Prospects for boosted top measurements at CMS

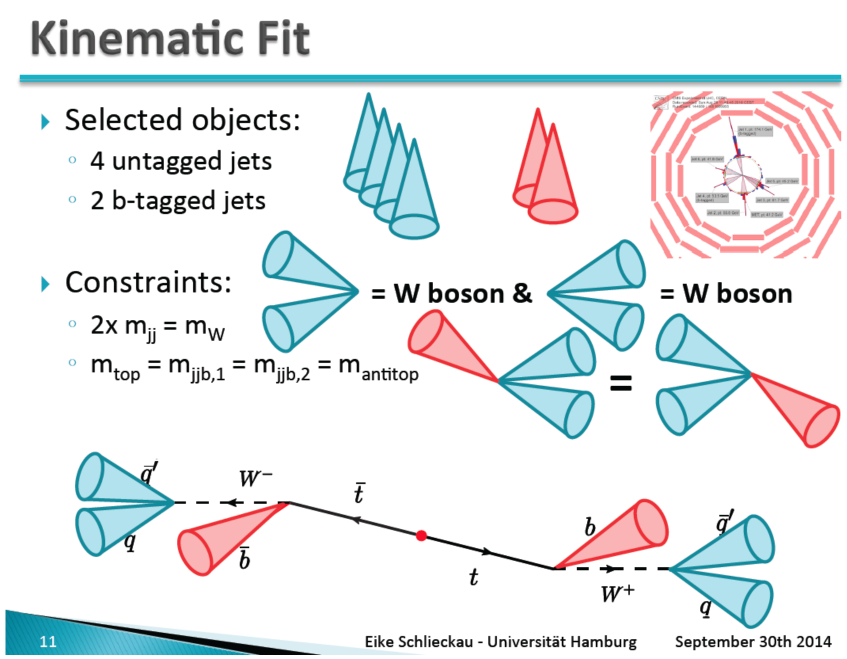
R. Kogler

Theory-Experimental Top Quark Mass Workshop
DESY, Hamburg
28-30th Jan, 2025

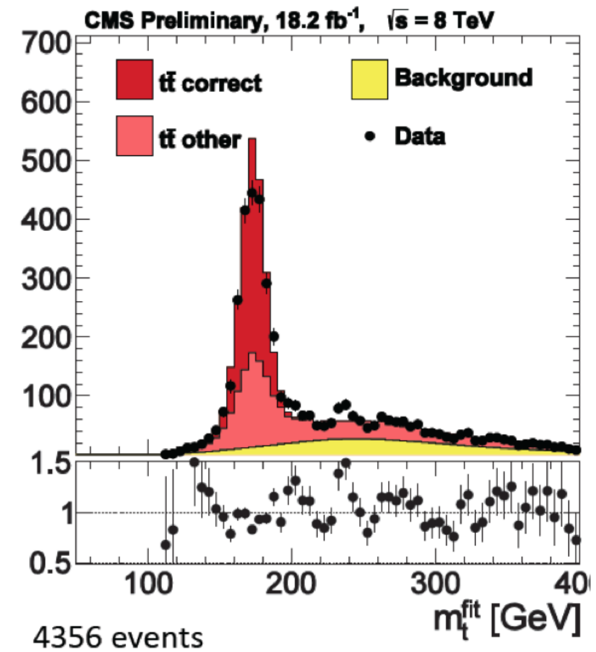
Most Precise Top Mass Measurements Method

LHC+Tevatron: Direct top mass measurements

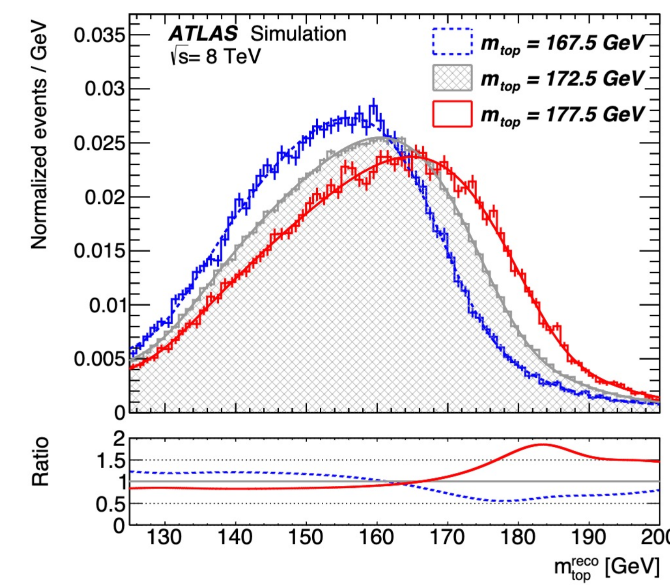
[A. Hoang]



CMS-PAS-TOP-14-002



4356 events



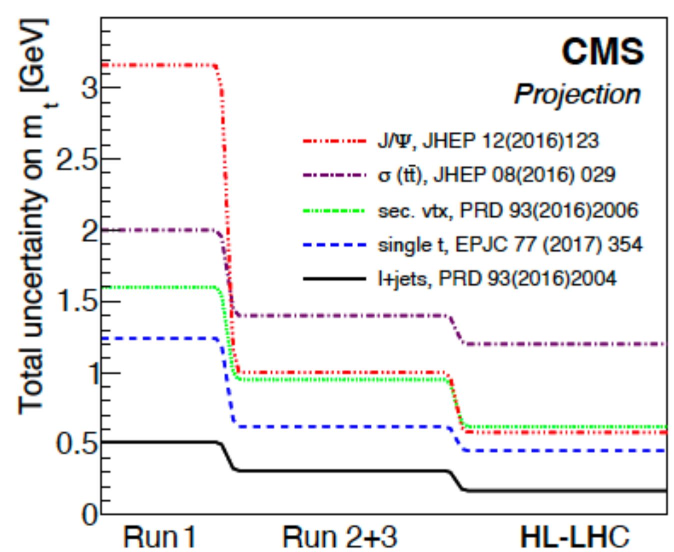
$$m_t^{\rm MC} = 171.77 \pm 0.37\ \text{GeV}$$

CMS collaboration. arXiv: 2302.01967

kinematic mass determination

based on the picture of a top quark particle

Determination of the best-fit value of the Monte-Carlo top quark mass parameter



⊕ High top mass sensitivity

⊖ Precision of MC ?

⊖ Meaning of m_t^{MC} ?

← Δm_t ~ 200 MeV (projection)

What is m_t^{MC} ?

[A. Hoang]

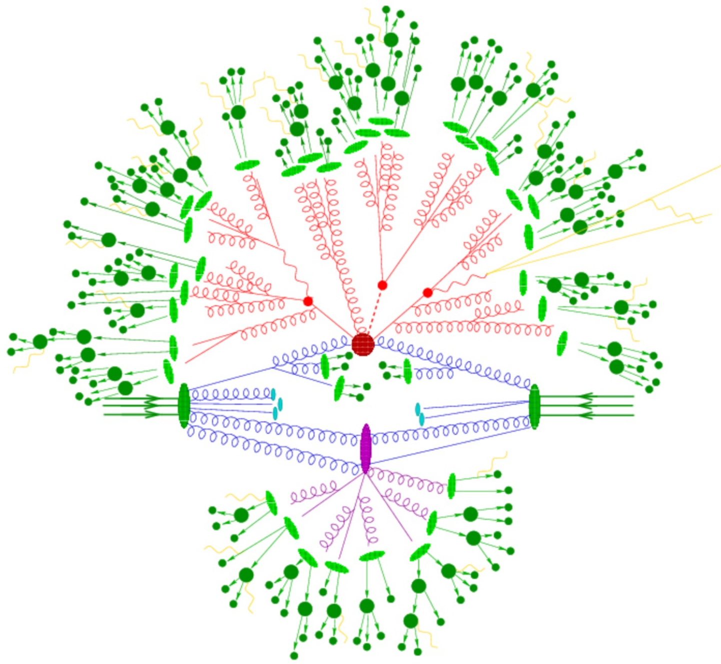
What does the question mean in the first place?

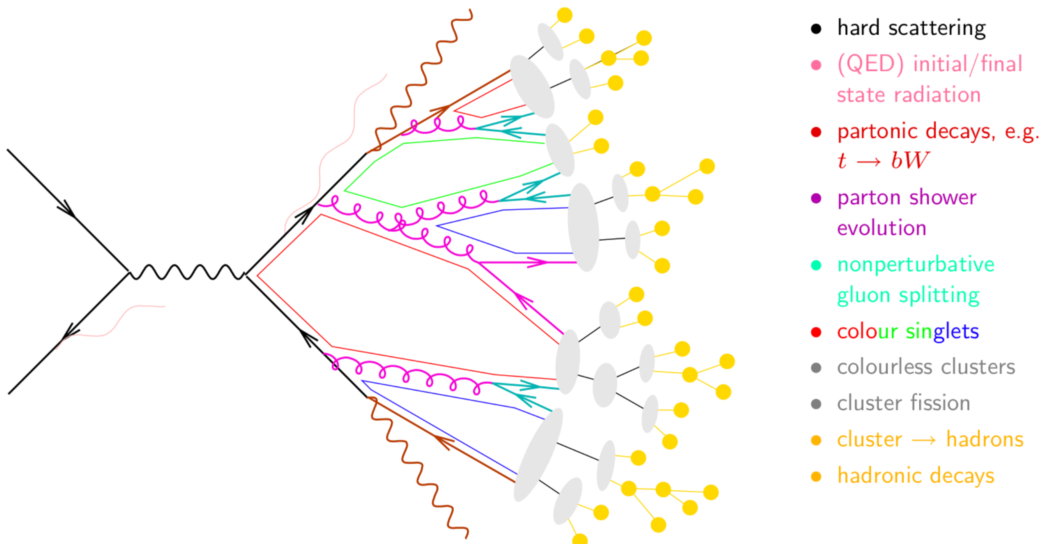
→ It means that we can provide the relation

$$m_t^{\rm MC} = m_t^{\rm scheme}(\mu) + \frac{\alpha_s(\mu)}{\pi}\delta m^{\rm scheme} + \ldots$$

where $\delta m^{\rm scheme}$ can be **computed in pQCD**

The issue is complicated as we must understand and control the interplay of the different components of MC event generators.





The nature of question is intrinsically theoretical.

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[A. Hoang]

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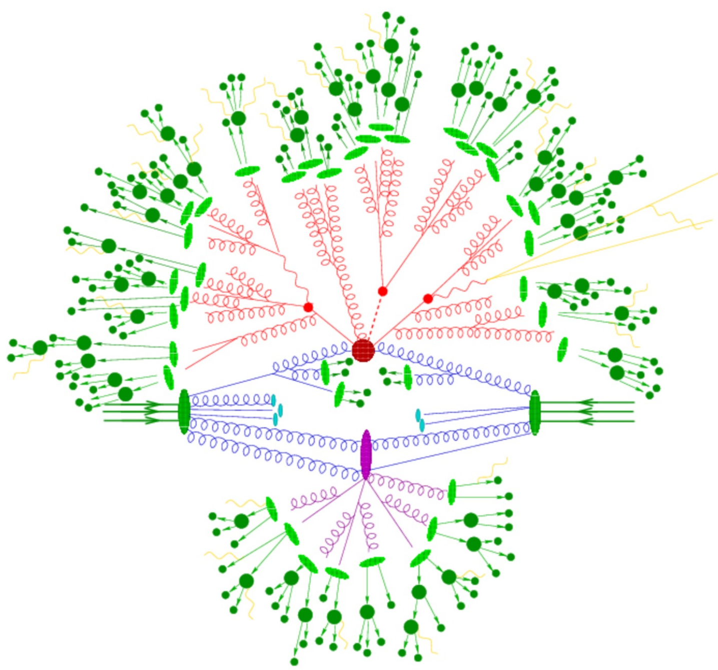
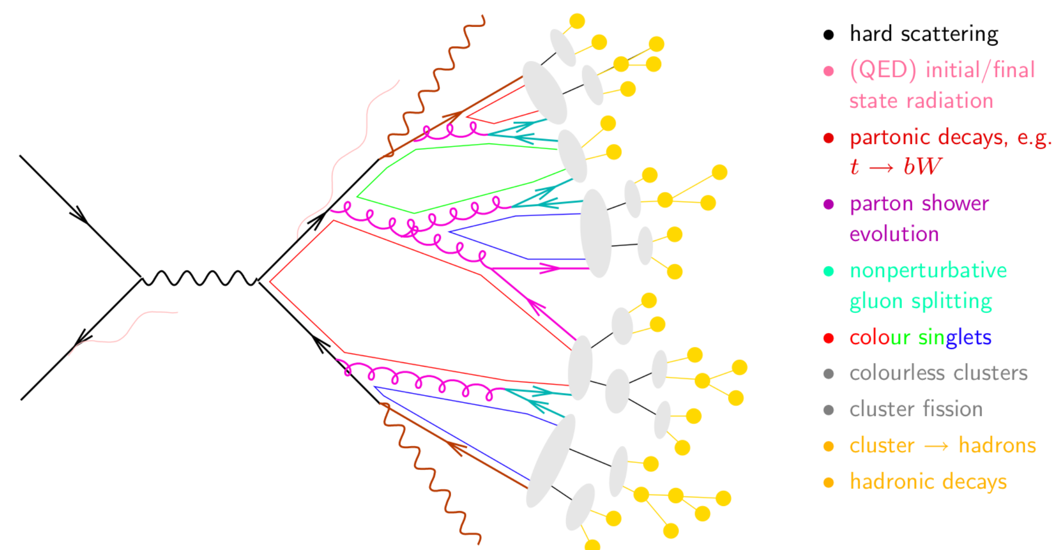


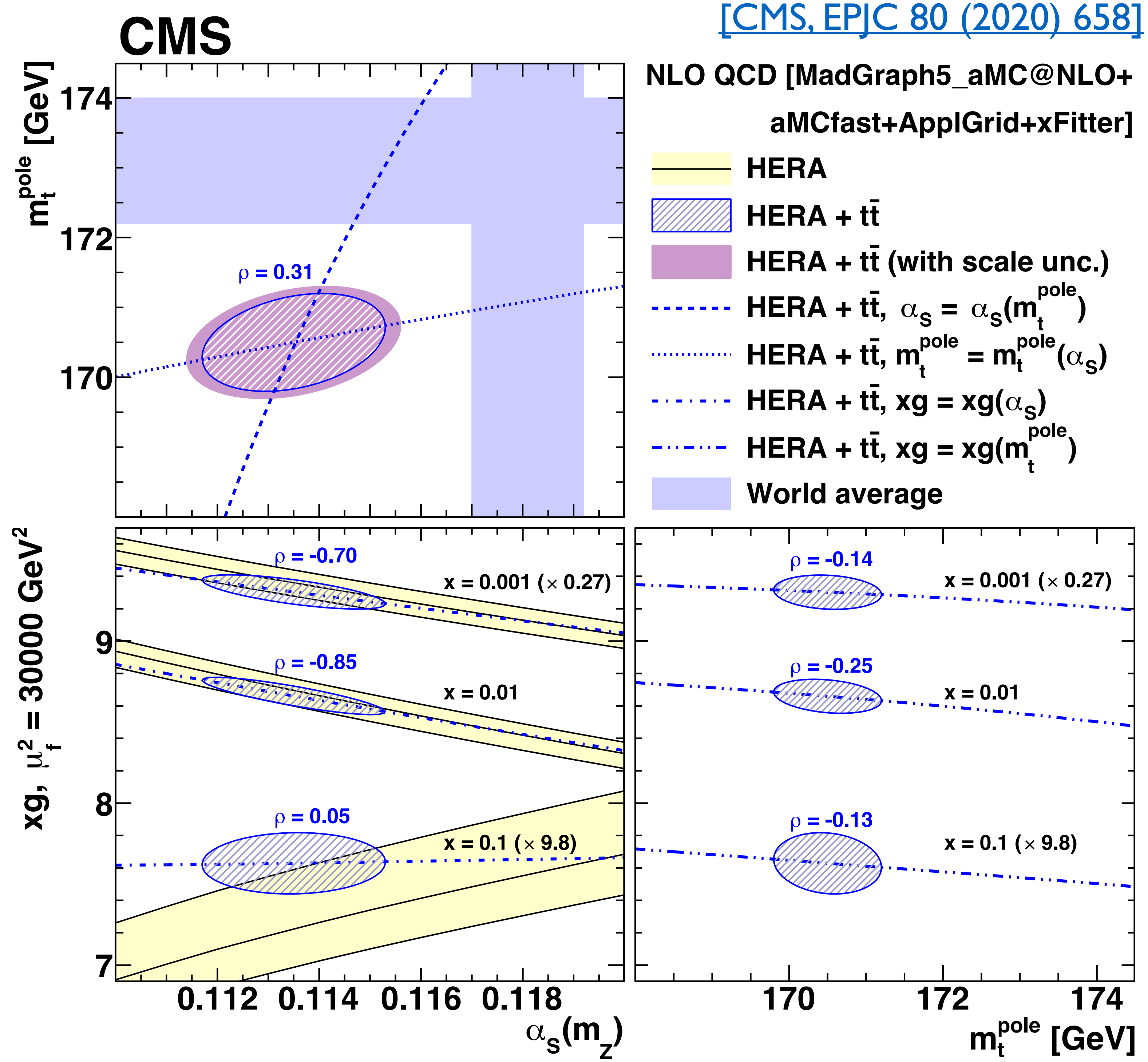


The nature of question is intrinsically theoretical.

Translation to pole mass: Additional uncertainty of about 500 MeV

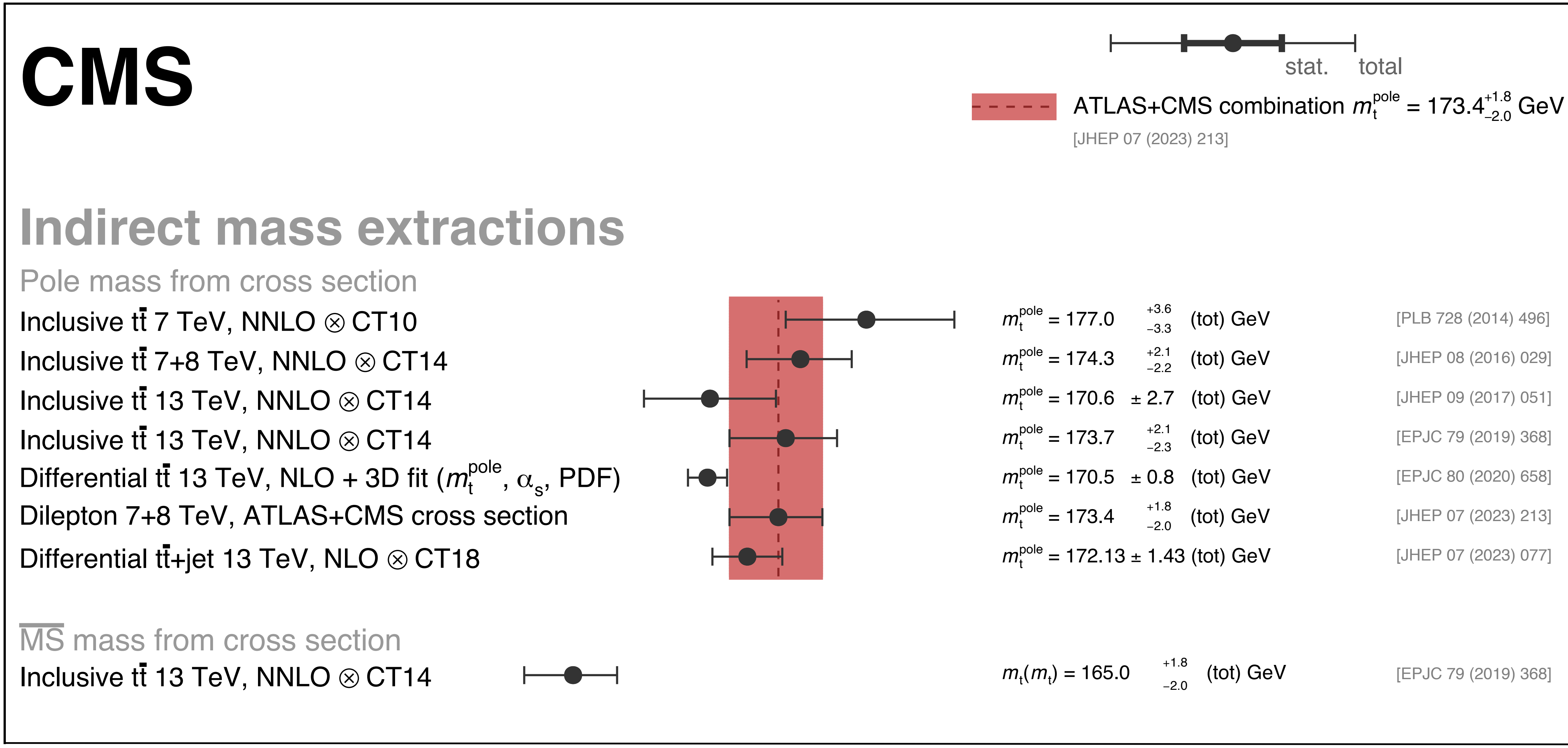
m_t: Indirect Determinations

[CMS, EPJC 80 (2020) 658]



m_t: Indirect Determinations

[CMS, arXiv:2403.01313]

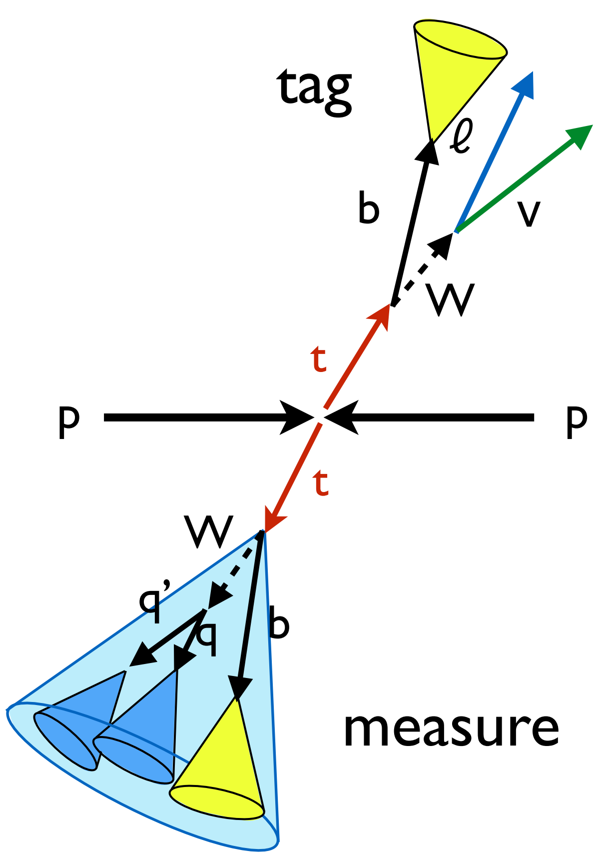


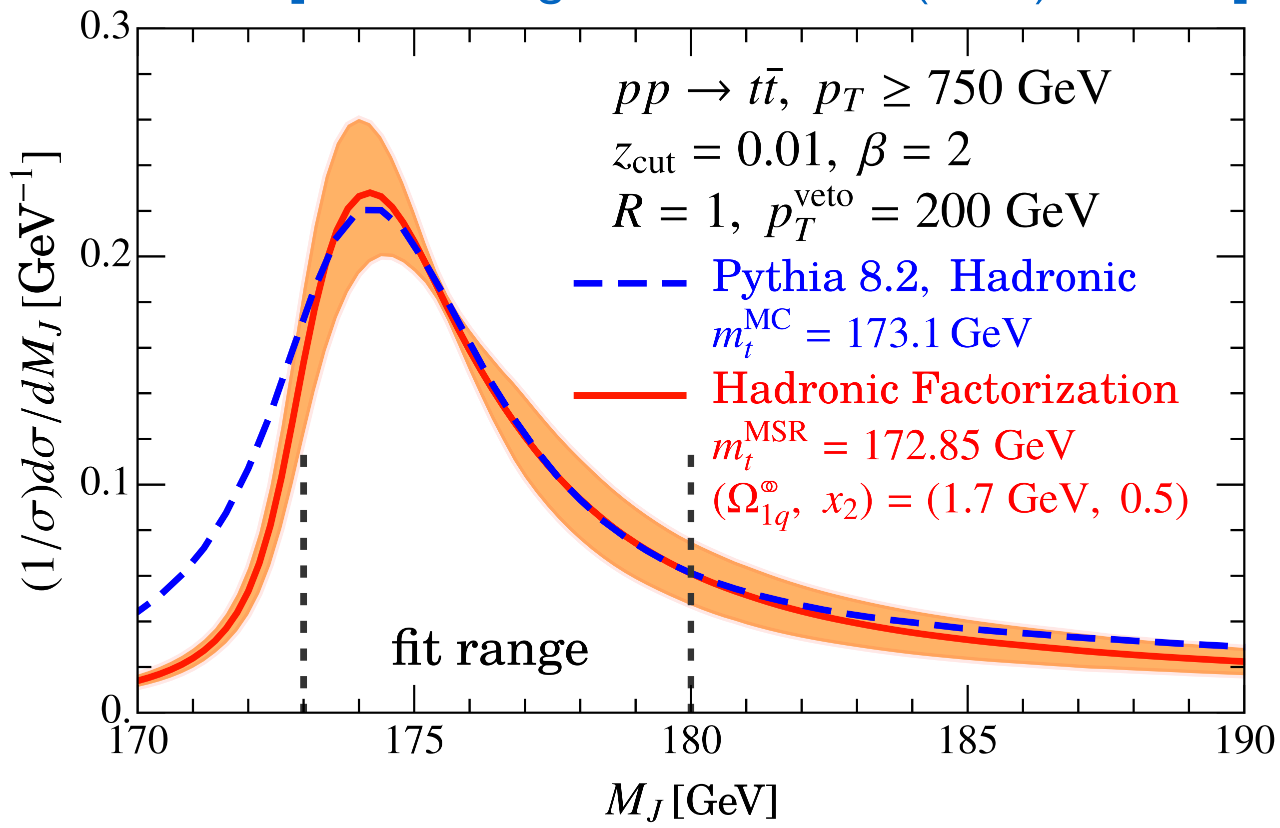
- Achieved precision: Between 1.4-2.2 GeV in m_t

Jet Mass in pp

[A. H. Hoang et al., PRD 100 (2019), 074021]

- Analytical calculation possible for fully-merged final states (SCET)
- Current calculations
  - Soft drop mass for R=1.0
  - p_T > 750 GeV





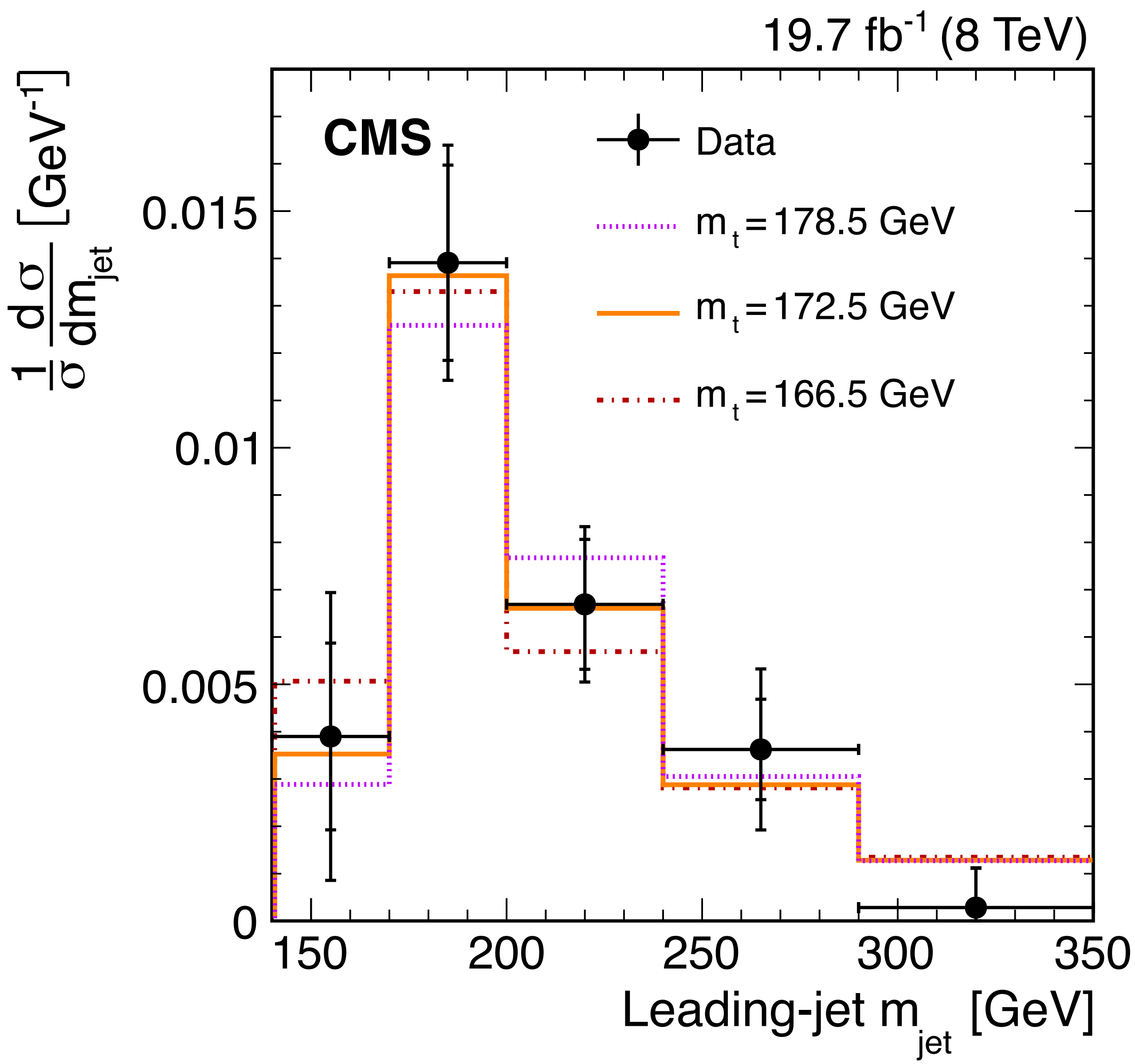
- Distribution in m_{jet}
  - Direct sensitivity to m_t
  - Can be measured at the LHC, at the level of stable particles

First measurement of m_{jet}

- Measurement at 8 TeV (2012 data)
- Ungroomed jet mass for R=1.2
  - p_T > 400 GeV
  - Uncertainties on mt:

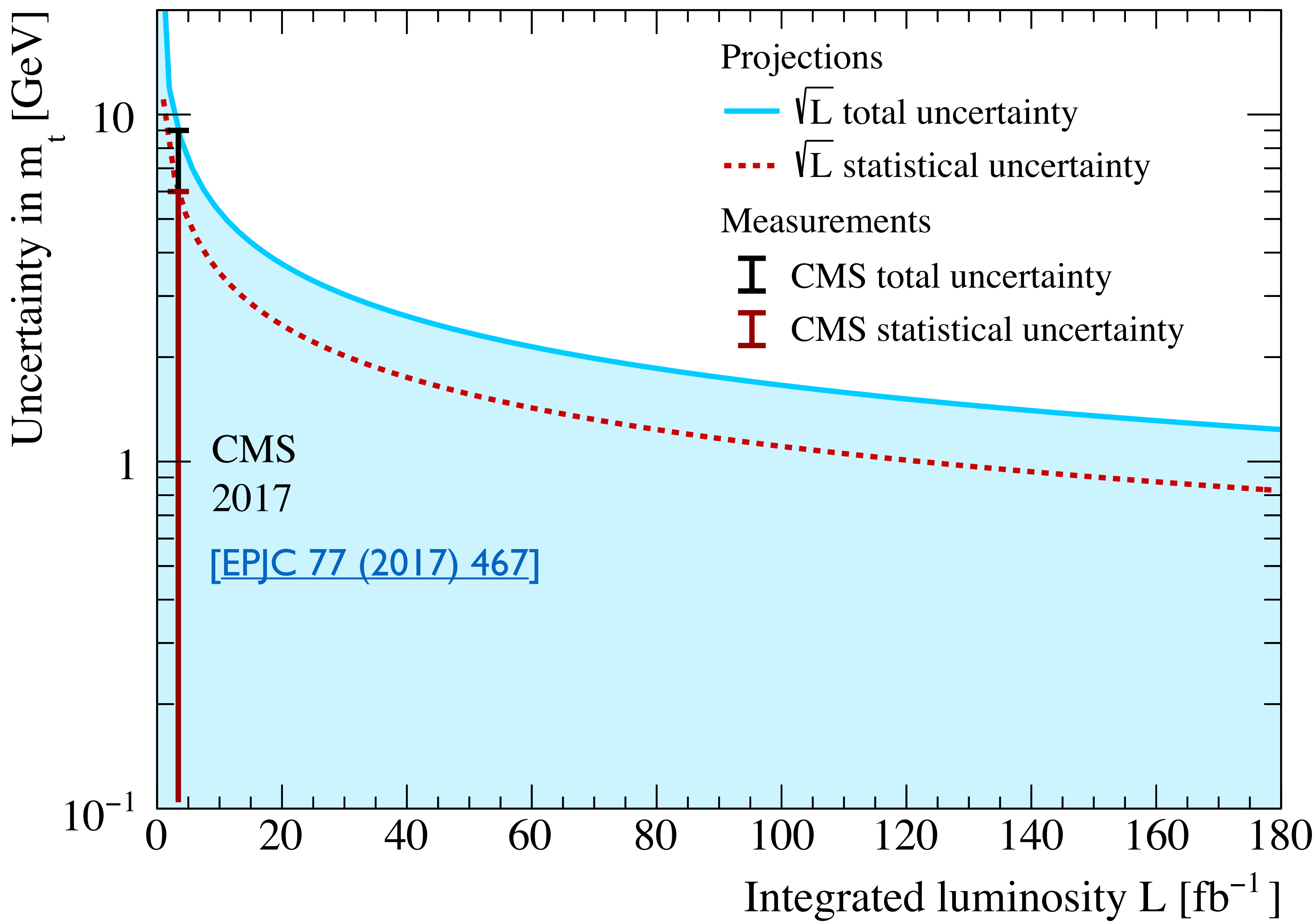
    ± 6 (stat)
    ± 2.8 (syst)
    ± 6 (theo)

    ± 9 (tot)

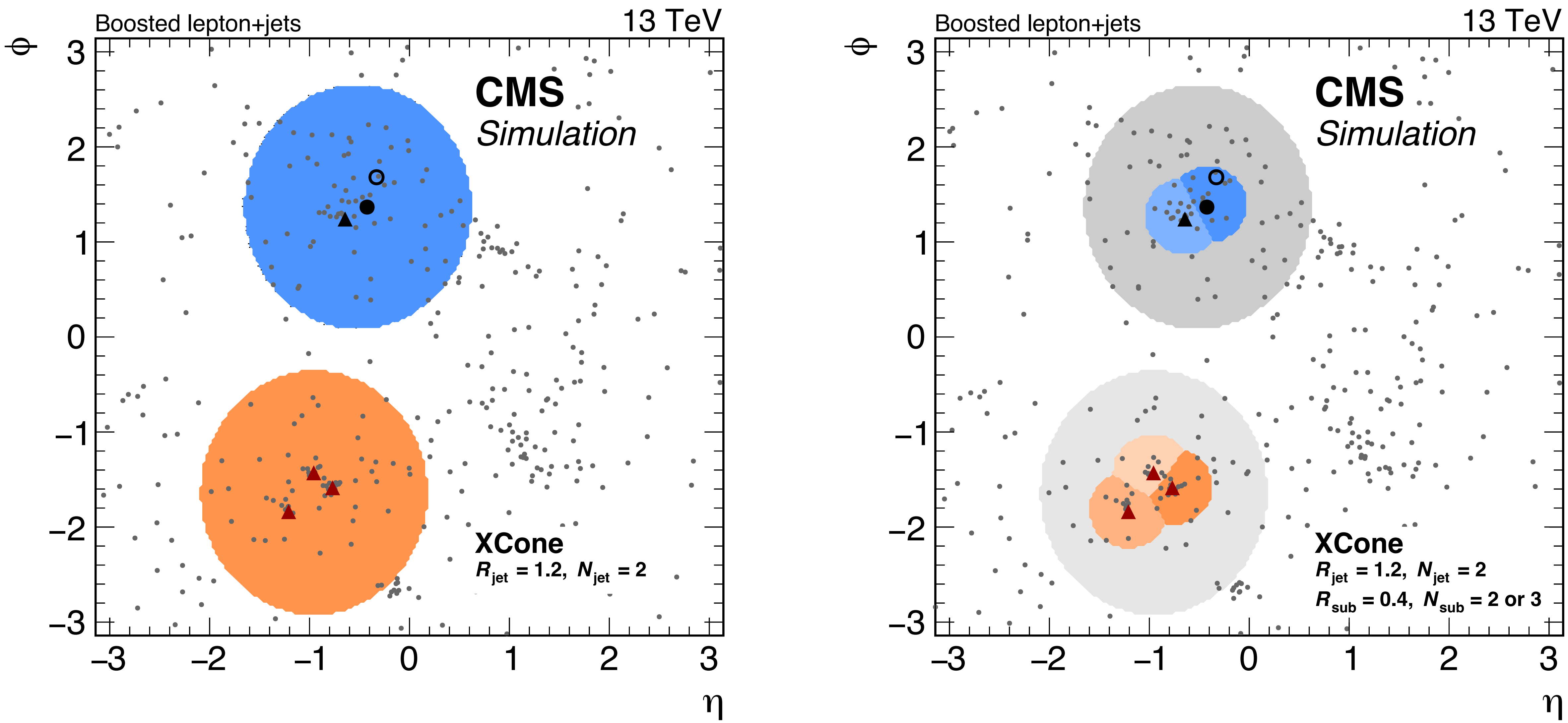


[CMS, EPJC 77 (2017), 467]

What do we expect?



New Techniques: XCone

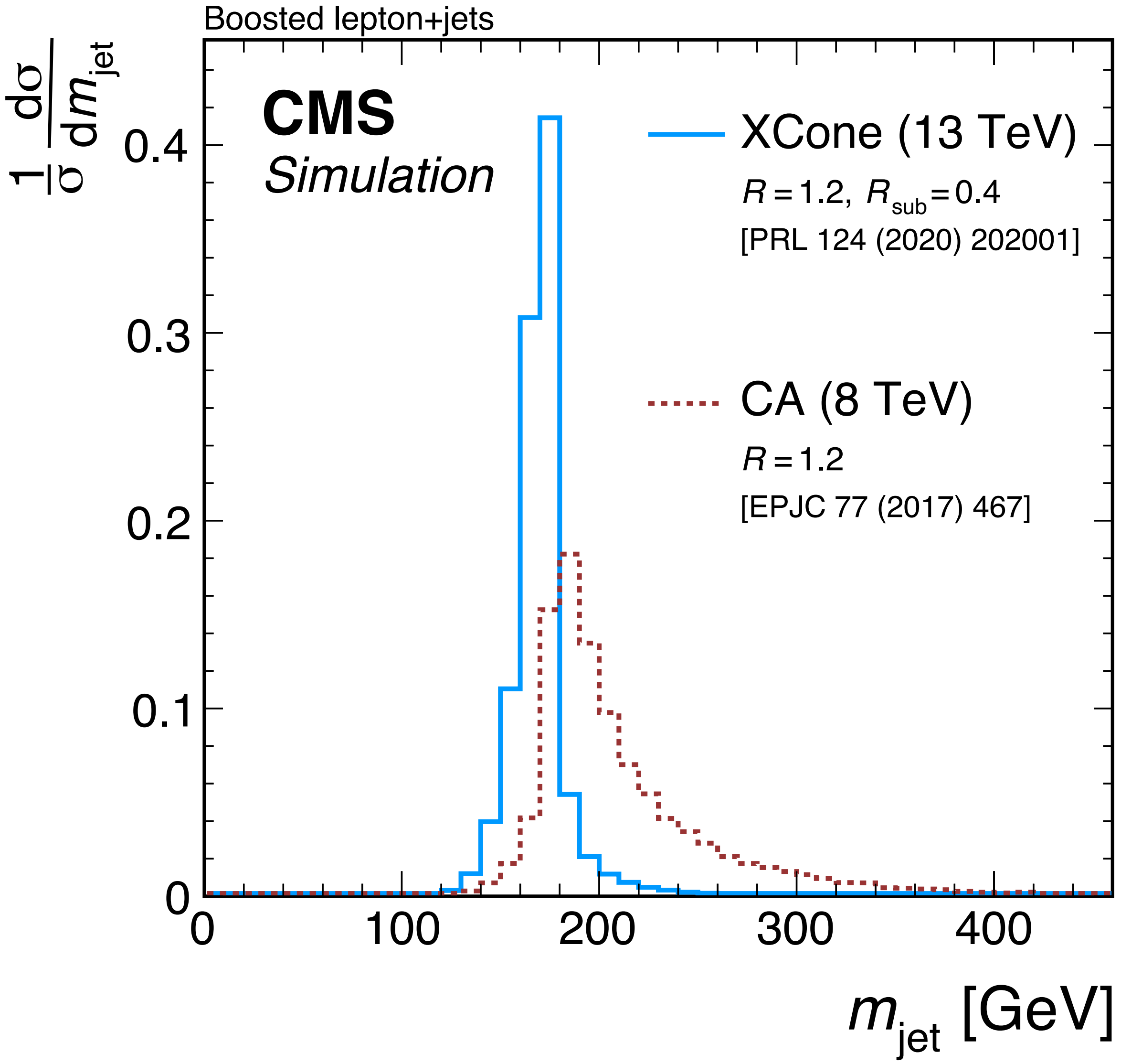


2-step jet clustering

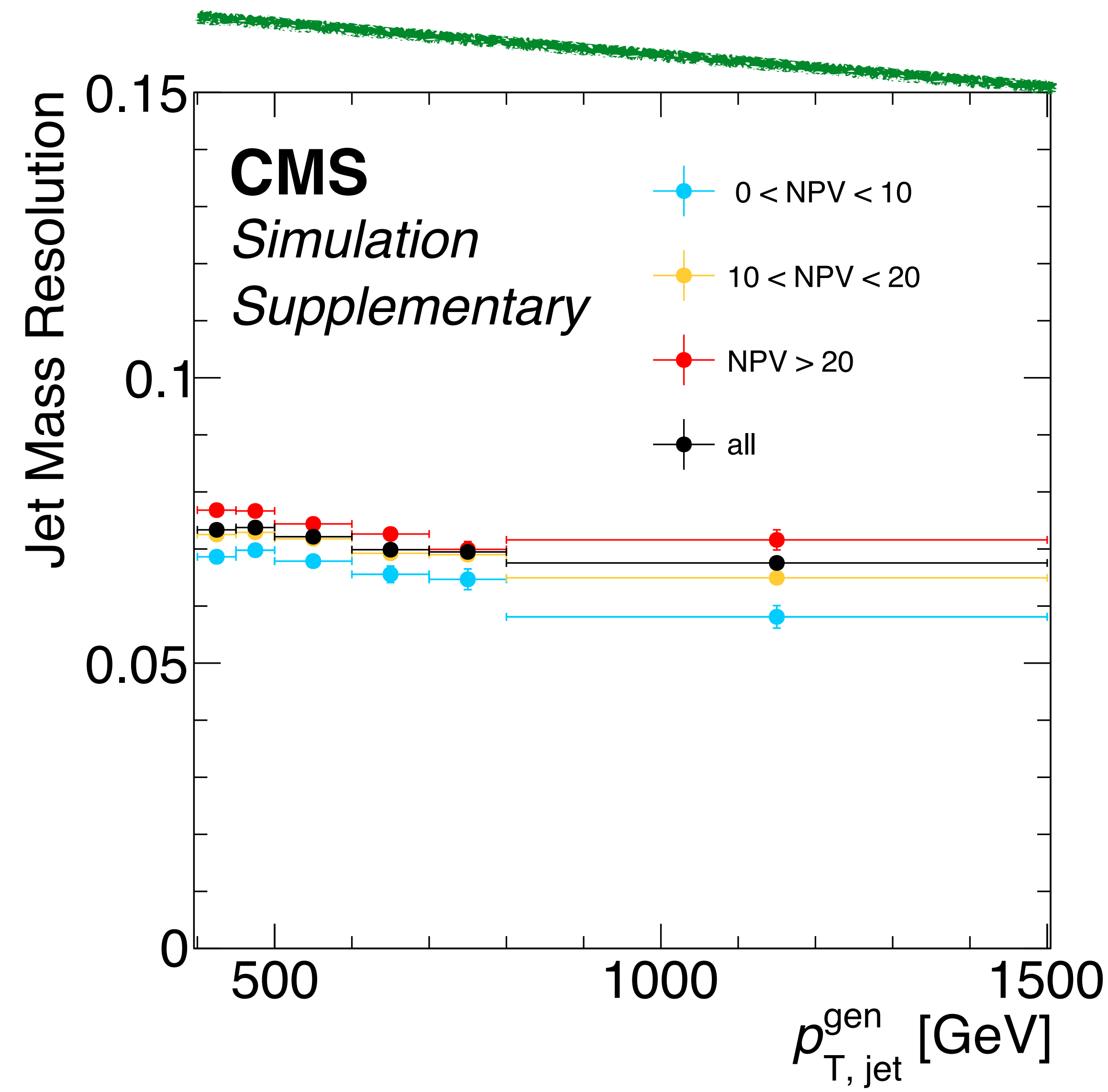
- Inherent grooming
- Dynamical effective radius

[CMS, PRL 124, 202001 (2020)]

Lineshape and Resolution

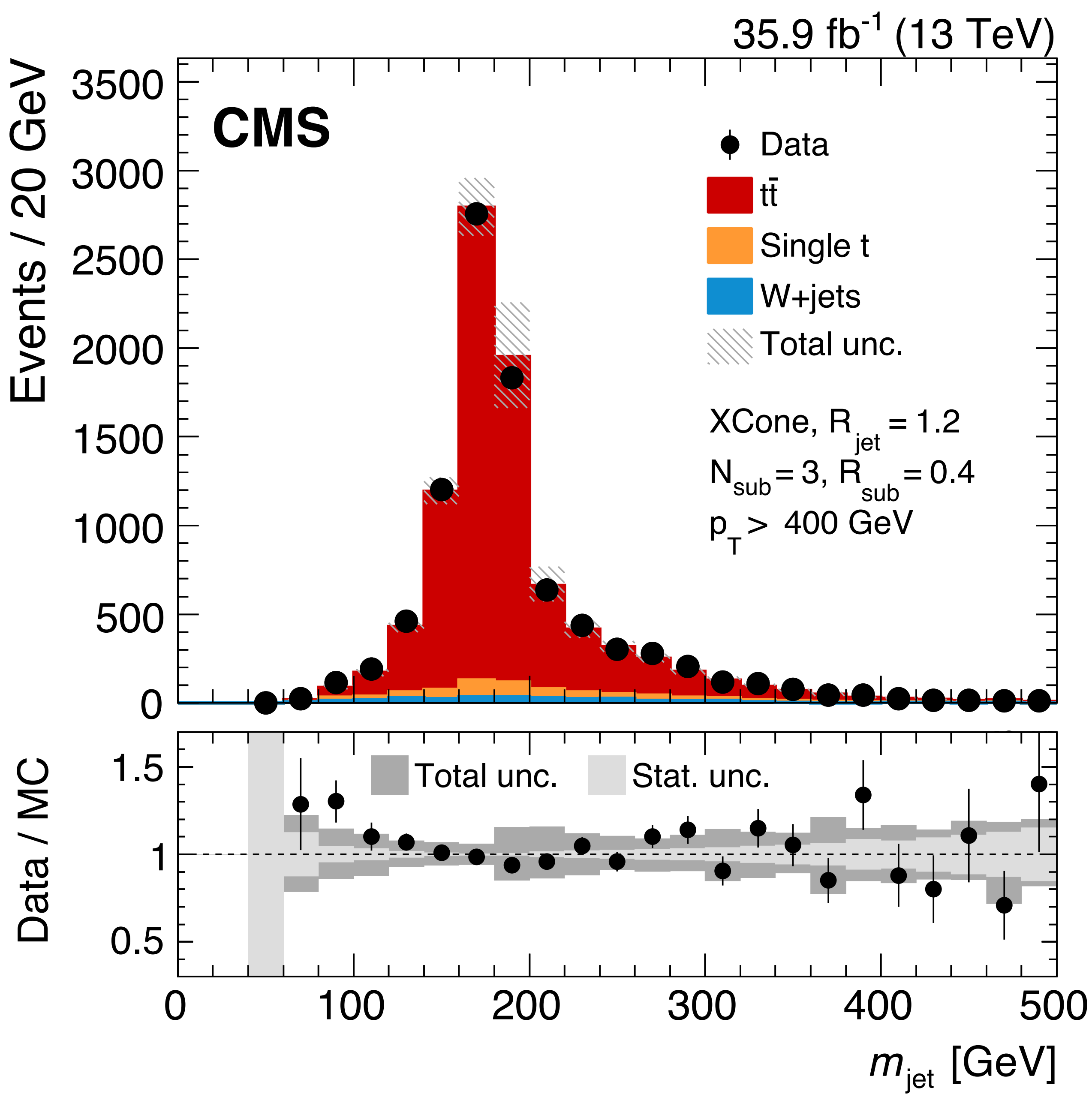


Resolution of 8 TeV measurement



[CMS, TOP-19-005]

Jet mass with XCone



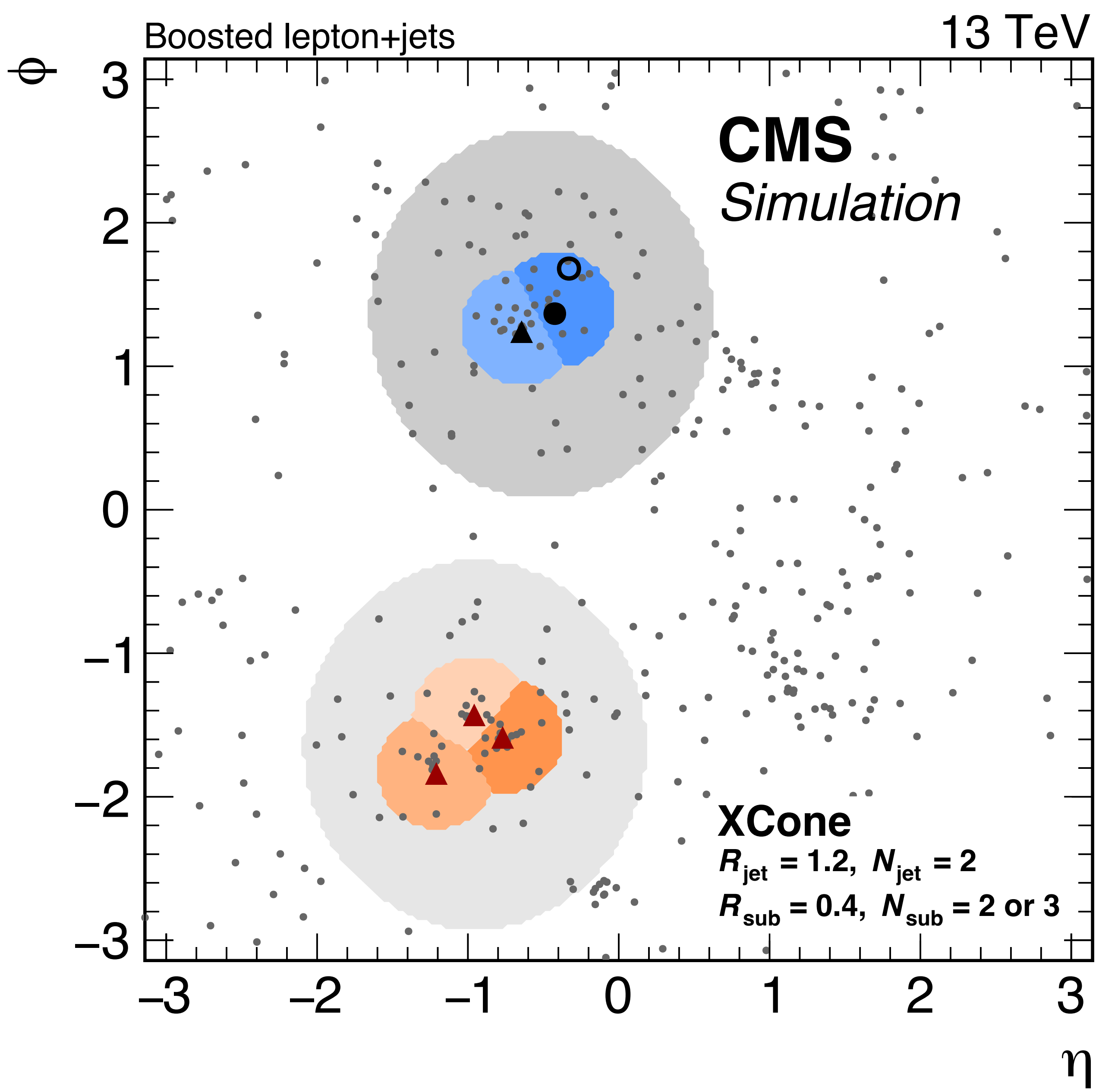
- Improved statistical uncertainty
- Less susceptibility to UE and hadronization
- Unfolding to particle level:
  - Reduction of all uncertainties

- $m_t = 172.6 \pm 2.5$ GeV
- Dominant uncertainties:
  - JES, ±1.5 GeV
  - FSR modelling, ±1.2 GeV

[CMS, PRL 124, 202001 (2020)]

Improving the Jetmass Scale 1

- XCone method allows for calibration of jet mass scale using m_W

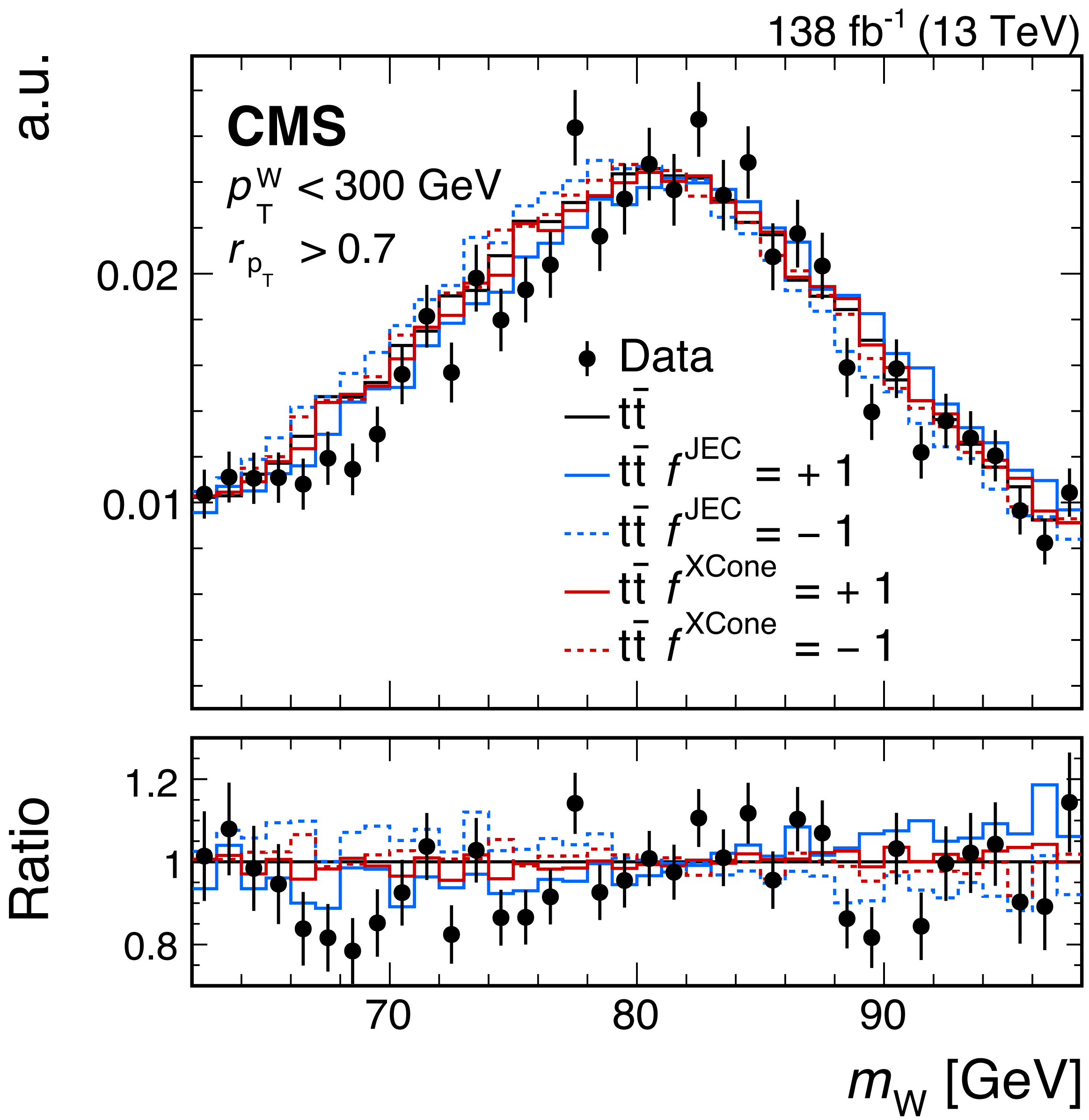


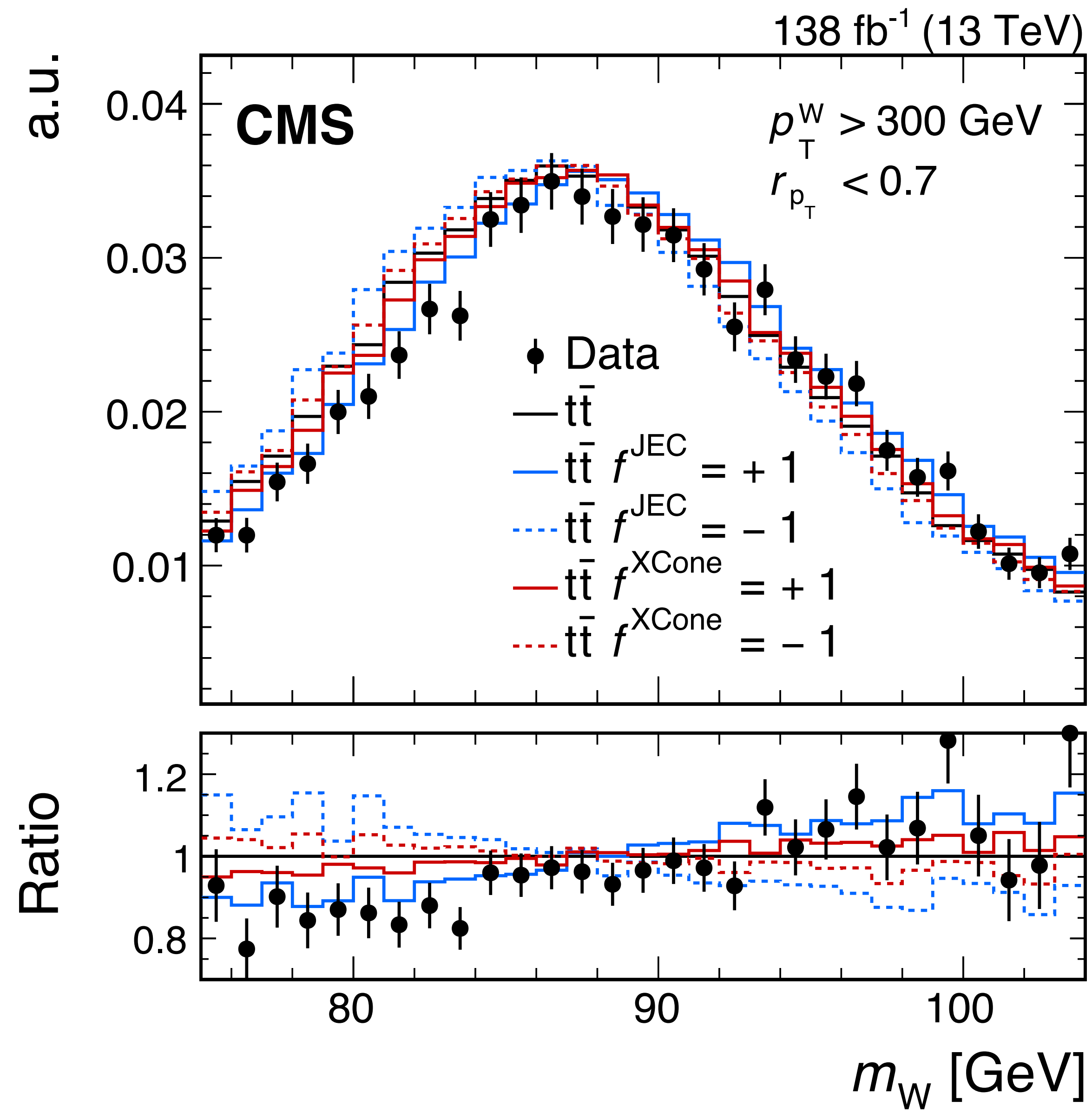
- Selection based on b-jet matching
  - XCone subjets matched to AK4 jets
- W candidate built from two light-quark subjets

[CMS, EPJC 83 (2023) 160]

Improving the Jetmass Scale 2

- Template fit of two factors driving the mass scale: four regions

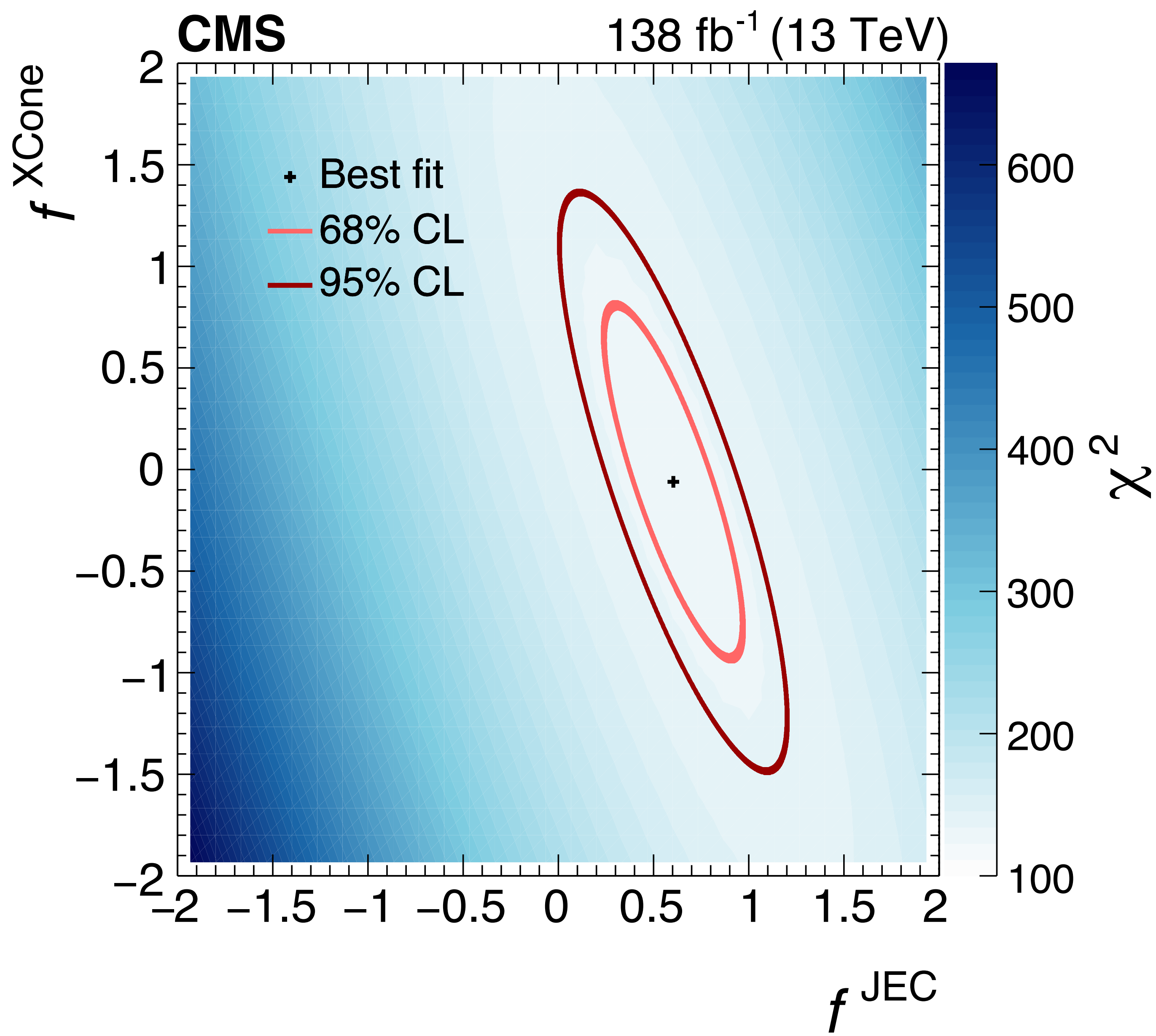


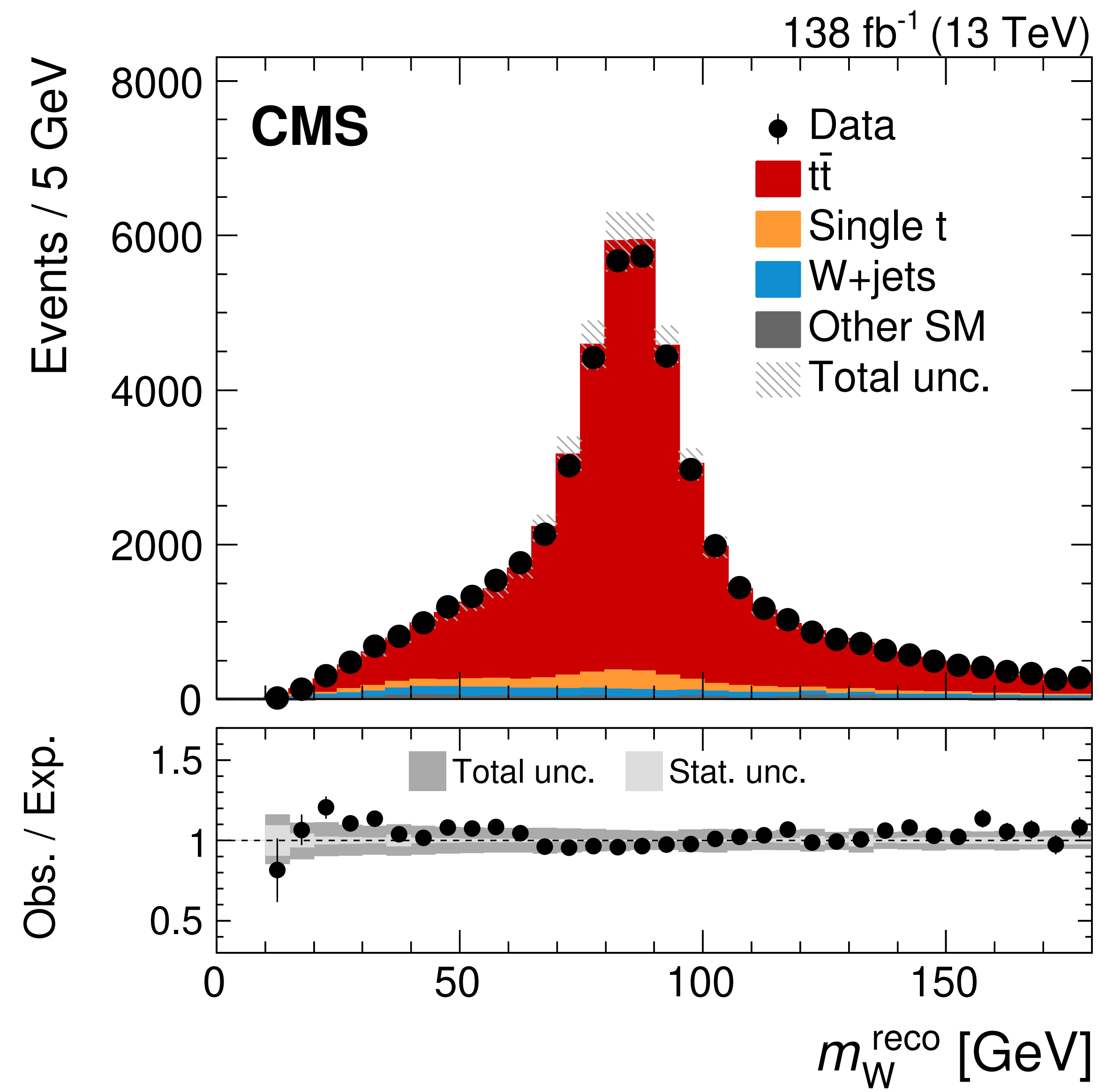


[CMS, EPJC 83 (2023) 160]

Improving the Jetmass Scale 3

- Constraints on both factors, improves JMS by more than 50%



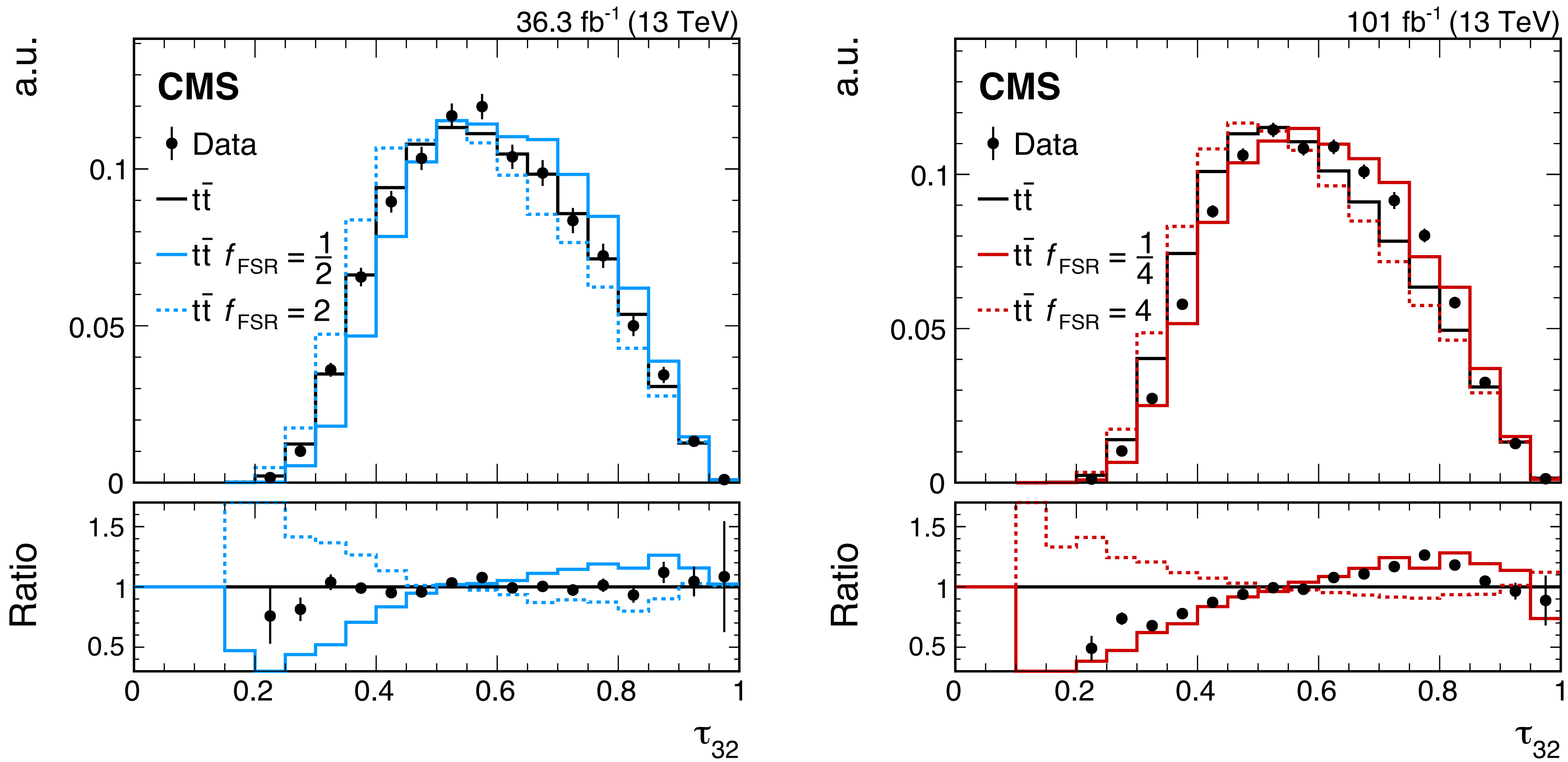


[CMS, EPJC 83 (2023) 160]

Improving the FSR Modelling

[CMS, EPJC 83 (2023) 160]

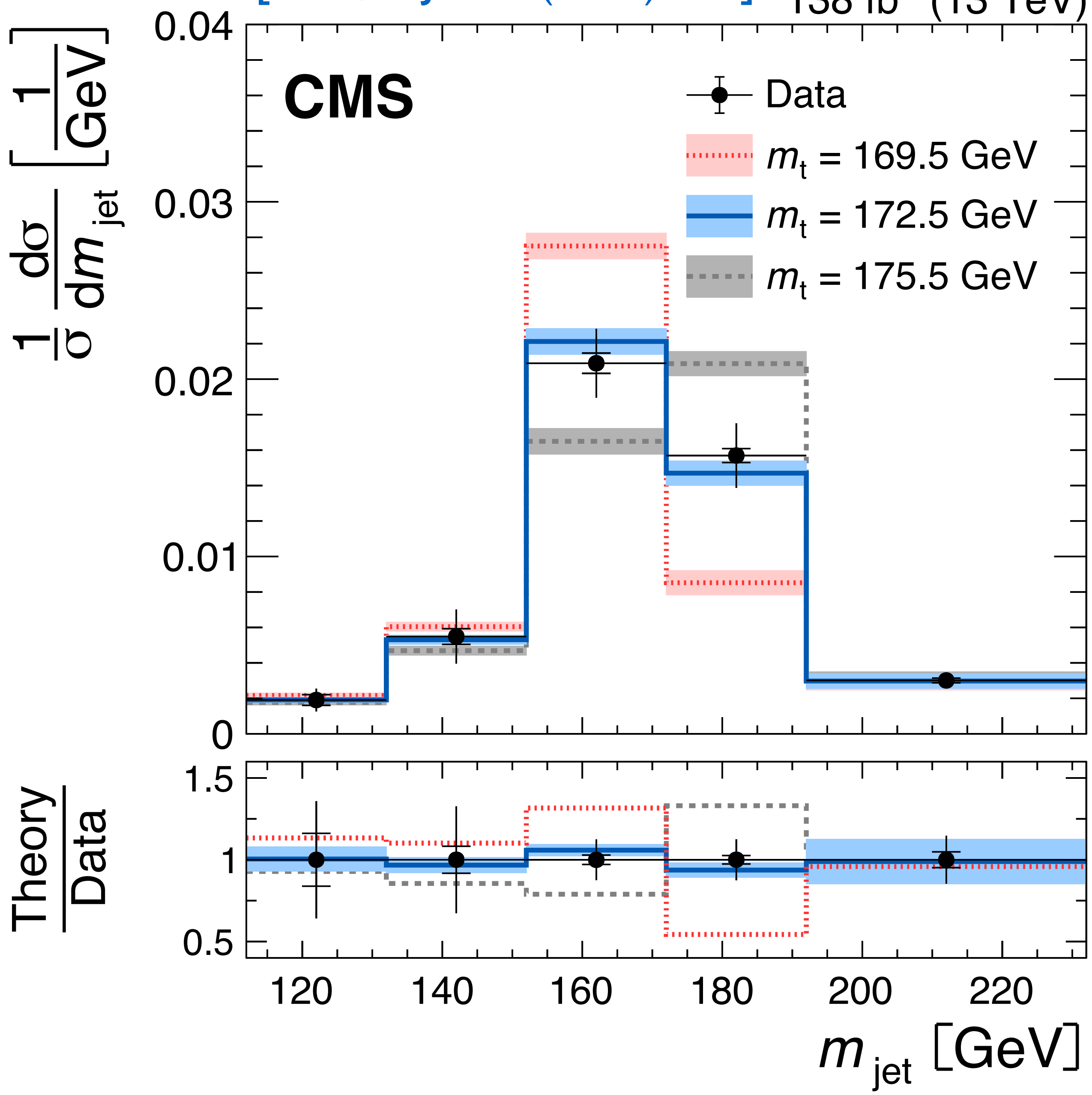
- Unfolding bias from FSR Modelling
  - Dimensionality of unfolding too small to capture all PS features
  - Regularization increases model dependence
- Tune MC modelling to describe data better: reduces unfolding bias

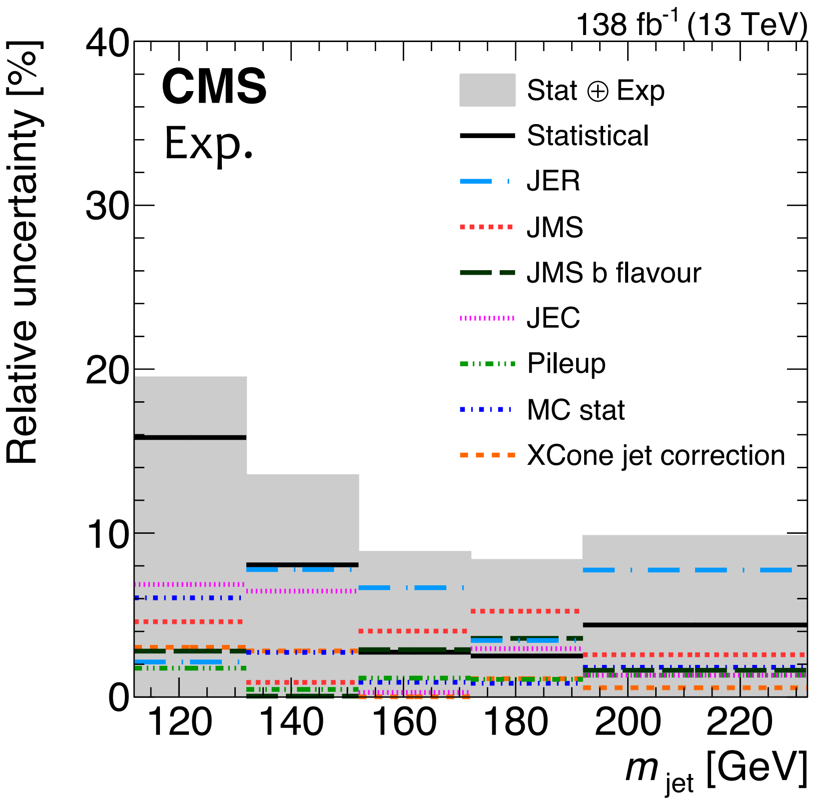


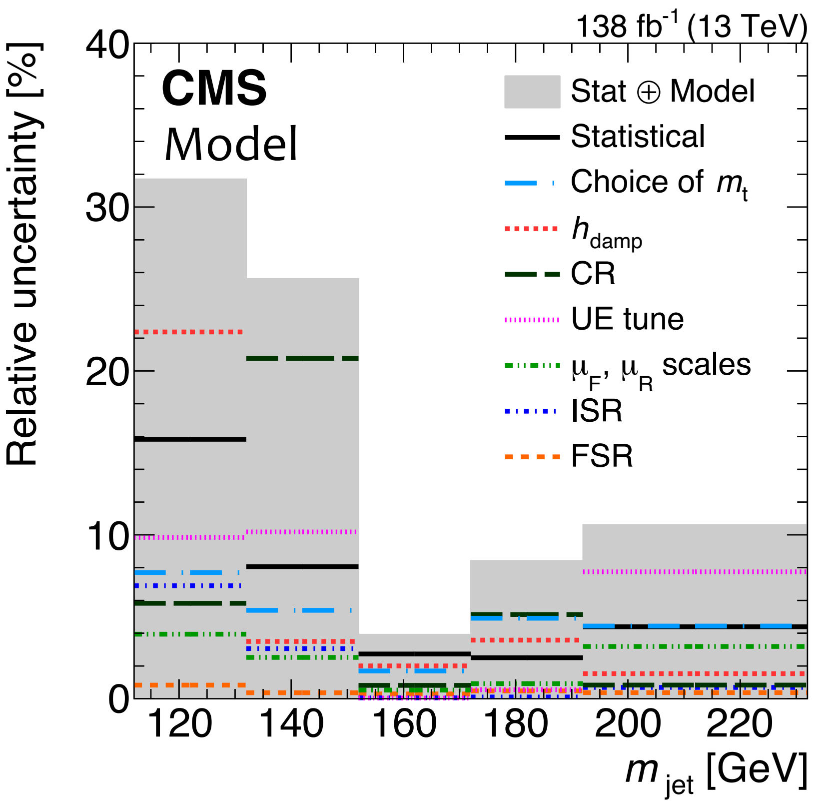
- Constrain FSR by measuring N-subjettiness ratio $\tau_{32} = \tau_3/\tau_2$
- Adjust f_{FSR} in $\alpha_S^{FSR}(f_{FSR}\,\mu_0)$, equivalent to choosing different $\alpha_S^{FSR}(M_Z)$

Cross section measurement

[CMS, EPJC 83 (2023) 160]





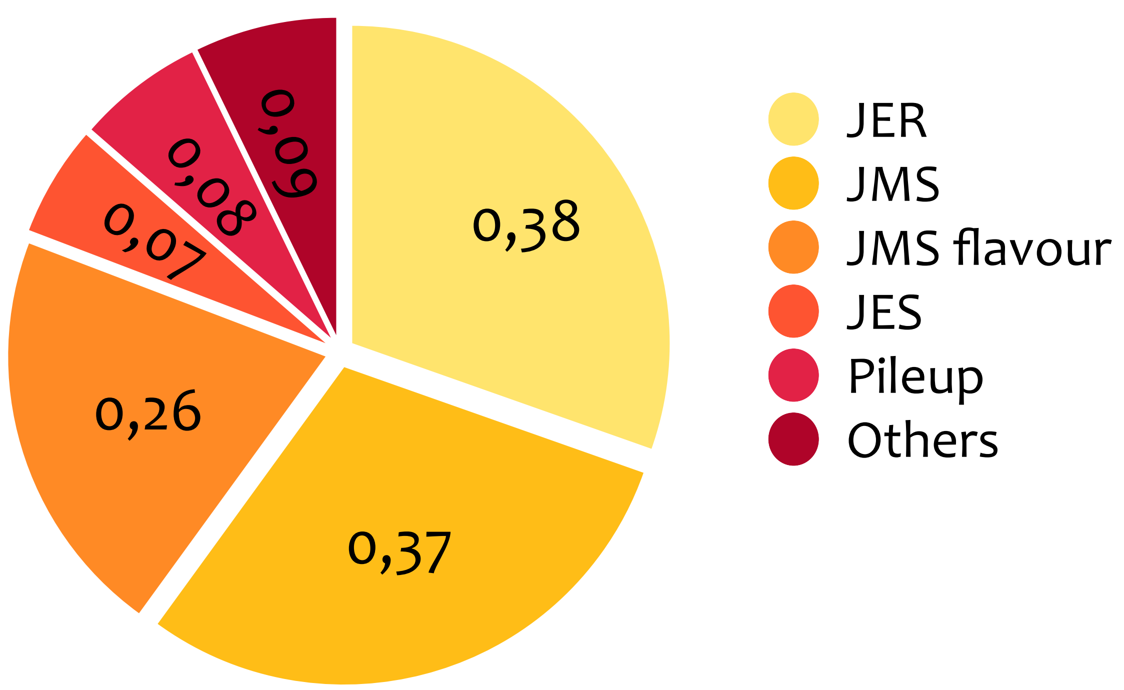


Determination of m_t

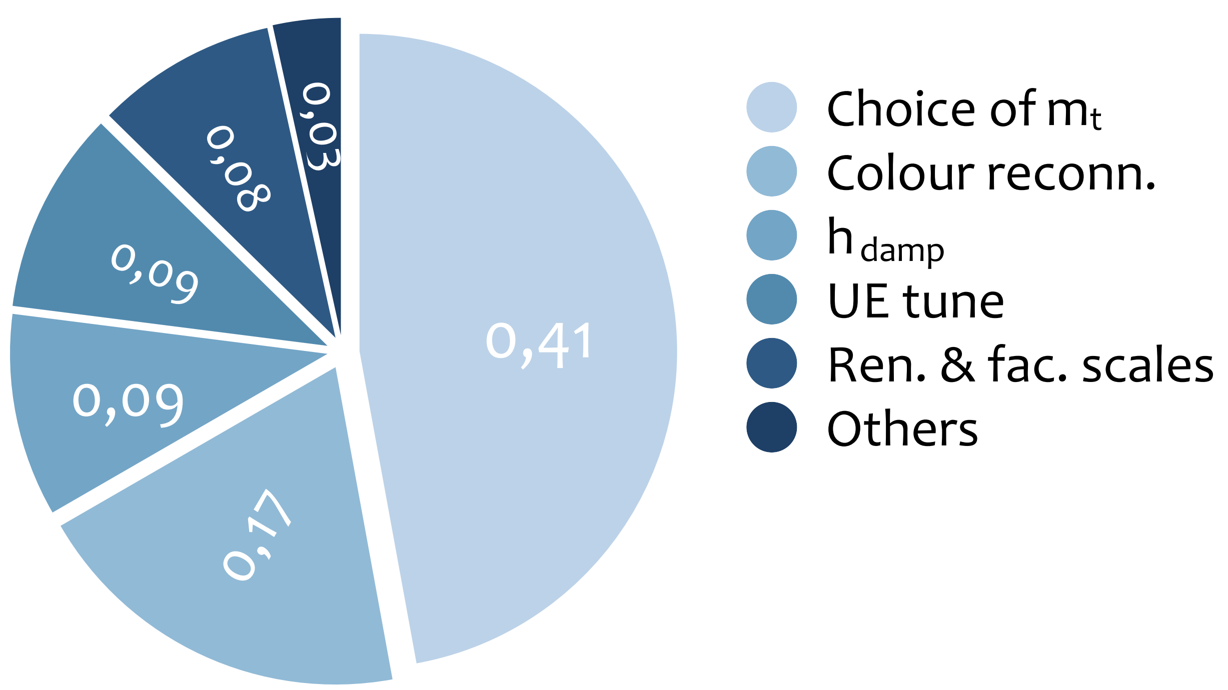
$$m_t = 173.06 \pm 0.84\,\mathrm{GeV}$$

± 0.24 (stat) ± 0.61 (exp) ± 0.47 (model) ± 0.23 (theo) GeV

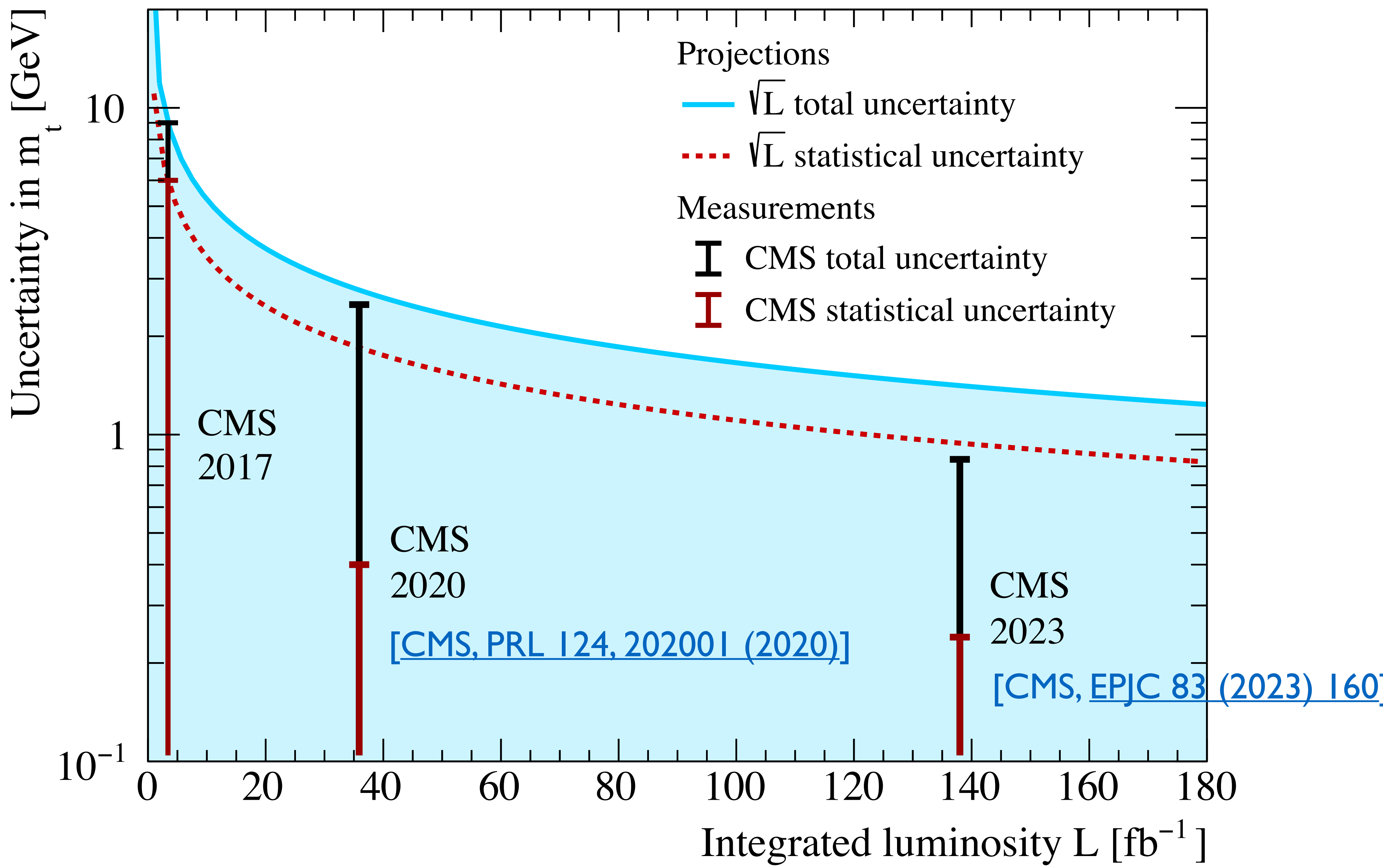
Experimental [GeV]



Model [GeV]

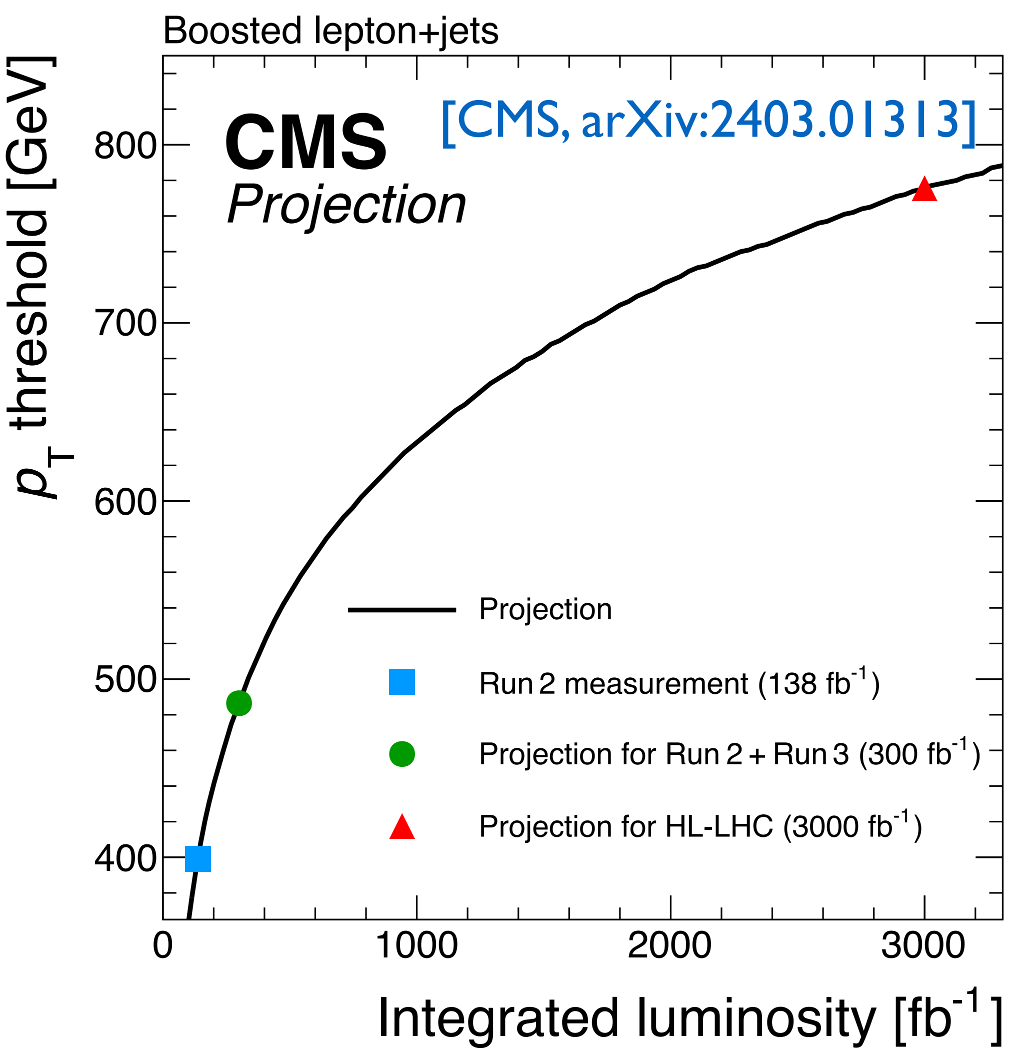


Summary on m_t from m_{jet}

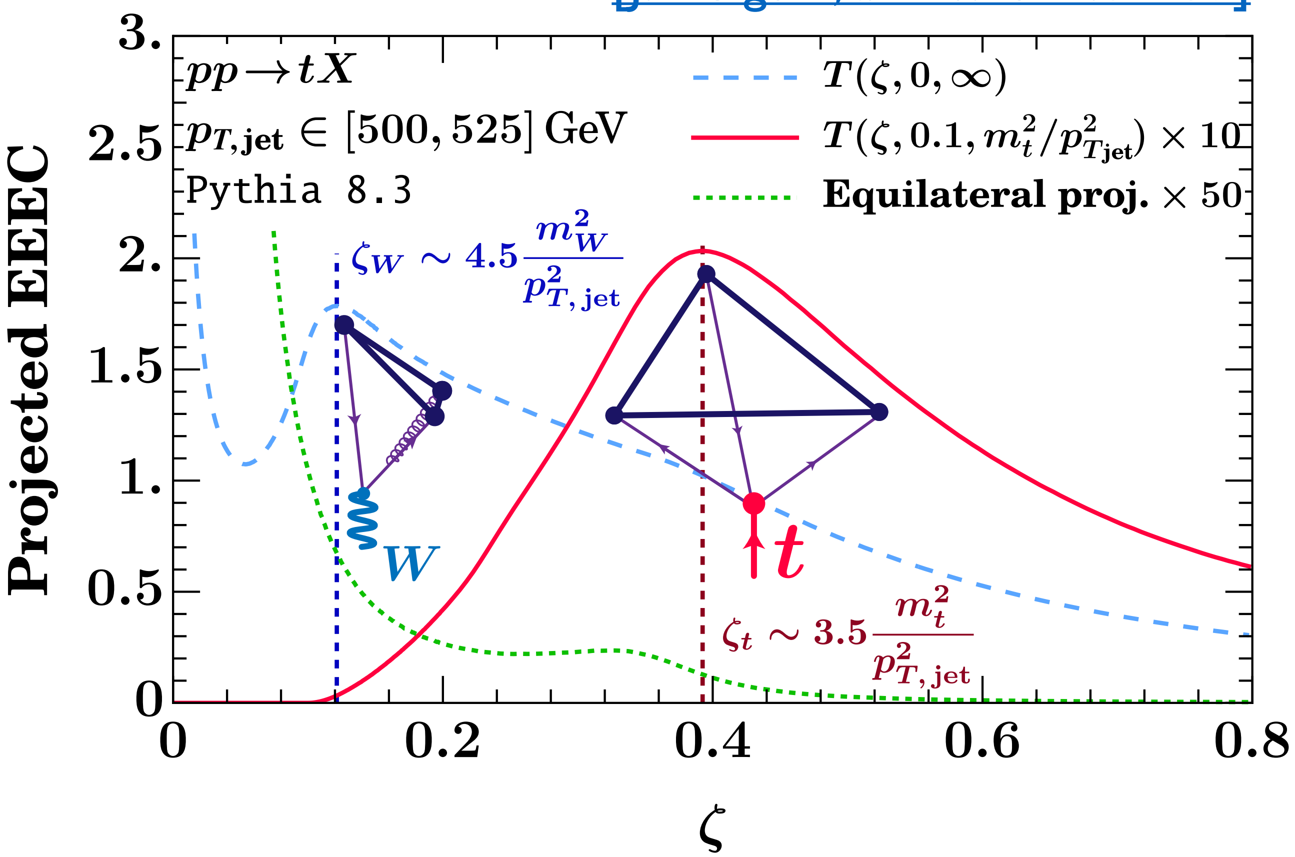


[A. Belvedere, C. Englert, R. Kogler, M. Spannowsky, EPJC84, 715 (2024)]

Future of m_t from Jetmass



[J. Holguin, arXiv:2311.02157]



Measuring top/W ratio turns

$$\zeta^{\mathrm{peak}} \sim \left(\frac{m_t^2}{p_{T,\mathrm{jet}}^2}\right) \to \left(\frac{m_t^2}{p_{T,\mathrm{jet}}^2}\frac{p_{T,\mathrm{jet}}^2}{m_W^2}\right) = \left(\frac{m_t^2}{m_W^2}\right)$$

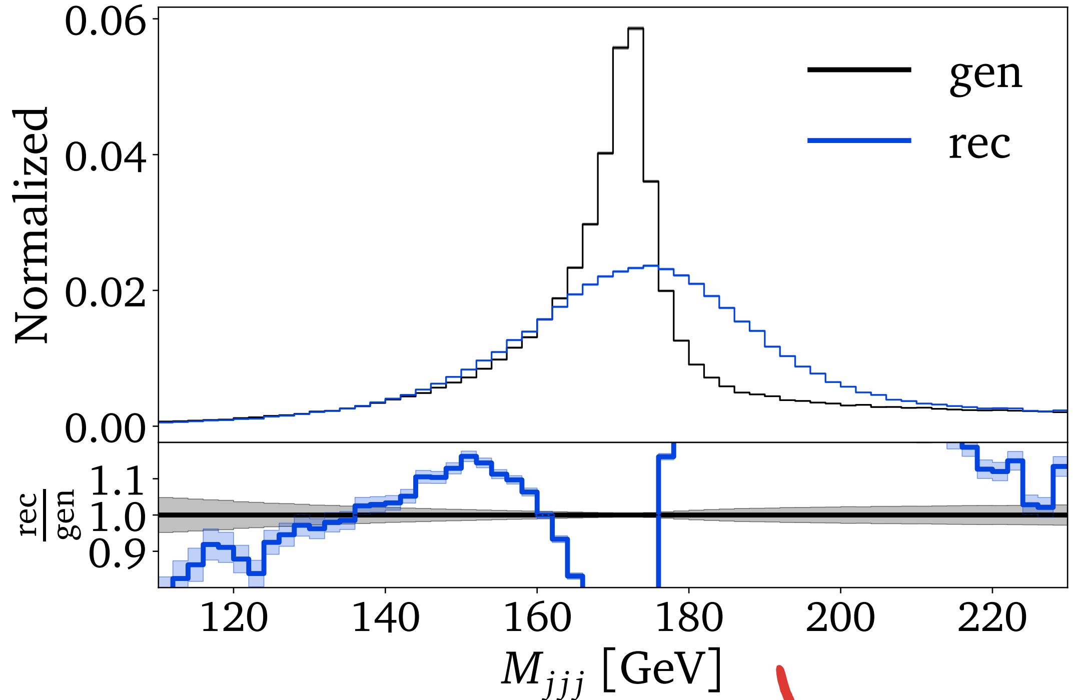
- New techniques in development, more data coming

Areas of improvement

Work in progress:

- Unfolding bias: Choice of m_t
- Signal modelling: ME+PS matching, PS, UE, hadronization
- Experimental:
  - Jet mass resolution
  - Jet mass scale
  - Jet mass flavour (b jet JES)

Unbinned, Multi-Dim Unfolding



$p_{\mathrm{sim}}(x_{\mathrm{gen}})$ $\quad\quad$ $p_{\mathrm{unfold}}(x_{\mathrm{gen}})$

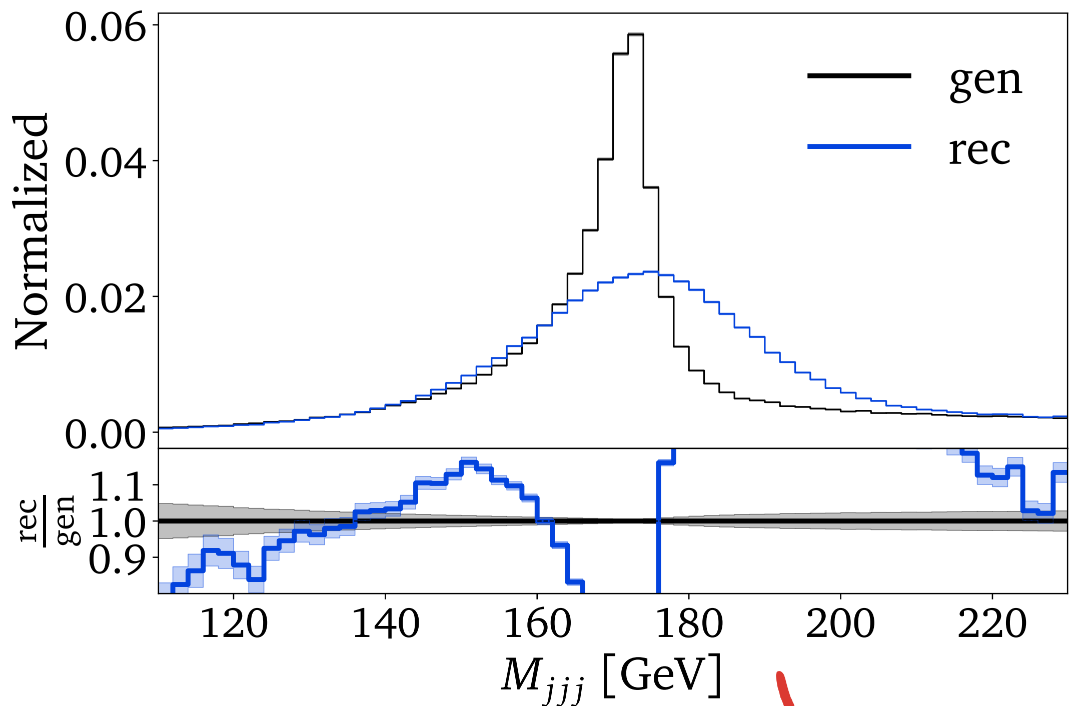
paired data $\updownarrow$ $\quad\quad$ $\uparrow p_{\mathrm{model}}(x_{\mathrm{gen}}|x_{\mathrm{reco}})$

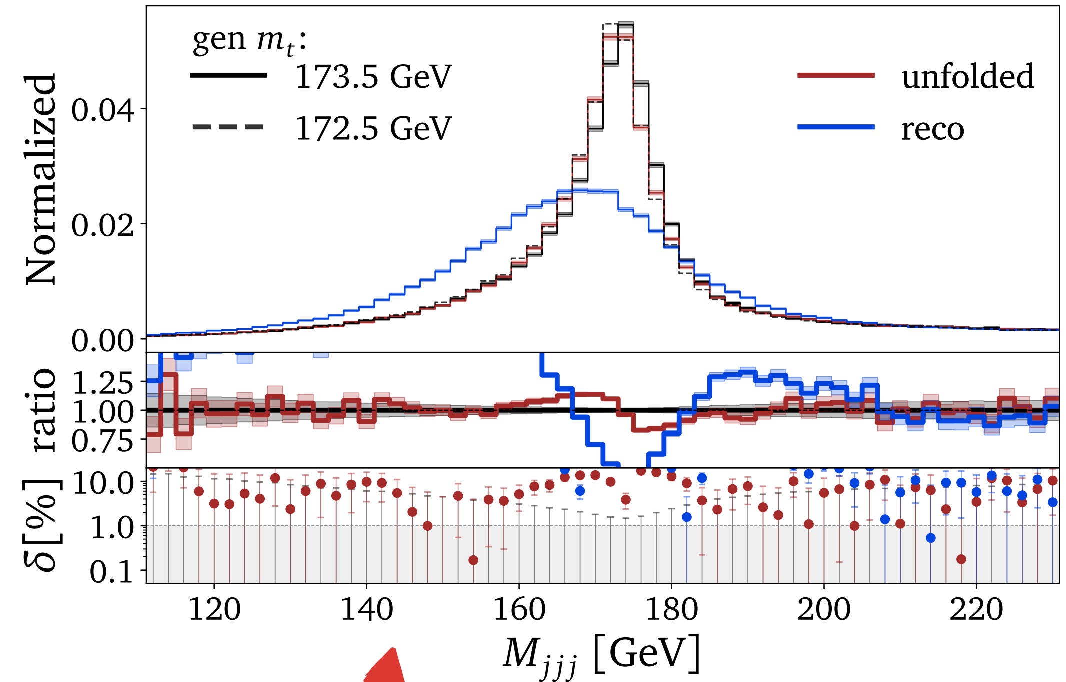
$p_{\mathrm{sim}}(x_{\mathrm{reco}}) \xleftrightarrow{\text{correspondence}} p_{\mathrm{data}}(x_{\mathrm{reco}})$

Generative Network:
Conditional Flow Matching

[L. Favaro, RK, A. Paasch, S. Palacios Schweitzer, T. Plehn, D. Schwarz, arXiv:2501.12363]

Unbinned, Multi-Dim Unfolding





$p_{\mathrm{sim}}(x_{\mathrm{gen}})$ $\xleftrightarrow{\text{paired data}}$ $p_{\mathrm{sim}}(x_{\mathrm{reco}})$

$p_{\mathrm{sim}}(x_{\mathrm{reco}})$ $\xleftrightarrow{\text{correspondence}}$ $p_{\mathrm{data}}(x_{\mathrm{reco}})$

$p_{\mathrm{data}}(x_{\mathrm{reco}}) \xrightarrow{p_{\mathrm{model}}(x_{\mathrm{gen}}|x_{\mathrm{reco}})} p_{\mathrm{unfold}}(x_{\mathrm{gen}})$

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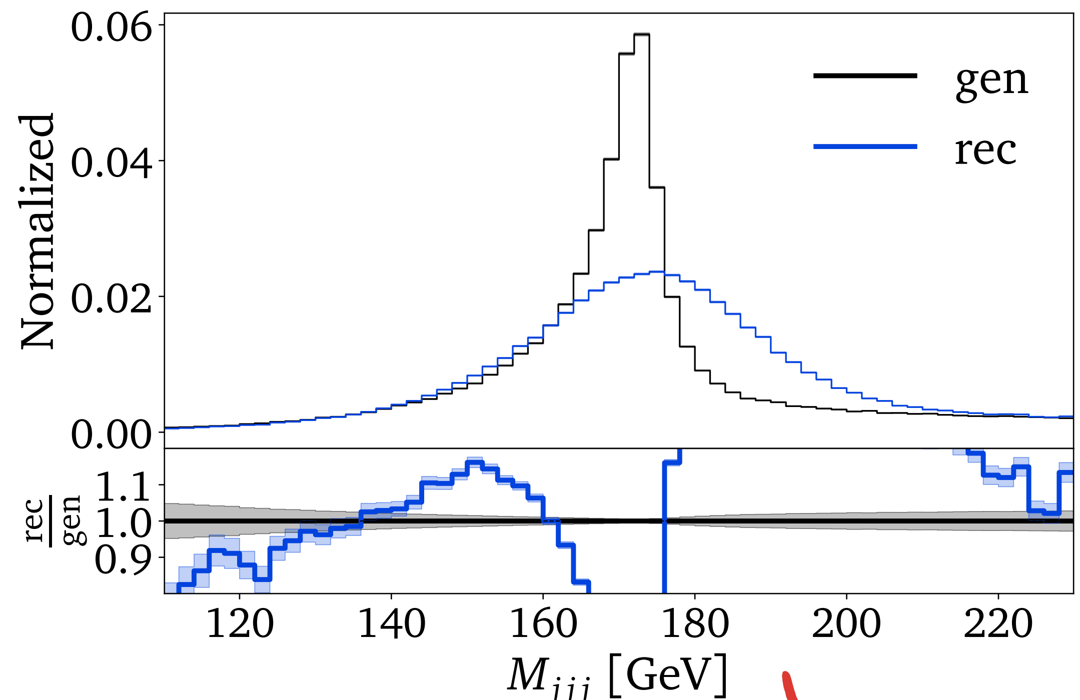

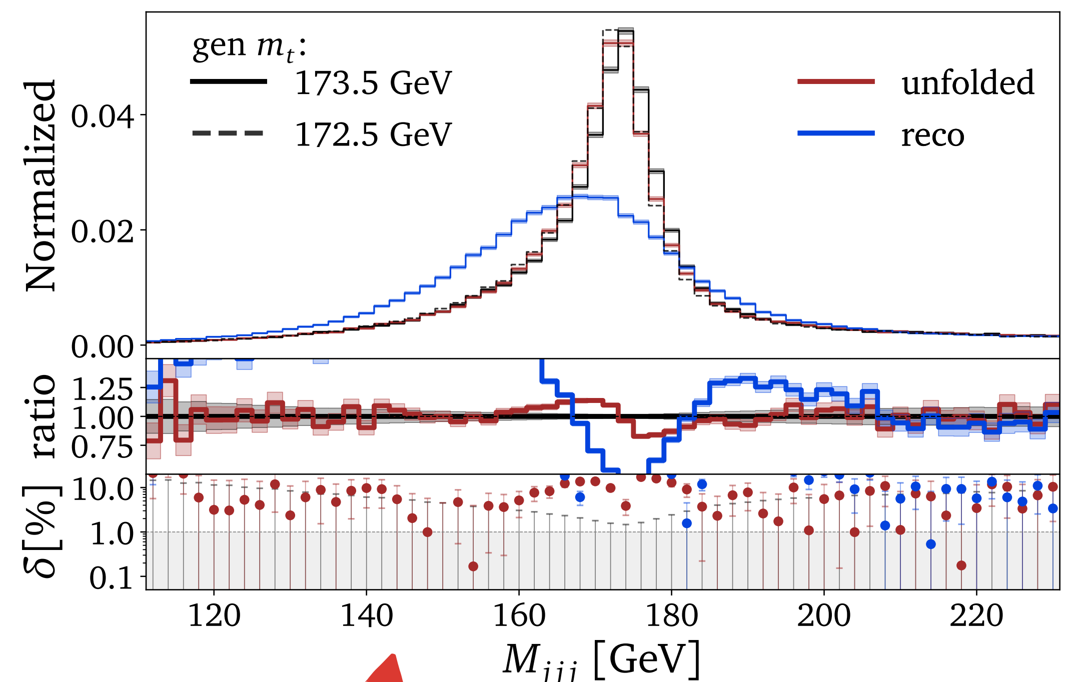

$$
\begin{tikzcd}
p_{\mathrm{sim}}(x_{\mathrm{gen}}|m_s) \arrow[d, "p(x_{\mathrm{reco}}|x_{\mathrm{gen}})"'] & & p_{\mathrm{unfold}}(x_{\mathrm{gen}}|m_s, \cancel{m_d}) \\
p_{\mathrm{sim}}(x_{\mathrm{reco}}|m_s) \arrow[rr, leftrightarrow, "\text{correspondence}"] & & p_{\mathrm{data}}(x_{\mathrm{reco}}|m_d) \arrow[u, "p_{\mathrm{model}}(x_{\mathrm{gen}}|x_{\mathrm{reco}}{,}m_s)"']
\end{tikzcd}
$$

Generative Network:
Conditional Flow Matching

"Nobody in their right mind would ever attempt to use unfolding for a mass measurement." [Lecturer at Terascale Statistics School]

[L. Favaro, RK, A. Paasch, S. Palacios Schweitzer, T. Plehn, D. Schwarz, arXiv:2501.12363]

Removing the Training Bias

- Add an estimator of m_t to the input data x_{reco}
- Weighted median of 3-jet mass: $M_{jjj}^{\text{batch}} \approx m_d \equiv m_t \Big|_{\text{data}}$
- For a batch size of about 10^4 events
- Training with three different values of $m_t = \{169.5, 172.5, 175.5\}$ GeV

[L. Favaro, RK, A. Paasch, S. Palacios Schweitzer, T. Plehn, D. Schwarz, arXiv:2501.12363]

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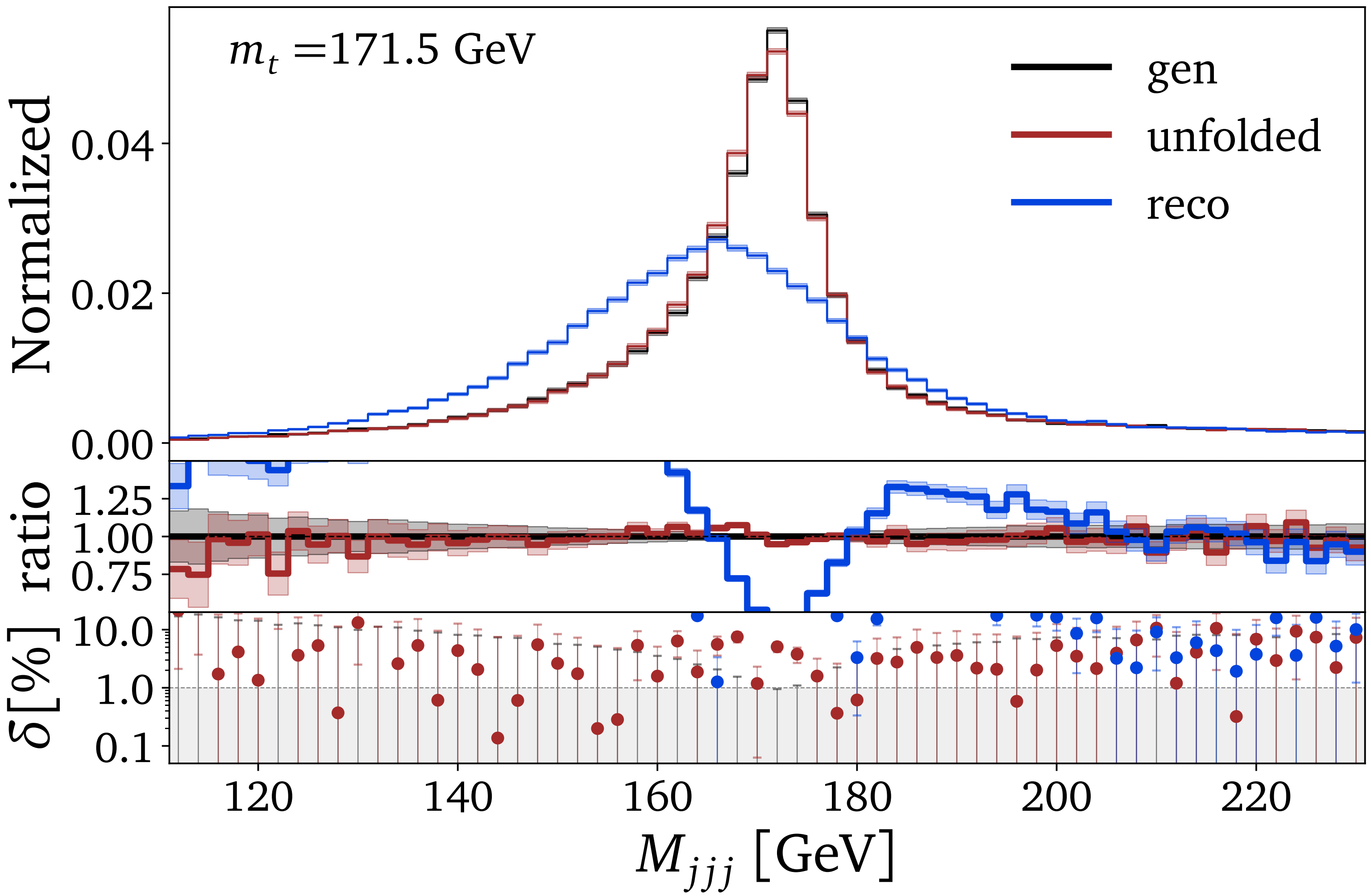


Result from 6-d unfolding:

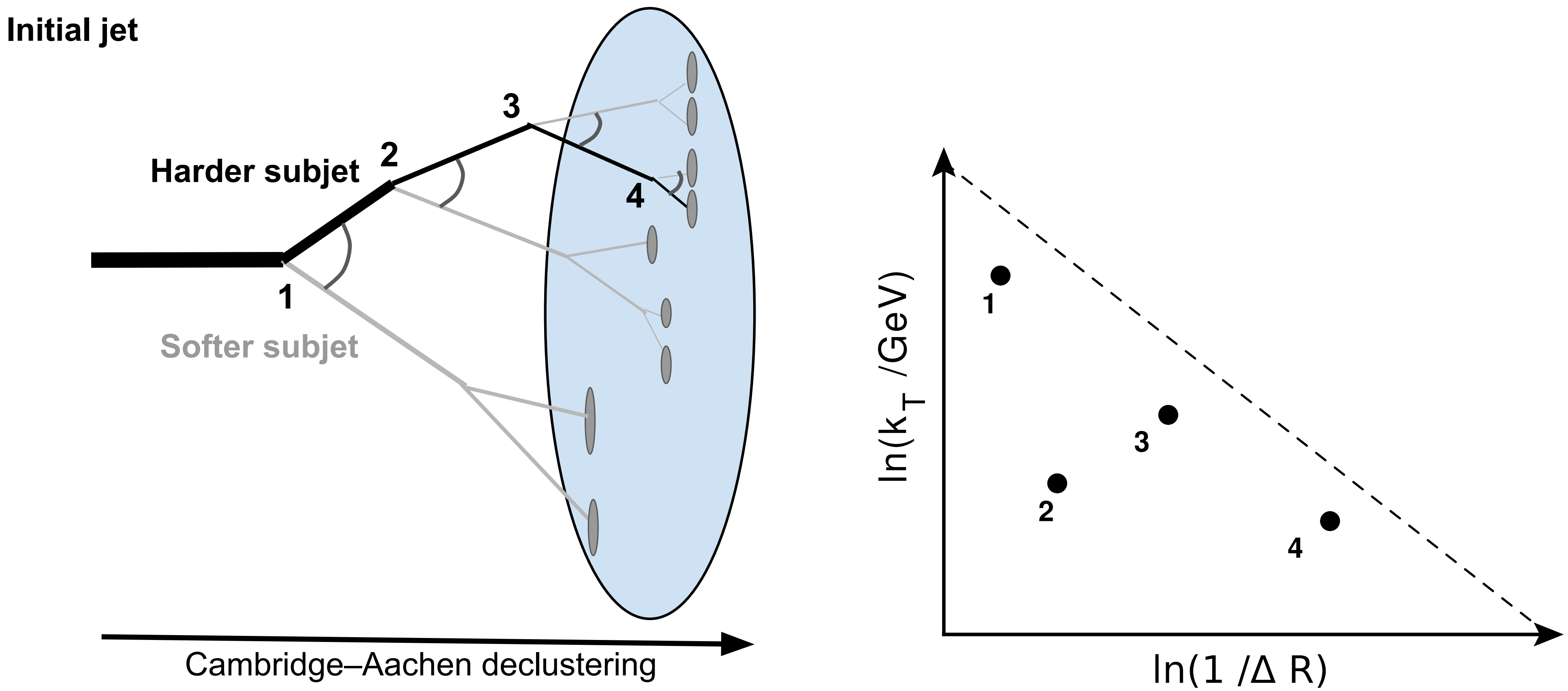
$$x = \left(\{m_i\}, \{M_{ik}\} \right)$$

Unfolding bias of < 100 MeV in m_t

[L. Favaro, RK, A. Paasch, S. Palacios Schweitzer, T. Plehn, D. Schwarz, arXiv:2501.12363]

Modelling: Lund Jet Plane

- Classify radiation by k_T and angular "hardness"



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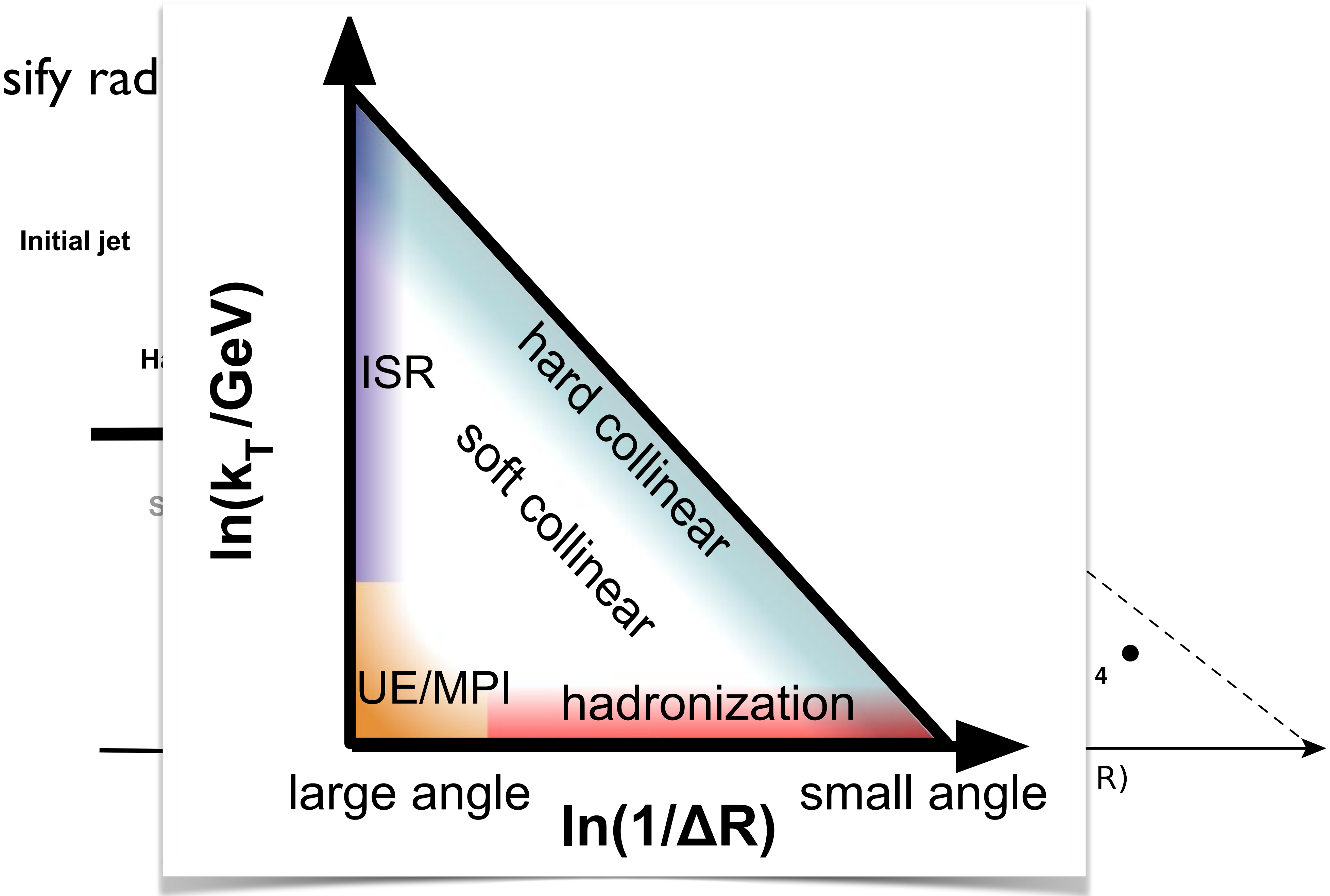

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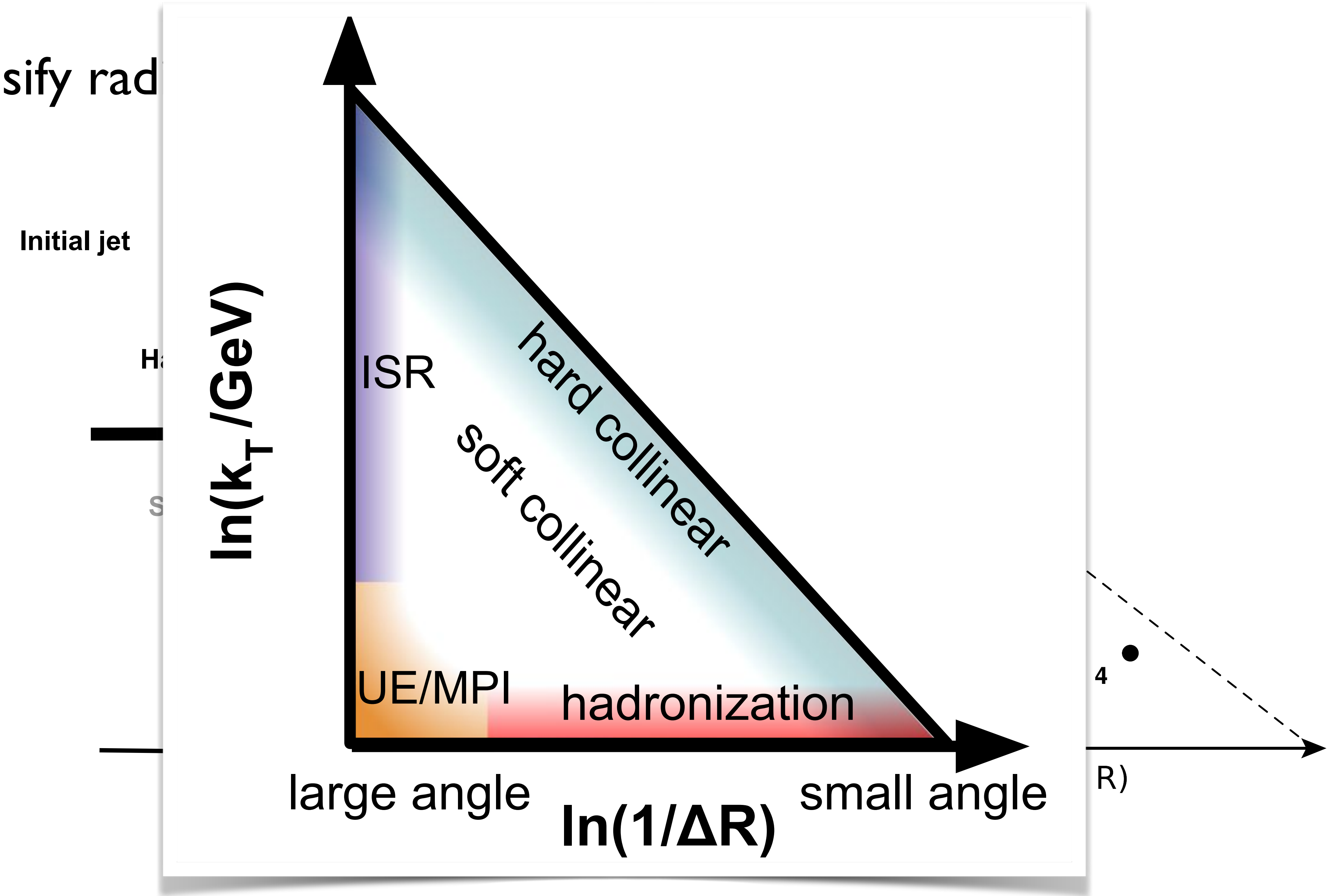
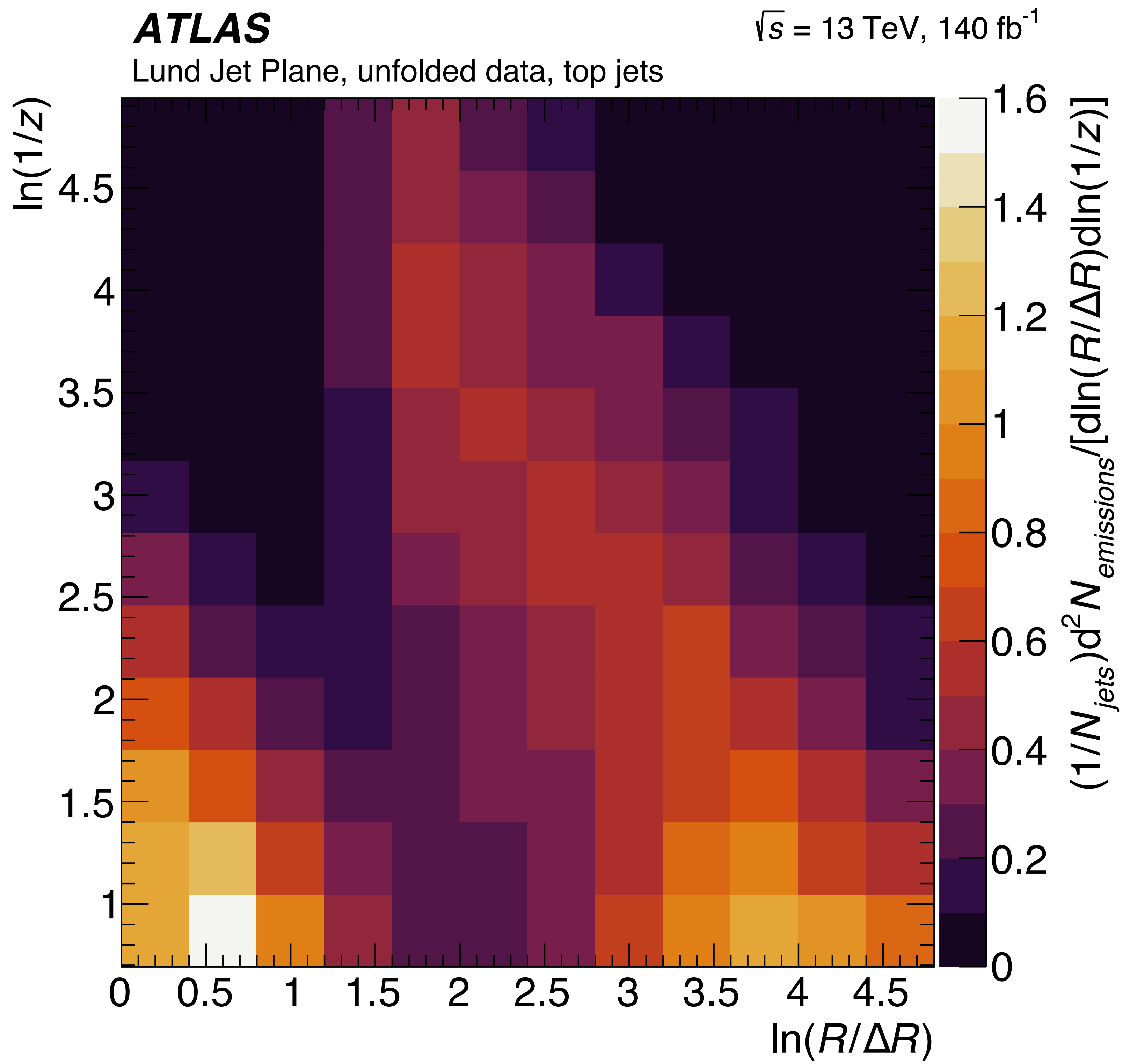


- Decluster top jets to measure LJP
- Possible to perform partial or full declusterings
- Access radiation pattern in top jets: rich structure

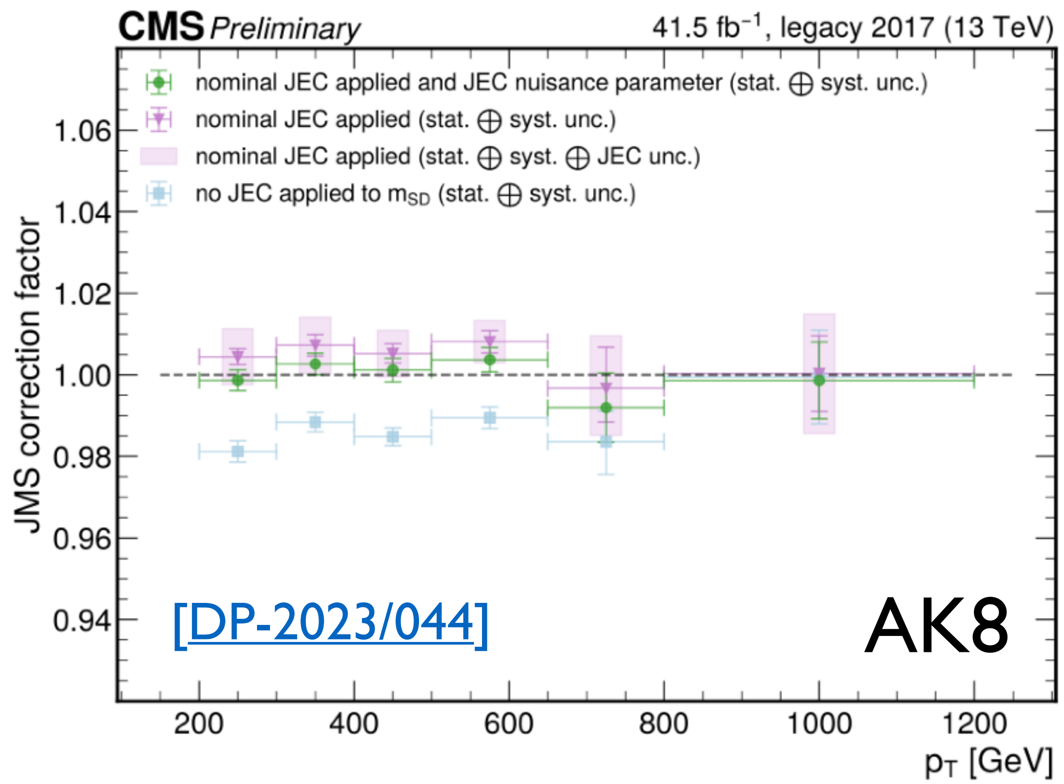
Lund Jet Plane for Tops

- Recent ATLAS measurement
  [ATLAS, arXiv:2407.10879]
- Access to
  - ME+PS matching
  - Shower
  - Shower cutoff
  - Hadronization
- Correct our models
  - LJP reweighting



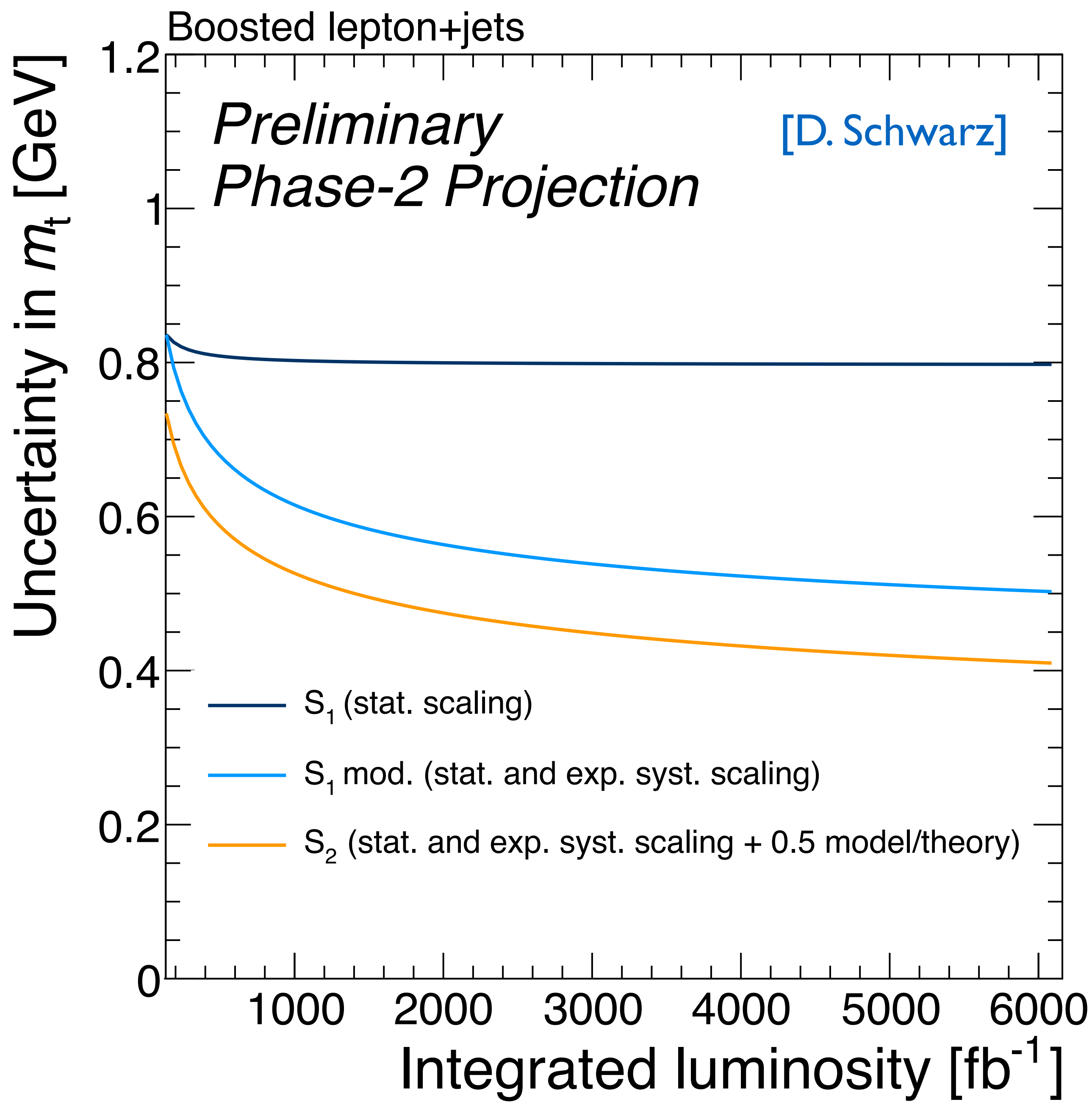
JMS and JMR Calibration

- Extend the current method to include the JMR



- Unbinned model, constrain JMR and JMS in-situ in the unfolding (!)
  - More developments needed
- b jet flavour uncertainty more difficult
  - Fragmentation differences between MC simulations
  - Detailed studies required to understand response differences

Finally: Theory Input!



Projections promise large improvement in prospective measurements

With HL-LHC, uncertainties of 400 MeV in m_t in reach

So far, always m_t^{MC} implicitly used, need calculations to turn the cross section measurements into m_t^{MSR} measurements!