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

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1. Motivation

- Top quark mass (m_{top}) plays a crucial role in the the Standard Model (SM)

  It's the heaviest particle and hence has the largest coupling to Higgs sector: stability of EW vacuum, internal consistency of SM, connection with BSM physics. The top mass is a free parameter of the SM that must be determined experimentally. Its definition depends on the renormalization scheme used

- It's determined experimentally by performing **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 $\rightarrow m_{top}^{pole,\bar{MS}}$ with O(1) GeV precision

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

  "Theoretical precision and quality of low-energy parton-shower and hadronization dynamics in MC's cannot yet be systematically controlled at a level such MC mass be can proven and identified with a field theoretic mass scheme from first principles"

arXiv.2004.12915

2. Goal

- The main goal of this analysis is

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

$$m_{top}^{MC} = m_{top}^{MSR}(1\ GeV) + \Delta m^{MSR}$$

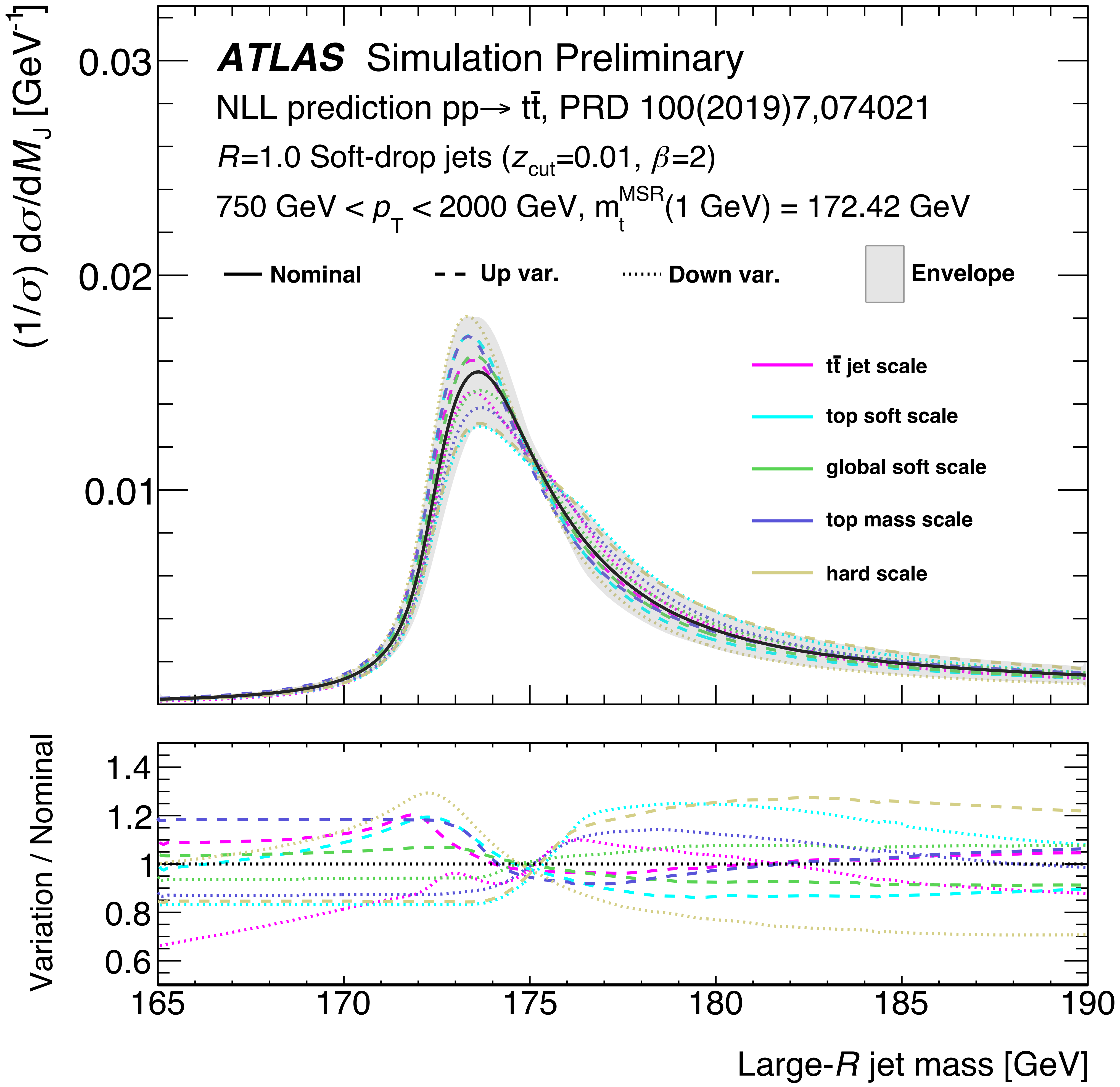
- A *calibration* is performed by comparing ATLAS MC predictions to a NLL calculation for two MC models: Pythia8 (P8) and Herwig7 (H7).
  The m_{top}^{MC} is set to 172.5 GeV.

  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

* *In this scheme, MSR top mass depends on R parameter. It can be understood as an intermediate mass between pole scheme ($R = 0$) and MS scheme ($R = m_{top}$). For $R = 1\ GeV$, it is numerically close to the pole mass.*

3. Theoretical calculation

- 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 $pp \rightarrow t\bar{t}$ events*

  I) XCone jet algorithm with R=1

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

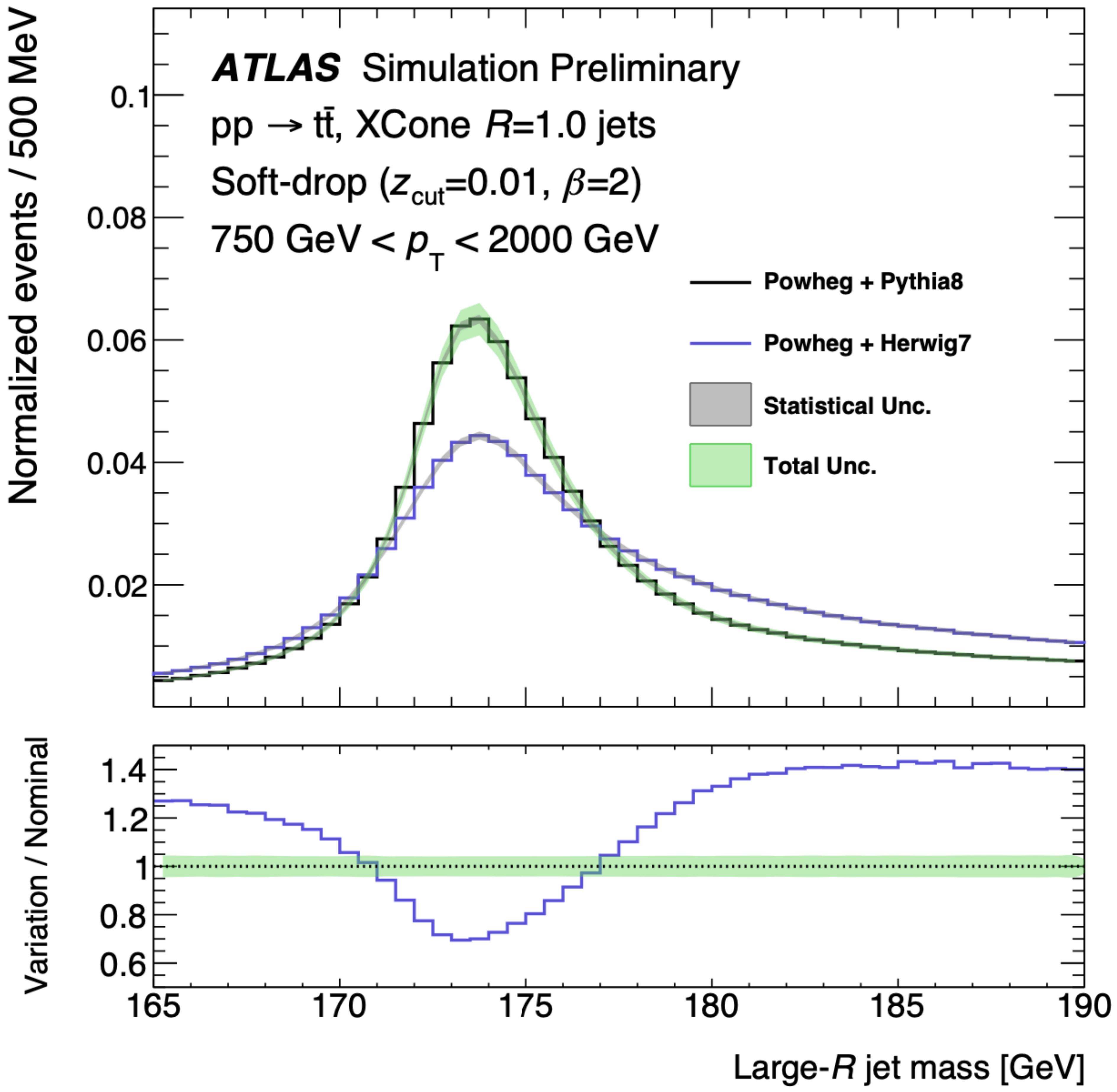
- **Boosted regime**: needed to capture all top decay products in a single jet.

  Three orthogonal p_T *bins considered:*

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

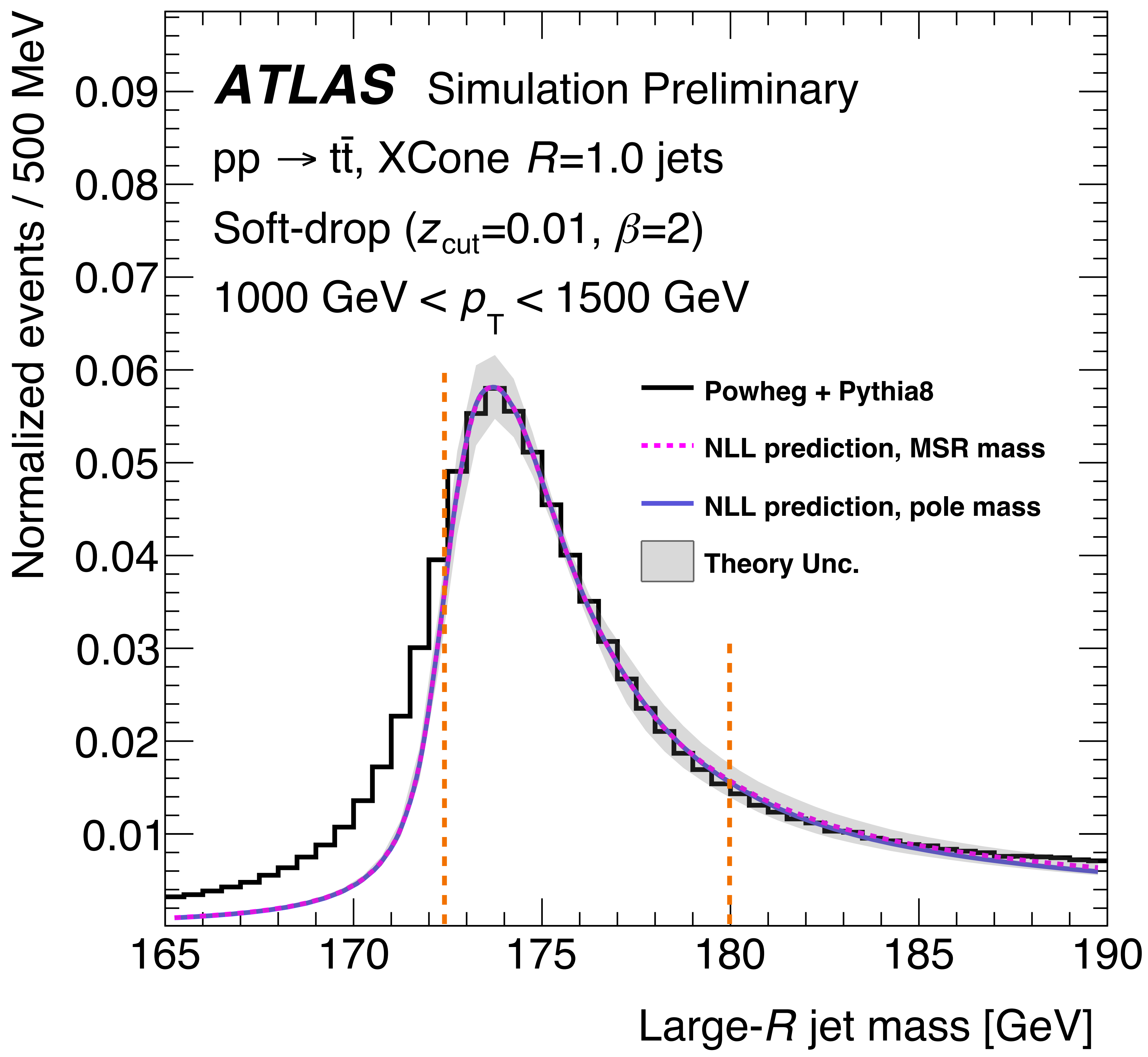
  Three free parameters of theory scale differently with the jet p_T

- 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:

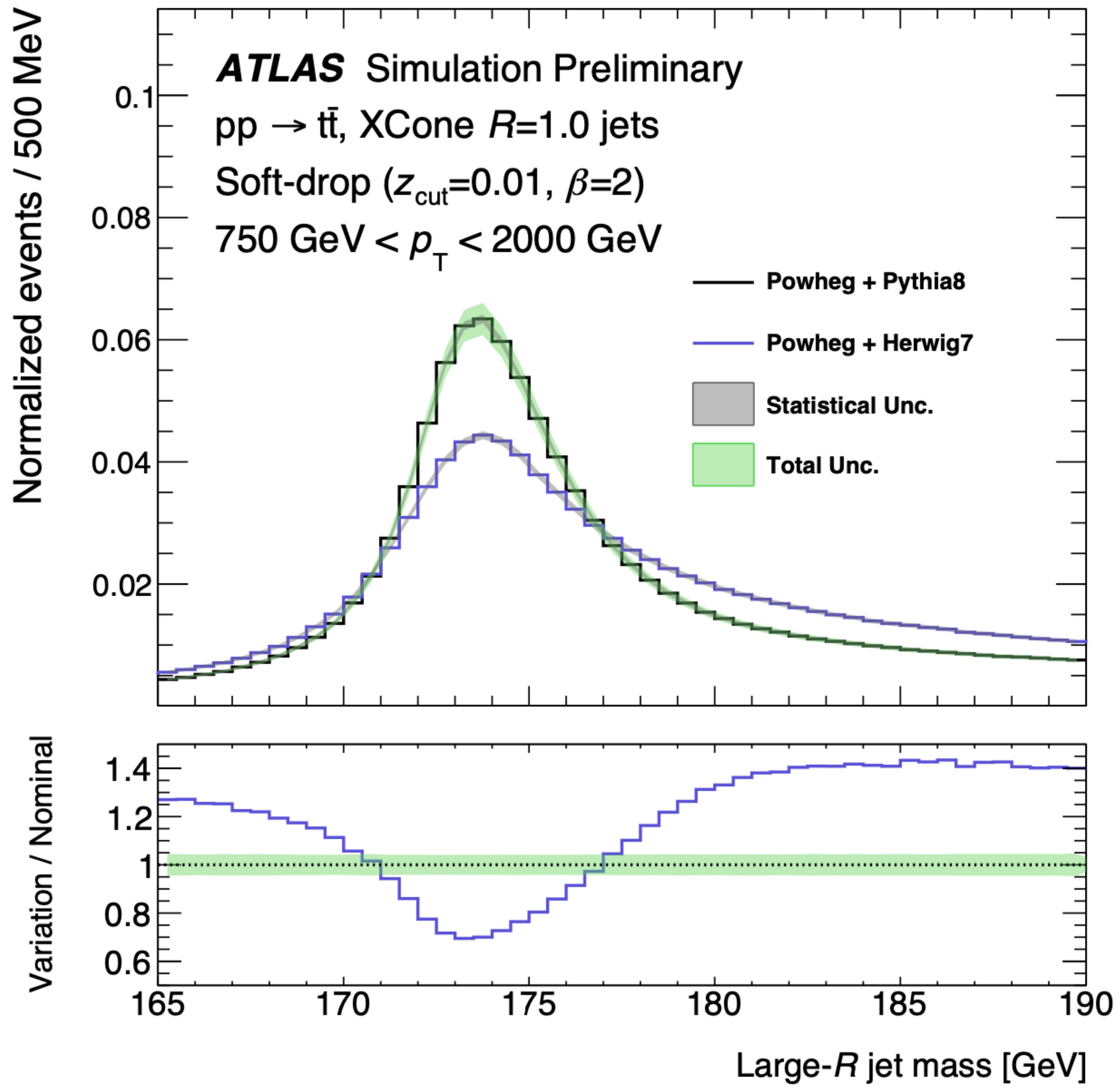
$$m_{top}^{MSR}(1\ GeV) = 172.42 \pm 0.10\ (stat.)\ GeV$$

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

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

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

- The calibration can be performed on any MC sample. We find 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 underlaying theory

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

6. Summary

- m_{top}^{MC} in ATLAS MC samples related to MSR mass at 1 GeV. For Powheg+Pythia8,

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

where missing higher orders in calculation, fit methodology, UE modelling and the limited MC statistics contribute to the total uncertainty. **This relation is found to be stable within 200 MeV** within restrictions imposed by the theory.

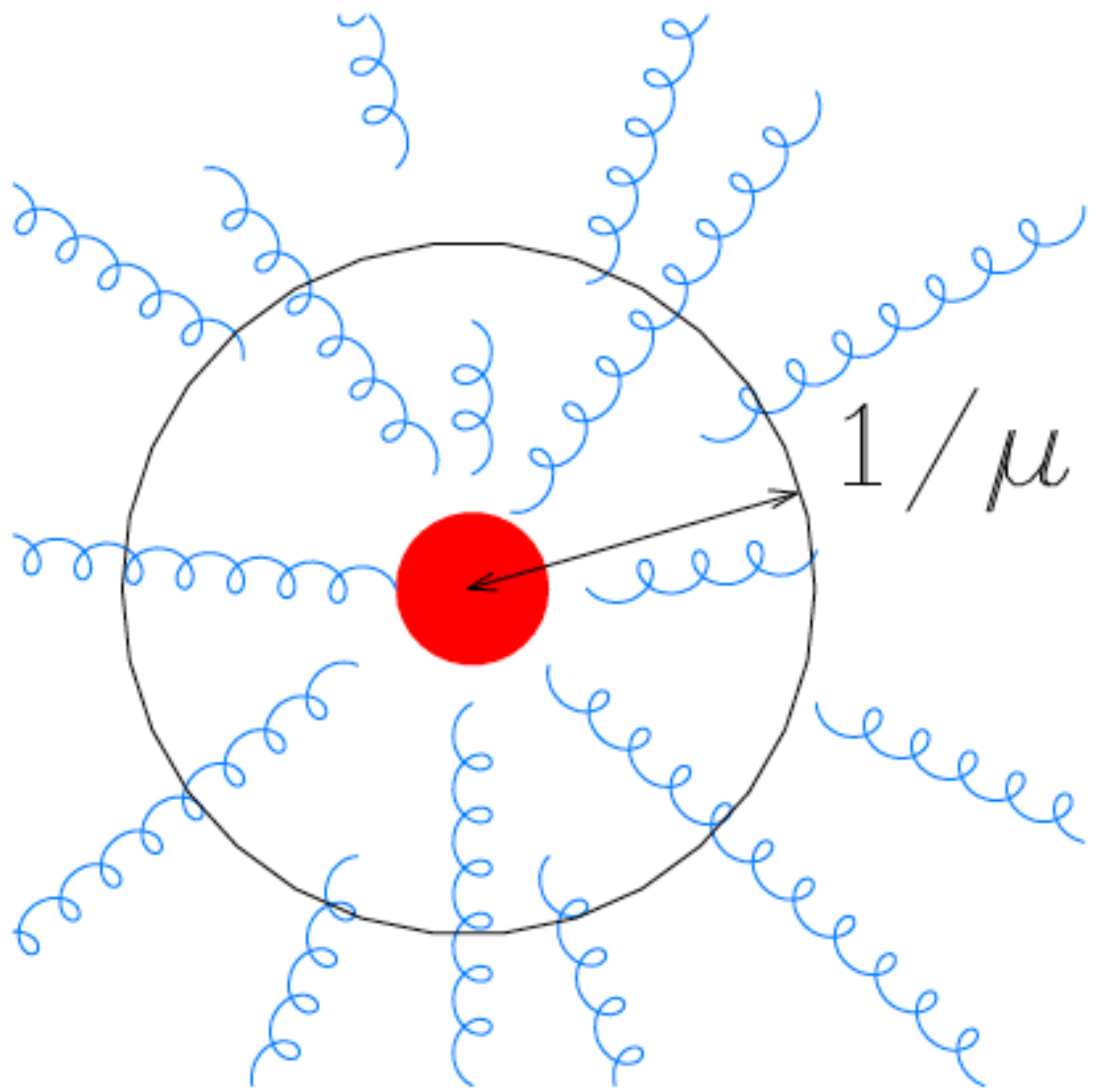
- This result is **compatible with that obtained in e^+e^-collisions**, and **future advances in the formal accuracy** of the theory calculation and in the treatment of non-perturbative corrections may lead to a sizable **reduction of the systematic uncertainties** (arXiv:1608.01318).

- To take advantage of this relation in an optimal way, a direct mass measurement in boosted top quark production (and ideally with the same observable) is required.

Bonus slides

Top quark mass definitions

QCD particles do not rest in peace but actually are permanently interacting. The mass of a heavy particle is also carried by the gluon field that it's accompanying it.



Up to which distance shall we consider the gluon cloud to be part of the top? **Up to infinity**?

(1) This is the pole mass!!

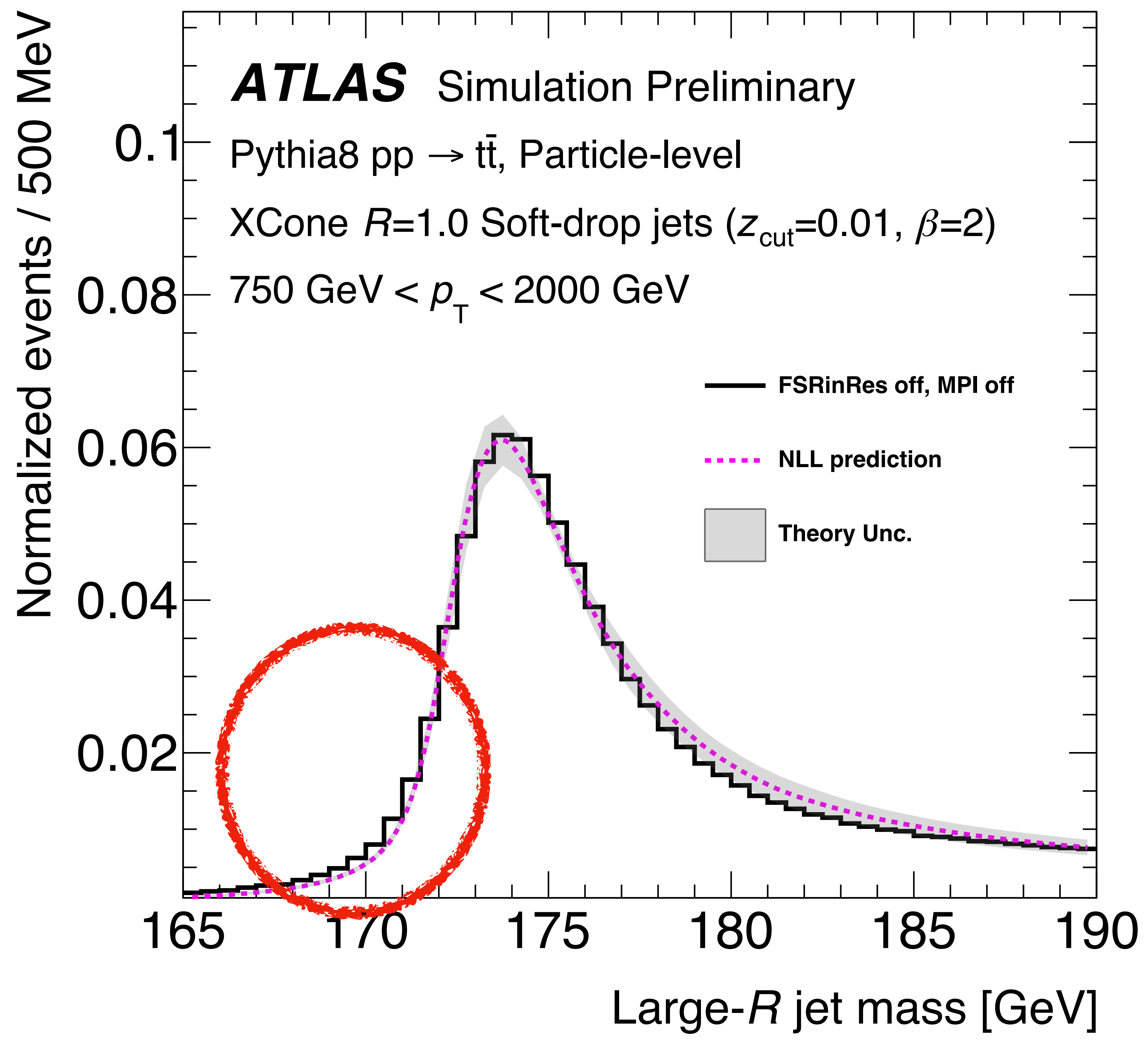
For $\mu < m_{top}$, the proper mass that captures **contributions below** $1/\mu$ is…

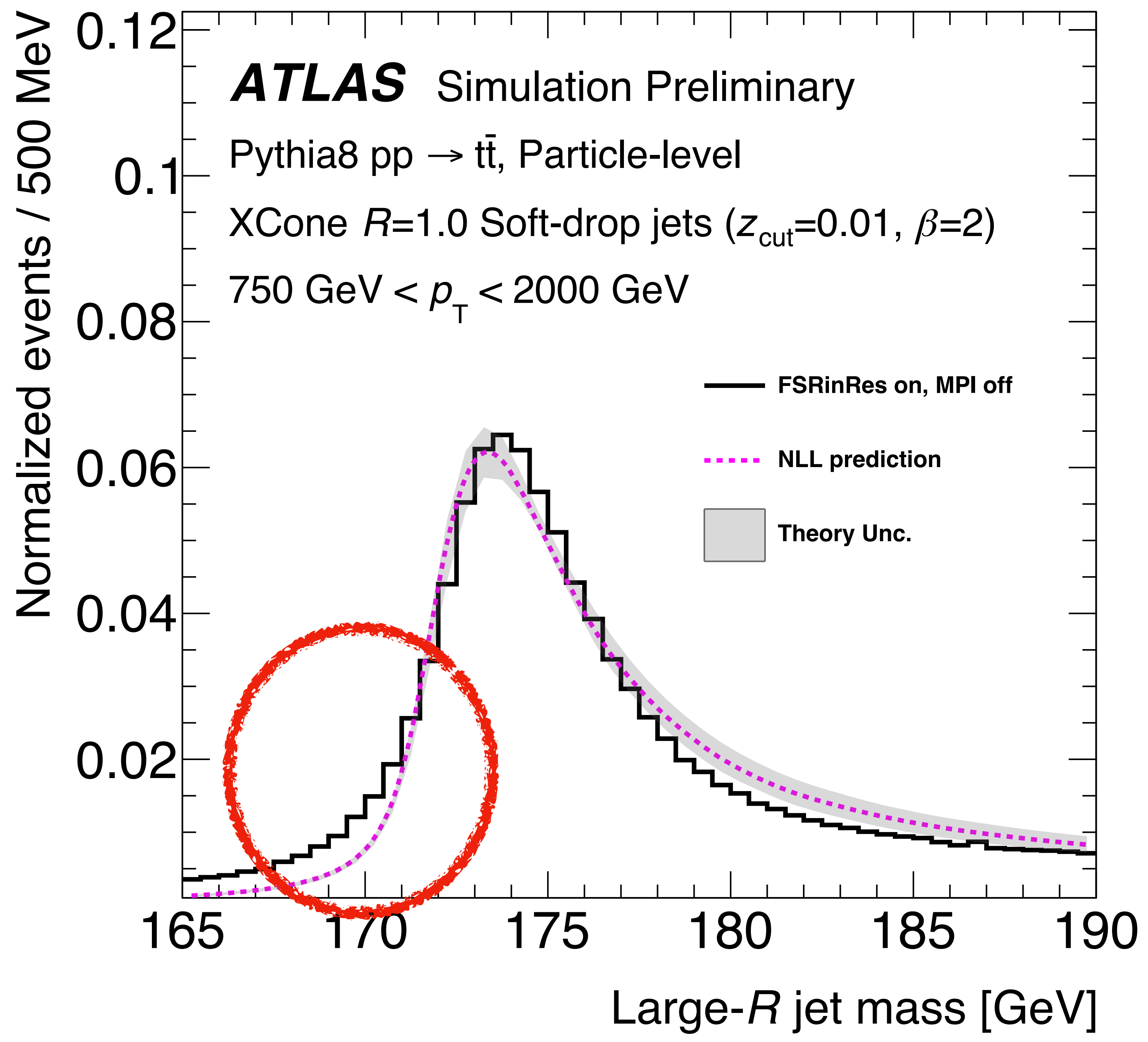
(2) The MSR mass!!

If **(2)** includes radiation effects down to very small scales, **(1)** and **(2)** are roughly the same!

Theory validity

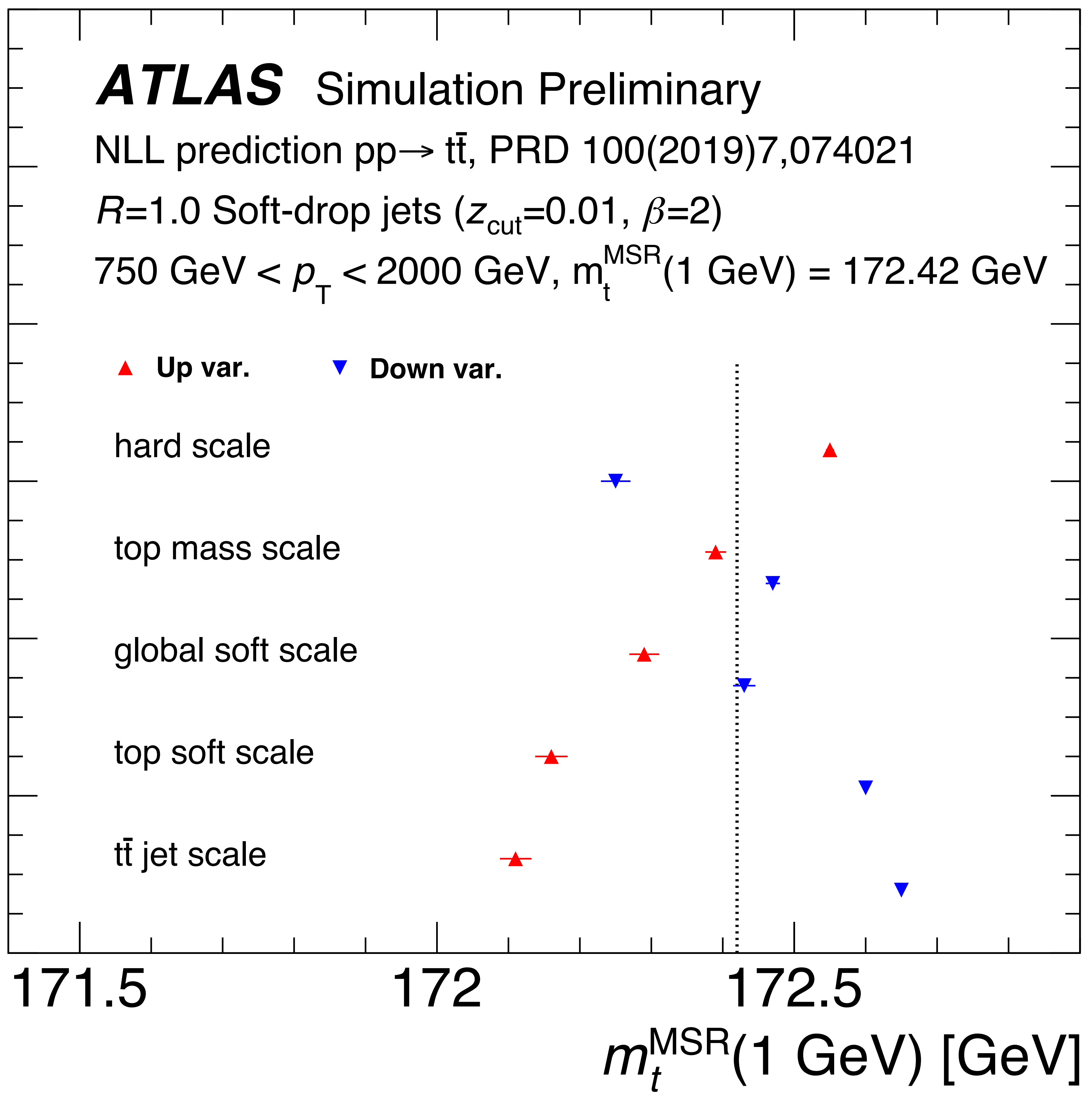
- Theory gives a inclusive treatment of the top decay products
- In some MC events, FSR of decay products are groomed away (FSRinRes setting), lifting up the left tail of the jet mass peak
- This can be handled by carefully adjusting the fit range



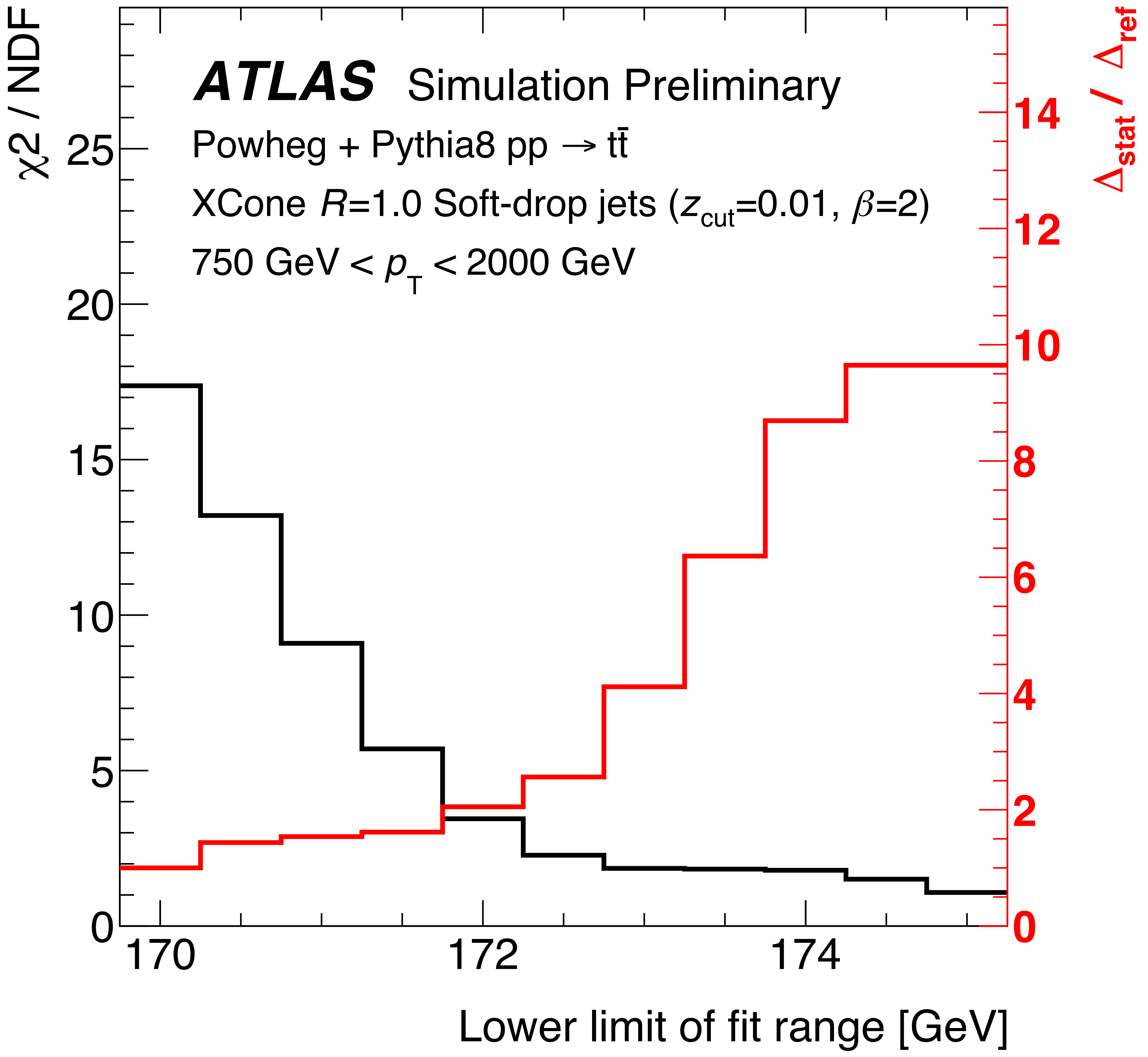


Theory Uncertainty

- Derived as the envelope of independent variations of scale sets



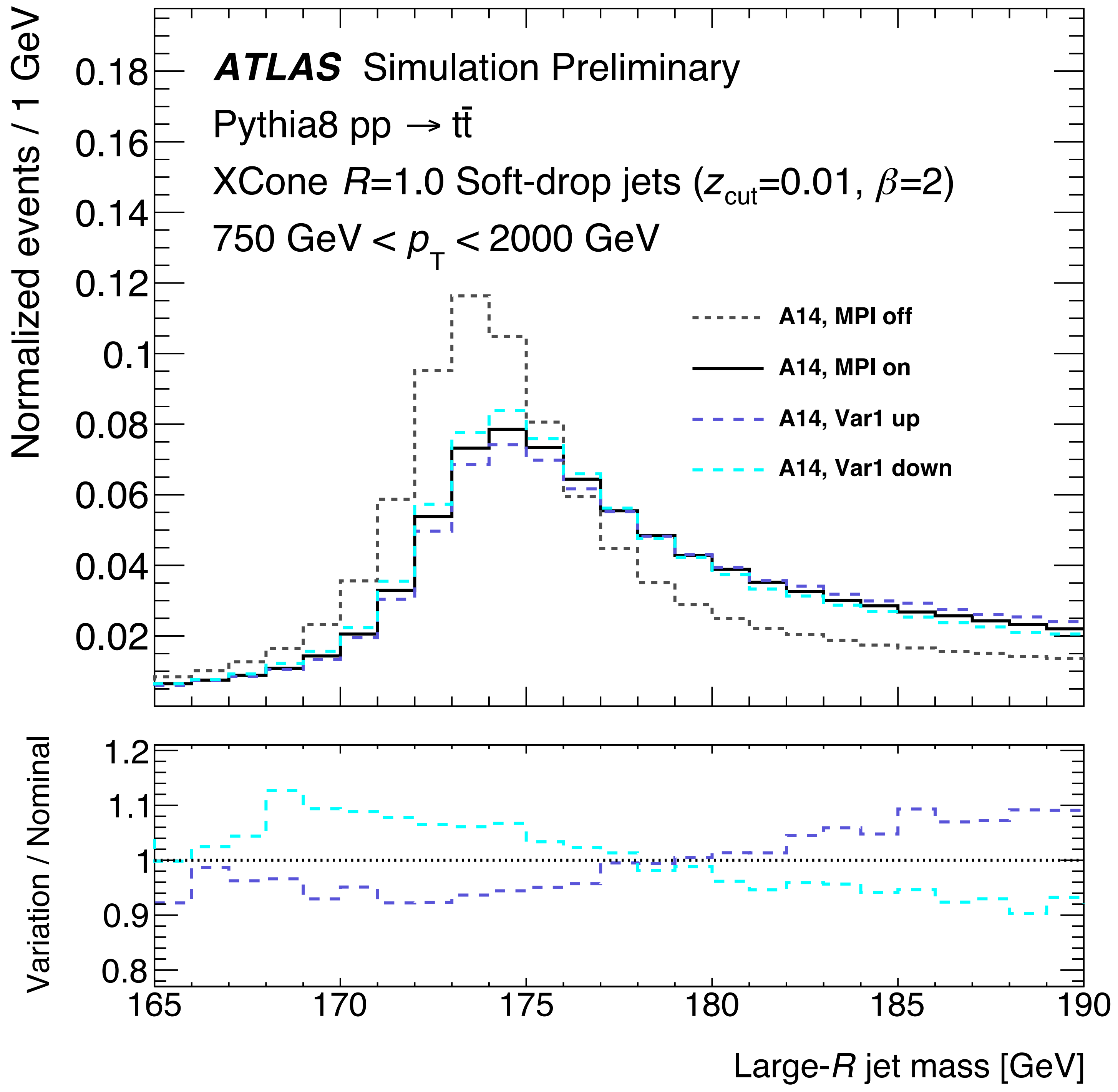
Fit range choice

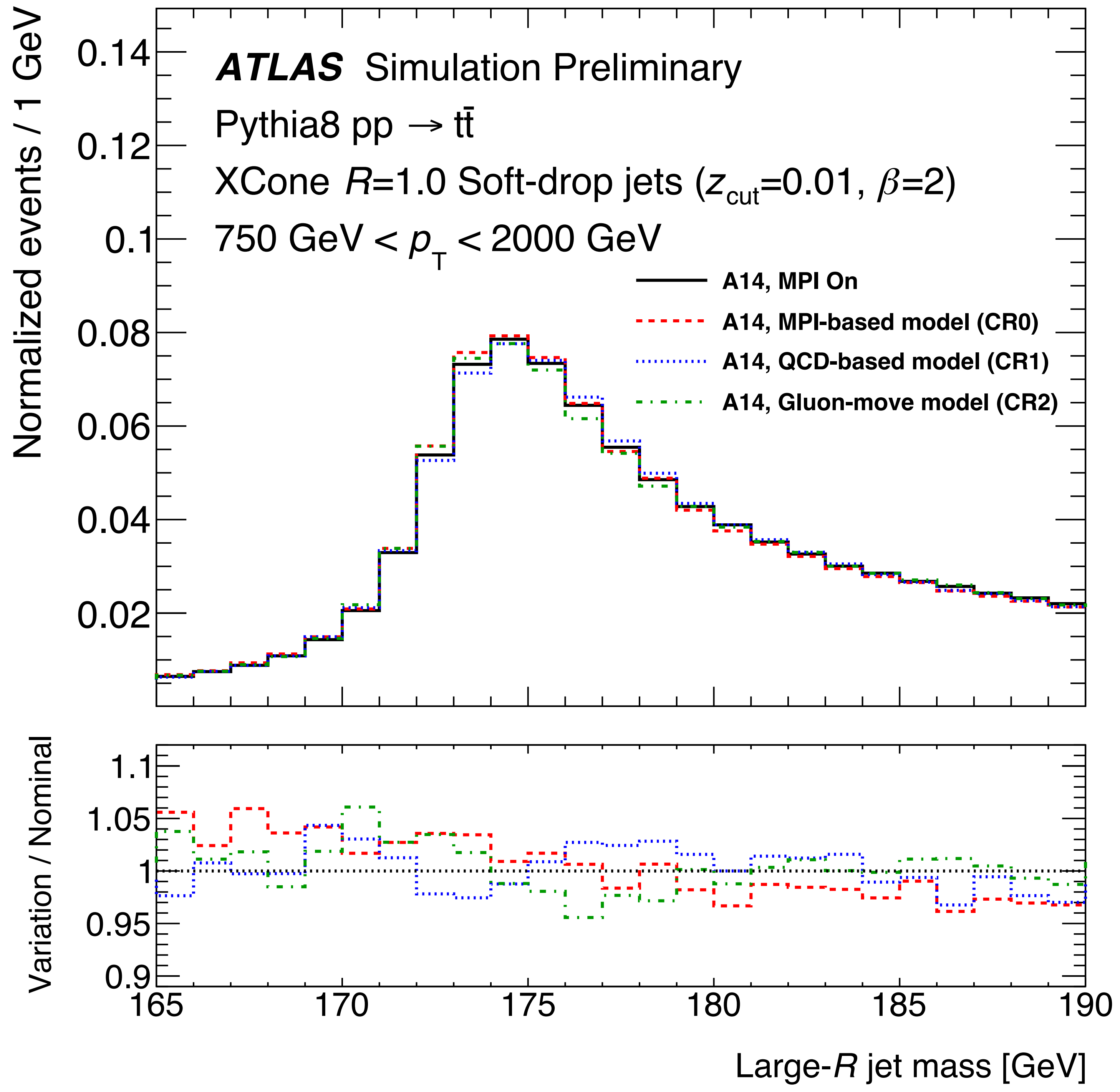


- Fit range set to 172.5 - 180.0 GeV
- Lower limit is identified with the m_{top}^{MC} the events were generated with.
- Fit is repeated with this value varied up and down by half GeV. Difference is registered as part of the methodological uncertainty.
- Variations of the upper limit have negligible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





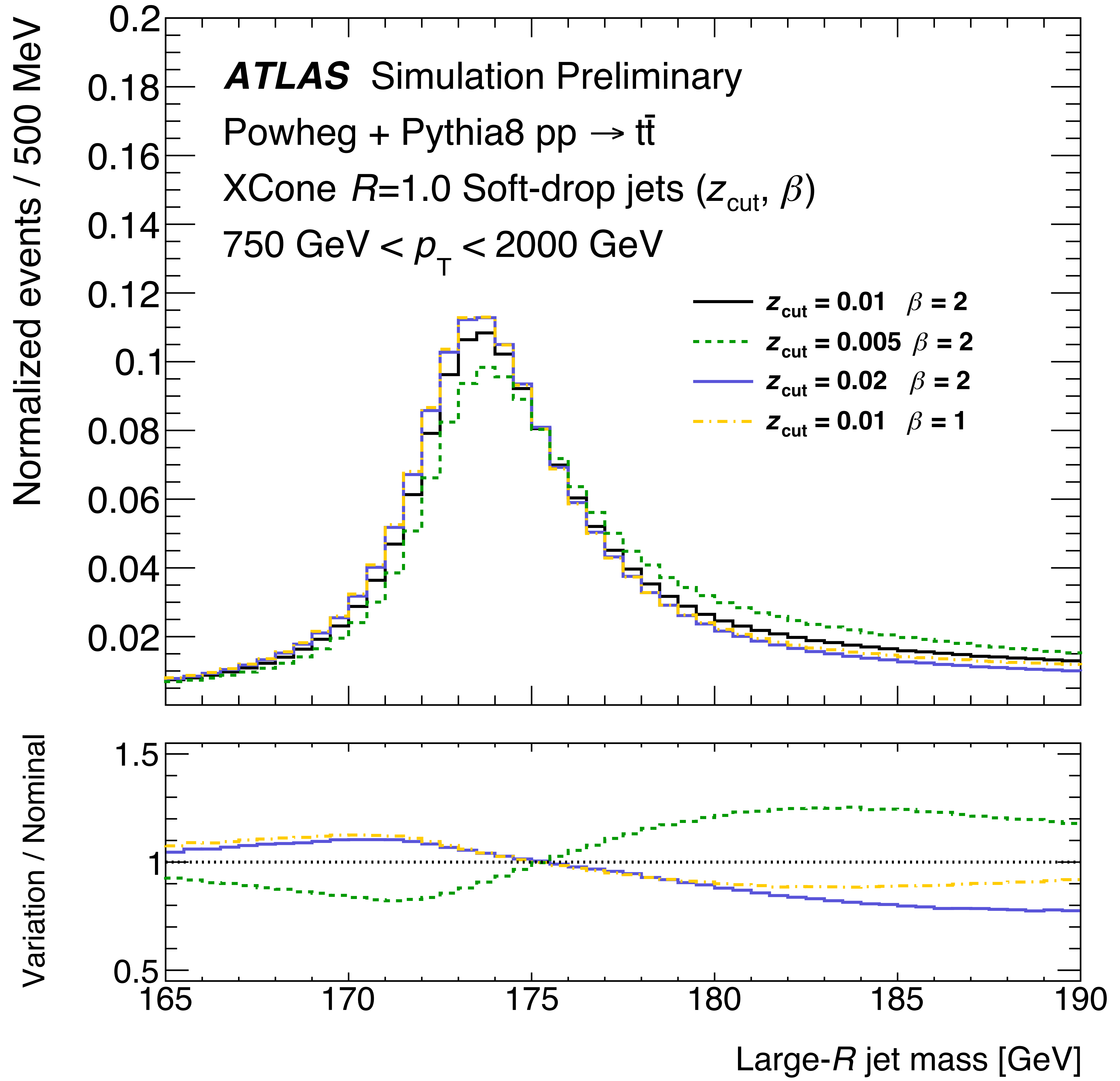
Stability

- 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



Further Pythia8 variations

- Some default Pythia8 settings could be tweaked
- A MC-based fit is performed to see how alternative Pythia8 settings may translate into different values of m_{top}^{MC}