Quantum entanglement and BSM with top in the final state

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Introduction

- The Standard Model (SM) is a Quantum Field Theory $\rightarrow$ fundamental properties of Quantum Mechanics can be tested using SM processes

- This gives the opportunity to study concepts of Quantum Information at High Energy colliders like LHC
  - Top quark pair production offers a very suitable case study for this, thanks to the top quark properties, the high production cross section and very clean reconstructed final state

- However, SM in also incomplete since it cannot explain for example Baryon Asymmetry in the Universe, Dark Energy and Dark Matter ...
  - Also in this case, studies considering final states with Top quark can lead to physics Beyond Standard Model (BSM portal)

2 Qubit (particle) Quantum state

- At LHC, no control over colliding particles initial state $\rightarrow$ in this case, a system can be described using a spin density matrix $\rho = \sum_i p_i \cdot |\psi_i><\psi_i|$

- Qubit: quantum system with two states, like a spin-1/2 particle

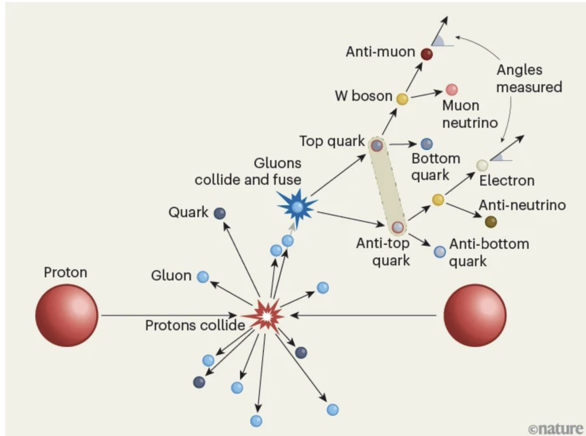
- Considering a 2 qubit (particle) system, the most general spin density matrix can be written as:

$$\rho = \frac{I_4 + \sum_i \left(B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i\right) + \sum_{i,j} C_{ij} \sigma^i \otimes \sigma^j}{4}$$

- 15 parameters included in $B_i^{\pm}$ and C_{ij}, corresponding to the spin polarisation of the individual particles $B^{\pm}$ (3+3 param.) and the spin correlation matrix C (9 param.)

Top quark pair production

- Top quark (t) is the heaviest particle in the SM with a lifetime of $\simeq 10^{-25}$ s
- Hadronisation in $\simeq 10^{-23}$ s and Spin-decorrelation in $\simeq 10^{-21}$ s
- The spin information is propagated in the top decay products
- Spin-correlations between a pair of top-quarks can be measured for example looking at the angles between the decay products in the $t\bar{t}$ rest frame

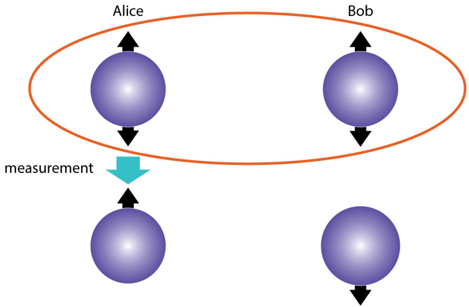


- Experimentally, spin polarisation and spin correlation measurement through angular differential cross section:

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1 + \mathbf{B}^+ \cdot \hat{\mathbf{q}}_+ - \mathbf{B}^- \cdot \hat{\mathbf{q}}_- - \hat{\mathbf{q}}_+ \cdot \mathbf{C} \cdot \hat{\mathbf{q}}_-}{(4\pi)^2}$$

Quantum Entanglement (QE)

- Quantum state of a particle cannot be described independently from another particle (*non-separable* state or *entangled* state)
  - Measurement performed on one system will influence the other system entangled with it



- Peres-Horodecki criterion for quantum entanglement: $Tr[C] <$ -1
- From spin measurement through $t\bar{t}$ differential cross section measurement:

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

- These can be related, allowing quantum entanglement measurement at LHC:

$$D = \frac{Tr[C]}{3} \rightarrow D < -\frac{1}{3}$$

Entanglement Measurement

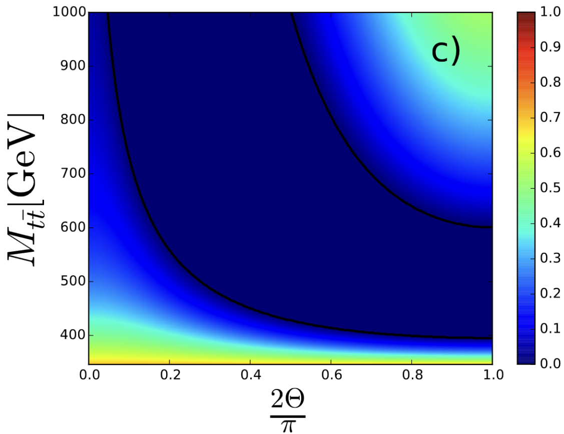
- Measuring spin-correlation is NOT equivalent to entanglement measurement, since spin-correlation can also be a classical property of a system
- We need to also know a phase-space where to perform the measurement

- Four maximally entangled states for:

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

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

  - low $m_{t\bar{t}}$: pseudo-scalar state (Ψ^-). In this case D is a good observable
  - high $m_{t\bar{t}}$: triplet vector-state ($\Phi^+ \pm \Phi^-$,Ψ^+). In this case there is a sign-flip in the spin correlation matrix: D is not anymore a good observable $\rightarrow$ introduce $\tilde{D}$ to correct to sign-flip



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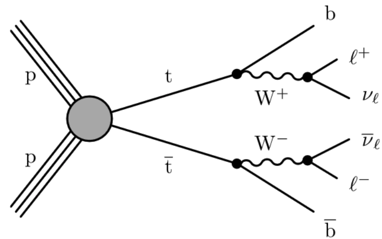
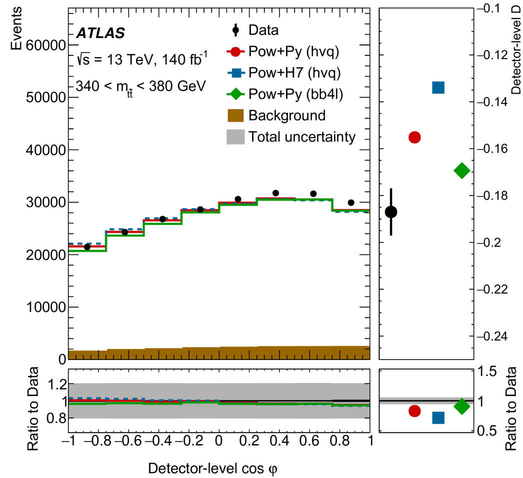
QE measurement in ATLAS

Nature 633 (2024) 542



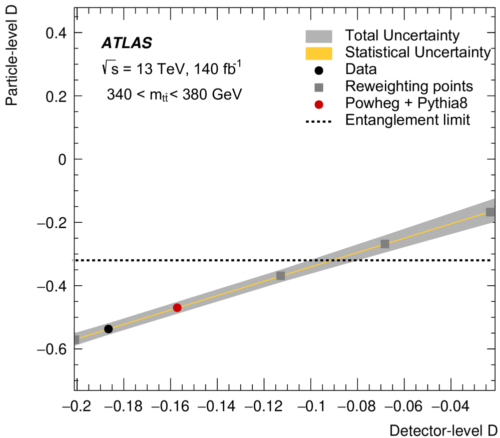
- Using di-leptonic $t\bar{t}$ decay final state selecting events using a single lepton trigger
- Analysis regions split in different $m_{t\bar{t}}$ intervals with a $t\bar{t}$ purity around 90%
- Particle level fiducial regions are defined using similar selection as the analysis regions
  - reduce extrapolation for particle level *D* measurement

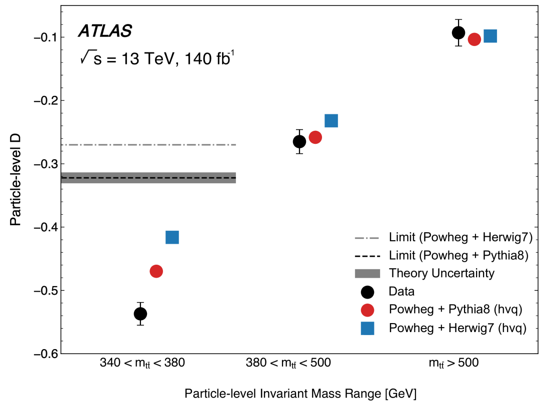


QE measurement in ATLAS

Nature 633 (2024) 542

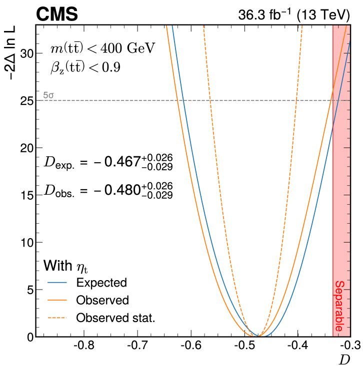
- Particle level *D* measured using a calibration curve built from alternative sets of reconstructed *D* and particle level *D*
- Results show no clear preference for a specific MC prediction
- *Entanglements* is measured with a significance of more than 5 σ, with obs. (exp.) D = -0.547 $\pm$ 0.002 (stat) $\pm$ 0.021 (syst) (-0.470 $\pm$ 0.002 (stat) $\pm$ 0.018 (syst))

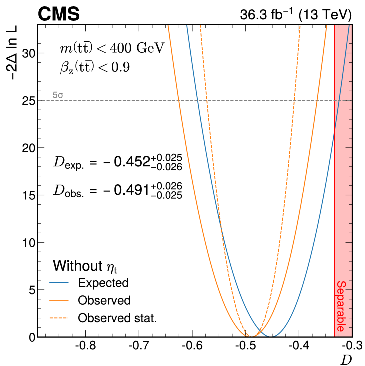


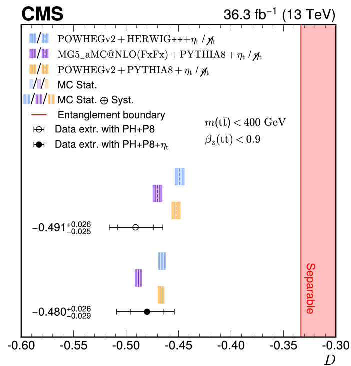


QE measurement in CMS

- CMS performed a similar measurement as ATLAS in the $t\bar{t}$ di-leptonic final state
- *Entanglements* is measured with an observed (expected) significance of 5.1 (4.7) σ
- Results available with/without including toponium (η_t)







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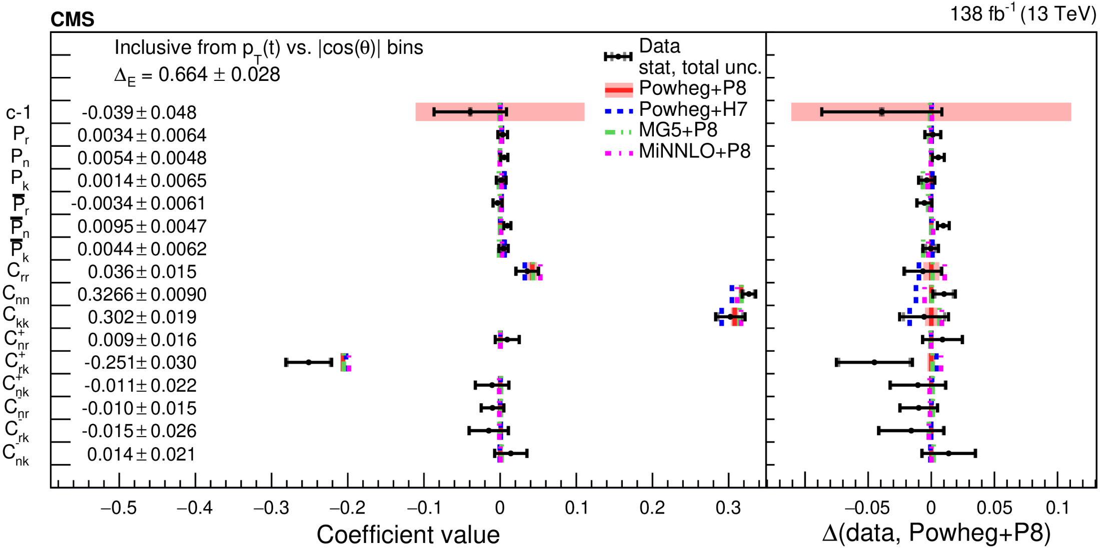
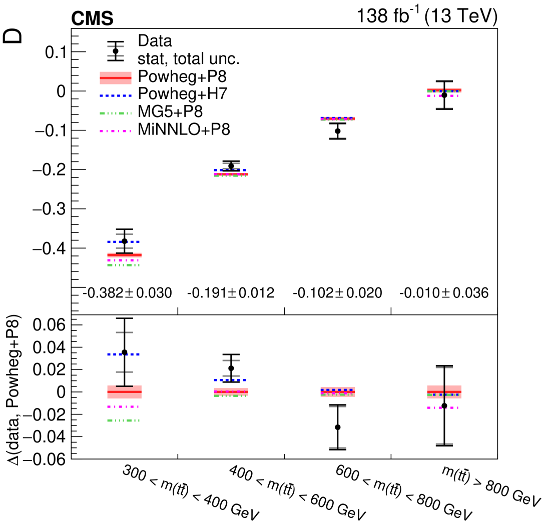
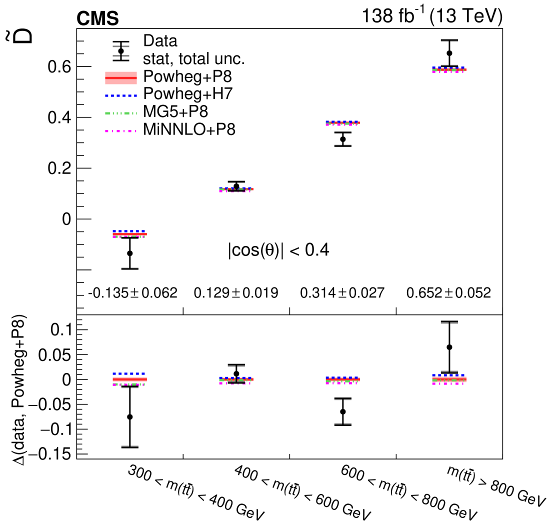
QE measurement in CMS CMS-TOP-23-007



- Performed measurement of the Spin-Density Matrix coefficients
- Top polarisation coefficients ≃ zero while 4-spin correlations coefficients are non-zero
- All results in agreement with SM expectation

QE measurement in CMS CMS-TOP-23-007

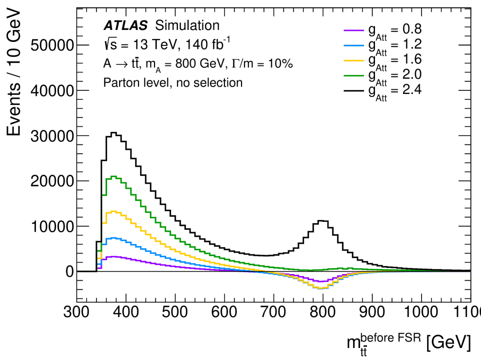




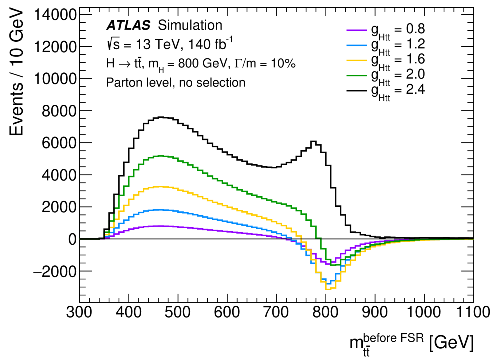
- For D measurement, entanglement observed at low $m_{t\bar{t}}$ values near to the production threshold
- For $\tilde{D}$ measurement, entanglement observed at high $m_{t\bar{t}}$ values while no entanglement near production threshold

Top quark pair as portal for BSM physics

- Several BSM models (2HDMs, hMSSM, ALPs, etc) predict new heavy scalar and pseudoscalar particles decaying in $t\bar{t}$
- Signature: peak-dip or peak-peak structure in $m_{t\bar{t}}$ spectrum
- Main challenge for this type of measurement is the strong interference between signal and SM $t\bar{t}$ background
  - Non-trivial to model and treat statistically
  - Interference patterns dependency on signal parameters
  - Low-$m_{t\bar{t}}$ peak expected event for resonance at high masses



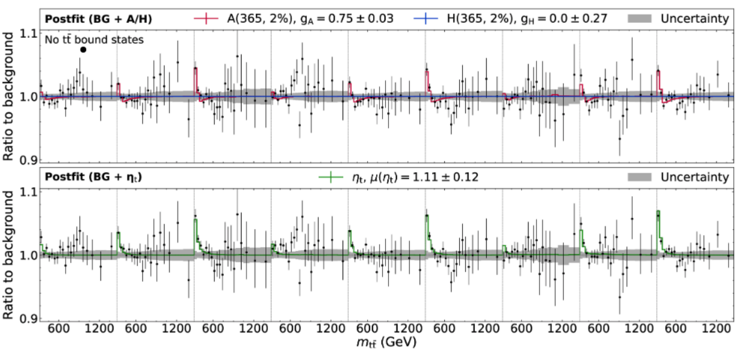
Pseudoscalar

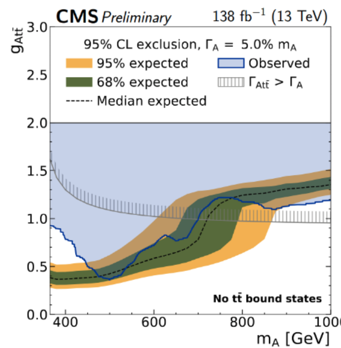


Scalar

CMS search for heavy (pseudo)-scalars

- Reported a $> 5\ \sigma$ deviation between data and prediction in the $m_{t\bar{t}} < 400$ GeV region
  - Consistent with the *toponium* quasi-bound $t\bar{t}$ state. Predicted by a simplified model on non-relativistic QCD with a cross section of 7.1 pb and an uncertainty of 11% . This yields to the best statistical compatibility with data.
  - Consistent also with a narrow pseudoscalar state with $m_A = 365$ GeV

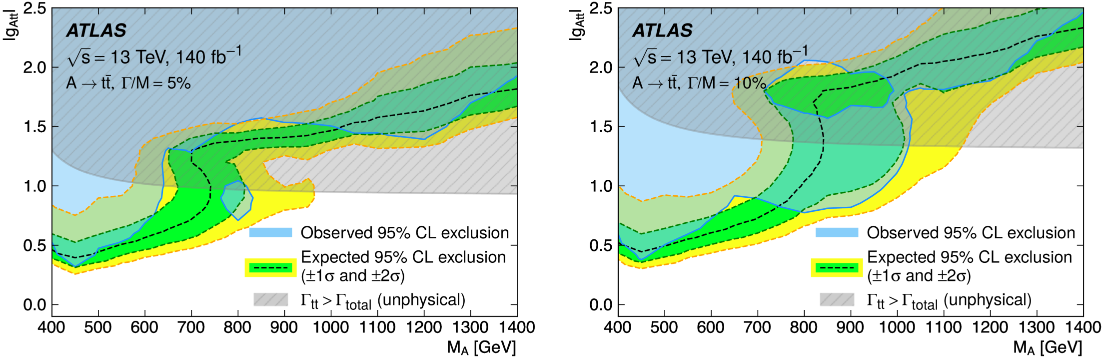




CMS-PAS-HIG-22-013

ATLAS search for heacy (pseudo)-scalars

- ATLAS has also performed a similar search for heavy (pseudo)-scalars decaying in $t\bar{t}$
- No excesses near the $m_{t\bar{t}}$ production threshold region
- No exclusion regions calculated for masses < 400 GeV:
  - LO signal model considered bad approximation of actual interference pattern
  - Large k-factor corrections



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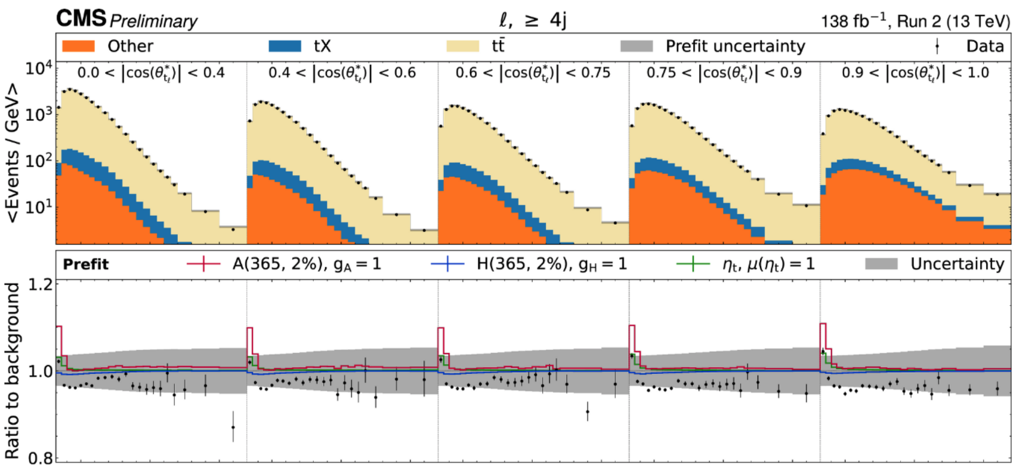
CMS vs ATLAS comparison

- There are several differences between ATLAS and CMS - DDifferent approach to higher order prediction of SM $t\bar{t}$ process, different strategies, differences in systematic uncertainties
- Focus comparison on 1L Resolved 2b regions as these are the most comparable



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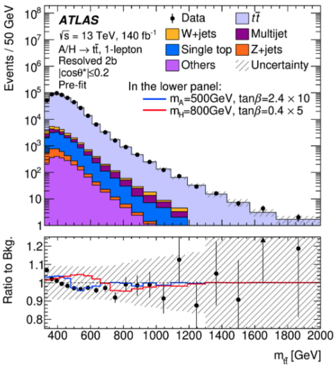
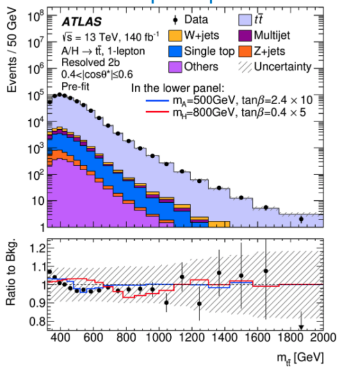
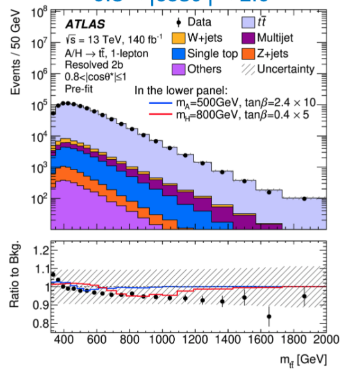
|cosθ*| < 0.2



0.4 < |cosθ*| < 0.6



0.8 < |cosθ*| < 1.0



- Compared to CMS:
  - Same kinematic range between the two experiments
  - Similar pre-fit modelling

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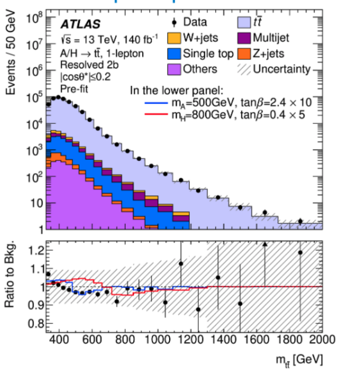

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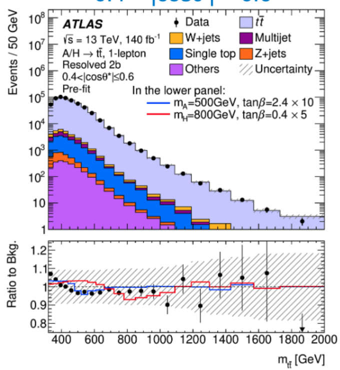

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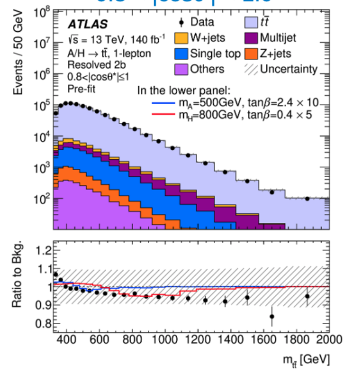

- Differences mostly in the statistical treatment ... still under investigation

Summary

- Top quark offers a great opportunity to study Quantum Information at High Energy colliders like LHC and also Beyond Standard Model physics
- Quantum Entanglement measured both by ATLAS and CMS experiments with a significance greater than 5σ
  - open the possibility to explore similar measurements also for bosons
- CMS reported a more than 5 σ deviation between data and prediction in the $m_{t\bar{t}} <$ 400 GeV region. Compatible with *toponium* final state, but not observed by ATLAS
  - ongoing cross-talk between the two experiments to carefully compare the measurements