Highlights on recent top-quark production results from CMS

Jeremy Andrea, on behalf of the CMS collaboration

Top-quark production : a playground for theory and modelling

- Top-quark production (and decays) is extensively studied at the LHC.

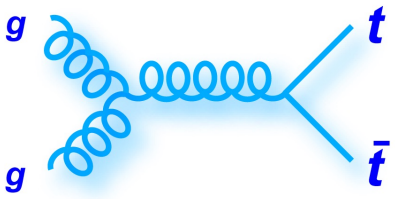
- The large luminosity allows to perform precise studies of the $t\bar{t}$ and the "not-so-rare-anymore" top processes (single top, associated production with bosons).
  - It allows to probe the Standard Model, test theory modelling,
  - To search for deviations, as a sign of new-physics (EFT).

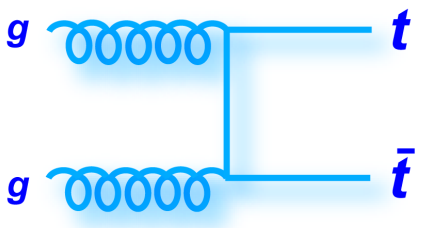
- Recent results of top-quark inclusive and differential cross sections are presented :
  - **TOP-23-005** : $t\bar{t}$ cross section at $\sqrt{s} = 5.02$ TeV,
  - **TOP-20-006** : multi-dim. $t\bar{t}$ cross section at $\sqrt{s} = 13$ TeV,
  - **TOP-23-008** : tW cross section at $\sqrt{s} = 13.6$ TeV,
  - **TOP-23-004** : $t\bar{t}Z + tWZ$ and tZq cross sections at $\sqrt{s} = 13$ TeV.

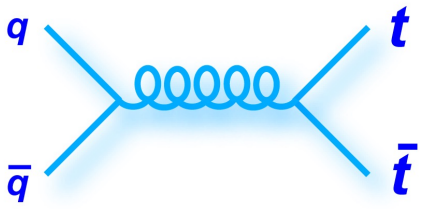
Inclusive and differential $t\bar{t}$ cross sections at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV

TOP-23-005
TOP-20-006, arXiv:2402.08486, submitted to JHEP

$t\bar{t}$ pair production





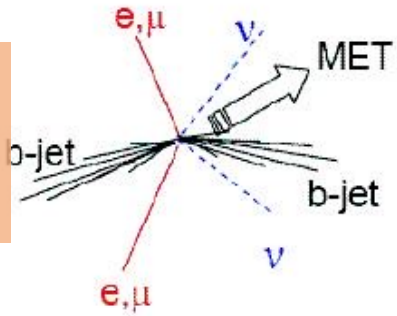


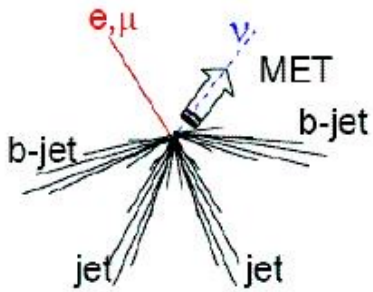
~90% at 14 TeV

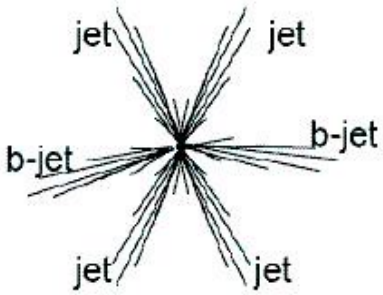
~10% at 14 TeV

Semi- lept. , good stat.,
Moderate backg. (Wjets, QCD)

Dileptonic
Lower stat.
Low backg
(Zjets,WW, tW)







All-hadronic
Highest stat.
Large backg.
(QCD)

$Br(e,\mu)\sim 6\%$

$Br(e,\mu)\sim 35\%$

$Br(e,\mu)\sim 45\%$

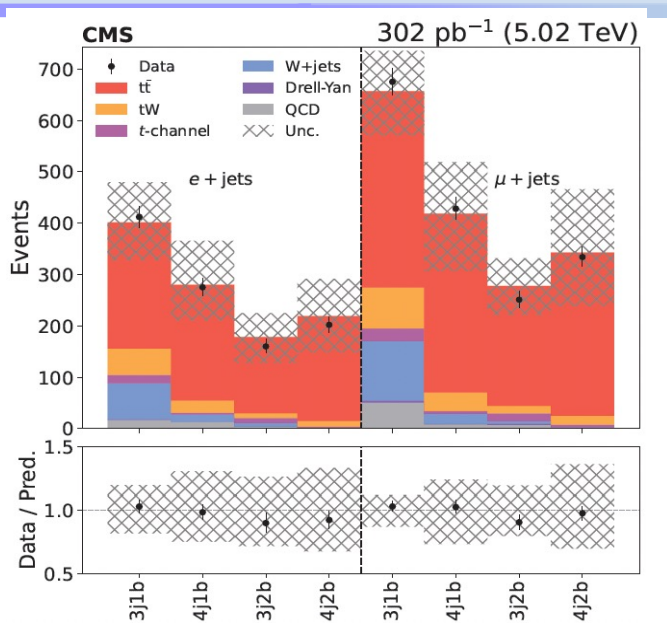
LHC is a Top Factory.

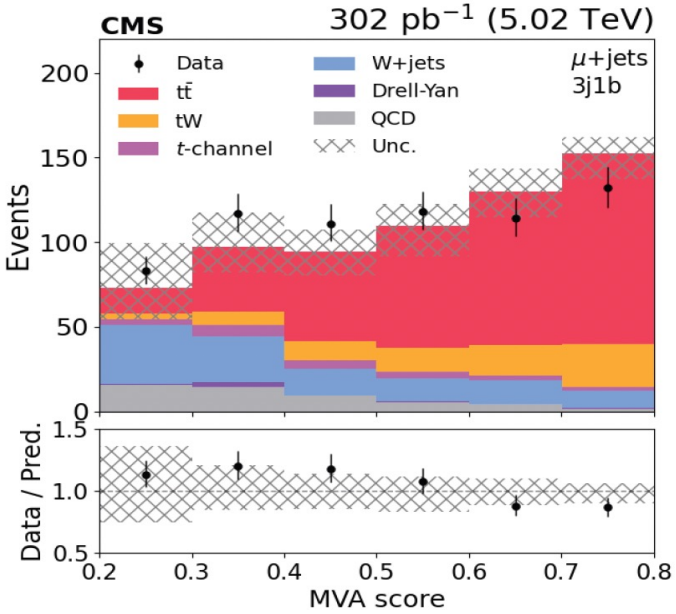
$$\sigma_{t\bar{t}}(13TeV) = 831^{+30}_{-20}(scale) \pm 4(PDF + \alpha_s)\ pb$$

$t\bar{t}$ cross section at 5.02 TeV

TOP-23-005

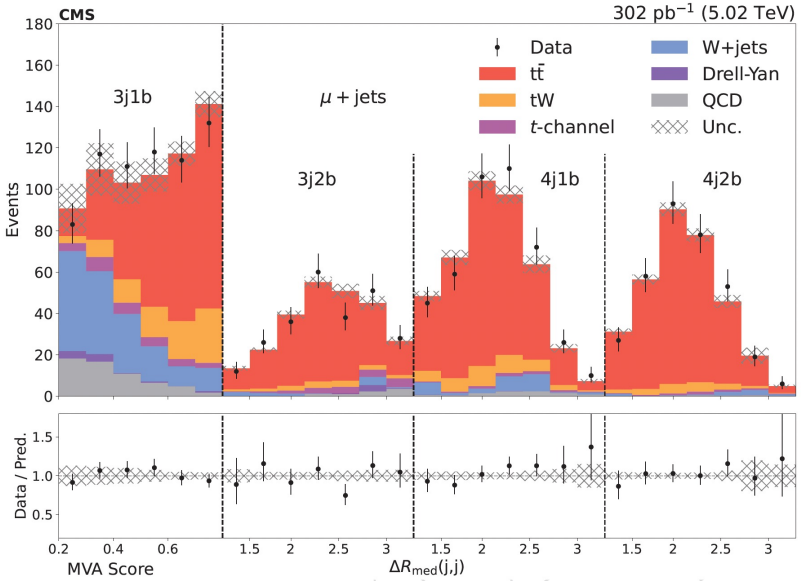
- Inclusive and differential cross sections at 5.02 TeV.
  - L=302 pb^{-1} of pp data (2017),
  - $\sigma_{t\bar{t}}\ vs\ \sqrt{s}$: important test of the SM, PDFs, modelling.
- Lepton+jet channel :
  - 1 lepton (e, μ), ≥ 3 jets, ≥ 1 b-jet, $\vec{p}_T^{miss} > 30$ GeV,
  - Categorisation of events : 3j1b, 4j1b, 3j2b, 4j2b,
  - QCD multi-jets : estimated from a control region + extrapolation factor.
- Signal extracted from ML fit.
  - 3j1b : W+jets separated from $t\bar{t}$ using multi-variate discriminant,
  - Other categories : median ΔR between all possible combinations of two jets ($\Delta R_{med}(j,j)$).

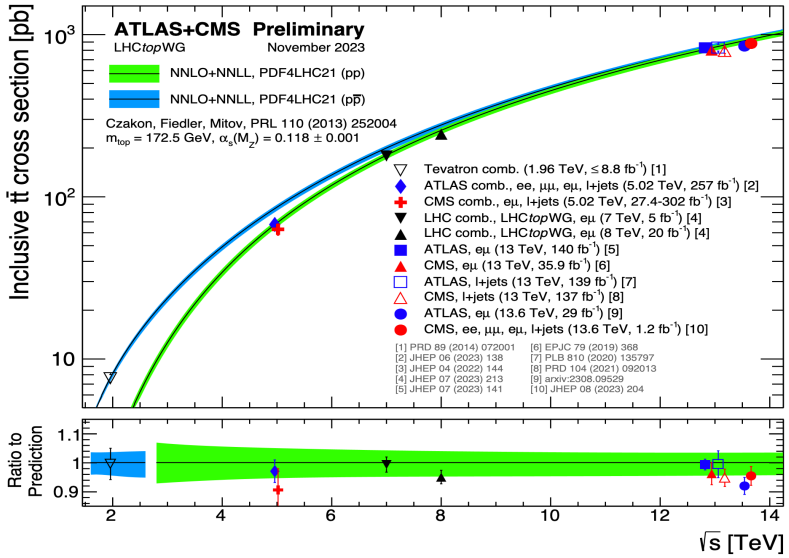




$t\bar{t}$ cross section at 5.02 TeV

TOP-23-005





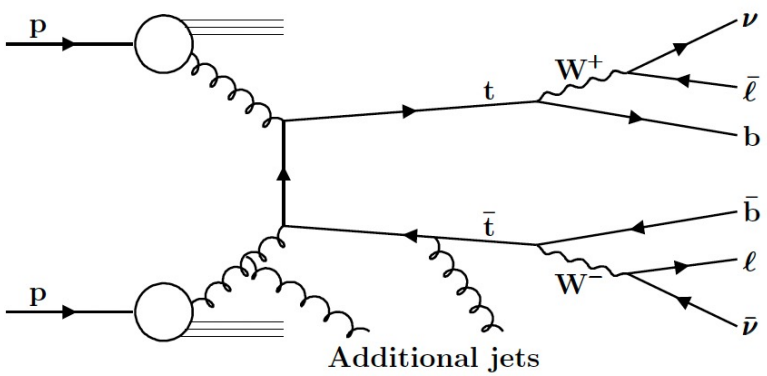
- Measured cross section :
  - $\sigma_{t\bar{t}} = 61.4 \pm 1.6(stat.) \pm 2.7(syst.) \pm 1.2(lumi.)$ pb.
  - Systematics dominated by b-tagging, ME/PS matching, trigger.

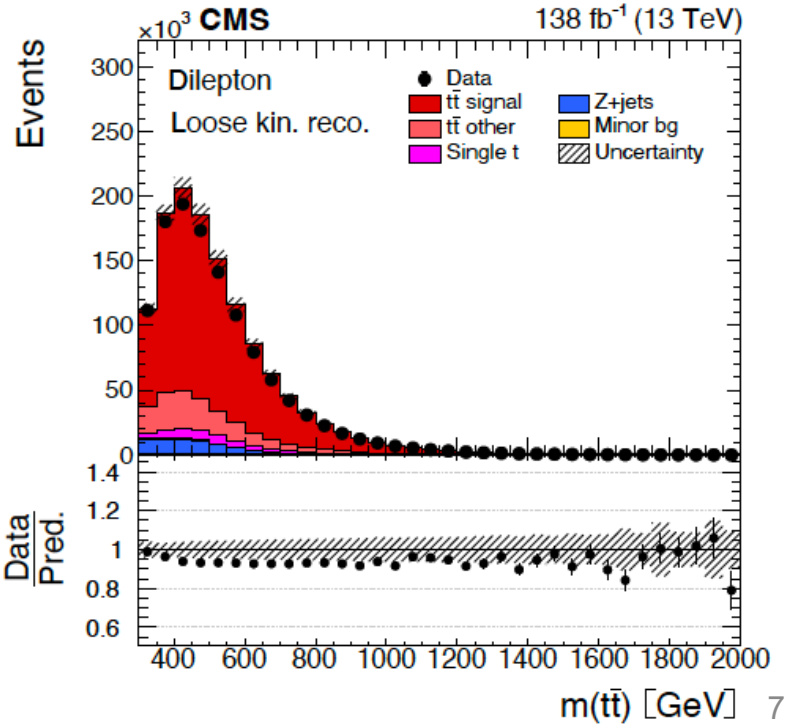
- Combination with CMS dilepton measurement (TOP-16-023)
  - $\sigma_{t\bar{t}} = 61.2 \pm 1.6(stat.) \pm 2.5(syst.) \pm 1.2(lumi.)$ pb.

$t\bar{t}$ cross section at 13 TeV

TOP-20-006 , arXiv:2402.08486

- Measurement with high statistic ($138 fb^{-1}$).
  - Multi-differential cross sections!
- In the dileptonic channel.
  - Lower background, lower sensitivity to hadronization/PS, less jet combinatorics.
  - Top quark reconstruction a bit more complicated, due to the presence of 2 neutrinos.
- Events selection and background.
  - 2 leptons (e or μ), ≥ 2 jets, ≥ 1 b-tag, $m_{ll} > 20$ Gev.
  - ee and $\mu\mu$ channels : Z-mass veto, $\vec{p}_T^{miss} > 40$ GeV.
  - Z-normalisation SF from Z peak region.
- Top reconstruction and unfolding at parton or particle levels.

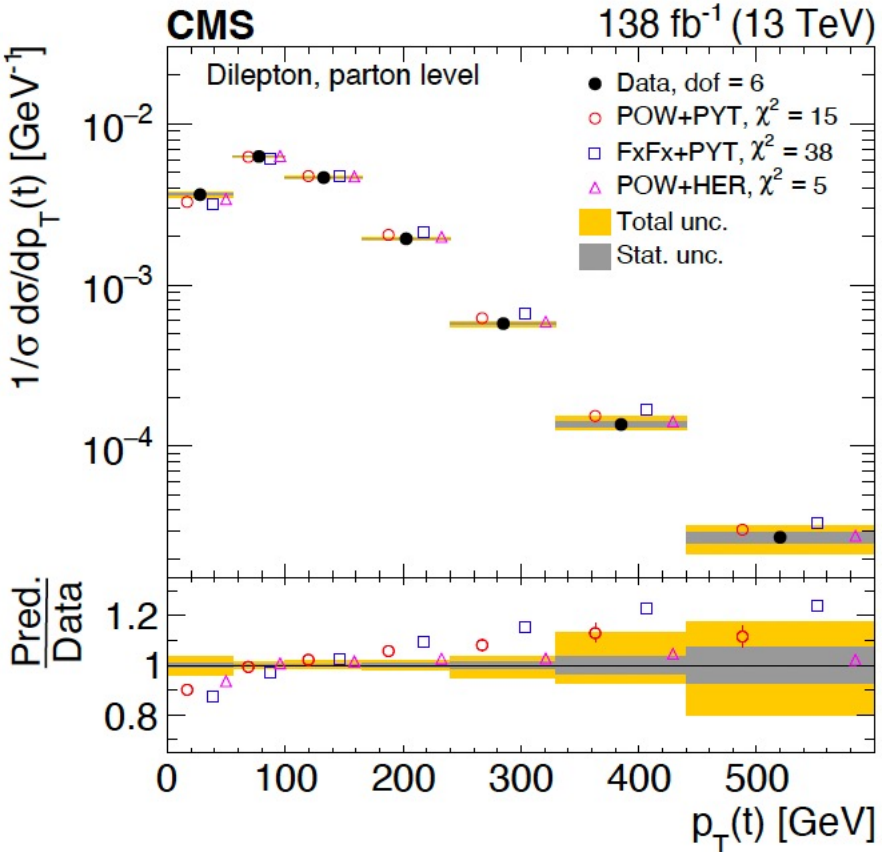


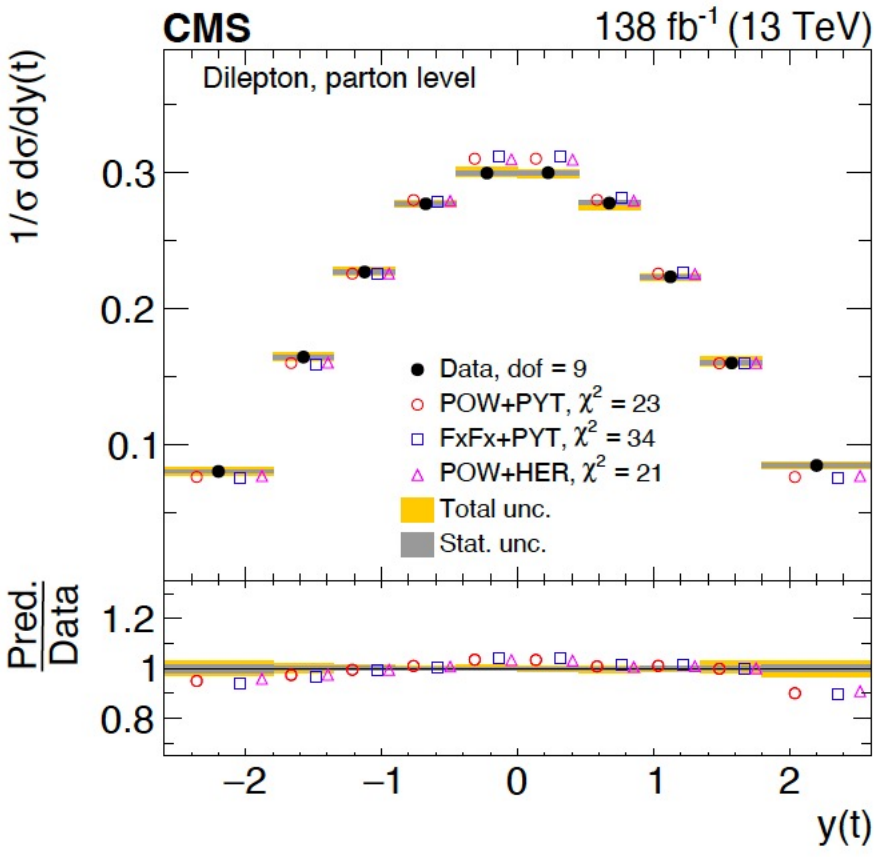


$t\bar{t}$ cross section at 13 TeV

TOP-20-006 , arXiv:2402.08486

- Models predict harder p_T spectra and more-central rapidity distributions.

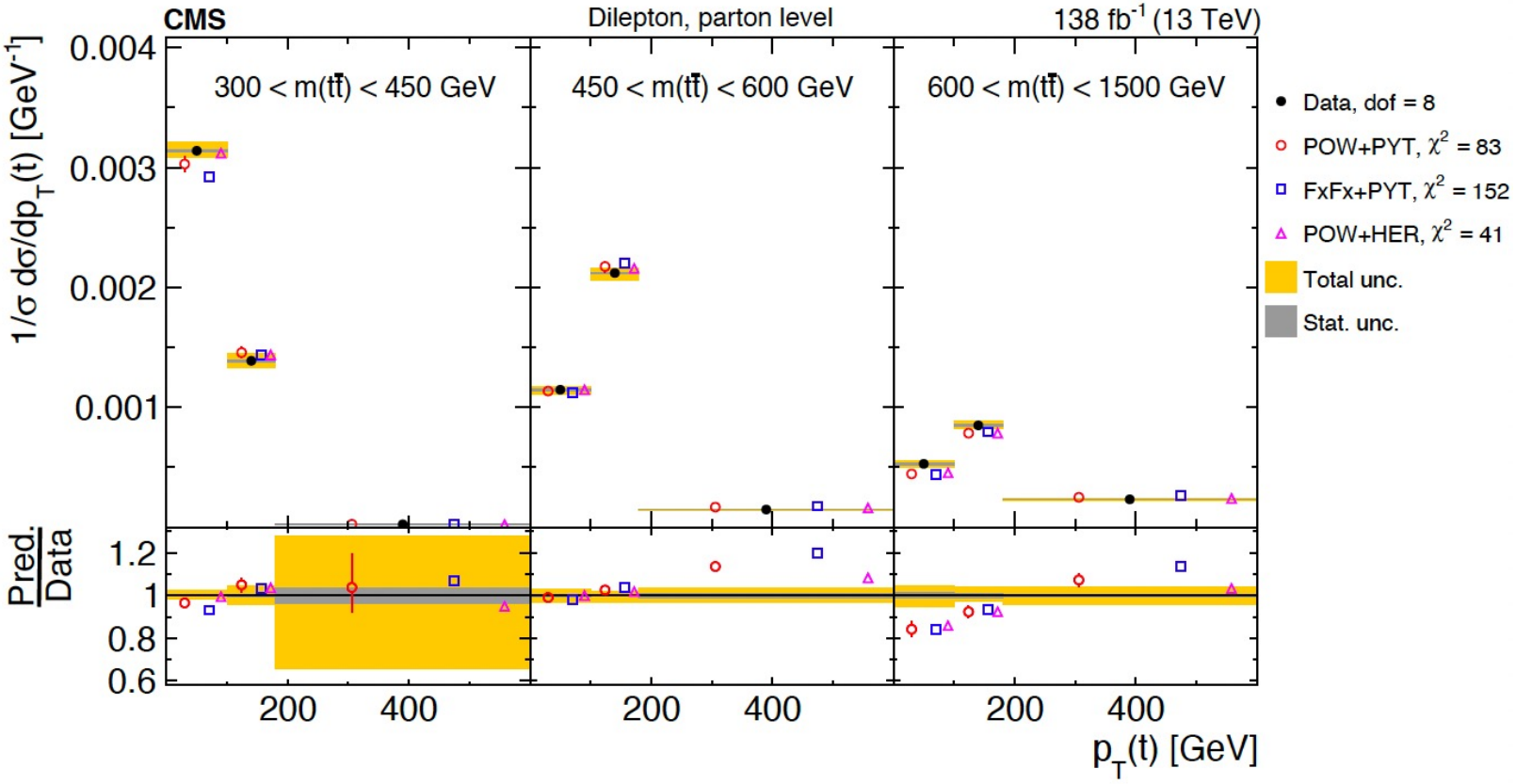




$t\bar{t}$ cross section at 13 TeV

TOP-20-006 , arXiv:2402.08486

- 2D differential distributions allow for deeper studies.
- Several distributions investigated ($p_T(t), p_T(t\bar{t}), m_{t\bar{t}}, y_T(t), y_T(t\bar{t}), \Delta\varphi(t\bar{t}), \Delta\eta(t\bar{t})$ ...).
- Harder p_T spectra clearly enhanced at large $m_{t\bar{t}}$.

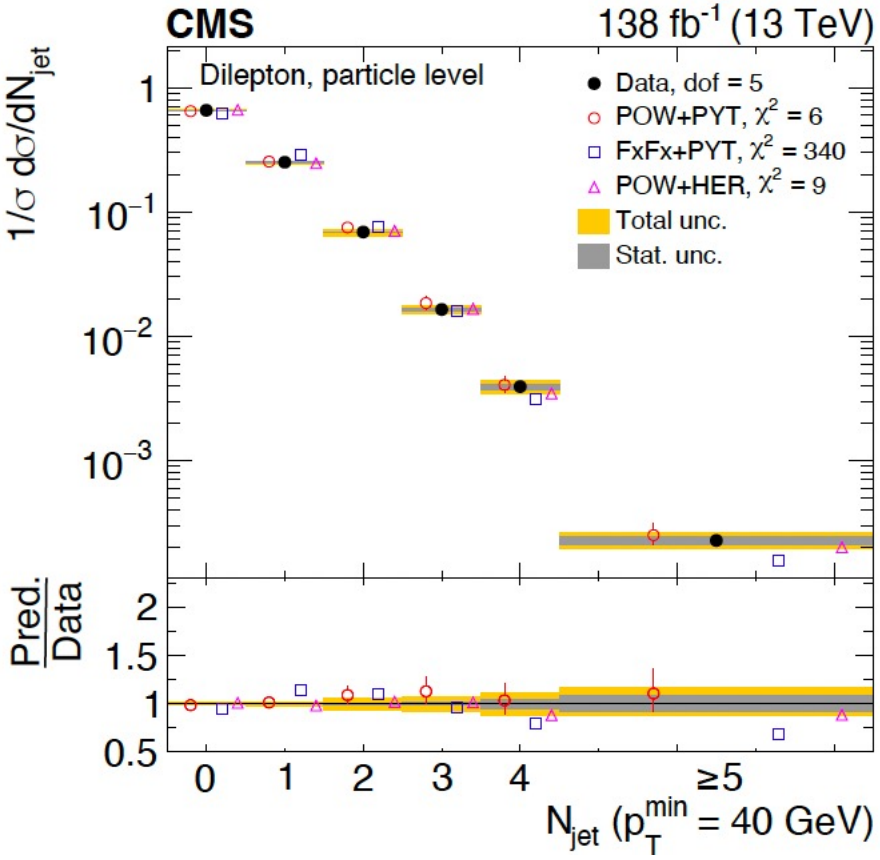


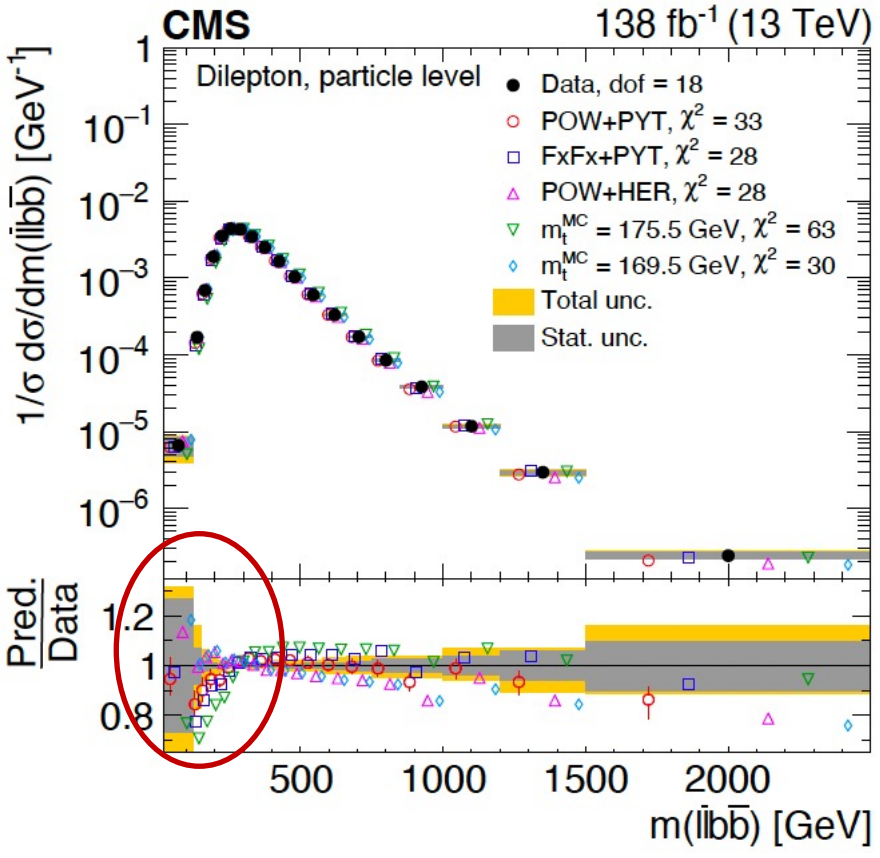
$t\bar{t}$ cross section at 13 TeV

TOP-20-006 , arXiv:2402.08486

- Best description from POW+PYT for the additional jet production.
- $m_{llb\bar{b}}$ and $m_{t\bar{t}}$ not well described below ~$2m_t$. Region sensitive to :
  - Toponium,
  - Top mass threshold effects,
  - Interferences with tW(b) single top.

Observation of Quantum entanglement in $t\bar{t}$ by the CMS collaboration (TOP-23-001)





Inclusive and differential single top tW cross section at $\sqrt{s} = 13.6$ TeV

TOP-23-008

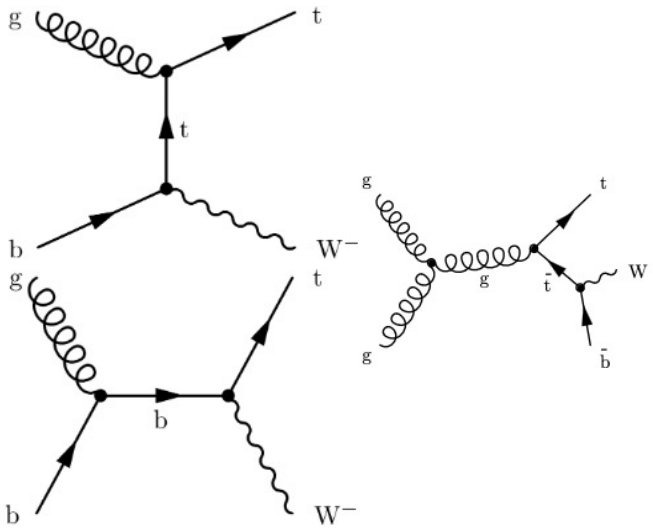
tW cross section

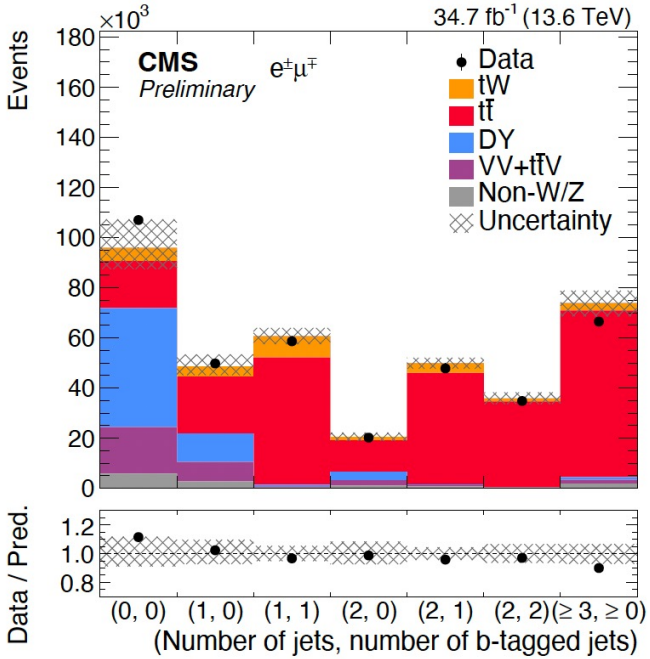
TOP-23-008

- tW cross section measurements : test of predictions, modelling, and sensitivity to interferences with $t\bar{t}$.
- At NLO, double counting from $t\bar{t}$ in MC production.
  - Treated with different approaches (DR, DR2, DS, DS-dyn),
  - Comparing approaches gives information on interferences.
- Only $e\mu$ channel, similar events selection and background estimation than $t\bar{t}$ dilepton.
- Inclusive measurement .
  - from ML multi-classifier in $1j1b$, $2j1b$ (tW-enriched)
  - + sub-leading jet p_T in $2j2b$ ($t\bar{t}$ enriched for constrain).

$$\sigma_{\mathrm{tW}} = 84.1 \pm 2.1\,(\mathrm{stat})\,^{+9.8}_{-10.2}\,(\mathrm{syst}) \pm 3.3\,(\mathrm{lumi})\,\mathrm{pb}.$$

- Dominant systematics : JES, non-prompt lepton, b-tagging.

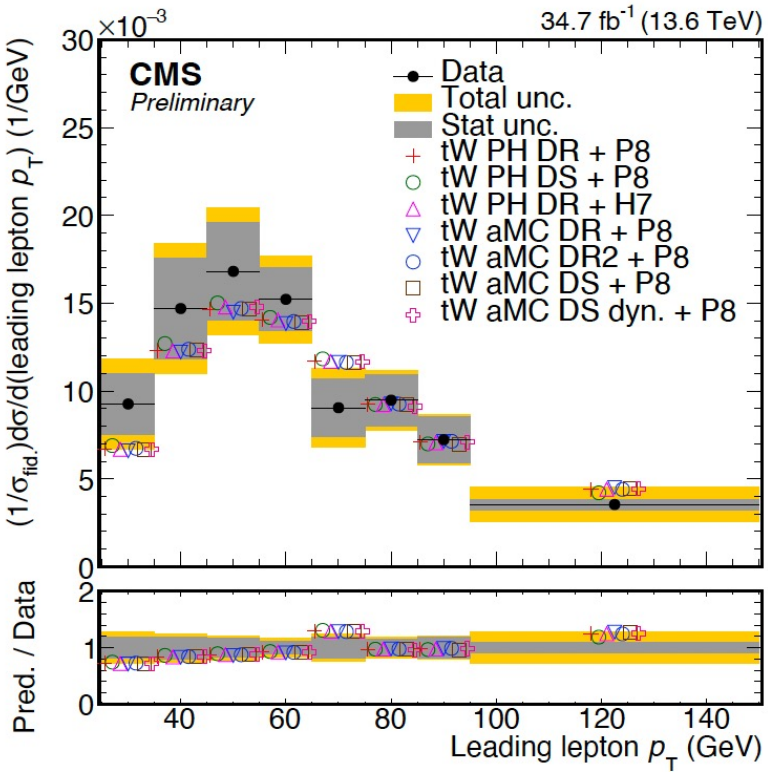


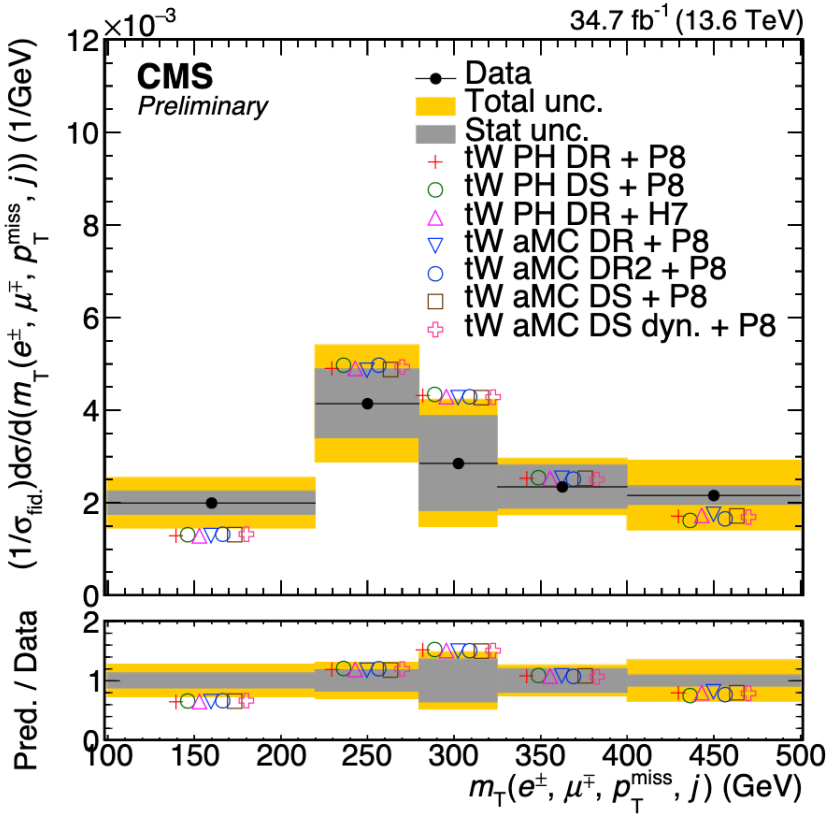


tW cross section

TOP-23-008

- Particle level differential cross sections (1j1b, no ML).
  - Overall good data/simulation agreements, given the (large) statistical uncertainty,
  - Comparisons of methods to treat $t\bar{t} - tW$ overlap/interferences gives similar results : limited impact of interferences ?



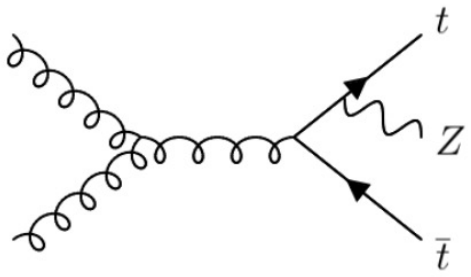


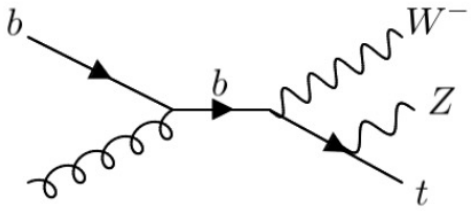
$t\bar{t}Z + tWZ$ and tZq cross sections at $\sqrt{s} = 13$ TeV

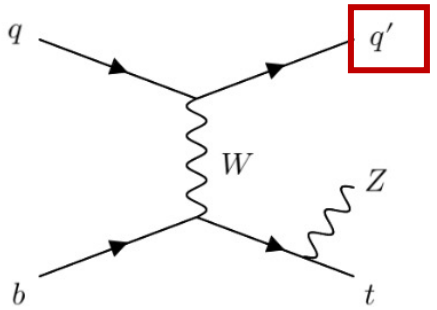
TOP-23-004

$t\bar{t}Z + tWZ$ and tZq cross sections

TOP-23-004



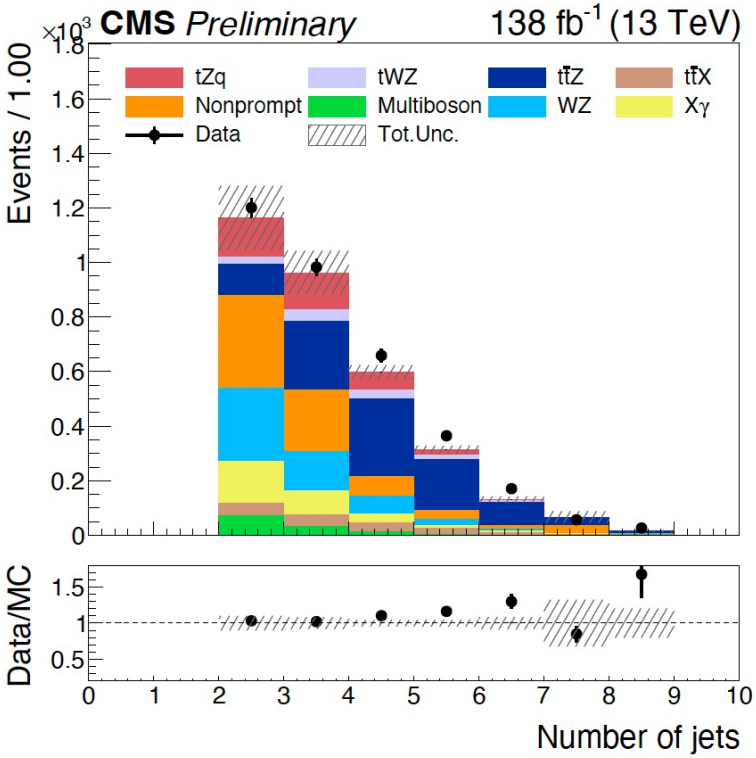




More forward

- Simultaneous measurement of $t\bar{t}Z + tWZ$ and tZq.
  - $t\bar{t}Z + tWZ$: treated as 1 signal process (interferences),
  - Proper accounting for correlations in the fit,
  - Maximum sensitivity to $t\bar{t} - Z$ EFT.

- Events selection and backgrounds.
  - 3 leptons (e, μ), ossf compatible with a Z mass,
  - $\geq$ 2jets with $|\eta| < 5$, $\geq$ 1b-tag,
  - Data-driven estimation of non-prompt background.



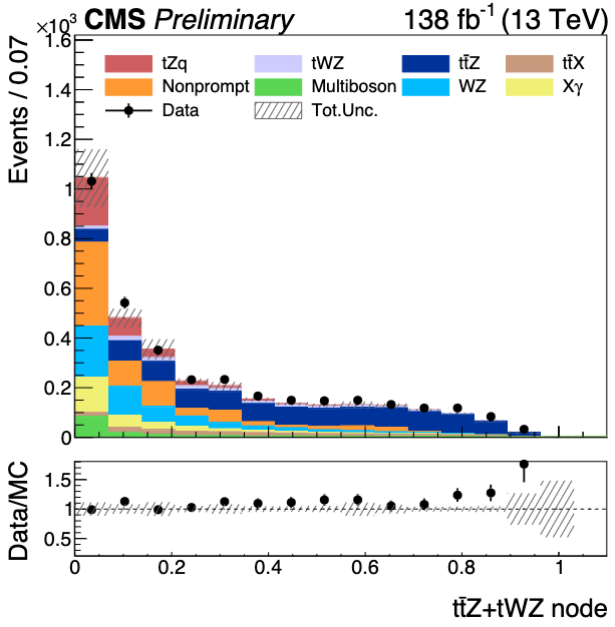
$t\bar{t}Z + tWZ$ and tZq cross sections

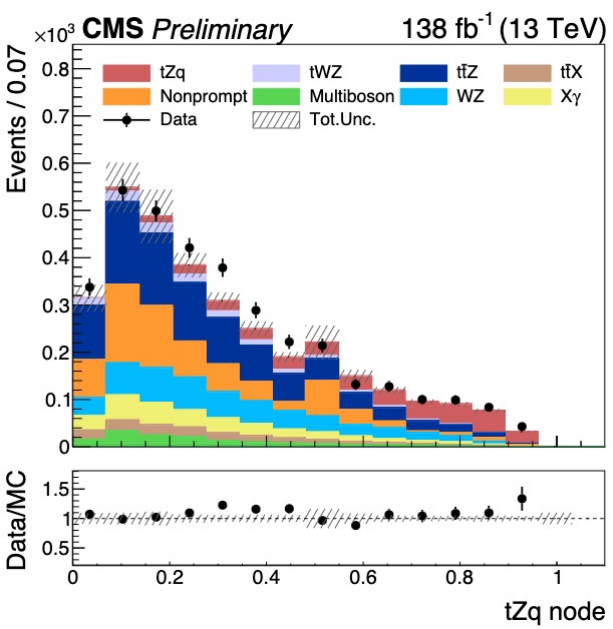
TOP-23-004

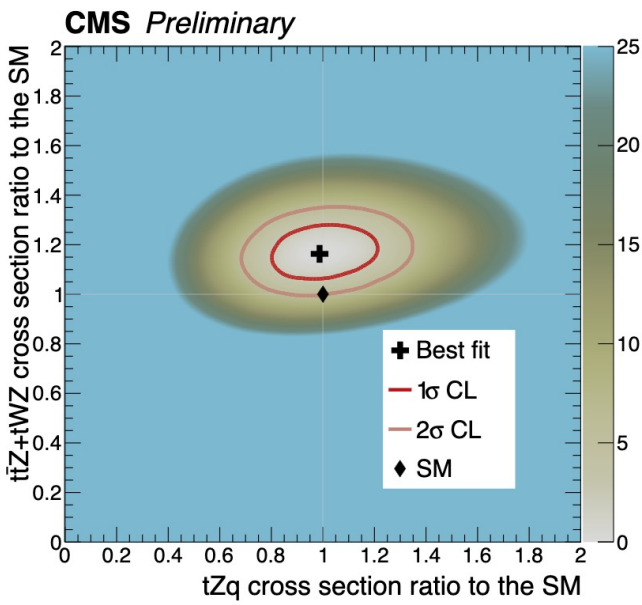
- Inclusive measurements from a multi-classifier ML ($t\bar{t}Z + tWZ$, tZq and backgrounds).

$$\sigma(\mathrm{t\bar{t}Z + tWZ}) = 1.14 \pm 0.05\ (\mathrm{stat}) \pm 0.04(\ \mathrm{syst})\ \mathrm{pb},$$
$$\sigma(\mathrm{tZq}) = 0.81 \pm 0.07\ (\mathrm{stat}) \pm 0.06\ (\mathrm{syst})\ \mathrm{pb}.$$

- Total uncertainties 6-11%, dominated by statistics.
- Measurement compatible with SM predictions.

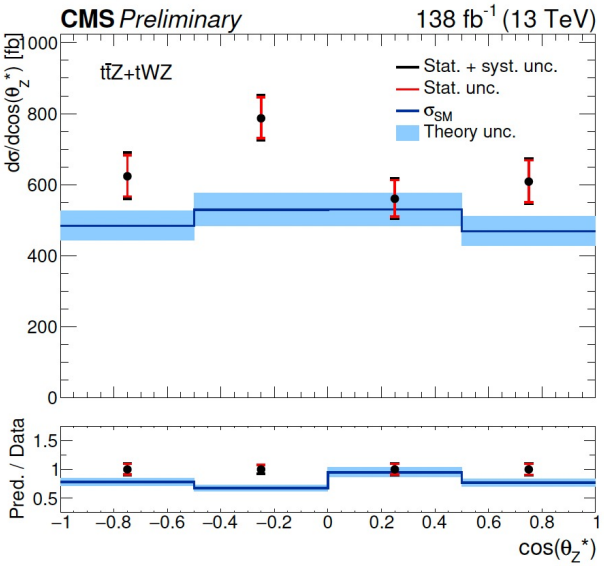


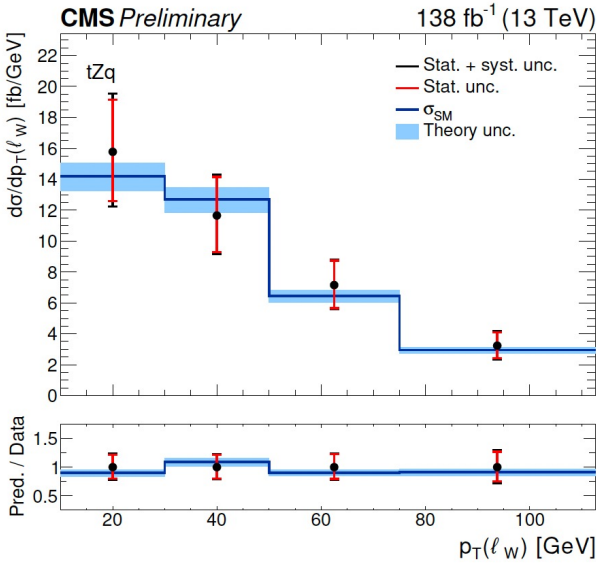


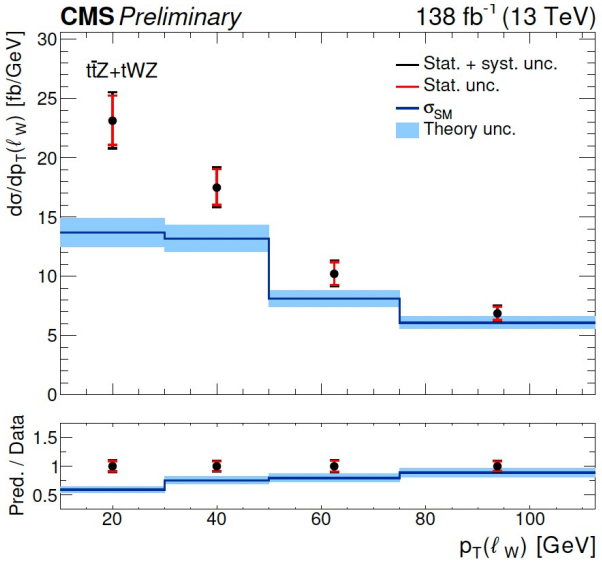


TOP-23-004

- Differential cross sections, as a function of variables sensitive to EFT.
- Good agreement for the tZq process.
- Clear trend as a function of $p_T(l_W)$ for $t\bar{t}Z + tWZ$.







Conclusion

- Inclusive and differential cross sections measurements.
  - At different collision energies,
  - At high luminosity (and high statistic),
  - For rare processes and associated production with boson.

- It allows for comparisons with MC models and SM predictions. And to potentially identify deviations.

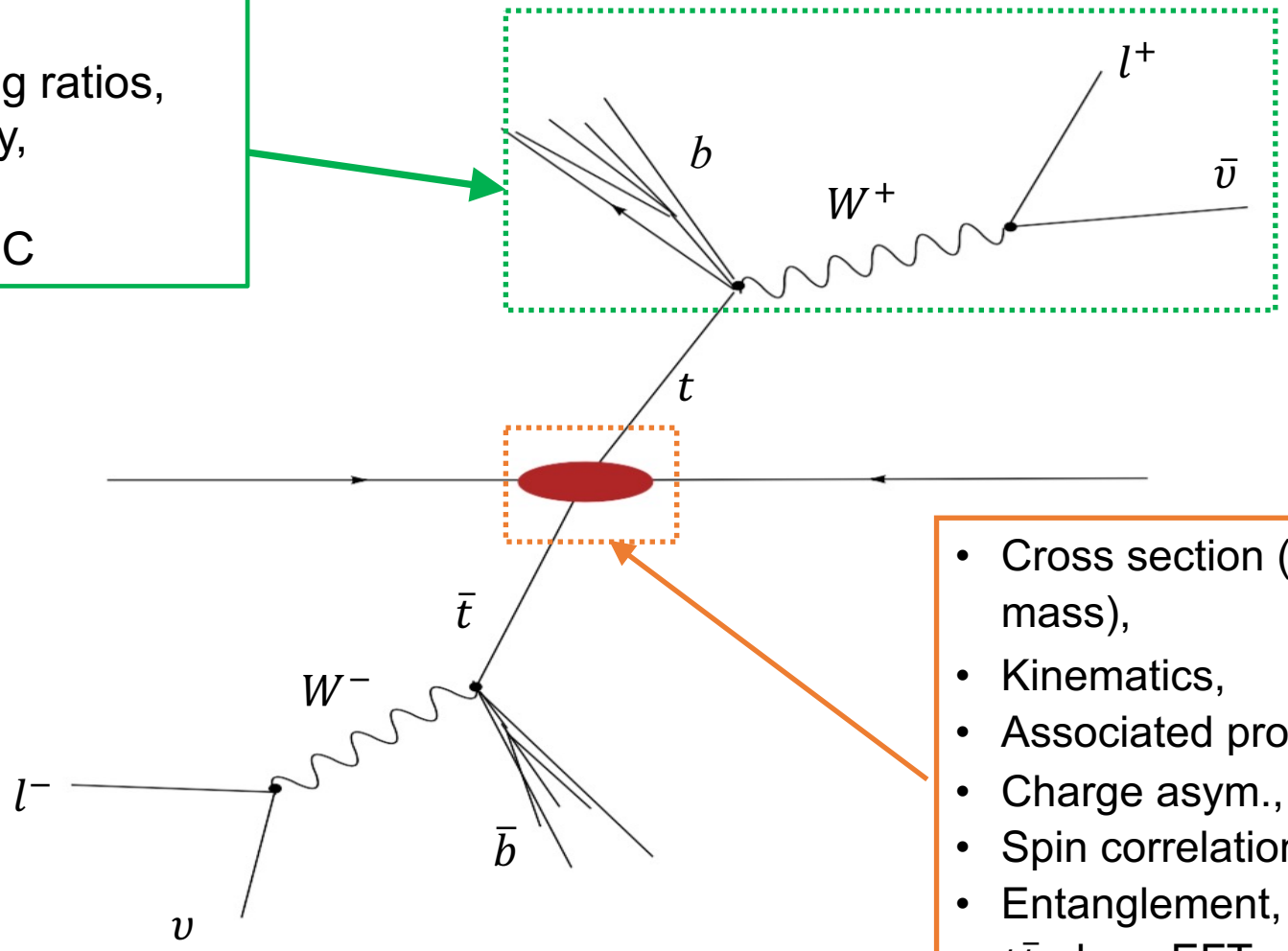
- Overall good agreements between SM and data observed. However some discrepancies can be seen :
  - Models predict harder p_T spectra in $t\bar{t}$ events,
  - Low $m_{t\bar{t}}$ region is not well described at low masses,
  - $t\bar{t}$ and tW interplay can be explored deeper,
  - Top-quark production with a Z boson shows softer lepton p_T in data.

- *Several recent results from CMS on top quark production are presented, improving our understanding of top quark physic, but also pointing to where more investigations could be needed.*

backup

The top quark pair production and properties

- Top mass,
- Charge,
- Branching ratios,
- W-helicity,
- EFT,
- Top FCNC



- Cross section (α_s, top mass),
- Kinematics,
- Associated production,
- Charge asym.,
- Spin correlation,
- Entanglement,
- $t\bar{t}$-gluon EFT.

FIXME : move to backup ?

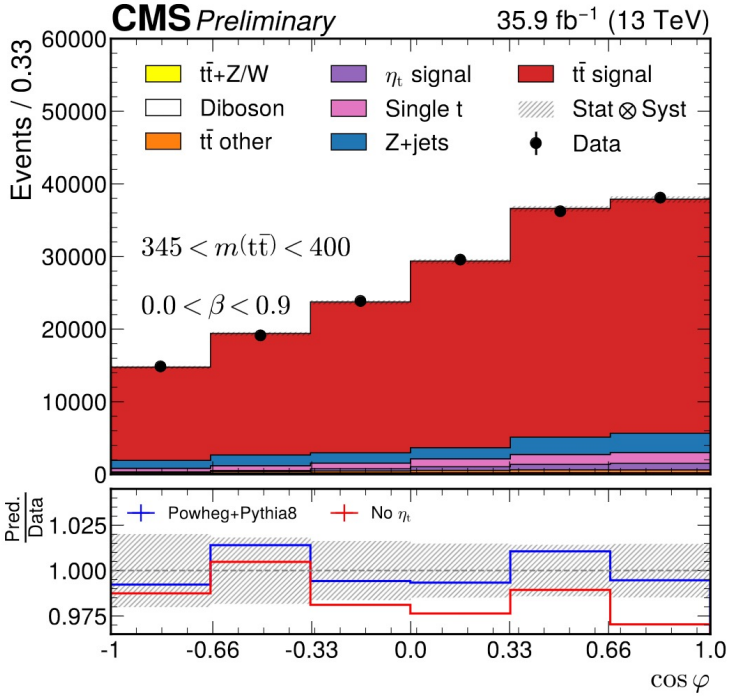
Observation of entanglement in $t\bar{t}$ events

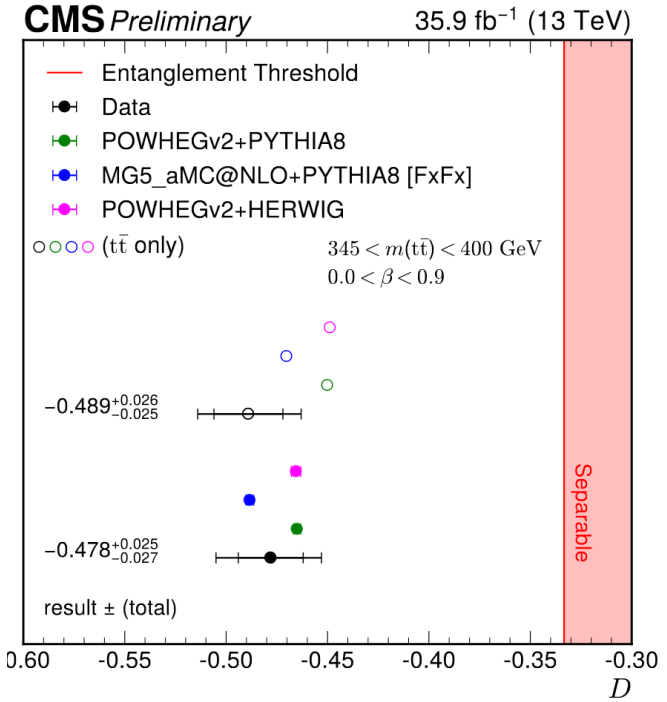
TOP-23-001

- Measurement of quantum entanglement in $t\bar{t}$ dilepton events.
  - Extracted from measurement of spin correlation at low $m_{t\bar{t}}$ values.
  - Similar events selection and reconstruction as for $t\bar{t}$ cross section,
  - Entanglement measured from the "D" parameter estimated from $\cos\varphi_{ll}$.

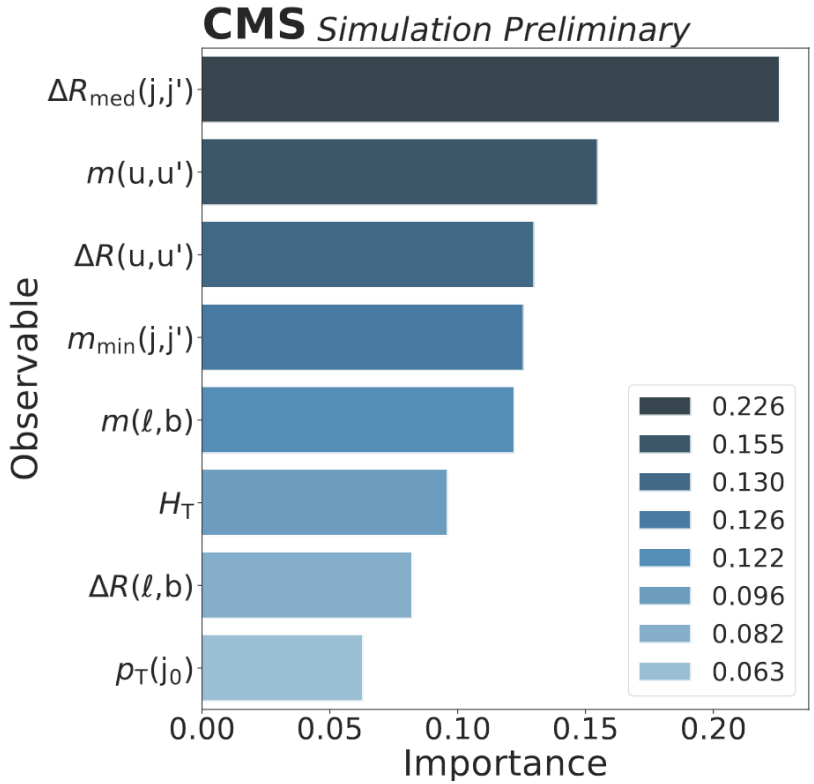
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)$$

- Expected (observed) significance of 4.7 (5.1) standard deviations



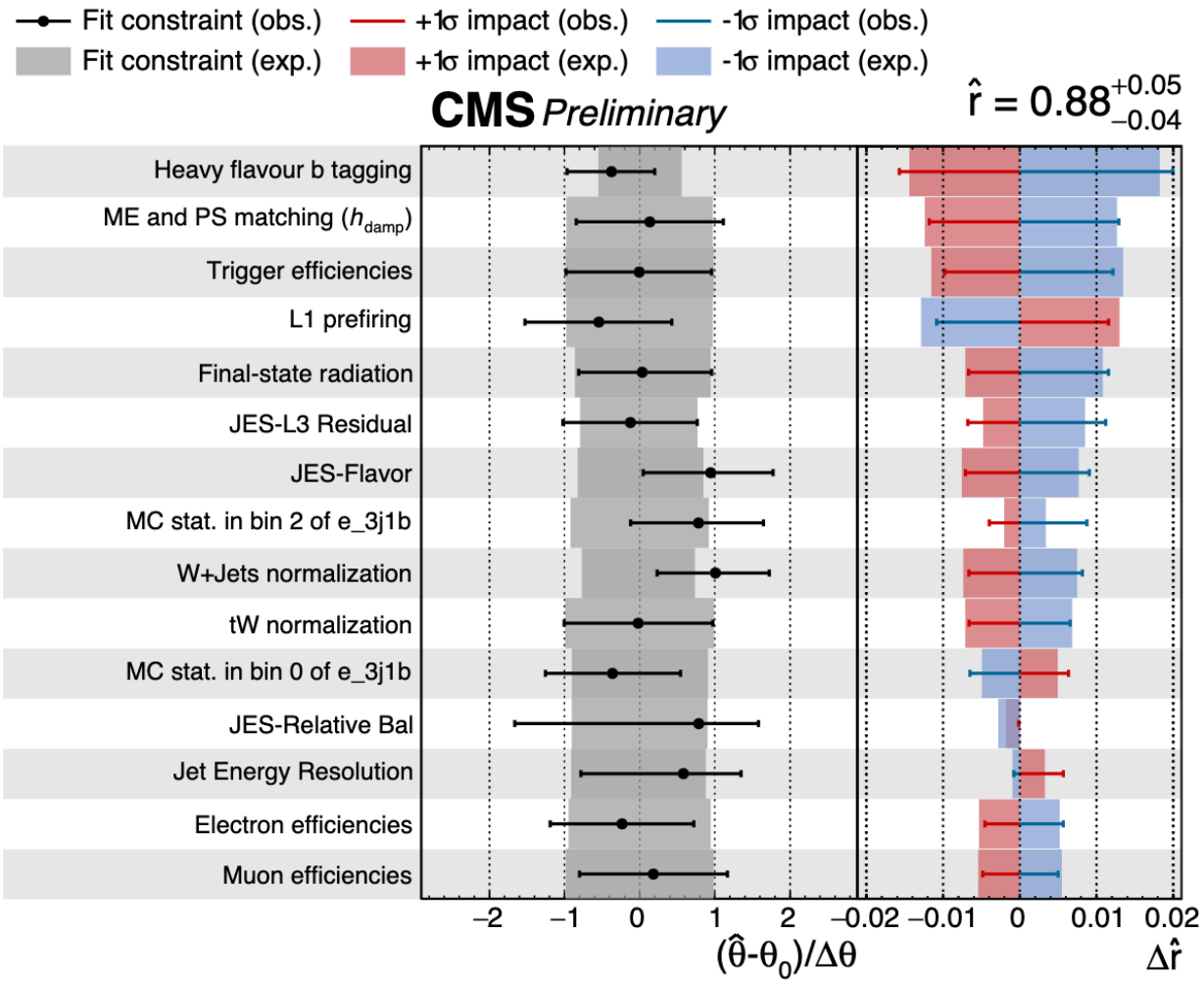


TOP-23-005 ML input variable

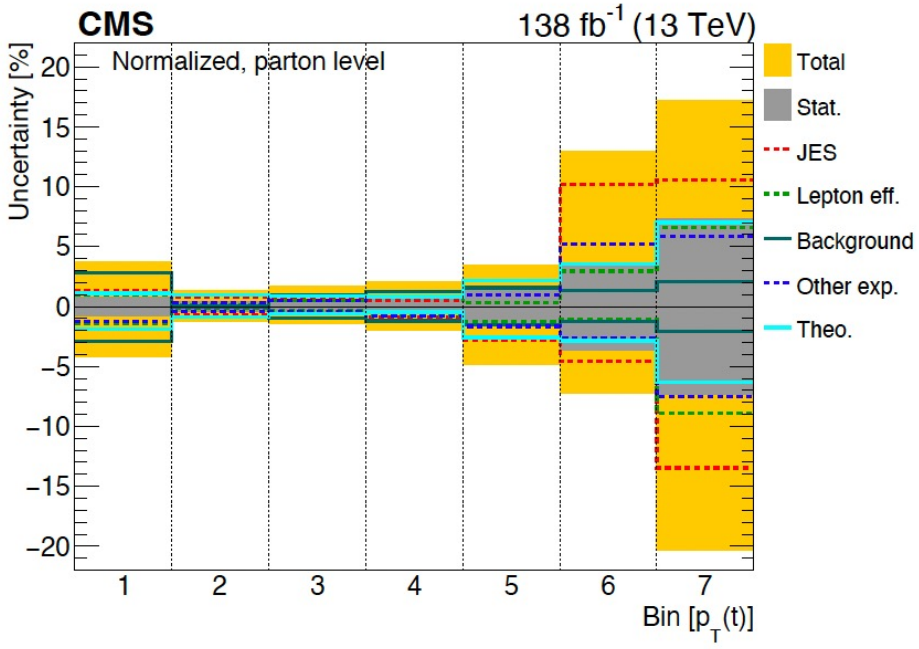


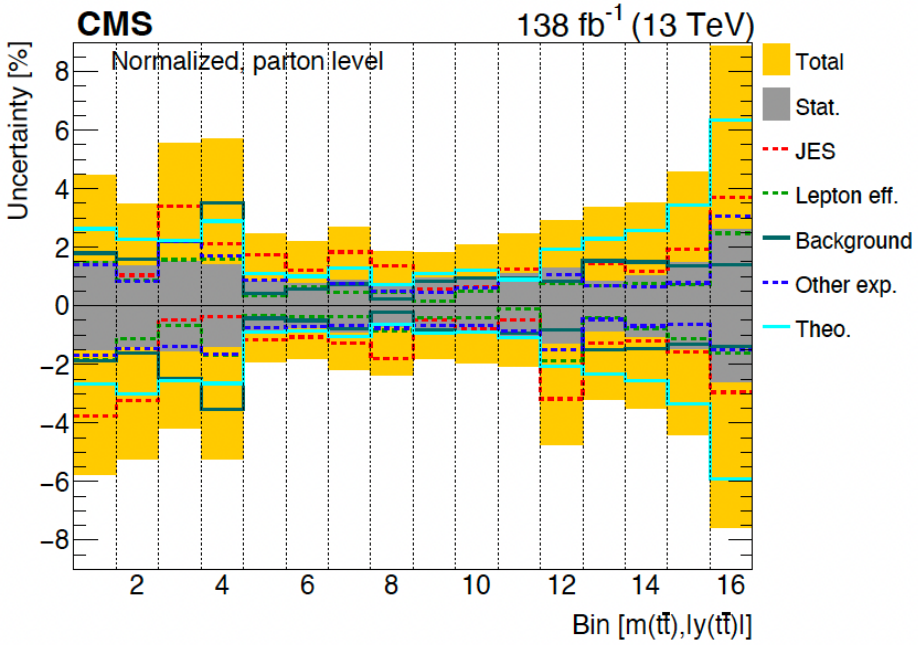
Variable	Definition
H_T	Scalar sum of the p_T of all jets in the event
$p_T(j_0)$	p_T of the leading jet
$m(u, u')$	Invariant mass of the two non-b-tagged jets
$\Delta R(u, u')$	ΔR between the two non-b-tagged jets
$m_{min}(j, j')$	Minimum invariant mass of all possible combinations of two jets
$\Delta R_{med}(j, j')$	Median ΔR between all possible combinations of two jets
$\Delta R(\ell, b)$	ΔR between the lepton and the b-tagged jet
$m(\ell, b)$	Invariant mass of the lepton and the b-tagged jet

Systematic TOP-23-005

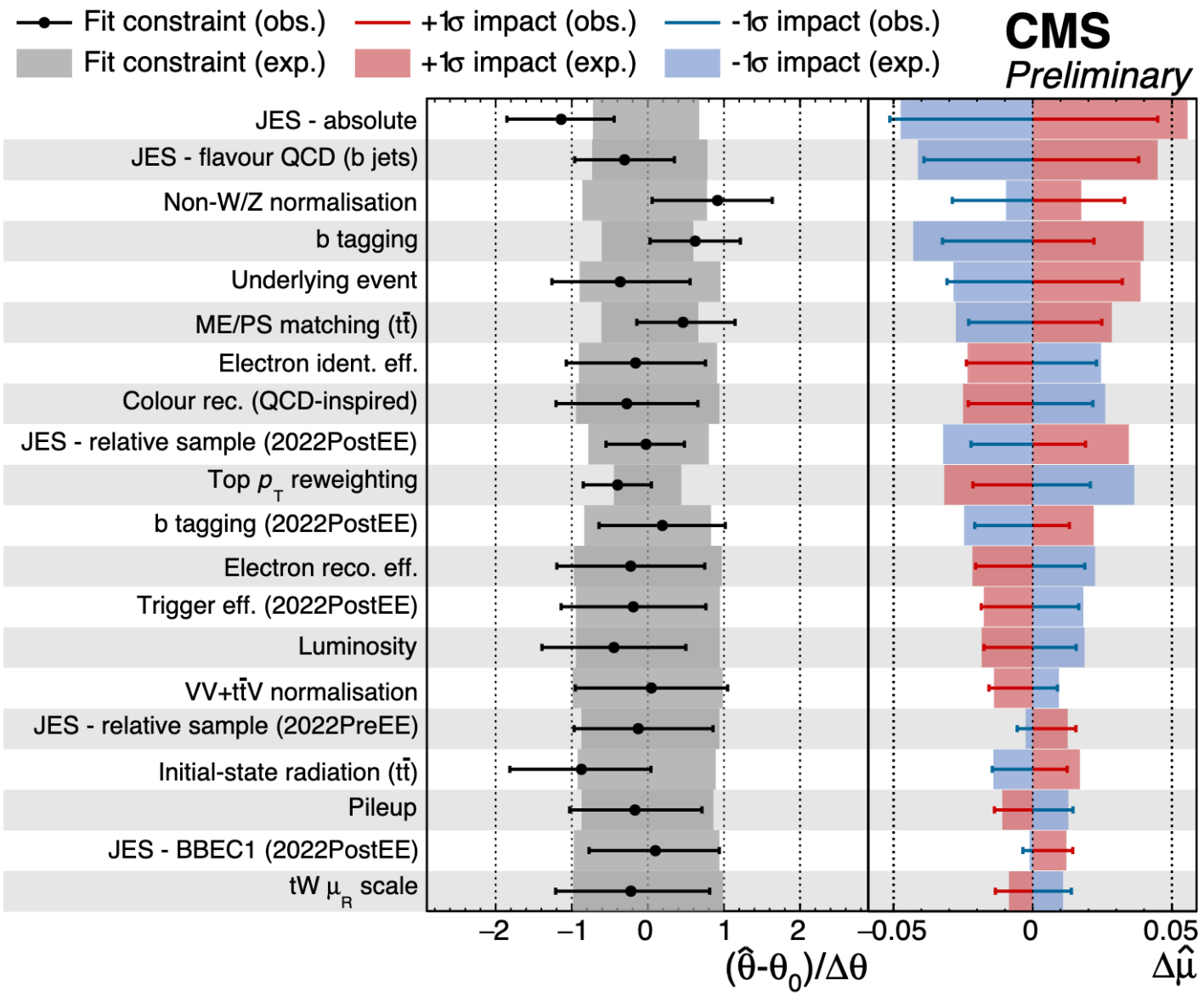


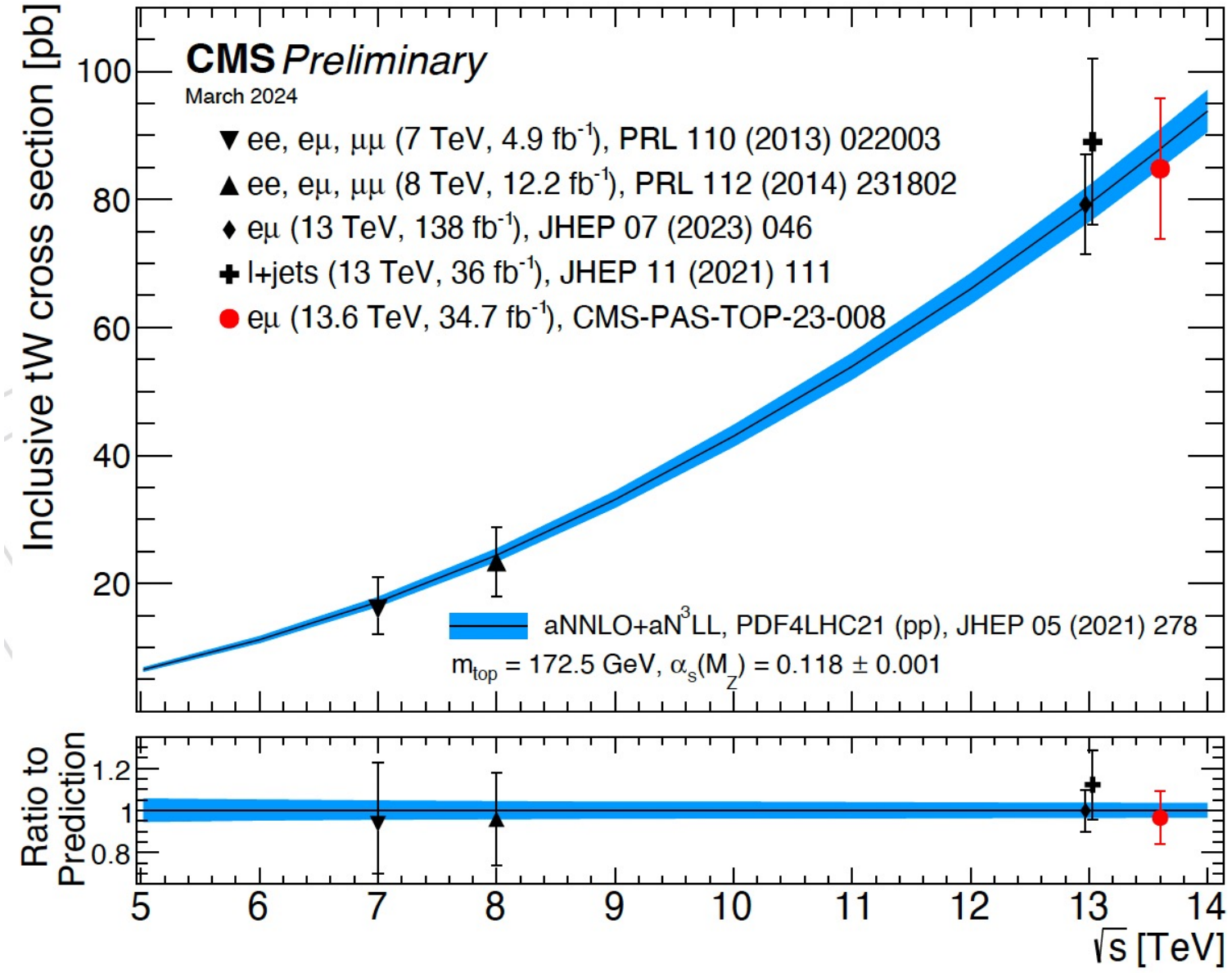
Systematic TOP-20-006





tW Systematic TOP-23-008




CMS Preliminary
March 2024
▼ ee, eμ, μμ (7 TeV, 4.9 fb-1), PRL 110 (2013) 022003
▲ ee, eμ, μμ (8 TeV, 12.2 fb-1), PRL 112 (2014) 231802
♦ eμ (13 TeV, 138 fb-1), JHEP 07 (2023) 046
✚ l+jets (13 TeV, 36 fb-1), JHEP 11 (2021) 111
● eμ (13.6 TeV, 34.7 fb-1), CMS-PAS-TOP-23-008
aNNLO+aN3LL, PDF4LHC21 (pp), JHEP 05 (2021) 278
mtop = 172.5 GeV, αs(MZ) = 0.118 ± 0.001
Inclusive tW cross section [pb]
Ratio to Prediction
√s [TeV]

Systematic TOP-23-004

Source	$\sigma(t\bar{t}Z + tWZ)$	$\sigma(tZq)$
Trigger	2%	2%
Trigger prefiring	<1%	2%
Lepton identification efficiencies	1%	2%
b tagging	1%	2%
Jet energy scale	1%	3%
Jet energy resolution	<1%	1%
Missing transverse momentum	<1%	3%
Nonprompt background	2%	3%
Pileup	<1%	1%
Luminosity	2%	2%
Statistical	3.7%	10%
Background modeling	2%	4%
Factorization scale	1%	1%
Renormalization scale	1%	2%
Parton shower	<1%	2%
PDF and α_S	<1%	<1%
Underlying event and color reconnection	1%	2%
tWZ modeling	<1%	<1%
MC statistical	<1%	1%
Total	6%	13%