QCD NLO corrections to $t\bar{t}Z$ production at the LHC including leptonic decays

Off-shell and parton-shower effects in $t\bar{t}Z$ signatures

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$t\bar{t}Z$ at the LHC

- Crucial for a complete measurement of top-quark EW couplings

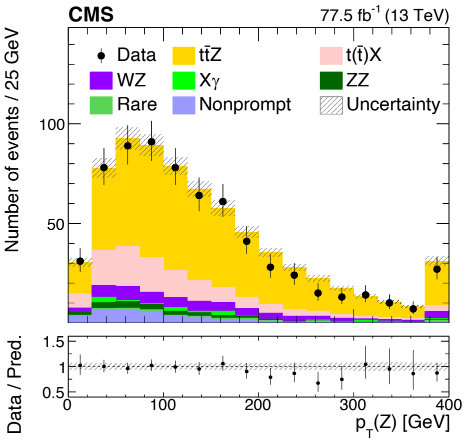
  (together with $t\bar{t}W$, $t\bar{t}\gamma$, $t\bar{t}H$, single-top processes, …)

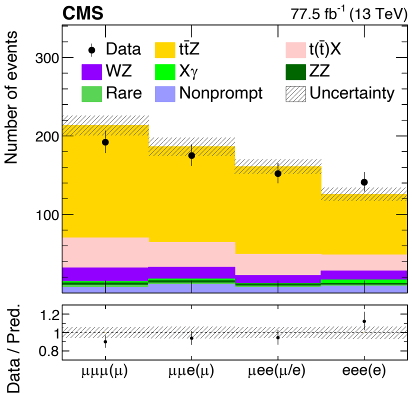
- Top-quark couplings @ (HL-)LHC as indirect probe of BSM physics
  - Top-quark, unique probe
  - (HL-)LHC: unprecedented number of top quarks
  - Unrivaled access to top-quark physics till future TeV-energy lepton collider
- Background to $t\bar{t}H$
  - Need accurate modeling of both $t\bar{t}Z$ and $t\bar{t}W$ to measure $t\bar{t}H$ ($\longrightarrow y_t$)
- Background to many searches of BSM physics
  - signatures with multi-leptons, b jets, and missing energy

Received focused experimental and theoretical attention

LHC Run2: access to event distributions

See talk by J. van der Linden

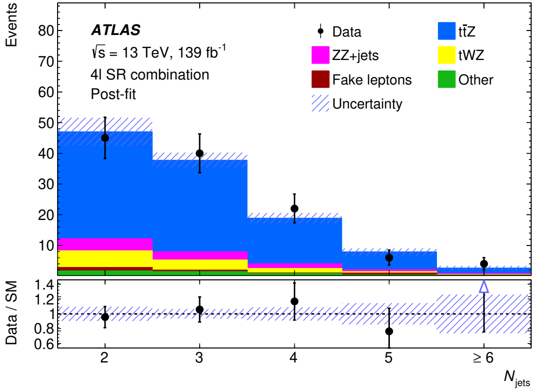


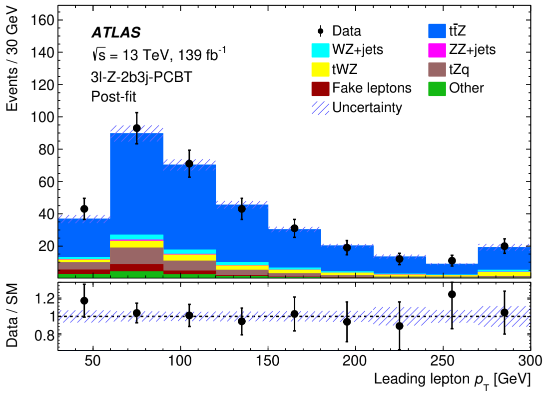


tt̄Z searches in 3l and 4l signatures

CMS [arXiv:1907.11270]

Interest in modelling tt̄Z leptonic signatures





ATLAS [arXiv:2103.12603]

Interpreting $t\bar{t}Z$ measurements ...

Anomalous top couplings

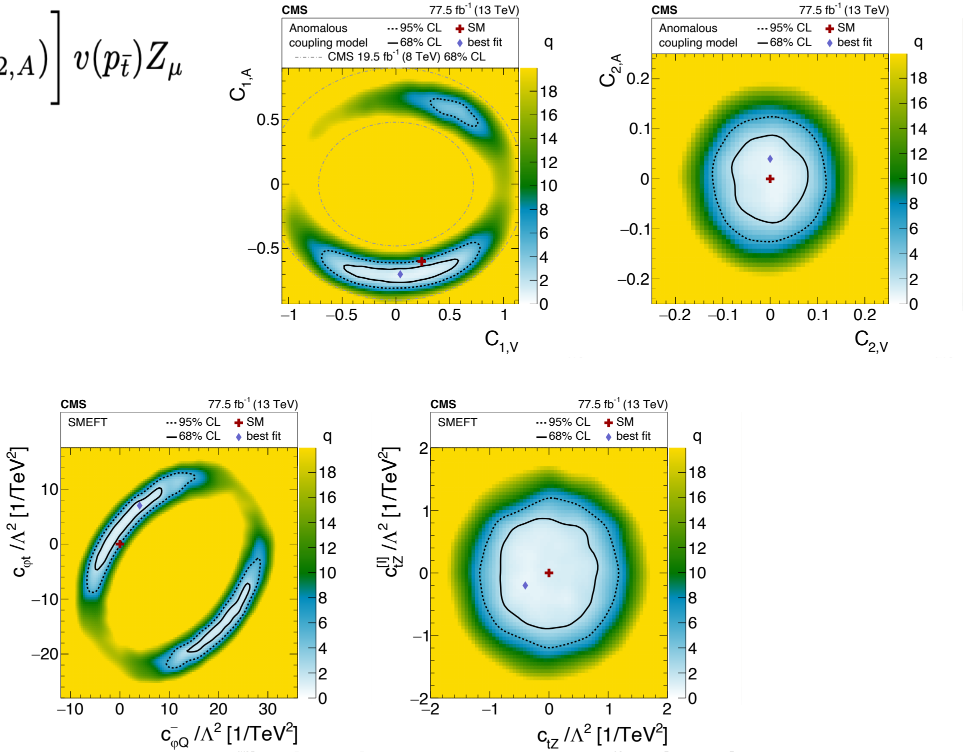
$$\mathcal{L} = e\bar{u}(p_t)\left[\gamma^\mu(C_{1,V}+\gamma_5 C_{1,A}) + \frac{i\sigma^{\mu\nu}q_\nu}{M_Z}(C_{2,V}+i\gamma_5 C_{2,A})\right]v(p_{\bar{t}})Z_\mu$$

Effective operators

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \left(\frac{1}{\Lambda^2}\sum_i C_i O_i + \text{h.c.}\right) + O(\Lambda^{-4})$$

$$\begin{aligned}
O_{uZ} &= -s_W O_{uB} + c_W O_{uW}\\
O_{uB} &= (\bar{q}\sigma^{\mu\nu}u)(\epsilon\varphi^* B_{\mu\nu})\\
O_{uW} &= (\bar{q}\tau^I\sigma^{\mu\nu}u)(\epsilon\varphi^* W^I_{\mu\nu})\\
O_{\varphi u} &= (\bar{u}\gamma^\mu u)(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)\\
O^-_{\varphi q} &= O^1_{\varphi q} - O^3_{\varphi q}\\
O^1_{\varphi q} &= (\bar{q}\gamma^\mu q)(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)\\
O^3_{\varphi q} &= (\bar{q}\tau^I\gamma^\mu q)(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)
\end{aligned}$$

...

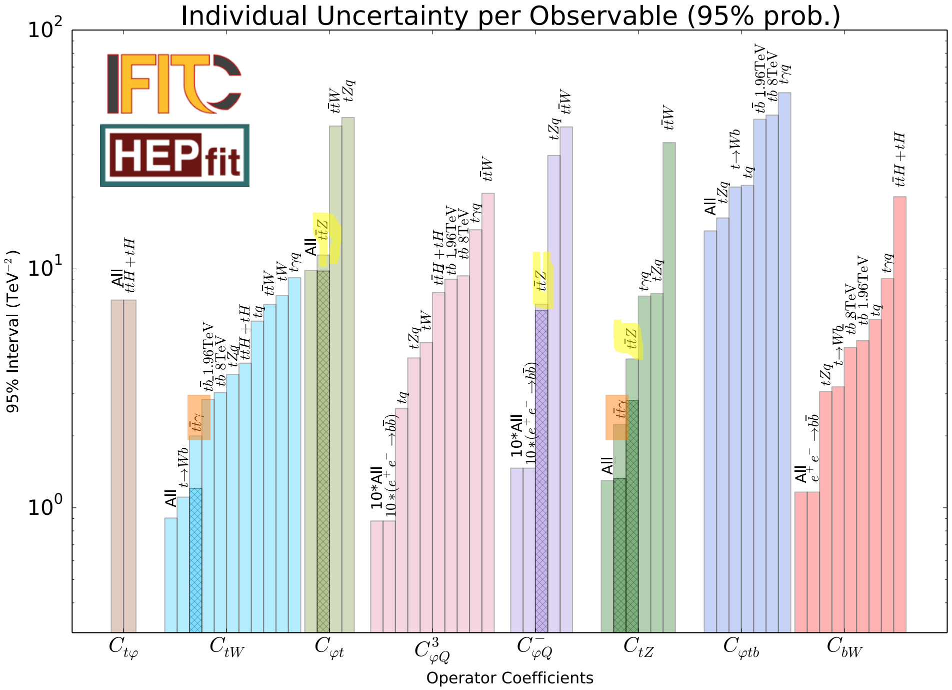


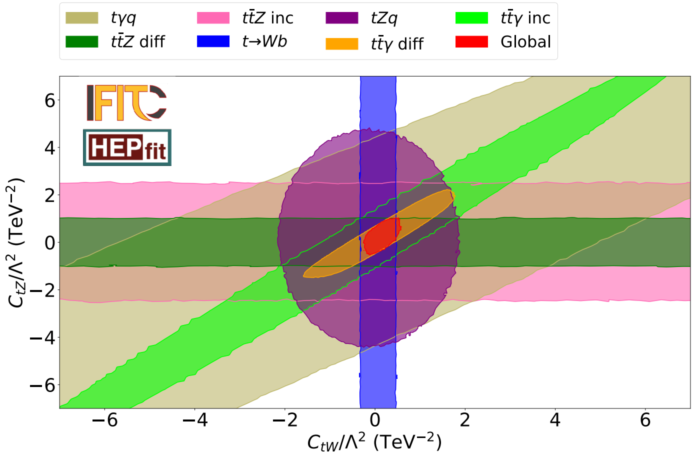
CMS [arXiv:1907.11270]

… through multiple and more sensitive probes

Global fits of top observables

V Miralles, M. Miralles López, M. Moreno Llacer, A. Peñuelas, M. Perelló, M. Vos [arXiv:2107.13917]





Kinematic distributions add substantial constraining power

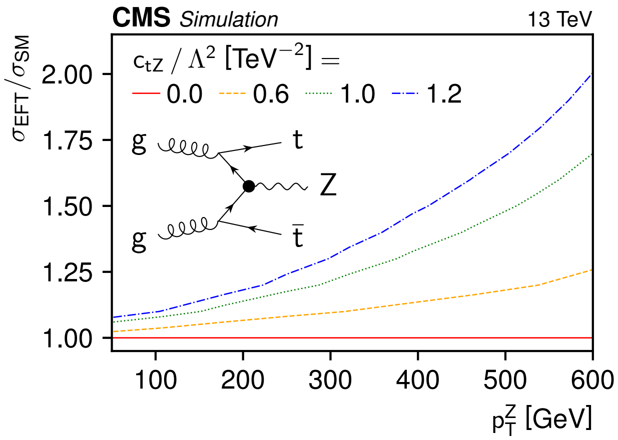
Accurate modelling of $t\bar{t}Z$ differential cross sections and signatures is crucial

… and through new explorations

See talks by J. Wilson, M. Madigan, J. McFayden

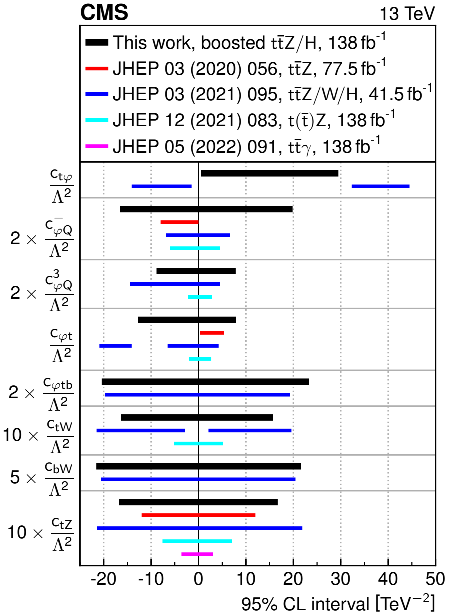
Top+additional leptons

Top pair + boosted Z/H

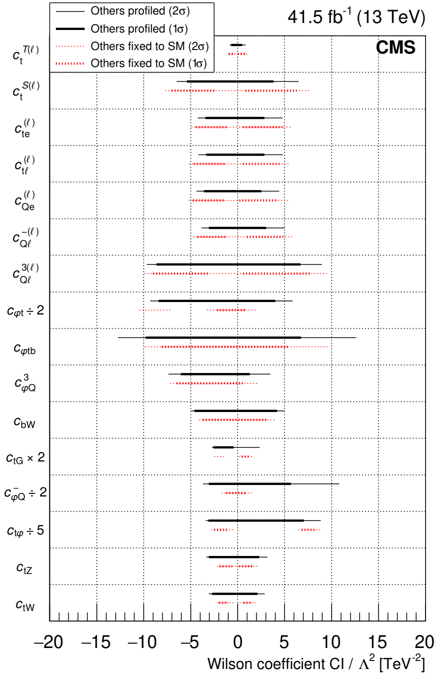


$$\delta\eta_{SM} \sim g^2_{BSM}\frac{E^2}{M^2}$$

Effects in tails of distributions but also anomalous shapes



[CMS: arXiv:2208.12837]



[CMS: arXiv:2012.04120]

Pointing to the need for precision in modelling the complex signatures from $t\bar{t}$+X processes in regions where on-shell calculations may not be accurate enough

$t\bar{t}Z$ hadronic production: theory overview

- On-shell ttZ: NLO QCD and EW
  - Lazopoulos, McElmurry, Melnikov, Petriello, PLB 666 (2008) 62 [0804.2220]
  - Kardos, Trocsanyi, Papadopoulos, PRD 85 (2012) 054015 [1111.0610]
  - Maltoni, Pagani, Tsinikos, JHEP 02 (2016) 113 [1507.05640]
  - Frixione, Hirschi, Pagani, Zaro, JHEP 06 (2015) 184 [1504.03446]
- On-shell ttZ: NNLL resummation
  - Broggio, Ferroglia, Ossola, Pecjak, Sameshima, JHEP 04 (2017) 105 [1702.00800]
  - Kulesza, Motyka, Schwartländer, Stebel, Theeuwes, Eur. Phys. J. C 79 (2019) 249 [1812.08622]
  - Broggio, Ferroglia, Frederix, Pagani, Pecjak, Tsinikos, JHEP 08 (2019) 039 [1907.04343]
  - Kulesza, Motyka, Schwartländer, Stebel, Theeuwes, Eur. Phys. J. C 80 (2020) 428 [2001.03031]
- On-shell ttZ: NLO QCD+PS
  - Garzelli, Kardos, Papadopoulos, Trocsanyi, PRD 85 (2012) 074022 [1111.1444] (PowHel)
  - Garzelli, Kardos, Papadopoulos, Trocsanyi, JHEP 11 (2012) 056 [1208.2665] (PowHel)
  - Process available in MG5_aMC@NLO, Sherpa, and Powheg-Box as well.

On-shell $t\bar{t}Z$: theory vs exp at a glance

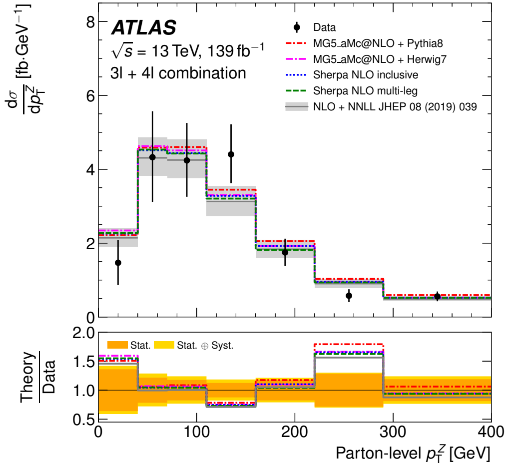
See talk by J. van der Linden

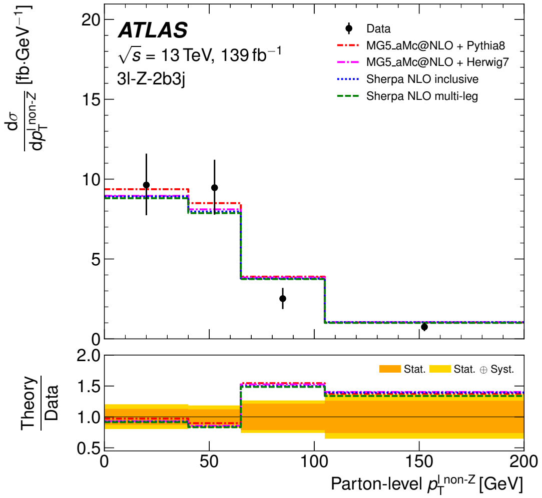
σ_{ttZ}[pb]

NLO+NNLL: $0.811^{+0.089(+11.0\%)+0.019(+2.4\%)}_{-0.078(-9.6\%)-0.019(-2.4\%)}$ [Broggio et al. arXiv:1907.04343]

ATLAS: $0.99 \pm 0.05\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst})$ [arXiv:2103.12603]

CMS: $0.95 \pm 0.05\,(\mathrm{stat}) \pm 0.06\,(\mathrm{syst})$ [arXiv:1907.11270]





Moving forward:

- ➢ Reduce theoretical systematics
- ➢ Describe full events more faithfully
  - ➢ Leptonic (and jet) observables
  - ➢ Z and tops off-shell

$pp \rightarrow t\bar{t}Z$: modeling events beyond on-shell production

- $pp \rightarrow t\bar{t}l^+l^-$ (l=lepton): NLO QCD + PS
  - On-shell top quarks with LO spin-correlations in decay ($t \rightarrow b\, l\, \nu$) (using NWA)
  - Include $Zt\bar{t}$ off-shell effects and $Zt\bar{t}/\gamma t\bar{t}$ interference
  - Interfaced with PS in the Powheg-Box-V2 framework (including on-shell $t\bar{t}Z$)

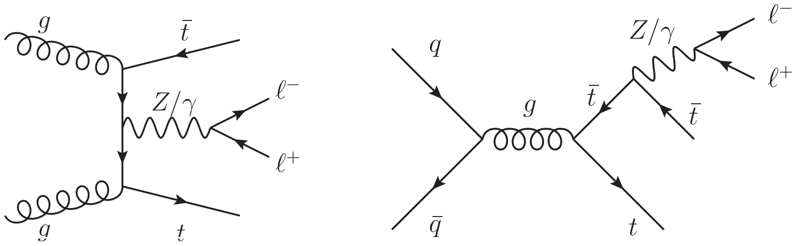
M. Ghezzi, B. Jäger, S. Lopez, L. Reina. D. Wackeroth, [arXiv:2112.08892]]

- Fully off-shell $pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$: NLO QCD
  - Both double-, single-, and non resonant contributions, interferences, and off-shell effects of top, Z, W, and photon.
  - All heavy resonances described by Breit-Wigner propagators.
  - Comparison with NWA calculation.

See poster by J. Nasufi

G. Bevilacqua, H.B. Hartanto, M. Kraus, J. Nasufi, M. Worek [arXiv:2203.15688]

$pp \longrightarrow t\bar{t}l^+l^-$ matched to parton shower



+ NLO QCD + PS

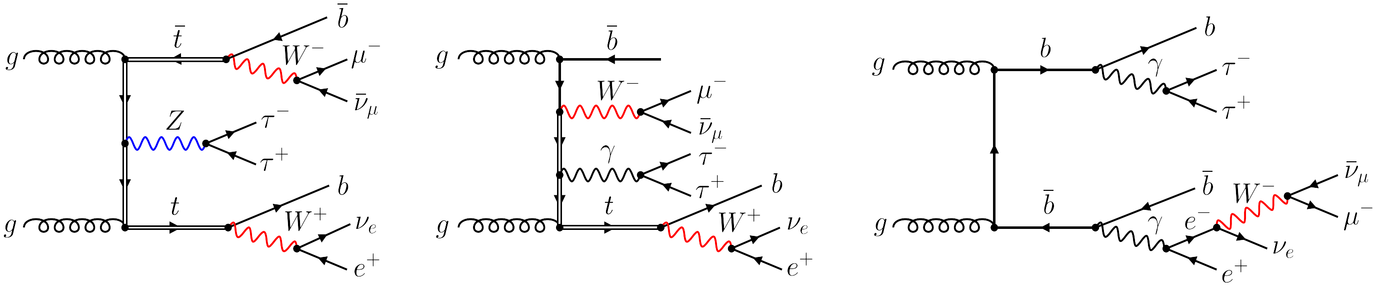
- One-loop matrix elements from NLOX [Honeywell, et al., arXiv:1812.11925]
- EW G_μ input scheme (G_μ,m_Z,m_W). Other inputs: m_t, Γ_t, Γ_W, Γ_Z
- Studied (μ_R,μ_F) scale dependence wrt to both a fixed and dynamical central scale (7-point variation)

$$\mu_0 = \frac{2m_t + m_Z}{2} \qquad \mu_0 = \frac{M_T(e^+e^-) + M_T(t) + M_T(\bar{t})}{3}$$

- PDF: CT18NLO with $\alpha_s(m_Z)$=0.118 ($\alpha_s(\mu)$ in Msbar, 5FS)
- PS: Pythia8

- Specific signature studied: $t\bar{t}e^+e^-$ with $t \longrightarrow b\,\mu\,\nu_\mu$ (with LO spin correlation)
  - $p_T^{e,\mu} > 10$ GeV, $|\eta^{e,\mu}| < 2.5$
  - $|M_{ee} - m_Z| < 10$ GeV (to mimic exp. fiducial region)

$pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$ full off-shell description



+ NLO QCD

- NLO QCD corrections obtained in the HELAC-NLO framework [Bevilacqua et al., arXiv:110.1499]
  - One-loop matrix elements with HELAC-1LOOP. Real radiation with HELAC-DIPOLES.
- EW G_μ input scheme (G_μ, m_Z, m_W). Other inputs: m_t, Γ_W, Γ_Z, Γ_t (LO, NLO, unstable-W and NWA)
- Unstable particles in complex mass scheme.
- Studied PDF dependence. Main results presented for NNPDF3.1
- Studied (μ_R,μ_F) scale dependence wrt to both a fixed and dynamical central scale (7-point variation)

$$\mu_0 = \frac{2m_t + m_Z}{2} \qquad \mu_0 = \frac{H_T}{3} \text{ for } H_T = \sum_i p_{T,i}$$

- Specific signature studied: $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$
  - $p_T^l > 20$ GeV, $|y_l| < 2.5$, $\Delta R_{ll} > 0.4$
  - $p_T^b > 20$ GeV, $|y_b| < 2.5$, $\Delta R_{bb} > 0.4$
  - $p_T^{miss} > 40$ GeV

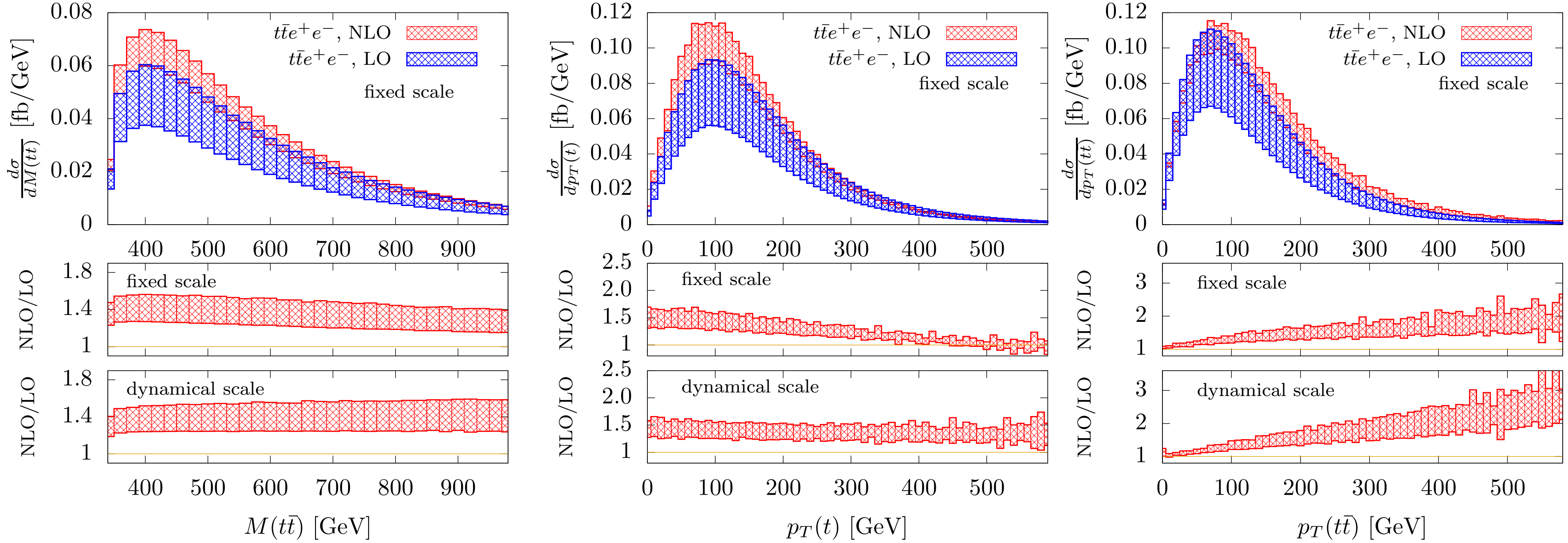
Theoretical systematic: pp $\longrightarrow t\bar{t}e^+e^-$

NLO QCD corrections are substantial and reduce the overall perturbative uncertainty

$$\sigma^{\rm LO}_{t\bar{t}e^+e^-} = 15.9^{+5.1}_{-3.6}\ \left(15.8^{+5.0}_{-3.5}\right)\ {\rm fb}$$
$$\sigma^{\rm NLO}_{t\bar{t}e^+e^-} = 21.9^{+2.0}_{-2.4}\ \left(22.1^{+2.2}_{-2.5}\right)\ {\rm fb}$$

⟵ Fixed and dynamic scales give very similar results (dyn. scale in parenthesis)

No uniform rescaling: different effects in different phase-space regions



Theoretical systematics: $pp \longrightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$

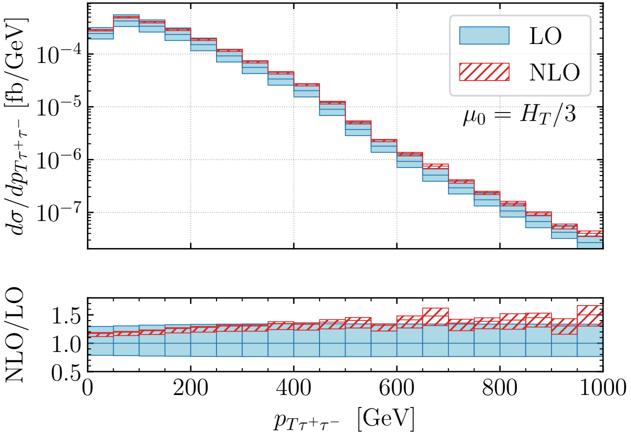
Very small residual systematic uncertainty at NLO QCD

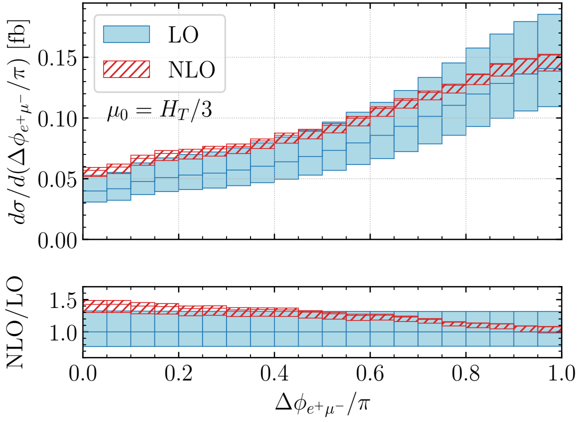
$$\sigma^{\rm LO}_{\rm full\ off\text{-}shell} = 80.32^{+25.51(32\%)}_{-18.02(22\%)} \left(76.98^{+24.30(32\%)}_{-17.17(22\%)}\right) \text{ab}$$

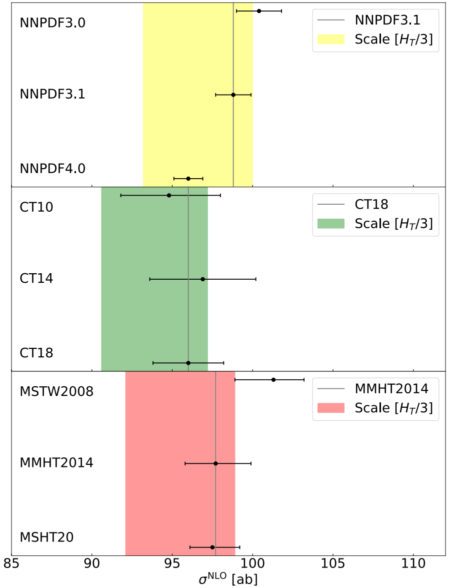
$$\sigma^{\rm NLO}_{\rm full\ off\text{-}shell} = 98.88^{+1.22(1\%)}_{-5.68(6\%)} \left(97.86^{+1.08(1\%)}_{-6.16(6\%)}\right) \text{ab}$$

Dynamic scale preferred over full range of distributions.

Not a uniform rescaling.

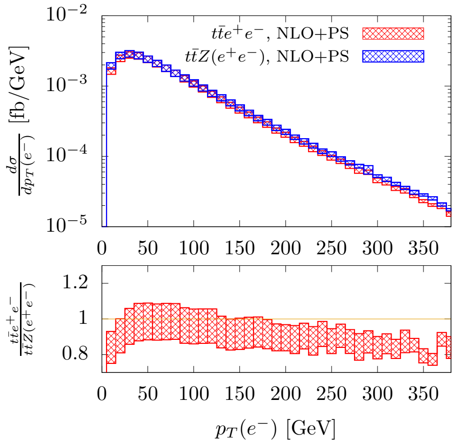


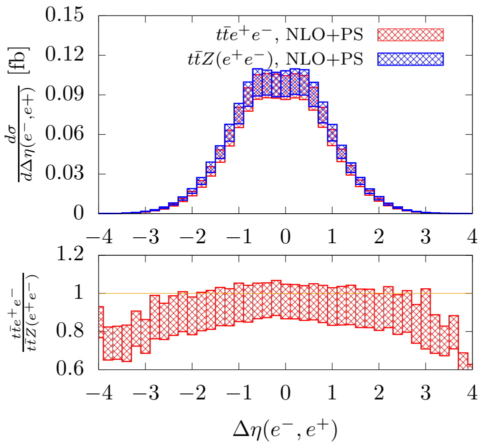




Small dependence on PDF

pp → $t\bar{t}e^+e^-$: partial off-shell and spin-correlation effects + PS





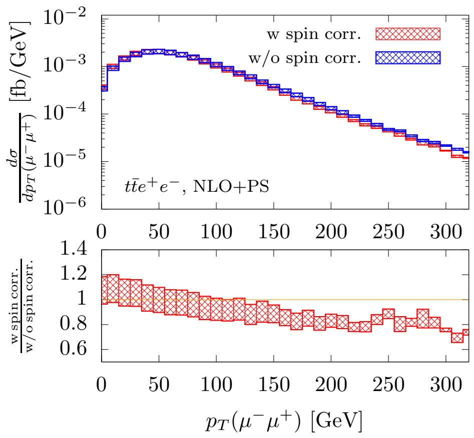
Compare $t\bar{t}Z$ and $t\bar{t}e^+e^-$ keeping stable top quarks:

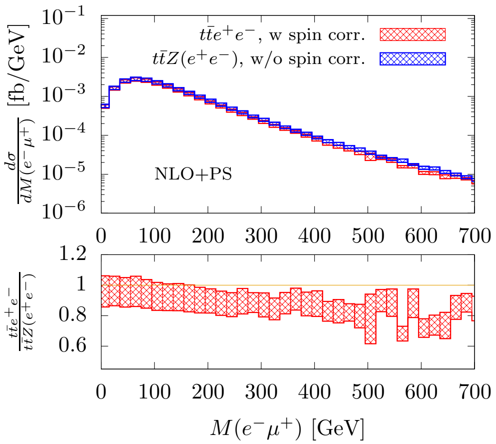
- Effects of off-shell Z
- Effects of e^+e^- spin correlations

10-20% effect in high p_T region and in the large absolute-value pseudorapidity difference region

Compare $t\bar{t}e^+e^-$ with and without modeling of top decays (NWA with LO spin correlations).

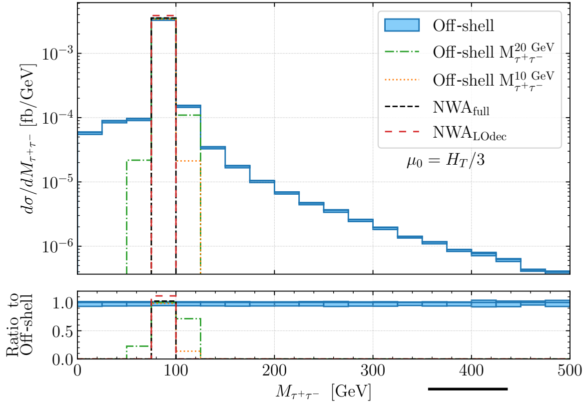
10-20% visible effects in the tails of distributions



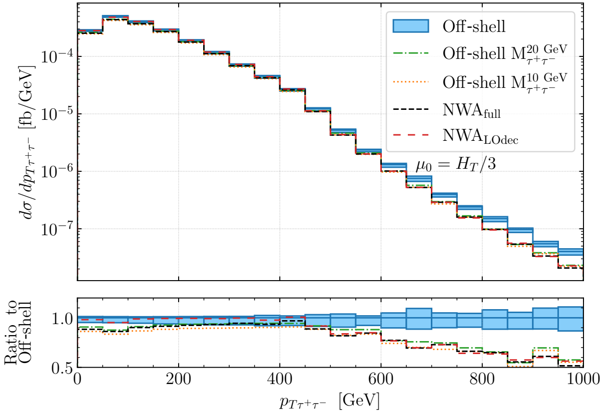


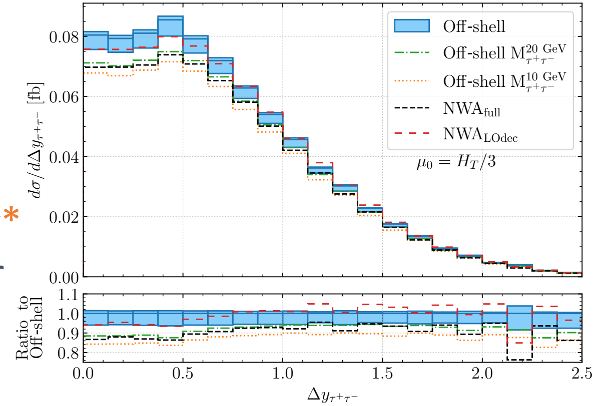
$pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b \bar{b} \tau^+ \tau^-$: fully off-shell vs NWA

Very thorough study of modelling effects



Modelling	σ_i^{NLO} [ab]	$\sigma_i^{\mathrm{NLO}}/\sigma_{\mathrm{NWA_{full}}}^{\mathrm{NLO}} - 1$
Off-shell	98.88	+11.4 %
Off-shell $M^{25\,\mathrm{GeV}}_{\tau^+\tau^-}$	91.00	+2.5 %
Off-shell $M^{20\,\mathrm{GeV}}_{\tau^+\tau^-}$	89.96	+1.4 %
Off-shell $M^{15\,\mathrm{GeV}}_{\tau^+\tau^-}$	88.44	−0.3 %
Off-shell $M^{10\,\mathrm{GeV}}_{\tau^+\tau^-}$	85.74	−3.4 %
$\mathrm{NWA_{full}}$	88.75	–
$\mathrm{NWA_{LOdec}}$	96.74	+9.0 %





- Large off-shell effects on total cross section (11%) originating from $t\bar{t}\gamma^*$ contribution (including Z/γ^* interference): studied imposing narrower $|M_{\tau\tau}-m_Z| < X$ (X=25,20,15,10 GeV) cut.
  Less evident in $t\bar{t}l^+l^-$ study because it used X=10 GeV.
- Large effect from including NLO QCD corrections to top-quark decay (9%)
- Sizable off-shell effects in specific fiducial regions of differential distributions even with narrow window cut around the Z peak.

Conclusions

- Enabling the top-physics precision program of the (HL)-LHC is a priority since no other collider will reach the necessary energy to explore it for at least a few decades

- $t\bar{t}$+X (X=W, Z, γ, H) processes are challenging but uniquely capable of testing the presence of new physics (NP) effects in top-quark interactions.
  - They are interconnected and may need to be approached as a whole
    Aim for **global fits of classes of signatures**
  - NP that modifies top-quark interactions is most likely heavy ⟶ EFT approach
    Effects most likely **in tails or endpoint of kinematic distributions**
  - Off-shell and parton-shower effects can be large in this kinematic regions and need to be included.

- This talk has reviewed progress made with **two studies of off-shell effects** for the particular case of $t\bar{t}Z$ production, including leptonic decays, PS, and partial or full off-shell effects, and confirmed the importance of extending the modelling of $t\bar{t}Z$ events to include them.