Energy correlators for the top quark mass

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Outline

- Precision top quark mass extraction from LHC data: a persistent challenge
- Novel proposal: extract the top mass from correlators of energy flow operators
- Parton-shower simulations: theoretical robustness and experimental feasibility
- Summary and outlook

J. Holguin, I. Moult, A. Pathak, MP, Phys. Rev. D 107 (2023)

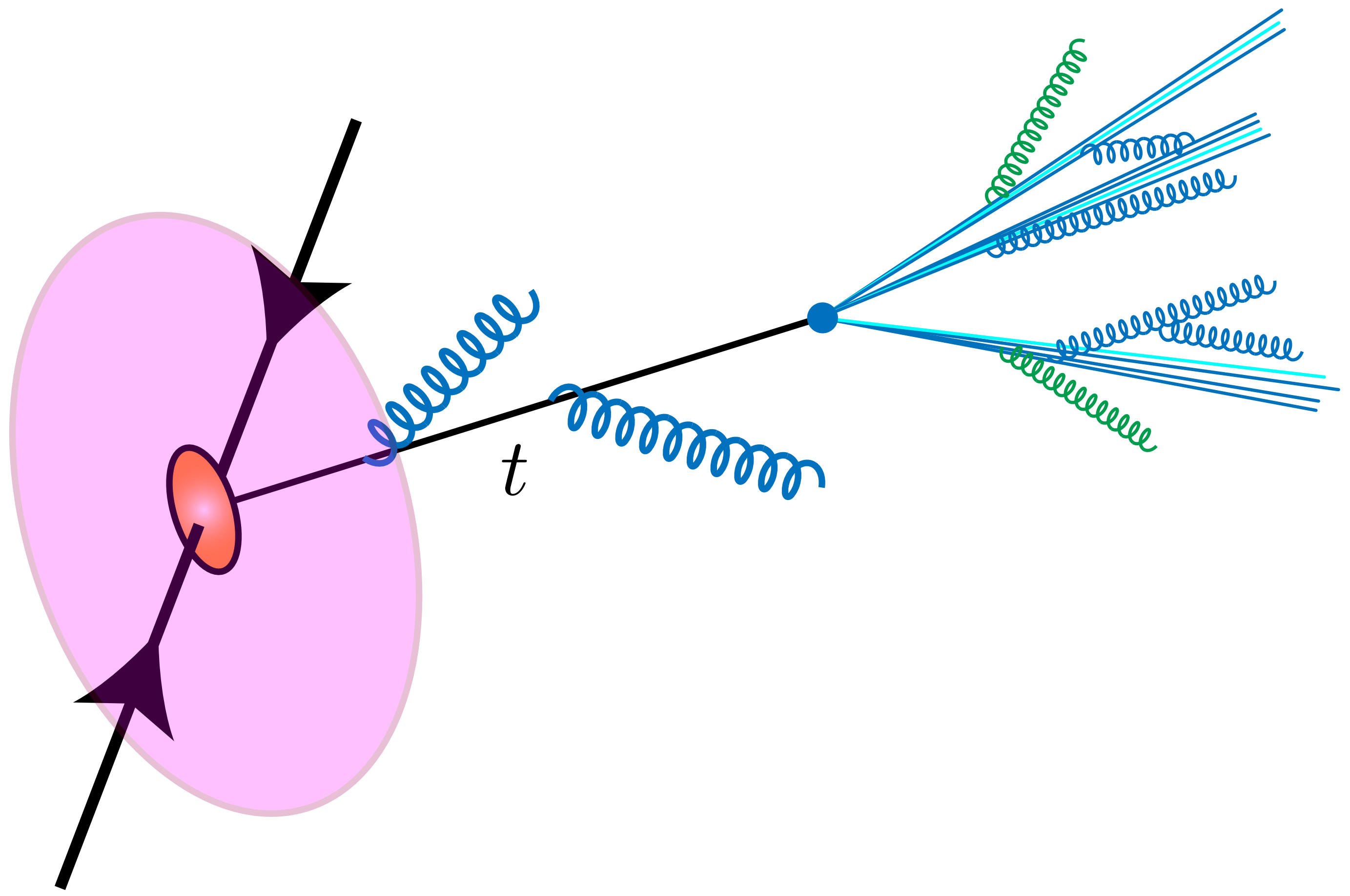
J. Holguin, I. Moult, A. Pathak, MP, R. Schöfbeck, D. Schwarz, 2311.02157, 2407.12900

The top quark mass: indirect measurements

- Top quark mass: SM parameter of fundamental importance in high-energy physics (EW precision tests, vacuum stability,...) High precision at LHC: persistent challenge

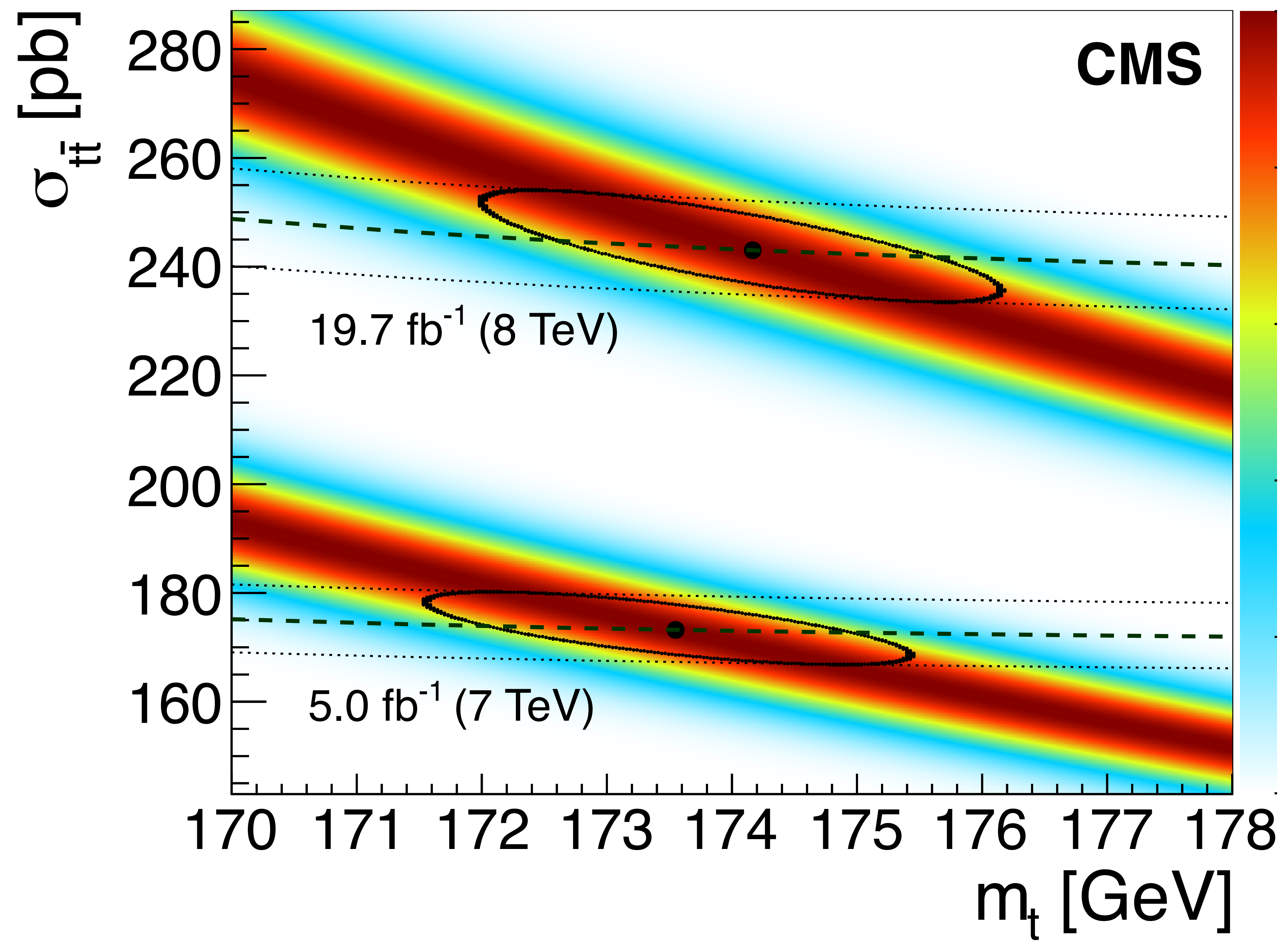
- Extracted by comparing theory vs data for collider observables, whose perturbative calculable contributions are evaluated in a specific renormalization scheme

- Good theoretical control for inclusive $t\bar{t}$ cross section (indirect top mass sensitivity, tied to hard interaction)
  Parton-level results for $\sigma(t\bar{t}+X)$ to NNLO+NNLL accuracy (Czakon, Mitov 1112.5675) used by ATLAS and CMS to extract m_t in the pole-mass scheme



The top quark mass: indirect measurements

CMS 1603.02303



$\Delta m_t^{\text{pole}} \sim \pm 2\,\text{GeV}$ from $\sigma_{t\bar{t}}$

ATLAS 1910.08819, CMS 1812.10505

Weakly sensitive to the top mass, strongly affected by PDF uncertainties

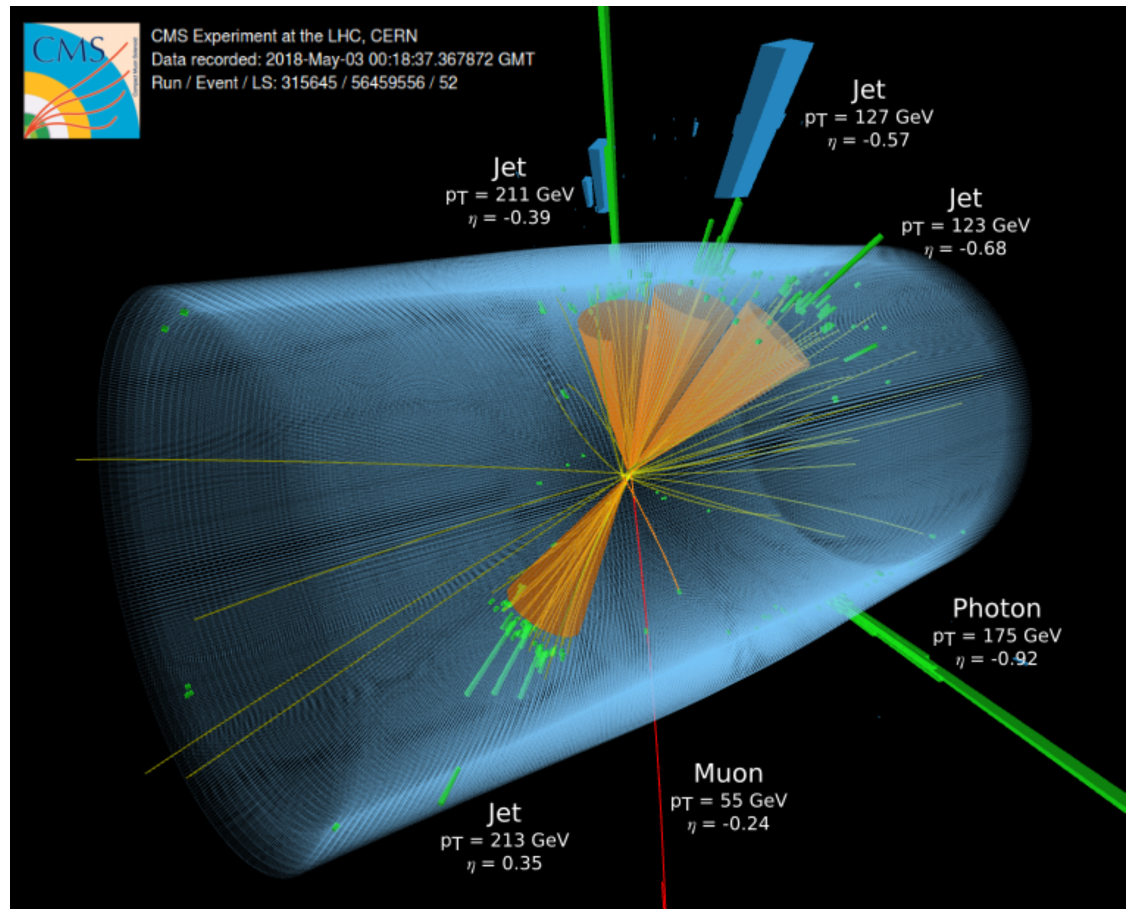
Higher sensitivity to the top mass achieved by considering differential distributions as well as $t\bar{t}+\text{jet}$ processes: $\Delta m_t^{\text{pole}} \sim \pm 1\,\text{GeV}$ ATLAS 1905.02302, CMS 1904.05237, Cooper-Sarkar et al. 2010.04171 ...

The top quark mass: direct measurements

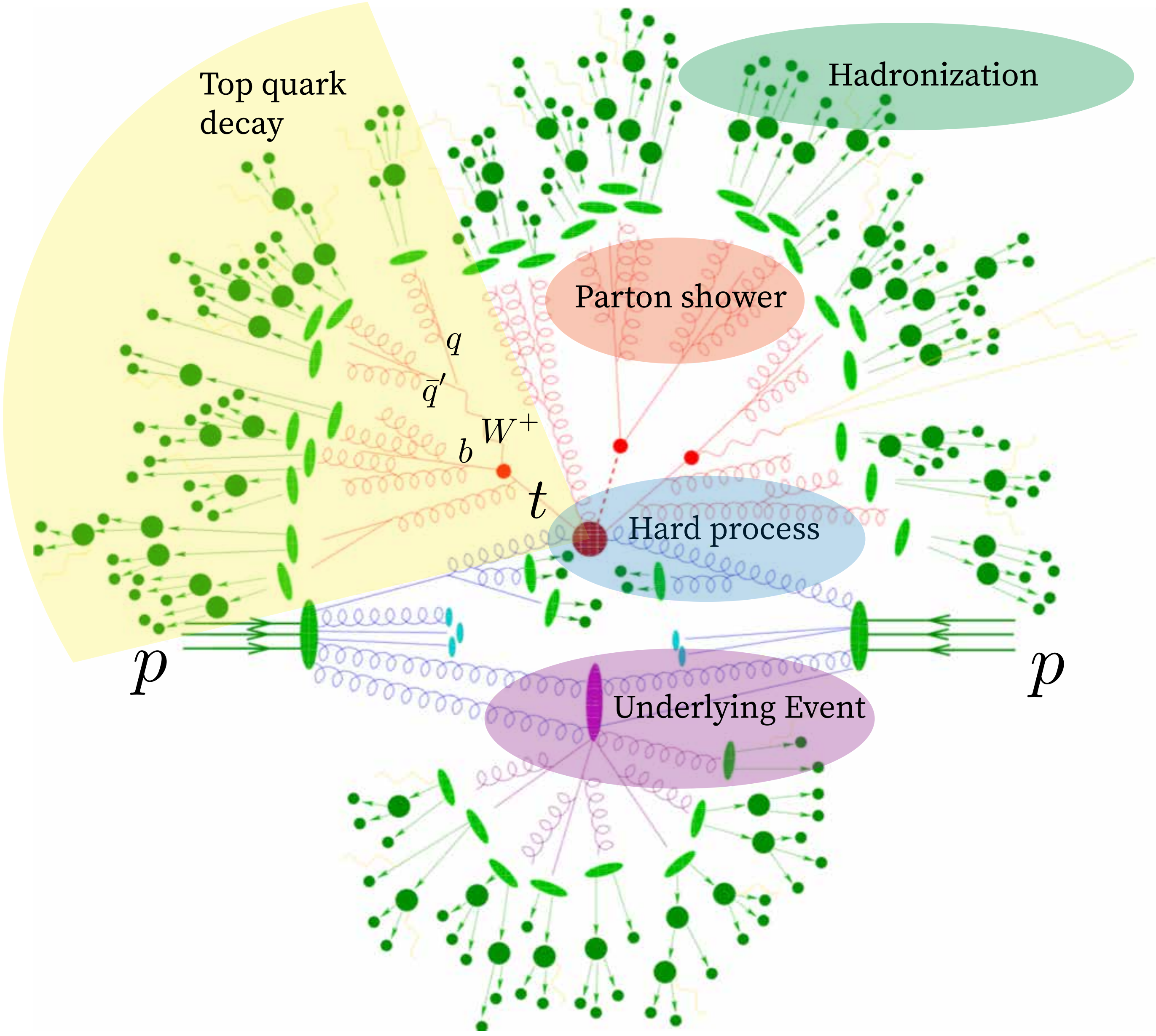
- Analysis of kinematic observables built out of reconstructed top decay products has yielded higher precision:

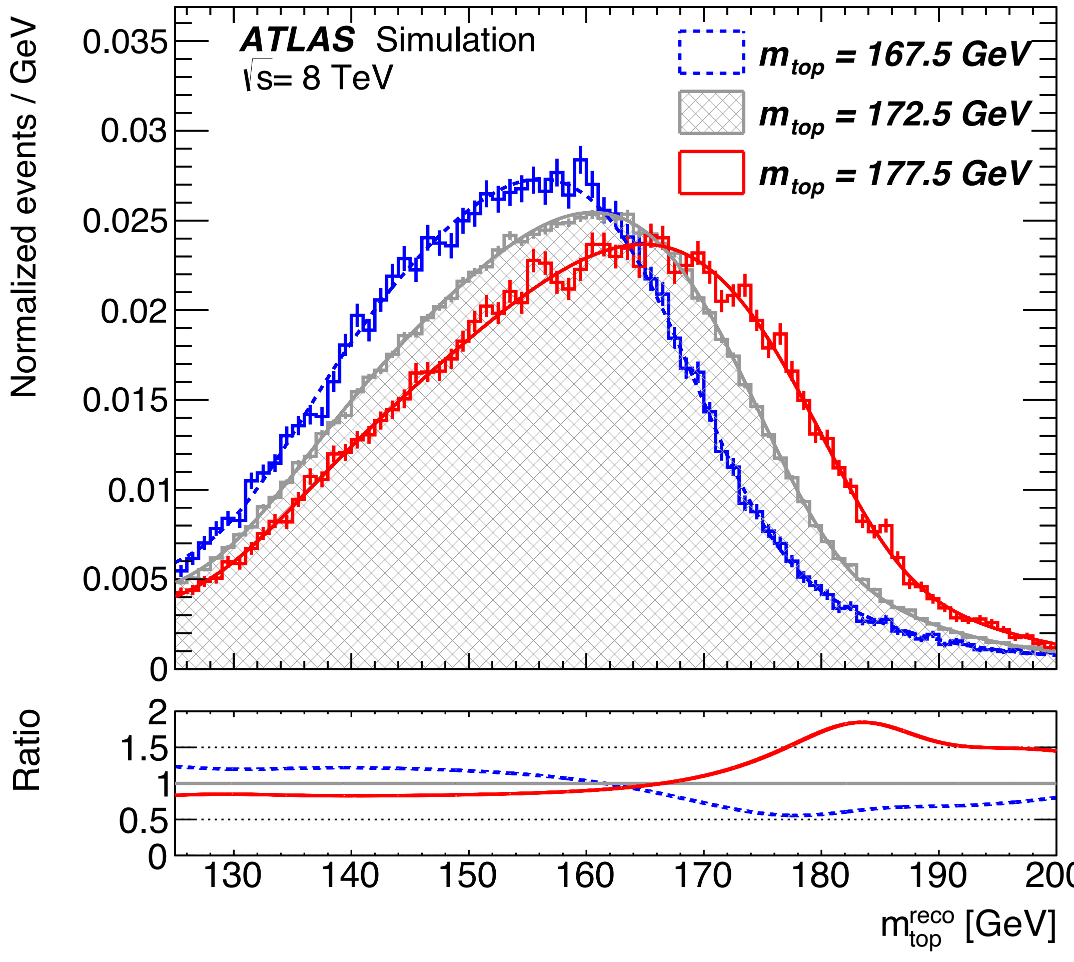
$$m_t^{\mathrm{MC}} = 171.77 \pm 0.37\,\mathrm{GeV}$$

CMS 2302.01967



- Approach relies entirely on parton showers and models of hadronization and UE in Monte Carlo event generators:
  Robust theory uncertainty?

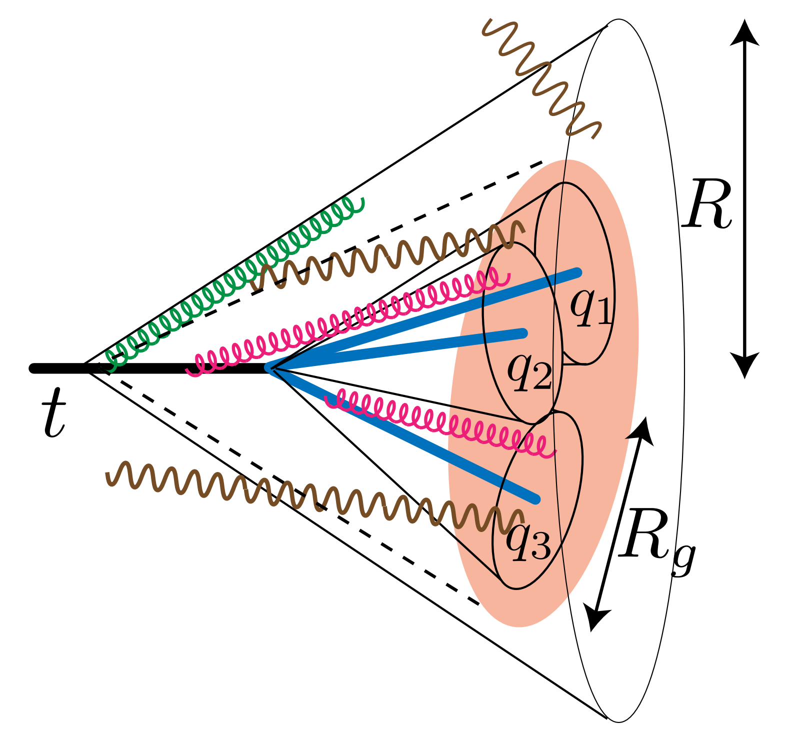


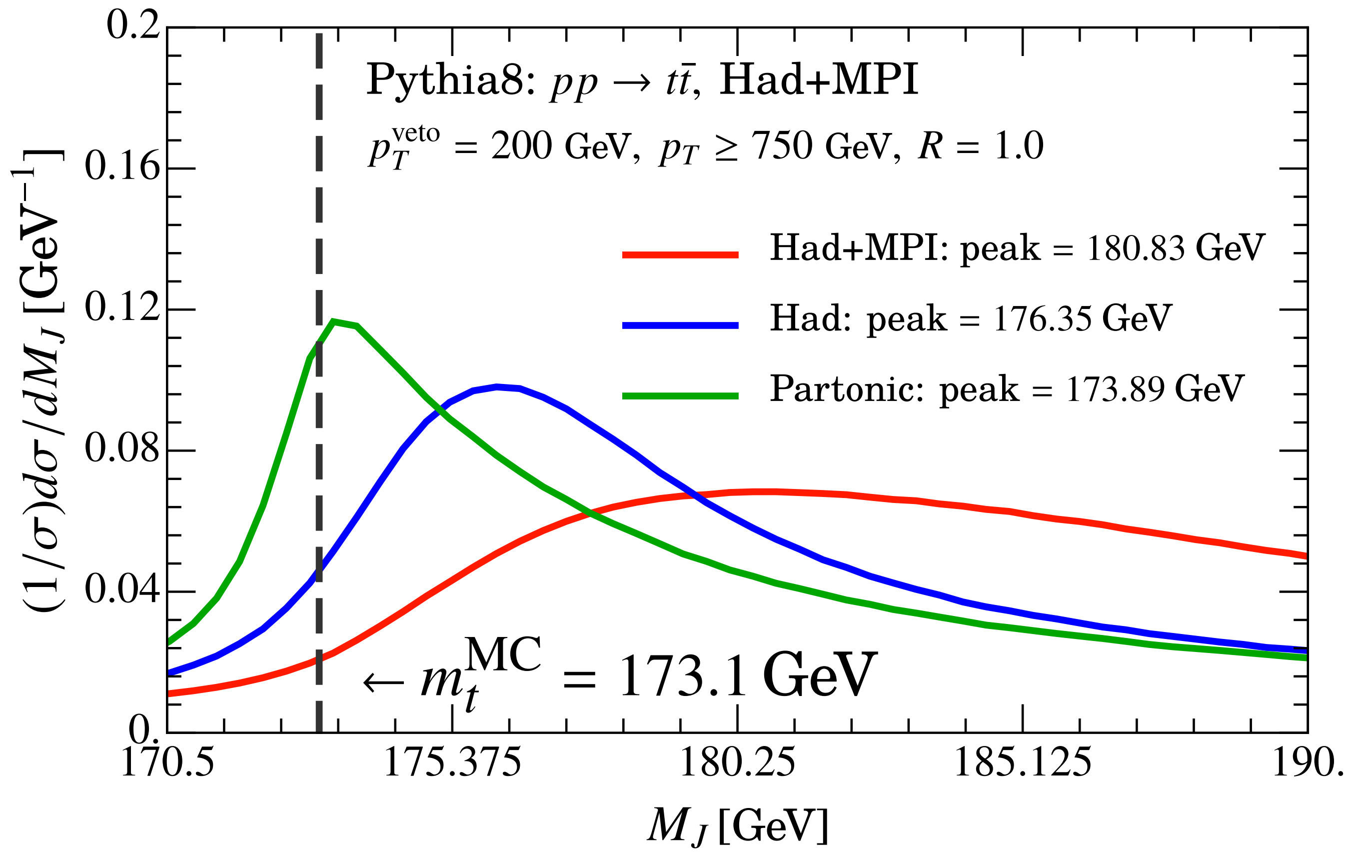


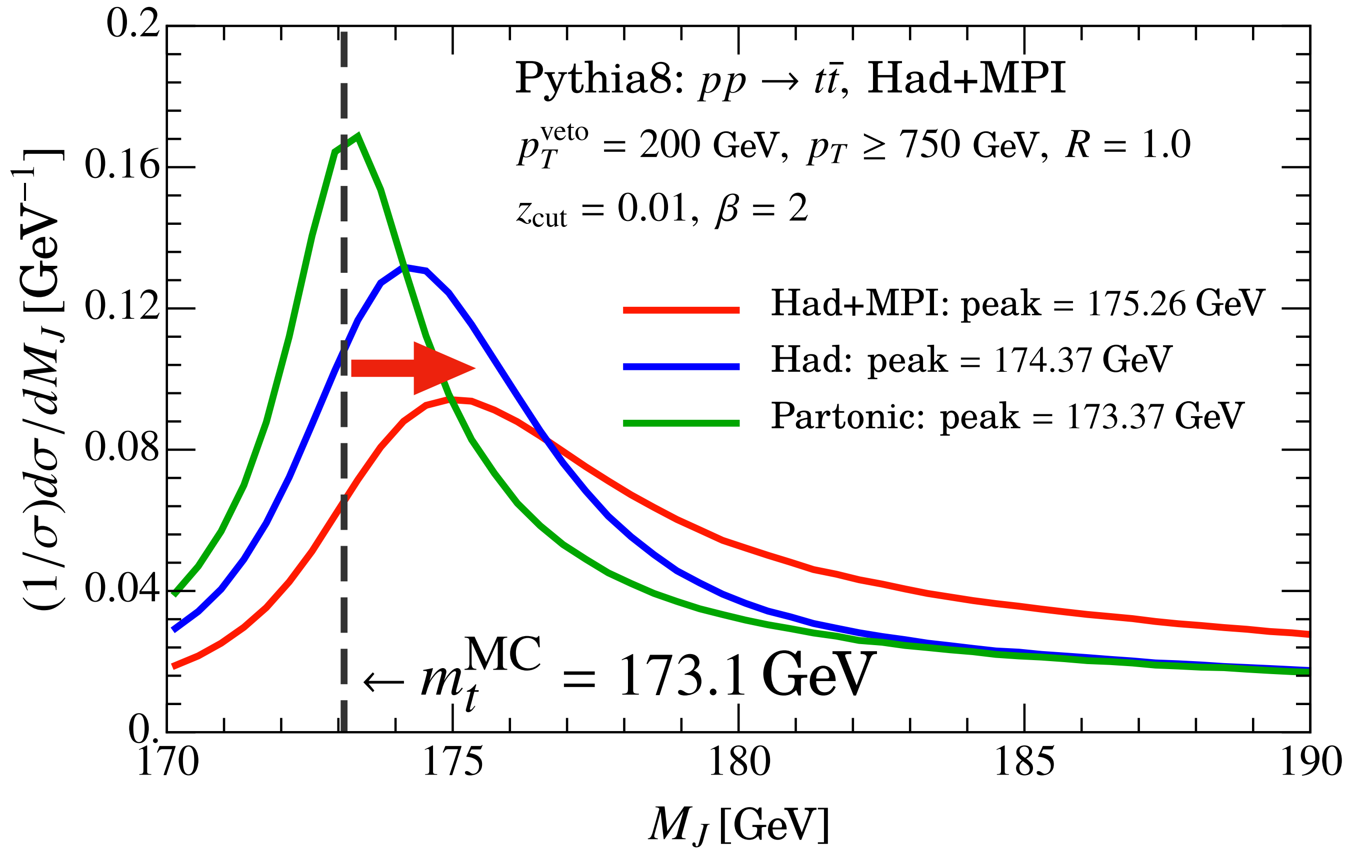
The top quark mass: groomed jet mass

- Observables in direct measurements exhibit threshold structures, which enhance the sensitivity to m_t but also to soft and collinear radiation as well as hadronization

- Higher level of theoretical control for the jet mass combined with jet grooming such as soft drop (Larkoski et al. 1402.2657) to mitigate effects from wide-angle soft radiation, UE contamination and hadronization





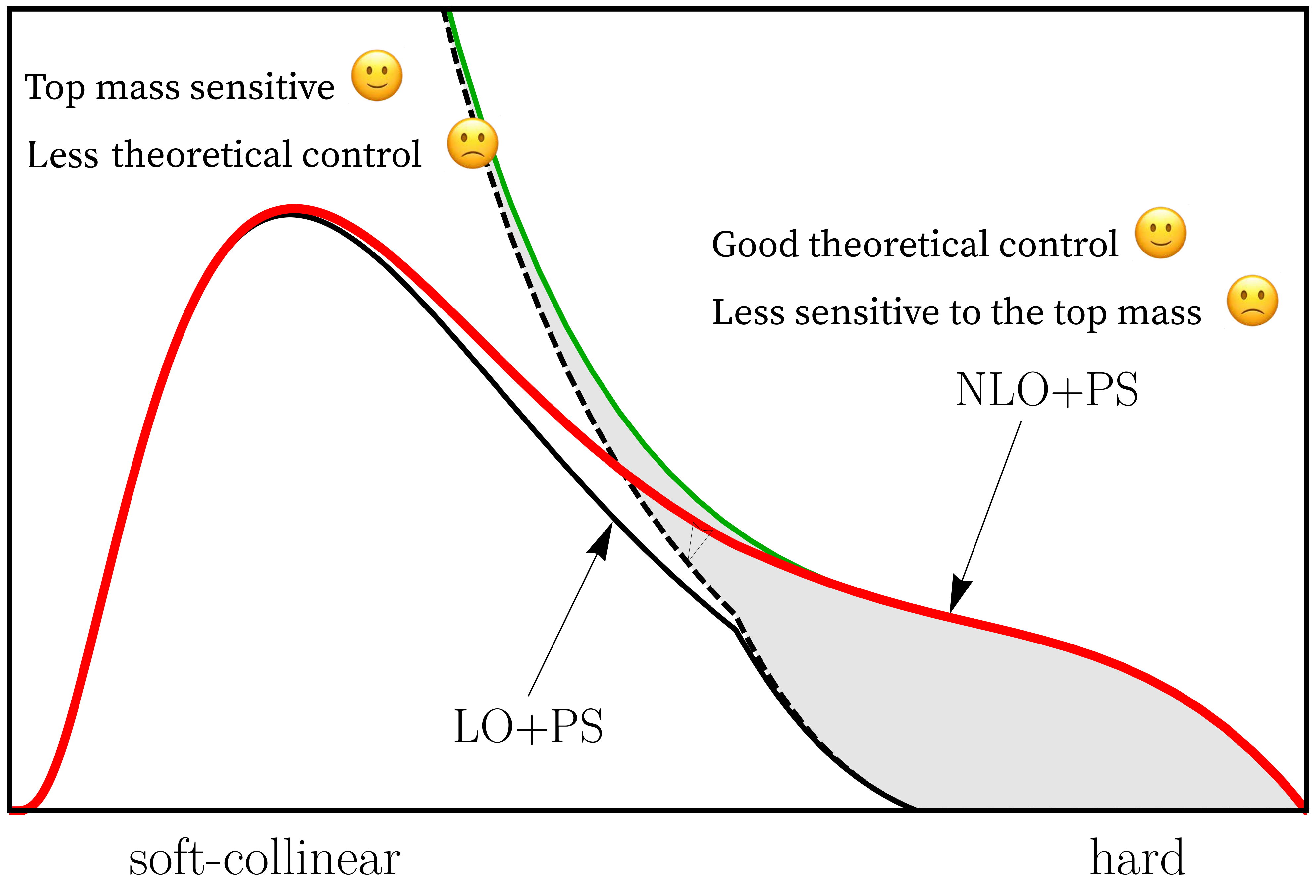


Even after grooming one needs to account for residual O(1 GeV) shifts

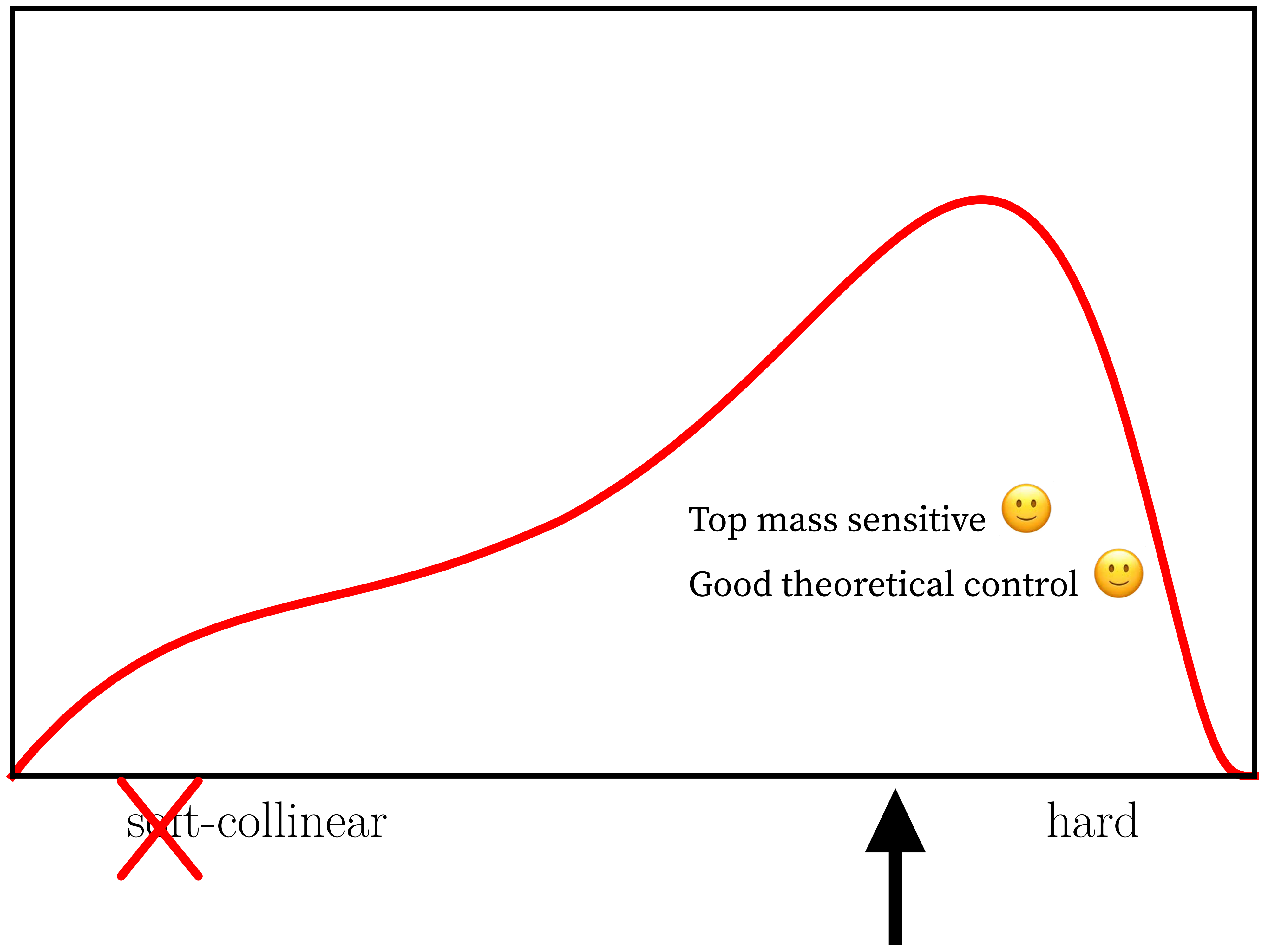
Hoang et al. 1708.02586, 1906.11843; Pathak et al. 2012.15568

Observables for the top mass extraction at LHC

from Hoang 2004.12915



vs.



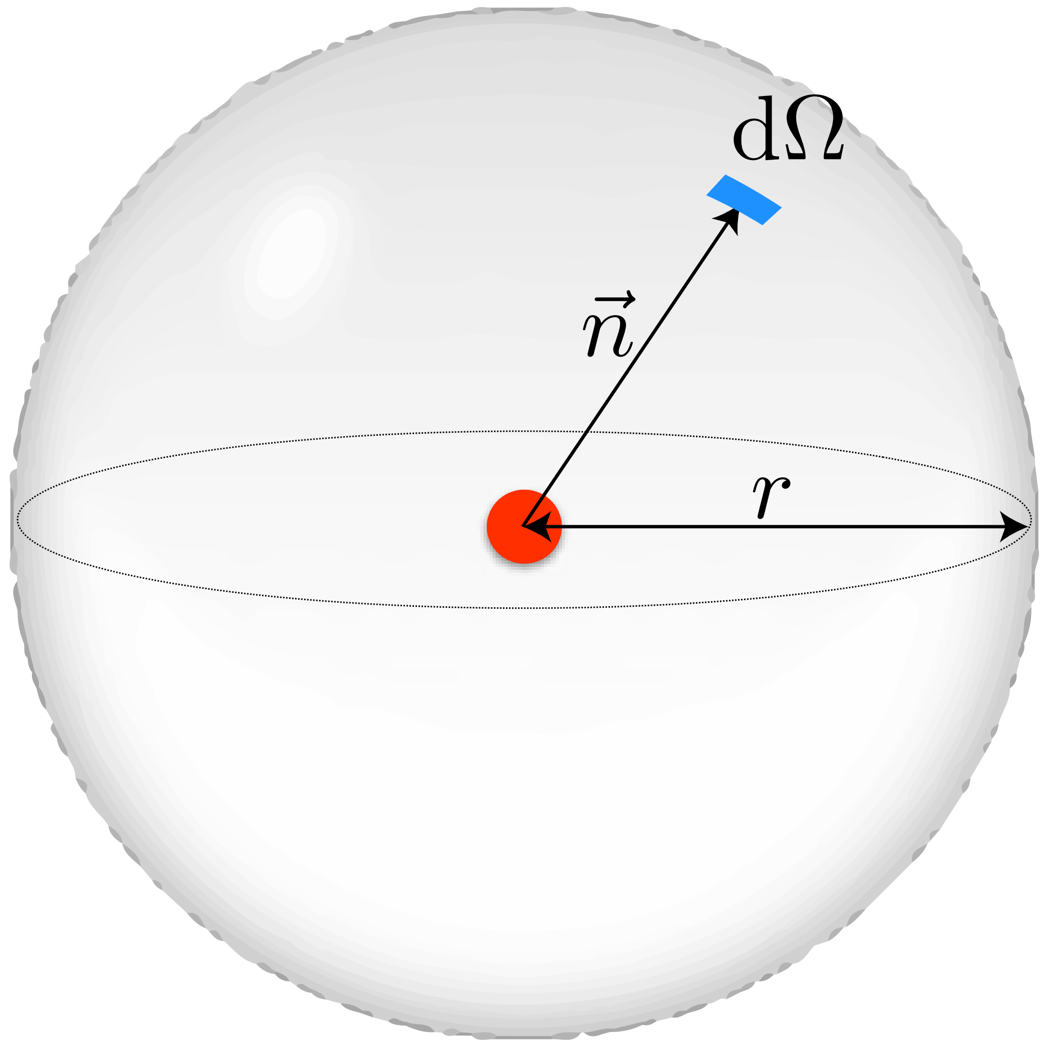
We explore possibility of precision extraction of top quark mass at the LHC from the measurement of energy-weighted angular correlations of boosted top decay products

Energy flow operators and correlators

- Energy flow operator:

$$\mathcal{E}(\vec{n}) = \int_0^\infty dt \lim_{r\to\infty} r^2 n^i T_{0i}(t, r\vec{n})$$

$$\mathcal{E}(\vec{n}) \simeq \int_0^\infty \mathrm{d}t \left(\text{Energy flux through } \mathrm{d}\Omega\right)$$



- N-point correlators of energy flow operators $\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\ldots\mathcal{E}(\vec{n}_N)\rangle$ related to cross sections where the contributions from final-state particles are weighted by the eigenvalues of the energy flow operators in the various directions

Two-point energy correlator in e+e- collisions

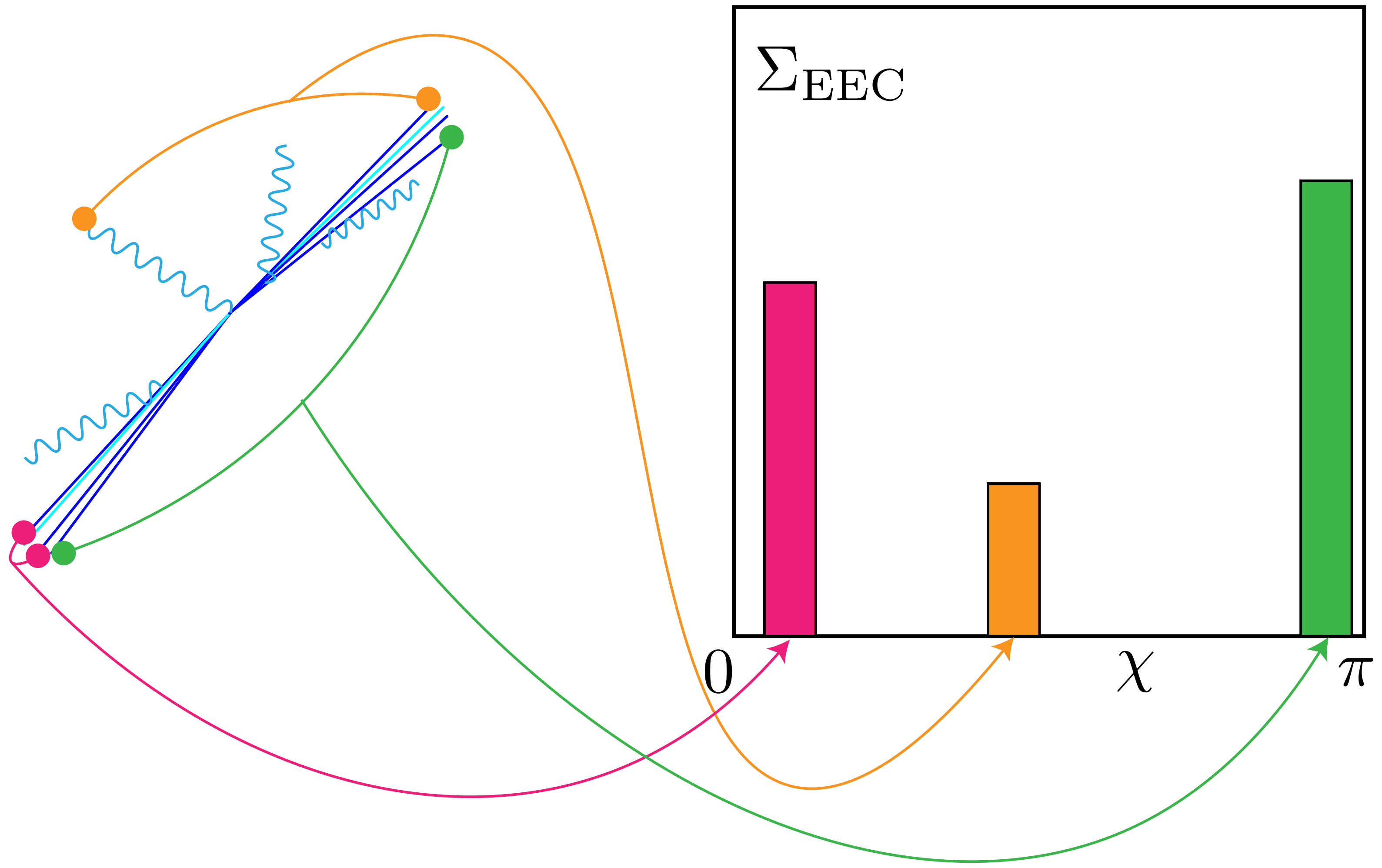
$$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle = \sum_{ij}\int \frac{d\sigma_{ij}}{d^2\vec{n}_i d^2\vec{n}_j} E_i E_j \delta^2(\vec{n}_1 - \vec{n}_i)\delta^2(\vec{n}_2 - \vec{n}_j)$$

Basham et al. PRL 41 (1978)

← two-particle inclusive QCD cross section

$$\rightarrow \quad \frac{d\Sigma}{d\cos\chi} = \int d^2 n_1 d^2 n_2 \, \delta(\vec{n}_1 \cdot \vec{n}_2 - \cos\chi) \frac{\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle}{Q^2}$$

At variance with standard event shapes, each event (collection of final state particles) contributes to multiple bins:



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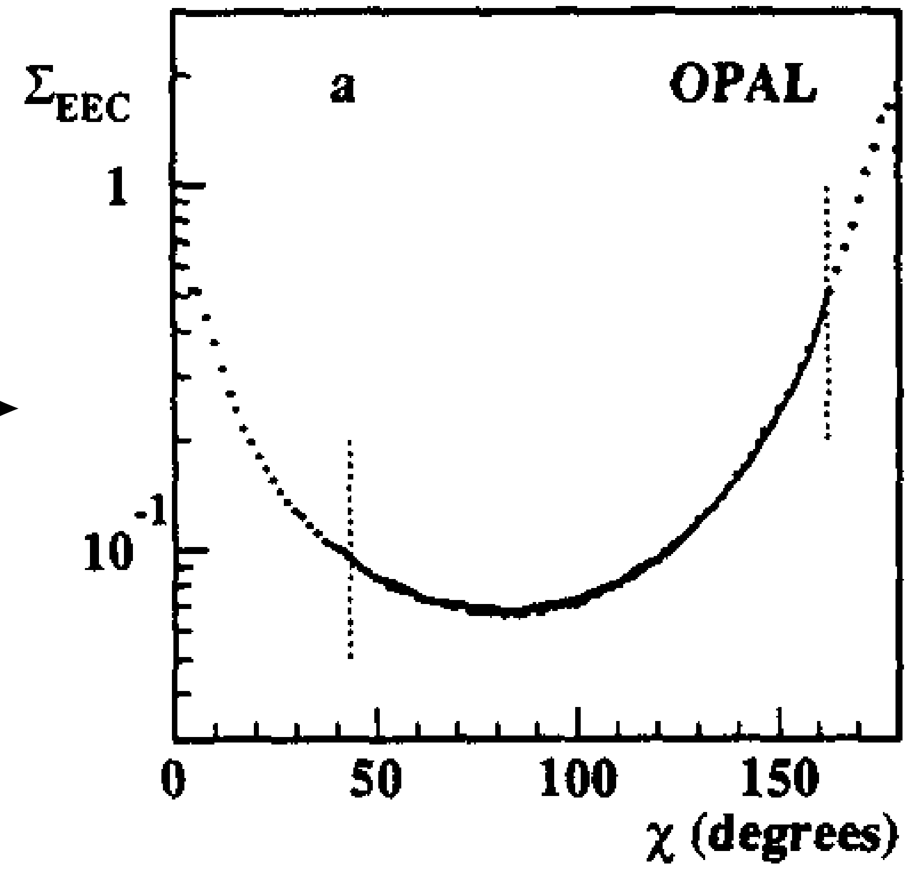
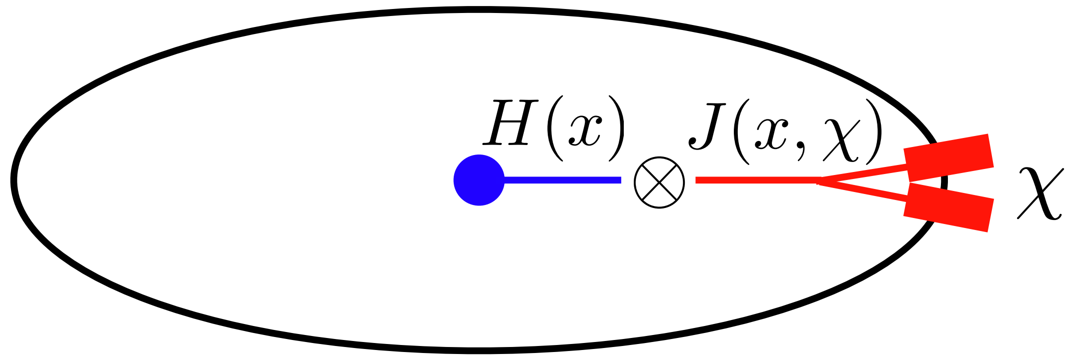


[Opal collboration, Z. Phys. C59 (1993) 21]

α_S extraction from EEC at NNLO+NNLL: Kardos et al. 1804.09146

Factorization theorems for energy correlators in e+e-

- In the collinear limit at leading power:

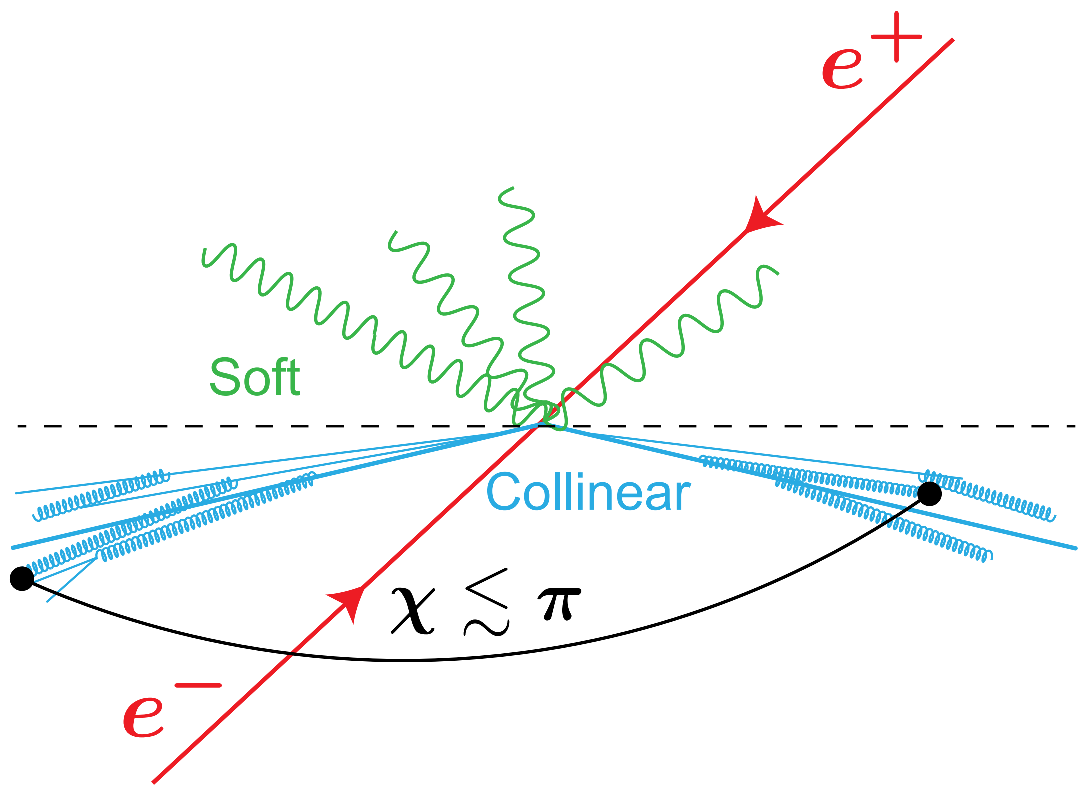


$$\Sigma\left(z, \ln\frac{Q^2}{\mu^2}, \mu\right) = \int_0^1 \mathrm{d}x\, x^2 \vec{J}_{\mathrm{EEC}}\left(\ln\frac{zx^2Q^2}{\mu^2}, \mu\right) \cdot \vec{H}\left(x, \frac{Q^2}{\mu^2}, \mu\right)$$

Dixon, Moult, Zhu 1905.01310

$$z = \frac{1-\cos\chi}{2}$$

- In the back-to-back limit at leading power:



$$\frac{d\sigma}{dz} = \frac{1}{2}\int d^2\vec{k}_\perp \int \frac{d^2\vec{b}_\perp}{(2\pi)^2} e^{-i\vec{b}_\perp\cdot\vec{k}_\perp}\ \delta\left(1-z-\frac{\vec{k}_\perp^2}{Q^2}\right)$$

$$\times \sum_f H_f(Q,\mu) J^f_{\mathrm{EEC}}(b_\perp,\mu,\nu) J^{\bar{f}}_{\mathrm{EEC}}(b_\perp,\mu,\nu) S_\perp(b_\perp,\mu,\nu)$$

Moult, Zhu 1801.02627

Computed up to N4LL: Duhr, Mistlberger, Vita 2205.02242

Energy correlators for jet substructure

- In recent years growing efforts to rethink jet substructure using energy correlators: insights from CFT and light-ray OPE

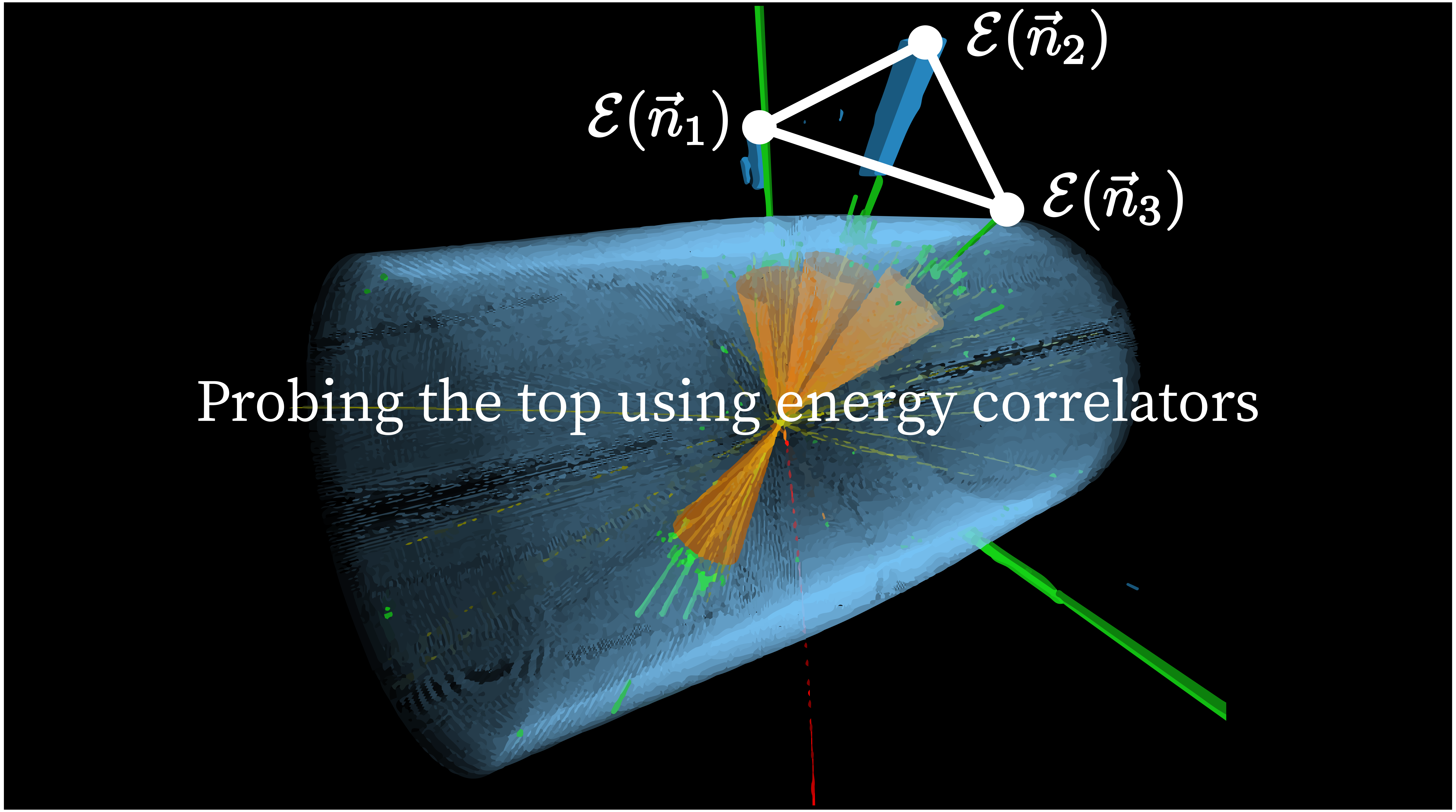
Chen et al. 2004.11381, Hofman and Maldacena 0803.1467, Belitsky et al. 1309.0769, 1309.1424, Kravchuk and Simmons-Duffin 1805.00098

- Energy weighting naturally suppresses soft radiation without grooming and enables novel precision calculations of LHC observables to get access to detailed scaling and shape information about the energy distribution within jets

Measured by CMS (2402.13864), RHIC (2309.05761) and ALICE (2409.12687) experiments

- Can be readily computed for track-based measurements to exploit the fine angular resolution of tracking detectors: energy weights get simply rescaled by moments of track functions (Chang et al. 1303.6637, 1306.6630)

Li et al. 2108.01674, Jaarsma et al. 2201.05166


$\mathcal{E}(\vec{n}_2)$
$\mathcal{E}(\vec{n}_1)$
$\mathcal{E}(\vec{n}_3)$
Probing the top using energy correlators

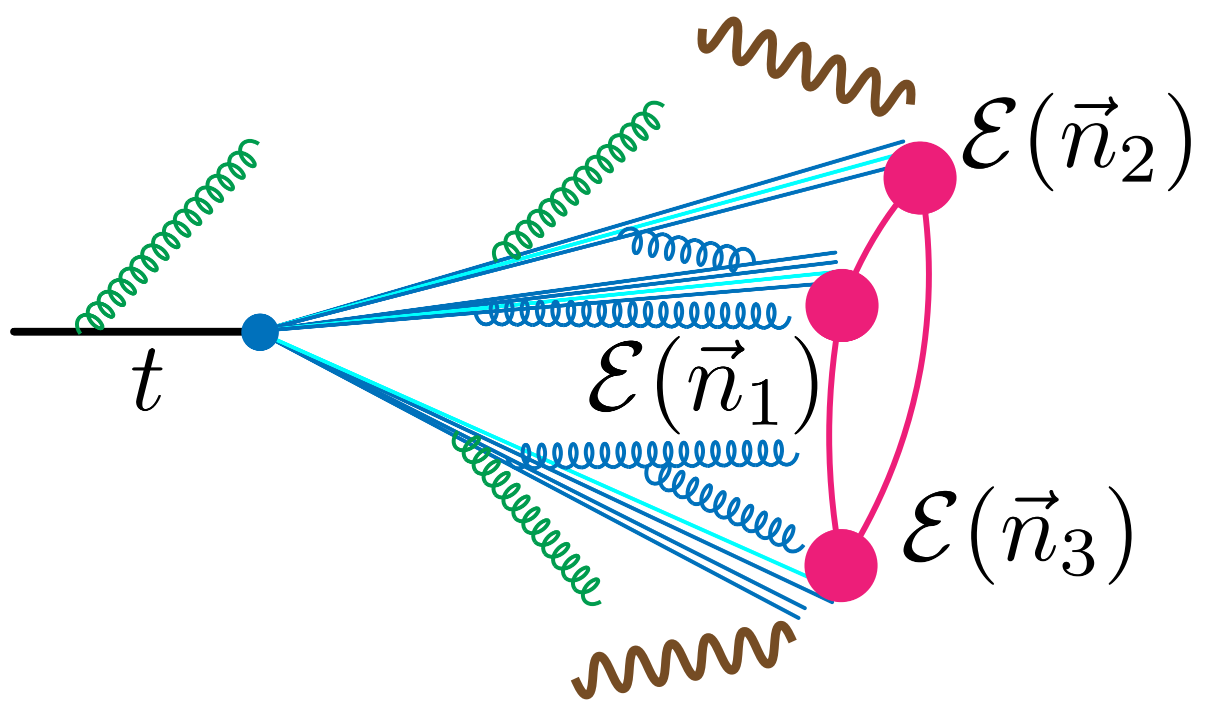
EEEC sensitivity to the top mass

Holguin, Moult, Pathak, MP 2201.08393

- Consider $e^+e^- \to t\bar{t} + X$ where t decays hadronically. The measurement operator is inclusive on top decay products:

$$\widehat{\mathcal{M}}^{(n)}(\zeta_{12}, \zeta_{23}, \zeta_{31}) = \sum_{i,j,k} \frac{E_i^n E_j^n E_k^n}{Q^{3n}} \delta\left(\zeta_{12} - \hat{\zeta}_{ij}\right) \delta\left(\zeta_{23} - \hat{\zeta}_{ik}\right) \delta\left(\zeta_{31} - \hat{\zeta}_{jk}\right)$$

$$\hat{\zeta}_{ij} = (1 - \cos\theta_{ij})/2$$



- At LO, for a boosted top, the distribution in $\zeta_{12} + \zeta_{23} + \zeta_{31}$ has a peak whose location is proportional to m_t^2/Q^2. The variance can be reduced by constraining the the shape of the energy flow (most simply achieved by requiring $\zeta_{12} \approx \zeta_{23} \approx \zeta_{31}$)

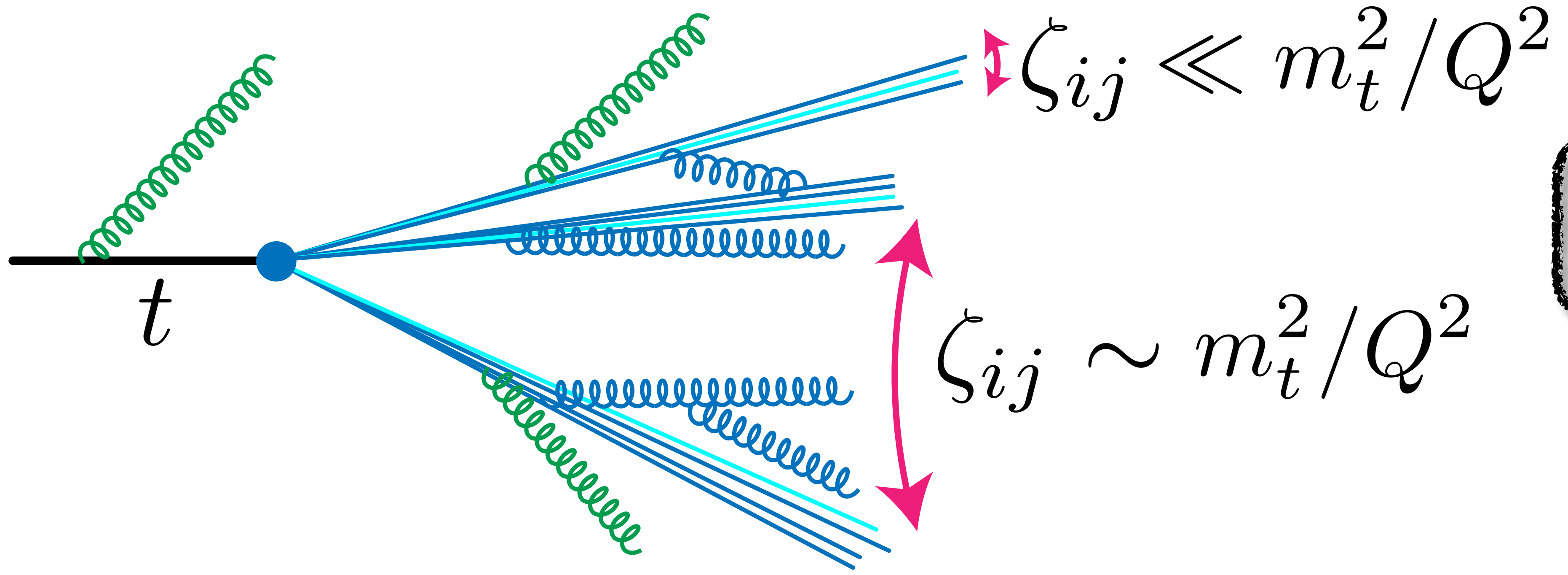
EEEC sensitivity to the top mass

Holguin, Moult, Pathak, MP 2201.08393

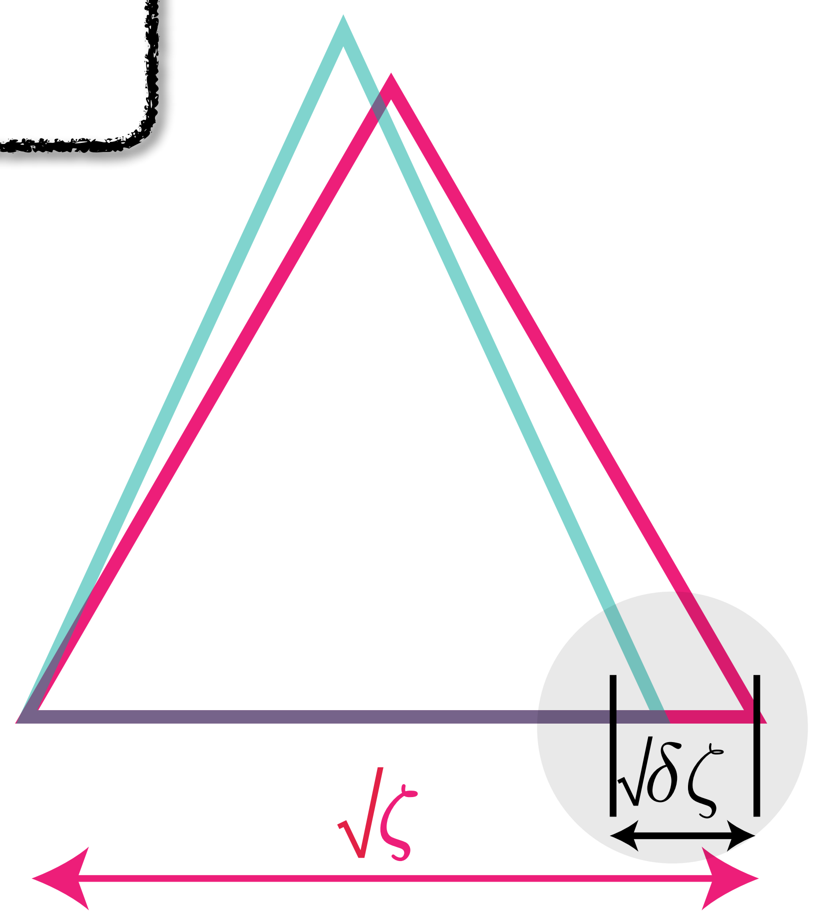
The key object in our first analysis where $\delta\zeta$ is asymmetry cut (shape parameter):

$$\frac{\mathrm{d}\Sigma(\delta\zeta)}{\mathrm{d}Q\mathrm{d}\zeta} = \int \mathrm{d}\zeta_{12}\mathrm{d}\zeta_{23}\mathrm{d}\zeta_{31} \int \mathrm{d}\sigma \widehat{\mathcal{M}}_{\triangle}^{(n)}(\zeta_{12},\zeta_{23},\zeta_{31},\zeta,\delta\zeta)$$

$$\widehat{\mathcal{M}}_{\triangle}^{(n)}(\zeta_{12},\zeta_{23},\zeta_{31},\zeta,\delta\zeta) = \sum_{i,j,k} \frac{E_i^n E_j^n E_k^n}{Q^{3n}} \delta\left(\zeta_{12}-\hat{\zeta}_{ij}\right)\delta\left(\zeta_{23}-\hat{\zeta}_{ik}\right)\delta\left(\zeta_{31}-\hat{\zeta}_{jk}\right)$$
$$\times\ \delta(3\zeta-\zeta_{12}-\zeta_{23}-\zeta_{31}) \prod_{l,m,n\in\{1,2,3\}} \Theta(\delta\zeta - |\zeta_{lm}-\zeta_{mn}|)$$



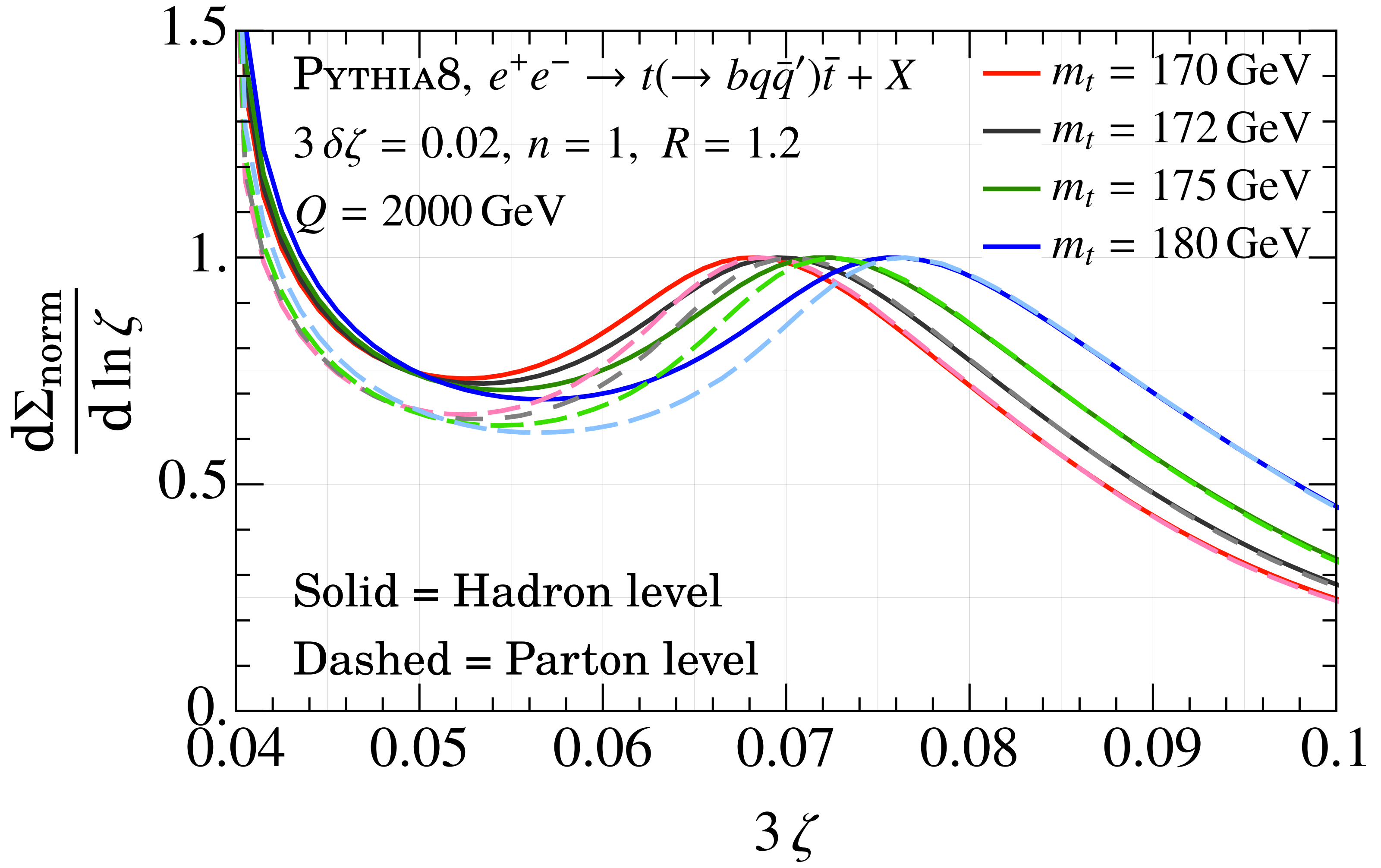
3-body hard kinematics: $\zeta_{\mathrm{peak}} \approx 3m_t^2/Q^2$

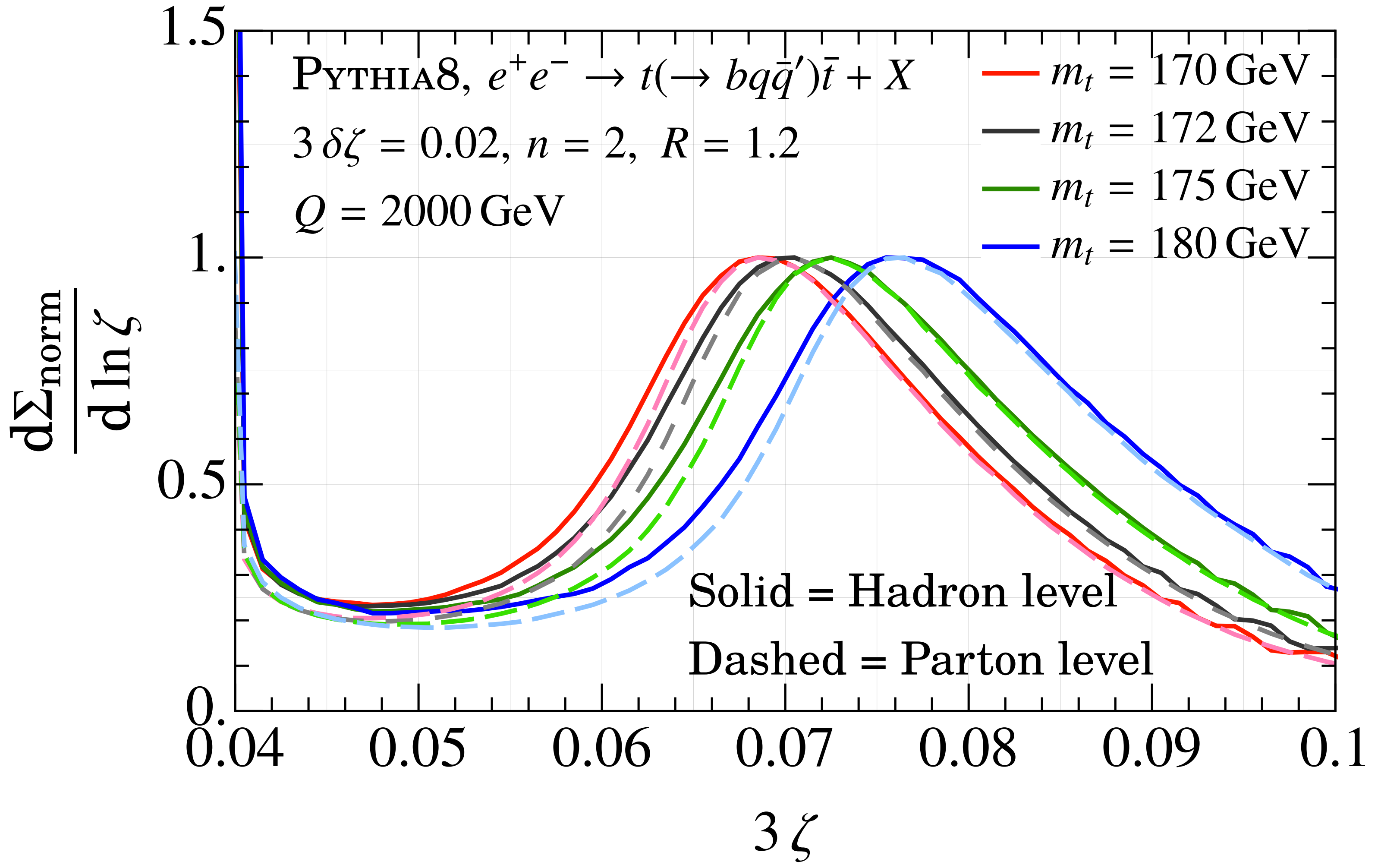


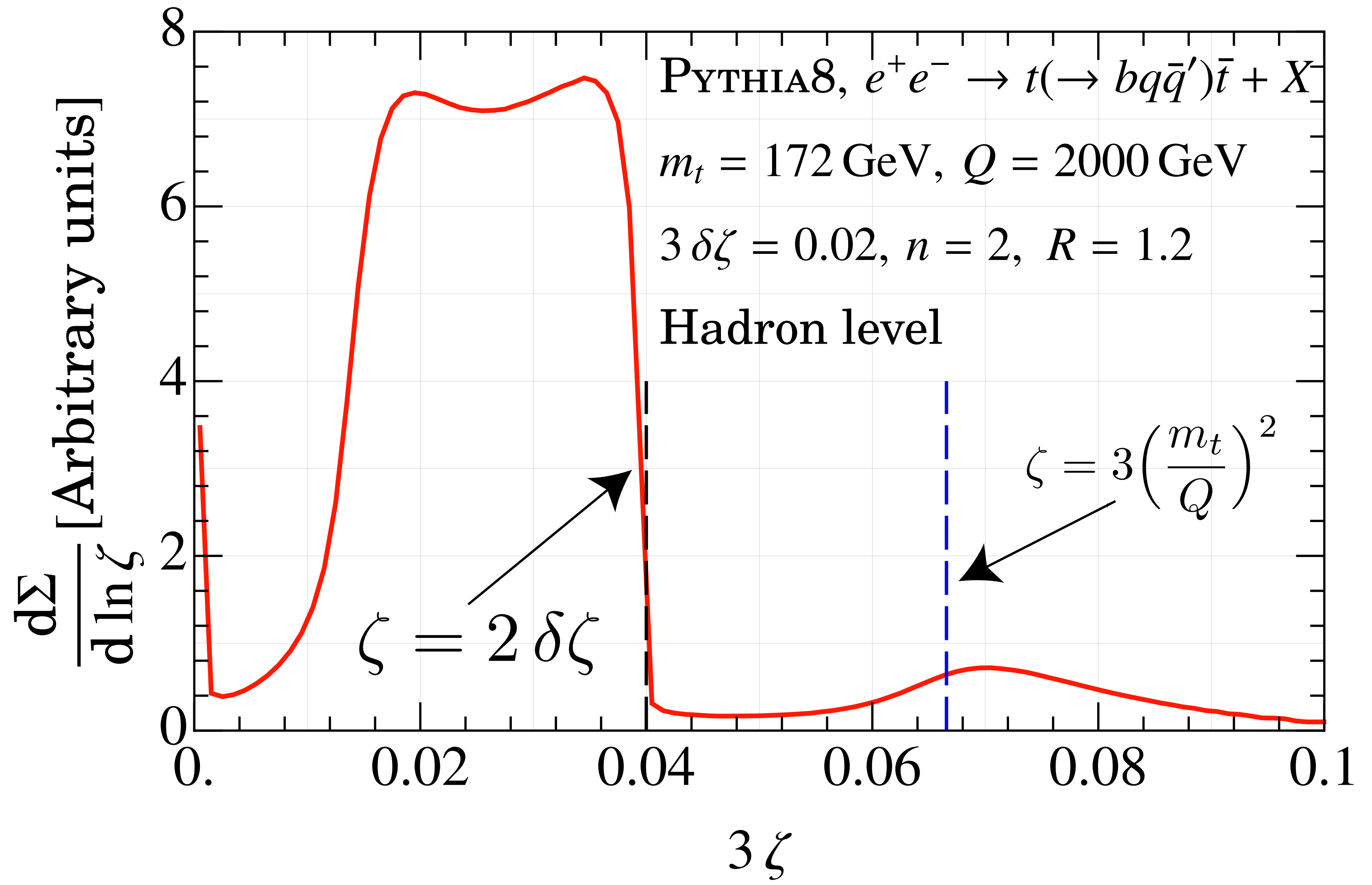
Top mass from EEEC in e+e- collisions (PYTHIA8)

Holguin, Moult, Pathak, MP 2201.08393

- Excellent sensitivity to the top mass (distributions normalized to peak heights):







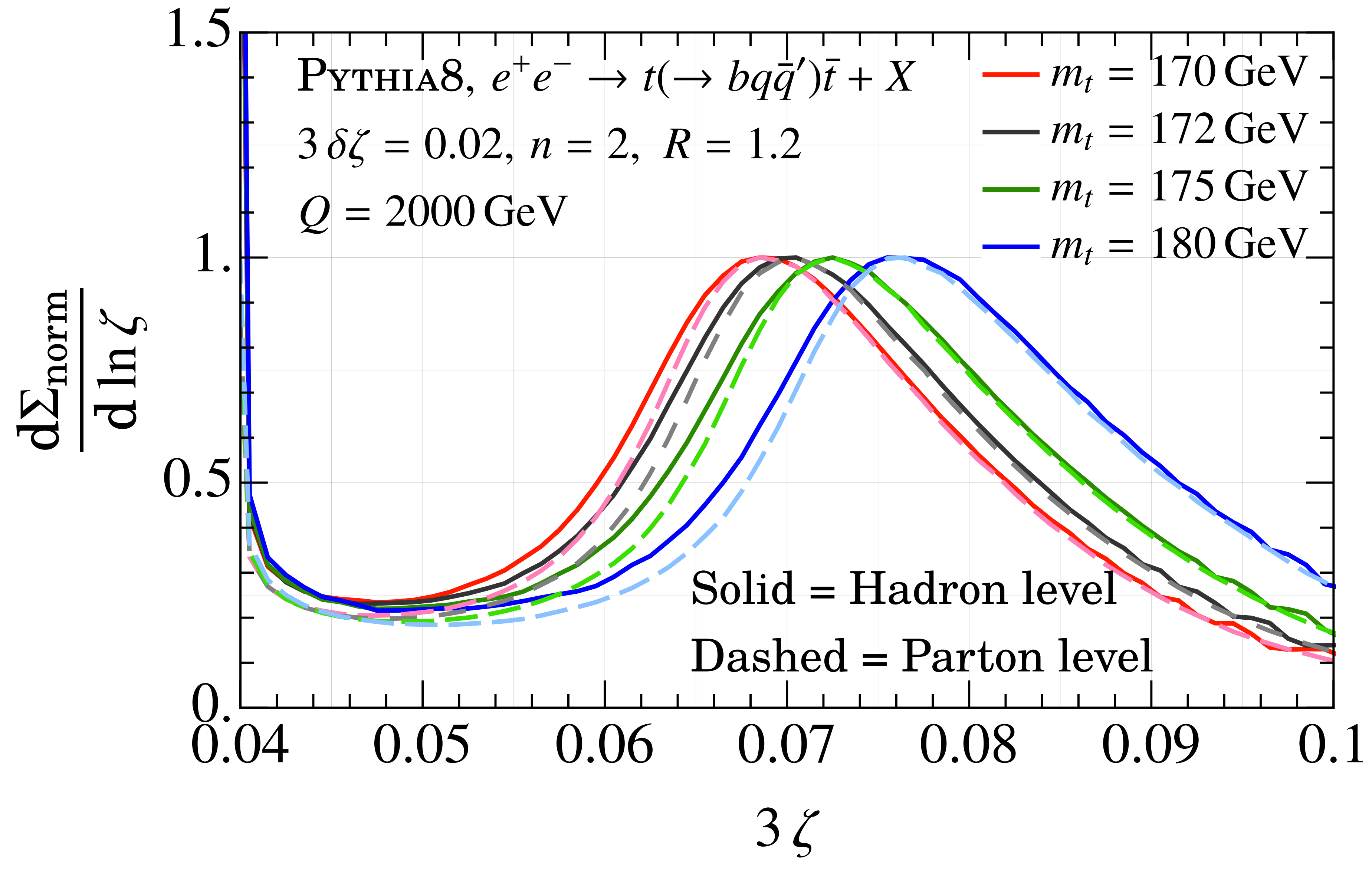
- Peak position dominantly determined by the LO hard process

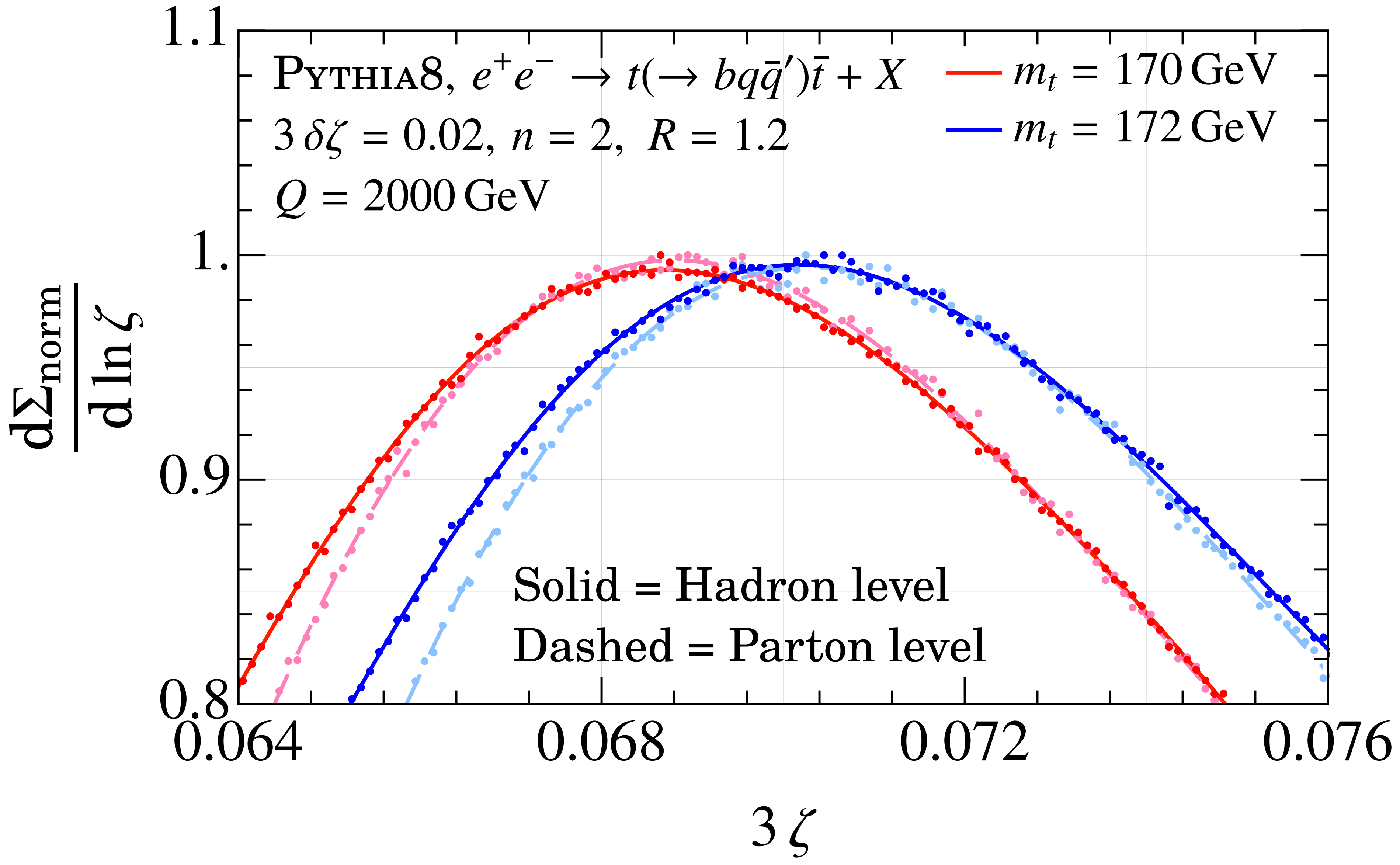
- For $\zeta < 2\delta\zeta$ large contribution from collinear splittings

Top mass from EEEC in e+e- collisions: hadronization

Non-perturbative effects in ECs are governed by an additive power law (Korchemsky, Sterman NPB 555, 1999)

Hadronization has a small effect on the peak of the normalized distribution:





$$\Delta m_t^{\text{Had}} \approx 150 \pm 50\,\text{MeV}$$

The case of pp collisions

Holguin, Moult, Pathak, MP 2201.08393

- Measurement operator on a boosted top quark jet:

$$\widehat{\mathcal{M}}^{(n)}_{(pp)}(\zeta_{12},\zeta_{23},\zeta_{31}) = \sum_{i,j,k\,\in\,\text{jet}} \frac{(p_{T,i})^n (p_{T,j})^n (p_{T,k})^n}{(p_{T,\text{jet}})^{3n}} \delta\left(\zeta_{12}-\hat{\zeta}^{(pp)}_{ij}\right)\delta\left(\zeta_{23}-\hat{\zeta}^{(pp)}_{ik}\right)\delta\left(\zeta_{31}-\hat{\zeta}^{(pp)}_{jk}\right)$$

$$\hat{\zeta}^{(pp)}_{ij} = \Delta R^2_{ij} = \Delta\eta^2_{ij} + \Delta\phi^2_{ij}$$

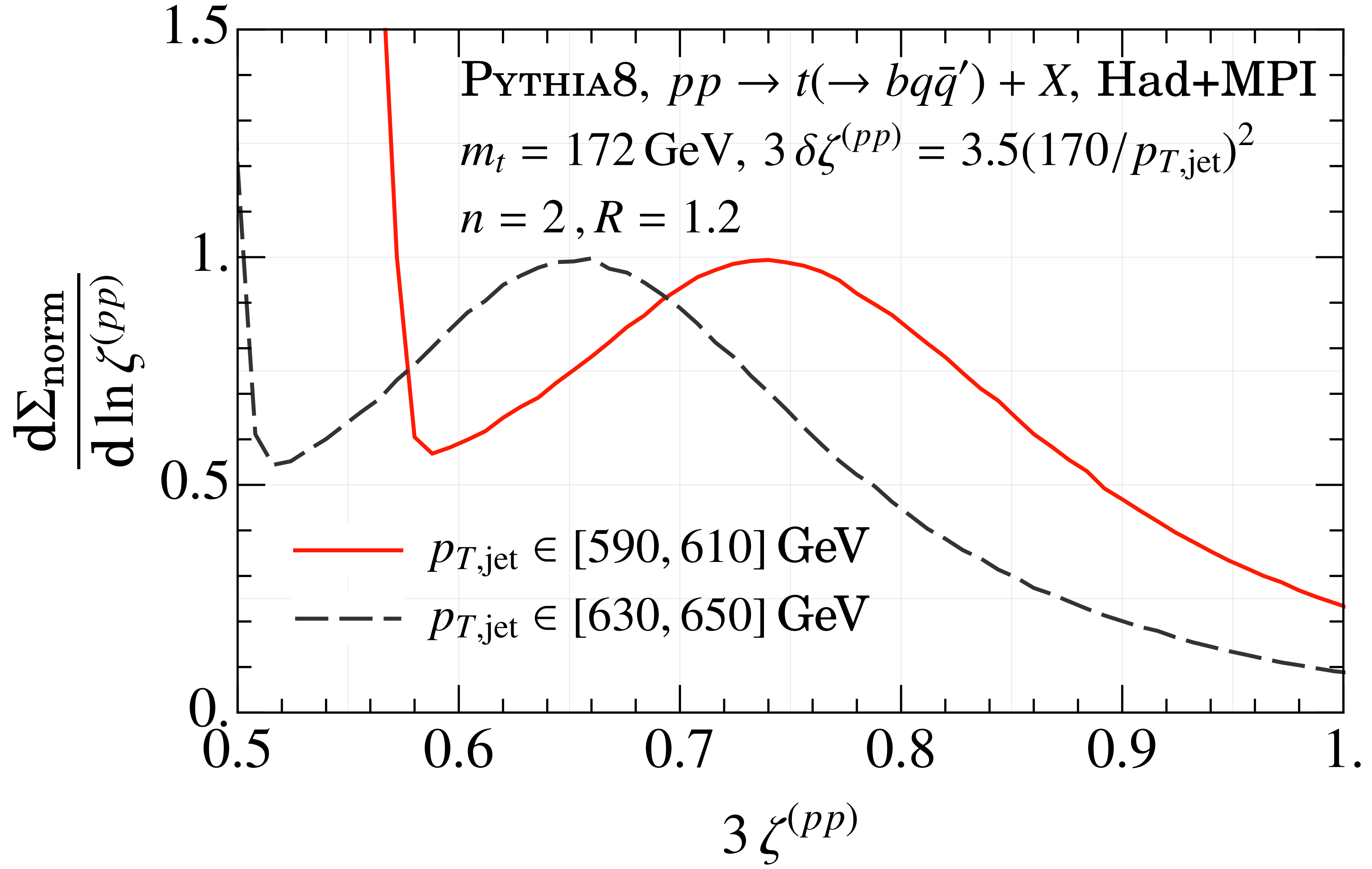
- The peak from hard kinematics is now at $\zeta^{(pp)}_{\text{peak}} \approx 3m_t^2/p_{T,t}^2$

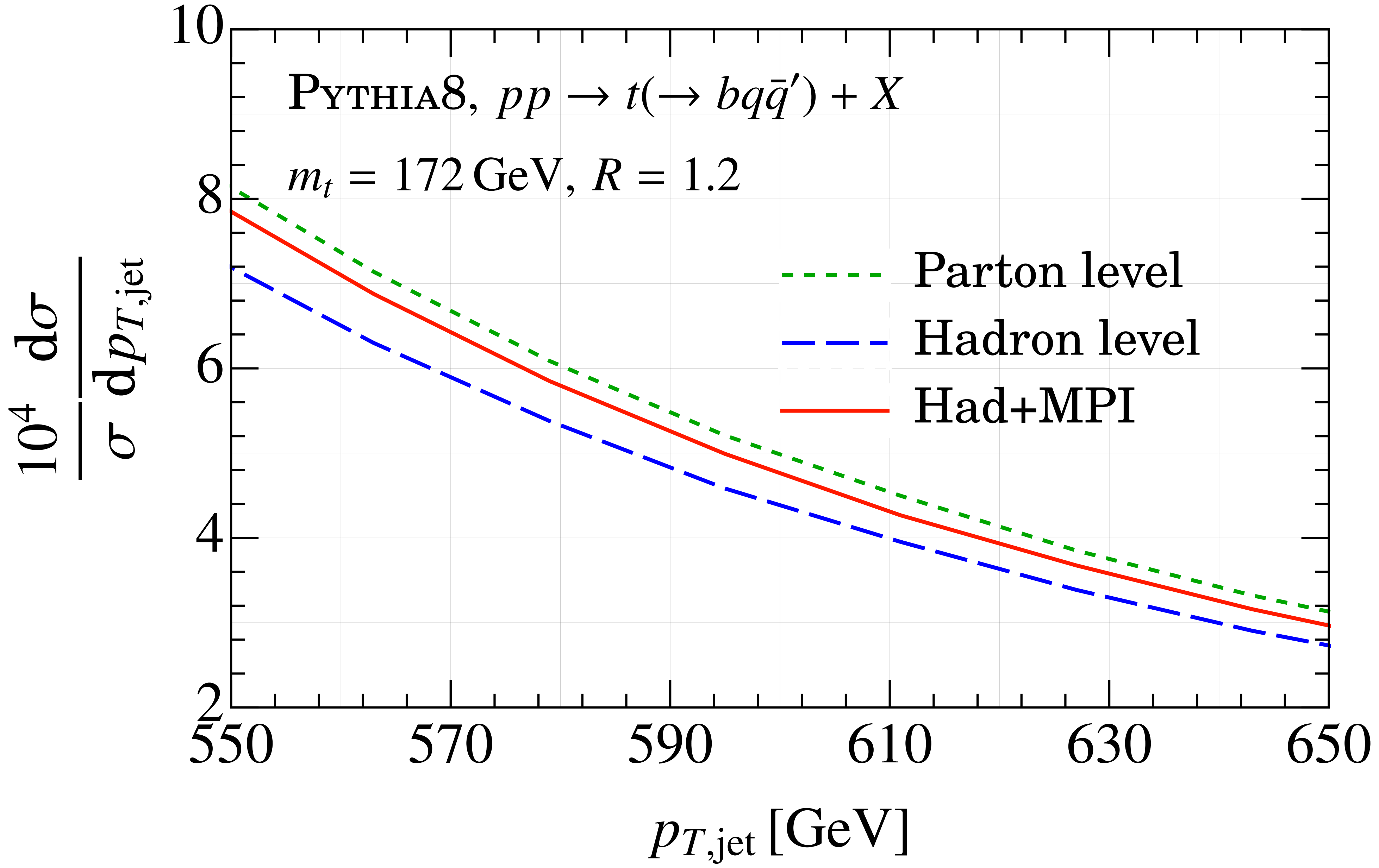
- Performed a proof-of-concept analysis to show how a precise characterization of the top-jet pT-spectrum would enable a precision top mass extraction from $\widehat{\mathcal{M}}^{(n)}_{(pp),\triangle}$

The case of pp collisions: top-jet pT-spectrum

Holguin, Moult, Pathak, MP 2201.08393

Need for a robust jet-pT measurement spoils the effectiveness of this approach:



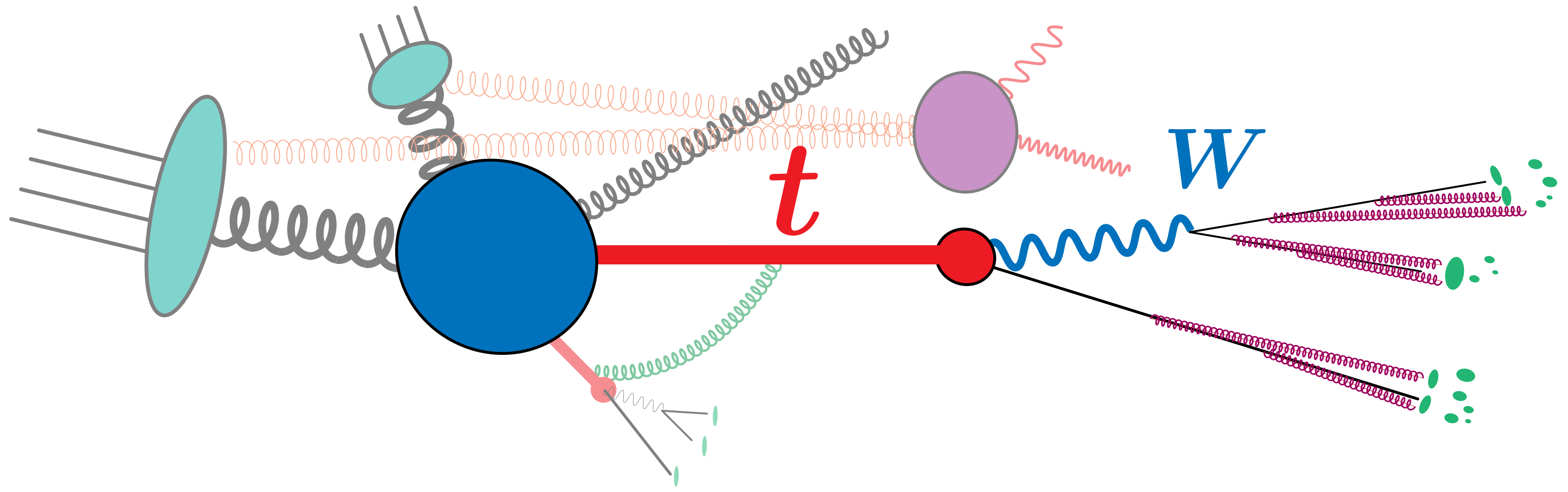


Shifts due to hadronization and UE in the jet pT-spectrum induce ~1 GeV shifts in the top mass extracted from the peak position

Novel approach: the W as a standard candle

Holguin, Moult, Pathak, MP, Schöfbeck, Schwarz 2311.02157, 2407.12900

We can trade the jet-pT scale by the mass of the W boson inside the boosted top jet:



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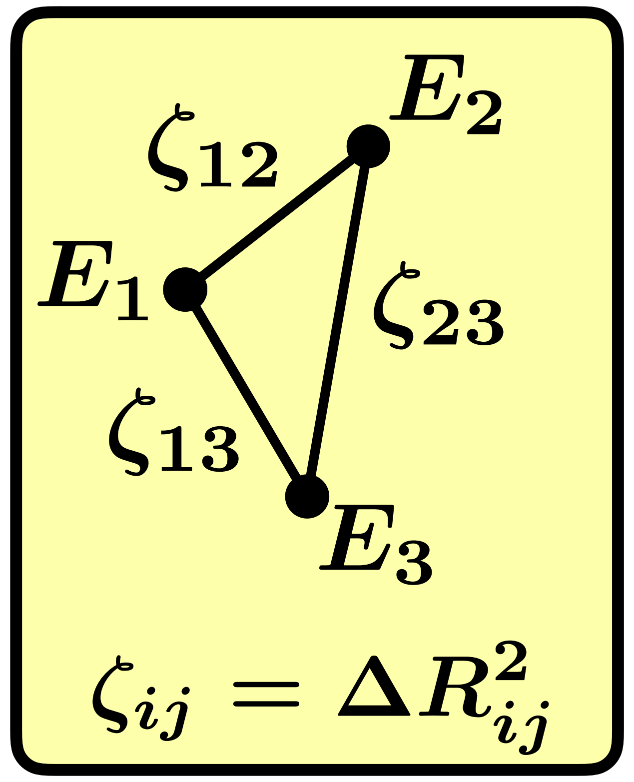

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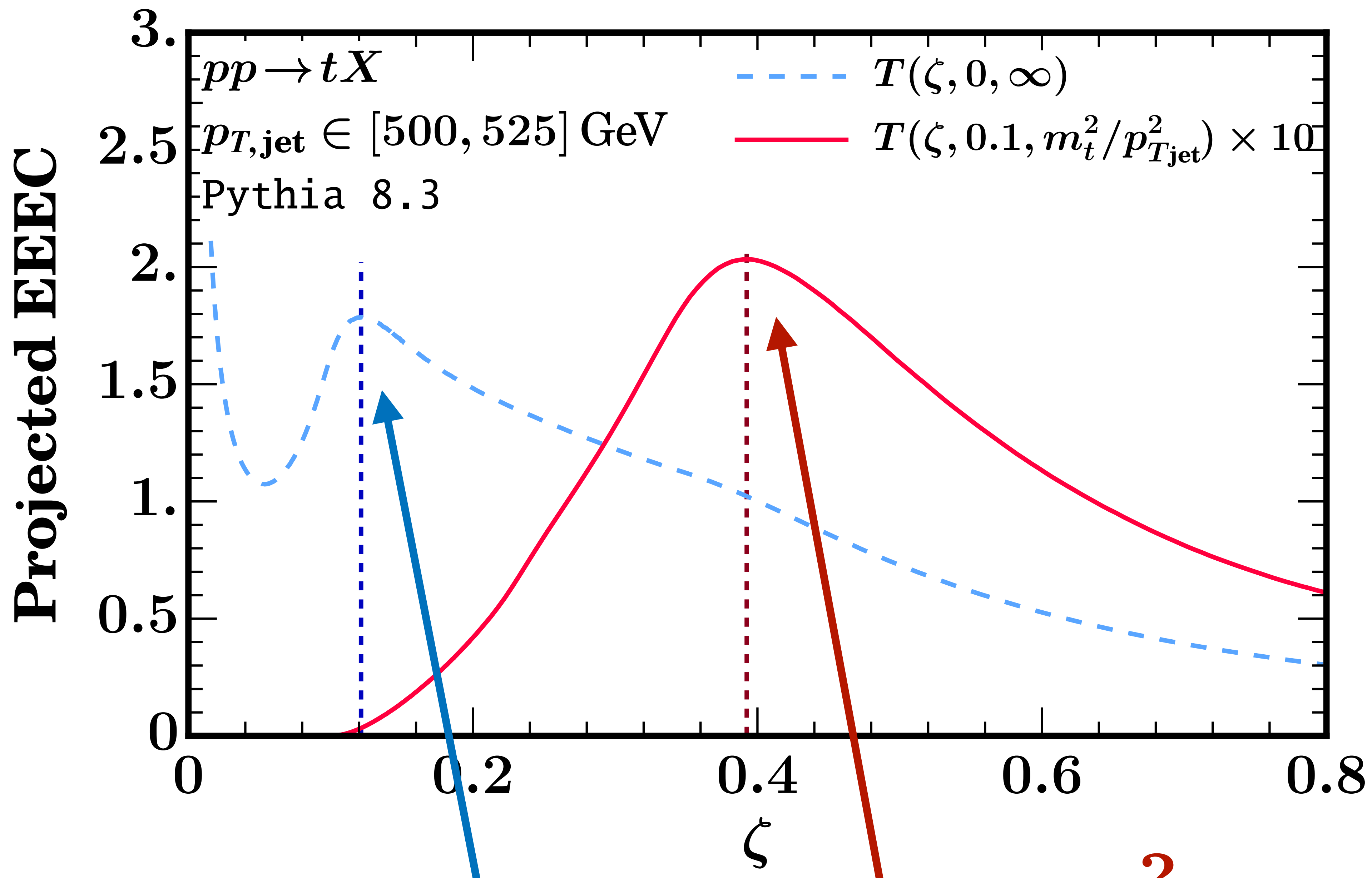


$$\zeta_W \propto \frac{m_W^2}{p_{T,\rm jet}^2} \qquad \zeta_t \propto \frac{m_t^2}{p_{T,\rm jet}^2}$$

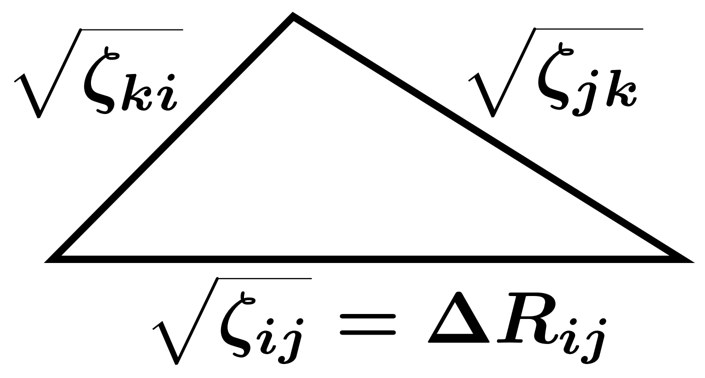
←

$$m_t \propto m_W \sqrt{\frac{\zeta_t}{\zeta_W}}$$

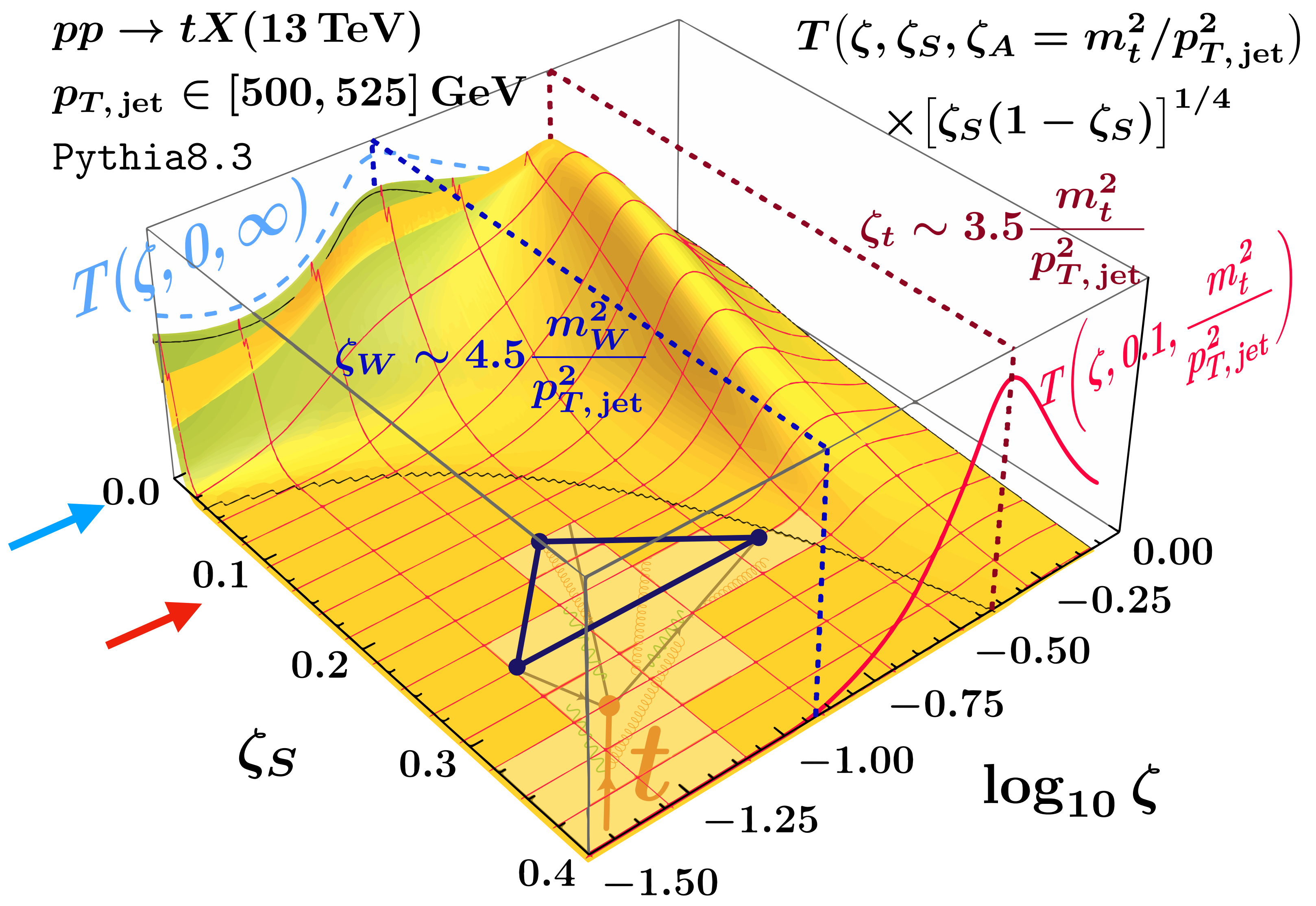
Novel approach: the W as a standard candle

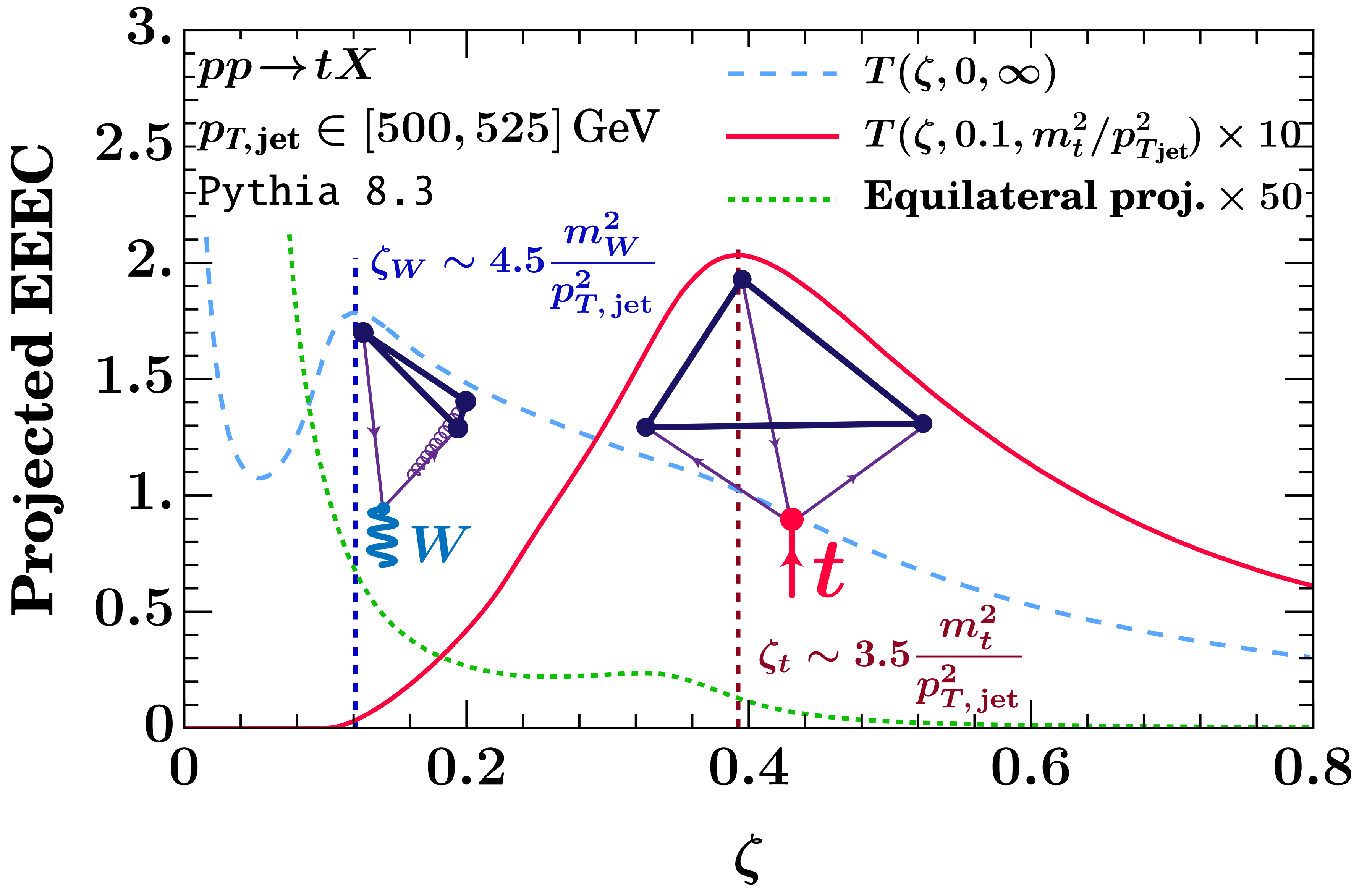
Holguin, Moult, Pathak, MP, Schöfbeck, Schwarz 2311.02157

The key object in our novel analysis is the integrated triple-energy correlator



$$T(\zeta, \zeta_S, \zeta_A) \equiv \sum_{\substack{\text{hadrons}\\ i,j,k}} \int d\zeta_{ijk} \frac{p_{T,i}\, p_{T,j}\, p_{T,k}}{(p_{T,\text{jet}})^3} \frac{d^3\sigma_{i,j,k}}{d\zeta_{ijk}} \delta\left(\zeta - \left(\frac{\sqrt{\zeta_{ij}} + \sqrt{\zeta_{jk}}}{2}\right)^2\right)$$
$$\times\, \Theta(\zeta_{ij} \geq \zeta_{jk} \geq \zeta_{ki} \geq \zeta_S)\, \Theta\left(\zeta_A > (\sqrt{\zeta_{ij}} - \sqrt{\zeta_{jk}})^2\right)$$



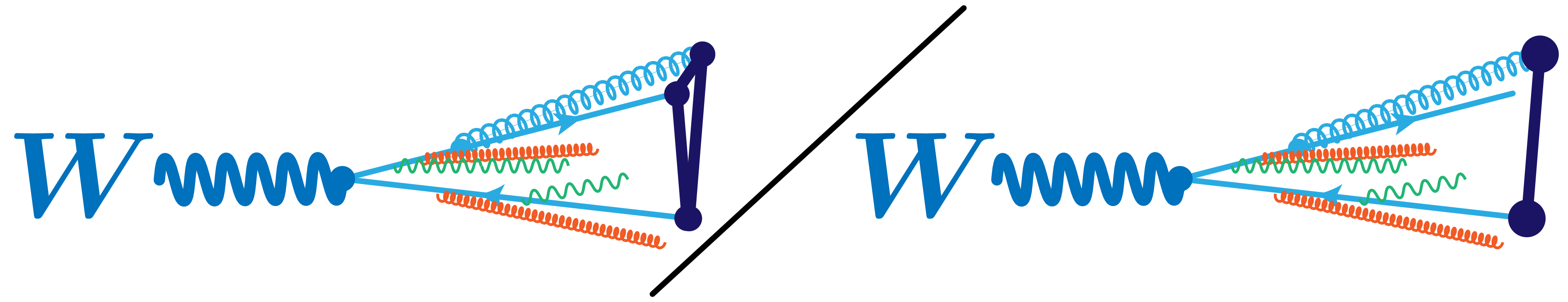


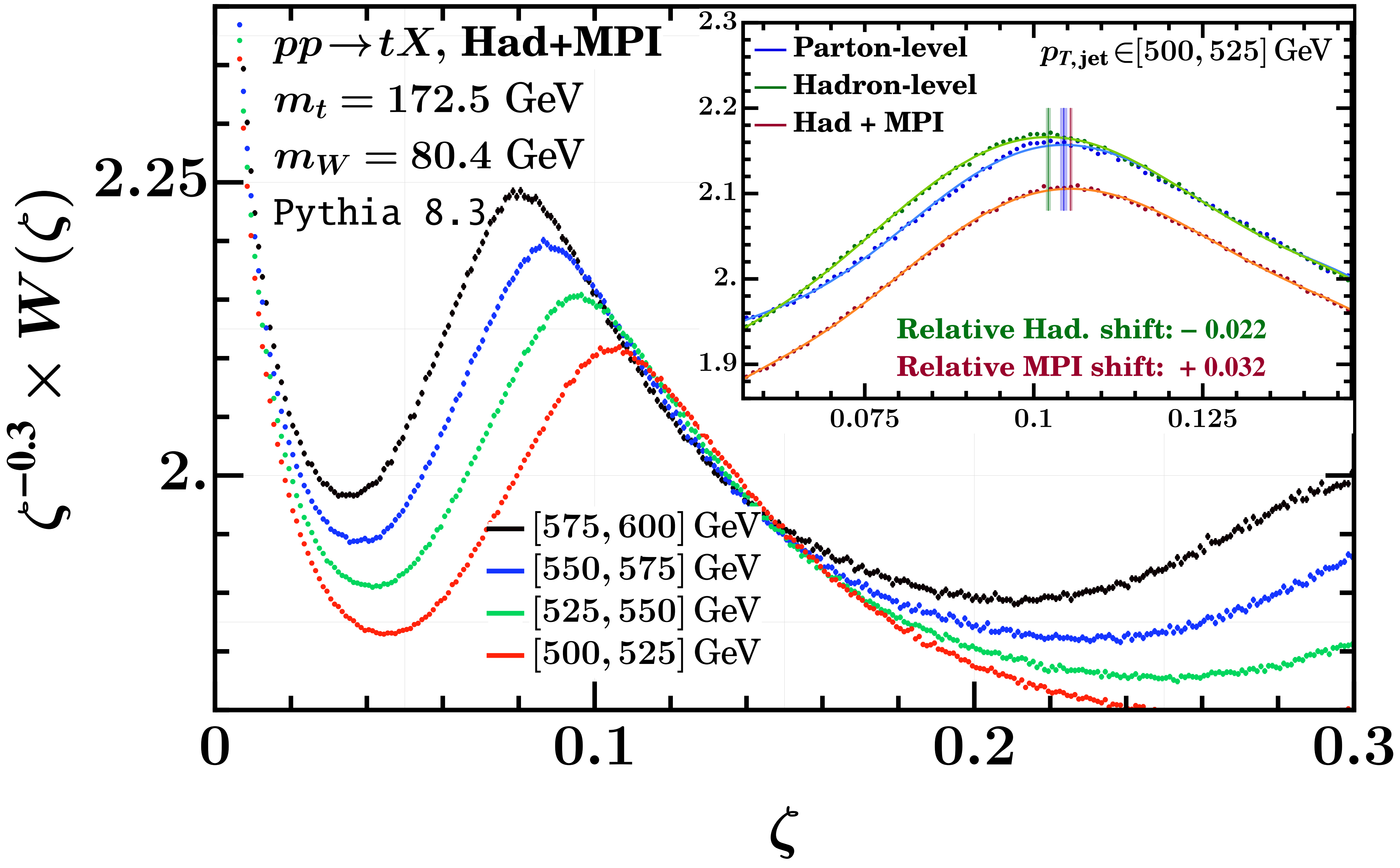
The standard candle observable

Holguin, Moult, Pathak, MP, Schöfbeck, Schwarz 2311.02157

To extract the W imprint we consider the ratio

$$W(\zeta) \equiv T(\zeta, 0, \infty) \left(\sum_{\substack{\text{hadrons} \\ i,j}} \int d\zeta_{ij} \, \frac{p_{T,i}\, p_{T,j}}{(p_{T,\text{jet}})^2} \frac{d\sigma_{i,j}}{d\zeta_{ij}} \, \delta(\zeta - \zeta_{ij}) \right)^{-1}$$





Peak is sensitive to the W-mass and shifts from hadronization and UE contamination are entirely due to correlated shift in $p_{T,\text{jet}}$

Top mass extraction: a feasibility study

Holguin, Moult, Pathak, MP, Schöfbeck, Schwarz 2407.12900

We exploit the high degree of correlation between top and W imprints. For large boosts:

$$m_t = m_W \left[C(\alpha_s, R) \sqrt{\frac{\zeta_t}{\zeta_W}} + \mathcal{O}\left(\frac{m_W}{p_{T,\mathrm{jet}}}, \frac{m_t}{p_{T,\mathrm{jet}}} \right) \right]$$

where C is governed by relative W boost, top decay and depends on the jet radius R.

For now, we extract C from parton-level simulations averaging over $p_{T,\mathrm{jet}} \in [400, 600]\ \mathrm{GeV}$

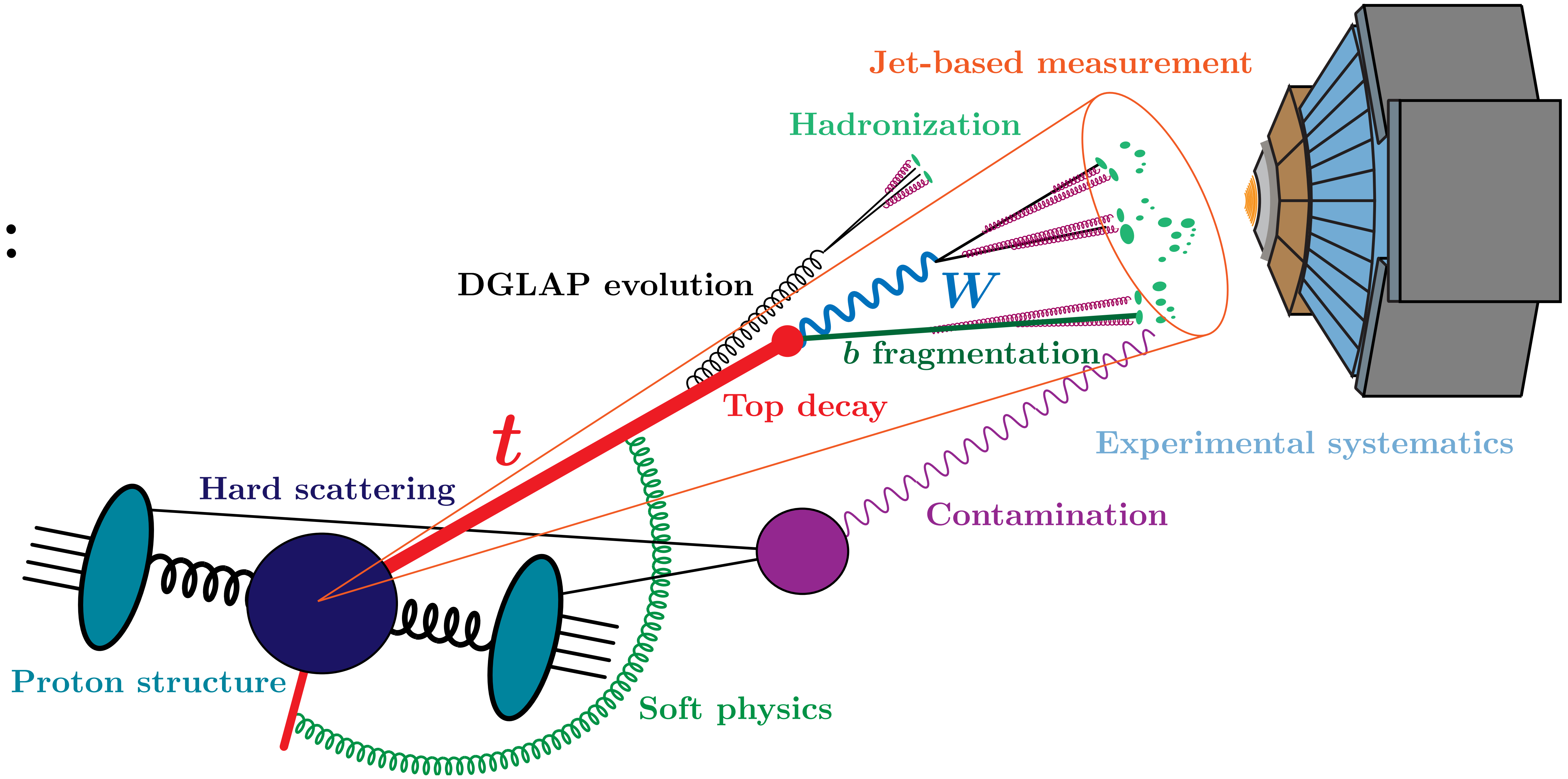
(Different event generators employ different approximations to description of top decay)

Shower	$R = 0.8$	$R = 1.0$	$R = 1.2$	$R = 1.5$
Pythia 8.3	1.076 ± 0.001	1.085 ± 0.001	1.094 ± 0.001	1.101 ± 0.001
Vincia 2.3	1.082 ± 0.001	1.087 ± 0.001	1.095 ± 0.001	1.103 ± 0.001
Herwig 7.3 Dipole	1.080 ± 0.001	1.087 ± 0.001	1.095 ± 0.001	1.101 ± 0.001
Herwig 7.3 A.O.	1.094 ± 0.001	1.101 ± 0.001	1.109 ± 0.001	1.115 ± 0.001

Top mass extraction: a feasibility study

Checklist for a precision top mass extraction:

- robustness against hadronization and UE
- vastly dominant effects perturbative
- negligible power suppressed effects
- resilience to experimental systematics

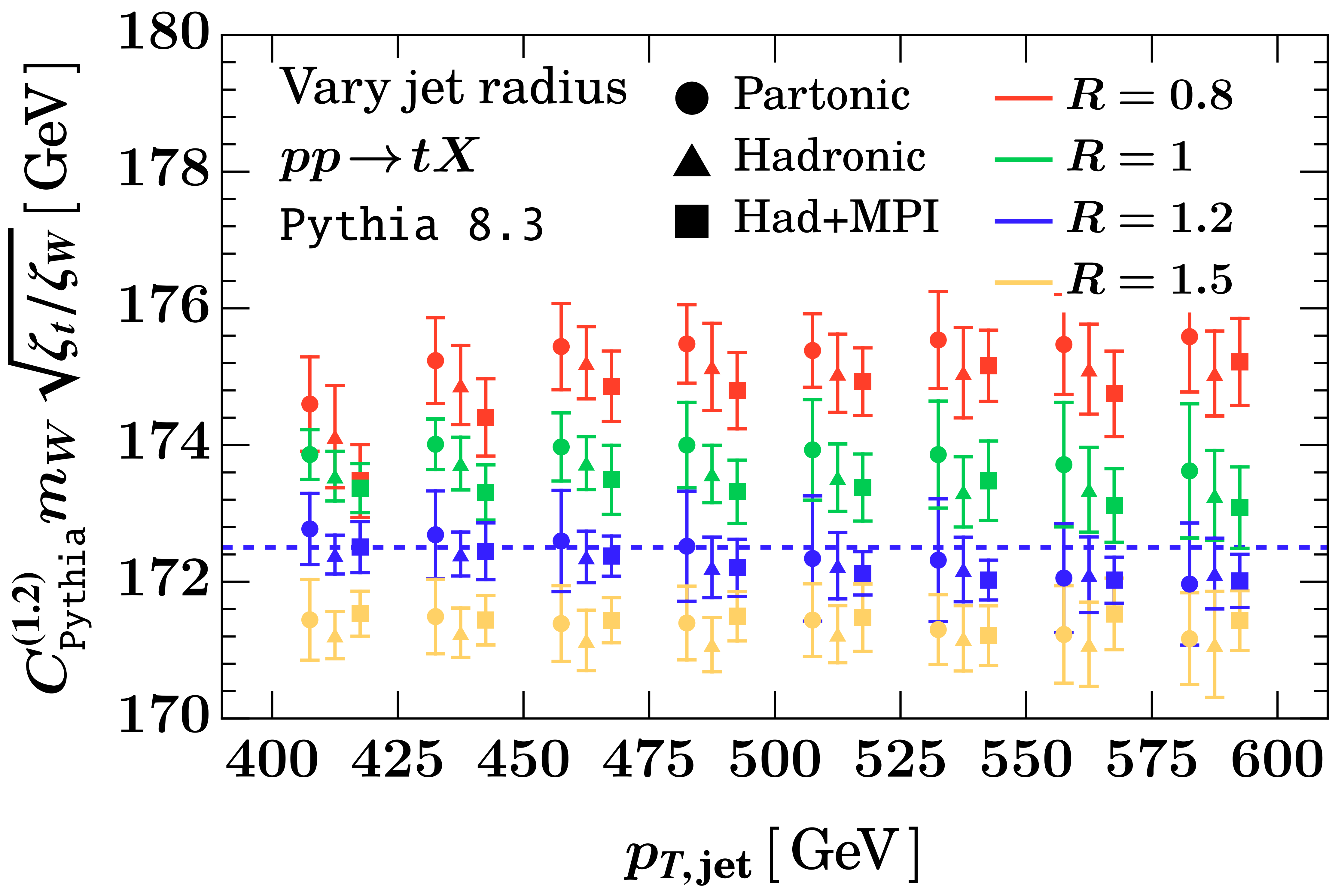


→ feasibility study using MC event generators

Holguin, Moult, Pathak, MP, Schöfbeck, Schwarz 2407.12900

Jet radius dependence

Varying R impacts both perturbative and non-perturbative jet features but the effect on the extracted top mass is dominantly perturbative



Production mechanism:

- PDF uncertainty ☐
- Hard scattering corrections ☐

Jet substructure:

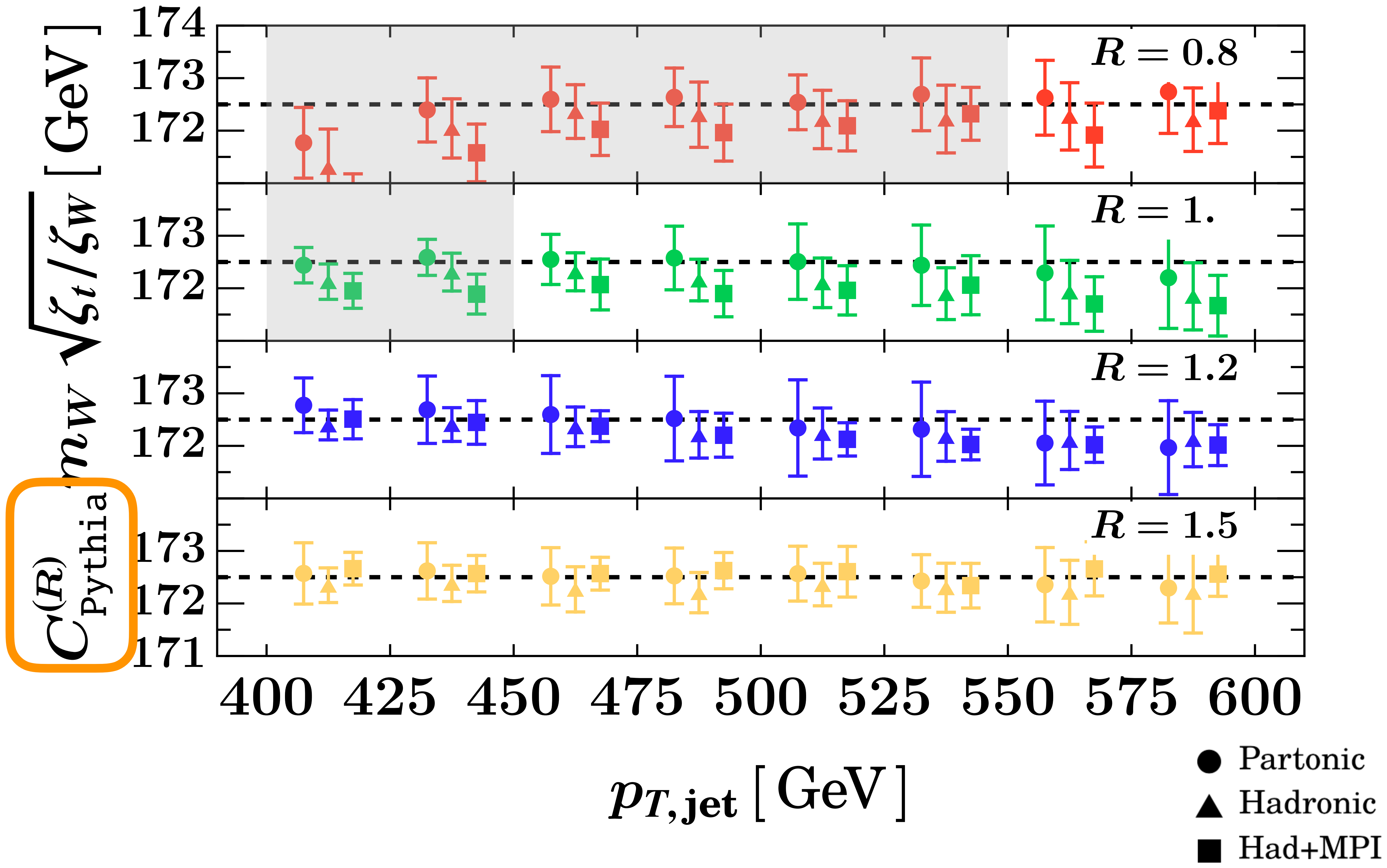
- Jet radius dependence ☐
- Hadronization effects ☐
- Impact of underlying event ☐
- Wide angle soft physics ☐
- Perturbative uncertainty ☐

Experimental feasibility:

- Statistical sensitivity ☐
- Jet energy scale ☐
- Constituent energy scale ☐
- Track efficiency ☐
- Heavy flavor dependence ☐

Jet radius dependence

Shift from hadronization/UE is about 200 MeV



Production mechanism:

- PDF uncertainty ☐
- Hard scattering corrections ☐

Jet substructure:

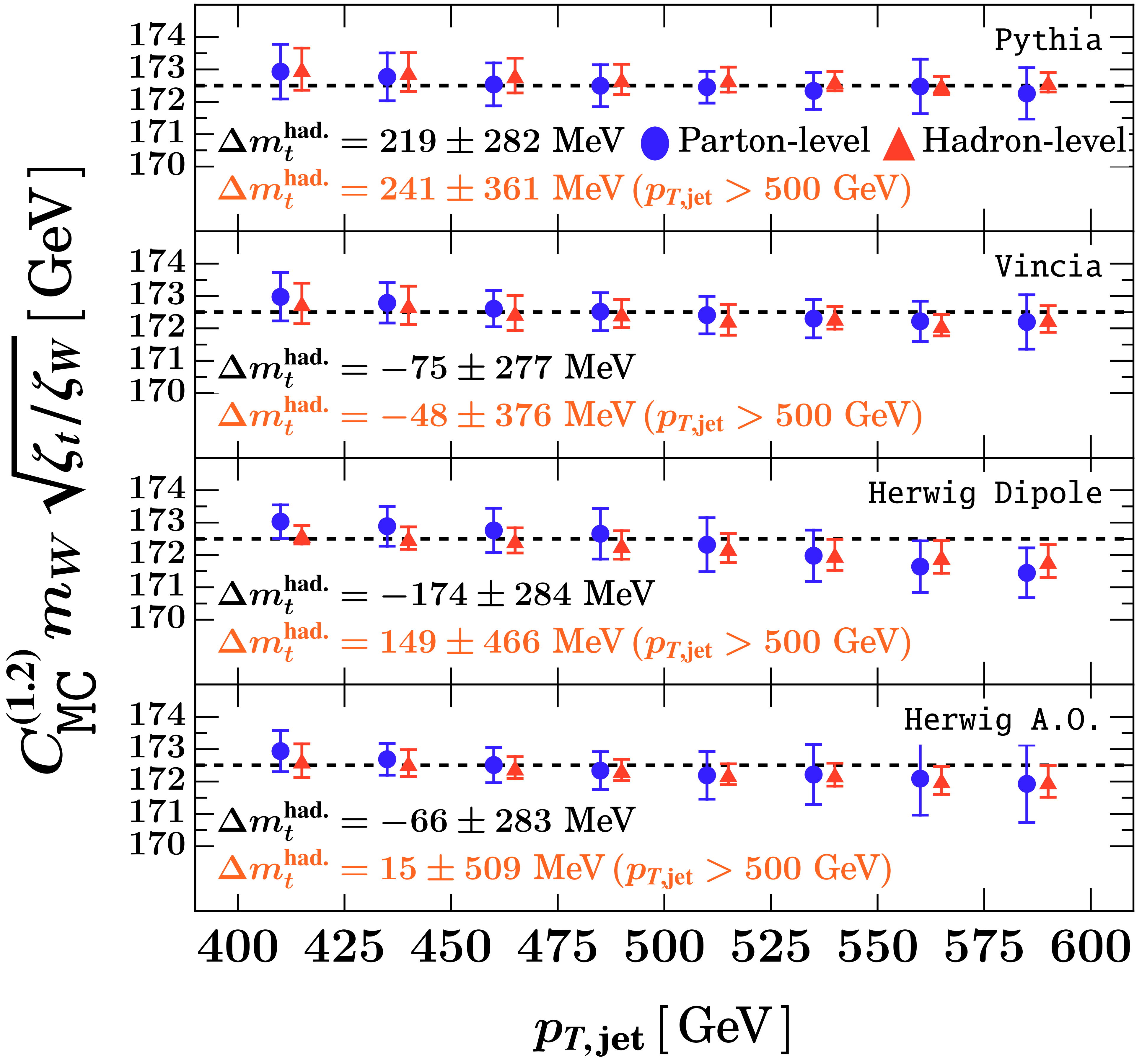
- Jet radius dependence ☑
- Hadronization effects ☐
- Impact of underlying event ☐
- Wide angle soft physics ☐
- Perturbative uncertainty ☐

Experimental feasibility:

- Statistical sensitivity ☐
- Jet energy scale ☐
- Constituent energy scale ☐
- Track efficiency ☐
- Heavy flavor dependence ☐

Hadronization effects

Small sensitivity to hadronization corrections in all parton shower generators



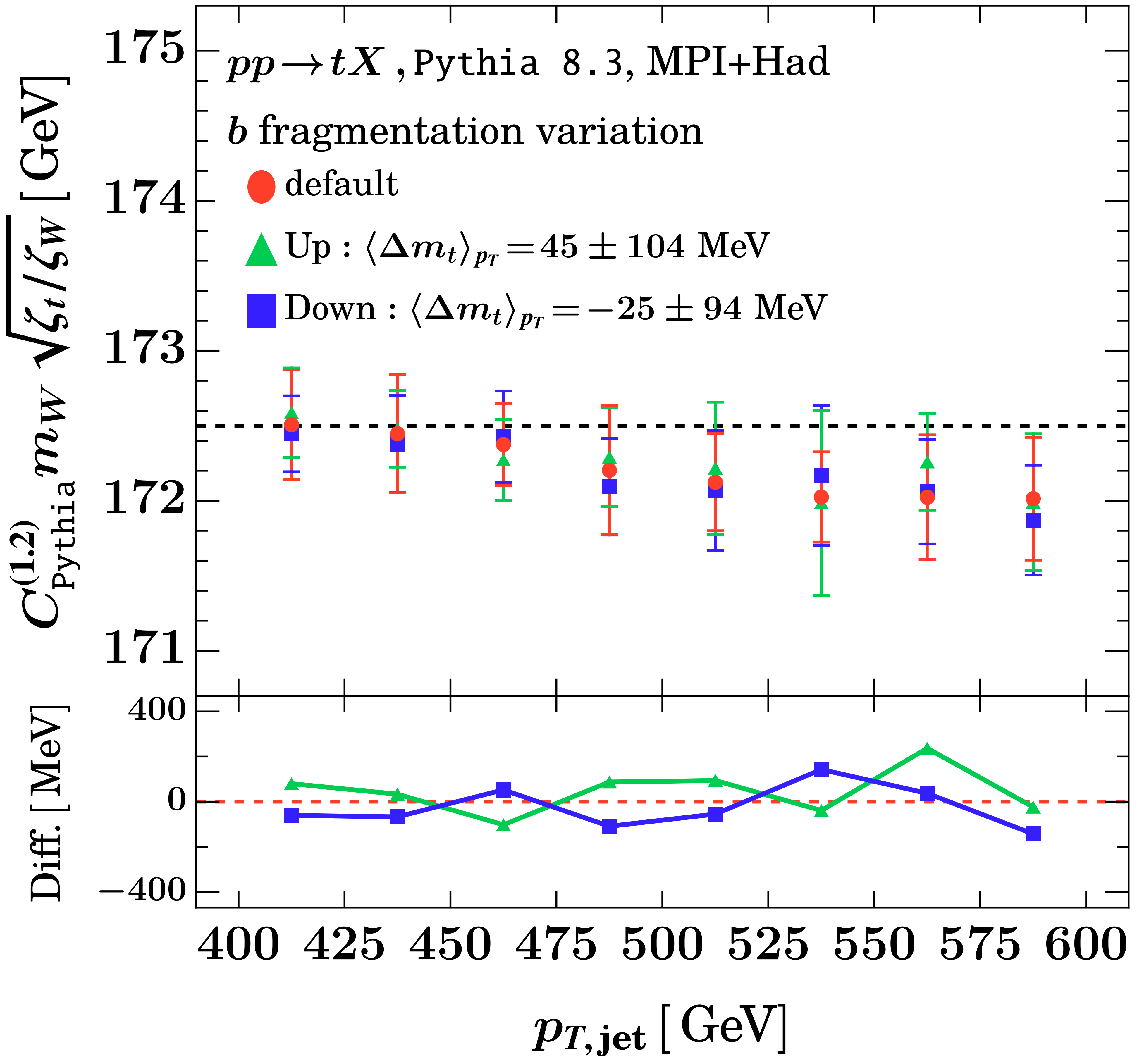
Production mechanism:
- PDF uncertainty ☐
- Hard scattering corrections ☐

Jet substructure:
- Jet radius dependence ☑
- Hadronization effects ☐
- Impact of underlying event ☐
- Wide angle soft physics ☐
- Perturbative uncertainty ☐

Experimental feasibility:
- Statistical sensitivity ☐
- Jet energy scale ☐
- Constituent energy scale ☐
- Track efficiency ☐
- Heavy flavor dependence ☐

b-quark fragmentation modelling

Negligible impact from b-quark hadronization models



Production mechanism:
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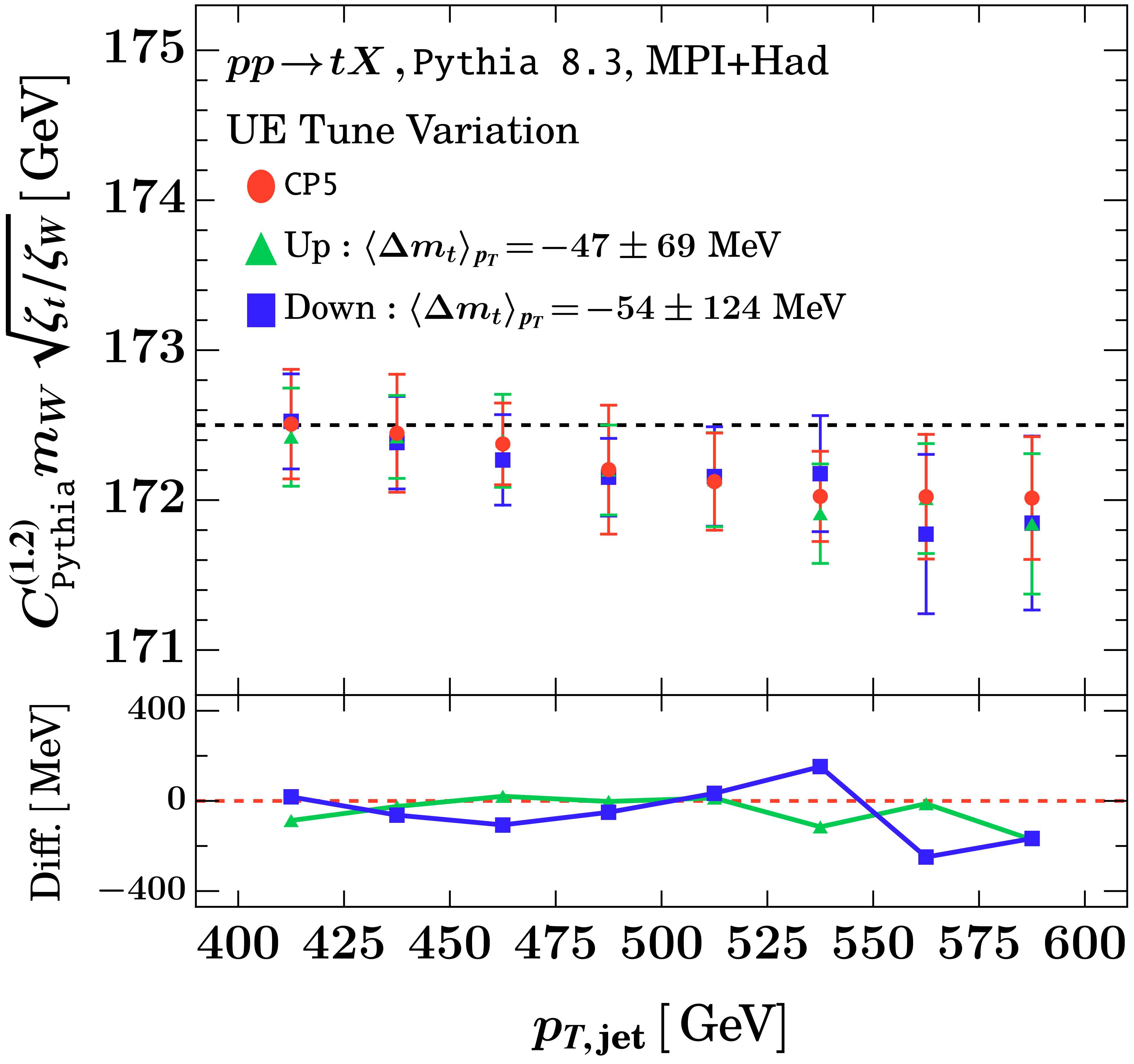
- Hard scattering corrections ☐

Jet substructure:
- Jet radius dependence ☑
- Hadronization effects ☑
- Impact of underlying event ☐
- Wide angle soft physics ☐
- Perturbative uncertainty ☐

Experimental feasibility:
- Statistical sensitivity ☐
- Jet energy scale ☐
- Constituent energy scale ☐
- Track efficiency ☐
- Heavy flavor dependence ☐

Underlying event contamination

Negligible impact from UE tune variations



Production mechanism:

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- Hard scattering corrections ☐

Jet substructure:

- Jet radius dependence ☑
- Hadronization effects ☑
- Impact of underlying event ☑
- Wide angle soft physics ☐
- Perturbative uncertainty ☐

Experimental feasibility:

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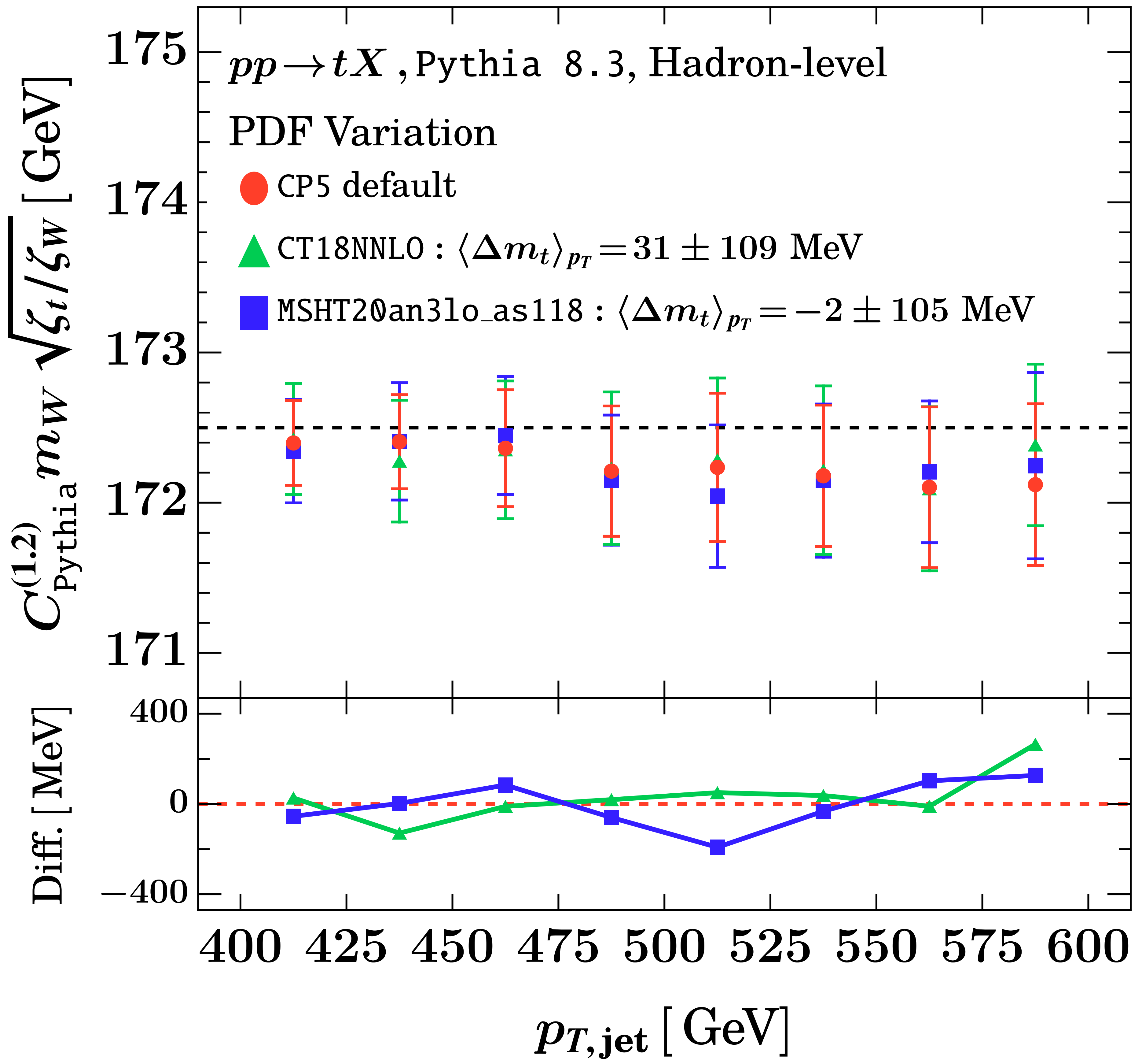
- Jet energy scale ☐
- Constituent energy scale ☐
- Track efficiency ☐
- Heavy flavor dependence ☐

PDF variations

Variations in PDFs lead to significant shifts and induce substantial uncertainties in $p_{T,\mathrm{jet}}$ distribution but the ratio of the peaks is extremely robust (negligible shifts)



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Experimental feasibility:

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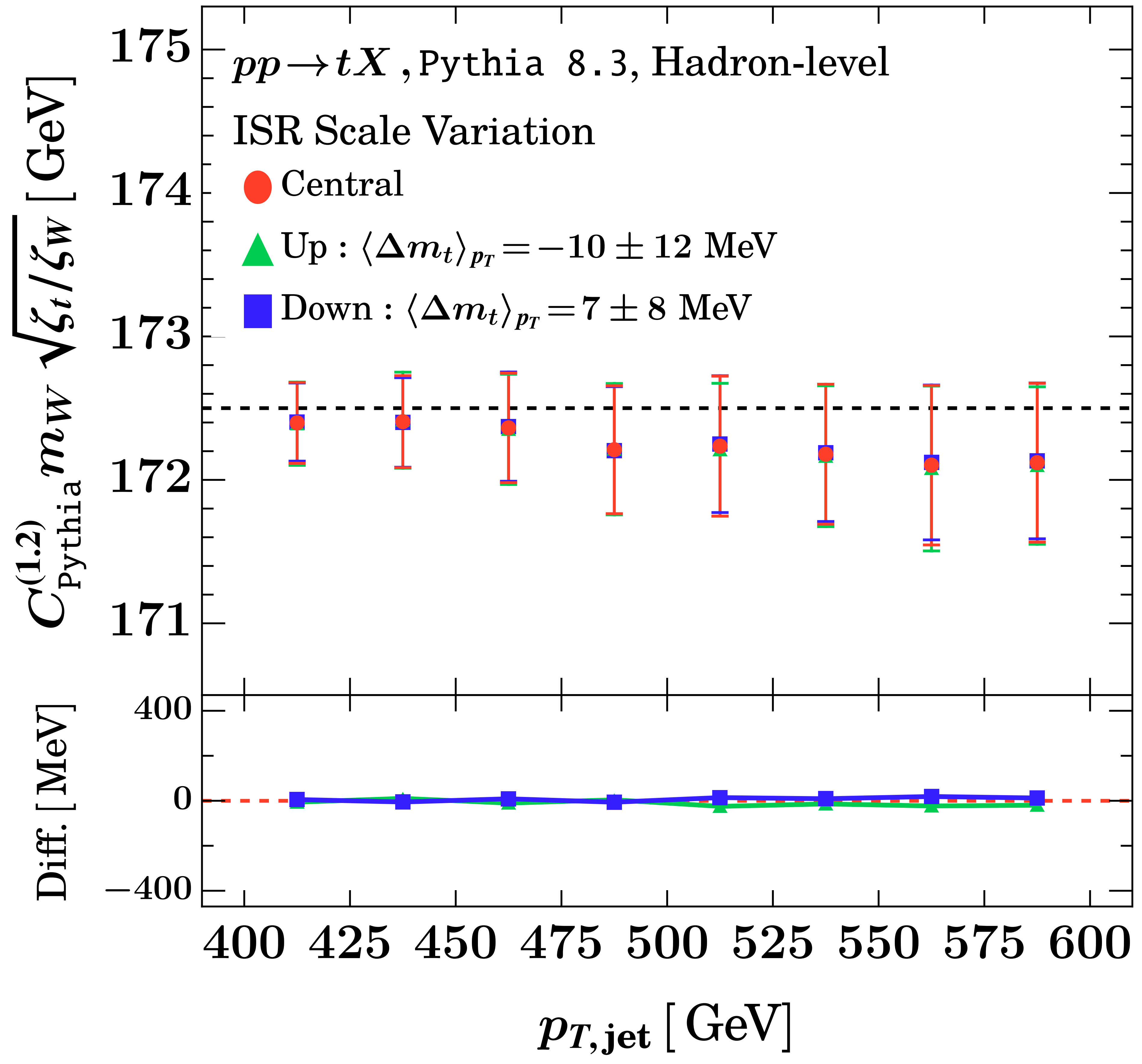
- Heavy flavor dependence ☐

Hard scattering corrections

Variations in the physics at the hard scale through scale variations of ISR: negligible impact



Production mechanism:

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- Hard scattering corrections ☐

Jet substructure:

- Jet radius dependence ☑
- Hadronization effects ☑
- Impact of underlying event ☑
- Wide angle soft physics ☐
- Perturbative uncertainty ☐

Experimental feasibility:

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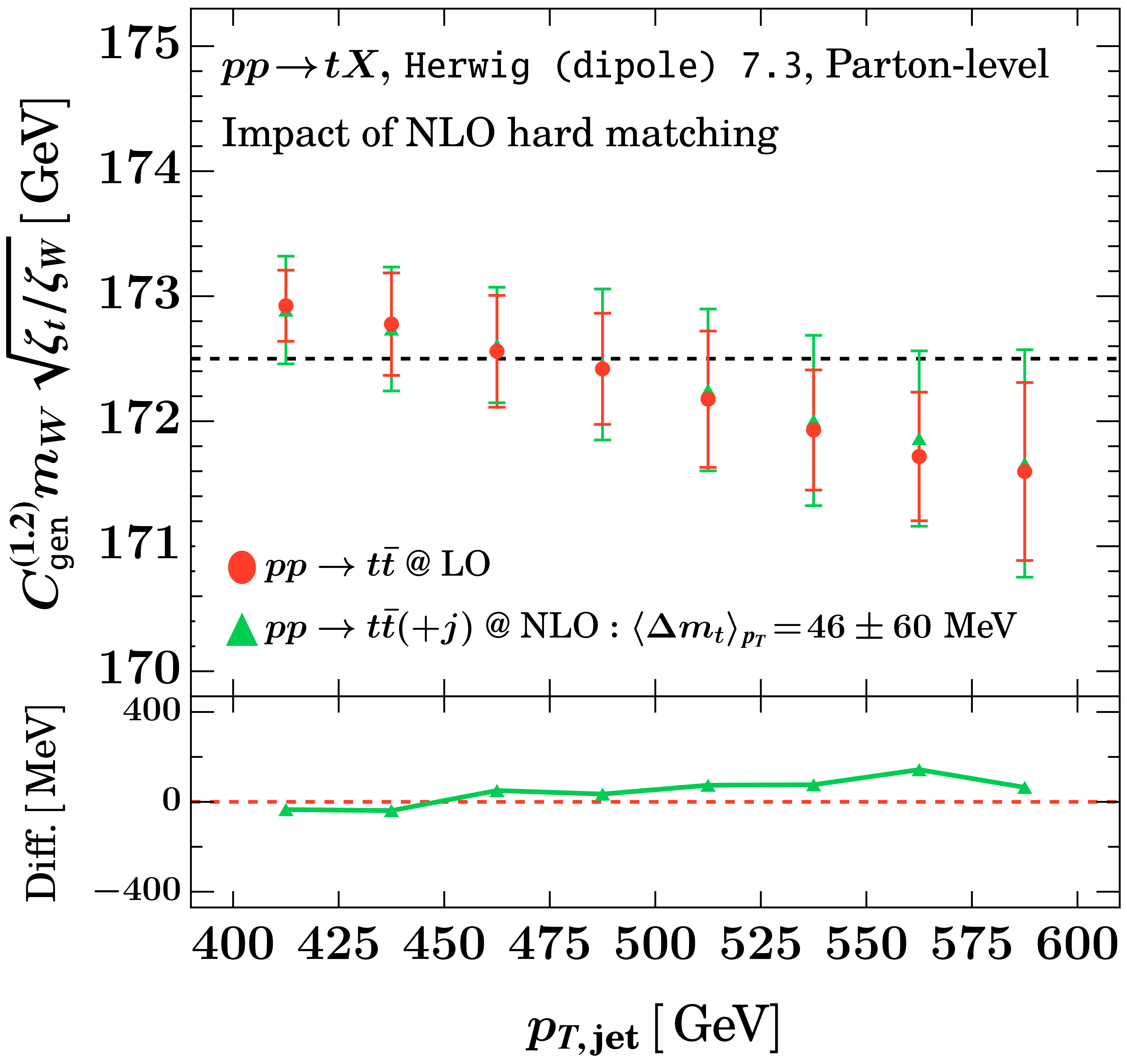
- Jet energy scale ☐
- Constituent energy scale ☐
- Track efficiency ☐
- Heavy flavor dependence ☐

Hard scattering corrections

Variations in the physics at the hard scale through NLO matching to $t\bar{t}+j$ process: negligible impact



Production mechanism:

- PDF uncertainty ☑
- Hard scattering corrections ☑

Jet substructure:

- Jet radius dependence ☑
- Hadronization effects ☑
- Impact of underlying event ☑
- Wide angle soft physics ☐
- Perturbative uncertainty ☐

Experimental feasibility:

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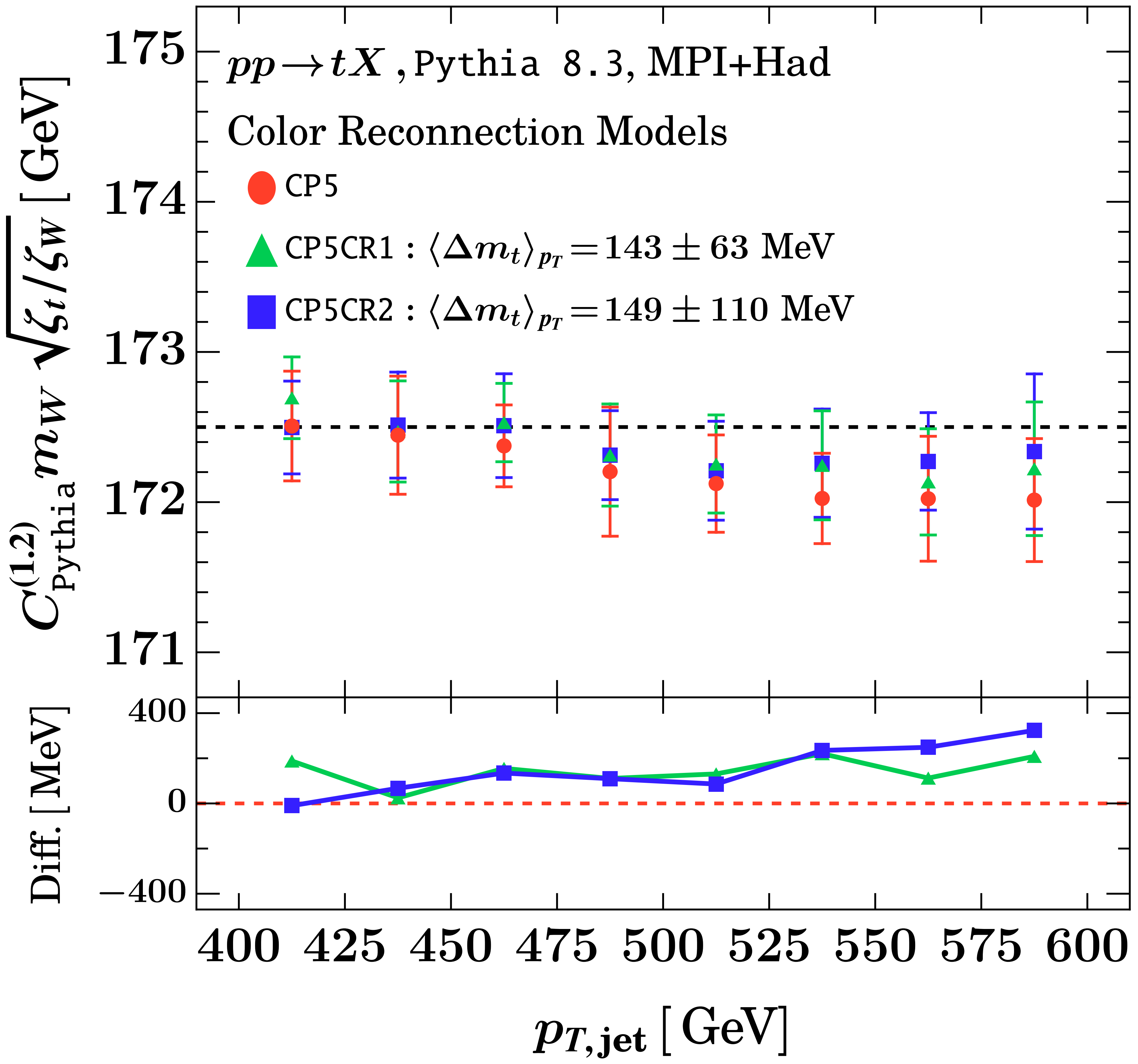
- Jet energy scale ☐
- Constituent energy scale ☐
- Track efficiency ☐
- Heavy flavor dependence ☐

Wide-angle soft physics

Models of color reconnection probe wide-angle soft physics at non-perturbative scales: small impact



Production mechanism:

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- Hard scattering corrections ☑

Jet substructure:

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- Hadronization effects ☑
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- Perturbative uncertainty ☐

Experimental feasibility:

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- Jet energy scale ☐
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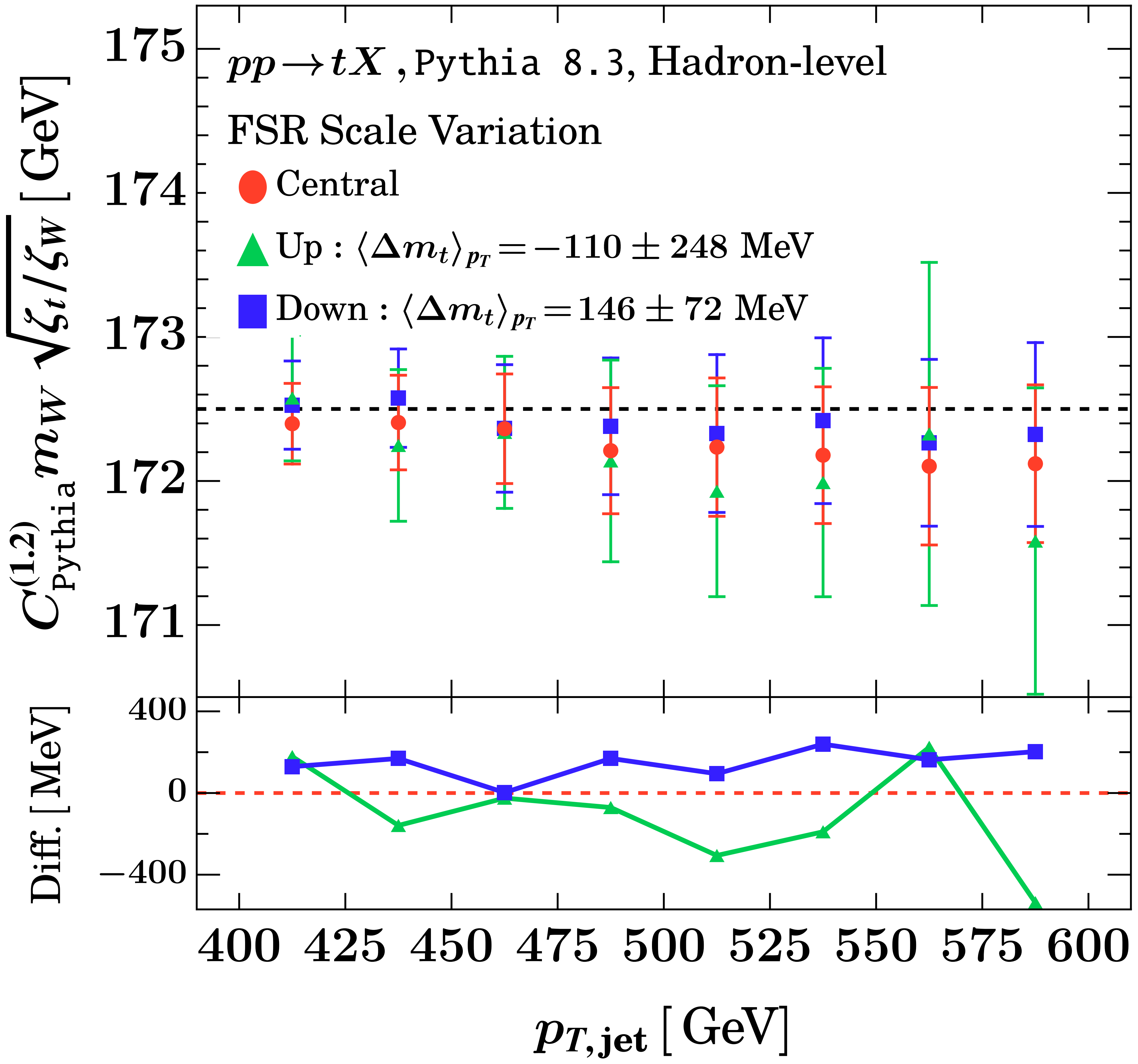
- Heavy flavor dependence ☐

Shower uncertainty: FSR scale variation

Results from LL showers + LO description of the top decay: small impact from FSR scale variation



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Jet substructure:

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- Hadronization effects ☑
- Impact of underlying event ☑
- Wide angle soft physics ☑
- Perturbative uncertainty ☐

Experimental feasibility:

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- Jet energy scale ☐
- Constituent energy scale ☐
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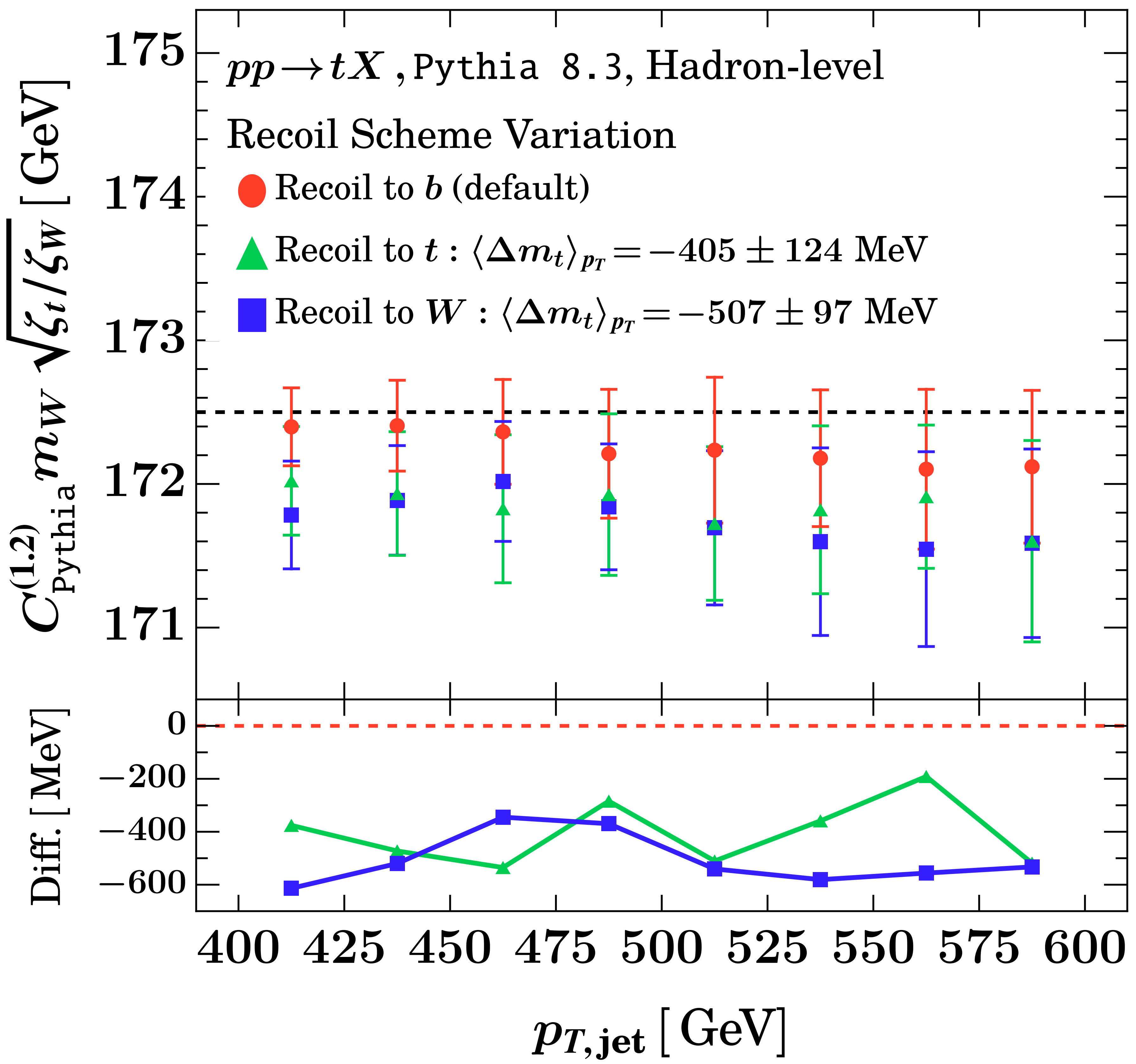
- Heavy flavor dependence ☐

Shower uncertainty: top jet recoil schemes

Top jet recoil schemes model NLO top-decay effects in parton showers: perturbative component dominates and significantly affects the top mass



Production mechanism:

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Jet substructure:

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- Hadronization effects ☑
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Experimental feasibility:

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- Jet energy scale ☐
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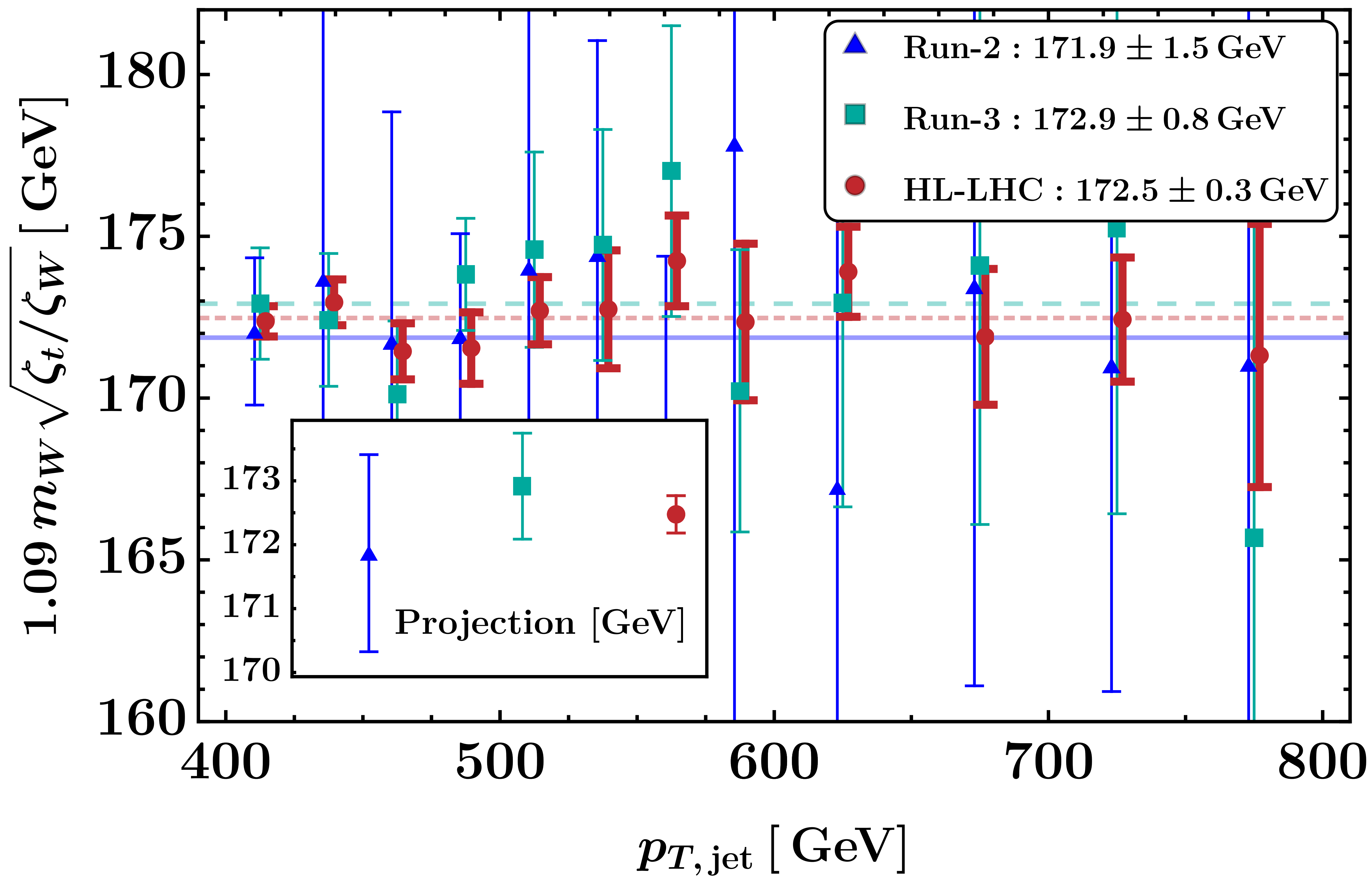
- Track efficiency ☐
- Heavy flavor dependence ☐

Experimental feasibility: statistics at the LHC

The measurement is statistically feasible at the LHC



Production mechanism:

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Jet substructure:

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- Perturbative uncertainty ☑

Experimental feasibility:

- Statistical sensitivity ☑
- Jet energy scale ☐
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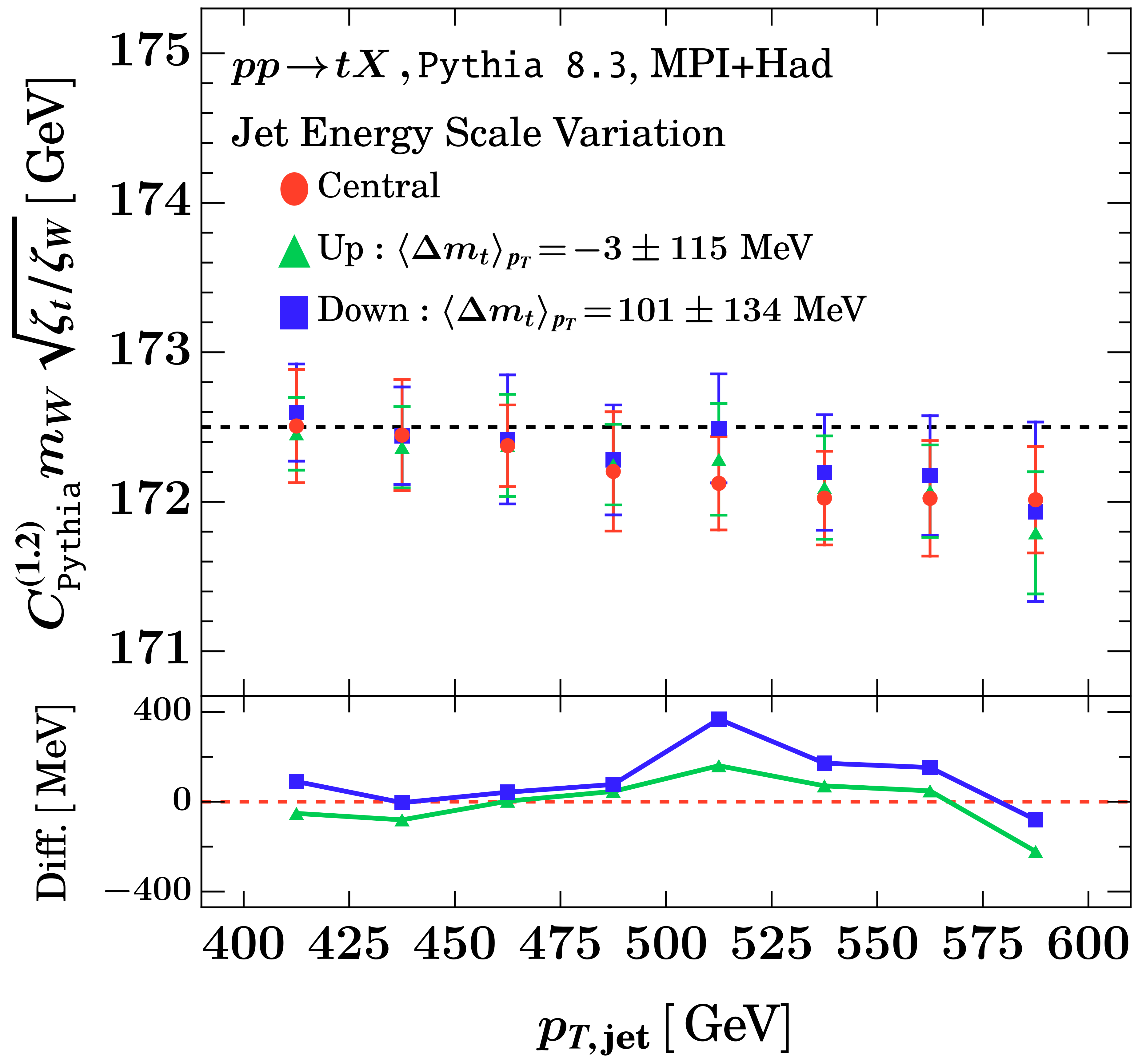
- Heavy flavor dependence ☐

Experimental feasibility: jet energy scale

We use the CMS model for jet energy scale uncertainty and vary accordingly $p_{T,\mathrm{jet}}$: very small impact



Production mechanism:

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Jet substructure:

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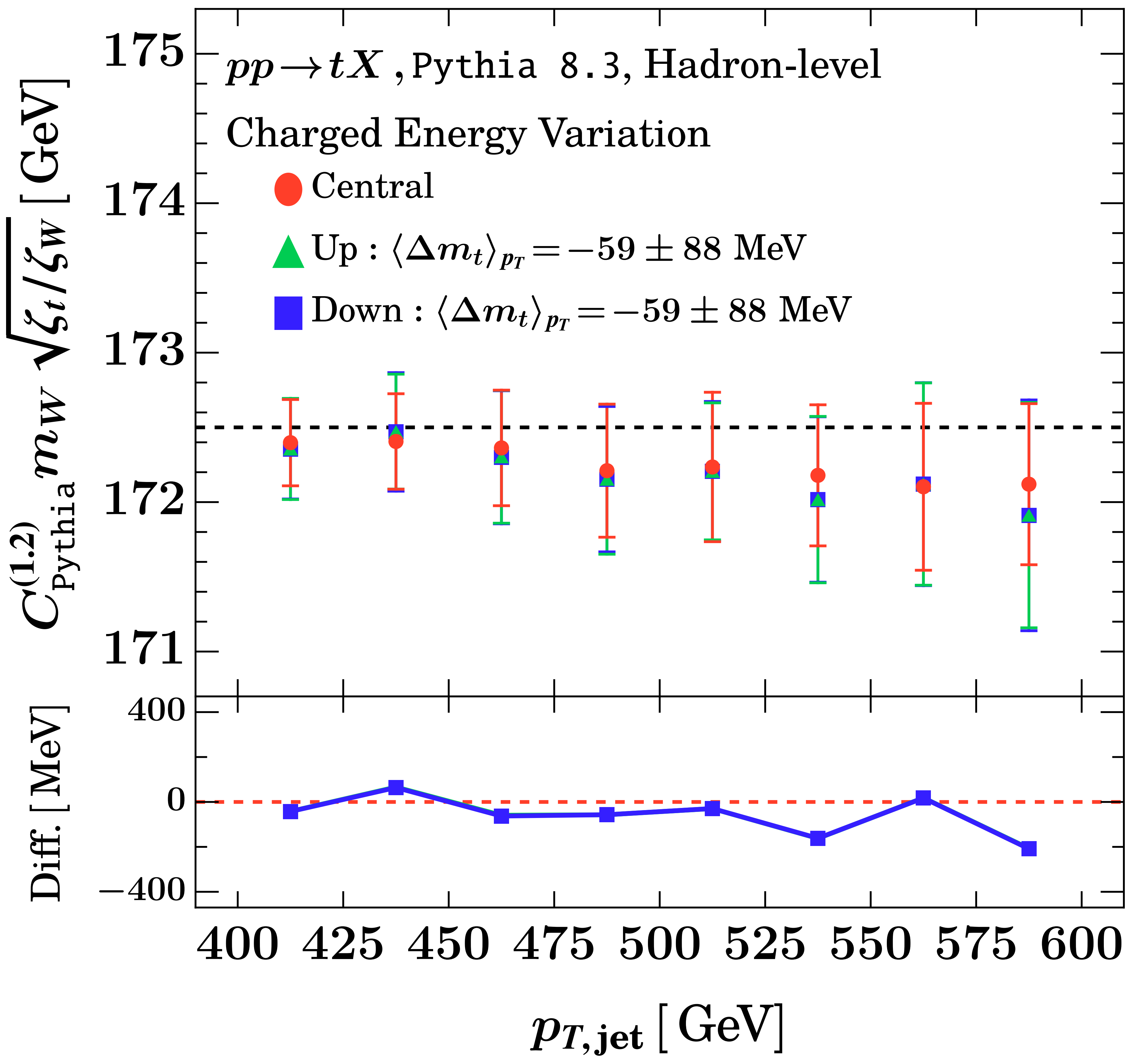
- Hadronization effects ☑
- Impact of underlying event ☑
- Wide angle soft physics ☑
- Perturbative uncertainty ☑

Experimental feasibility:

- Statistical sensitivity ☑
- Jet energy scale ☑
- Constituent energy scale ☐
- Track efficiency ☐
- Heavy flavor dependence ☐

Experimental feasibility: constituent energy scale

Effects of varying the momenta of the jet constituents (1% for charged, 3% for photons and 5% for neutrals): very small impact



Production mechanism:

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Jet substructure:

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- Hadronization effects ☑
- Impact of underlying event ☑
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- Perturbative uncertainty ☑

Experimental feasibility:

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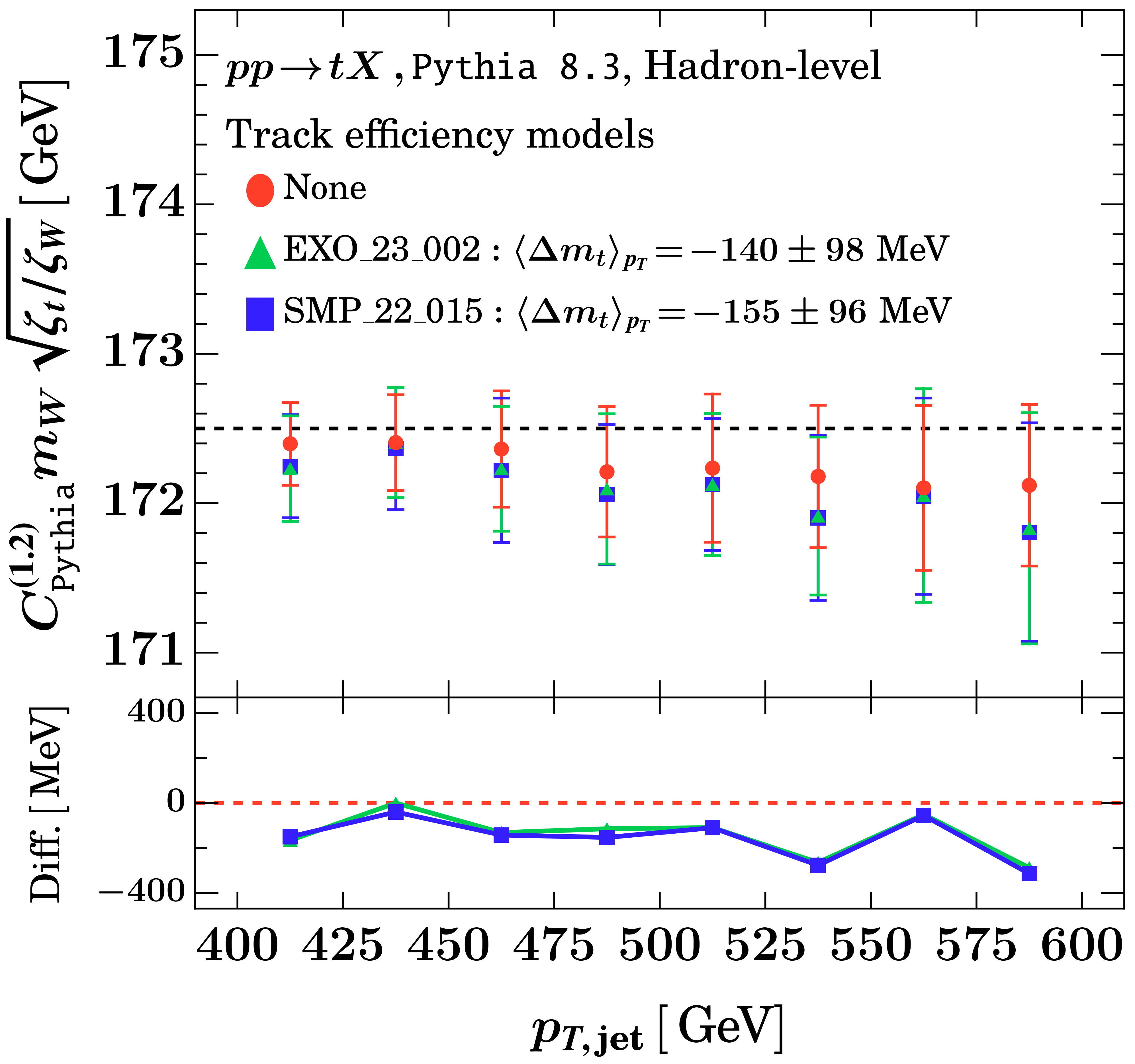
- Jet energy scale ☑
- Constituent energy scale ☑
- Track efficiency ☐
- Heavy flavor dependence ☐

Experimental feasibility: track efficiency

CMS track efficiency models: small impact



Production mechanism:

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Jet substructure:

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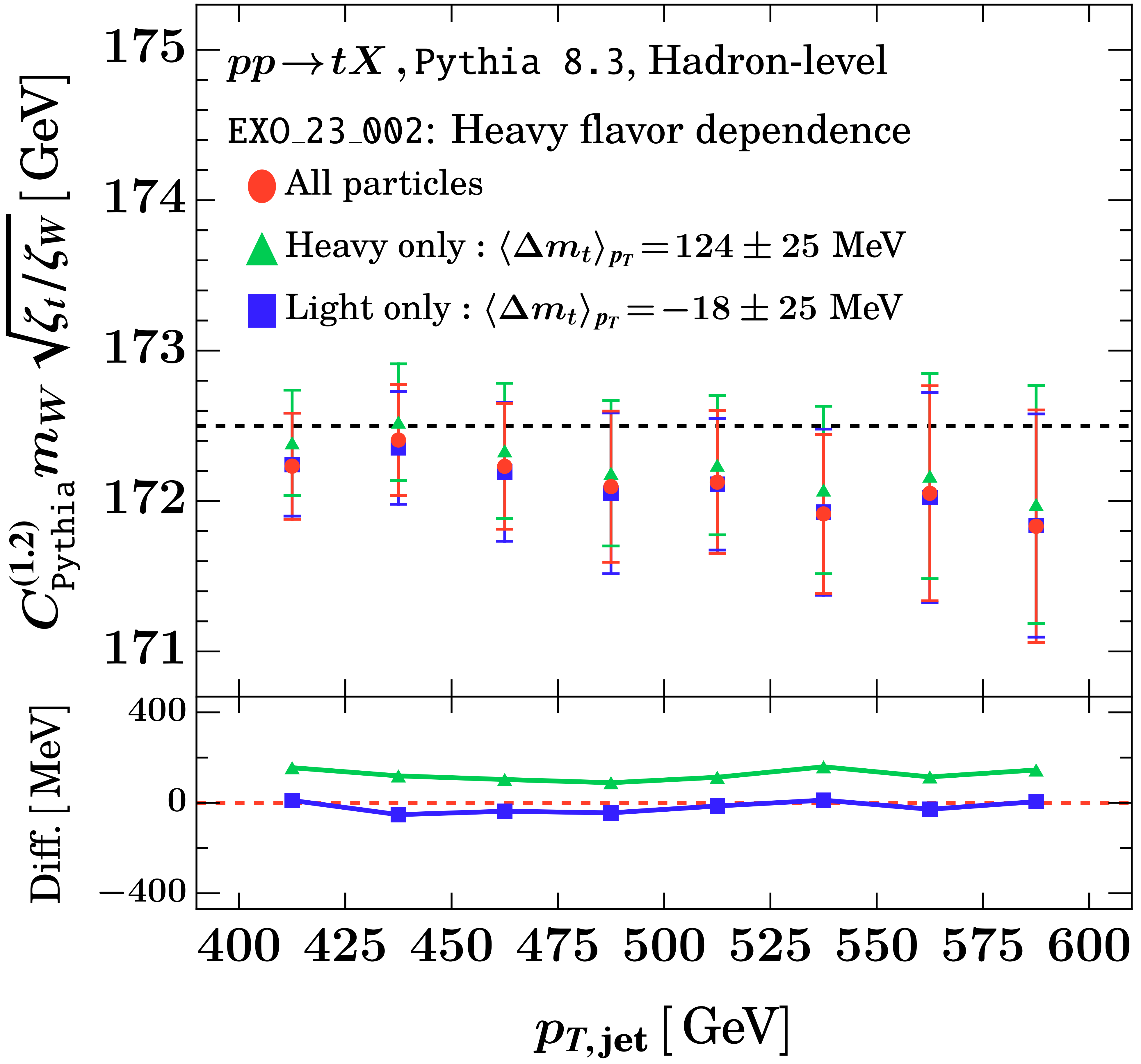
- Hadronization effects ☑
- Impact of underlying event ☑
- Wide angle soft physics ☑
- Perturbative uncertainty ☑

Experimental feasibility:

- Statistical sensitivity ☑
- Jet energy scale ☑
- Constituent energy scale ☑
- Track efficiency ☑
- Heavy flavor dependence ☐

Experimental feasibility: heavy flavor dependence

CMS models for different jet response between jets originated by a light quark vs b-quark: small effect



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Experimental feasibility:

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- Jet energy scale ☑
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- Track efficiency ☑
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Summary and outlook

- Triple energy correlators measured on boosted top jets: enhanced top-mass sensitivity dominated by hard kinematics (perturbatively calculable effects)

- By exploiting both top and W imprints in the triple energy correlator, high level of resilience against soft radiation effects, underlying event contamination and hadronization. Theoretical robustness and experimental feasibility

- Our MC-based analysis motivates novel precision calculations of energy correlators on top decays and further exploration of the experimental measurement.
  Goal: a novel, theoretically clean, precision extraction of the top mass in a well-defined short-distance scheme based on energy correlators measured on boosted top jets at LHC