Top-quark mass related studies

LHC top Working Group Open Meeting, Dec 1- 3

Javier Aparisi and Matteo Defranchis,

on behalf of the ATLAS and CMS collaborations

Material covered in this talk

- *“Towards a precise interpretation of the top quark mass parameter in the ATLAS MC samples”*

  ATL-PHS-PUB-2021-034

- “Running of the top quark mass from proton-proton collisions at $\sqrt{s} = 13\ TeV$”

  CMS-TOP-19-007

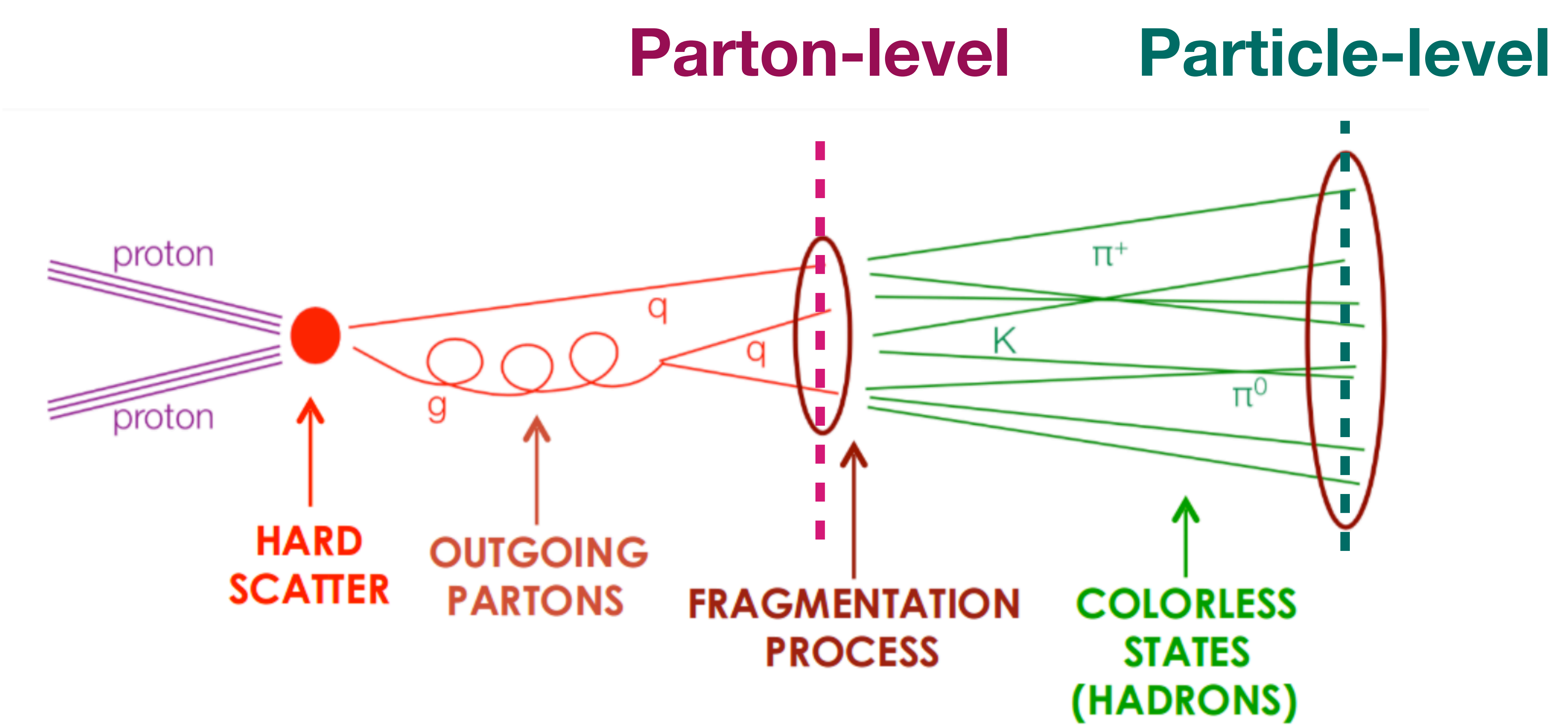
Towards a precise interpretation of the top quark mass parameter in the ATLAS MC samples

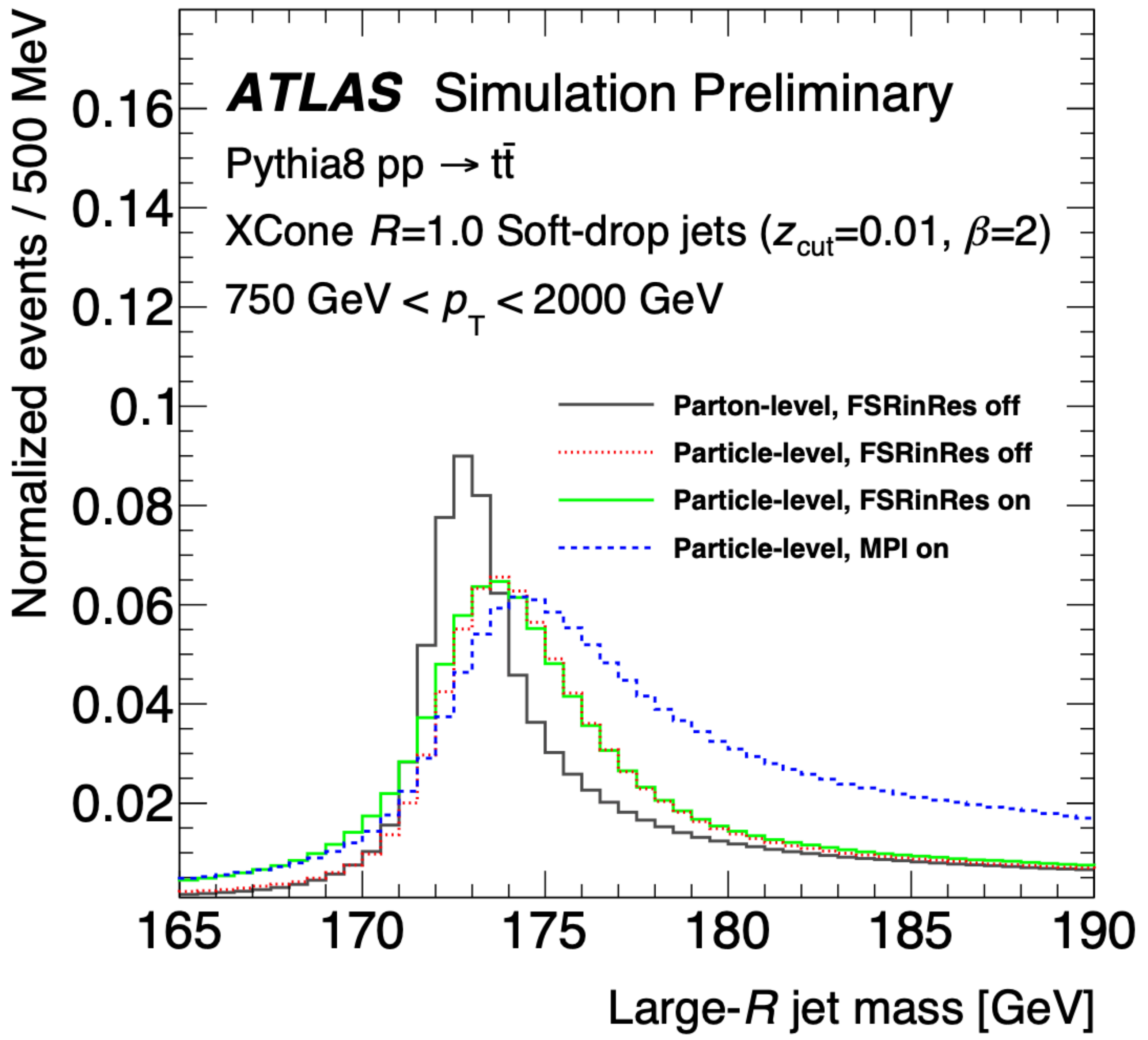
1. Motivation

- Top quark mass experimentally determined in **direct** and **indirect** measurements:

  - **DM**: Monte Carlo (MC) fits to data at detector level $\rightarrow m_{top}^{MC}$ with O(600) MeV precision
  - **IM**: fixed-order theory fits to data at parton level $\rightarrow m_{top}^{pole,\overline{MS}}$ with O(1) GeV precision

- Can the m_{top}^{MC} be identified with a well-defined mass scheme m_{top} with a precision better than 500 MeV?





2. Goal

- The main goal of the analysis is

the interpretation of the top mass in official ATLAS MC generators in light of a renormalized mass in the MSR scheme*:

$$m_{top}^{MC} = m_{top}^{MSR}(R) + \Delta m^{MSR}$$

The top MSR mass is a short-distance mass that depends on an R parameter, above which top self-interactions are absorbed. For $R = 1\ GeV$*, it is conceptually close to the top MC mass (*$\Lambda^{PS} \sim 1\ GeV$*):*

$$m_{top}^{MSR}(R = 0\ GeV) \rightarrow m_{top}^{pole}, \quad m_{top}^{MSR}(R = m_t) \rightarrow m_{top}^{\overline{MS}}$$

2. Goal

- The main goal of the analysis is

the interpretation of the top mass in official ATLAS MC generators in light of a renormalized mass in the MSR scheme*:

$$m_{top}^{MC} = m_{top}^{MSR}(R) + \Delta m^{MSR}$$

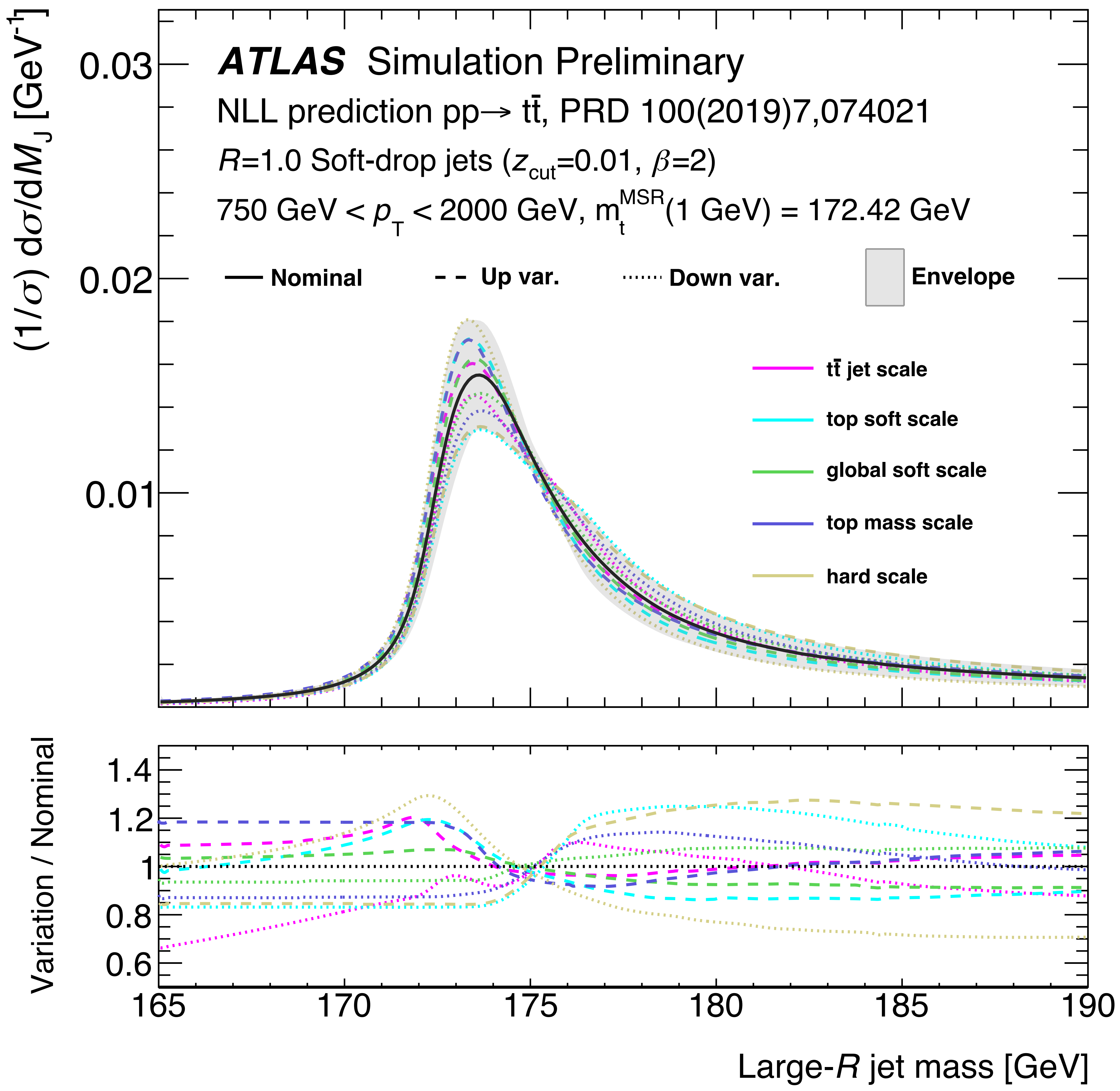
- A *calibration* is performed by comparing ATLAS MC predictions to a NLL calculation for two MC models: Pythia8 (P8) and Herwig7 (H7).
  The m_{top}^{MC} is set to 172.5 GeV.

  Internal variations of the nominal MC (Pythia8) are studied as well in order to check their impact in the MSR-MC mass relation determined in the nominal setup

3. Theoretical calculation

$$\frac{\partial\sigma^{tot}}{\partial M_J} = \frac{\partial\sigma^{pQCD}}{\partial M_J} \otimes \frac{\partial\sigma^{npQCD}}{\partial M_J}$$

- SCET-based theory at NLL accuracy
- Differential jet mass cross section at particle-level
- Strong **sensitivity to m_{top} in the jet mass peak** region
- Main ingredients:
  1. Inclusive treatment of hadronic top quark decays
  2. Light soft-drop grooming to remove soft-wide radiation
  3. Three free parameters: m_{top} and Ω_{1q}^{had} and x_2 for **non-perturbative corrections**
- ***Does not account for UE effects***



4. Jet reconstruction & selection

- The observable is a **particle-level groomed jet mass**, built from stable particles in $pp \to t\bar{t}$ events*

  I) ***XCone*** *jet algorithm with R=1*

  II) ***Light soft-drop grooming*** *applied* ($z_{cut} = 0.01,\ \beta = 2$)

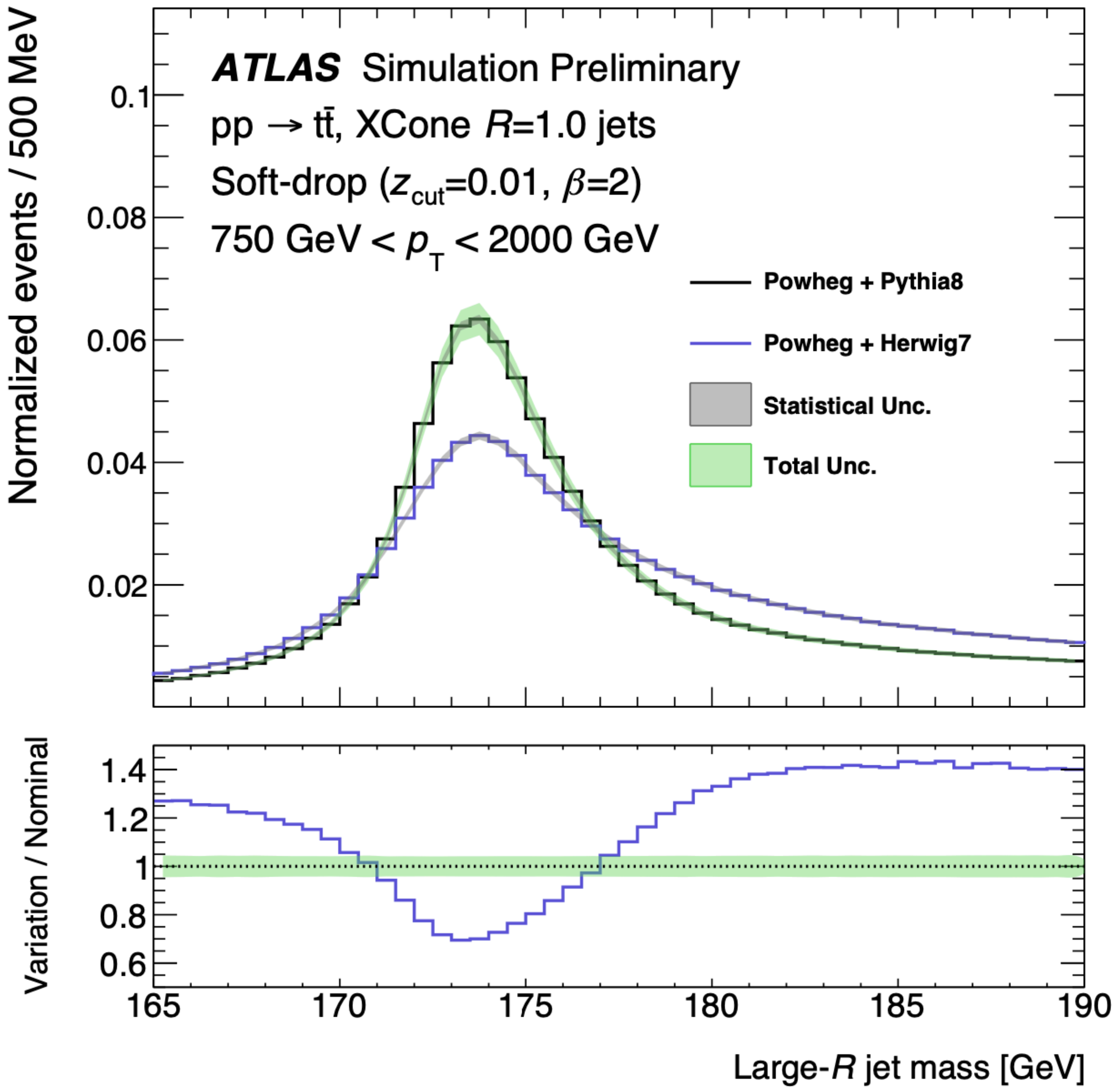
- **Boosted regime**: needed to capture all top decay products in a single jet.

  Three orthogonal p_T *bins considered:*

  $$p_T^{jet} \in [750{,}1000\},[1000{,}1500\},[1500{,}2000]\ GeV$$

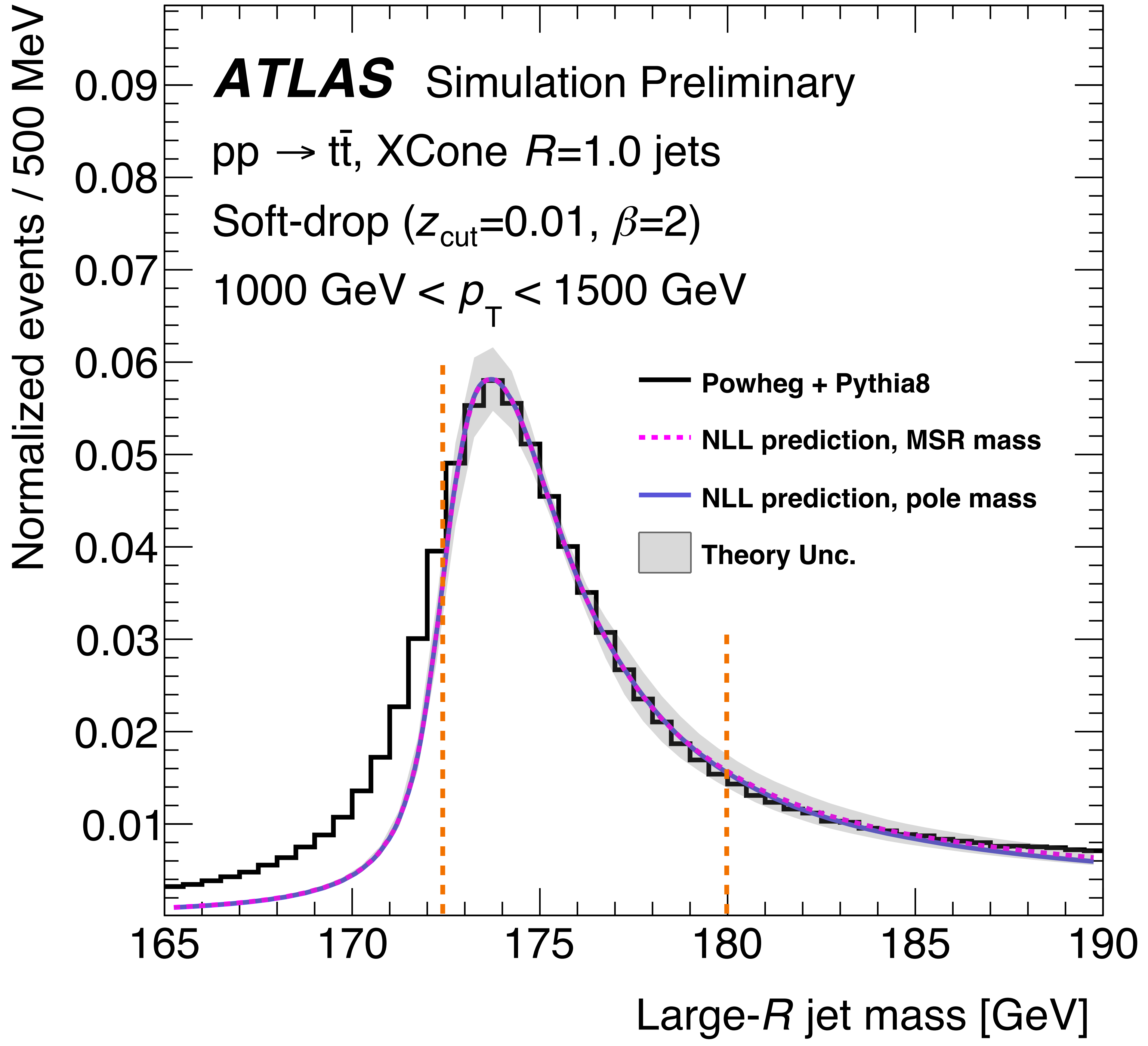
  Three free parameters of theory scale differently with the jet p_T

- Large-R jet to hadronically decaying top parton matching applied: $\Delta R(jet, top) < 1$



*Events generated with MPI setting switched off in order to not include UE effects

5. Results (I)



Fit range: 172.5 - 180.0 GeV

- $\chi 2$ fit and minimization to find the theory prediction that best describes MC:

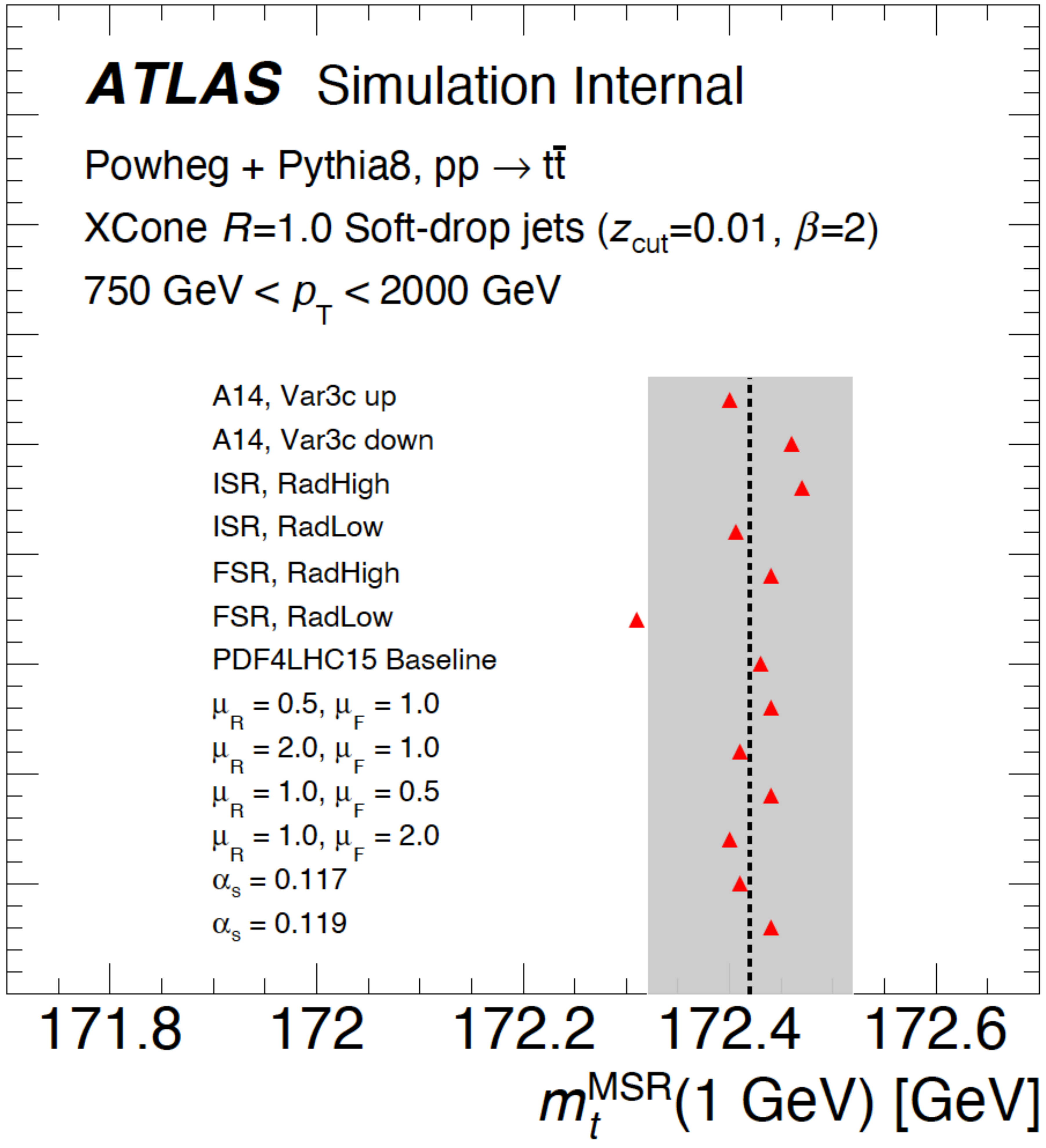
Ph+P8: $m_{top}^{MSR}(1\ GeV) = 172.42 \pm 0.10\ (stat.)\ GeV$

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

with **theory** component **dominating** total uncertainty:

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**	

5. Results (II)



- $\chi 2$ fit and minimization to find the theory prediction that best describes MC:

Ph+P8:

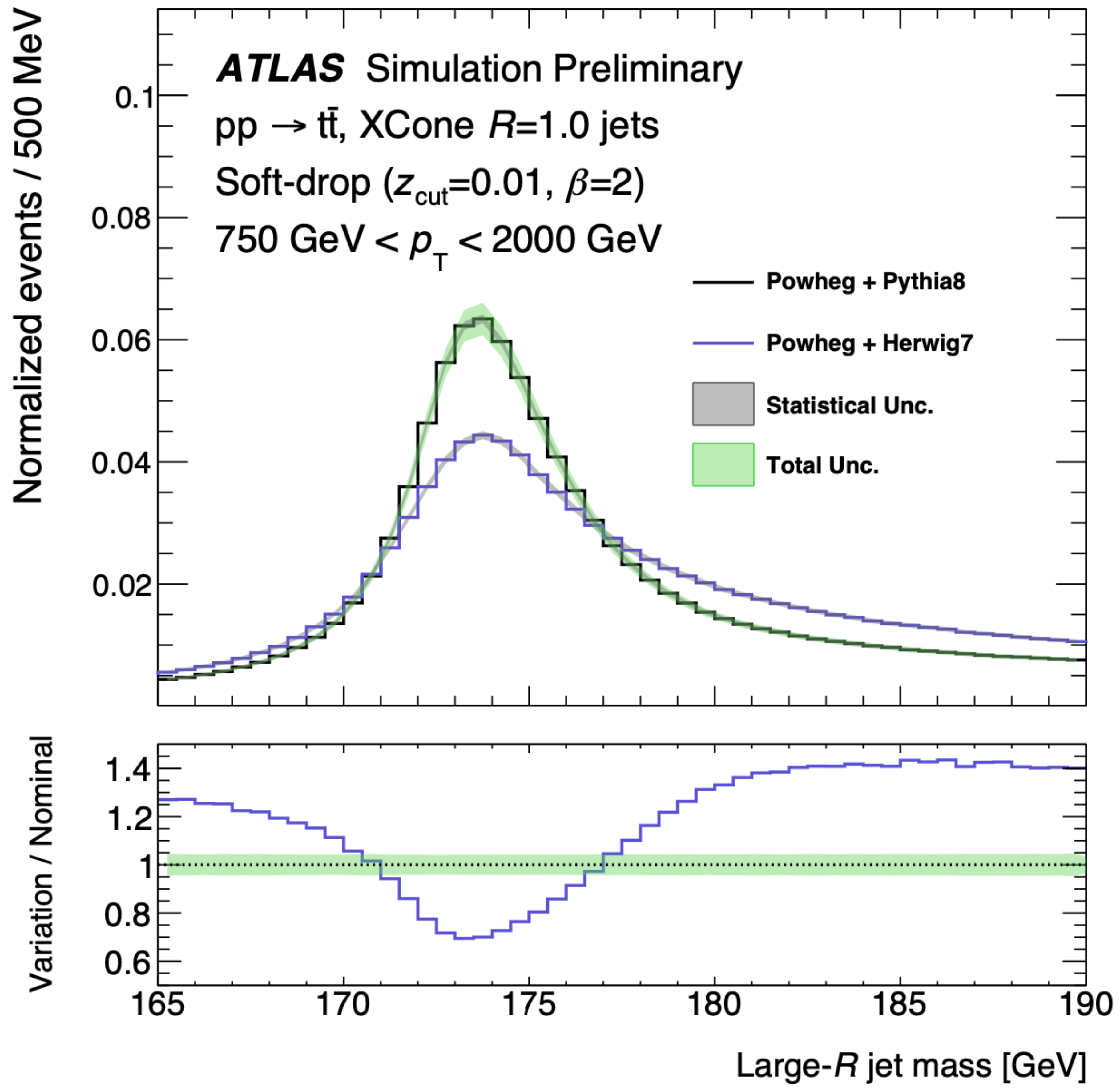
$$m_{top}^{MSR}(1\ GeV) = 172.42 \pm 0.10\ (stat.)\ GeV$$

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

with **theory** component **dominating** total uncertainty:

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**	

5. Results (III)



- $\chi 2$ fit and minimization to find the theory prediction that best describes MC:

Ph+P8: $m_{top}^{MSR}(1\ GeV) = 172.42 \pm 0.10\ (stat.)\ GeV$

Ph+H7: $m_{top}^{MSR}(1\ GeV) = 172.27 \pm 0.09\ (stat.)\ GeV$

- The calibration can be performed on any MC sample. Surprisingly **similar results for Powheg+Pythia8 and Powheg+Herwig7**, even if these two Monte Carlo setups predict very different jet mass distributions.

- These **MSR-MC mass relations are found to be stable within 200 MeV**, when repeating this exercise considering related observables accesible with the underlying theory

Related observables: Anti-kt and softer/harder SD configuration

Running of the top quark mass from proton-proton collisions at $\sqrt{s} = 13\ TeV$

1. Introduction

- In the $\overline{MS}$ scheme, the **evolution** of any **quark mass** with the energy scale μ is **governed by the RGE**:

$$\mu^2 \frac{dm(\mu)}{d\mu^2} = -\gamma\left(\alpha_S(\mu)\right) m(\mu)$$

- The running of the **b-quark and the charm-quark mass** have been **already studied** using data from CERN LEP, SLAC SLC and DESY HERA.

- The **top-quark mass running is first studied** in $t\bar{t}$ events with $39.5\ fb^{-1}$ of data collected by the **CMS detector** at $\sqrt{s} = 13\ TeV$.

2. Strategy

- Measure the **differential $t\bar{t}$ cross-section** as a function of the $t\bar{t}$ **invariant mass $m_{t\bar{t}}$** in the following bins:

Bin	$m_{t\bar{t}}$ [GeV]	Fraction [%]	μ_k [GeV]
1	<420	30	384
2	420–550	39	476
3	550–810	24	644
4	>810	7	1024

so **the scale of the process is chosen to be given by the center-of-gravity of bin k, μ_k.**

- Compare with fixed-order **NLO prediction in QCD** at parton level to extract the **top $\overline{MS}$ mass** simultaneously at each $m_{t\bar{t}}$ bin.

- Test the **running hypothesis** considering that at each k bin, $m_t(\mu) = m_t(\mu_k)$

3. Event selection and categorization

- $t\bar{t}$ events selected in the **dileptonic channel**:

  - At least one e and one μ with opposite charge where: $p_T^{lead} > 25\ GeV$, $p_T^{slead} > 20\ GeV$ and $|\eta| < 2.4$
  - Jets with $p_T^{jet} > 30\ GeV$ and $|\eta| < 2.4$.

- **Kinematic reconstruction of $m_{t\bar{t}}$** from combination of jets, leptons and MET ($m_W = 80.4\ GeV$) in events with at least two jets -> **dependence on m_t^{MC} mitigated in the fit**

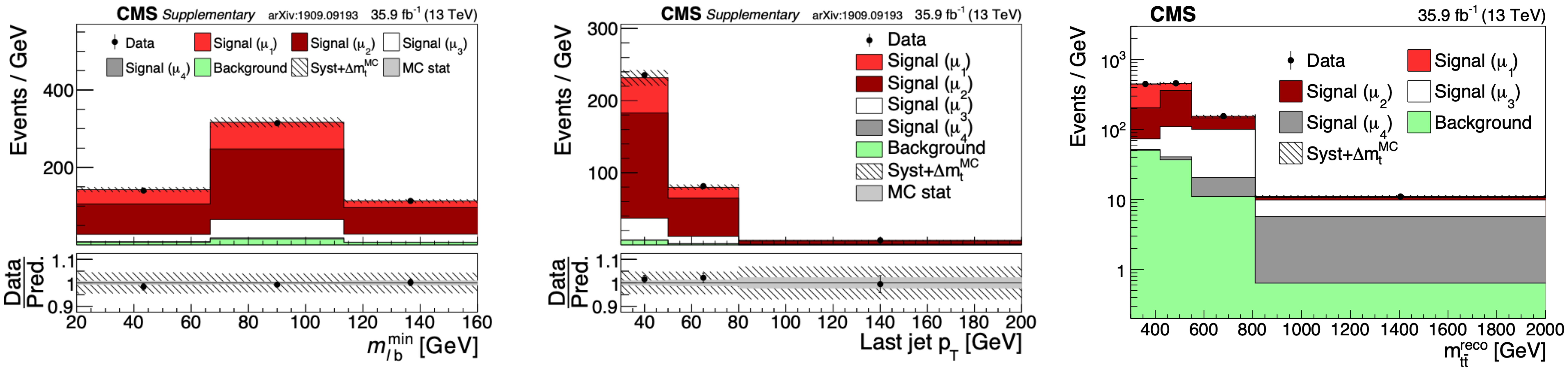
- **Events** are **categorized according to b-tagged jets multiplicity** (1, 2 or (0 and >2)) and further divided into **subcategories of $m_{t\bar{t}}^{reco}$**.

- The **observables** used are the p_T **of the softest jet**, the invariant mass of the b-jet and lepton system m_{lb} and the **event yield**.

Bin	$m_{t\bar{t}}$ [GeV]	Fraction [%]	μ_k [GeV]
1	<420	30	384
2	420–550	39	476
3	550–810	24	644
4	>810	7	1024

4. Fit procedure

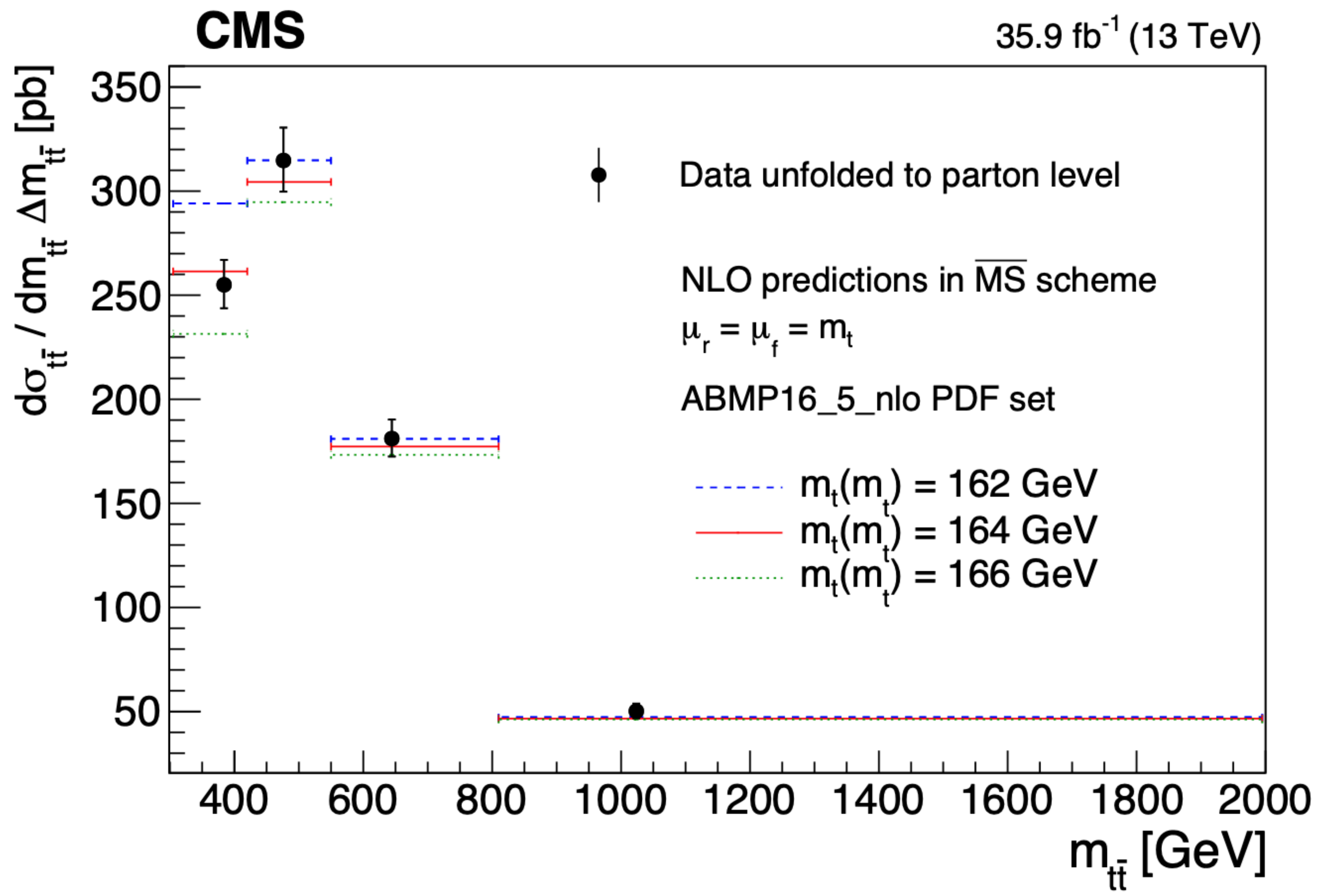
- $d\sigma_{t\bar{t}}/dm_{t\bar{t}}$ determined directly **at parton level with a maximum-likelihood fit** to distributions of final-states observables:
  - **Unfolding implicit** in the likelihood fit: *$t\bar{t}$ simulated sample splitted into $m_{t\bar{t}}$ bins, treated as independent signals and interpreted as $t\bar{t}$ cross-section at the physical scale μ_k.*
  - **Syst. unc.** treated as **nuisance parameters** → constrained with soft jet p_T and **b-jet categorization**
  - m_t^{MC} is a floating parameter → **fitted from m_{lb}** distribution



Illustrative figures of data and post-fit MCs for $m_{t\bar{t}}^{reco} \in \{420{,}550\}\ GeV$

5. Results (I): extraction of the top $\overline{MS}$ quark mass

- Value of $m_t(m_t)$ is determined independently in each bin from $\chi 2$ fit to NLO QCD calculation.
- It is evolved from $m_t(m_t)$ to $m_t(\mu_k)$ with RGE at one-loop precision ($n_f = 5$, $\alpha_s(m_Z) = 0.1191$)



$$\sigma_{t\bar{t}}^{(\mu_1)} = 255 \pm 11\,(\mathrm{syst}) \pm 2\,(\mathrm{stat})\,\mathrm{pb},$$
$$\sigma_{t\bar{t}}^{(\mu_2)} = 315 \pm 15\,(\mathrm{syst}) \pm 2\,(\mathrm{stat})\,\mathrm{pb},$$
$$\sigma_{t\bar{t}}^{(\mu_3)} = 181 \pm 9\,(\mathrm{syst}) \pm 1\,(\mathrm{stat})\,\mathrm{pb},$$
$$\sigma_{t\bar{t}}^{(\mu_4)} = 50 \pm 3\,(\mathrm{syst}) \pm 1\,(\mathrm{stat})\,\mathrm{pb}.$$

→

$$m_t(\mu_1) = 155.4 \pm 0.8\,(\mathrm{fit}) \pm 0.2\,(\mathrm{PDF}+\alpha_S) \pm 0.1\,(\mathrm{extr})\,^{+0.9}_{-0.6}\,(\mathrm{scale}),$$
$$m_t(\mu_2) = 150.9 \pm 3.0\,(\mathrm{fit})\,^{+1.1}_{-0.7}\,(\mathrm{PDF}+\alpha_S)\,^{+0.4}_{-0.5}\,(\mathrm{extr})\,^{+3.9}_{-4.3}\,(\mathrm{scale}),$$
$$m_t(\mu_3) = 148.2 \pm 4.6\,(\mathrm{fit})\,^{+2.0}_{-1.4}\,(\mathrm{PDF}+\alpha_S)\,^{+0.9}_{-1.0}\,(\mathrm{extr})\,^{+7.3}_{-9.5}\,(\mathrm{scale}),$$
$$m_t(\mu_4) = 136.4 \pm 9.0\,(\mathrm{fit})\,^{+3.8}_{-3.0}\,(\mathrm{PDF}+\alpha_S)\,^{+2.8}_{-2.3}\,(\mathrm{extr})\,^{+9.6}_{-16.1}\,(\mathrm{scale}).$$

5. Results (II): testing the top quark mass running

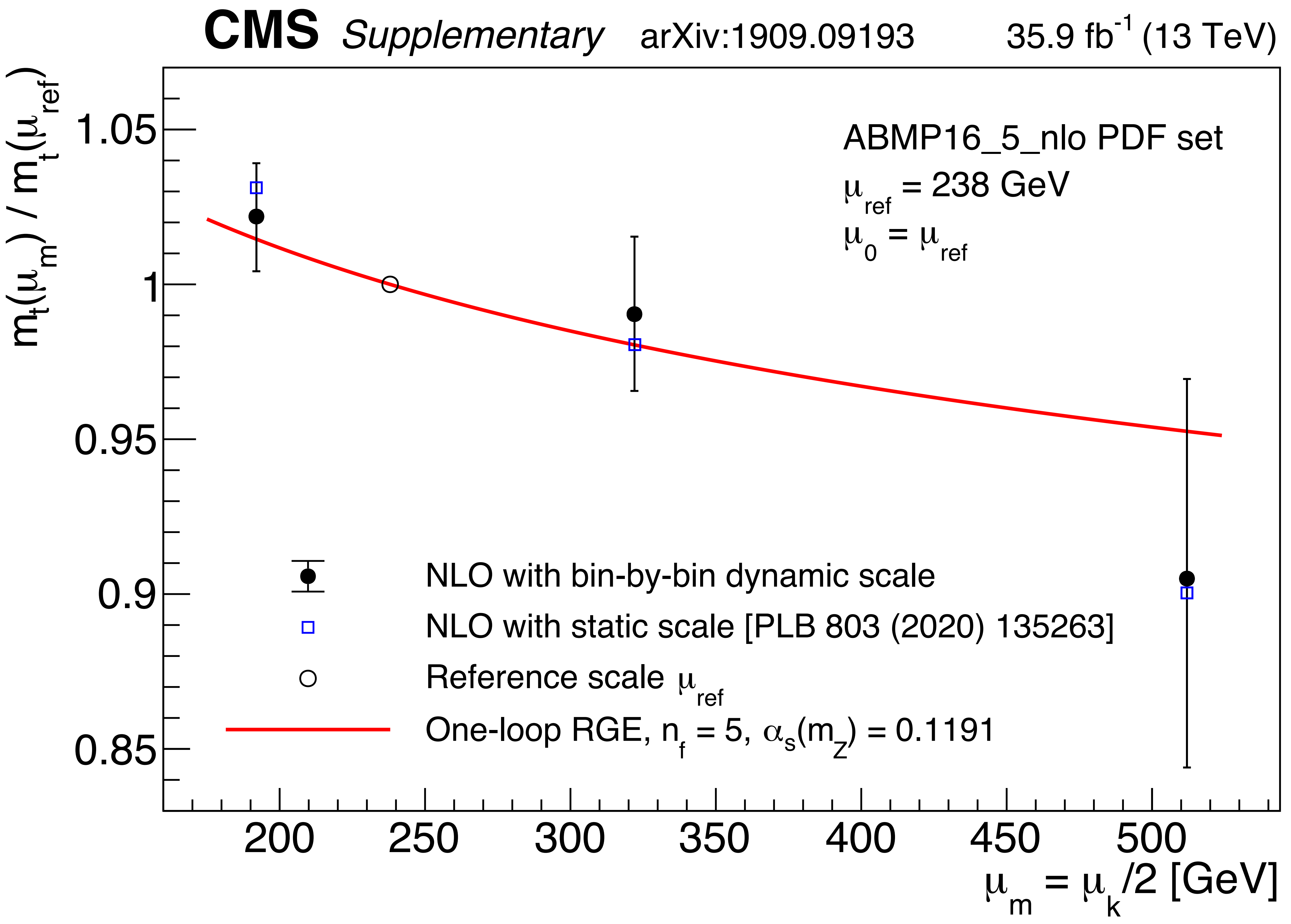
- Finally, the **ratios $r_{ij} = m_t(\mu_i)/m_t(\mu_j)$ are considered**

- Taking $\mu_j = \mu_{ref} = \mu_2/2 = 238\ GeV$ (final result independent from μ_{ref} choice), the **running is parametrized with x**:

$$f(x, \mu) = x\left[\underbrace{r_{ij} - 1}_{\text{RGE evolution}}\right] + 1 \begin{cases} x = 0 : \textbf{No running} \\ x = 1 : \textbf{SM running} \end{cases}$$

For fixed scale: $\chi 2$

$$\hat{x} = 2.05 \pm 0.61\ (fit)\ ^{+0.31}_{-0.55}\ (PDF + \alpha_S)\ ^{+0.24}_{-0.49}\ (extr)$$



Results obtained with dynamic (filled circles) and static (empty squares) scales in the theory calculation.

Summary

- *“Towards a precise interpretation of the top quark mass parameter in the ATLAS MC samples”*

$$m_t^{MC(P8)} = m_{top}^{MSR}(1\ GeV) + 80^{+350}_{-410}\ MeV$$

_Theory error dominates. Significant improvement expected with NNLL calculation

_Compatible with m_t^{MC} calibration in $e^+e^- \rightarrow t\bar{t}$ events (arXiv:1608.01318)

_Enables direct top mass measurement in boosted tops with cleaner interpretation

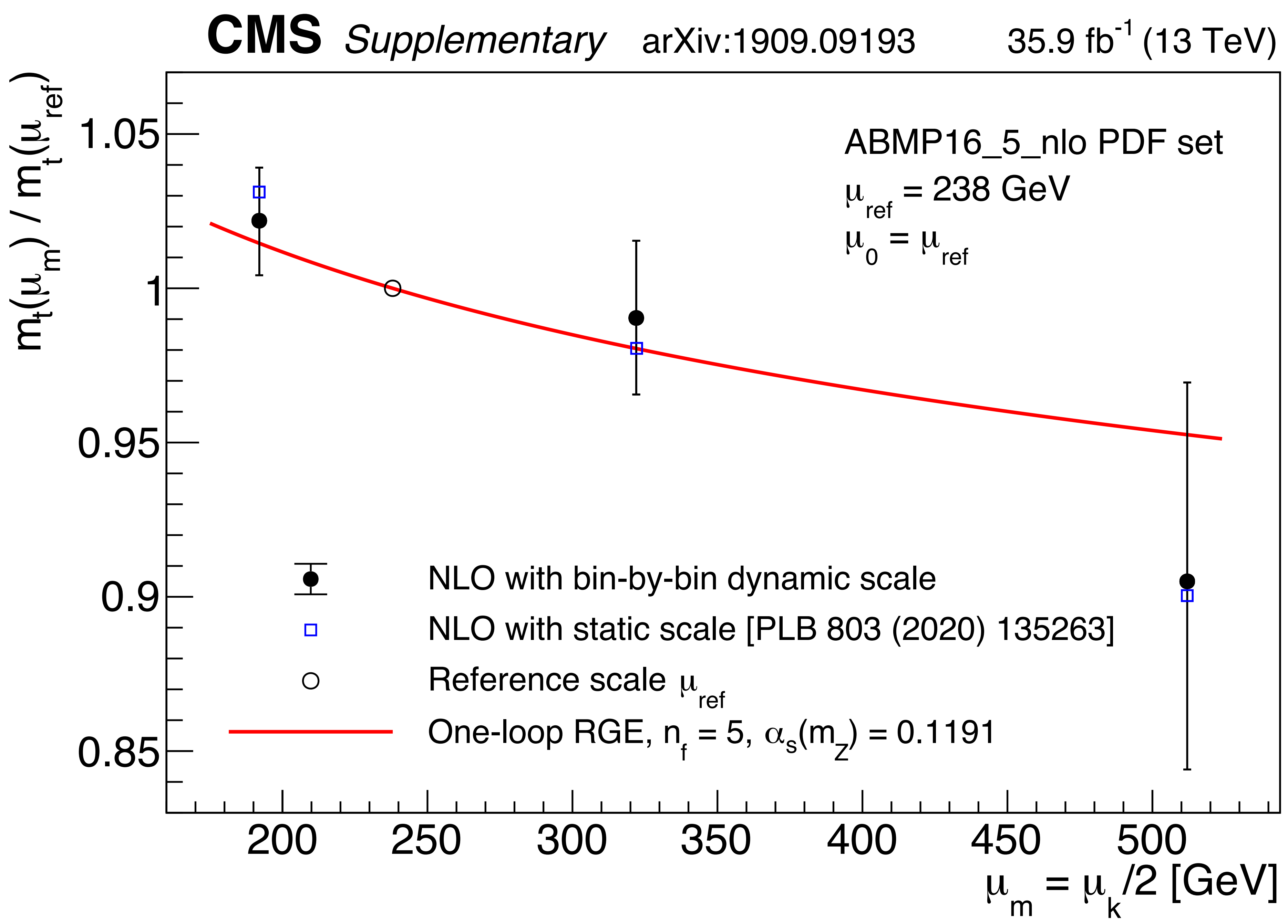
Summary

- "Running of the top quark mass from proton-proton collisions at $\sqrt{s} = 13\ TeV$"

_Top $\overline{MS}$ mass extracted from $d\sigma_{t\bar{t}}/dm_{t\bar{t}}$ with NLO QCD calculation

_Top mass running probed up to $\sim 1\ TeV$. In agreement with RGE SM within 1.1σ

_ No-running scenario ruled out at above $\% 95\ CL$

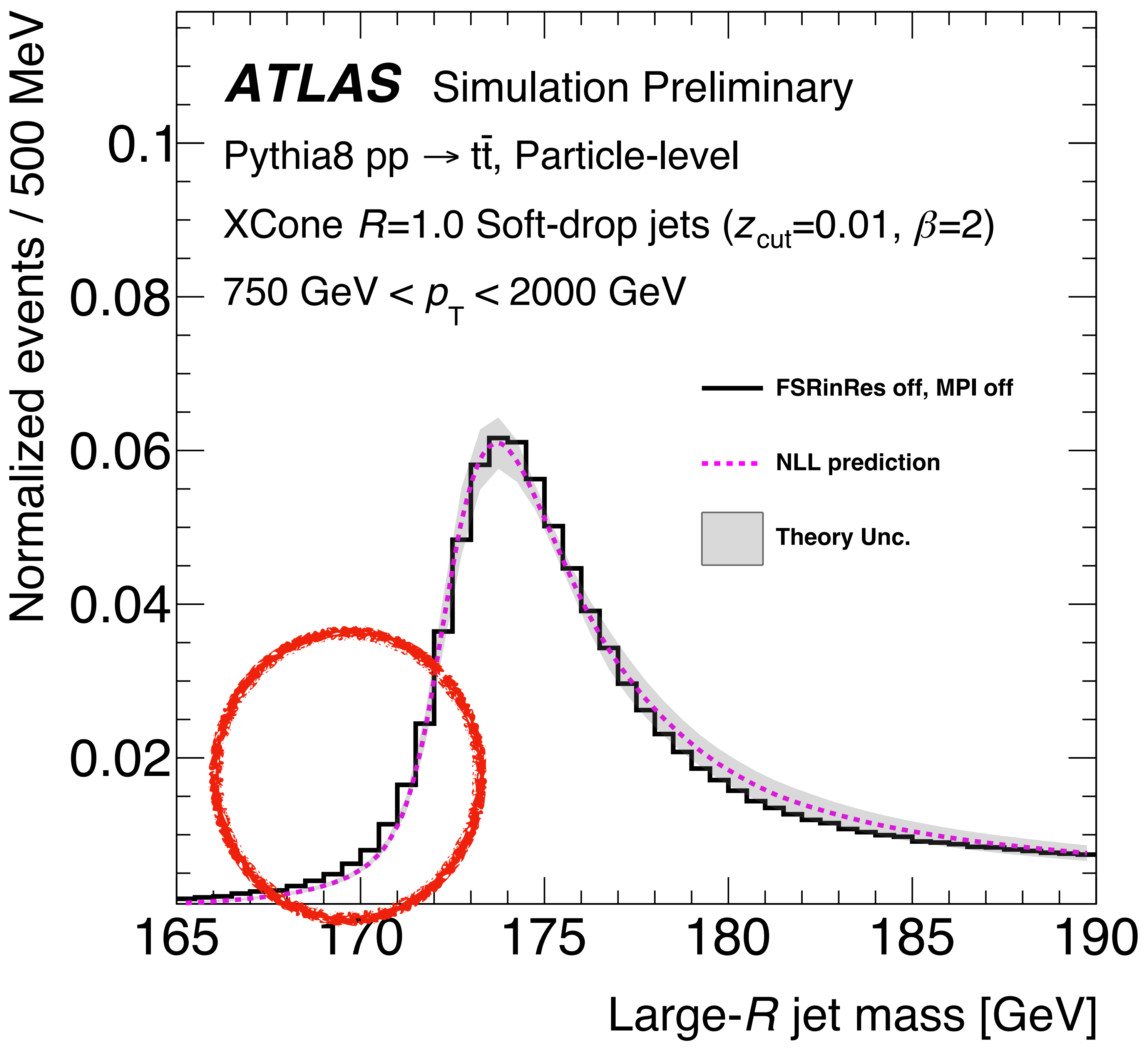


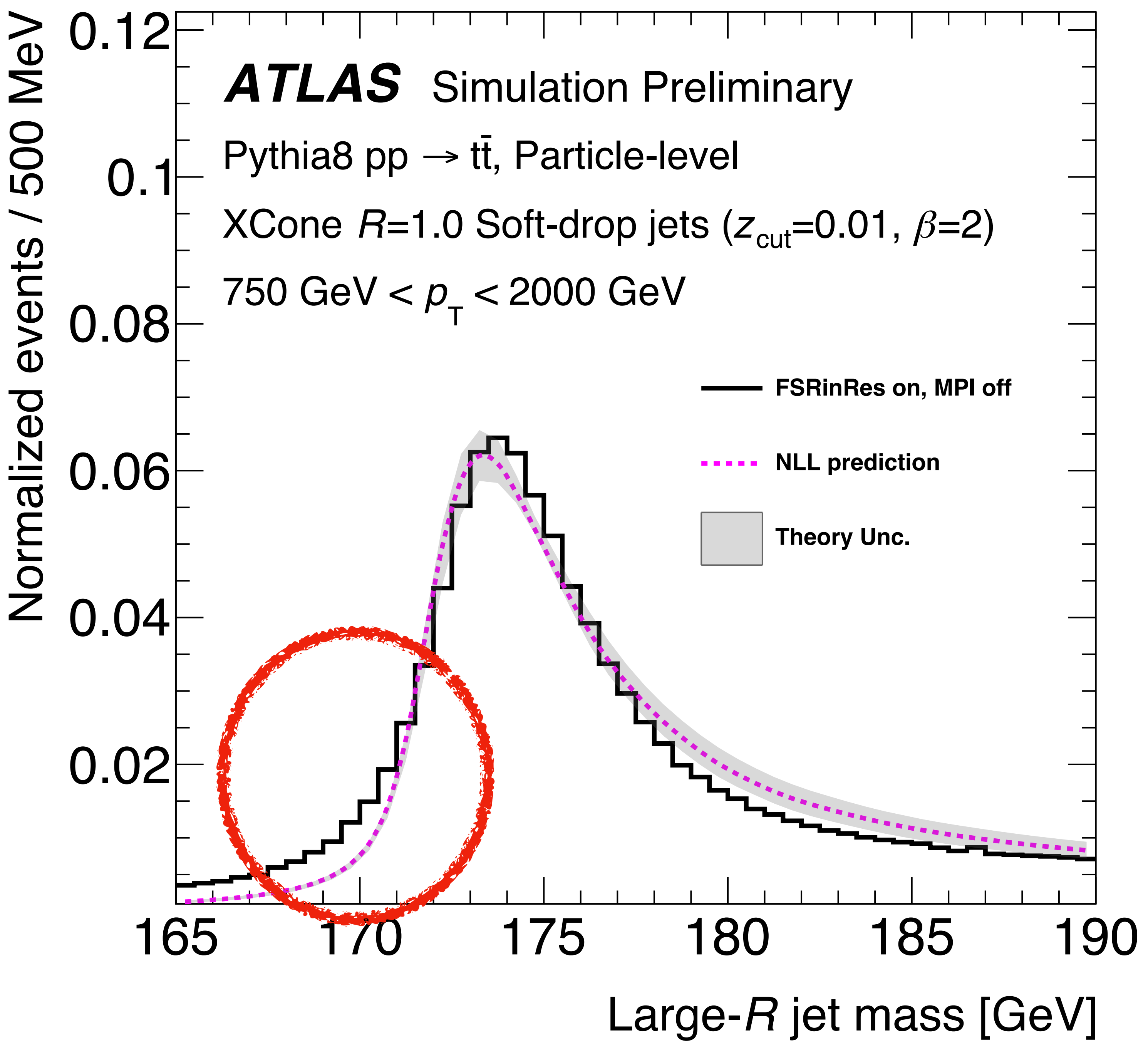
Thanks for your attention!

BACK-UP

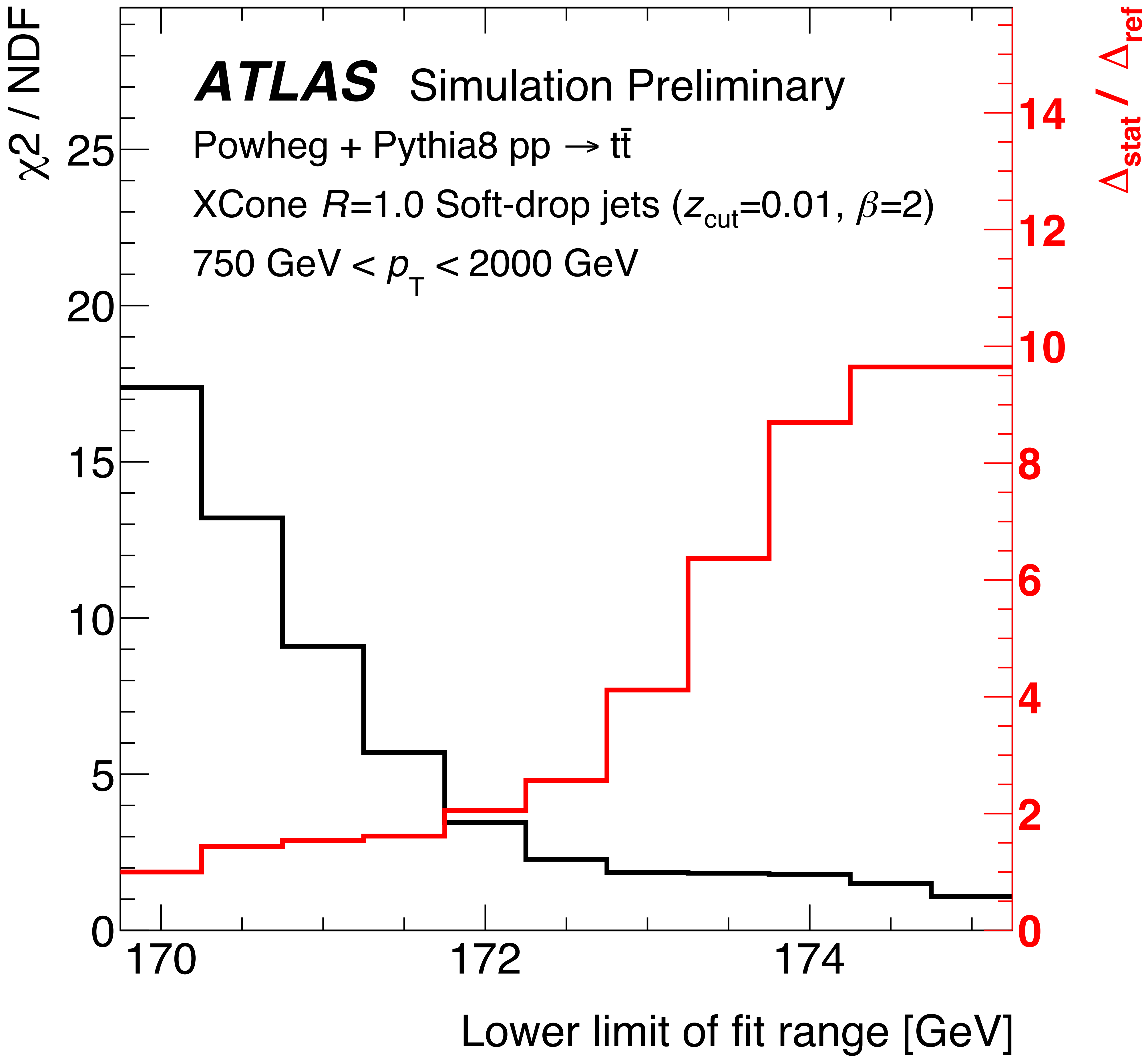
Theory validity

- Theory gives a inclusive treatment of the top decay products
- In some MC events, FSR of decay products are groomed away (FSRinRes setting), lifting up the left tail of the jet mass peak
- This can be handled by carefully adjusting the fit range





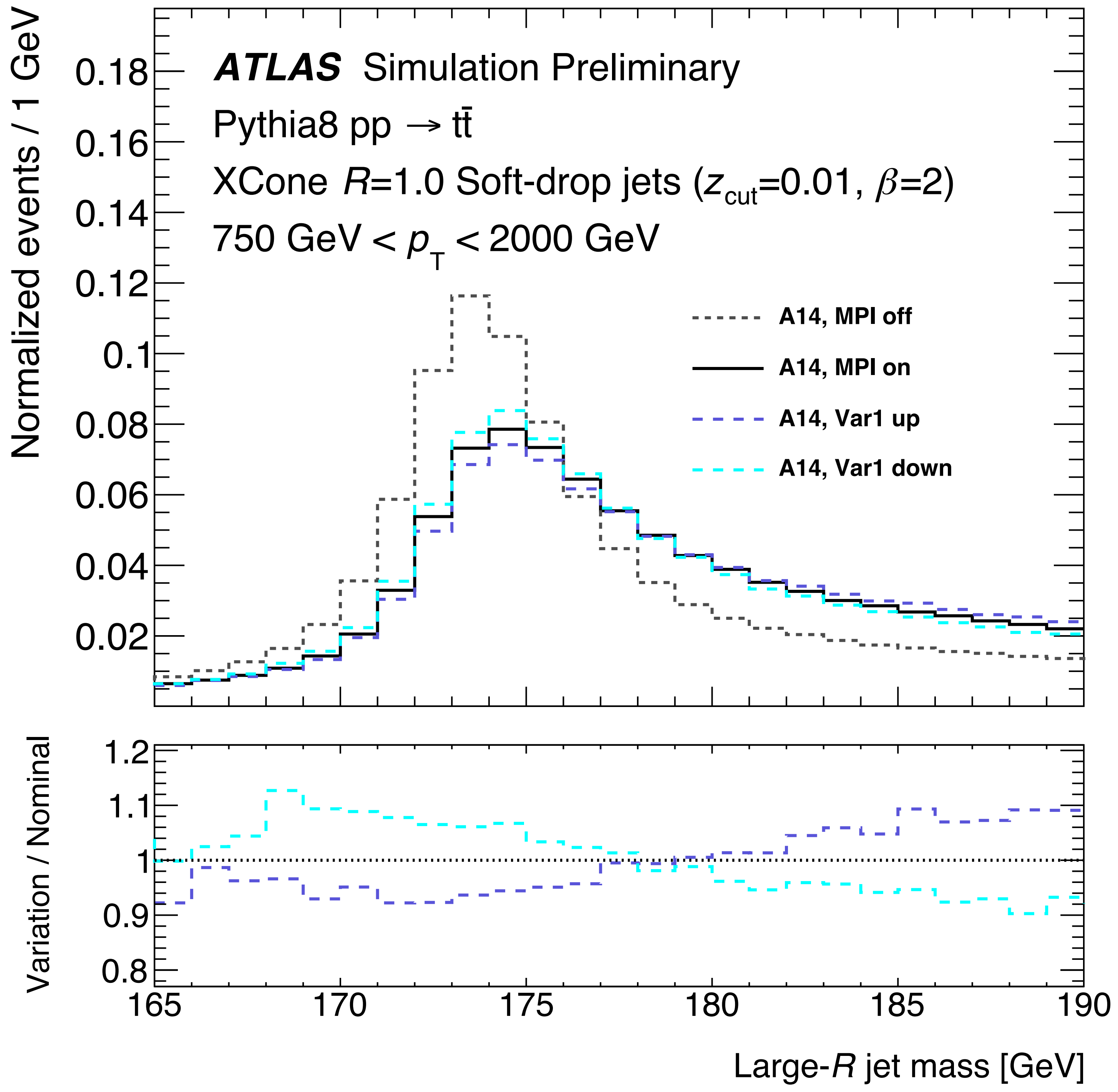
Fit range choice

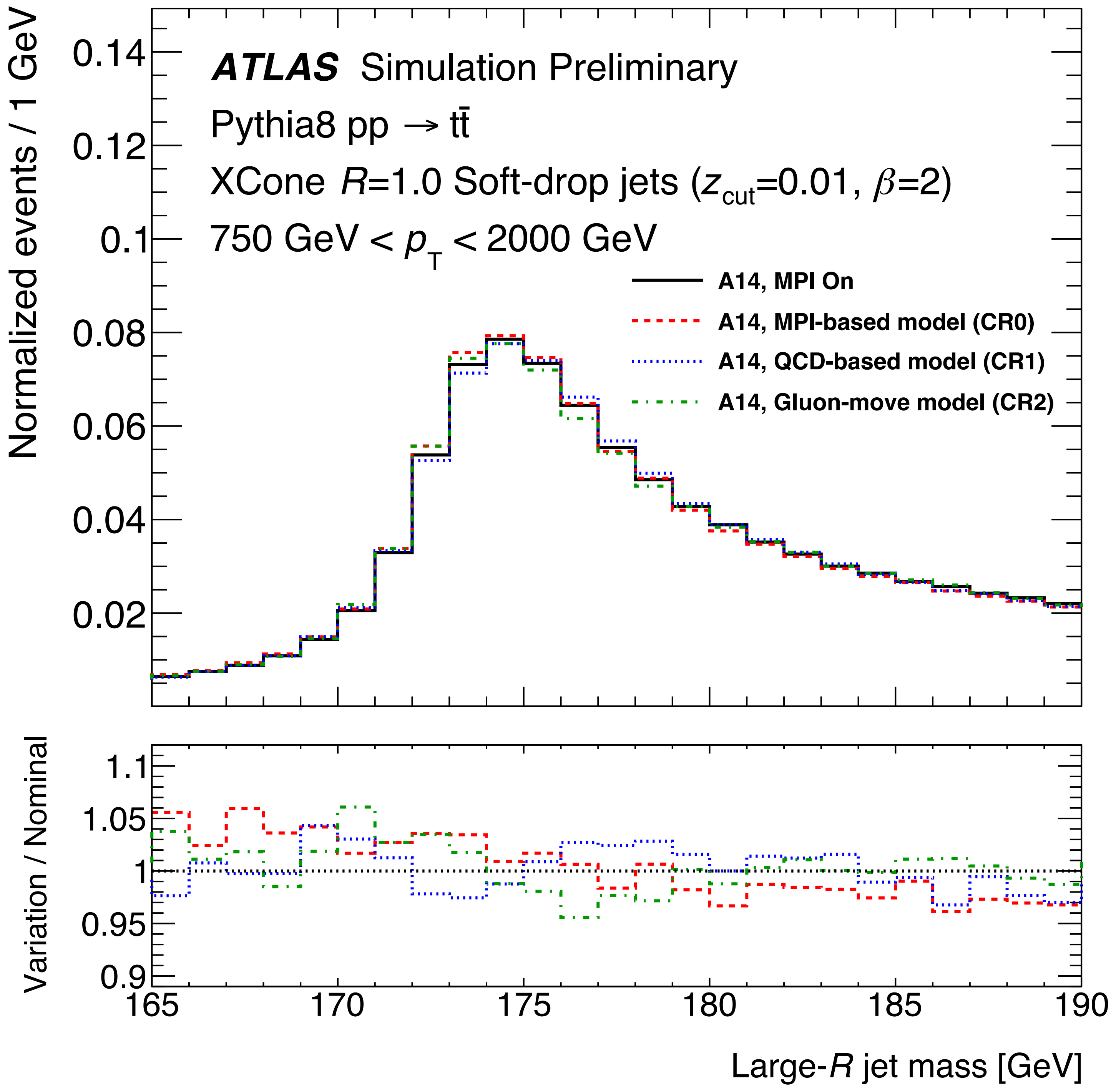


- Fit range set to 172.5 - 180.0 GeV
- Lower limit is identified with the m_{top}^{MC} the events were generated with.
- Fit is repeated with this value varied up and down by half GeV. Difference is registered as part of the methodological uncertainty.
- Variations of the upper limit have negligible impact on the fit result

Underlaying Event treatment

- Since theory cannot describe properly UE effects, another approach must be followed
- Var1 eigentune variations of A14 tune (devoted to provide coverage of UE modelling uncertainties) are considered along with alternative CR models
- MC-based templates used to estimate the shift in terms of the m_{top}^{MC} in the nominal MC sample due to such alternative samples





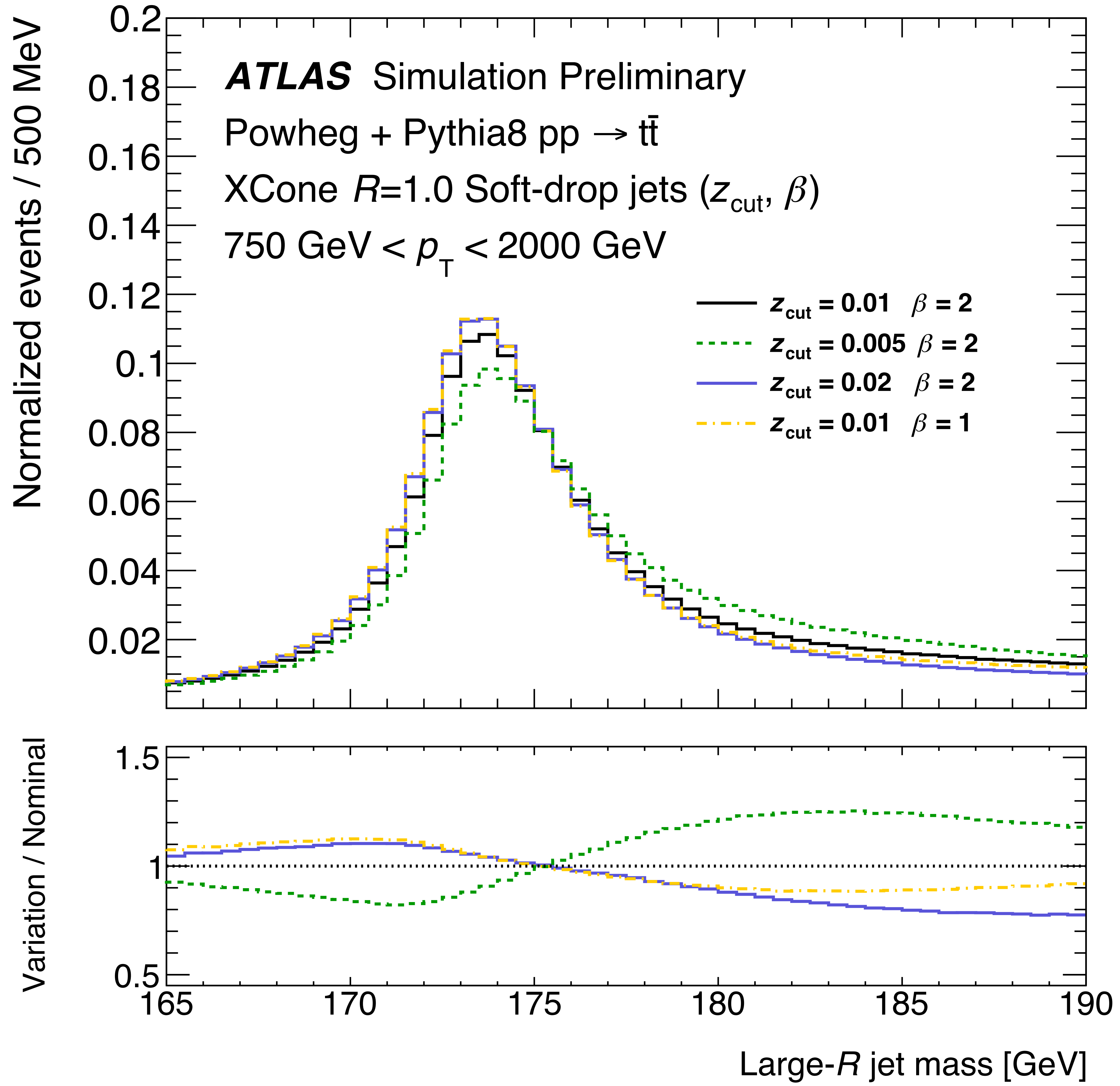
Stability

- The MSR-MC mass relations obtained could be applied to direct measurements in order to correct for universal effects (those independent from observables, kinematic regime, selection…)

- Stability of the *MC calibration* is studied for a number of related observables accesible with the first-principles calculation used

  Aspects of the jet reconstruction and grooming technique are varied

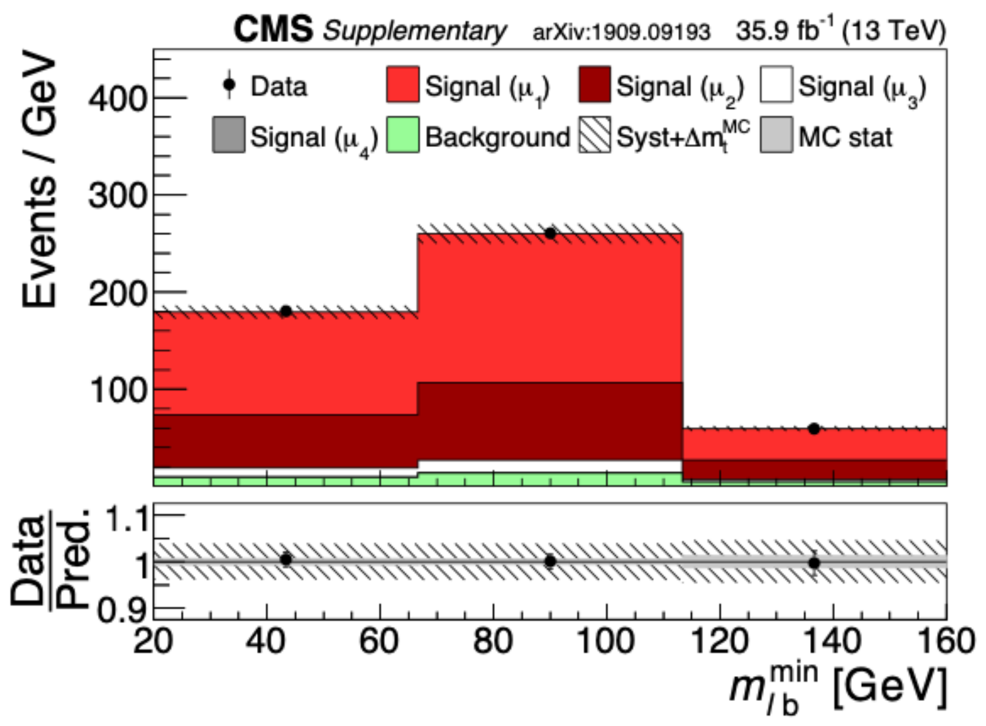
- **The relation is found to be stable within 200 MeV,** within the restrictions of the underlaying theoretical framework

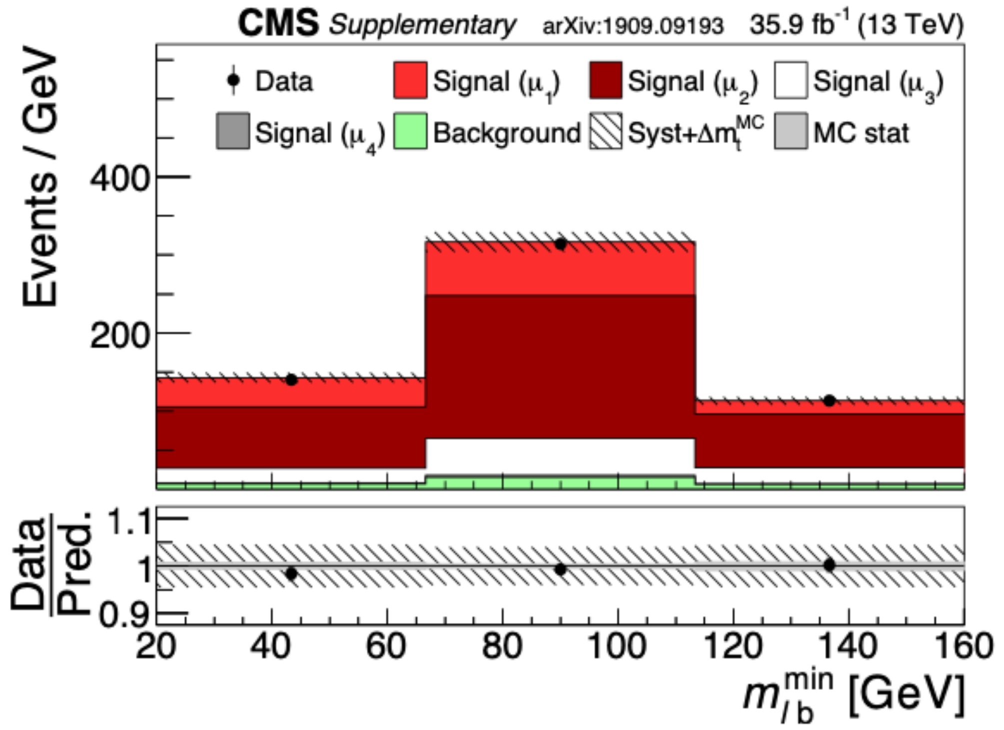


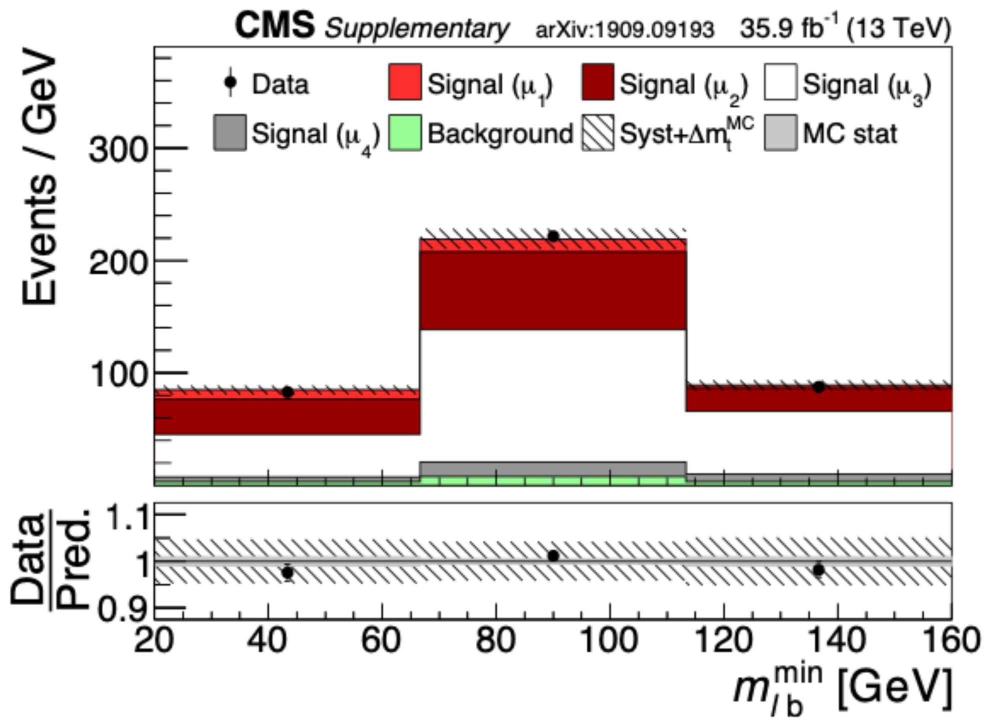
Post-fit distributions of final-state observables

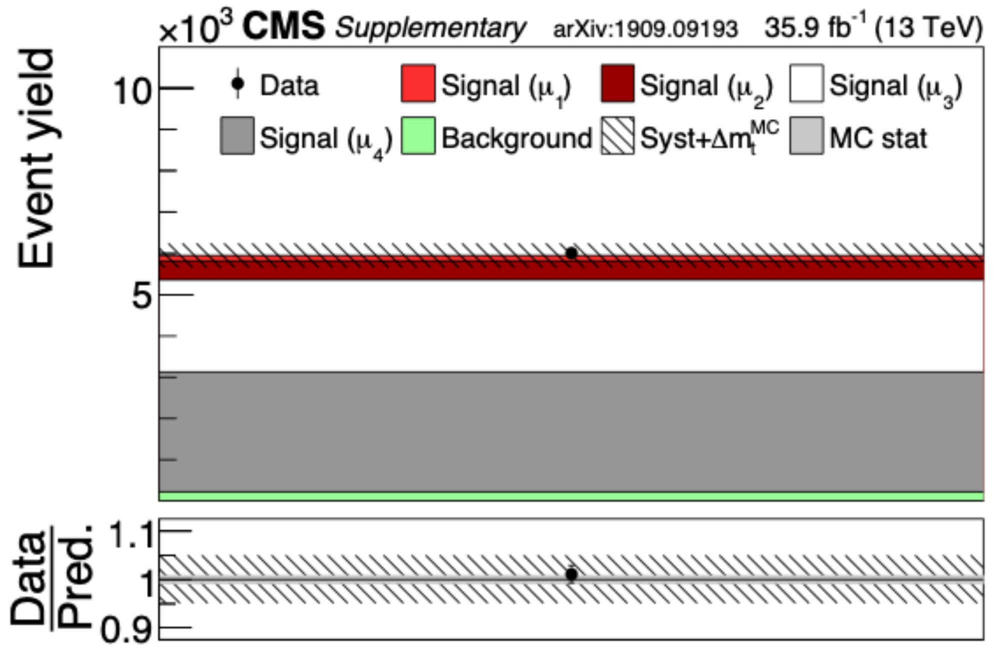
$m_{t\bar{t}}^{reco} \in$ {0,420] GeV {420,550] GeV {550,810] GeV {810,∞] GeV

$N_{bjet} = 1$

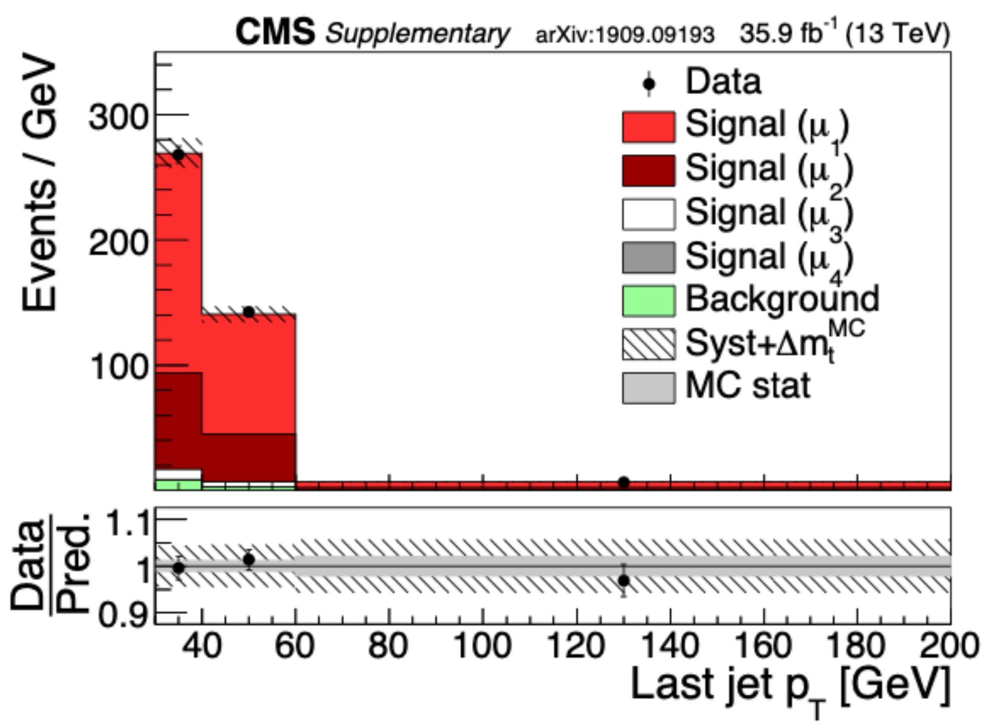


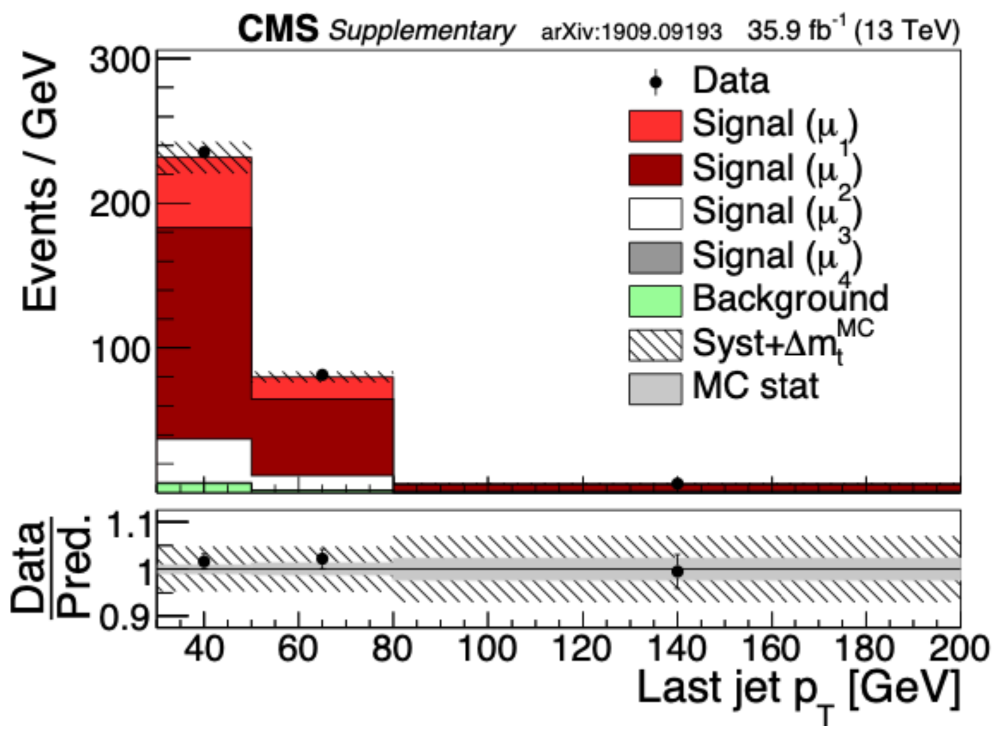


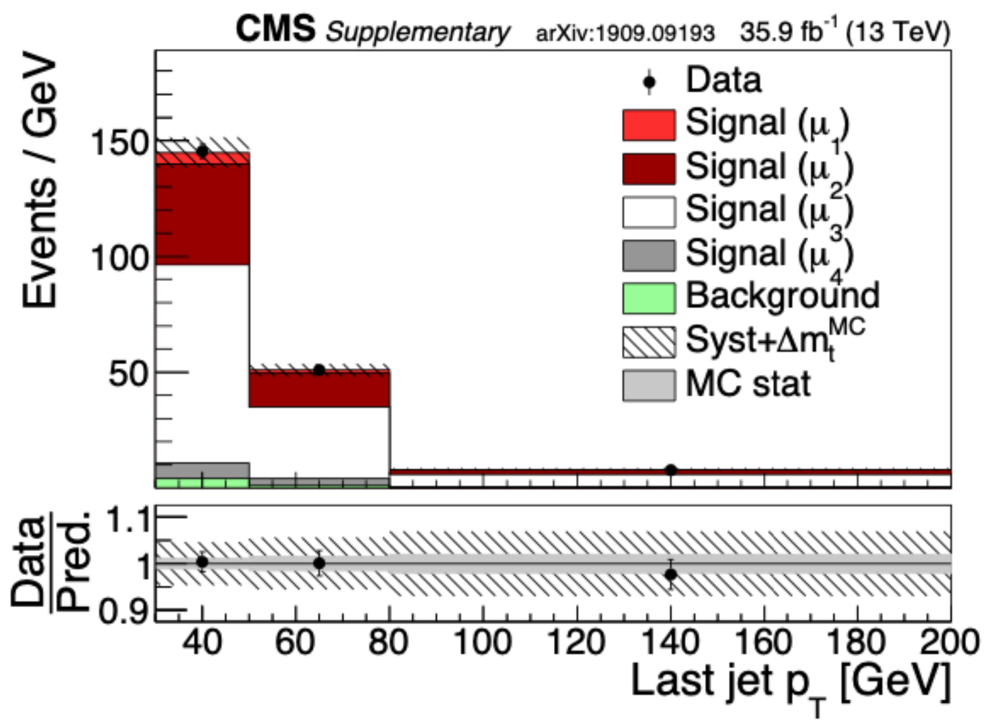


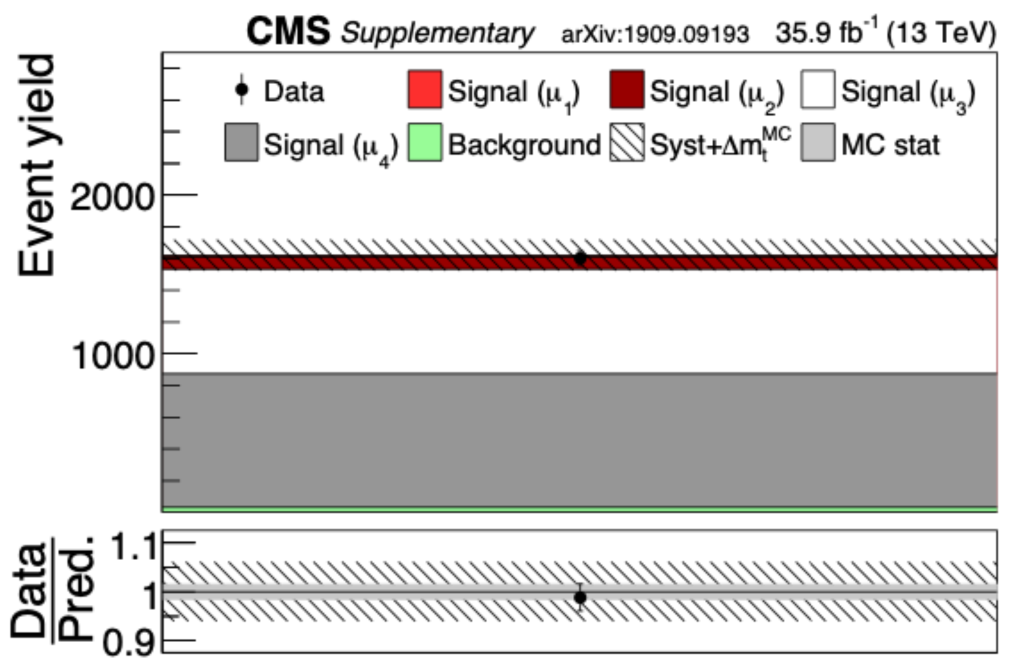


$N_{bjet} = 2$





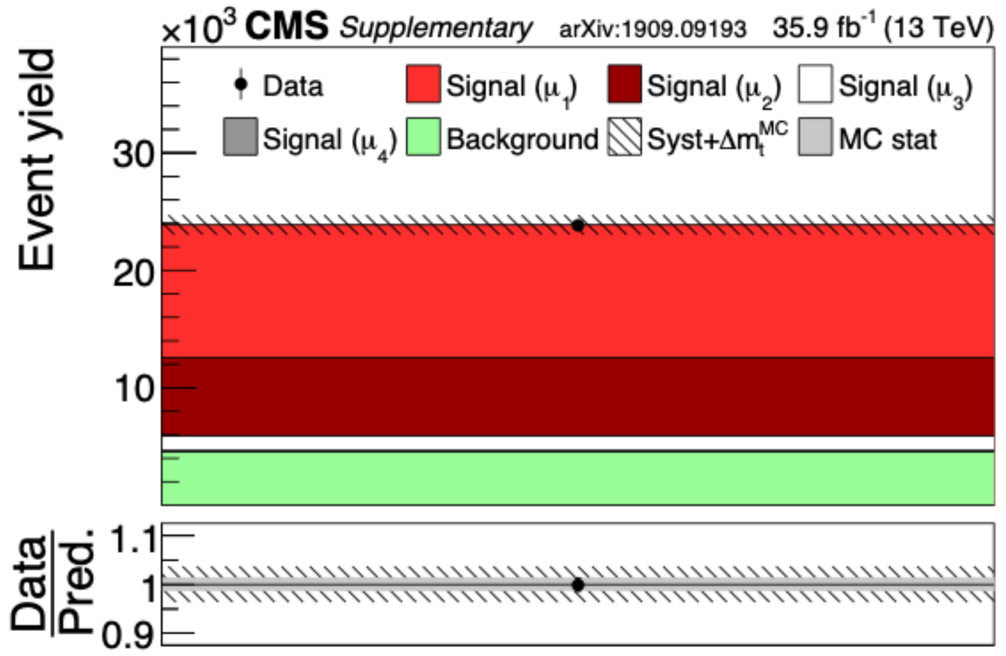


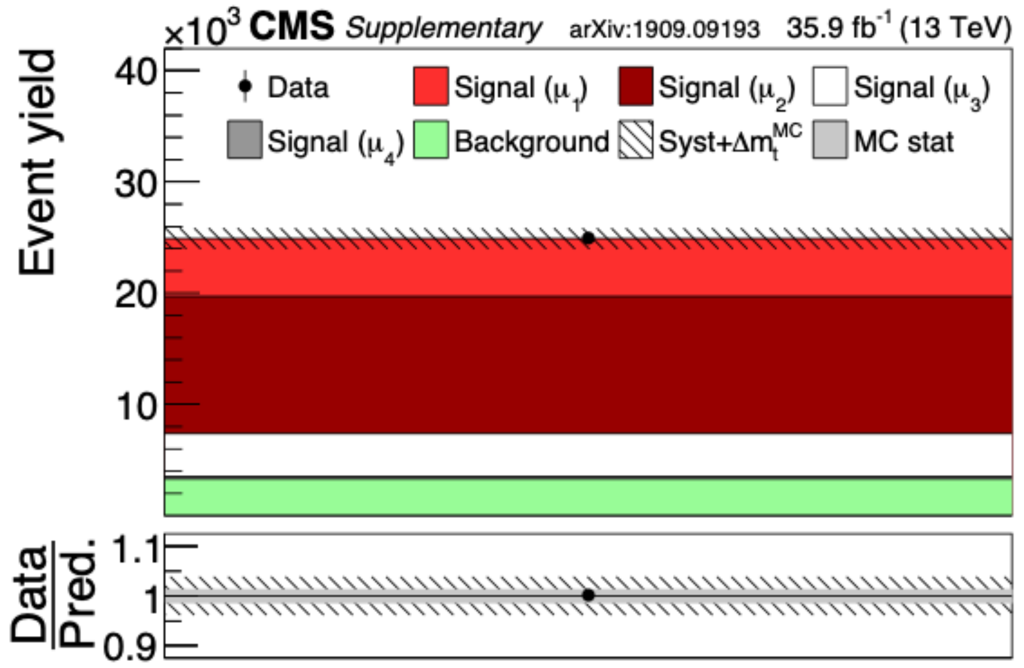


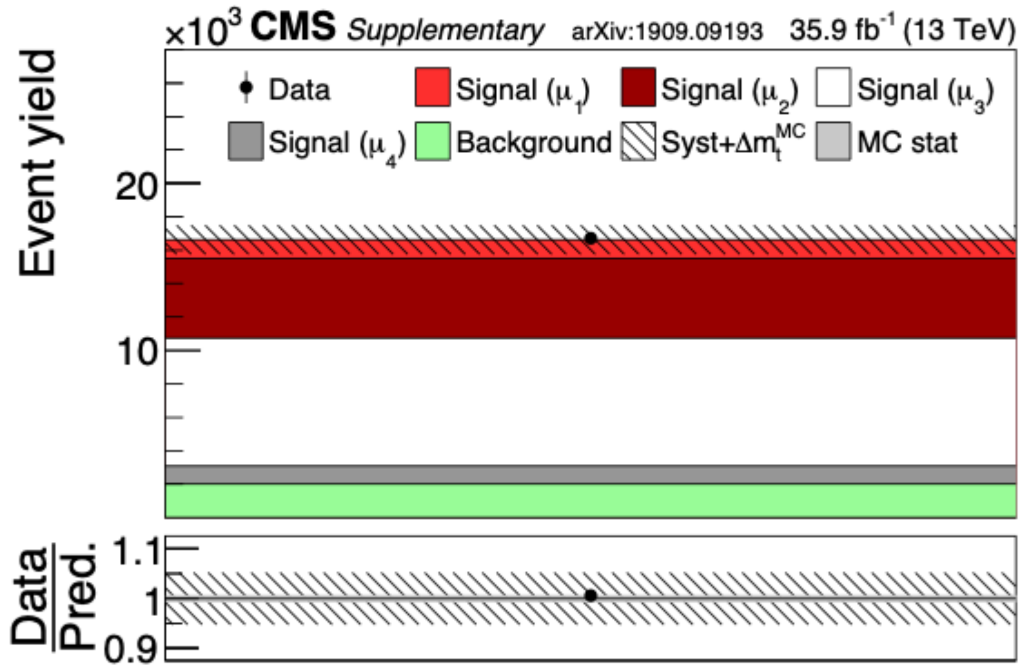
Post-fit distributions of final-state observables

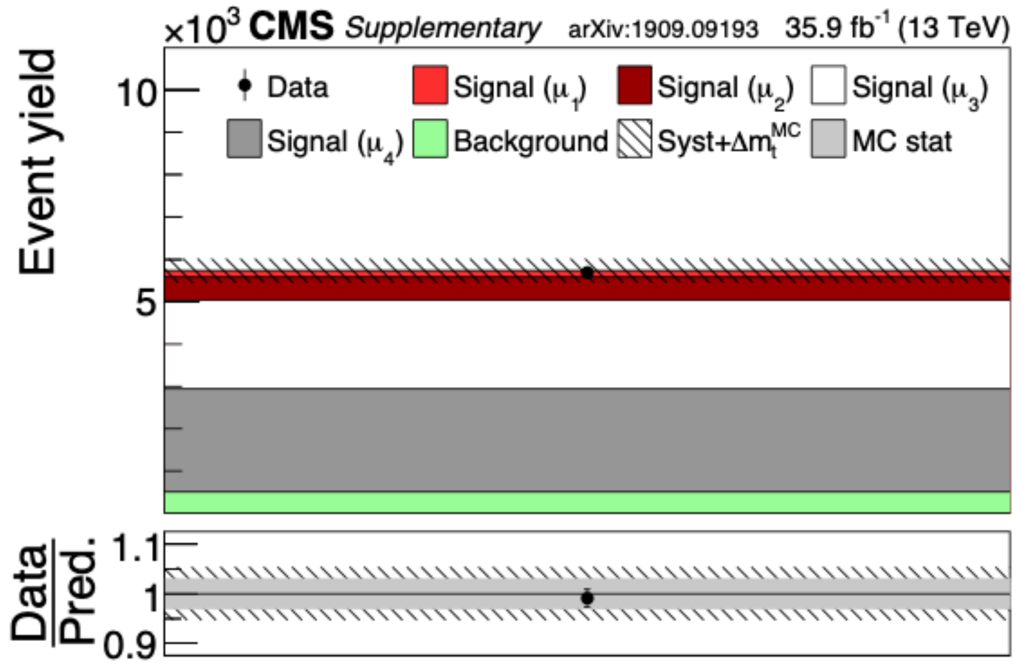
$m_{t\bar{t}}^{reco} \in$ $\{0,420]$ GeV $\{420,550]$ GeV $\{550,810]$ GeV $\{810,\infty]$ GeV

$N_{bjet} = 0$ & $N_{bjet} > 2$

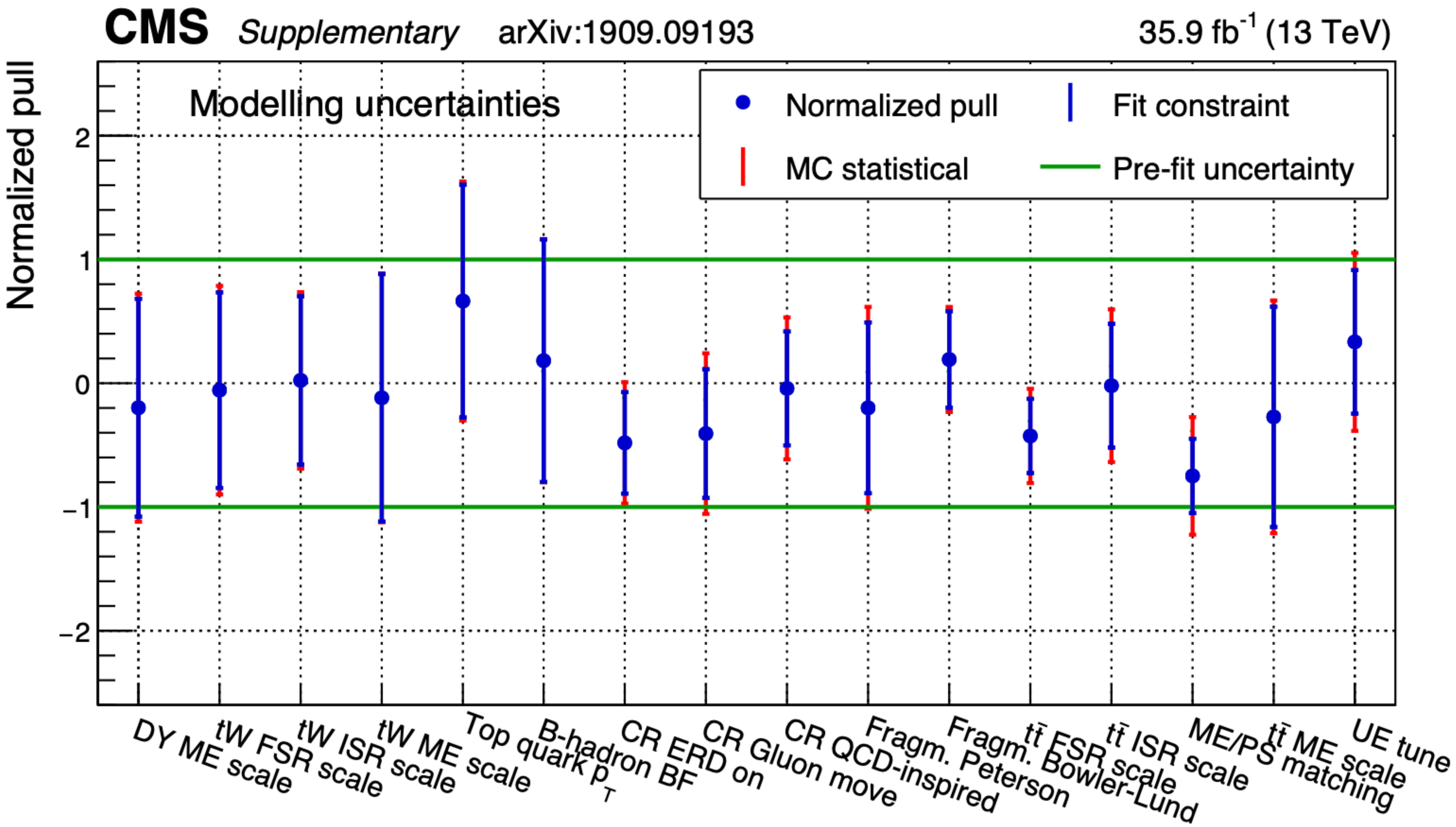








Pulls and constraints of nuisance parameters



Correlations of measured differential cross-section

$$\sigma_{t\bar{t}}^{(\mu_1)} = 255 \pm 11\,(\text{syst}) \pm 2\,(\text{stat})\,\text{pb},$$
$$\sigma_{t\bar{t}}^{(\mu_2)} = 315 \pm 15\,(\text{syst}) \pm 2\,(\text{stat})\,\text{pb},$$
$$\sigma_{t\bar{t}}^{(\mu_3)} = 181 \pm 9\,(\text{syst}) \pm 1\,(\text{stat})\,\text{pb},$$
$$\sigma_{t\bar{t}}^{(\mu_4)} = 50 \pm 3\,(\text{syst}) \pm 1\,(\text{stat})\,\text{pb}.$$

	$\sigma_{t\bar{t}}^{(\mu_1)}$	$\sigma_{t\bar{t}}^{(\mu_2)}$	$\sigma_{t\bar{t}}^{(\mu_3)}$	$\sigma_{t\bar{t}}^{(\mu_4)}$
$\sigma_{t\bar{t}}^{(\mu_1)}$	1.00			
$\sigma_{t\bar{t}}^{(\mu_2)}$	0.64	1.00		
$\sigma_{t\bar{t}}^{(\mu_3)}$	0.72	0.60	1.00	
$\sigma_{t\bar{t}}^{(\mu_4)}$	0.32	0.65	0.47	1.00

Inclusive and differential measurements