



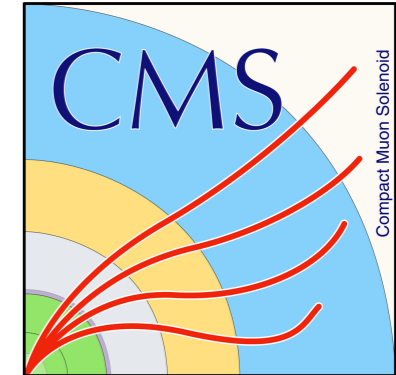
Universität Hamburg

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GEFÖRDERT VOM

Bundesministerium  
für Bildung  
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# Measurement of the jet mass distribution in decays of boosted top quarks and the top quark mass with CMS

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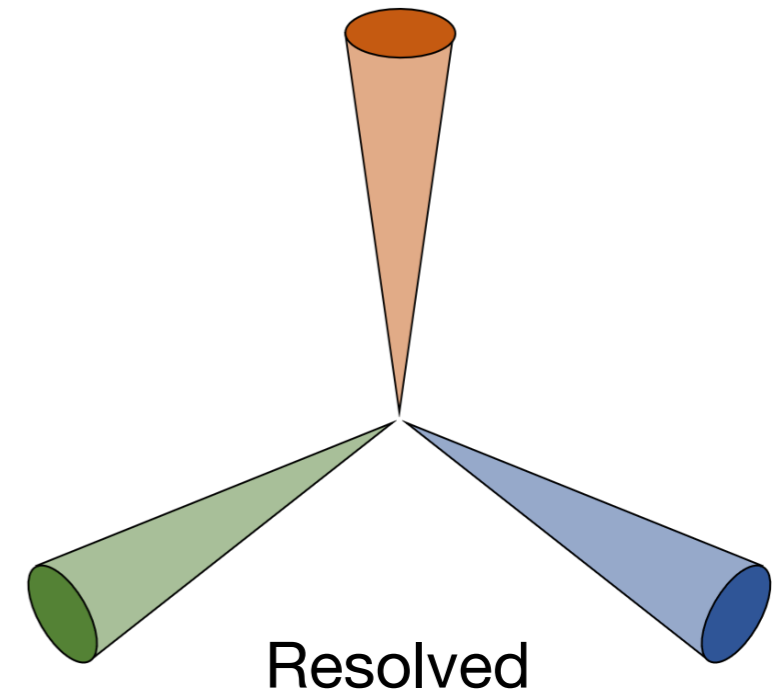


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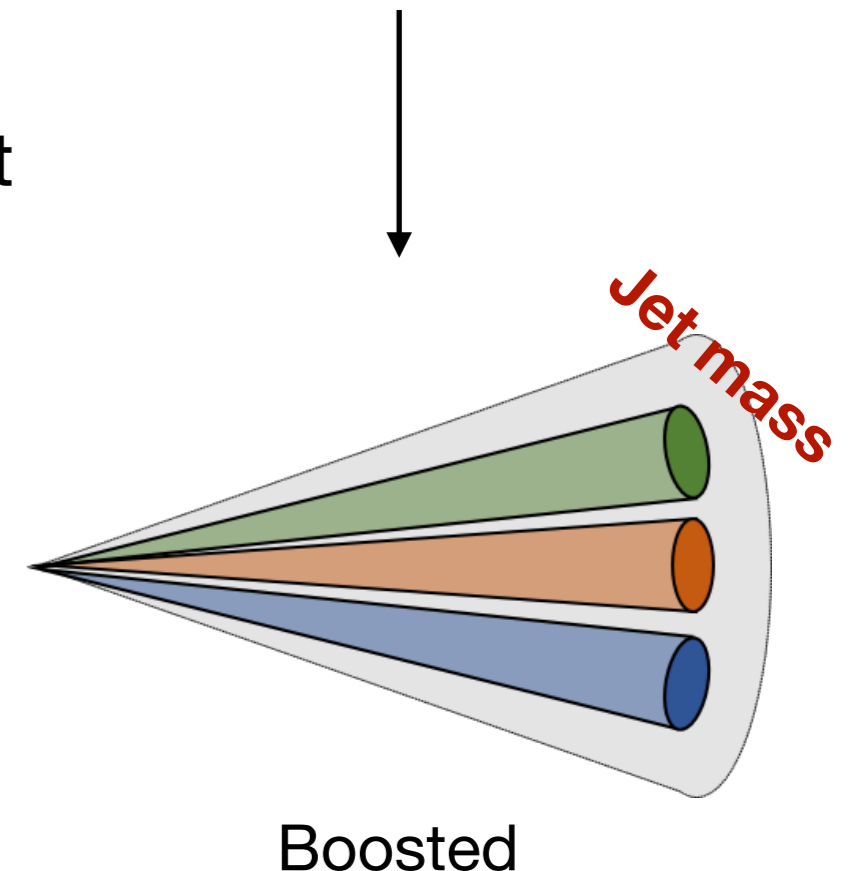
## Direct measurements

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



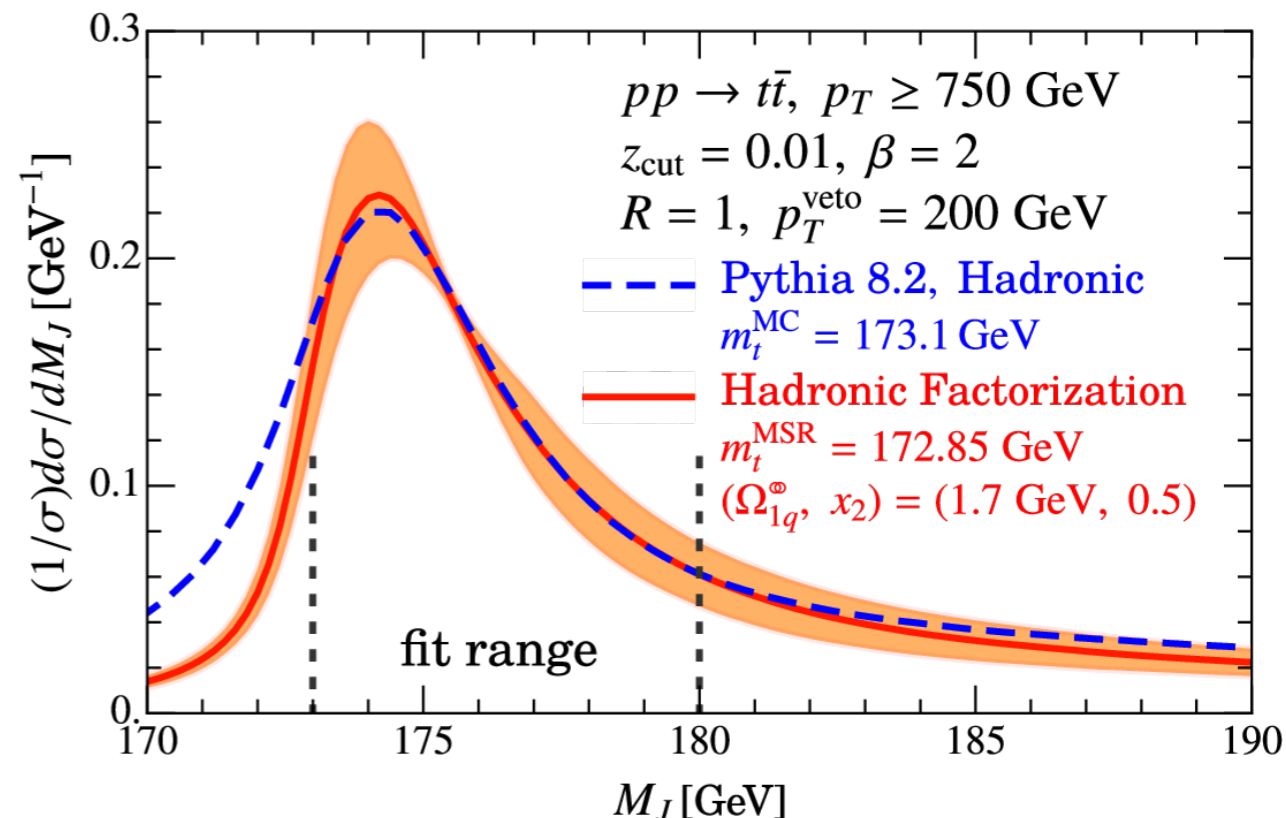
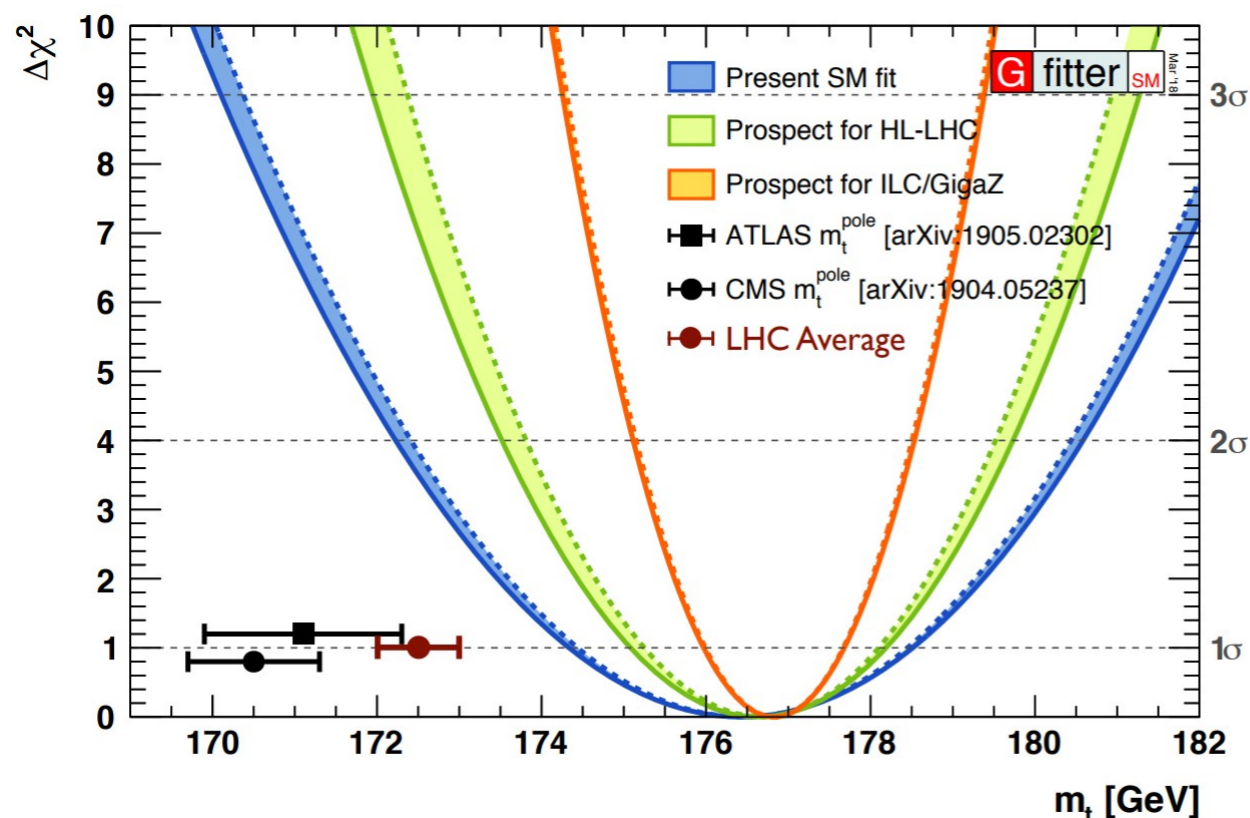
## This approach

- ▶ Reconstruct hadronic top quark decay in single jet  
(Boosted regime,  $p_{T,\text{jet}} > 400$  GeV)
- ▶ Measure jet mass:  $m_{\text{jet}} = \sqrt{p_{\text{jet}}^2}$
- ▶ Unfold to particle level
- ▶ Aiming for analytic calculations



# Why boosted top quarks?

- ▶ Tension between predictions and measurements
- ▶  $m_{\text{top}}$  measurements dominated by threshold production
  - Explore boosted regime
- ▶ Comparison to analytic calculations
  - Avoid ambiguities in event generators
  - Phase-space not accessible yet



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

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

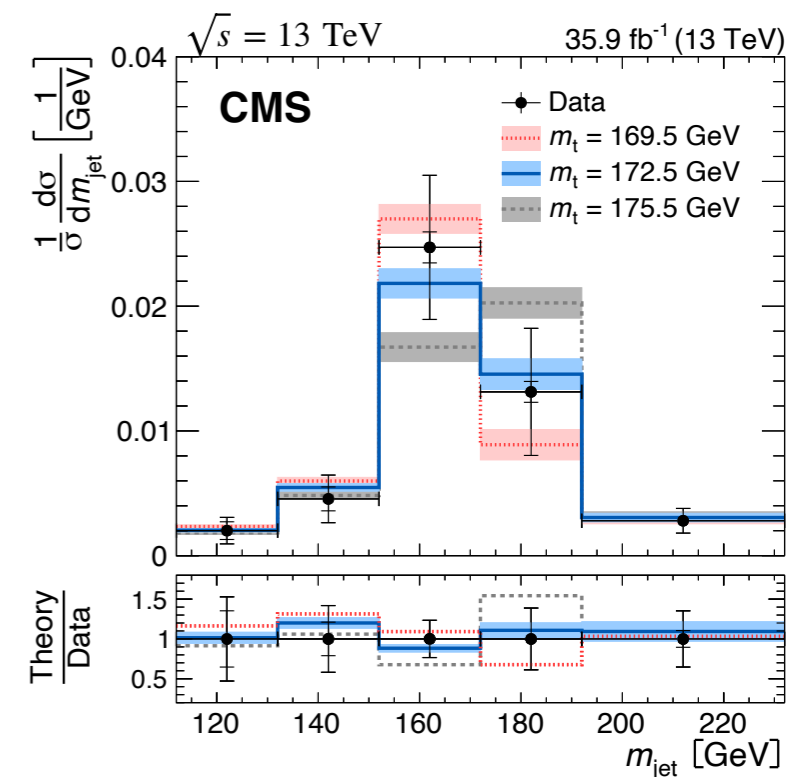
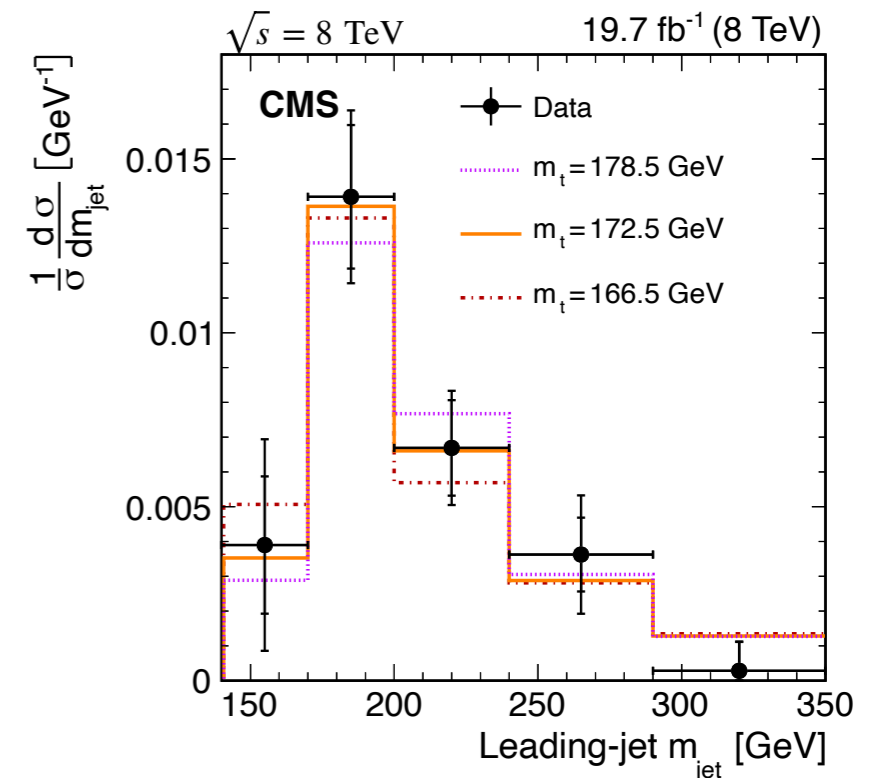
- ▶ Cambridge/Aachen with  $R = 1.2$
- ▶  $m_{\text{top}} = 170.8 \pm 9.0$  GeV

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

- ▶ Data from 2016
- ▶ X Cone jet algorithm
- ▶  $m_{\text{top}} = 172.6 \pm 2.5$  GeV

## Now improve analysis with full Run II

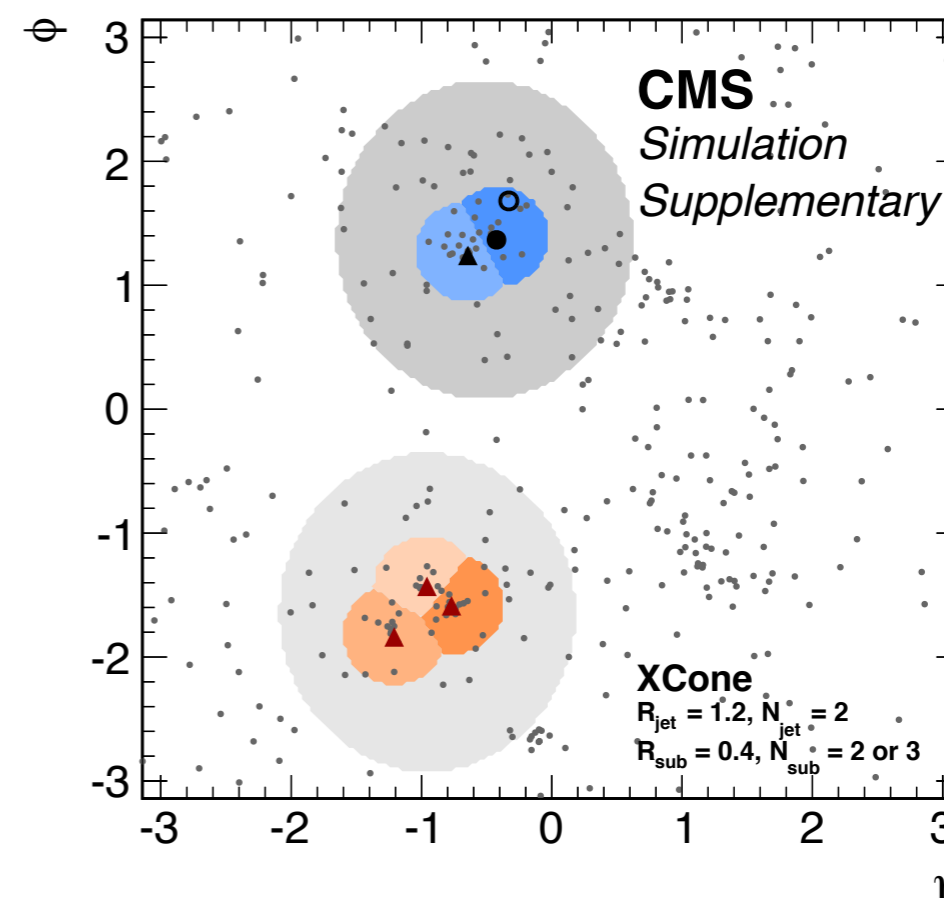
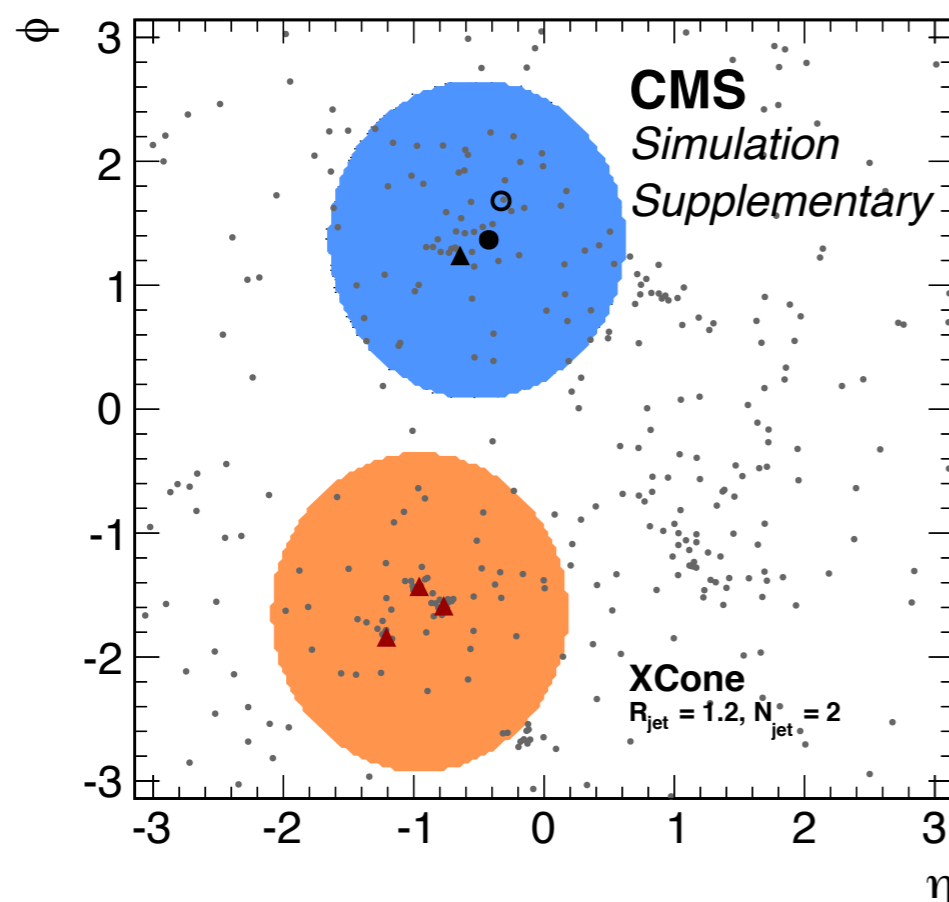
- ▶ Dedicated studies on dominant systematic uncertainties



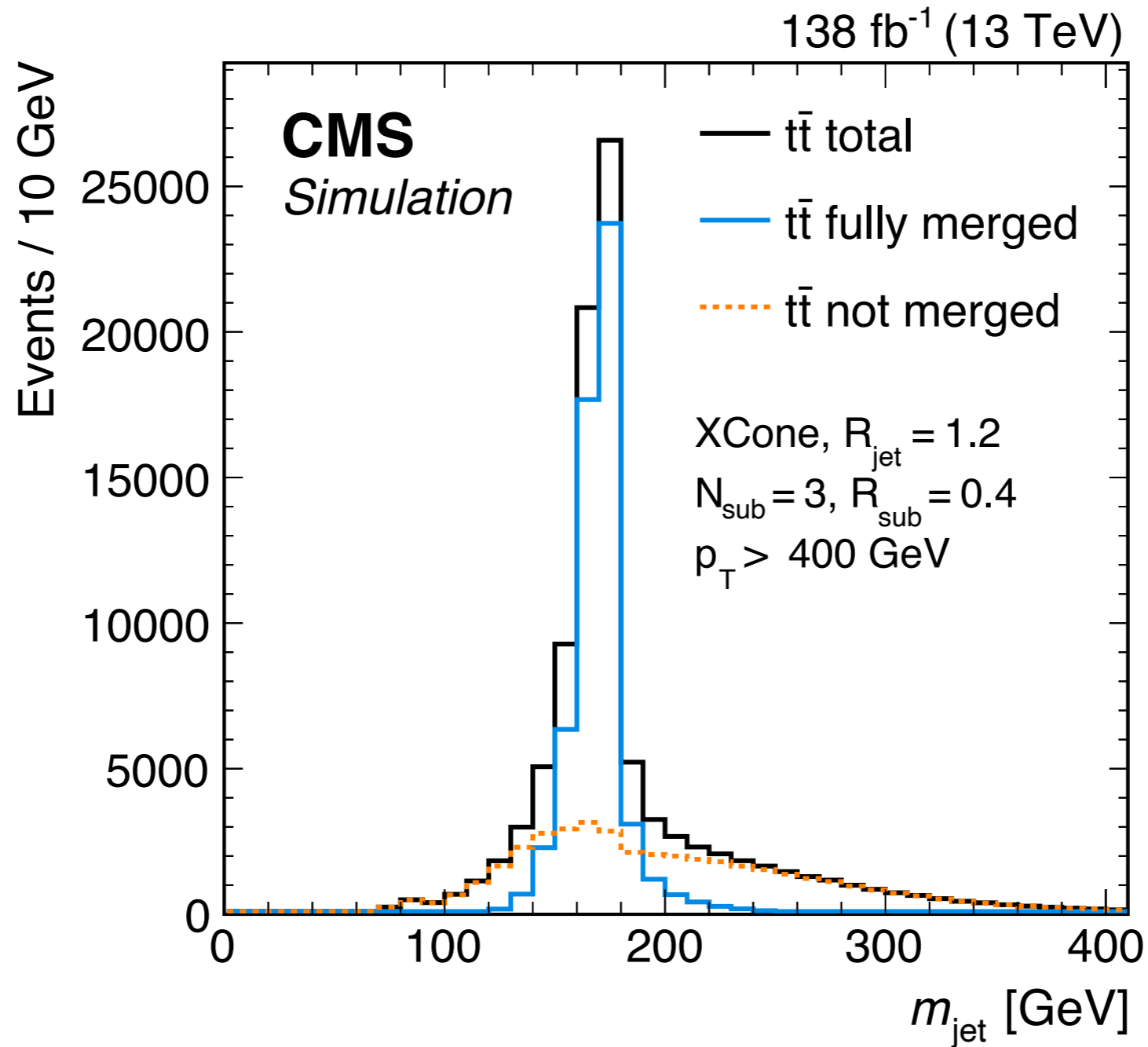
## 2-step clustering using XCone jet algorithm [\[JHEP 2015, 72\]](#)

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

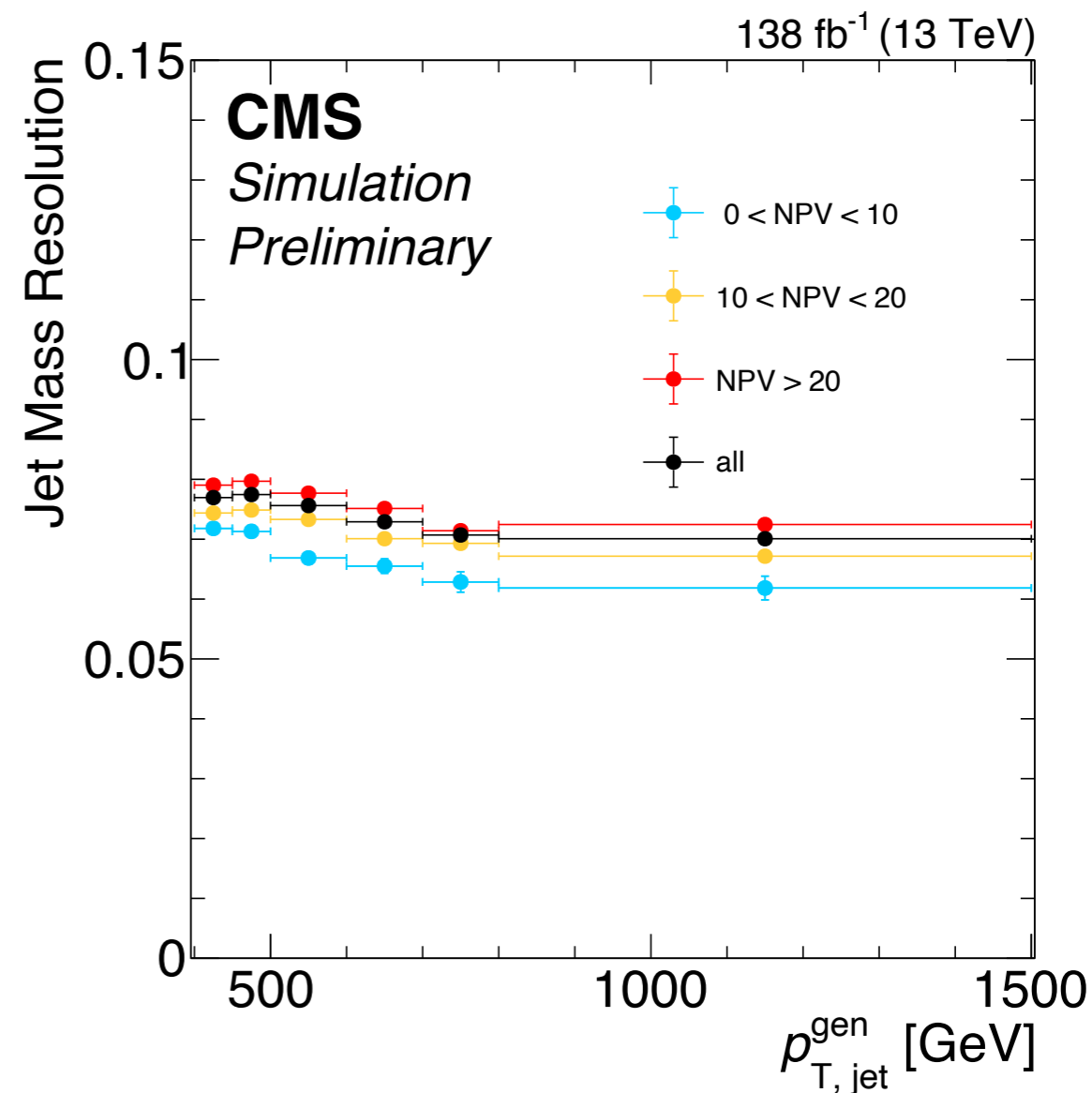
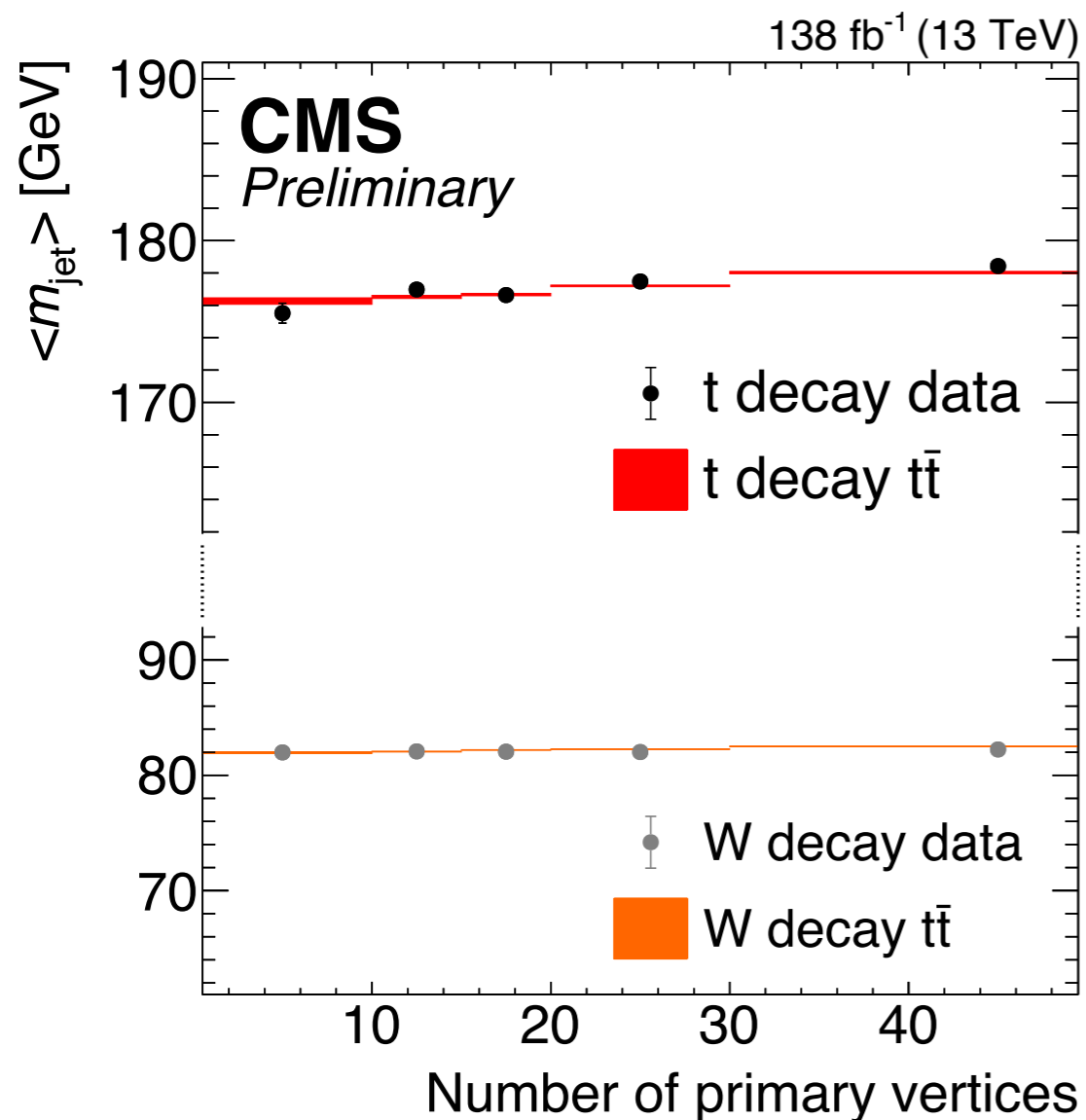
## Dedicated corrections for the XCone subjects depending on $\eta$ and $p_T$



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



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



- ▶  $m_{\text{jet}}$  stable against PU
- ▶ Good agreement with MC

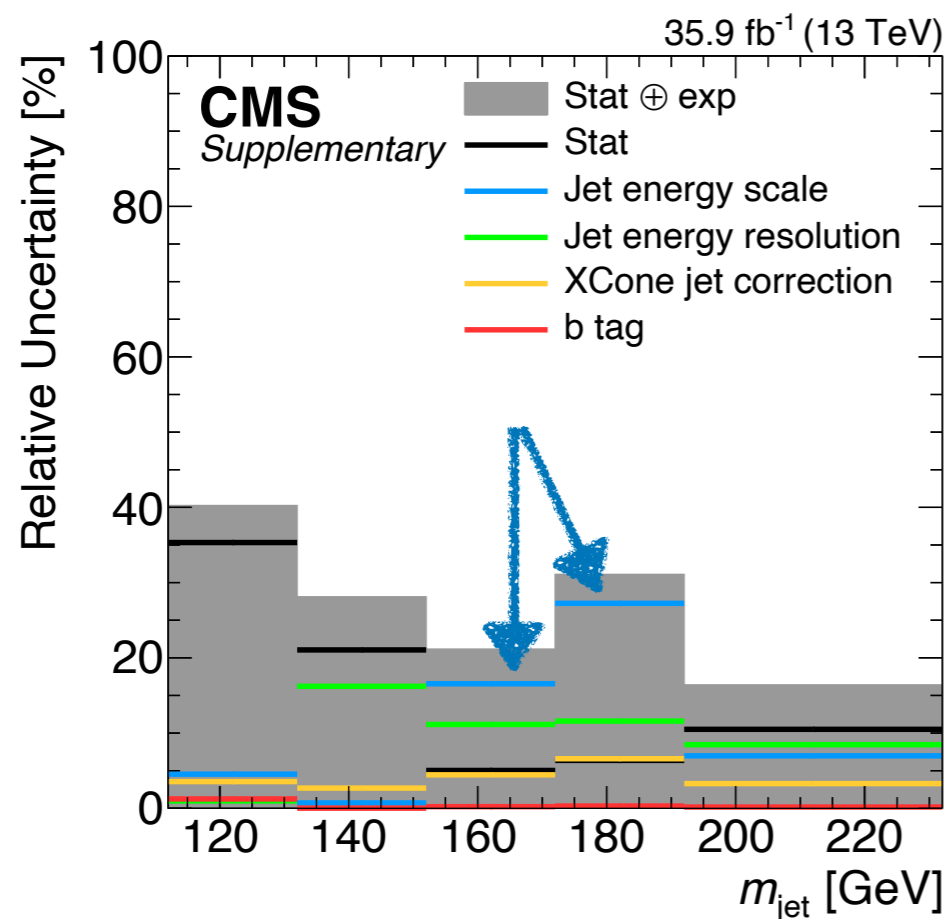
- ▶  $m_{\text{jet}}$  resolution at 6-8%  
(14% for jet with  $R = 1.2$ )

## Two dominant uncertainties in the measurement with 2016 data:

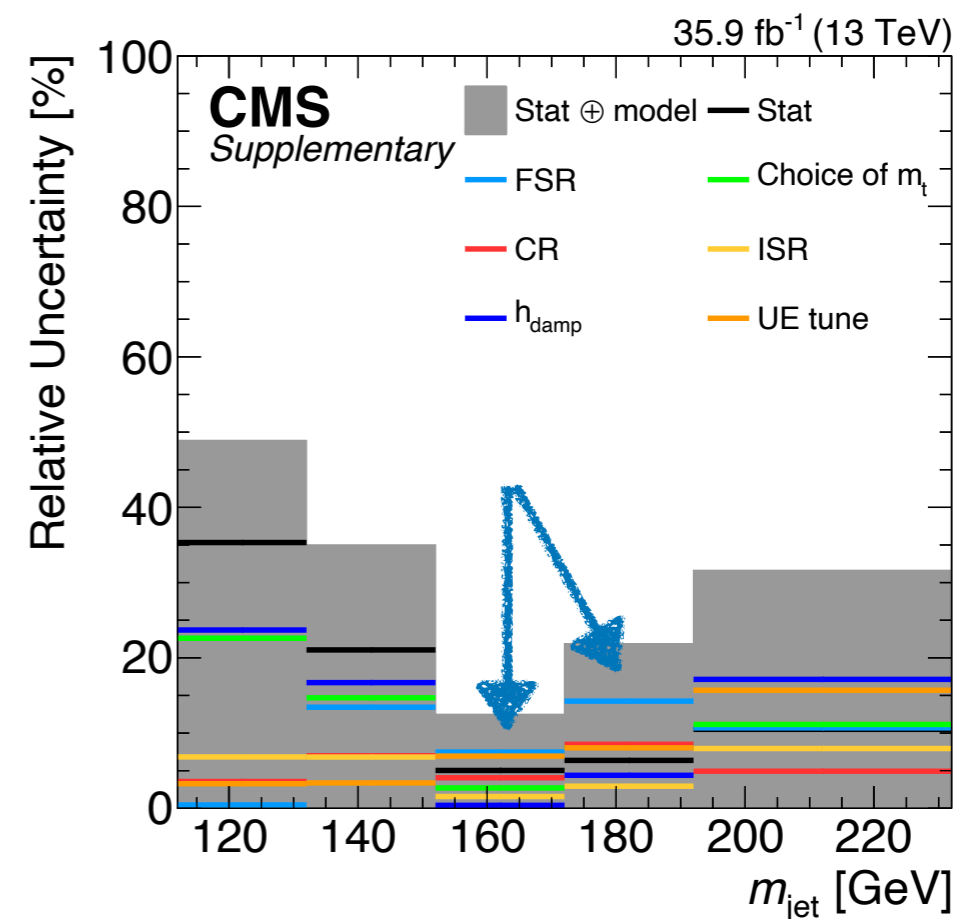
- ▶ Calibration of the JES (experimental),  $\Delta m_{\text{top}} = 1.5 \text{ GeV}$
- ▶ Modeling of the FSR (modeling),  $\Delta m_{\text{top}} = 1.2 \text{ GeV}$

## Constrain both uncertainties for full Run II

### Experimental uncertainties



### Model uncertainties



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



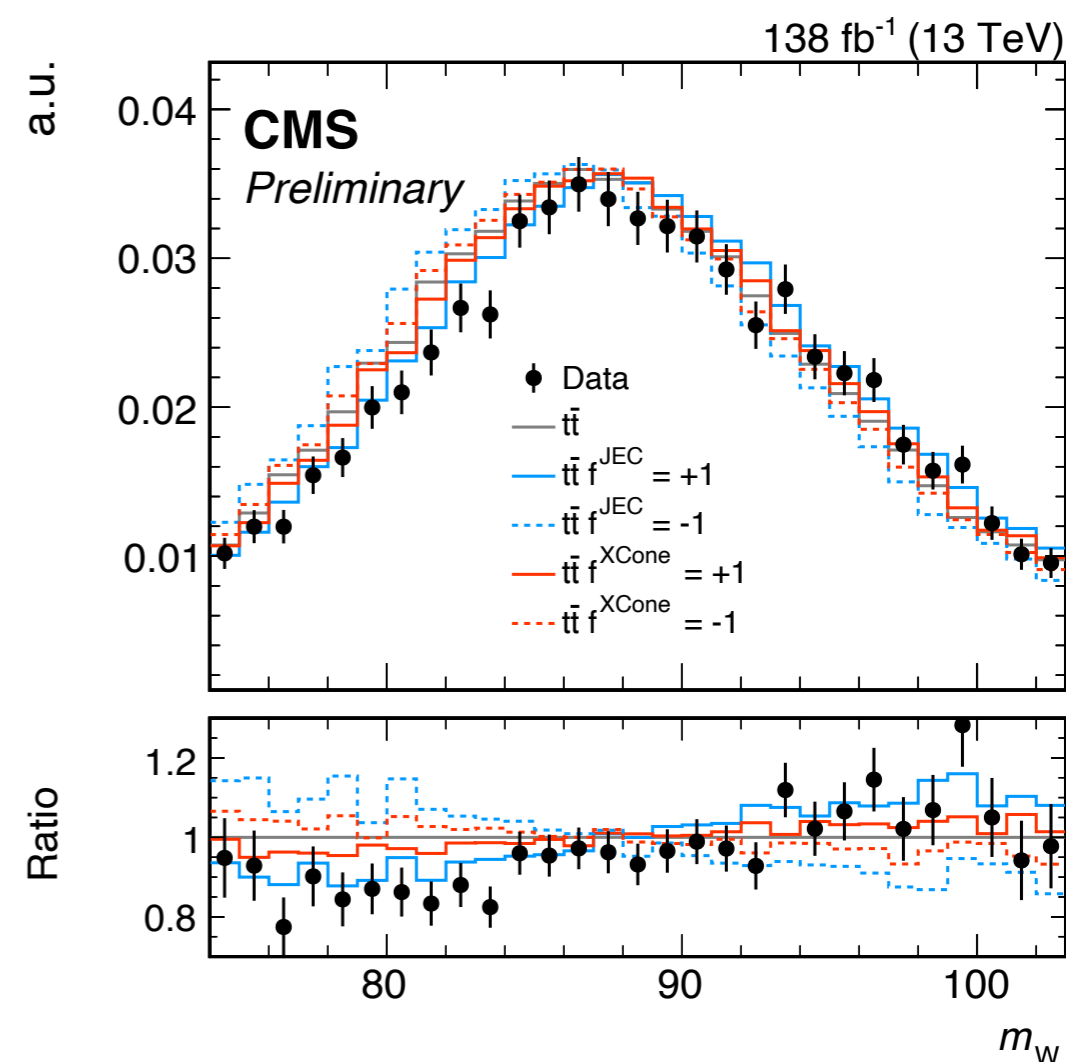
► **Before:** Jet mass scale estimated with jet energy scale

- 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 X Cone subjects

► Fit AK4 JES ( $f^{\text{JEC}}$ ) and X Cone corrections ( $f^{\text{XCone}}$ ) simultaneously

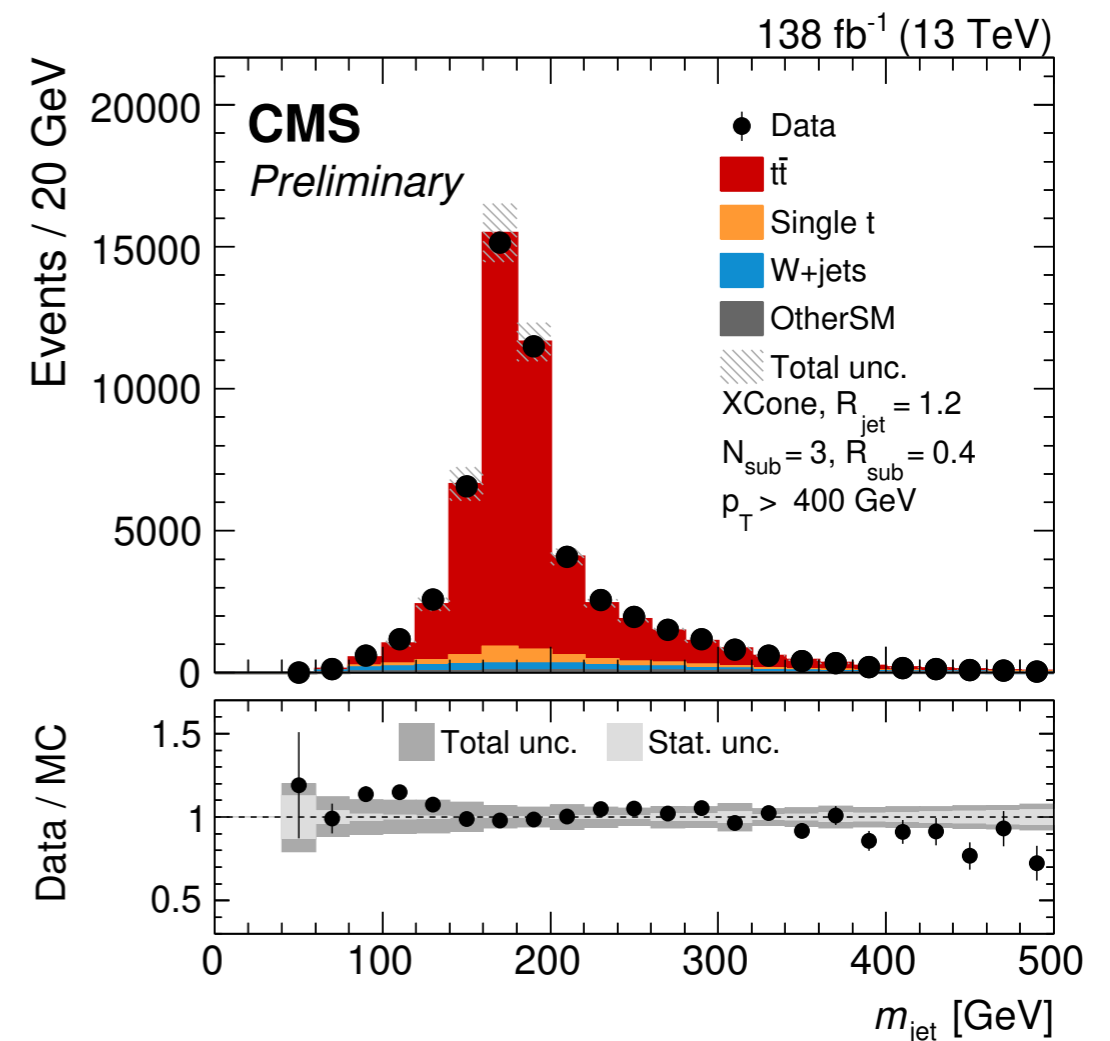
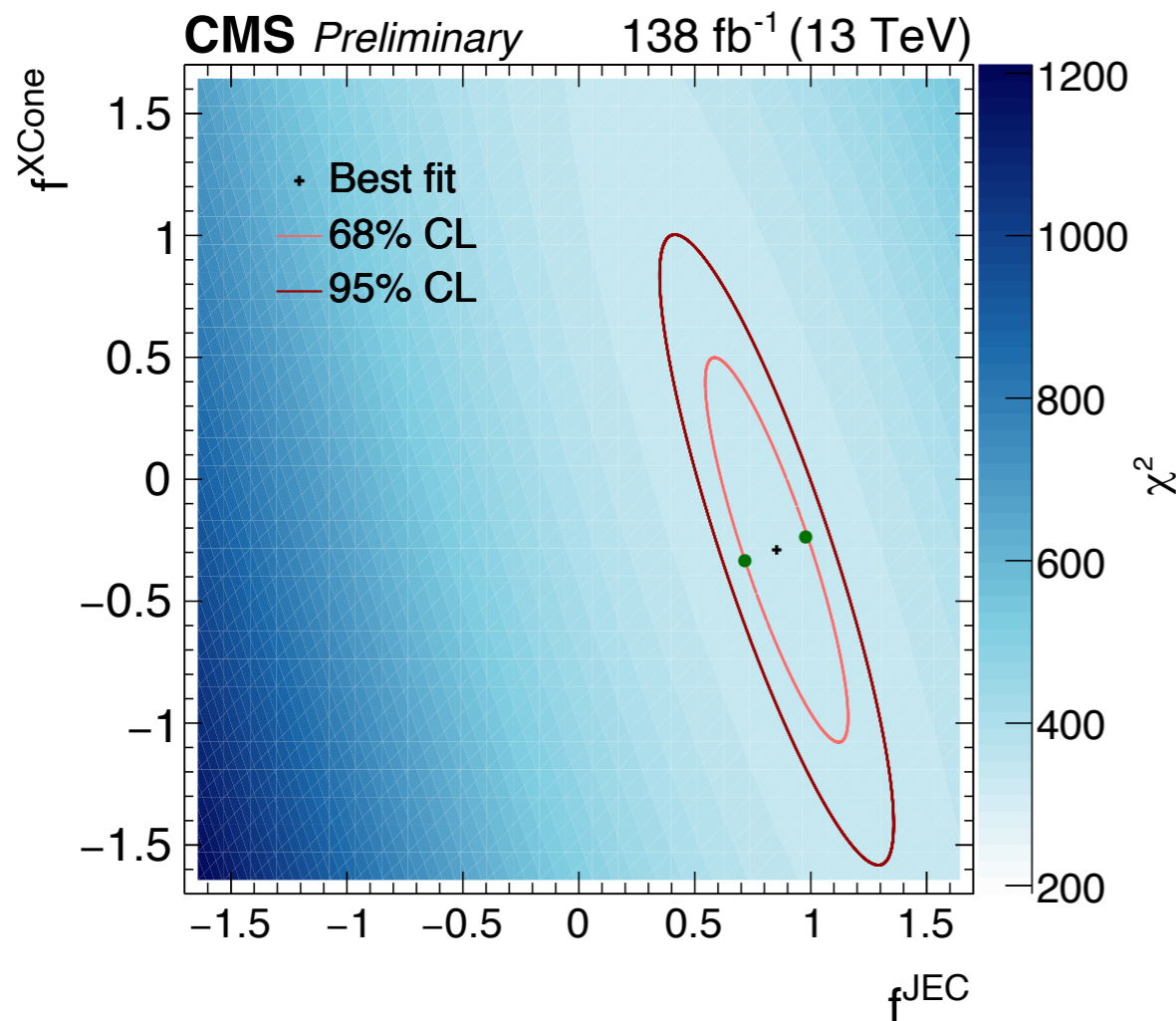


- ▶ Measure JMS with 2D  $\chi^2$ 
  - Vary correction within the 68% CL ellipse
- ▶ Additional flavour uncertainty
  - Cover difference of light and b quarks

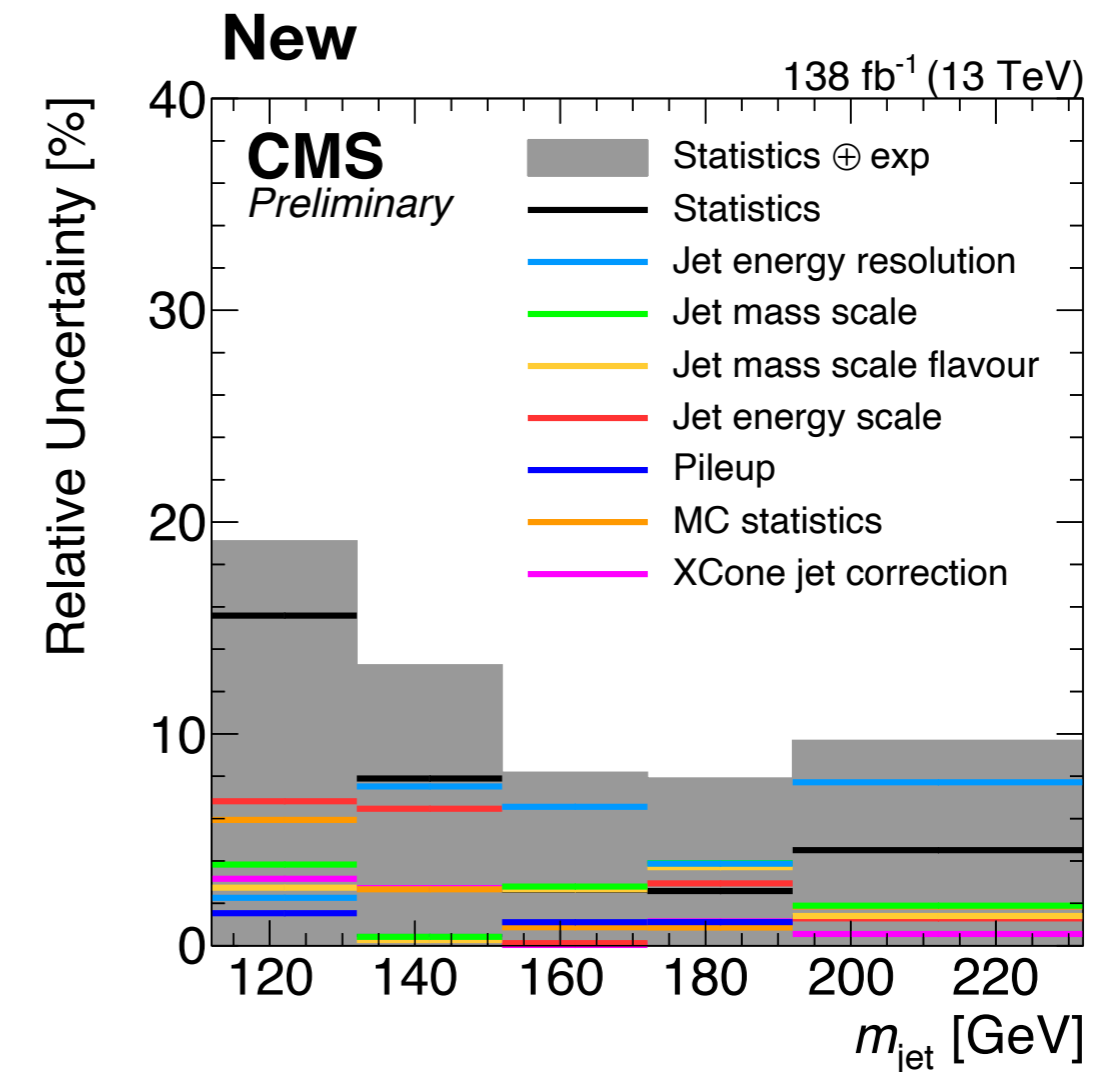
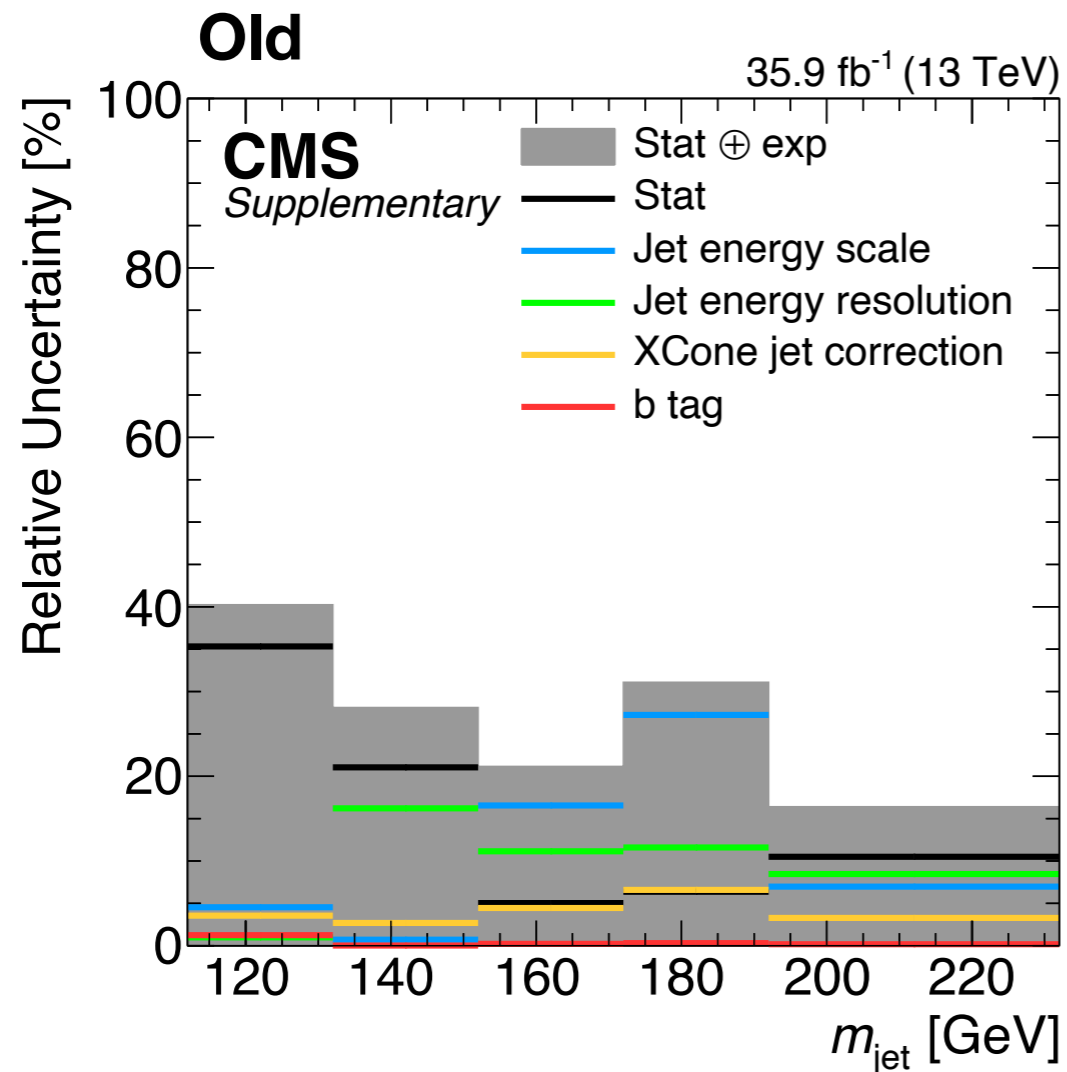
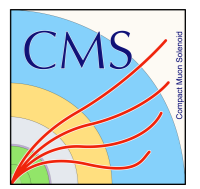
$$f_{\text{JEC}}^{\text{JMS}} = 0.85 \pm 0.15$$

$$f_{\text{XCone}}^{\text{JMS}} = -0.29 \pm 0.4$$

→ Projection of the 68% CL ellipse



# Comparison to 2016 measurement



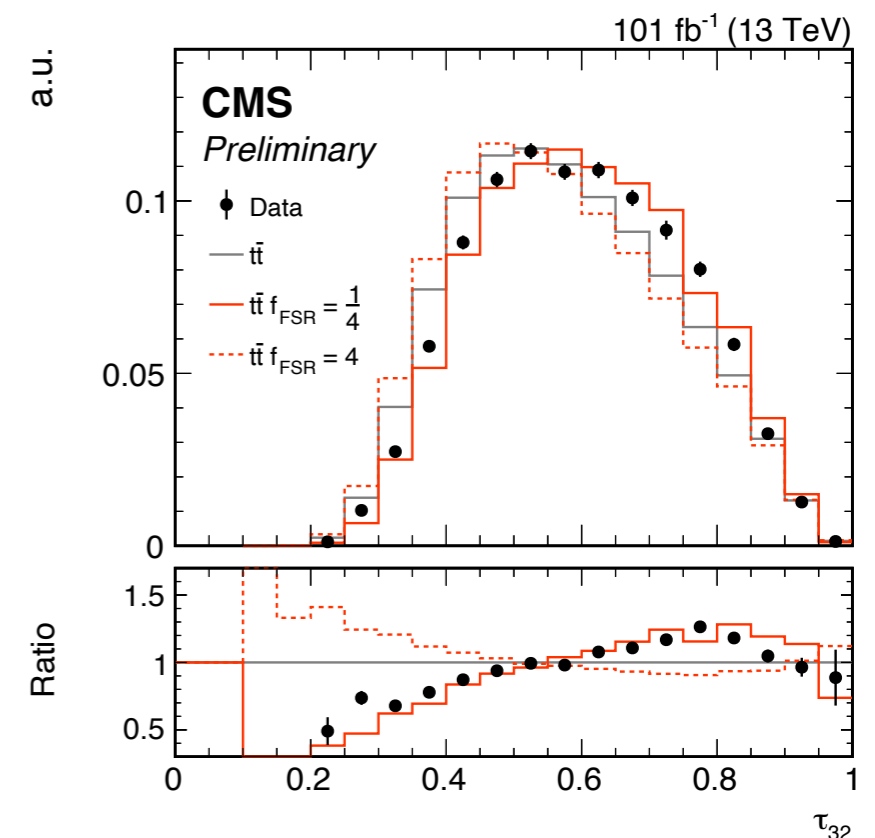
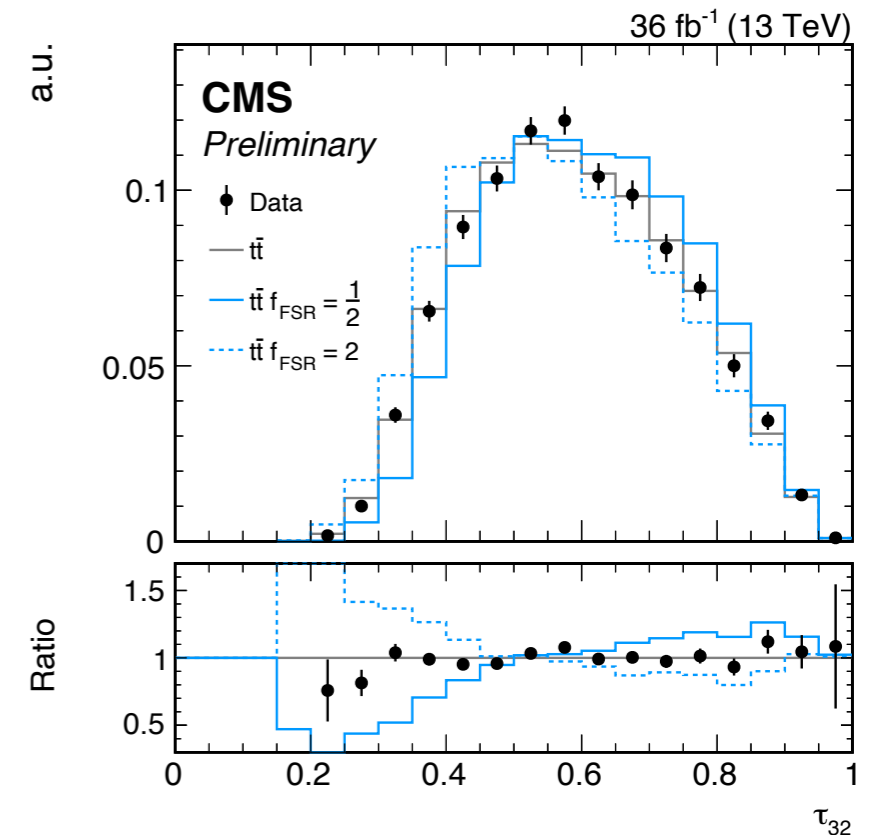
→ Note change in y-scale!

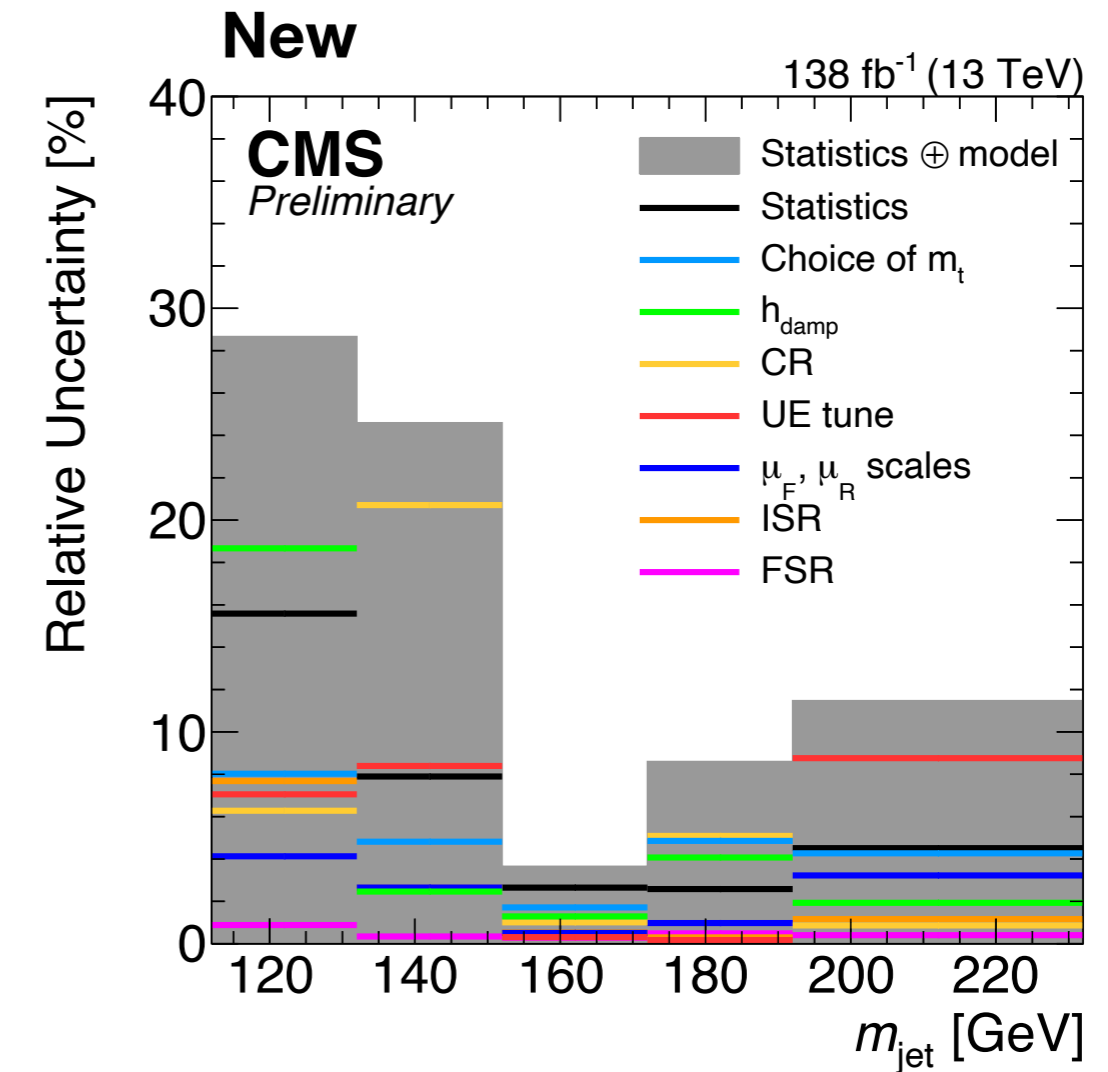
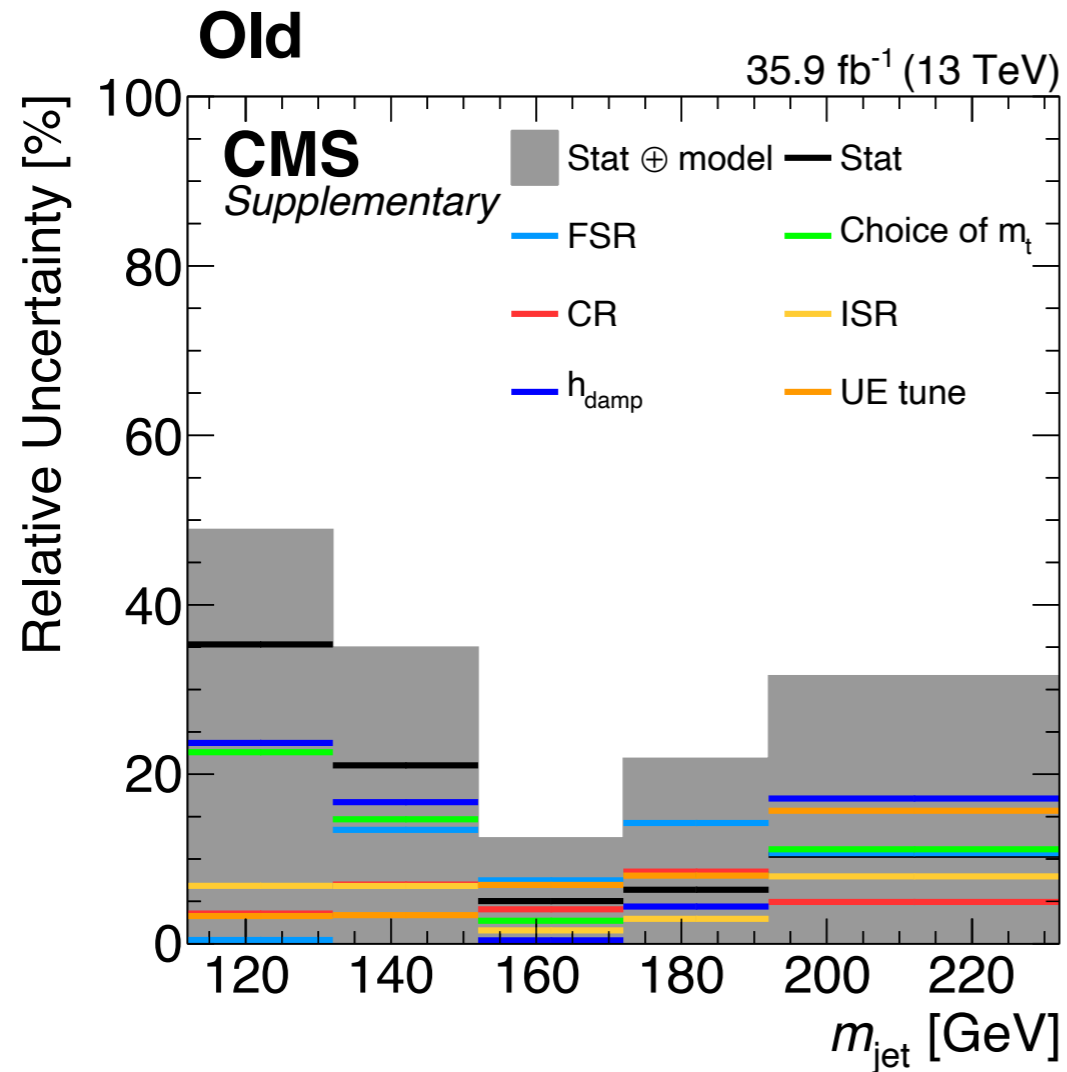
- ▶ Now JES only affects  $p_T$  of the subjets
- ▶ Introduce jet mass scale as separate uncertainty
- ▶  $\Delta m_t(\text{JES}) = 1.5 \rightarrow \Delta m_t(\text{JES} + \text{JMS} + \text{flavour}) = 0.39 \text{ GeV}$

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

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

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

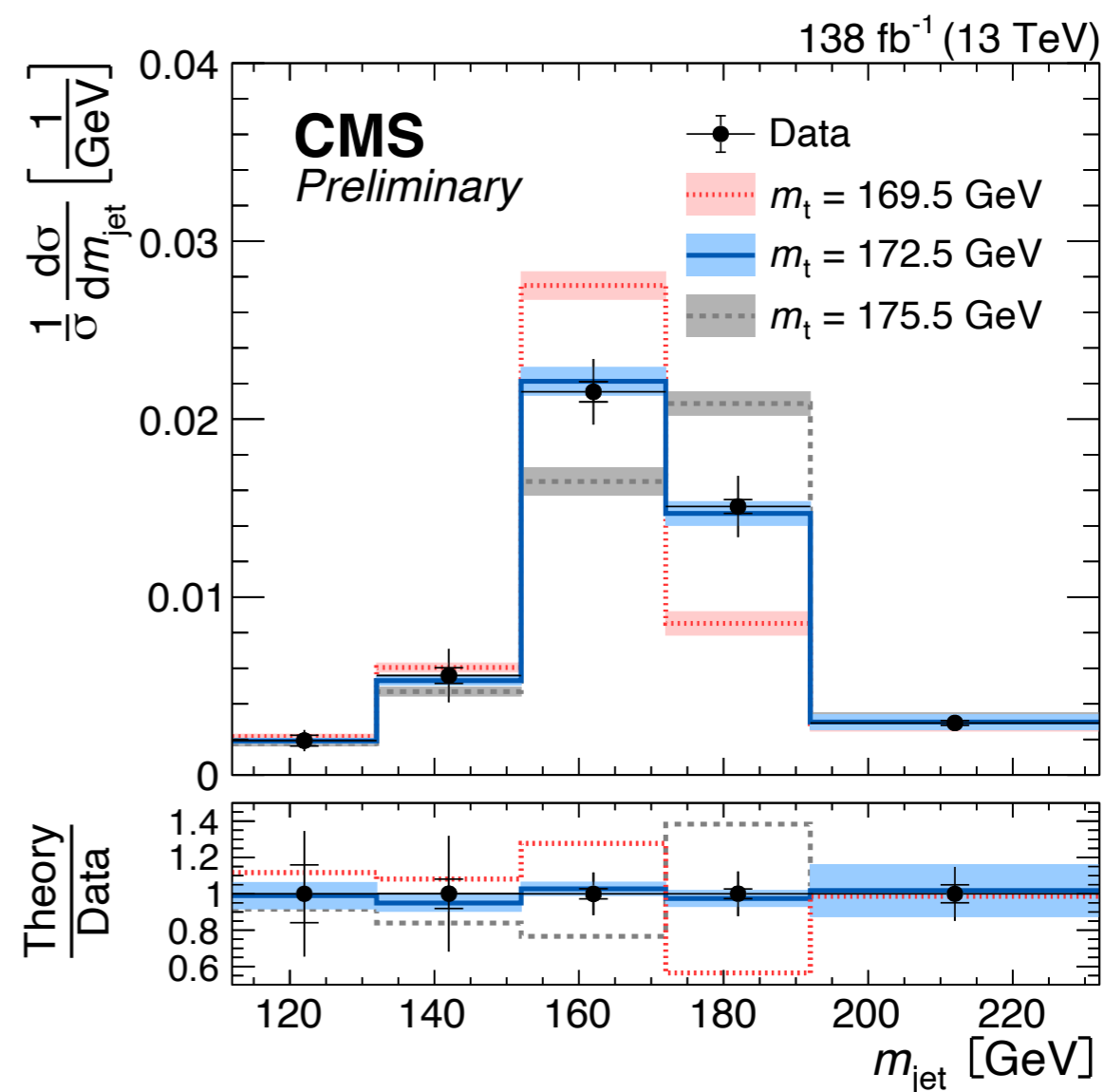
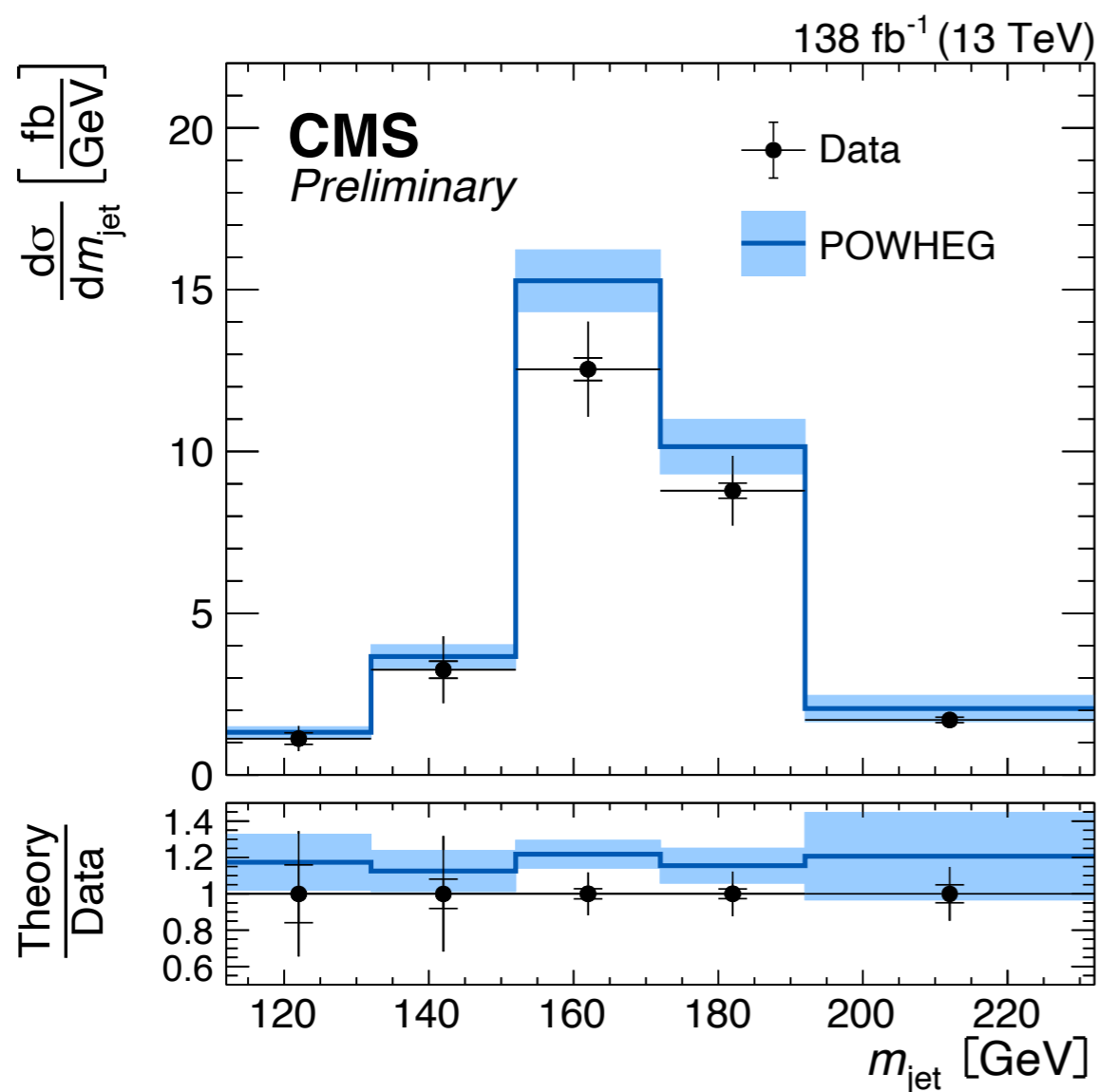




→ Note change in y-scale!

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

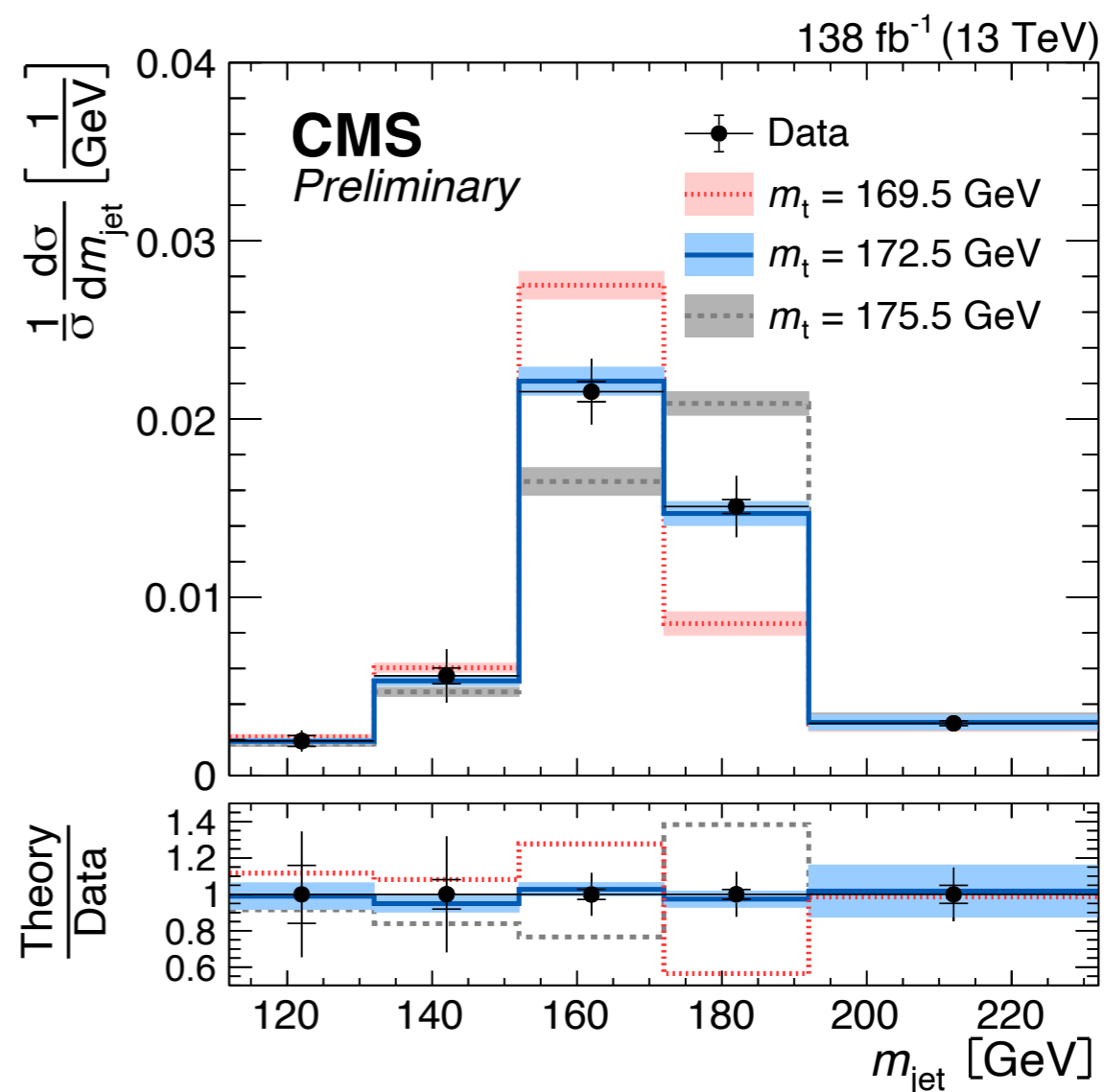
- ▶ Regularized unfolding using TUnfold
- ▶ Differential cross section as a function of  $m_{\text{jet}}$
- ▶ Extract  $m_{\text{top}}$  from normalized distribution



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

► Main uncertainties:

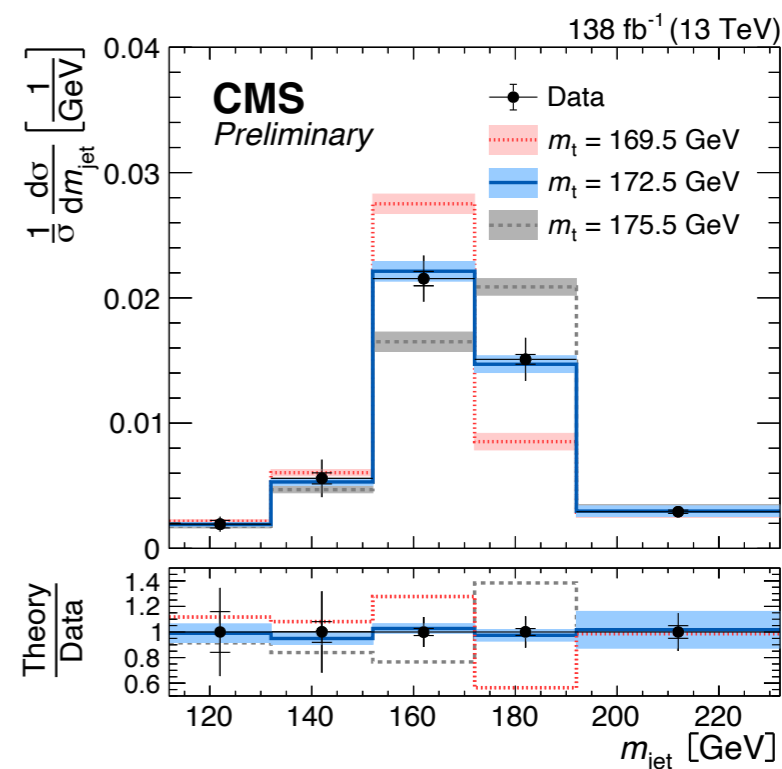
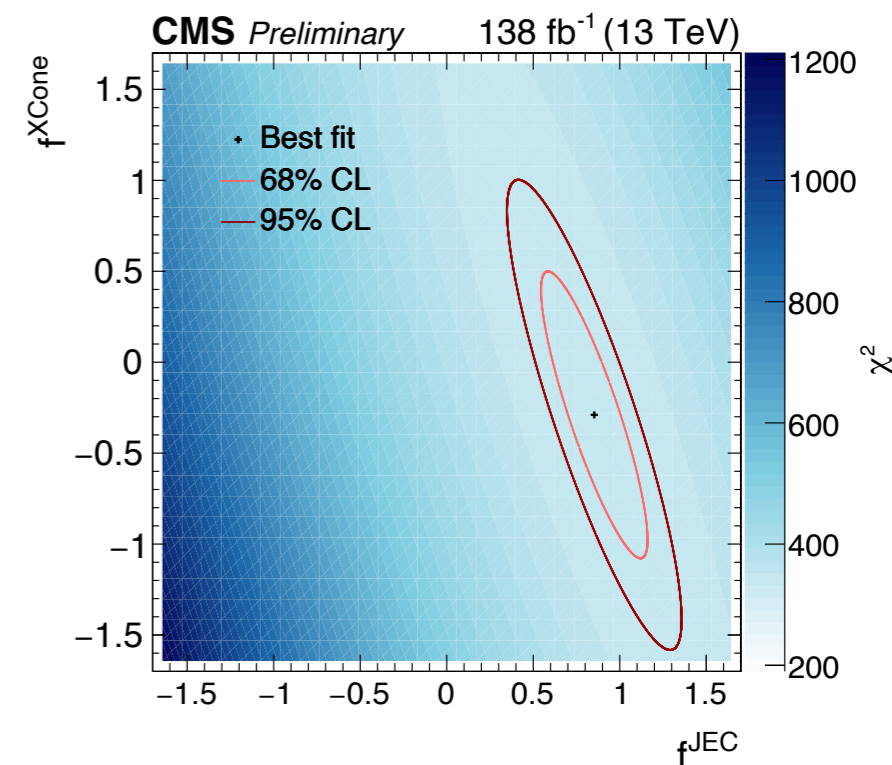
Source	Uncertainty [GeV]
Statistical uncertainty	0.22
Experimental uncertainty	0.57
JER	0.40
JMS	0.27
JMS flavour	0.27
JES	0.10
Model uncertainty	0.48
Choice of $m_{\text{top}}$	0.37
CR	0.19
$h_{\text{damp}}$	0.19
FSR	0.02



- ▶ Measured jet mass distribution in decays of boosted top quarks with the full Run-2 data set
- ▶ Significantly reduced dominant uncertainties of an earlier measurement
  - Calibration of the jet mass scale
  - Modeling of the final state radiation
- ▶ Increased precision of  $m_{\text{top}}$  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

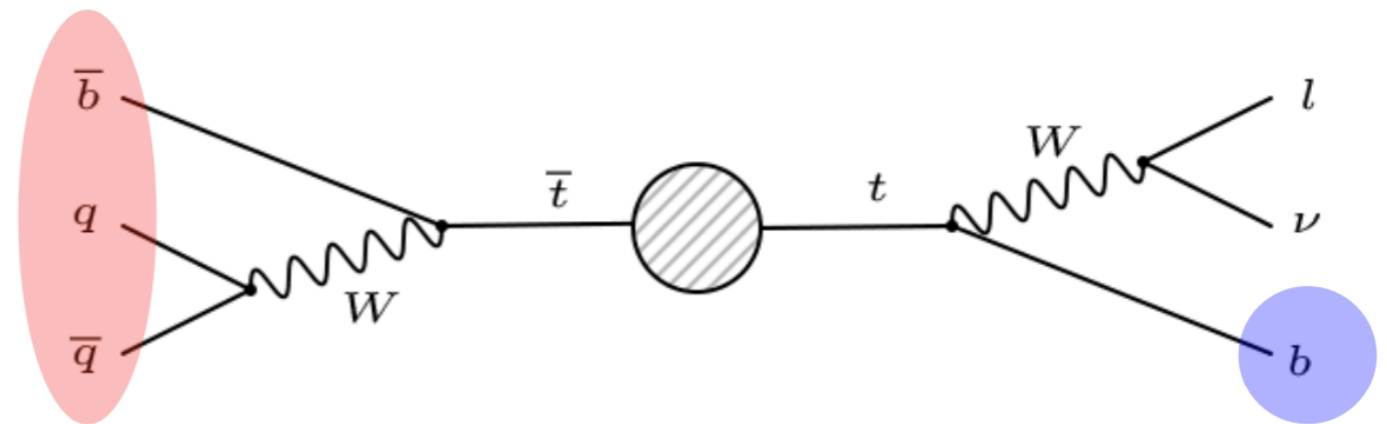




# **Additional Material**

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

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

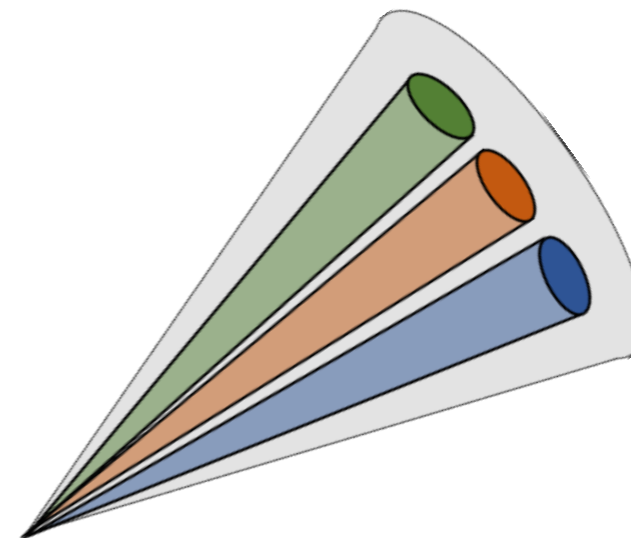


## Select boosted top quarks

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

## Suppress unmerged top quark decays

- ▶  $m_{\text{hadjet}} > m_{\text{lepjet}+\ell}$



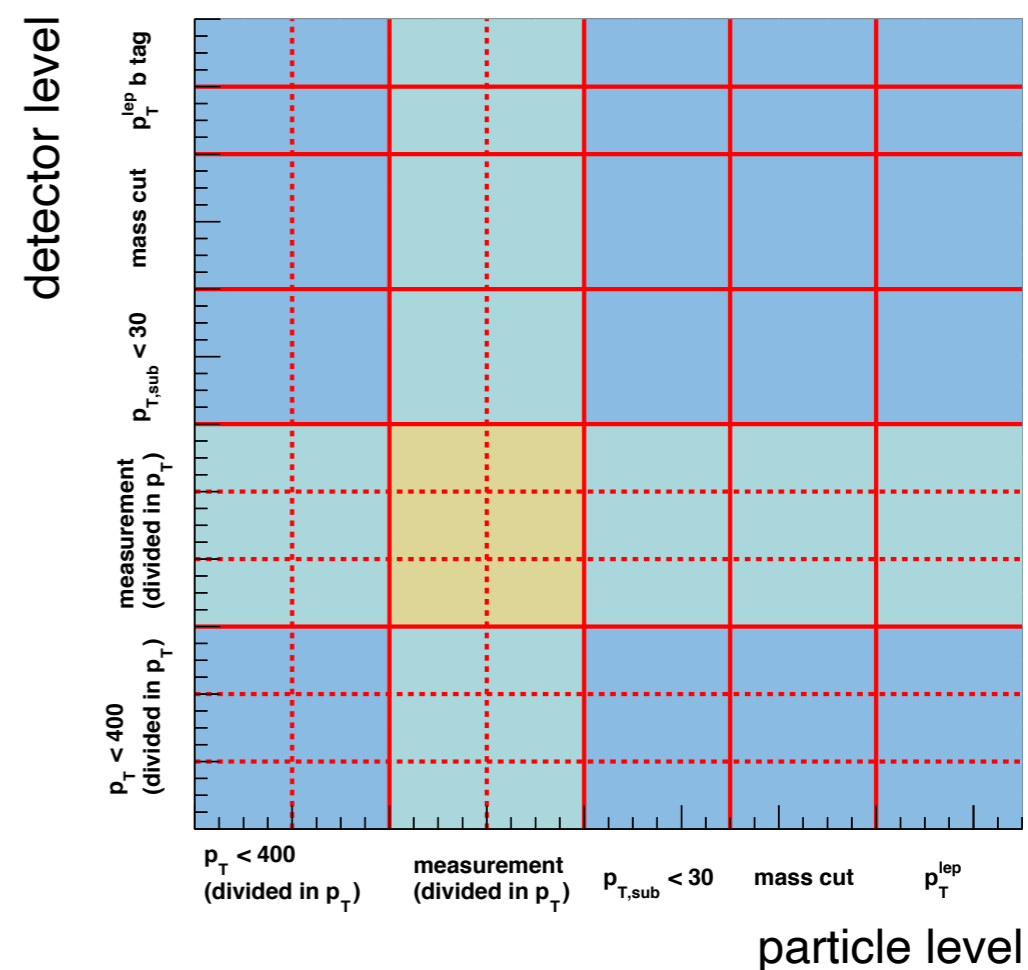
- ▶ **CPETP8M2T4** describes data better than **CP5**
- ▶ After calibration  $\alpha_S^{\text{FSR},2016} \sim \alpha_S^{\text{FSR},2017+2018}$
- ▶ From original tune:

$$\alpha_S^{\text{FSR},\text{CPETP8M2T4}} = 0.1365$$

$$\alpha_S^{\text{FSR},\text{CP5}} = 0.118$$

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

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



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

