Measurement of the top mass with boosted jets

Alexander M. Paasch on behalf of the ATLAS and CMS Collaborations

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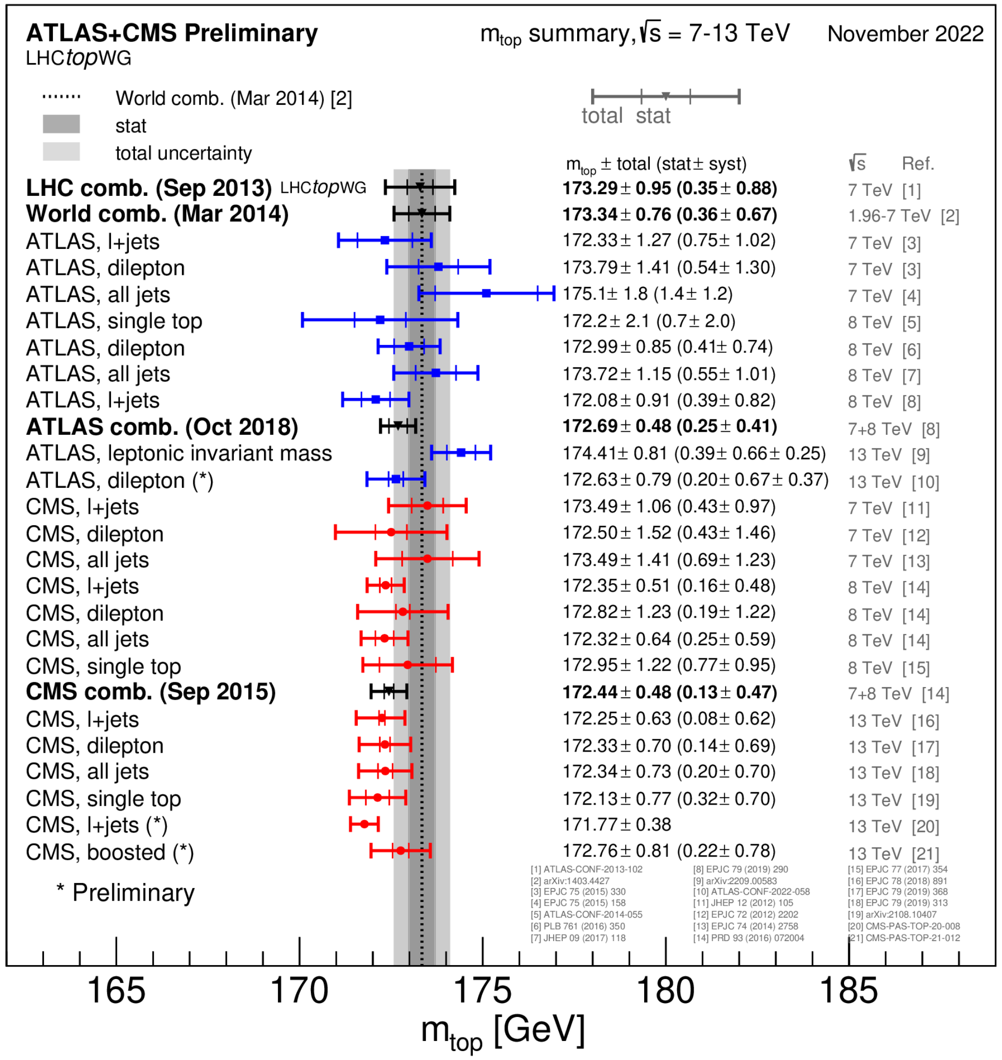
Why boosted top quarks?

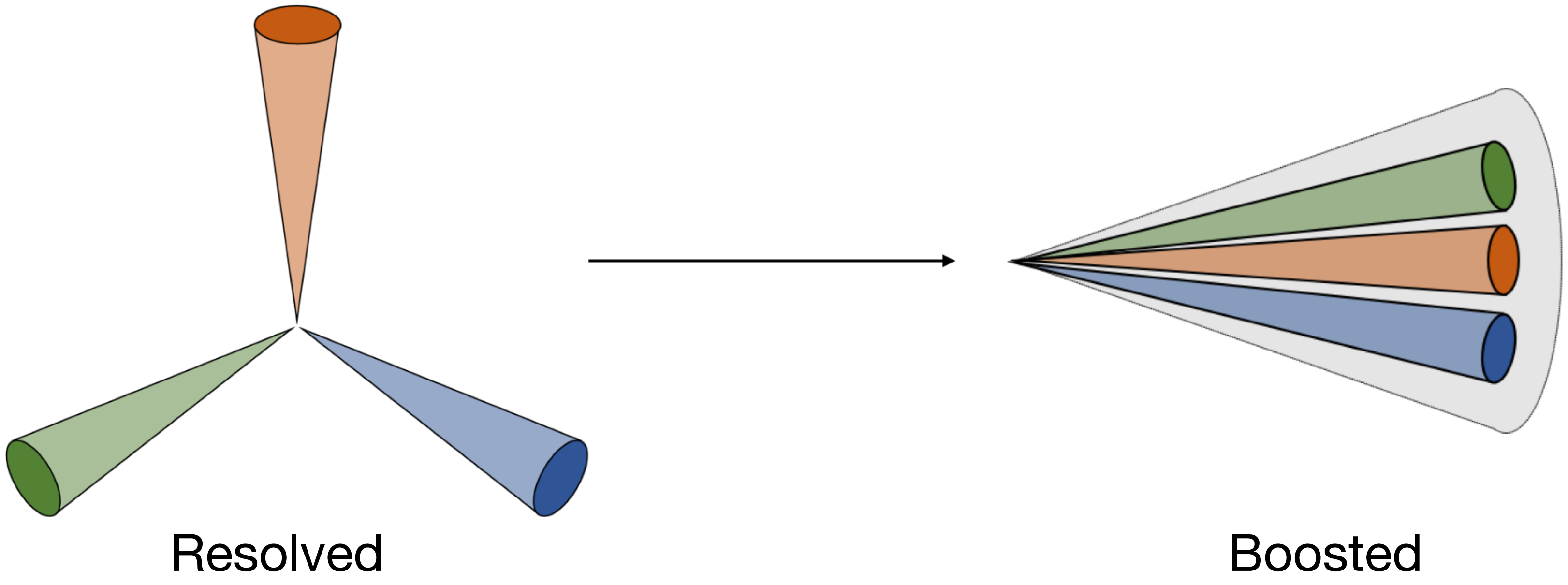


- Many approaches to measure top mass m_{top} at the LHC
- Dominated by threshold production

→ Explore boosted regime

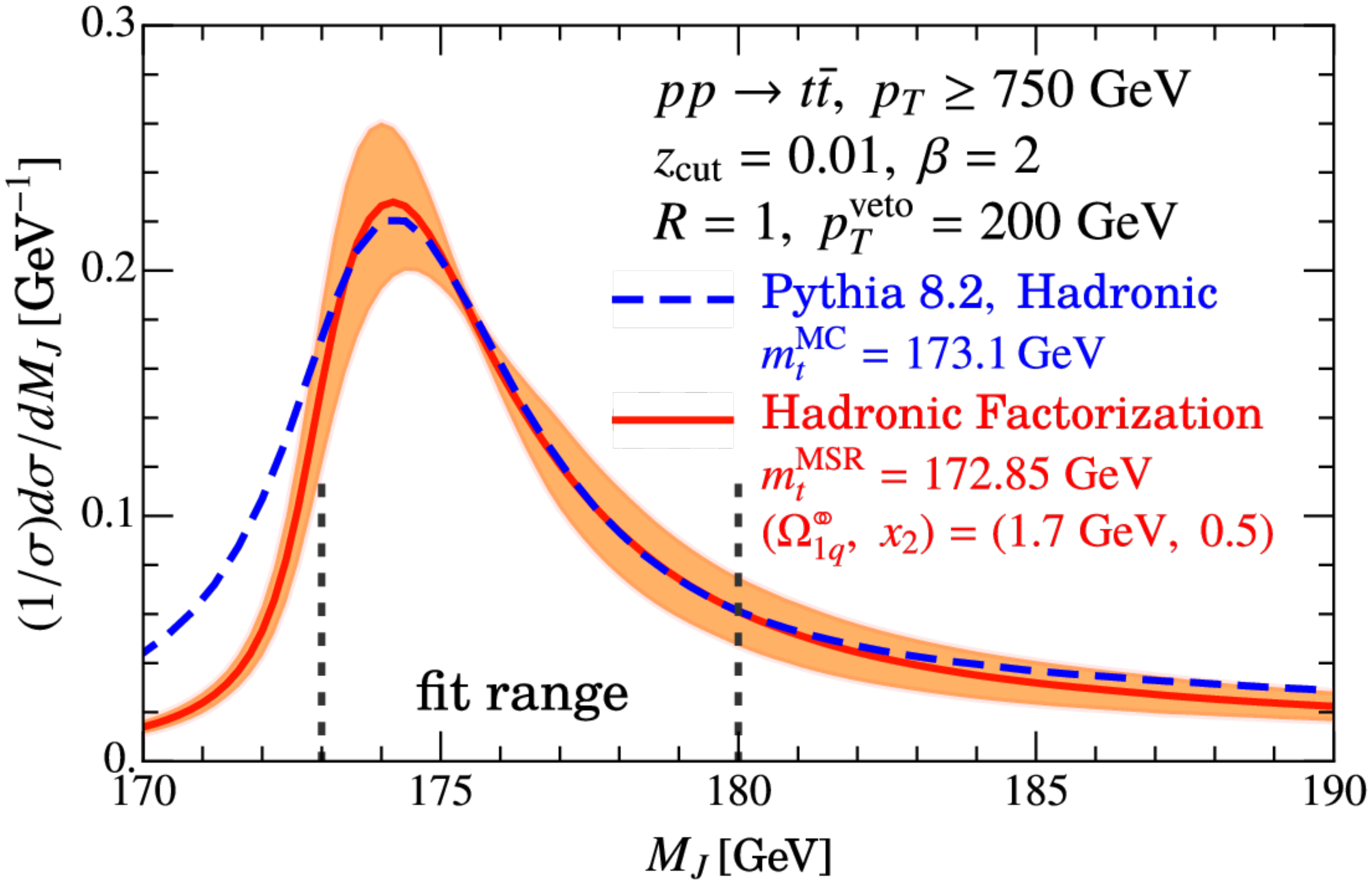
(Reconstruct top quark decay in single-large radius jet)

In this talk: aim for the jet mass m_{jet}



Well defined m_{top} with large-radius jets

- Compare measurement to well-defined field theory parameter
  - Avoid ambiguities in event generators
- Phase-space of theory and experiment not compatible yet
- First comparison to event generators from ATLAS
  - Translate $m_{\mathrm{top}}^{\mathrm{MC}}$ to a well-defined scheme

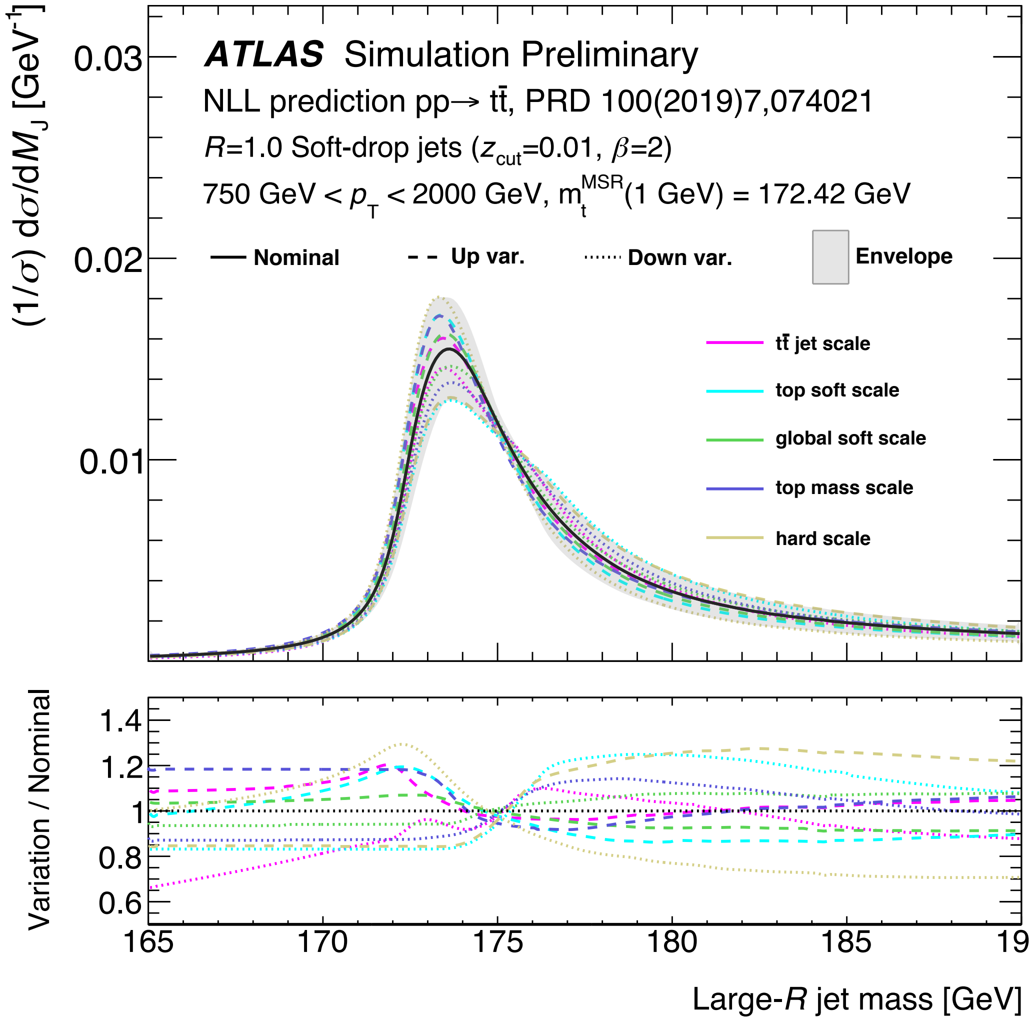


[A. H. Hoang et al., Phys.Rev.D 100 (2019) 7, 074021]

Methodology

[ATLAS, ATL-PHYS-PUB-2021-034]

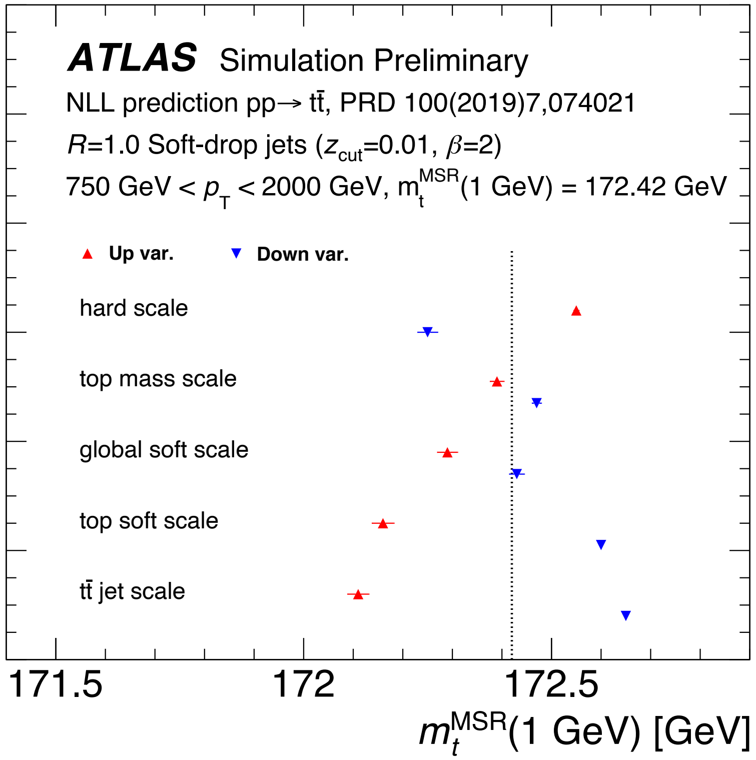
- Aim for m_{top} in MSR renormalization scheme with $m_{\text{top}}^{\text{MSR}}(1\ \text{GeV})$
- Jet mass spectrum depends on three parameters ($m_{\text{top}}^{\text{MSR}}$, Ω, x)
  - Ω accounts for leading hadronization effects
  - x accounts for hadronic corrections
- Reconstruction of $t\bar{t}$ events in MC with XCone jet algorithm
  - Radius of $R = 1$
  - Light soft-drop grooming
  - At least on jet with $p_{\text{T}} > 750\ \text{GeV}$
- Template fit to compare Powheg+Pythia MC to NLL calculations

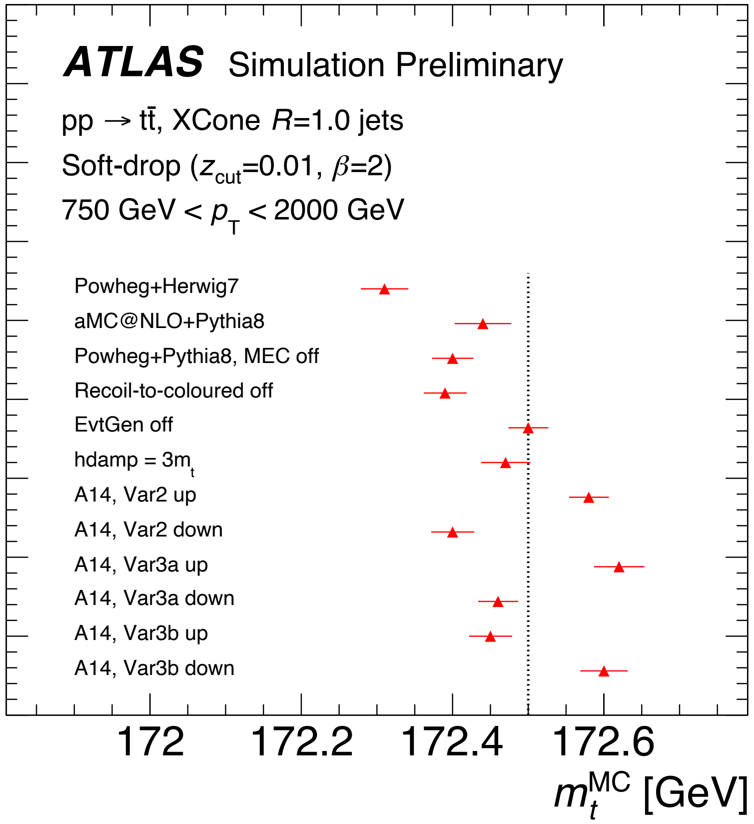


Systematic uncertainties

[ATLAS, ATL-PHYS-PUB-2021-034]

- Varying scales in calculations
  - Account for missing higher-order corrections
- Detailed studies of model dependent parameters
  - Impact of UE (underlying event) and CR (color reconnection)
- Different $t\bar{t}$ modeling like parton shower and matrix element generators not considered
  - Dedicated calibration for each modeling





Source	Size [MeV]	Comment
Theory (higher-order corrections)	+230/−310	Envelope of NLL scale variations
Fit methodology	±190	Choice of fit range, p_{T} bins
Underlying Event model	±155	A14 eigentune variations, CR models
Total Systematic	**+340/−340**	
Statistical Uncertainty	±100	
Total Uncertainty	**+350/−410**	

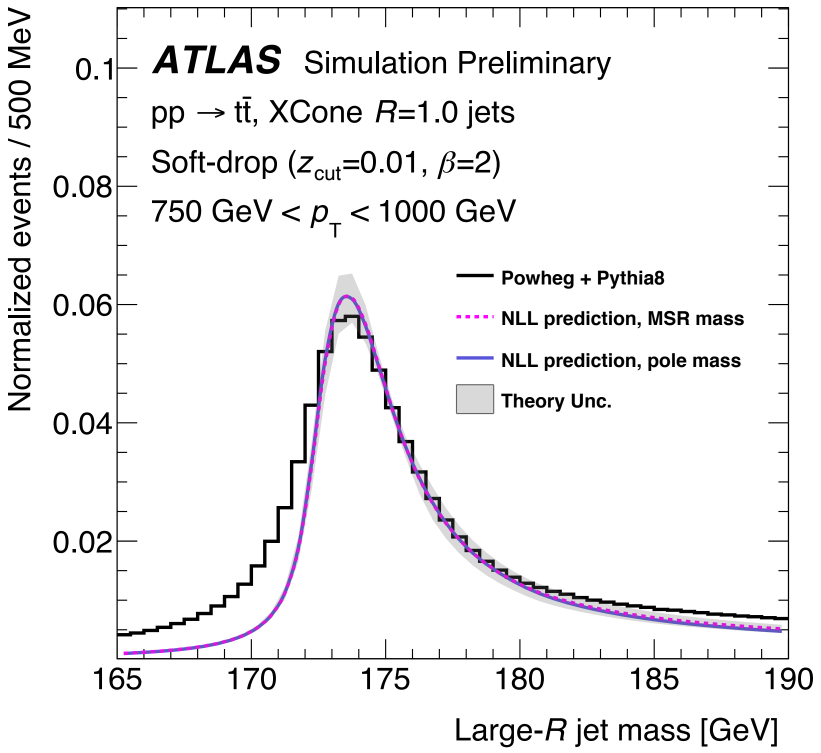
Translation from MC to well defined mass

[ATLAS, ATL-PHYS-PUB-2021-034]

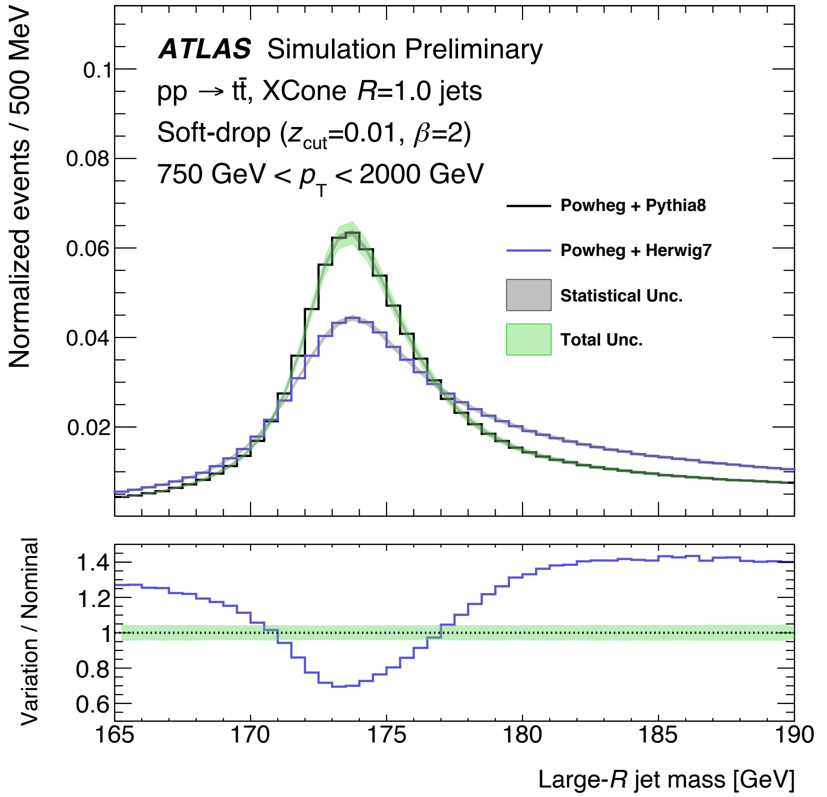
$$m_{\text{top}}^{\text{MSR}}(1\ \text{GeV}) = m_{\text{top}}^{\text{MC}} - 80^{+350}_{-410}\ \text{MeV}$$

$$m_{\text{top}}^{\text{pole}} = m_{\text{top}}^{\text{MC}} - 350^{+300}_{-360}\ \text{MeV}$$

→ Additional uncertainty arising from translation from $m_{\text{top}}^{\text{MC}}$ to $m_{\text{top}}^{\text{MSR}}$



- Relatively stable for other jet clustering algorithms
- Comparison of Pythia and Herwig
  - Very different mass spectra
  - Similar $m_{\text{top}}^{\text{MSR}}$ but different Ω and x
  - Further studies are necessary!



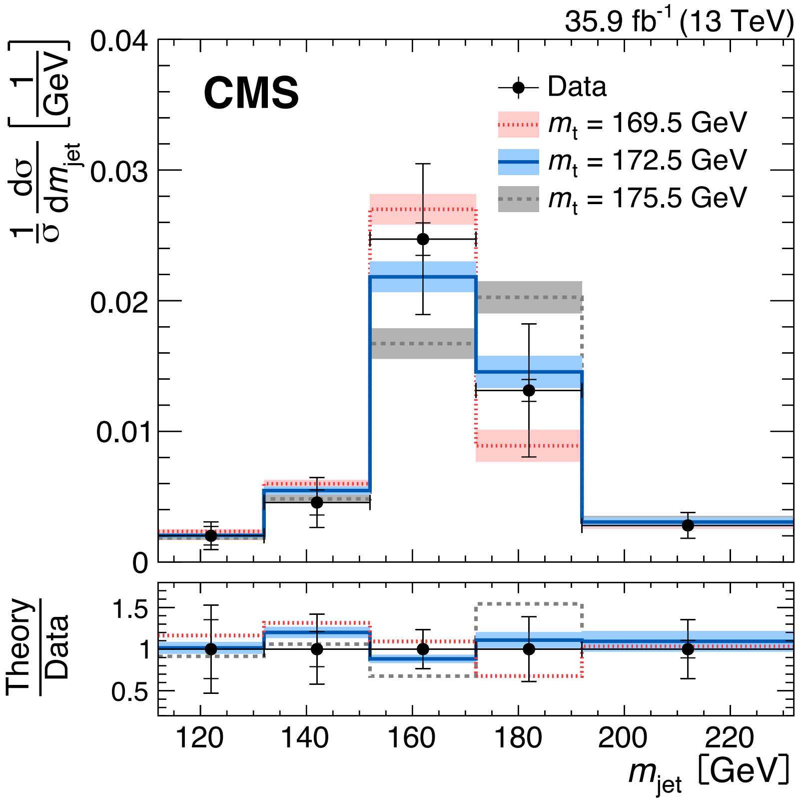
Measurement with CMS

[CMS, Phys. Rev. Lett. 124, 202001]

$$m_{\mathrm{jet}} = \sqrt{(\sum_i p_i)^2}$$

- Aim for a large-radius jet including the hadronic top quark decay
  - Select boosted regime: $p_{\mathrm{T,jet}} > 400\ \mathrm{GeV}$
  - Measure differential cross section as function of m_{jet}
  - Extract m_{top} from unfolded distribution
- Measurement with data from 2016: $m_{\mathrm{top}} = 172.6 \pm 2.5\ \mathrm{GeV}$

$172.8 \pm 9.0\ \mathrm{GeV}$ at 8 TeV analysis [CMS, Eur. Phys. J. C volume 77 (2017), 467]



Now improve analysis with full Run II dataset

[arxiv:2211.01456]

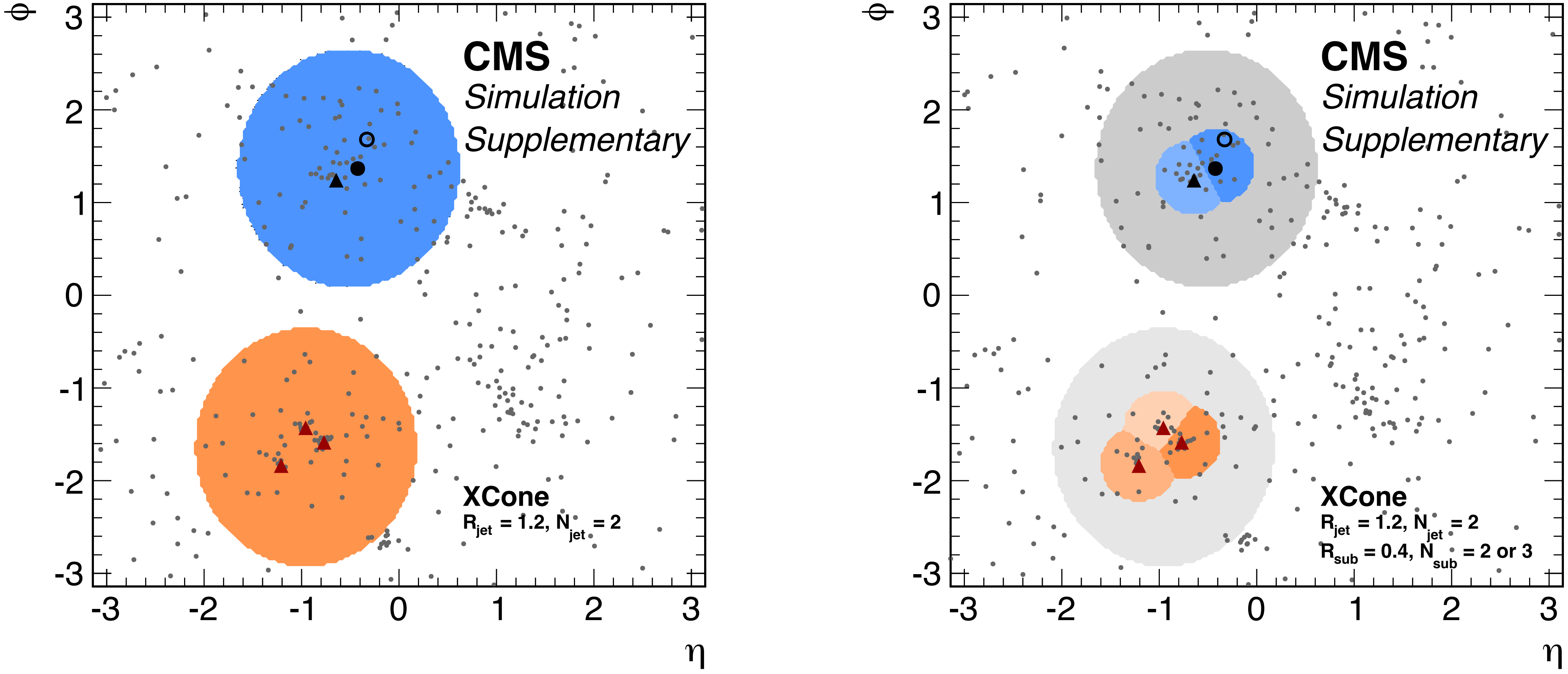
- Reduce dominant uncertainties from 2016
  - Calibration of the jet energy scale
  - Modeling of the final state radiation

Event reconstruction with XCone

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

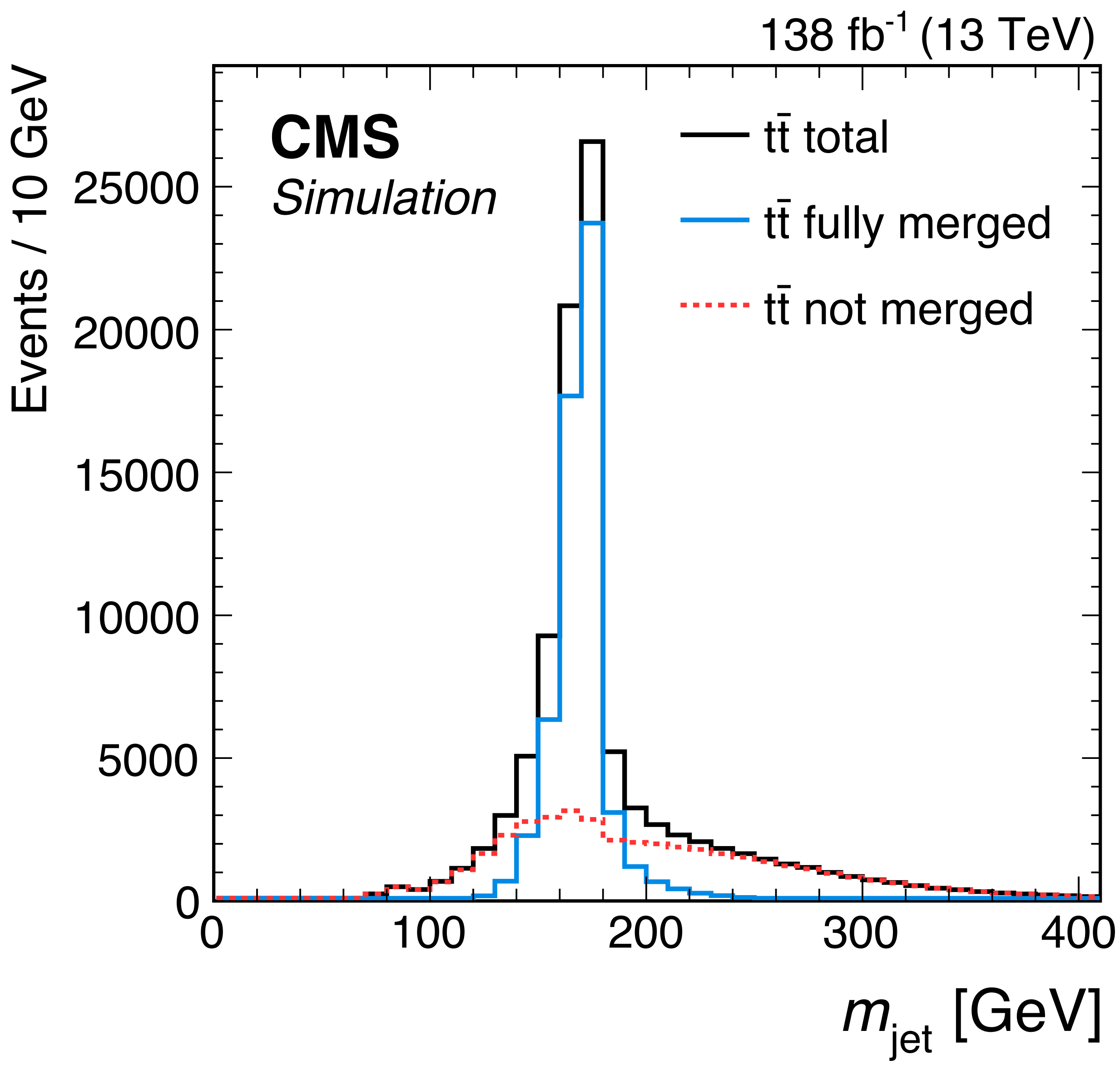
Dedicated corrections for the XCone subjects depending on η and p_T



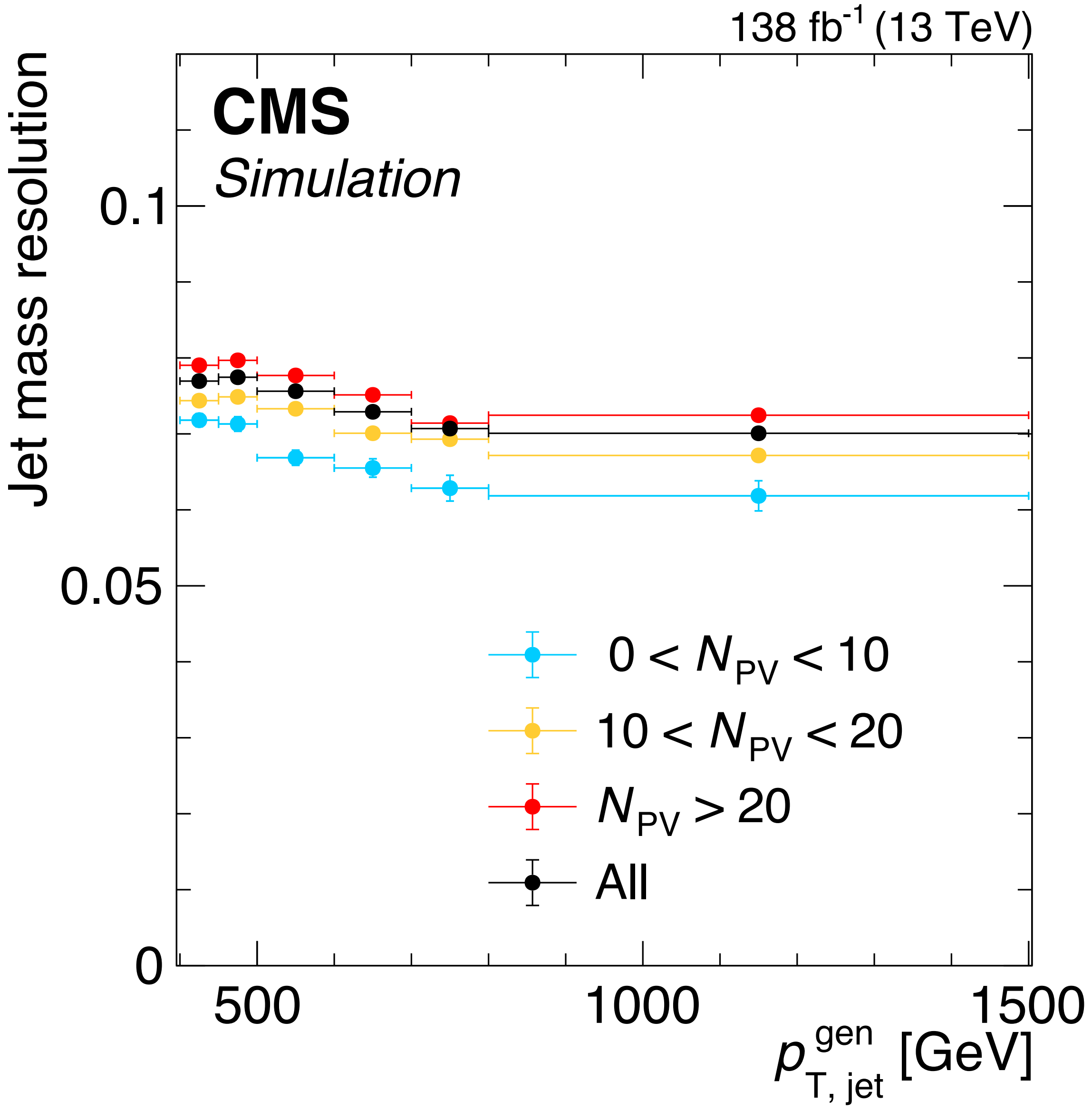
Suppl. Material of [Phys. Rev. Lett. 124, 202001]

Performance at generator and detector level

[CMS, arxiv:2211.01456]



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

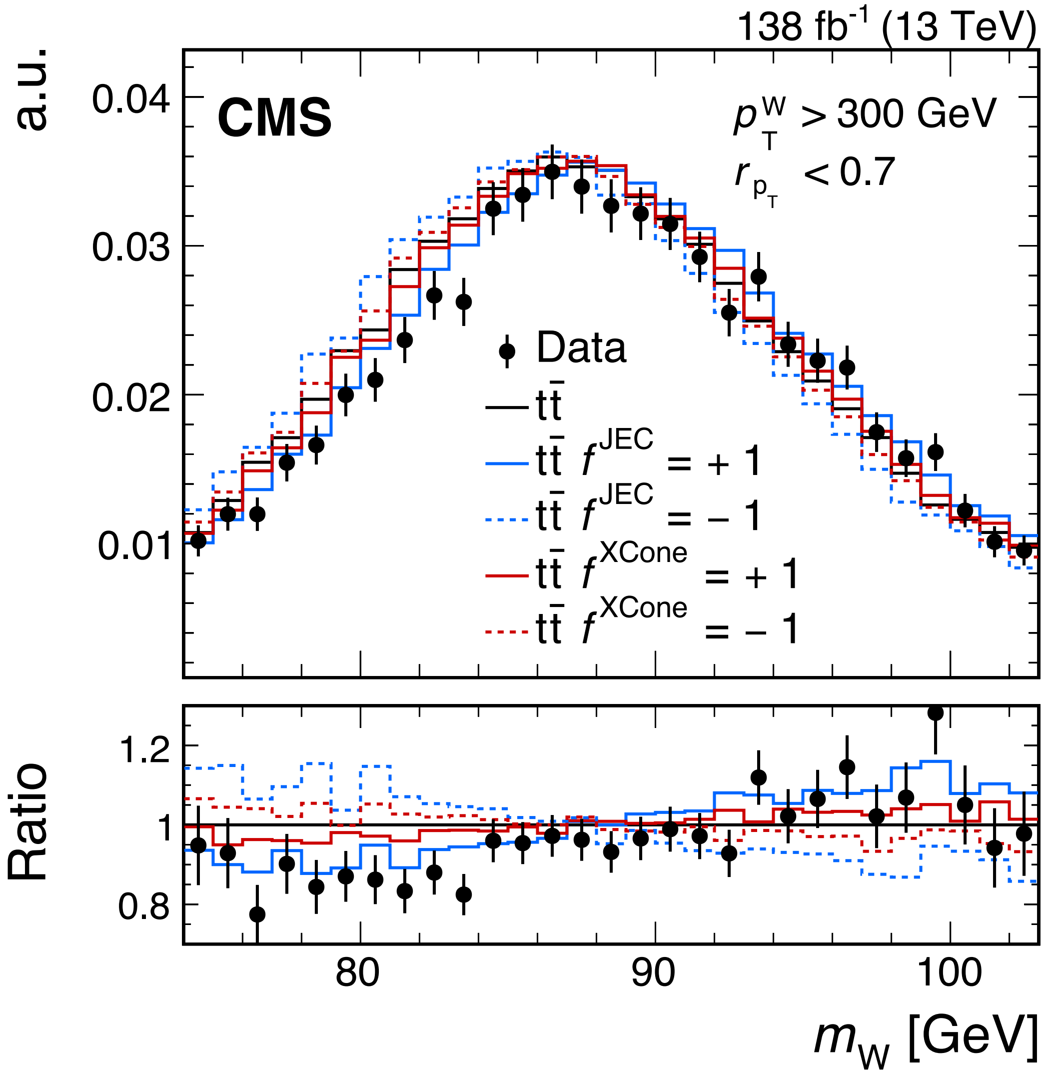


- m_{jet} resolution at 6-8%
- 14% for jet with $R = 1.2$

Calibration of the jet mass scale

[CMS, arxiv:2211.01456]

- **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 two XCone subjets
- Fit AK4 JES (f^JEC) and XCone corrections (f^XCone) simultaneously

Jet mass scale

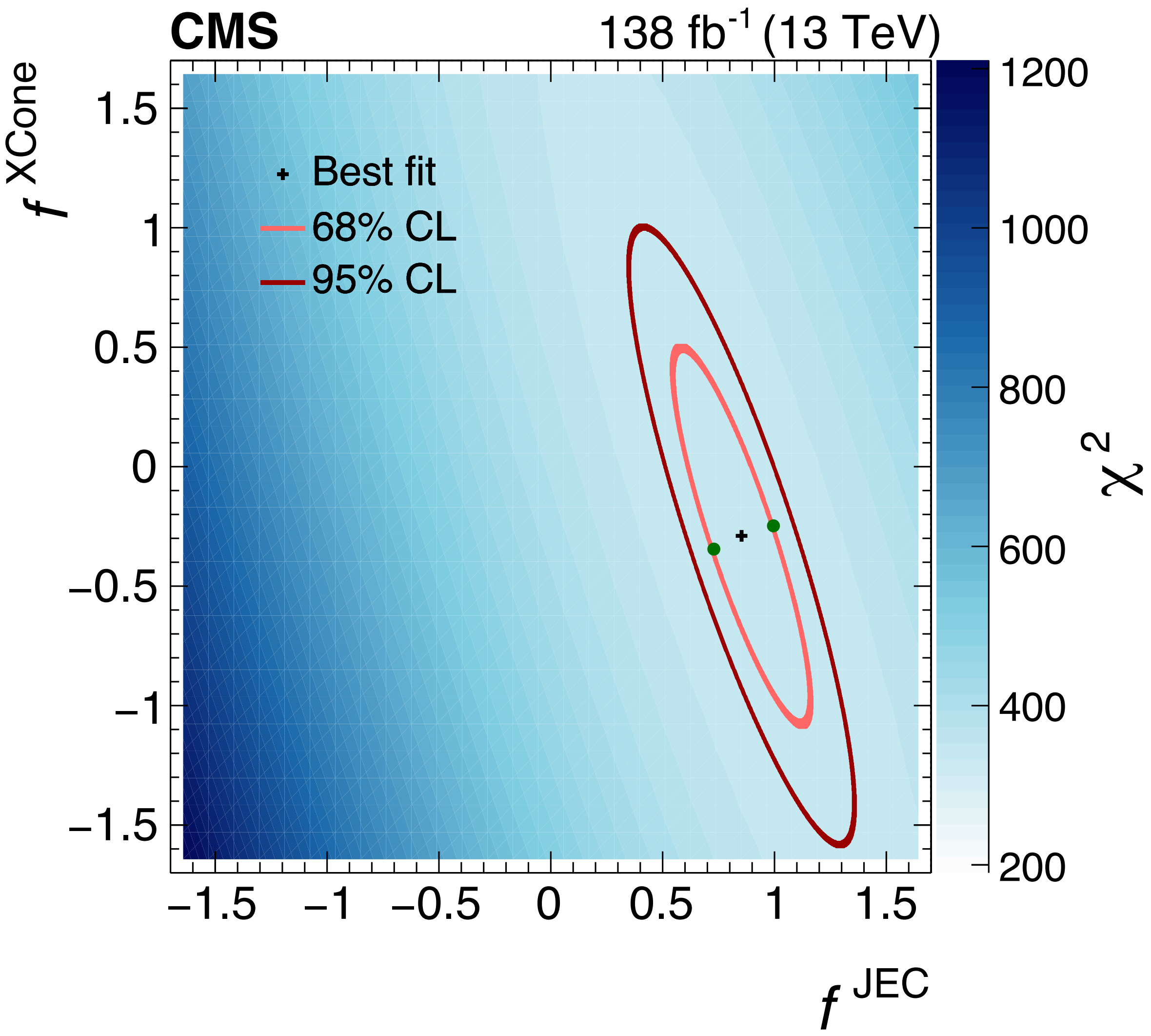
[CMS, arxiv:2211.01456]

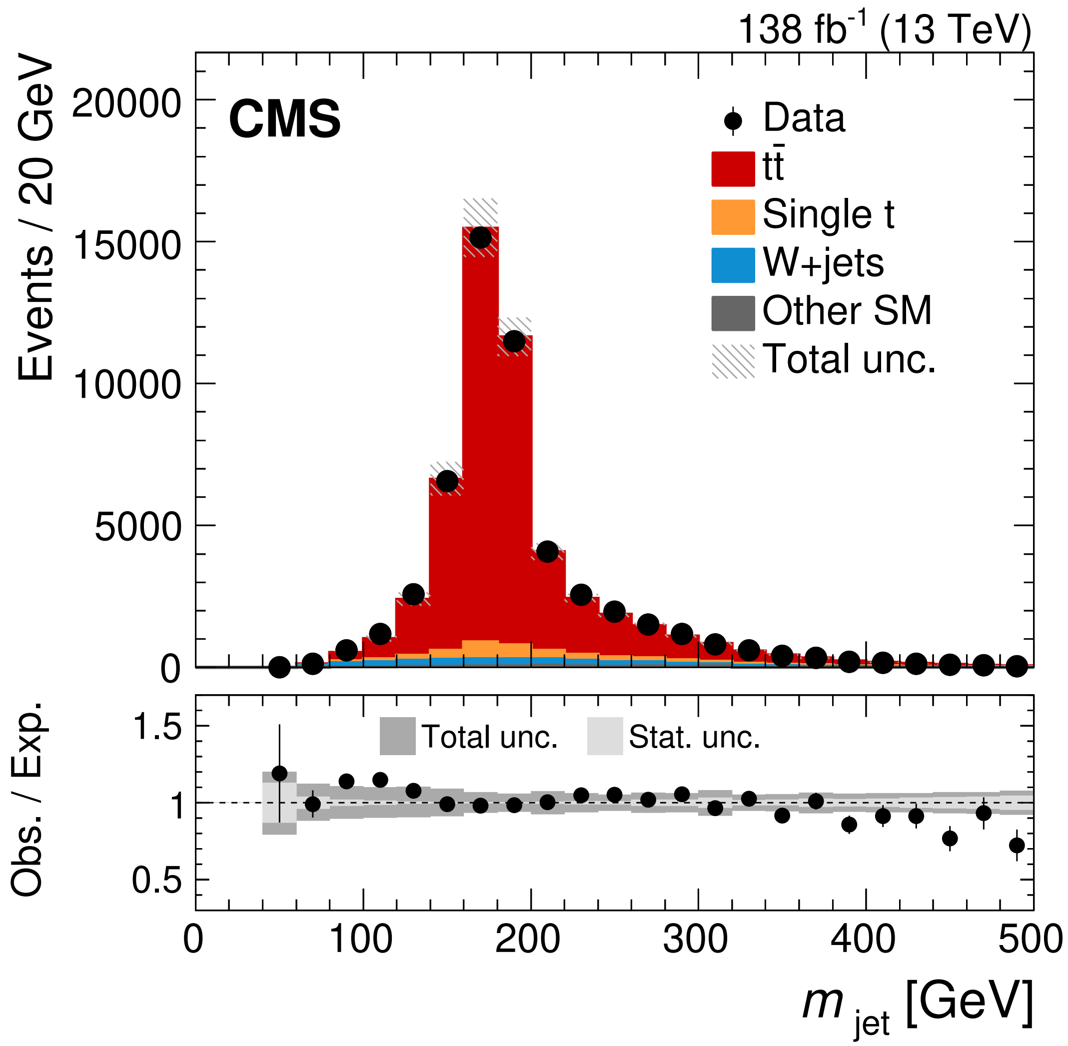
- Measure JMS with 2D χ^2
  - Extract uncertainties from the 68% CL
- Additional flavour uncertainty
  - Cover difference of light and b quarks

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

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

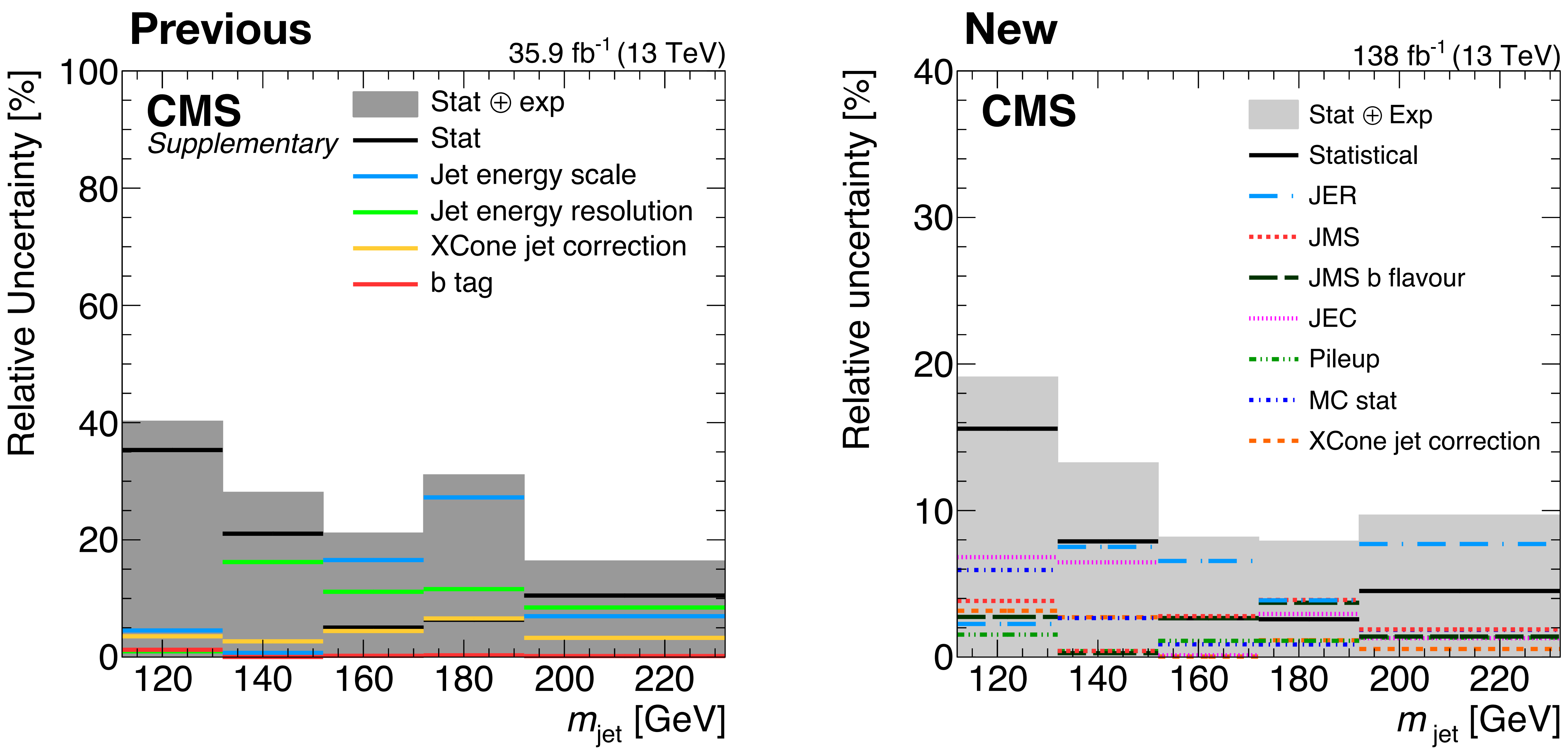
→ Projection of the 68% CL ellipse





Comparison to 2016 measurement

[CMS, arxiv:2211.01456]



→ **Note change in y-scale!**

- Now JES only affects p_{T} of the subjets
- Introduce jet mass scale as separate uncertainty
- $\Delta m_{\mathrm{t}}^{2016}(\mathrm{JES}) = 1.5 \rightarrow \boxed{\Delta m_{\mathrm{t}}^{\mathrm{Run2}}(\mathrm{JES} + \mathrm{JMS} + \mathrm{flavour}) = 0.39\ \mathrm{GeV}}$

Calibration of FSR modeling

[CMS, arxiv:2211.01456]

- FSR scale steers strong coupling for additional radiation with $\alpha_S(f_{\mathrm{FSR}} \cdot \mu_0)$

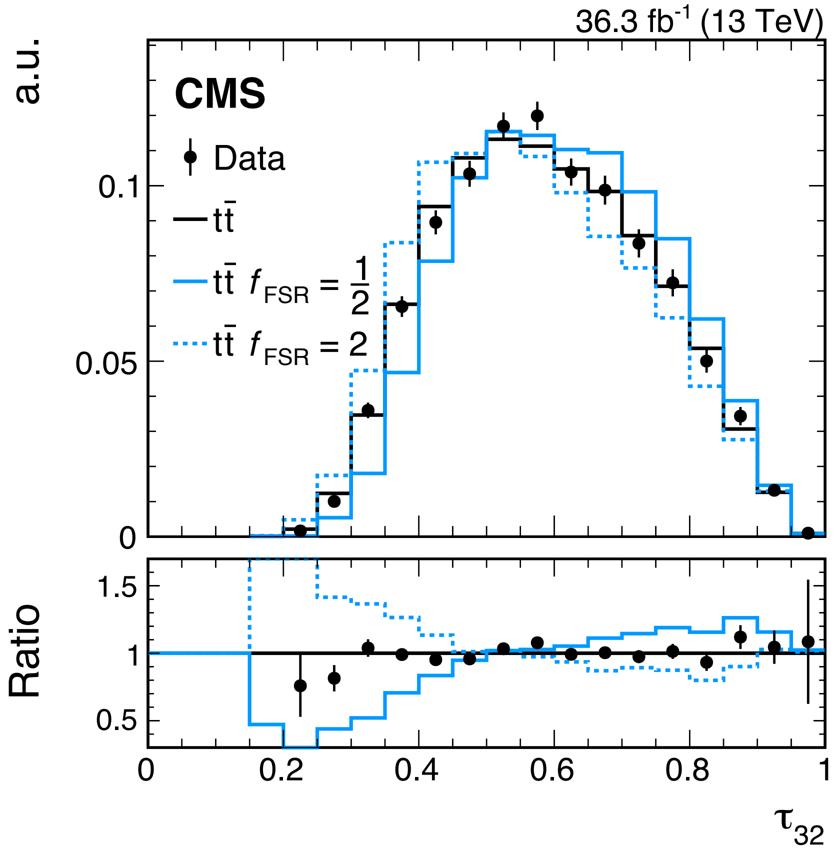
- **Before:** Estimate FSR scale with $f_{\mathrm{FSR}} \in \{\frac{1}{2}, 2\}$
- **Now:** Dedicated calibration of FSR scale

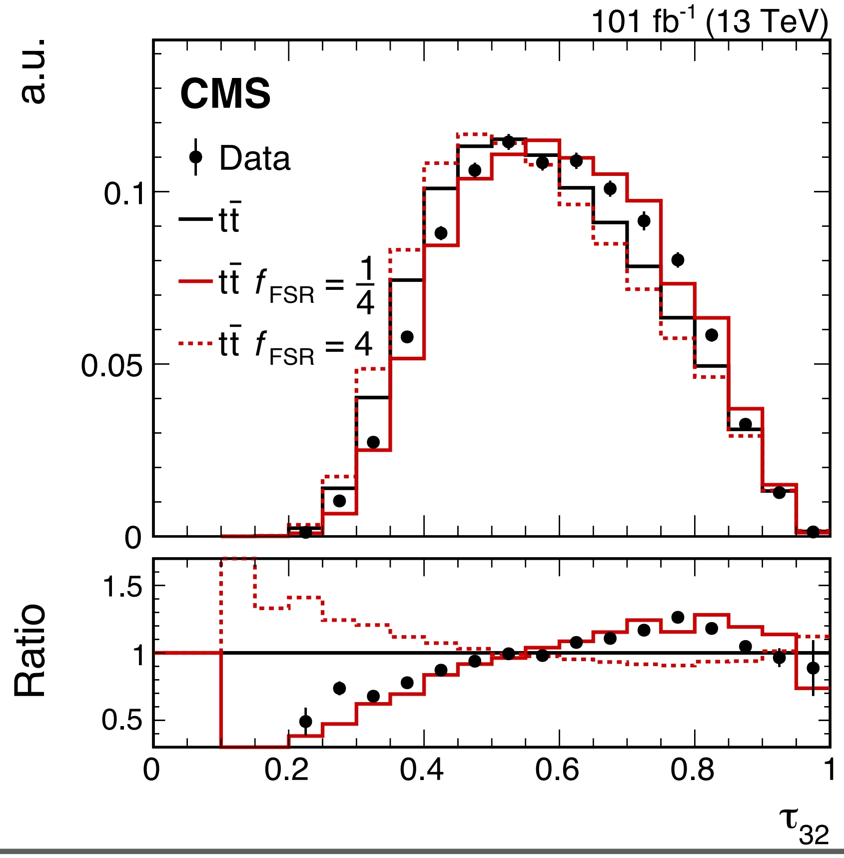
- Jet substructure observable τ_{32} sensitive to additional radiation

- Split datasets into 2016 and 2017+2018
  - Different tune in $t\bar{t}$ simulation

$$\mathrm{f}_{\mathrm{FSR}}^{2016} = 0.97 \pm 0.07$$ Tune CUETP8M1

$$\mathrm{f}_{\mathrm{FSR}}^{2017+2018} = 0.33 \pm 0.02$$ Tune CP5

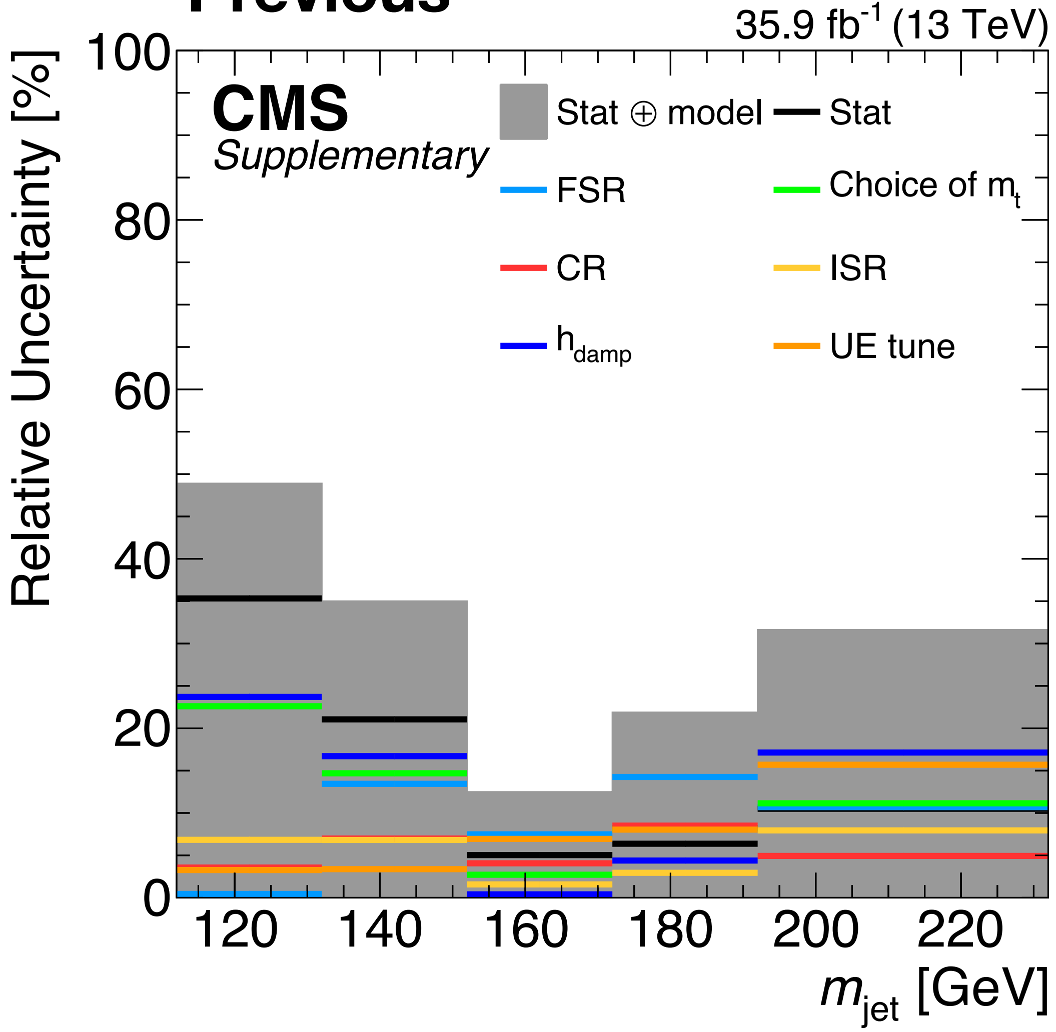




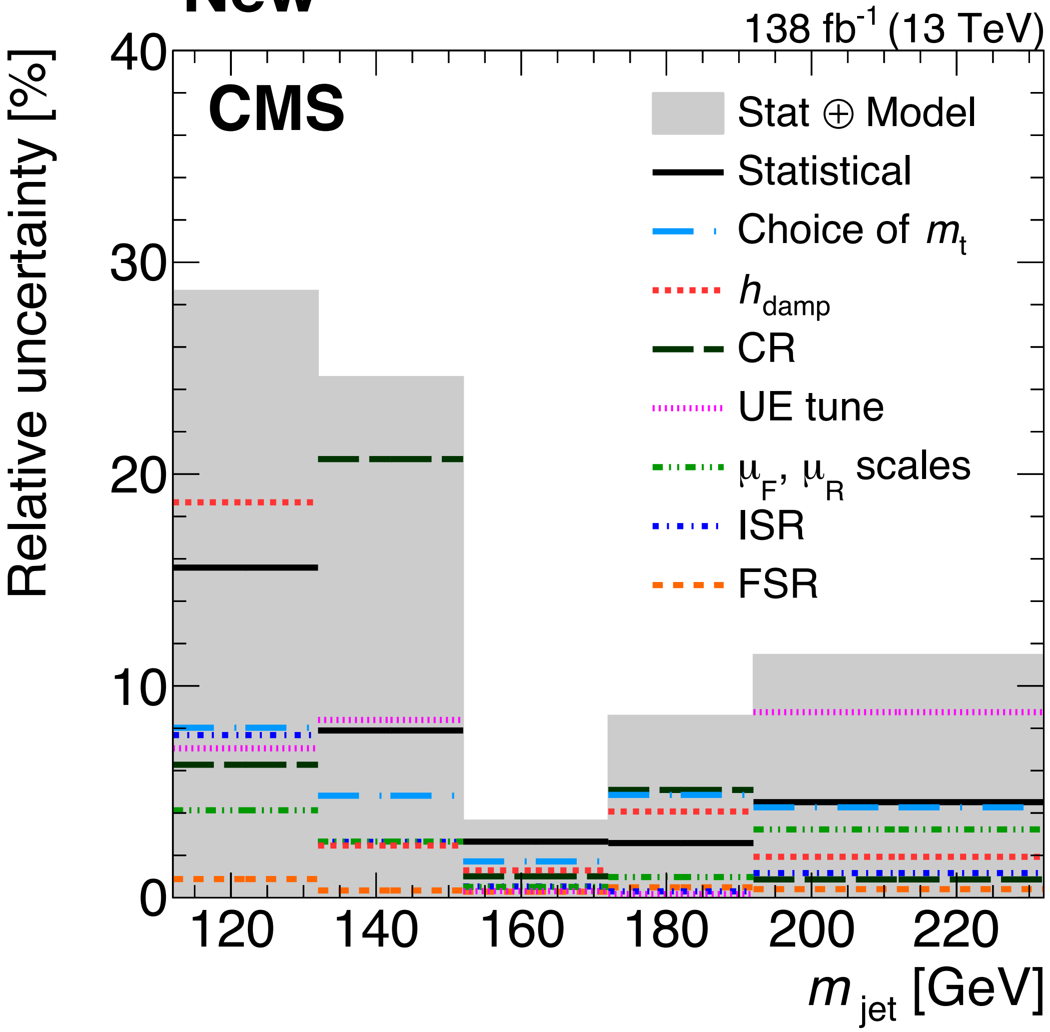
Comparison to 2016 measurement

[CMS, arxiv:2211.01456]

Previous



New



→ **Note change in y-scale!**

- Uncertainty from the modeling of the FSR is drastically reduced
- Similar values of $\alpha_S^{FSR}(M_Z)$ for both tunes
- $\Delta m_t^{2016}(\mathrm{FSR}) = 1.2 \rightarrow \boxed{\Delta m_t^{\mathrm{Run2}}(\mathrm{FSR}) = 0.02\ \mathrm{GeV}}$

Unfolded results

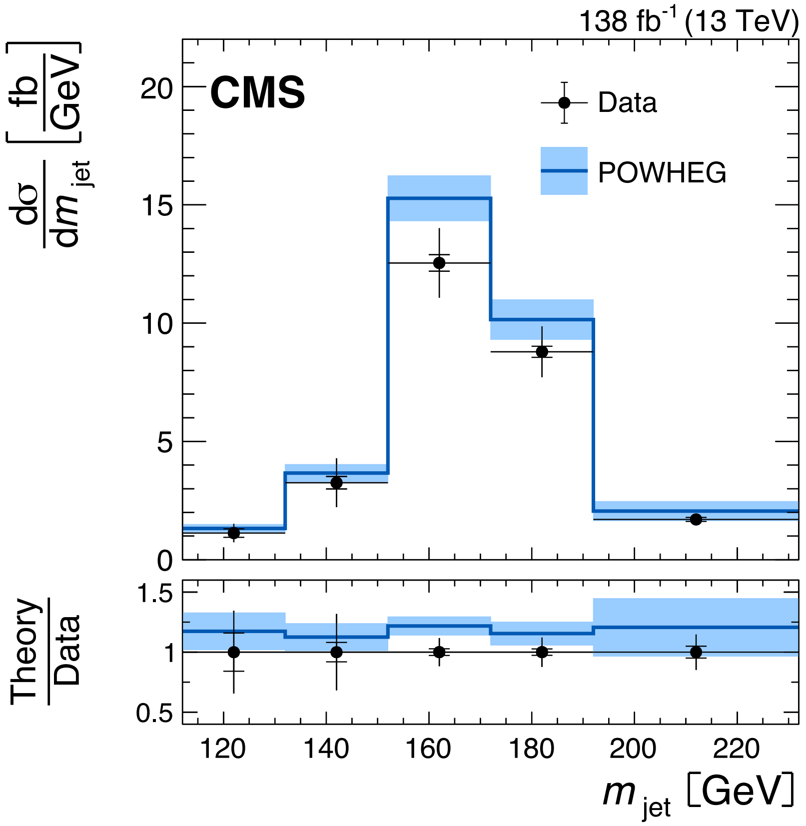
- Regularized unfolding using TUnfold
- Extract m_{top} from normalized distribution

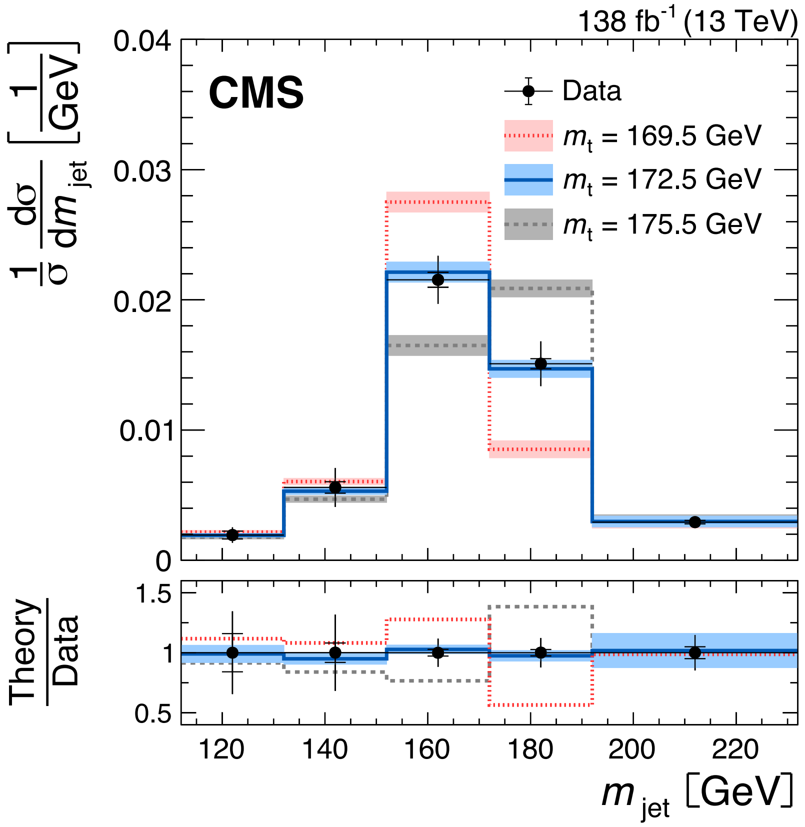
$$\boxed{m_{\text{top}} = 172.76 \pm 0.81\ \text{GeV}}$$

- Largely reduced 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

→ Many uncertainties on the same level

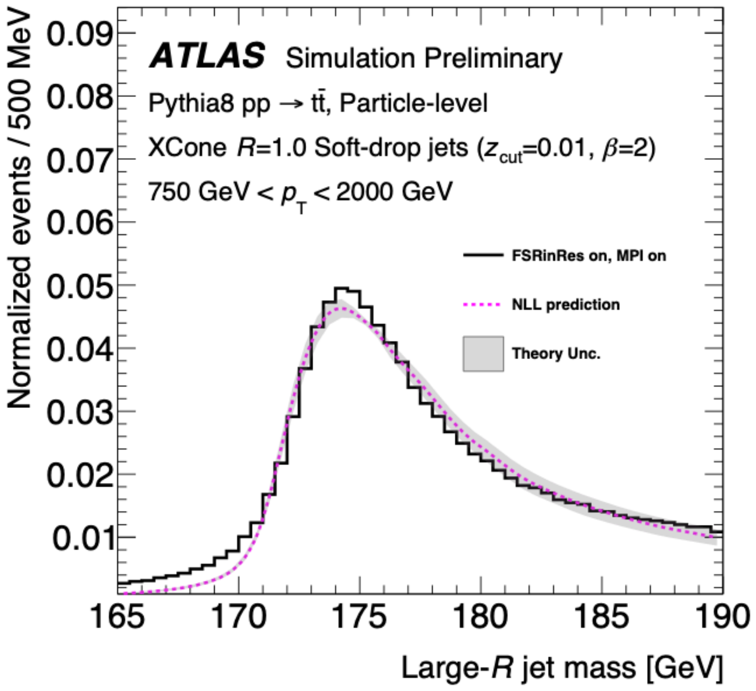




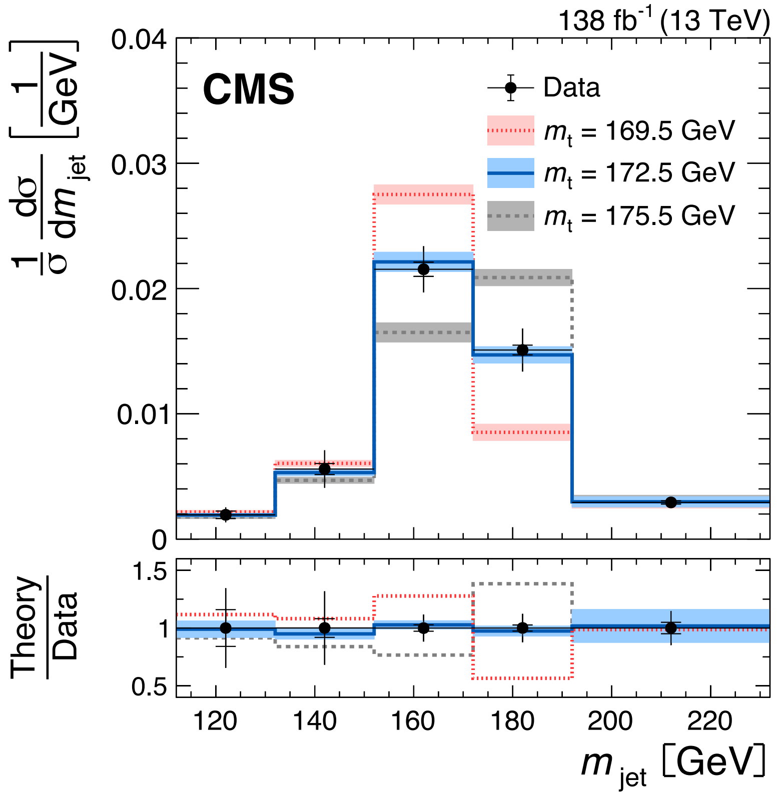
Summary & Outlook

[CMS, arxiv:2211.01456], [ATLAS, ATL-PHYS-PUB-2021-034]

- First comparison of NLL calculations to event generators with boosted top quarks
  - $\mathcal{O}(400\ \mathrm{MeV})$ uncertainty in relation between $m_{\mathrm{top}}^{\mathrm{MSR}}$ and $m_{\mathrm{top}}^{\mathrm{MC}}$



- Measure differential cross section as a function of m_{jet} from boosted hadronic top quark decays
  - Dominant uncertainties of analysis with 2016 data largely reduced
  - Now public [arxiv:2211.01456] and submitted to EPJC
- Aim to compare data to calculations soon

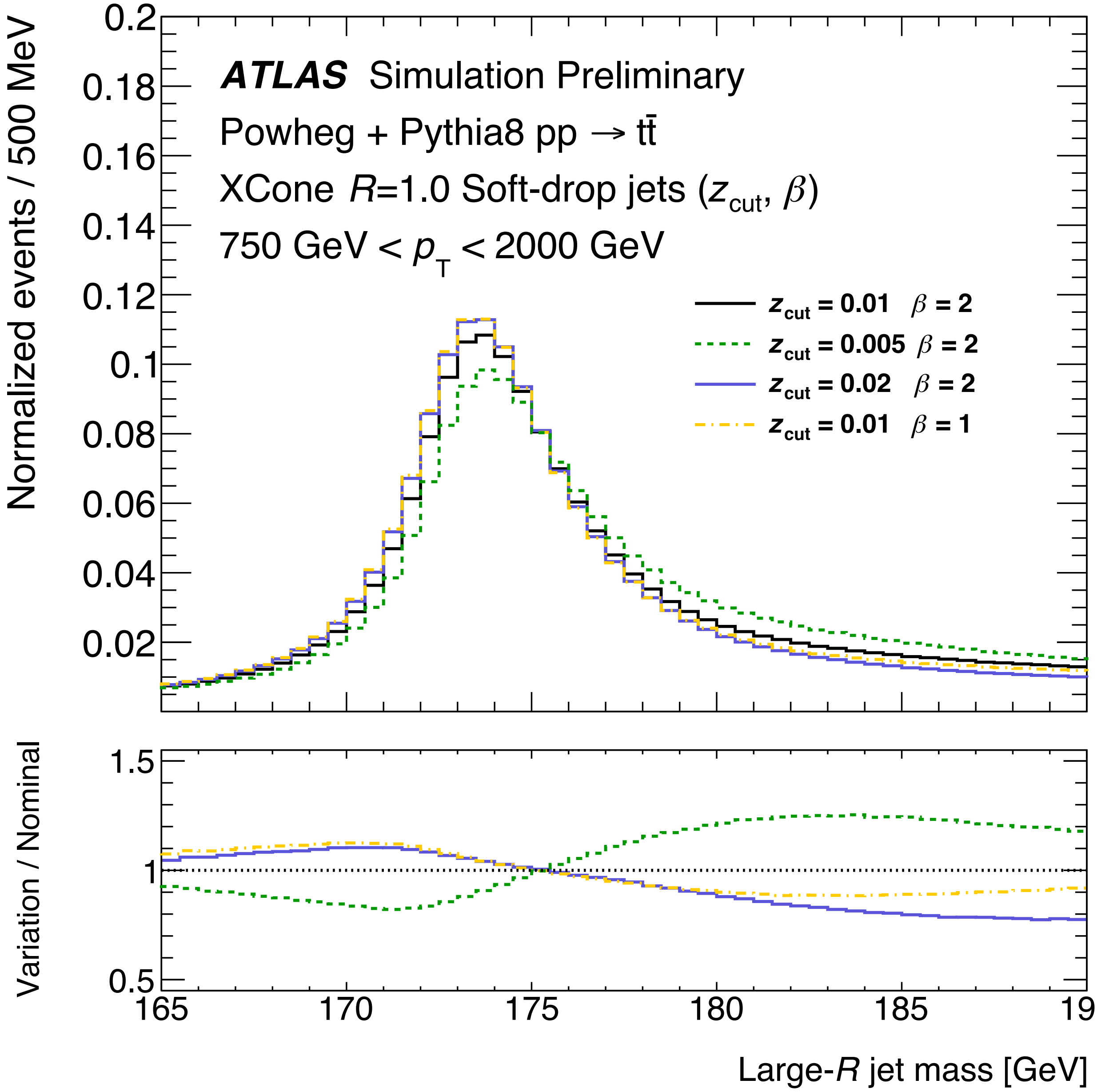


Additional Material

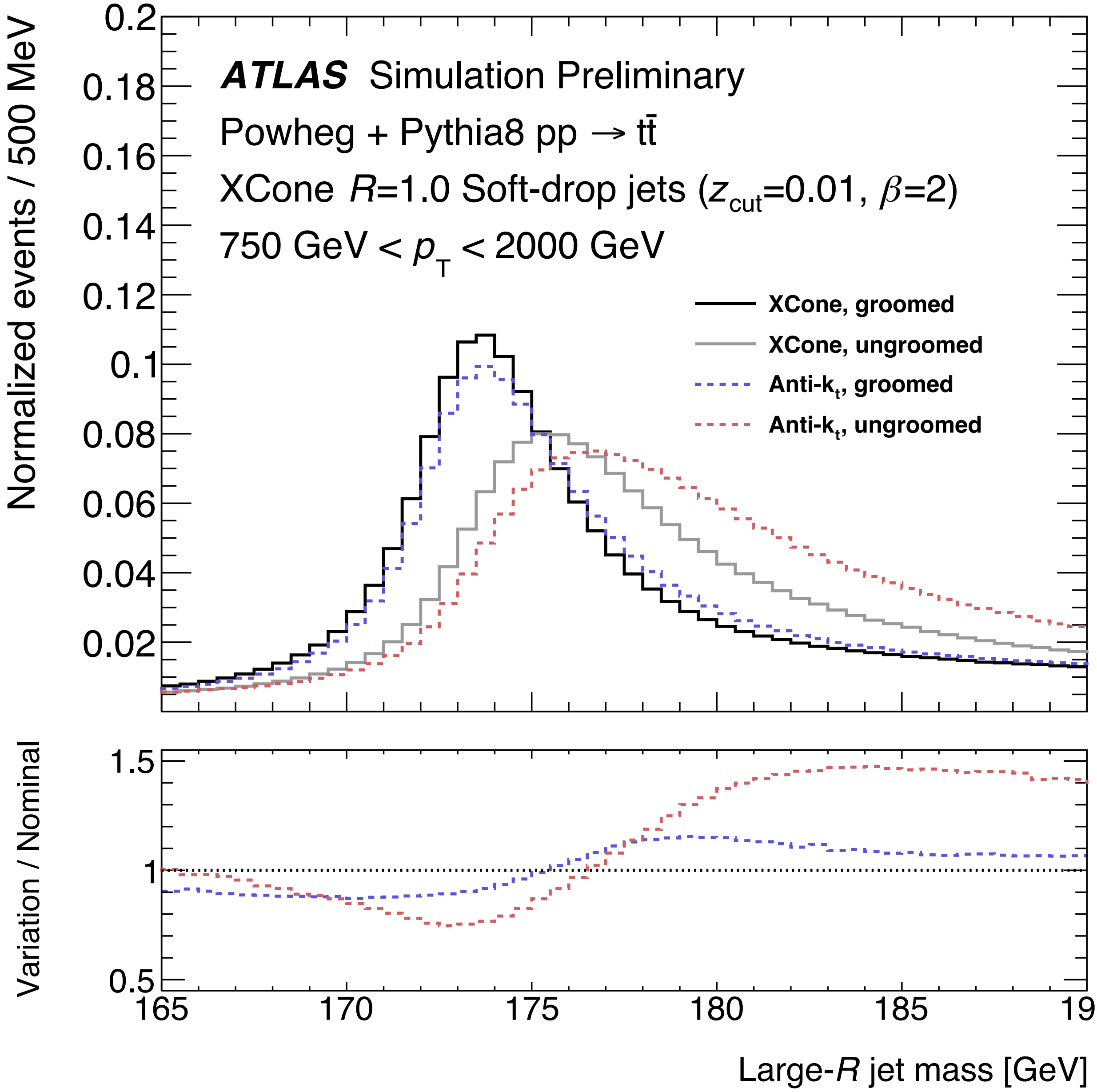
Mass of large-R jets

[ATLAS, ATL-PHYS-PUB-2021-034]

Study impact of different grooming



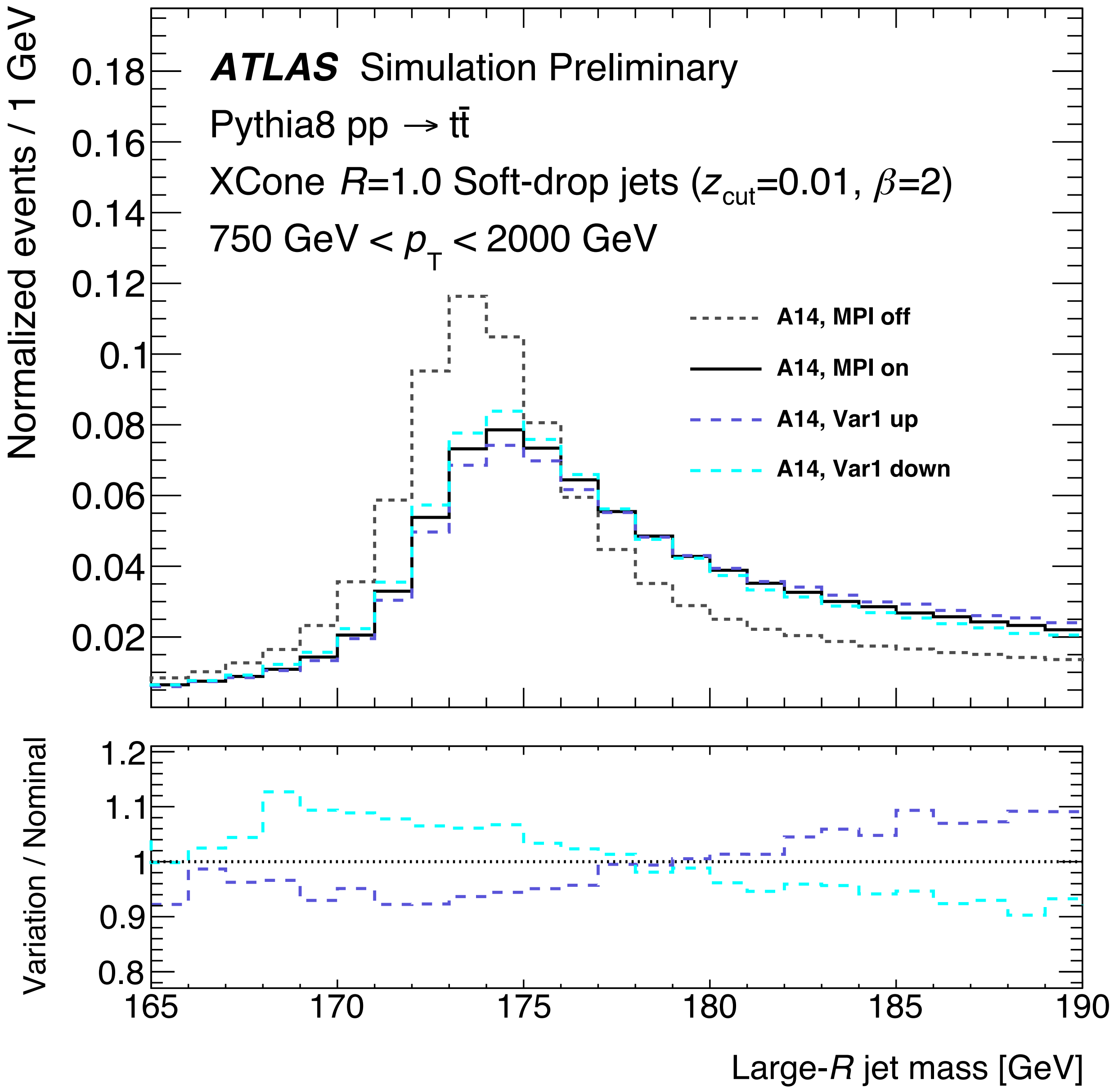
Study different jet clustering algorithms with same radius

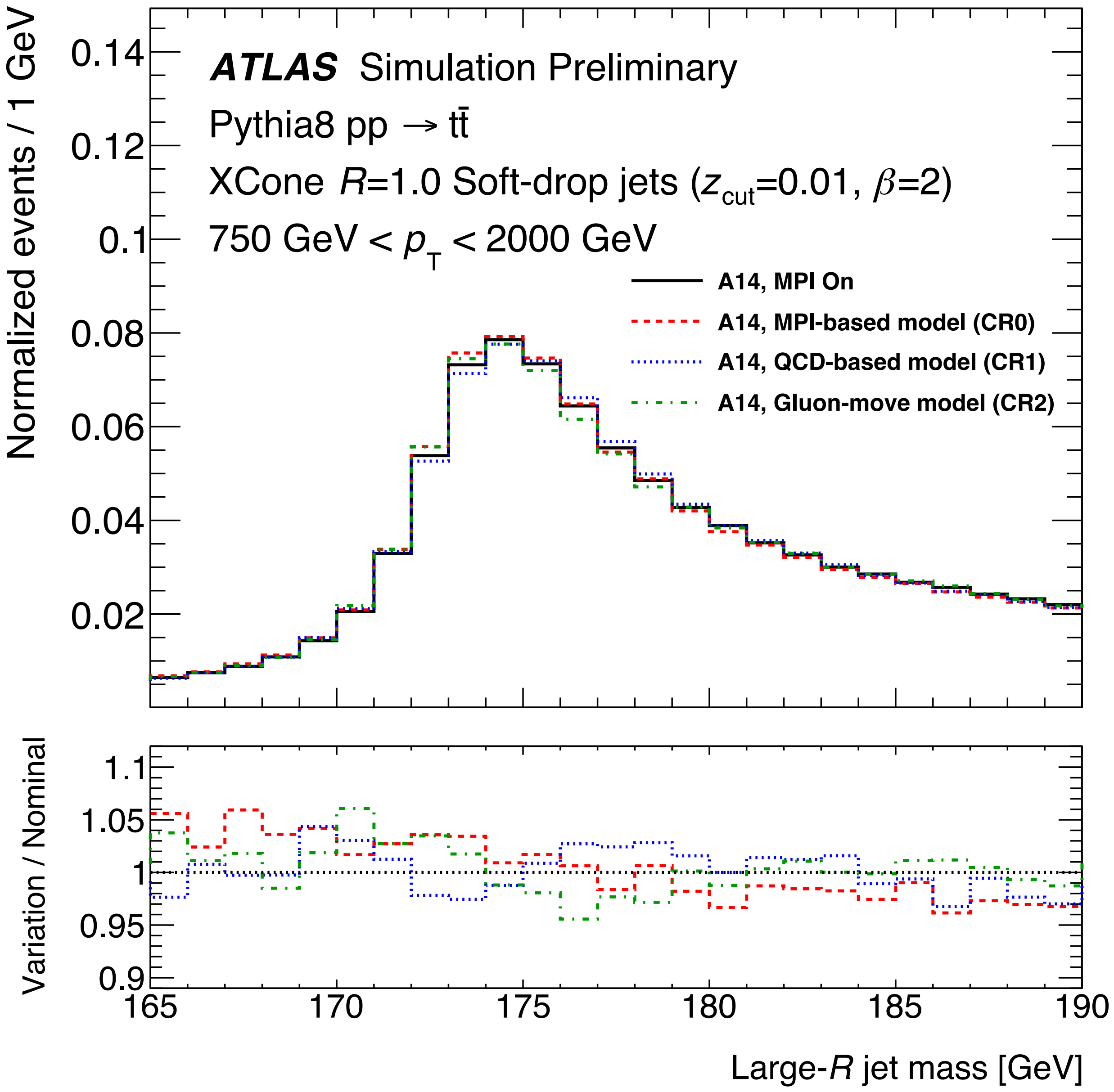


Mass of large-R jets

[ATLAS, ATL-PHYS-PUB-2021-034]

Impact of UE and color reconnection models

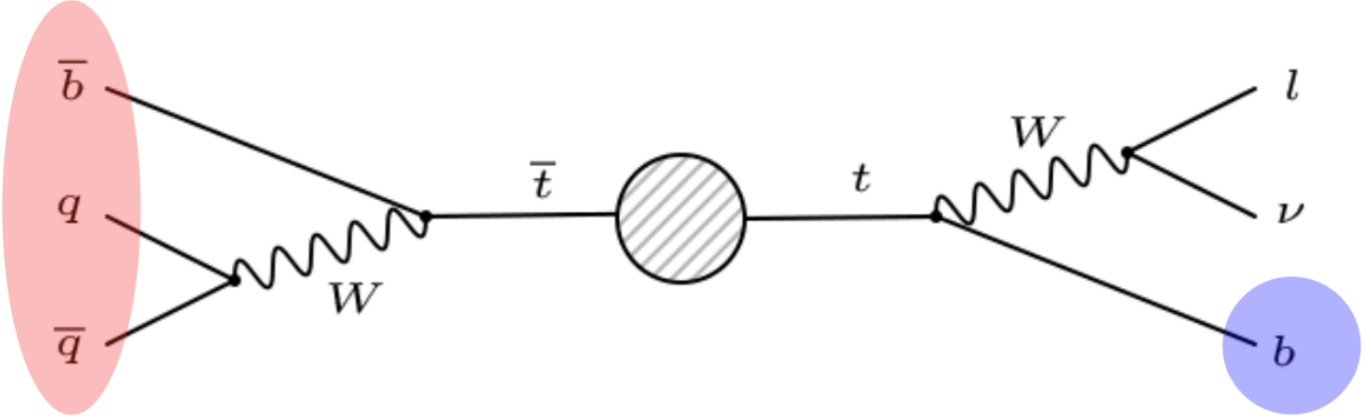




Selection of highly energetic $\mathrm{t\bar{t}}$ events

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)

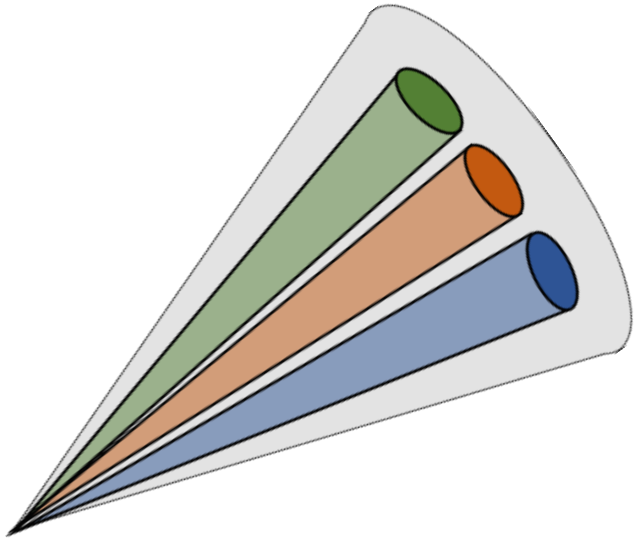


Select boosted top quarks

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

Suppress unmerged top quark decays

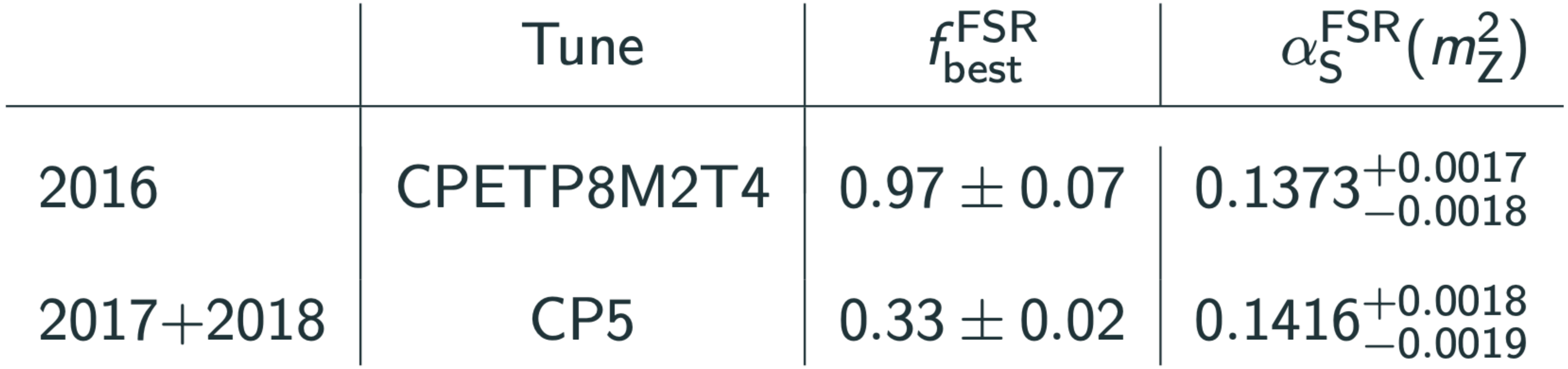
- $m_{\mathrm{hadjet}} > m_{\mathrm{lepjet}+\ell}$



Comparison of f_{FSR}

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

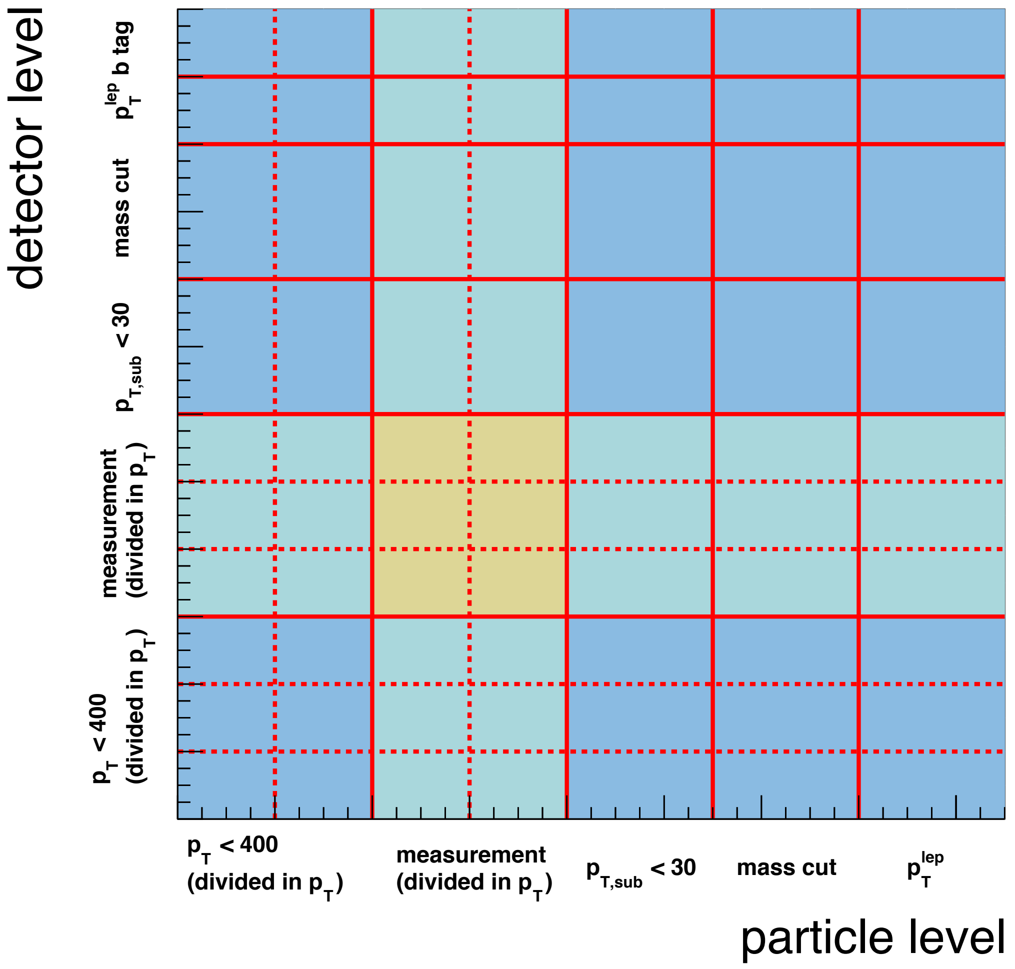
$$\begin{aligned}\alpha_{\mathrm{S}}^{\mathrm{FSR,CPETP8M2T4}} &= 0.1365\\ \alpha_{\mathrm{S}}^{\mathrm{FSR,CP5}} &= 0.118\end{aligned}$$



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

Unfolding setup

- 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



Extraction of m_{top} in simulation

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