Top quark property measurements with the CMS experiment

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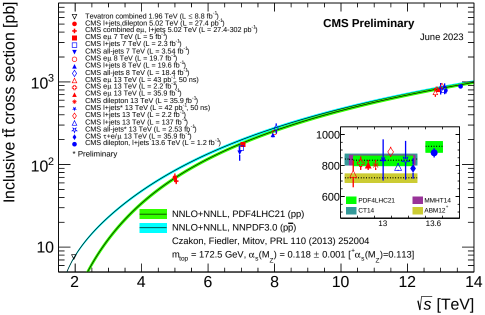
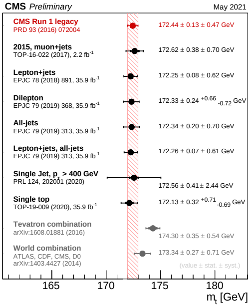
Cross sections of 830 pb (920 pb) at 13 TeV (13.6 TeV) → about 100M $\mathrm{t\bar{t}}$ pairs in Run 2





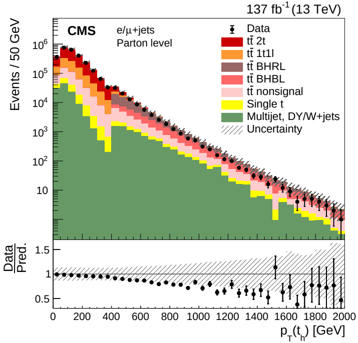
- Status and conclusions from (multi) differential cross sections measurements
- News from measurements of spin correlations and observation of entanglement
- New techniques for m_{t} measurements

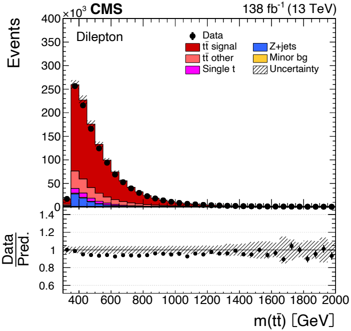
e/μ+jets 137 fb^{-1}: *Phys. Rev. D 104, 092013*:

- analysis performed using resolved (3 jets) and boosted (1 fat jet) reconstruction
- cross section extracted fitting all reconstruction categories simultaneously.

dilepton 138 fb^{-1}: *Submitted to JHEP*

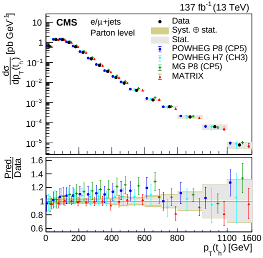
- selection: ee, $e\mu$, $\mu\mu$ at least 2 jets, at least 1 b jet.
- find analytic solutions for neutrino momenta; use solution with lowest $m(t\bar{t})$. Repeat procedure 100 times varying objects within their resolutions.

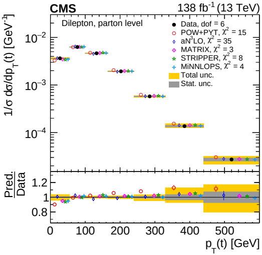




BHRL: boosted t_h, resolved t_l; BHBL: boosted t_h and t_l

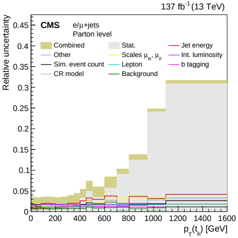
Results

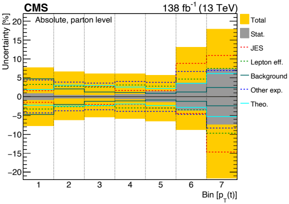




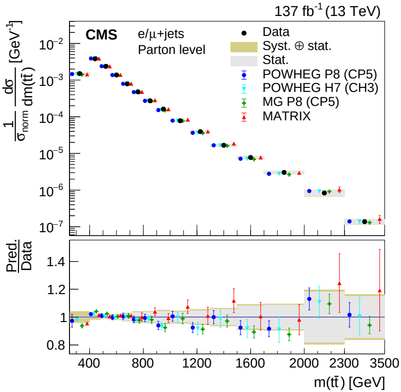
- p_{T} better described by NNLO calculation.
- trend of harder spectrum in NLO calculations disappears above 600 GeV

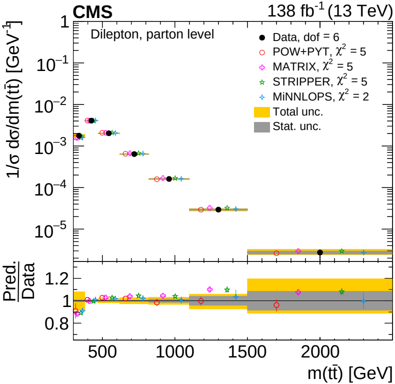
Uncertainties





- depending on the phase space region the precision is limited by systematic or statistical uncertainty.
- systematic dominated by experimental uncertainties like jet energy calibration and b-tagging.

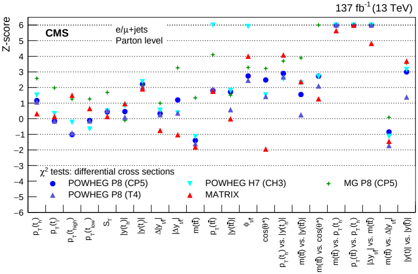


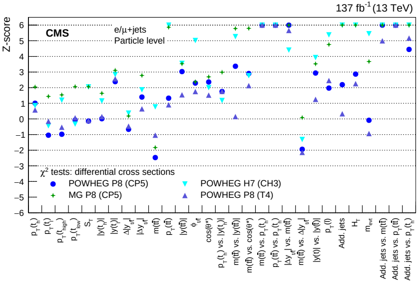


- measurements show excess of data at the $m(t\bar{t})$ production threshold.
- uncertainties in measurements are large in the first bins. Experimental and modelling uncertainties contribute.
- uncertainties in POWHEG+PYTHIA8 are sizable in this bin (This is the only model shown with the full set of variations)

Comparison of measurements to various predictions using χ^2-tests

uncertainties in measurements and predictions are take into account.





Most of the predictions are in good agreement with the measurement—with a few exceptions:

- $m(\mathrm{t\bar{t}})$ vs. $p_\mathrm{T}(\mathrm{t_h})$ and $p_\mathrm{T}(\mathrm{t\bar{t}})$ vs. $p_\mathrm{T}(\mathrm{t_h})$ shows largest disagreements.
  but theory uncertainties might be underestimated using fully correlated scale variations
- at particle level additional jets vs. kinematic observable are not well described.
  depends strongly on PS tuning

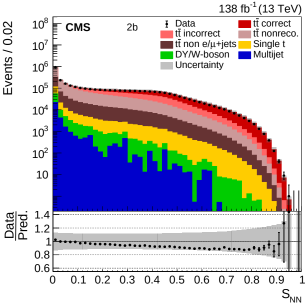
Cross section measurements are used: m_t and α_s extraction, PDF fits, EFT interpretation ...

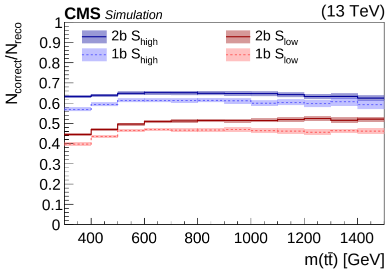
138 fb^{-1}, 13 TeV, *submitted Phys. Rev. D*

- in the helicity-frame the differential cross section of particles from $t\bar{t}$ decays can be parameterized by the polarization vector P and the spin correlation matrix C:

$$\frac{d^4\sigma}{d\mathbf{\Omega} d\bar{\mathbf{\Omega}}} \propto 1 + \kappa \mathbf{P}\cdot\mathbf{\Omega} + \bar{\kappa}\bar{\mathbf{P}}\cdot\bar{\mathbf{\Omega}} + \kappa\bar{\kappa}\mathbf{\Omega}\cdot C\bar{\mathbf{\Omega}}$$

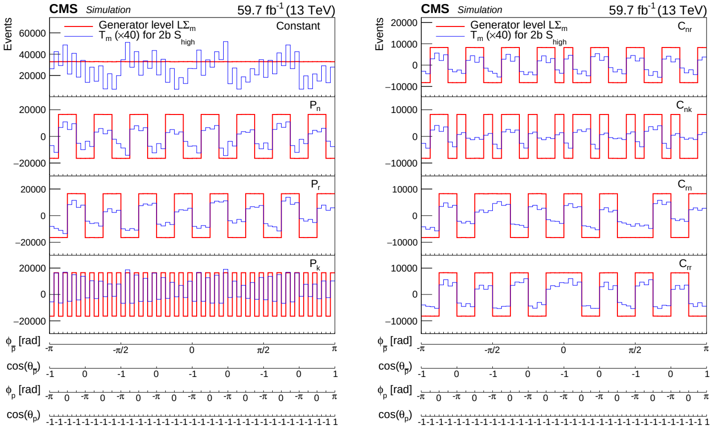
- together with an overall normalization factor there are 16 parameters to determine
- spin analyzing powers κ depend on the decay particle of the top quark used in the analysis. Best sensitivity ($\kappa = 1$) for charged lepton and down-type quarks from W decays.
- e/μ+jets final-state: easy reconstruction of top quark momenta, high branching fraction, but challenging to identify the down-type quarks.
- use ML for identification of top decay products based on kinematic and flavor-tagging information (half of the time there is a c-jet in the W decay)





Extraction method

According to the cross section formula each coefficient is proportional to a function depending on the angles of the two decay products (2 bins in $\cos(\theta_{p/\bar{p}})$ and 4 bins in $\phi_{p/\bar{p}}$):

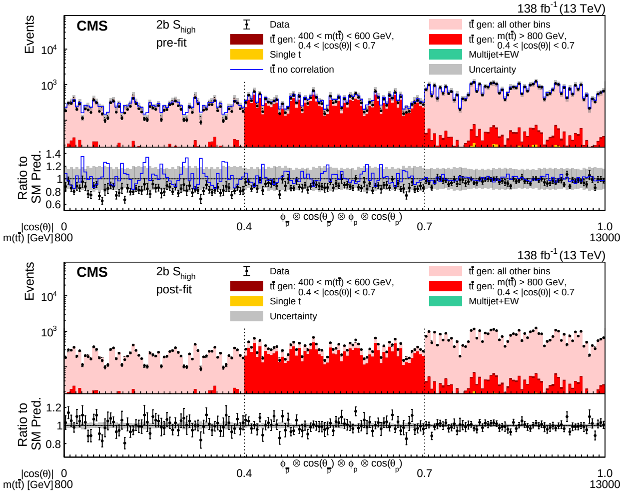


The blue lines show how the detector affects the theoretical shapes (red) due to acceptance, resolution, efficiencies ...

→Fit linear combination of the detector-level templates to data.

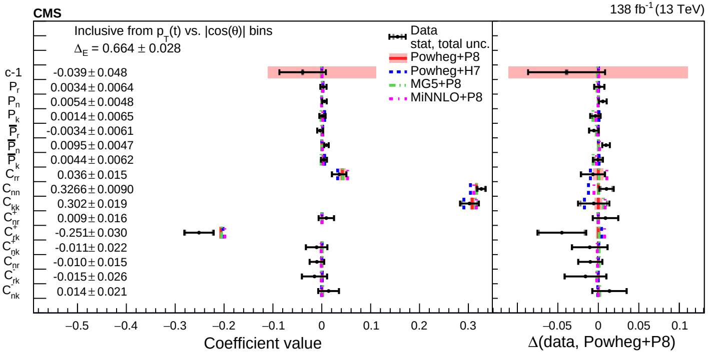
Using the SM $t\bar{t}$ simulation to construct the templates can result into a bias in the measured coefficients.

$\rightarrow$avoided by fitting in bins of $t\bar{t}$ distributions: $m(t\bar{t})$ vs $\cos(\theta_t)$ or $p_T(t)$ vs $\cos(\theta_t)$:



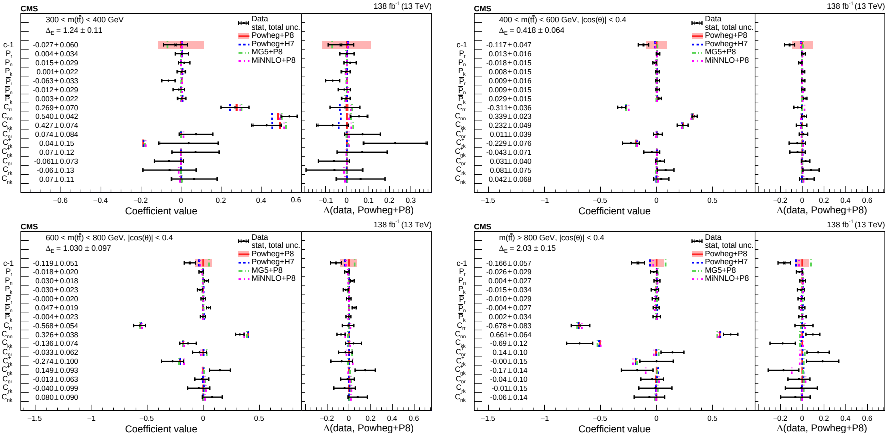
Inclusive results

From the combination of bins, the inclusive polarization and spin correlation are obtained:



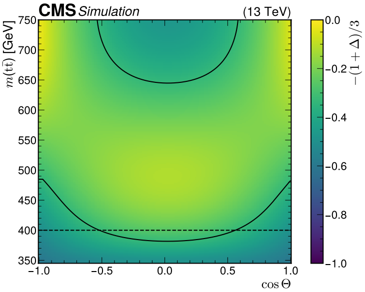
These are in good agreement with the SM expectations; reduction of of uncertainties by about a factor of two with respect to previous measurement (dilepton, with 36 fb^{-1}, *Phys. Rev. D 100 (2019) 072002*)

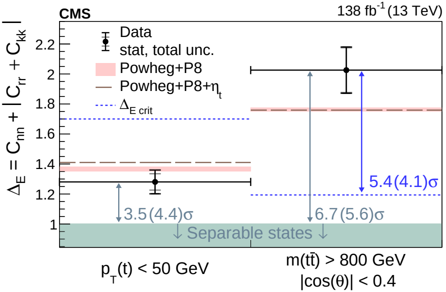
Differential Results



- the diagonal elements are changing for different $m(\mathrm{t}\bar{\mathrm{t}})$ and $\cos(\theta_\mathrm{t})$ regions
- statistical uncertainties dominant in most bins →room for improvement with more data

Quantum Entanglement





- at the threshold and at high $m(t\bar{t})$ with low $|\cos(\theta_t)|$ $t\bar{t}$ is expected to be produced in entangled quantum states

  A criterion for entanglement (based on Peres–Horodecki): $\Delta E = C_{nn} + |C_{rr} + C_{kk}| > 1$

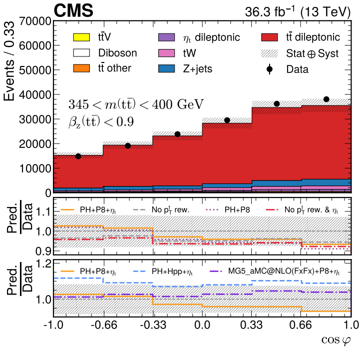
First observation of the signature of an entangled quantum state at high $m(t\bar{t})$.

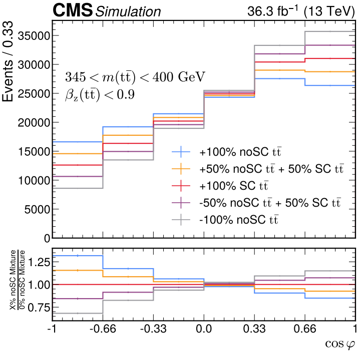
36 fb^{-1}, 13 TeV, *accepted by ROPP*

At the $t\bar{t}$ production threshold, where all diagonal elements of C are positive $D = -\frac{1}{3}\Delta E$

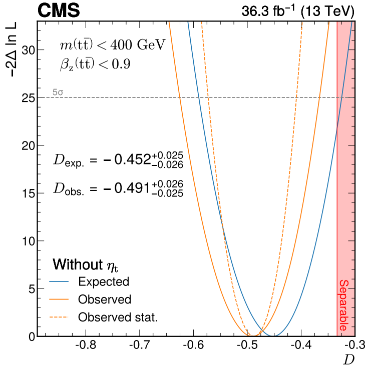
$$\frac{d\sigma}{d\cos(\phi)} \propto 1 - D\cos(\phi)$$

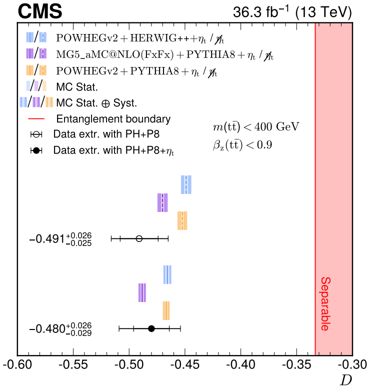
This allows for the extraction of the entanglement sensitive observable using the single differential distribution of the opening angle between the two leptons in the helicity-frame.





Results



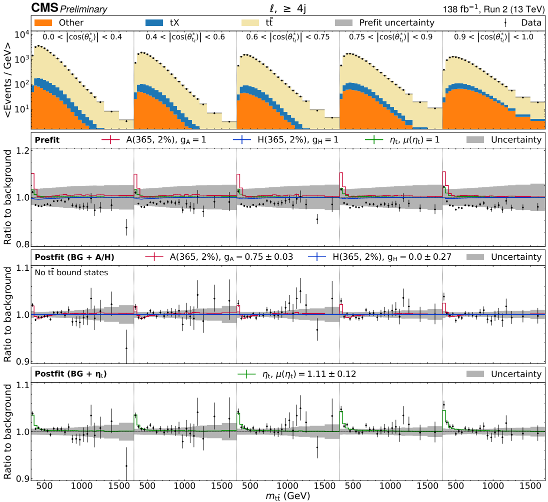


- observation of signature of entanglement with high significance $D < 1/3$
- uncertainties in the measurement do not allow for a separation between SM hypotheses with and without toponium. (Simulated as pseudo scalar particle with mass of 343 GeV and a production cross section of 6.4 pb.)

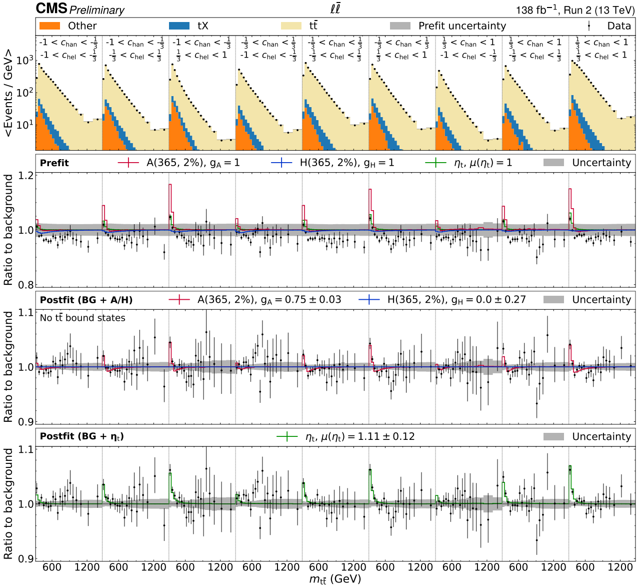
138 fb^{-1}, 13 TeV, *HIG-22-013*

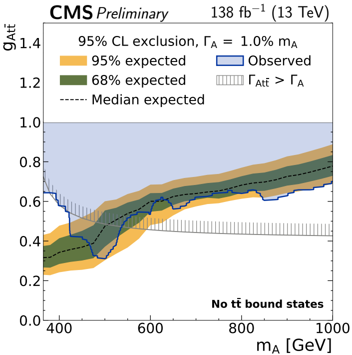
A search for heavy scalar. and pseudo-scalar Higgs is performed in the e/μ+jets and dilepton final-states

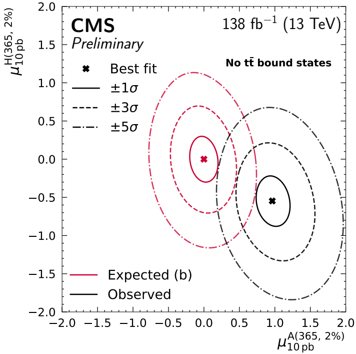
- e/μ+jets channel uses the scattering angle cos(θ_t) to separate based on the spin



- dilepton channel uses c_{hel}(same as $\cos(\phi)$, angle between two charged leptons) and c_{han} as search variables. Can separate scalar and pseudo scalar states



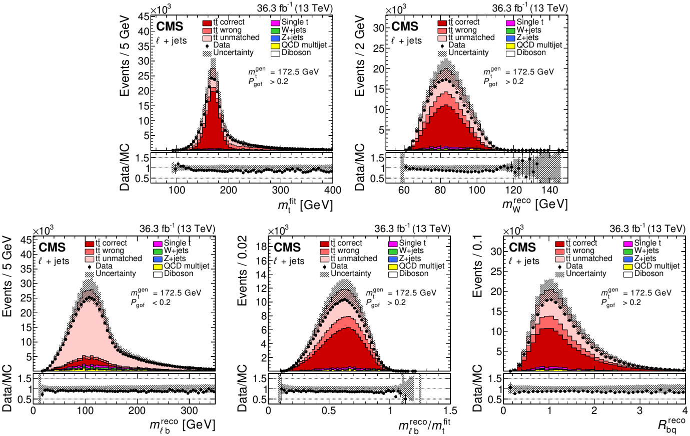


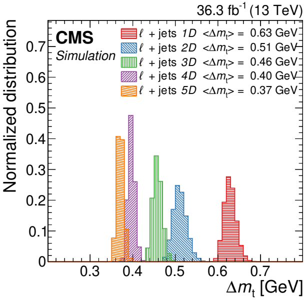


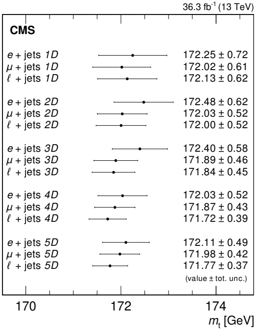
- both channels observe significant excess at the $t\bar{t}$ production threshold
- data prefer a pseudo scalar contribution for the excess (using the same production cross section for both, tested here with 365 GeV).
- fitted cross section for simple toponium model: 7.1 pb with 11% uncertainty.

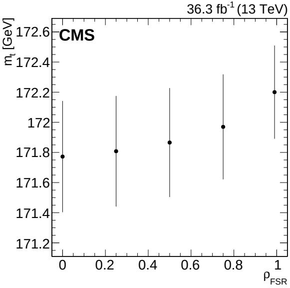
$36\,\mathrm{fb}^{-1}$, 13 TeV, *Eur. Phys. J. C 83 (2023) 963*

- select events with e/μ and $>=$ 4jets
- perform kinematic fitting with constraints of two equal top quark masses and W mass
- goodness of fit also used to determine best parton-jet assignment (47% correct)
- up to 4 distributions + one control region used to extract m_t









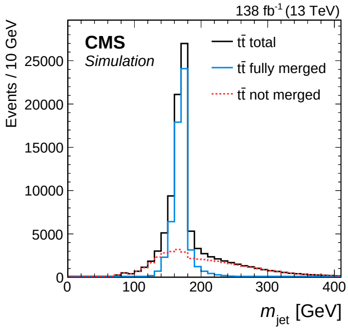
- best fitted value $m_{\mathrm{t}} = 171.77 \pm 0.37\,\mathrm{GeV}$
- leading uncertainty is final-state PS scales 0.21 GeV *in contrast to previous measurements uncorrelated scales for different branchings ($g \to q\bar{q}$, $q \to gq$ ...) used*
- modelling very important for this measurement

138 fb^{-1}, 13 TeV, *Eur. Phys. J. C 83 (2023) 560*

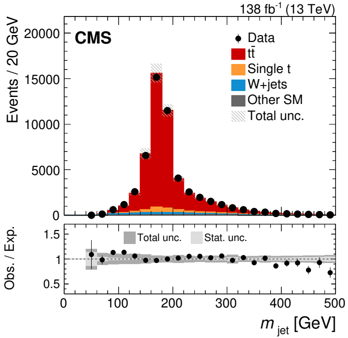
Measure m_t from unfolded particle-level jet mass

- use XCone jet algorithm ($r = 1.2$) to find 2 jets: the boosted hadronically decay products ; the lepton and b-jet from the leptonically decay
- use XCone ($r = 0.4$) to identify the three subjets (combined $p_T > 400$ *GeV*, each subjet $p_T > 30$ *GeV*)

particle-level



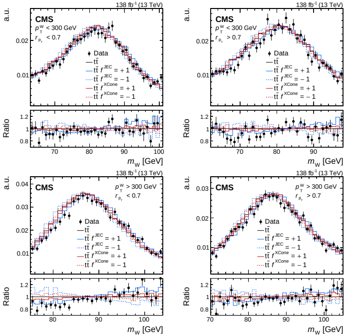
detector-level

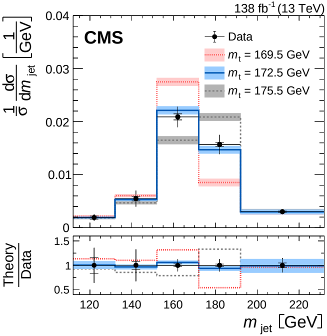


- after excluding the b-subjet the W mass of the remaining two jets is used for the calibration of the jet energy
- from the unfolded jet mass:

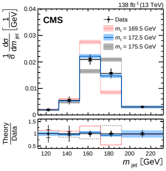
$$m_{\mathrm{t}} = 173.06 \pm 0.84\,\mathrm{GeV}$$

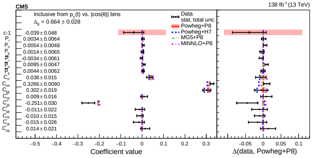
with jet energy and mass calibration being the largest uncertainties.

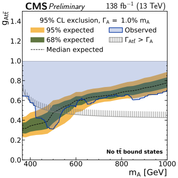


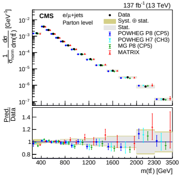


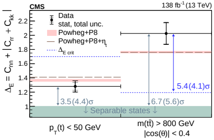
This method using boosted top quarks provides complementary measurement compared to measurements using low p_{T} top quark closer to the threshold, in particular with respect to theoretical uncertainties.

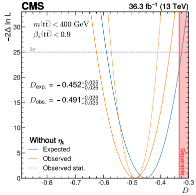












Measurement of (multi) differential cross sections:

- performed in many channels; resolved and boosted reconstructions
- used to determine: m_t, PDFs, EFT limits, MC tunes

Spin correlations:

- first measurement of spin correlations in various regions of the $t\bar{t}$ phase space
- first characterization of $t\bar{t}$ quantum state as entangled

Significant pseudo-scalar-like excess at the $t\bar{t}$ production threshold

Top quark mass:

- new precise and complementary measurements with boosted top quarks
- improved techniques leveraging in-situ constraints for higher precision