ATLAS EXPERIMENT

Universität Siegen

HEP Experimental High Energy Physics
CPPS Center for Particle Physics Siegen

Entanglement effects at high energies (including top quark pair production at threshold) at ATLAS and CMS

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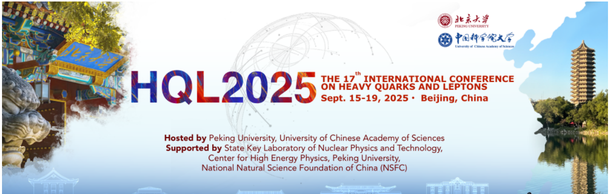
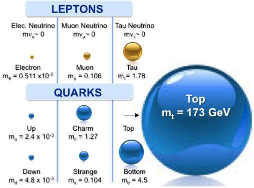
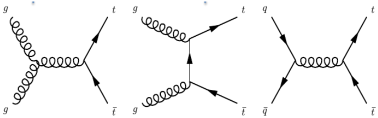
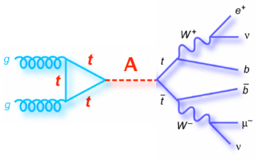


Introduction

- Most massive elementary particle known
- Largest Yukawa coupling
- Might couple to new physics
- Short-lived, decays before hadronising
    - Spin correlation measurements: test SM prediction and tool for BSM effects
    - Can also test some of the core properties of quantum mechanics $\rightarrow$ unique tests of actual quantum behaviour of quarks at LHC
- QCD predicts a quasi-bound state close to the threshold for low momentum top quarks







The large datasets collected by ATLAS and CMS allow extending the scope and reach of precision measurements!

$\rightarrow$ **Here: recent observations of quantum entanglement and bound $t\bar{t}$ at threshold**

Spin correlations in $t\bar{t}$

- Spin information is preserved through the top quark decay

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

- Top quark and antiquark produced in pairs $\rightarrow$ S_i and S_j correlated $=$ two qubit system

$$\rho = \frac{1}{4}\left(1 \otimes 1 + \sum_{i=1}^{3} B_i\,\sigma_i \otimes 1 + \sum_{j=1}^{3} \bar{B}_j\,1 \otimes \sigma_j + \sum_{i=1}^{3}\sum_{j=1}^{3} C_{ij}\,\sigma_i \otimes \sigma_j\right)$$

$$\langle S_i \rangle = B_i, \quad \langle \bar{S}_j \rangle = \bar{B}_j, \quad \langle S_i \bar{S}_j \rangle = C_{ij}$$

- 15 parameters in total that describe the quantum state of a $t\bar{t}$
    - 6 polarisations, 9 correlation coefficients

Measuring spin correlations

- The spin of the top quarks can not be measured directly: extracted based on the direction of the final state particles
  - Relation created by the weak decay
  - *Strength* given by the spin analysing power, it depends on the particle flavour

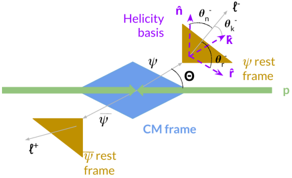
$$\frac{1}{\Gamma_T}\frac{d\Gamma}{d\cos\chi_i} = \frac{1+\alpha_i\cos\chi_i}{2} \qquad \alpha_i = \begin{cases} +1.0 & \ell^+ \text{ or } \bar{d}\text{-quark} \\ -0.31 & \bar{\nu} \text{ or } u\text{-quark} \\ -0.41 & b\text{-quark} \end{cases} \quad \text{at LO}$$

- Each element of the spin density matrix can be probed through a unique angular distribution.

- Angular distributions measured in helicity bases → defined in the parent particle frame

Helicity basis

$$\hat{k} = \text{top direction}, \quad \hat{r} = \frac{\hat{p} - \hat{k}\cos\theta}{\sin\theta}, \quad \hat{n} = \frac{\hat{p}\times\hat{k}}{\sin\theta}$$



Spin correlation and entanglement

There are four maximally entangled states

$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle \right),$$

$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle \right).$$

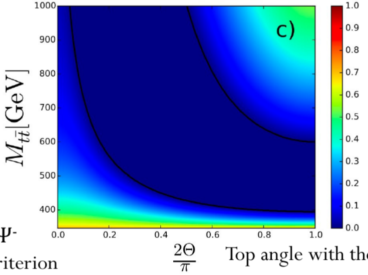
at high $M_{t\bar{t}}$ triplet vector state

(Φ^+-Φ^-, Ψ^+, Φ^++Φ^-)

Peres-Horodecki criterion

$$\Delta_E = C_{nn} - C_{rr} - C_{kk} = 3\tilde{D} > 1$$

$$\tilde{D} > \frac{1}{3}$$



Top angle with the beam axis

at low $M_{t\bar{t}}$ singlet pseudoscalar state Ψ^-

Peres-Horodecki criterion

$$\Delta_E = Tr(C) = -3D > 1$$

$$D < -\frac{1}{3}$$

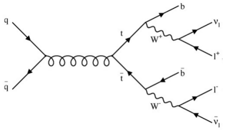
Plot from Afik, De Nova EPJP136(2021)9,907 hep-ph:2003.02280

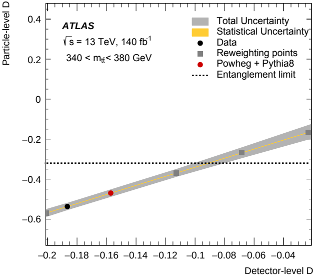
From R. Demina, LHCP2024

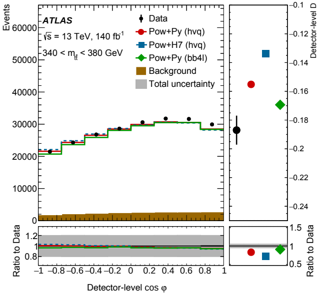
Quantum entanglement in dileptonic $t\bar{t}$

[Nature 633 (2024) 542, Rep. Prog. Phys. 87 (2024) 117801]

- ATLAS uses $e\mu$ final state: very clean (90% purity), while CMS measurement used all three dilepton channels
- Measure entanglement proxy $D = -\Delta/3 = -Tr[C]/3$ extracted from angle between charged leptons: $\frac{1}{\sigma}\frac{d\sigma}{d\cos\phi} = \frac{1}{2}(1 - D\cos\phi)$
- ATLAS:
  - *Calibration curve* method: use the nominal MC to map the detector-level D value (average of the distribution) to the fiducial particle-level D.
  - Define entanglement signal region and validation regions based on $m_{t\bar{t}}$
- CMS: D extracted at parton level from binned profile likelihood fit to $\cos\phi$ in $m_{t\bar{t}} < 400$ GeV and $\beta_{z,t\bar{t}} < 0.9$



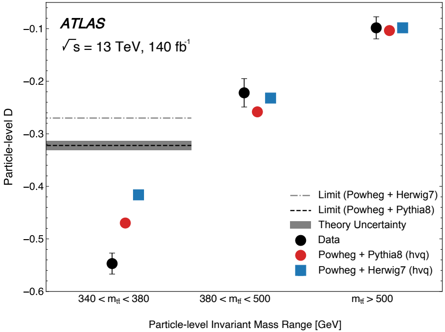


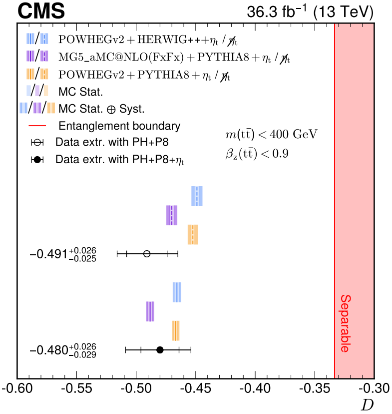


Observation of top quark entanglement

[Nature 633 (2024) 542, Rep. Prog. Phys. 87 (2024) 117801]

- $D < -1/3$ established at 5σ level





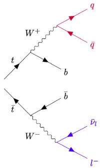
non-relativistic QCD effects close to threshold not included in MC generators

$\rightarrow$ more on threshold effects in a few slides!

$\sim 1.5\sigma$ tension with the expectation if *toponium* is not included

Taking it a step further [Phys. Rev. D 110 (2024) 112016]

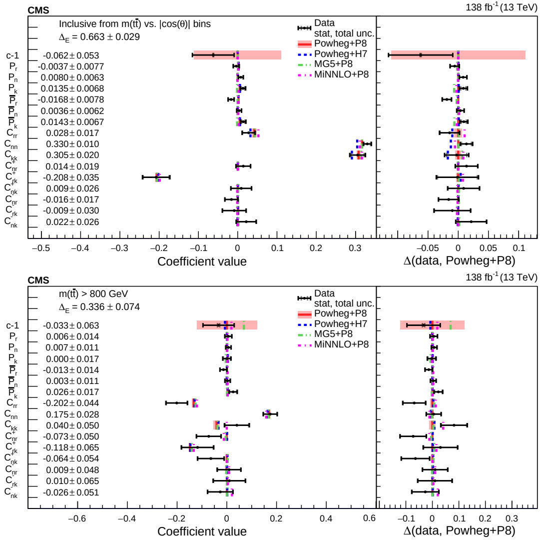
- Measuring the correlation matrix in single-lepton $t\bar{t}$ events
- All coefficients of polarization vectors and correlation matrix from fit to the angles of the down-type quark and the charged lepton in the W boson decays.
- Challenging identification of down-type quark in W decay
- Using NN to reconstruct the $t\bar{t}$ system
- Δ from the full matrix, or from two proxies: D and $\tilde{D} = 3(C_{33} - C_{11} - C_{22})$ for high masses



Observable	Coefficient
$\cos\theta_k^1$	B_k^1
$\cos\theta_r^1$	B_r^1
$\cos\theta_n^1$	B_n^1
$\cos\theta_k^2$	B_k^2
$\cos\theta_r^2$	B_r^2
$\cos\theta_n^2$	B_n^2
$\cos\theta_k^1 \cos\theta_k^2$	C_{kk}
$\cos\theta_r^1 \cos\theta_r^2$	C_{rr}
$\cos\theta_n^1 \cos\theta_n^2$	C_{nn}
$\cos\theta_k^1 \cos\theta_r^2 + \cos\theta_r^1 \cos\theta_k^2$	$C_{rk} + C_{kr}$
$\cos\theta_r^1 \cos\theta_k^2 - \cos\theta_k^1 \cos\theta_r^2$	$C_{rk} - C_{kr}$
$\cos\theta_r^1 \cos\theta_n^2 + \cos\theta_n^1 \cos\theta_r^2$	$C_{nr} + C_{rn}$
$\cos\theta_n^1 \cos\theta_r^2 - \cos\theta_r^1 \cos\theta_n^2$	$C_{nr} - C_{rn}$
$\cos\theta_k^1 \cos\theta_n^2 + \cos\theta_n^1 \cos\theta_k^2$	$C_{nk} + C_{kn}$
$\cos\theta_n^1 \cos\theta_k^2 - \cos\theta_k^1 \cos\theta_n^2$	$C_{nk} - C_{kn}$
$\cos\varphi$	D

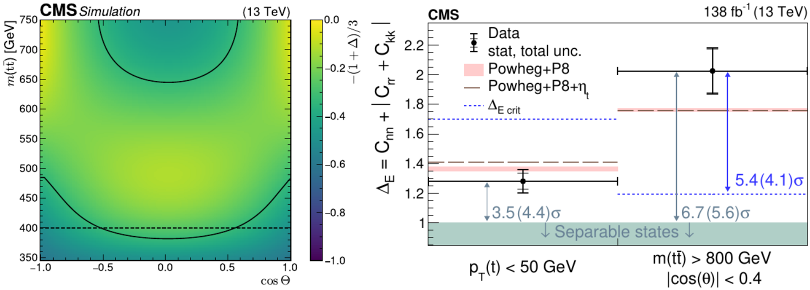
Spin density matrix [Phys. Rev. D 110 (2024) 112016]

- Only C^{+}_{rk} invariant under C and P transformation: only non-zero off-diagonal
- Diagonal elements: transition from dominant spin-singlet at low $m_{t\bar{t}}$ to triplet-state at high $m_{t\bar{t}}$
- All coefficients in good agreement with SM Values



Quantum entanglement at high $m_{t\bar{t}}$ (from full SDM)

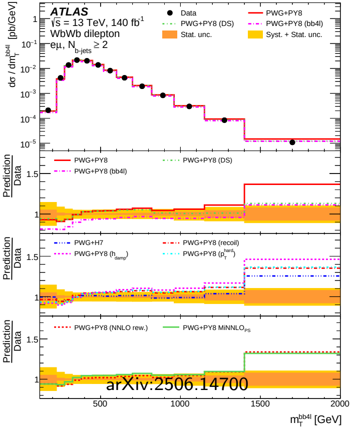
[Phys. Rev. D 110 (2024) 112016]

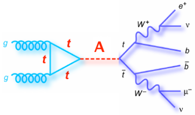


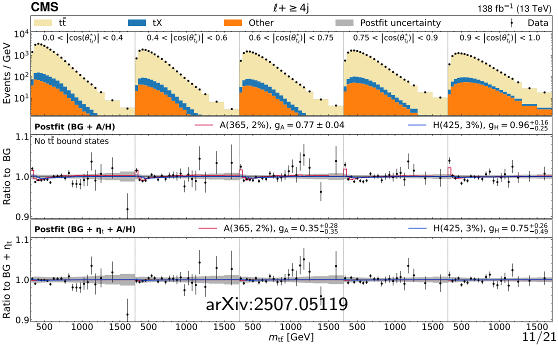
- At high $m_{t\bar{t}}$ with low $\cos\theta_t$: entangled states
- Criterion: $\Delta E = C_{nn} + |C_{rr} + C_{kk}| > 1$
- First observation of an entangled quantum state at high $m_{t\bar{t}}$

Top quark production at threshold

- Excesses of events at the threshold over the prediction observed by both ATLAS and CMS, in both lepton+jets and dilepton channels
- Excess found compatible with $t\bar{t}$ pairs in a pseudoscalar state
- As just mentioned, threshold region also relevant in the context of quantum entanglement



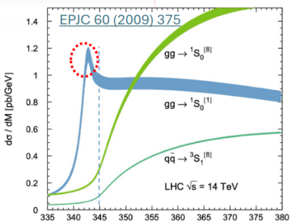




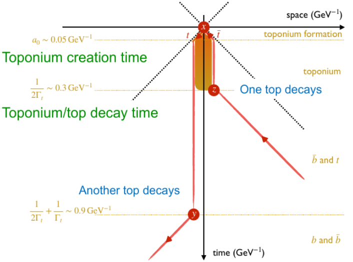
Top quark production at threshold

[Rep. Prog. Phys. 88 (2025) 087801, CONF-TOPQ-2025-03]

- SM predicts a quasi-bound state below the $t\bar{t}$ threshold
  - Coulomb potential with gluon and soft-gluon emissions between the top quarks
  - It behaves dominantly like a pseudoscalar but it is not an s-channel resonance
- $\sigma(\eta_t) = 6.4$ pb
  - $\sim$0.6% that of inclusive $t\bar{t}$ at 13 TeV
  - $m_{t\bar{t}}$ resolution too poor to see it directly
- Need to use spin-sensitive observables to exploit the pseudoscalar component



From B. Fuks



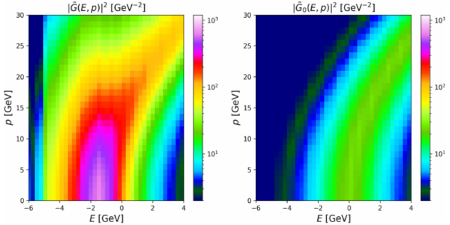
Hadronization time scale: ~5 GeV^{-1}

Toponium modelling [Rep. Prog. Phys. 88 (2025) 087801, CONF-TOPQ-2025-03]

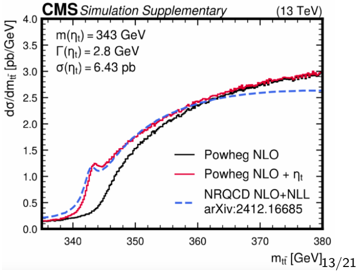
- ATLAS: S-wave, colour-singlet state with Green's function of non-relativistic (NRQCD) - EPJC 85 (2025) 157
- Generate $gg \to t\bar{t}$ with MG5_aMC, including spin correlations.
- Reweight matrix element with the corresponding QCD Green's squared functions

$$|\mathcal{M}|^2 \quad \to \quad |\mathcal{M}|^2 \left| \frac{\widetilde{G}(E;\, p^*)}{\widetilde{G}_0(E;\, p^*)} \right|^2$$

$\tilde{G}$: Green's function considering QCD potential
$\tilde{G}_0$: Free Green's function

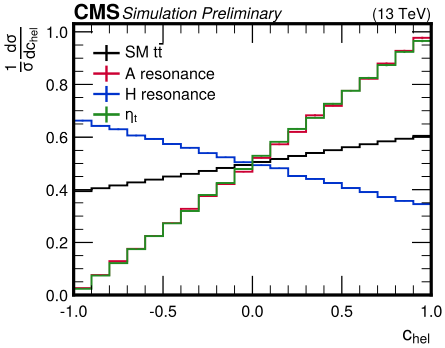


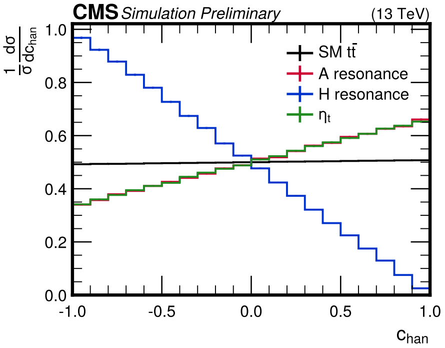
- CMS: Simplified model - JHEP 03 (2024) 099
- Approximate $t\bar{t}$ bound states by generating $gg \to \eta \to WbWb$ in MG5_aMC at LO: generic particle with direct couplings to gluons and tops use $M(\eta_t)$=343 GeV $\Gamma(\eta_t)$=2.8 GeV from fit to NRQCD



Sensitive variables [Rep. Prog. Phys. 88 (2025) 087801, CONF-TOPQ-2025-03]

- CMS and ATLAS: use dilepton events
- Reconstruct top quarks and use spin-sensitive observables
  - $c_{hel} = \vec{\ell}_+ \cdot \vec{\ell}_-$ (helicity basis, used to extract D)
    $\rightarrow$ a maximum slope for a spin-singlet state.
  - c_{han}: defined similarly, but flipped sign of ℓ in the t frame $\rightarrow$ maximum slope for a spin-triplet state.



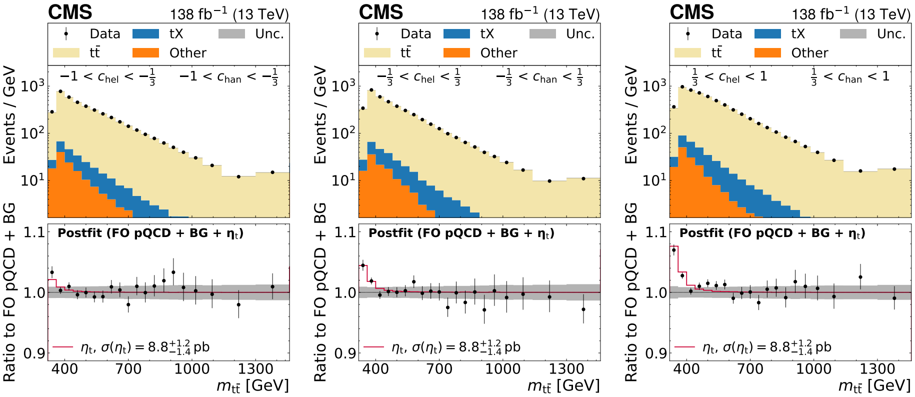


Background modelling [Rep. Prog. Phys. 88 (2025) 087801, CONF-TOPQ-2025-03]

- Challenging measurement: precise modelling of the $t\bar{t}$ threshold region crucial
- $t\bar{t}$: Fixed-order perturbative QCD NLO MC Powheg v2 hvq + Pythia8, using narrow-width approximation, $m_t = 172.5$ GeV
  - 2D kinematic reweighting in $(\cos\theta^*, m_{t\bar{t}})$ to higher order predictions: NNLO QCD with MATRIX, NLO EW with HATHOR
    θ^*: $\angle$ between p^t in the $t\bar{t}$ c.o.m. frame and $\mathrm{p}^{t\bar{t}}$ in the lab frame
  - Normalised to NNLO+NNLL cross section
- Alternative: $t\bar{t}$ Powheg v2 bb4l + Pythia8 $pp \to bl\nu bl\nu$ including off-shell, non-resonant contributions, and exact spin correlations at NLO

CMS measurement [Rep. Prog. Phys. 88 (2025) 087801]

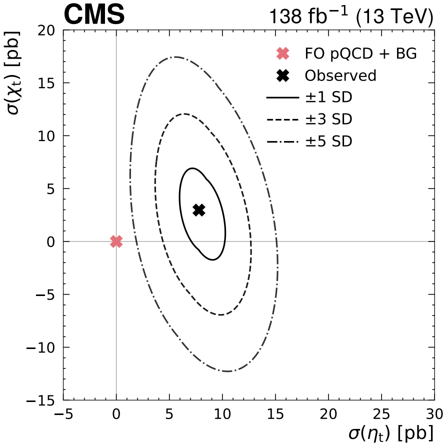
- Signal model with simplified model
- Profile likelihood fit to $m_{t\bar{t}}$ (20 bins) in 9 regions split by c_{hel} and c_{han}
- Z+jets production: Data-driven normalisation from Z peak



$$\boxed{\sigma(\eta_t) = 8.8^{+1.2}_{-1.4}\ \text{pb} = 8.8 \pm 0.5\ (\text{stat.})^{+1.1}_{-1.3}\ (\text{syst.})\ \text{pb}}$$

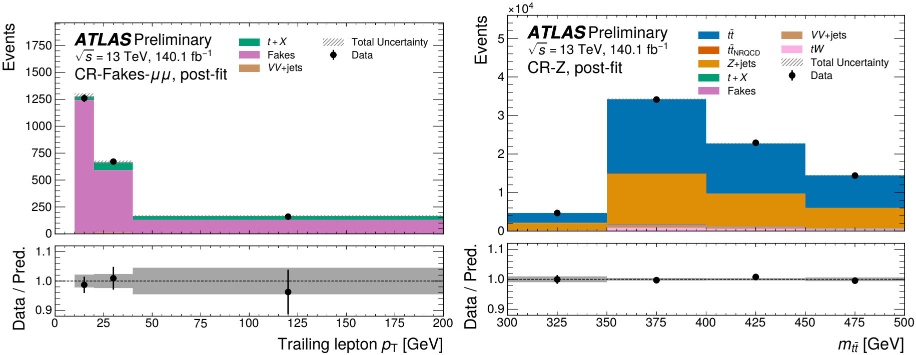
CMS Results: Pseudoscalar or scalar [Rep. Prog. Phys. 88 (2025) 087801]

- Also studied compatibility with a scalar toponium, χ_t: $3P_0^{[1]}$ spin-0, CP-even, color-singlet
- Data prefers pseudoscalar over scalar toponium $[\sigma(\chi_t) = 3.0^{+2.6}_{-3.3}\ \mathrm{pb}]$



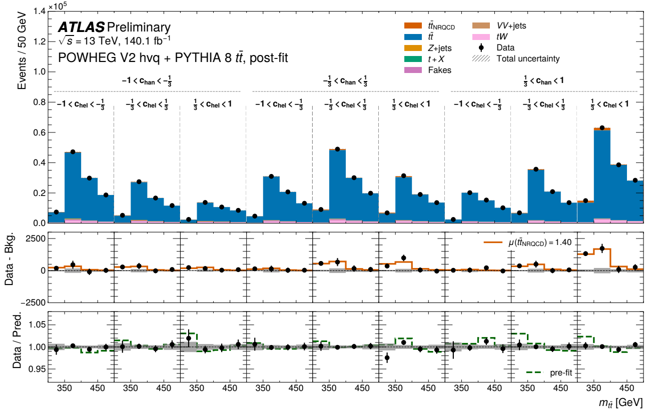
ATLAS measurement [CONF-TOPQ-2025-03]

- Selecting region $m_{t\bar{t}} < 500$ GeV
- Fit to $m_{t\bar{t}}$ (4 bins) in 9 signal regions split by angular variables
  - $t\bar{t}$ contribution free-floating
- Control regions to extract normalisation of
  - fake/non-prompt leptons (heavy-flavour and photon-conversion electron fakes, and heavy-flavour muon fakes) by fitting sub-leading lepton p_T distribution
  - Z+jets to normalise the Z+b process



ATLAS results [CONF-TOPQ-2025-03]

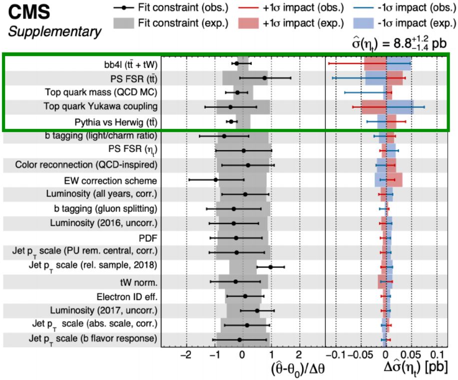
- Observed (expected) significance: 7.7σ (5.7σ)
- Goodness-of-Fit: 0.93
- Results also obtained for simplified signal model: Observed (expected) significance of 7.8σ (4.0σ)



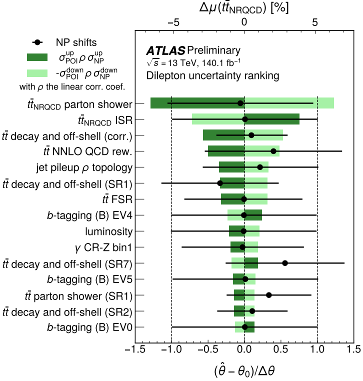
$$\sigma(t\bar{t}) = \ 9.0 \pm 1.3 \text{ pb} \ = \ 9.0 \pm 1.2 \text{ (stat.)} \pm 0.6 \text{ (syst.) pb}$$

Systematic uncertainties [Rep. Prog. Phys. 88 (2025) 087801, CONF-TOPQ-2025-03]

- ATLAS vs CMS: Slightly different set of uncertainties considered for $t\bar{t}$ modelling and signal
- Modelling uncertainties partially decorrelated in the ATLAS measurement to avoid large constraints



$t\bar{t}$ modelling: variation in final state radiation



Quasi-bound state modelling: Parton shower [Herwig7], $t\bar{t}$ decay and off-shell [comparison to bb4l], NNLO QCD rew.: NNLO QCD scale variations

Summary and outlook

- First observation of quantum entanglement at the LHC!
  - Top quark polarization and spin correlation measurement: interesting in its own right as a test of the SM, but it also provides new opportunities for testing quantum mechanics
  - Angular distributions of the top and antitop quarks used to measure their polarization and spin correlation matrix
- $t\bar{t}$ production at threshold Excess of events observed over the NNLO perturbative QCD prediction, with 7.7σ (5.7σ) by ATLAS
  - Excess consistent with color-singlet, S-wave, quasi-bound $t\bar{t}$ states predicted by NRQCD with cross-section of 9.0 $\pm$ 1.3 pb
  - Confirms observation by CMS with $\sigma(\eta_t) = 8.8^{+1.2}_{-1.4}$ pb