Towards improved theoretical predictions for $t\bar{t}Z$ and $t\bar{t}W$ at the LHC

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DESY-HU Theory Seminar

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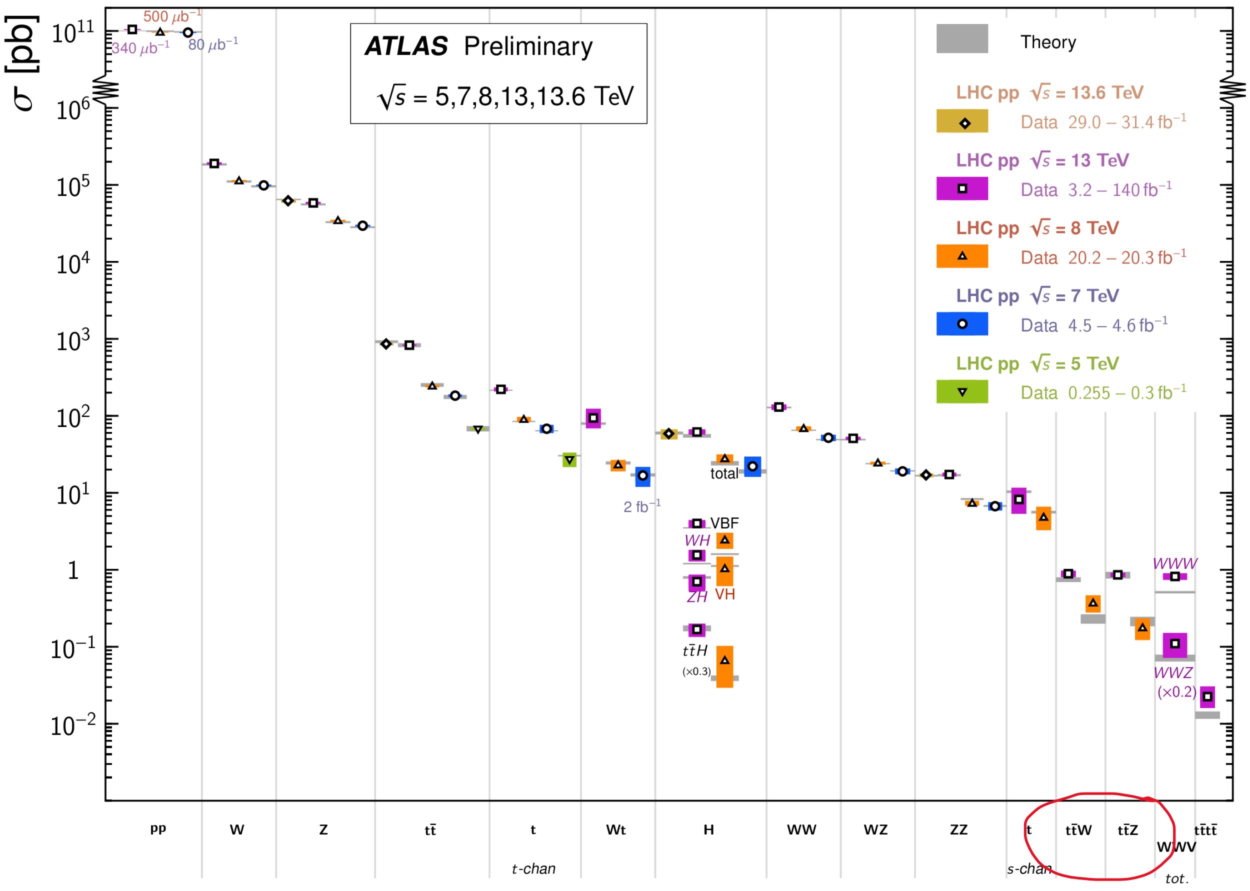
$t\bar{t}Z/W$ central to the (HL)LHC top-quark physics program

Standard Model Total Production Cross Section Measurements

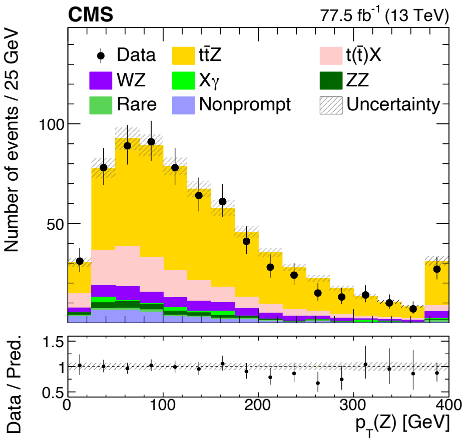
Status: October 2023

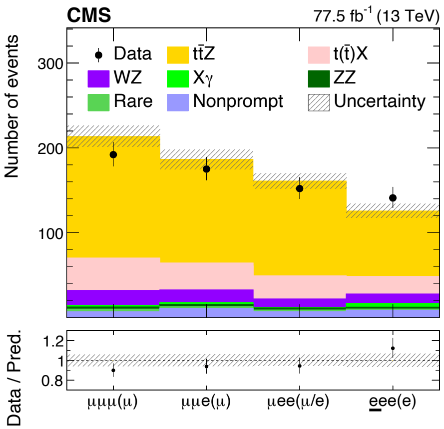


- Crucial for a complete measurement of top-quark EW couplings
  ($t\bar{t}Z$, together with $t\bar{t}\gamma$, $t\bar{t}H$, single-top processes, …)
- Top-quark couplings @ (HL-)LHC as indirect probe of BSM physics
  - Top-quark, unique probe
  - (HL-)LHC: unprecedented number of top quarks
  - Unrivaled 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

Have received focused experimental and theoretical attention

LHC Run2: access to event distributions

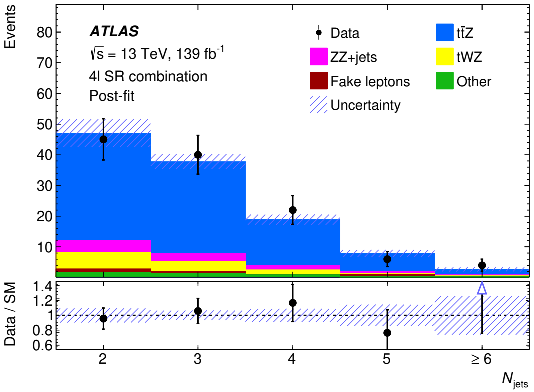


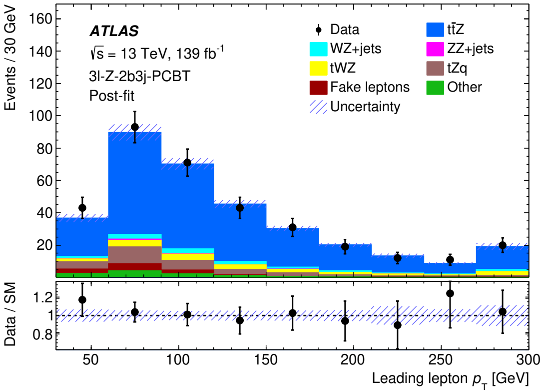


CMS [arXiv:1907.11270]

$t\bar{t}Z$ measurements in
3l and 4l signatures

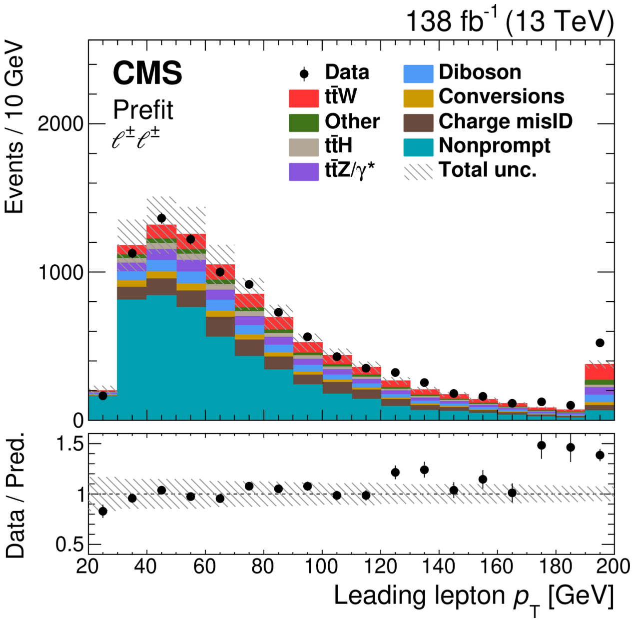
Interest in modelling $t\bar{t}Z$ leptonic signatures





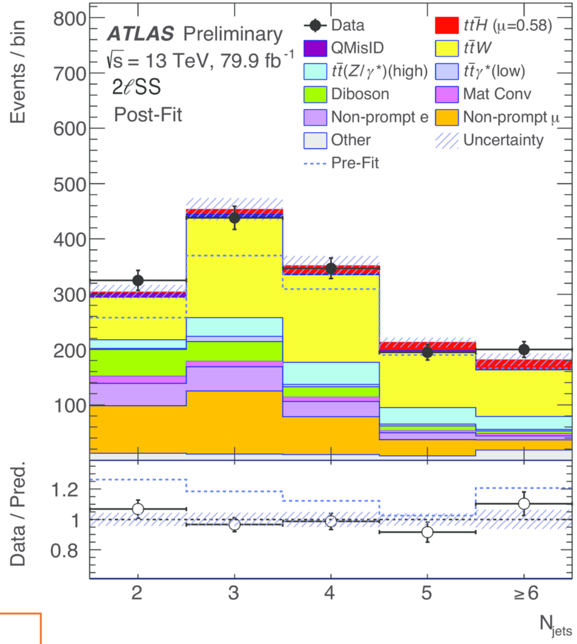
ATLAS [arXiv:2103.12603]

$t\bar{t}W$ measured in multilepton signatures, $2lSS$ and $3l$



CMS [arXiv:2208.06485]

Multilepton signatures, $2lSS$ and $3l$, also important in $t\bar{t}H$ searches



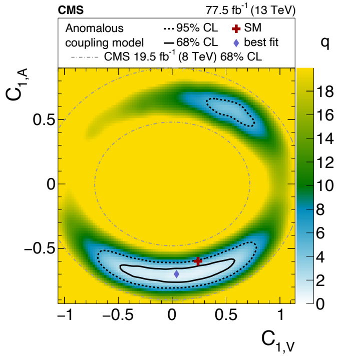
ATLAS-CONF-2019-045

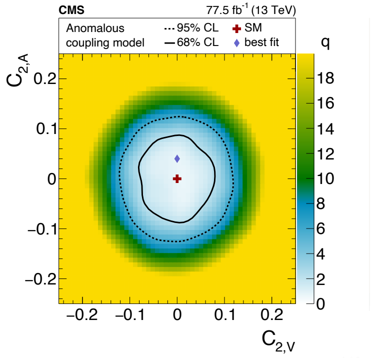
$t\bar{t}W$ background shows largest theory vs data tensions in multilepton signatures

Interpreting $t\bar{t}X$ measurements …

Anomalous top couplings

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



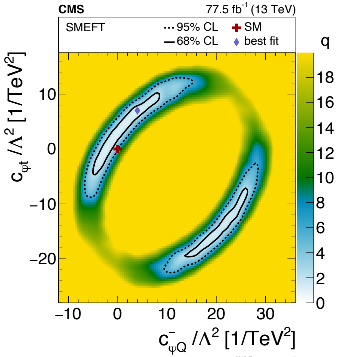


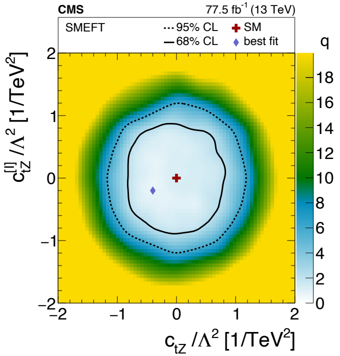
Effective operators

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

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

…



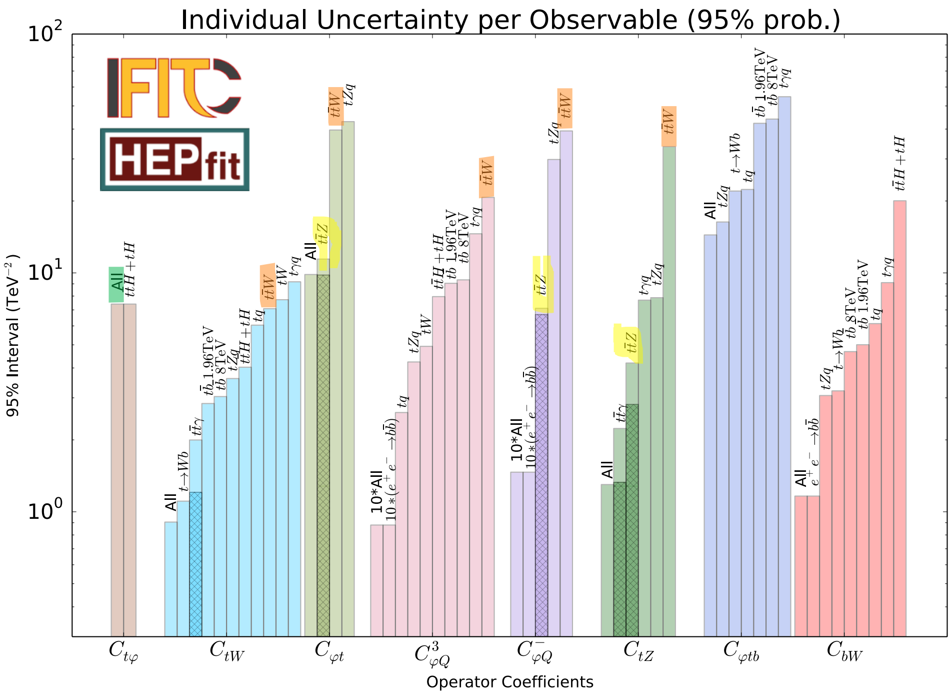


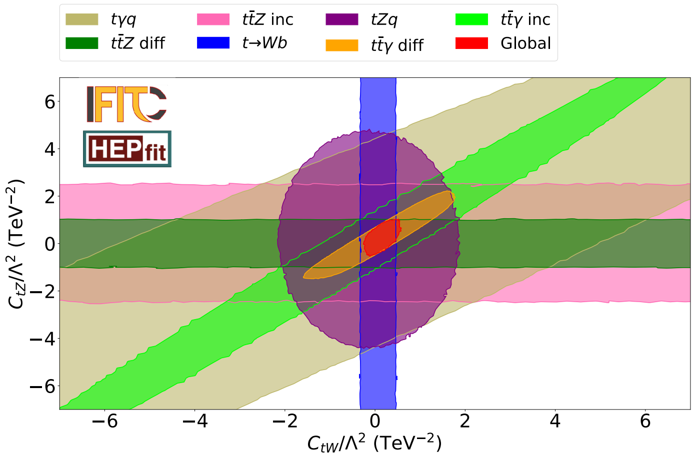
CMS [arXiv:1907.11270]

… through multiple probes

Global fits of top observables

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



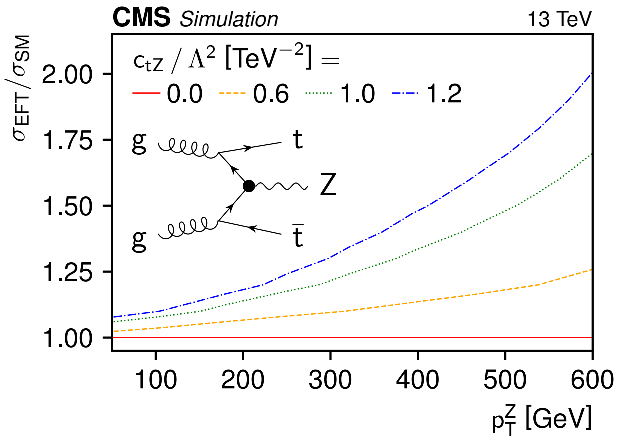


Kinematic distributions add substantial constraining power

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

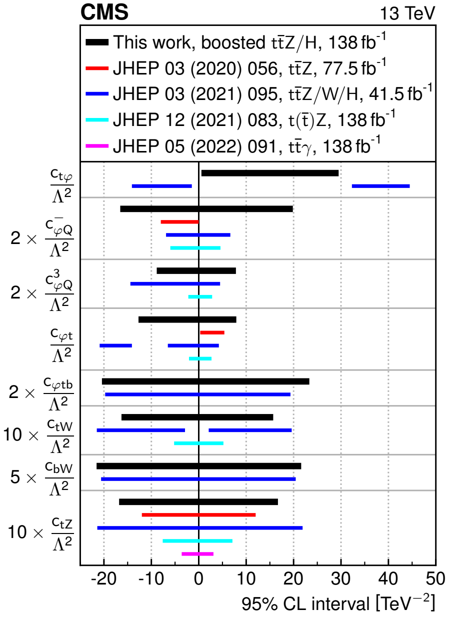
… and through new explorations

Top pair + boosted Z/H



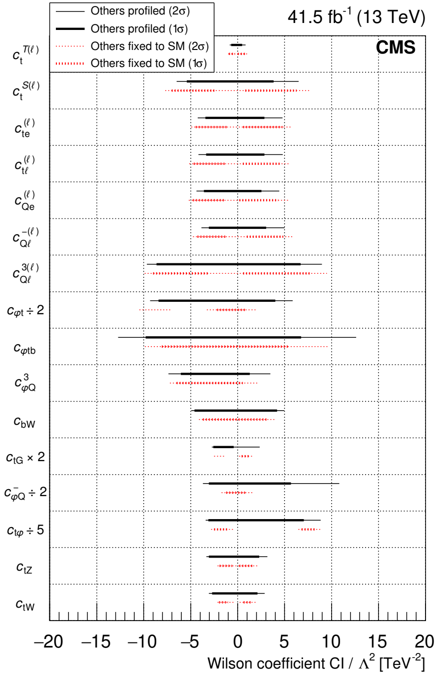
$$\delta\eta_{SM} \sim g^2_{BSM} \frac{E^2}{M^2}$$

Effects in tails of distributions but also anomalous shapes



[CMS: arXiv:2208.12837]

Top+additional leptons



[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

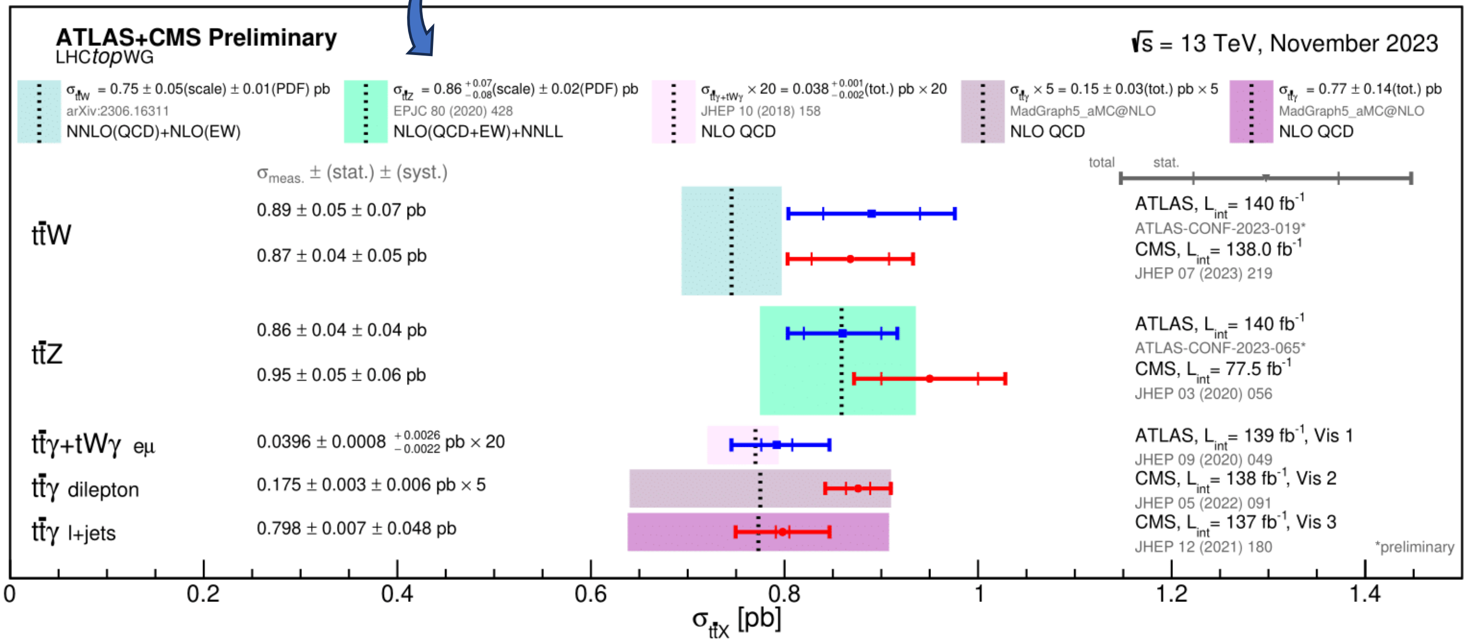
Theory versus data at a glance

Comparison of most recent results

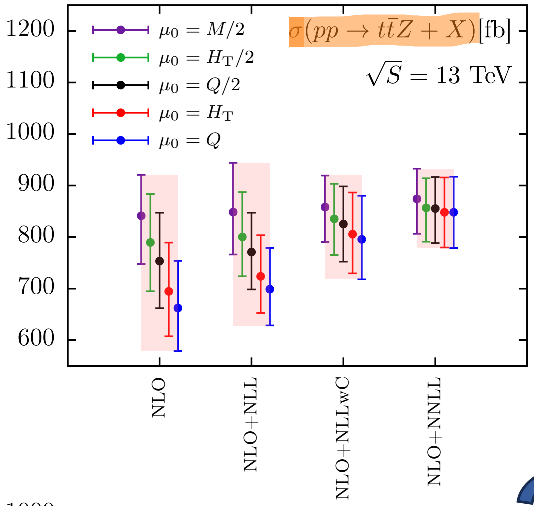
Buonocore, Devoto, Grazzini, Kallweit, Mazzitelli, Rottoli, Savoini

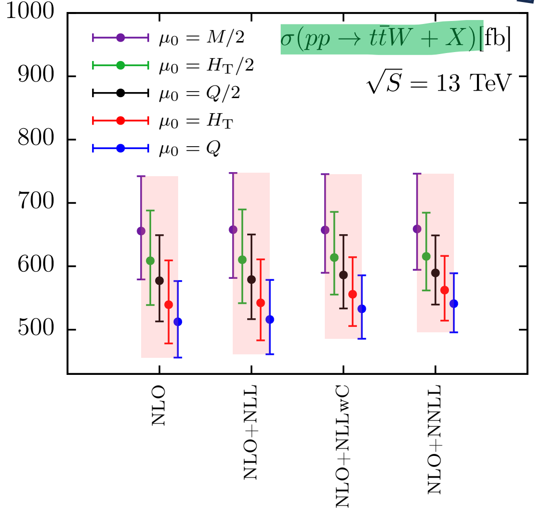
[NNLO QCD (no finite 2-loop)]

Kulesza, Motyka, Schwartländer, Stebel, Theeuwes

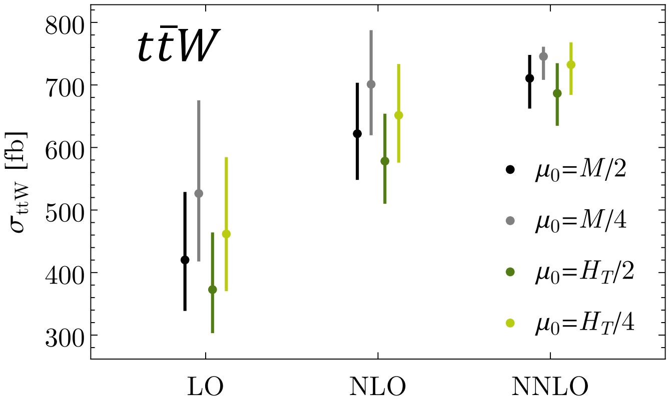


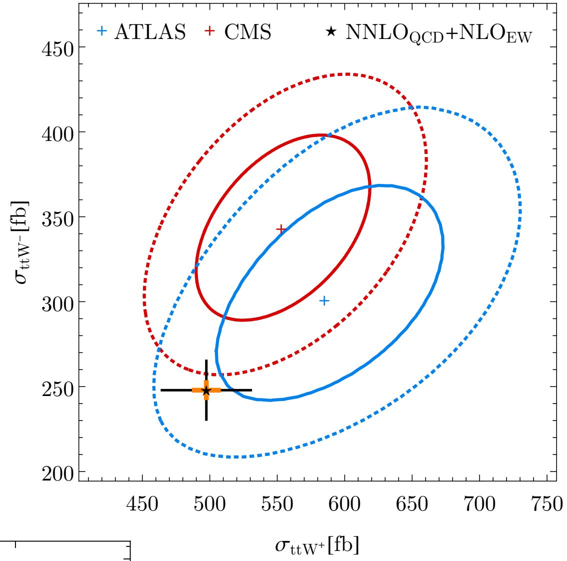
Kulesza et al.



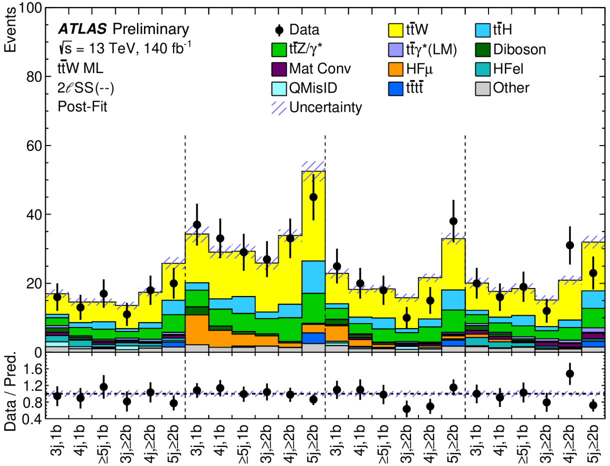


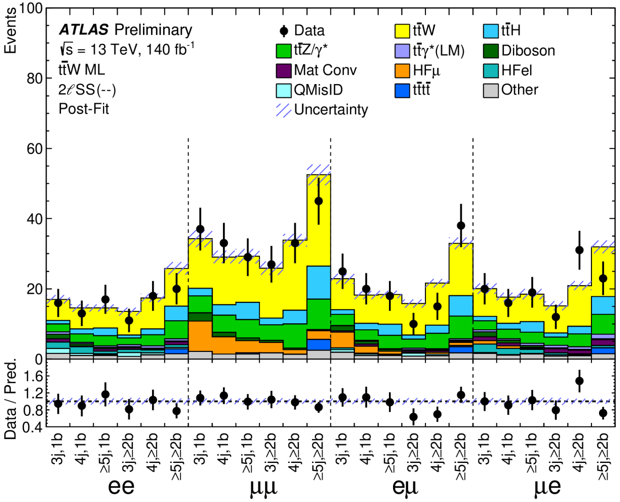
(N)NLO QCD (+NNLL) greatly reduces theory systematics from perturbative truncation





Buonocore et al.





Still large residual uncertainty from modelling

	$\frac{\Delta\sigma(t\bar{t}W)}{\sigma(t\bar{t}W)}$ [%]	$\frac{\Delta\sigma_{\text{fid}}(t\bar{t}W)}{\sigma_{\text{fid}}}$ [%]	$\frac{\Delta R(t\bar{t}W)}{R(t\bar{t}W)}$ [%]	$\frac{\Delta A_C^{\text{rel}}}{A_C^{\text{rel}}}$ [%]
$t\bar{t}W$ ME and PS modelling	6.0	7.0	6.0	8.0
Prompt lepton bkg. norm.	2.6	2.5	1.6	2.2
Lepton isolation BDT	2.3	2.3	1.0	1.2
Fakes/VV/$t\bar{t}Z$ norm. (free-floated)	2.3	2.7	1.8	2.5
Non-prompt lepton bkg. modelling	1.9	1.7	2.3	3.1
Trigger	1.9	1.8	0.5	0.7
MC statistics	1.5	1.6	1.9	2.5
$t\bar{t}W$ PDF	1.5	1.4	2.1	2.8
Jet energy scale	1.4	1.9	0.8	1.1
Prompt lepton bkg. modelling	1.3	1.3	1.3	1.9
Luminosity	1.0	1.0	0.08	0.13
Charge Mis-ID	0.7	0.7	0.4	0.5
Jet energy resolution	0.5	0.6	0.7	0.31
Flavour tagging	0.28	0.33	0.5	1.0
$t\bar{t}W$ Scale	0.21	0.9	1.4	1.9
Electron/photon reco.	0.15	0.2	0.12	0.3
MET	<0.10	<0.10	0.17	0.4
Muon	<0.10	<0.10	<0.10	0.4
Pile-up	<0.10	0.25	<0.10	0.3
Total syst.	8	10	8	10
Data statistics	5	5	10	16
Total	9	11	13	19

Moving forward:

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

The case of $t\bar{t}Z$

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

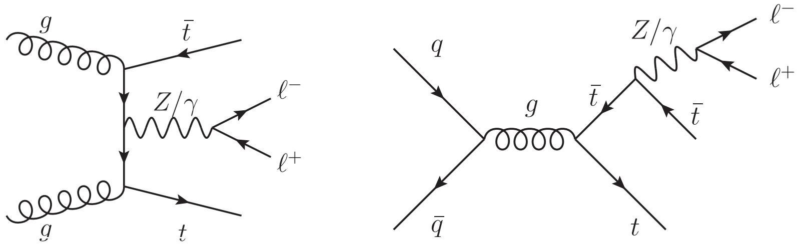
- $pp \to t\bar{t}l^+l^-$ (l=lepton): NLO QCD + parton shower (PS)
  - On-shell top quarks with LO spin-correlations in decay ($t \to bl\nu$) (using NWA)
  - Include $t\bar{t}Z$ off-shell effects and $t\bar{t}Z/t\bar{t}\gamma$ interference
  - Interfaced with PS in the Powheg-Box-V2 framework (including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

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

- Fully off-shell pp $\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$: 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.

G. Bevilacqua, H.B. Hartanto, M. Kraus, J. Nasufi, M. Worek [arXiv:2203.15688]
[See also Denner et al., 2306.13535]

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



+ NLO QCD + PS

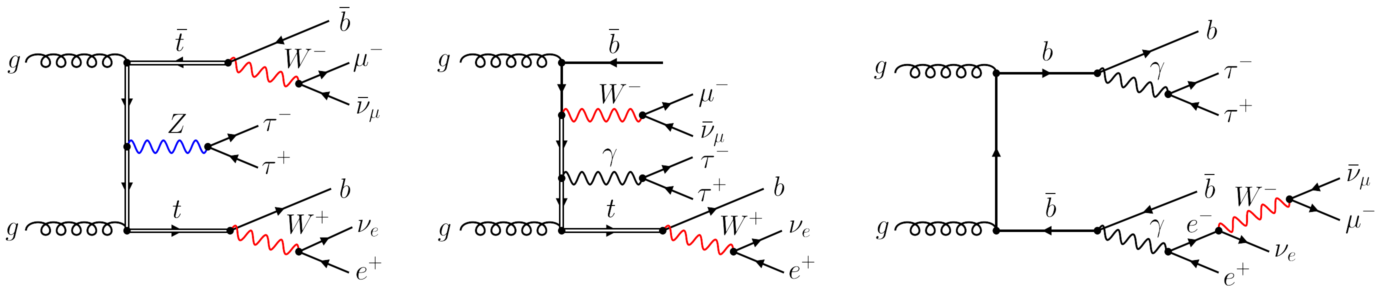
- One-loop matrix elements from NLOX [Honeywell et al., arXiv:1812.11925]
- EW G_μ input scheme (G_μ,m_Z,m_W). Other inputs: m_t , Γ_t , Γ_W , Γ_Z
- Studied (μ_R,μ_F) scale dependence wrt to both a fixed and dynamical central scale (7-point variation)

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

- PDF: CT18NLO with $\alpha_s(m_Z)$=0.118 ($\alpha_s(\mu)$ in Msbar, 5FS)
- PS: Pythia8
- $\sqrt{s}$ = 13 TeV

- Specific signature studied: $t\bar{t}e^+e^-$ with $t \to b\mu\nu_\mu$ (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)

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



+ NLO QCD

- NLO QCD corrections obtained in the HELAC-NLO framework [Bevilacqua et al., arXiv:1110.1499]
  - 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)
- $\sqrt{s} = 13$ TeV

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

- Specific signature studied: $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$
  - $p_T^l > 20$ GeV, $|y_l| < 2.5$, $\Delta R_{ll} > 0.4$
  - $p_T^b > 25$ GeV, $|y_b| < 2.5$, $\Delta R_{bb} > 0.4$
  - $p_T^{miss} > 40$ GeV

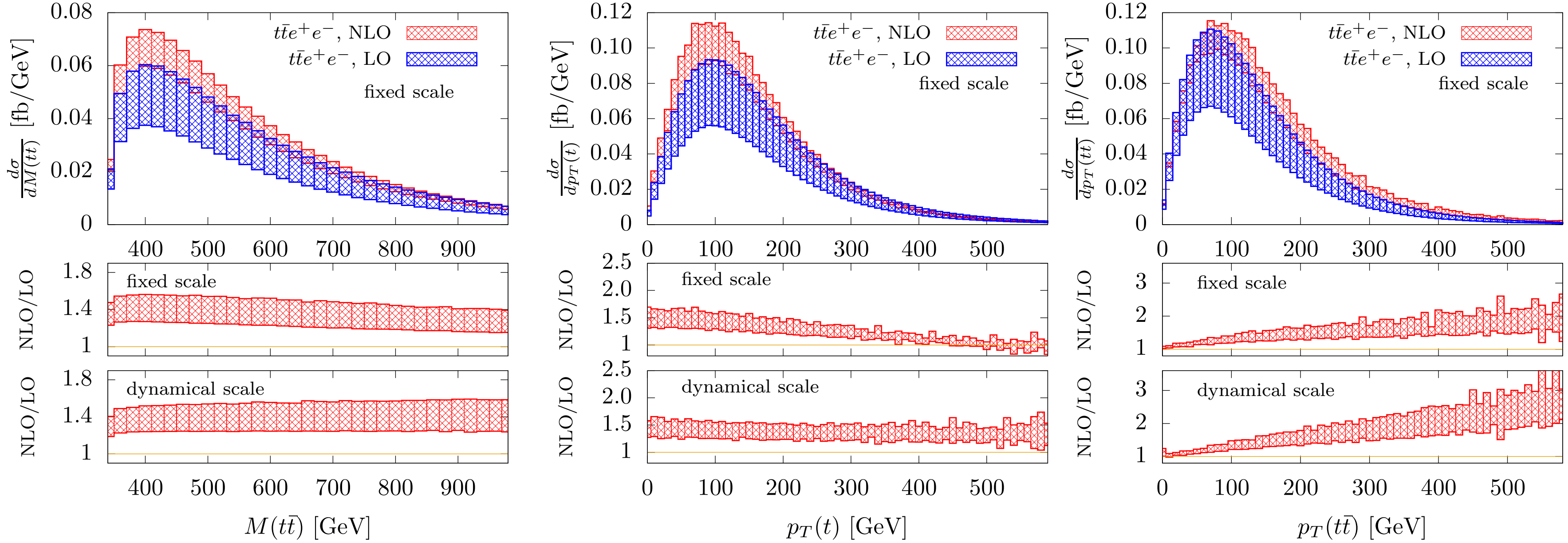
Theoretical systematics: $pp \to t\bar{t}e^+e^-$

NLO QCD corrections are substantial and reduce the overall perturbative uncertainty

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

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

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

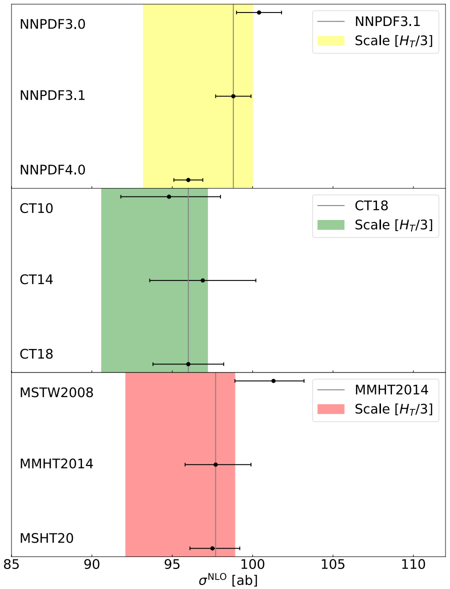


Theoretical systematics: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$

Very small residual systematic uncertainty at NLO QCD

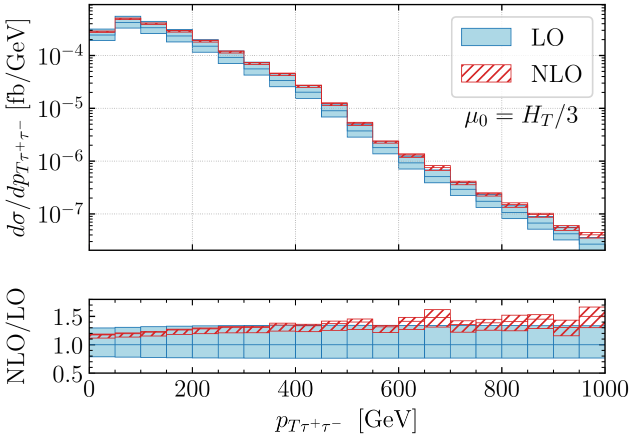
$$\sigma^{\rm LO}_{\rm full\ off\text{-}shell} = 80.32^{+25.51(32\%)}_{-18.02(22\%)} \left(76.98^{+24.30(32\%)}_{-17.17(22\%)}\right) \text{ ab}$$

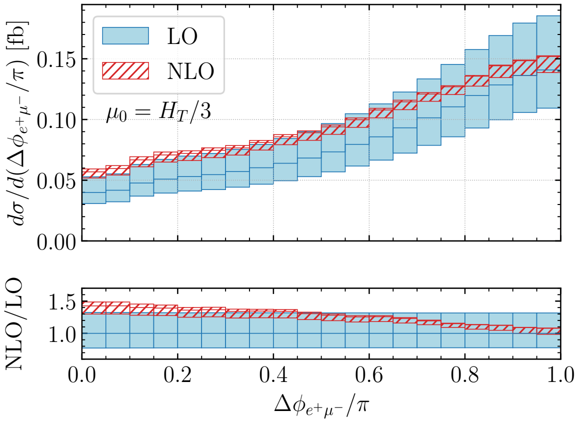
$$\sigma^{\rm NLO}_{\rm full\ off\text{-}shell} = 98.88^{+1.22(1\%)}_{-5.68(6\%)} \left(97.86^{+1.08(1\%)}_{-6.16(6\%)}\right) \text{ ab}$$



Dynamic scale preferred over full range of distributions.

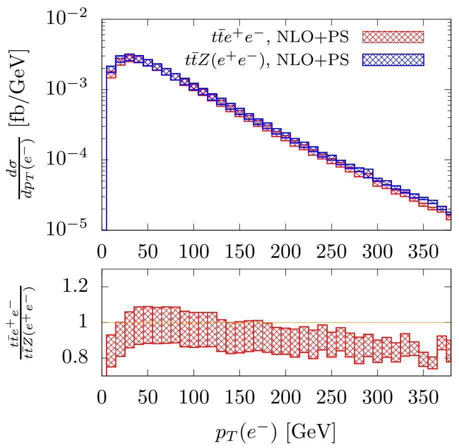
Not a uniform rescaling.

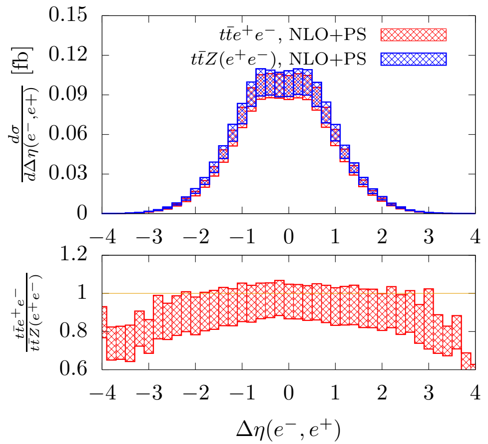




Small dependence on PDF

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





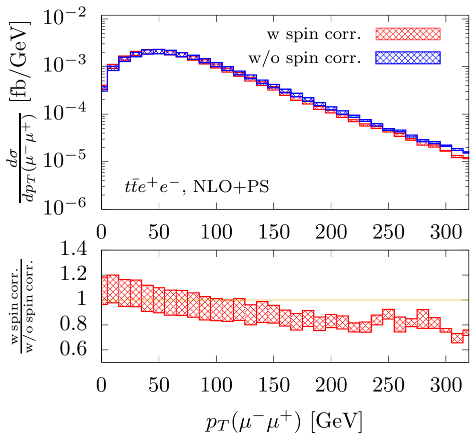
Compare $t\bar{t}Z$ and $t\bar{t}e^+e^-$ keeping stable top quarks:

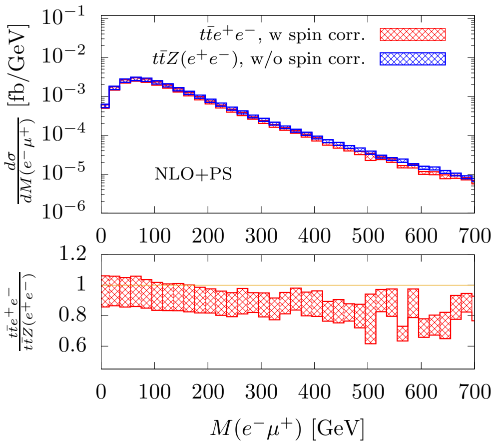
- Effects of off-shell Z
- Effects of e^+e^- spin correlations

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).

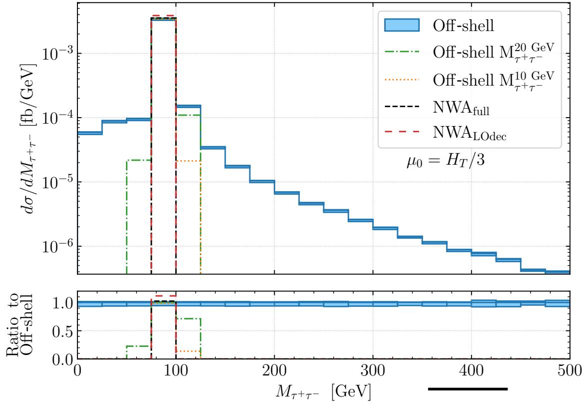
10-20% visible effects in the tails of distributions



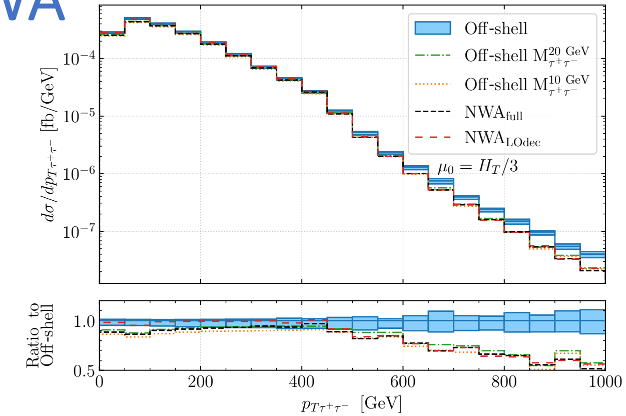


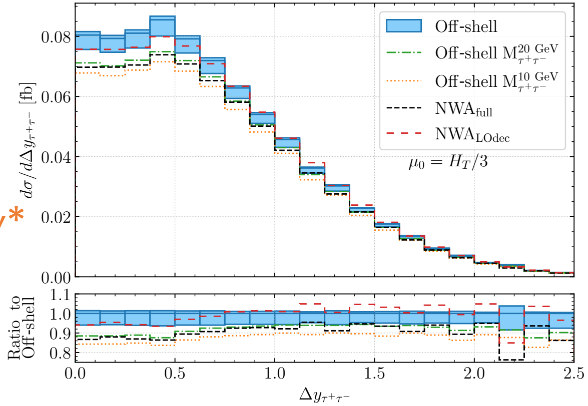
$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\tau^+\tau^-$: fully off-shell vs NWA

Very thorough study of modelling effects



Modelling	σ_i^{NLO} [ab]	$\sigma_i^{\mathrm{NLO}}/\sigma^{\mathrm{NLO}}_{\mathrm{NWA_{full}}} - 1$
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.

The case of $t\bar{t}W$

$pp \to t\bar{t}W$: modeling events beyond on-shell production

- Fixed-order higher-order corrections to fully decayed final states ($3l$)
  - Bevilacqua et al. (NLO QCD) [arXiv:2005.09427, 2012.01363]
  - Denner et al. (NLO QCD+EW) [arXiv:2007.12089]

- Comparing and combining NLO QCD off-shell with NLO QCD+PS
  - Frederix and Tsinikos [arXiv:2004.09552, arXiv:2108.07826] aMC@NLO+FxFx
  - Buddenbrock et al. [arXiv:2009.00032] aMC@NLO+FxFx
  - [ATL-PHYS-PUB-2020-024] - aMC@NLO+FxFx and SHERPA
  - Febres Cordero, Kraus, Reina [arXiv:2108.07826] – POWHEG-BOX

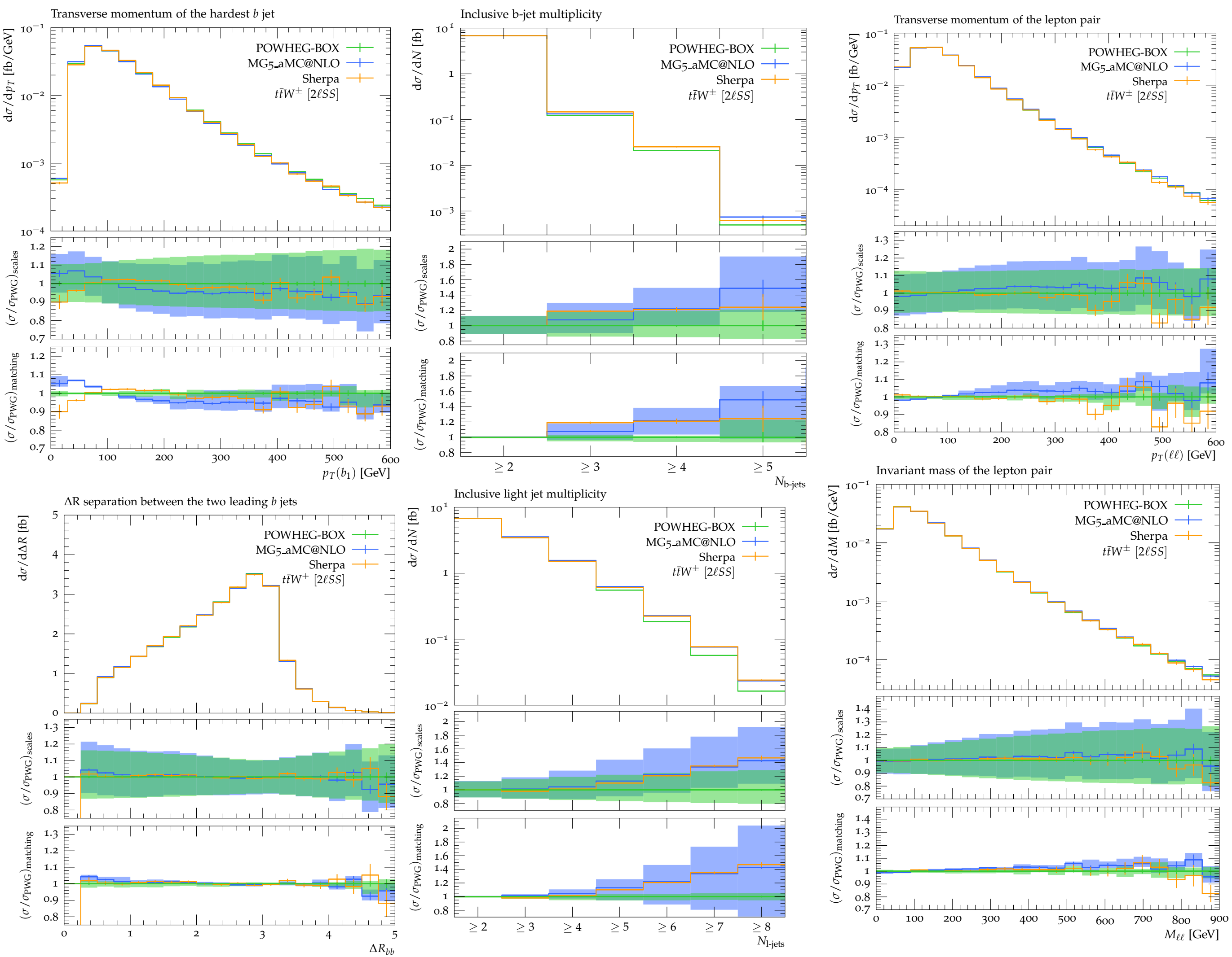
- NLO QCD + parton shower, including $O(\alpha_s^3\alpha)$ and $O(\alpha_s\alpha^3)$, LO spin correlations in decays, jet merging
  - Bevilacqua, Bi, Febres Cordero, Hartanto, Kraus, Nasufi, Reina, Worek [arXiv:2109.15181]

Comparison of different NLO PS frameworks

[Febres Cordero, Kraus, Reina, arXiv:2101.11808]

- Considered POWHEG BOX, MG5aMC@NLO, and SHERPA.
- First public POWHEG BOX implementation.
- $O(\alpha_s^3\alpha)$ and $O(\alpha_s\alpha^3)$ included (one-loop via NLOX).
- Scale and PS uncertainties thoroughly studied.
- Spin correlations included at LO.
- Signature: 2lSS+jets:
    - $p_T(l) > 15$ GeV, $|\eta(l)| < 2.5$
    - $p_T(j) > 25$ GeV, $|\eta(j)| < 2.5$, anti-kT with R = 0.4
    - $N_b \geq 2$, $N_j \geq 2$
    - Using PYTHIA 8.303

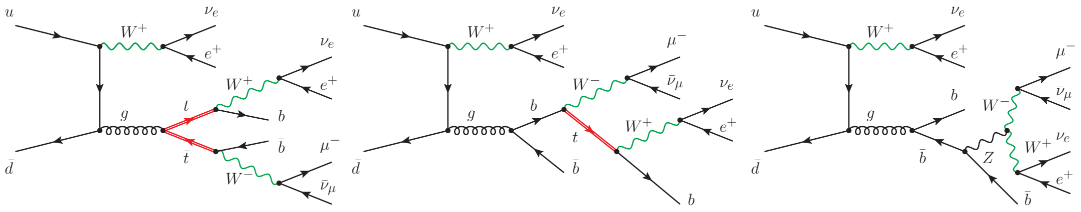
Use as baseline for further estimate of theoretical uncertainty/systematics



Overall good agreement within theoretical uncertainties that can now be quantified and used as a base to estimate residual modelling uncertainties

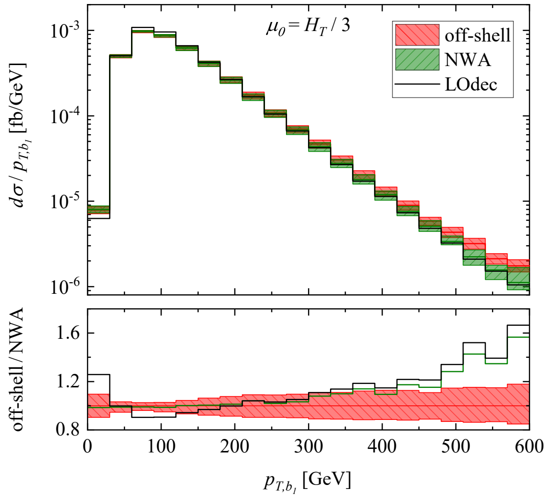
Considering off-shell effects

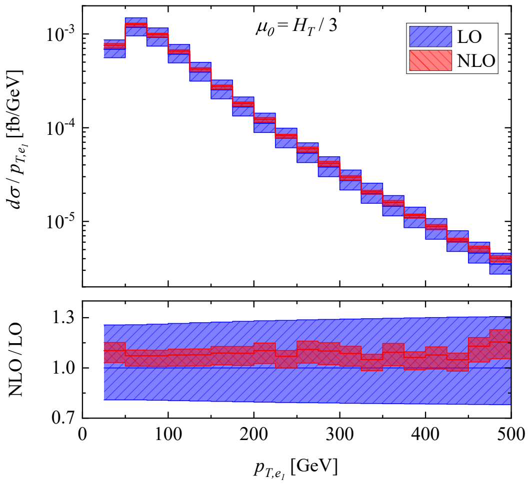
Off-shell fixed order NLO QCD calculation of $3l$ signature: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu e^+ b\bar{b}$



- Off-shell: uncertainty below 10% independently of scale choice (fixed/dynamic).

- Large off-shell effects in the tails of distributions.





Bevilacqua et al. arXiv:2005.09427

See also Denner et al., arXiv:2007.12089, 2102.03246

Combining parton-shower and off-shell effects

[Bevilacqua, Bi, Febres Cordero, Hartanto, Kraus, Nasufi, Reina, Worek, arXiv:2109.15181]

$$pp \to b\bar{b}\ell^{\pm}\nu_{\ell}\ell^{\pm}\nu_{\ell}\ell^{\pm}\nu_{\ell}$$

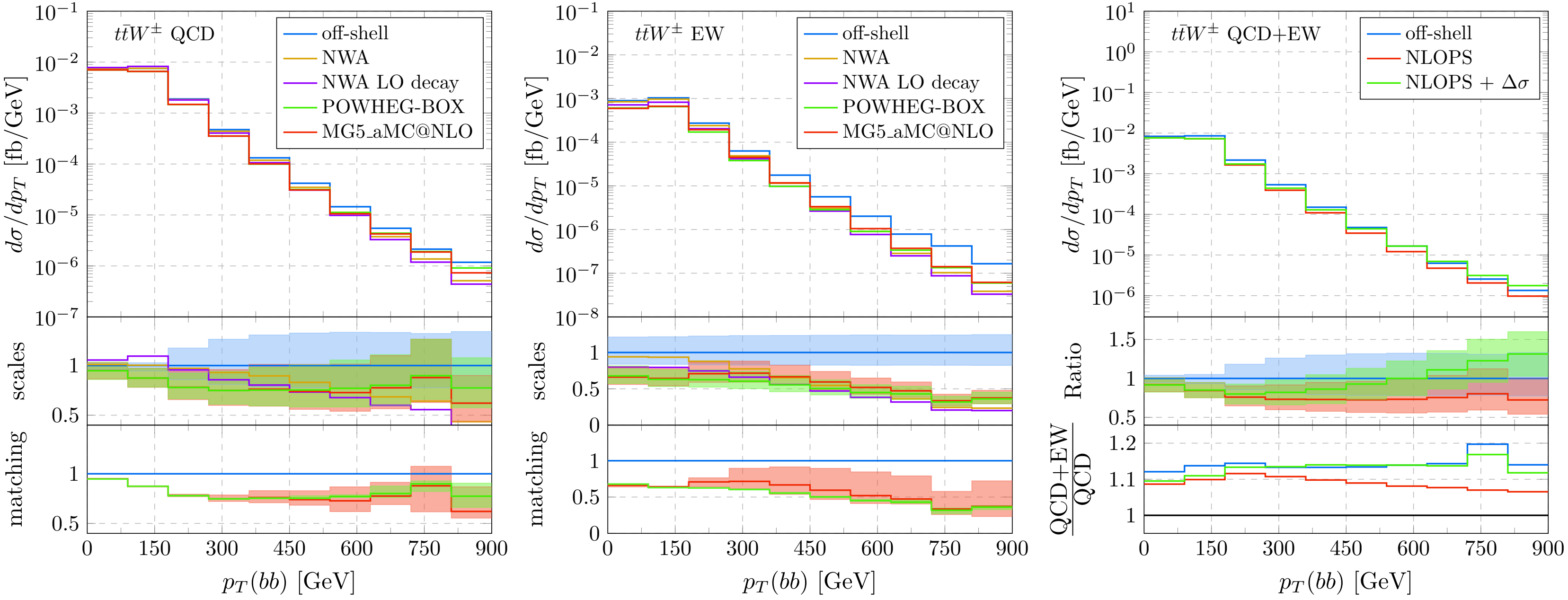
fixed-order

- top decay at NLO
- spin correlations
- double, single and non-resonant contributions or NWA
- only one extra parton

parton showers

- Additional radiation
- Hadronization
- More flexiable
- NLO only for production
- LO spin correlations

[From M. Kraus]



- Off-shell effects very visible in tails of distributions – PS misses single-resonant and non-resonant effects
- PS effects affect broader regions of PS, e.g. low-p_T regions

$$\frac{d\sigma^{\mathrm{th}}}{dX} = \frac{d\sigma^{\mathrm{NLO+PS}}}{dX} + \frac{d\Delta\sigma_{\mathrm{off-shell}}}{dX} \quad \text{with} \quad \frac{d\Delta\sigma_{\mathrm{off-shell}}}{dX} = \frac{d\sigma^{\mathrm{NLO}}_{\mathrm{off-shell}}}{dX} - \frac{d\sigma^{\mathrm{NLO}}_{\mathrm{NWA}}}{dX}$$

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 **studies of PS and off-shell effects** for the particular case of $t\bar{t}Z$ and $t\bar{t}W$ production, including leptonic decays, and confirmed the importance of extending the modelling of $t\bar{t}Z$ and $t\bar{t}W$ events to include such effects.