Recent top quark and QCD results from ATLAS and CMS

Harish Potti on behalf of the ATLAS and CMS collaborations

The University of Sydney

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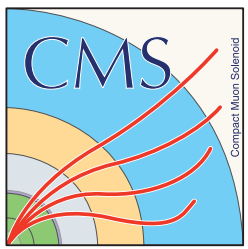
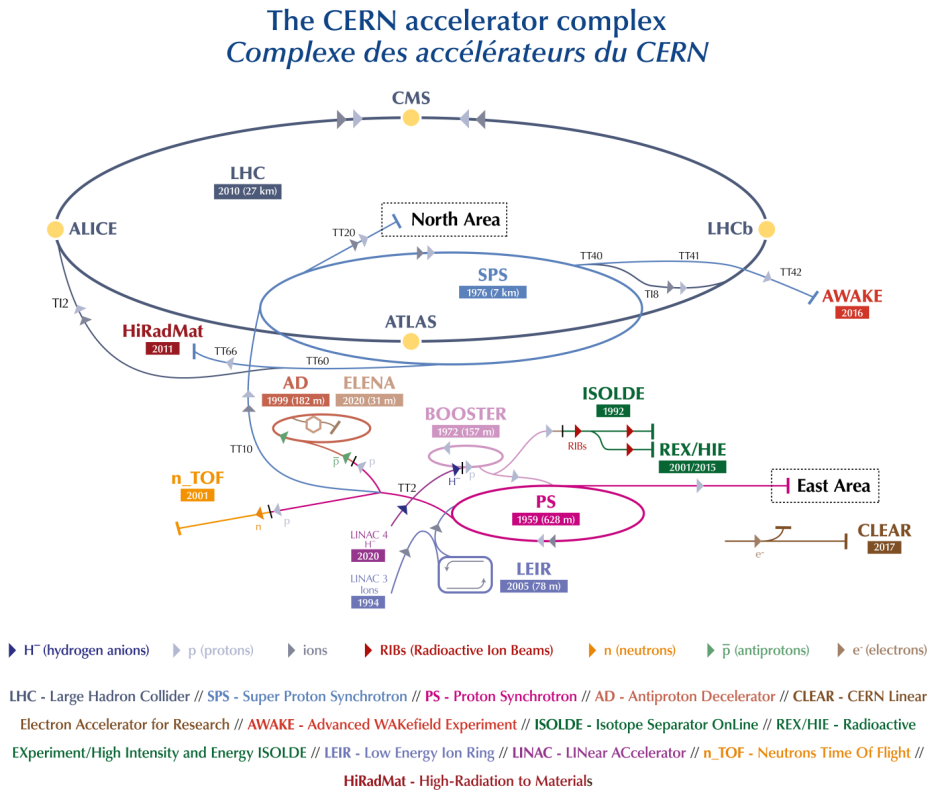


The Large Hadron Collider

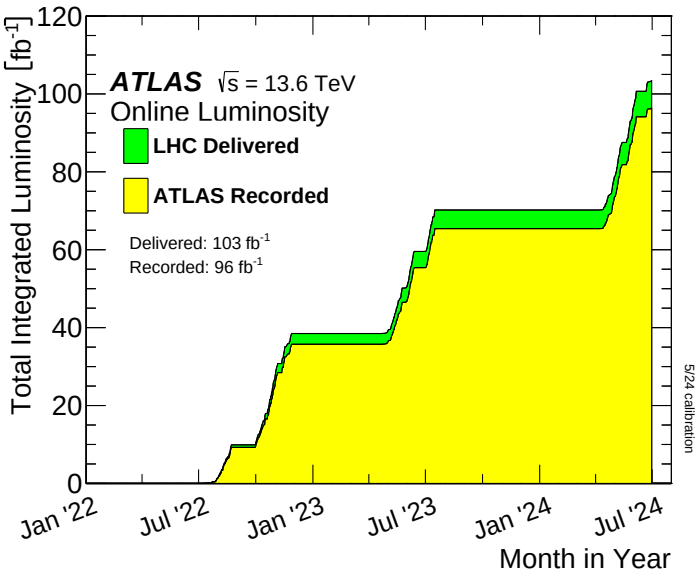
- The Large Hadron Collider (LHC) is a circular particle accelerator
- High-energy proton beams are made to collide at E_{CM} up to 13.6 TeV

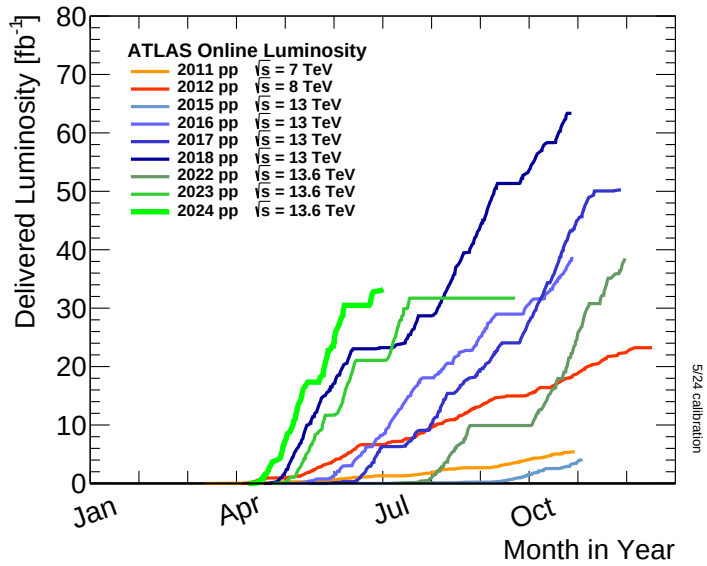


- 27 km in circumference and located 100 m beneath the surface
- Two general purpose detectors: ATLAS and CMS
- Two specialized detectors: LHC*b* and ALICE
- Superconducting coils are used to provide a magnetic field of up to 8.3 T

LHC STATUS

- During LHC Run-2 data taking period (2015-18), the ATLAS experiment recorded ~ 140 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV
- Run-3 started in 2022 with pp collisions at $\sqrt{s} = 13.6$ TeV
- LHC already delivered 103 fb^{-1} of data
- This new dataset presents an exciting opportunity to improve the precision of top quark measurements and push the boundaries of the search for BSM physics
- Analyses with Run-3 data are slowing ramping up as many of them are still working with full Run-2 dataset





TOP QUARK: INTRODUCTION

- Heaviest quark, yet fundamental
- First observed in 1995 by CDF and D0 experiments
- Yukawa coupling $(y_t) \sim 1 \implies$ may play a special role in the EWSB mechanism
- Very short lifetime $\sim 10^{-25}s \implies$ Top quark does not form hadrons
- Decays almost always to $Wb \implies$ Good probe for $|V_{tb}|$
- Precision measurements of top quark properties provides an important test for the SM
- Any observation of deviations would indicate physics beyond the SM

OUTLINE

In this talk, I will highlight a few selected top quark and QCD results from the ATLAS and CMS collaborations.

Top mass & Lepton Flavour Universality

Quantum Entanglement in top quarks

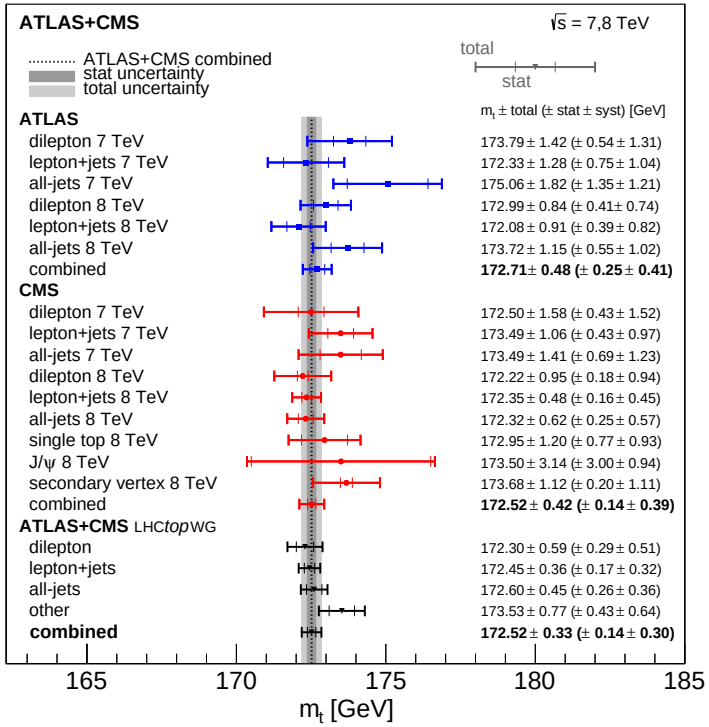
Top + X

Top cross section

Jet cross section measurements

MEASUREMENT OF THE TOP QUARK MASS

- Top quark mass (m_t) is a free parameter in the SM $\Longrightarrow$ Must be measured experimentally
- m_t plays a central role in understanding the stability of the Electroweak vacuum



Combination of the ATLAS and CMS measurements at 7 & 8 TeV

- 15 measurements: 6 from ATLAS, 9 from CMS
- $m_t = 172.52 \pm 0.14$ (stat.) ± 0.30 (syst.) GeV ($<$ 2 permille precision!!)
- **Most precise value of the top quark mass to date**
- More details: Phys. Rev. Lett. 132, 261902 (2024)

Lepton Flavour Universality in W boson decays to electrons and muons

- Lepton flavour universality is a key axiom of the SM
- It means the coupling of the charged leptons (e, μ, τ) to the electroweak gauge bosons are independent of the lepton flavor
- This assumption can be tested by measuring, for example, $R_W^{\mu/e} = \mathcal{B}(W \to \mu\nu)/\mathcal{B}(W \to e\nu)$

New ATLAS measurement with full Run-2 data

- Full results: arxiv: 2403.02133
- Probes dileptonic $t\bar{t}$ production process
  - large cross-section at the LHC
  - provides a clean source of W bosons
  - small backgrounds (Dominant background is Z+jets)

LFU IN W BOSON DECAYS: RESULTS

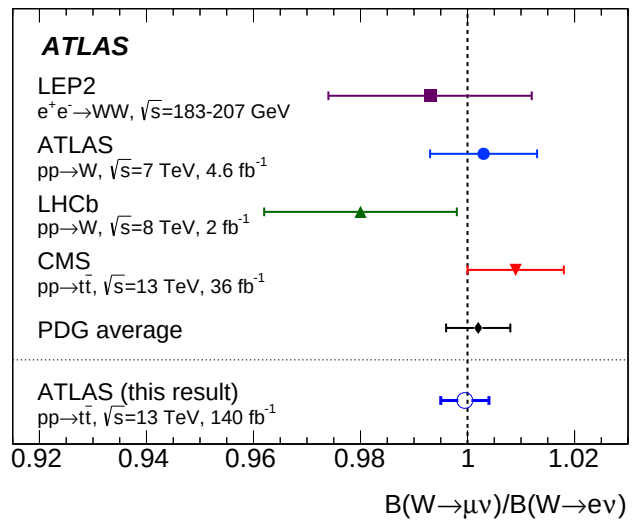
- Systematic uncertainties due to lepton identification & trigger efficiencies are minimized by simultaneously measuring $R_W^{\mu/e}$ and $R_Z^{\mu\mu/ee}$ with POI:

$$R_{WZ}^{\mu/e} = \frac{R_W^{\mu/e}}{\sqrt{R_Z^{\mu\mu/ee}}}$$

- $R_W^{\mu/e}$ is determined by utilizing the high-precision measurement of $R_Z^{\mu\mu/ee}$ by the LEP and SLD collaborations

$$R_W^{\mu/e}\,(\text{ATLAS}) = R_{WZ}^{\mu/e}\,(\text{ATLAS}) \times \sqrt{R_Z^{\mu\mu/ee}}\,(\text{LEP+SLD})$$

- $R_W^{\mu/e}$ **= 0.9995 ± 0.0022 (stat) ± 0.0036 (syst) ± 0.0014 (ext)**
- Compatible with the Standard Model assumption at the 0.5% level
- Most precise result to date (**better than the PDG average of all previous measurements**)



Top mass & Lepton Flavour Universality

Quantum Entanglement in top quarks

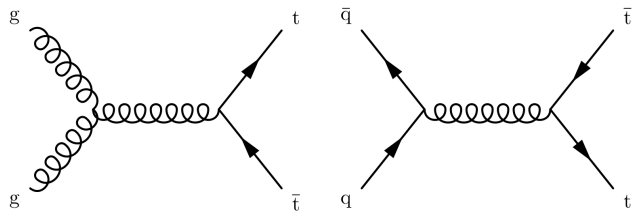
Top + X

Top cross section

Jet cross section measurements

QUANTUM ENTANGLEMENT IN $t\bar{t}$ PAIRS

At the $m_{t\bar{t}}$ threshold, 80% of $t\bar{t}$ pairs produced in spin-singlet state - maximally entangled



$t\bar{t}$ events provide a unique probe for entanglement via spin

- Top quark lifetime ($\sim 10^{-25}s$) is shorter than its hadronization ($\sim 10^{-24}s$) and spin decorrelation time ($\sim 10^{-21}s$)
- As a result, spin information is preserved in $t \to Wb$ decays
- For $W \to \ell\nu$ decays, ℓ measurements allow access to the top quark spin

$$\text{Entanglement marker } D \;=\; -3 \left\langle \cos\varphi \right\rangle$$

where, φ = angle between the leptons in their parent top quark frames

Measurement of $D \;<\; -1/3$ implies entanglement

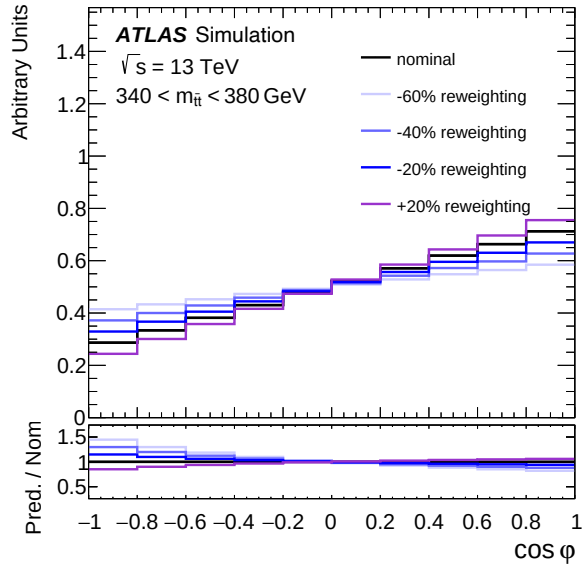
Observation of Quantum Entanglement in $t\bar{t}$ pairs [ATLAS]

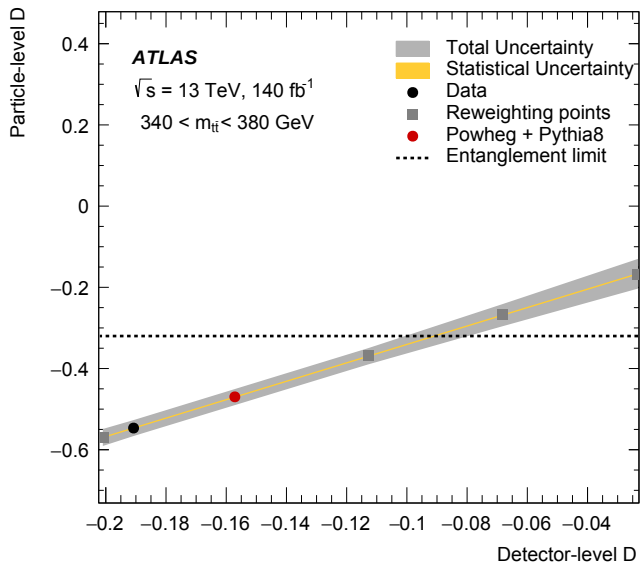
ATLAS (arxiv:2311.07288) strategy

- Targets $e\mu$ channel with ≥ 1 b-jet with full Run-2 dataset
- Signal region at production threshold is defined as $340 < m_{t\bar{t}} < 380$ GeV
- Two validation regions with higher $m_{t\bar{t}}$
- Neutrinos reconstructed based on kinematic constraints on top and W mass

D distorted by detector response

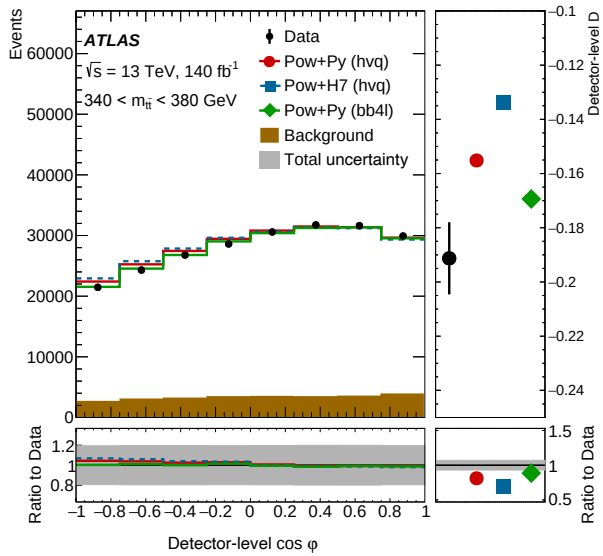
- Calibration curve approach – derive true D vs detector-level D dependence
- Event-by-event reweighting $\Rightarrow \cos\varphi$ distributions for various D

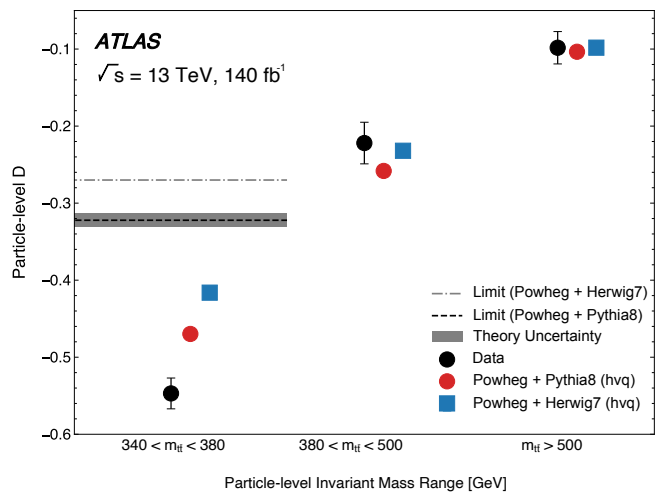




Observation of Quantum Entanglement in $t\bar{t}$ pairs [ATLAS] arxiv:2311.07288

- Calculated detector-level D from data and corrected using the calibration curve
- Good agreement between measured and predicted D in validation regions
- $D_{obs} = -0.547 \pm 0.002$ (stat.) ± 0.021 (syst.)
- $D_{exp} = -0.470 \pm 0.002$ (stat.) ± 0.018 (syst.)
- Observed and expected significances with respect to the entanglement limit are $> 5\,\sigma$
- Measurement is dominated by systematic uncertainties (leading one: signal modelling)





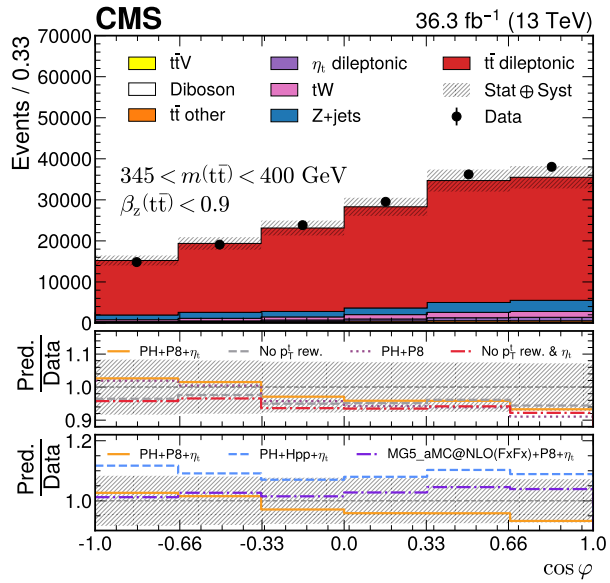
Physics Briefings on this result

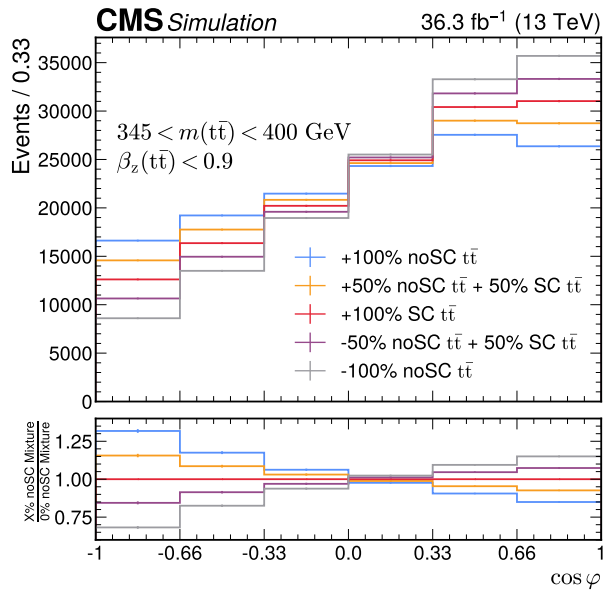
https://atlas.cern/Updates/Briefing/Top-Entanglement
https://cerncourier.com/a/highest-energy-observation-of-entanglement/

Observation of Quantum Entanglement in $t\bar{t}$ pairs [CMS]

CMS measurement (arxiv:2406.03976):

- Targets events with two leptons of opposite charge with ≥ 1 b-jet
- Uses 2016 data with 36.3 fb $^{-1}$
- Signal region at production threshold: $345 < m_{t\bar{t}} < 400$ GeV
- Cut on velocity along the beam line of the $t\bar{t}$ system to increase fraction of $gg/q\bar{q}$
- Perform a profile maximum likelihood fit of the $\cos\varphi$ distribution in the signal region
- Effects due to non-relativistic quasi bound-states were considered in this analysis





Observation of Quantum Entanglement in $t\bar{t}$ pairs [CMS] arxiv:2406.03976

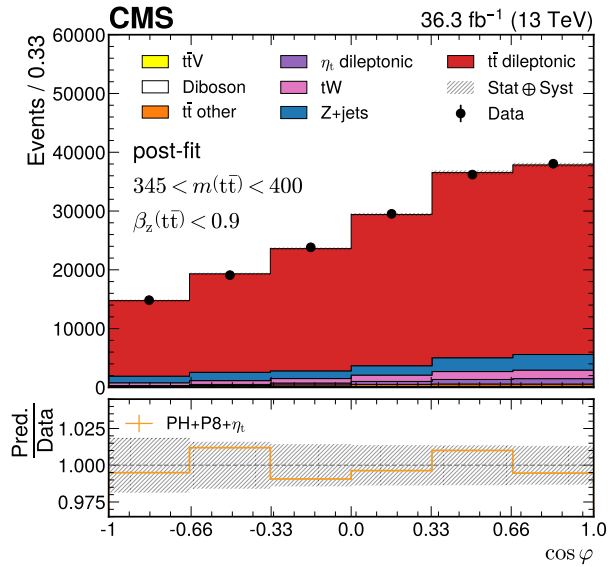
Results without considering effects due to η_t:

$$D_{obs} = -0.480^{+0.026}_{-0.029}$$

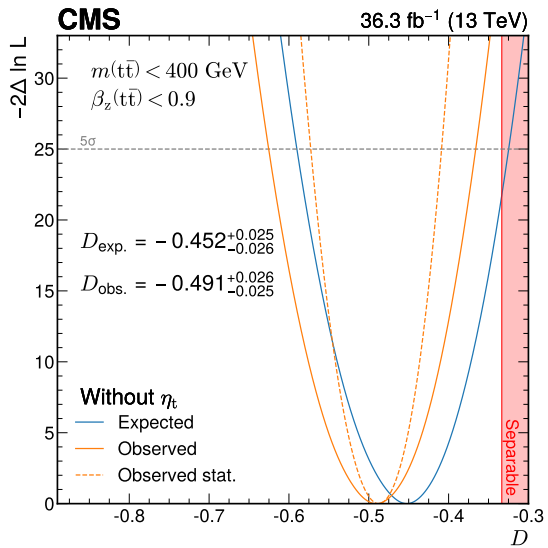
$$D_{exp} = -0.467^{+0.026}_{-0.029}$$

Significance: 6.3σ obs. (4.7σ exp.)

$\Rightarrow$ Observation of top quarks entanglement at $t\bar{t}$ threshold



Thus, the ATLAS and CMS measurements provide a new probe of Quantum Mechanics at the highest energies ever produced



Latest CMS result

Spin correlations and entanglement in top quark pairs using lepton+jets events: CMS-PAS-TOP-23-007

Top mass & Lepton Flavour Universality

Quantum Entanglement in top quarks

Top + X

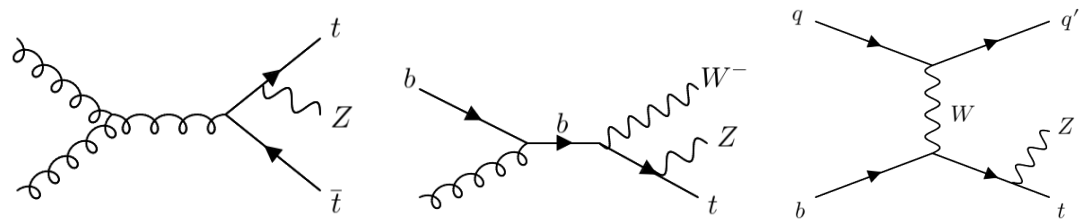
Top cross section

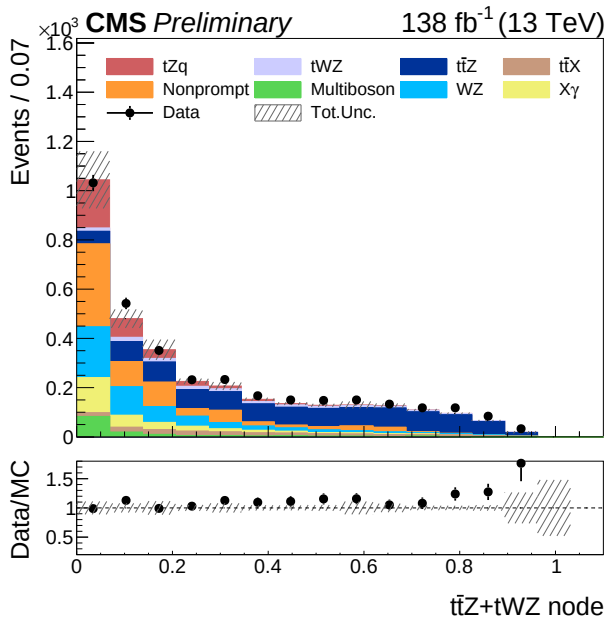
Jet cross section measurements

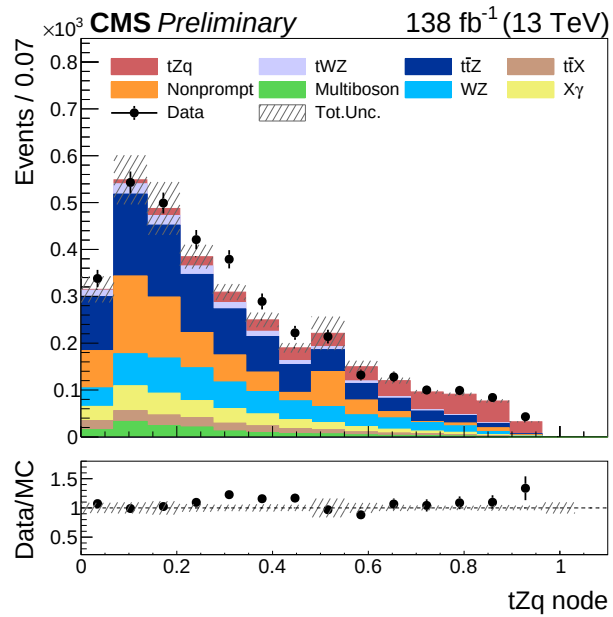
TOP QUARK IN ASSOCIATION WITH A Z BOSON

CMS-PAS-TOP-23-004

- Simultaneous measurement of $t\bar{t}Z + tWZ$ and $tZq \implies$ High sensitivity to possible anomalous coupling between the top quark and Z boson
- Considers 3 lepton final state (2 from Z; 1 from W)
- Multi-class DNN is used for separation of signal and backgrounds



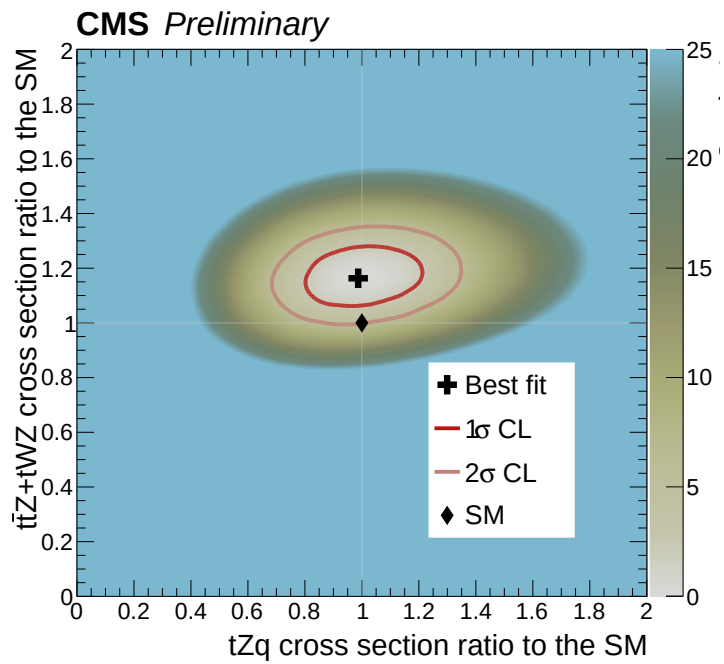




INCLUSIVE CROSS SECTION MEASUREMENT

CMS-PAS-TOP-23-004

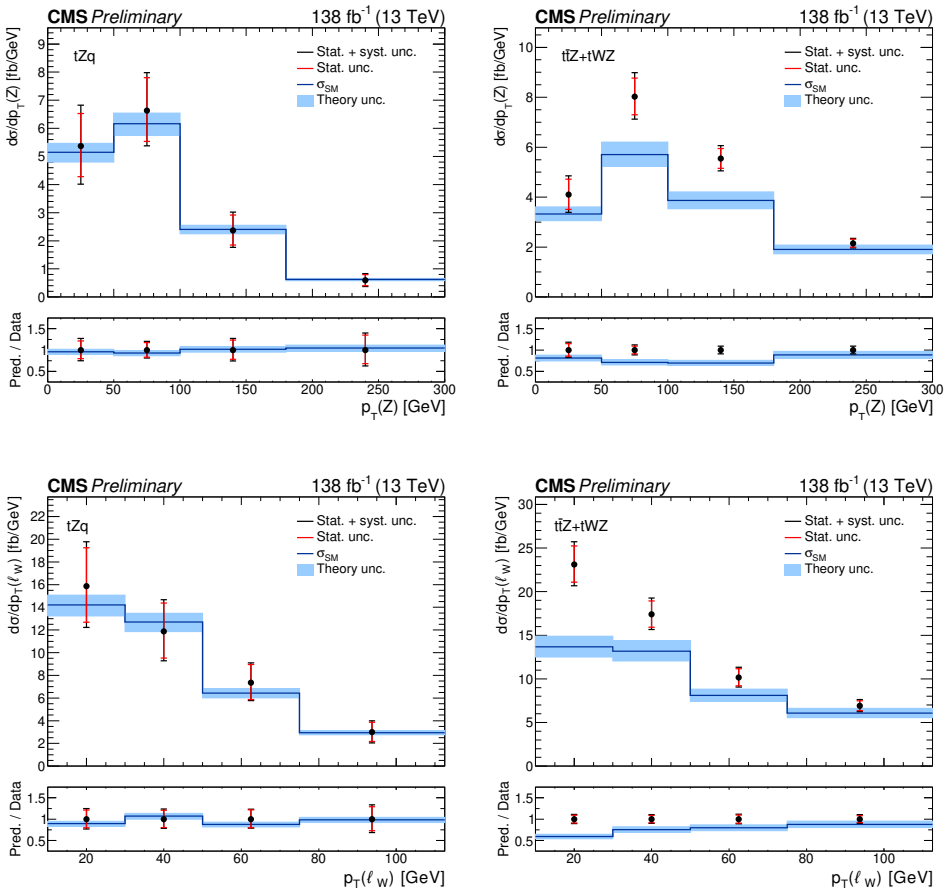
- Includes 4ℓ ($t\bar{t}Z$ enriched) and 0 b-jets (WZ enriched) channels
- $\sigma(t\bar{t}Z + tWZ) = 1.14 \pm 0.05$ (stat) ± 0.04 (syst) pb
- $\sigma(tZq) = 0.81 \pm 0.07$ (stat) ± 0.06 (syst) pb
- Dominated by statistical uncertainties
- $\mu_{t\bar{t}Z+tWZ} = 1.17 \pm 0.07$ (slightly higher than the SM prediction)
- $\mu_{tZq} = 0.99 \pm 0.13$ (agrees with the SM prediction)



DIFFERENTIAL CROSS-SECTION MEASUREMENTS

CMS-PAS-TOP-23-004

- Measured as a function of five observables: $p_T(Z)$, $p_T(\ell_W)$, $\Delta\phi(\ell^+, \ell^-)$, $\Delta R(Z, \ell_W)$ and $cos\theta^*_Z$
- These observables are sensitive to QCD modelling, BSM physics and useful for EFT interpretations



- Significant discrepancy in the region of low $p_T(\ell_W)$
- Reason for the slightly higher measured cross-section

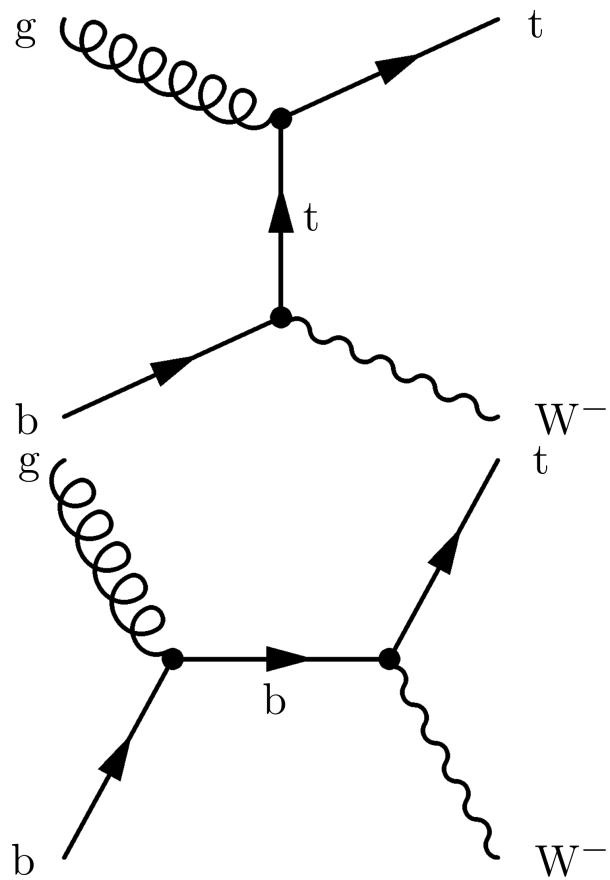
MEASUREMENT OF tW PRODUCTION IN $e\mu$ CHANNEL WITH THE CMS EXPERIMENT CMS-PAS-TOP-23-008

tW production is very interesting due to:

- its interference with $t\bar{t}$ at NLO in QCD
- sensitivity to new physics
- its role as a background in many SM and new physics searches

First Run-3 single top measurement

- Inclusive and differential X-section measurements were performed in $e\mu$ final state
- Uses 2022 run-3 data (34.7 fb^{-1})



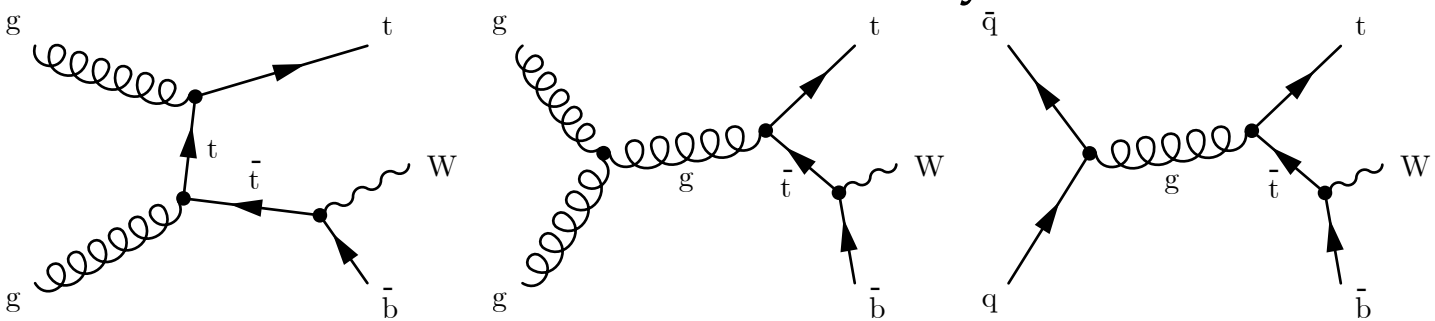
TREATMENT OF tW AND $t\bar{t}$ INTERFERENCE

CMS-PAS-TOP-23-008

Four schemes are used for modelling tW production:

- **Diagram Removal (DR)**: Remove doubly resonant diagrams from signal definition
- **DR2**: Includes the terms corresponding to the interference between tW and $t\bar{t}$
- **Diagram Subtraction (DS)**: Subtract gauge-invariant term to cancel the interference
- **Alternate DS**: a dynamic factor is used to model the top quark resonance, instead of a fixed one

DR is used as the default in the analysis



EVENT SELECTION CMS-PAS-TOP-23-008

Baseline event Selection:

- Single lepton and dilepton triggers
- $\geq$2 leptons with $p_T > 20$ GeV and $|\eta| < 2.4$
- Leading lepton pair must be opposite sign $e\mu$ pair
- Leading lepton $p_T > 25$ GeV
- M(ℓ_i, ℓ_j) > 20 GeV for all lepton pair combinations

Categorization based on:

- Jets: $p_T > 30$ GeV and $|\eta| < 2.4$
- Loose jets: 20 GeV $< p_T < 30$ GeV

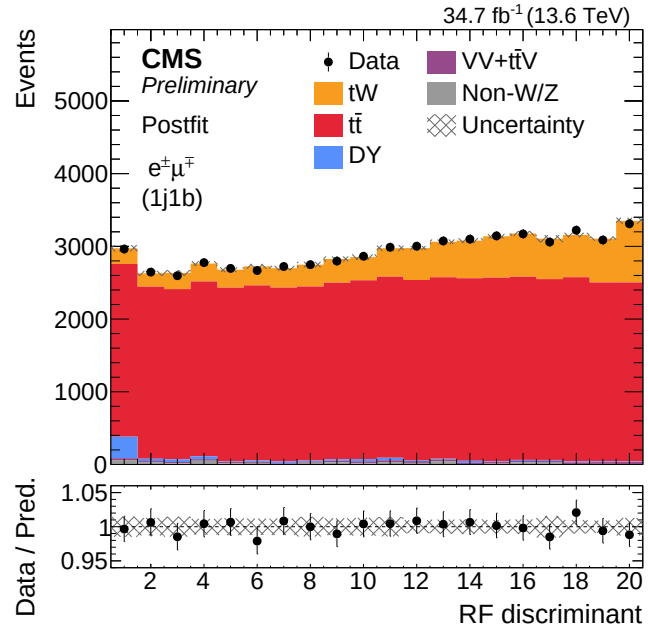
Inclusive measurement:

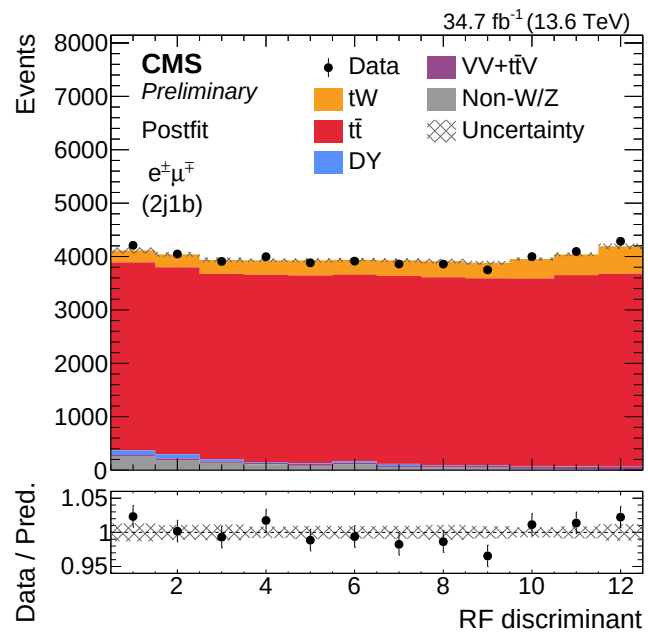
- 1j1b + 2j1b: sensitive to tW
- 2j2b: Control region for $t\bar{t}$

Differential measurement:

- 1j1b region events with zero loose jets

Random Forest (RF) multiclassifiers are trained to separate tW signal from $t\bar{t}$ background.



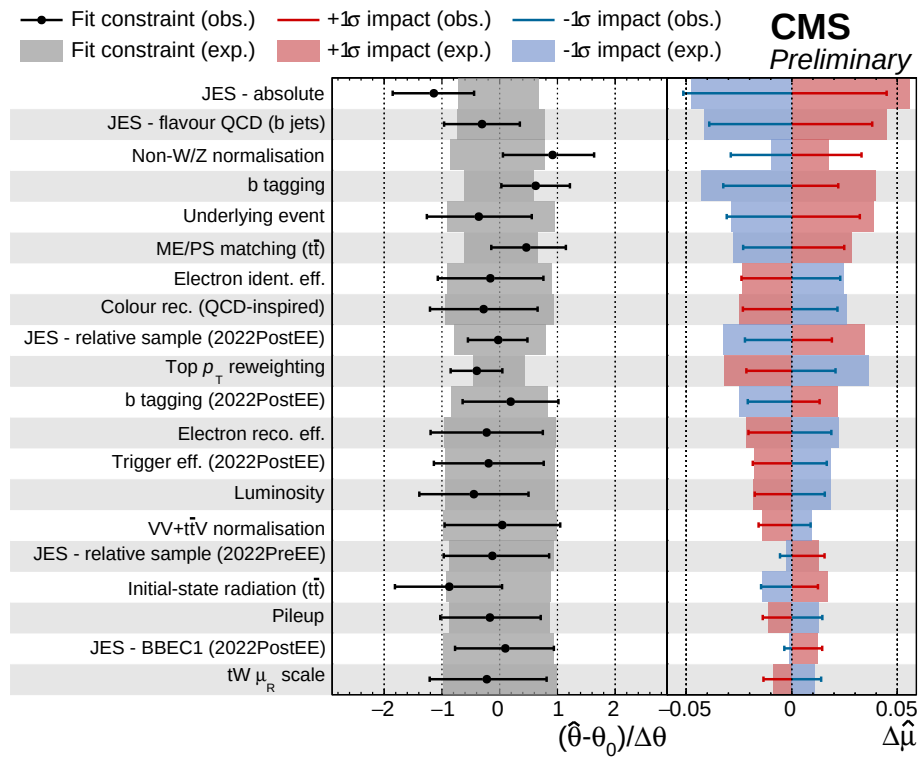


INCLUSIVE tW MEASUREMENT CMS-PAS-TOP-23-008

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

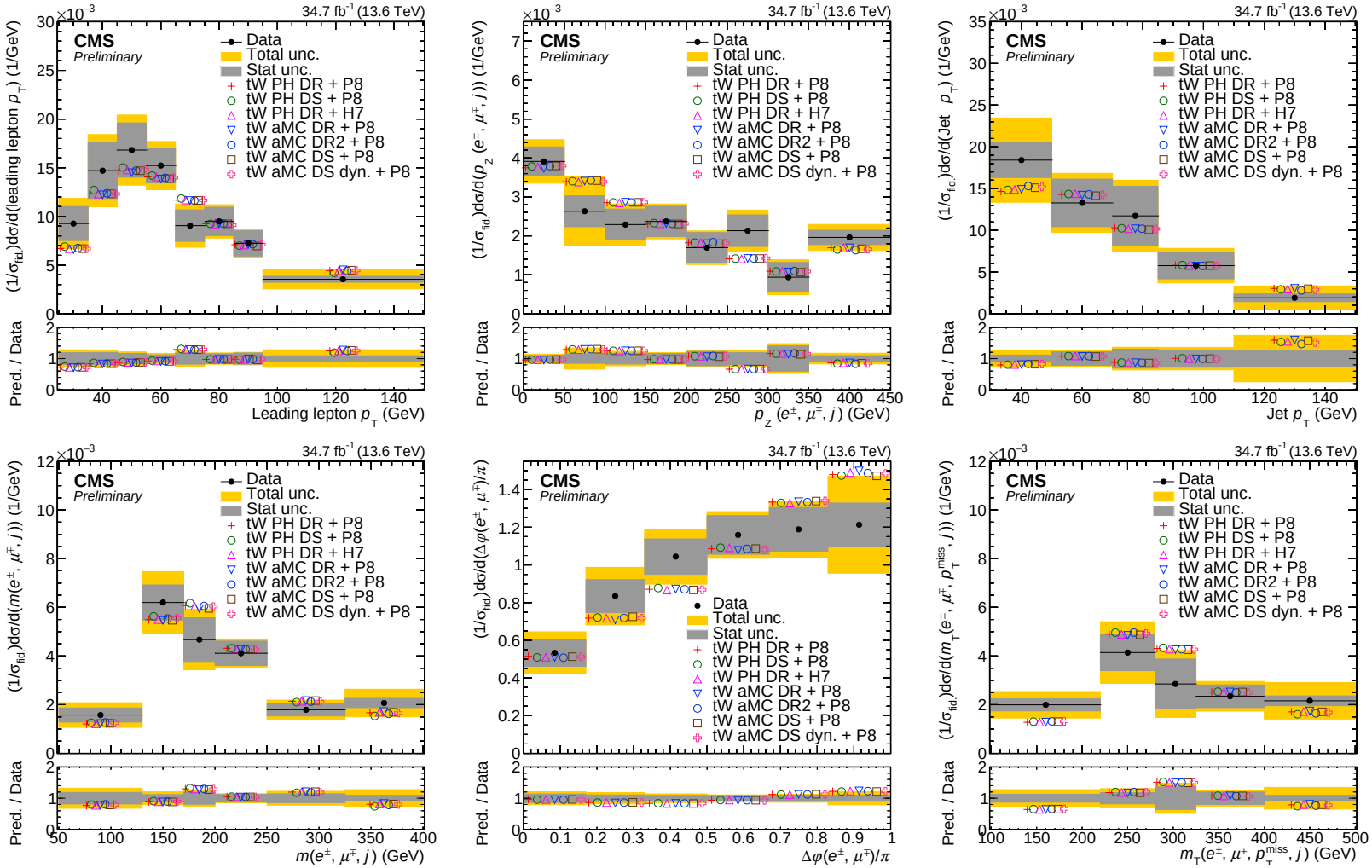
- In agreement with prediction
  $\sigma^{SM}_{tW} = 87.9\,^{+2.0}_{-1.9}\,(\text{scale}) \pm 2.4(\text{PDF}+\alpha_s)$ pb (aN^{3}LO QCD)

- Measurement is clearly dominated by systematic uncertainties
- Leading syst. unc. sources: JES, Non-W/Z normalization and b-tagging efficiencies



DIFFERENTIAL tW MEASUREMENT CMS-PAS-TOP-23-008

- Overall, the measurements are in good agreement with predictions
- **All methods, DR, DR2, DS, and DS with a dynamic factor, show similar compatibility with data**
- Overall uncertainties in range of 30-40% (limited stats.)



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$t\bar{t}$ PRODUCTION IN p+Pb COLLISIONS

Measurement of top quarks in p+Pb collisions provide

- Novel probes of nuclear modifications to parton distribution functions (nPDFs) in a poorly constrained kinematic region Phys. Rev. D 93, 014026 (2016)
- Insights to better understand the properties of the strongly interacting quark-gluon plasma produced in Pb+Pb collisions

New ATLAS result

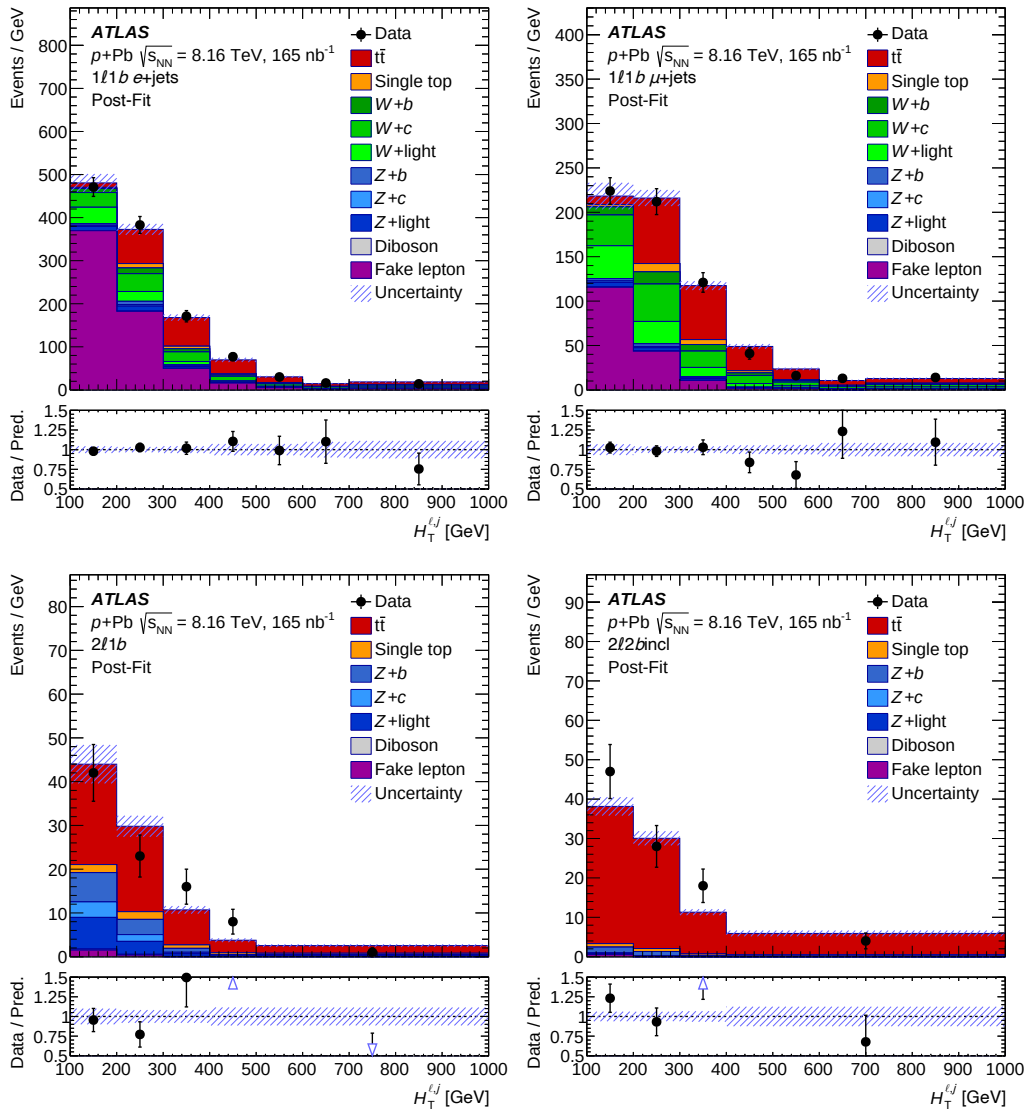
Observation of $t\bar{t}$ production in the combined ℓ**+jets** and **dilepton (first time in HI collisions)** channels in p+Pb collisions
arxiv: 2405.05078

- W boson, Z boson, b-jet, and τ-lepton have already been observed in Pb+Pb collisions
- CMS previously reported the observation of $t\bar{t}$ production using the ℓ**+jets** channel Phys. Rev. D 93, 014026 (2017)
- Uses 165 nb^{-1} p+Pb collision data collected by the ATLAS experiment in 2016 ($\langle \mu \rangle = 0.18$)

$t\bar{t}$ PRODUCTION IN p+Pb COLLISIONS: STRATEGY

arxiv: 2405.05078

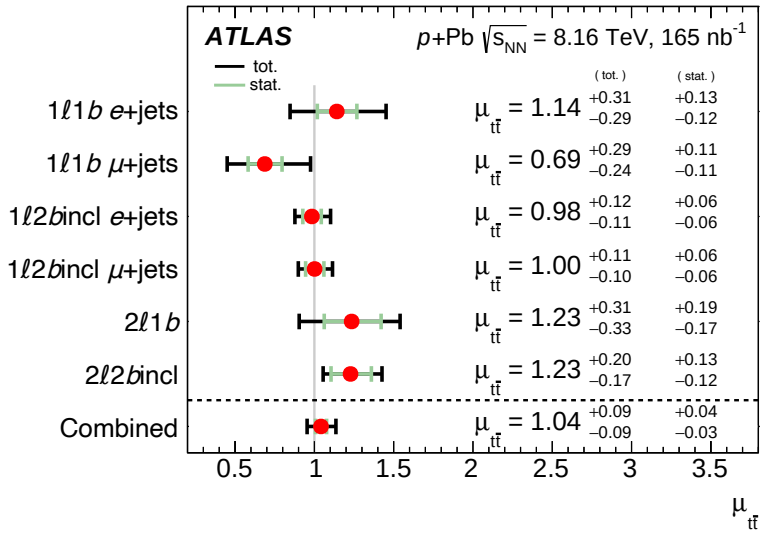
- Six signal regions are defined based on the # b-jets and # leptons
  - $1\ell 1b$ e+jets
  - $1\ell 2b$incl e+jets
  - $1\ell 1b$ μ+jets
  - $1\ell 2b$incl μ+jets
  - $2\ell 1b$
  - $2\ell 2b$incl
- Fake lepton backgrounds are estimated using a data-driven method (Matrix Method)

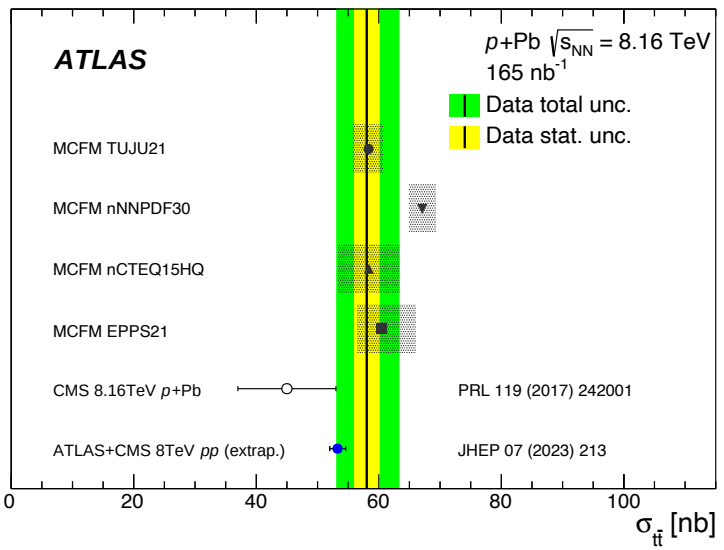


$t\bar{t}$ PRODUCTION IN p+Pb COLLISIONS: RESULTS

arxiv: 2405.05078

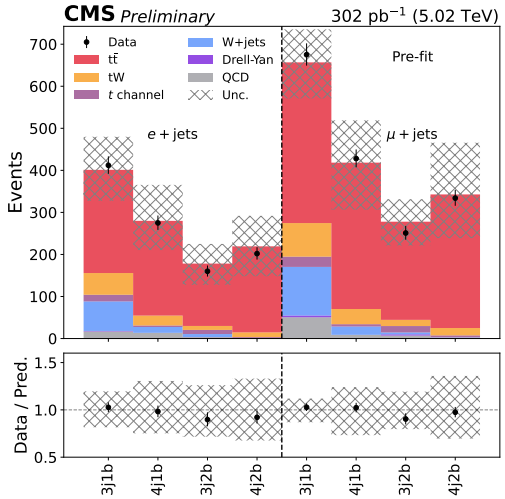
- Background only hypothesis is rejected with more than 5σ in ℓ**+jets** and **dilepton** channels separately
- Measured cross-section: $\sigma_{t\bar{t}} = 58.1 \pm 2.0\ (\text{stat.})\ ^{+4.8}_{-4.4}\ (\text{syst.})$ nb
- The total systematic uncertainty amounts to 9%, which makes it the **most precise $t\bar{t}$ measurement in HI collisions**
- Leading systematic uncertainties come from fake lepton estimation, signal modelling and jet energy scale
- This result is in agreement with the CMS result within 1.4 standard deviations
- A good agreement is found with NNLO calculation based on several nPDF sets

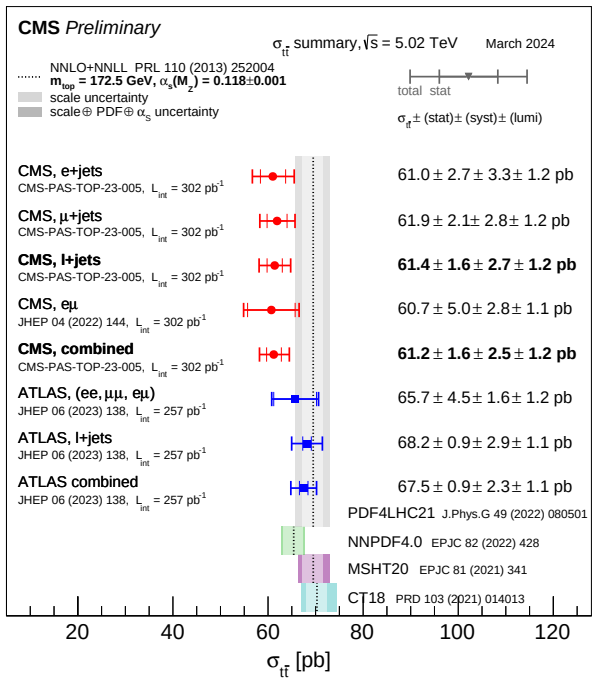




Inclusive $t\bar{t}$ cross-section at $\sqrt{s} = 5.02$ TeV

- New CMS result: CMS-PAS-TOP-23-005
- Uses 302 pb^{-1} low-intensity pp collision data collected in 2017 ($\langle \mu \rangle$ =2)
- ℓ+jets final state
- QCD background is estimated using a data driven method
- Combined with the previously published dilepton result
- Limited by luminosity and b-tagging uncertainties





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Top cross section

Jet cross section measurements

JET CROSS SECTION MEAUREMENTS

Jet cross section measurements are

- Important inputs to parton distribution function (PDF) fits
  - Particularly important for aspects like the high-x gluon PDF
  - Not calculable from first principles $\Longrightarrow$ need measurements
- Tests of perturbative QCD predictions
- Sensitive to the strong coupling constant and its running

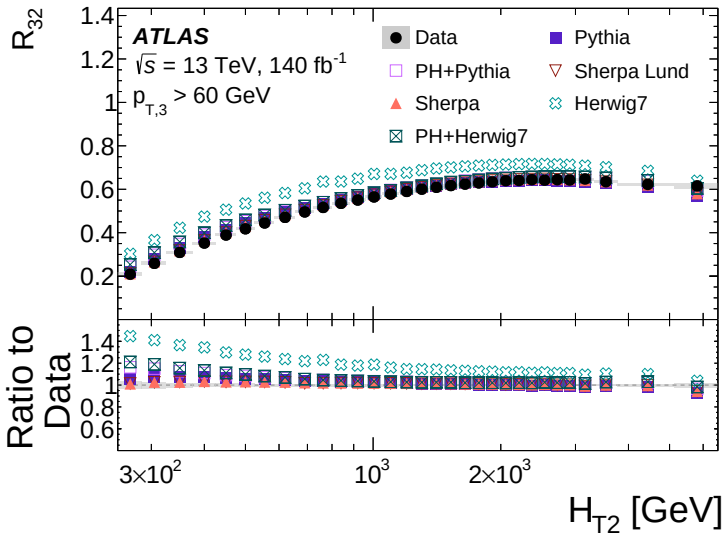
New ATLAS measurements of jet cross sections

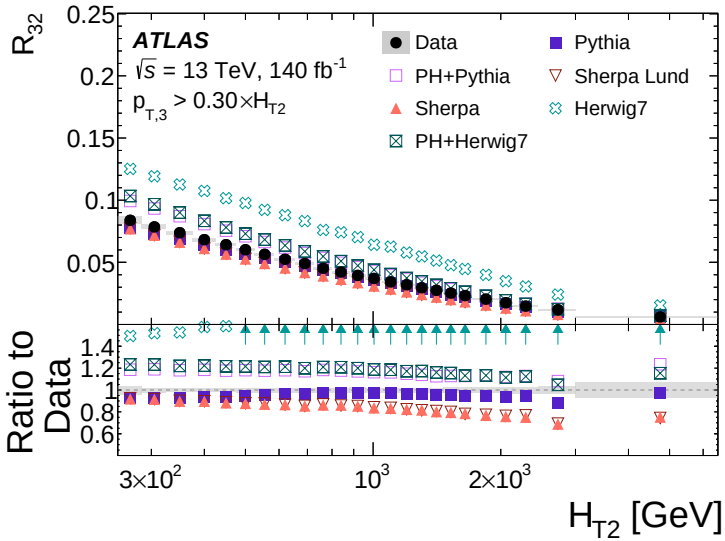
- ATLAS-STDM-2020-04
- Uses full run-2 data (140 fb^{-1})
- Includes improvements to the treatment of the jet energy scale uncertainties $\Longrightarrow$ **significant improvement in the precision of the results**

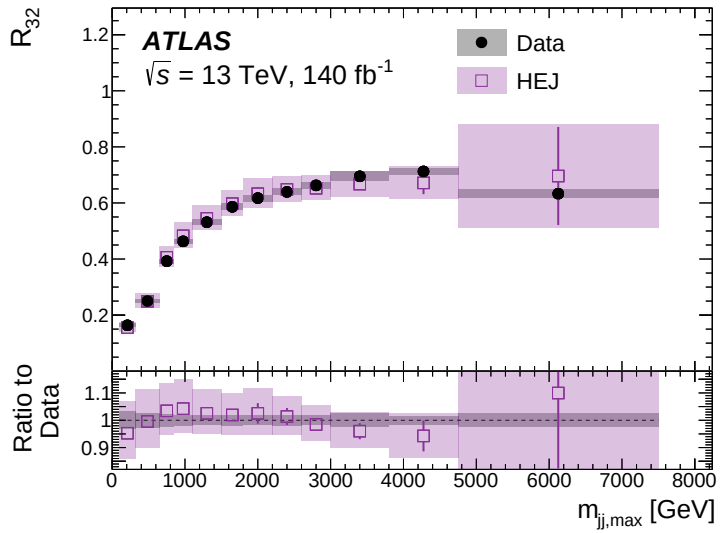
ATLAS Jet cross section meaurements

ATLAS-STDM-2020-04

$$H_{T2} = p_{T,1} + p_{T,2} \; ; R_{32} = \sigma_{3j} \; / \; \sigma_{2j}$$







- Good description by Pythia of R_{32} vs H_{T2} at low and high p_{T3} scales
  - Rest of MC models fail to describe R_{32} at large p_{T3}
- Prediction from HEJ models the data well in the studied m_{jj} range

Conclusions

- The ATLAS and CMS experiments measured top quark mass and properties to a very high precision with LHC data
- The LHC offers a great environment to study things like LFU and Quantum Entanglement. Many more exciting measurements can be found here:
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/
  - CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/
- The ongoing Run-3 presents exciting improvements. So, stay tuned for future results!!

Thank You