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Measurement of the jet mass distribution in decays of boosted top quarks and the top quark mass with CMS

Alexander Paasch[1], Johannes Haller[1], Roman Kogler[2], Dennis Schwarz[3]

16.06.2022, LHC TOP WG

1. Universität Hamburg
2. DESY, Hamburg
3. Austrian Academy of Sciences, Vienna

FSP CMS
Erforschung von Universum und Materie

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

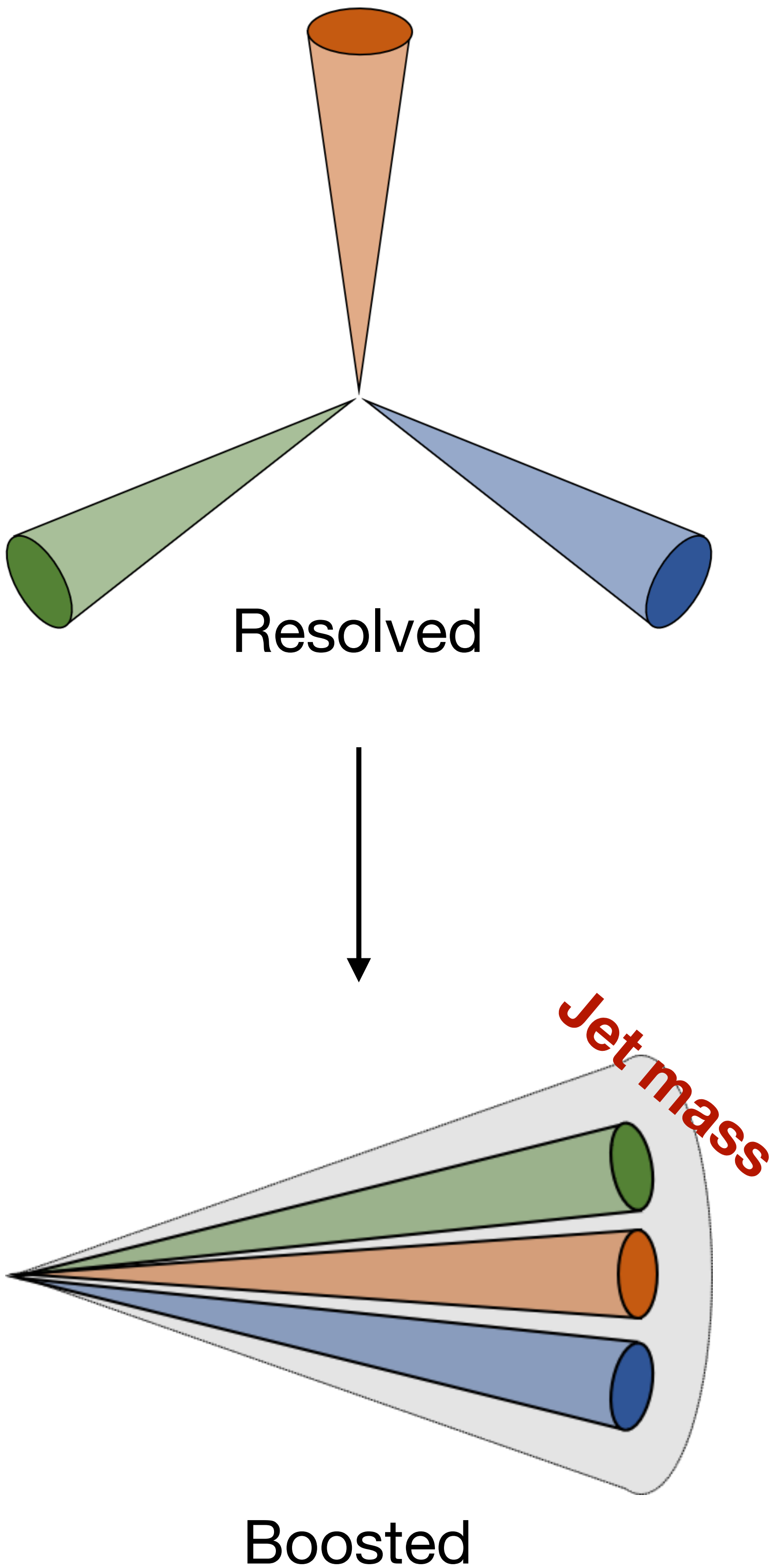
Analysis goal

Direct measurements

- Reconstruct $t\bar{t}$ in resolved regime
- Reconstruct top mass → Fit MC to data
- Most precise measurements of m_{top}

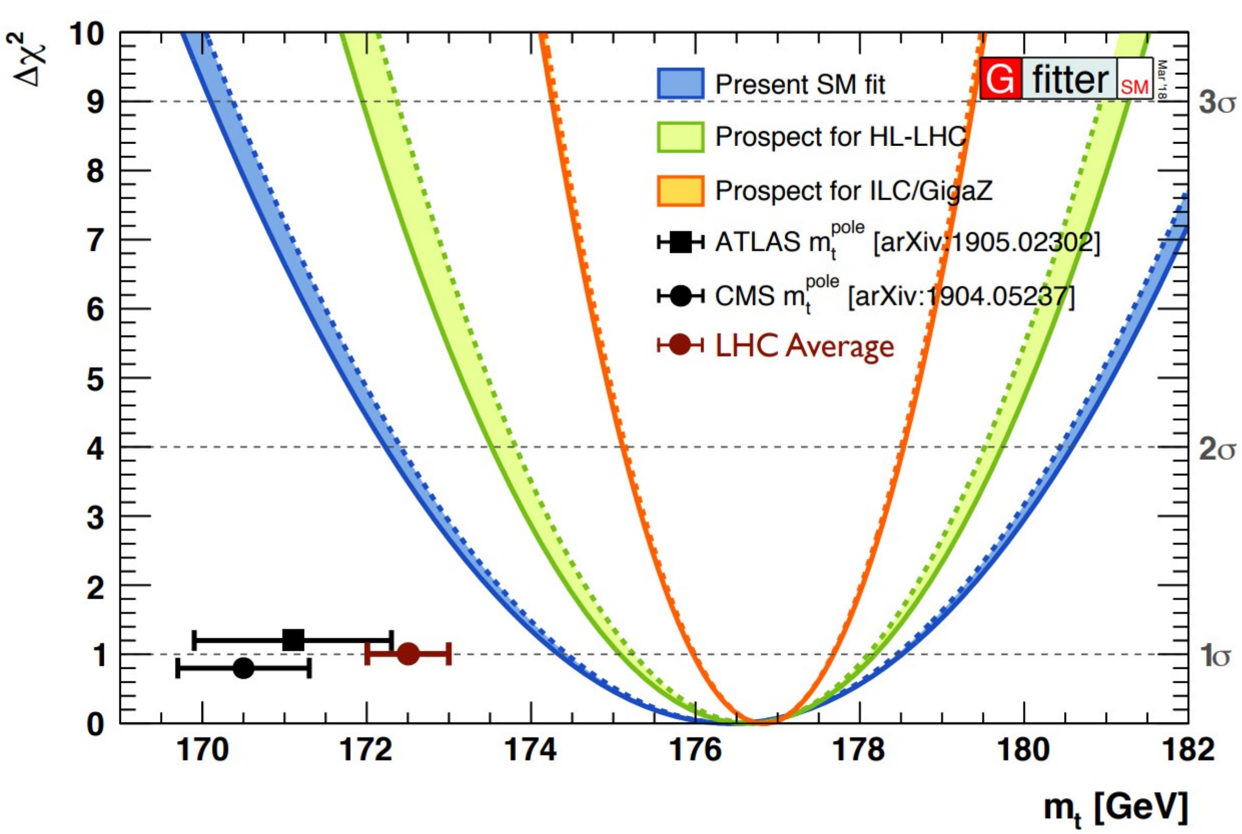
This approach

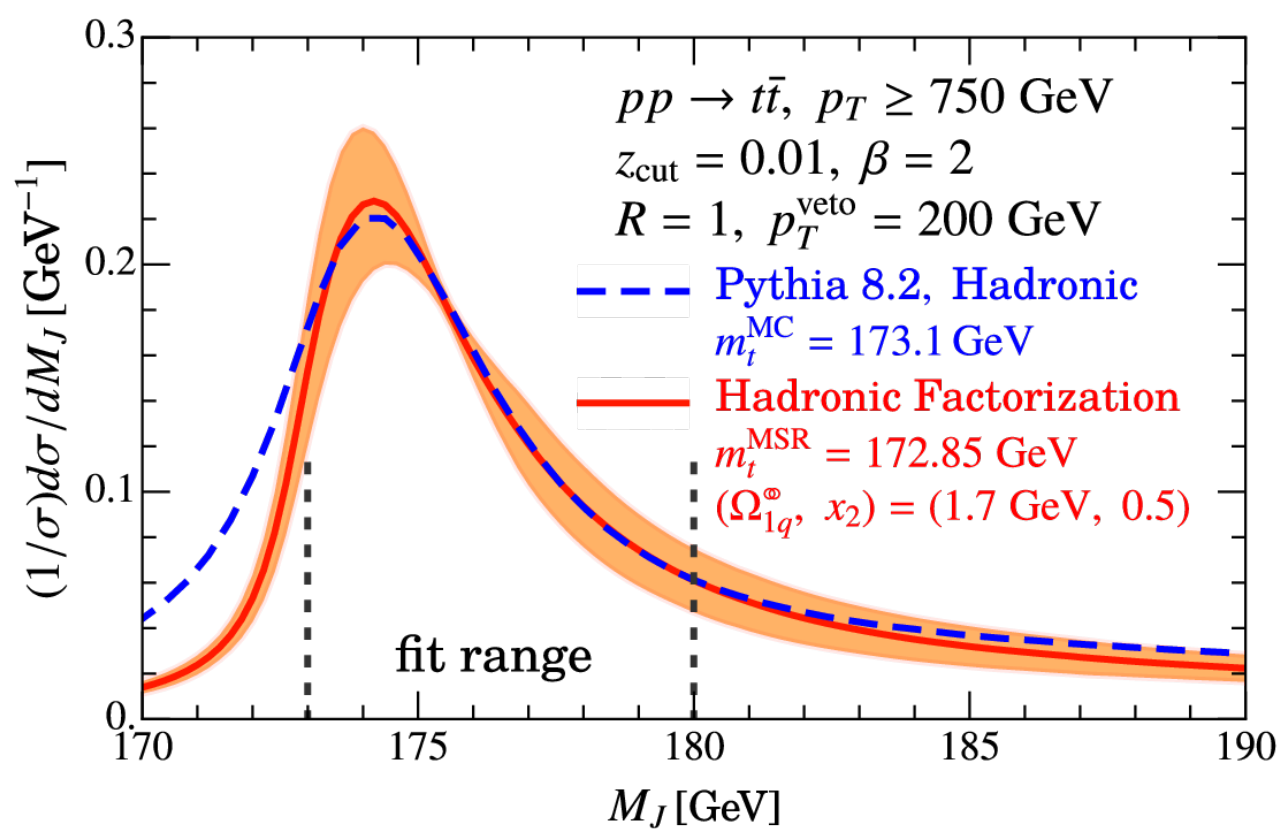
- Reconstruct hadronic top quark decay in single jet (Boosted regime)
- Measure jet mass: $m_{\mathrm{jet}} = \sqrt{p^2_{\mathrm{jet}}}$
- Unfold to particle level
- Aiming for analytic calculations



Why boosted top quarks?

- Tension between predictions and measurements
- m_{top} measurements dominated by threshold production
  - Explore boosted regime
- Comparison to analytic calculations → Not relying on simulations
  - Phase-space not accessible yet



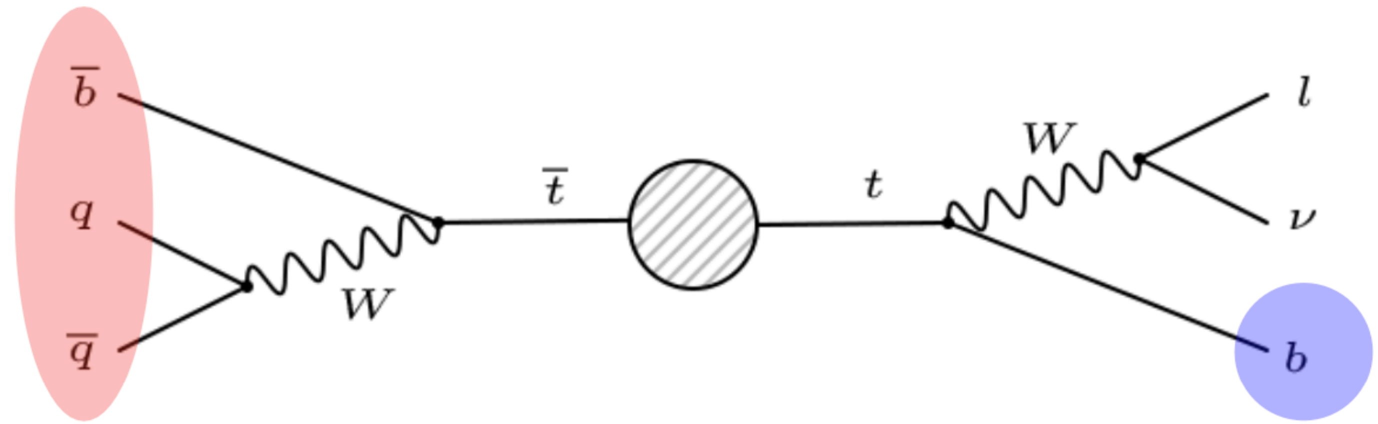


[A. H. Hoang et al., Phys.Rev.D 100 (2019) 7, 074021]

Selection of highly energetic $\mathrm{t\bar{t}}$ events

Aiming for $\ell + \mathrm{jets}$ channel of $\mathrm{t\bar{t}}$ events

- Use leptonic decay as a tag for $\mathrm{t\bar{t}}$ events
- Exactly one lepton (μ or e)

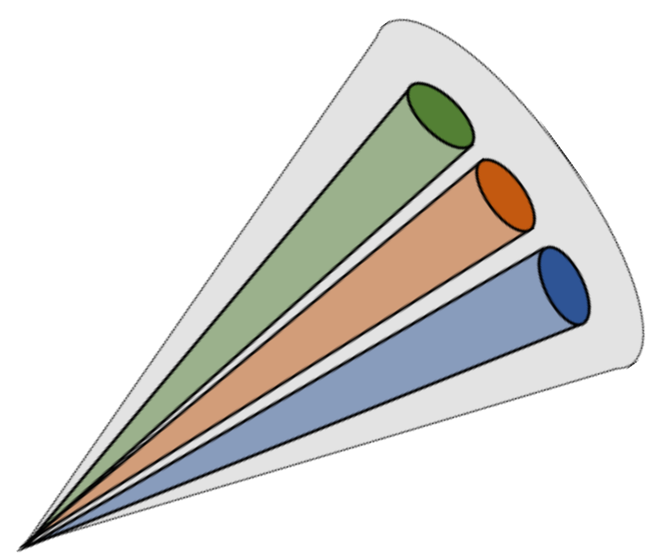


Select boosted top quarks

- $p_{\mathrm{T,\ hadjet}} > 400\ \mathrm{GeV}$

Suppress unmerged top quark decays

- $m_{\mathrm{hadjet}} > m_{\mathrm{lepjet}+\ell}$



Previous Measurements at CMS

Run I at $\sqrt{s} = 8$ TeV [EPJC volume 77, 467]

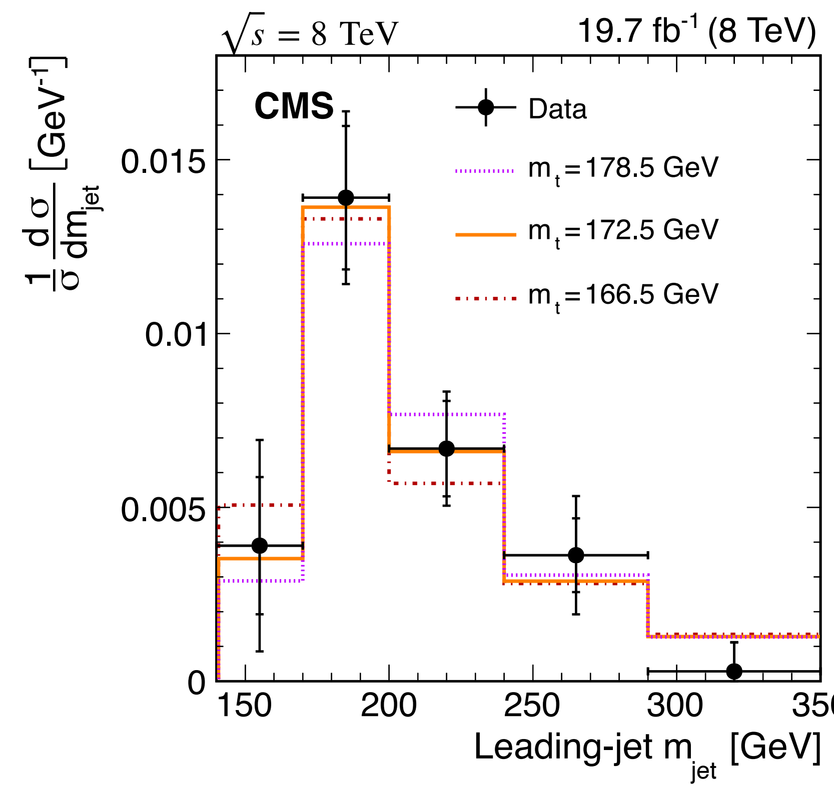
- Cambrigde/Aachen with $R = 1.2$
- $m_{\text{top}} = 170.8 \pm 9.0$ GeV

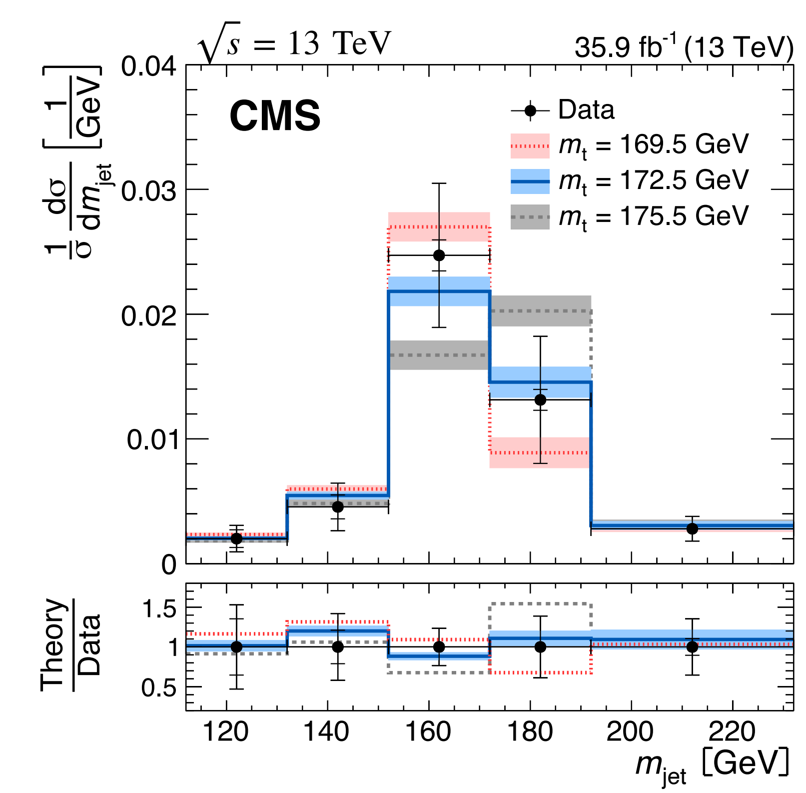
Run II at $\sqrt{s} = 13$ TeV [Phys. Rev. Lett. 124, 202001]

- Only data from 2016
- XCone jet algorithm
- $m_{\text{top}} = 172.6 \pm 2.5$ GeV

Now improve analysis with full Run II

- Dedicated studies on dominant systematic uncertainties

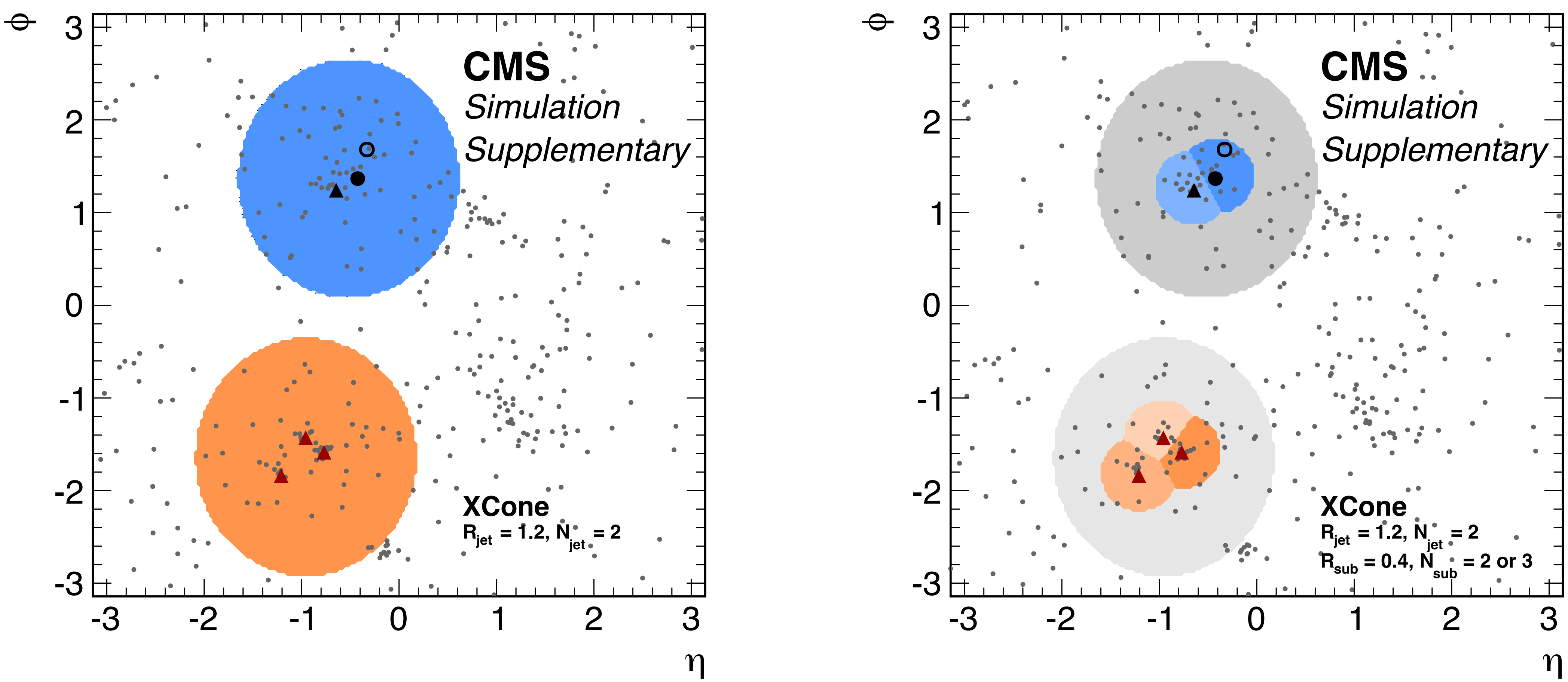




2-step clustering using XCone jet algorithm [JHEP 2015, 72]

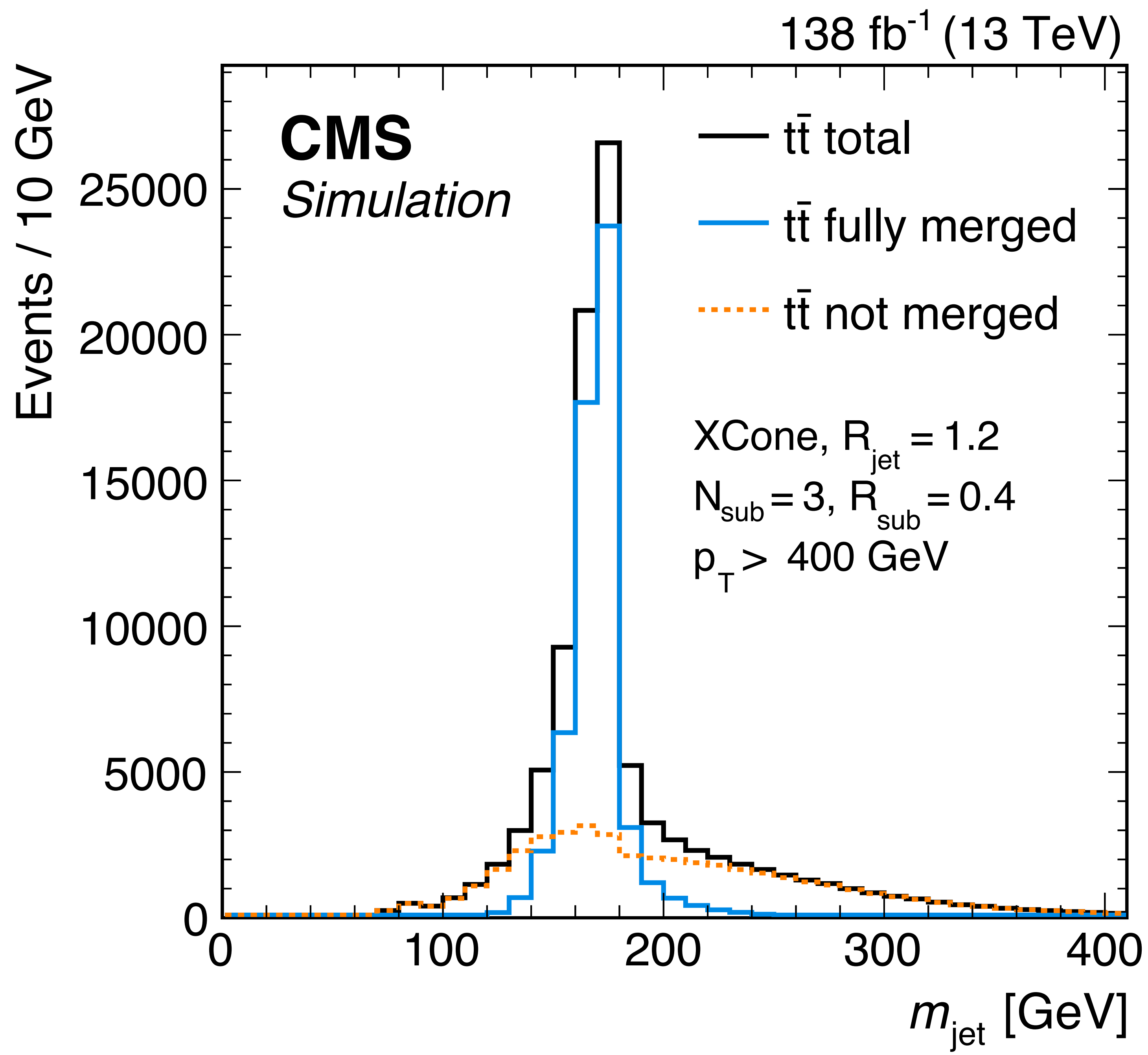
- Cluster two jets with large radius
- Rerun clustering with $N = 3$ to find subjets
- Combine subjets to final jet

Dedicated corrections for the XCone subjects depending on η and p_{T}



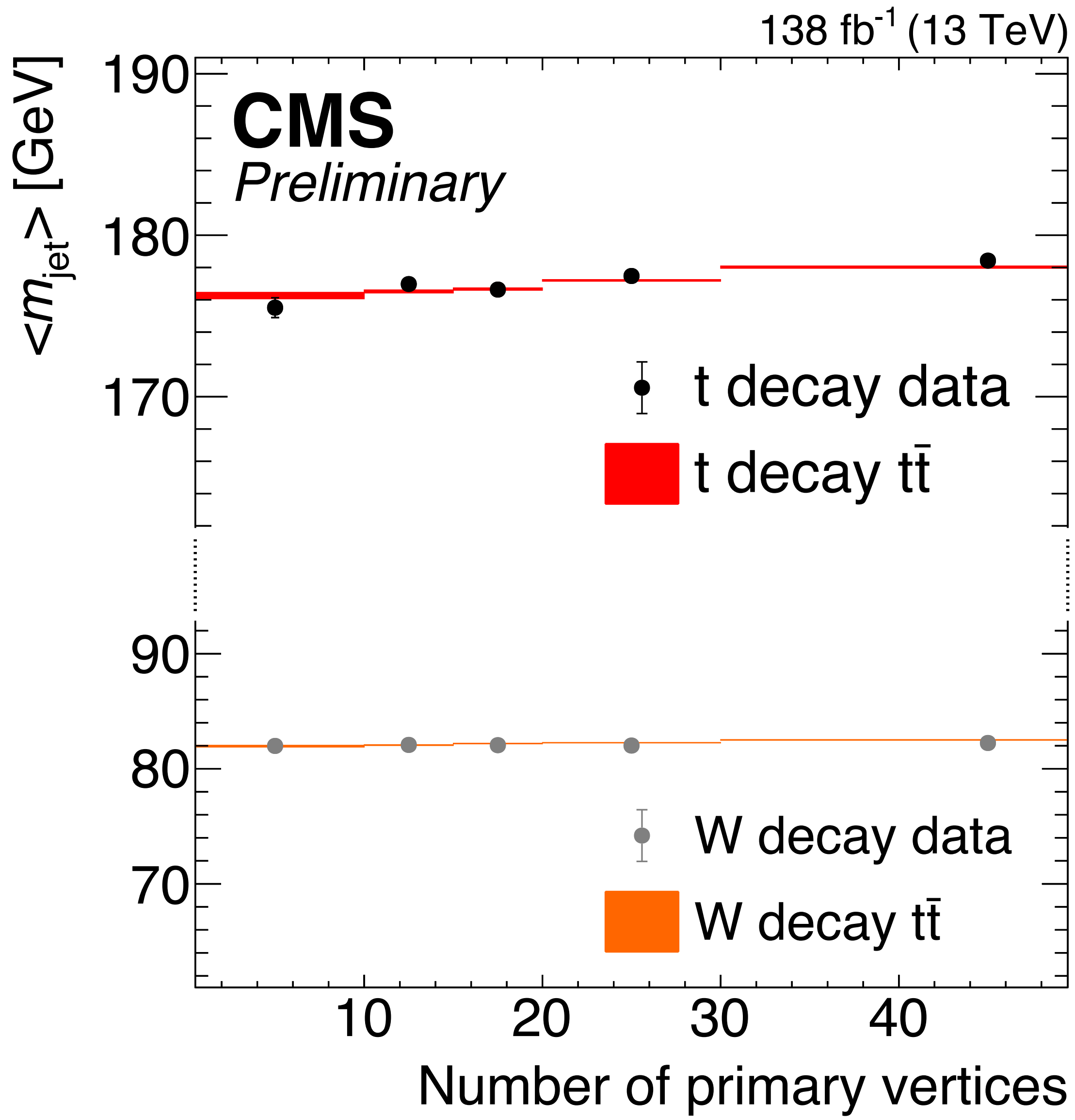
Suppl. Material of [Phys. Rev. Lett. 124, 202001] , TOP-19-005

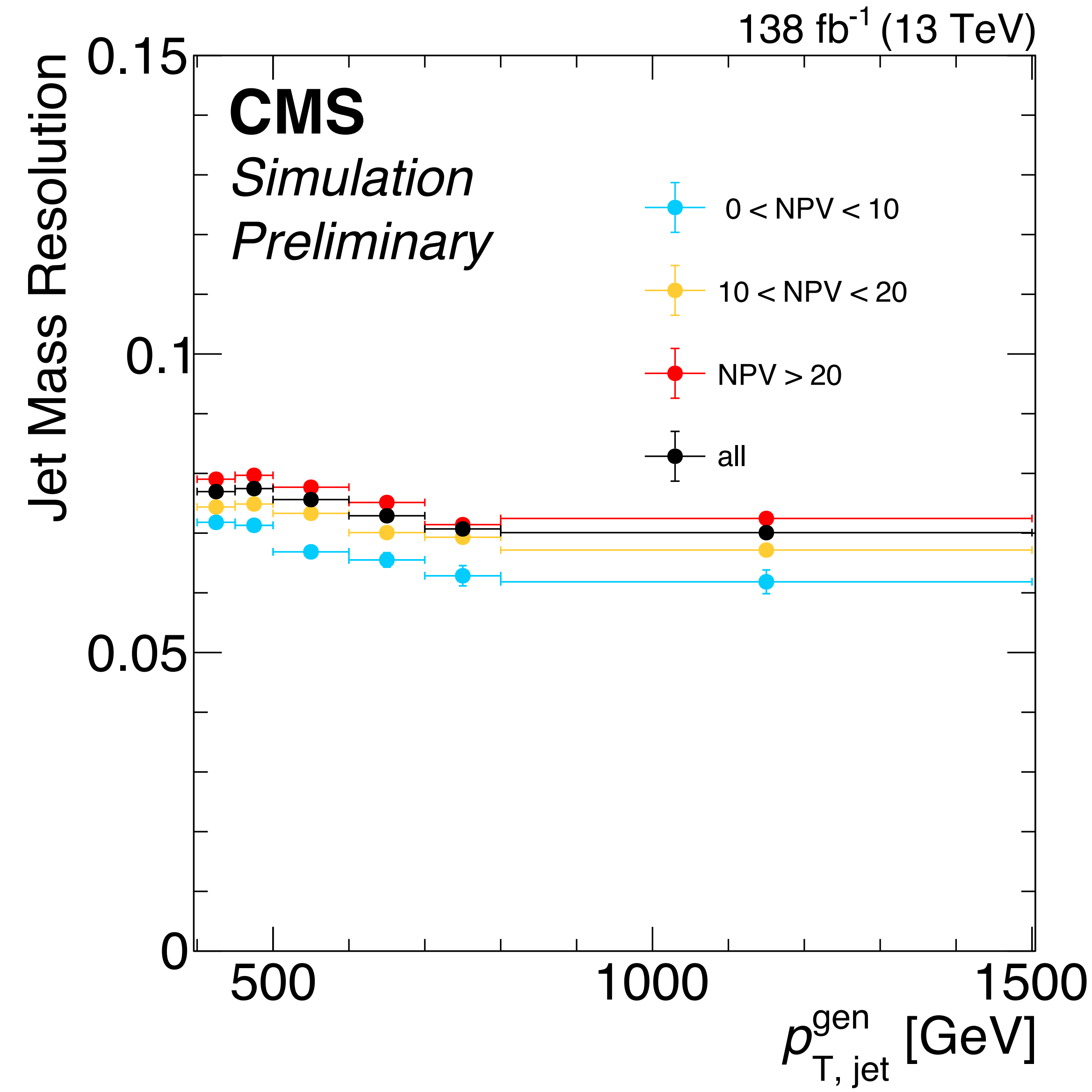
Particle level



- Narrow peak close to m_{top}
- 75% of merged top quark decays in peak

Performance at the detector level





- m_{jet} stable against PU
- Good agreement with MC

- m_{jet} resolution at 6-8%
- (14% for jet with $R = 1.2$)

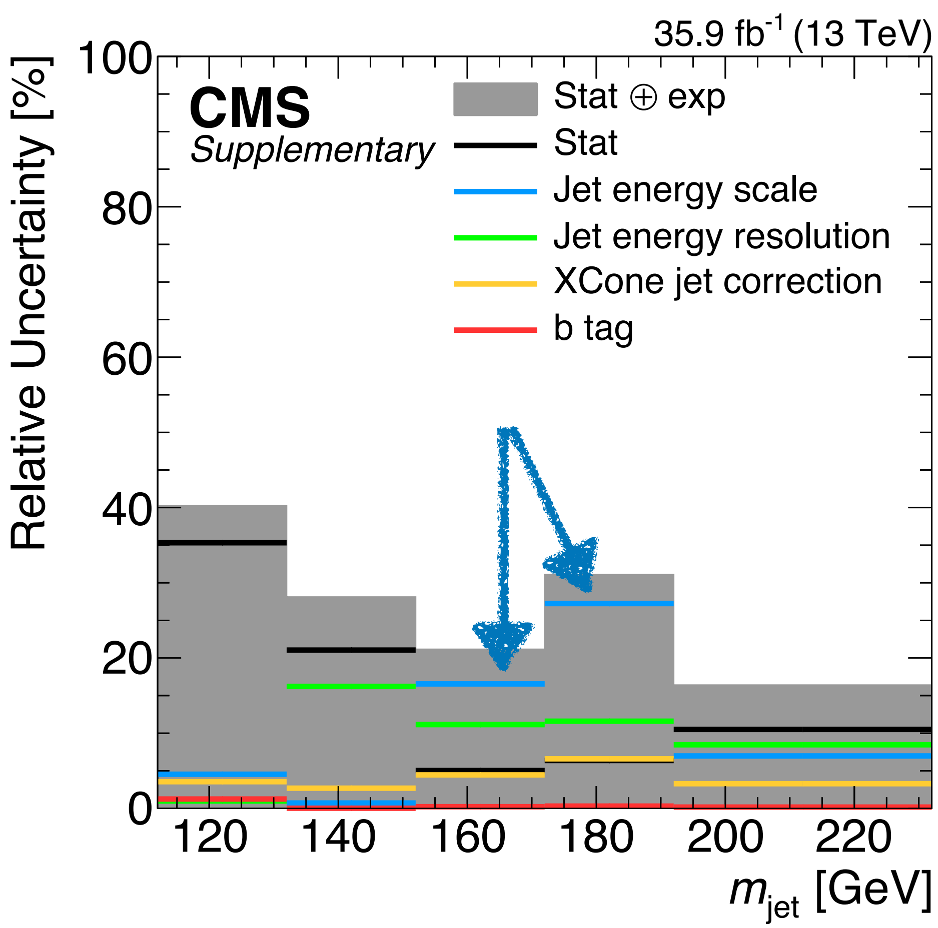
Uncertainties from 2016 measurement

Two dominant uncertainties in the measurement with 2016 data:

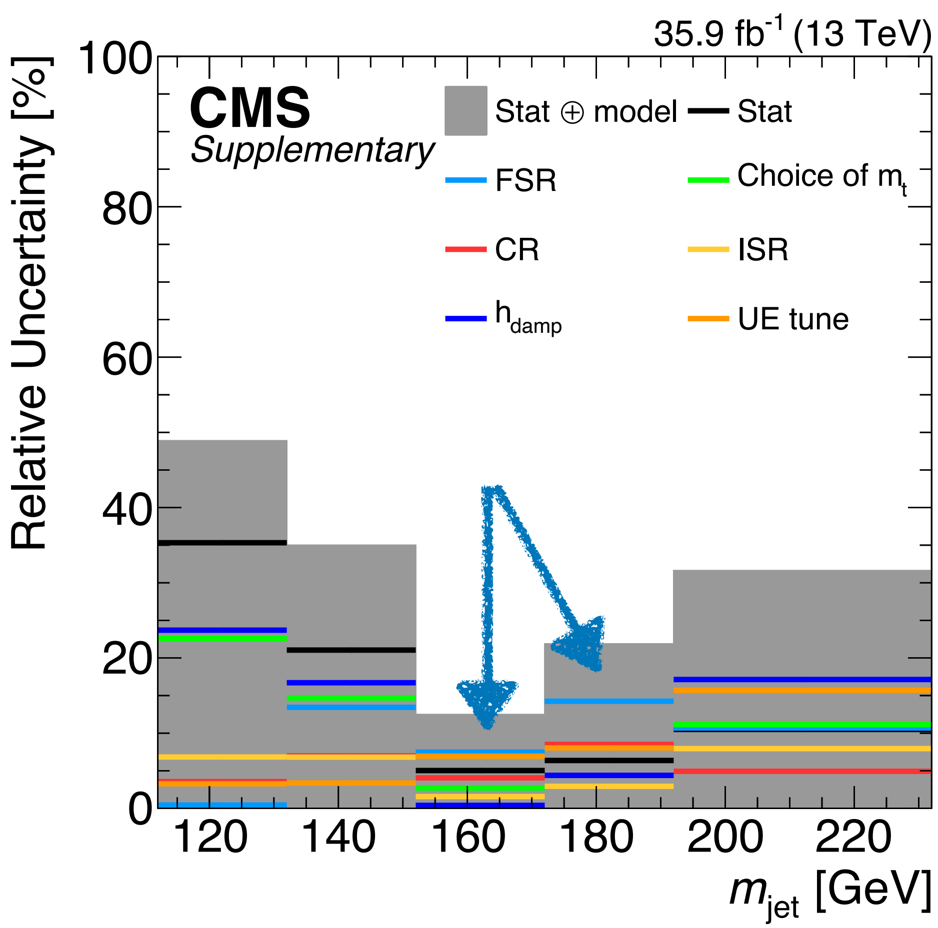
- Calibration of the JES (experimental), $\Delta m_{\text{top}} = 1.5\ \text{GeV}$
- Modeling of the FSR (modeling), $\Delta m_{\text{top}} = 1.2\ \text{GeV}$

Constrain both uncertainties for full Run II

Experimental uncertainties



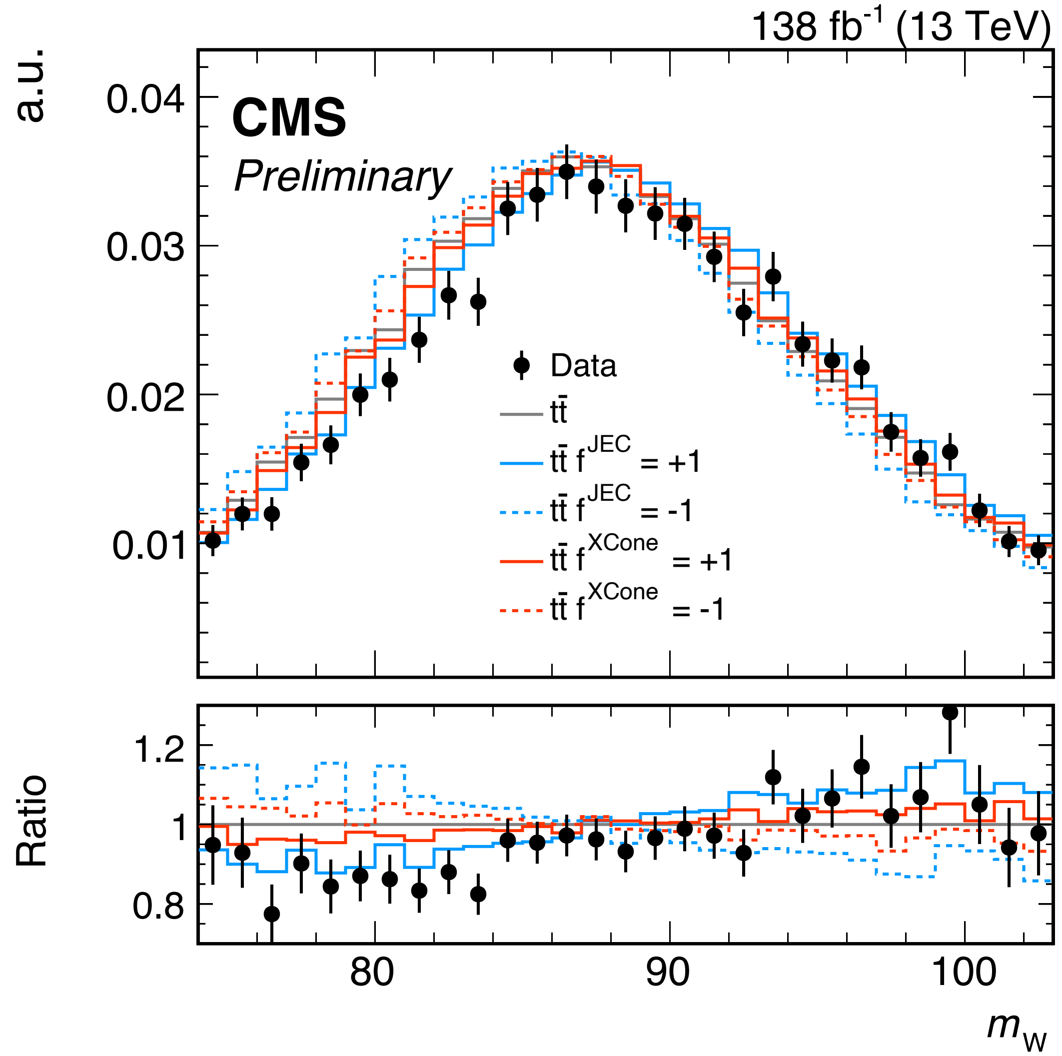
Model uncertainties



Suppl. Material of [Phys. Rev. Lett. 124, 202001] , TOP-19-005

Calibration of the jet mass scale

- **Before:** Jet mass scale estimated with jet energy scale
  - JES derived from calibrations to jet p_T
  - No calibration to jet mass yet
- **Now:** Measure JMS independently using m_W

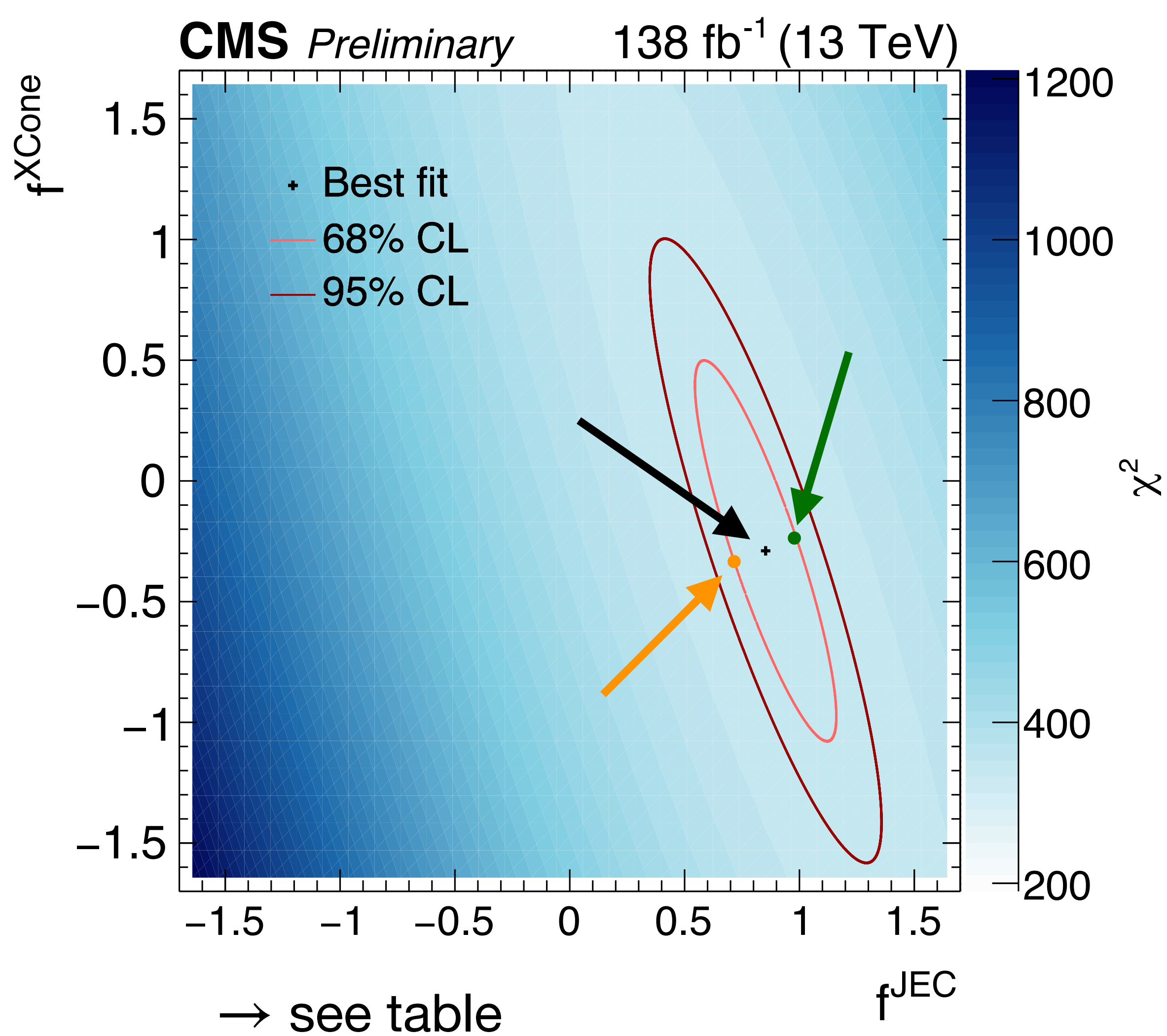


- Hadronic W decay reconstructed from XCone subjects
- Fit AK4 JES (f^{JEC}) and XCone corrections (f^{XCone}) simultaneously

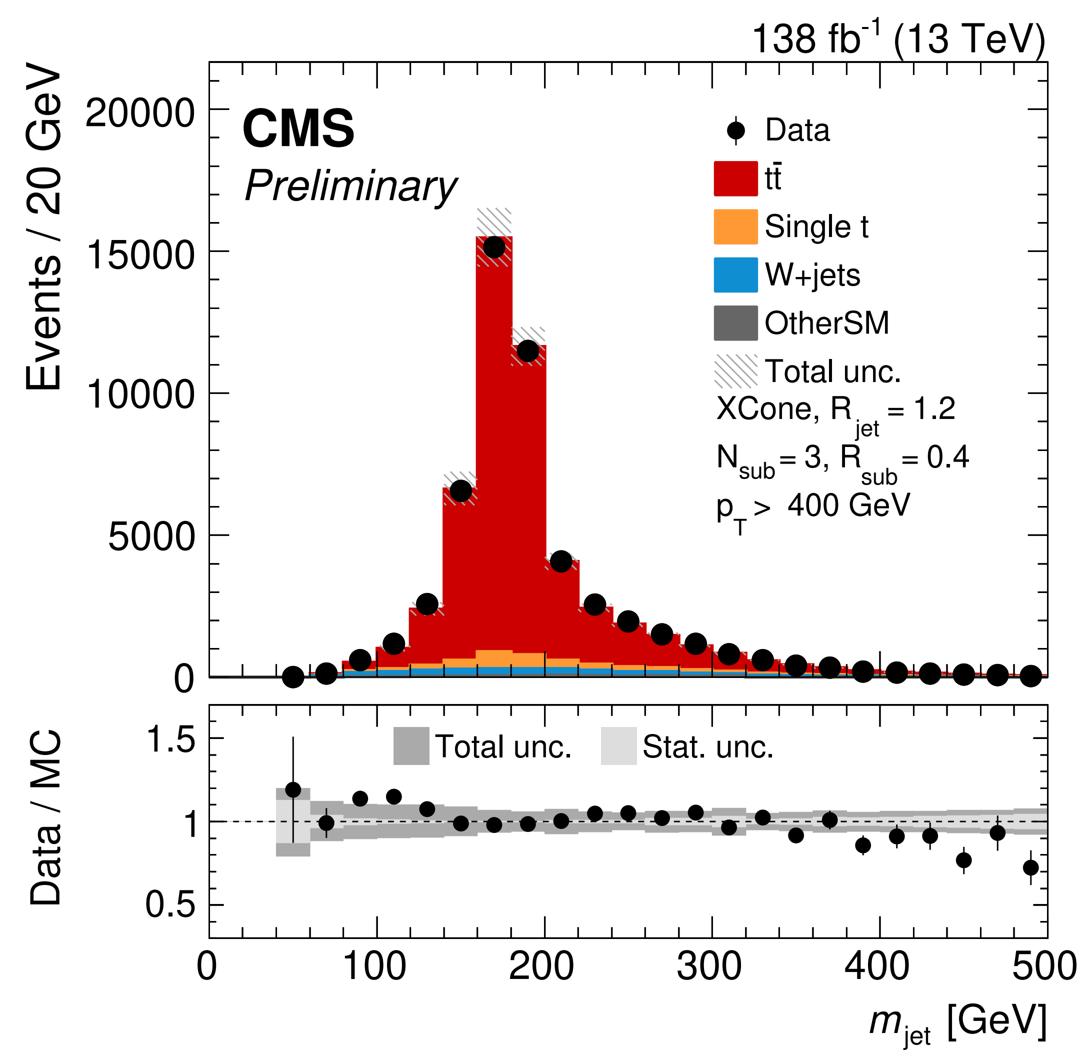
Jet mass scale

- Measure JMS with 2D χ^2
- Additional flavour uncertainty
  - Cover difference of light and b quarks

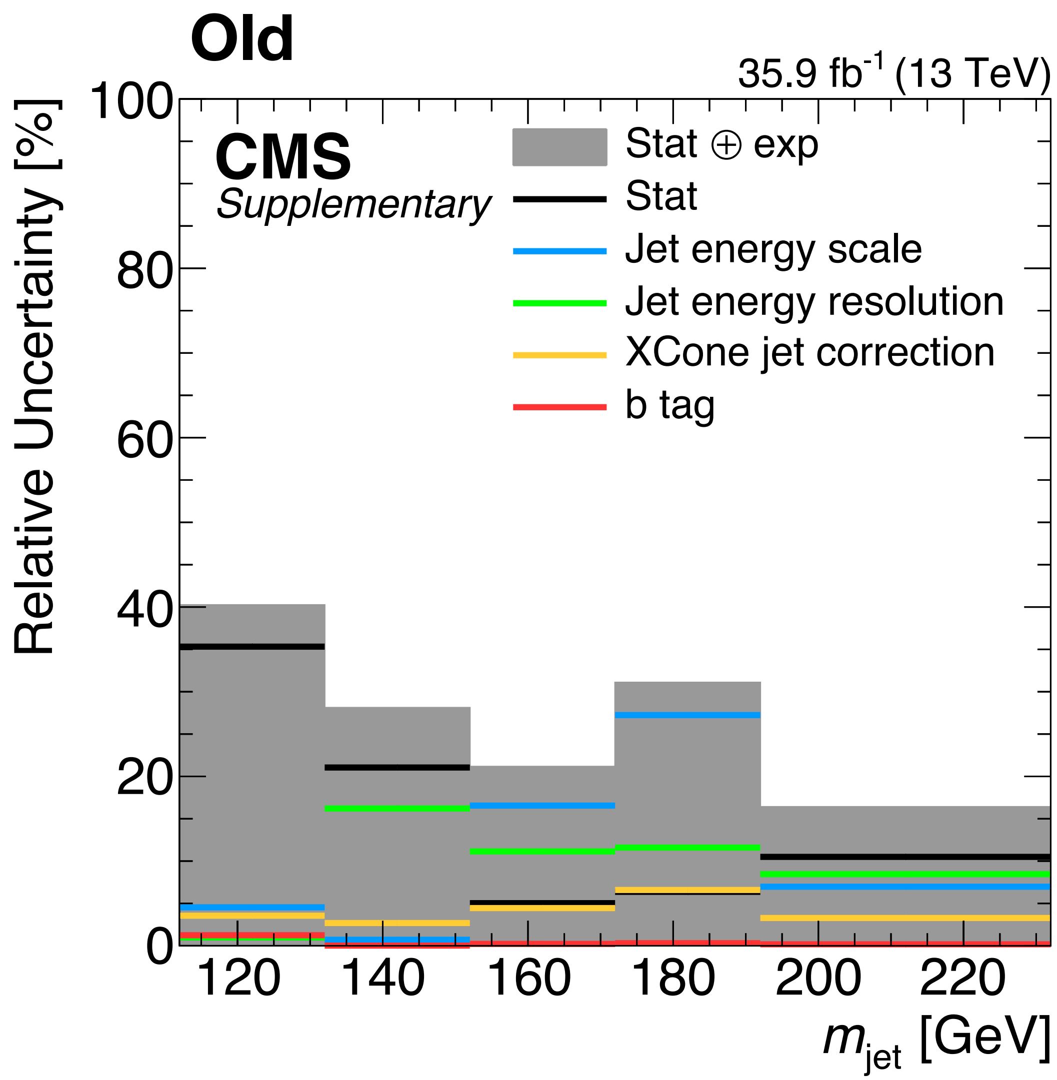
	f^{JMS}_{JEC}	f^{JMS}_{XCone}
Best	0.85	-0.29
Up	0.98	-0.24
Down	0.72	-0.34

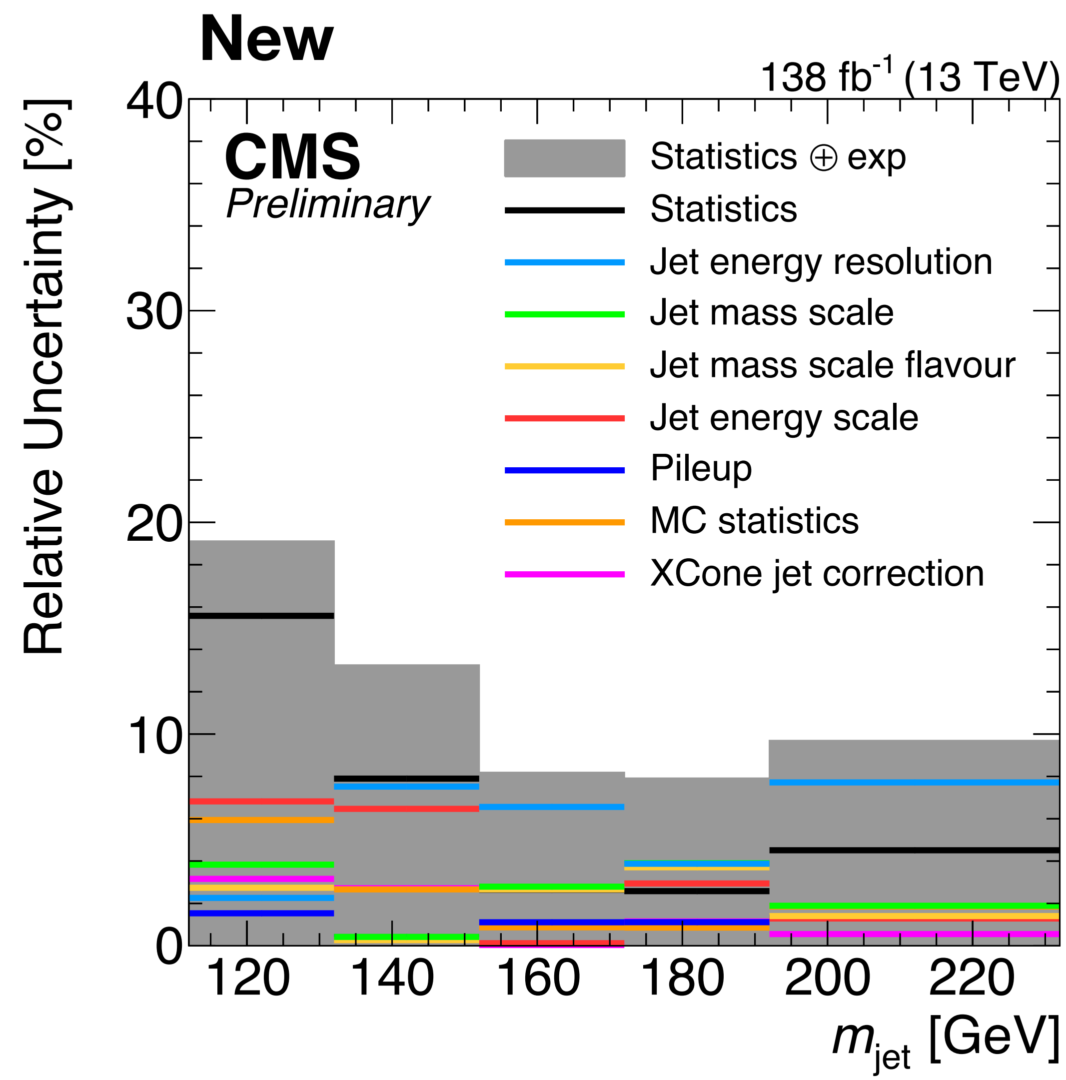


→ see table



Comparison to 2016 measurement





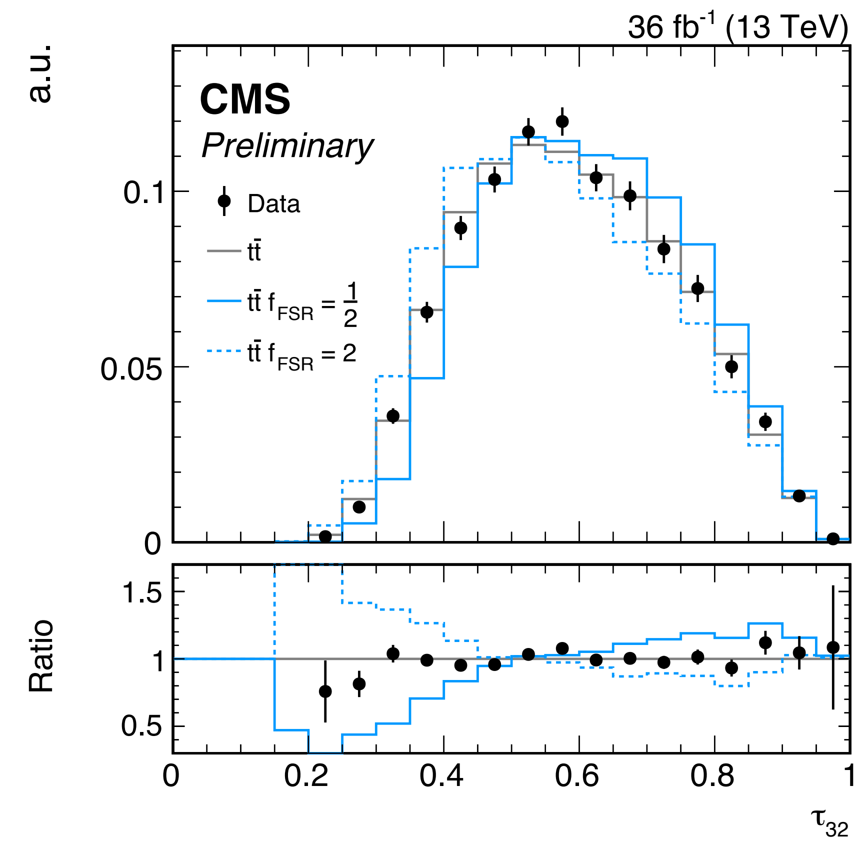
- Now JES only affects p_T of the subjets
- Introduce jet mass scale as separate uncertainty
- $\Delta m_\mathrm{t}(\mathrm{JES}) = 1.5 \rightarrow \Delta m_\mathrm{t}(\mathrm{JES} + \mathrm{JMS} + \mathrm{flavour}) = 0.39\ \mathrm{GeV}$

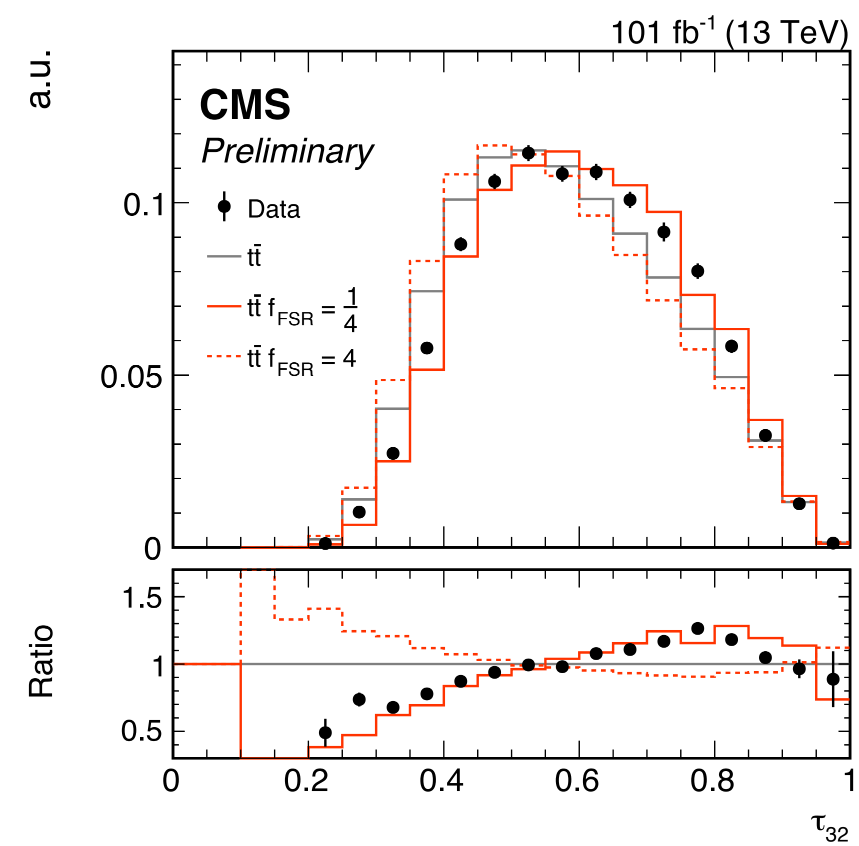
Calibration of FSR modeling

- FSR scale steers strong coupling for additional radiation with $\alpha_S(f_{FSR} \cdot \mu_0)$
- **Before:** Estimate FSR scale with $f_{FSR} \in \{\frac{1}{2}, 2\}$
- **Now:** Dedicated calibration of FSR scale
- Jet substructure observable τ_{32} sensitive to additional radiation
- Split datasets into 2016 and 2017+2018
  - Different tune in $t\bar{t}$ simulation

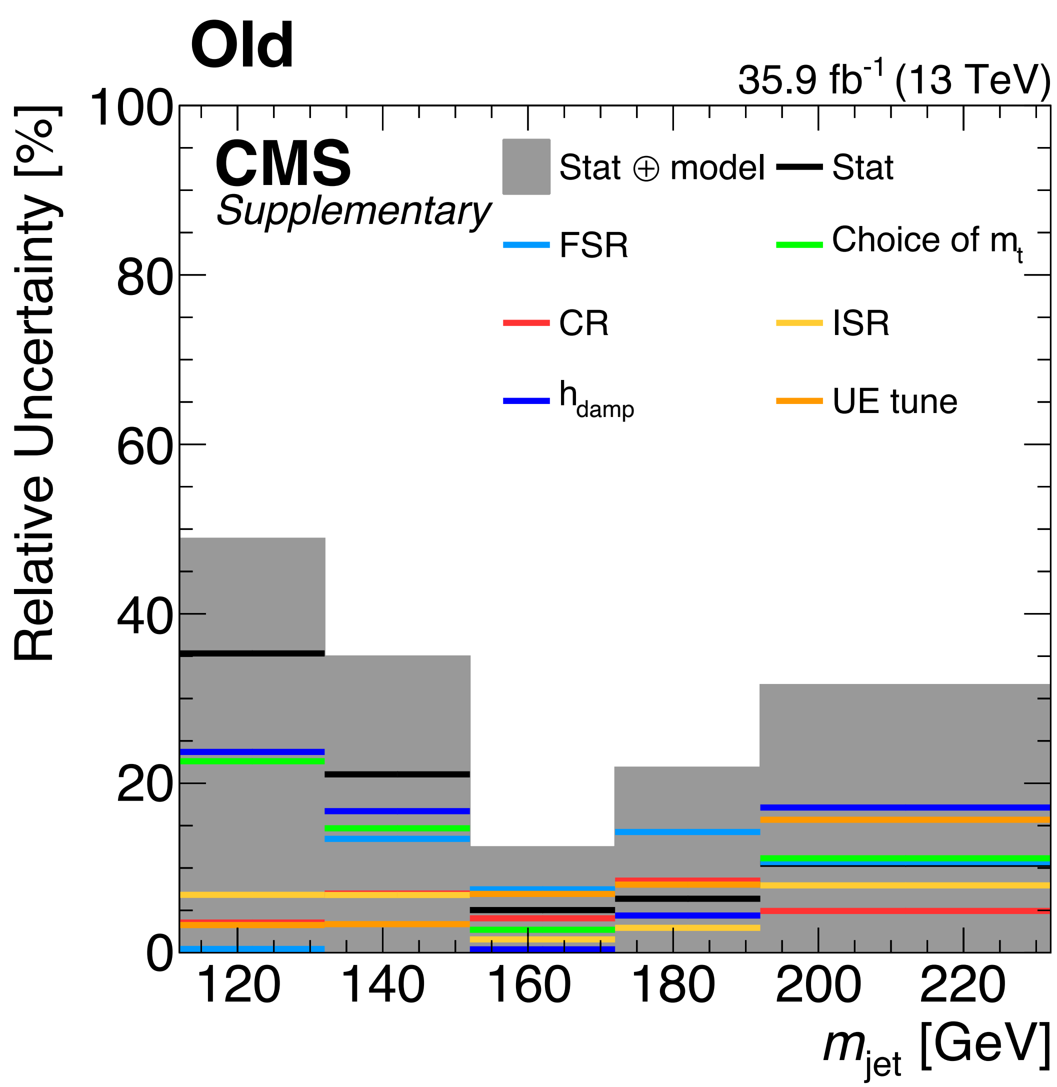
$$f_{FSR}^{2016} = 0.97 \pm 0.07$$

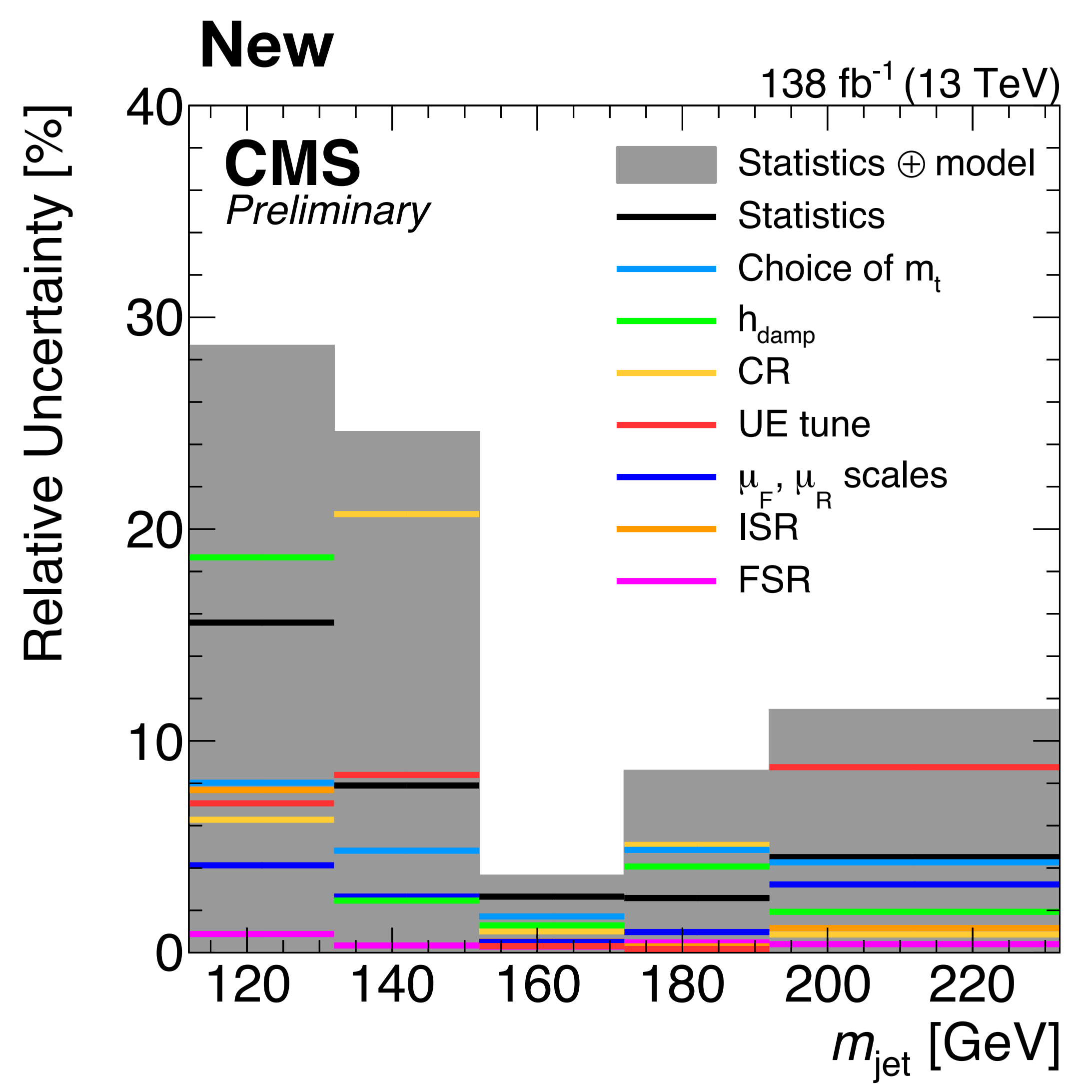
$$f_{FSR}^{2017+2018} = 0.33 \pm 0.02$$





Comparison to 2016 measurement

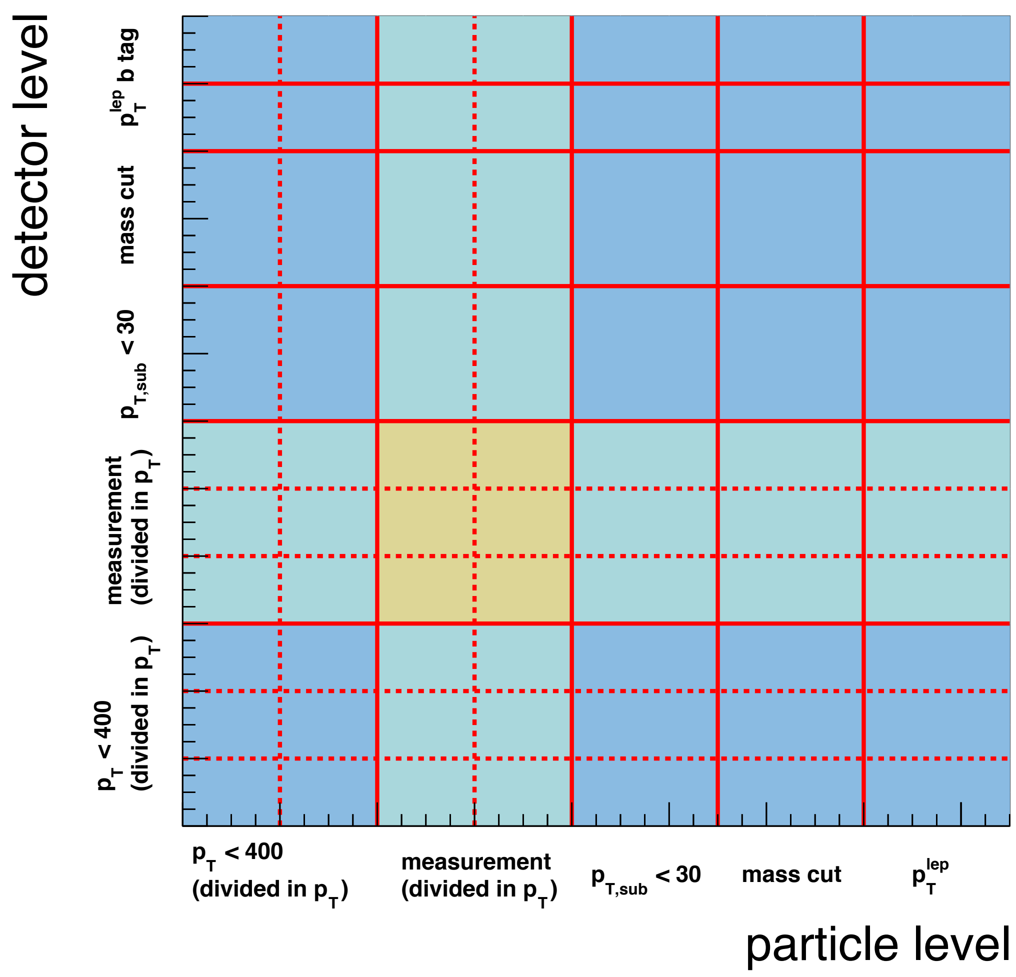




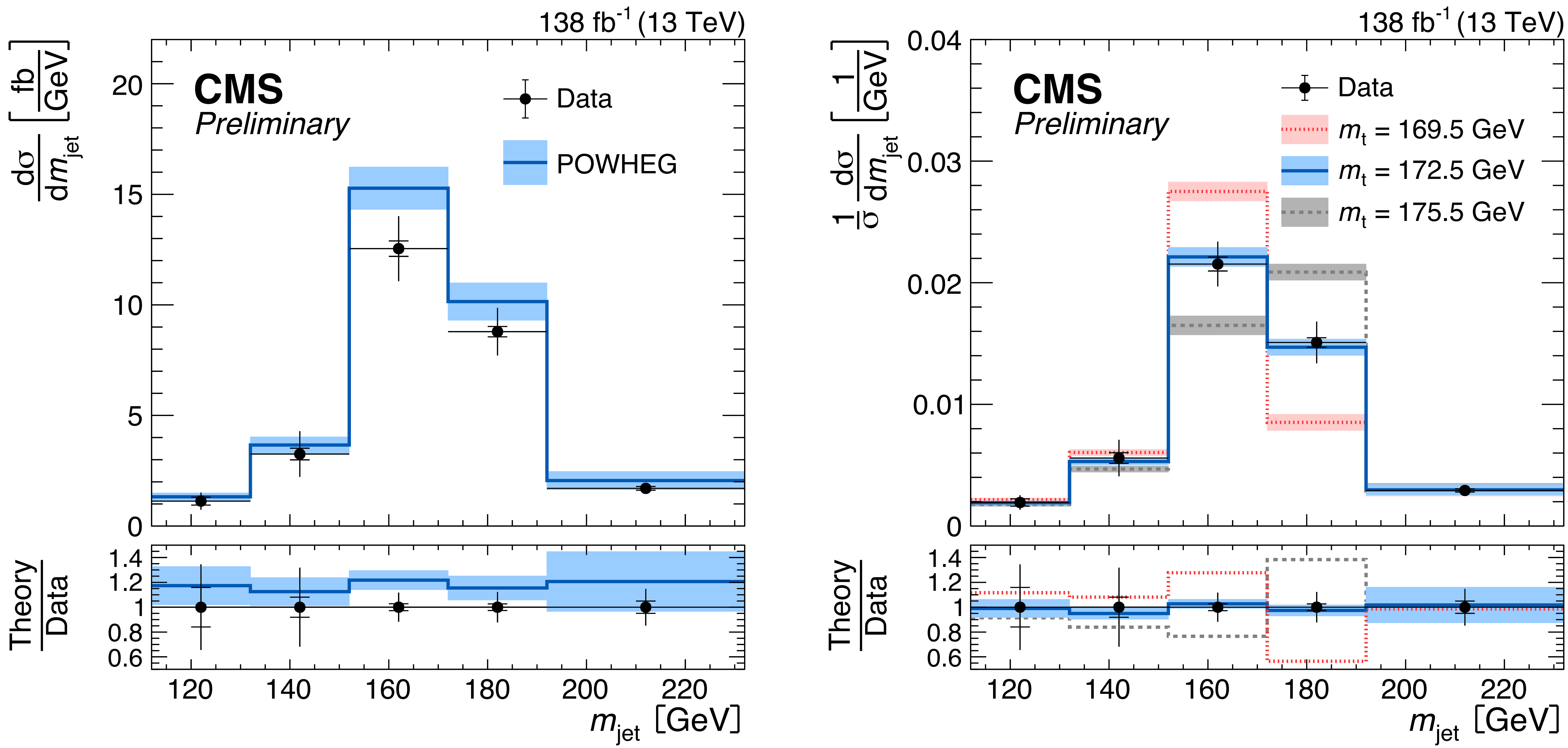
- Uncertainty from the modeling of the FSR is drastically reduced
- Similar values of $\alpha_S^{FSR}(M_Z)$ for both tunes
- $\Delta m_t(\text{FSR}) = 1.5 \rightarrow \Delta m_t(\text{FSR}) = 0.02\ \text{GeV}$

Unfolding setup

- Regularized unfolding using TUnfold
- Response matrix constructed constructed with POWHEG $t\bar{t}$
- Construct multiple sideband regions by lowering selection threshold
  - 200 bins on detector level
  - 72 bins on particle level



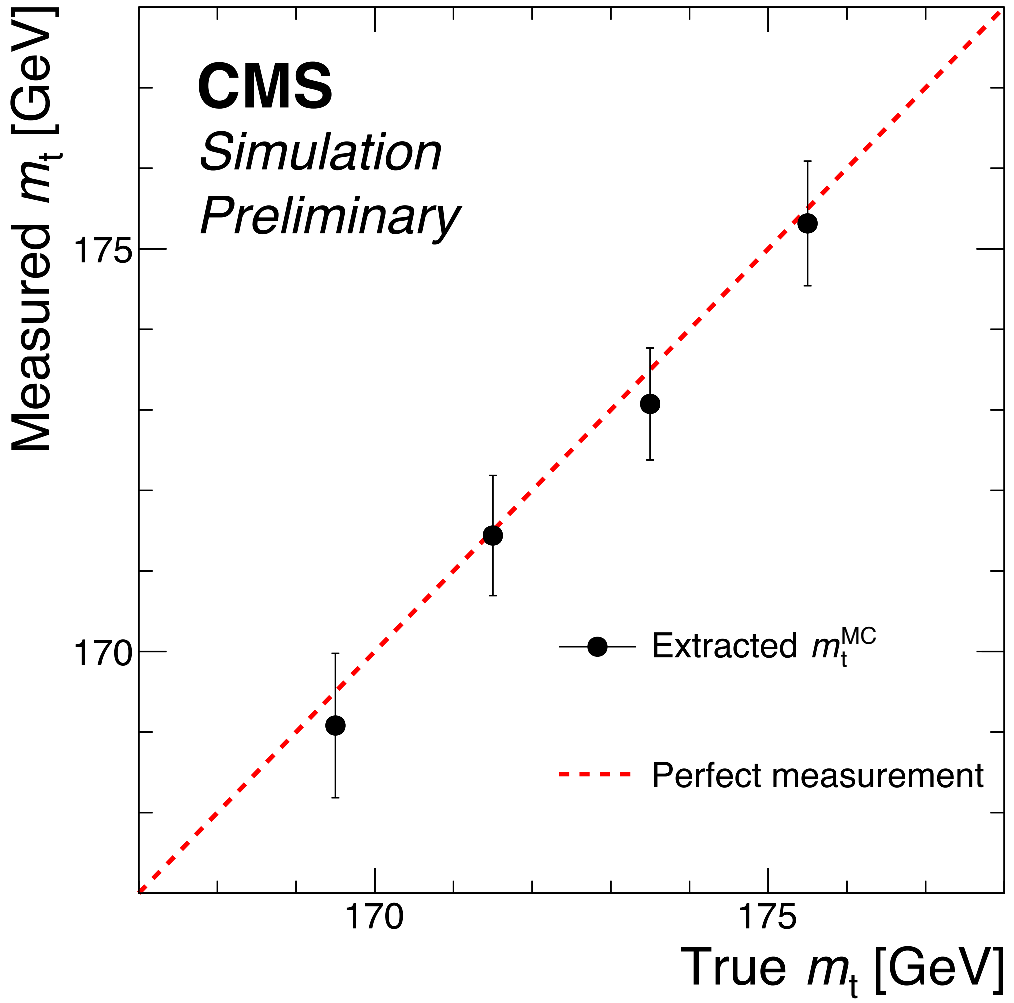
Unfolded results



- Differential cross section as a function of m_{jet}
- Extract m_{top} from normalized distribution

Extraction of m_{top} in simulation

- Test extraction with simulated samples
- Good agreement between true value and measurement
- Continue with real data

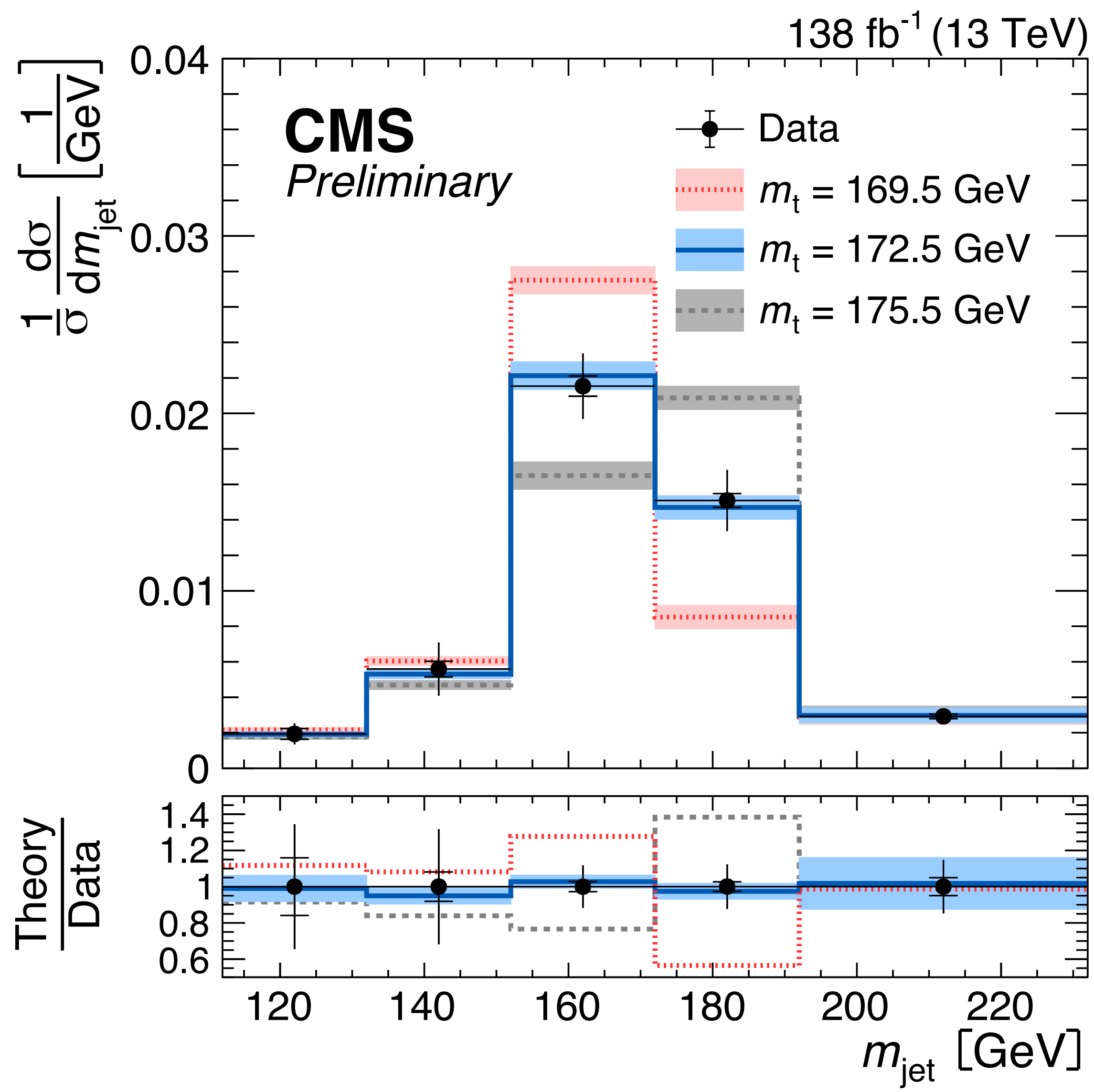


Extraction of m_{top} in data

$$m_{\text{top}} = 172.76 \pm 0.81 \text{ GeV}$$

- Main uncertainties:

Source	Uncertainty [GeV]
Statistical uncertainty	0.22
Experimental uncertainty	0.57
JER	0.40
JMS	0.27
JMS flavour	0.27
JES	0.10
Model uncertainty	0.48
Choice of m_{top}	0.37
CR	0.19
h_{damp}	0.19
FSR	0.02



Summary & Outlook

- Measured jet mass distribution in decays of boosted top quarks with the full Run-2 data set

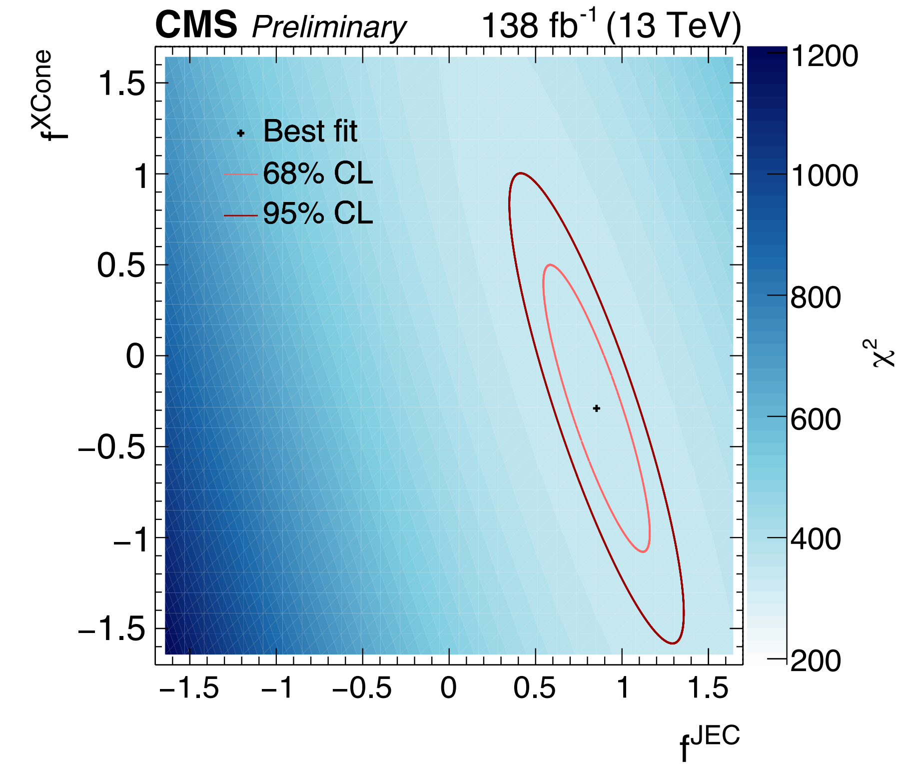
- Drastically reduced dominant uncertainties of an earlier measurement
  - Calibration of the jet mass scale
  - Modeling of the final state radiation

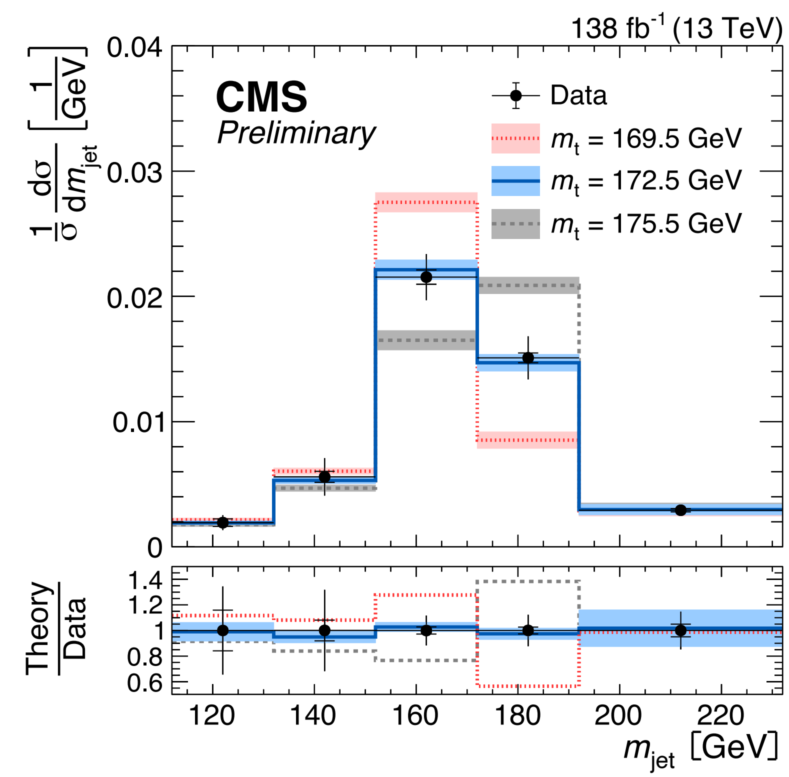
- Increased precision of m_{top} from 2.5 GeV to below 1 GeV

$$m_{\text{top}} = 172.76 \pm 0.81 \text{ GeV}$$

- CMS-PAS-TOP-21-012 now public

- Hope to compare to analytic calculations soon





Additional Material

Comparison of f_{FSR}

- **CPETP8M2T4** describes data better than **CP5**
- After calibration $\alpha_S^{\mathrm{FSR,2016}} \sim \alpha_S^{\mathrm{FSR,2017+2018}}$
- From original tune:

$$\alpha_S^{\mathrm{FSR,CPETP8M2T4}} = 0.1365$$
$$\alpha_S^{\mathrm{FSR,CP5}} = 0.118$$

	Tune	$f_{\mathrm{best}}^{\mathrm{FSR}}$	$\alpha_S^{\mathrm{FSR}}(m_Z^2)$
2016	CPETP8M2T4	0.97 ± 0.07	$0.1373^{+0.0017}_{-0.0018}$
2017+2018	CP5	0.33 ± 0.02	$0.1416^{+0.0018}_{-0.0019}$