Top Quark Mass and Properties at CMS Experiment

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On Behalf of the CMS Collaboration

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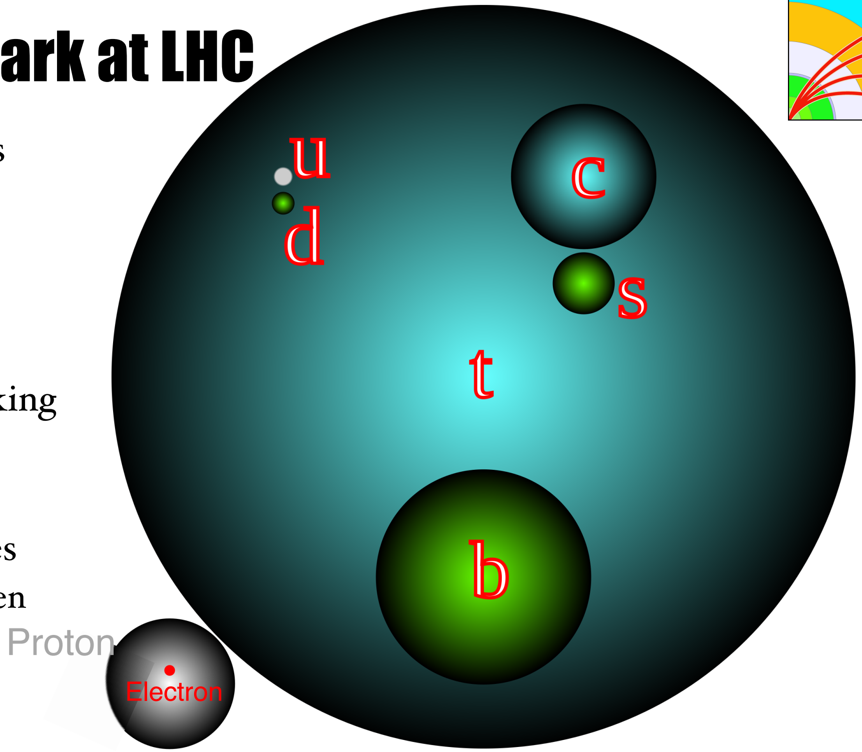
Introduction to the Top Quark at LHC

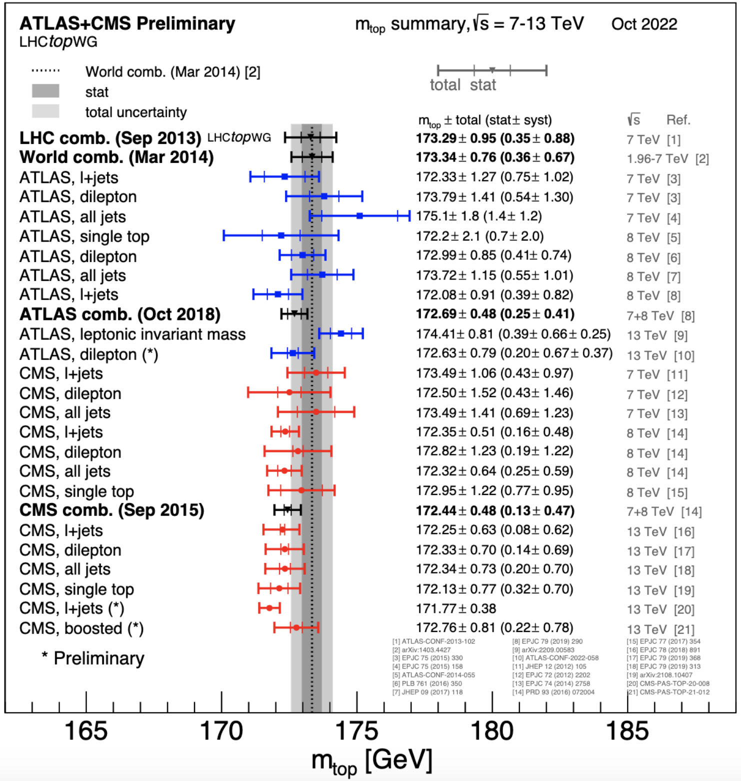
- The top quark is one of the most fascinating particles due to its unique properties.
  - Heaviest of the quarks. But why?
    - ~Mass of a gold atom
  - Largest Yukawa coupling of all particles
    - Essential to Electroweak symmetry breaking
  - Top decays before hadronization
    - Lifetime of ~ $5 * 10^{-25}$ seconds
    - This allows study of bare quark properties
- ~120M top-anti top pairs per experiment during run 2, even more in run 3!
  - This large amount of data allows for precise measurements of **the mass**, width, **charge asymmetry** and spin correlation of the Top quark



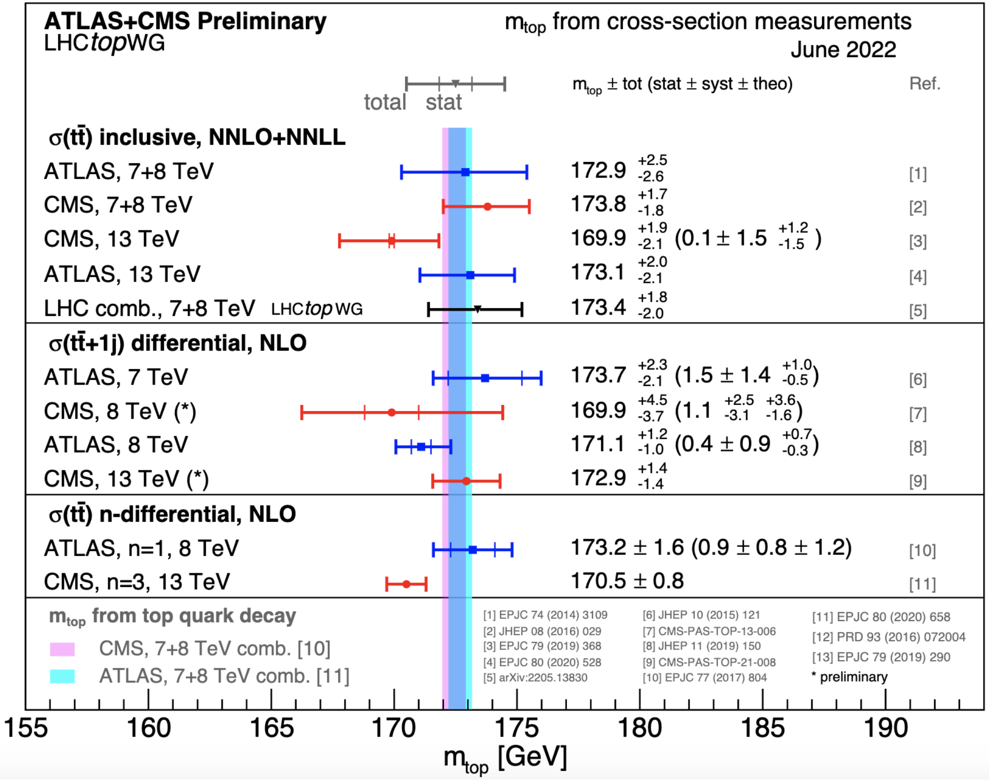
LHC TOP WG Summary plots

Direct vs Indirect Measurements of Top Mass

- Direct
  - MC mass - Uncertainty ~ 0.4 GeV



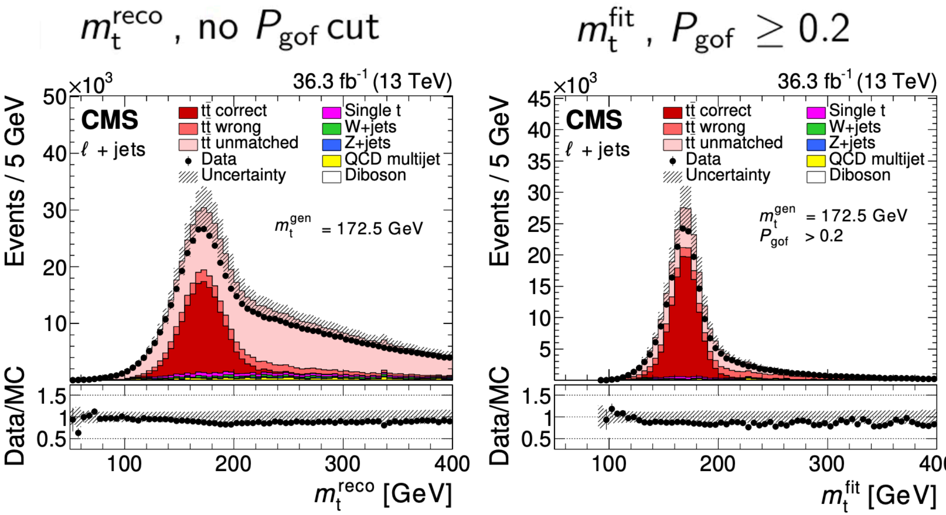
- Indirect
  - Pole mass - Uncertainty ~0.8 GeV

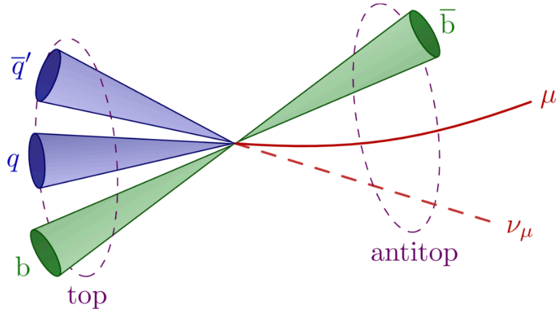


arXiv:2302.01967

Profile Likelihood based Top Mass

- Selected events with 1 lepton + 4 jets
- Kinematic fit with input: four-momenta of the lepton and of the four leading jets, p_T^{miss}, and the resolutions of these variables
- By applying kinematic fit and goodness of fit cut, $P_{gof} = exp(\frac{-\chi^2}{2})$, improvements are made in:
  - Jet-Parton assignment
  - Signal fraction
  - Resolution of invariant top mass distribution
- 5D Maximum likelihood fit to determine top mass
  - Likelihood depends on the top mass and nuisance parameters which incorporate the systematic uncertainties



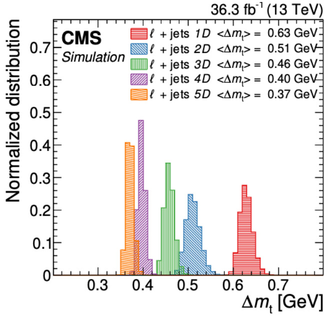


arXiv:2302.01967

Profile Likelihood based Top Mass cont.

- **This approach significantly improves the precision over previous measurements**
  - Jet Energy scale and FSR are dominant uncertainties

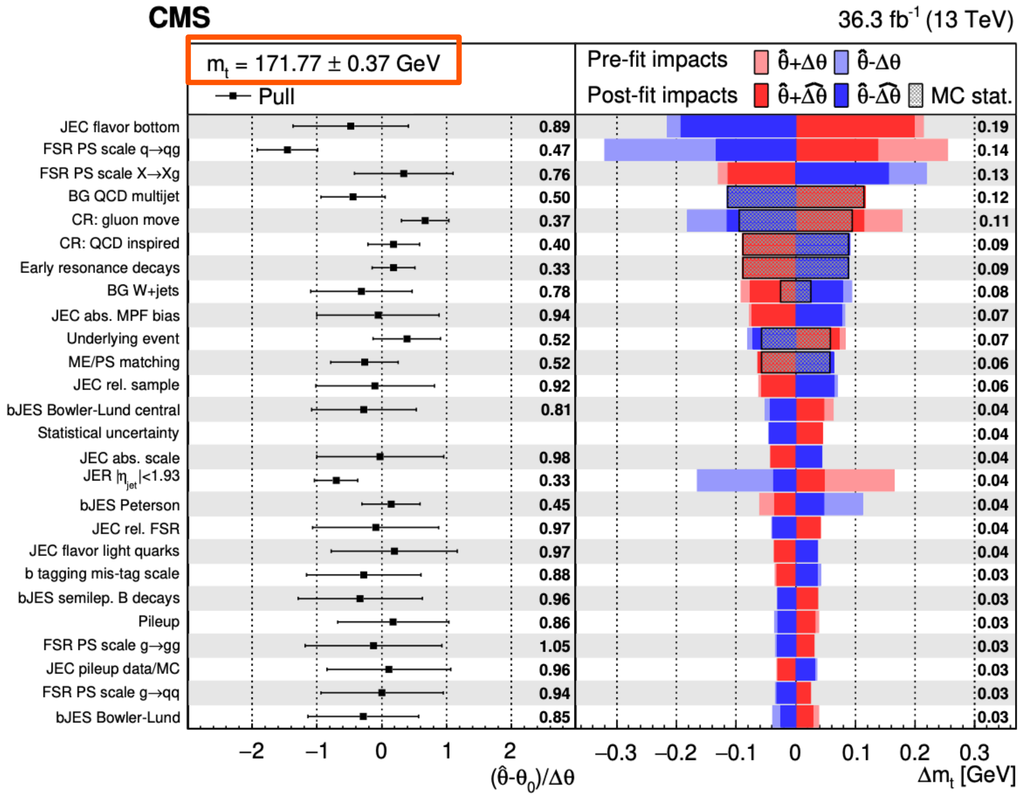
Histogram		Set label				
Observable	Category	*1D*	*2D*	*3D*	*4D*	*5D*
m_t^{fit}	$P_{gof} > 0.2$	×	×	×	×	×
m_W^{reco}	$P_{gof} > 0.2$		×	×	×	×
$m_{\ell b}^{reco}$	$P_{gof} < 0.2$			×	×	×
$m_{\ell b}^{reco} / m_t^{fit}$	$P_{gof} > 0.2$				×	×
R_{bq}^{reco}	$P_{gof} > 0.2$					×



$$R_{bq}^{reco} = \frac{p_{T\,b1}^{reco} + p_{T\,b2}^{reco}}{p_{T\,q1}^{reco} + p_{T\,q2}^{reco}}$$

The total predicted uncertainty is reduced by the inclusion of every additional observables.

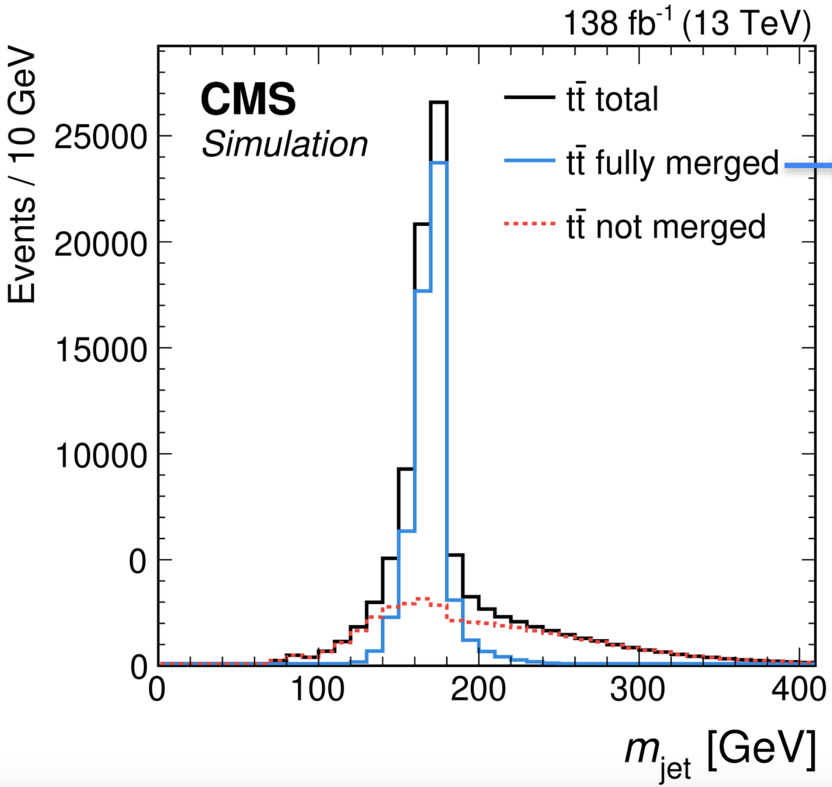
The biggest improvement comes from including m_W^{reco}.

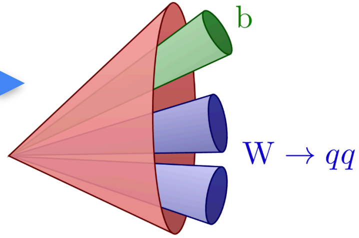


arXiv:2211.01456

Measurement of Top Mass in Boosted Tops

- Measurement of the jet mass distribution and top quark mass in hadronic decays of boosted top quarks
- Boosted tops approach a regime in which the MC mass is well defined
- MC studies show top mass distribution at different momenta





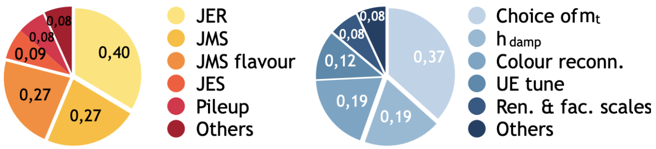
arXiv:2211.01456

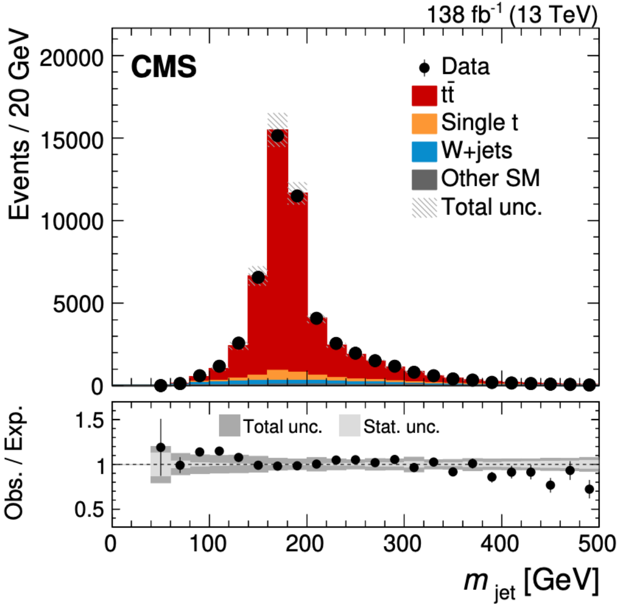
Measurement of Top Mass in Boosted Tops cont.

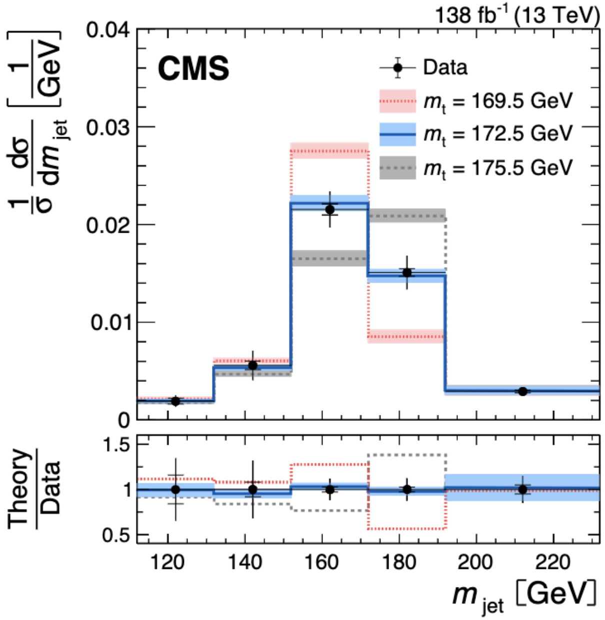
- Determined m_t from the unfolded normalised differential $t\bar{t}$ production cross section w.r.t. jet mass
- eXclusive Cone, XCone, jet reconstruction algorithm, with $N_{sub} = 3$ used for boosted top reconstruction
  - Anti-k_T jets were used for identification of b jets and studying influence of FSR on substructure

$$m_t = 172.76 \pm 0.81\ \text{GeV}$$

± 0.22 (stat) ± 0.57 (exp) ± 0.48 (model) ± 0.24 (theo) GeV







arXiv:2207.02270

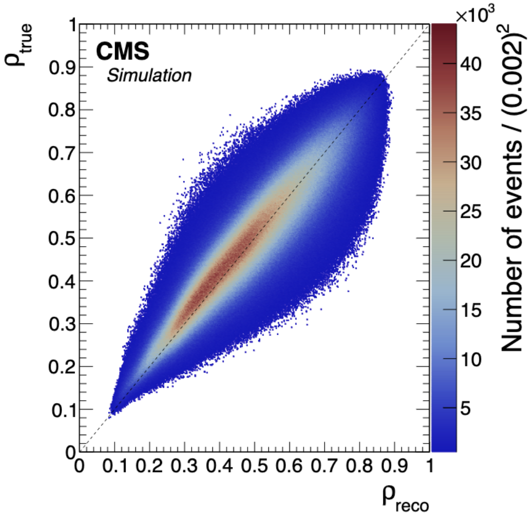
Indirect Measurement of Top Mass

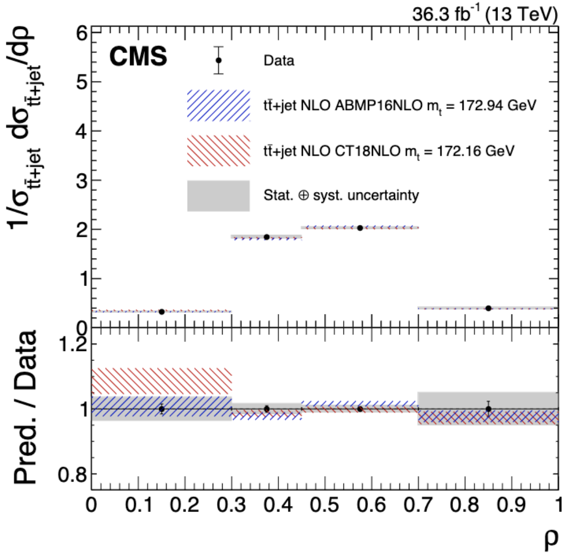
$$m_t^{\text{pole}} = 172.94 \pm 1.27\,(\text{fit})\,^{+0.51}_{-0.43}\,(\text{scale})\,\text{GeV}$$

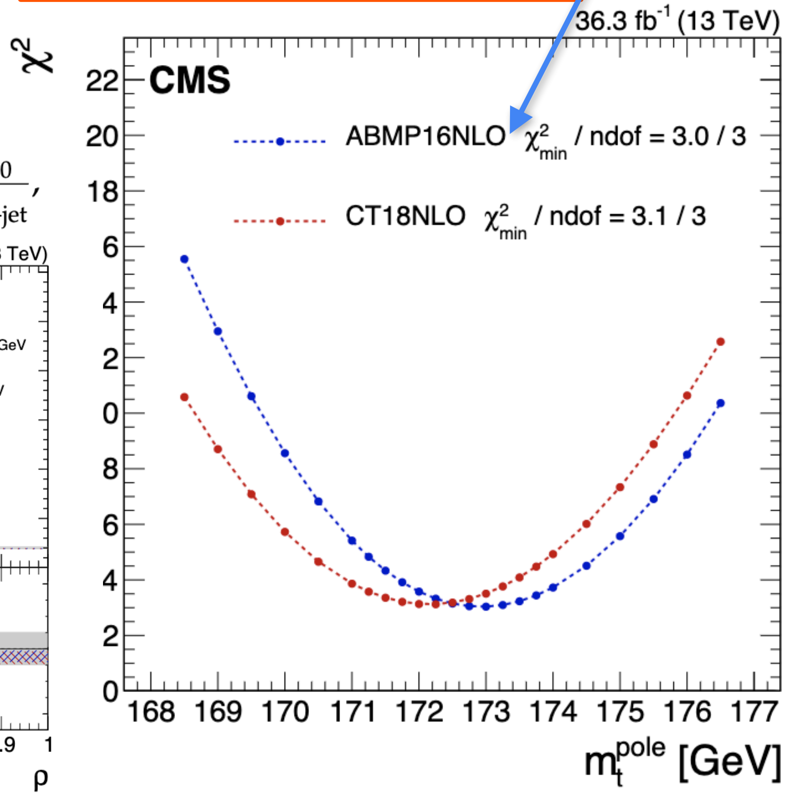
$$m_t^{\text{pole}} = 172.16 \pm 1.35\,(\text{fit})\,^{+0.50}_{-0.40}\,(\text{scale})\,\text{GeV}.$$

- Measurement of the top quark pole mass using $t\bar{t}$ +jet events in the dilepton final state
- Differential cross section as a function of dimensionless mass, ρ, where the scaling constant is m_0= 170 GeV
- Extracted pole mass from 2 different PDF sets

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





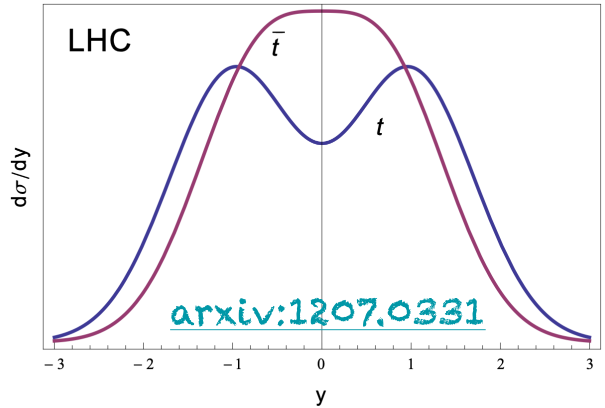


Introduction to Charge Asymmetry with Top Quarks

- Measured by comparing rapidity distributions from top and anti-top quarks
- Charge asymmetry measurements show agreement with theoretical predictions
- Important in testing the standard model and searching for BSM physics
- A new 13TeV measurement published last year by CMS drastically improved precision

$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

with $\Delta|y| = |y_{top}| - |y_{antitop}|$



arxiv:1711.03945

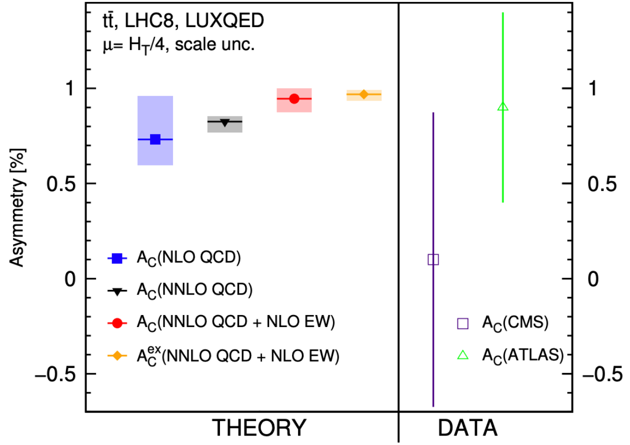


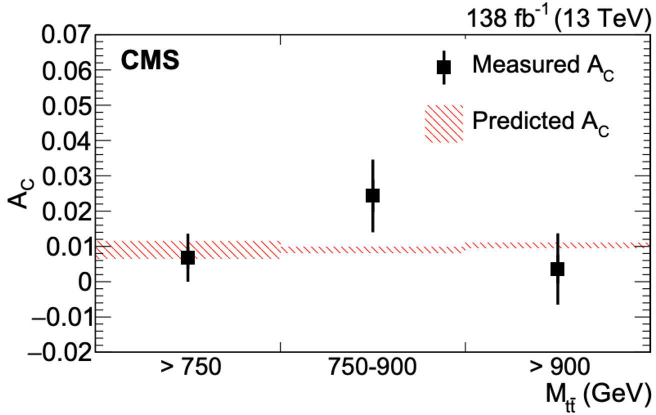
FIG. 1: Inclusive charge asymmetry A_C for the LHC at 8 TeV in NLO QCD, NNLO QCD and NNLO QCD + NLO EW versus CMS and ATLAS measurements [29, 30].

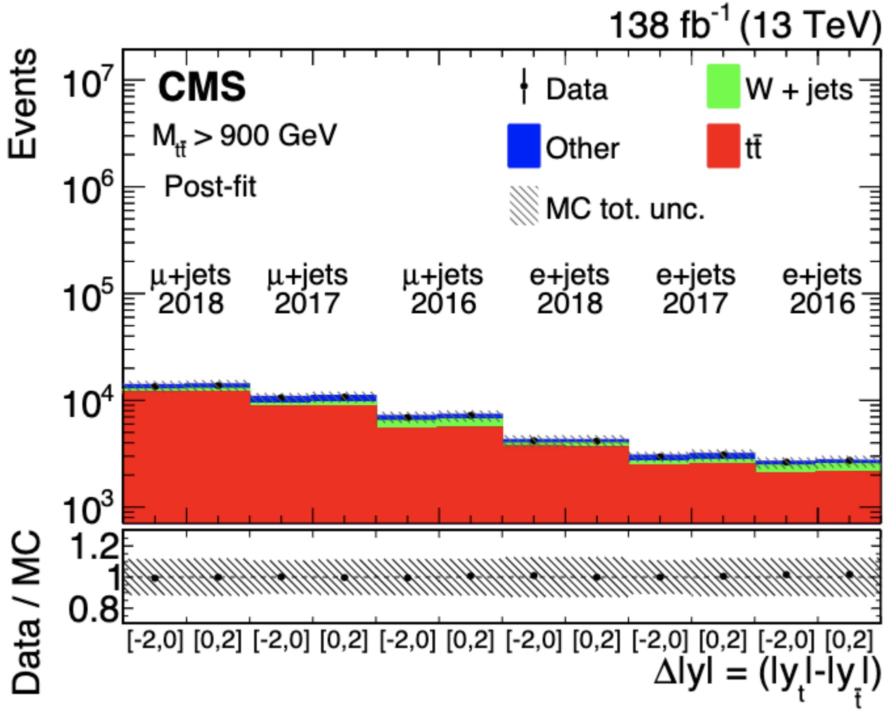
arXiv:2208.02751

Charge Asymmetry in the Boosted Regime

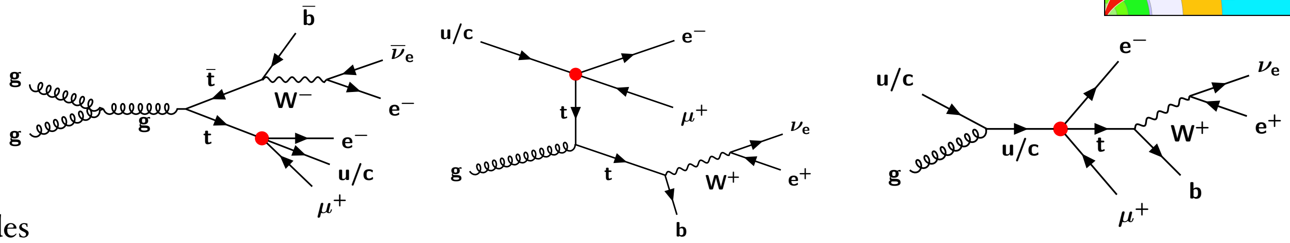
- CMS measured A_C using lepton + jets events
- Dedicated hadronic and leptonic selections
  - Selection is optimised for top quarks produced with large Lorentz boosts
  - **Non isolated leptons, unlike previous CMS results**
  - Selected top events in 3 categories : fully merged, partially merged and not merged (see slide 6 for definitions)

- Measured for events with a $t\bar{t}$ invariant mass larger than 750 GeV
- Compared to theoretical prediction with NNLO QCD and NLO EW corrections



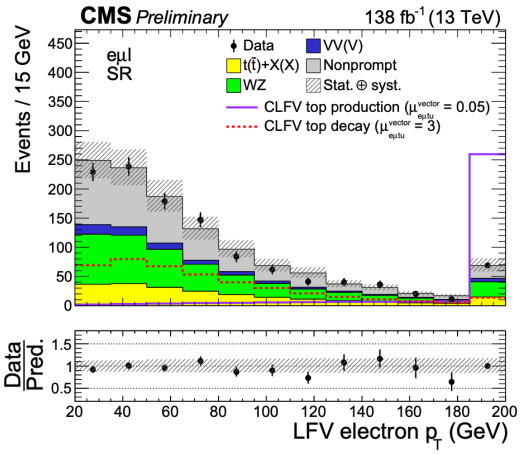


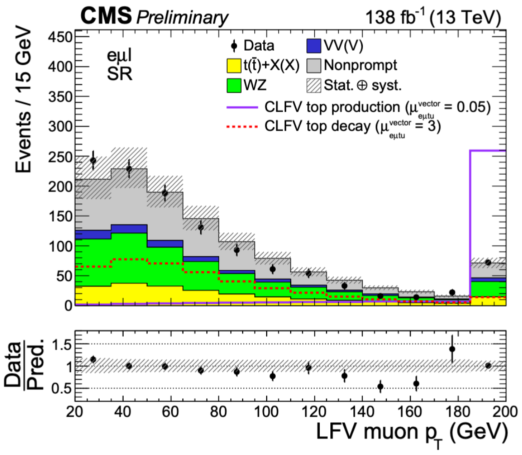
Search for Charged Lepton Flavour Violation



- Studied the trilepton channel
- Includes top production and decay modes
- Set limits on the branching ratio $B(t \to e^{\mp}\mu^{\pm}q)$
  - Here q is an up or charm quark

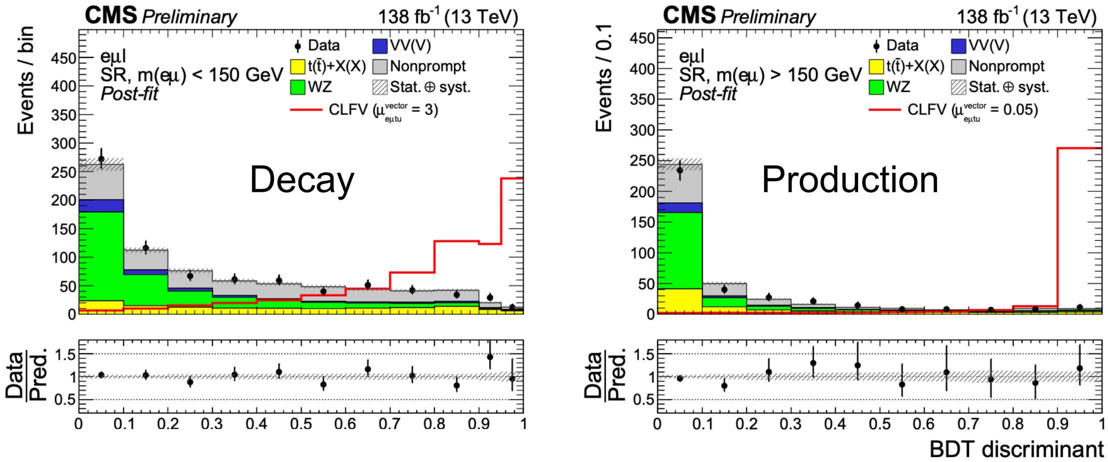
- Signal is defined by:
  - Opposite charge $e\mu$ pair
  - 3rd lepton from leptonic top
  - One b jet and 0 or 1 light jets
- Prompt lepton background estimate with MC
- Non prompt lepton background estimated using a data driven 3D matrix method
- Model independent EFT approach
- Parametrised signal with dimension 6 EFT operators





Search for Charged Lepton Flavour Violation cont.

- BDT used to distinguish signal and background
  - One signal region targets production and another targets decay
- Upper limits on the Wilson coefficients are converted to upper limits on the branching fraction
- **Most stringent limits to date on this process!**

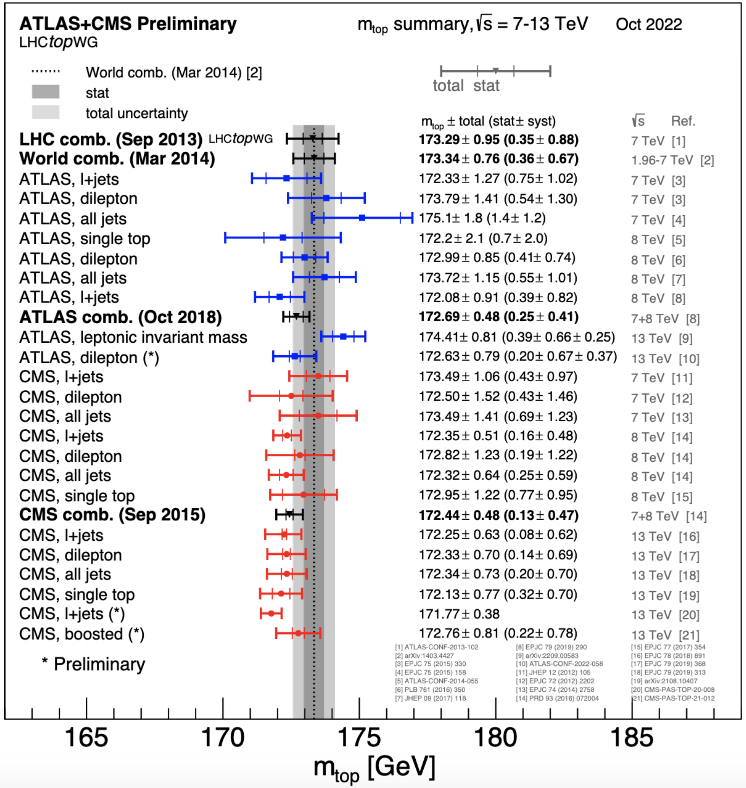


CLFV coupling	Interaction type	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ Exp (68% range)	Obs
eμtu	tensor	0.019 (0.013-0.029)	**0.023**
	vector	0.013 (0.009-0.020)	**0.016**
	scalar	0.007 (0.005-0.011)	**0.009**
eμtc	tensor	0.209 (0.143-0.311)	**0.258**
	vector	0.163 (0.111-0.243)	**0.199**
	scalar	0.087 (0.060-0.130)	**0.105**

[Overview of all CMS TOP results can be found here]

Summary

- CMS has made significant progress in measuring the mass and properties of the top quark
  - **MC vs Pole Mass:**
    - **The precision on the top MC mass has now reached below 0.4 GeV**
    - Pole mass precision has been reduced to ~0.8 GeV
      - Pole mass precision has significantly improved but is still ~2 times worse than MC mass
  - CMS produced a new charge asymmetry measurement this year!
  - cLFV search from CMS set limits 1 order of magnitude more stringent than previous CMS result !



Thank you for your time 😊

I found the jet graphics here

BACKUP

arXiv:2211.01456

Measurement of Top Mass in Boosted Tops cont.

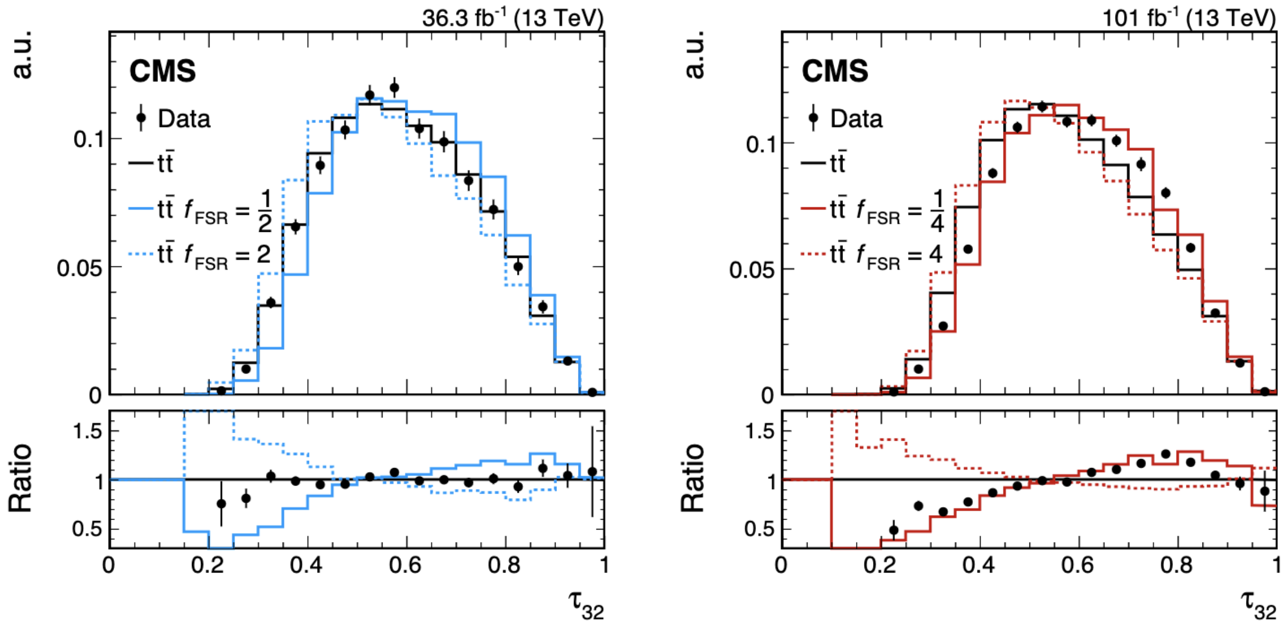


Figure 8: The normalised distributions in τ_{32} for AK8 jets with $m_{\text{jet}} > 140\,\text{GeV}$ from the hadronic decay of boosted top quarks. Shown are distributions for 2016 (left) and the combination of 2017 and 2018 (right). The background-subtracted data are compared to $t\bar{t}$ simulations with the UE tunes CUETP8M2T4 for 2016 and CP5 for the combination of 2017 and 2018, and different values of f_{FSR} are shown as well. The lower panels show the ratio to the $t\bar{t}$ simulation with $f_{\text{FSR}} = 1$.