Top measurements and properties

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On behalf of the CMS and ATLAS Collaborations

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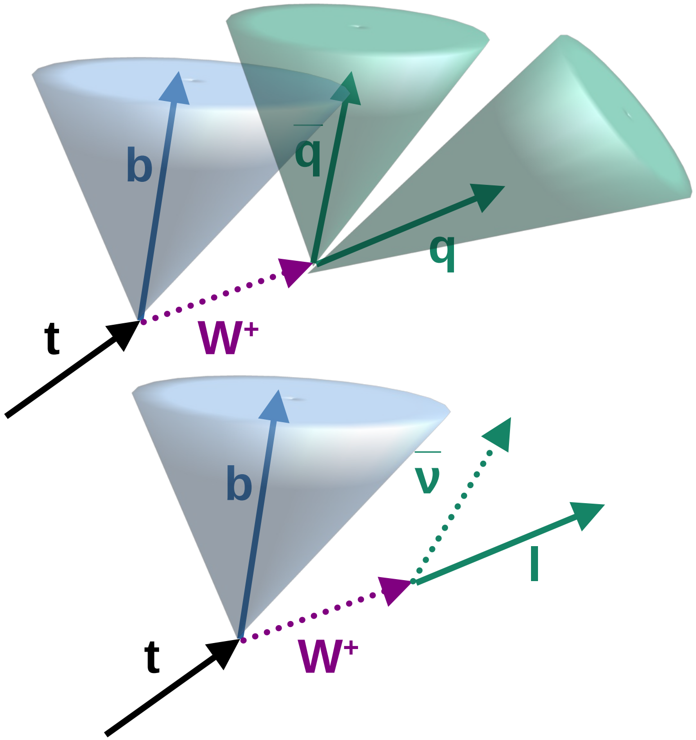
Why top quark physics?

- The top quark is the heaviest elementary particle in the Standard Model
- Very short lifetime: $\tau_{top}\sim10^{-25}$ s << $t_{had}\sim10^{-24}$ s
  Unique opportunity to study a "bare" quark
- Precision tests of the SM, thanks to
  - large samples collected at the LHC
  - advances in theoretical calculations
- Connections with fundamental questions (and possibly with BSM physics)



Many new top quark physics results obtained in the last year.
The complete list is available at these links:
ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Top quark properties

- Precision measurements and tests of the SM parameters
- Latest results in this talk:
  - Top quark mass
  - Charge asymmetry in top anti-top pair production
  - W helicity fractions in top quark decay
- Top production cross-sections and searches for new physics effects presented in other talks at this conference:

➔ **Carlos Vico**: tX and $t\bar{t}X$ production

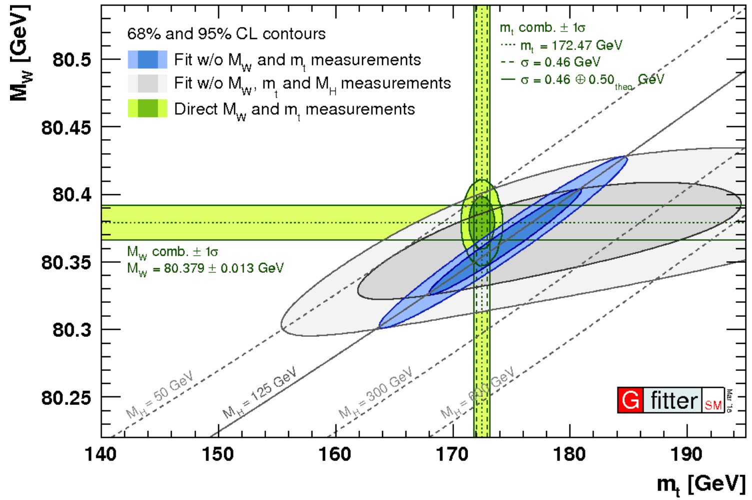
➔ **Luca Martinelli**: Measurement of top-quark pair inclusive and differential cross-sections in the eμ channel with ATLAS

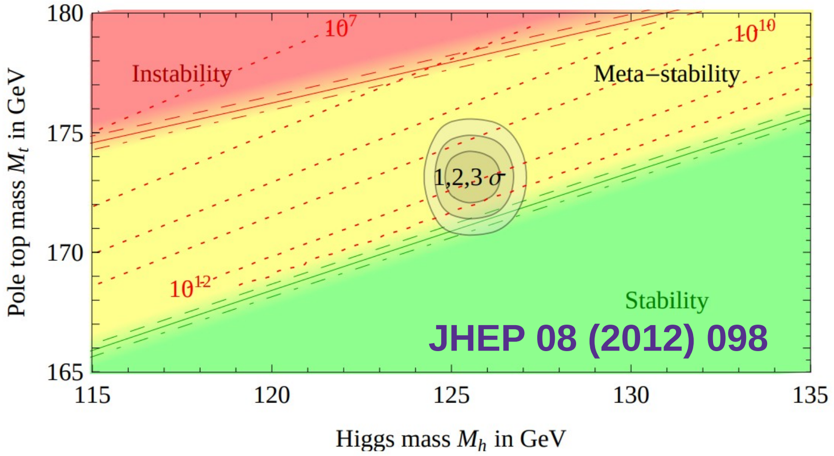
➔ **Kelci Mohrman**: Search for new physics in top quark production with additional leptons using the framework of effective field theory

➔ **Sahibjeet Singh**: top-quark pair production cross-section in the single-lepton channel at $\sqrt{s}$=5.02 TeV with ATLAS

Top quark mass

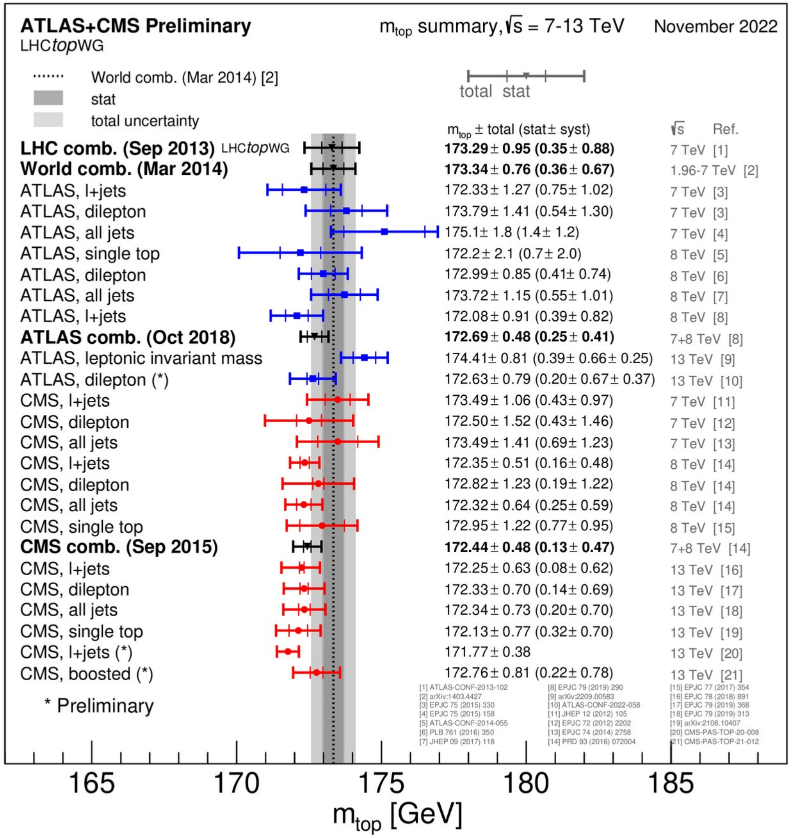
- m_{top} is a fundamental parameter of the SM
- Enters in global fits to test the internal consistency of the SM
- Has implications on the fate of the universe (assuming the validity of the SM up to very large energy scales)
- The top quark is not a free particle.
  Its mass can be determined through comparison with theoretical calculations:
  - **“Direct” measurements:** reconstruct invariant mass of decay products, or some other quantity highly sensitive to m_{top}, compare with MC calculations (**m_{top}^{MC}**)
  - **“Indirect” measurements:** measure production cross-section (also differential) that can be compared to first-principle calculations (**m_{top}^{POLE}**)



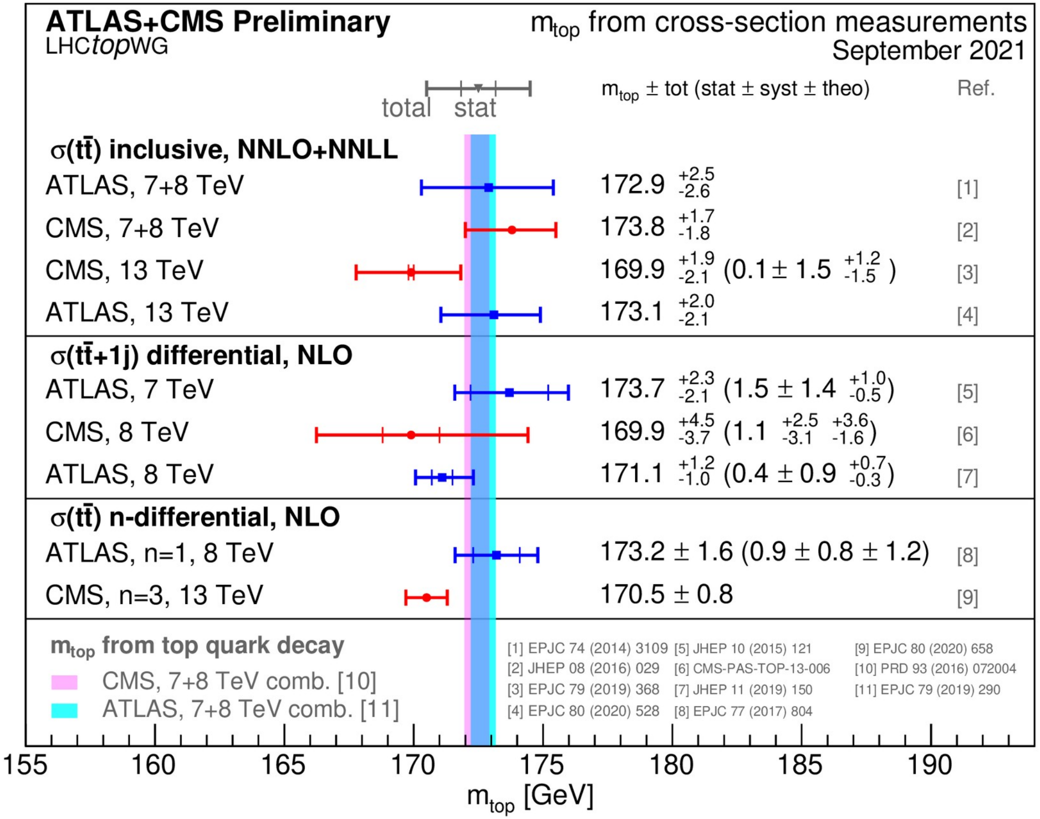


Overview of top quark mass measurements

Direct measurements



Indirect measurements



Uncertainty in combinations:

~0.5 GeV (0.3%)

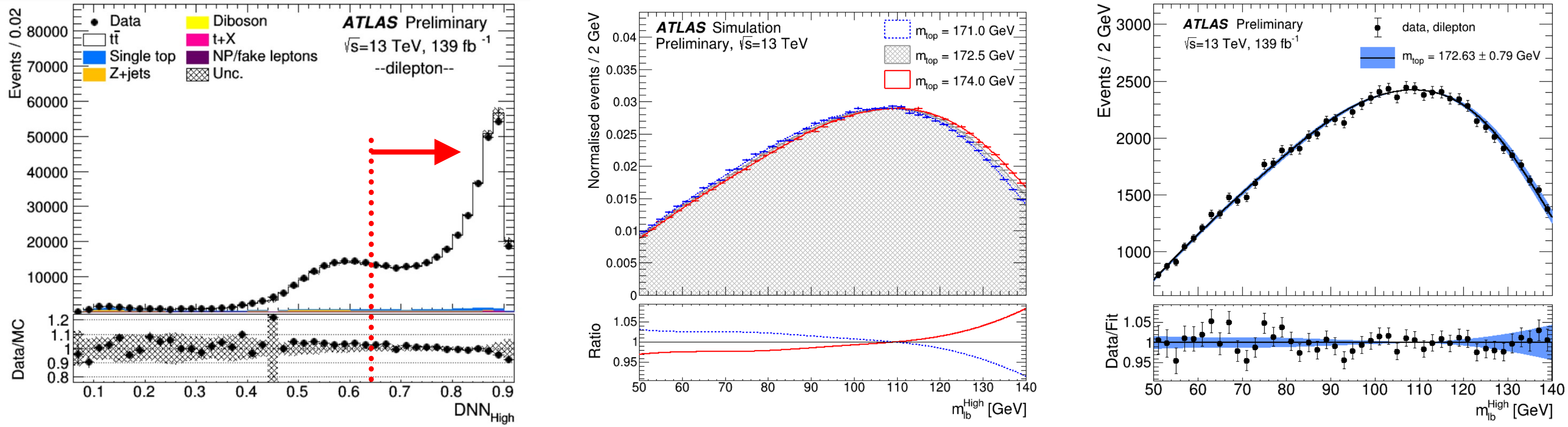
m_{top} dilepton channel

13 TeV - 139 fb^{-1}
ATLAS-CONF-2022-058

- DNN used to match lepton and b-jet → DNN>0.65 selected to improve precision
- Using only the lb pair with larger $p_{T,lb}$ to reduce signal modeling and jet-related uncertainties
- Template fit to the m_{lb} distribution

$$m_t = 172.63 \pm 0.20\,(stat) \pm 0.67\,(syst) \pm 0.37\,(recoil)\,GeV = 172.63 \pm 0.79\,GeV$$

Effect of different treatments of recoil in gluon emission (recoil against b or t quark) in Pythia quoted separately



m_{top} with profile likelihood approach

13 TeV - 36 fb^{-1}
CMS-PAS-TOP-20-008

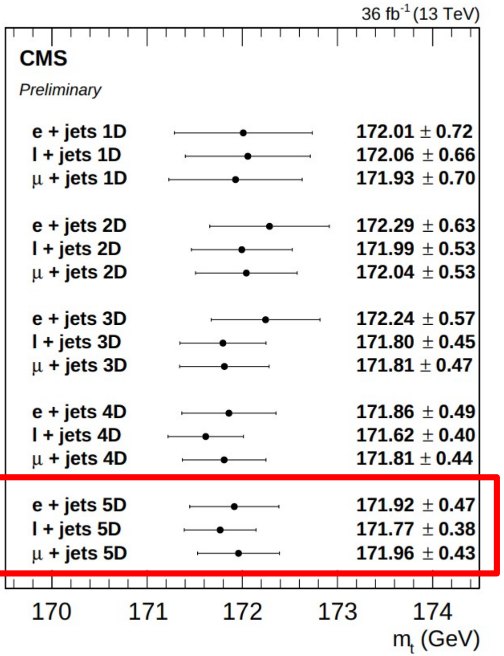
l+jets channel

Profile likelihood fit applied up to 5 observables

- m_t^{fit}, m_{lb}^{reco}: sensitive to m_{top}
- m_W^{reco}, m_{lb}^{reco}/m_t^{fit}, R_{bq}^{reco}: additional constraint on $t\bar{t}$ modeling

$$R_{bq}^{reco} = \frac{p_T^{b1} + p_T^{b2}}{p_T^{q1} + p_T^{q2}}$$

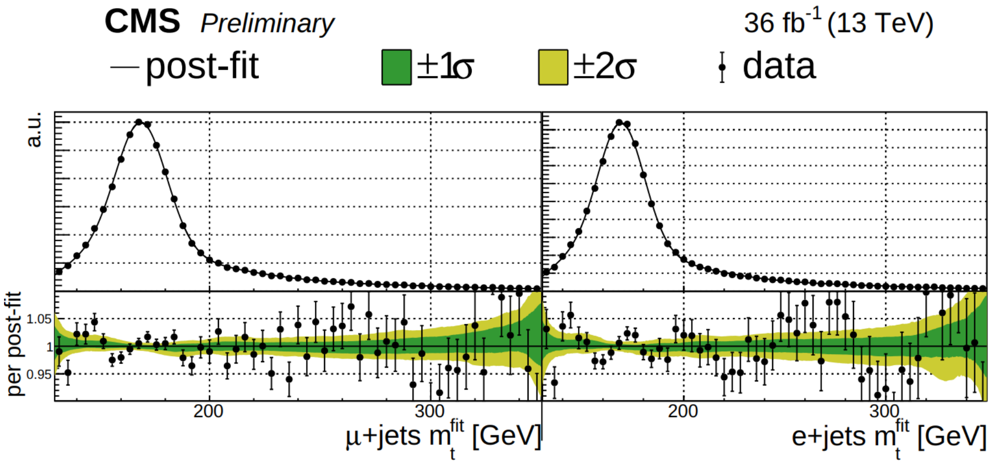
$$m_t^{5D} = 171.77 \pm 0.38\, GeV$$

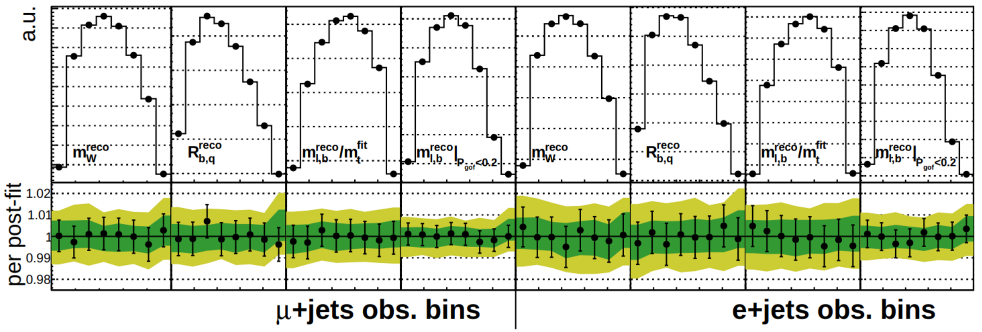


Unprecedented precision in single measurement

Dominant uncertainties from MC modeling:

- parton shower
- color reconnection





Agreement between post-fit model and data

Jet mass distribution and m_{top}

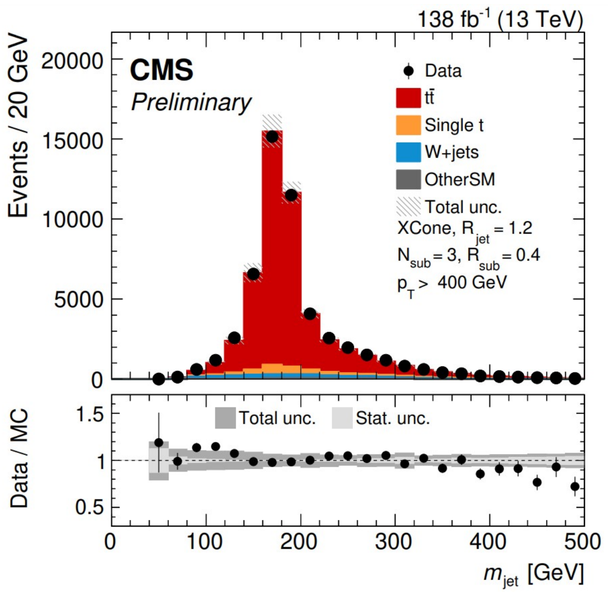
13 TeV - 138 fb^{-1}
CMS-PAS-TOP-21-012

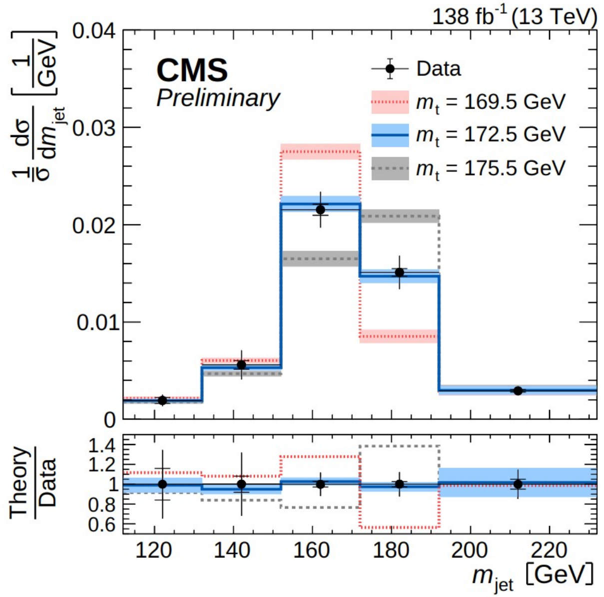
Boosted top production, l+jets chan. → decay products tend to collimate in a large-R jet (XCone R=1.2)
→ The large-R jet mass peak position is sensitive to m_t

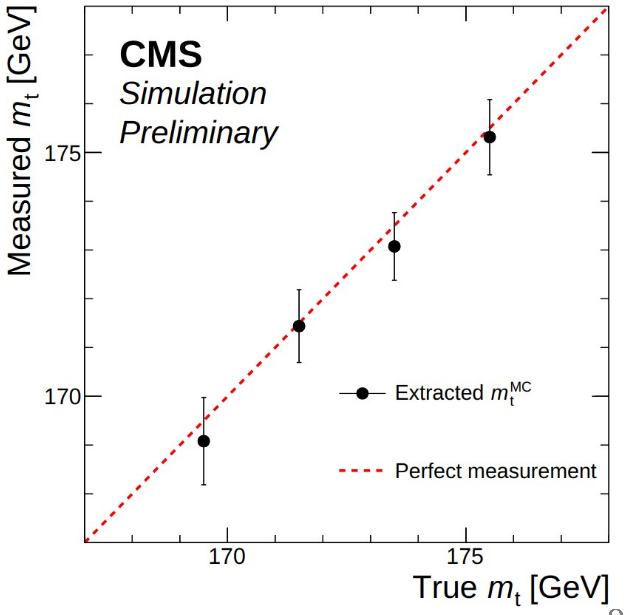
- Using top quark decays with p_T>400 GeV, unfolded at particle level
- Dedicated JMS calibration exploiting the mass of the two XCone sub-jets from hadronic W decay

$$m_t = 172.76 \pm 0.22\,(stat) \pm 0.57\,(\exp) \pm 0.48\,(model) \pm 0.24\,(theo)\,GeV = 172.76 \pm 0.81\,GeV$$

Sensible improvement with respect to previous m_t measurements using boosted tops





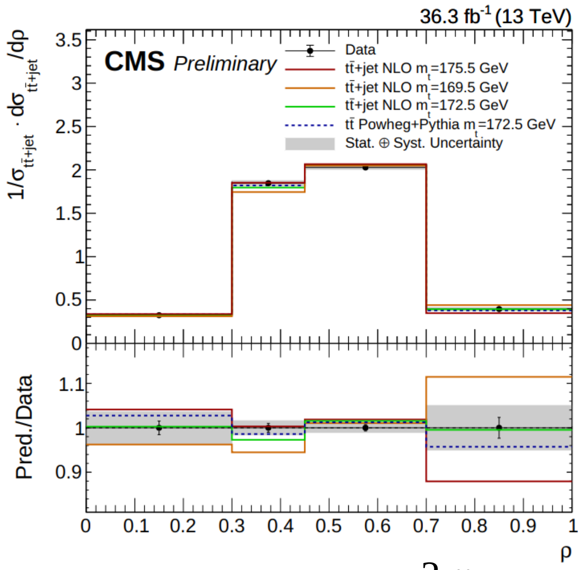


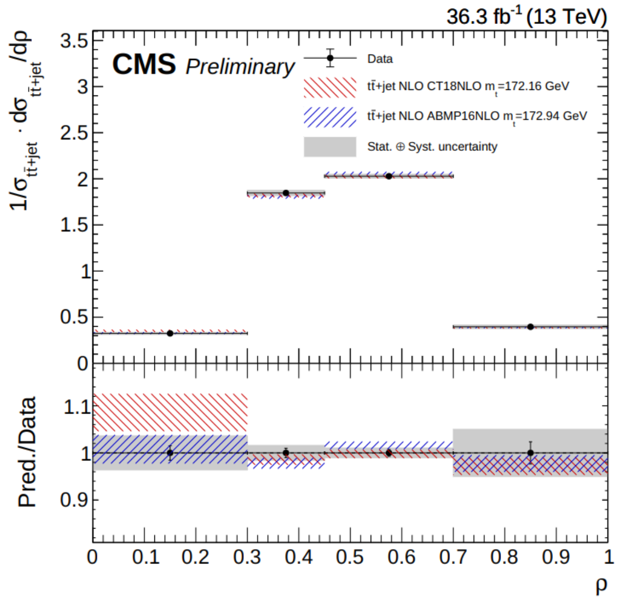
m_{top} from $t\bar{t}$+jet

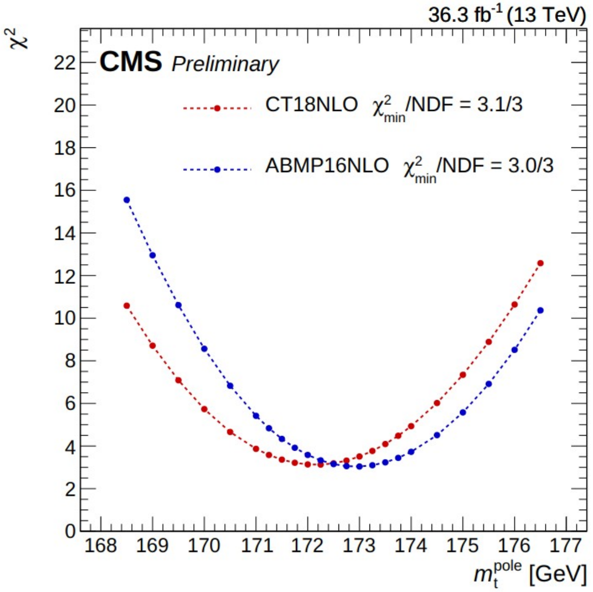
13 TeV - 36.3 fb^{-1}
CMS-PAS-TOP-21-008

- The distribution of invariant mass of $t\bar{t}$+jet can be computed analytically. Sensitivity to m_t^{pole} in the production threshold region.
- Normalized ρ distribution measured using the dileptonic $t\bar{t}$ channel (2 leptons, 3 jets)
- NN event classification + NN regression used in the reconstruction of ρ (inputs include reconstructed $m_{t\bar{t}+jet}$)
- χ^2 fit to NLO calculations used to extract m_t^{pole}

$$m_t^{pole} = 172.94 \pm 1.37\, GeV$$

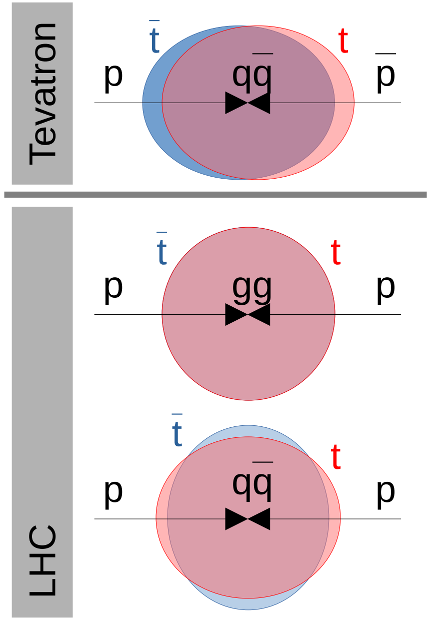






$$\rho = \frac{2\, m_0}{m_{t\,\bar{t}+\,jet}}$$

Charge asymmetry in $t\bar{t}$ production



- An asymmetry between t and $\bar{t}$ originates from higher order contributions in the process $q\bar{q} \rightarrow t\bar{t}$: top (anti-)quark preferentially produced in the direction of incoming (anti-)quark
- At the LHC:
  - The main production mode is $gg \rightarrow t\bar{t}$, that is symmetric
  - The original valence quark momentum is in average larger than that of the sea anti-quark. This implies more forward rapidity t and more central rapidity $\bar{t}$
  - Also, a leptonic asymmetry can be defined in the dileptonic channel (top reconstruction not required but asymmetry slightly diluted)

$$A_C^{t\bar{t}} = \frac{N(\Delta|y_{t\bar{t}}|>0) - N(\Delta|y_{t\bar{t}}|<0)}{N(\Delta|y_{t\bar{t}}|>0) + N(\Delta|y_{t\bar{t}}|<0)} \qquad \Delta|y_{t\bar{t}}| = |y_t| - |y_{\bar{t}}|$$

$$A_C^{l\bar{l}} = \frac{N(\Delta|\eta_{l\bar{l}}|>0) - N(\Delta|\eta_{l\bar{l}}|<0)}{N(\Delta|\eta_{l\bar{l}}|>0) + N(\Delta|\eta_{l\bar{l}}|<0)} \qquad \Delta|\eta_{l\bar{l}}| = |\eta_l| - |\eta_{\bar{l}}|$$

SM calculation:
NNLO(QCD)+NLO(EW)
$A_C^{t\bar{t}} = 0.0064^{+0.0005}_{-0.0006}$
PRD 98 (2018) 014003

SM calculation:
NLO(QCD)+NLO(EW)
$A_C^{l\bar{l}} = 0.0040^{+0.0002}_{-0.0001}$
PRD 86 (2012) 034026

- BSM processes (i.e. anomalous vector or axial-vector couplings) can interfere with SM processes and alter A_C, in some cases as a function of $m_{t\bar{t}}$

Charge asymmetry in $t\bar{t}$ production

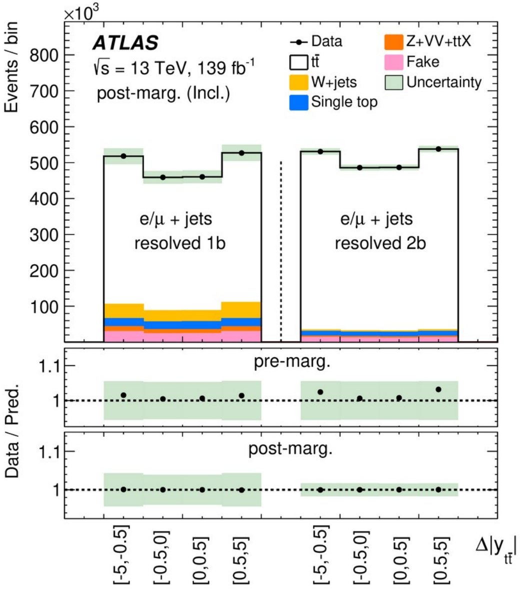
13 TeV - 139 fb^{-1}
arXiv:2208.12095

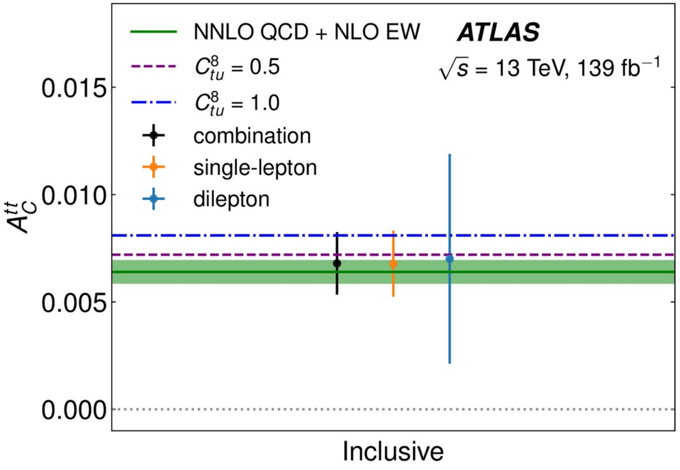
A_C measured inclusively and as a function of $m_{t\bar{t}}$, $p_{T,t\bar{t}}$, $\beta_{z,t\bar{t}}$ ← Longitudinal boost of the $t\bar{t}$ system

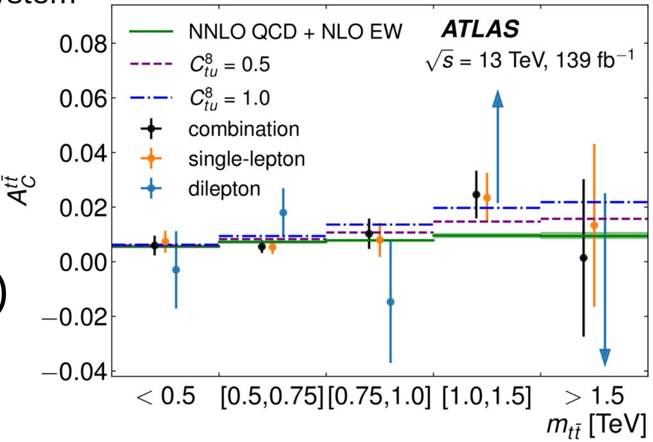
Analysis of l+jets and dilepton channels, resolved and boosted topologies

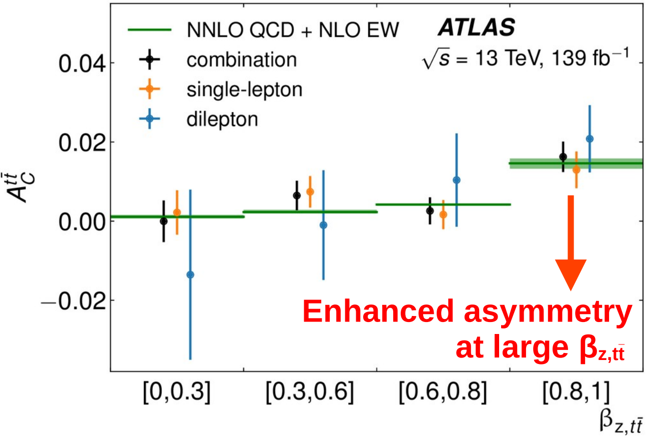
$$A_C^{t\bar{t}} = 0.0068 \pm 0.0015\,(stat + syst)$$ → 4.7σ from no asymmetry

Main uncertainties: statistical (0.0010), $t\bar{t}$ modeling syst. (0.0006)







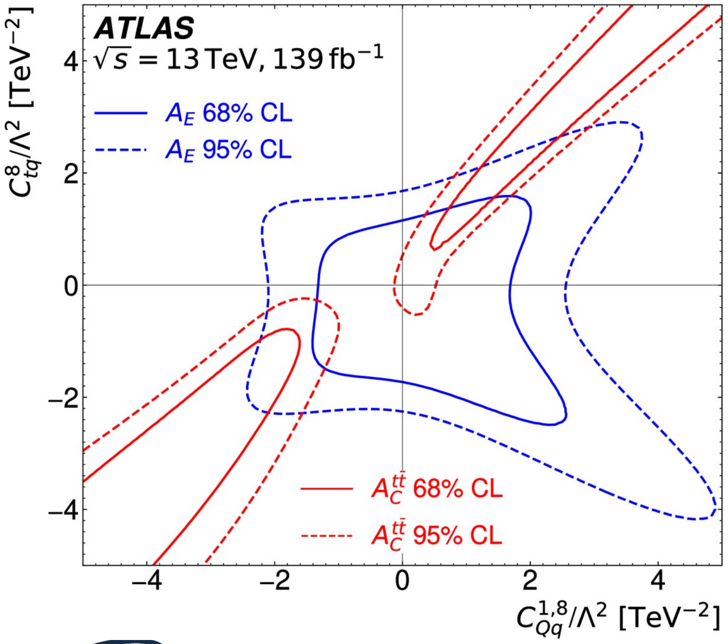


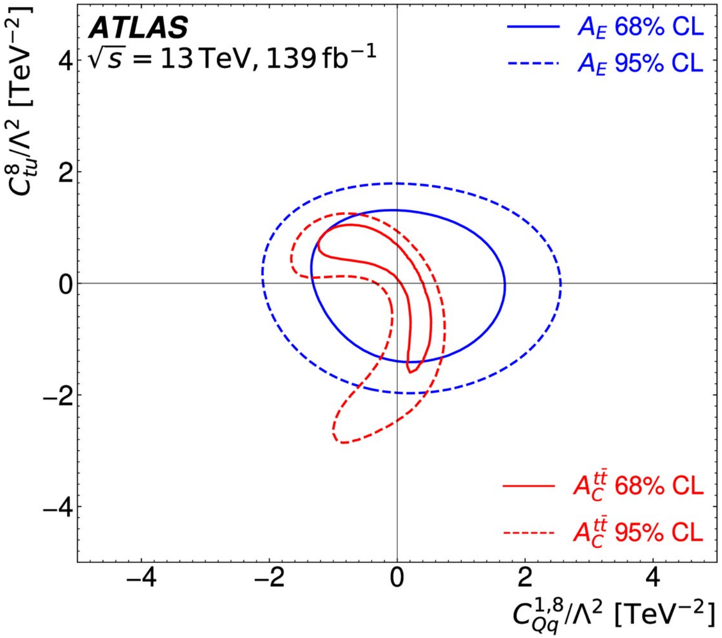
Charge asymmetry in $t\bar{t}$ production

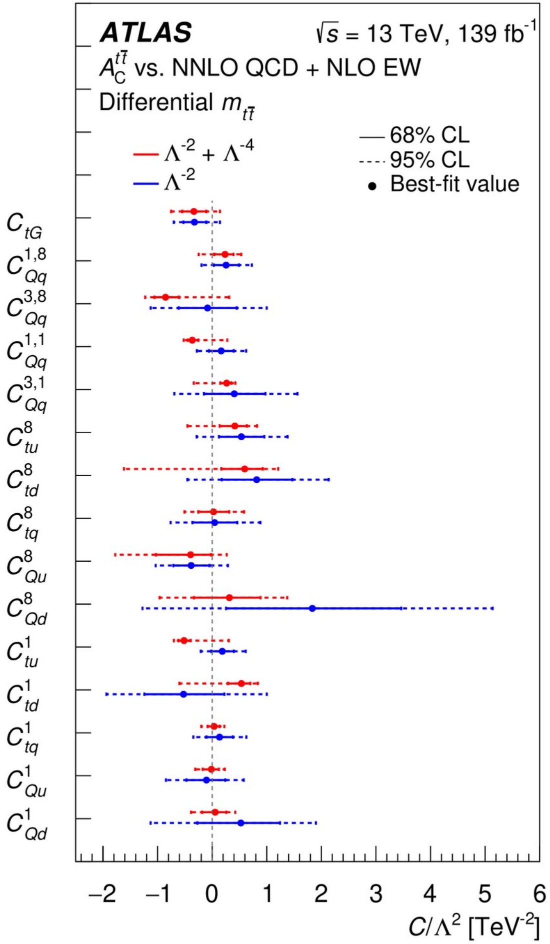
13 TeV - 139 fb^{-1}
arXiv:2208.12095

Interpretation as limits on Wilson coefficients in SMEFT fits

Complementarity with respect to previous limits obtained from the energy asymmetry A_E (Eur. Phys. J. C 82 (2022) 374)







Charge asymmetry in boosted $t\bar{t}$

13 TeV - 138 fb^{-1}
arXiv:2208.02751

l+jets chan boosted top reconstruction optimized for $m_{t\bar{t}} > 750$ GeV.
Enhanced contribution from $q\bar{q}$ initial state.

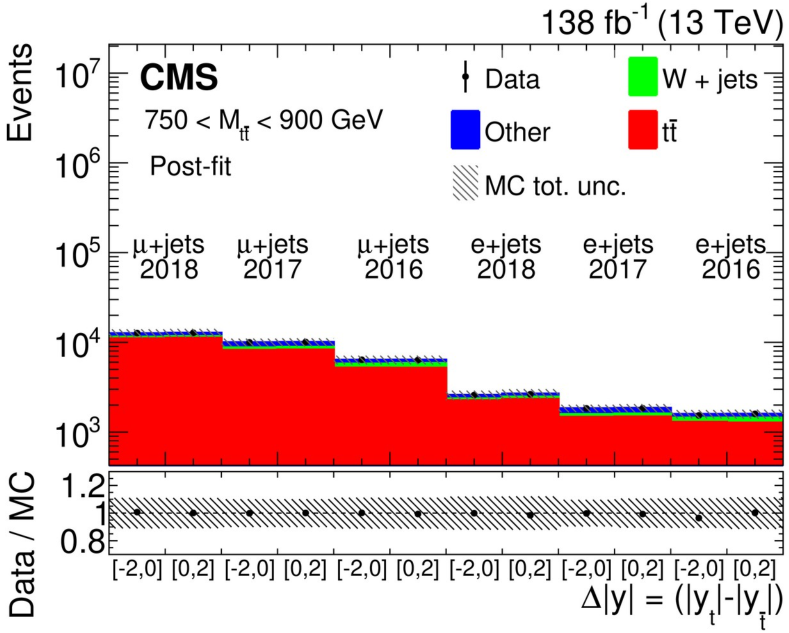
Asymmetry corrected to the full phase-space in good agreement with the SM
Measurement still limited by statistical uncertainty

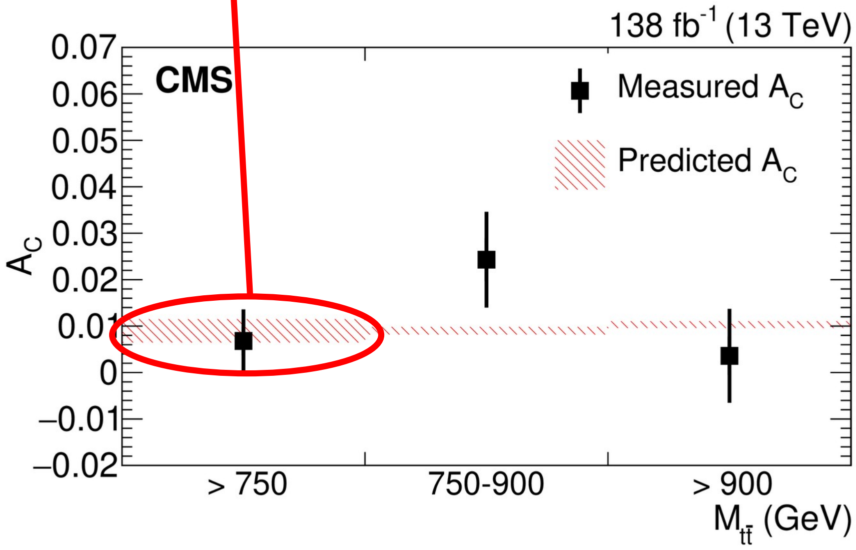
$$A_C^{full} = 0.0069^{+0.0065}_{-0.0069}$$

SM calculation:
NNLO(QCD)+NLO(EW)

$$A_C^{full} = 0.0094^{+0.0005}_{-0.0007}$$

PRD 98 (2018) 014003





Enhanced A_C in $t\bar{t}$+W and $t\bar{t}$+γ

13 TeV - 139 fb^{-1}
arXiv:2212.10552
arXiv:2301.04245

- **$t\bar{t}$+γ**: dominant contribution arises from interference between QED ISR and FSR
- **$t\bar{t}$+W**: enhanced $q\bar{q}$ initial state + additional polarization of $q\bar{q}$ due to W emission

$$A_C(t\bar{t}\gamma) = -0.003 \pm 0.024(stat) \pm 0.017(syst)$$

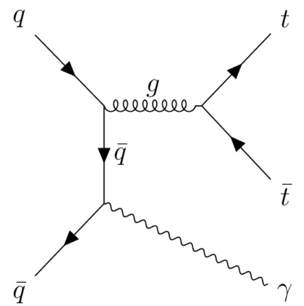
$$A_{C,SM}(t\bar{t}\gamma) = -0.014 \pm 0.001(scale)$$

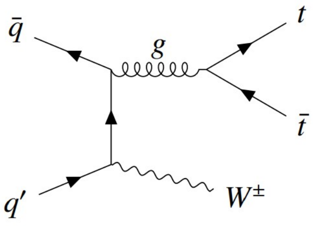
MG5_aMC@NLO

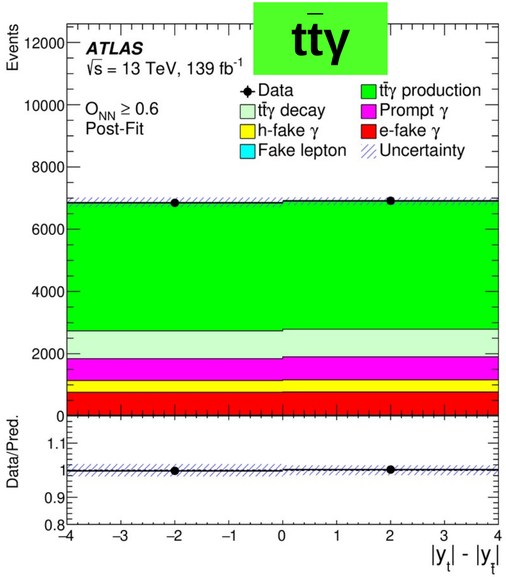
$$A_C^l(t\bar{t}W) = -0.123 \pm 0.136(stat) \pm 0.051(syst)$$

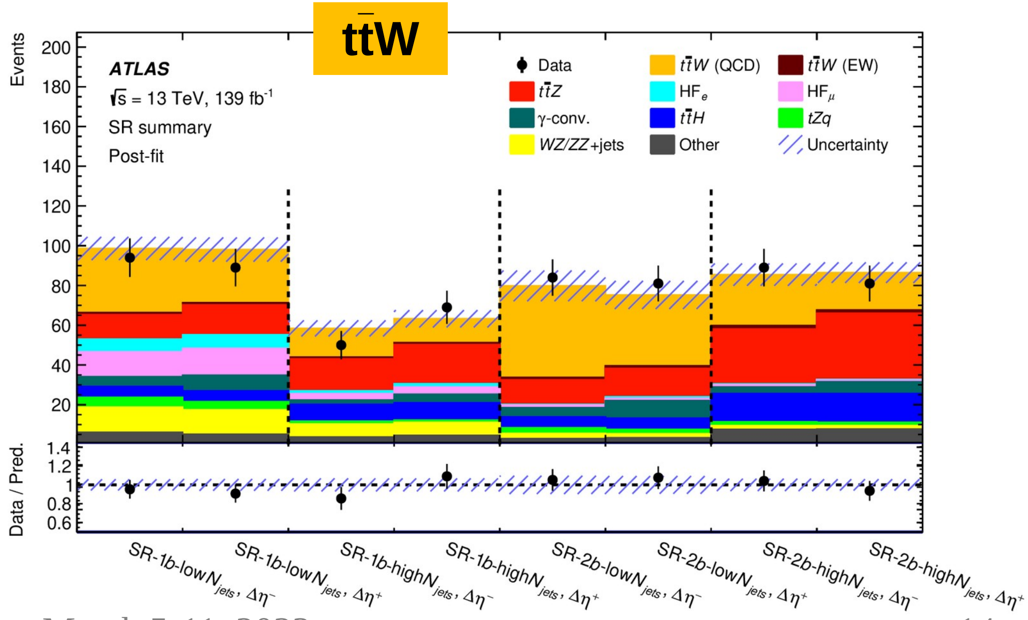
$$A_{C,SM}^l(t\bar{t}W) = -0.084^{+0.005}_{-0.003}(scale) \pm 0.006(MCstat)$$

Asymmetry measurements limited by statistical uncertainty







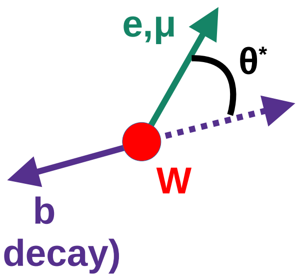


W polarization in top quark decays

- The properties of the top-quark decay vertex Wtb are determined by the V-A structure of the weak interaction in the SM
- Test compatibility with the SM of the fractions of longitudinal (f_0), left-handed (f_L) and right-handed (f_R) polarised W bosons (helicity fractions)
- W helicity fractions can be extracted from measurements of the angular distribution of the decay products of the W boson and the top quark

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*}=\frac{3}{4}(1-\cos^2\theta^*)f_0+\frac{3}{8}(1-\cos\theta^*)^2 f_L+\frac{3}{8}(1+\cos\theta^*)^2 f_R$$

θ*: angle between the momentum direction of the charged lepton from W decay and the reversed momentum direction of the b-quark from top decay, computed in the W rest frame



NNLO calculation

$$f_0=0.687\pm0.005$$
$$f_L=0.311\pm0.005$$
$$f_R=0.0017\pm0.0001$$

PRD 81 (2010) 111503

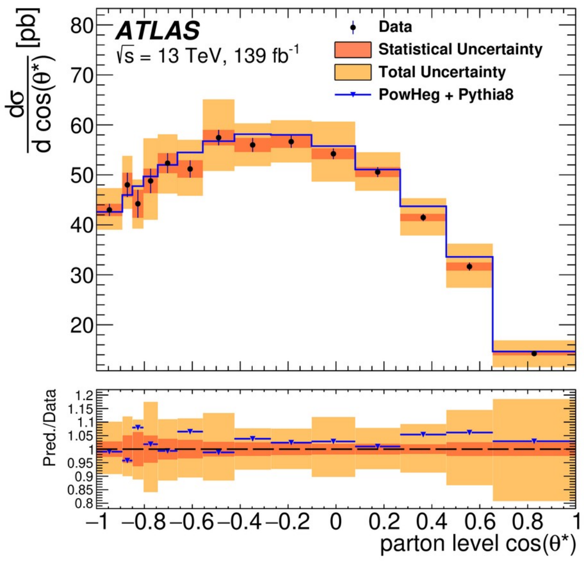
W polarization in top quark decays

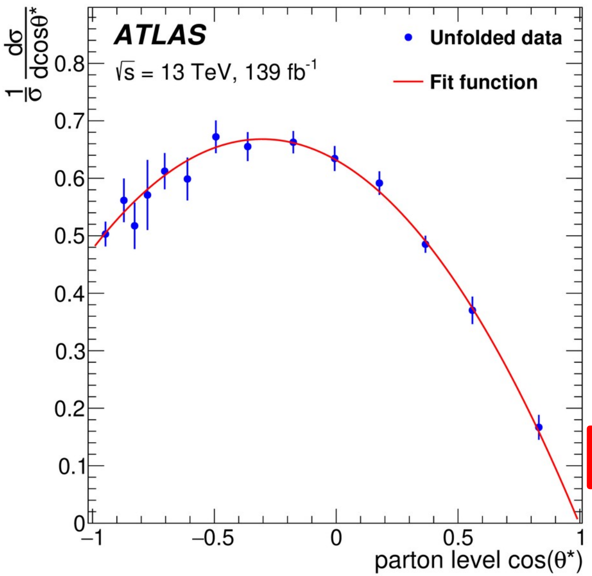
13 TeV - 139 fb^{-1}
arXiv:2209.14903

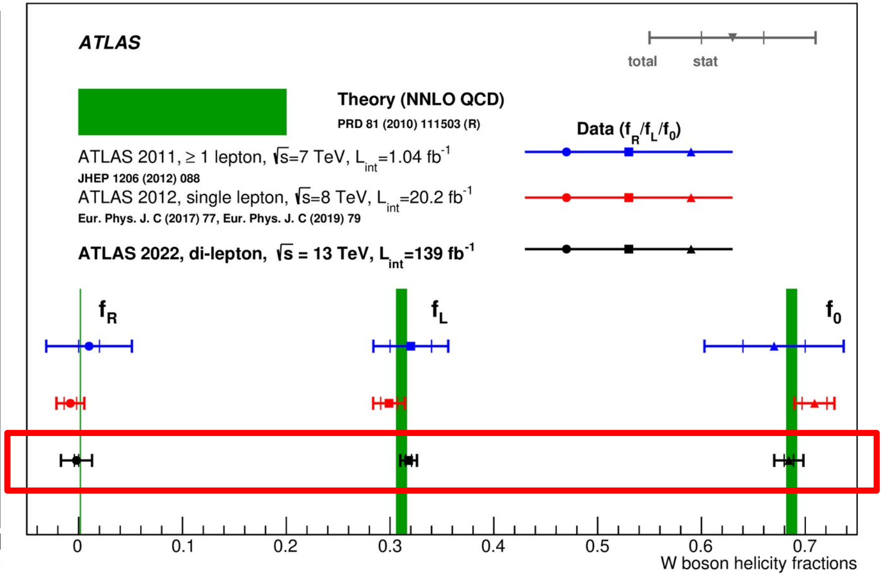
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*}$$ measured at parton-level

$$f_0 = 0.684 \pm 0.005(stat) \pm 0.014(syst)$$
$$f_L = 0.318 \pm 0.003(stat) \pm 0.008(syst)$$
$$f_R = -0.002 \pm 0.002(stat) \pm 0.014(syst)$$

Systematic uncertainty dominated by the $t\bar{t}$ production modelling (choice of matrix-element generator)







Summary

- The measurement of top quark properties is a very active field of study
- Precision measurements offer the opportunity to push tests of the SM and searches for new physics effects
  - Top quark **mass**:
    - measured with several techniques
    - uncertainties routinely at sub-GeV level
  - Broad campaign of $\mathbf{A_C}$ measurements, exploiting different channels and topologies
  - **W helicity fractions** measured with unprecedented precision
- Many new results in the pipeline to be released soon