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Electroweak and QCD corrections to off-shell tZj production at the LHC

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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.

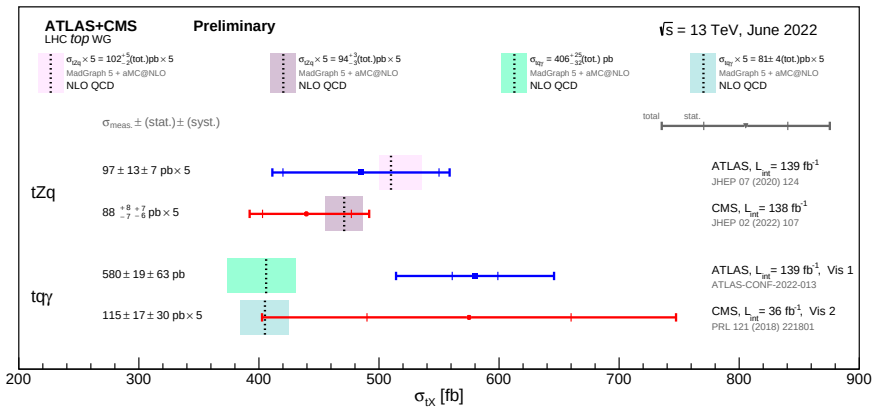
This talk has a focus on

→ tZj at the LHC (mostly based on Denner GP Schwan JHEP 10 (2022) 125 [2207.11264])

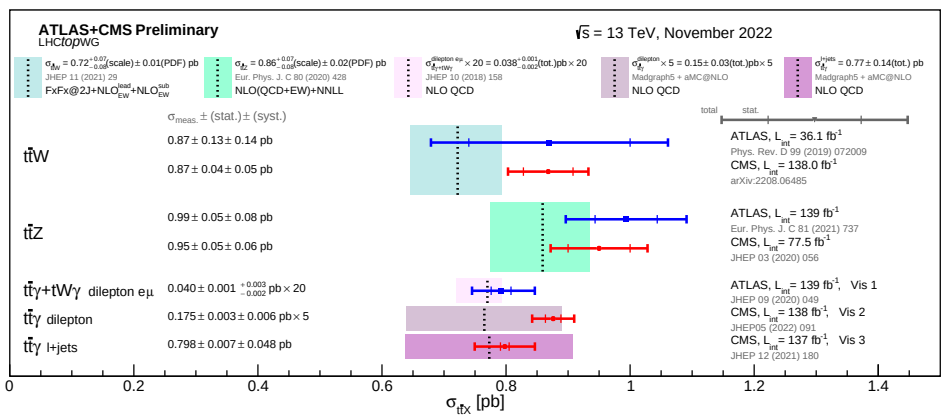
Rare processes

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

- ⋆ a single (anti)top quark: $\mathrm{t}V\mathrm{j}/\bar{\mathrm{t}}V\mathrm{j} \rightarrow$ EW induced



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



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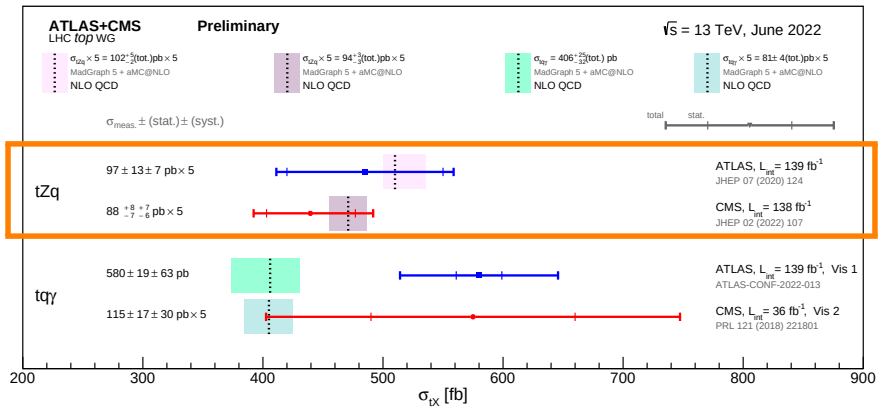

← this talk

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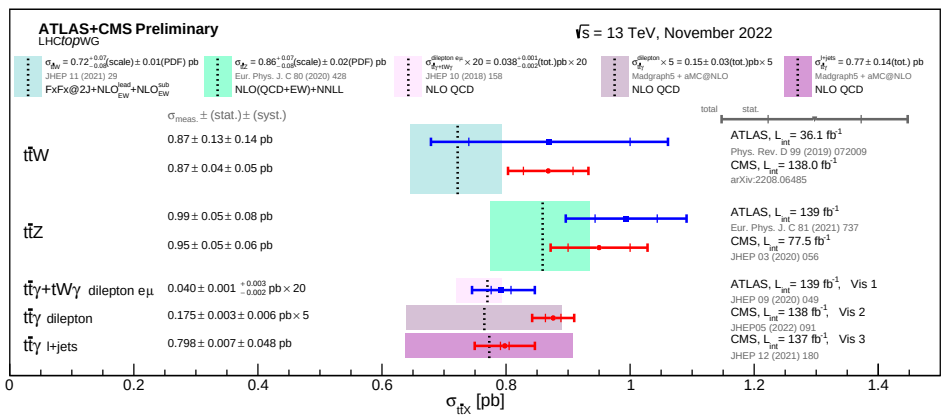


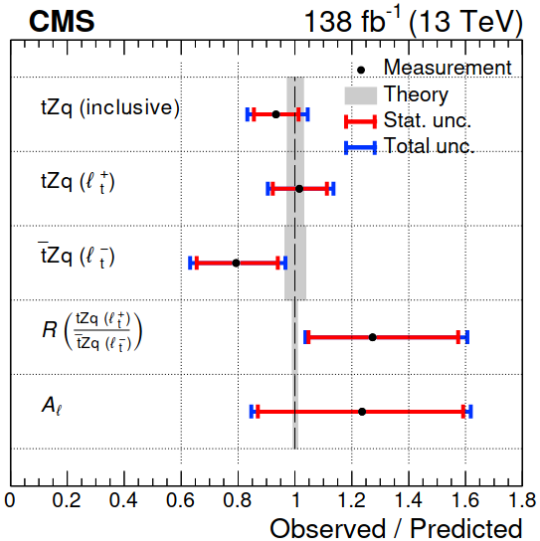
Theory motivations and experimental measurements

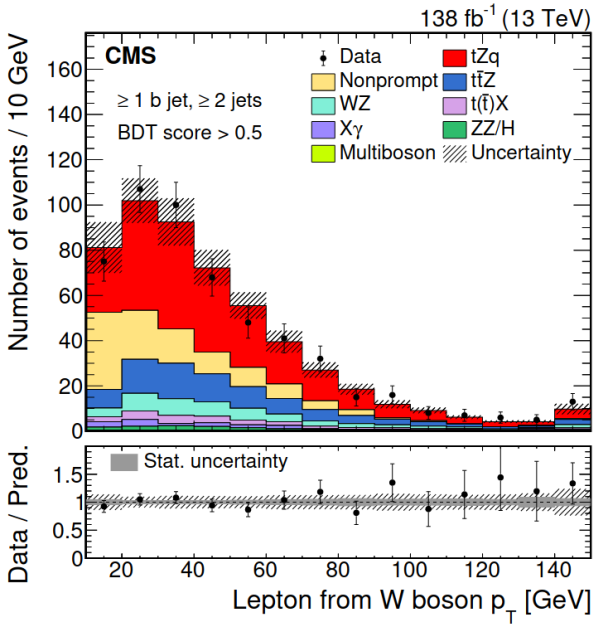
Gives access to top-quark-to-Z-boson (more directly than $t\bar{t}Z$), triple-gauge (WWZ) and Wtb couplings to constrain new physics.

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

Observed with Run-2 data [CMS 1812.05900, ATLAS 2002.07546].

First differential-cross-section measurement [CMS 2111.02860] (figure below)





Beyond the Standard Model

Phenomenological studies with vector-like top partners [Reuter Tonini 1409.6962], anomalous couplings [Li et al. 1103.5122, Kidonakis 1712.01144, Liu Moretti 2010.05148].

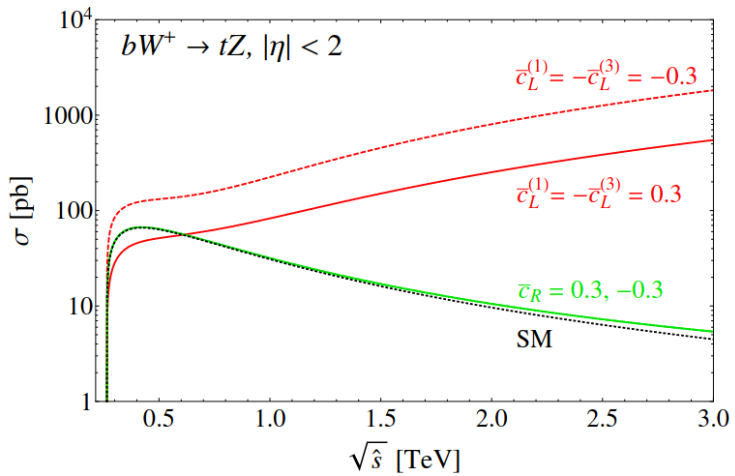
Broad SMEFT interpretation for tZj and tHj [Degrande et al. 1804.07773].

Owing to embedded $bW^+ \to tZ$ scattering, high sensitivity to anomalous Z-fermions and triple-gauge couplings, controlling leading energy-growth of amplitude:

$$\mathcal{A}_{(-,0,-,0)} \propto \sqrt{s(s+t)} \left(g_L^{Zb} - g_L^{Zt} + g^{WZ} \right)$$

Anomalous couplings lead to gauge/unitarity violations
[Dror et al. 1511.03674, Maltoni et al. 1904.05637]

figure from [Dror et al. 1511.03674]



Standard Model predictions

So far, SM modelling with on-shell approx., off-shell effects needed in fiducial regions:

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

NLO QCD+EW, on-shell: 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.

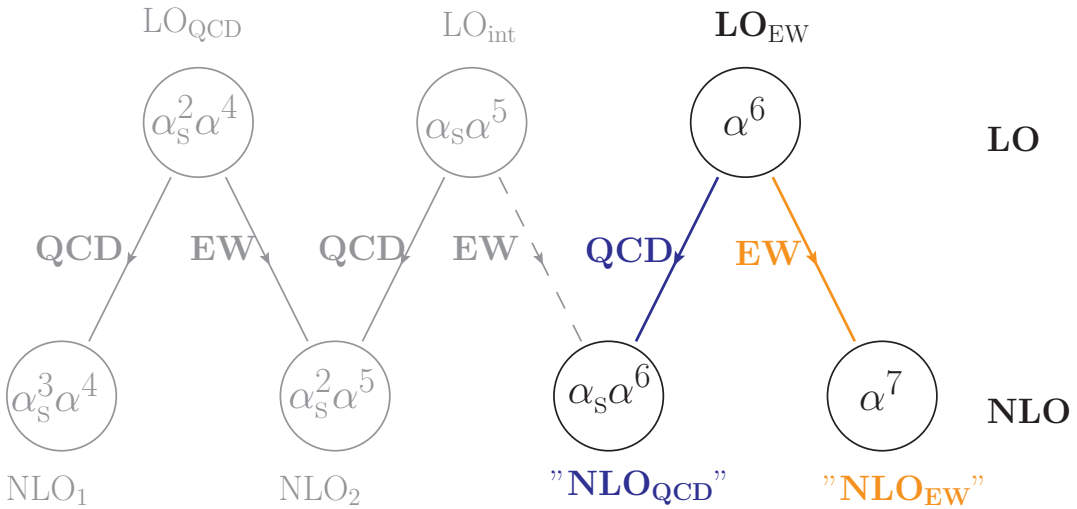
Soft-gluon resummation: exact NLO + soft-gluon corr. [Kidonakis Yamanaka 2210.09542].

LO contributions

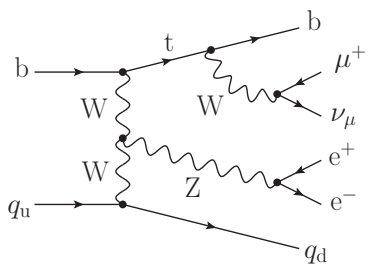
$p\,p \to e^+e^-\,\mu^+\nu_\mu\,j_b\,J + X$

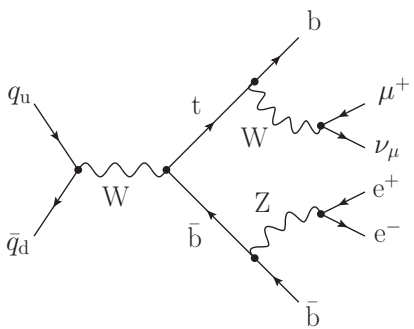
j_b = b-tagged jet

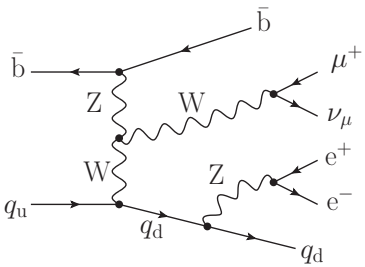
J = any jet

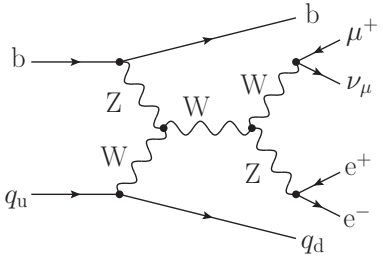


LO: LO_{QCD} non-resonant, LO_{int} vanishes (CKM unit matrix), single-top in LO_{EW}.
Channels with initial states $q\bar{q}$, qb







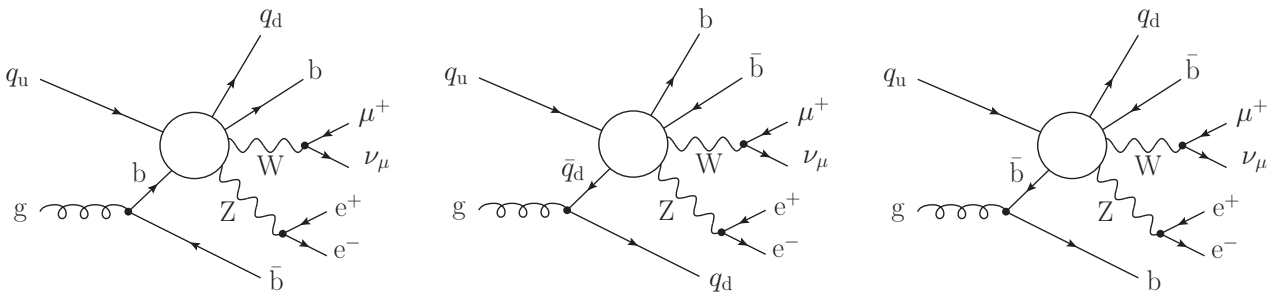


t-channel resonant *s*-channel resonant non-resonant VBS-like

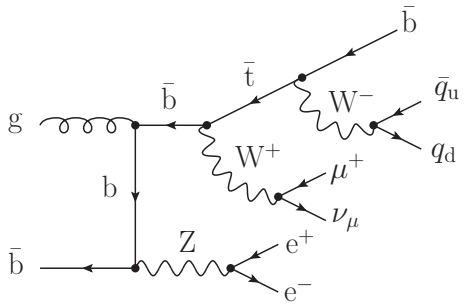
NLO contributions

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.

Setup

$p\,p \to e^+e^-\,\mu^+\nu_\mu\,j_b\,J + X$ 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 (j_b) and light jets (j) clustered with k_t algorithm [Catani et al. Nucl.Phys.B406(1993)] and $R = 0.4$, $N_b \geq 1$, $N_{j_b} + N_j \geq 2$, $p_{T,j_b}, p_{T,j} > 35\text{GeV}$, $|y_{j_b}| < 2.5$, $|y_j| < 4.5$

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

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

Recontruction of top-quark and spectator-jet observables

Missing p_T owing to single neutrino: reconstructing top quark is possible.

Strategy for single-top [Cao et al. 0504230], used in differential tZj analysis [CMS 2111.02860].

Identify top-decay (j_t) and spectator (j_s) jets (recall that $N_b \geq 1$ and $N_{j_b} + N_j \geq 2$):

- $N_{j_b} + N_j = 2$:
  - $N_{j_b} = 1$, $N_j = 1$: no ambiguity for j_t, j_s
  - $N_{j_b} = 2$: minimize $|M_{j_b \ell\nu^{rec}} - m_{top}|$ for j_t, other is j_s
- $N_{j_b} + N_j > 2$:
  - $N_{j_b} = 1$: no ambiguity for j_t, hardest-p_T light jet is j_s
  - $N_{j_b} \geq 2$: minimize $|M_{j_b \ell\nu^{rec}} - m_{top}|$ for j_t, hardest-p_T light jet is j_s

Reconstruct neutrino with resonance-aware on-shell requirement $M^2_{\ell\nu^{rec}} = M^2_W$ (quadratic eq.):

- if complex sol., take real part
- if 2 real sol., minimize $|M_{j_t \ell\nu^{rec}} - m_{top}|$ ($M_{j_b \ell\nu^{rec}}$ if ambiguity for j_t)

Integrated cross-sections

Fiducial cross-sections
[Denner GP Schwan 2207.11264]

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

Contribution	Default setup σ [fb]	δ [%]	Z-peak setup σ [fb]	δ [%]
$\mathcal{O}(\alpha^6) = \text{LO}$	$0.6416\ ^{+8.9\,\%}_{-13.5\,\%}$	100.0	$0.5846\ ^{+9.0\,\%}_{-13.5\,\%}$	100.0
$\mathcal{O}(\alpha_s\alpha^6)$	0.1987(5)	31.0	0.1788(5)	30.6
$\mathcal{O}(\alpha^7)$	−0.0416(6)	−6.5	−0.0499(6)	−8.5
NLO QCD	$0.8402(5)\ ^{+8.6\,\%}_{-3.9\,\%}$	131.0	$0.7634(5)\ ^{+8.6\,\%}_{-3.9\,\%}$	130.6
NLO EW	$0.5999(6)\ ^{+9.4\,\%}_{-13.9\,\%}$	93.5	$0.5348(6)\ ^{+9.4\,\%}_{-13.9\,\%}$	91.5
NLO QCD+EW	$0.7986(8)\ ^{+9.4\,\%}_{-4.2\,\%}$	124.5	$0.7135(8)\ ^{+9.8\,\%}_{-4.4\,\%}$	122.0

Z-peak setup: $81\text{GeV} < M_{e^+e^-} < 101\text{GeV}$ (default: $M_{e^+e^-} > 30\text{GeV}$).

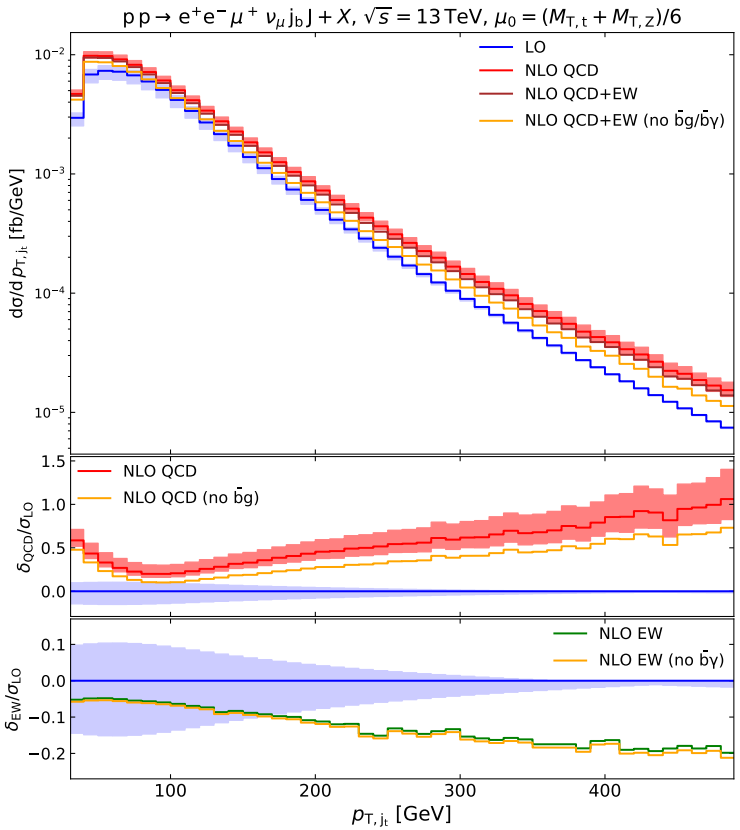
Off-shell [Denner GP Schwan 2207.11264] vs on-shell [Pagani et al. 2006.10086] in Z-peak setup: same EW correction (relative to NLO QCD), differences at NLO QCD.

	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 $\bar{b}\gamma$, $\bar{b}g$ channels

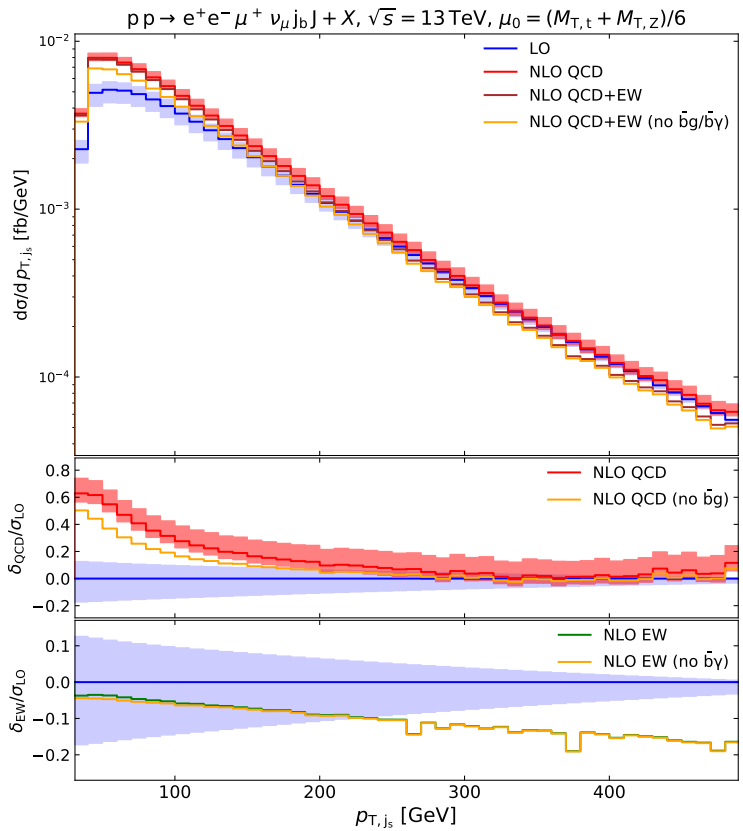
Transverse-momentum of jets

Top-decay jet



- increasing positive QCD corrections (up to 100%) due to LO suppression
- EW-Sudakov enhancement in the tail

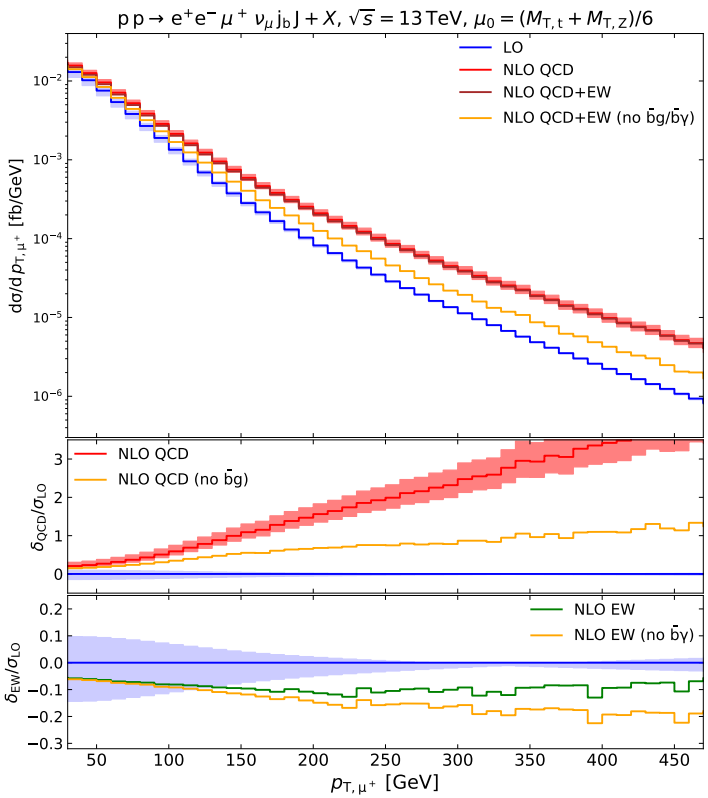
Spectator jet



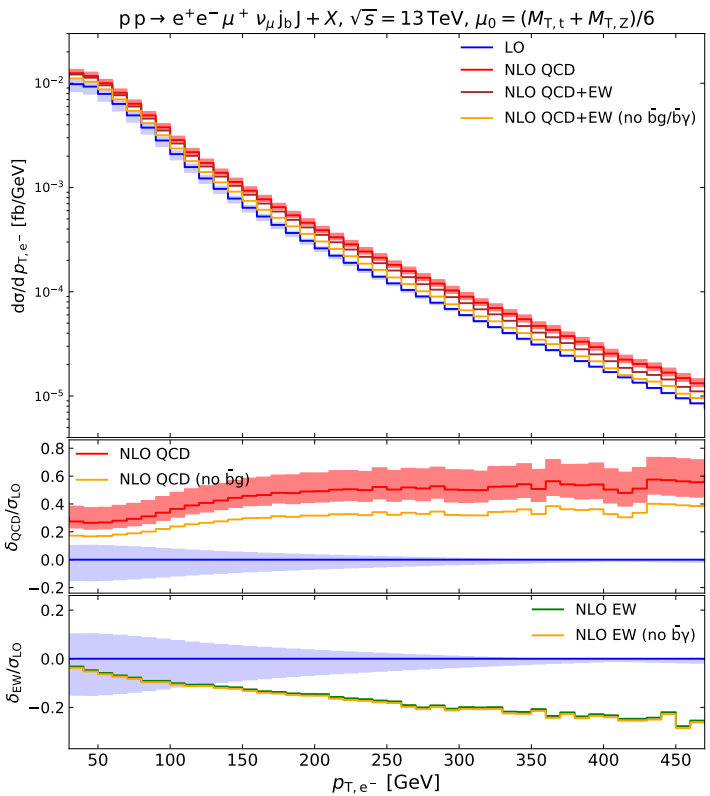
- decreasing QCD corrections ($\to 0$ at large p_T), no LO suppression
- tZ system recoils against j_s (Z typically soft or close to top)

Transverse-momentum of leptons

Antimuon (top-quark decay)



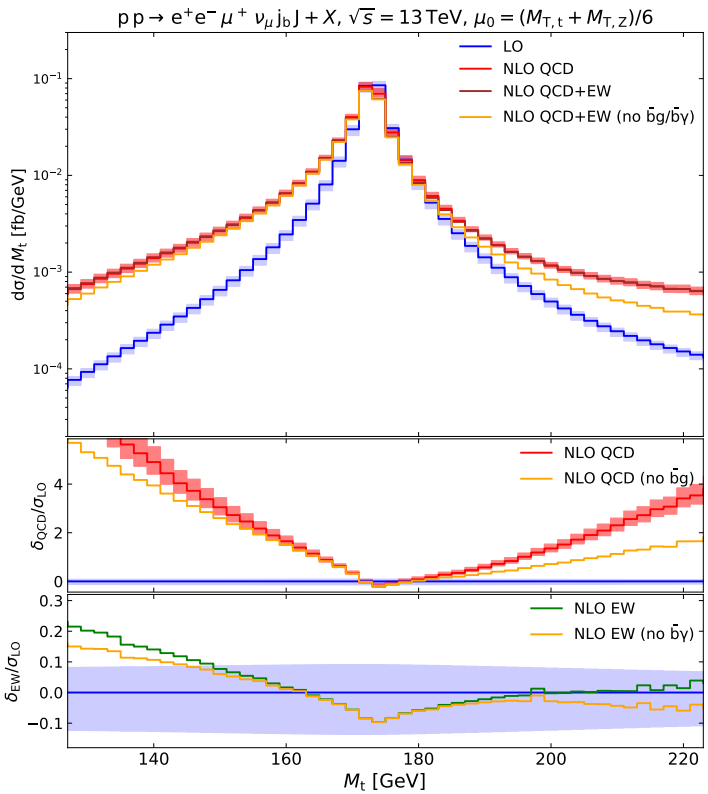
Electron (Z-boson decay)



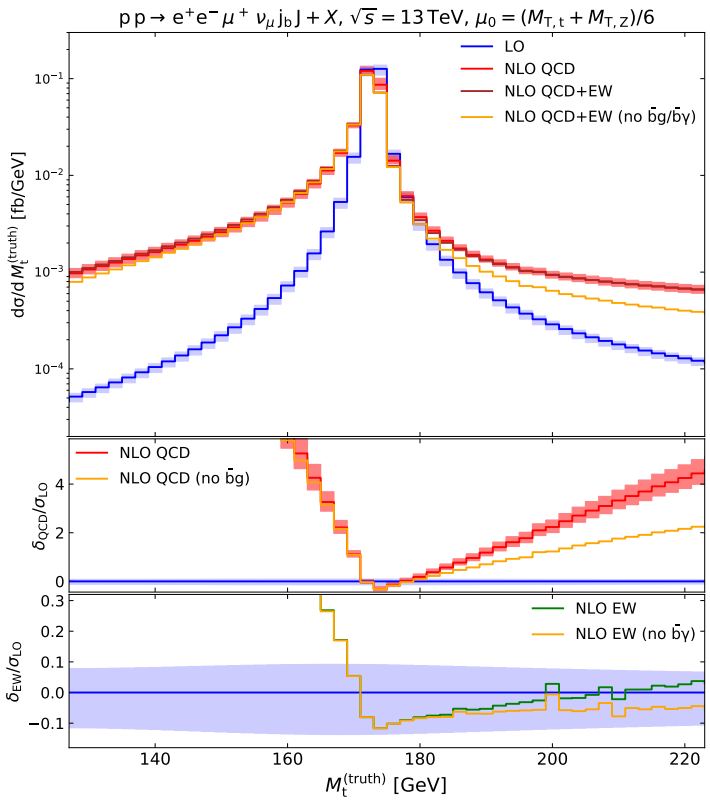
- EW corr. flat for μ^+: $\bar{\text{b}}\gamma$ contributions cancel NLO EW to LO channels.
- dominance of EW Sudakov logs for e^-
- QCD effects stronger for μ^+ than for Z-decay leptons

Invariant-mass of the top quark

Reconstructed top quark



MC-truth top quark

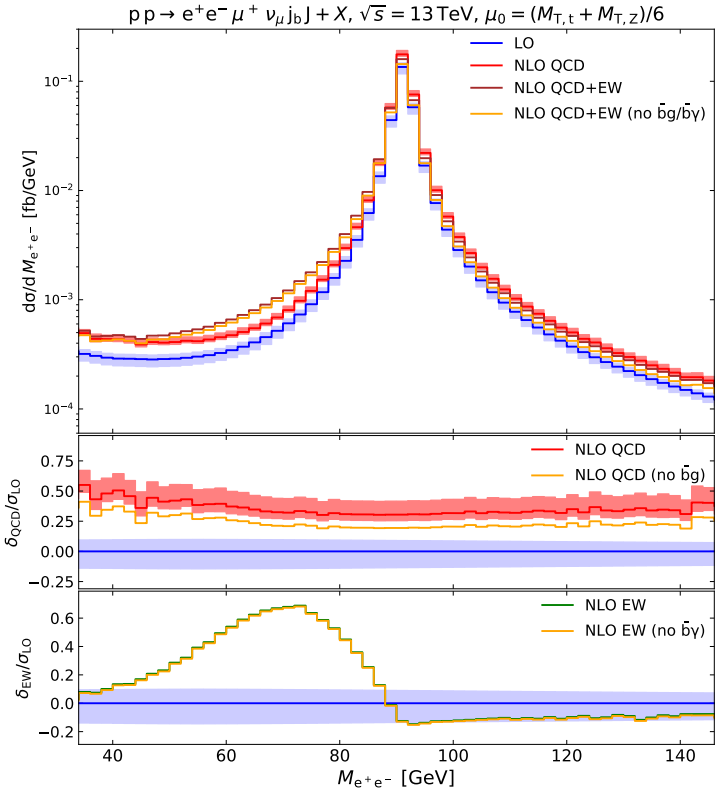


Recontruction mostly affects radiative-return tail at low mass (both EW and QCD)

Negative NLO corr. at peak, positive otherwise

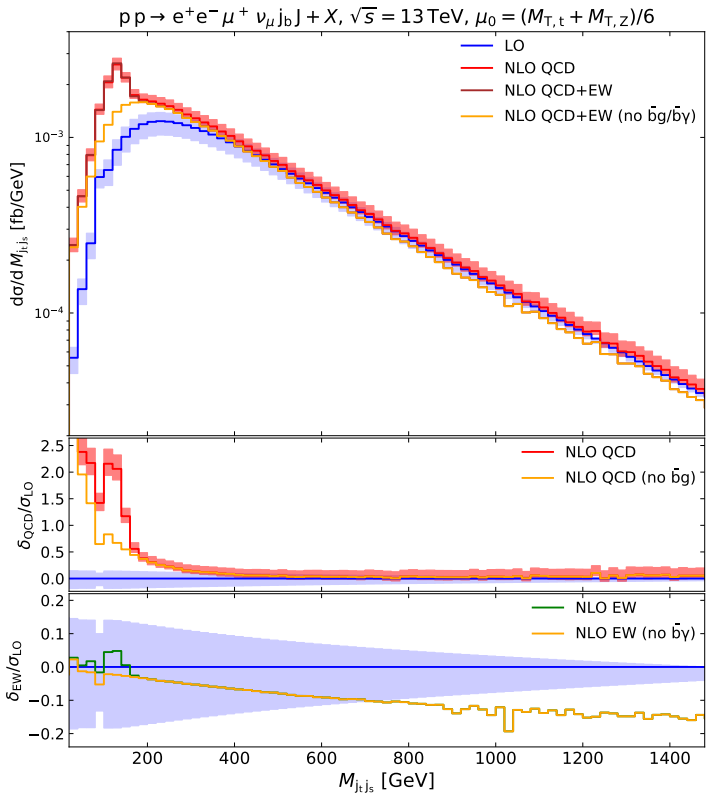
Invariant-mass of the Z boson and the di-jet system

Z-boson



- rather flat QCD corrections
- large EW radiative return below peak (soft photons)

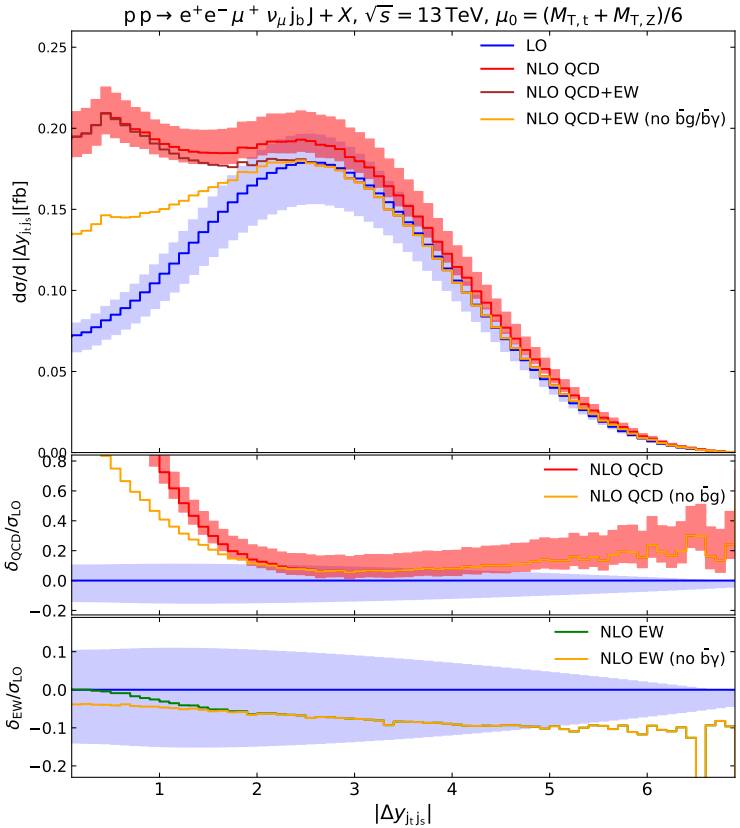
Di-jet



- hadronic-antitop peak at 165GeV (below m_{top}, owing to jet-identification)

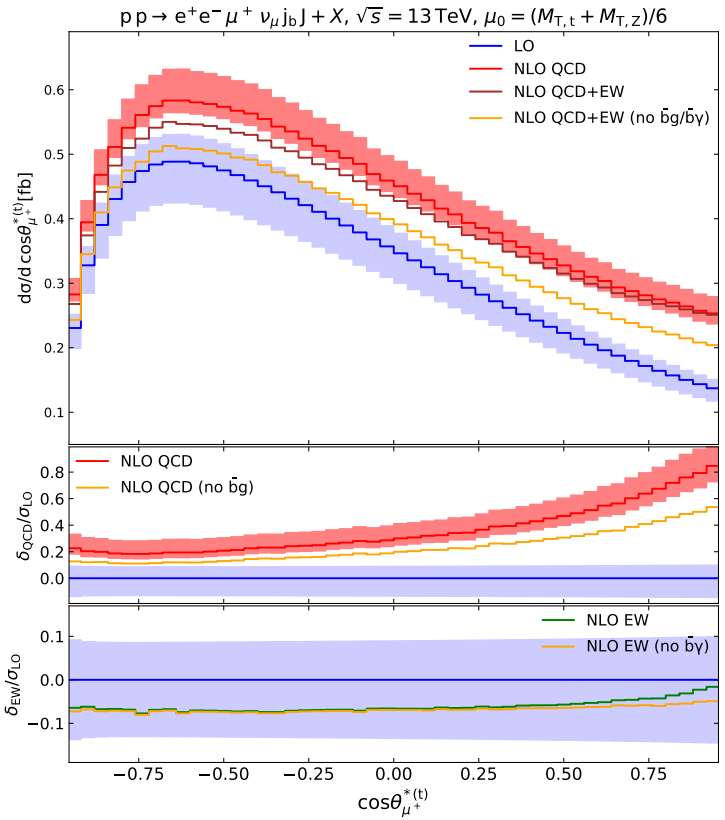
Rapidity and angular observables

Rapidity separation between top-decay jet and spectator jet



- tZ topology peaks at $|\Delta y_{j_t j_s}| \approx 2.5$
- large hadronic-antitop contamination for $|\Delta y_{j_t j_s}| < 1$)

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



- definition similar to helicity basis
- depletion of anti-collinear region due to cuts, top-quark mostly left handed

Conclusions

Essential to properly model off-shell/decay effects in top-quark-associated processes for upcoming fiducial and differential LHC measurements .

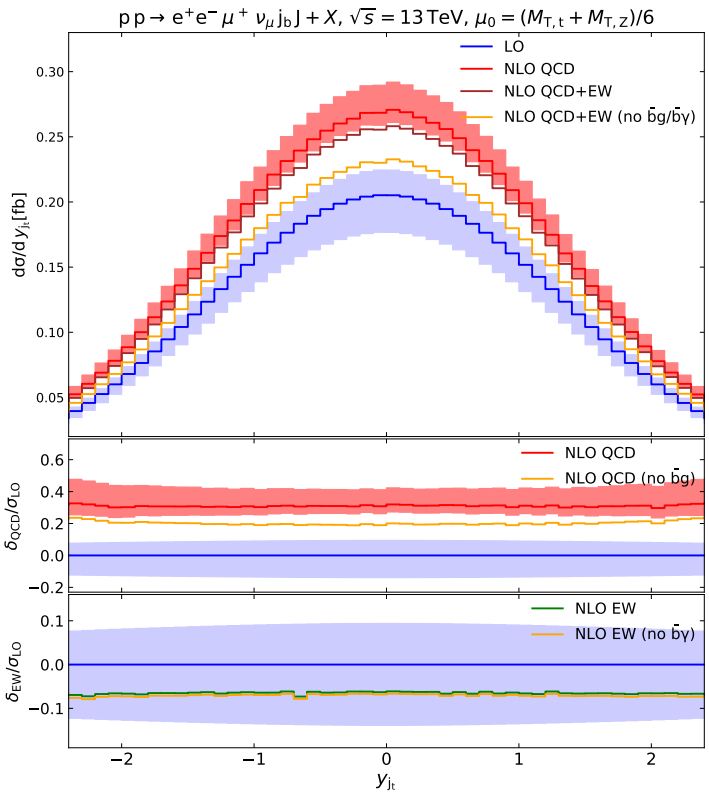
Take-home messages from tZj:

- QCD-scale uncertainties not so reduced owing to EW production mechanism
- NLO EW corrections negative and scale-independent
- EW-Sudakov enhancement in tails of p_T and mass distributions.
- opening of new sub-processes with higher-orders
- overlap with other resonance structures in fiducial volume ($\bar{t}WZ$)
- combined NLO may exceed scale-unc. of the NLO_{QCD}, not severe in tZj
- off-shell effects relevant in the tails of several distributions (mass, p_T)
- both EW and QCD corrections change distribution shapes (also angular ones)

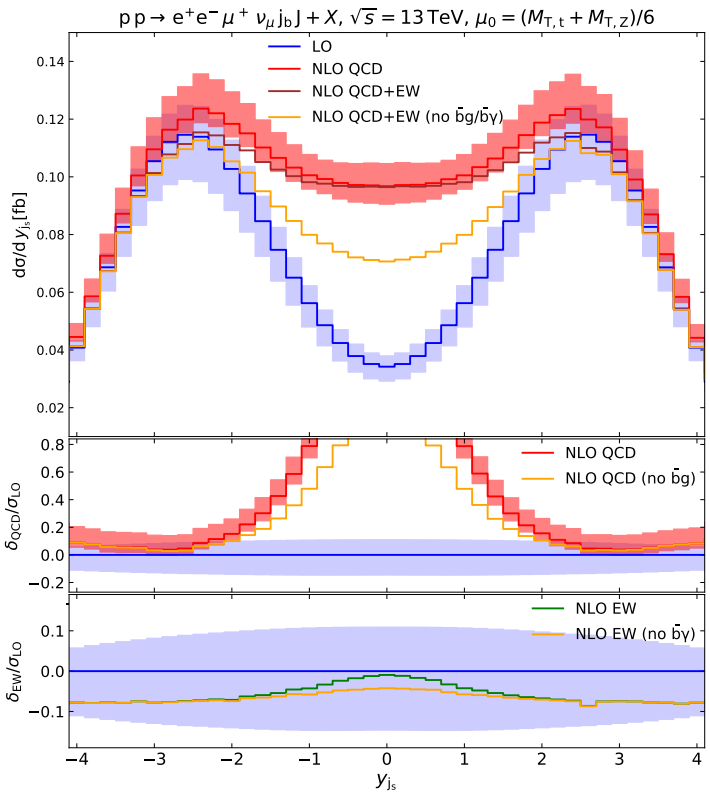
BACKUP

Rapidity distributions

Top-decay jet



Spectator jet



Partonic channels

ch.	$\delta^{\text{LO}}_{\text{sum}}$ [%]	$\delta^{\text{NLO EW}}_{\text{sum}}$ [%]	$\delta^{\text{NLO QCD}}_{\text{sum}}$ [%]	$\delta^{\text{NLO QCD+EW}}_{\text{sum}}$ [%]	$\delta^{\mathcal{O}(\alpha^7)}_{\text{ch.}}$ [%]	$\delta^{\mathcal{O}(\alpha_s\alpha^6)}_{\text{ch.}}$ [%]	$\delta^{\mathcal{O}(\alpha^7)+\mathcal{O}(\alpha_s\alpha^6)}_{\text{ch.}}$ [%]
$q_{\text{u}}\text{b}$	82.9	76.3	59.7	53.1	−8.0	−28.0	−36.0
$\text{g}q_{\text{u}}$			30.6	30.6			
$\bar{\text{b}}\text{g}$			11.1	11.1			
gb			10.4	10.4			
$\bar{q}_{\text{d}}\text{b}$	14.5	13.5	10.2	9.3	−6.4	−29.5	−35.9
$\bar{q}_{\text{d}}\text{g}$			5.5	5.5			
$\bar{q}_{\text{d}}q_{\text{u}}$	1.9	1.7	3.0	2.8	−10.5	54.7	44.2
γb		0.7		0.7			
$\bar{\text{b}}\gamma$		0.6		0.6			
$\bar{\text{b}}q_{\text{u}}$	0.6	0.5	0.5	0.4	−13.0	−19.3	−32.3
γq_{u}		0.1		0.1			
$\bar{\text{b}}\bar{q}_{\text{d}}$	0.1	0.1	0.1	0.1	−11.1	−22.3	−33.4
$\bar{q}_{\text{d}}\gamma$		0.02		0.02			