Top physics at the LHC

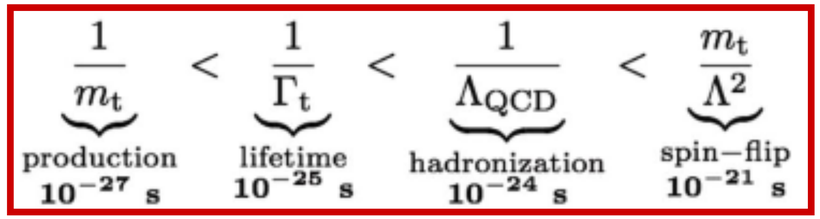
María Aldaya (DESY)
for the ATLAS and CMS Collaborations

ICFA Seminar 2026, 3-6 November 2026



Top quark: not just another particle

- **Heaviest elementary particle** known: $m_{top} \sim 172.5$ GeV
- **Very short-lived**, decays before hadronizing



—> access to spin and quantum correlations

- **Largest Yukawa coupling to Higgs**: $y_t \sim 1$

—> Key role in Higgs physics and EW radiative corrections

- **Powerful probe of Standard Model and beyond**
  - Precision tests of SM fundamental parameters
  - Sensitivity to new particles and interactions

Top quark: not just another particle

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$$\underbrace{\frac{1}{m_t}}_{\text{production } 10^{-27}\text{ s}} < \underbrace{\frac{1}{\Gamma_t}}_{\text{lifetime } 10^{-25}\text{ s}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\text{hadronization } 10^{-24}\text{ s}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\text{spin-flip } 10^{-21}\text{ s}}$$

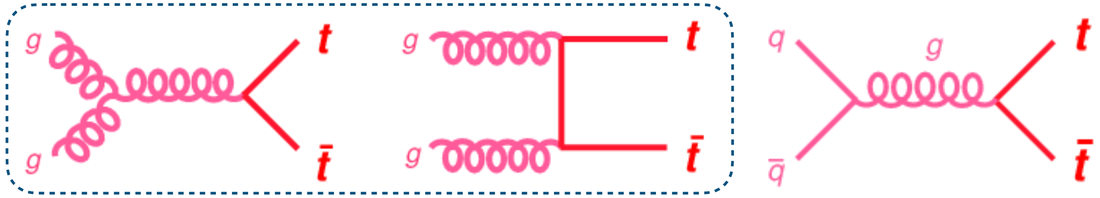
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- **Largest Yukawa coupling to Higgs**: $y_t \sim 1$

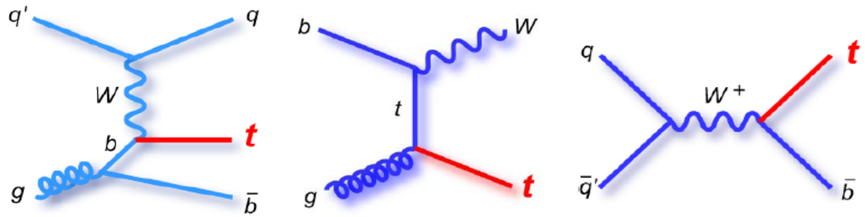
—> Key role in Higgs physics and EW radiative corrections

- **Powerful probe of Standard Model and beyond**
  - Precision tests of SM fundamental parameters
  - Sensitivity to new particles and interactions

- Dominant: QCD **top pair ($t\bar{t}$) production**

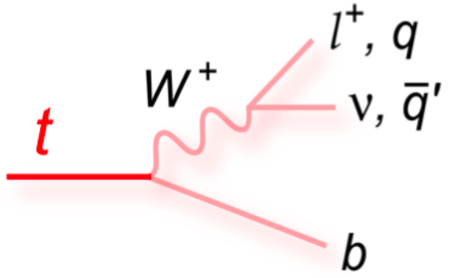


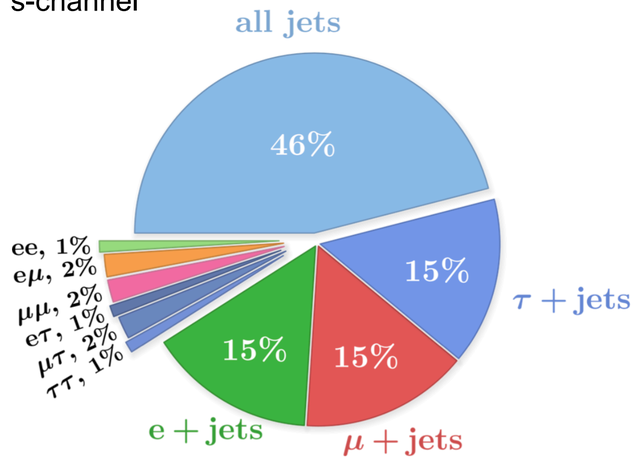
- Electroweak **single top production**



t-channel tW-channel s-channel

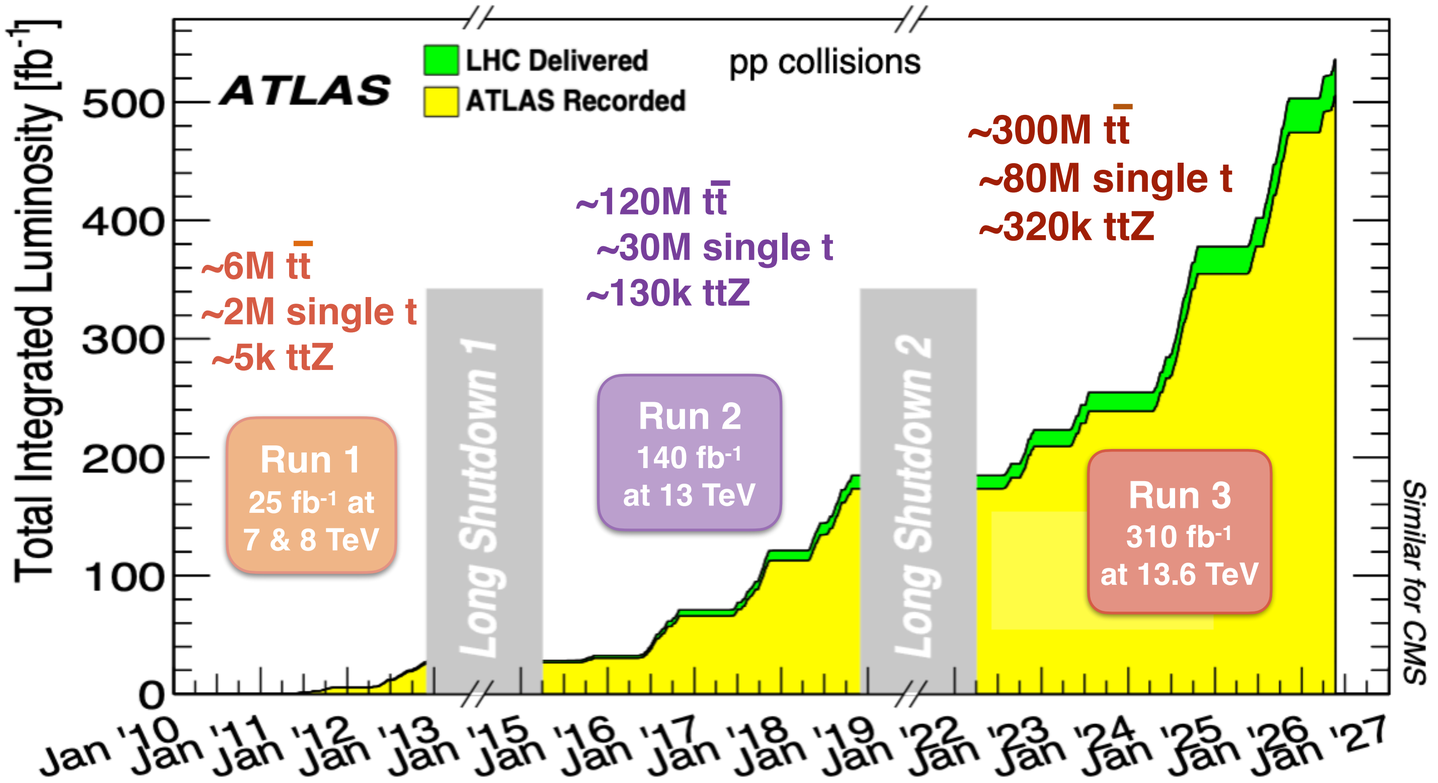
- Electroweak **top decay**





The LHC top factory

Much of Run3 data remains unexplored !



- **Vibrant LHC top physics programme,** enabled by
  - Accelerator and detector performance
  - Improved reconstruction and analysis, including machine-learning (ML)
  - Precision theory

From rediscovery & characterization

- Pair and single top production
- mass, decays, spin

increasing precision and expanding reach

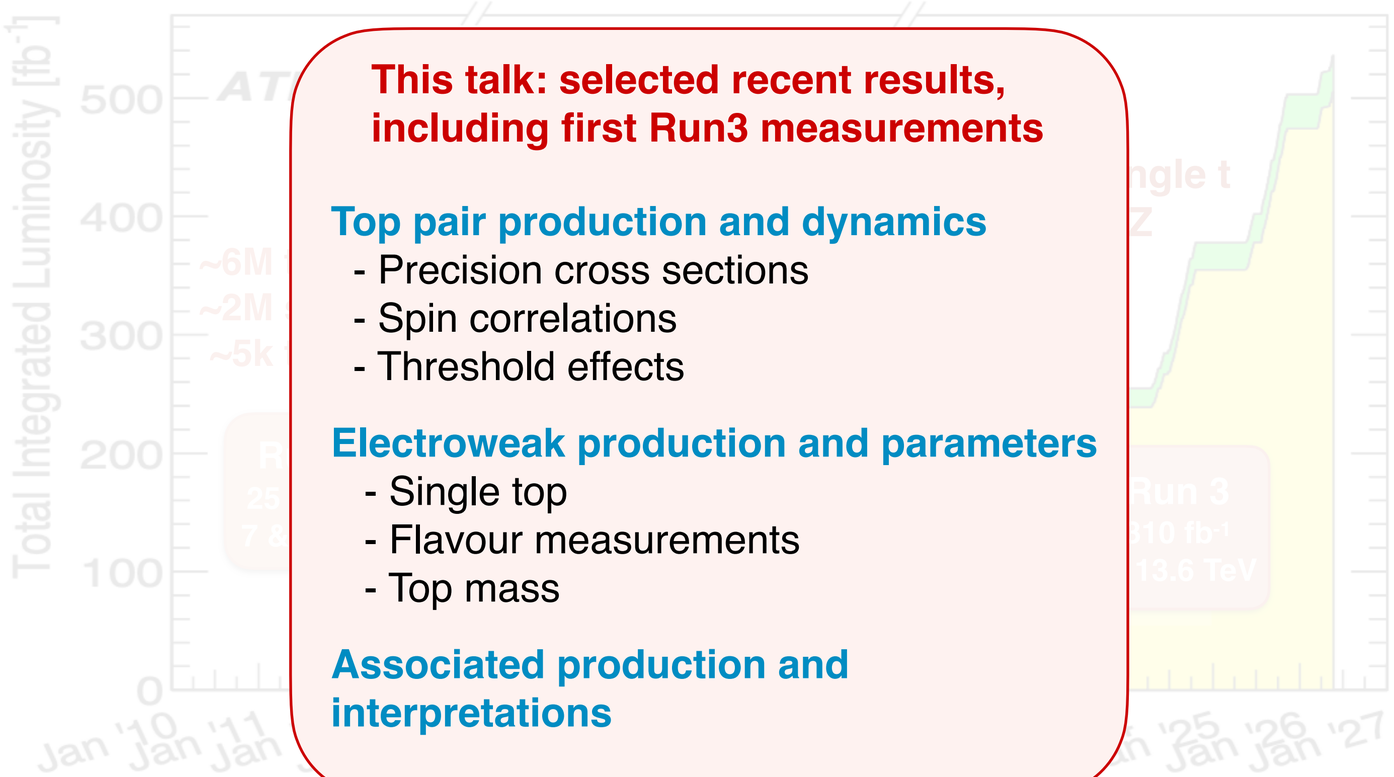
- Resolve subtle production dynamics
- Reconstruct the top-pair quantum state
- Determine fundamental parameters
- Access rare interactions

Towards higher precision and broader sensitivity in Run3 & HL-LHC

- Rarer processes and smaller deviations
- Sharper tests of properties & couplings

Challenge: experimental and theoretical control must match the precision of the data

The LHC top factory



Much of Run3 data remains unexplored !

This talk: selected recent results, including first Run3 measurements

Top pair production and dynamics
- Precision cross sections
- Spin correlations
- Threshold effects

Electroweak production and parameters
- Single top
- Flavour measurements
- Top mass

Associated production and interpretations

- **Vibrant LHC top physics programme,** enabled by
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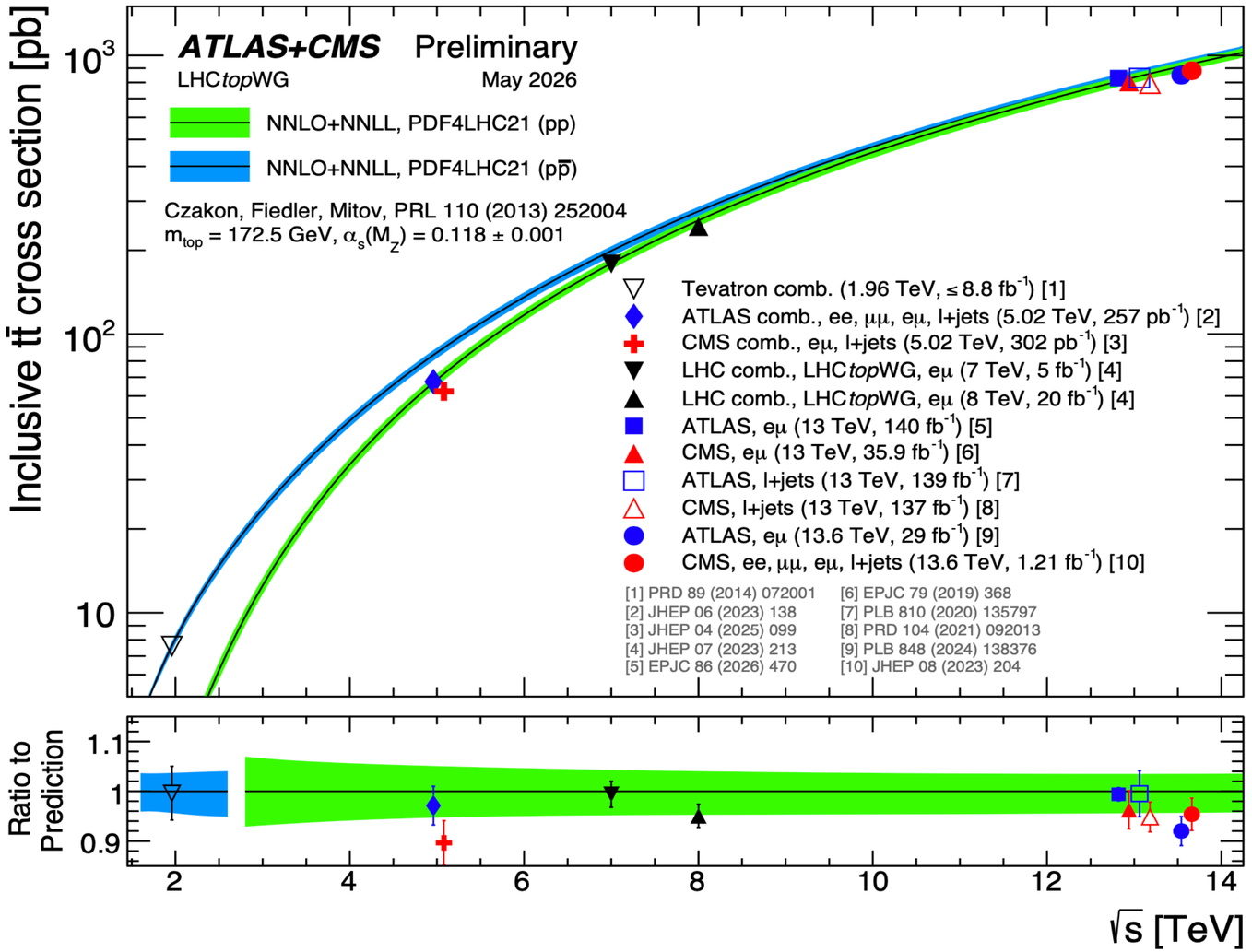
- Rarer processes and smaller deviations
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Challenge: experimental and theoretical control must match the precision of the data

$t\bar{t}$ cross sections: precision and new frontiers

Inclusive and differential cross sections provide stringent tests of QCD predictions and Monte Carlo modelling

- Wealth of measurements becoming more precise:
  - Investigate top properties
  - Extract SM parameters and set limits on BSM physics
  - Sensitive to interesting physics in challenging corners of phase space
- Inclusive $t\bar{t}$ cross sections at **percent-level precision**
  - Measured at 5 different energies, all final states
  - Good agreement with NNLO+NNLL predictions
- LHCb extends the programme to forward rapidities, complementing ATLAS and CMS

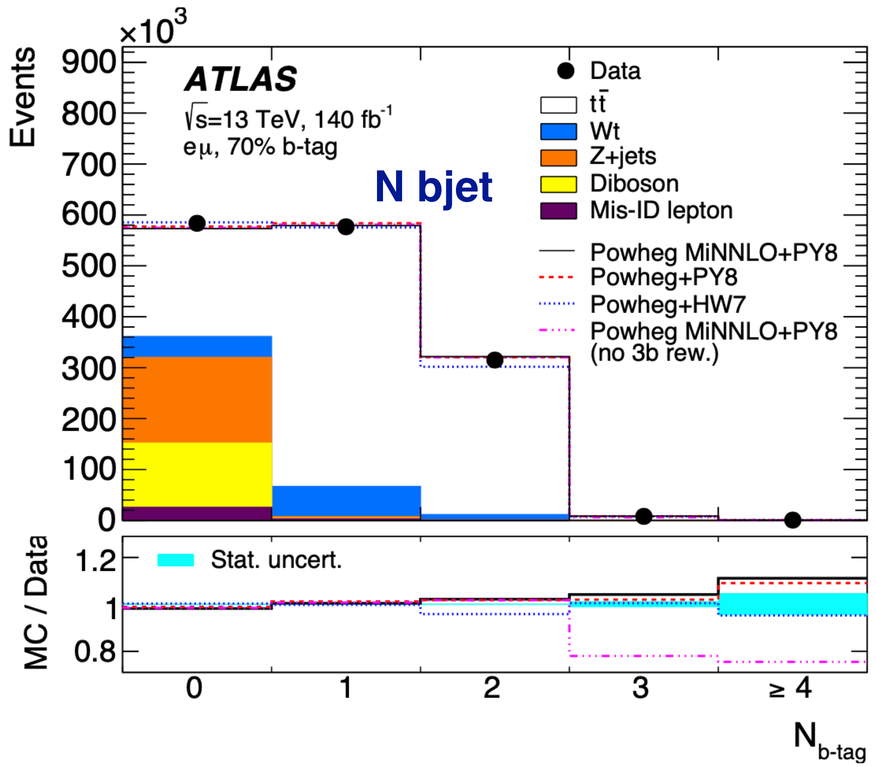


LHCtopWG Summary Plots

$t\bar{t}$ cross sections: precision and new frontiers

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  - Investig
  - Extract BSM ph
  - Sensitiv challeng
- Inclusiv
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  - Good a
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ATLAS: re-analysis of Run2 data, counting events with 1 or 2 b-tagged jets in eμ final state

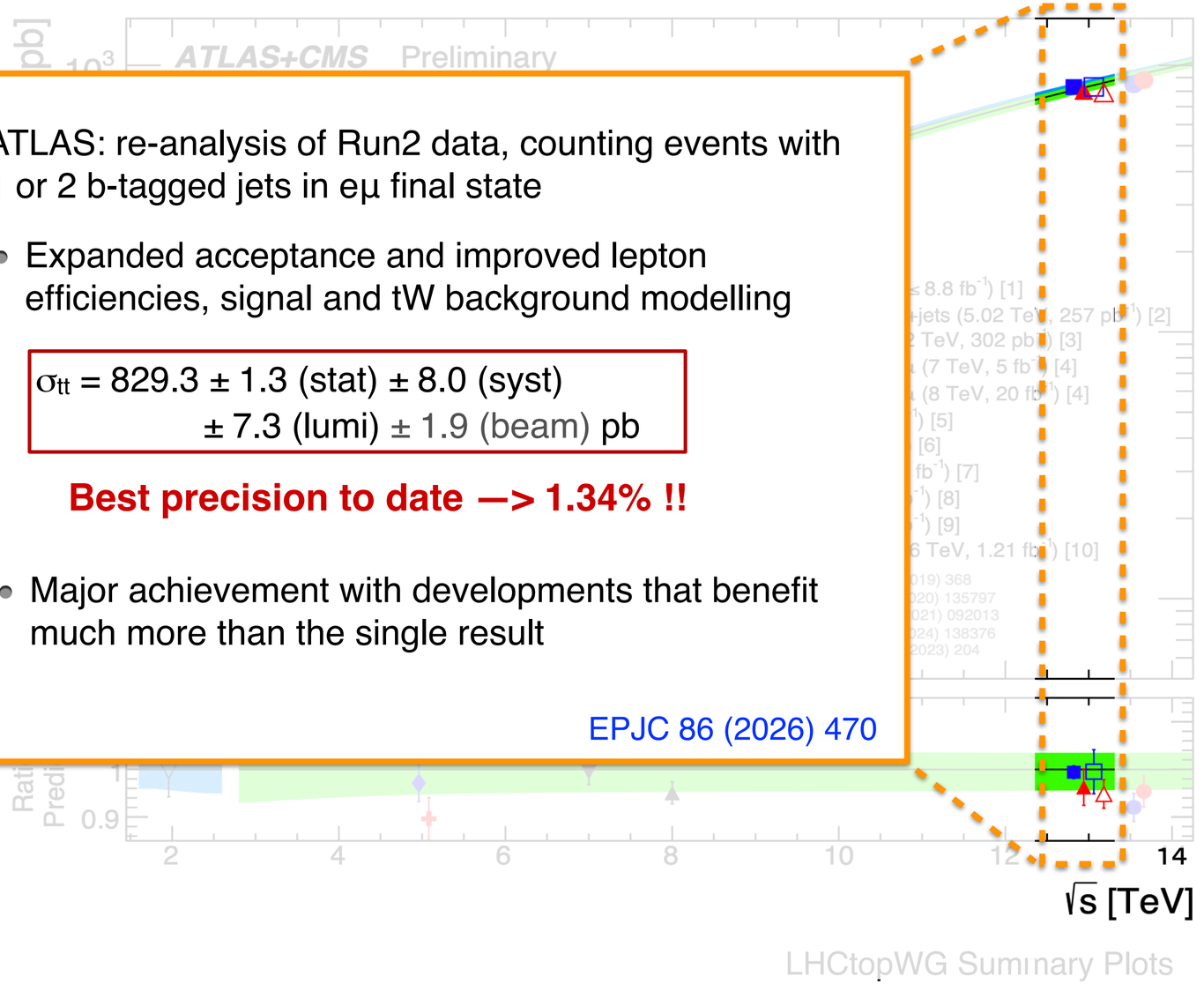
- Expanded acceptance and improved lepton efficiencies, signal and tW background modelling

$$\sigma_{tt} = 829.3 \pm 1.3\ (\text{stat}) \pm 8.0\ (\text{syst}) \pm 7.3\ (\text{lumi}) \pm 1.9\ (\text{beam})\ \text{pb}$$

Best precision to date —> 1.34% !!

- Major achievement with developments that benefit much more than the single result

EPJC 86 (2026) 470



Precision requires the full final state: WbWb

Probing phase space regions sensitive to off-shell contributions and interference effects

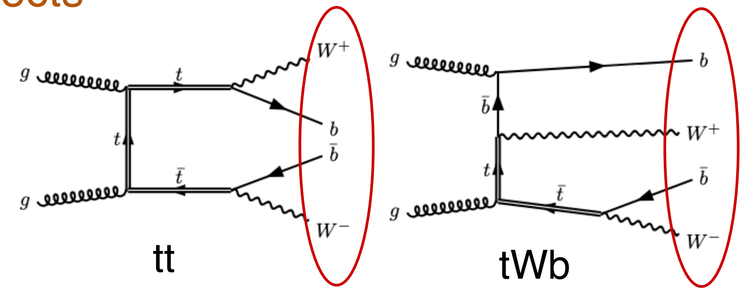
$t\bar{t}$ and **tWb** contribute to the same **WbWb** final state: their scattering amplitudes interfere

—> modelling their overlap is a major uncertainty for many measurements and searches

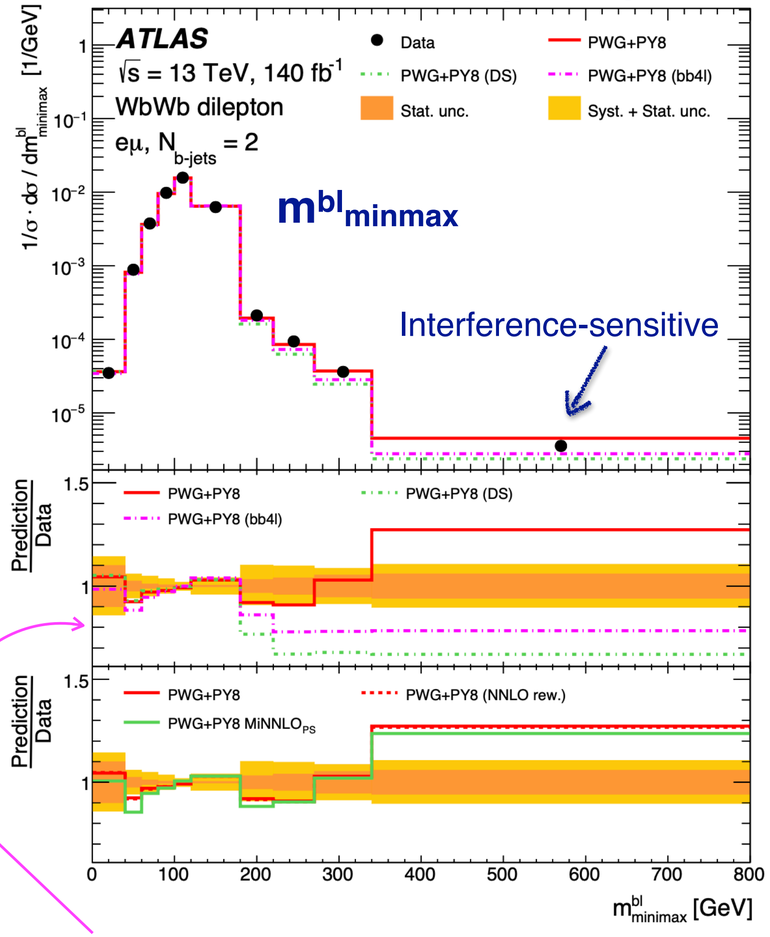
- ATLAS measures differential WbWb cross sections in dilepton and single-lepton events, probing off-shell and interference effects
- Modern generators improve the description, but none describes every measured distribution

Reliable precision measurements require a consistent description of the full final state

$$m^{bl}_{\text{minimax}} \equiv \min\left\{\max\left(m^{b_1 l_1}, m^{b_2 l_2}\right), \max\left(m^{b_1 l_2}, m^{b_2 l_1}\right)\right\}$$

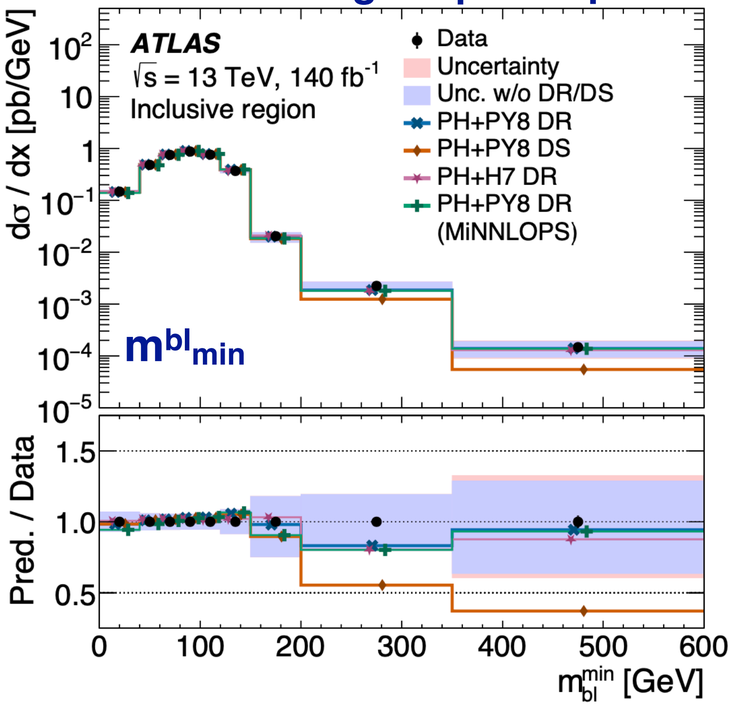


dilepton eμbb



bb4l: unified NLO treatment of the final state, including interference and off-shell effects

single lepton e/μbb



JHEP 02 (2026) 153, JHEP 07 (2026) 028

Reconstructing the top-pair spin state

Decay angles connect production dynamics to the pair's quantum state

- Top quarks decay before hadronizing; their decay angles retain the **spin information**
- In top pair production, small individual polarizations coexist with sizeable **correlations** between the top and antitop spins
- Angular measurements determine all 15 independent coefficients of the normalized spin density matrix:

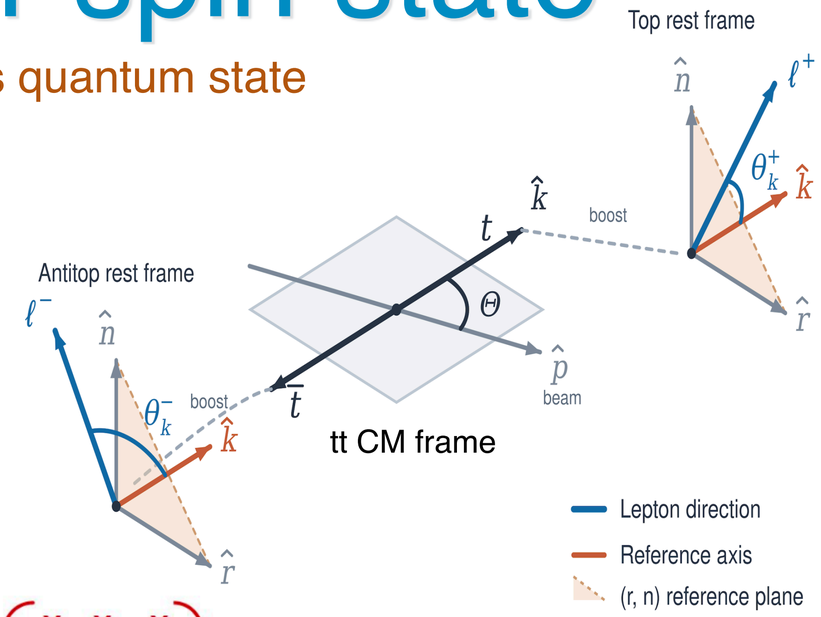
$$\frac{1}{\sigma}\frac{d^4\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}\left(1 + \vec{B}_1 \cdot \hat{\ell}^1 + \vec{B}_2 \cdot \hat{\ell}^2 - \hat{\ell}^1 \cdot C \cdot \hat{\ell}^2\right)$$

$$\vec{B}_{1/2} = \begin{pmatrix} x \\ x \\ x \end{pmatrix}$$

top polarization

$$C = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}$$

spin correlation

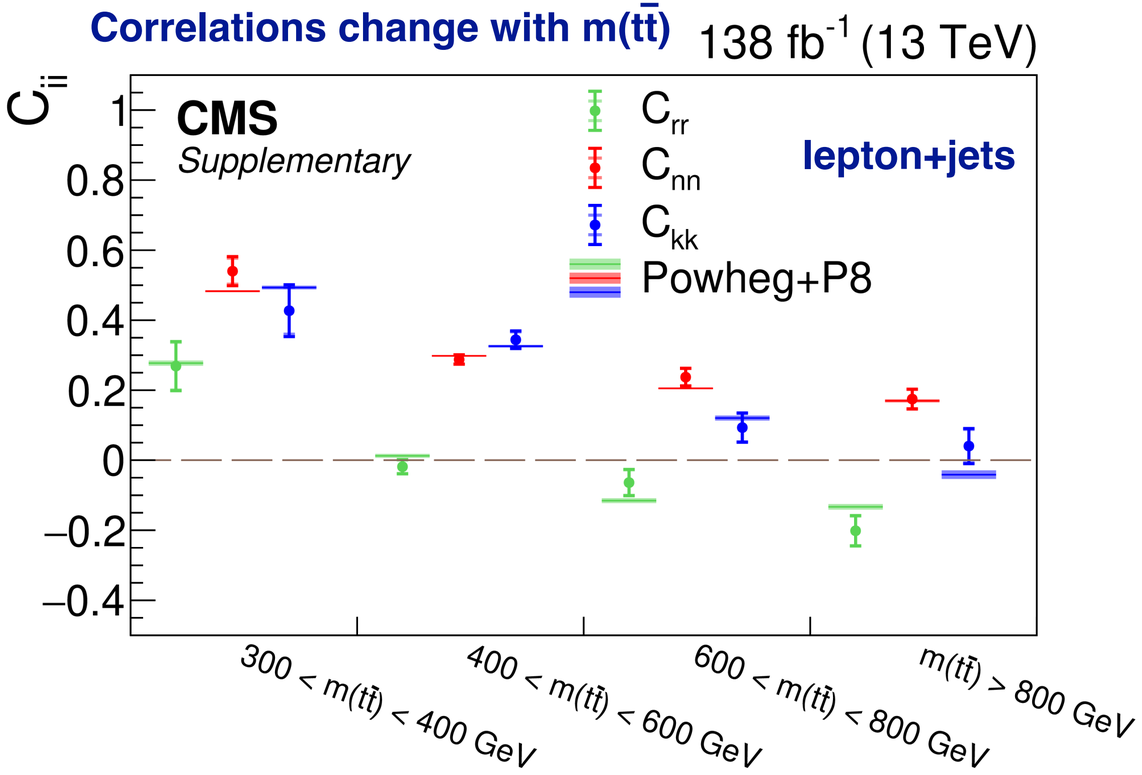


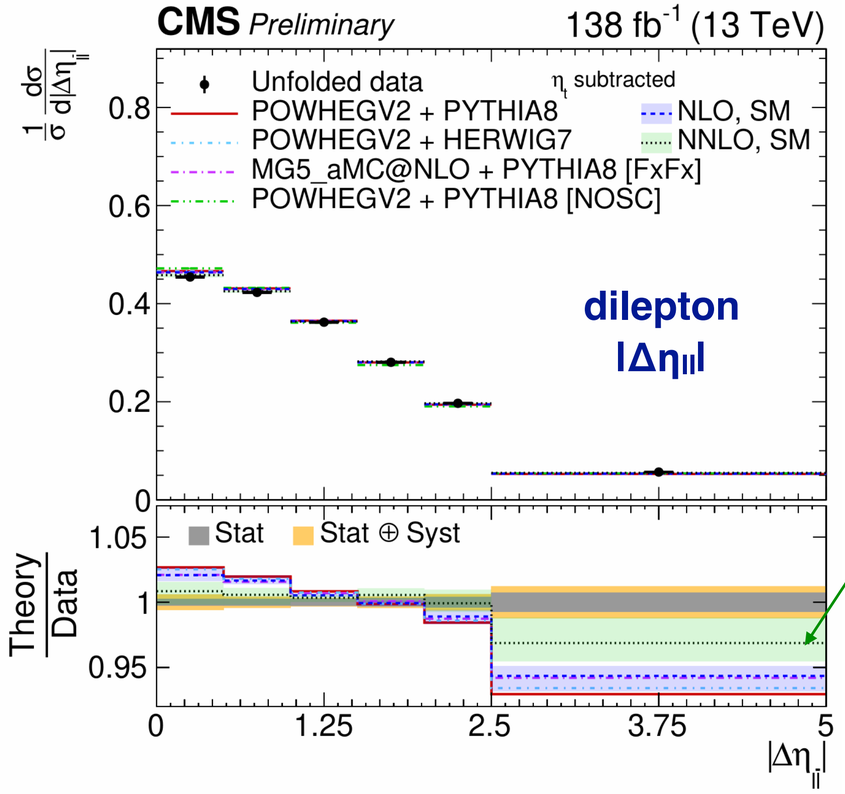
- Full spin tomography: 6 polarization + 9 spin correlation terms
- Entanglement: correlations incompatible with any mixture of independent top and antitop spins

Top spins as precision probes

The correlation pattern tests production dynamics and possible new interactions

- Recent CMS measurements map all 15 spin coefficients in dilepton and lepton+jets events, inclusively and differentially
- Overall agreement with the SM, with precision angular measurements exposing limits of standard generators





Better described by NNLO

Run 3 and HL-LHC: finer maps of the spin state need matching precision in theory

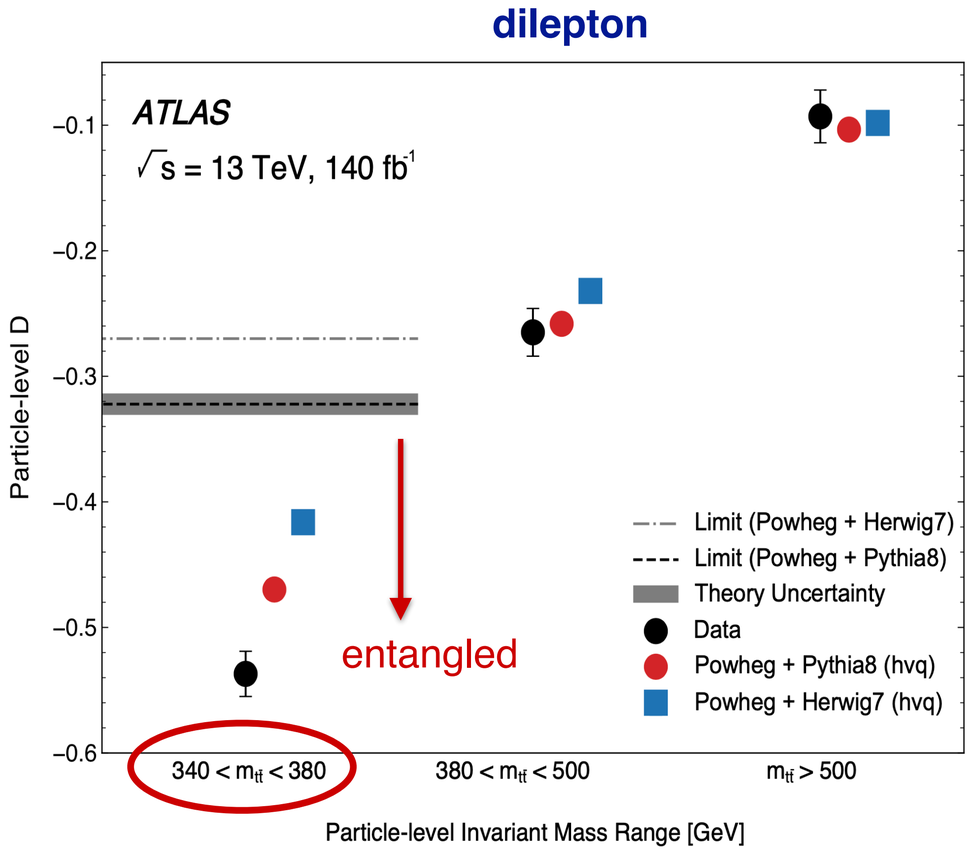
PRD 110 (2024) 112016

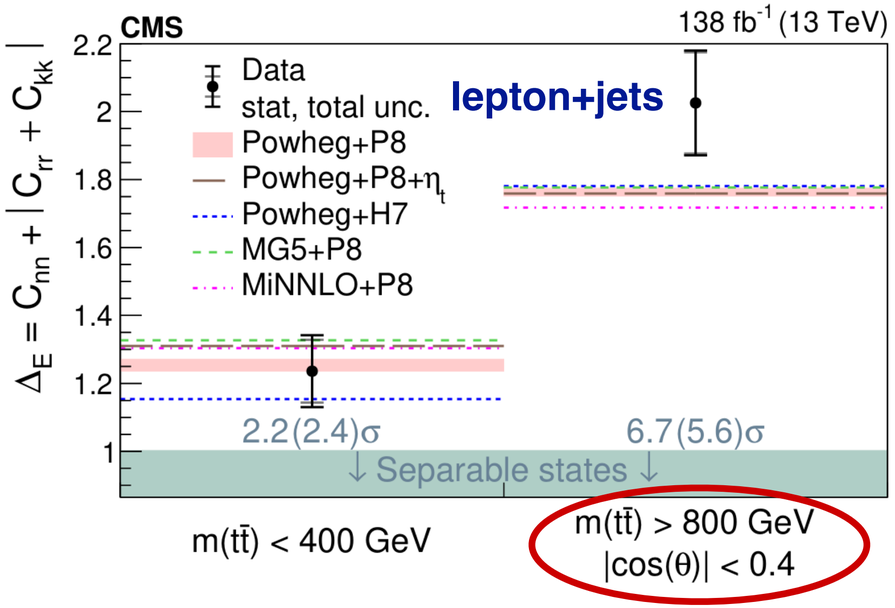
CMS-PAS-TOP-23-006

Quantum entanglement in top pairs

Measured spin correlations identify entangled states in selected regions of phase space

- Entanglement is established by comparing spin correlations with the bounds for separable states
- ATLAS and CMS observe entanglement near threshold in dilepton events
- CMS also observes it at high mass and centrally produced $t\bar{t}$ pairs in lepton+jets events
- More precise differential measurements can test how production dynamics shape the quantum state





Near threshold, the pair's QCD interaction shapes the measured spin state

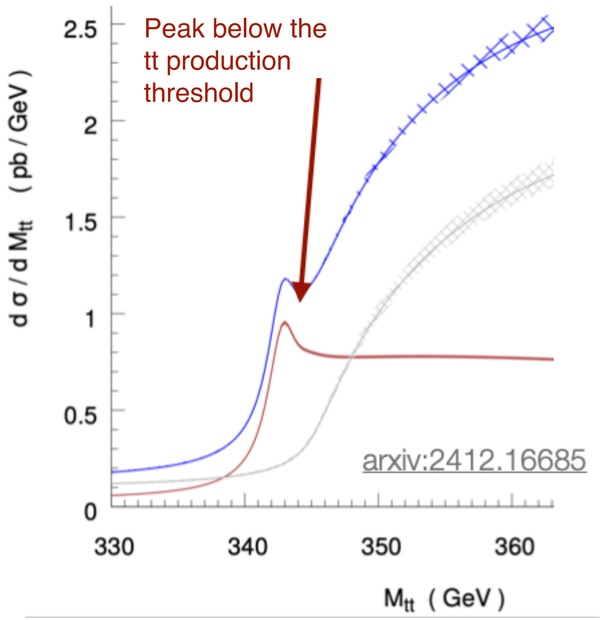
ROPP 87 (2024) 117801

Nature 633 (2024) 542 PRD 110 (2024) 112016

Excess at $t\bar{t}$ threshold region

CMS and ATLAS observe enhancement at $t\bar{t}$ production threshold in dilepton events

- Near $m_{tt} \sim 2m_t$, slowly moving top quarks are sensitive to the QCD potential
- Non-relativistic QCD predicts an enhancement, including a colour-singlet quasi-bound state contribution
- **Mass and spin-sensitive distributions allow investigating this region**

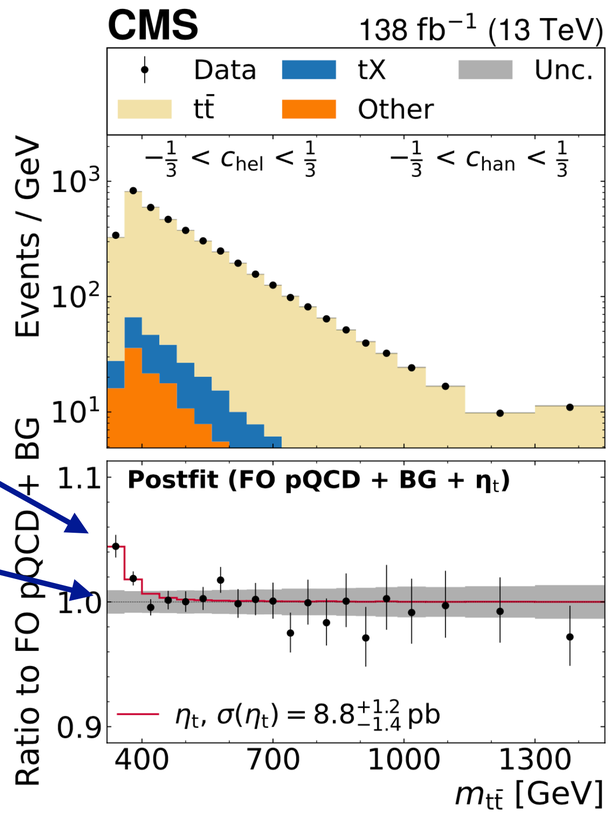


Fit the tt continuum and tt continuum + quasi-bound state effect models (*) to extract cross sections

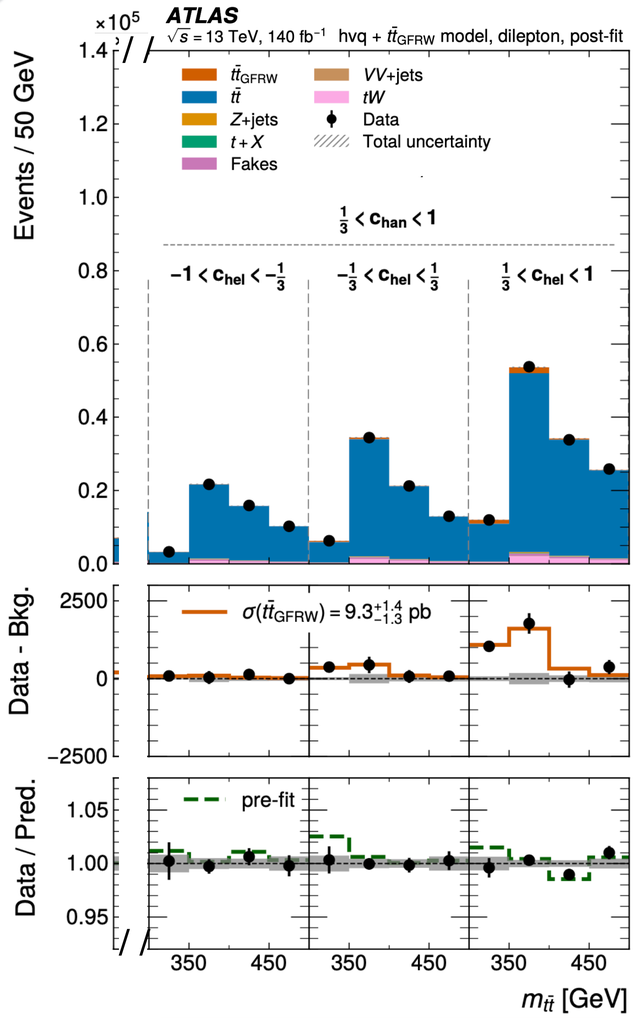
(*) η_{tt} model: JHEP 03 (2024) 099

tt GFRW model: EPJC 85 (2025) 157

Large impact from tt modelling uncertainties



$\sigma(\eta_t)=8.8^{+1.2}_{-1.4}$ pb



$\sigma(\eta_t)=13.1^{+1.9}_{-1.7}$ pb

$\sigma(t\bar{t}_{GFRW})=9.3^{+1.4}_{-1.3}$ pb

C_{hel}: cosine of opening angle between charged leptons in parent top rest frame

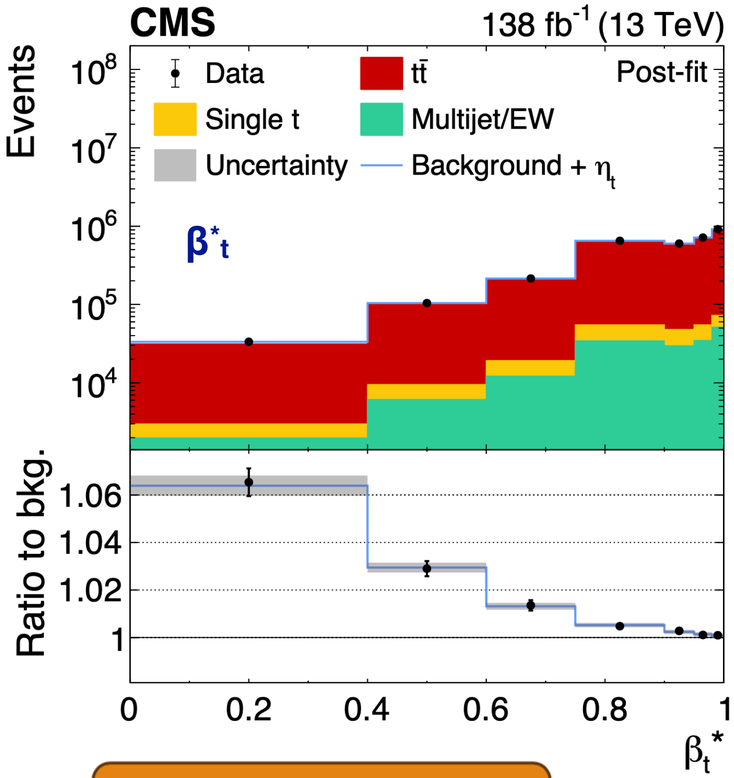
C_{han}: same, but with sign flip along the t direction

ROPP 88 (2025) 087801, ROPP 89 (2026) 057801

Excess at $t\bar{t}$ threshold region

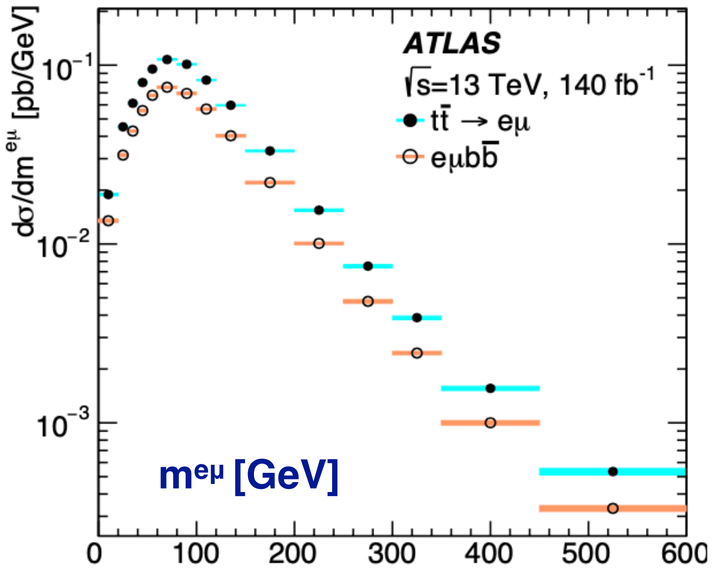
Complementary measurements and further channel studies support enhancement compatible with NRQCD effects

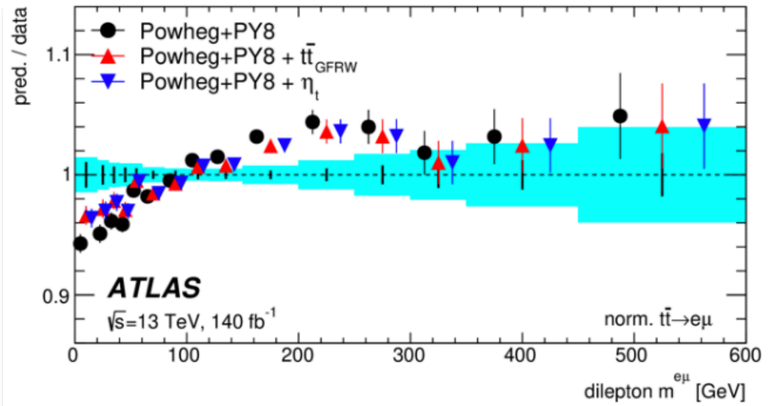
- CMS (lepton+jets): similar to dilepton, but using the relative velocity of top-antitop

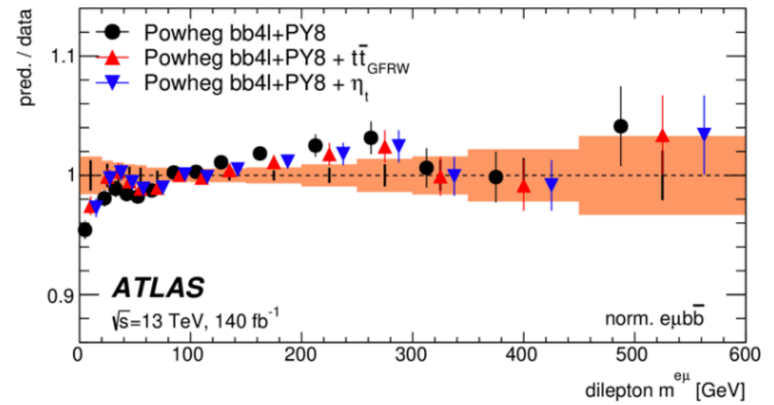


$\sigma(\eta_t)=5.1\pm0.9$ pb

- ATLAS (dilepton): reinterpreting eμbb differential observables, better described by models including quasi-bound state effects







$\sigma(\eta_t)=8.9\pm2.6$ pb

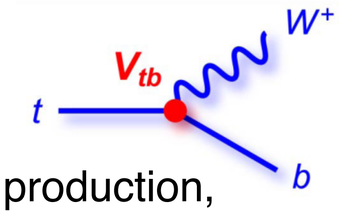
$\sigma(t\bar{t}_{GFRW})=7.8\pm2.4$ pb

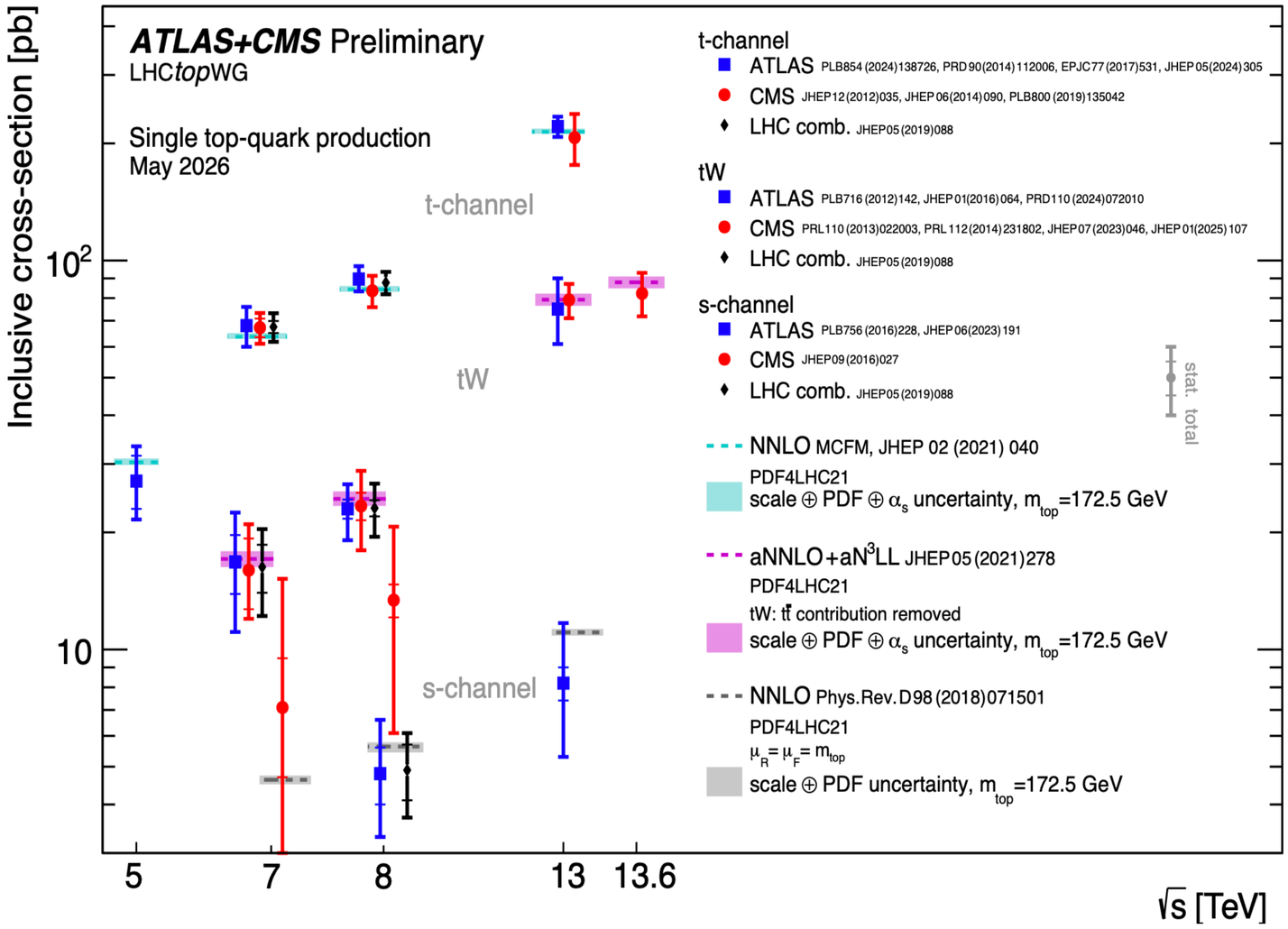
Significant ongoing theory work to better combine perturbative and non-relativistic contributions

arXiv:2608.19546

arXiv:2605.02341

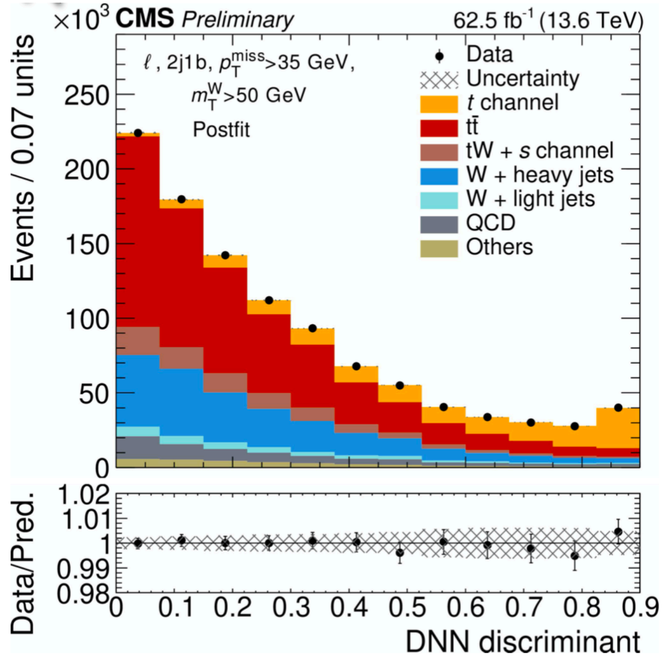
Single top production

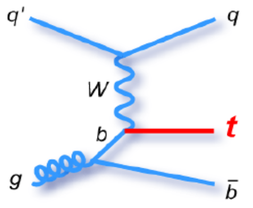




- Probes the Wtb vertex directly in production, sensitive to u/d-PDFs and b-PDF

CMS: First Run3 t-channel cross section





$\sigma(tq + \bar{t}q) = 223.1^{+9.3}_{-9.1}(\text{syst}) \pm 1.2(\text{stat})\ \text{pb}$ **(~4%)**

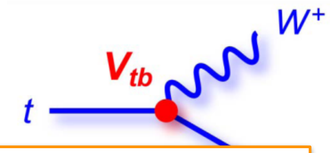
SM: $232.2^{+2.6}_{-1.9}(\text{scale})^{+3.4}_{-2.2}(\text{PDF} + \alpha_s)$ pb

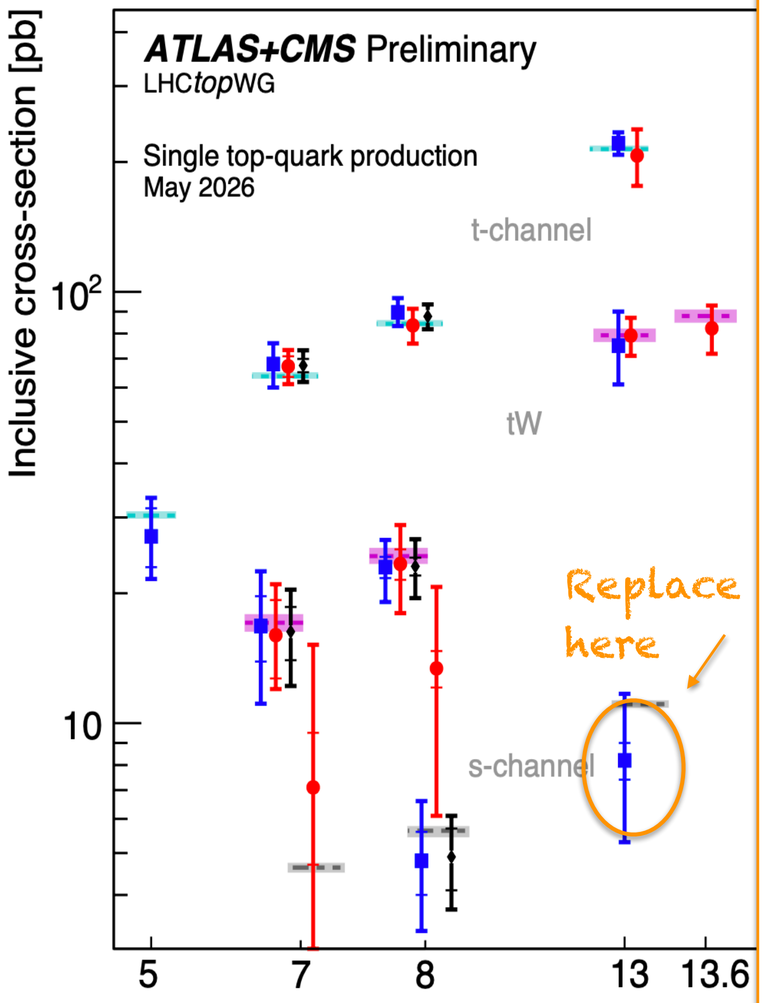
Main syst from jet calibration, btagging

CMS-PAS-TOP-25-018

LHCtopWG Summary Plots

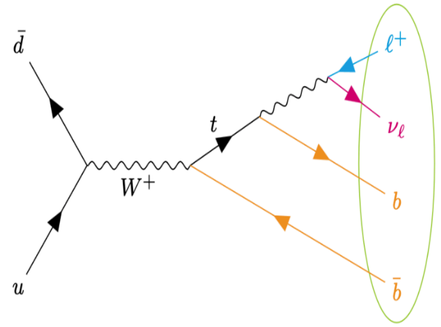
Single top production

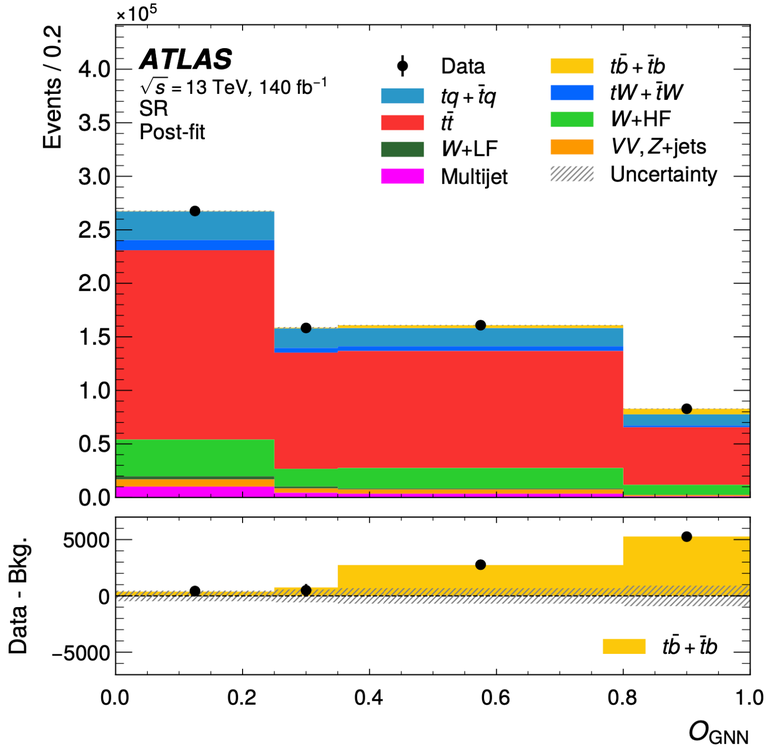




ATLAS: Observation of s-channel production at the LHC

- Complementary test of charged-current top production
- Observed at Tevatron, only evidence at LHC by ATLAS





- Re-analysis of Run2 data
- Improvements: larger acceptance, better btagging, signal & bg modelling, multivariate classifiers, background control

$$\sigma(t\bar{b} + \bar{t}b) = 10.8 \pm 1.5\ (stat.) \pm 1.6\ (syst.)\ pb$$ **(20.4%)**

SM (NNLO QCD): $11.07 \pm 0.19\ pb$

Main syst from tt bg modelling, jet calibration

5.1σ obs. (5.2 exp.) ==> Completing the single top trilogy !

arXiv:2610.11465

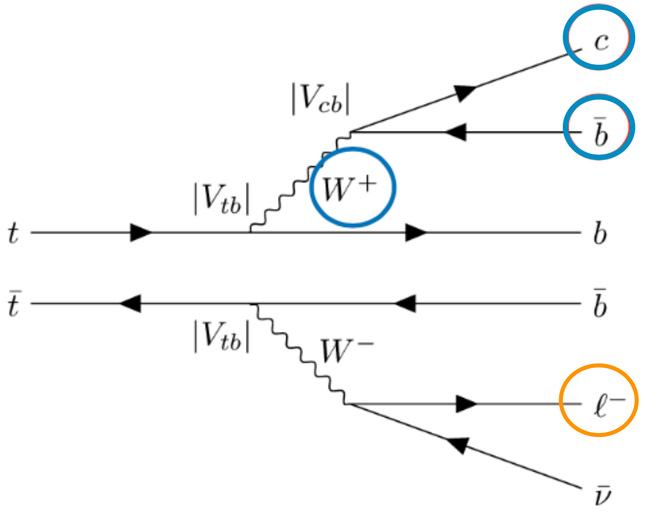
LHCtopWG Summary Plots

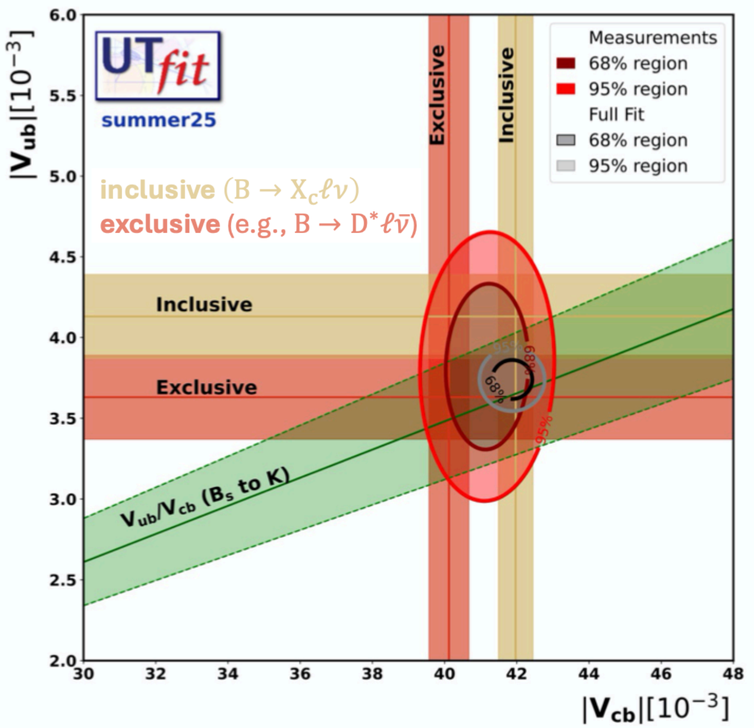
Top as tool: $|V_{cb}|$ in $t\bar{t}$ events

Use tt events as a source of real W bosons to measure CKM matrix element $|V_{cb}|$ at the EW scale

- $|V_{cb}|$ governs b-c charged-current transitions
- Traditional measurements from inclusive and exclusive B-hadron decays are in **tension**
  —> motivates an independent determination
- ATLAS and CMS have performed the first $|V_{cb}|$ measurements in tt events using (rare!) W —> cb decays at high energy
  - Different systematics wrt traditional measurements

$$V_{\mathrm{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

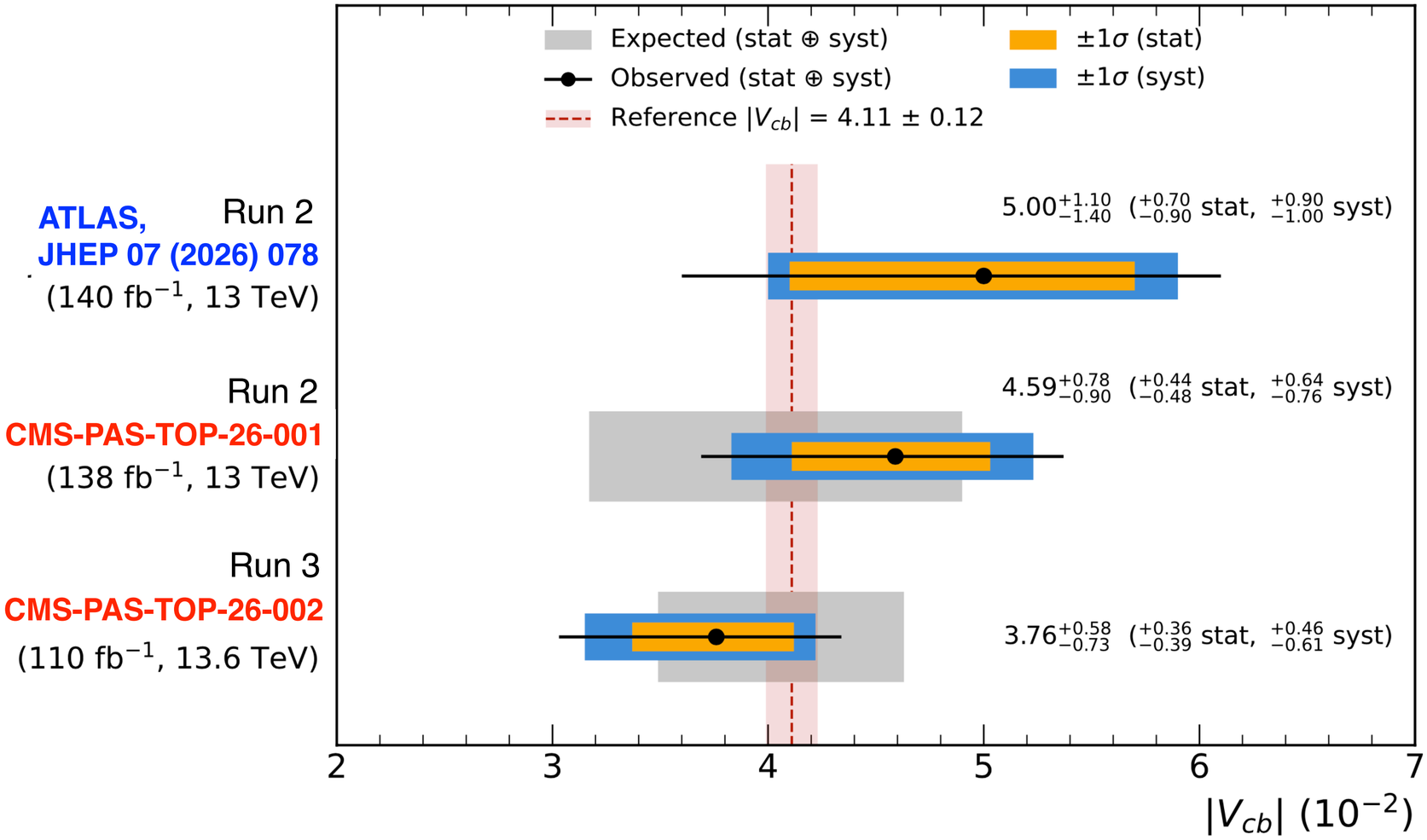




- Analysis strategies rely on:
  - Events with 1 lepton (used to trigger) and 4 jets
  - ML-classifiers to categorize events according to b/c multiplicities and enhance sensitivity to W—> cb signal
  - Advanced ML-based tools for heavy flavour (HF) tagging

Top as tool: $|V_{cb}|$ in $t\bar{t}$ events

Three complementary determinations, at two centre-of-mass energies



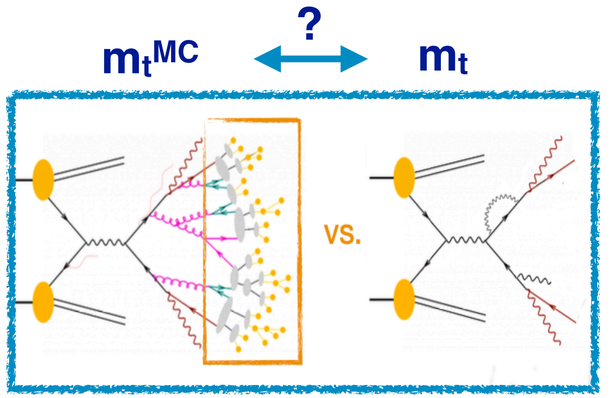
- Compatible with B-decay determinations, with best precision around 15–20%
- CMS Run3 result already profiting from the state-of-the-art flavour taggers
- Further progress requires larger samples, better $t\bar{t}$+HF modelling, and improved flavour tagging

New avenues for flavour physics at the electroweak scale

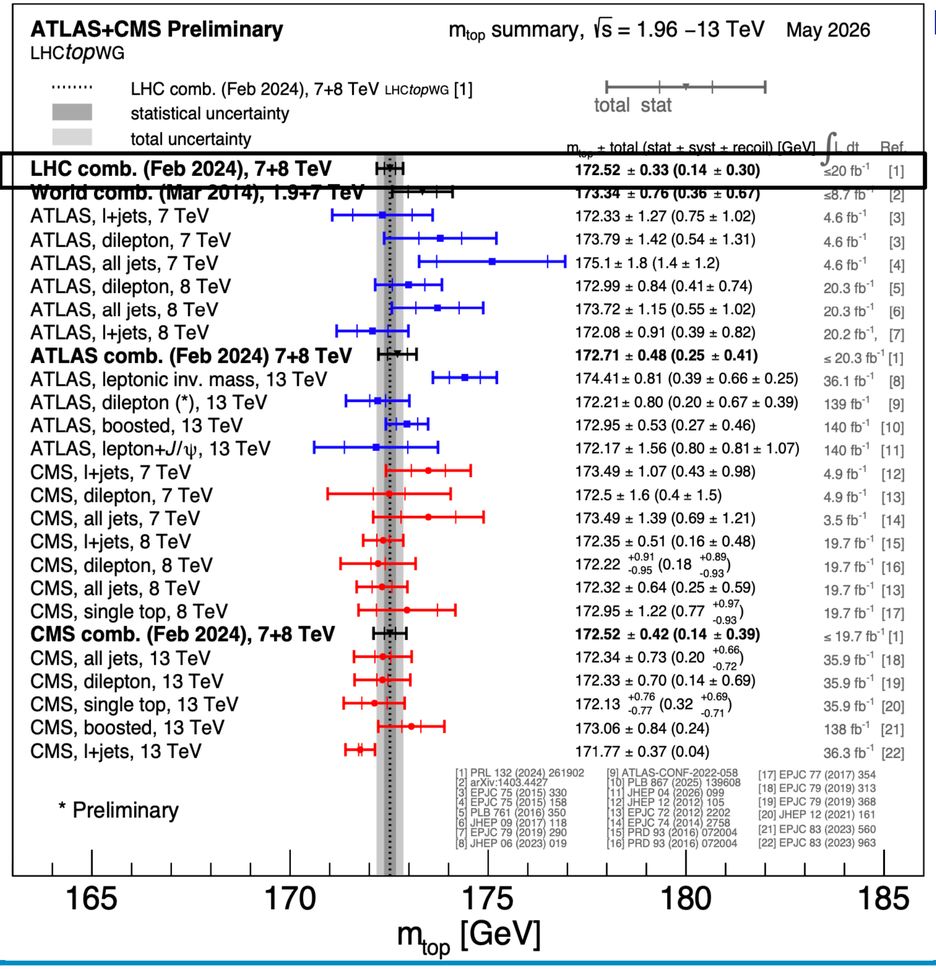
Top mass

Fundamental parameter, key role in EW vacuum stability and consistency of SM

- Direct methods: reconstructed mass from decay products (m_t^{MC}) —> best precision: 0.33 GeV
- Indirect methods: field-theory mass from cross sections (m_t) —> best precision: ~1 GeV

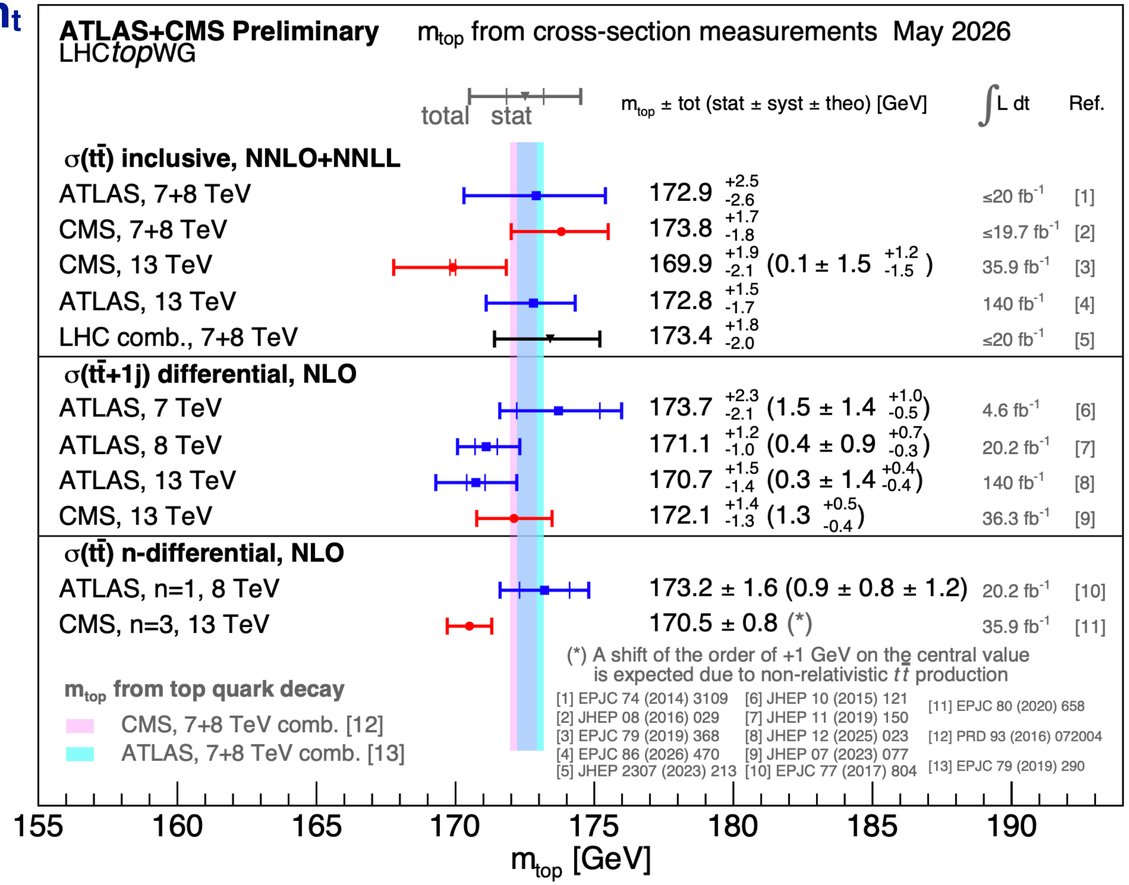


m_t^{MC}



Sub-GeV precision requires significant theory+experiment work on modelling uncertainties and results interpretation

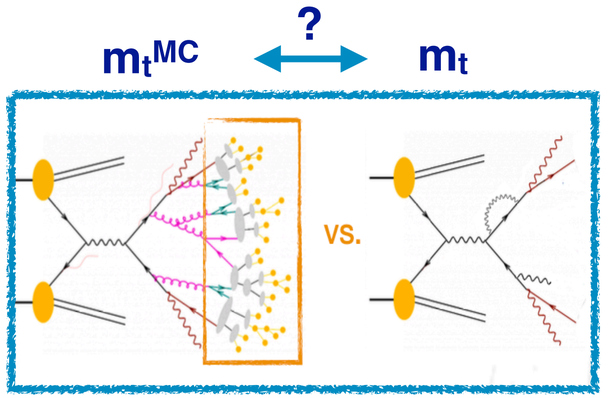
m_t



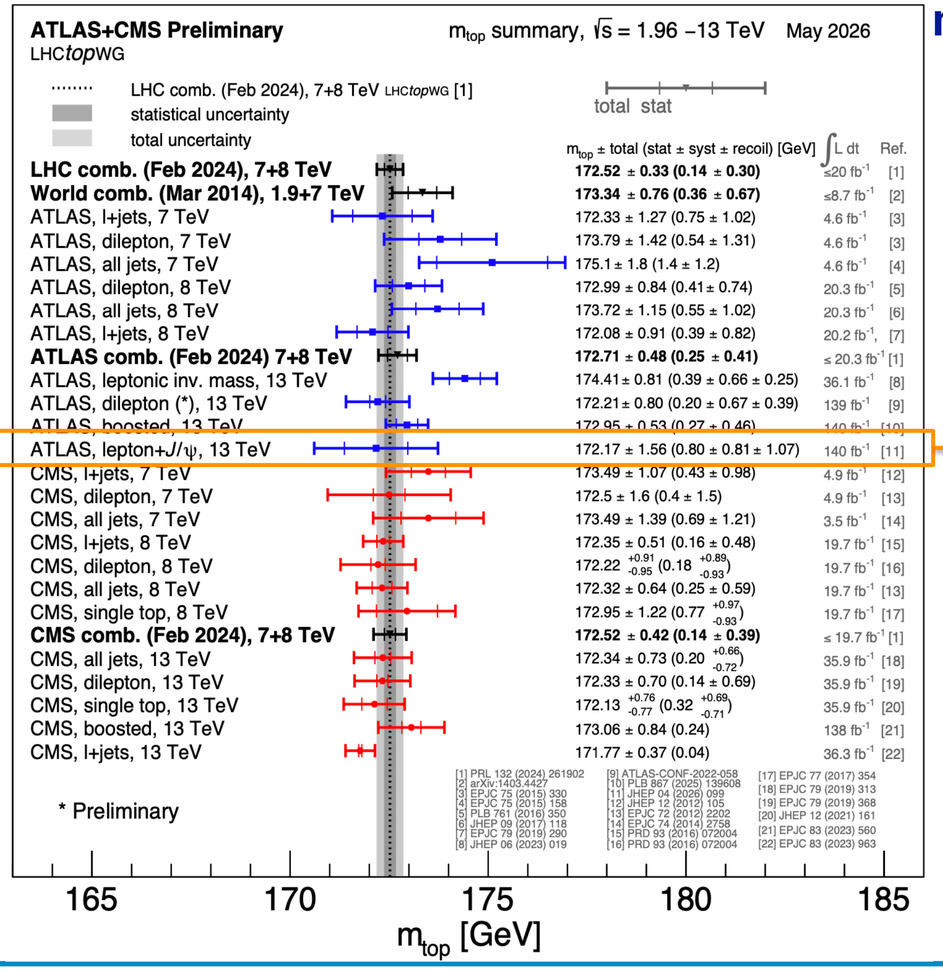
LHCtopWG Summary Plots

Top mass

Fundamental parameter, key role in EW vacuum stability and consistency of SM



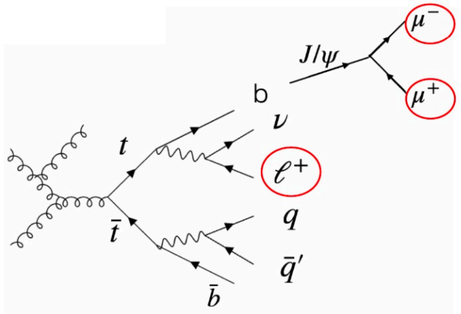
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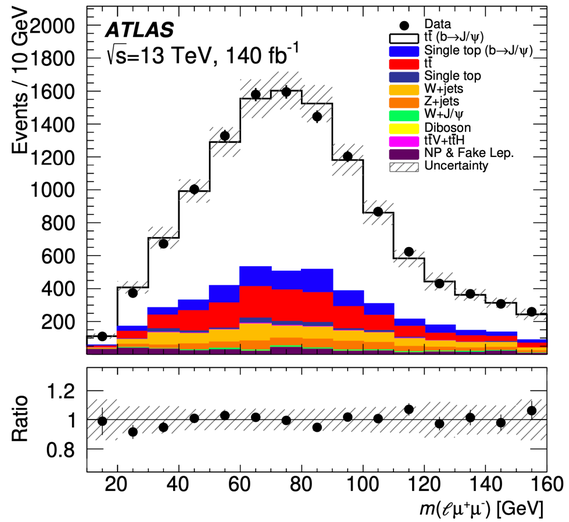


m_t^{MC}

Complementary measurements with different systematics can help in future combinations

- ATLAS: m_{top} from J/ψ decays in $t\bar{t}$+tW events
- Small branching fraction but fully leptonic decay (lμμ)





Mass estimator m(lμμ)

Less sensitive to jet uncertainties, but strong dependence on modelling of gluon recoil

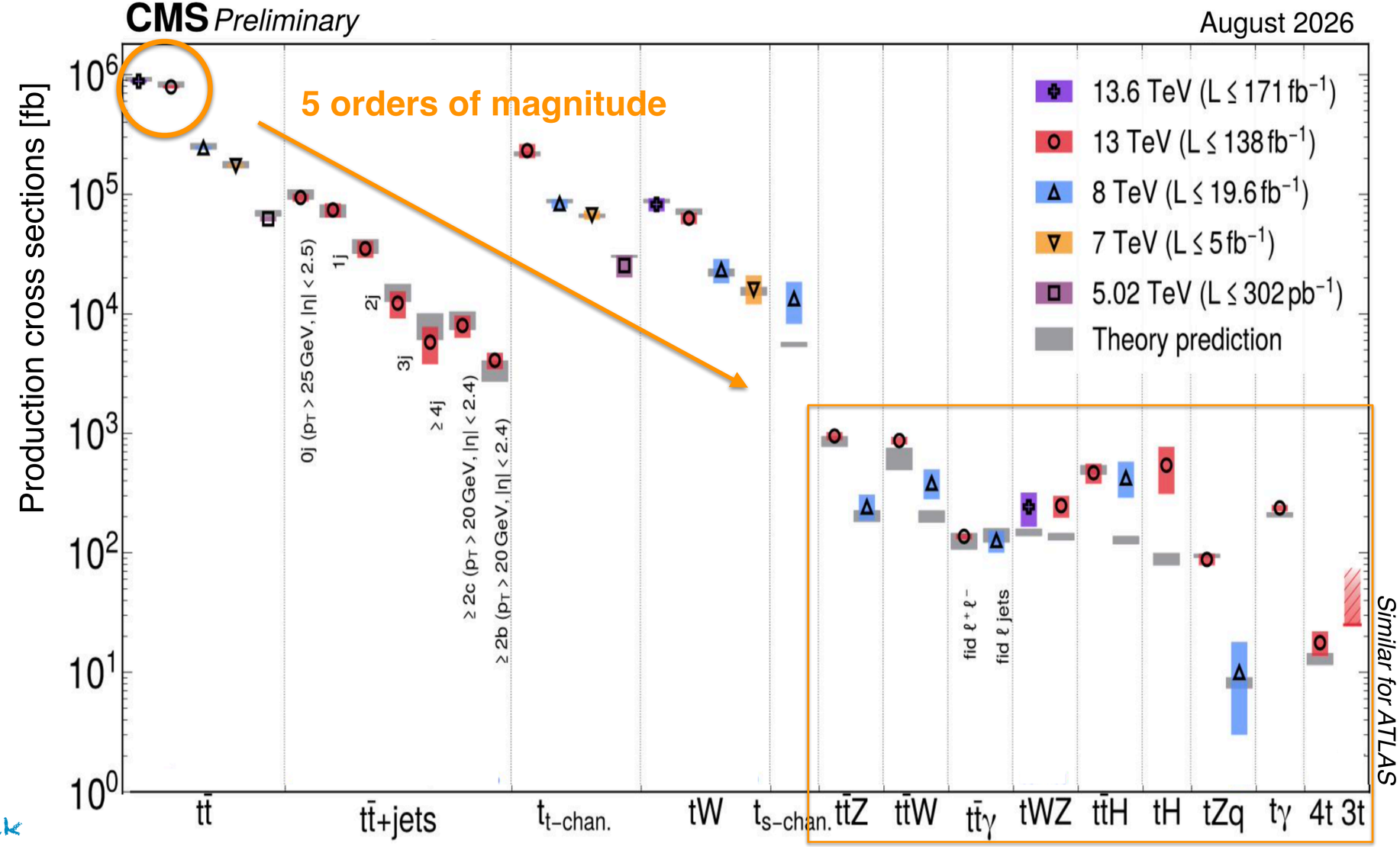
m_t^{MC} = 172.17 ± 0.80 (stat) ± 0.81(syst) ± 1.07 (recoil) GeV

JHEP 04 (2026) 099

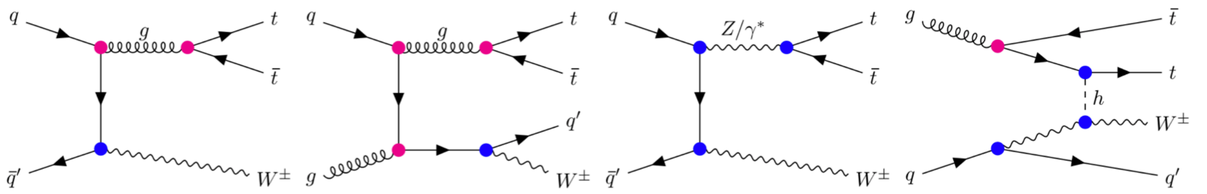
Associated top production

- High energy scale processes probing top couplings and possible new interactions
- Complex analyses, theoretically and experimentally
  - Interpretability of results affected by availability of higher-order predictions
- Former “rare processes” now entering precision regime and support differential measurements
- “Rarer” processes becoming experiementally accesible

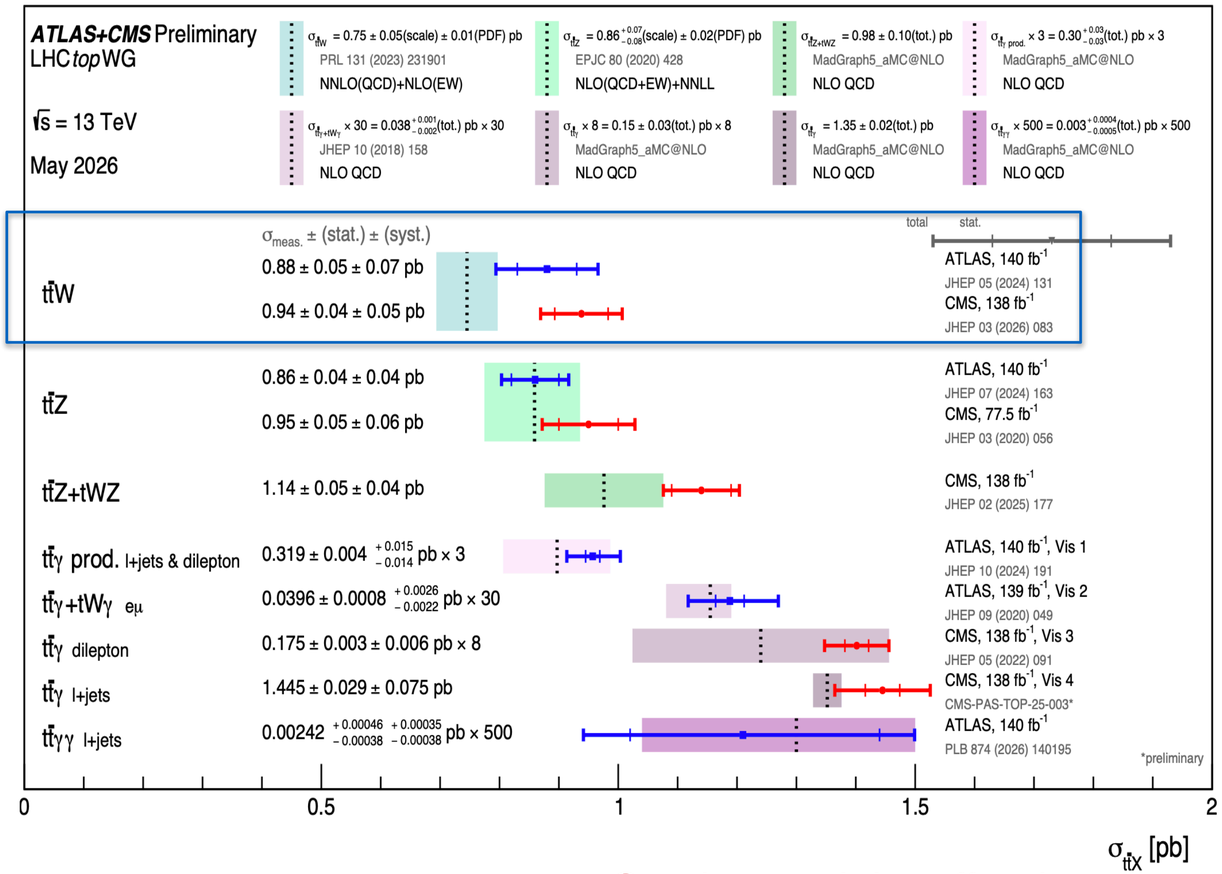
→ for t(t)H, see P. Francavilla’s talk



$t\bar{t}W$ production

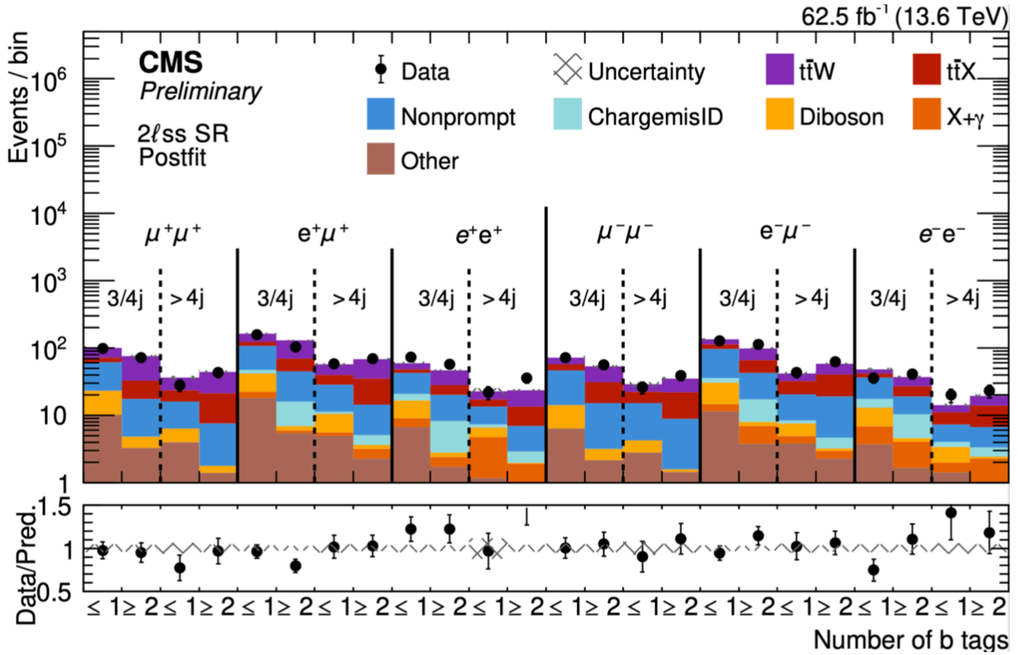


- $t\bar{t}W$ production receives important contributions from QCD and EW corrections —> challenging process
- ATLAS and CMS measurements are typically above the existing predictions



LHCtopWG Summary Plots

- CMS extends the measurement to 13.6 TeV
  - Same-sign dilepton or trilepton events, different lepton charge, jet, and b-jet multiplicities



$$\sigma_{ttW} = 1118^{+90}_{-88}(syst)^{+73}_{-72}(stat)fb$$

$$\sigma_{ttW-pred.} = 855^{+23}_{-20}\ fb$$

from aN3LO (QCD) + NLO (EW) (PLB 854 (2024) 138708)

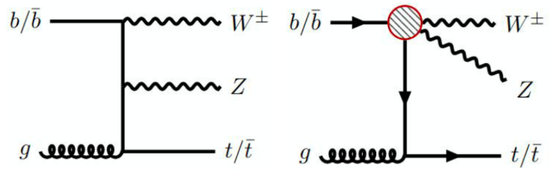
CMS-PAS-TOP-25-014

Continuous joint effort between experiment and theory is essential

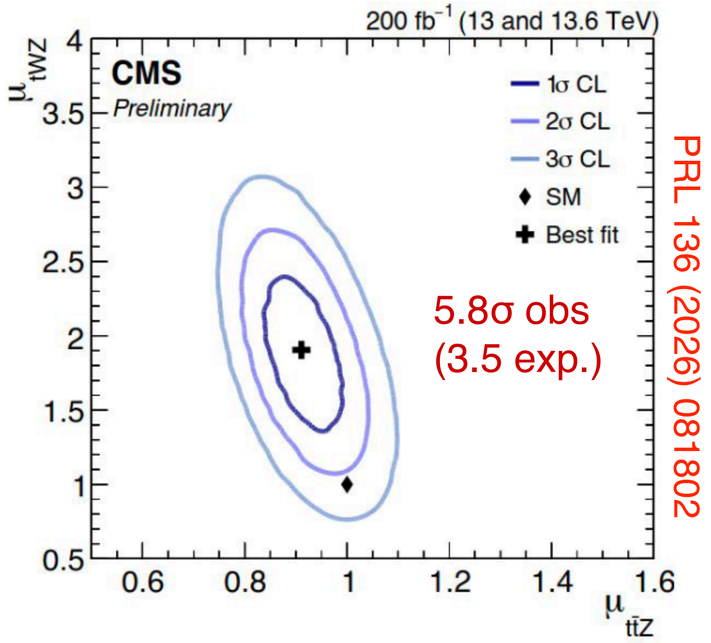
Rarer processes becoming accessible

Additional electroweak bosons provide complementary tests of top interactions and possible new physics

- CMS: Observation of tWZ (Run2 + partial Run3)

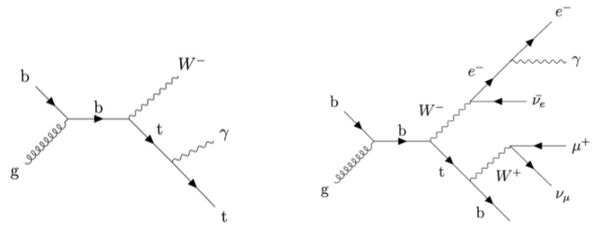


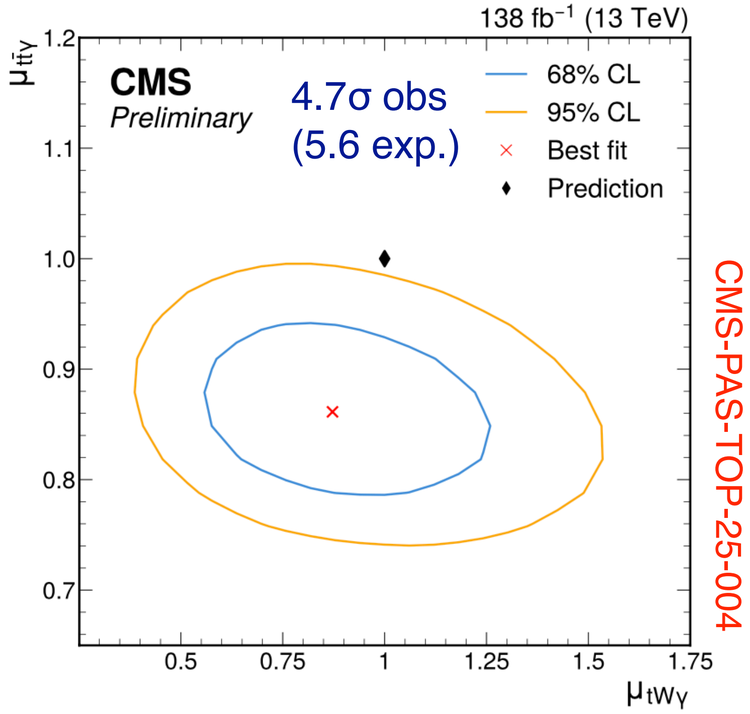
- Improved tWZ/ttZ separation with respect to Run2 evidence result



PRL 136 (2026) 081802

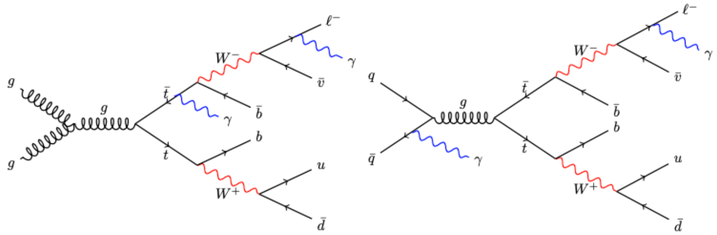
- CMS: First measurement of tWγ

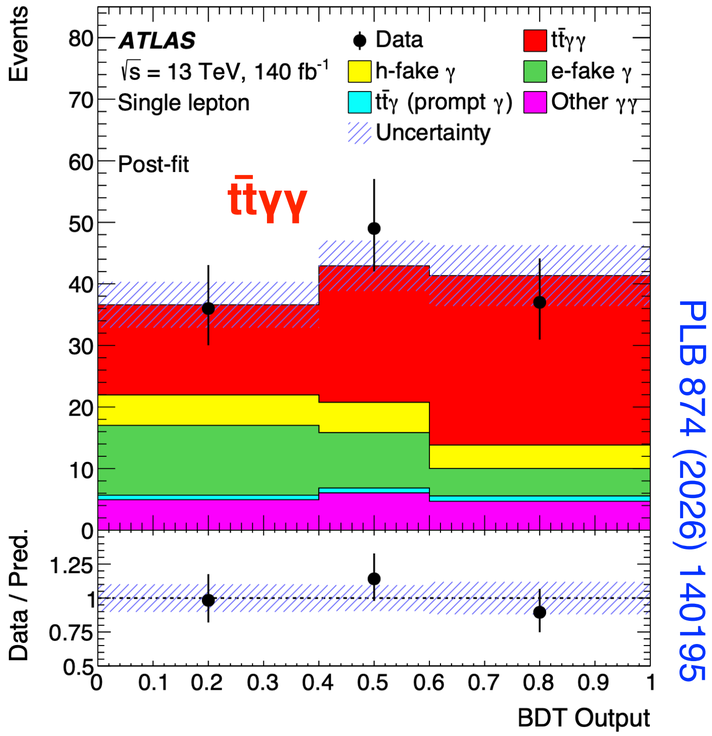




CMS-PAS-TOP-25-004

- ATLAS: Observation of $t\bar{t}\gamma\gamma$





PLB 874 (2026) 140195

$$\sigma_{t\bar{t}\gamma\gamma} = 2.42^{+0.46}_{-0.38}\,(\text{stat})\,^{+0.35}_{-0.38}\,(\text{syst})\ \text{fb}$$

A glimpse of EFT

- Many measurements of tt+X and t+X are interpreted in Effective Field Theory
  - New physics parametrized as an expansion in the scale Λ

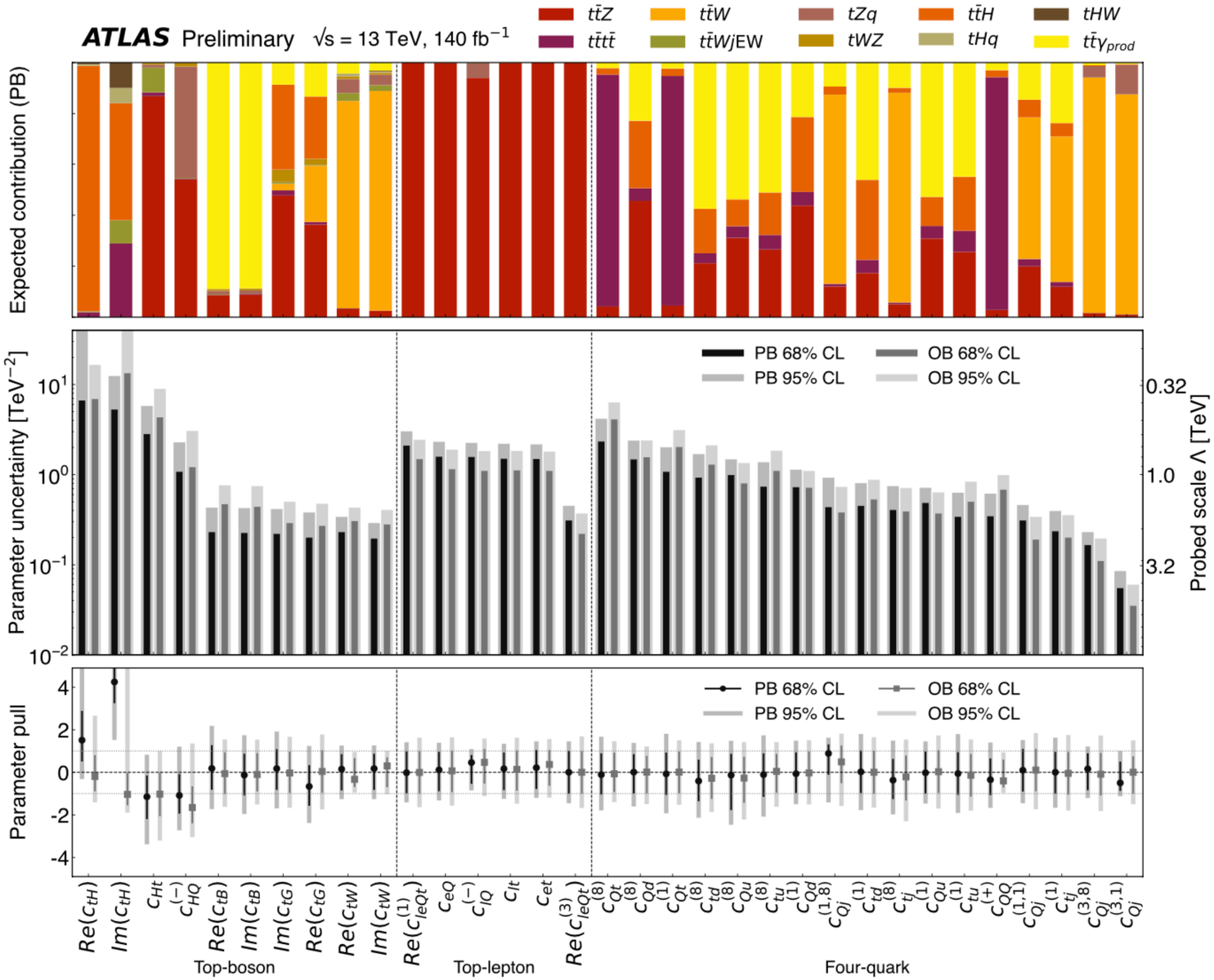
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} O_i + \cdots$$

  - Interpret in terms of constraints on dimension 6 operators

- Different processes and distributions constrain complementary combinations of coefficients

- New ATLAS result: combined measurement of EFT effects on top+X and top+Higgs, probing 33 EFT parameters simultaneously

- Top measurements are now being included in global fits using Higgs and EW bosons



→ see H. Mildner's talk

to appear in TOPQ-2023-34

Conclusion

- **Unprecedented LHC top samples have brought our knowledge of top quark physics to the next level**
  - **Precision is exposing subtle dynamics**
    Higher-order QCD, interference, and mass interpretation are central to further progress
  - **Spin and threshold measurements reveal additional structure**
    The quantum state and QCD interactions of top pairs are experimentally accessible
  - **New tests of flavour and rare electroweak interactions**
    Complementary flavour determinations and increasingly rare electroweak processes

- **Run3 data and HL-LHC will extend this reach**
  - **Sharper measurements of properties and couplings**
  - **Differential tests of rare interactions**
  - **Enhanced sensitivity to BSM phenomena in the top quark sector**

- **Realising this potential requires experimental innovation and theoretical progress together**

The ultimate potential for top quark physics is ahead of us

ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP