BOOST 23 - Lawrence Berkeley National Lab

Interpretation of the top quark mass parameter in Monte Carlo samples at NNLL precision

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Top quark mass measurements - Direct

- m_t determined experimentally by studying the top quark decay products.

- Hard reactions at high energy + low energy QCD effects.

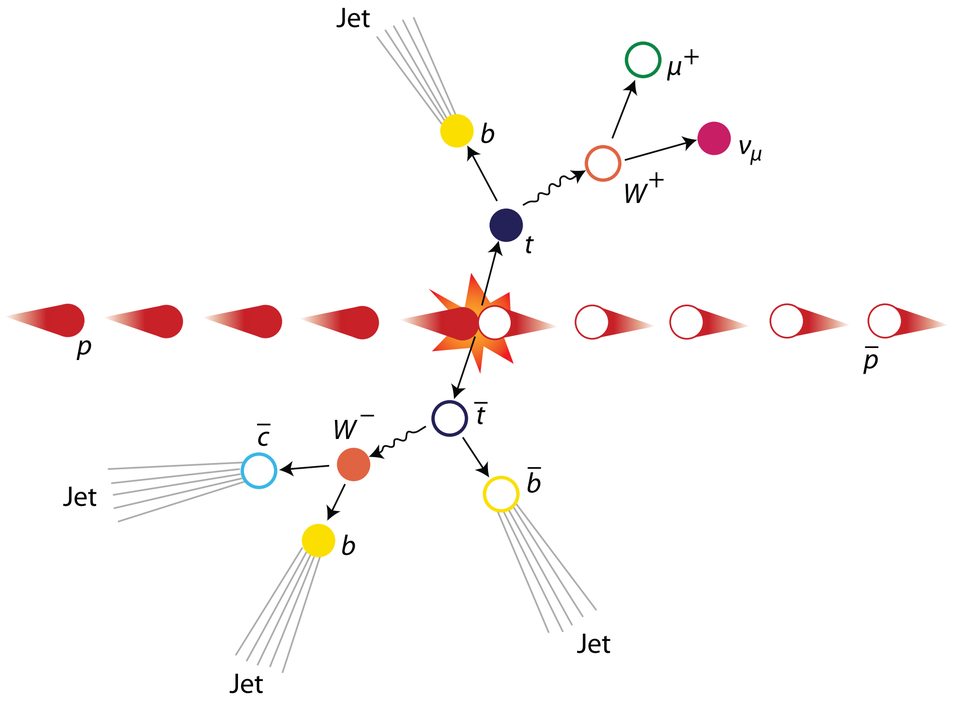
- MC-based templates at detector level - combination of first principle QCD calculations and modelling techniques (e.g. hadronisation and parton shower).

- Most precise determination of top quark mass m_t^{MC} **O (380) MeV** precision.

- Average m_t^{MC} from PDG:

$$m_t^{MC} = 172.69 \pm 0.30 \text{ GeV}$$

LHC top WG combination that takes into account all correlations properly is desirable.



Top quark mass measurements - Indirect

- m_t determined by analysing parton-level production cross-sections (inclusive and differential).
  - Calculations involve hard reactions at high energy scales, where top quarks are produced.
  - Taking into account both fixed-order calculations and resummation of certain contributions.

- m_t in these calculations is the "renormalised top quark mass", which considers the effects of quantum corrections (m_t^{pole} vs $m_t^{\bar{M}S}$).

- Most precise measurements **O(1) GeV** precision.

Average m_t^{pole} value from PDG:

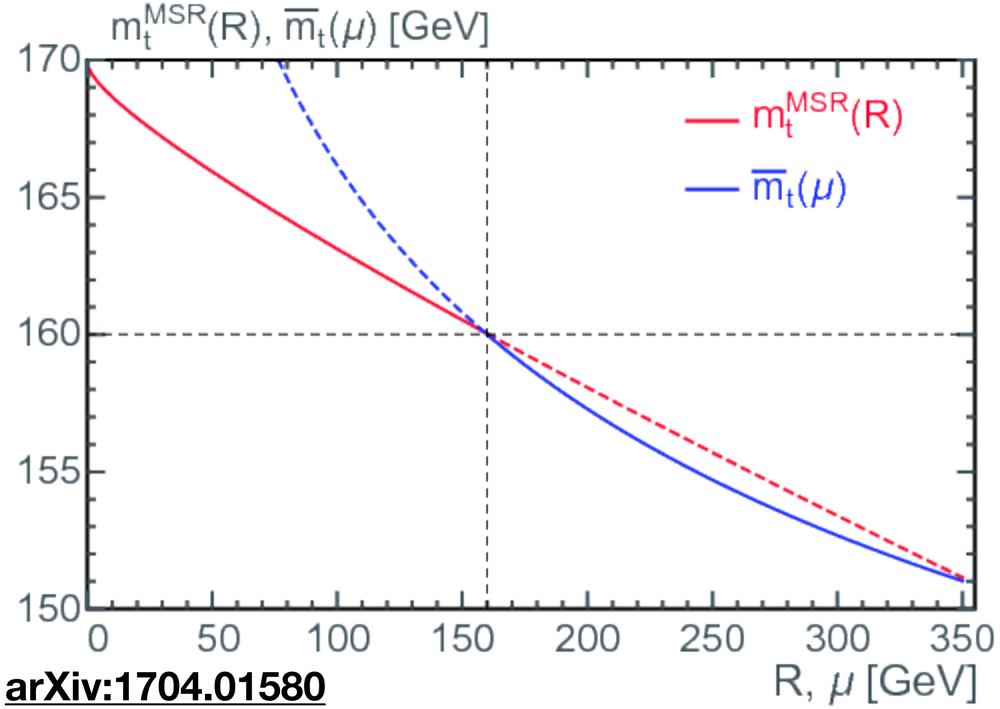
$$m_t^{pole} = 172.5 \pm 0.7 \text{ GeV}$$

LHC top WG combination that takes into account all correlations properly is desirable.

MSR scheme

arXiv:20004.12915

- Pole mass in perturbative QCD analogous to the mass of a free particle in the propagator.
- However, suffers from inherent theoretical uncertainty related to infrared (IR) effects in QCD.
  - Infrared effects arise from the behaviour of particles with low momenta or long distances.
- The renormalon leads to an intrinsic ambiguity in the pole mass of order 100-300 MeV.
- Thus, want different renormalisation schemes to obtain short-distance mass that numerically not too far from the pole mass.



arXiv:1704.01580

- $\bar{MS}$ **scheme**: $\bar{m}_t(\mu)$ is defined at fixed scale where $\mu \approx m_t$
- **MSR scheme:** $m_t^{MSR}(R)$ is defined at evolving scale where typically R **<<** m_t
  - Better separates long and short distance effects.

MSR mass can be converted to any other mass (i.e. $\bar{MS}$) with negligible loss in precision.

Goal of analysis

- **The interpretation of the top mass in an MC generator, in terms of a renormalised mass in the MSR scheme:**

$$\mathbf{m_t^{MC} = m_t^{MSR}(R = 1GeV) + \Delta m_t^{MSR}}$$

- Previously, theory uncertainties at NLL were a large source of uncertainty. ***arXiv:1608.01318***, ***arXiv:1708.02586***, ***ATL-PHYS-PUB-2021-034***.

- Calibration performed with **new NNLL calculation** compared against **Pythia MC** predictions with NNPDF3.0 NLO PDF set and A14 set of tuned parameters.

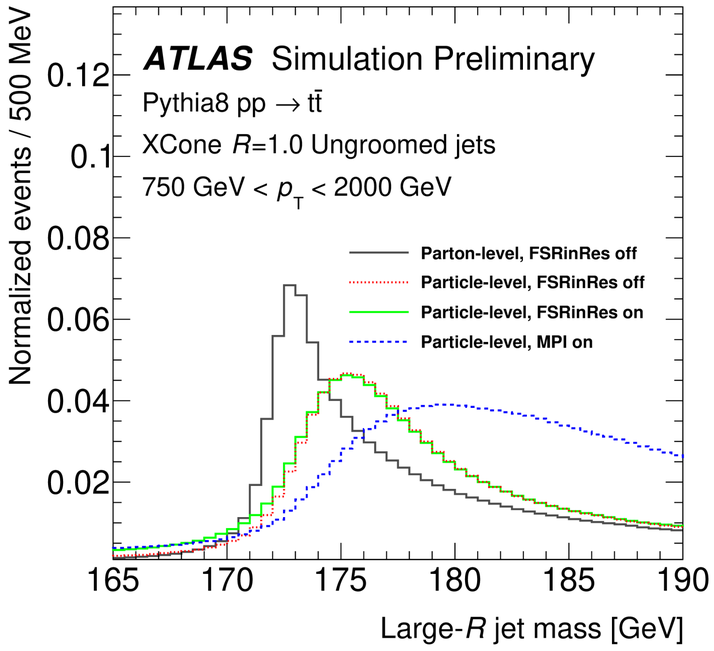
m_t^{MC} **is set to 172.5 GeV.**

Large-R Jet Mass

- Top mass determined by measuring large-R jet mass containing hadronic top.
  - Mass reconstructed using information from decay products of top quark within large-R jet.

- Light grooming applied to large-R jet mass
  - Reduces undesirable effects of soft radiation on the jet mass spectrum.
  - Considerably reduces UE impact. Shift of ~5 GeV down to ~1 GeV.

arXiv:1708.02586



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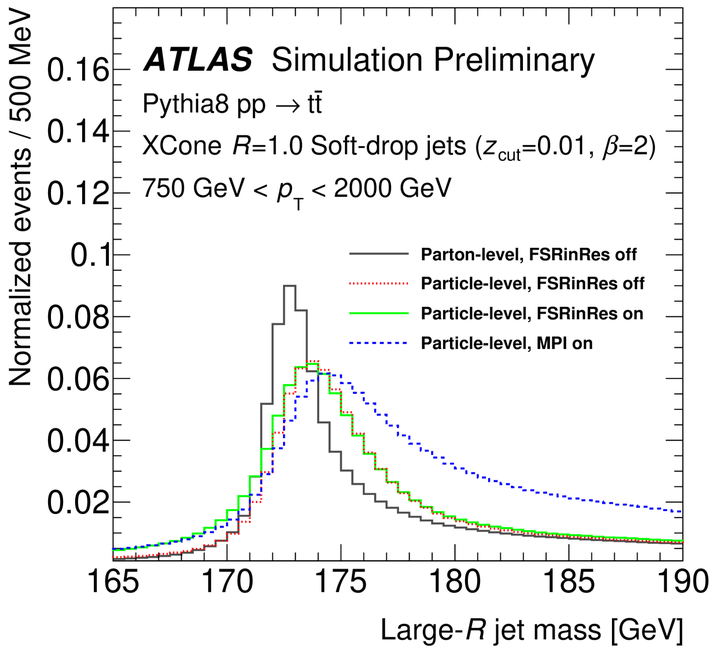


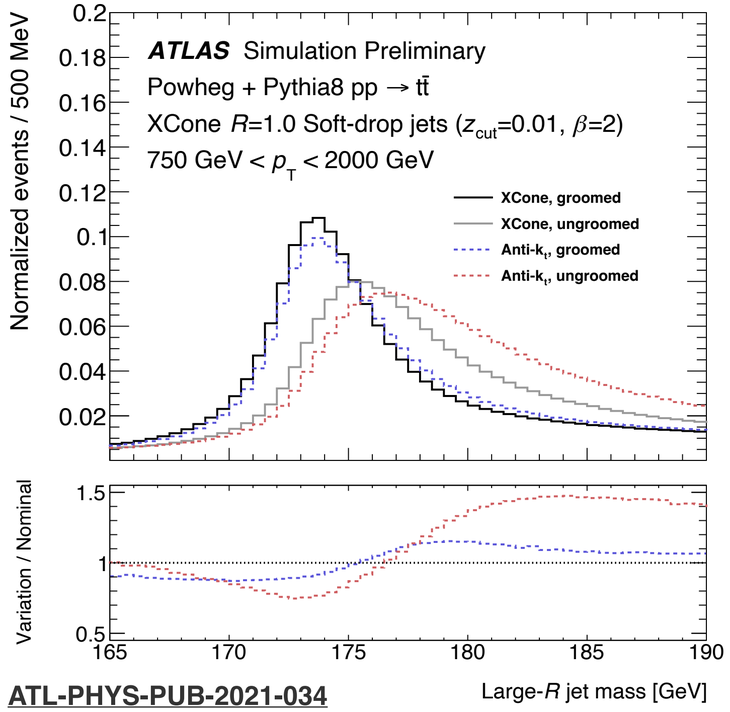
Jet building

- Focus on particle-level hadronic top quark decay in $pp \to t\bar{t}$ processes.

- Boosted jet: Inclusive treatment of decay products.
  - **Four orthogonal jet p_T bins**:

$$p_T^{jet} \in \{750, 1000, 1500, 2000, 2500\}\text{GeV}.$$

- Jets built with:
  - **XCone** jet algorithm with **R = 1**.
  - Parton matching $\Delta R(jet, top) < 1$.
  - **Soft-drop light grooming** applied to remove soft-wide radiation **($z_{cut} = 0.01, \beta = 2$).**



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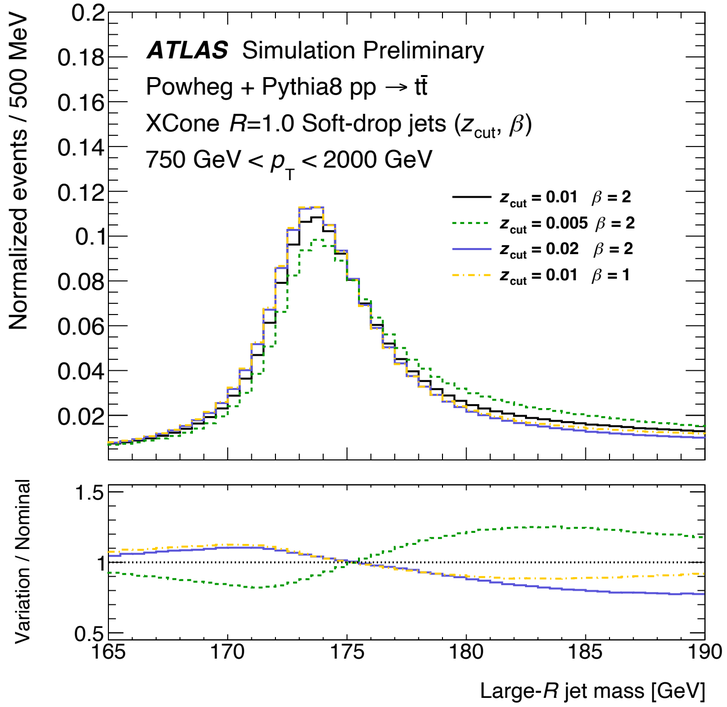
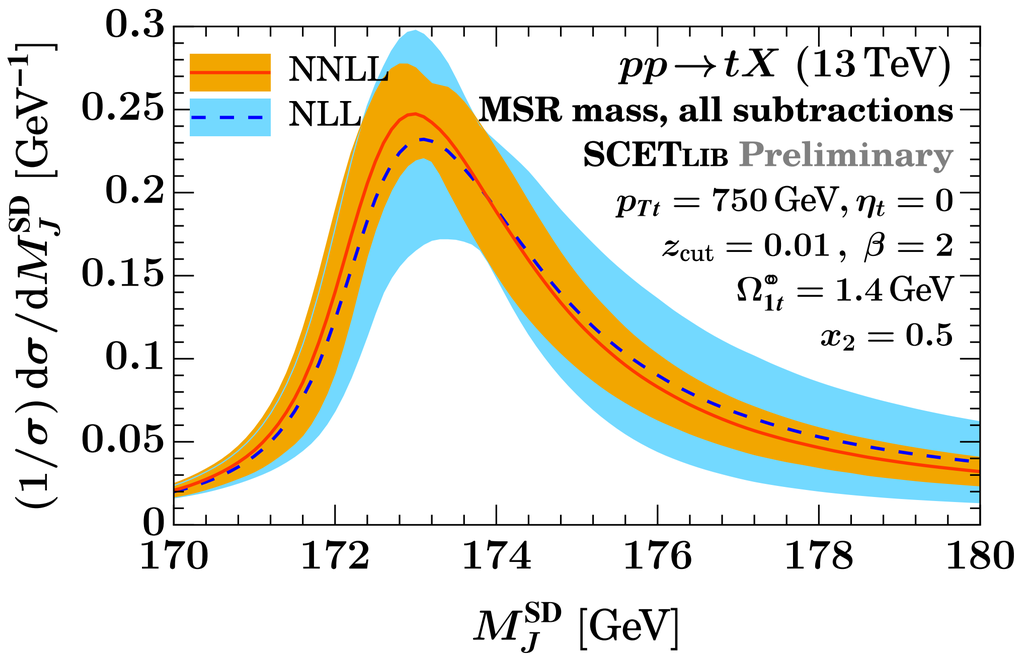


Theoretical Calculation

- Continuation of the top mass interpretation with NLL accuracy found at ATL-PHYS-PUB-2021-034.

- Model uses three parameters, m_t, Ω_{1q}^{had}, and x_2 associated with **first-** and **second-moment non-perturbative corrections.**

- Using SCET-based theory with NNLL accuracy
  - Improved perturbative stability
  - Renormalon subtraction - increased stability in peak of differential cross-section of jet mass. Renders the first-moment non-perturbative correction renormalon free.



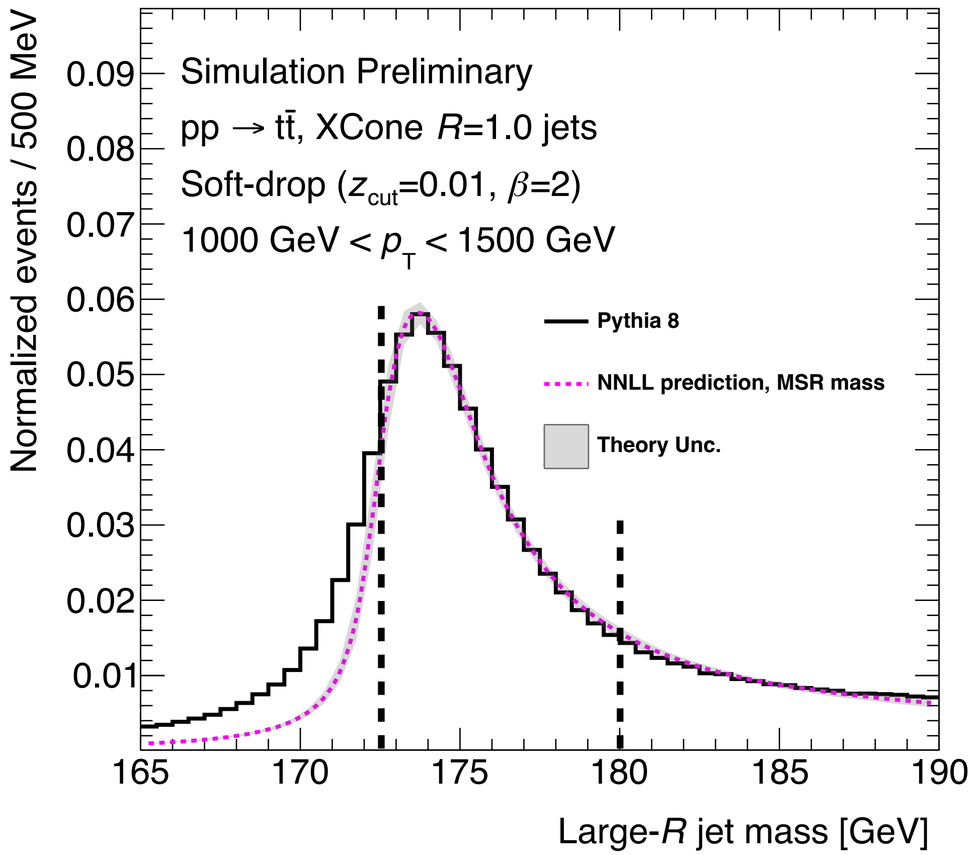
Mantry, Michel, Pathak, Stewart
Preliminary

Fitting Details

- Idea is to obtain **value of parameters in NNLL theory** calculation that **best describe MC prediction.**

- m_t, Ω_{1q}^{had}, and x_2 varied:
  - χ^2 minimisation fit applied to the three parameters to find the global minimum.

- Fit range set to 172.5-180 GeV.
  - In grooming procedure, theory does not accurately describe the low-mass tail present in the generator prediction due to decay product FSR effects that are not yet included.
  - Restrict fit range to avoid the low jet-mass tail, that would bias the extracted top mass to lower values.



Top mass interpretation results

$$m_t^{MSR}(1GeV) = 172.18 \pm 0.05 \text{ GeV}$$

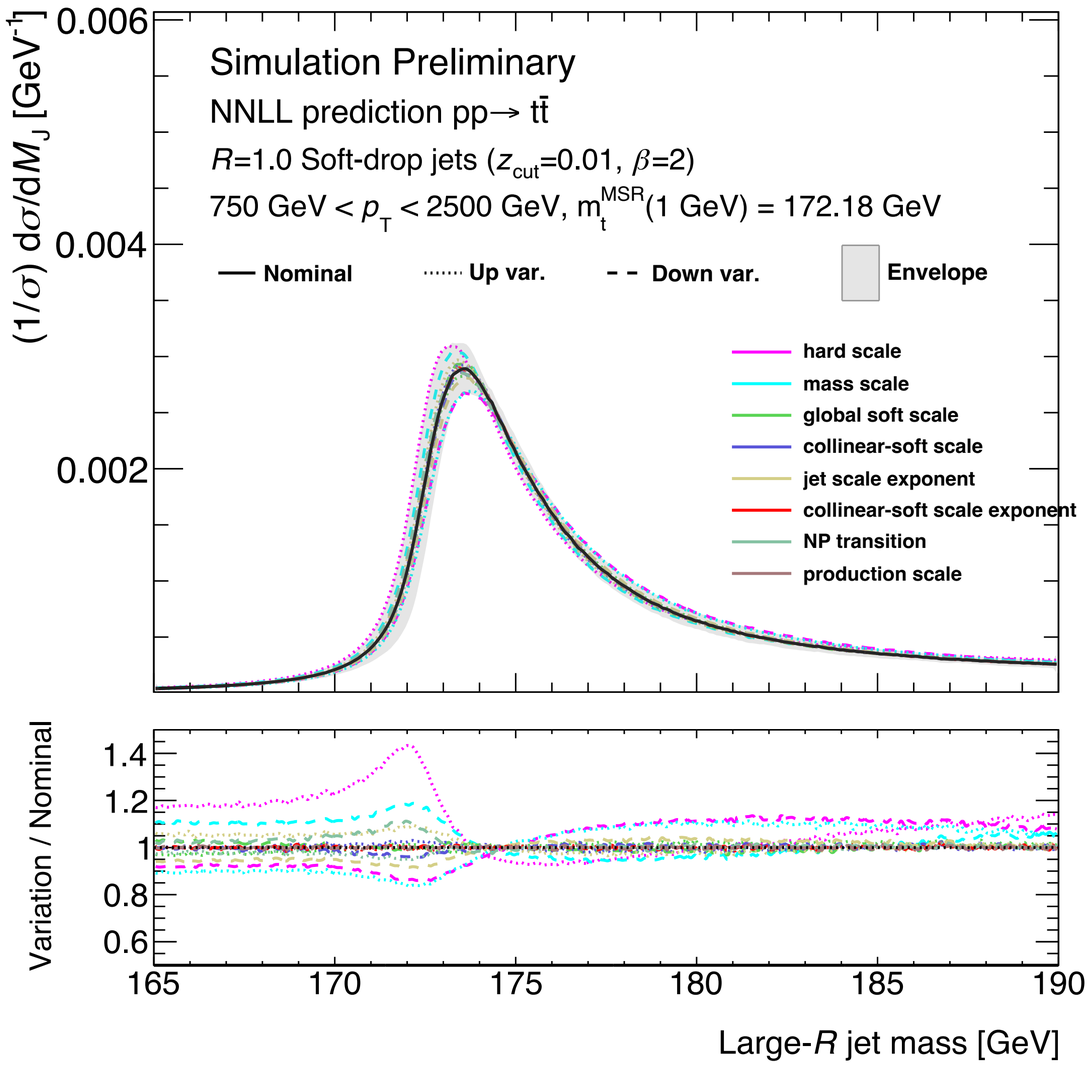
Uncertainty corresponding to statistical uncertainty of MC sample.

Mass relation of:

$$\Delta^{MSR} = m_t^{MC} - m_t^{MSR}(1 \text{ GeV}) = 320^{+97}_{-490} \text{ MeV}$$

Uncertainty corresponding to the theoretical variations of the model.

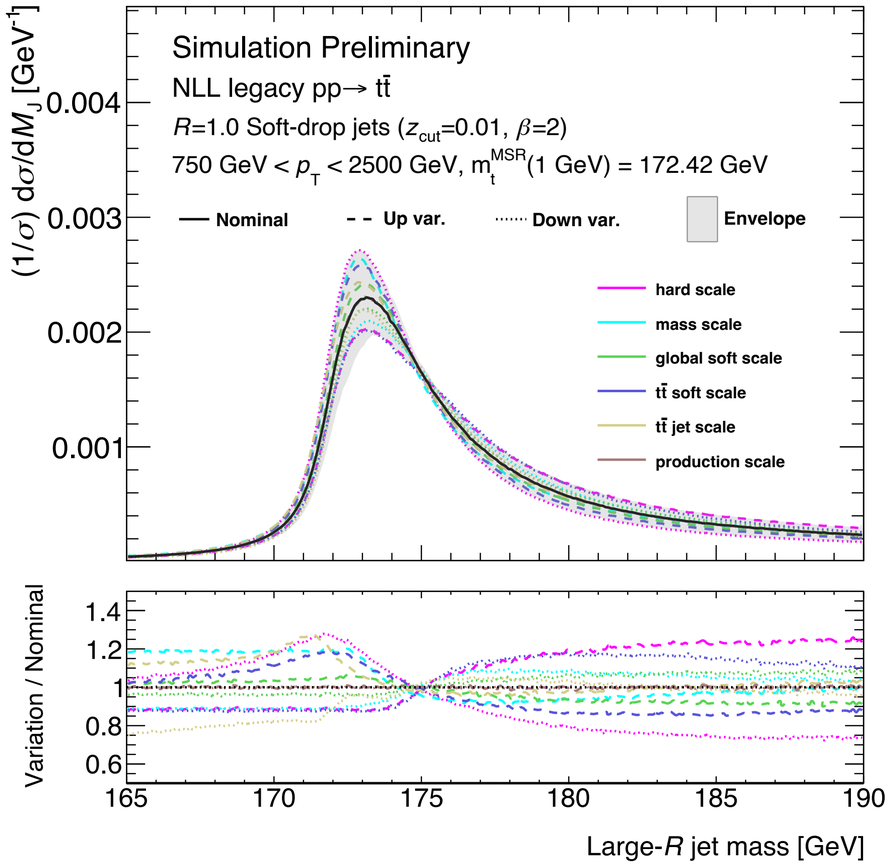
Also possible to vary the R value. Currently have fit MSR (3 GeV) with consistent results. Using 1 GeV for ease of comparison.



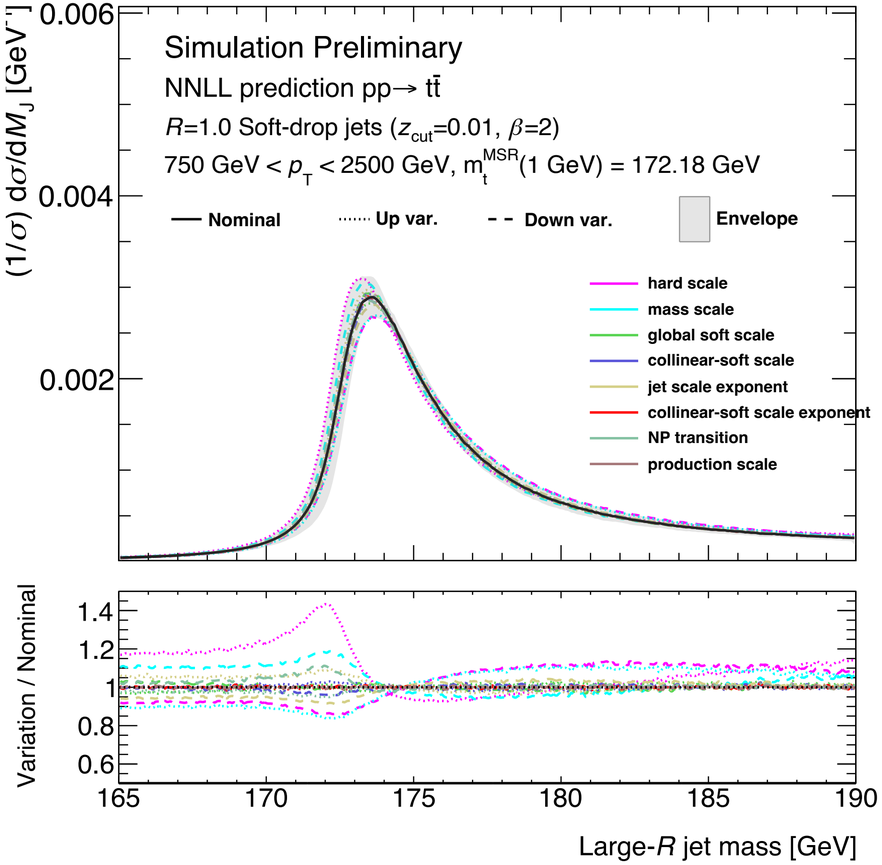
Theoretical scale variations are normalised to the nominal curve.

NNLL vs NLL

NLL



NNLL



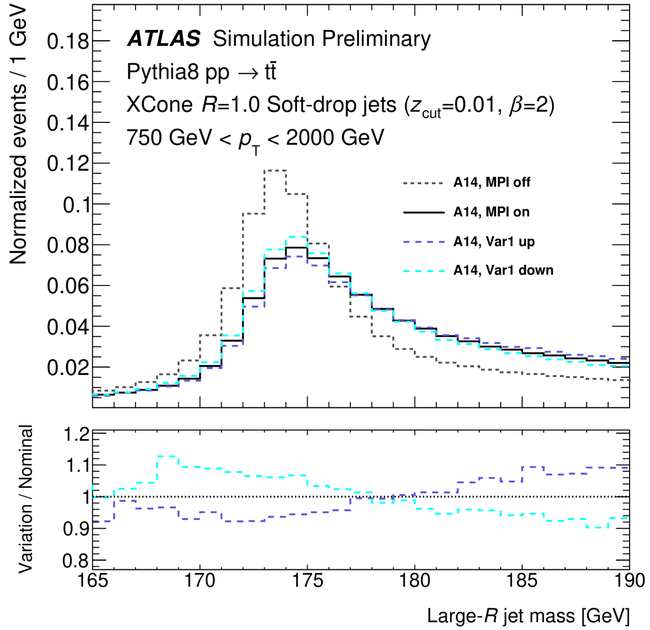
- **Overall theoretical uncertainty from scale variations reduced!**
  - All scale uncertainties, except for hard variation at and below the peak, are reduced (further investigation in progress)
- **Underlying event (UE)** effects not yet accounted for by the theory model.

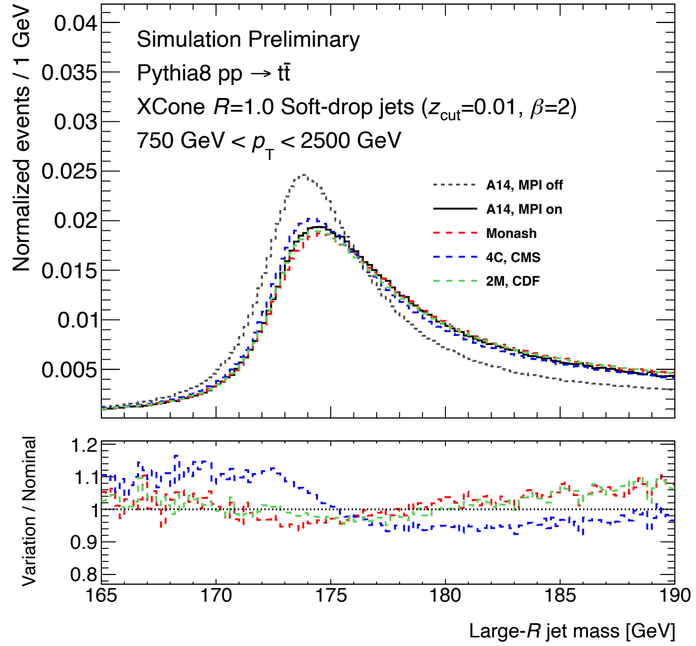
Results and Uncertainties

ATL-PHYS-PUB-2021-034

Working on including uncertainties related to:

- **Underlying event**
  - Comparing nominal MPI-on Pythia against A14 Var1 eigentune variations (coverage of UE variations modelling uncertainties).
  - Previously only had Var1 eigentunes. Plan to extend to inclusion of MPI-on Pythia against different tunes to evaluate the effect.
- **Fit methodology** - Comparing fit ranges.





Conclusions and Future

- **New SCET-based theoretical model yields NNLL predictions for $pp \to t\bar{t}$ with a decrease of theoretical uncertainties.**

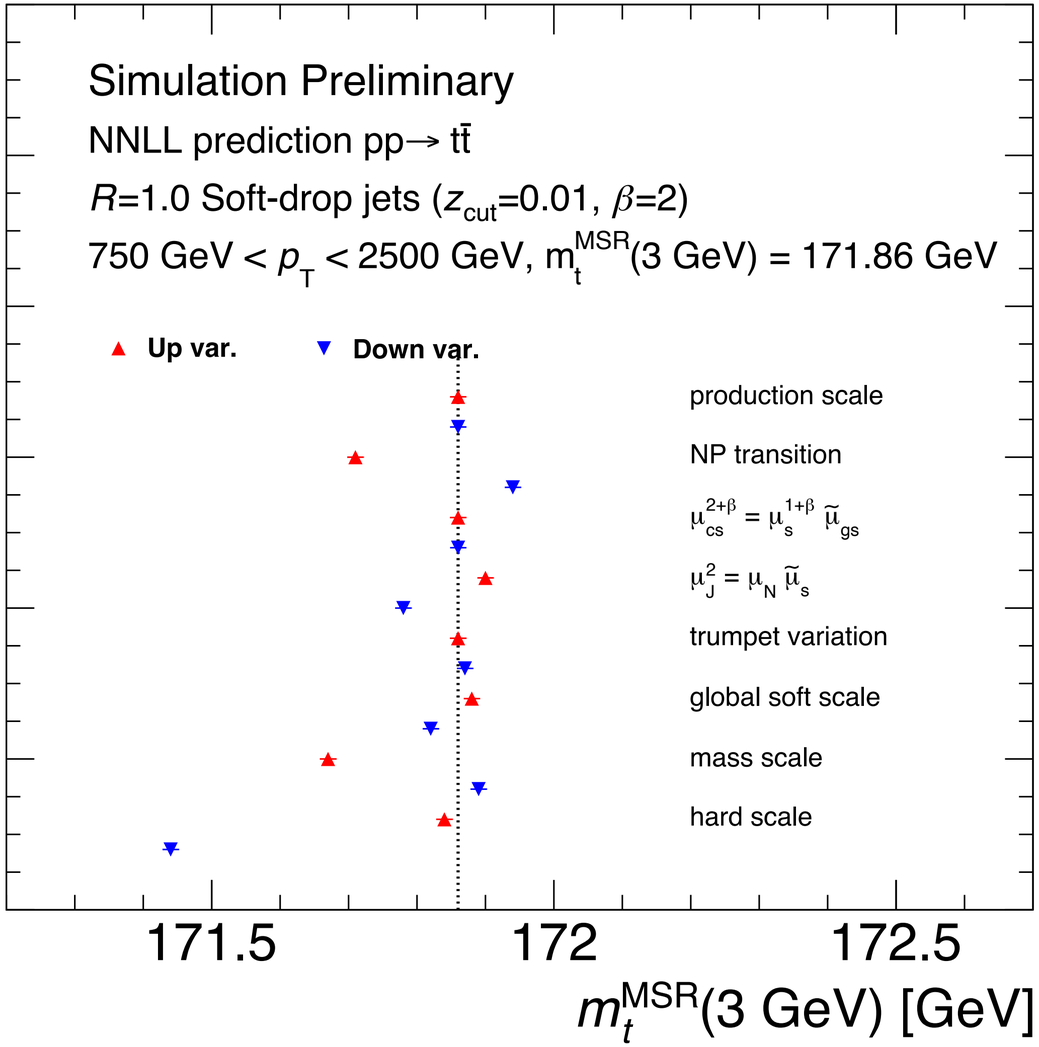
- **Preliminary Pythia MC top mass with MSR top mass at 1 GeV computed:**

$$m_t^{MC} = m_t^{MSR}(1 \text{ GeV}) - 320^{+97}_{-490} \text{ MeV}$$

- **Consistent results with previous result at NLL ($\Delta^{MSR} = 80^{+350}_{-400}$).**

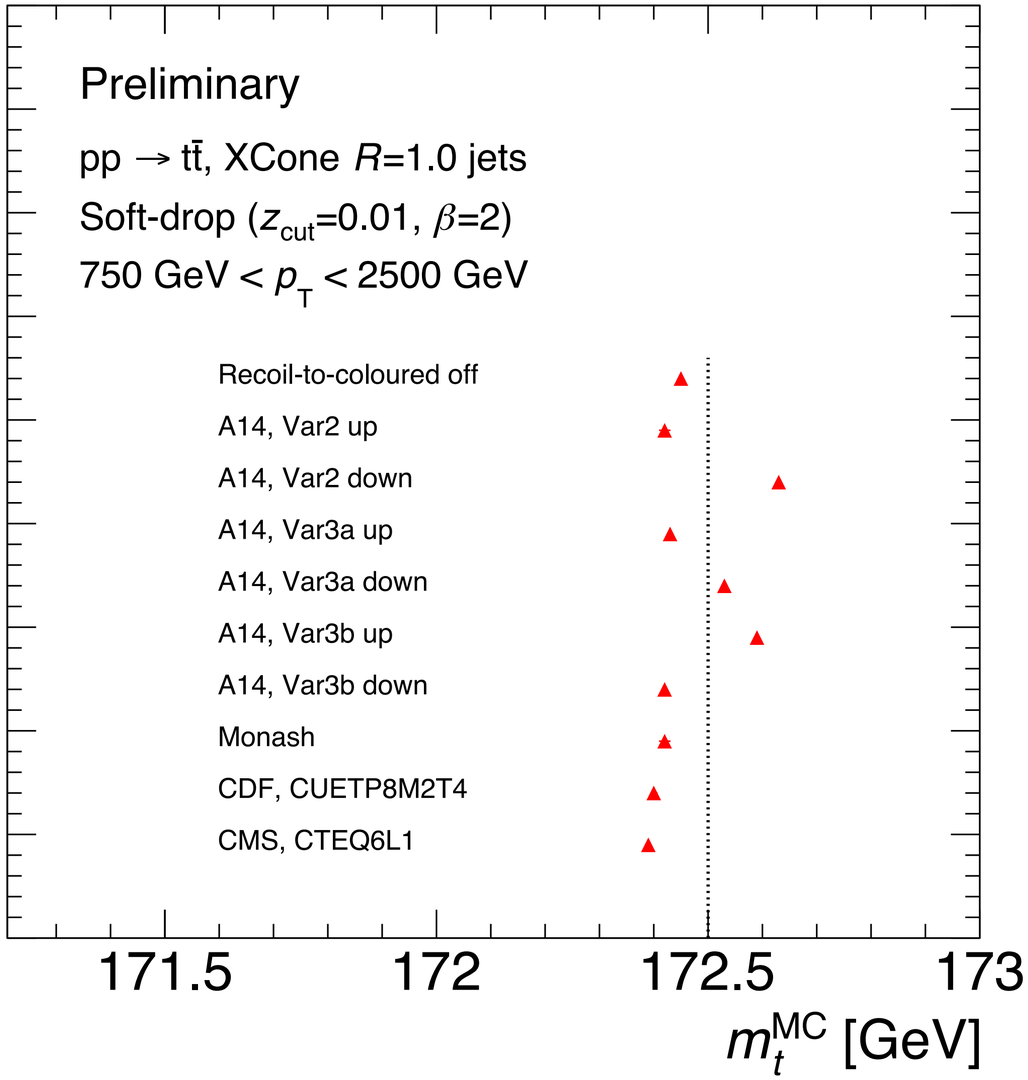
- Still a work in progress:
  - Finalise theoretical uncertainty analysis (hard-scale variation).
  - Inclusion of UE and fit methodology uncertainties.

Theory Uncertainties



Theory uncertainty derived as a sum in quadrature of the individual variations.

Further Pythia8 Variations



Study performed to observe how further Pythia variations affect the m_t^{MC} observable.

MSR scale variations

MSR mt (R=1) GeV	MSR mt (R=2)GeV	MSR mt (R=3) GeV	Change in mt
Mt = 172.18 GeV Omega1 = 1.85 GeV X2 = 0.46	**Mt = 171.99 GeV** Omega1 = 1.85 GeV X2 = 0.46	**Mt = 171.86 GeV** Omega1 = 1.85 GeV X2 = 0.46	MSR 1 -> MSR 2 = **190 MeV** MSR 2 -> MSR 3 = **130 MeV**

Comparison of parameters for different ranges of x2 corresponding to the 3 minima in their chi^2 distributions

Study to see how m_t^{MSR} varies with different R values.