BOOST 2024: Genova, Italy

Interpretation of the MC top mass parameter with the soft-dropped groomed jet mass

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TOP QUARK MASS INTERPRETATION

- The physical mass of the top quark is that found in the Lagrangian. However, MC top quark mass has much lower uncertainties.
  - **Want to interpret direct mass measurements within a field-theoretical renormalisation scheme.**
    - **Test the relation between the two mass parameters:**

$$m_t^{MC} = m_t^{theo} + \Delta_{t,MC}$$

- The ambiguity can be reduced through dedicated ‘calibration’ studies.

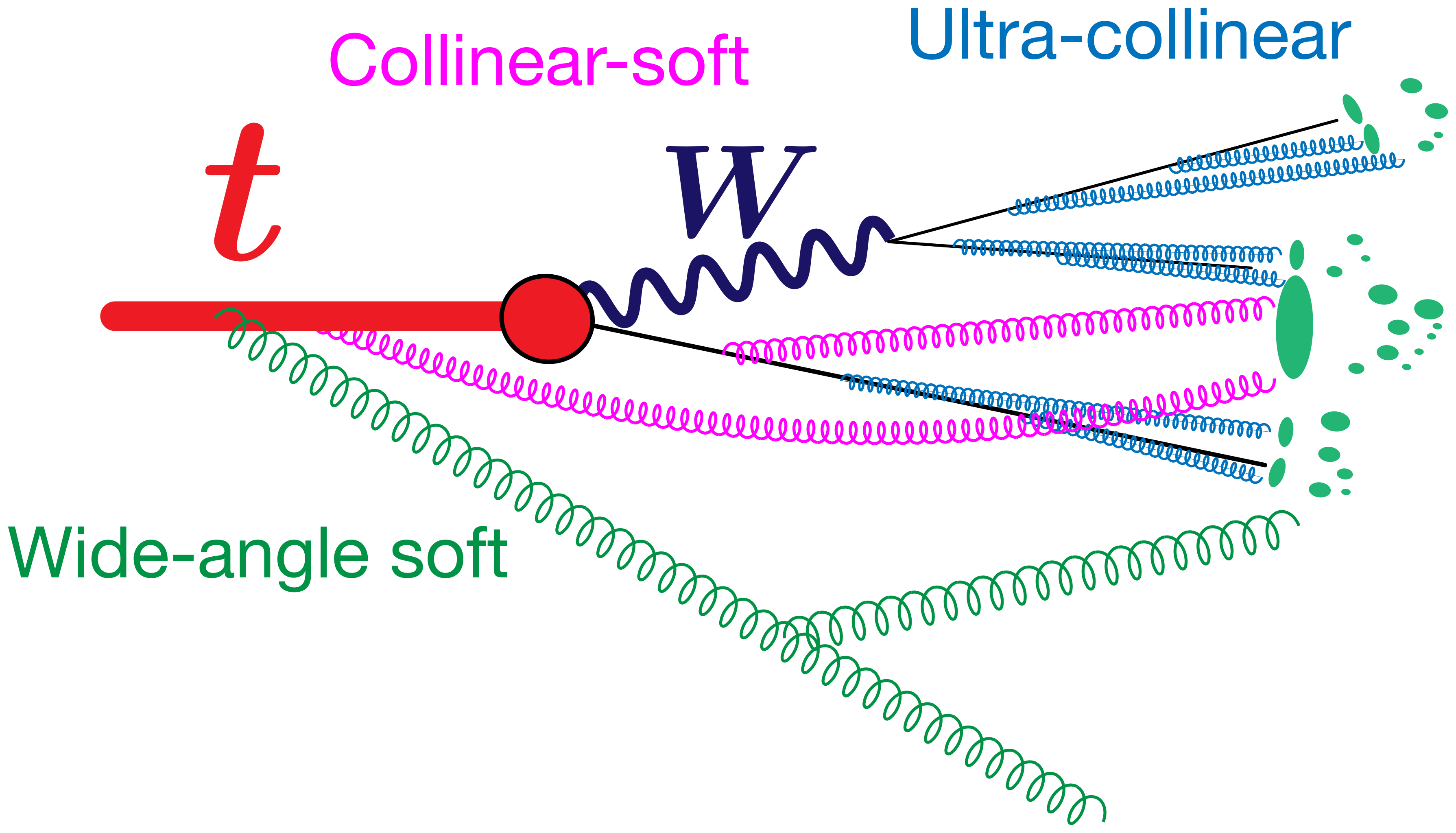
➡ Is m_t^{MC} only effective in matching experimental data, using mass parameters that don't directly correspond to fundamental QCD parameters?

➡ Or, if closely aligned with QCD, can m_t^{MC} represent the physical mass in a given scheme of the top quark as in the QCD Lagrangian.

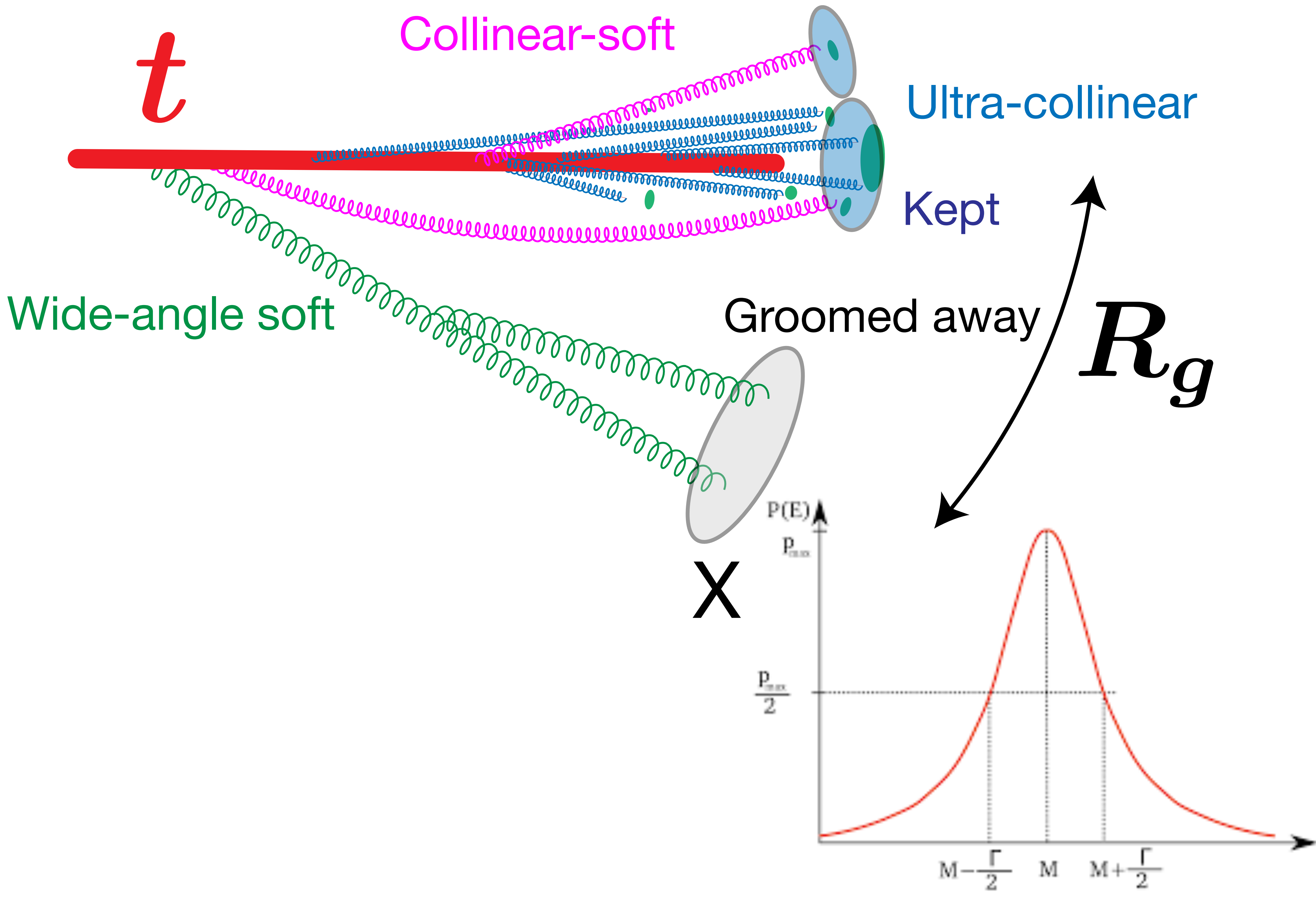
INTRODUCTION

The top quark presents unique challenges with jet substructure with its intricate three-body electroweak decay.

- For observables that do not resolve the details of the top decay (inclusive over the top quark decay) the jet substructure can be described by considering a stable top quark that radiates and including the decay effects via Breit Wigner distribution. Phys.Rev.D 77 (2008) 074010
- Currently no theoretical framework describing the decay of the top in an exclusive way i.e. when the decay products are resolved.
- Top quark mass studies with soft-dropped grooming typically focuses on **light grooming region**.
  - Enables a relatively simple inclusive description of the top quark decay.
- In this talk we test how far we can push the limit of inclusive description
- **The first step towards trying to build a more robust groomed observable for pp collisions.**



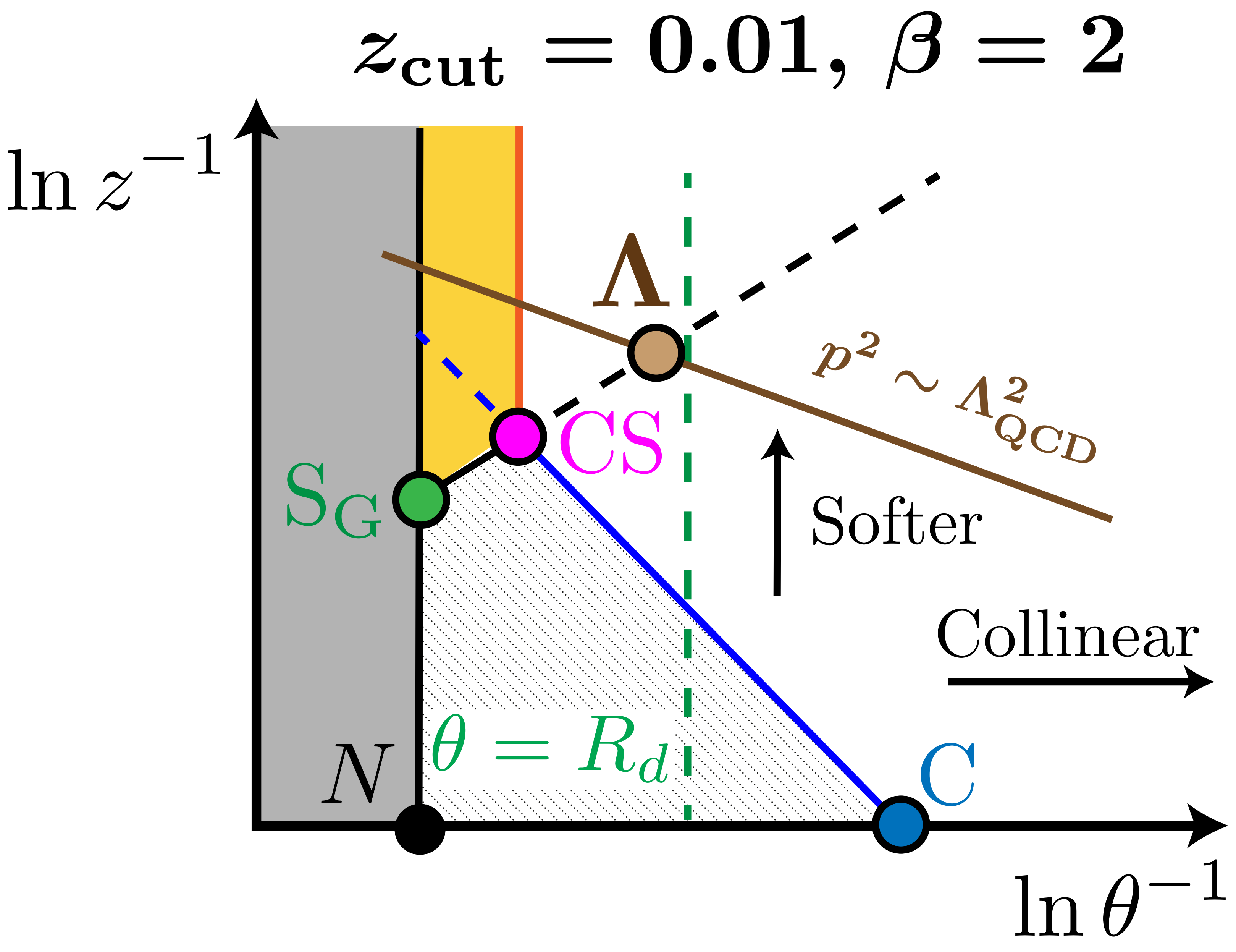
Inclusive treatment of the decay products



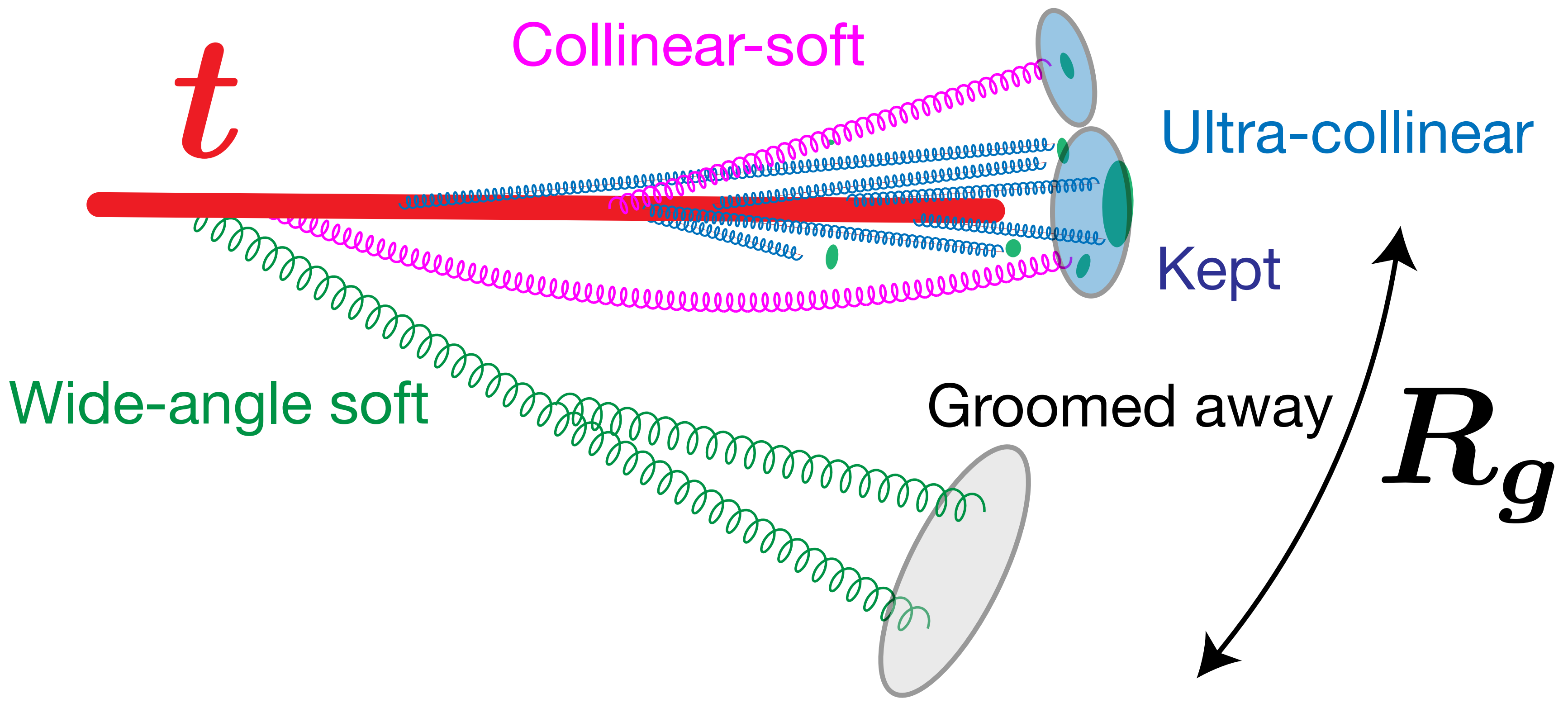
SOFT DROP JET MASS OF BOOSTED TOP QUARKS

[JHEP 12 (2019) 002].

Effective field theory modes Sg, CS, C capture physics at different phase space points in the Lund plane.



Inclusive treatment of the decay products



- This Lund plane picture is the same as for light quark and gluon jets.
  - Straightforward generalisation to the case of top quarks called the light grooming region.
    - Enables an "inclusive" description of the top quark decay.
  - For light grooming, the soft drop never encounters the ultracollinear radiation at small angular scales where the C mode is.
    - For light grooming ($z_{cut} = 0.01$ and $\beta = 2$) the soft drop stops at angles larger than the decay product opening angle: $r_g > r_d$
    - Retain control over the mass scheme probed by this observable (main goal of this study).
- The mode Λ sits on the line $p^2 \sim \Lambda^2_{QCD}$ and captures the leading non-perturbative effects on the groomed jet mass.

SOFT DROP JET MASS OF BOOSTED TOP QUARKS

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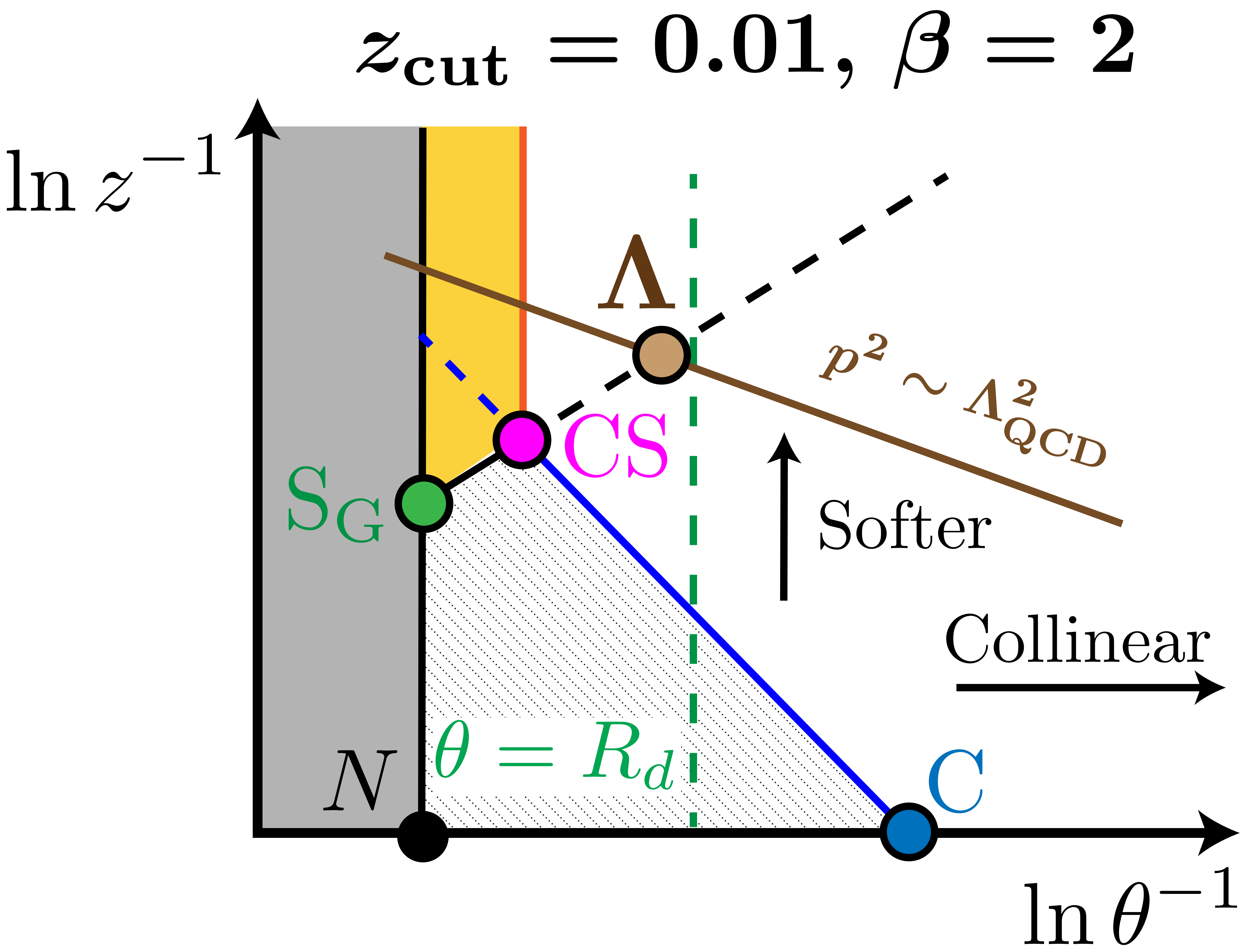


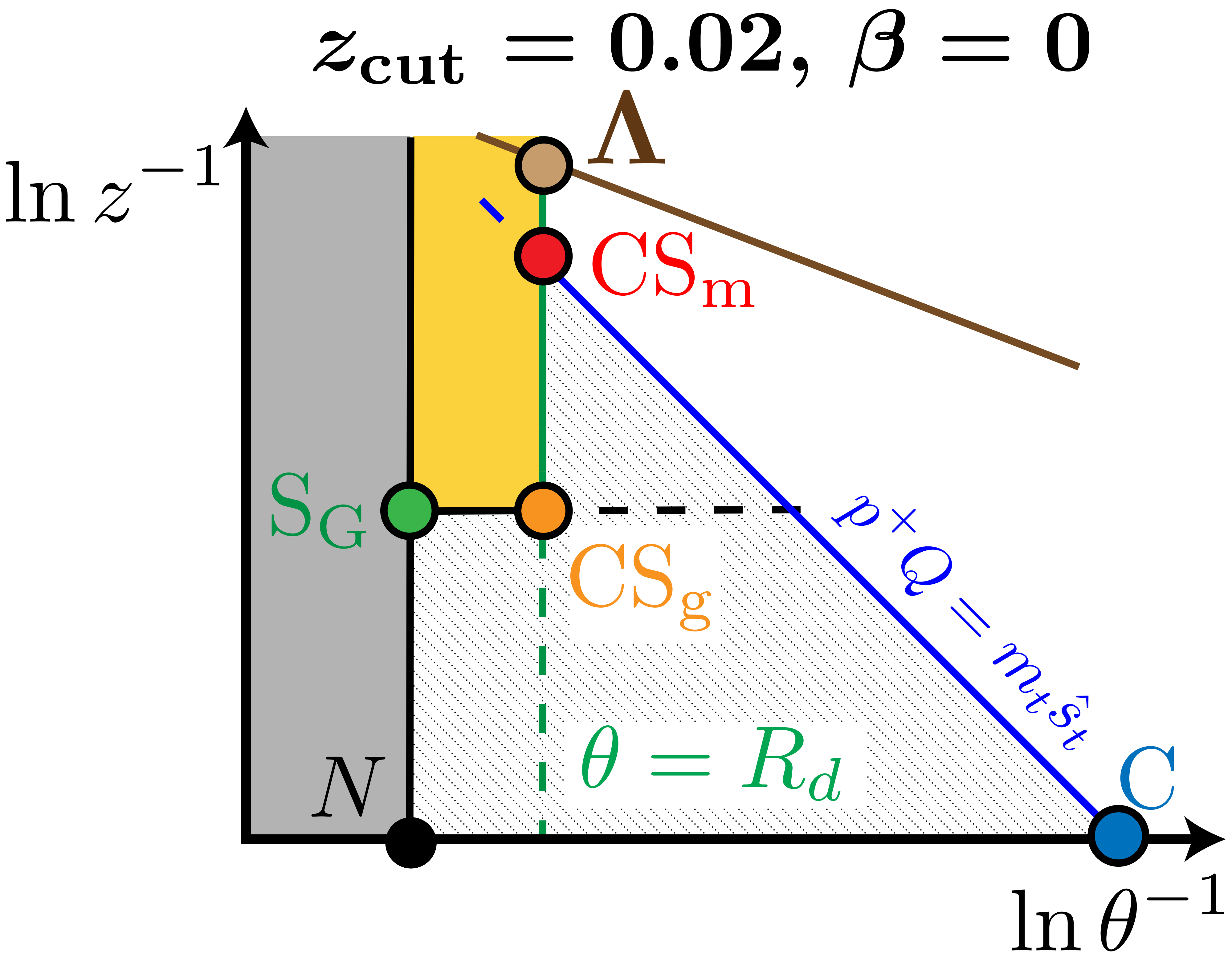
- However, there are some undesirable features of this light grooming:
  - Firstly, the grooming is small and it is not very effective in removing contamination.
  - Secondly, a more theoretical reason is that the Λ mode sits on the intersection of the jet mass and the soft drop line.

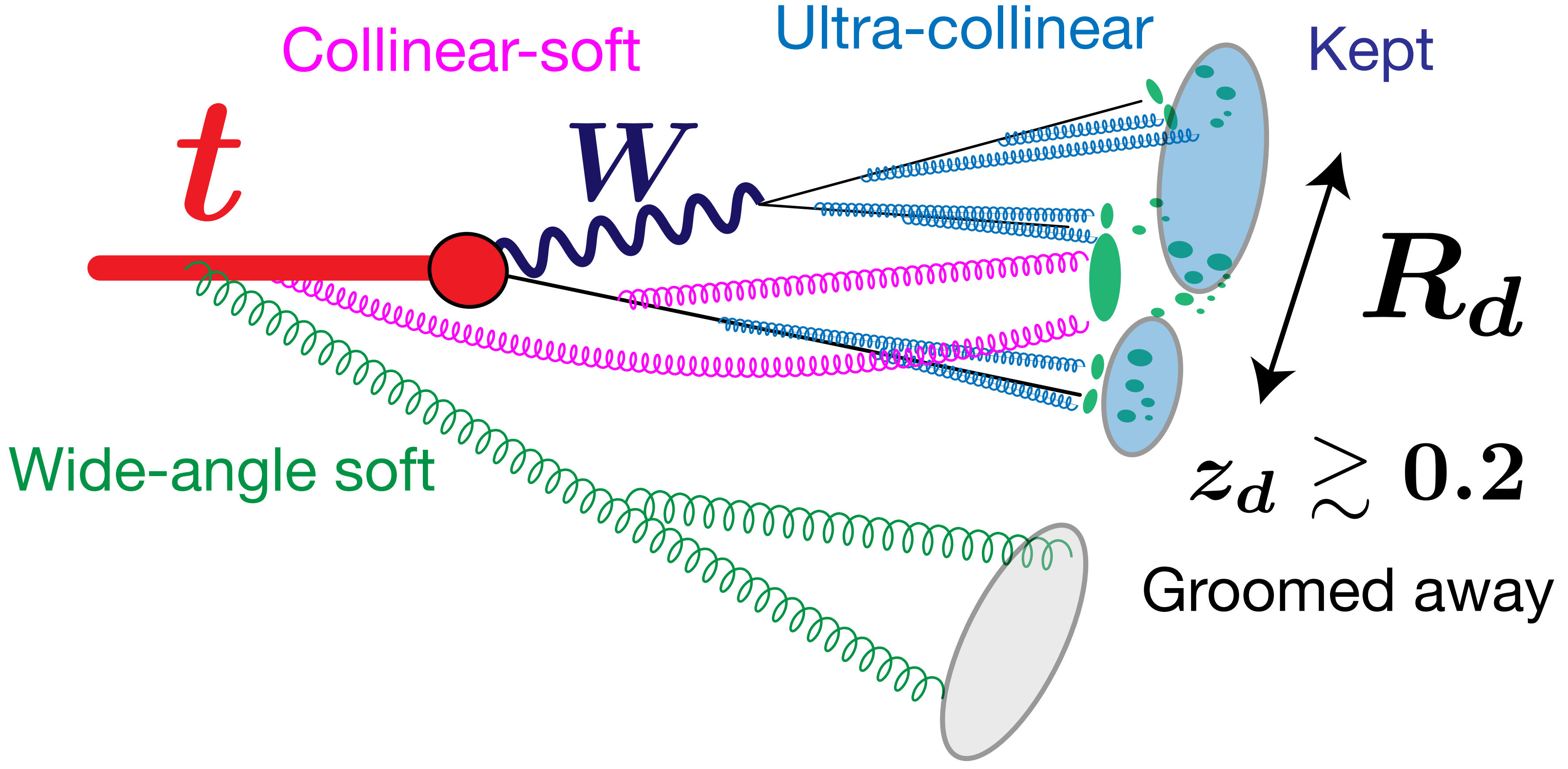
➡Means leading nonperturbative corrections are governed by the dynamics of soft drop.

- Not like in the case of ungroomed jets and makes things complicated.

CAN WE PUSH THIS FURTHER?

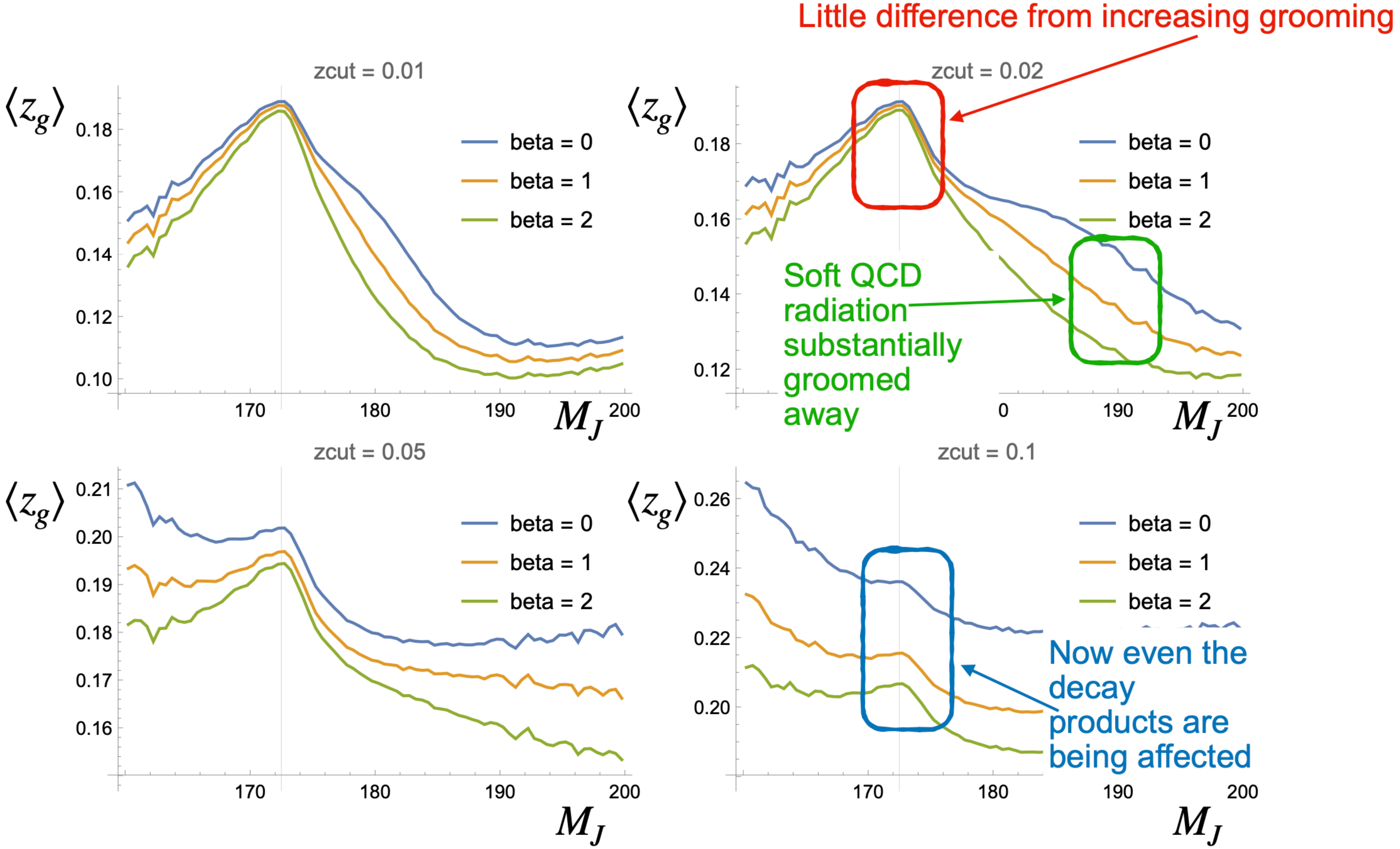
- **How can we apply more aggressive grooming but still retain the inclusive description of the top decay.**
- The top decay products effectively shield the ultra collinear radiation at small angular scales
  - The ultracollinear radiation remains clustered with the decay products.
- In this case a different set of modes are present in the factorisation.
  - Instead of the CS mode, the soft sector is now split into CSg and CSm modes.
- Here, the decay products effectively render interior of the jet as ungroomed.
  - **The Λ mode location is now determined by the opening angle of the decay product r_d and is not influenced by the soft drop.**
  - **Enables a simpler description of the nonperturbative effects like ungroomed jets.**





PROOF OF CONCEPT

The decay products protect the ultra-collinear radiation.



Little difference from increasing grooming

Soft QCD radiation substantially groomed away

Now even the decay products are being affected

GOAL OF ANALYSIS

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

$$\mathbf{m_t^{MC} = m_t^{pole} + \boxed{\Delta m_t^{pole}}}$$

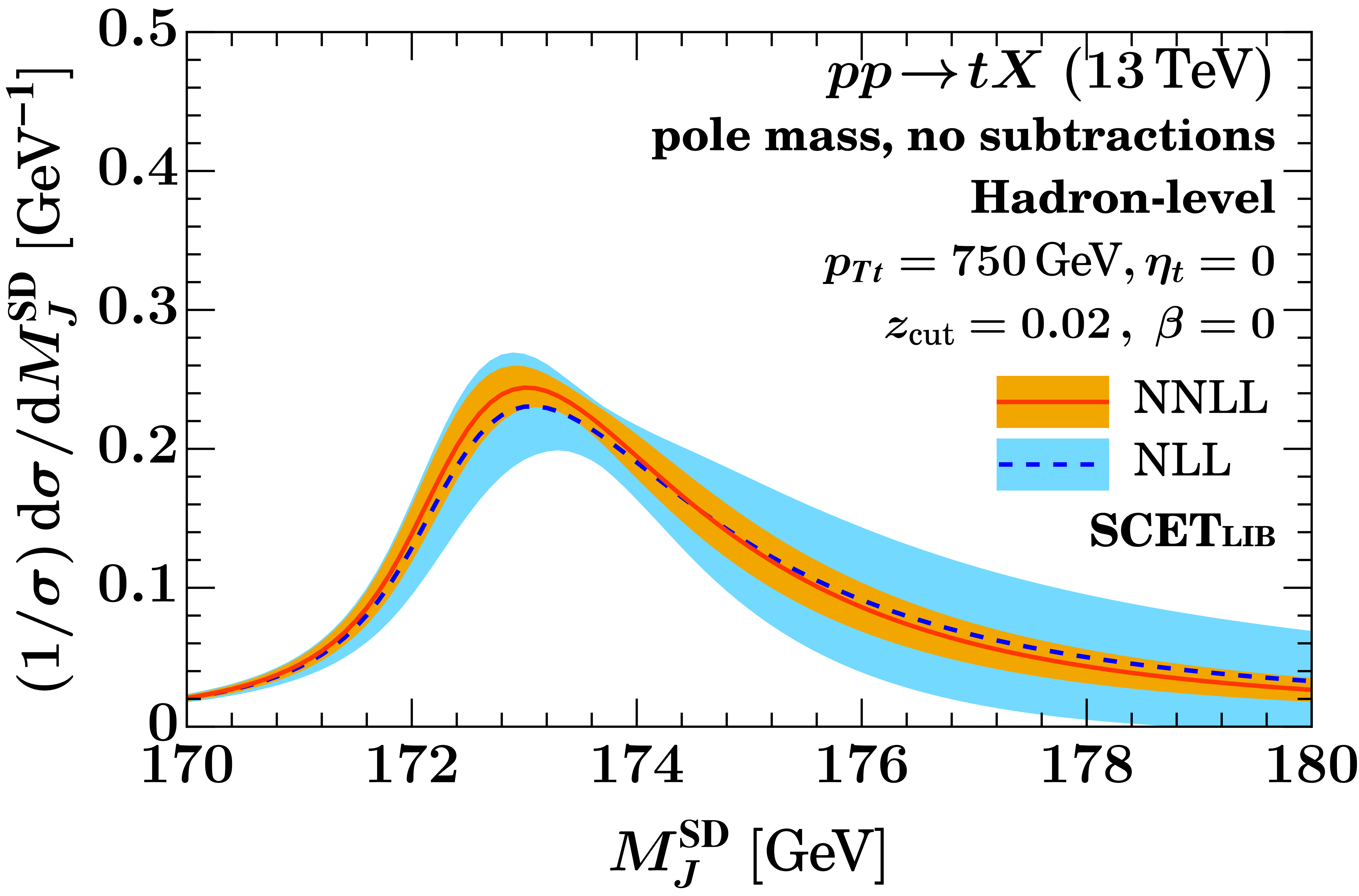
- Calibration performed with **NNLL calculation** compared against **Pythia MC** predictions with NNPDF3.0 NLO PDF set and A14 set of tuned parameters.

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

THEORETICAL CALCULATION

- **First-principle calculation with good control over the mass scheme.**
  - Yields particle-level predictions that can be compared directly to MC for a limited set of inclusive observables in boosted top production.
- **Continuation of top mass interpretations:**
  - $e^+e^- \rightarrow t\bar{t}$ processes NLL and NNLL accuracy. [Phys.Rev.Lett. 117 (2016) 23, 232001]

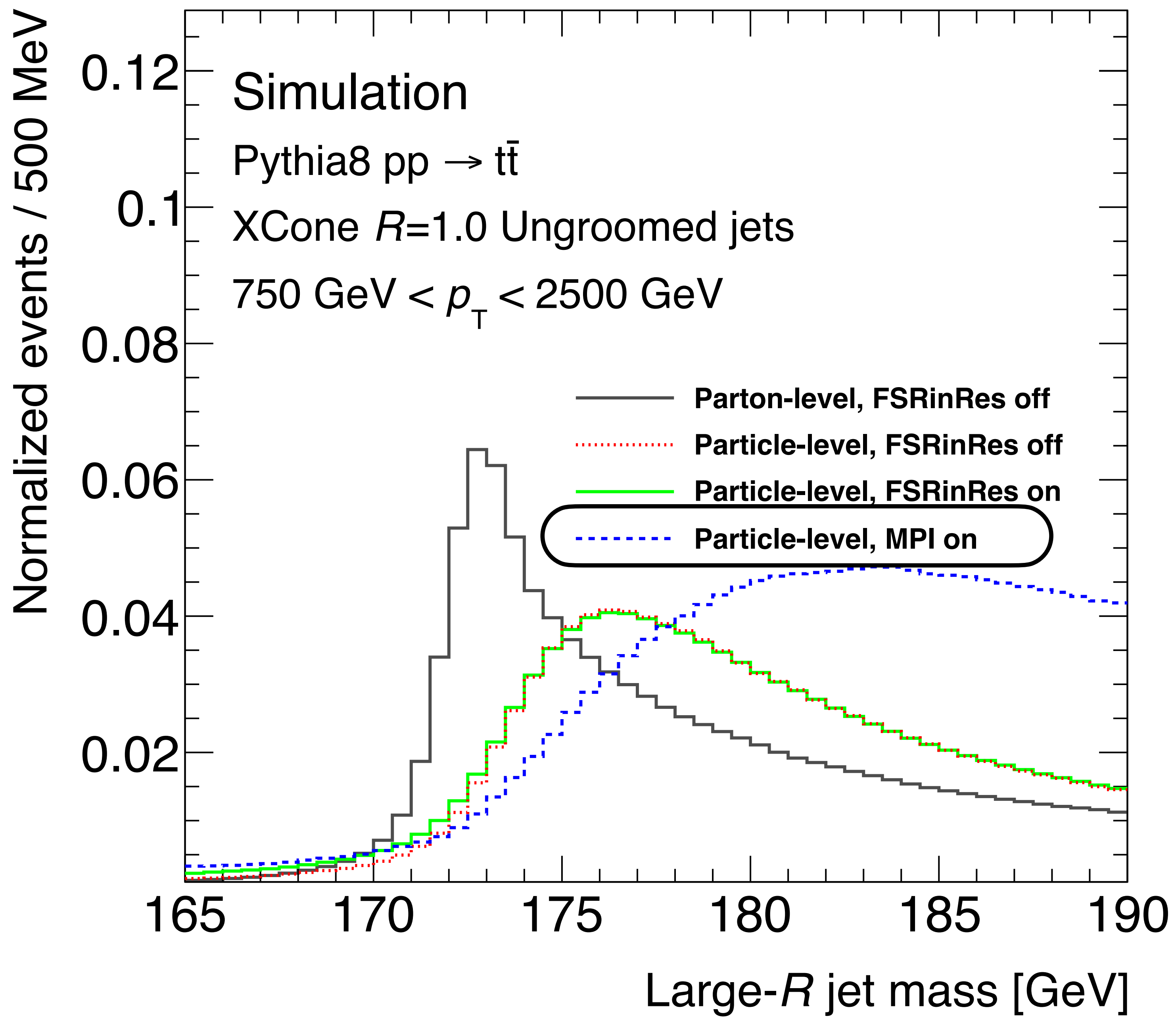
    [JHEP 12 (2023) 065]
  - $pp \rightarrow t\bar{t}$ processes at NLL accuracy. [ATL-PHYS-PUB-2021-034]
- **Using SCET-based calculation with NNLL accuracy**
  - Improved perturbative stability.

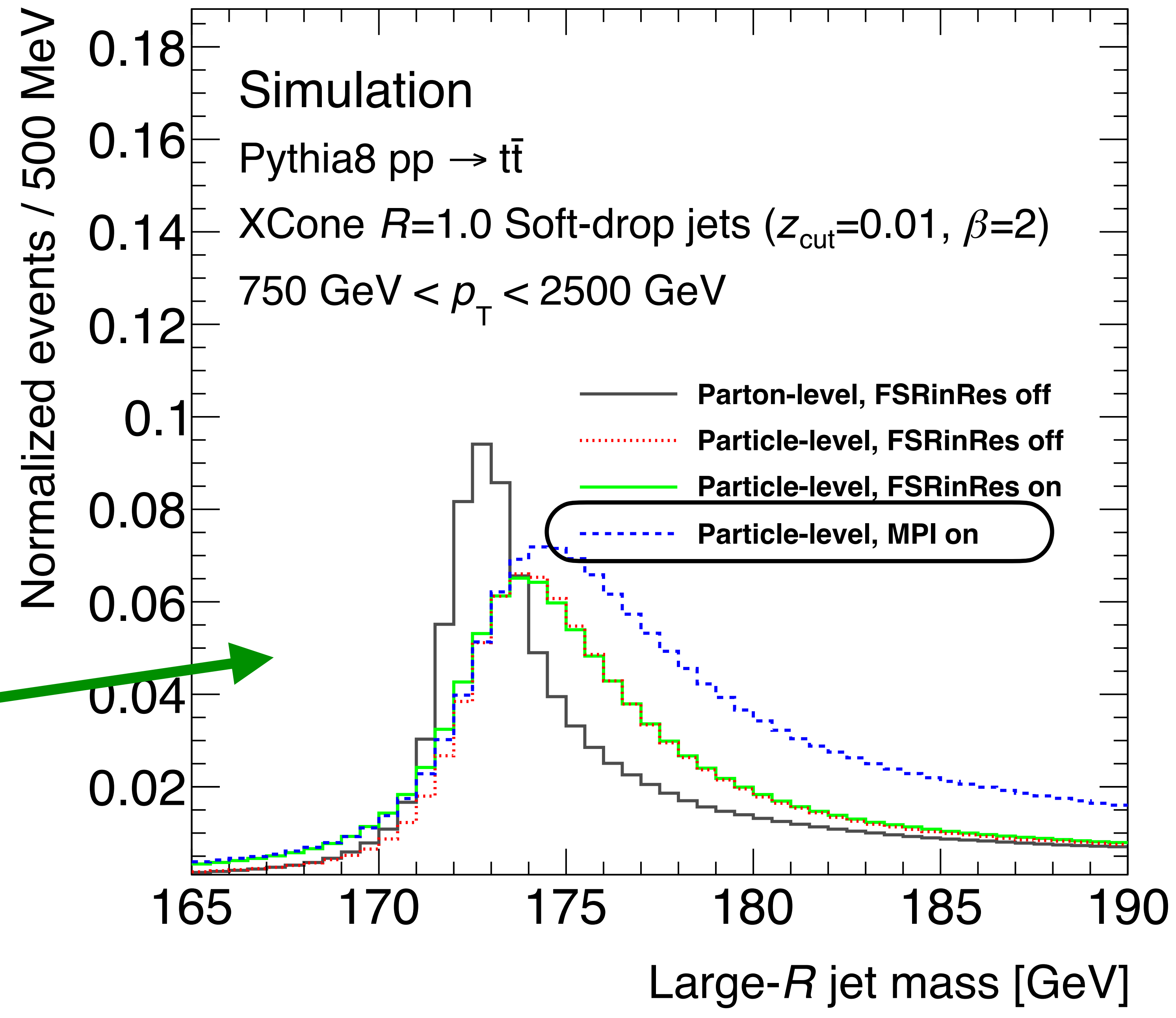


MICHEL, PATHAK, STEWART
IN PREPARATION

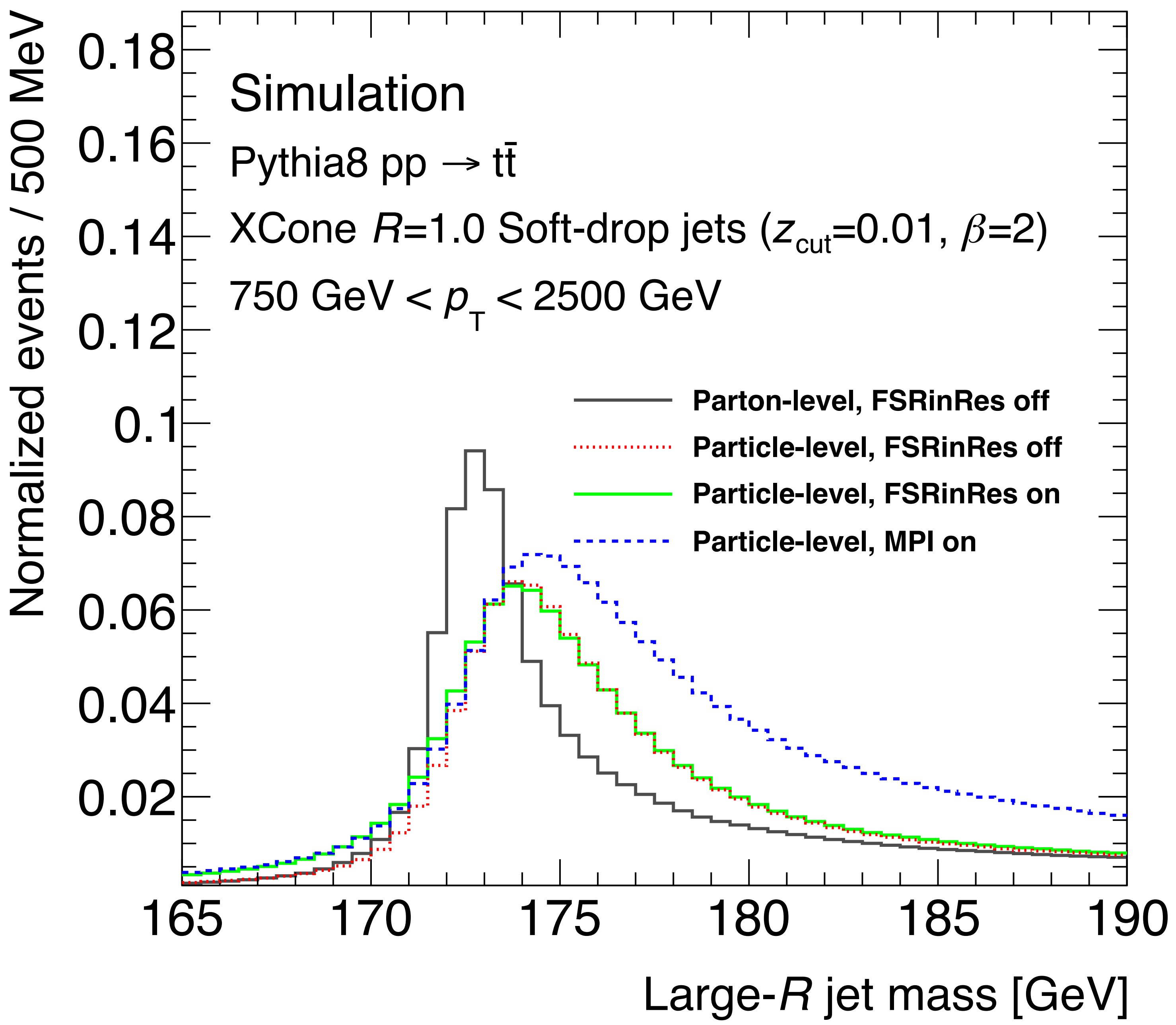
JET BUILDING

- Focus on particle-level hadronic top quark decay in $pp \to t\bar{t}$ and $e^+e^- \to t\bar{t}$ processes.
  - Top mass determined by fitting large-R jet mass containing hadronic top.
  - Mass reconstructed using information from decay products of top quark within large-R jet.
- Large-R jets built with:
  - **XCone** jet algorithm with **R = 1**.
    - Jet algorithm minimising N-jettiness. Useful filtering out unwanted jets in densely populated events (useful in boosted regime where signal jets may partially overlap.)
  - **Soft-drop light grooming** applied to remove soft-wide radiation (**$z_{cut} = 0.01$, $\beta = 2$).**
    - Considerably reduces UE impact. Shift of ~5 GeV down to ~1 GeV.

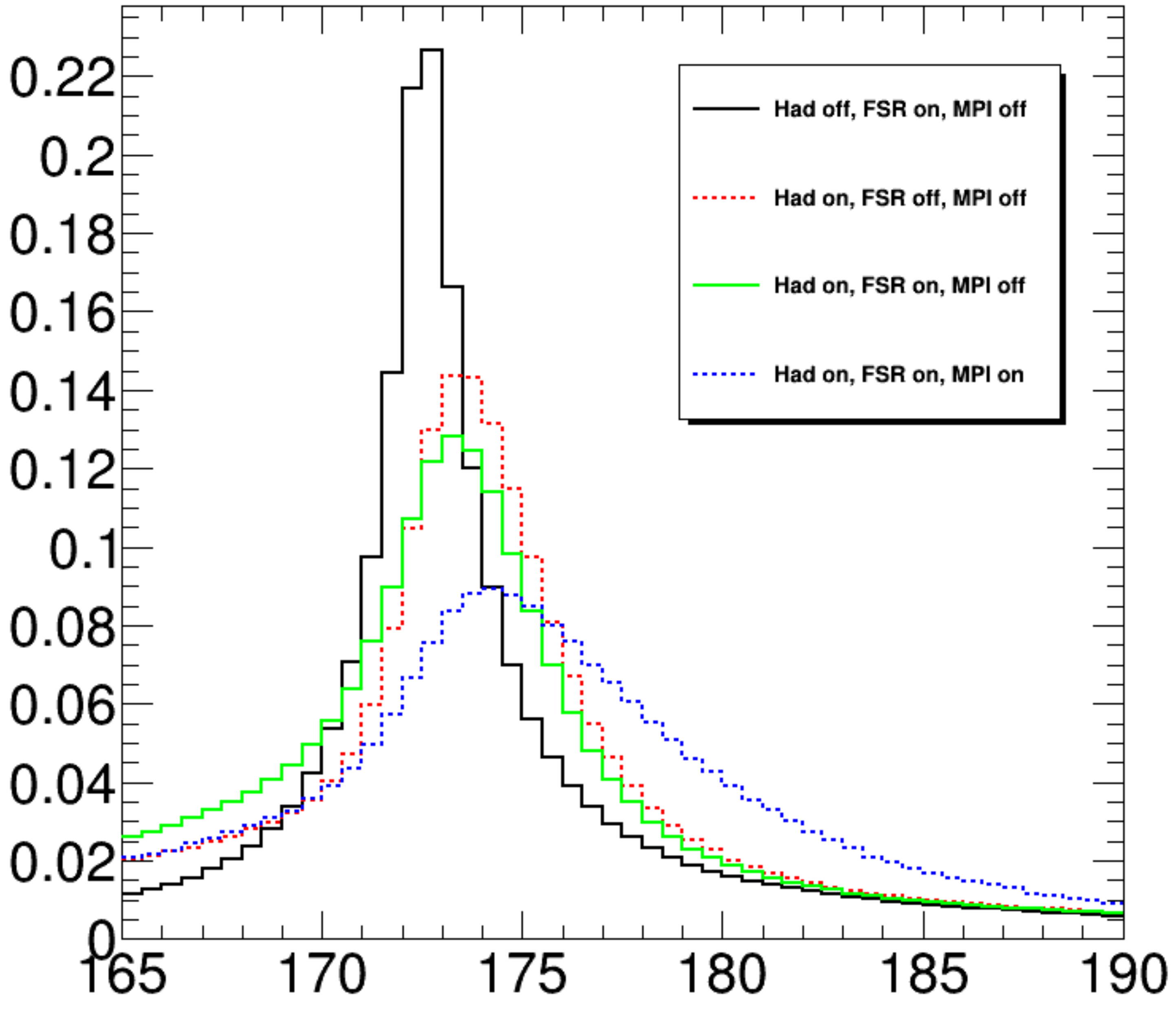




NEW JET BUILDING



- **Soft-drop light grooming** applied to remove soft-wide radiation **(**$z_{cut} = 0.01, \beta = 2$**).**
  - Considerably reduces UE impact. Shift of ~5 GeV down to ~1 GeV.
- **Now possible to use a more aggressive grooming scheme (**$z_{cut} = 0.02, \beta = 0$**).**
  - Reduces UE impact even further.



HADRONIZATION AND UNDERLYING EVENT: EXPECTATION

- Peak position in new grooming scheme:

$$M_J^{Peak} \sim m_t + \Gamma_t(1 + \alpha_s \ldots) + \underbrace{h \times \Omega_1}_{\text{Hadronisation effects}} + \underbrace{\left\langle R_d^4 \right\rangle_{M_J} \Lambda_{UE}}_{\text{UE effects}}$$

- The top quark jet only depends on h, defined as $R_d = \frac{m_t}{p_T} h$
  - We now also bin in h in addition to p_T (an independent variable).
  - Underlying event contribution Λ_{UE} depends on p_T (depends on the catchment area). Can disentangle underlying event by considering different p_T bins.

JET BUILDING

- Focus on particle-level hadronic top quark decay in $pp \rightarrow t\bar{t}$ and $e^+e^- \rightarrow t\bar{t}$ processes.
  - Top mass determined by fitting large-R jet mass containing hadronic top.
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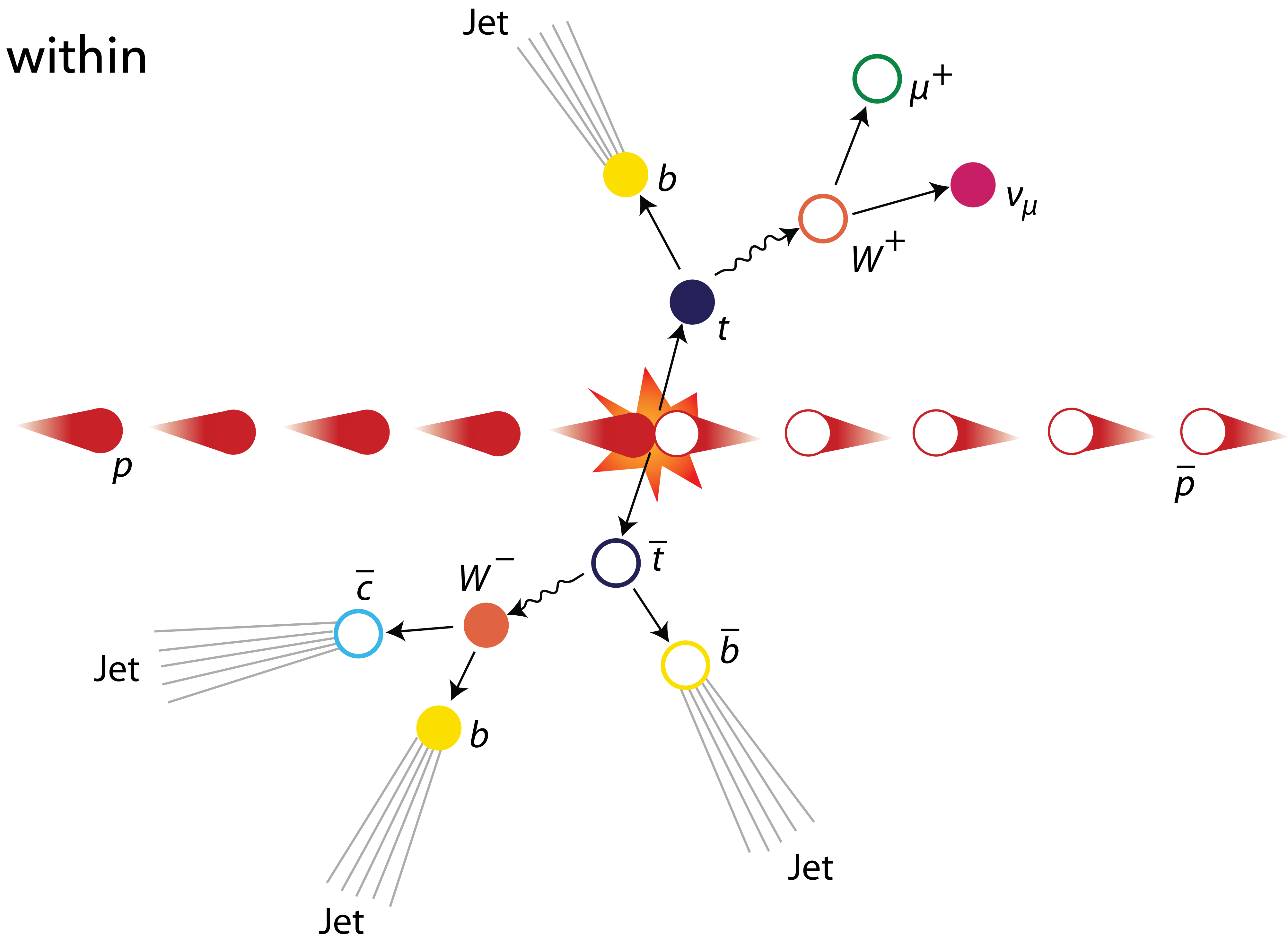


- Boosted jet - Inclusive treatment of decay products:
  - **Previously used four orthogonal jet p_T bins:**

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

  - **Now use two orthogonal jet p_T bins:**

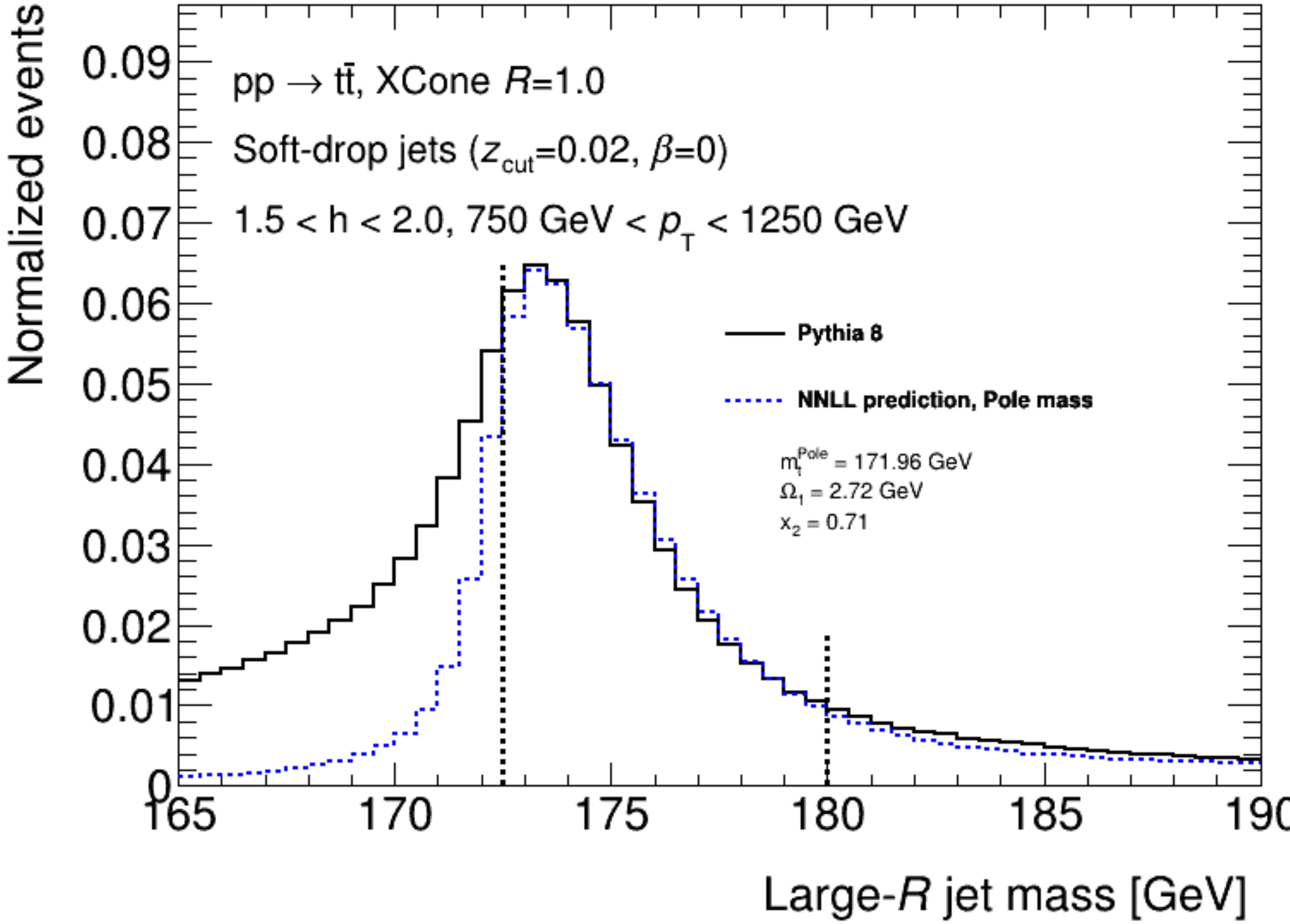
$p_T^{jet} \in \{750,1250,2500\}$GeV.

  - **and four jet h bins:**

$h^{jet} \in \{1.5,2,2.5,3,3.5\}$.

FITTING DETAILS

- Model uses three parameters, $\mathbf{m_t}^{Pole}$, $\mathbf{\Omega_1^{had}}$, and $\mathbf{x_2}$ associated with **first-** and **second-moment non-perturbative corrections.**
- Idea is to obtain **value of parameters in NNLL theory** calculation that **best describe MC prediction.**
- m_t^{Pole}, Ω_1^{had}, and x_2 varied:
    - Best fit of MC-to-theory distributions found for variations of the three parameters.
    - χ^2 minimisation fit applied to the three parameters to find the global minimum.
    - **This is how we extract the top quark pole mass.**

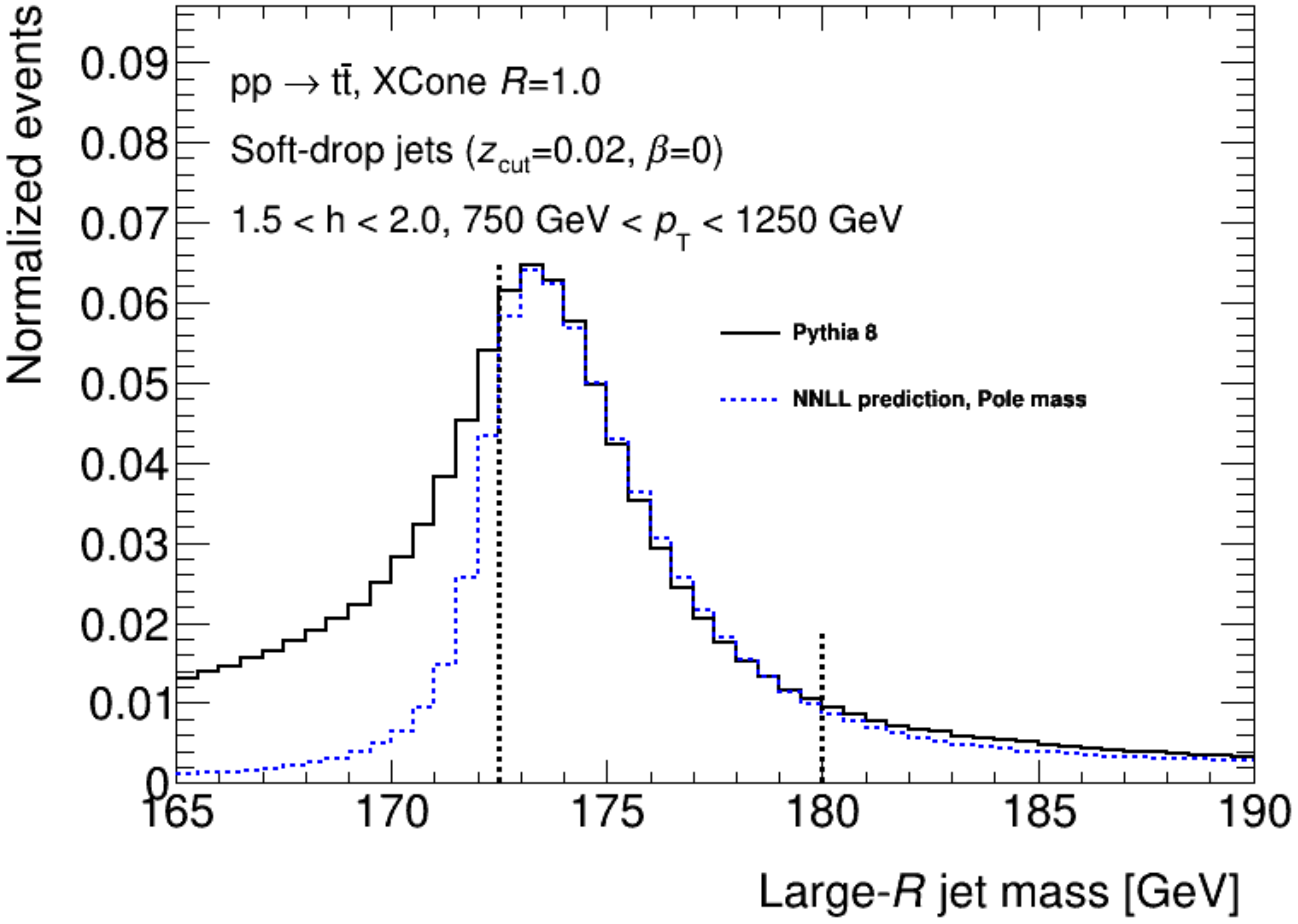


FITTING DETAILS

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

- **Decay product FSR effects are not yet included in calculation where we treat decay inclusively.**
  - In grooming procedure, theory does not accurately describe the low-mass tail present in the generator prediction.
  - Must restrict fit range to avoid the low jet-mass tail, that would bias the extracted top mass to lower values.

➡ **Fit range set to 172.5-180 GeV.**



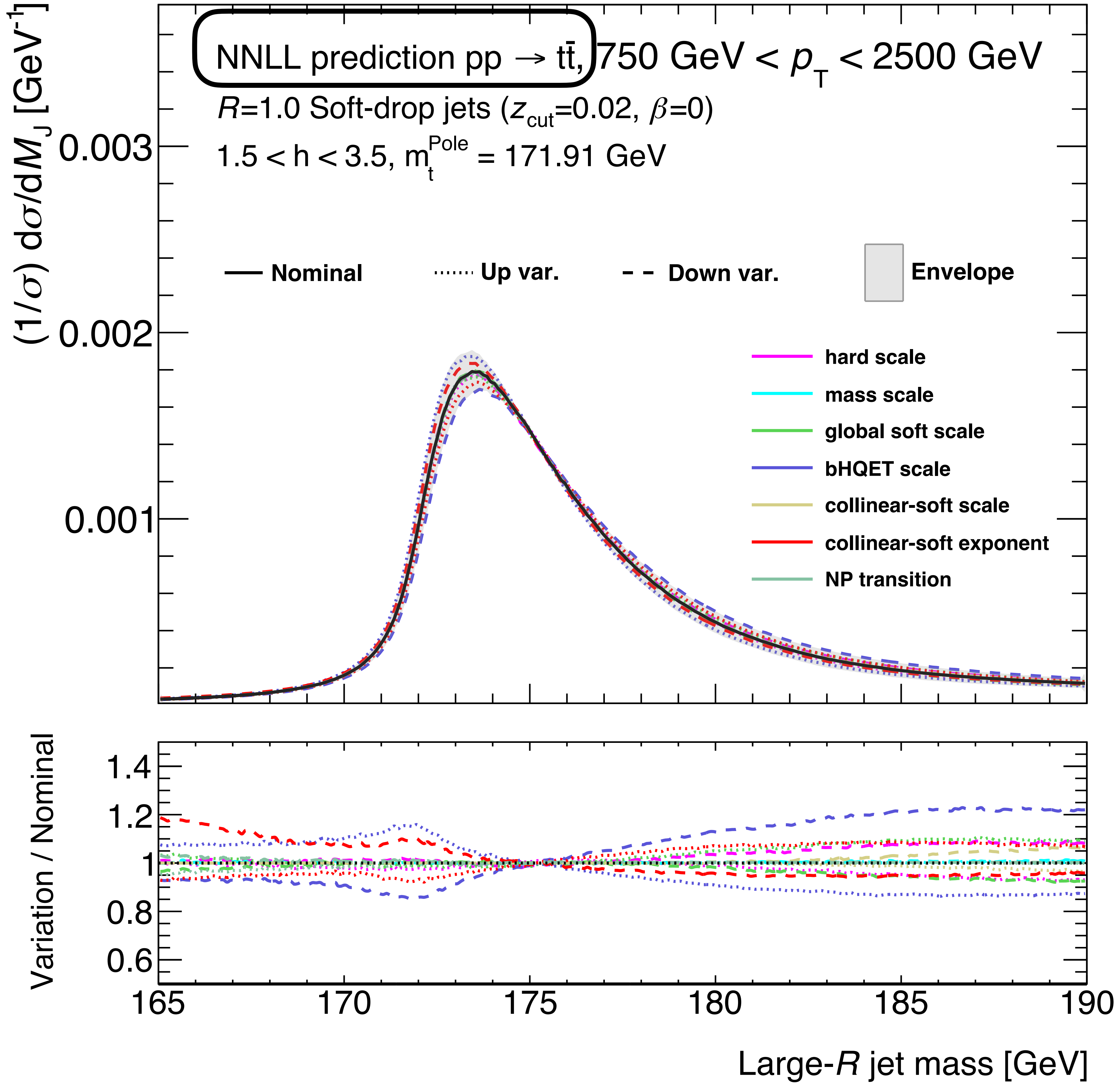
- Perform a **fit range study.**
  - Measure the top quark mass value at 172-180 GeV and 173-180 GeV

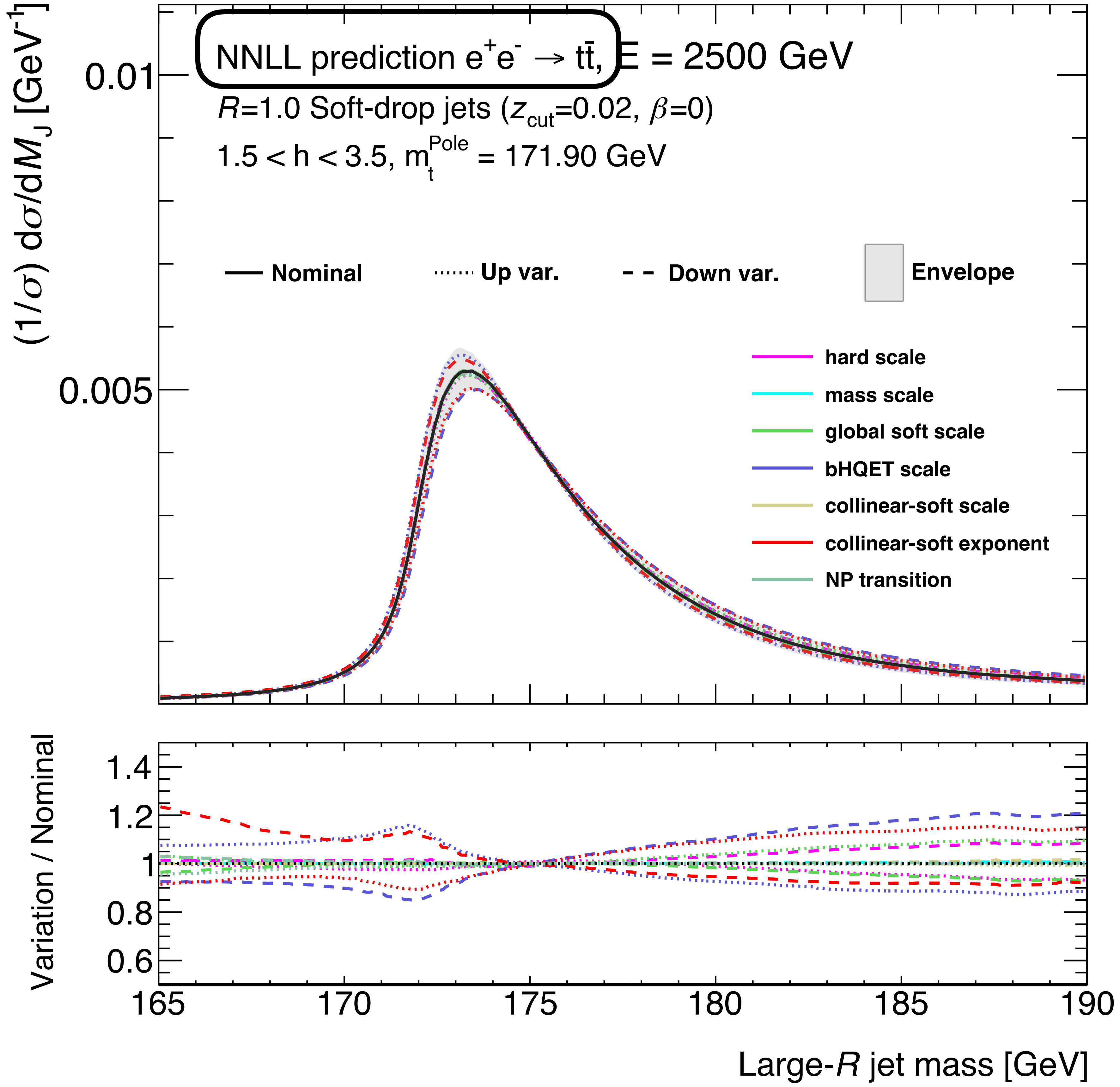
➡ Estimate an uncertainty.

THEORETICAL UNCERTAINTIES

- Theoretical uncertainty determined by jet mass dependent renormalisation scales that to estimate the perturbative uncertainty.

Scale variations on these dependencies measured and compared to central value.





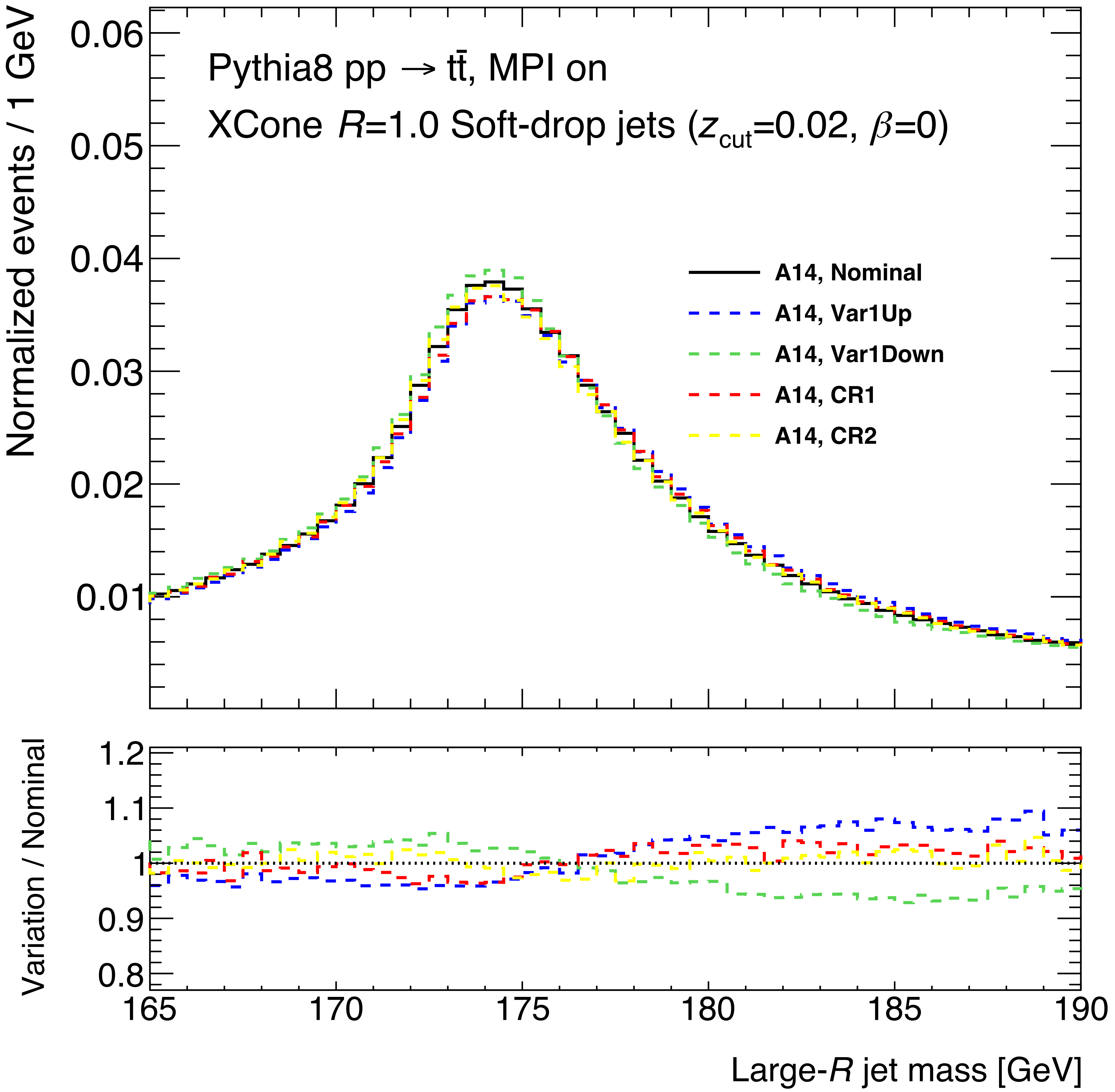
FITTING DETAILS

- Need to cover any bias of the influence of the kinematic ranges on the mass relation.
    - **Impact of the choice of large-R jet h is evaluated.**
    - **Compare fits on sub-sets of three h intervals for all permutations of the set of the 4 h bins.**
    - **Maximum variation taken as the uncertainty.**

- Also apply this for p_T impact.

UNDERLYING EVENT UNCERTAINTIES

- UE for now must be estimated through simulation parameter changes in MC-to-MC fits.
  - Comparing nominal MPI-on Pythia against A14 eigentune variations (coverage of UE variations modelling uncertainties).
- Not yet testing the UE peak shift hypothesis
- UE contribution of the jet mass peak is disentangled from hadronisation effects:
  - Can be possible to calculate the UE effect on the relation result.
  - Future work.



UNCERTAINTY

- Uncertainties are applied to account for:

- **Estimation of perturbative uncertainty in calculation.**
- **Fitting methodology (FSR estimation not present in calculation).**
- h **and** p_T **influence of large-R jet.**
- **UE not yet present in the calculation.**

	Uncertainty (ee) [MeV]	**Uncertainty (pp) [MeV]**
Theoretical	+160/-210	+150/-250
Fitting	220	260
Kinematic range	-30/-50	+20/-90
Underlying event	N/A	+225/-180
Total	**+275/-215**	**+375/-320**

RELATION RESULTS

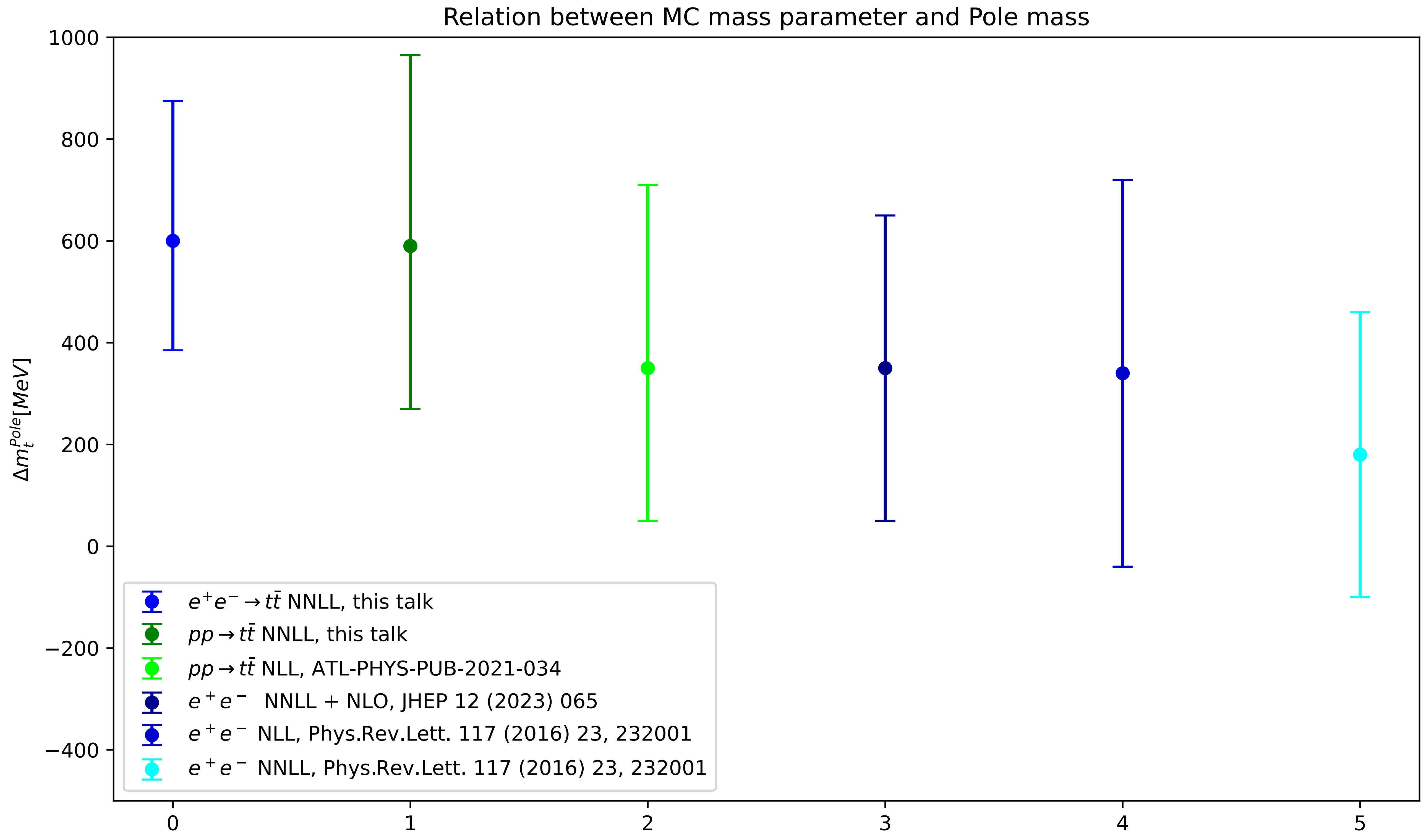
Mass relation (pp):

$$\Delta^{Pole} = m_t^{MC} - m_t^{Pole} = 590^{+375}_{-320}\ \text{MeV}$$

Mass relation (e^+e^-):

$$\Delta^{Pole} = m_t^{MC} - m_t^{Pole} = 600^{+275}_{-215}\ \text{MeV}$$

Suggests universality between the e^+e^- and pp processes.



- Comparisons with previous top quark mass interpretations in pp and e^+e^- collision regimes.
    - All results compatible within uncertainties.

CONCLUSION

- **Preliminary results have found a working procedure for the new grooming method described in this talk.**

- Accounts for more physics effects while giving a relatively accurate result.

- Relation results of 590 and 600 MeV for pp and e^+e^-, respectively are promising considering their compatibility.
  - Suggests universality for different processes of $t\bar{t}$ interactions.

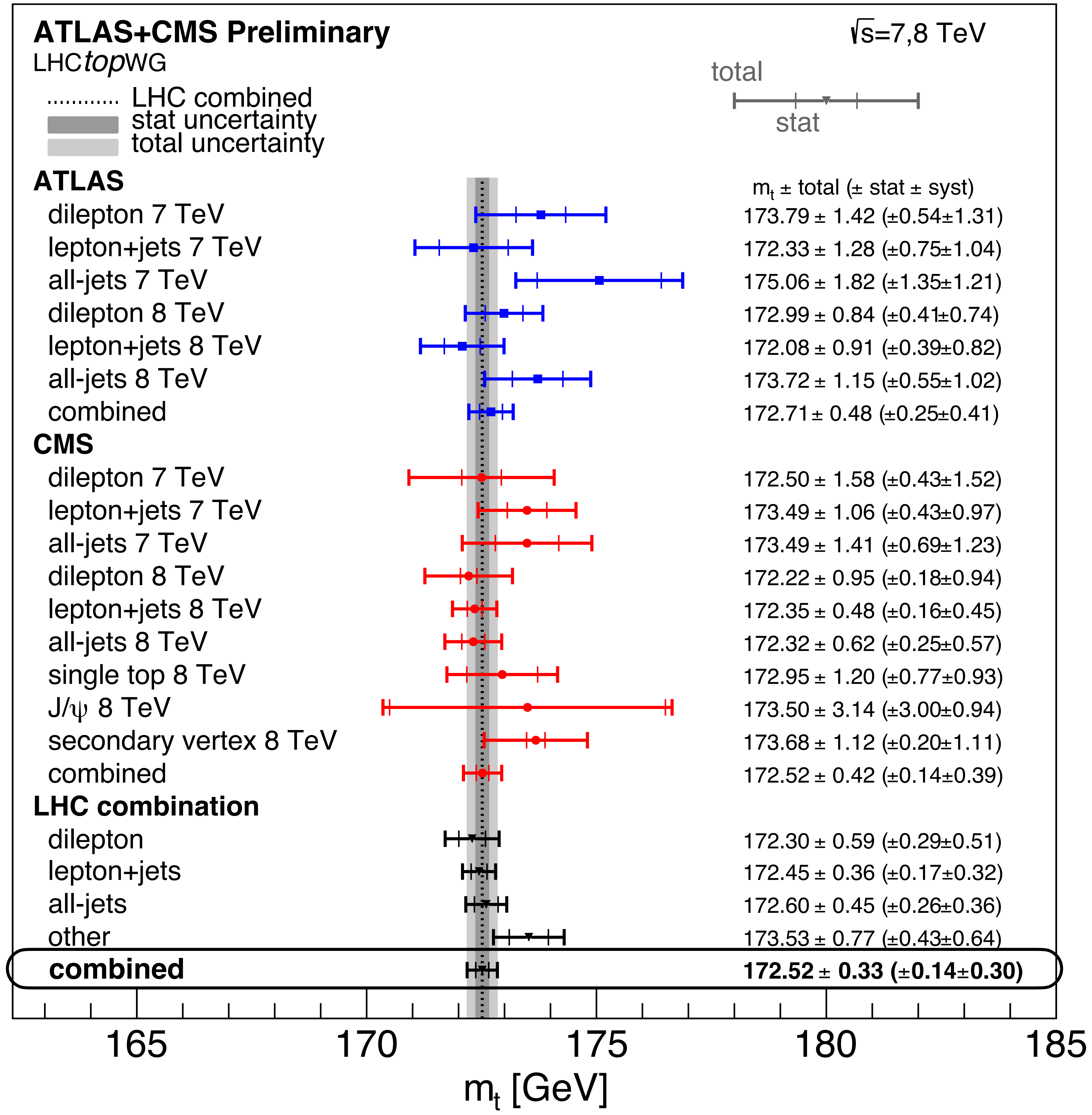
- Work to be done with Herwig samples that should closer reflect the hadronisation effects of the theory and give more accurate results.

- More time necessary to fully understand these results and write into a comprehensive paper.

- Future would be applying this to MSR mass for more accurate and applicable results.

Thanks for listening

TOP QUARK MASS MEASUREMENTS - DIRECT



Phys. Rev. Lett. 132, 261902

- m_t determined experimentally by studying top quark decay products.
  - MC-based templates at detector level - combination of first principle QCD calculations and modelling techniques (e.g. hadronisation and parton shower).
  - Hard reactions at high energy + low energy QCD effects.
- Most precise determination of top quark mass m_t^{MC} $\mathcal{O}$ **(330) MeV** precision.

Average m_t^{MC} from LHC top WG combination:

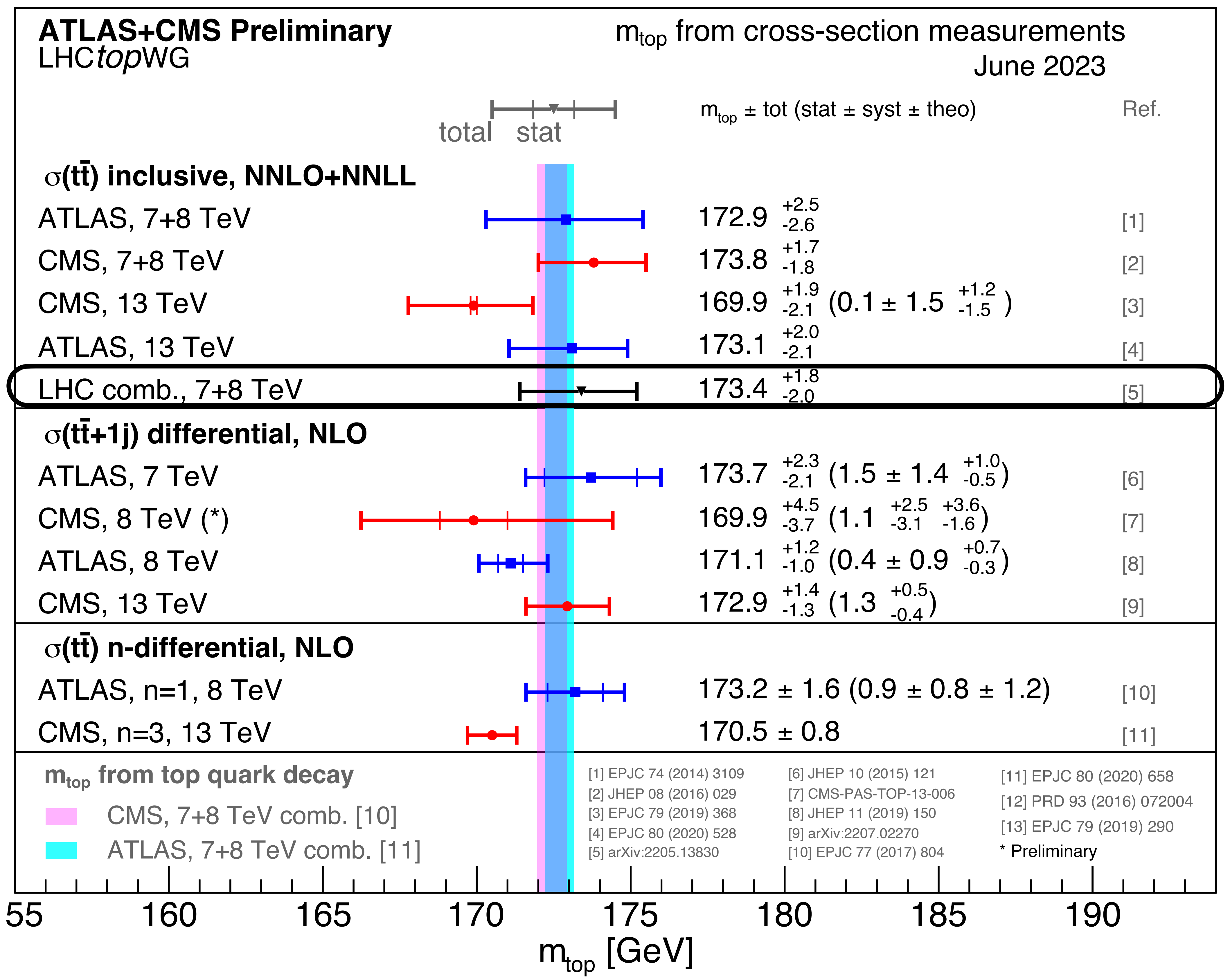
$$m_t^{MC} = 172.52 \pm 0.33 \text{ GeV}$$

TOP QUARK MASS MEASUREMENTS – INDIRECT

- Aims for accurate measurements in terms of the **Lagrangian mass parameter**.
- m_t determined by analysing parton-level production cross-sections (inclusive and differential).
  - Calculations sensitive to hard scatter at high energy scales, where top quarks are produced.
- Most precise measurements $\mathcal{O}$**(1) GeV** precision.
  - m_t^{pole} value from **inclusive** cross section measurements LHC top WG combination:

$$m_t^{pole} = 173.4^{+1.8}_{-2.0}\ \text{GeV}$$

Phys. Rev. Lett. 132, 261902



Differential cross sections yield more precise results.

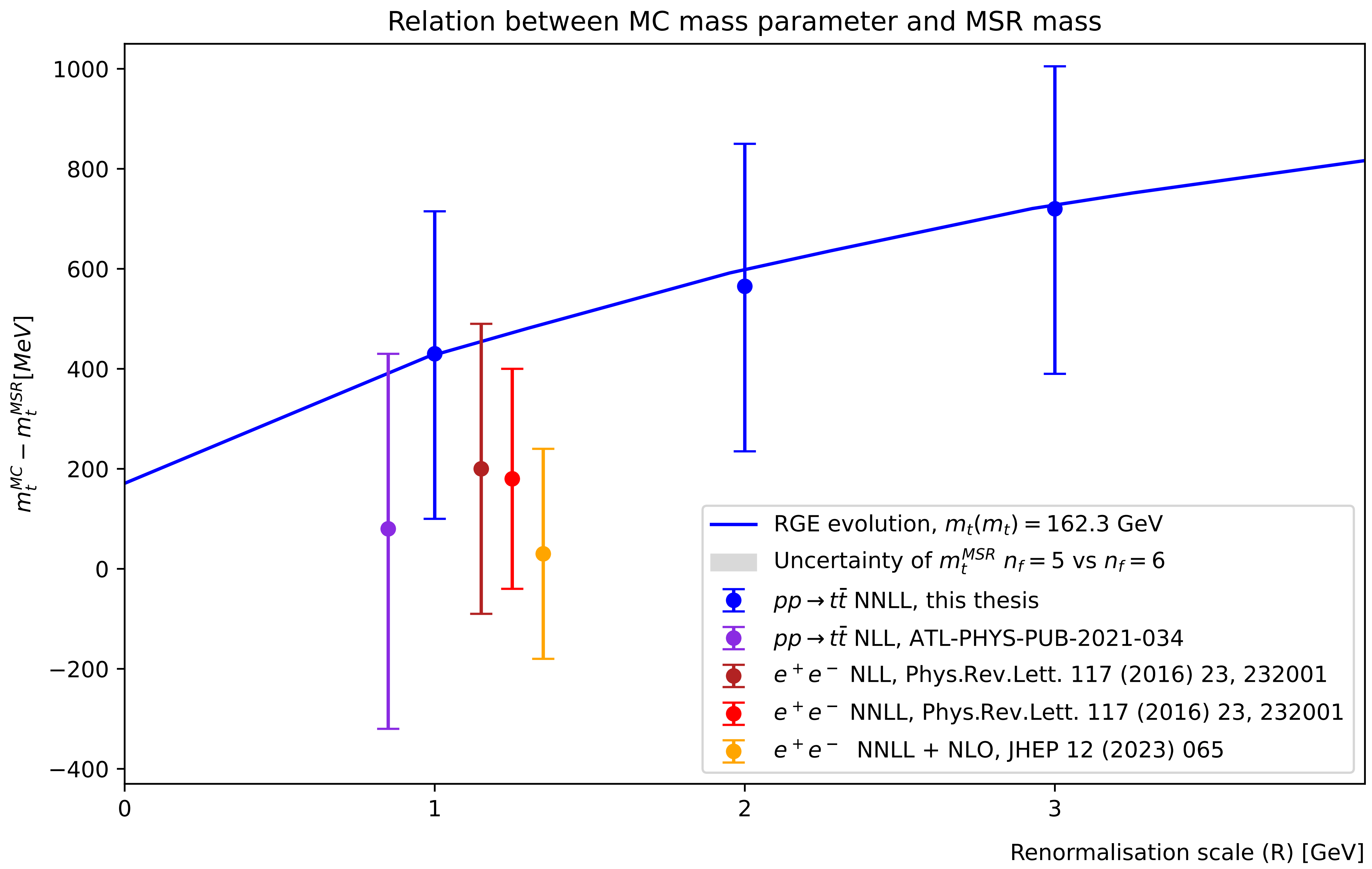
PREVIOUS RESULT

- Previously, we performed a study on the MSR mass for calibration in $pp \rightarrow t\bar{t}$ processes.

Mass relation of:

$$\Delta^{MSR} = m_t^{MC} - m_t^{MSR}(R = 3\ \text{GeV}) = 720^{+285}_{-330}\ \text{MeV}$$

- Uncertainties decreased significantly from previous relation with pp processes.
- Optimised R value and improved NNLL calculation.



- Comparisons with previous top quark mass interpretations in pp and e^+e^- collision regimes.
    - All results compatible within uncertainties.

Comps eB = 2 vs normal

Nominal result p_T = 750-1250 GeV:

m_t^{pole} = 171.92

Ω_1 = 2.58

x_2 = 0.84

Nominal result E = 2500 GeV:

m_t^{pole} = 171.90

Ω_1 = 2.72

x_2 = 0.89

Nominal result p_T = 750-1250 GeV (eB=2):

m_t^{pole} = 171.54

Ω_1 = 2.33

x_2 = 0.60

Nominal result E = 2500 GeV (eB=2):

m_t^{pole} = 171.75

Ω_1 = 2.42

x_2 = 0.76

pp Nominal results

Nominal result p_T = 750-1250 GeV (eB=2):

m_t^{pole} = 171.54

Ω_1 = 2.33

x_2 = 0.60

Nominal result p_T = 750-1250 GeV:

m_t^{pole} = 171.92

Ω_1 = 2.58

x_2 = 0.84

Nominal result combined p_T:

m_t^{pole} = 171.91

Ω_1 = 2.59

x_2 = 0.75

Nominal result p_T = 1250-2500 GeV:

m_t^{pole} = 171.91

Ω_1 = 2.56

x_2 = 0.72

ee Nominal results

Nominal result combined E:

m_t^{pole} = 171.90

Ω_1 = 2.79

x_2 = 0.88

Nominal result E = 2500 GeV:

m_t^{pole} = 171.90

Ω_1 = 2.72

x_2 = 0.89

Nominal result E = 3500 GeV:

m_t^{pole} = 171.90

Ω_1 = 2.82

x_2 = 0.89

h bin comparison