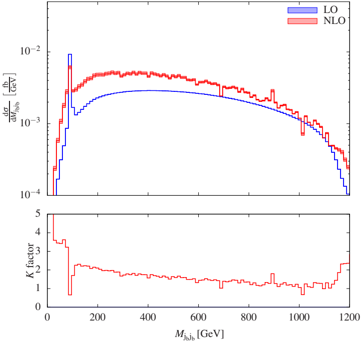
$t\bar{t}$ at lepton colliders: differential results

Invariant mass of the two-light-jet system, $\sqrt{s} = 365\text{GeV}$



- strong distortion of M_{jj} spectrum with huge radiative tail
- hard-gluon radiation modify also the high-energy tail (larger effects at 1.5TeV)

Invariant mass of the two-b-jet system, $\sqrt{s} = 1.5\text{TeV}$



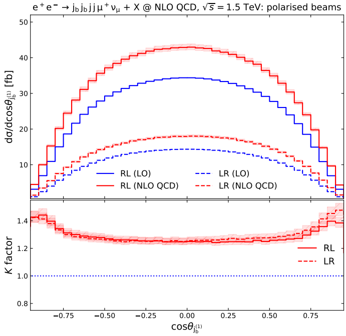
- peak at the Z mass: $Z \to \mathrm{j_b j_b}$ sitting on top of $t\bar{t}$ and single-top
- small QCD corr. approaching maximum allowed (on-shell top), larger towards end-point.

Polarisation of $e^{\pm}$ along beam axis: only LR and RL states allowed (annihilation).

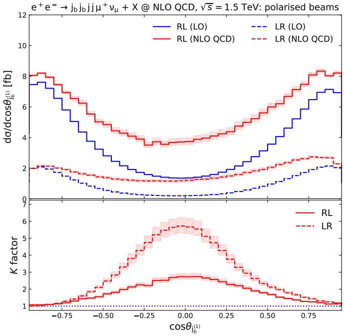
Around threshold QCD effects are independent of polarised-beam effects.

At high energy very different K-factors for LR and RL: real radiation opens up helicity configurations that are suppressed at LO, and to increased irreducible bgks (with different helicity structure).

$\sqrt{s} = 365\text{GeV}$



$\sqrt{s} = 1.5\text{TeV}$



Cosine of the polar angle of the leading b jet.

Conclusions

Essential to model full off-shell top-quark processes at least at NLO QCD and EW accuracy, both at LHC and at lepton colliders.

Typically dominated by top-resonant contributions, but non-resonant ones may be sizeable, depending on:

- type of process (QCD or EW induced),
- decay channel (leptonic or hadronic),
- energy regime (at threshold, boosted topologies, . . .),

and NLO corrections may open up kinematic configurations that are suppressed at LO.

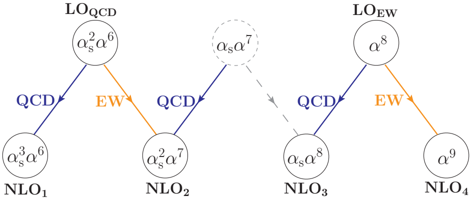
A good practice: compare full off-shell calculations with production $\times$ decay approximations (narrow width, pole) for a quantitative estimate of off-shell effects.

Backup ($t\bar{t}W$)

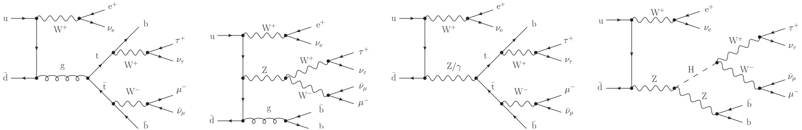
A quick glance at $t\bar{t}W$

The situation here is even more involved $\rightarrow$ QCD induced but large EW contributions.

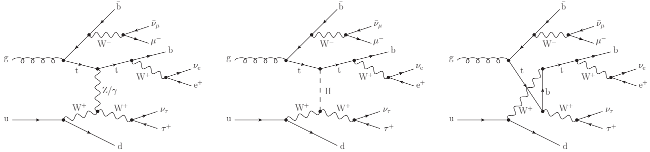
$\mathrm{p\,p} \rightarrow \mathrm{b\,\bar{b}\,e^+}\nu_\mathrm{e}\,\mu^-\bar{\nu}_\mu\,\tau^+\nu_\tau\ +X$
at NLO accuracy
Several "signal" contributions.



LO

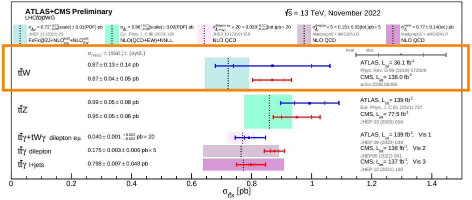


$\mathrm{NLO_3}$ (real)



Rare processes at the LHC: weak boson(s) V in association with

- ⋆ a top-antitop pair: $t\bar{t}V$ → QCD induced (but large EW contribution)



← this talk

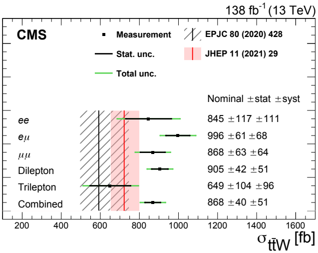
A tension to be addressed

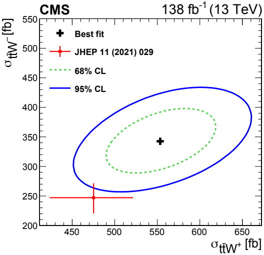
Hadro-production of $t\bar{t}W^{\pm}$ at the LHC gives access to $t\bar{t}V$ couplings in the SM, new-physics effects [Dror et al. 1511.03674, Bylund et al. 1601.08193] and charge asymmetries [Maltoni et al. 1406.3262]. Important background to $t\bar{t}h$ [Maltoni et al. 1507.05640].

Measured with Run-2 dataset [ATLAS 1609.01599, 1901.03584, CMS 1711.02547, 2208.06485].

Tension between data and SM for both $t\bar{t}W$ analyses [CMS 1711.02547, ATLAS 1901.03584] and as background to $t\bar{t}h$ [CMS 1804.02610, ATLAS 1806.00425].

Latest results [CMS 2208.06485], full Run-2 dataset: improved theory, 2σ tension remains.





Theory status (SM)

NLO, on-shell/NWA: NLO QCD [Maltoni et al. 1406.3262], subleading NLO orders [Frixione et al. 1504.03446, Frederix et al. 1711.02116, 1804.10017]. NLO QCD in NWA [Campbell Ellis 1204.5678].

Soft-gluon resummation: NLO+NNLL (on-shell) [Broggio et al. 1907.04343, Kulesza et al. 2001.03031].

NLOPS matching: 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] in NWA (LO decays).

Multi-jet merging: NLO on-shell [von Buddenbrock et al. 2009.00032], in NWA (LO decays) [Frederix Tsinikos 2108.07826].

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

Broad comparison between full off-shell, NWA and PS-matched predictions [Bevilacqua et al. 2109.15181] in the 3ℓ channel.

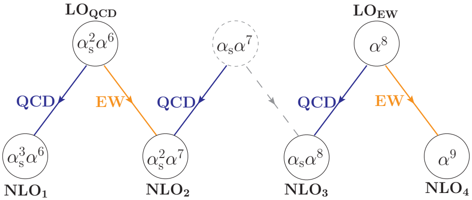
LO and NLO_1 contributions

LHC process:

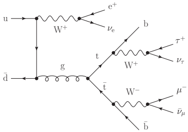
$\mathrm{p\,p} \to \mathrm{b\,\bar{b}\,e^+}\nu_{\mathrm{e}}\,\mu^-\bar{\nu}_\mu\,\tau^+\nu_\tau\; + X$

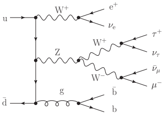
at NLO accuracy

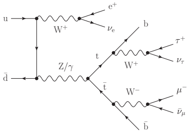
$\to$ several contributions.

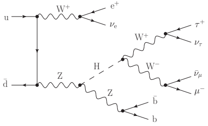


LO: double-resonant ($\mathrm{t\bar{t}}$), single-resonant (t or $\mathrm{\bar{t}}$), non-resonant diagrams. Interference of order $\mathcal{O}(\alpha_s\alpha^7)$ vanishes (if CKM is unit matrix).







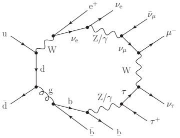


NLO_1: genuine NLO QCD to LO QCD (expected to be dominant NLO), up to 7-point functions in virtual corr., challenging real corr. (high-multiplicity). Real channels with initial states $q\bar{q}$, gq. First computed [Bevilacqua et al. 2005.09427, Denner GP 2007.12089].

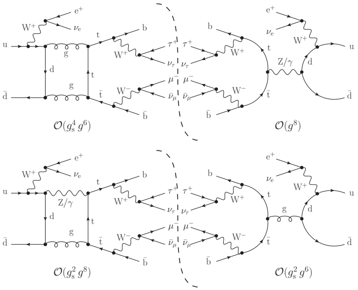
NLO$_2$ contribution

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

Up to 10-point functions in virtuals.



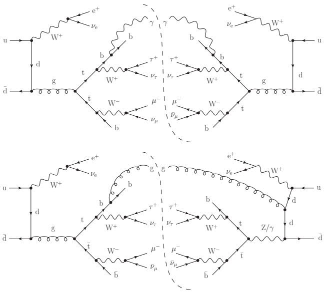
Two contributions:



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.



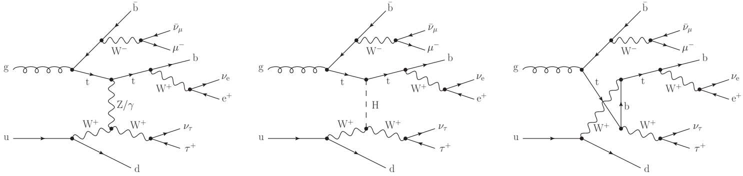
Virtual IR poles for $\mathcal{O}(g_s^2 g^8) \times \mathcal{O}(g_s^2 g^6)$ are cancelled by both classes of reals: only the sum of all contributions is IR safe!

NLO_3 and NLO_4 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 $\text{tW}^+ \rightarrow \text{tW}^+$ scattering:



NLO_4: EW corrections to LO_{EW}, amount at 0.04% of LO_{QCD} at inclusive level [Frederix et al. 1711.02116]. Out of reach (fiducial phase-space) even at HL-LHC $\rightarrow$ negligible.

Combining NLO EW and QCD: setup

$\mathrm{pp} \to \mathrm{b}\,\bar{\mathrm{b}}\,\mathrm{e}^+\nu_\mathrm{e}\,\mu^-\bar{\nu}_\mu\,\tau^+\nu_\tau + \mathrm{X}$ at $\mathcal{O}(\alpha_\mathrm{s}^3\alpha^6)$, $\mathcal{O}(\alpha_\mathrm{s}^2\alpha^7)$, $\mathcal{O}(\alpha_\mathrm{s}\alpha^8)$ [Denner GP 2102.03246]

- 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 [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; $N_F = 5$
- Γ_t computed including NLO QCD+EW corrections [Basso et al. 1507.04676] (for both LO and NLO).

Selections, mimic those of Ref. [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, $|\eta_\ell| < 2.5$, $\Delta R_{\ell\mathrm{b}} > 0.4$).

Three central-scale choices: $\mu_0^{(\mathrm{c})} = H_\mathrm{T}/3$, $\mu_0^{(\mathrm{d})} = \sqrt{M_{T,\mathrm{t}} M_{\mathrm{T},\bar{\mathrm{t}}}}$, $\mu_0^{(\mathrm{e})} = \sqrt{M_{T,\mathrm{t}} M_{\mathrm{T},\bar{\mathrm{t}}}}/2$.

Combining NLO EW and QCD: integrated cross-sections

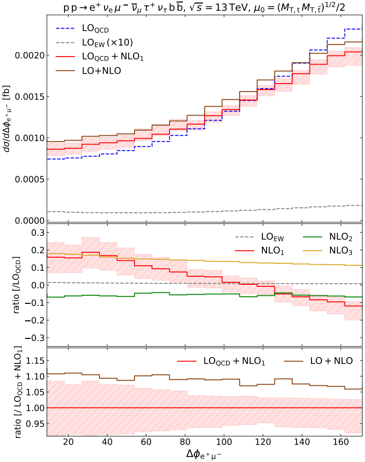
Fiducial cross-sections [Denner GP 2102.03246]:

	$\mu_0^{(c)}$		$\mu_0^{(d)}$		$\mu_0^{(e)}$	
order	σ (fb)	ratio	σ (fb)	ratio	σ (fb)	ratio
$\mathrm{LO_{QCD}}$ ($\alpha_s^2\alpha^6$)	$0.2218(1)^{+25.3\%}_{-18.8\%}$	1	$0.1948(1)^{+23.9\%}_{-18.1\%}$	1	$0.2414(1)^{+26.2\%}_{-19.3\%}$	1
$\mathrm{LO_{EW}}$ (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
$\mathrm{NLO_1}$ ($\alpha_s^3\alpha^6$)	0.0147(6)	0.066	0.0349(6)	0.179	0.0009(7)	0.004
$\mathrm{NLO_2}$ ($\alpha_s^2\alpha^7$)	−0.0122(3)	−0.055	−0.0106(3)	−0.054	−0.0134(4)	−0.056
$\mathrm{NLO_3}$ ($\alpha_s\alpha^8$)	0.0293(1)	0.131	0.0263(1)	0.135	0.0320(1)	0.133
$\mathrm{LO_{QCD}+NLO_1}$	$0.2365(6)^{+2.9\%}_{-6.0\%}$	1.066	$0.2297(6)^{+5.5\%}_{-7.3\%}$	1.179	$0.2423(7)^{+3.5\%}_{-5.2\%}$	1.004
$\mathrm{LO_{QCD}+NLO_2}$	$0.2094(3)^{+25.0\%}_{-18.7\%}$	0.945	$0.1840(3)^{+23.8\%}_{-17.9\%}$	0.946	$0.2277(4)^{+25.9\%}_{-19.2\%}$	0.944
$\mathrm{LO_{EW}+NLO_3}$	$0.03142(4)^{+22.2\%}_{-16.8\%}$	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

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

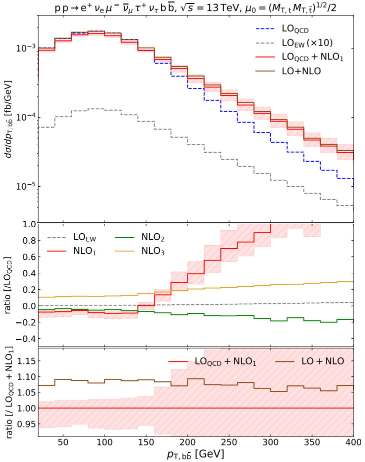
Combining NLO EW and QCD: differential results

Azimuthal separation between e^+ and μ^-



- NLO_1 diminish with constant slope, $\text{NLO}_2+\text{NLO}_3$ give a rather flat correction to $\text{LO}+\text{NLO}_1$.

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



- Very large NLO_1 correction for $p_{T,bb} > 150$ GeV. Small NLO corrections in the soft region.

NLO$_1$: numerical setups

"Aachen group" [Bevilacqua et al. 2005.09427]

- ⋆ $\mathrm{pp} \to \mathrm{b}\,\bar{\mathrm{b}}\,\mathrm{e}^+\nu_\mathrm{e}\,\mu^-\bar{\nu}_\mu\,\mathrm{e}^+\nu_\mathrm{e} + \mathrm{X}$ (+ cc)
  - Full tree/one-loop amplitudes and MC integration with HELAC-NLO framework [G. Bevilacqua et al. 1110.1499]
  - Dipole [Catani, Seymour 9605323] and Nagy-Soper [Bevilacqua et al. 1308.5605] subtractions
  - Complex-mass [Denner et al. 9904472] for top, fixed width for W, Z.
  - CT14, MMHT14 and NNPDF3.0 (N)LO PDFs, $N_F = 5$
- ⋆ Selections: 2 b-jets (anti-k_t, $R = 0.4$, $p_{\mathrm{T,b}} > 25$ GeV, $|\eta_\mathrm{b}| < 2.5$), 3 ch. leptons ($p_{\mathrm{T},\ell} > 25$ GeV, $|\eta_\ell| < 2.5$, $\Delta R_{\ell\mathrm{b}} > 0.4$, $\Delta R_{\ell\ell} > 0.4$).

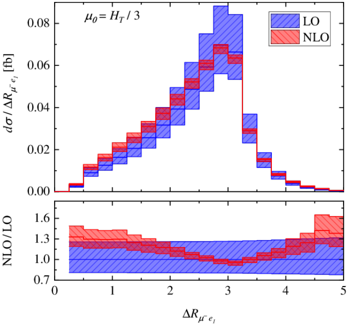
"Würzburg group" [Denner, GP 2007.12089]

- ⋆ $\mathrm{pp} \to \mathrm{b}\,\bar{\mathrm{b}}\,\mathrm{e}^+\nu_\mathrm{e}\,\mu^-\bar{\nu}_\mu\,\tau^+\nu_\tau + \mathrm{X}$
  - Full tree/one-loop amplitudes with RECOLA [Actis et al. 1605.01090] + COLLIER [Denner et al. 1604.06792], MC integration with MOCANLO
  - Dipole subtraction [Catani, Seymour 9605323]
  - Complex-mass scheme [Denner et al. 9904472] for W, Z, top
  - NNPDF3.1 (N)LO PDFs, $N_F = 5$
- ⋆ Selections: 2 b-jets (anti-k_t, $R = 0.4$, $p_{\mathrm{T,b}} > 25$ 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$_1$: comparison of the two calculations

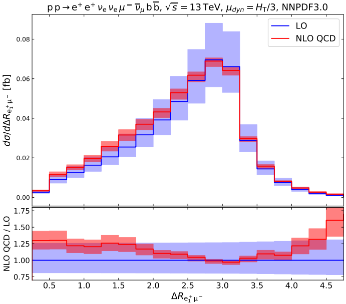
Good agreement using the setup of Ref. [Bevilacqua et al. 2005.09427], both at integrated and differential level (also for scale unc. and K-factors).

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



[Bevilacqua et al. 2005.09427]

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

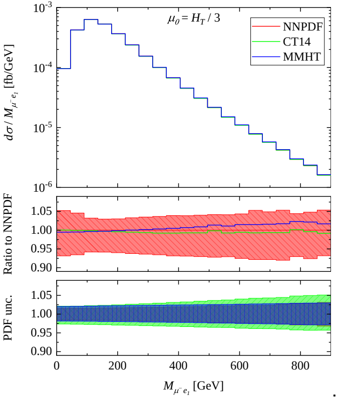


[Denner, GP 2007.12089]

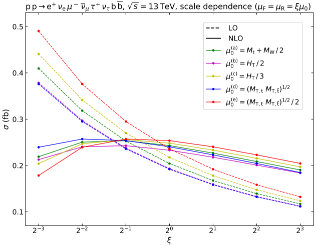
NLO_1: theory uncertainties and scale dependence

NLO QCD corrections substantially reduce scale-uncertainties (from 25% to 5%) [Bevilacqua et al. 2005.09427, Denner GP 2007.12089].

QCD-scale variations give the dominant source of theory unc., PDF unc. are of order 2-3% [Bevilacqua et al. 2005.09427]



QCD K-factors range between 1.07 and 1.25 depending on the central-scale choice [Denner GP 2007.12089]:

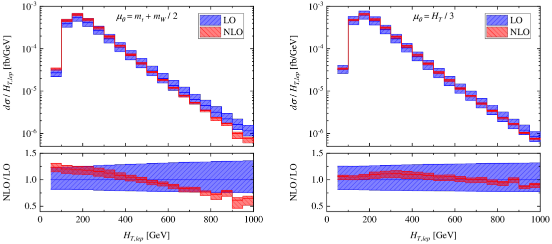


central scale	K-fact.
$\mu_0^{(a)} = M_t + M_W/2$	1.20
$\mu_0^{(b)} = H_T/2$	1.21
$\mu_0^{(c)} = H_T/3$	1.13
$\mu_0^{(d)} = \left(M_{T,t} M_{T,\bar{t}}\right)^{1/2}$	1.25
$\mu_0^{(e)} = \left(M_{T,t} M_{T,\bar{t}}\right)^{1/2}/2$	1.07

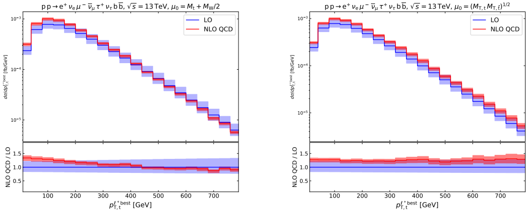
NLO$_1$: fixed vs dynamical scale

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

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



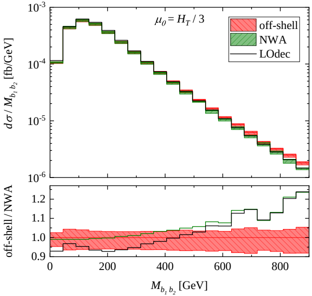
The resonance-aware choice ($\sqrt{M_{T,t} M_{T,\bar{t}}}$) also performs well, similar results as $H_T/3$ (larger scale unc.). Fig: best-reco. top p_T [Denner, GP 2007.12089].



Full off-shell vs narrow-width

Comparison at NLO QCD between full off-shell calculation and two narrow-width approximations (NWA, with/without NLO corr. in $t/\bar{t}$ decays) [Bevilacqua et al. 2005.09427].

$\mu_0 = H_T/3$	LO	NLO QCD
full off-shell	$115.1^{+30.5\,(26\%)}_{-22.5\,(20\%)}$	$124.4^{+4.3\,(3\%)}_{-7.7\,(6\%)}$
NWA	$115.1^{+30.4\,(26\%)}_{-22.4\,(19\%)}$	$124.2^{+4.1\,(3\%)}_{-7.7\,(6\%)}$
$\text{NWA}_{\text{LO decay}}$	"	$130.7^{+13.6\,(10\%)}_{-13.2\,(10\%)}$



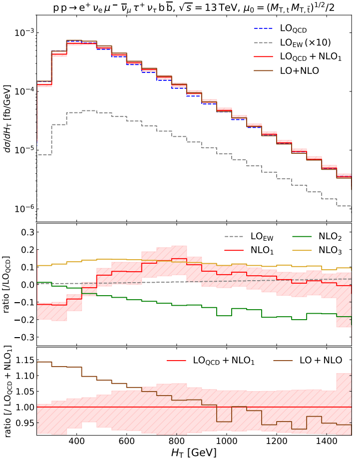
More recent detailed comparison → [Bevilacqua et al. 2109.15181].

NLO EW and QCD: integrated cross-sections

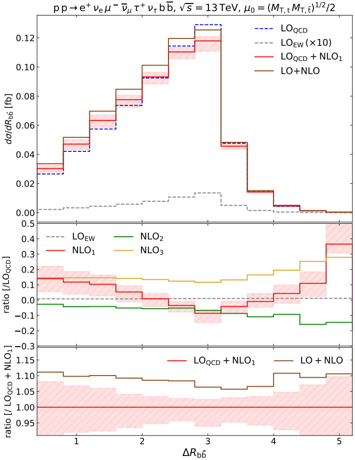
central scale	LO	NLO QCD	K-fact.
$\mu_0^{(a)} = M_t + M_W/2$	$0.2042(1)^{+23.8\%}_{-18.0\%}$	$0.2452(7)^{+4.5\%}_{-6.8\%}$	1.20
$\mu_0^{(b)} = H_T/2$	$0.1931(1)^{+23.0\%}_{-17.5\%}$	$0.2330(9)^{+4.2\%}_{-6.5\%}$	1.21
$\mu_0^{(c)} = H_T/3$	$0.2175(1)^{+24.2\%}_{-18.2\%}$	$0.2462(8)^{+2.8\%}_{-5.8\%}$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

NLO EW and QCD: more distributions (1)

H_T variable

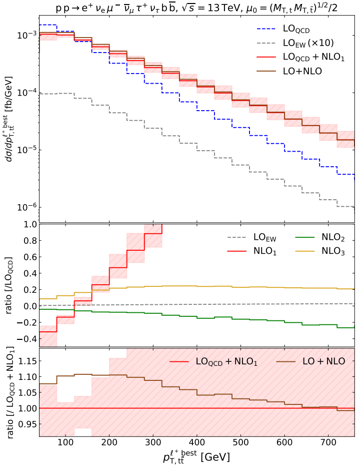


R-distance between the two b-jets

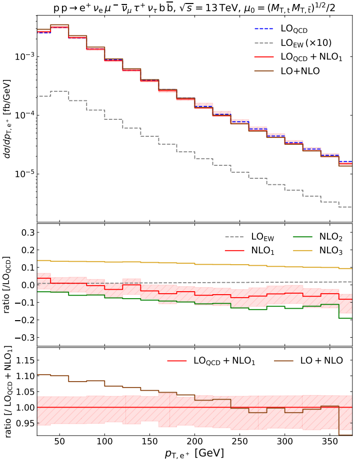


NLO EW and QCD: more distributions (2)

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

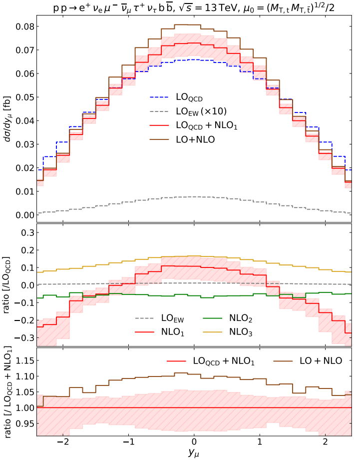


Transverse momentum of the positron

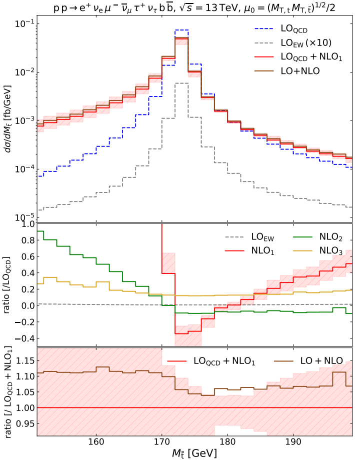


NLO EW and QCD: more distributions (3)

Rapidity of the muon



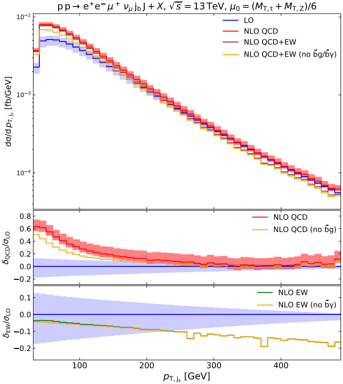
Invariant mass of the antitop quark



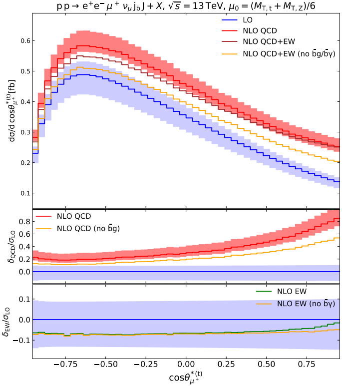
Backup (tZj)

Transverse-momentum and angular distributions

Transverse momentum of the spectator jet

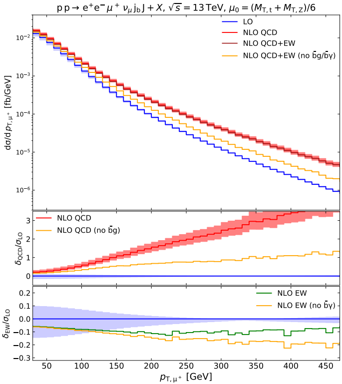


Polarisation-sensitive polar angle of the antimuon in the top-quark rest frame

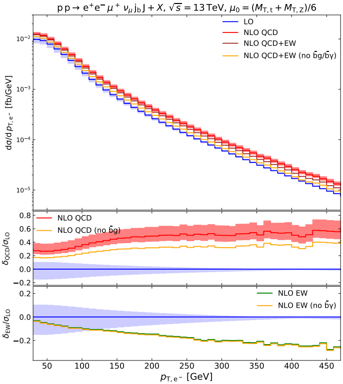


Transverse-momentum distributions for leptons

Antimuon (top-quark decay)

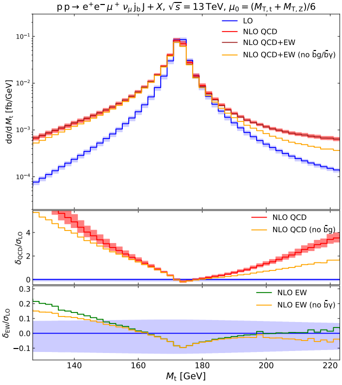


Electron (Z-boson decay)

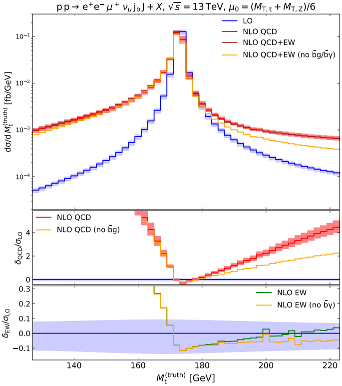


Invariant-mass distributions (1)

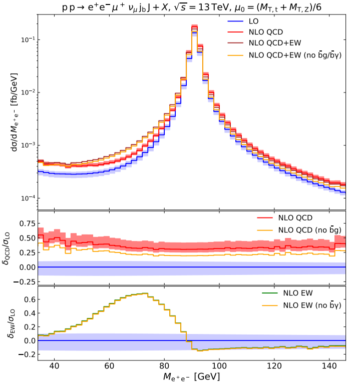
Reconstructed top quark



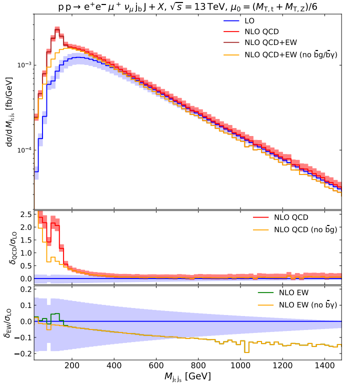
MC-truth top quark



Z-boson

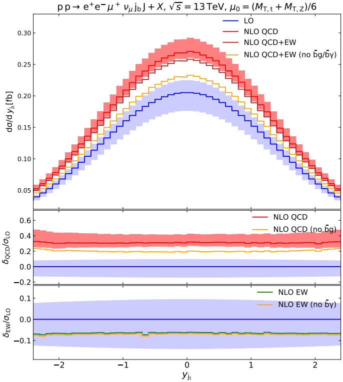


Di-jet

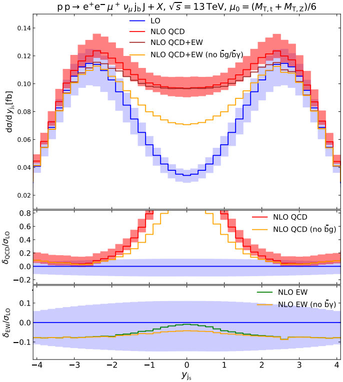


Rapidity distributions

Top-decay jet



Spectator jet



Combining NLO EW and QCD: setup

$\mathrm{p\,p} \to \mathrm{e^+e^-}\,\mu^+\nu_\mu\,\mathrm{j_b}\,\mathrm{J} + X$ at $\mathcal{O}(\alpha_s\alpha^6)$ and $\mathcal{O}(\alpha^7)$ [Denner GP Schwan 2207.11264]

- 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 [Catani Seymour 9605323, Dittmaier 9904440]
- complex-mass scheme [Denner et al. 9904472] for W, Z, top
- NNPDF3.1 NNLO LUXQED PDFs (photon included, [Bertone et al. 1712.07053]);
- Γ_t computed including NLO QCD+EW corrections [Basso et al. 1507.04676].

Selections mimic those of [ATLAS 2002.07546].

Jets: b-jets ($\mathrm{j_b}$) and light jets (j) clustered with k_t algorithm [Catani et al. Nucl.Phys.B406(1993)] and $R = 0.4$, $N_\mathrm{b} \geq 1$, $N_{\mathrm{j_b}} + N_\mathrm{j} \geq 2$, $p_{\mathrm{T,j_b}}, p_{\mathrm{T,j}} > 35\mathrm{GeV}$, $|y_{\mathrm{j_b}}| < 2.5$, $|y_\mathrm{j}| < 4.5$

Leptons 3 dressed leptons clustered with k_t algorithm and $R = 0.1$, $p_{\mathrm{T},\ell_1} > 28\mathrm{GeV}$, $p_{\mathrm{T},\ell} > 20\mathrm{GeV}$, $|y_\ell| < 2.5$, $M_{\mathrm{e^+e^-}} > 30\mathrm{GeV}$, $\Delta R_{\ell\mathrm{J}} > 0.4$

Central-scale choice: $\mu_0 = (M_{T,\mathrm{t}} + M_{\mathrm{T,Z}})/6$ (inspired by [Pagani et al. 2006.10086]).