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Top Properties and Tests in Top Quark Decays

19 May 2022, LHCP 2022

Mark Owen on behalf of the ATLAS & CMS Collaborations
The University of Glasgow

Why the top quark?

- In the SM it's the only quark:
  1. With a natural mass:

$$m_{top} = y_t v/\sqrt{2} \approx 173 \text{ GeV} \Rightarrow y_t \approx 1$$

  - Top quark interacts strongly with the Higgs sector - special role in EWSB?

  2. That decays before hadronizing:

$$\tau_{had} \approx 2 \times 10^{-24} s$$

$$\tau_{top} \approx 5 \times 10^{-25} s$$

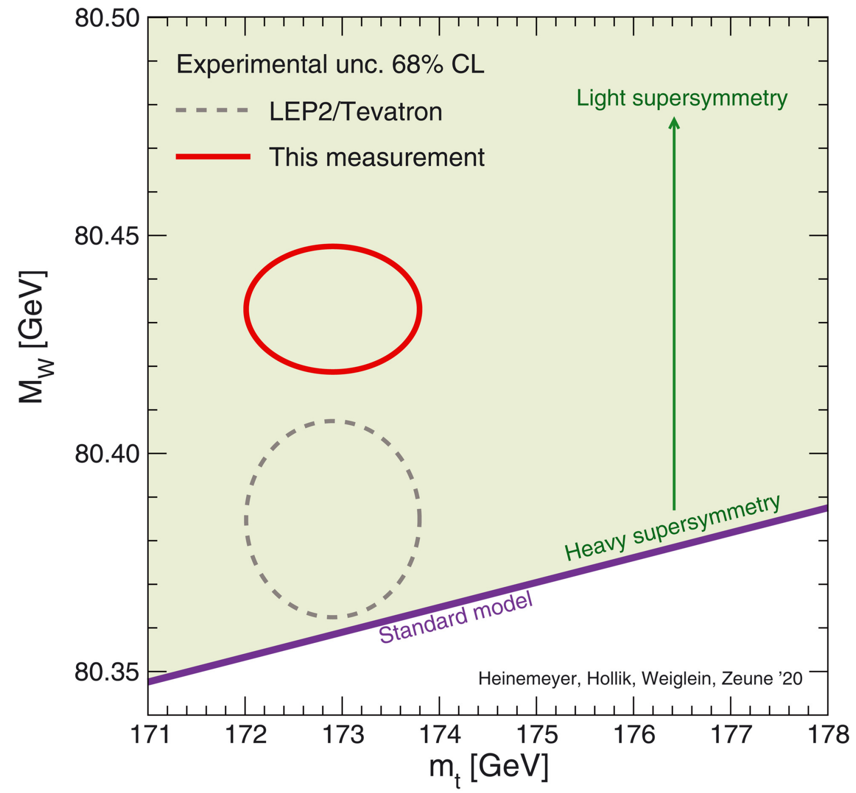
- Copious production rate at the LHC allows for precise tests of SM.

Why top quark properties?

- Many properties well predicted in SM - huge LHC statistics allow for precision tests.
  - EFT now frequently used to evaluate BSM sensitivity in model-independent way.

$$\mathscr{L}_{EFT} = \mathscr{L}_{SM} + \sum_{i,D} \frac{C_i^D}{\Lambda^{D-4}} O_i^D = \mathscr{L}_{SM} + \frac{C_i}{\Lambda^2} O_i^{D=6}$$

- Top quark mass is essential probe of SM consistency:



Science 376, 170 (2022)

Outline

- Asymmetry measurements
- $t\bar{t}$ + Z / photon
- Top quark mass measurements

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Asymmetry measurements

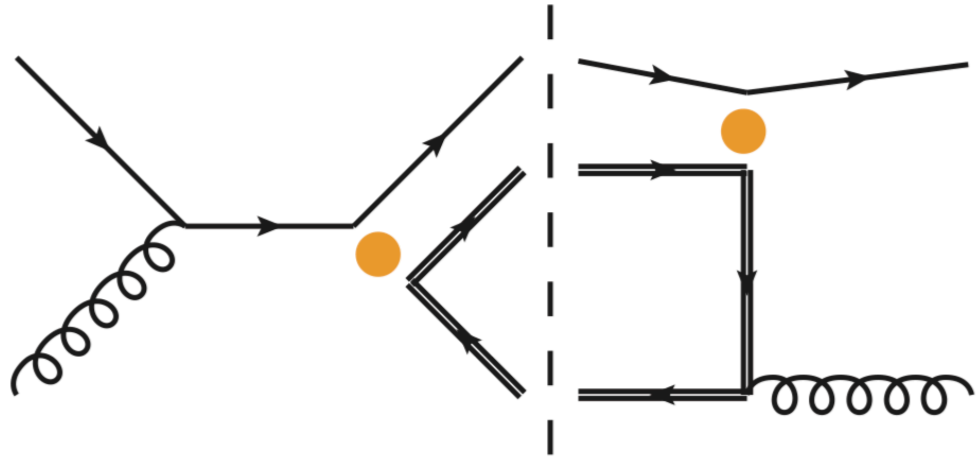
Energy asymmetry

- Observable defined for ttj production, where the energy asymmetry of the top quarks $\Delta E = E_t - E_{\bar{t}}$ is measured in bins of the scattering angle of the additional jet, θ_j:

$$A_E(\theta_j) \equiv \frac{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) - \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) + \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}$$

- QCD asymmetry is closely related to the charge asymmetry in inclusive $t\bar{t}$ production.

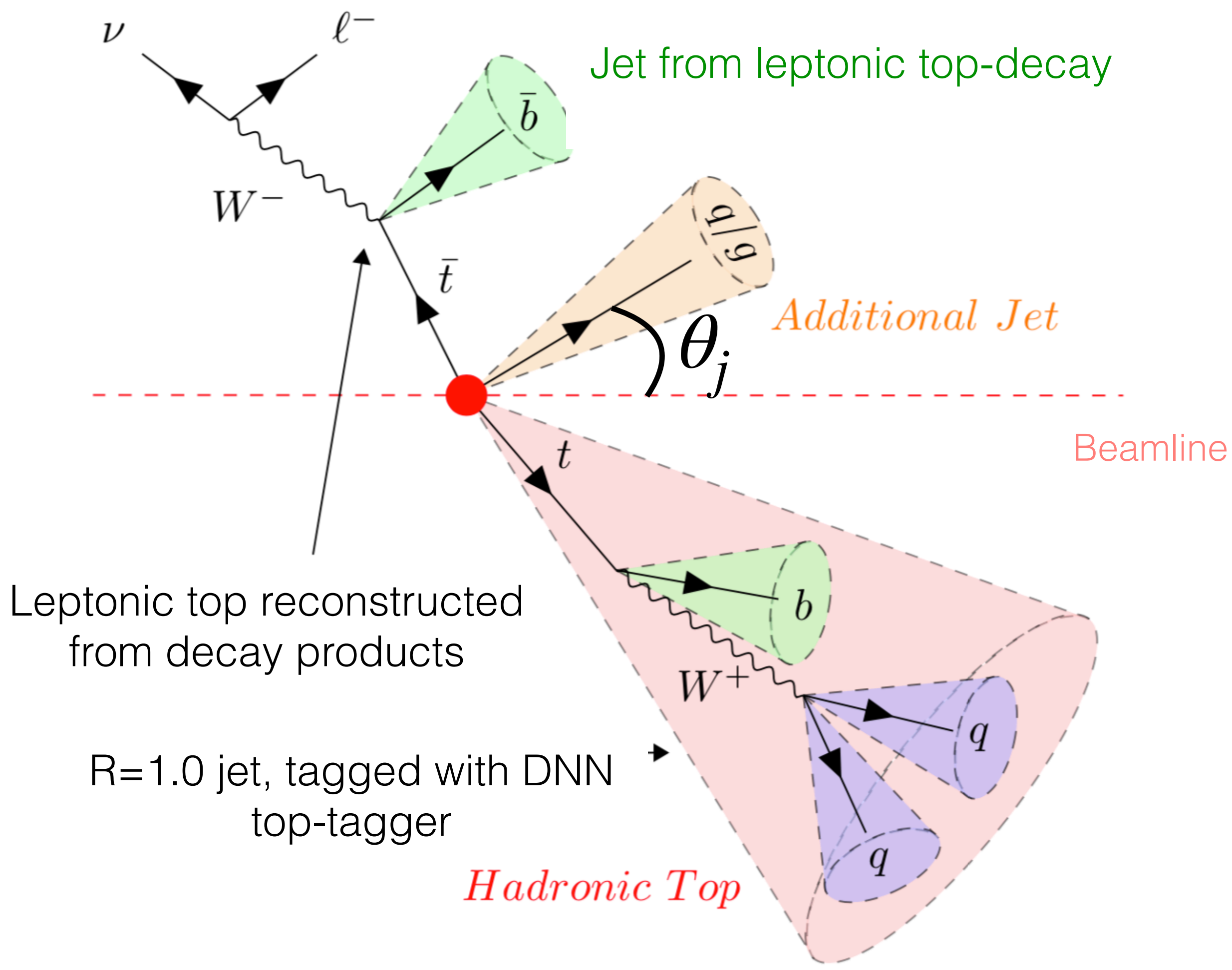
- Observable probes for possible new physics in $t\bar{t}j$ events:



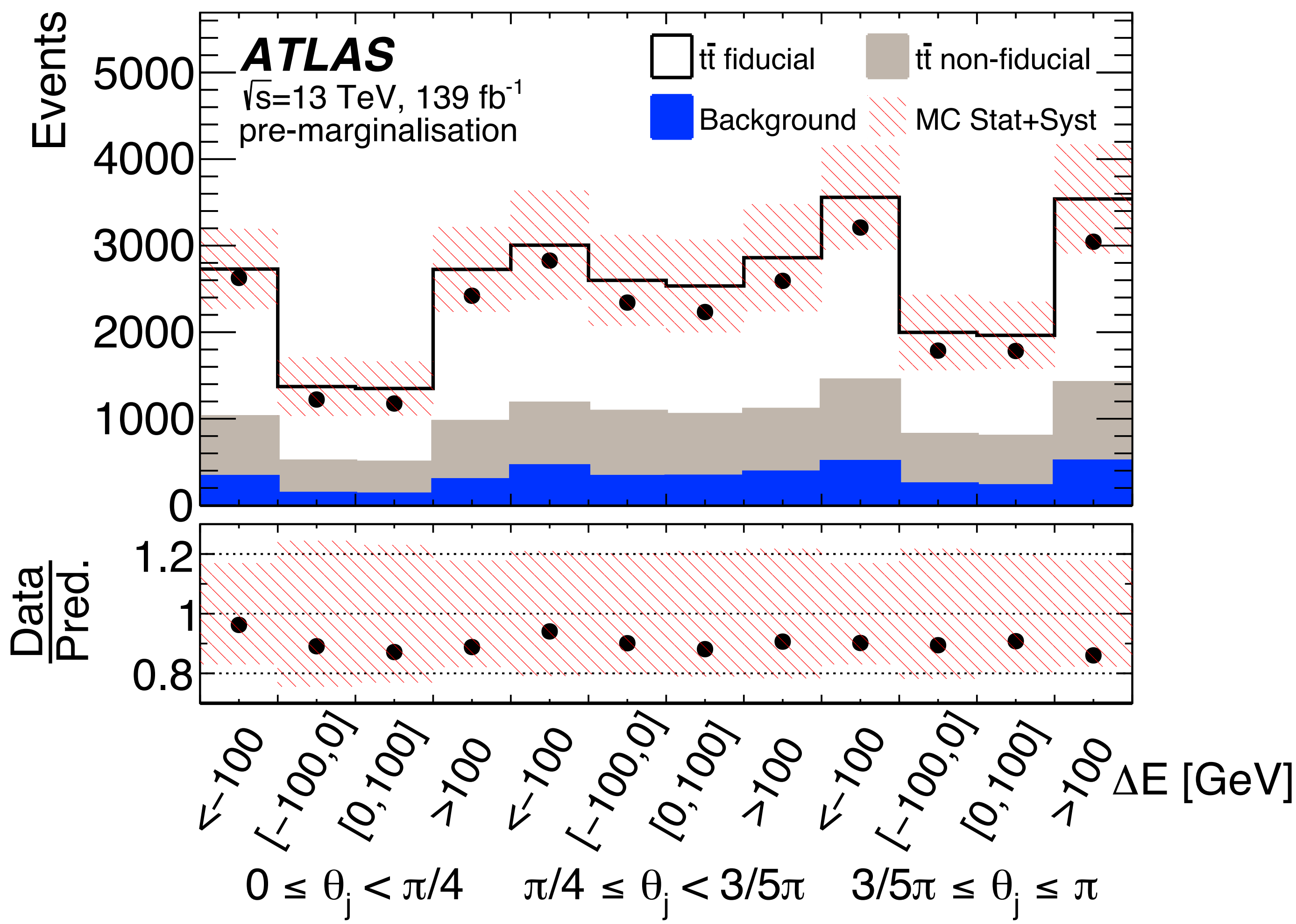
Eur. Phys. J. C 82 (2022) 374

Energy asymmetry

- Select l+jets with high p_T hadronic top (p_T > 350 GeV):



$$A_E(\theta_j) \equiv \frac{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) - \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) + \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}$$



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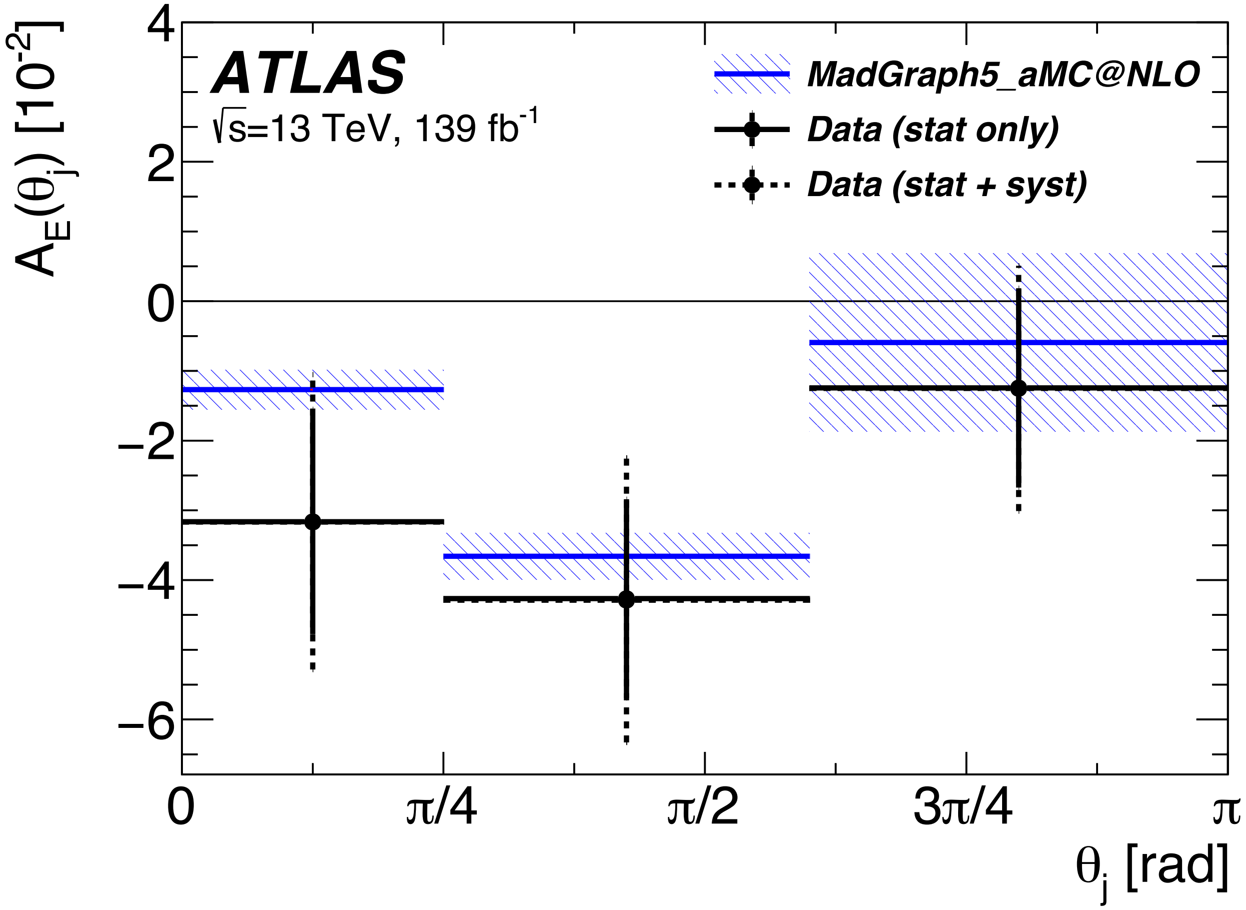
Energy asymmetry

- Data is unfolded with Fully Bayesian Unfolding method.



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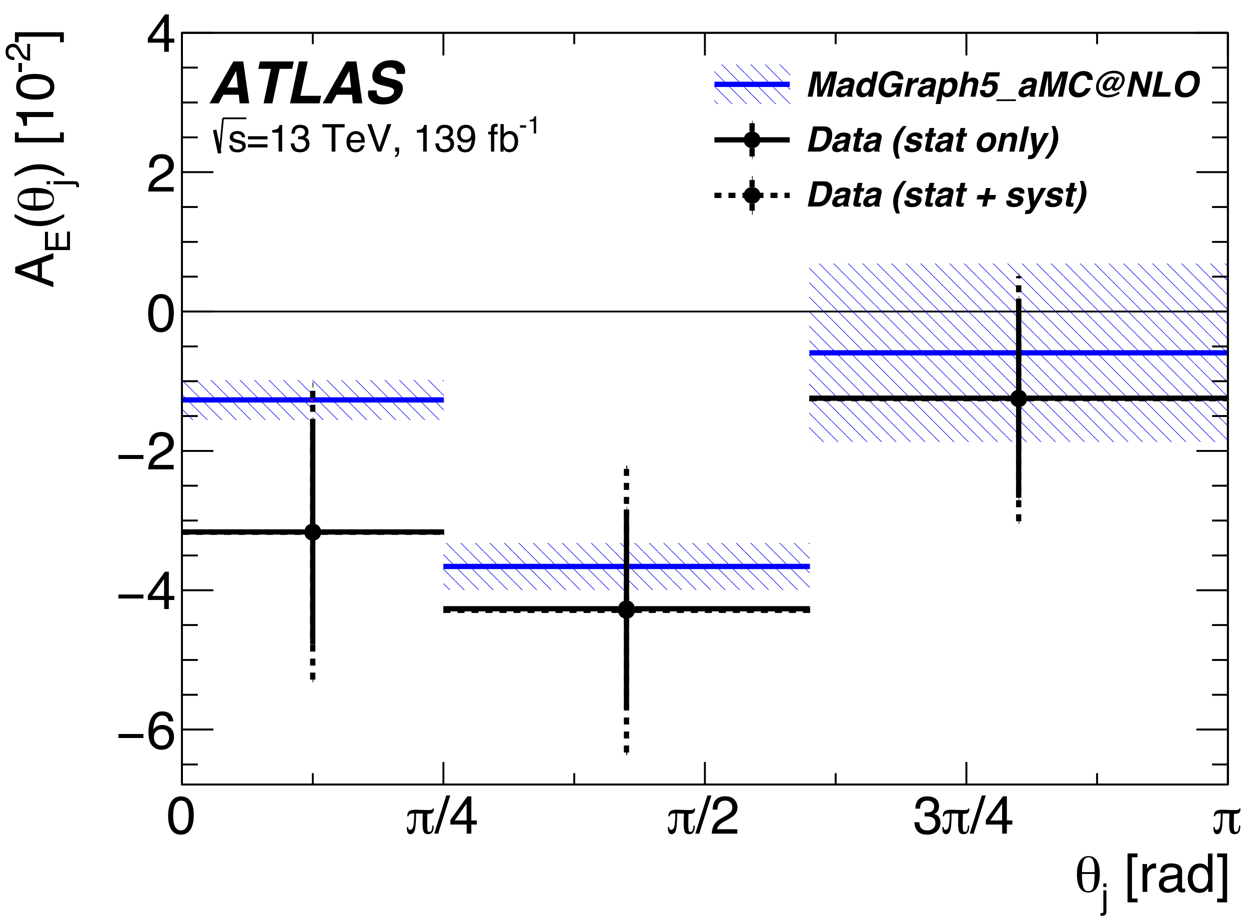
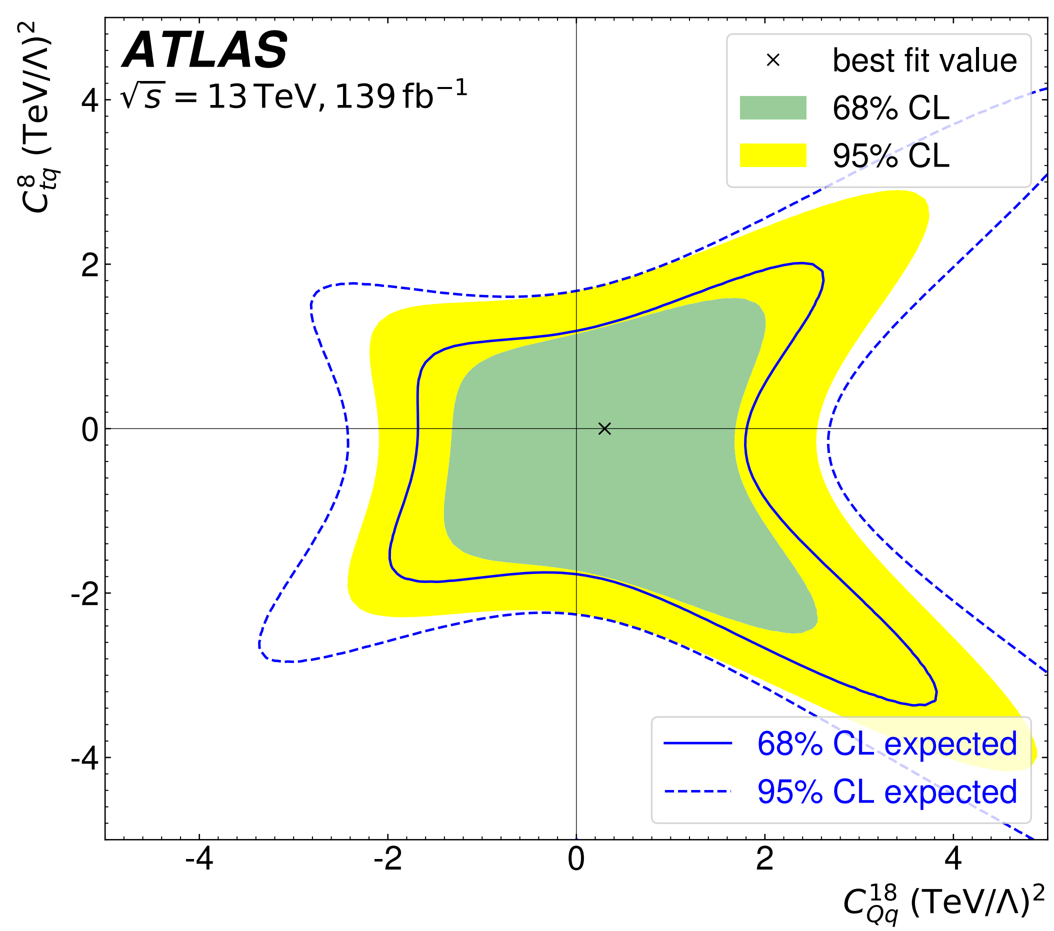
Energy asymmetry

- Data is unfolded with Fully Bayesian Unfolding method.
- Then interpreted as limits on EFT four-quark operators.





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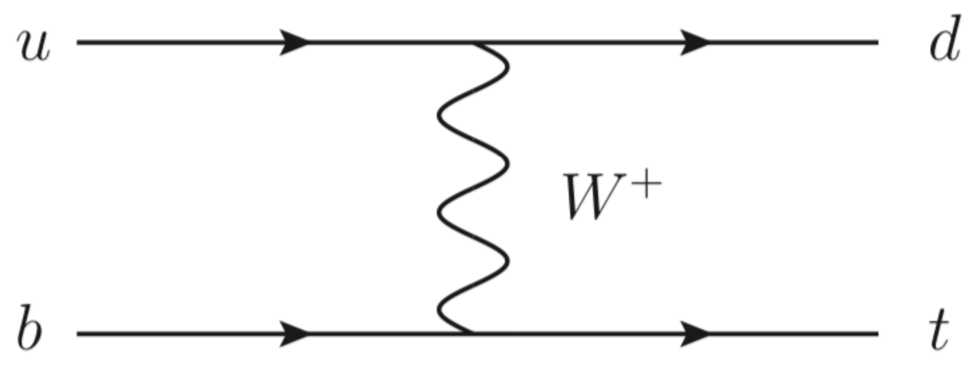
Single top polarisation

- In SM, (V-A) structure of Wtb vertex results in production of polarised top-quarks in t-channel single-top production:



- Top quarks are predicted to be polarised (P=0.965±0.004) at NNLO) along the direction of the spectator quark (d).
  - Anti-top quarks P=-0.957±0.01.

arXiv:2202.11382

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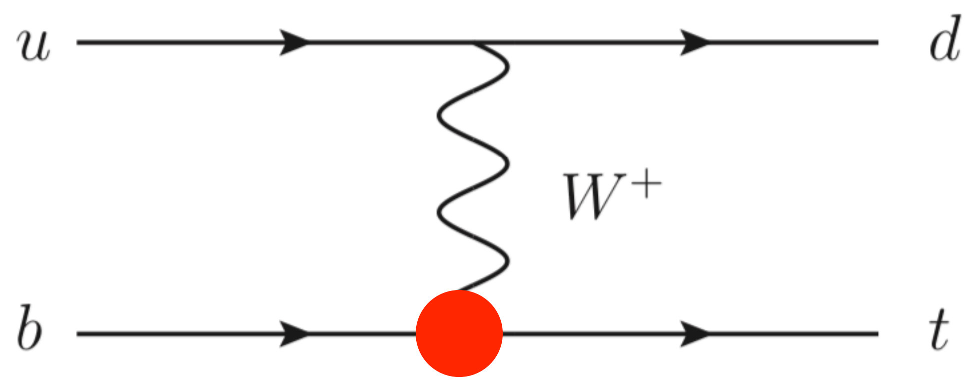

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    - Anti-top quarks P=-0.957±0.01.

- New physics can potentially modify the polarisation - parameterise this effect via EFT operator O_{tW}.

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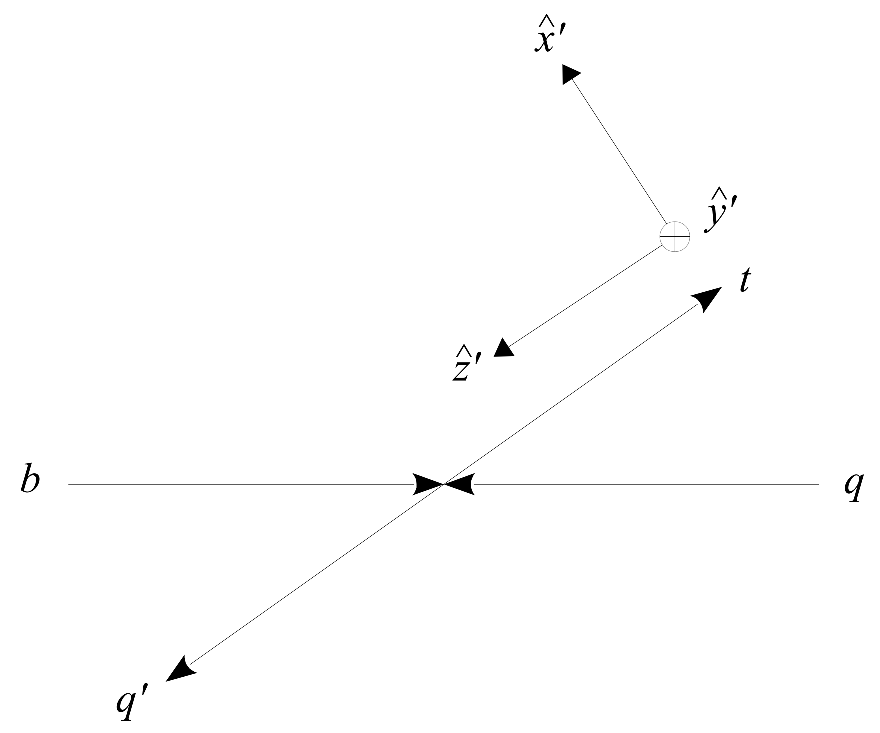
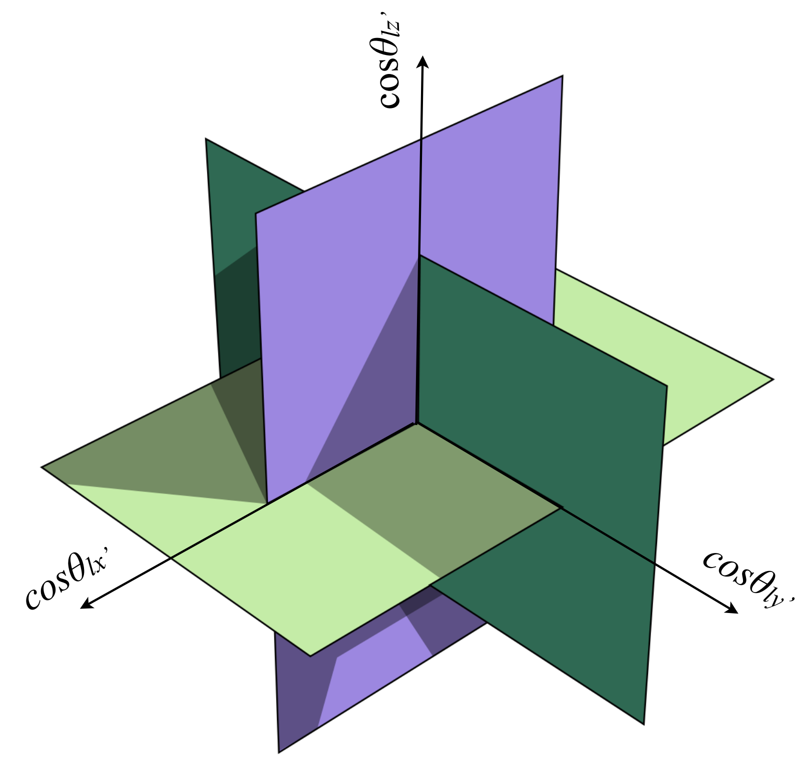
Single top polarisation

- Events are required to have 1 lepton, 2 jets (1 of which is b-tagged). Additional kinematic cuts are used to reduce the background.
- Measure the polarisation along 3 orthogonal axes by fitting the numbers of events in each quadrant of the sign of the cosine of the angle of the lepton in the top-quark rest frame (θ) to each axis.





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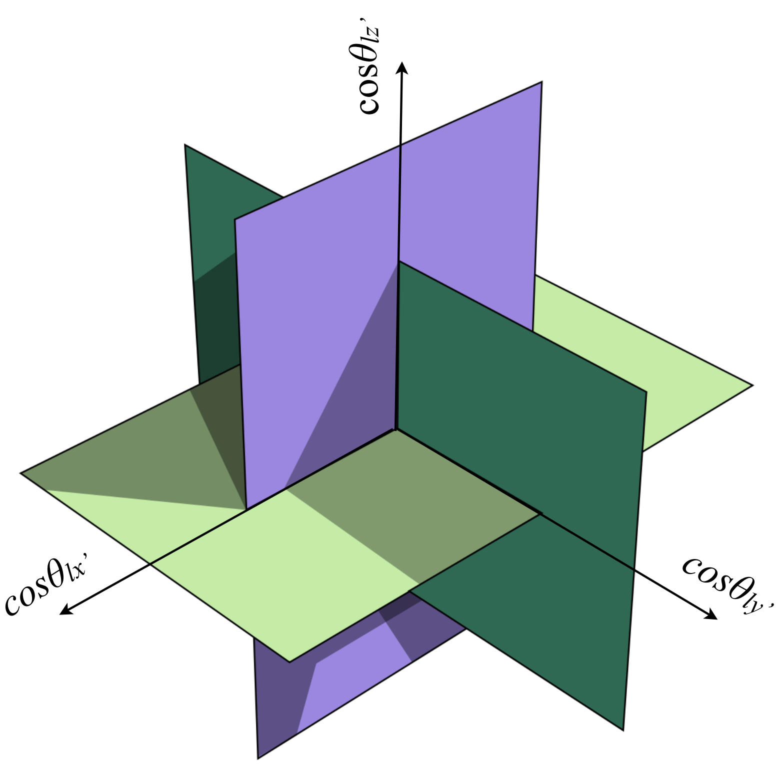
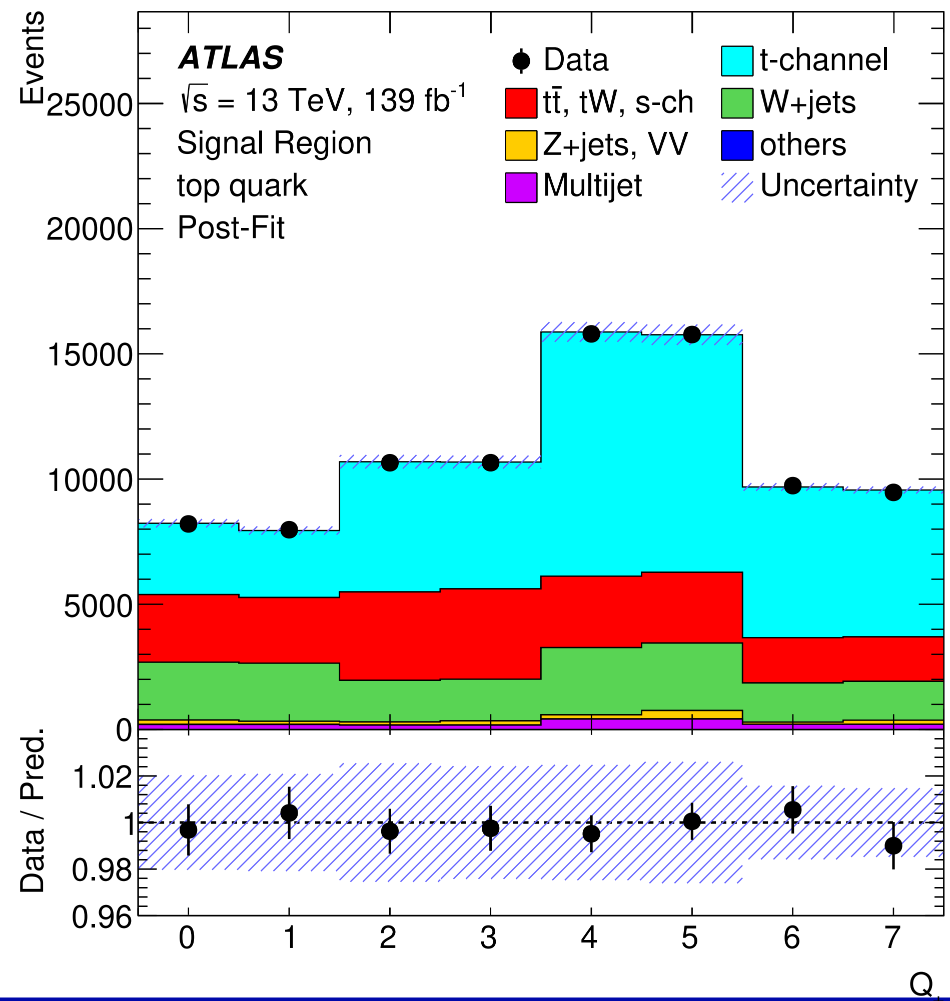


$$Q = 4 \cdot \Theta(\cos\theta_{\ell z'}) + 2 \cdot \Theta(\cos\theta_{\ell x'}) + \Theta(\cos\theta_{\ell y'})$$



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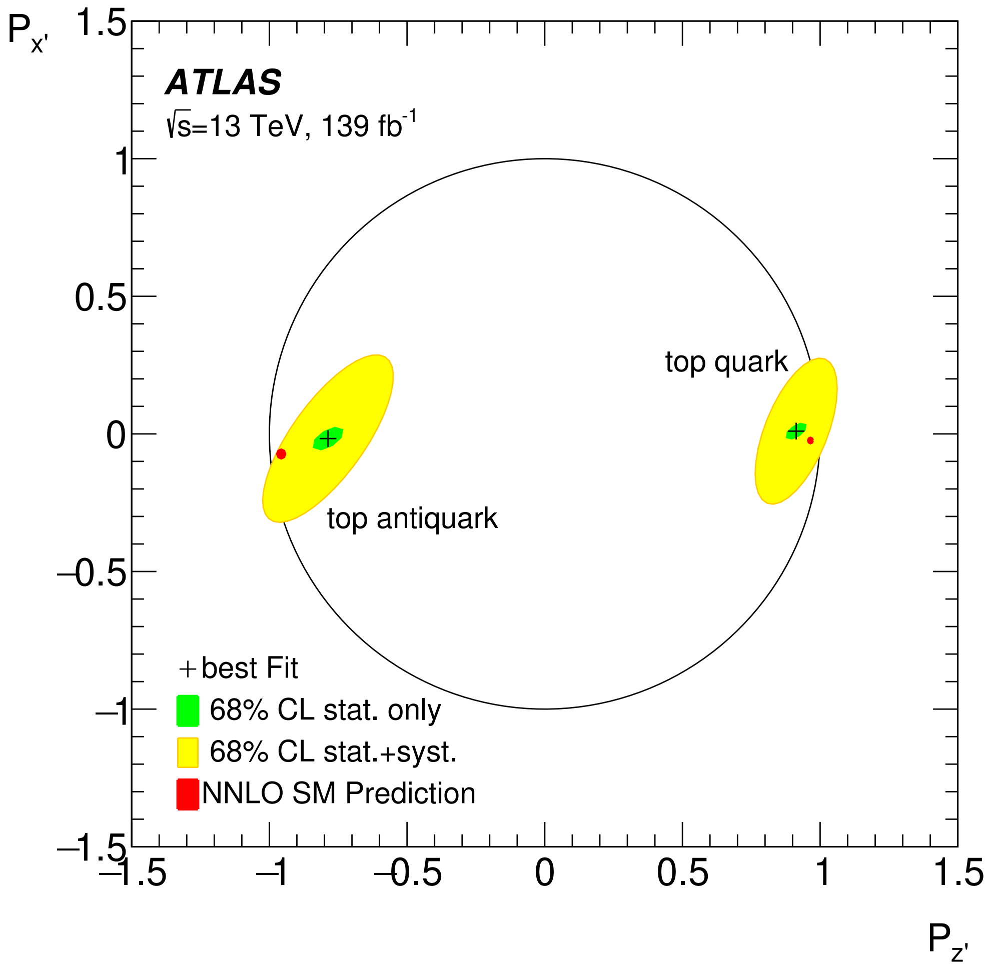
Single top polarisation

- Good agreement with SM predictions, largest systematic JER:



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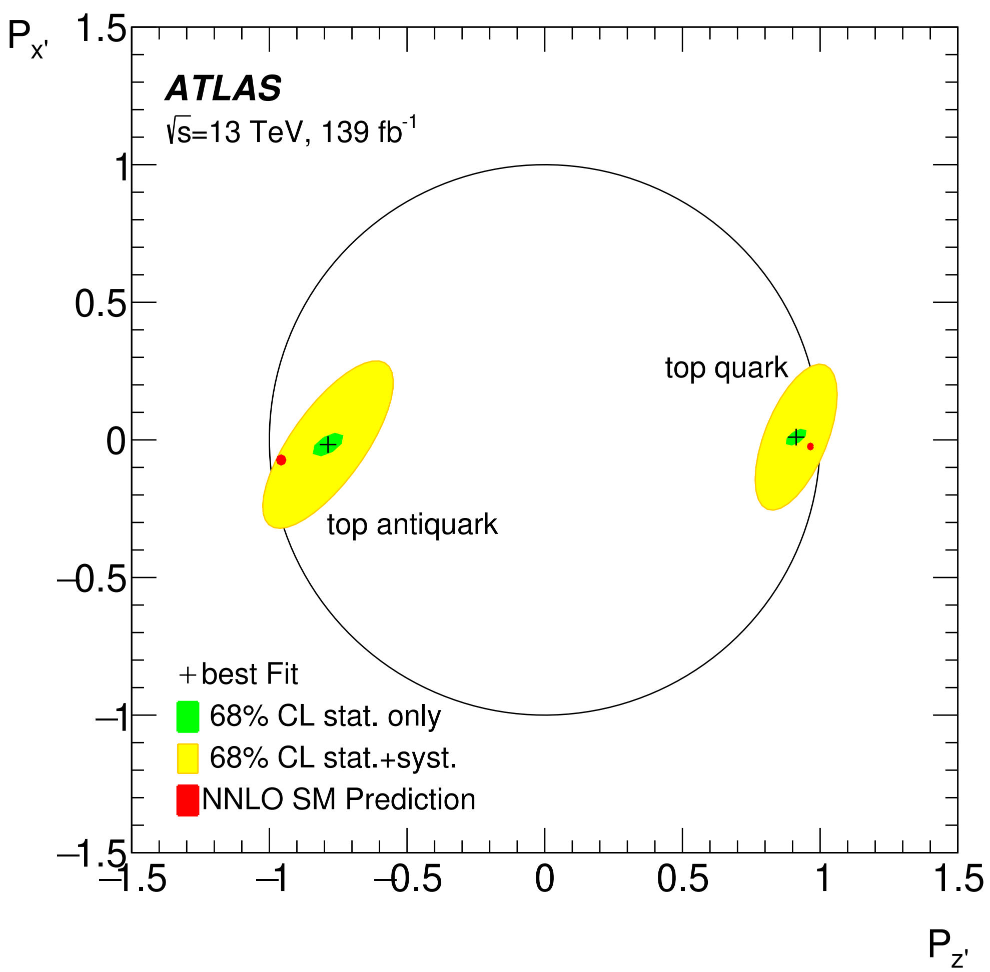
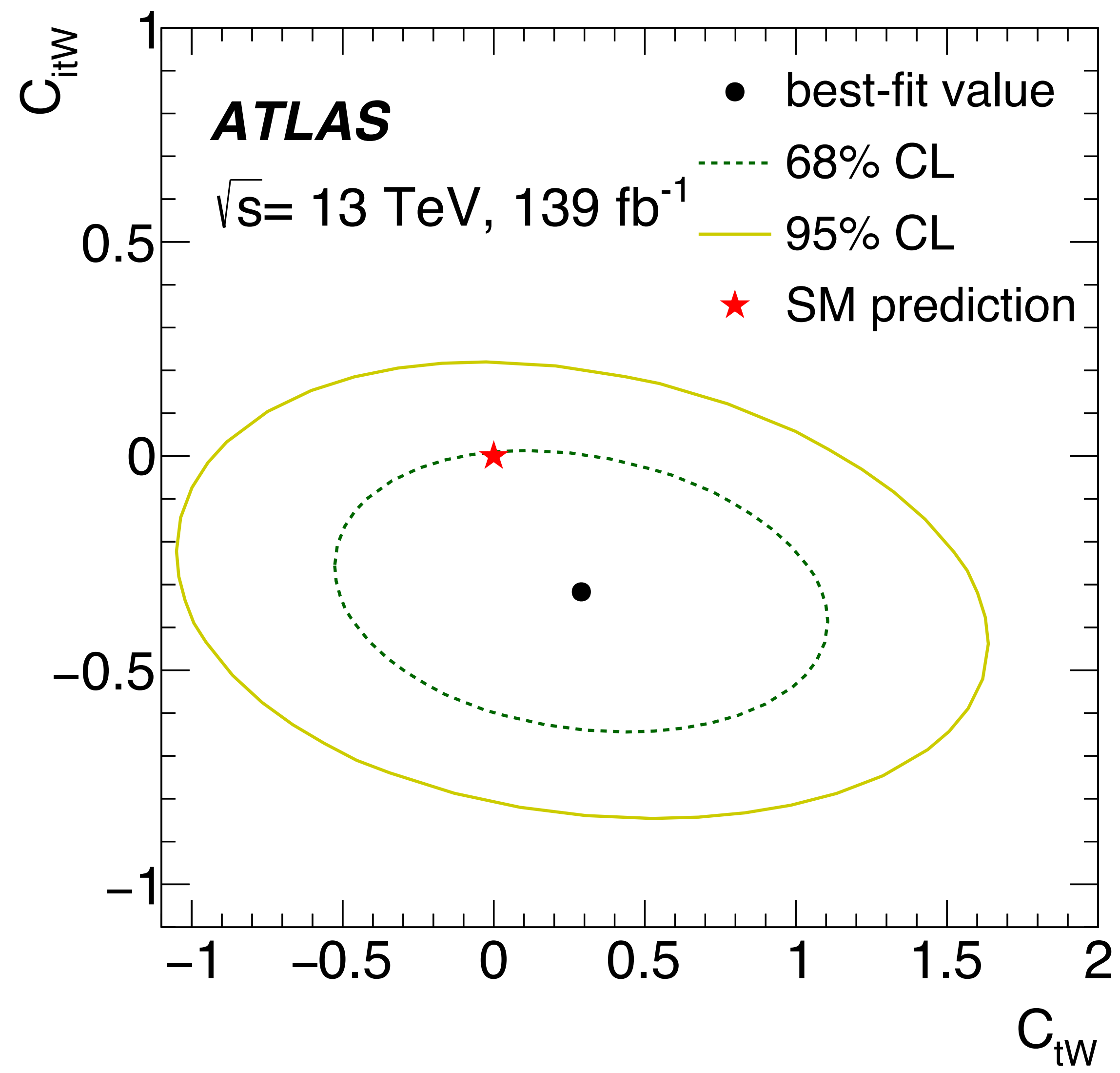
Single top polarisation

- Good agreement with SM predictions, largest systematic JER:
- Interpretation in EFT:





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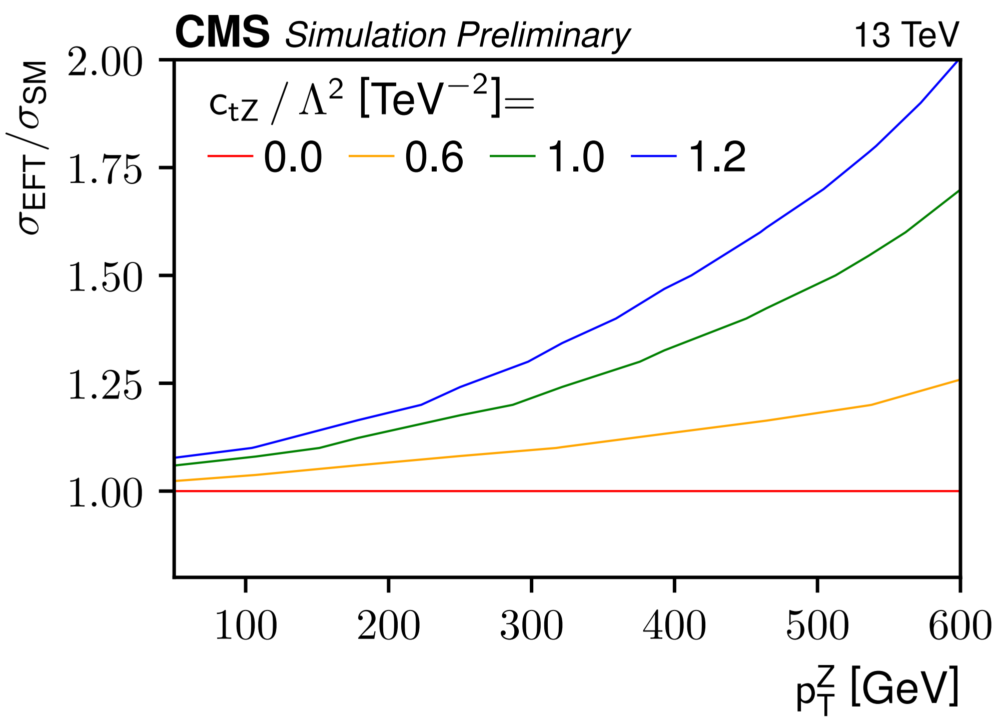
$$t\bar{t} + X$$

Boosted $t\bar{t}Z/H$

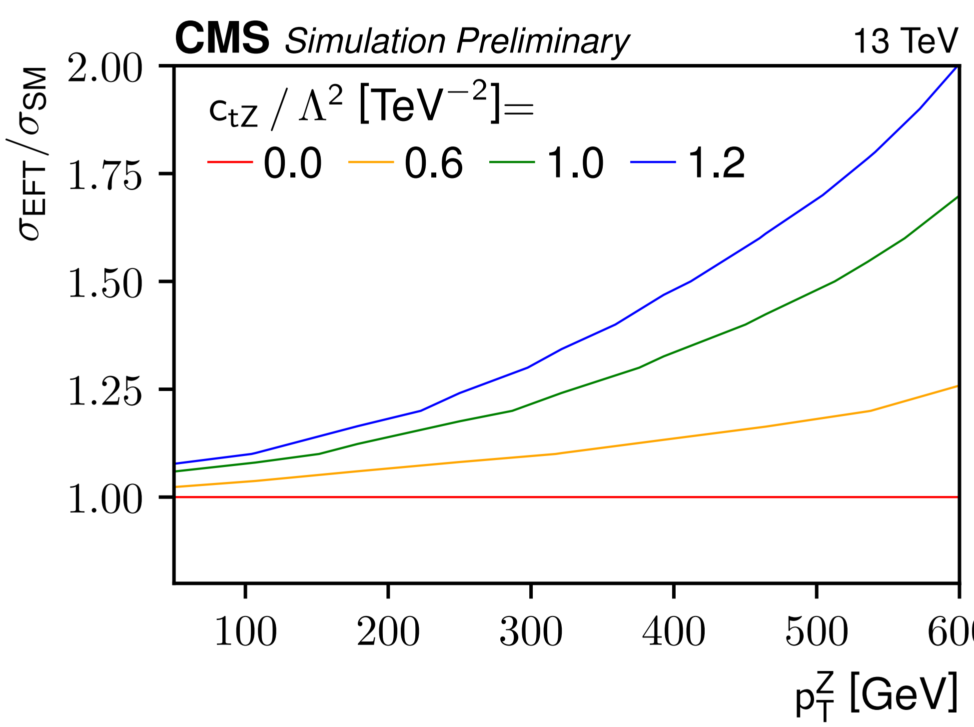
- New CMS analysis searching for $t\bar{t}Z/H$ at high Z/H pT - allows to use hadronic Z/H decays.

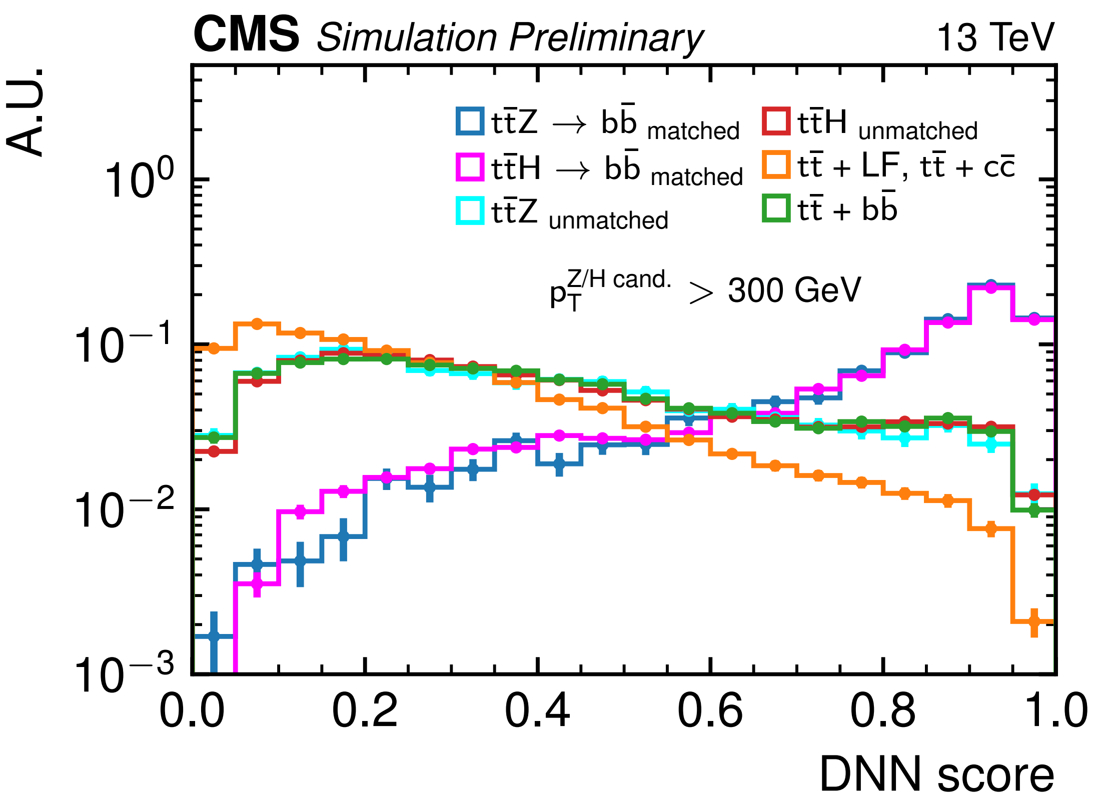


TOP-21-003

Boosted $t\bar{t}Z/H$

- New CMS analysis searching for $t\bar{t}Z/H$ at high Z/H pT - allows to use hadronic Z/H decays.
- Boosted Z/H selected using 0.8 anti-kT jets with a DNN targeting $b\bar{b}$ final states.
- Discrimination of background & signal achieved with another NN.

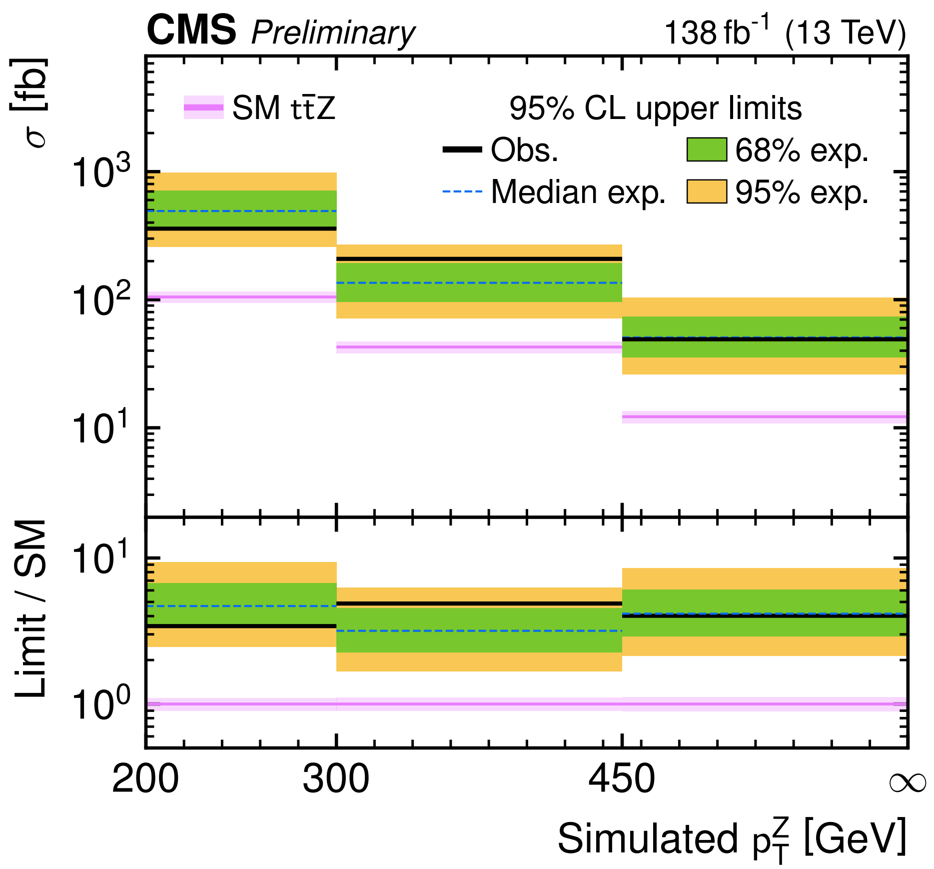


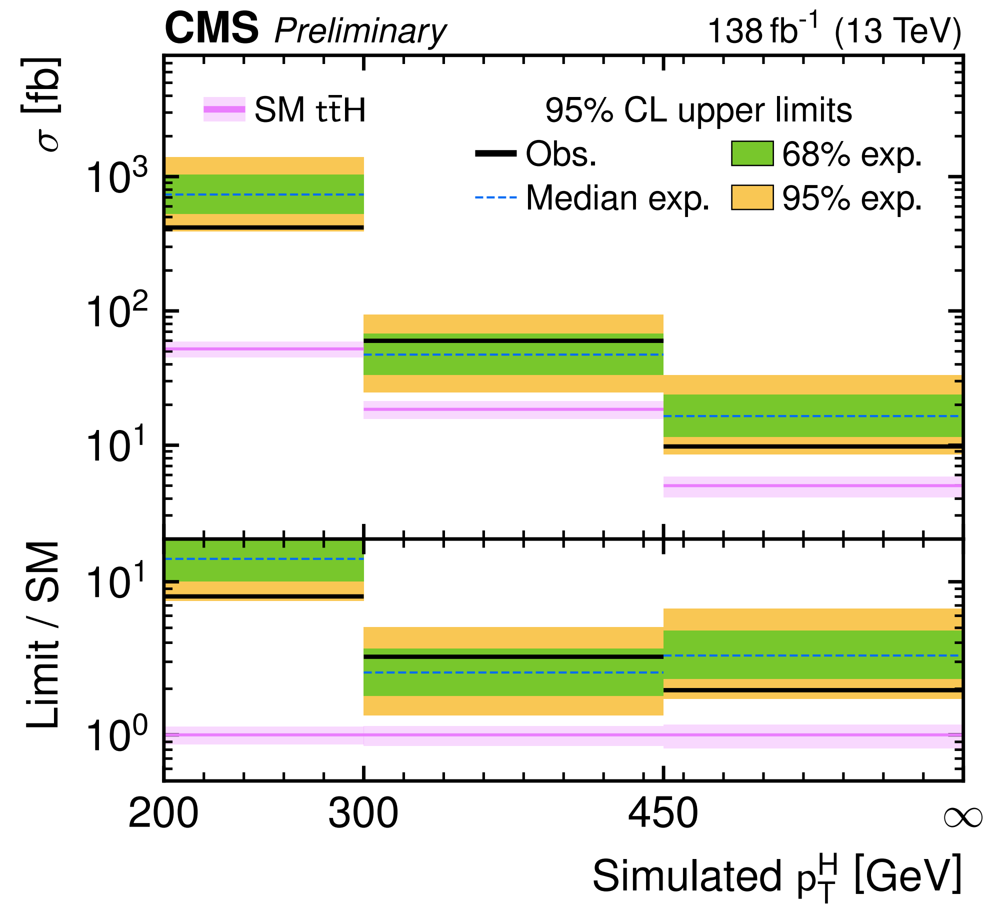


TOP-21-003

Boosted $t\bar{t}Z/H$

- Analysis reaches high pT, but does not see significant signal:





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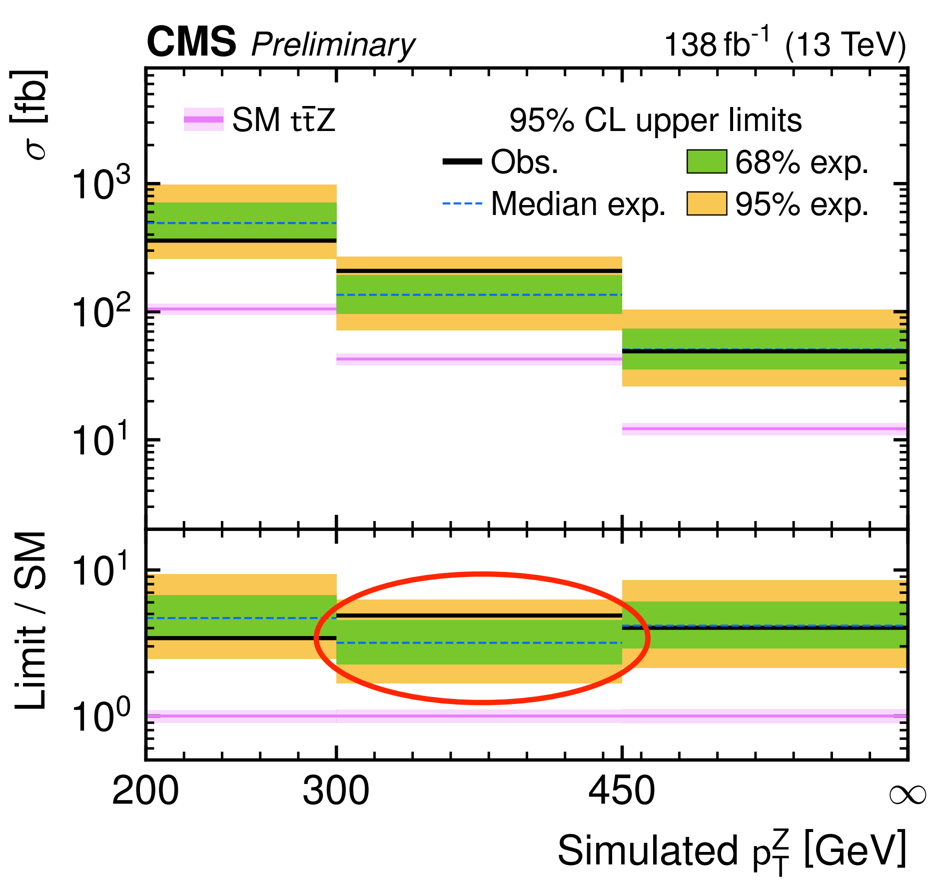

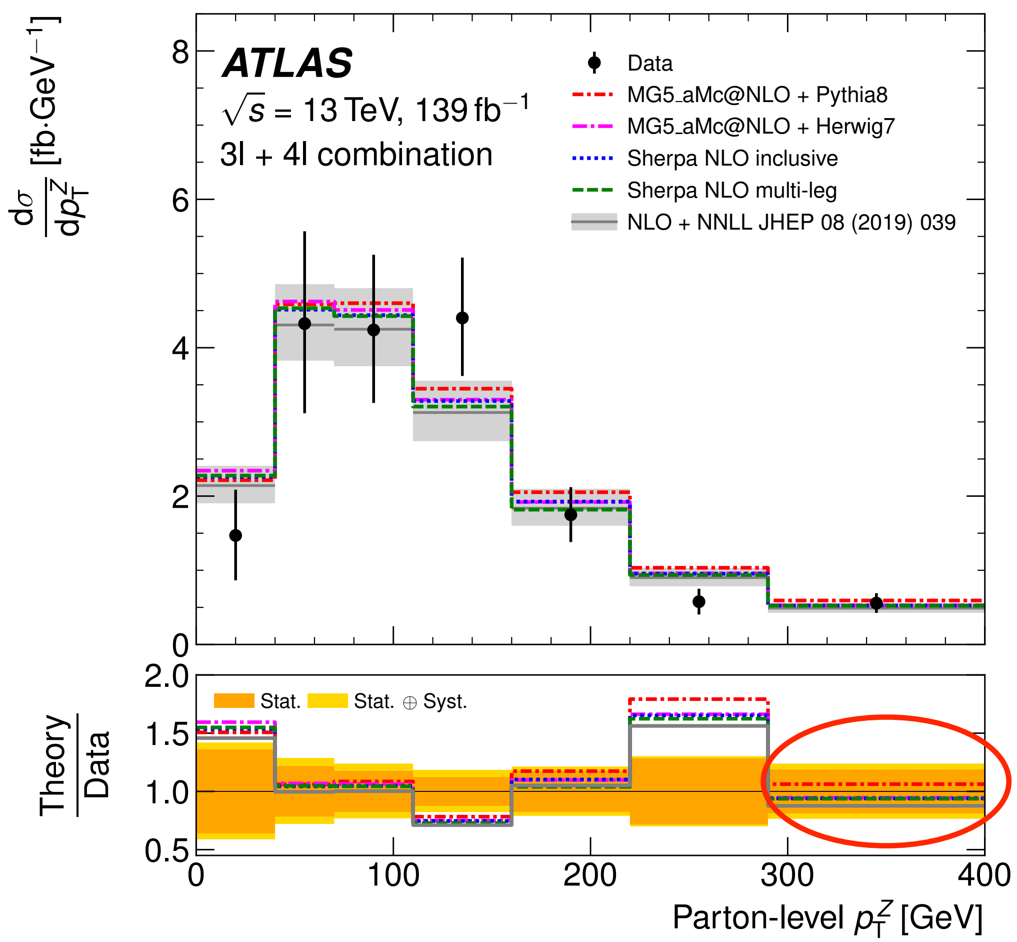

- Note, precision not currently competitive with leptonic ttZ channels.

TOP-21-003

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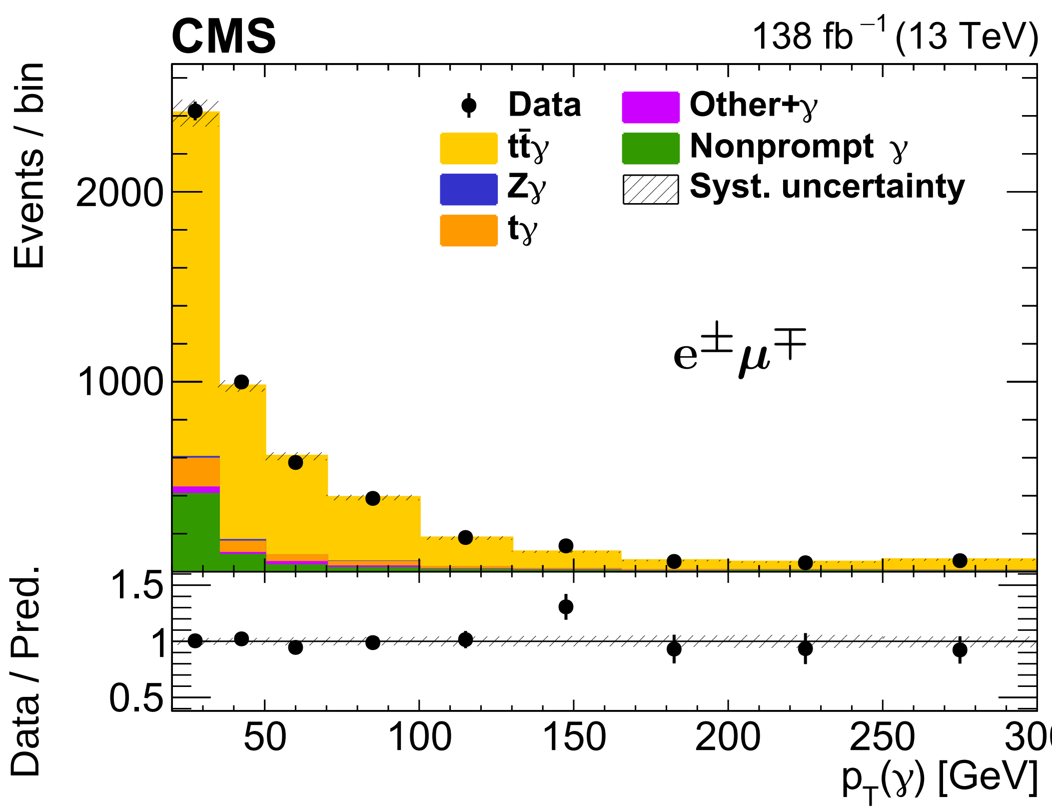
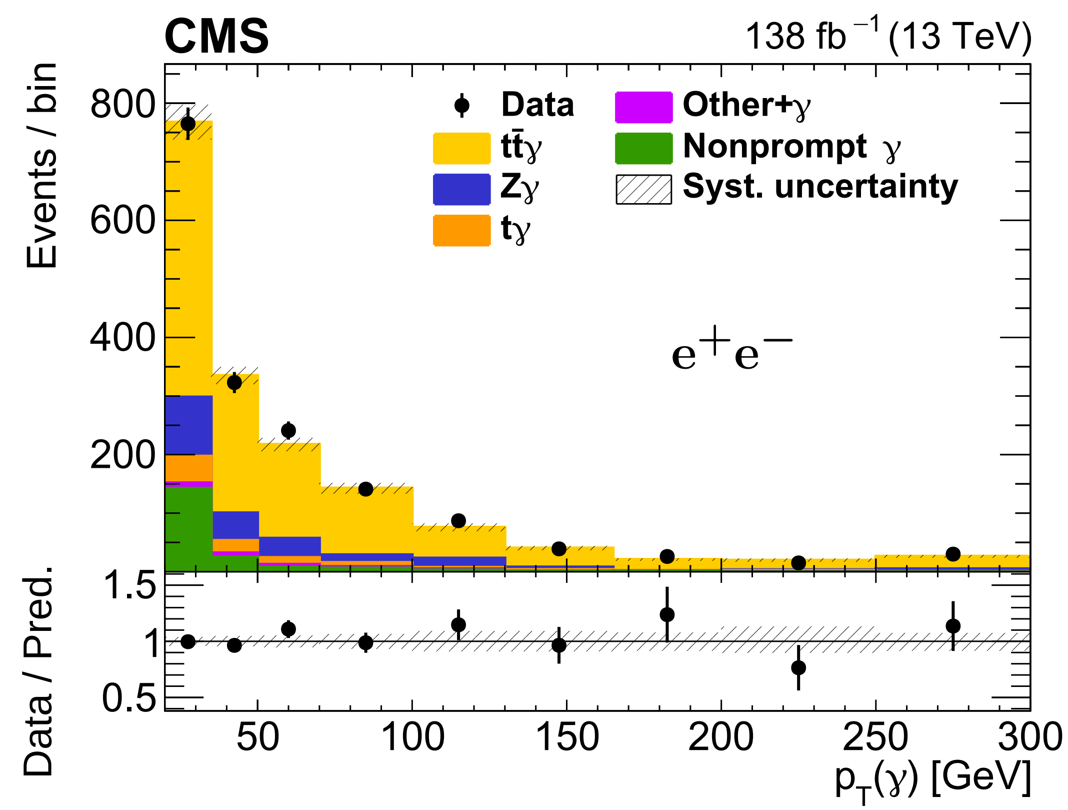
$t\bar{t}\gamma$

- Relatively high production cross-section allows for differential measurements & improved BSM sensitivity.
- Dilepton selection with >= 1 b-jet and >= 1 photon (p_T > 20 GeV) gives pure ttγ sample:

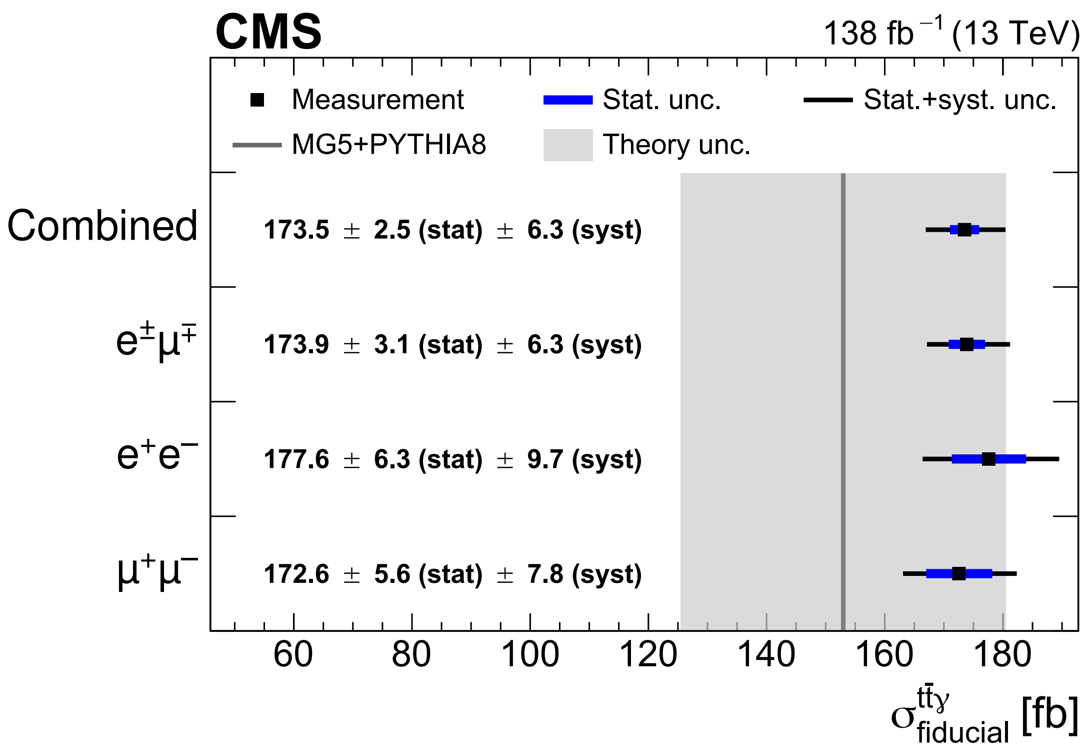




arXiv:2201.07301

$t\bar{t}\gamma$

- Profile-likelihood fit gives excellent precision on inclusive cross-section of 3.9%.
  - Largest uncertainties from luminosity, MC model & photon ID.



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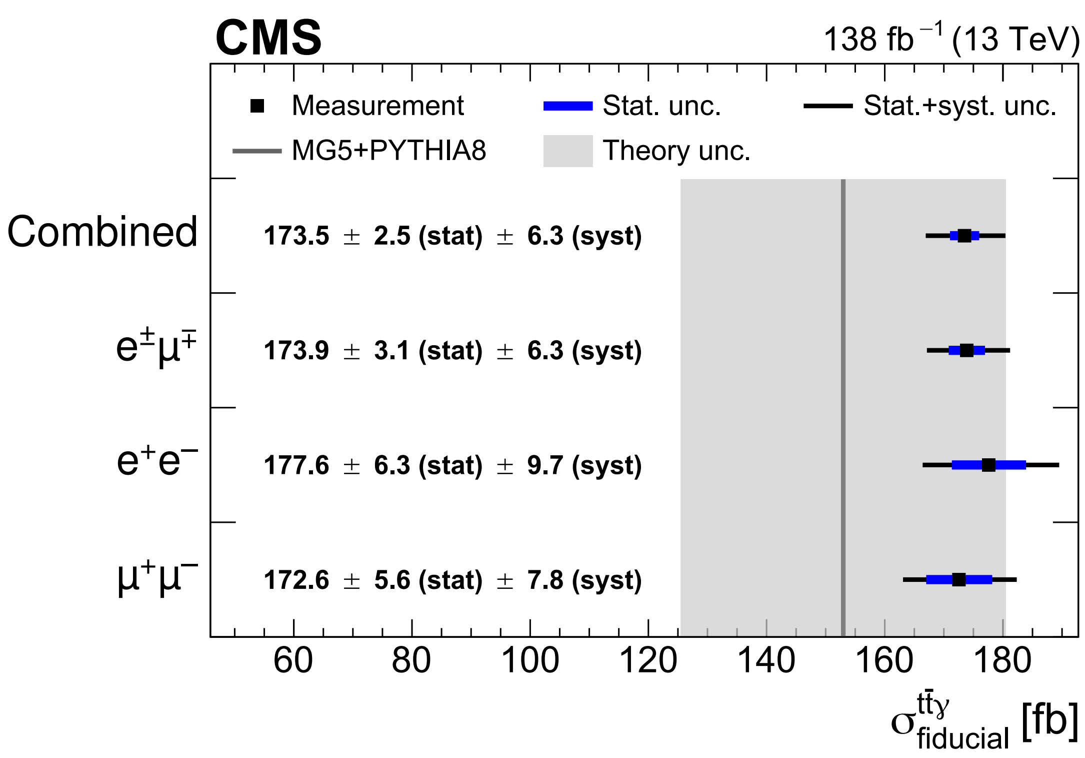

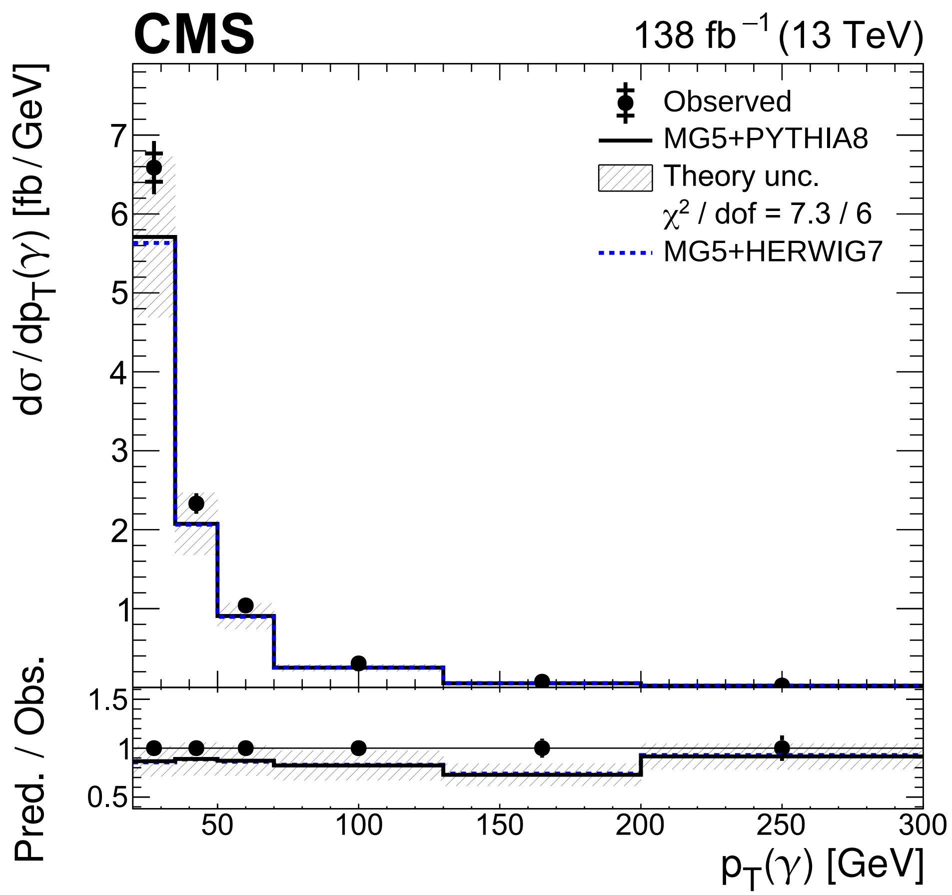

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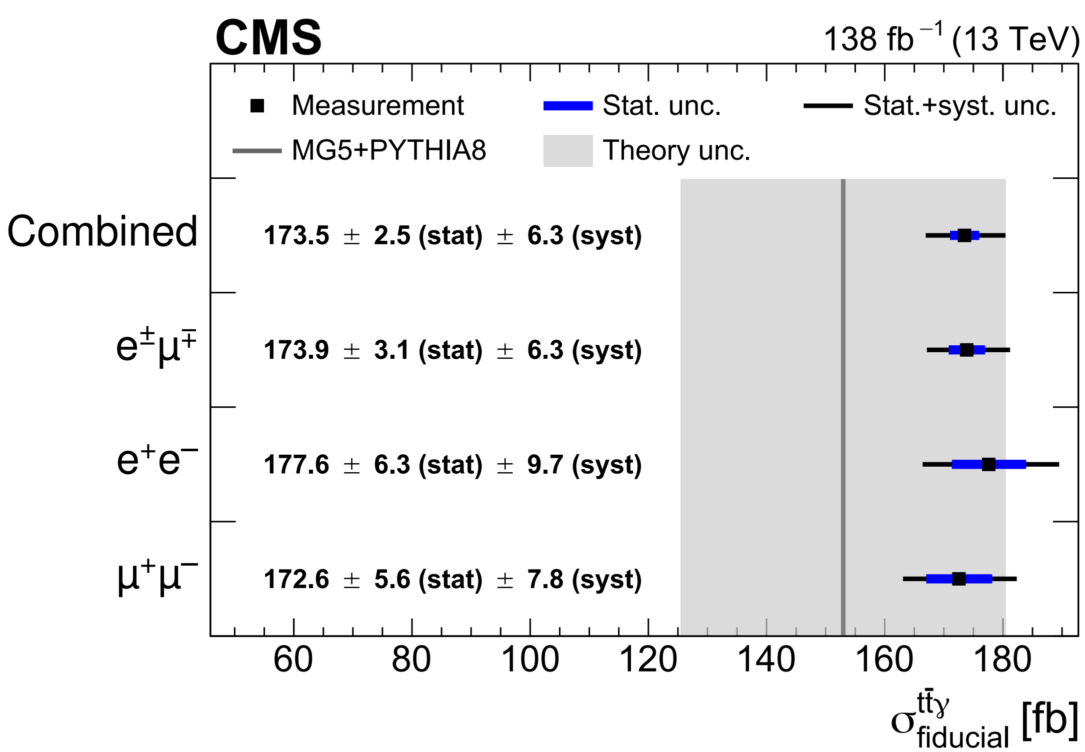

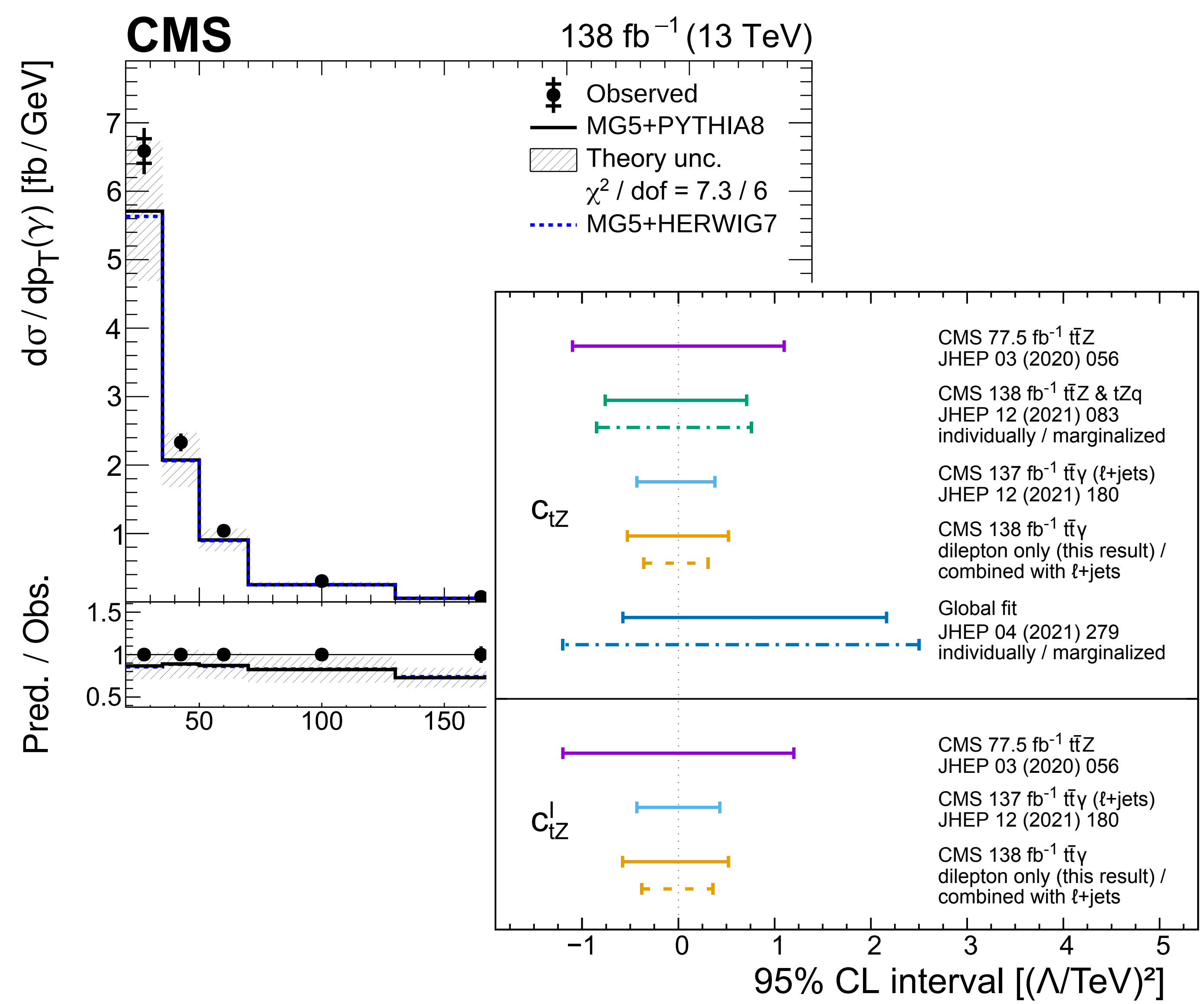

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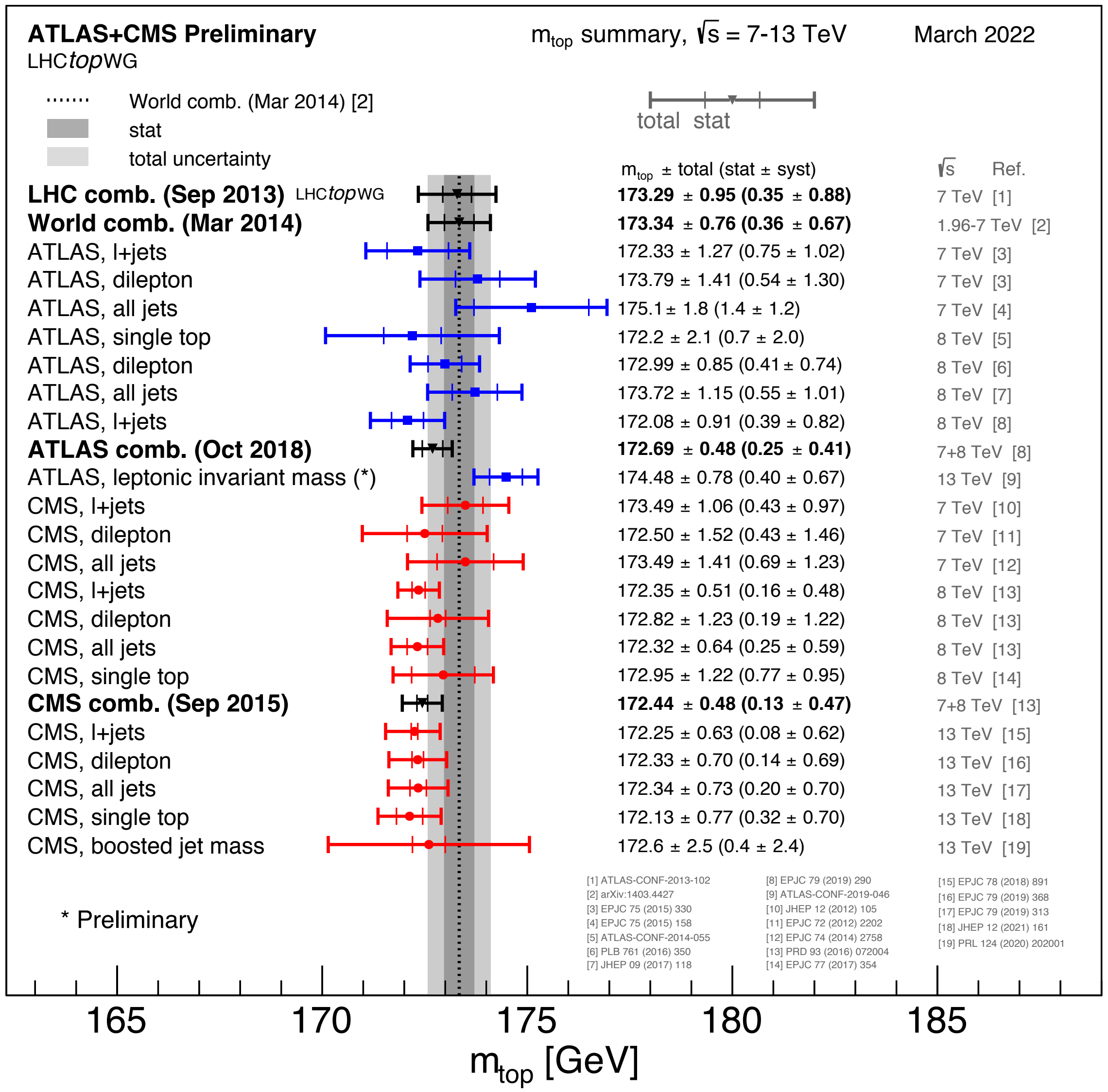
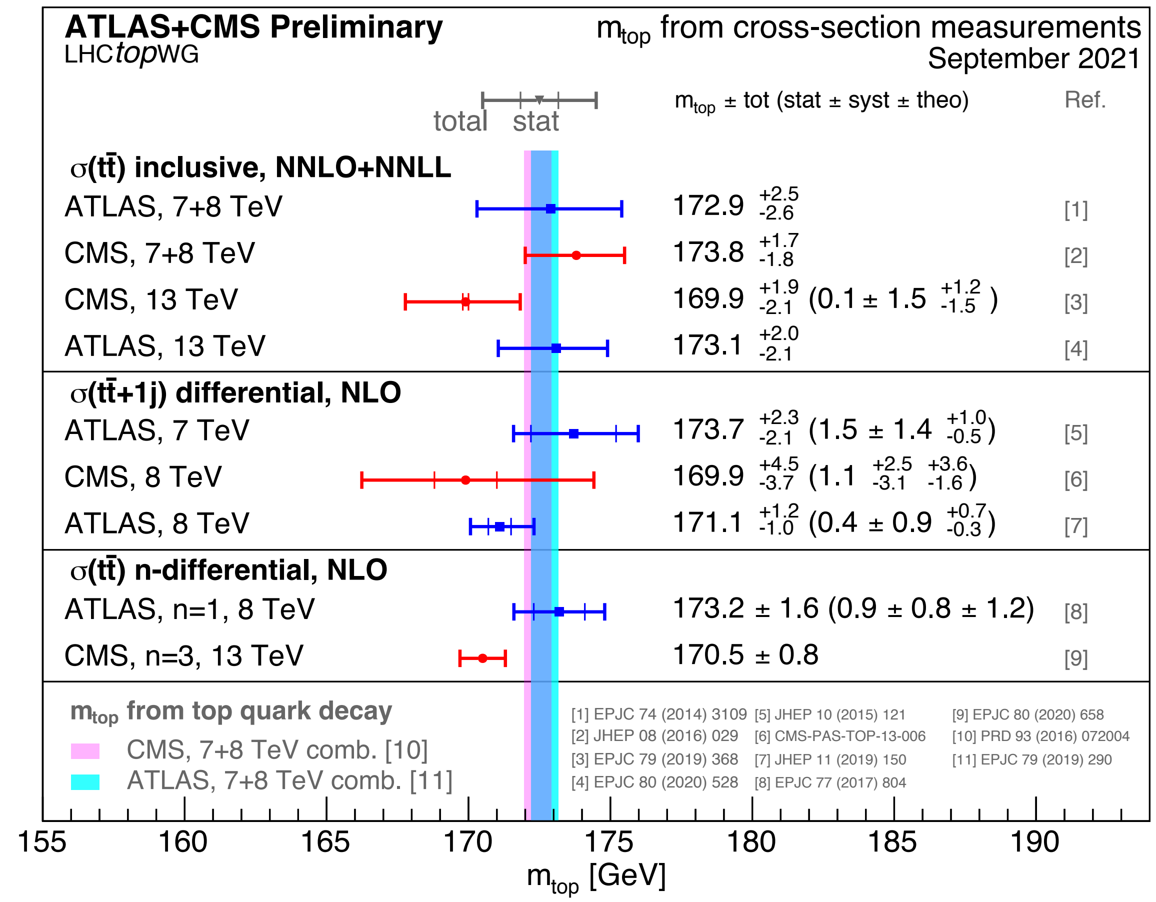
Top mass

Top mass

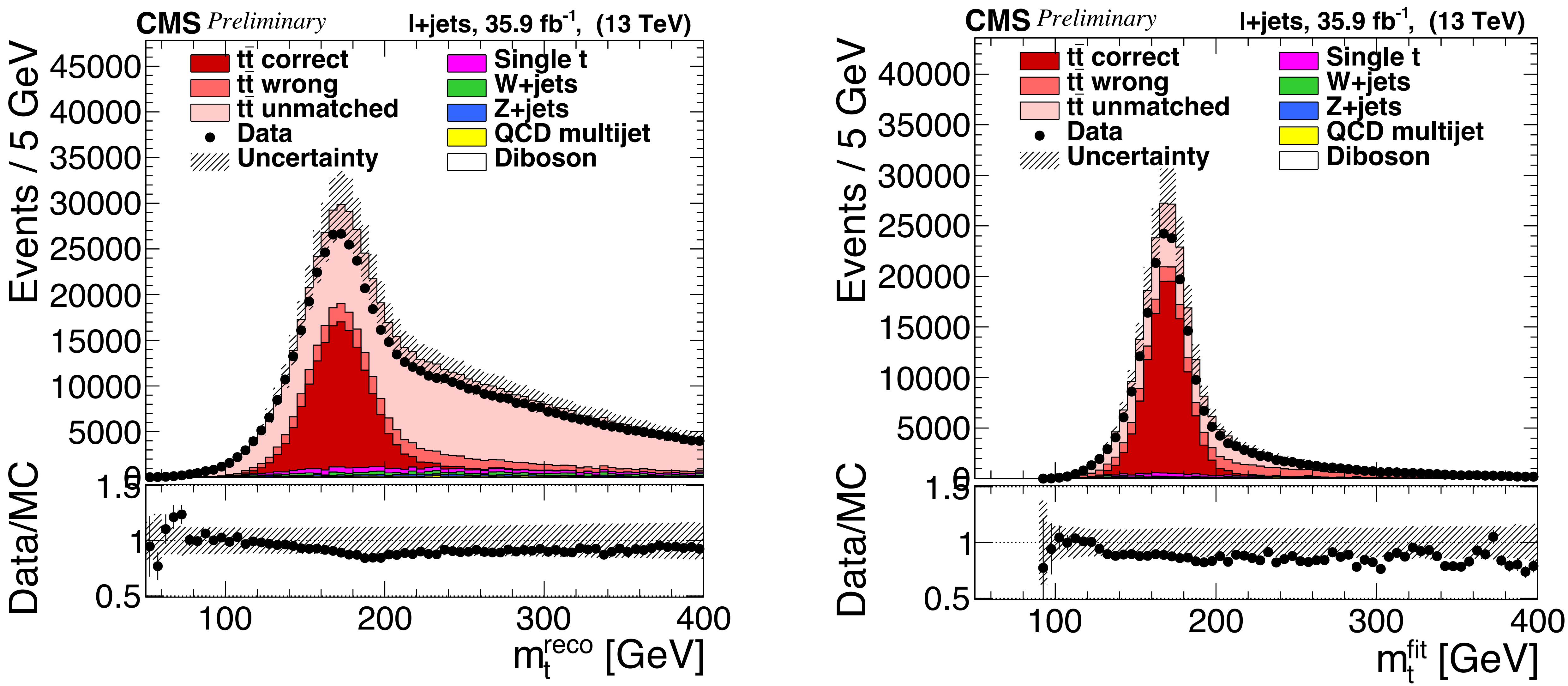




- “Standard” measurements reached ~0.5 GeV in run-1.
- Extractions from cross-section observables consistent, but not as precise.

Top mass

- Recent measurement in lepton+jets channel at 13 TeV.
- 1 lepton, >=4 jets, >= 2 b-jets and kinematic fit is used to reconstruct the top-quarks from the decay products:



TOP-20-008

Top mass

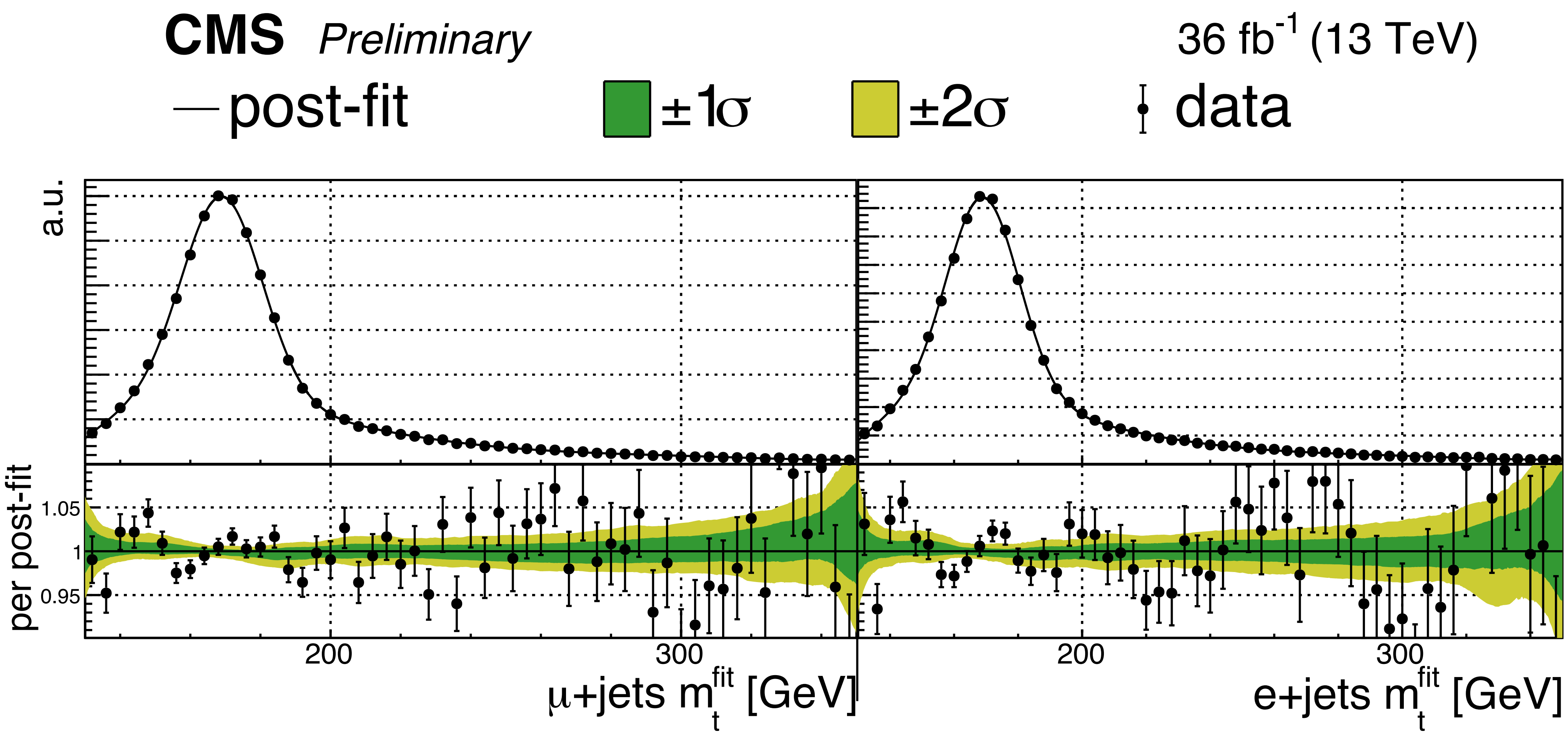
- Five fit variables used to help constrain uncertainties:

histogram		set label				
observable	category	1D	2D	3D	4D	5D
m_{t}^{fit}	$P_{gof} \geq 0.2$	x	x	x	x	x
m_{W}^{reco}	$P_{gof} \geq 0.2$		x	x	x	x
$m_{\ell b}^{reco}$	$P_{gof} < 0.2$			x	x	x
$m_{\ell b}^{reco} / m_{t}^{fit}$	$P_{gof} \geq 0.2$				x	x
R_{bq}^{reco}	$P_{gof} \geq 0.2$					x

- Systematic uncertainties are constrained in the profile-likelihood fit.
  - m_t^{fit} distribution is parameterised by Voigt profile + Chebyshev polynomials - important assumption of the fit is this function can capture all systematic effects.
  - Statistical uncertainties from the parameterisation are also included - essential to avoid underestimate of the uncertainty.

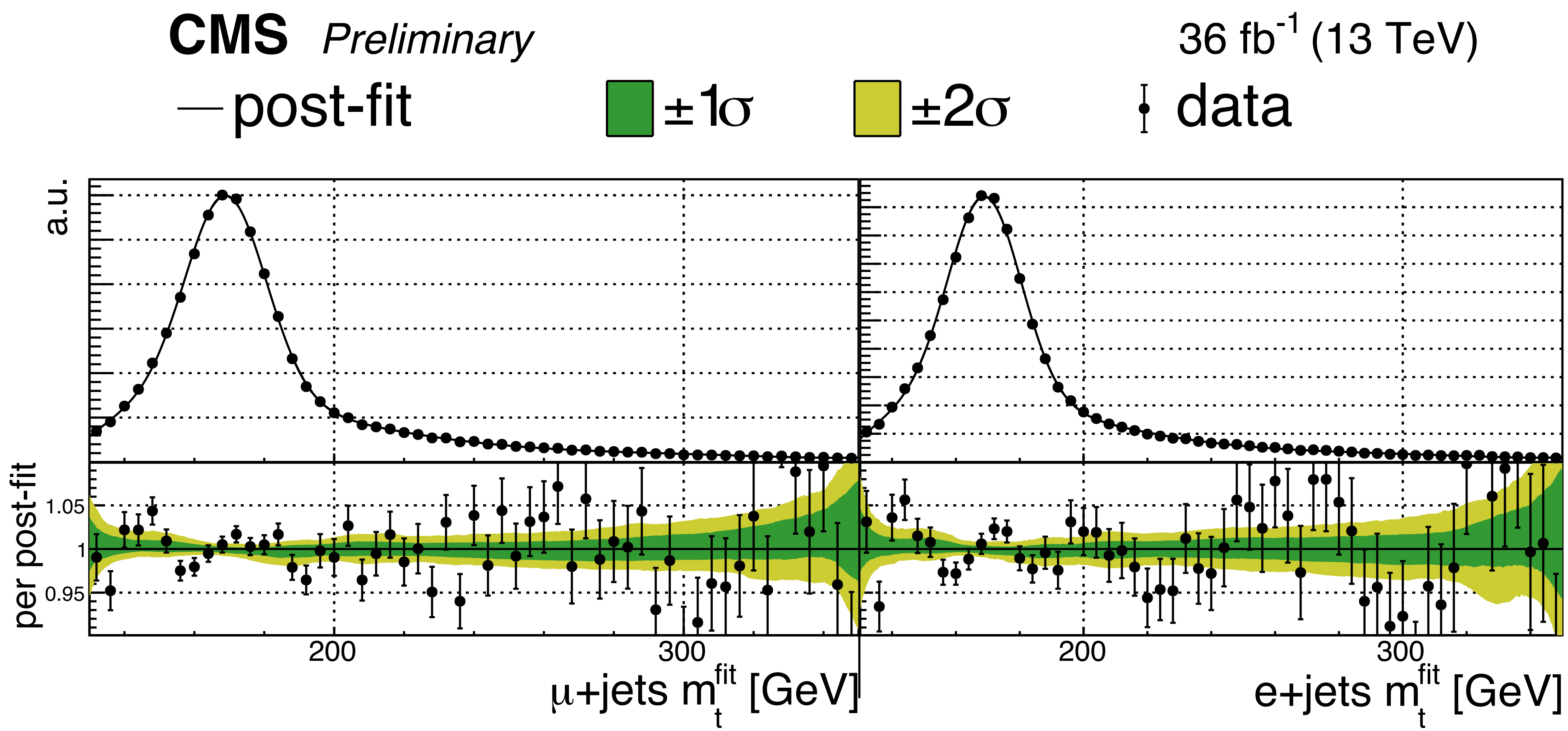
TOP-20-008

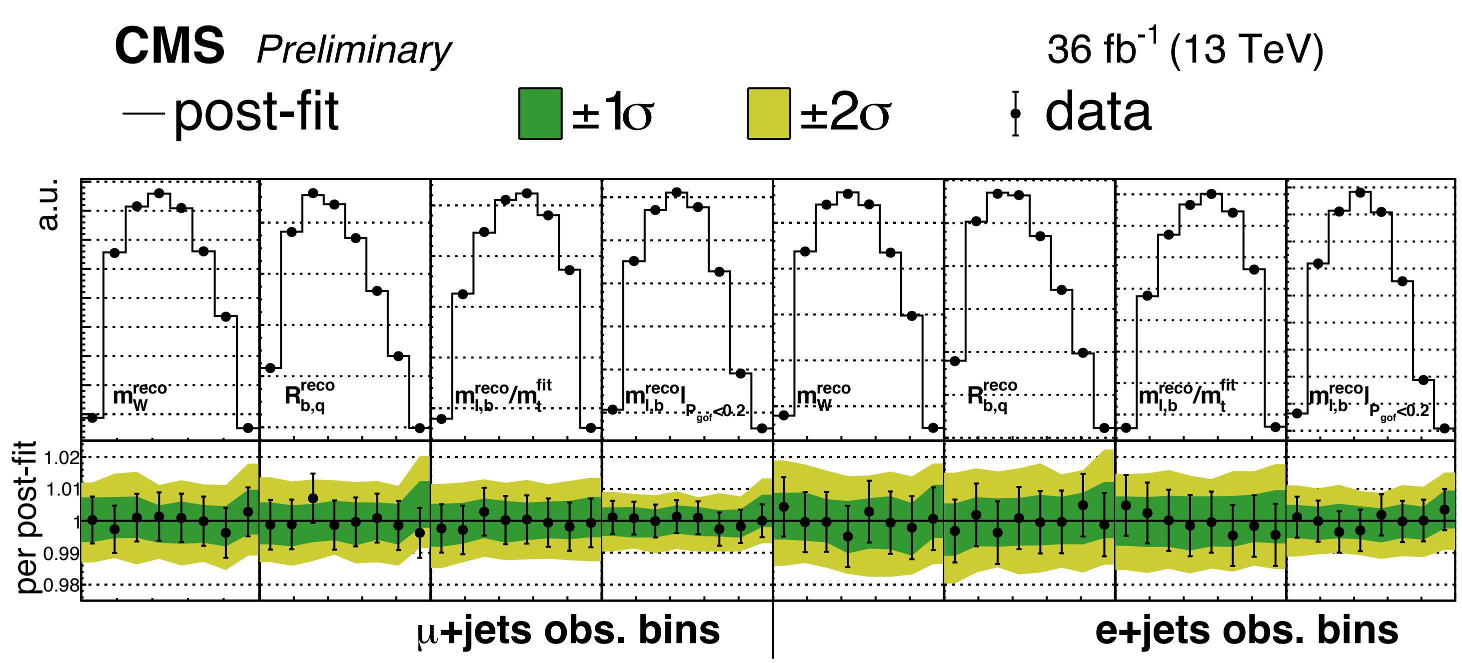
Top mass



TOP-20-008

Top mass





TOP-20-008

Top mass

- Most precise m_t to date: $m_t = 171.77 \pm 0.38$ GeV

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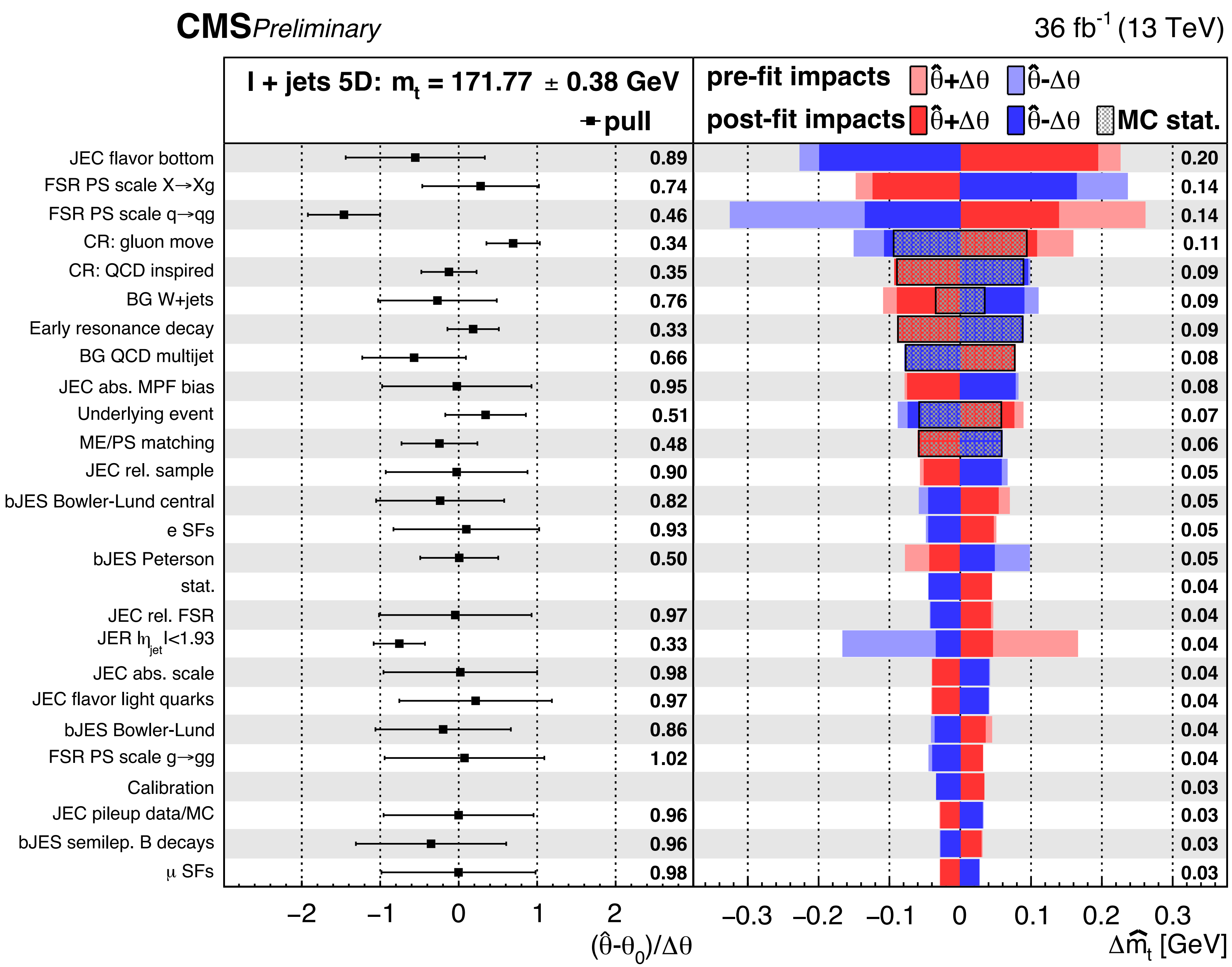

TOP-20-008

- FSR shower scales & JER uncertainties significantly constrained in the fit.
- Largest systematics are b-jet energy scale & FSR scales.

Top mass

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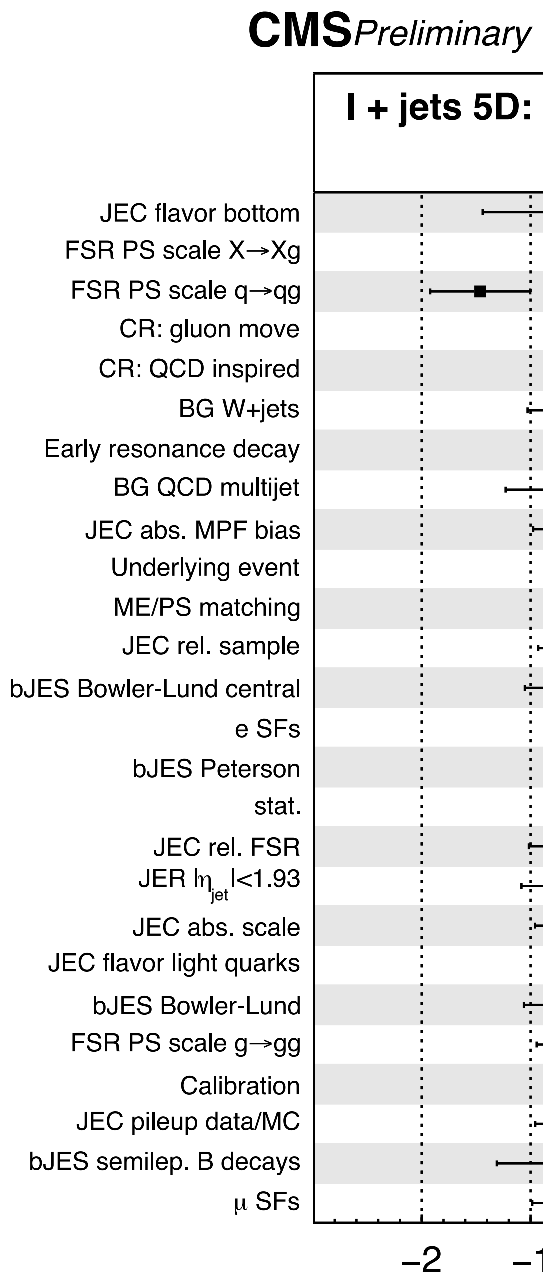

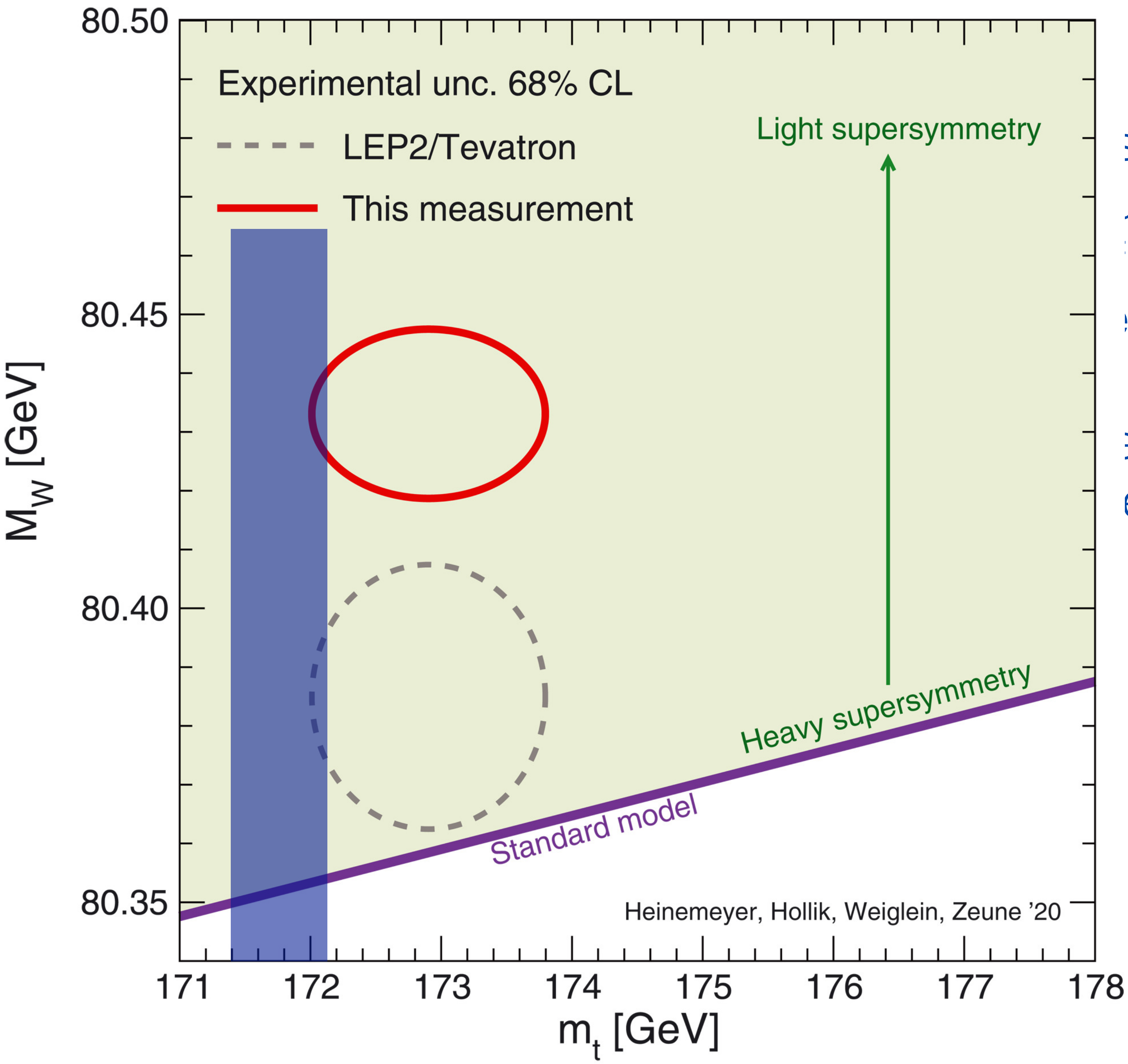

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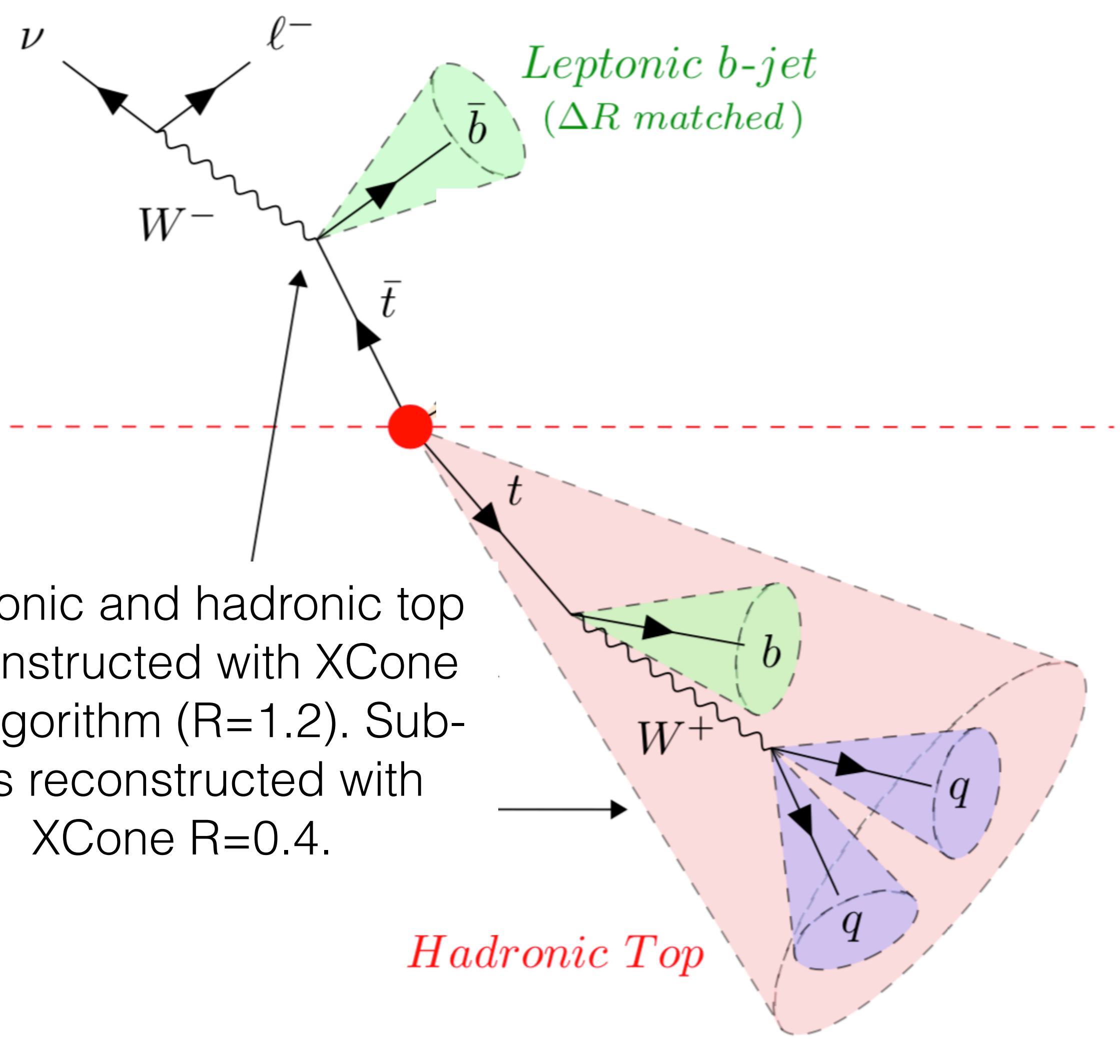
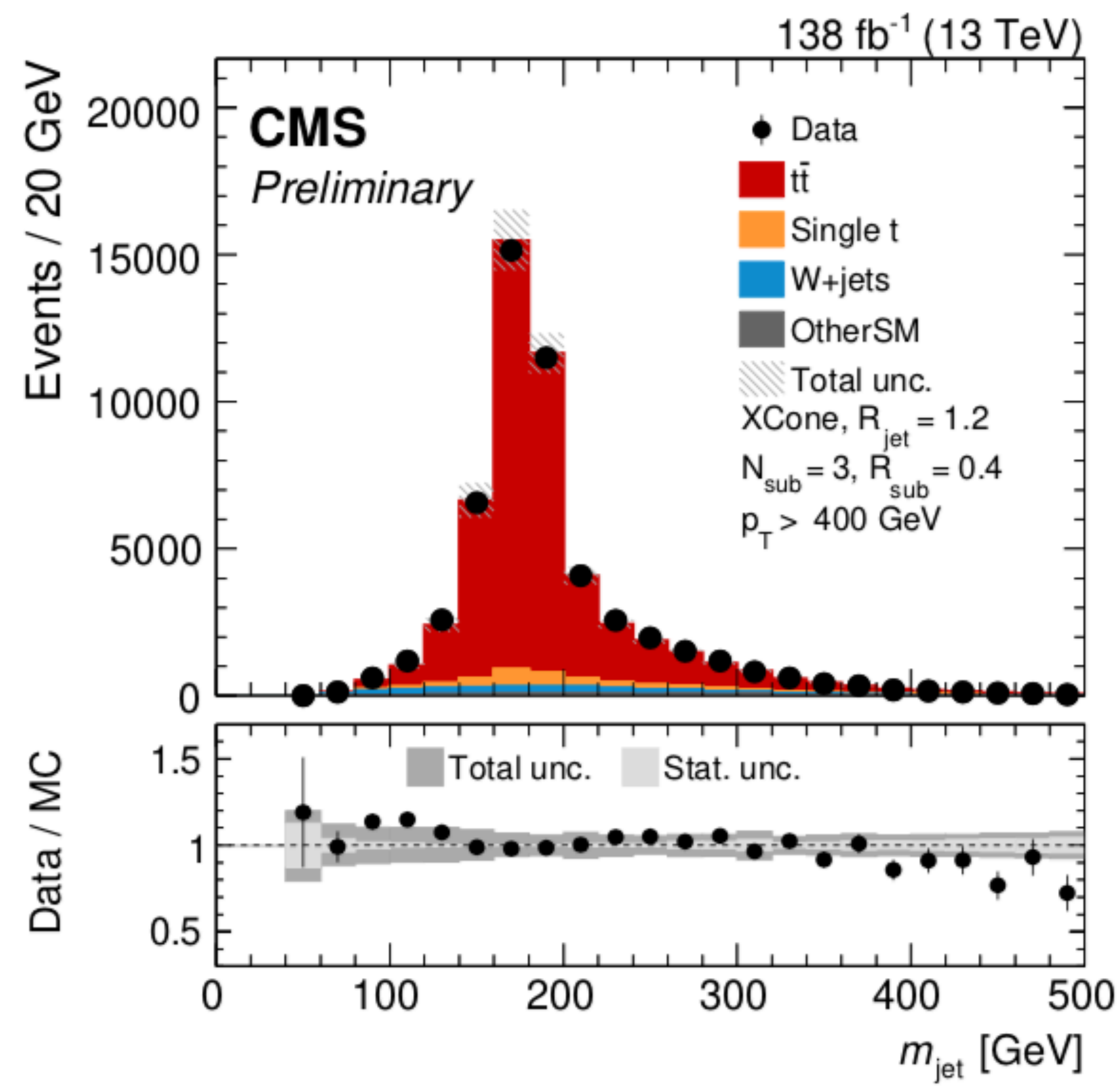
TOP-20-008

Top mass

- New measurement measuring top mass in events with a boosted hadronically decaying top quark.



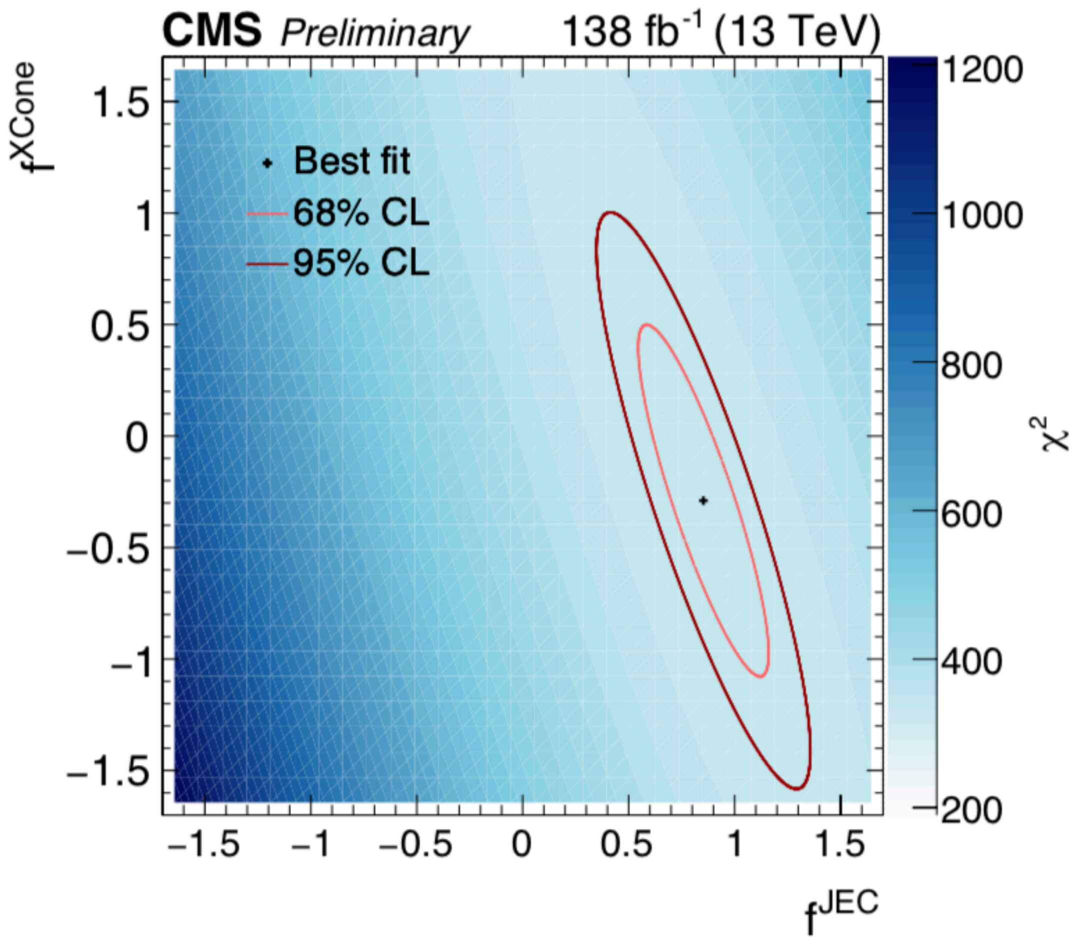
Leptonic and hadronic top reconstructed with XCone jet algorithm (R=1.2). Sub-jets reconstructed with XCone R=0.4.



TOP-21-012

Top mass

- Use of XCone algorithm means each boosted large-R top-quark jet has exactly 3 sub-jets.
- Invariant mass of 2 non-b sub-jets is used to calibrate the energy scale of the jets & hence the mass scale of the large-R jet:



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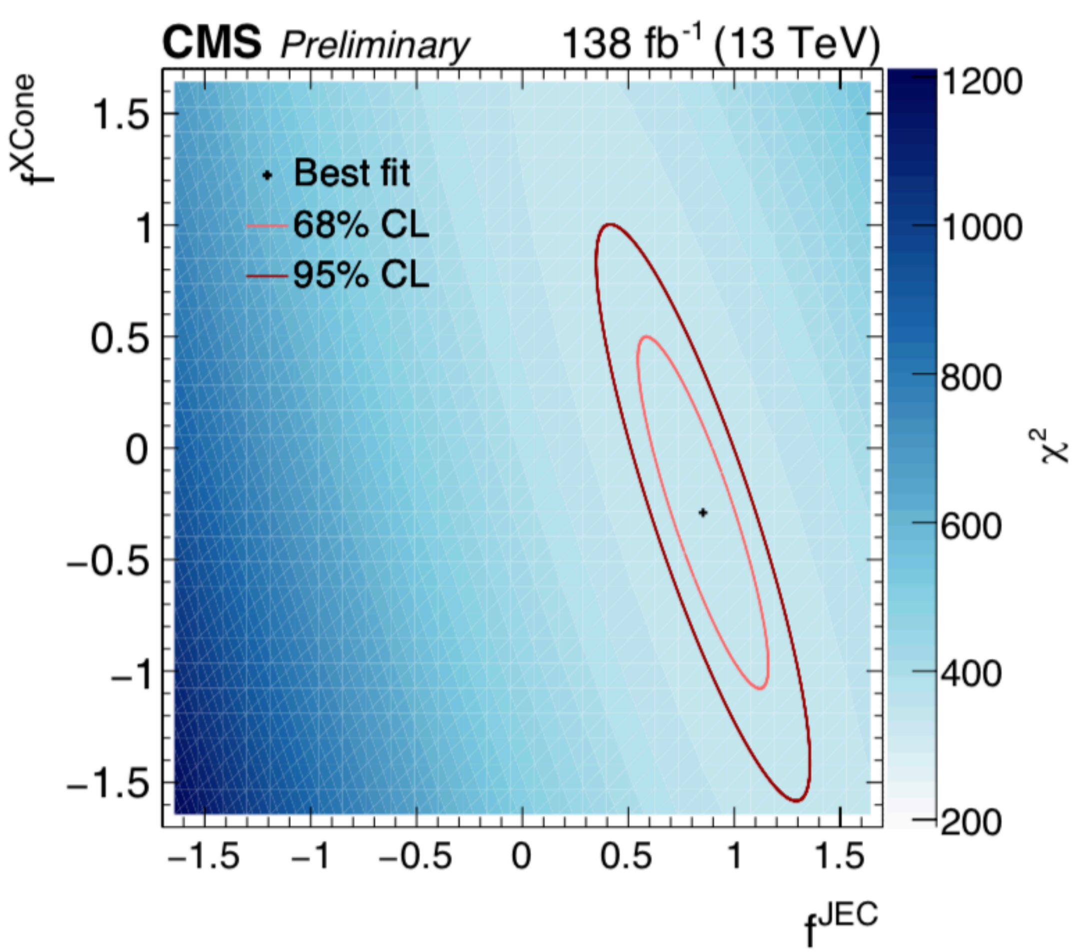
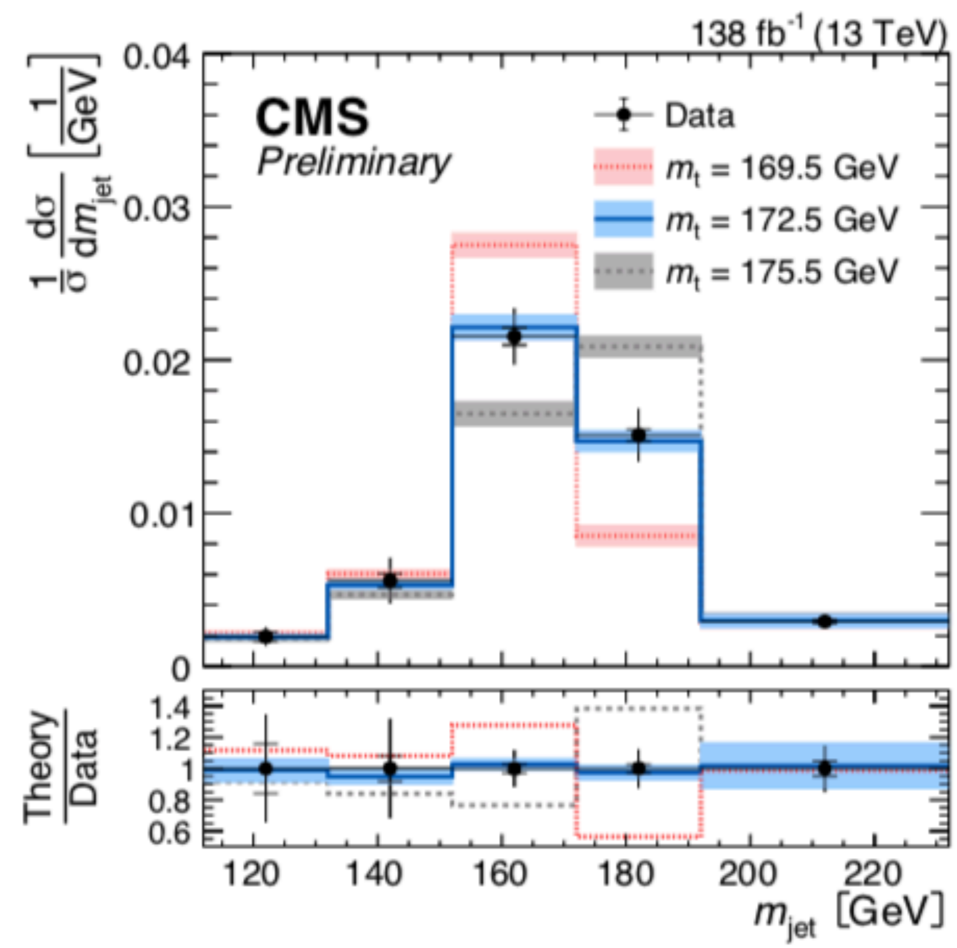
- Mass of top-quark jet is unfolded to particle-level:





TOP-21-012

Top mass

- Top mass is extracted from unfolded distribution.
  - Use of unfolded distribution means in future data can be compared to improved theoretical calculations.

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

  - More than factor 3 improvement from first measurement with boosted top-quarks!

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Source	Uncertainty [GeV]
Total	0.81
Statistical	0.22
Experimental total	0.57
Jet energy resolution	0.40
Jet mass scale	0.27
Jet mass scale flavour	0.27
Jet energy scale	0.09
Pileup	0.08
MC statistics	0.07
Additional XCone corrections	0.03
Backgrounds	0.01
Model total	0.48
Choice of m_t	0.37
h_{damp}	0.19
Colour reconnection	0.19
Underlying event tune	0.12
μ_F, μ_R scales	0.07
ISR	0.06
FSR	0.03
Theory total	0.24
FSR	0.14
Underlying event tune	0.13
Colour reconnection	0.10
μ_F, μ_R scales	0.06
h_{damp}	0.06
ISR	0.06

TOP-21-012

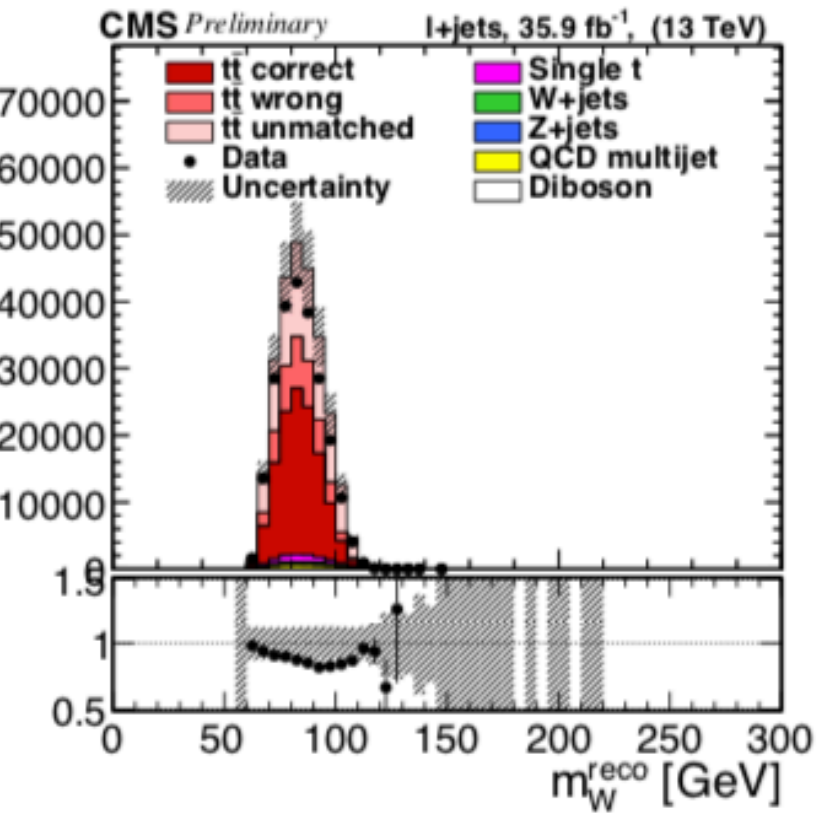
Summary

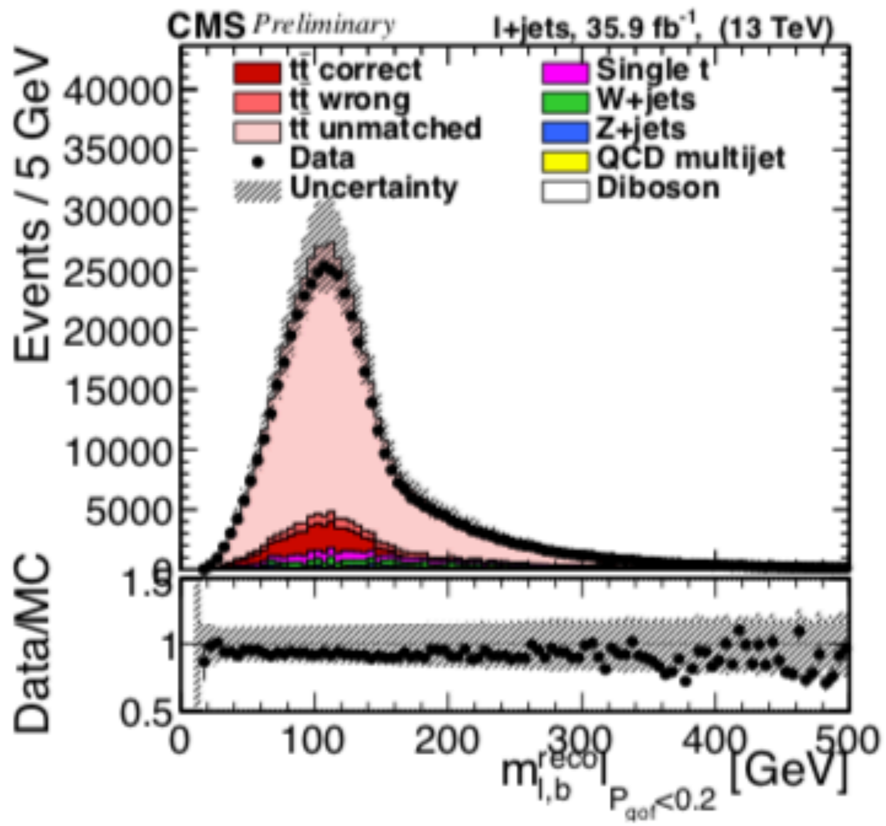
- LHC delivers as a top factory - ATLAS & CMS now make precise measurements of top-quark properties and interesting ttX processes.
- No new physics seen in the data, EFT providing nice way to interpret the measurements.
- Latest CMS top-quark mass results with impressive precision demonstrates the possibilities for continuing to improve our measurements through run-3.

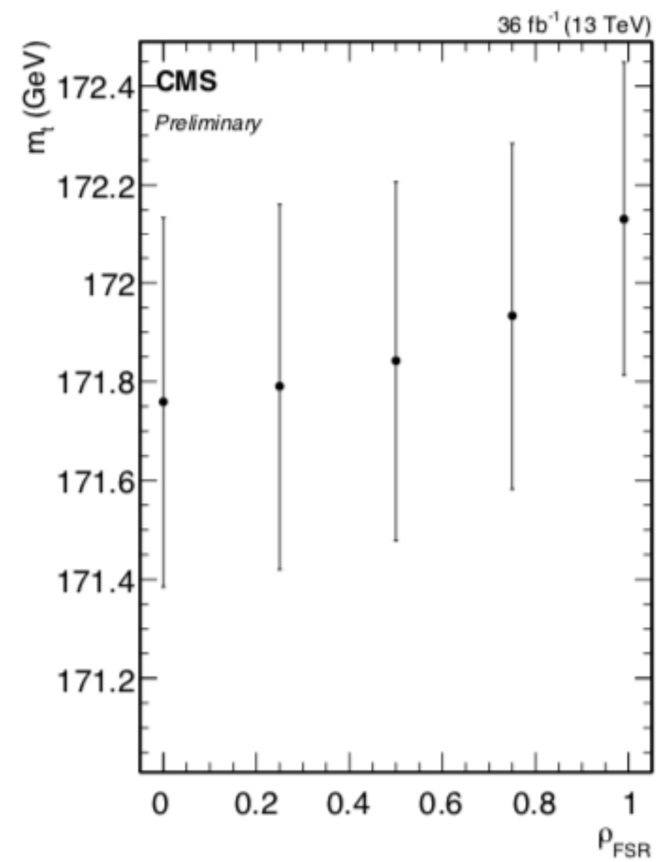
Backup

Top mass

- Pre-fit mW and mlb distributions and dependence of m(t) on correlation between FSR nuisance parameters.







Top mass measurement in ttbar+jets

- Dilepton channel with >= 1 jet (p_T > 30 GeV) is used to measure:

$$\frac{d\sigma}{d\rho}; \rho = \frac{2m_0}{m_{t\bar{t}+\text{jet}}}$$

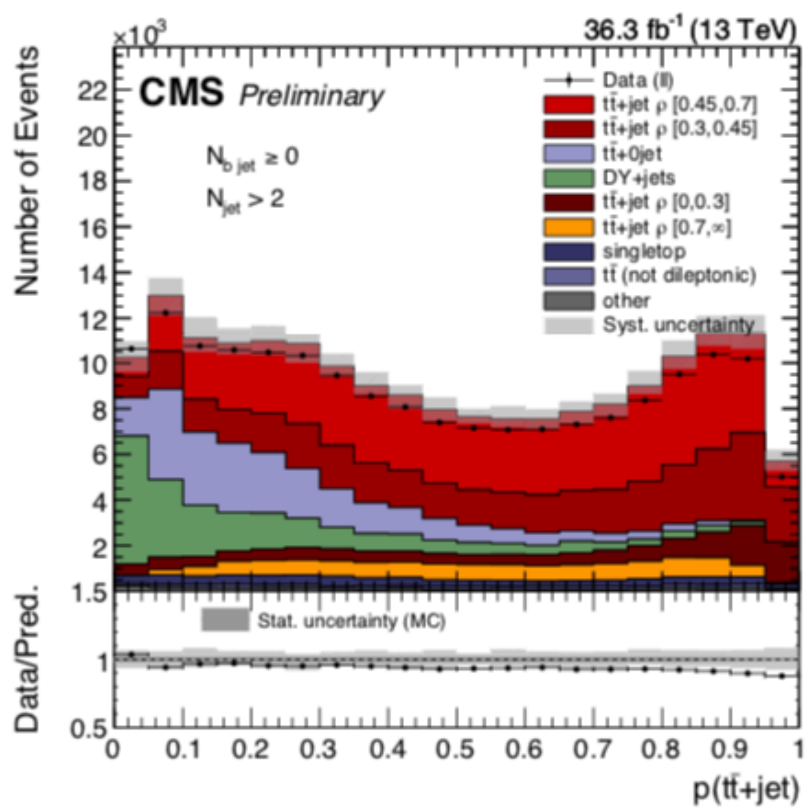
- Two kinematic reconstruction techniques are used, one assuming mt = 172.5 GeV and the other with no mt assumption.
- The ρ variable from each reconstruction technique, plus 8 additional variables are used as input to a regression NN to provide an improved estimate of ρ.
- An additional NN is used to separated tt+jet, Z+jets and tt+0 jet events.

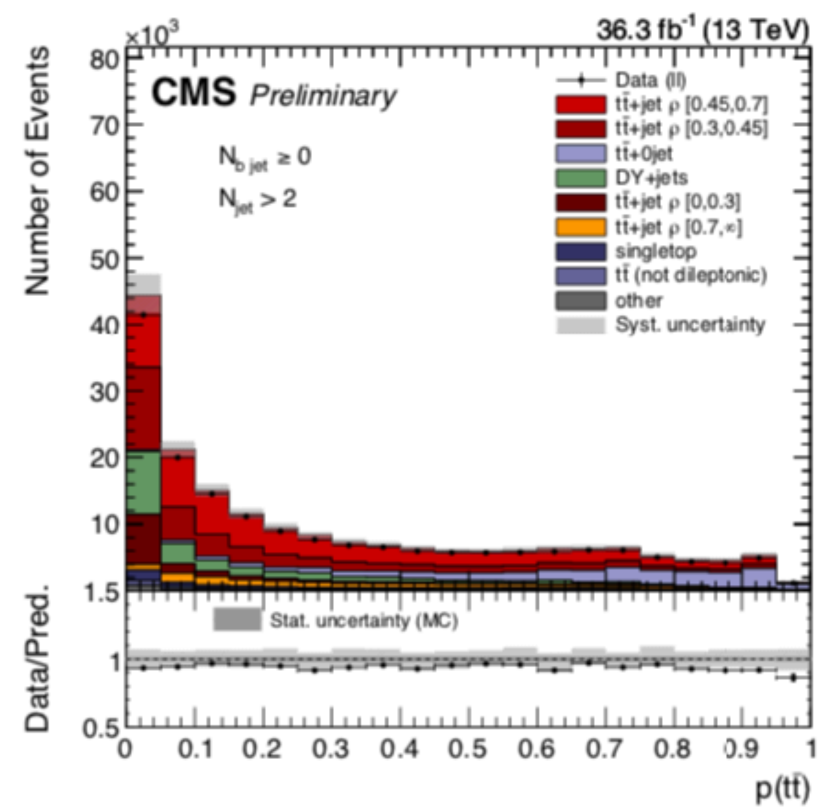
Top mass measurement in ttbar+jets

- Cross-section is measured from a fit to multiple regions / observables.
- Fit includes m_t(MC) as free parameter to remove dependence from the measured cross-section.

	reconstructed ρ				no reconstructed ρ	
	$N_{\text{jet}} = 3$				$N_{\text{jet}} \leq 1$	$N_{\text{jet}} = 2$
	$\rho < 0.3$	$0.3 < \rho < 0.7$	$0.45 < \rho < 0.7$	$\rho > 0.7$		
$N_{\text{b jet}} = 1$	R_{NN}	R_{NN}	R_{NN}	R_{NN}	$p_T^{\text{first jet}}$	$p_T^{\text{second jet}}$
$N_{\text{b jet}} \geq 2$	R_{NN}	R_{NN}	R_{NN}	R_{NN}	—	$m_{\ell b}^{\text{min}}$

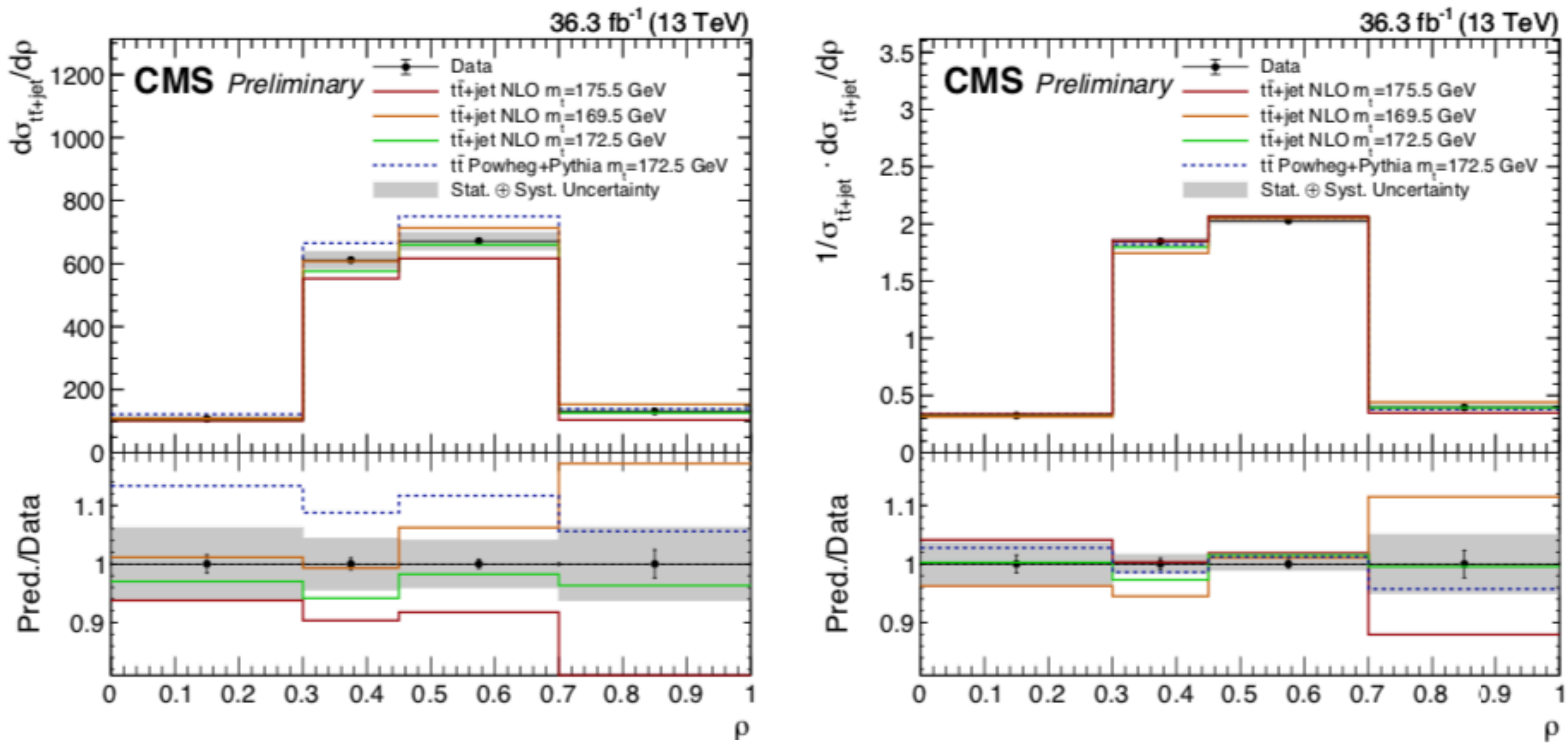
$$R_{\text{NN}} = \frac{p(t\bar{t}+\text{jet})}{p(t\bar{t}+\text{jet}) + p(t\bar{t}+0\,\text{jet})}$$





Top mass measurement in ttbar+jets

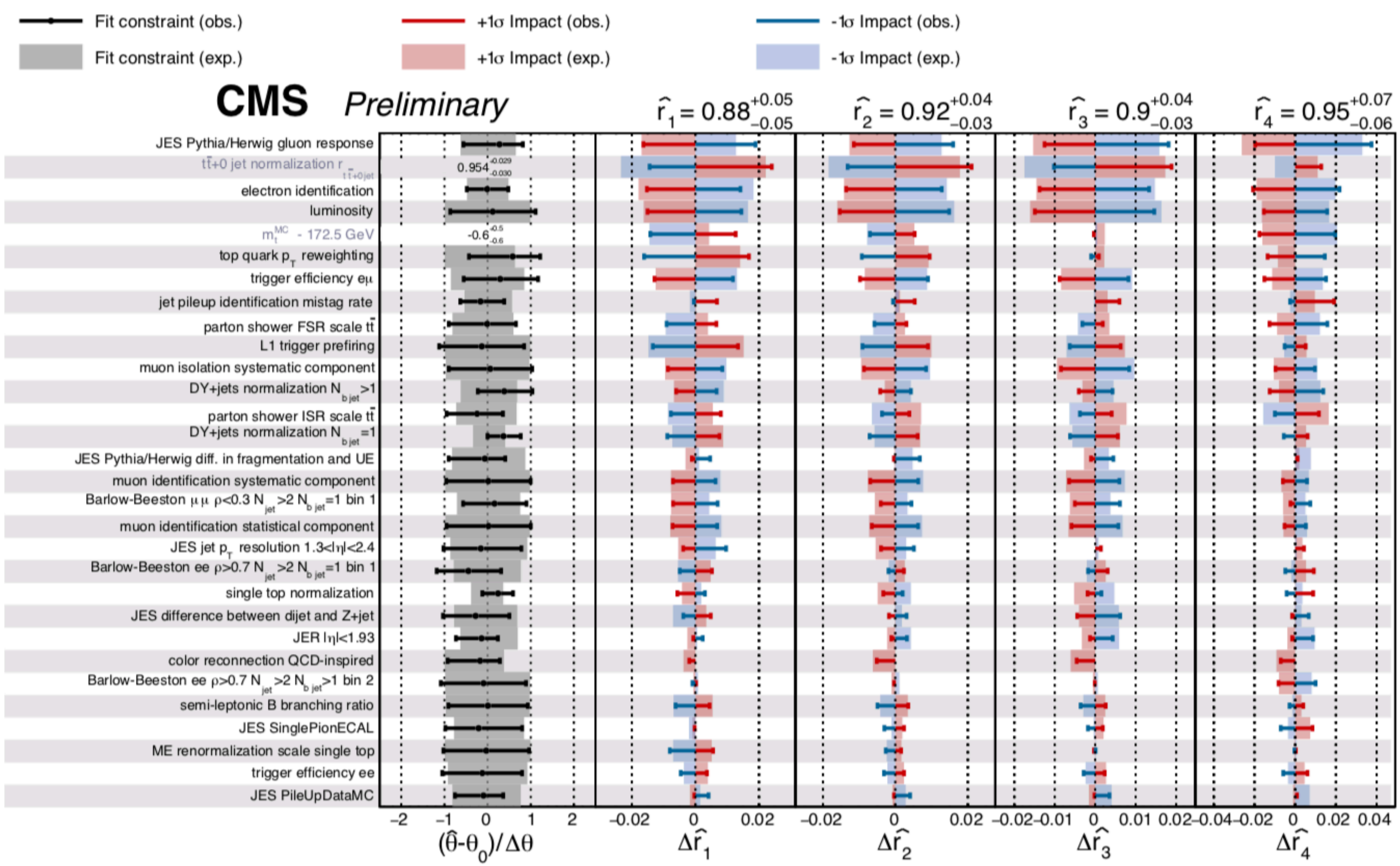
- Measured cross-section is used to extract mt by comparison with NLO prediction:



$$m_t^{pole} = 172.94 \pm 1.27(\text{fit+PDF+extr}) \pm^{0.51}_{0.43} (\text{scale})\,\text{GeV}$$ ABMP16NLO PDF

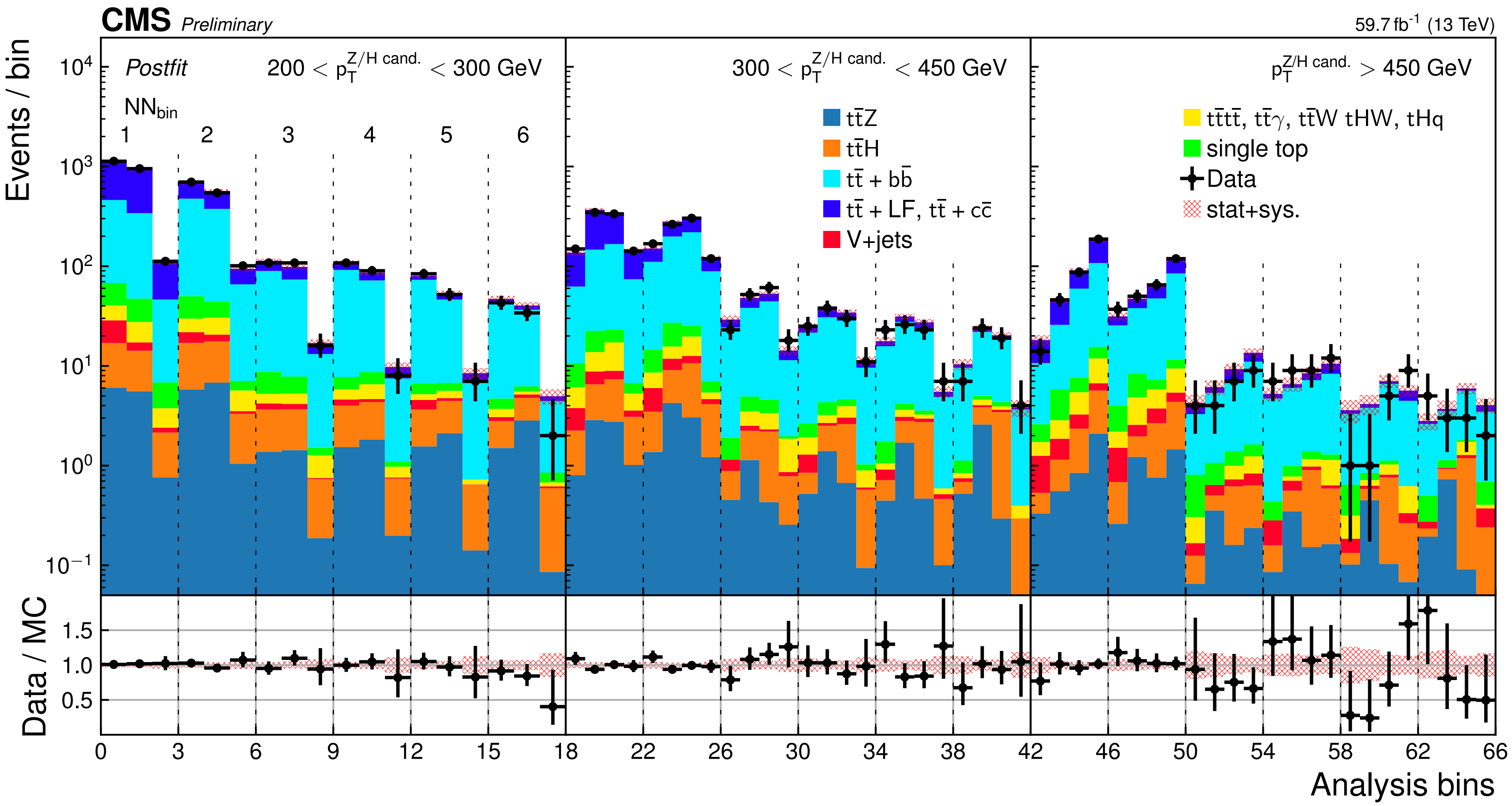
$$m_t^{pole} = 172.16 \pm 1.35(\text{fit+PDF+extr}) \pm^{0.50}_{0.40} (\text{scale})\,\text{GeV}.$$ CT18NLO PDF

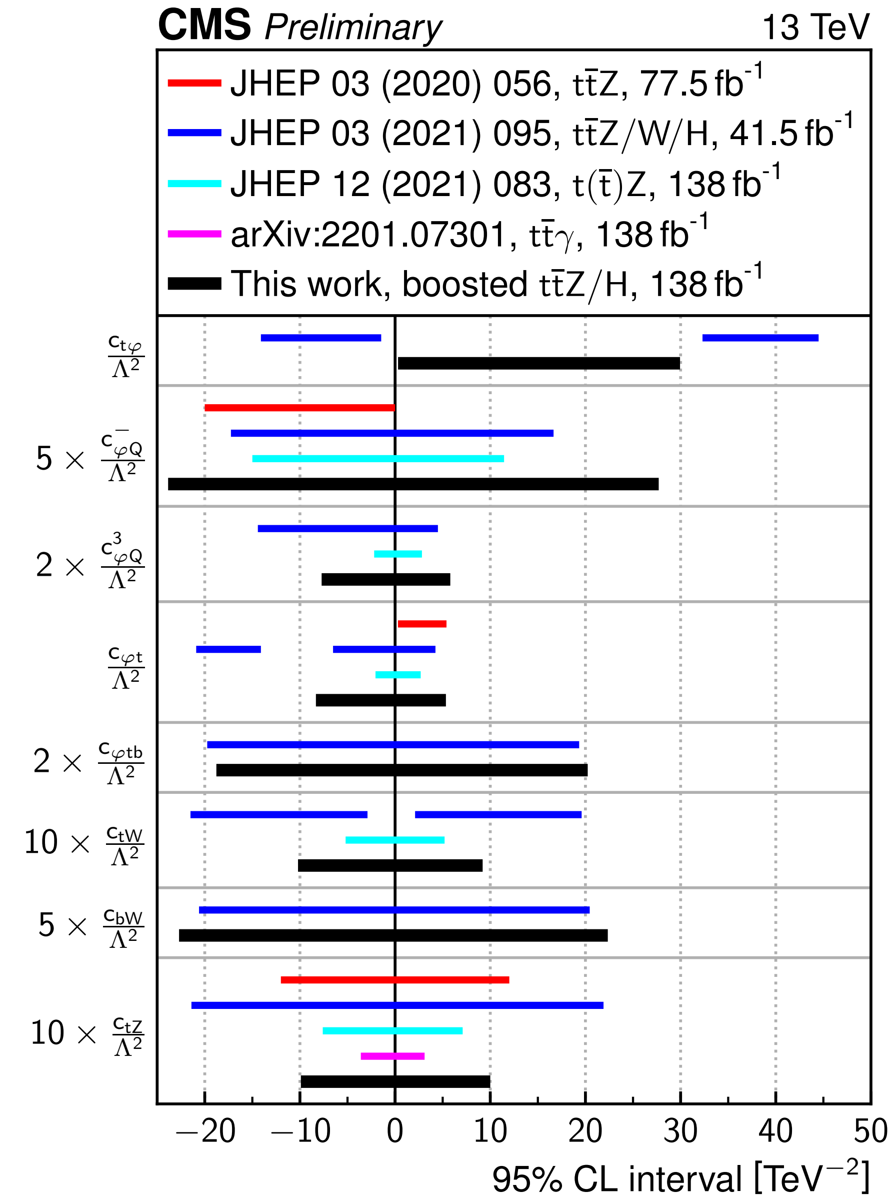
Top mass measurement in ttbar+jets



Boosted $t\bar{t}Z/H$

- Fitted distribution (2018 data) and EFT limits:





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