Using the W as a standard candle to reach the top

Aditya Pathak

Energy Correlators at the Collider Frontier 2024, MITP

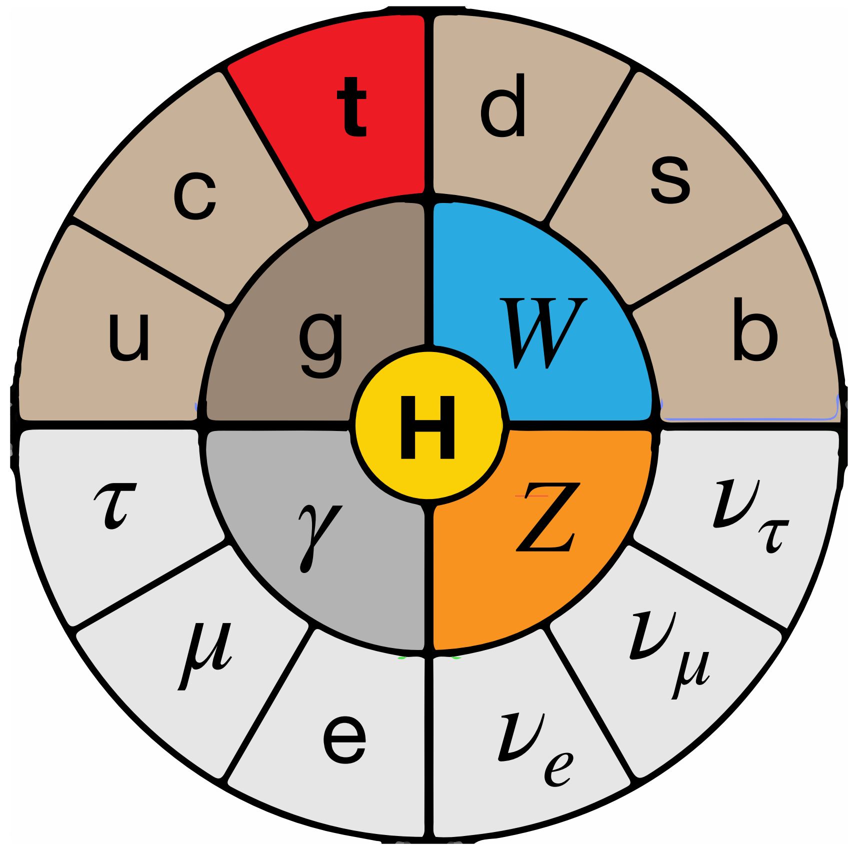
Based on:
Phys.Rev.D 107 (2023): J. Holguin, I. Moult, AP, M. Procura
2311.02157: J. Holguin, I. Moult, AP, M. Procura, R. Schöfbeck, D. Schwarz
2407.xxxx: J. Holguin, I. Moult, AP, M. Procura, R. Schöfbeck, D. Schwarz

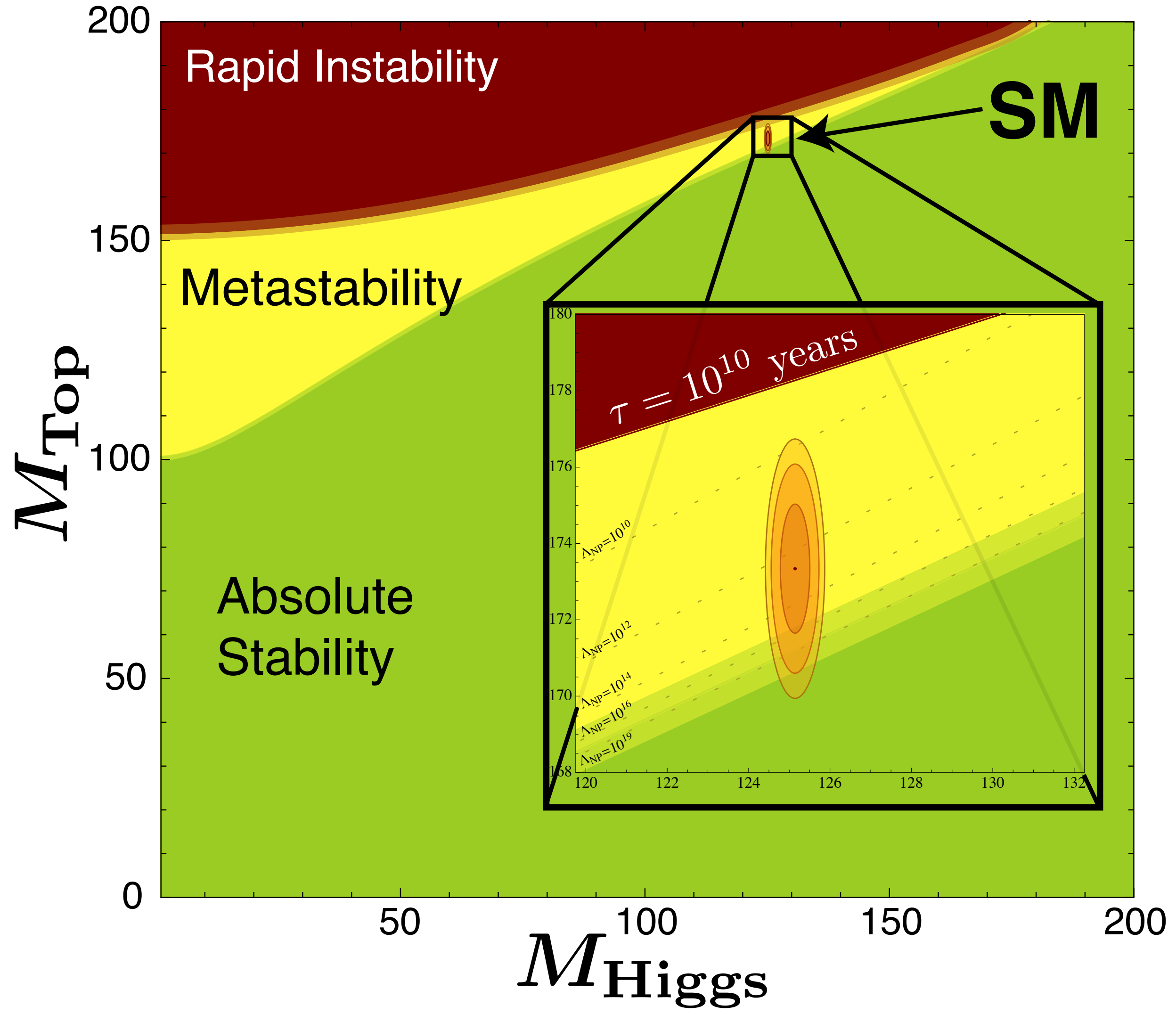
Outline

- Motivation
- EECs on boosted top quarks
- The Standard Candle approach
- Demonstrating Robustness and Experimental Feasibility

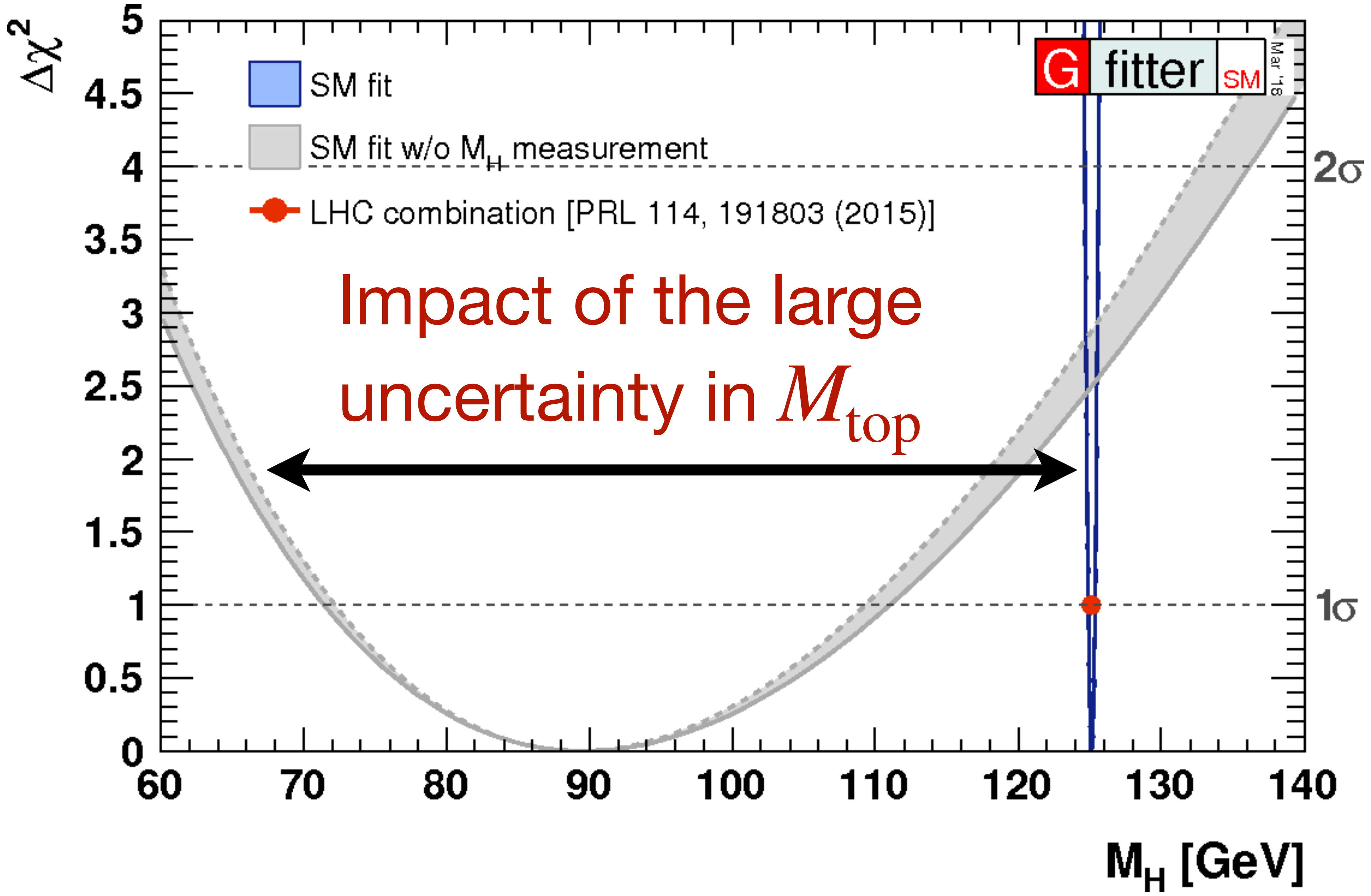
Precision top mass: A longstanding problem

- **Key to new physics:** Precision measurements and consistency tests.
- The masses of the Higgs, W and Z bosons known to $<$ 0.2% precision, but …
- Top mass is not as precise as you'd like it to be:
  - Largest uncertainty $\delta M_W^{m_t} = 4\,\mathrm{MeV}$ from δM_t
  - 20 GeV uncertainty in indirect M_H from δM_t
- The outcome of EW vacuum stability depends sensitively on the precision on the top quark mass.
- Need sub-percent ($< 1\,\mathrm{GeV}$) M_{top}: a longstanding problem for three decades.
- **What is halting the progress?**





Andreassen, Frost, Schwartz 2014

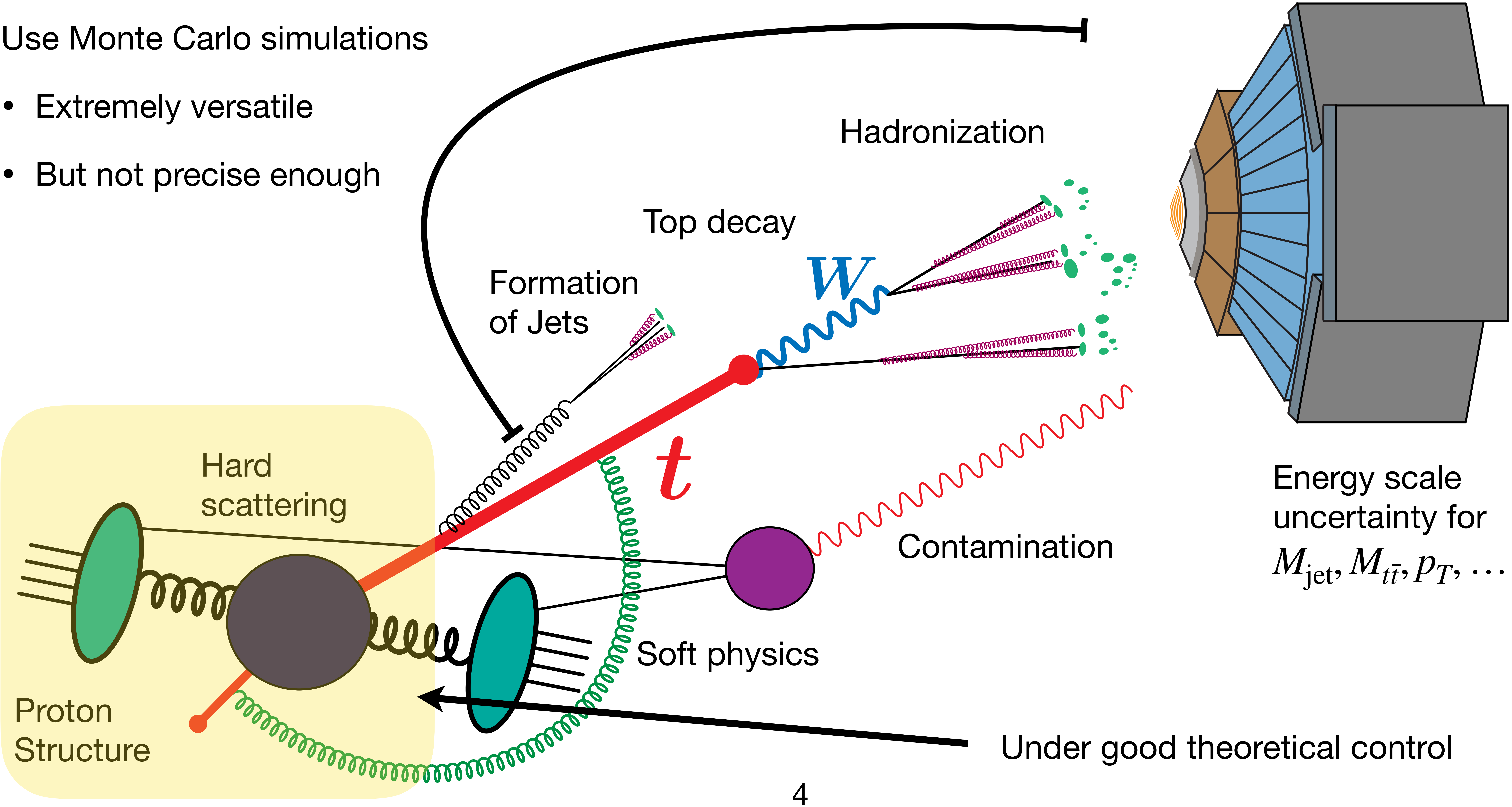


Impact of the large uncertainty in M_{top}

The current status of collider QCD

Use Monte Carlo simulations

- Extremely versatile
- But not precise enough



Hadronization

Top decay

Formation of Jets

Hard scattering

Proton Structure

Contamination

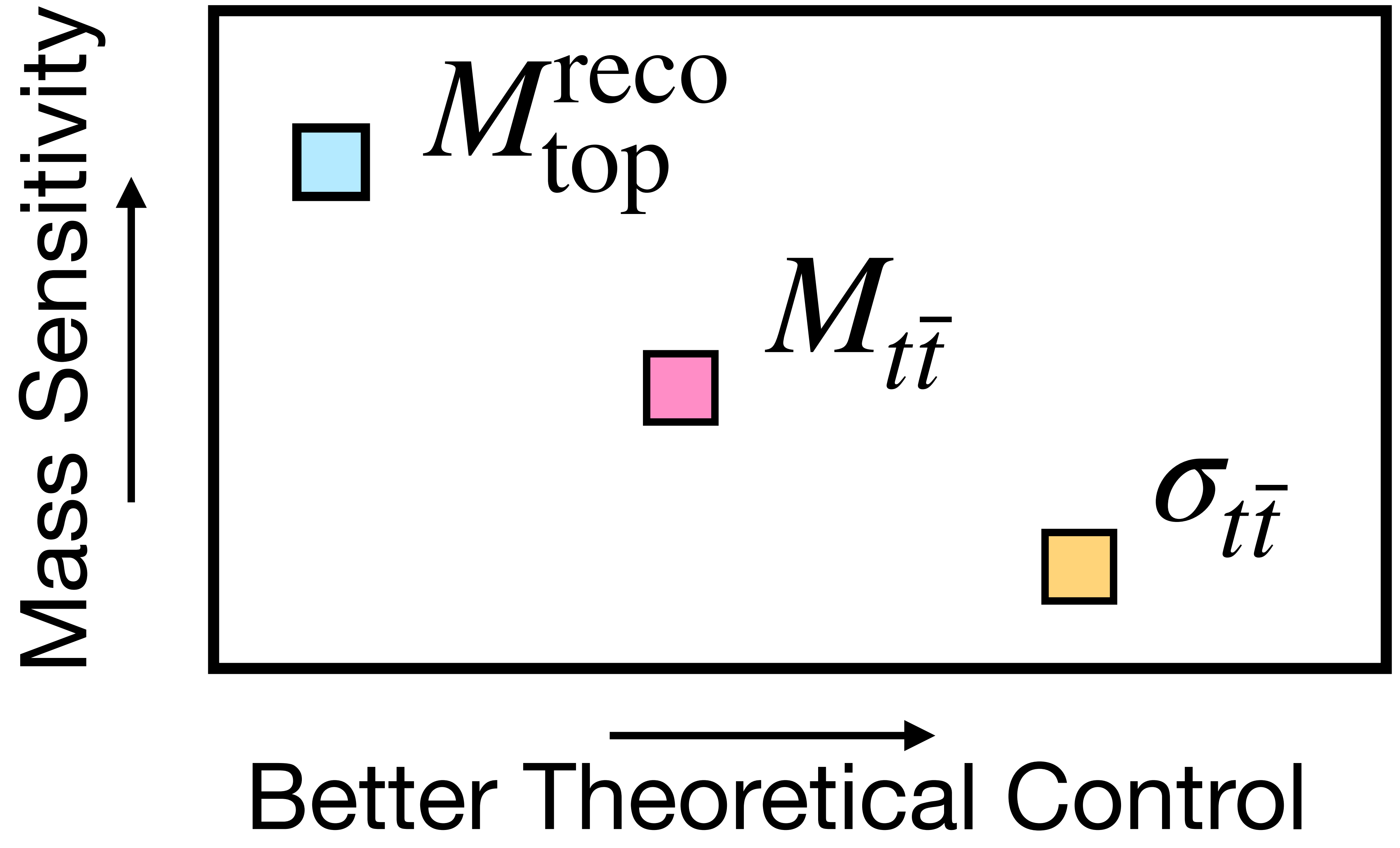
Soft physics

Energy scale uncertainty for $M_{\text{jet}}, M_{t\bar{t}}, p_T, \ldots$

Under good theoretical control

Problems with top mass measurements

Current Paradigm:



$$\Delta m_t^{\overline{\text{MS}}} \sim \pm 2\,\text{GeV}$$

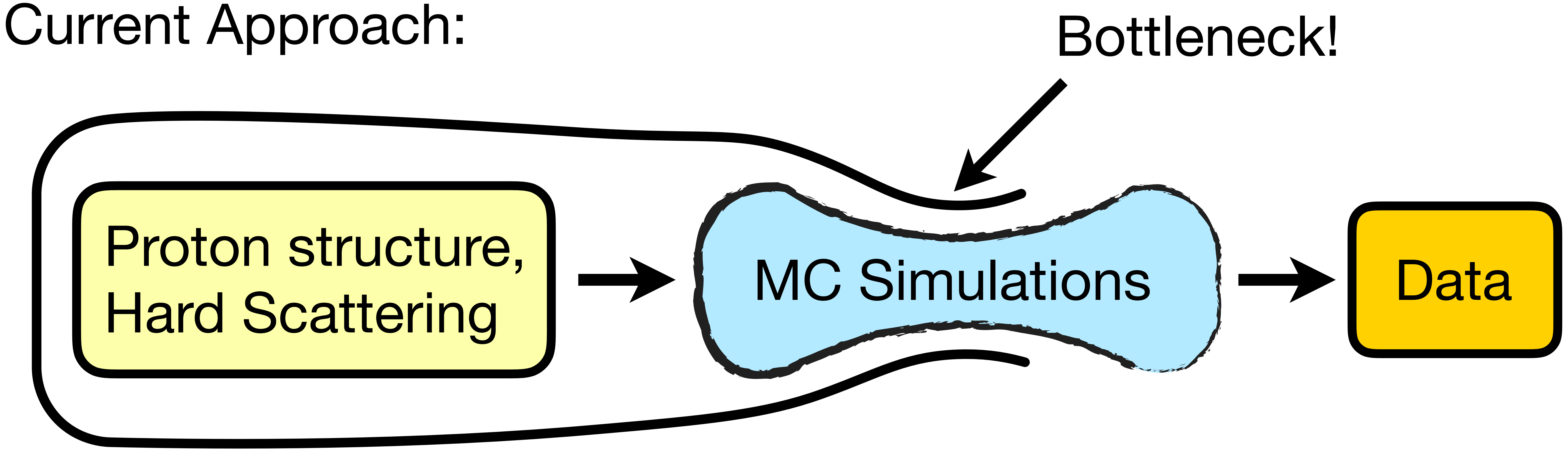
$$\Delta m_t^{\text{pole}} = \pm 0.7\,\text{GeV}$$
$$+\mathcal{O}(1\,\text{GeV})$$ (soft physics)

$$\Delta m_t^{\text{MC}} = \pm 0.3\,\text{GeV}$$
$$+\mathcal{O}(1\,\text{GeV})$$
(Modeling hadronization)

- **Compromise between** theoretical control and mass sensitivity.

Problems in the current paradigm

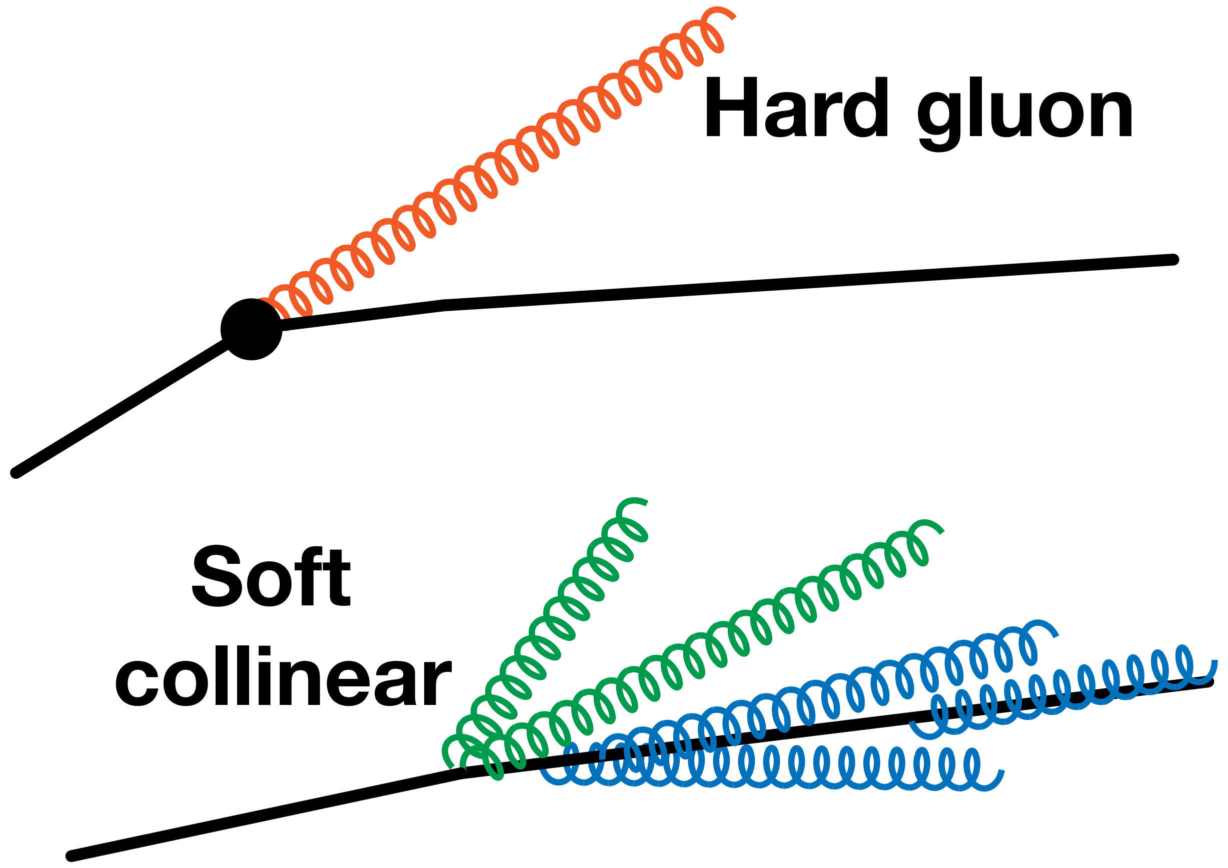
Current Approach:



Bottleneck!

Proton structure, Hard Scattering → MC Simulations → Data

- Fixed order calculations only really impact the region less sensitive to the top mass.
- The highest sensitivity arises in the region dominated by resummation and large nonperturbative effects.
- Extremely challenging to improve MCs beyond NLL and no systematic way to estimate intrinsic uncertainties of hadronization models.



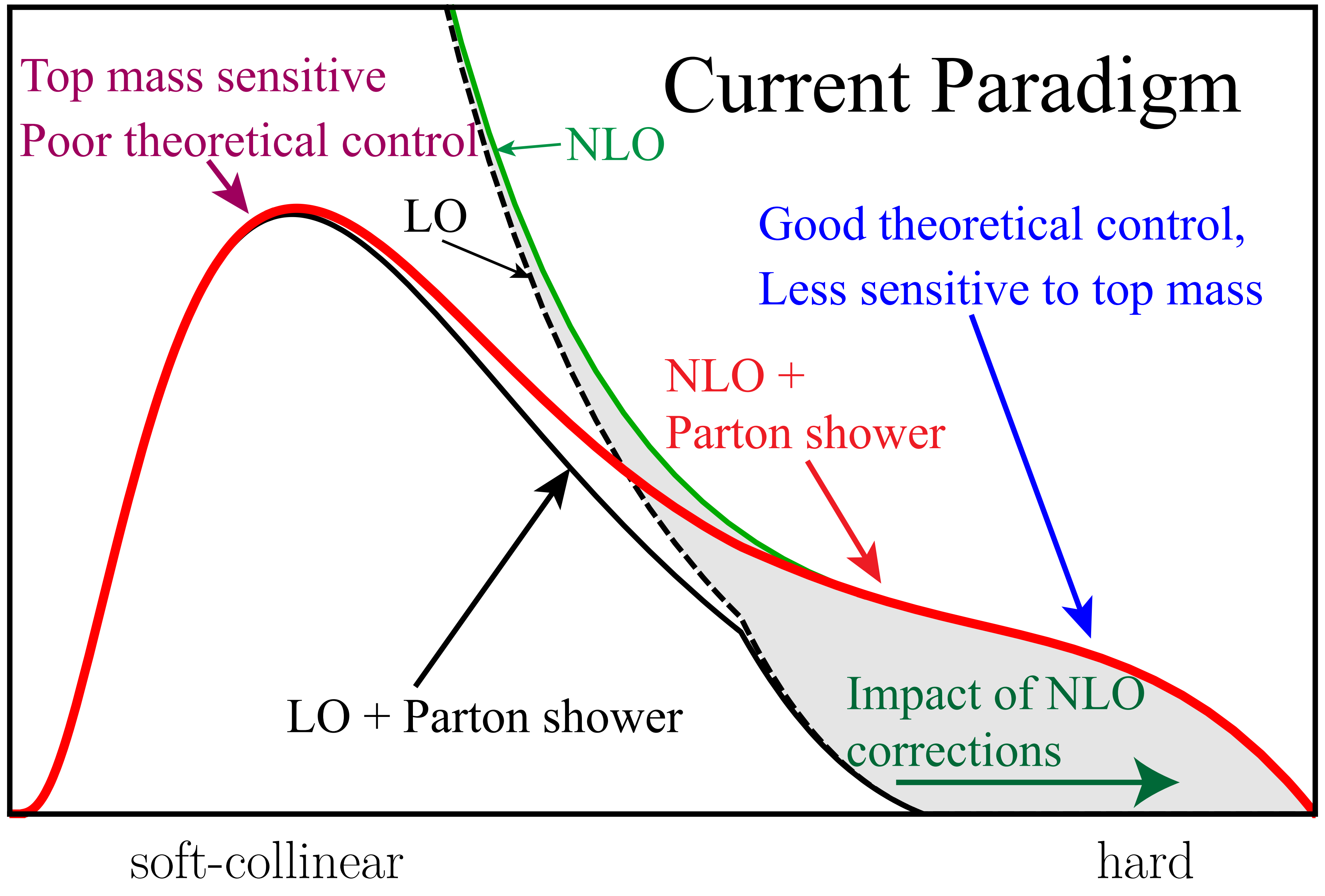
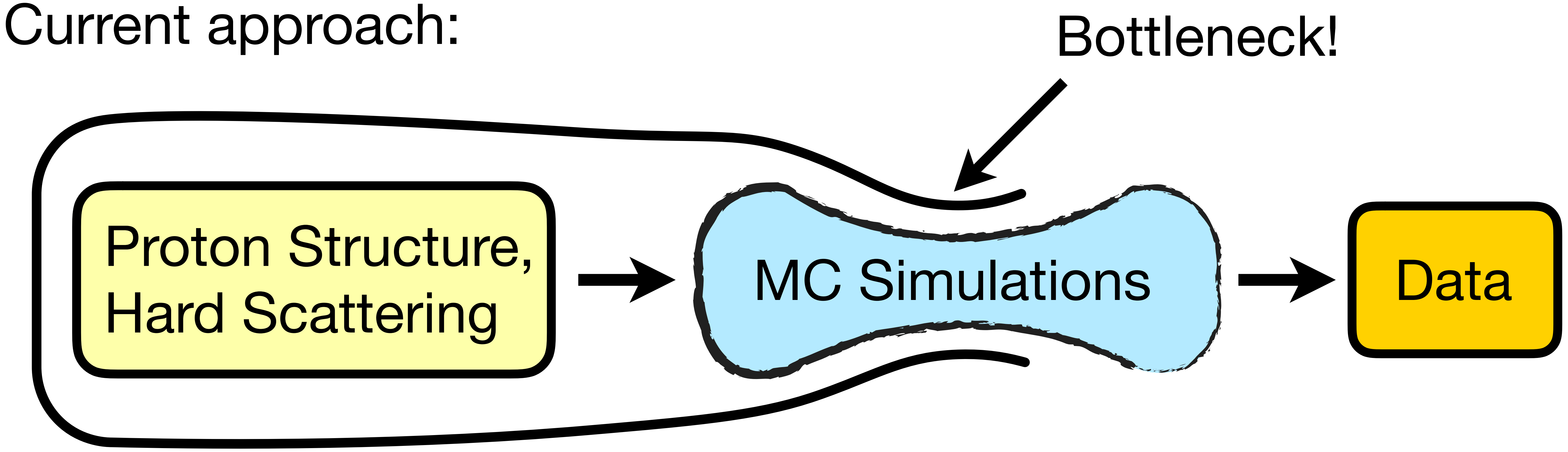


Figure adapted from Hoang 2004.12915

Proposed approach

Current approach:



Bottleneck!

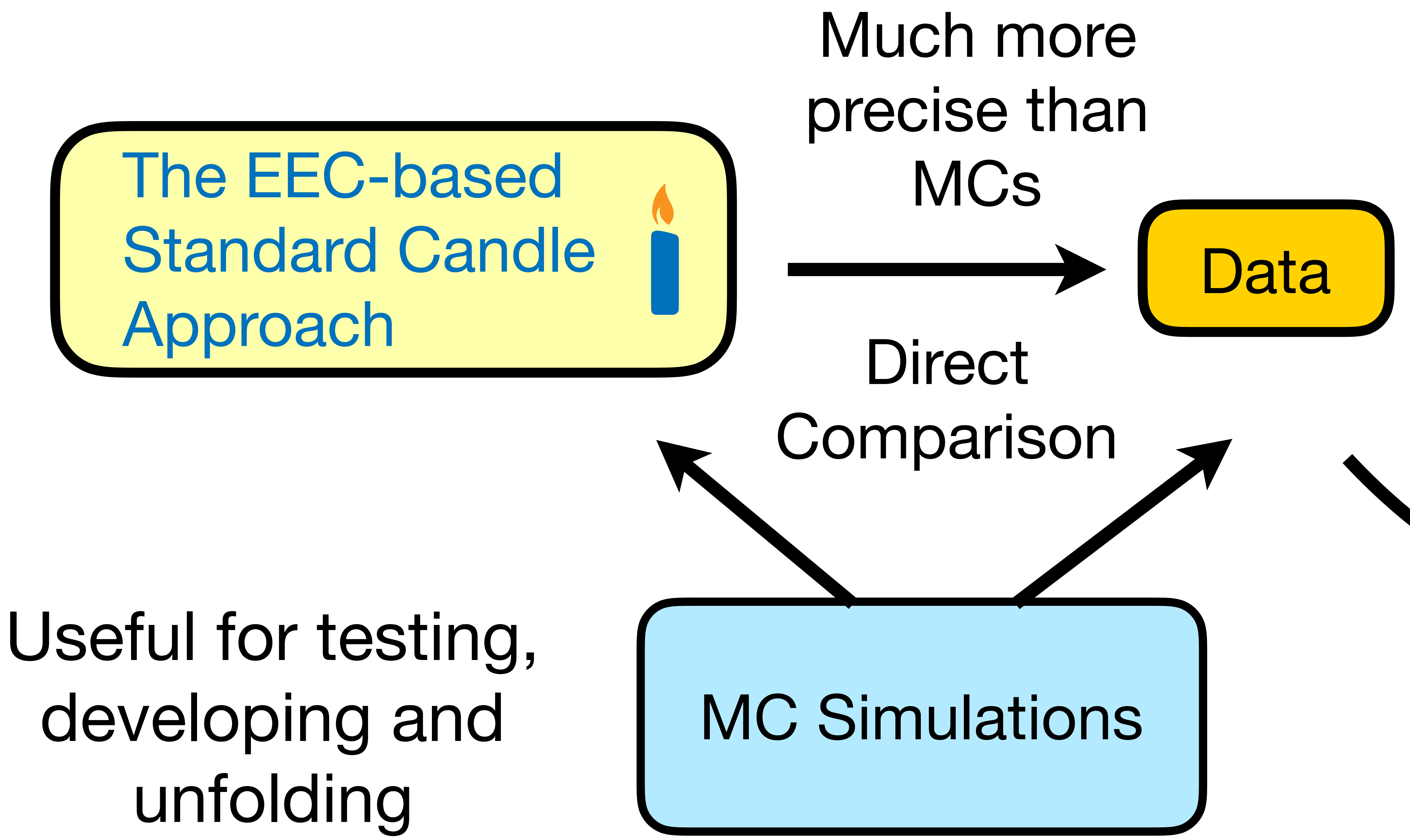
Proton Structure, Hard Scattering

MC Simulations

Data

Goal:

- Eliminate over-reliance on MC by seeking observables with high top mass sensitivity and excellent theoretical control



The EEC-based Standard Candle Approach

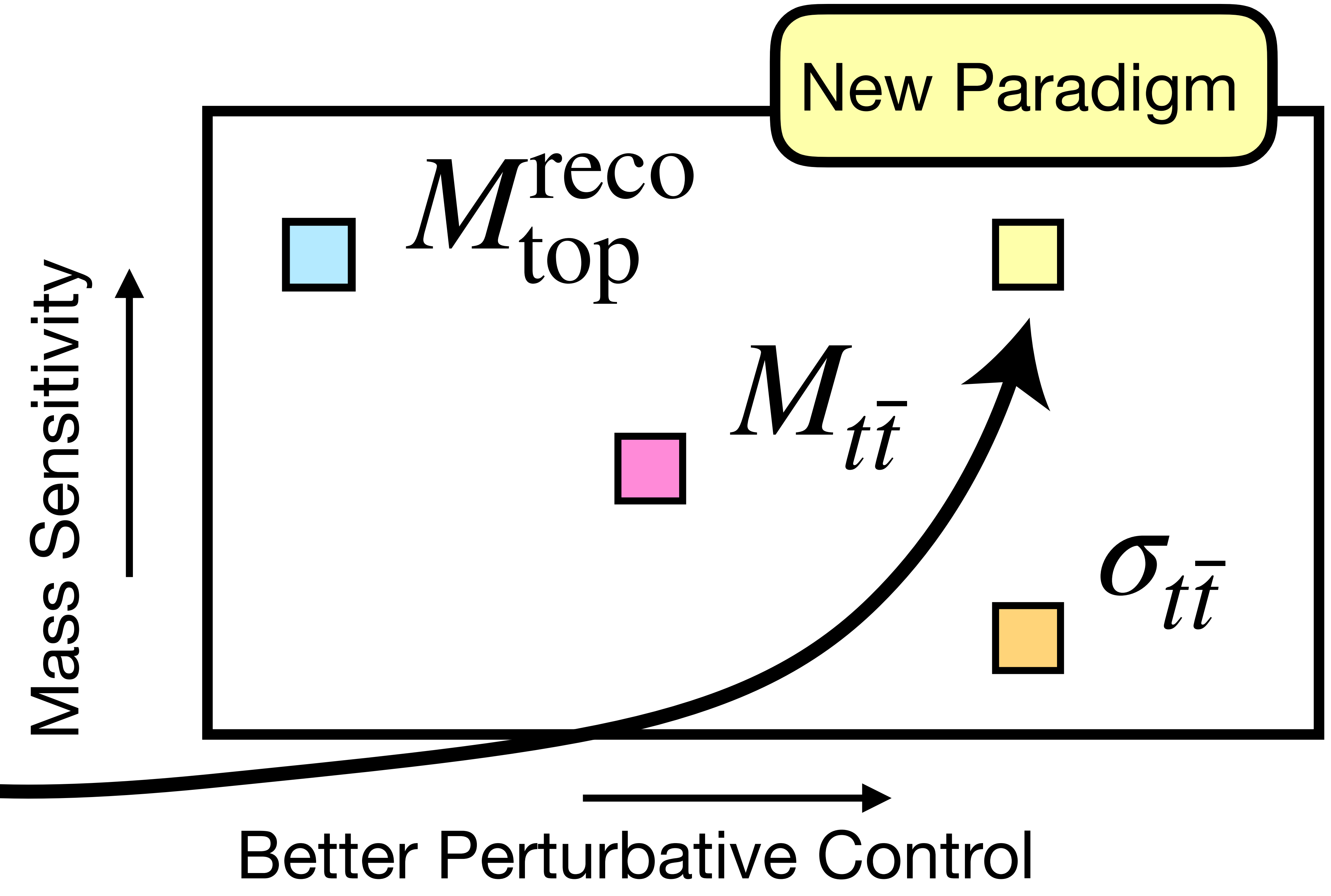
Much more precise than MCs

Direct Comparison

Data

Useful for testing, developing and unfolding

MC Simulations



New Paradigm

$M_{\text{top}}^{\text{reco}}$

$M_{t\bar{t}}$

$\sigma_{t\bar{t}}$

Mass Sensitivity

Better Perturbative Control

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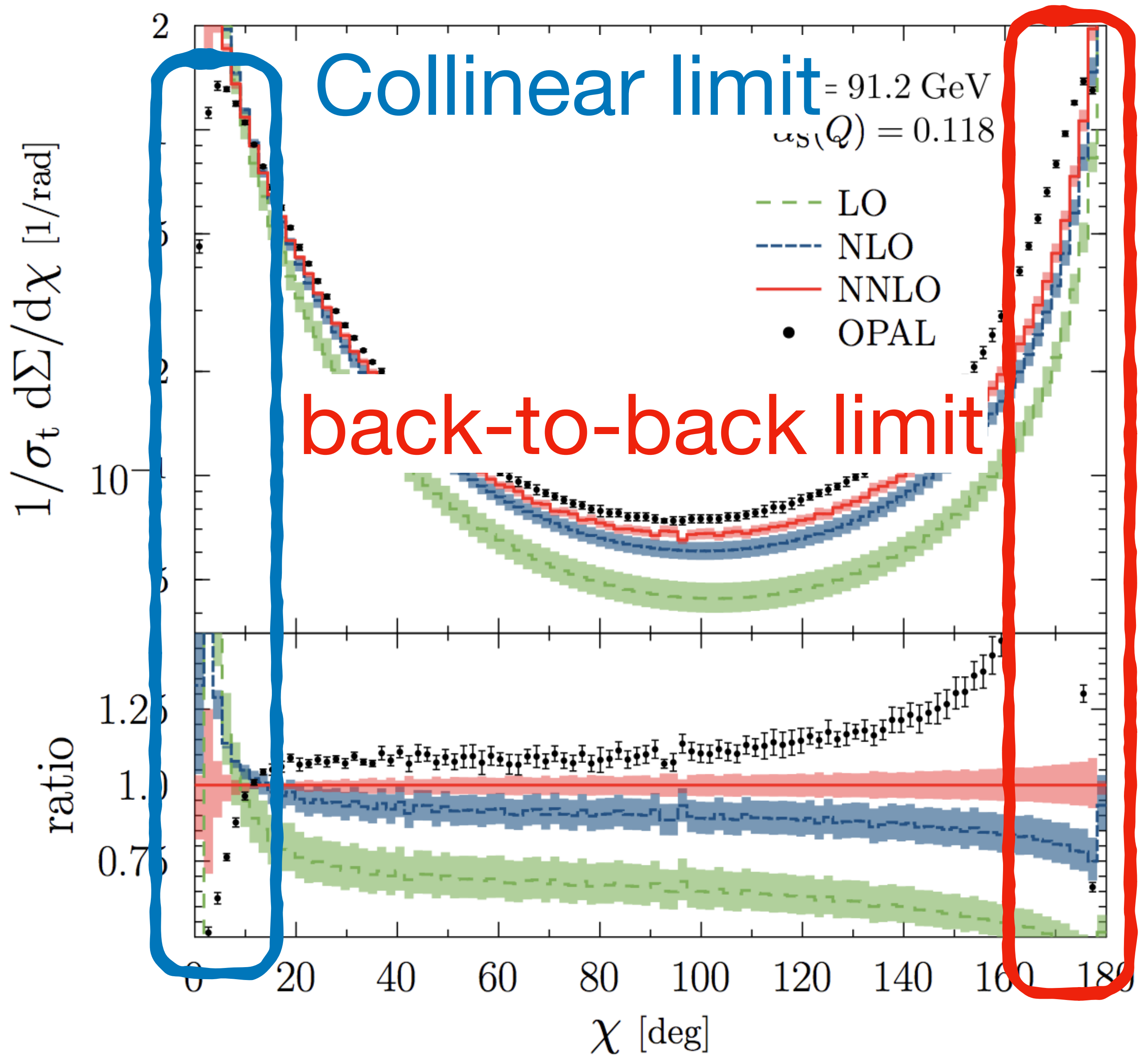
Jet substructure as correlation functions



Energy-Energy Correlator: One of the very first event shapes and a QCD correlation observable:

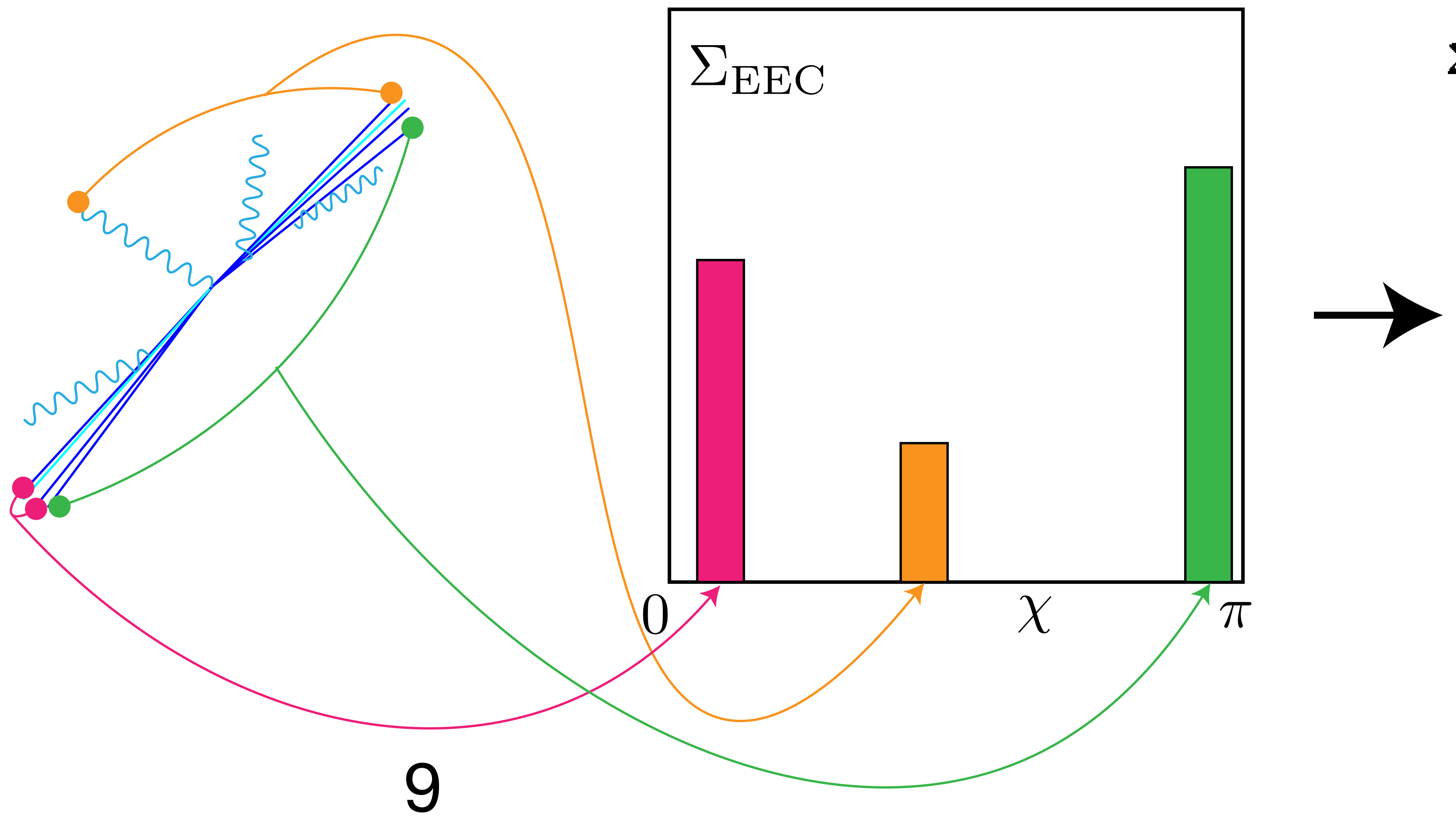
Basham et al. 1978

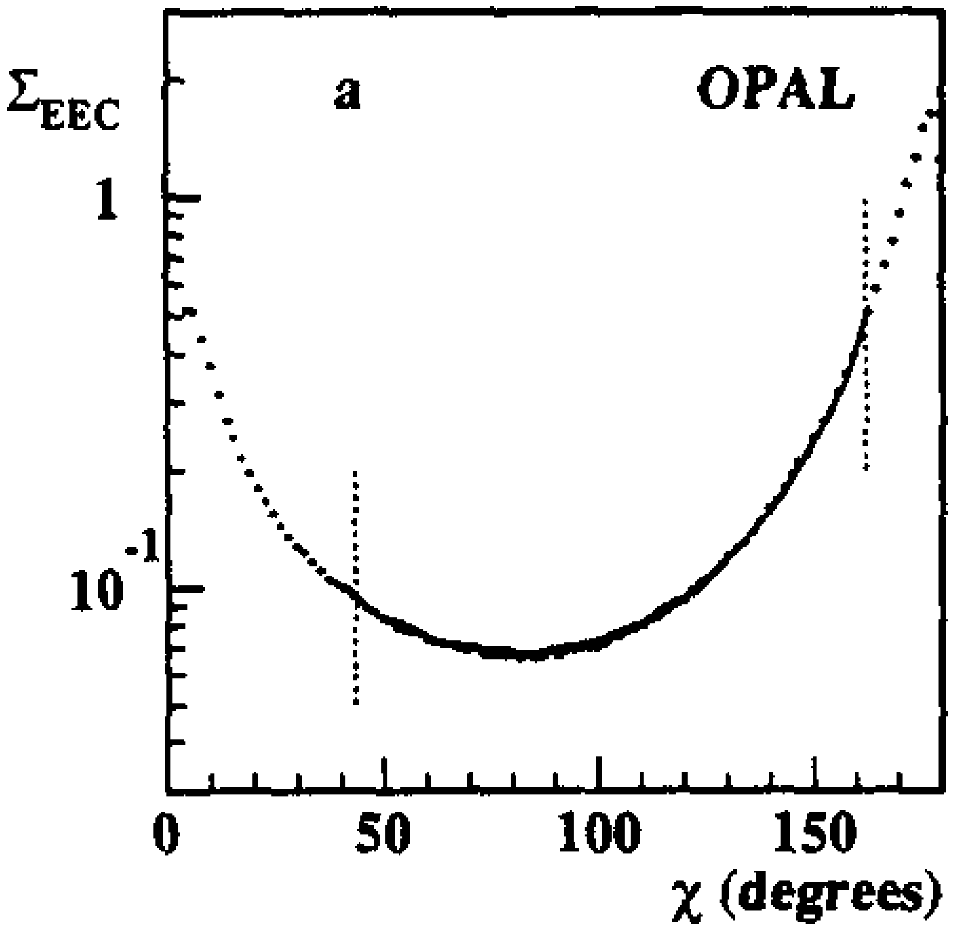
$$\frac{d\Sigma}{d\cos\chi} = \sum_{ij} \int \frac{E_i E_j}{Q^2} \delta(\vec{n}_i \cdot \vec{n}_j - \cos\chi) d\sigma$$

Two limits exhibiting a rich all-orders structure:

- Collinear limit: $\chi \to 0$
- Back-to-back limit: $\chi \to \pi$

Each event contributes to multiple bins, with the final distribution being an ensemble average over all events:





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

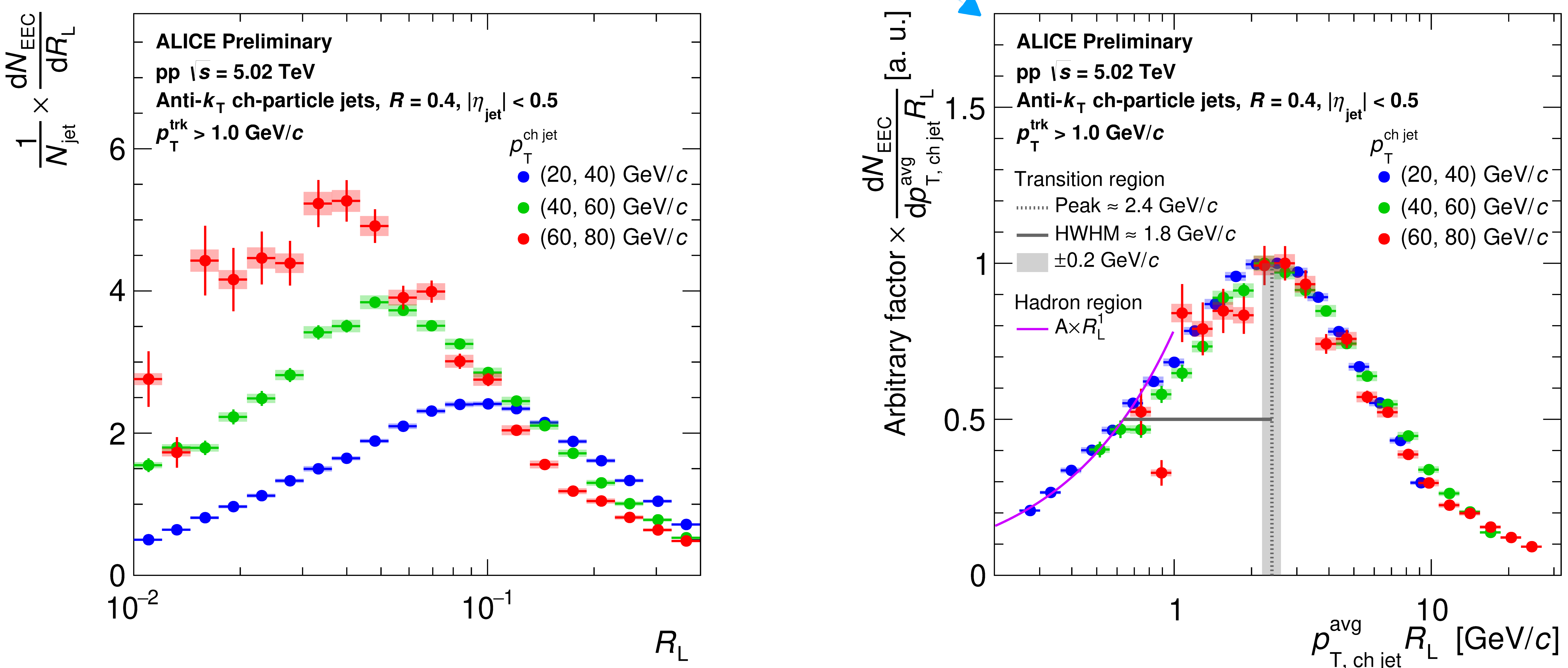
Universal behavior in the collinear limit

In QCD a time-like factorization formula can be derived to resum large logs in the collinear limit:

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

Dixon, Moult, Zhu 2019

$R_L \rightarrow p_T R_L$



ALI-PREL-540213

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Scaling the x-axis by p_T brings out the universal collinear physics captured by EECs.

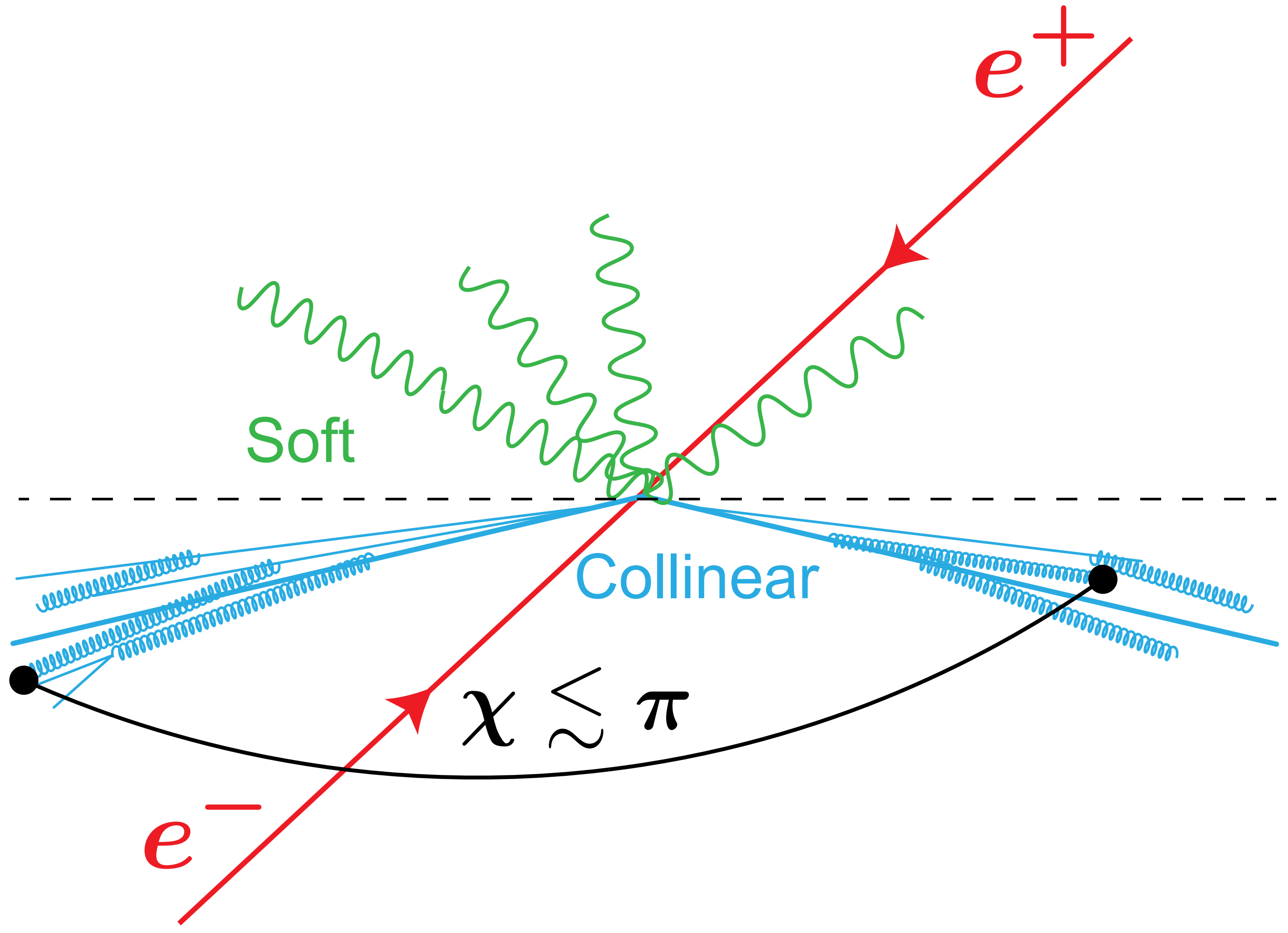
The back-to-back region of EEC

The back-to-back limit in e^+e^- collisions is dominated by both soft and collinear physics, and is described by a Drell-Yan-like factorization formula:

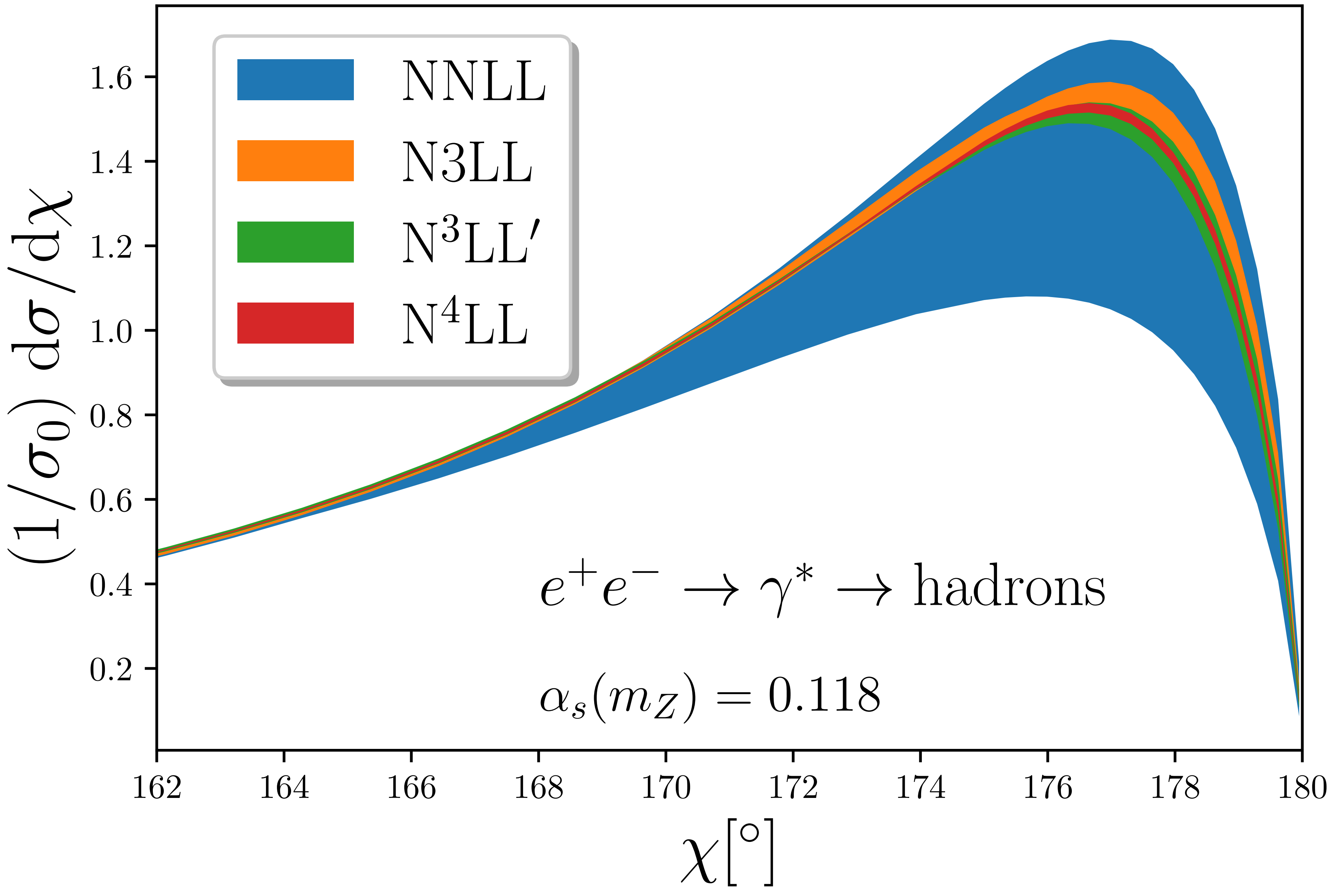
Moult, Zhu 2018

$$\frac{\mathrm{d}\Sigma_{\mathrm{EEC}}}{\mathrm{d}z} = \frac{1}{4}\int \mathrm{d}\boldsymbol{q}_T \int \frac{\mathrm{d}^2\boldsymbol{b}_T}{(2\pi)^2}\, e^{-\mathrm{i}\boldsymbol{b}_T\cdot\boldsymbol{q}_T}\,\delta\left(1 - z - \frac{\boldsymbol{q}_T^2}{Q^2}\right)$$
$$\times \sum_f H_f(Q,\mu) J^f_{\mathrm{EEC}}(b_\perp,\mu,\mu) J^{\bar f}_{\mathrm{EEC}}(b_\perp,\mu,\nu) S_\perp(b_\perp,\mu,\nu) \times \Big(1 + \mathcal{O}(1-z)\Big)$$

This involves the same hard and soft functions as in Drell-Yan measurement



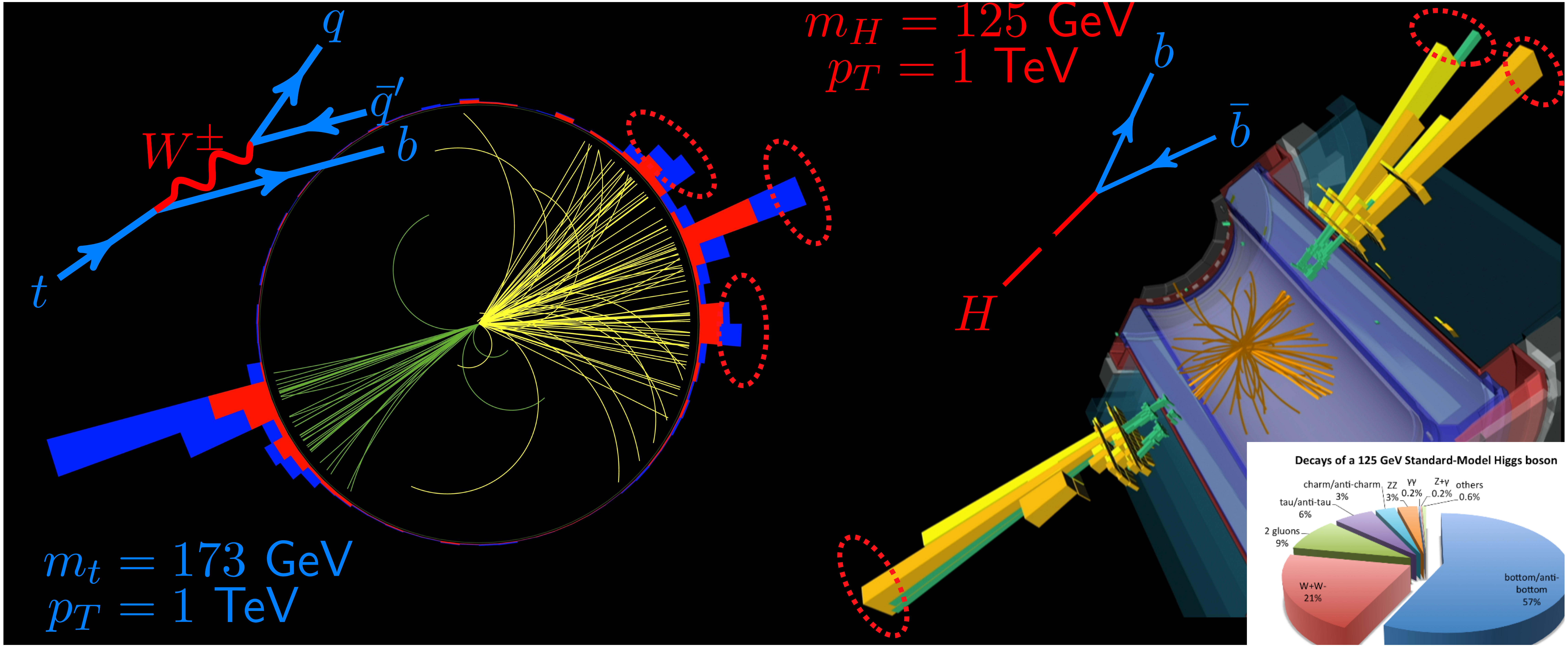
Moult, Zhu, Zhu 2022
Duhr, Mistelberger, Vita 2022



The most precisely known event shape: N^{4}LL accuracy

Is b2b limit relevant for the LHC?

The back-to-back, or more generally, *the threshold limit*, becomes relevant in boosted electroweak decays!



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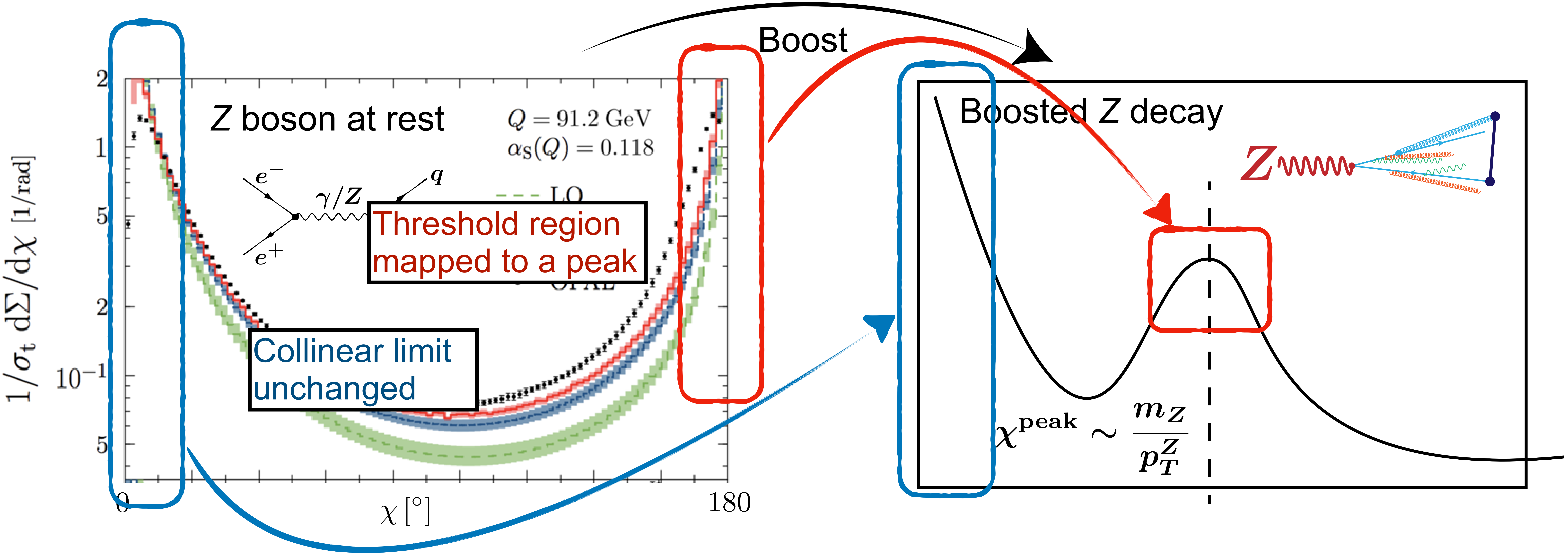


Boost

Threshold region mapped to a peak

Collinear limit unchanged

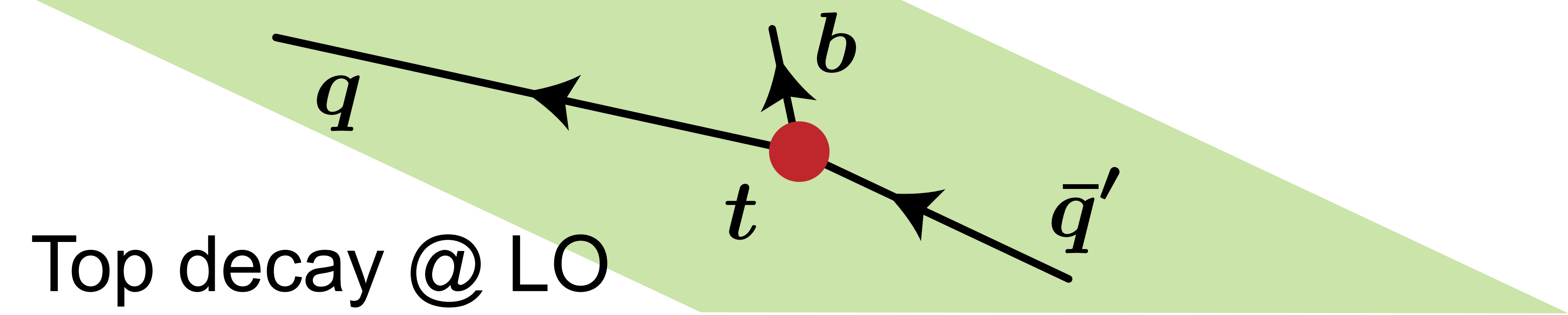
$$\chi^{\text{peak}} \sim \frac{m_Z}{p_T^Z}$$

- The $\chi \to 0$ limit probes the same quark/gluon collinear fragmentation dynamics
- The back-to-back region now appears as a peak corresponding to the opening angle of the boosted heavy particle decay.

What EEC can well characterize the top decay?

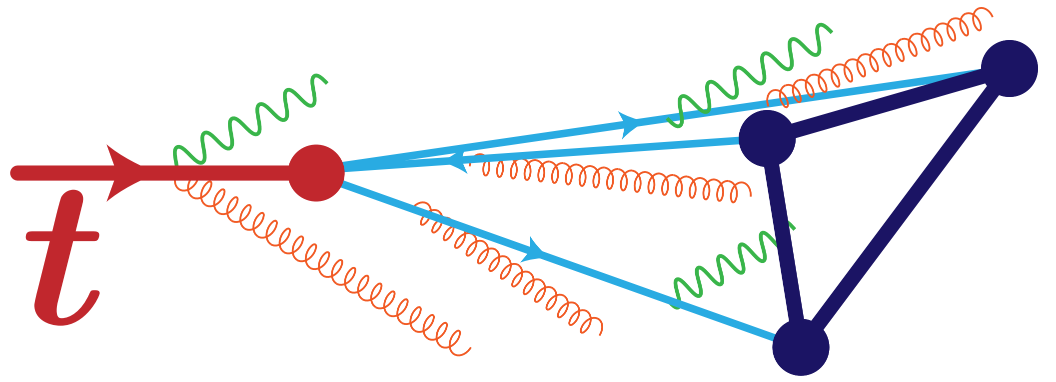
Holguin, Moult, AP, Procura 2022

Threshold limit for the top: At leading order the top quark exhibits a near planar decay:



Top decay @ LO

The three-point correlator picks out the characteristic three-body top quark decay



Measurement function ($\zeta_{ij} = \Delta R_{ij}^2$):

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

The correlator is sensitive to angles between the decay products. At LO:

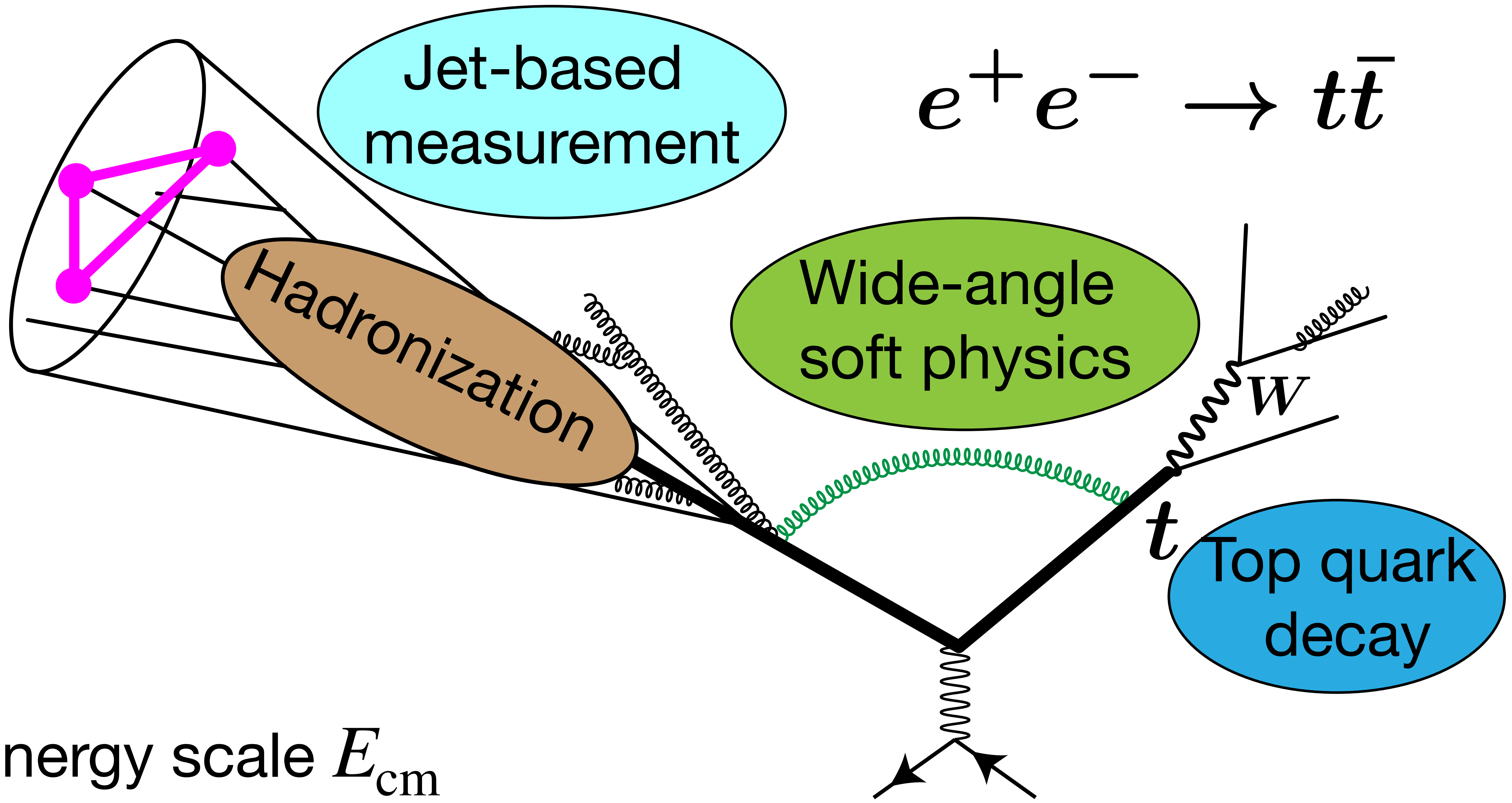
- Top rest frame : $\tilde{\zeta}_t = \tilde{\zeta}_{12} + \tilde{\zeta}_{23} + \tilde{\zeta}_{31} \in [2,2.25]$,
- Lab frame (boosted): $\zeta_t \equiv \sum_{i<j} \zeta_{ij} \approx \left(\frac{m_t^2}{p_T^2}\right)^2 \sum_{i<j} \tilde{\zeta}_{ij}$,

→

A feature at the characteristic angle $\langle \zeta_t \rangle \approx 3m_t^2/p_T^2$.

Boosted tops in e^+e^- collisions

Consider a simpler scenario of boosted tops in e^+e^- collisions:

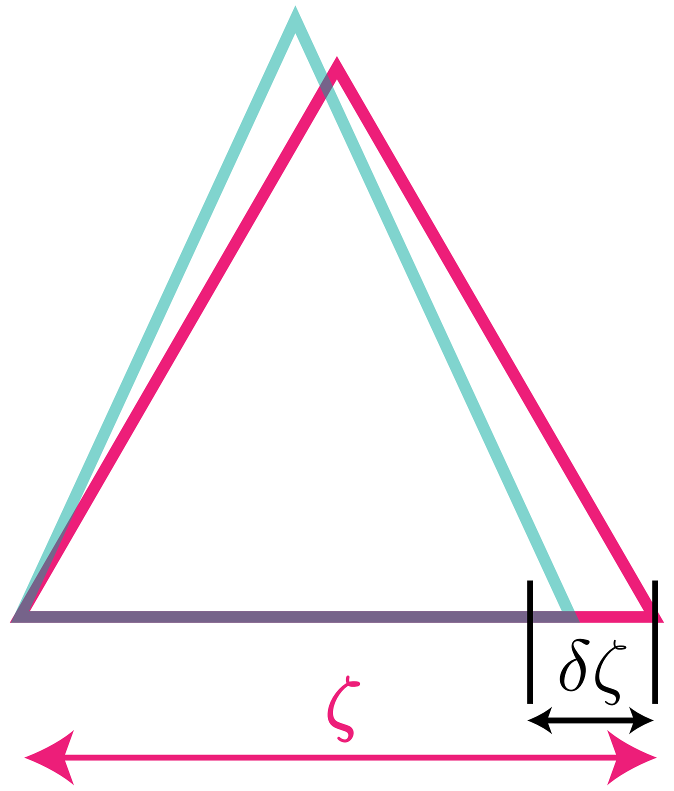


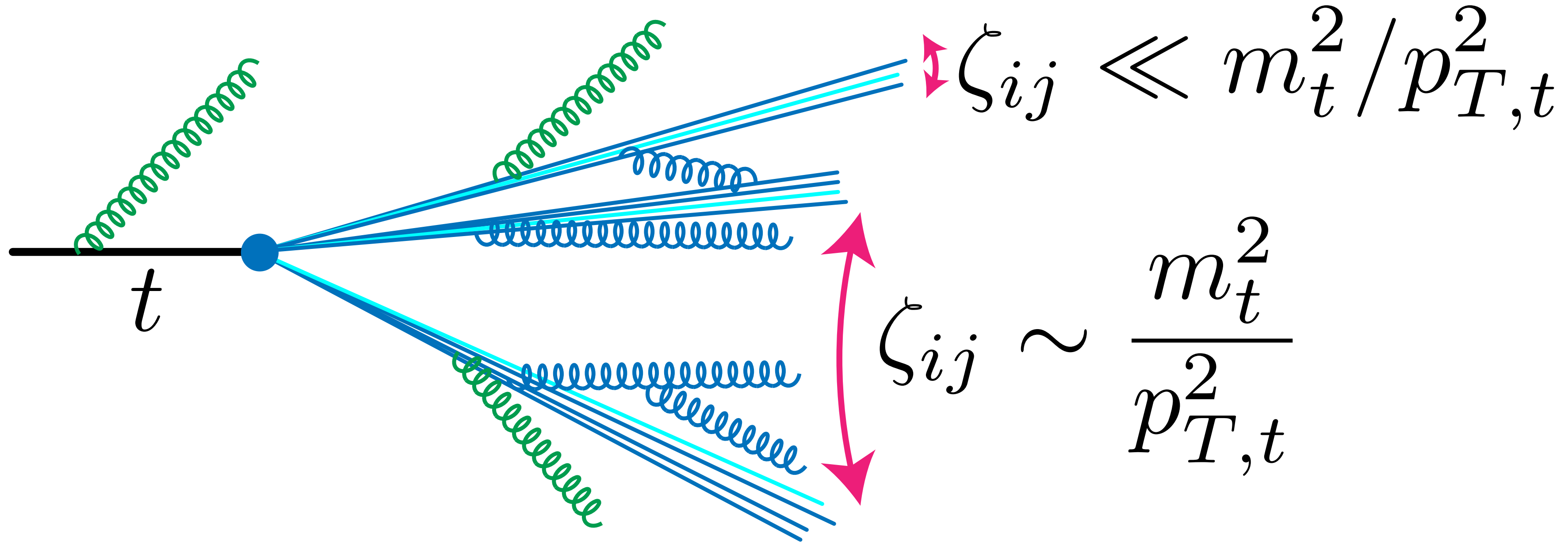
Simplifications:

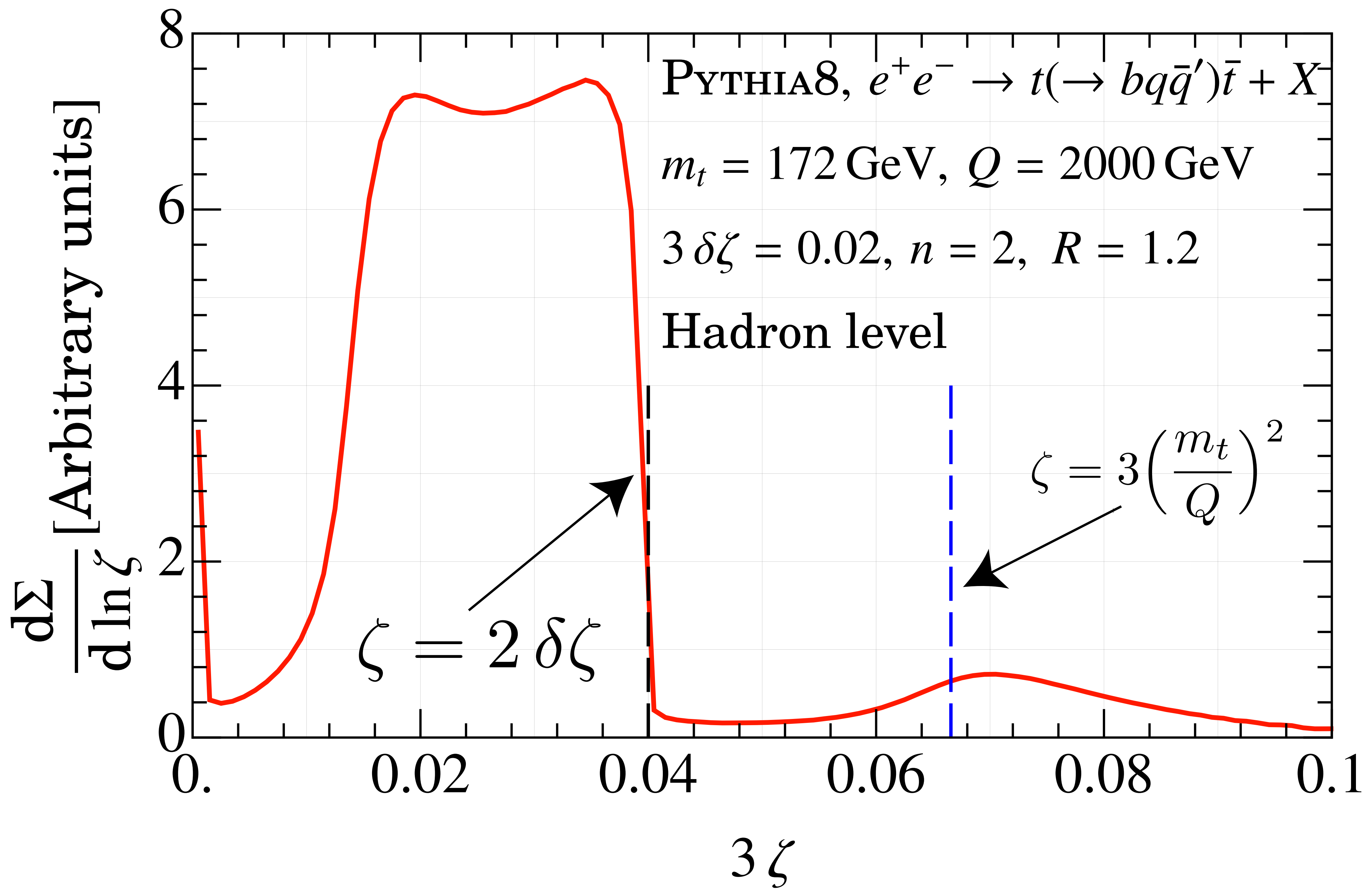
- Top quarks produced with a fixed hard energy scale E_{cm}
- No underlying event
- No PDFs
- Focus on the impact hadronization and perturbative corrections in the EEC measurement alone.

The top quark imprint in EEEC

Holguin, Moult, AP, Procura 2022



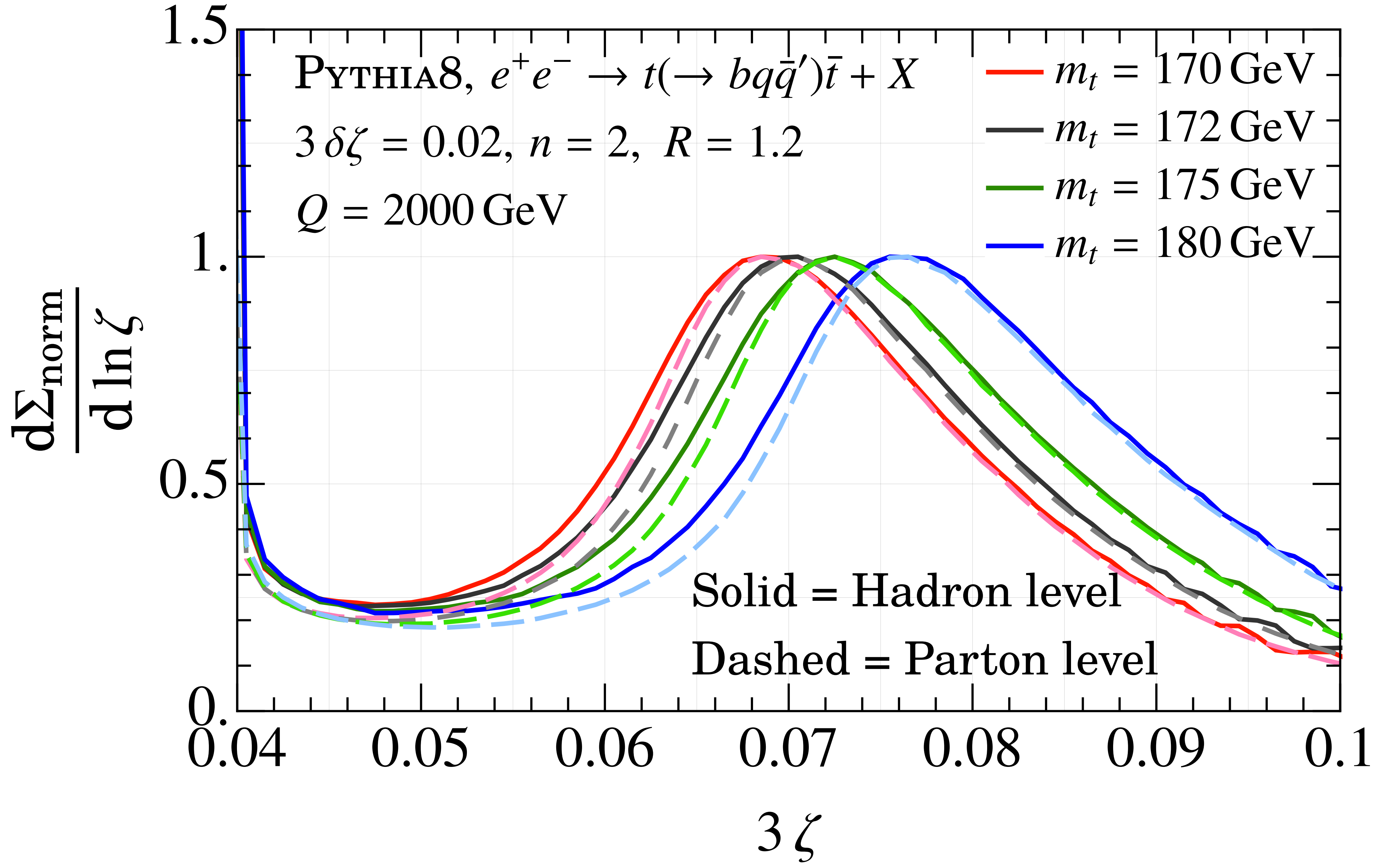


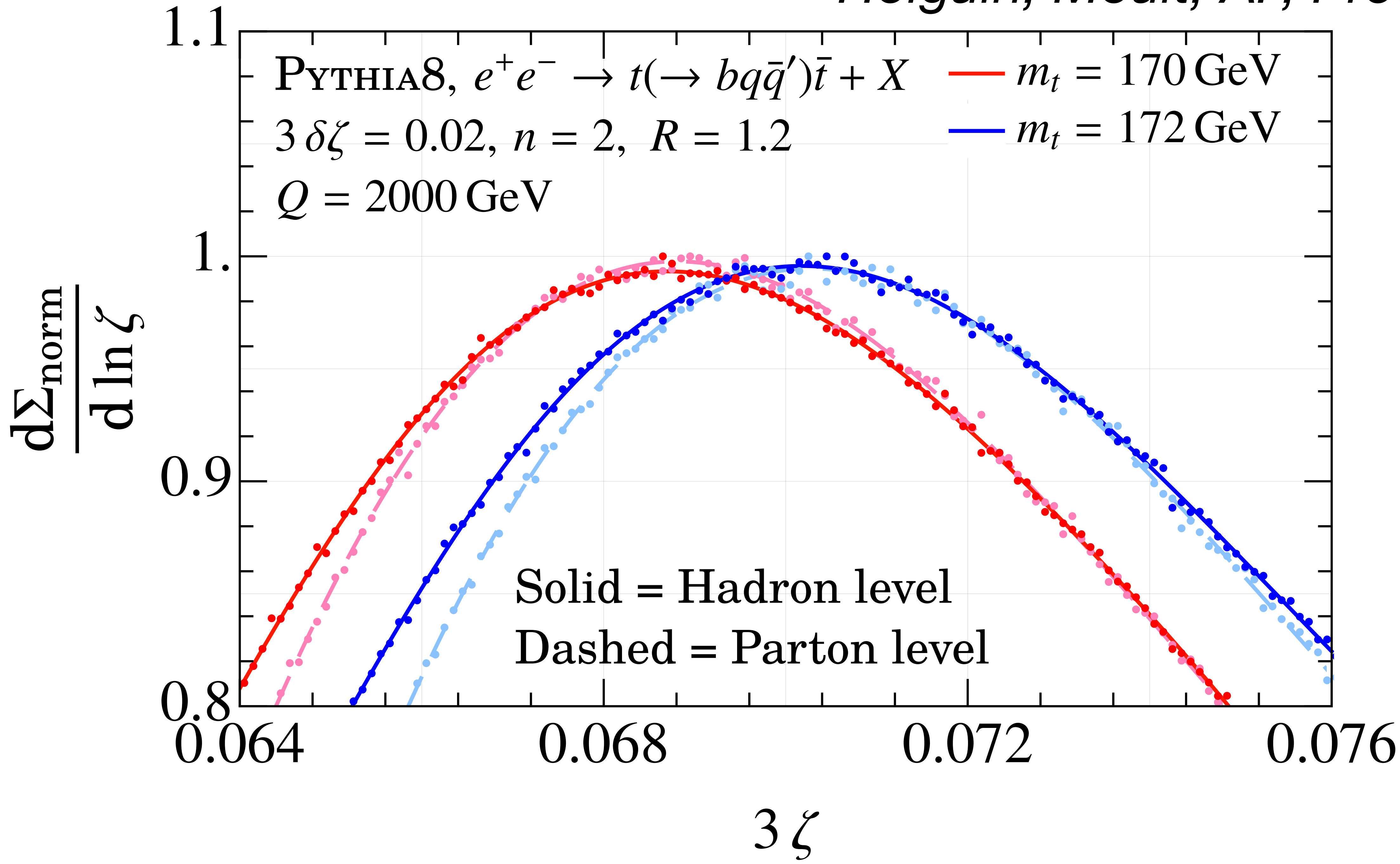


- Distinct peak at $\zeta_t \sim 3(m_t/Q)^2$: peak dominated by hard decay of the top
- Resilient to collinear radiation, $\alpha_s \ln \zeta_t^{\text{peak}} < 1$
- The asymmetry cut $\delta\zeta < m_t^2/p_T^2$ eliminates the otherwise overwhelming contribution of collinear splittings.

Excellent top mass sensitivity and robustness to hadronization

Holguin, Moult, AP, Procura 2022

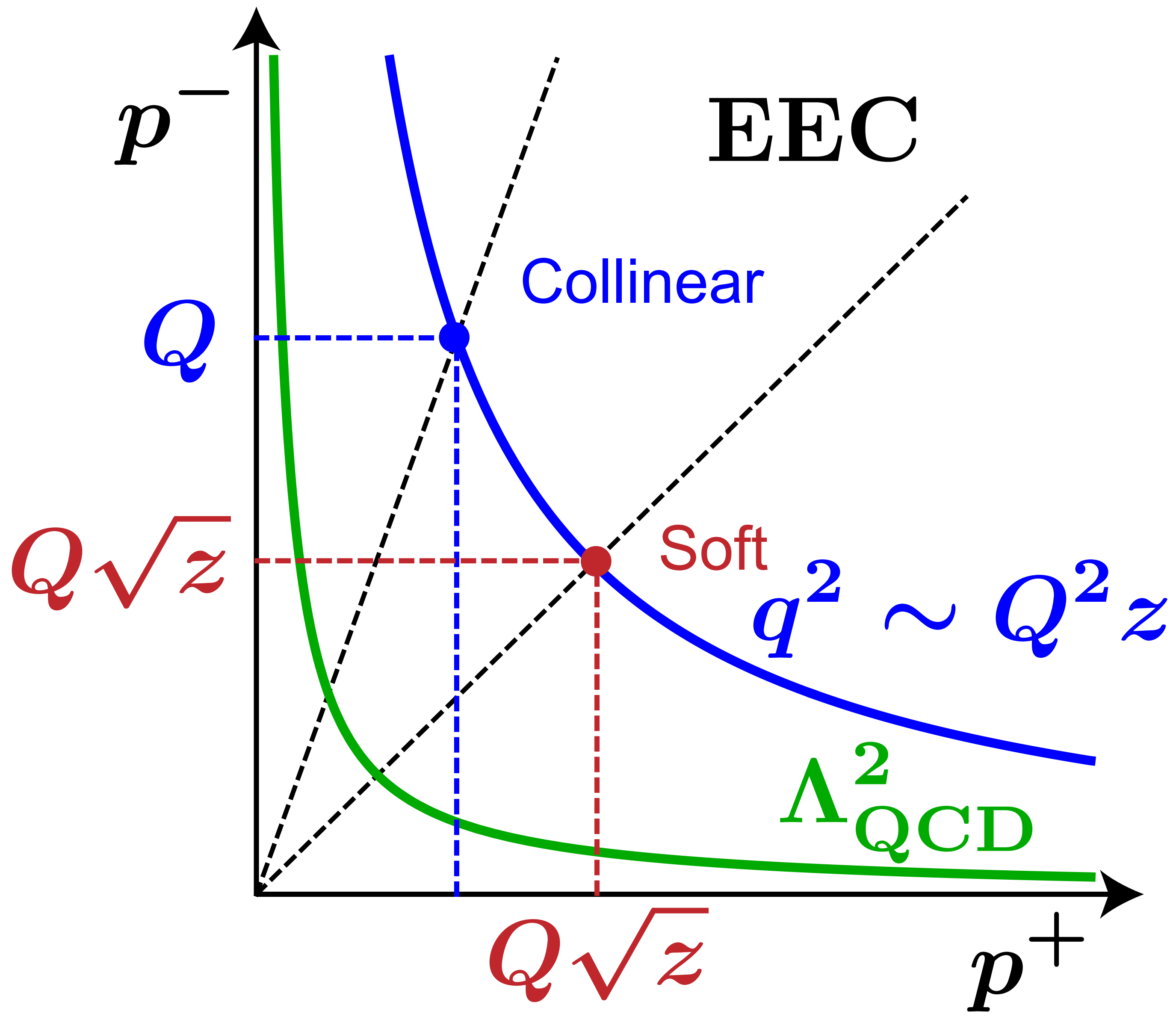


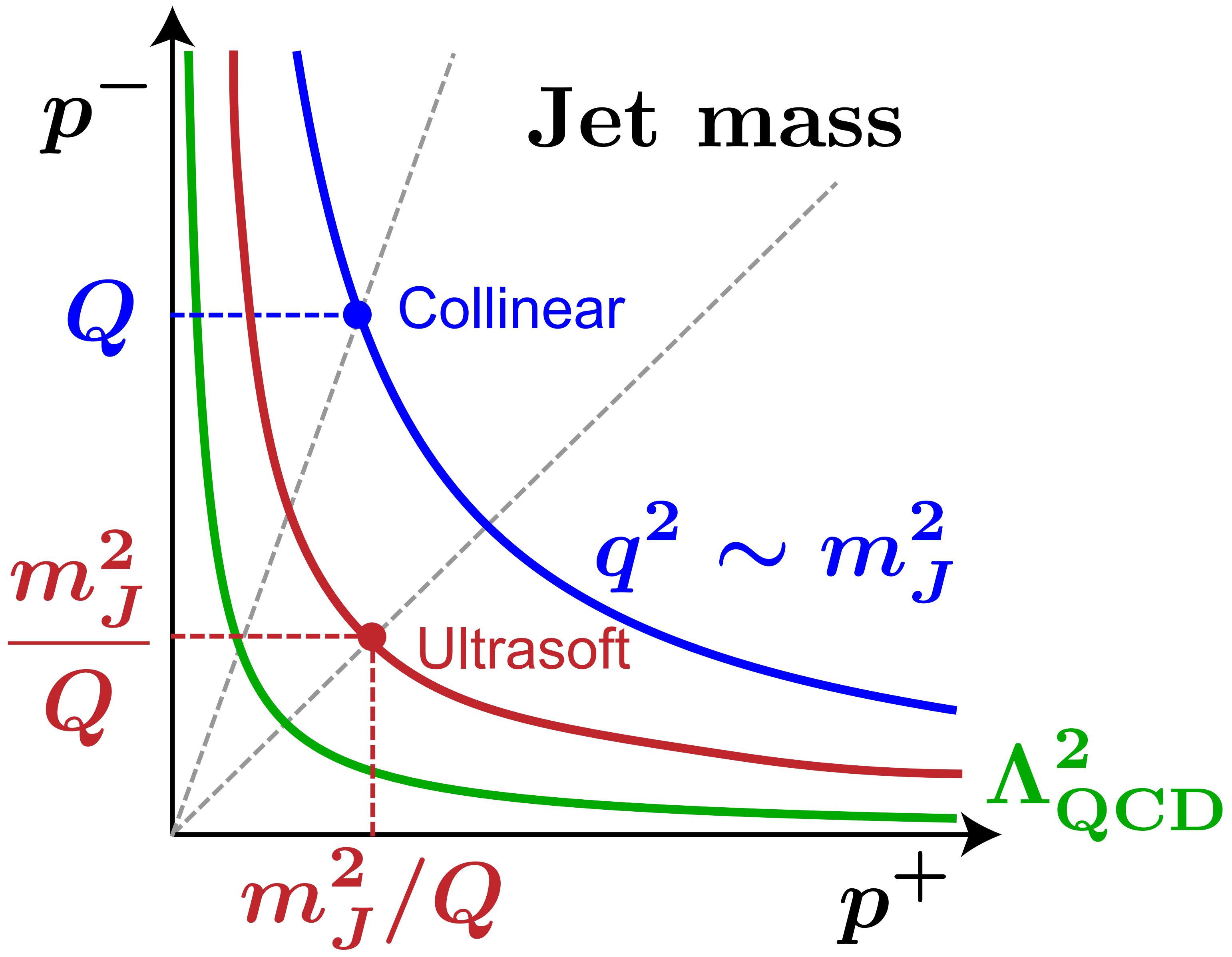


- The imprint of the top quark is extremely sensitive to the top quark mass
- Nonperturbative effects have a very small effect on the peak, $\Delta m_t^{\text{hadr.}} \approx 150 \pm 0.5\,\text{MeV}$
  - This is in a stark contrast to the jet mass with $\sim 1\,\text{GeV}$ shifts in the peak.

Why is EEC robust against hadronization?

Unlike the jet mass, the EEC is a SCET_{II} observable:





- Top width Γ_t provides a cutoff and renders hadronization effects tiny
- Jet mass sensitive to a ultra soft mode at scales lower than Γ_t and hence has large sensitivity to hadronization

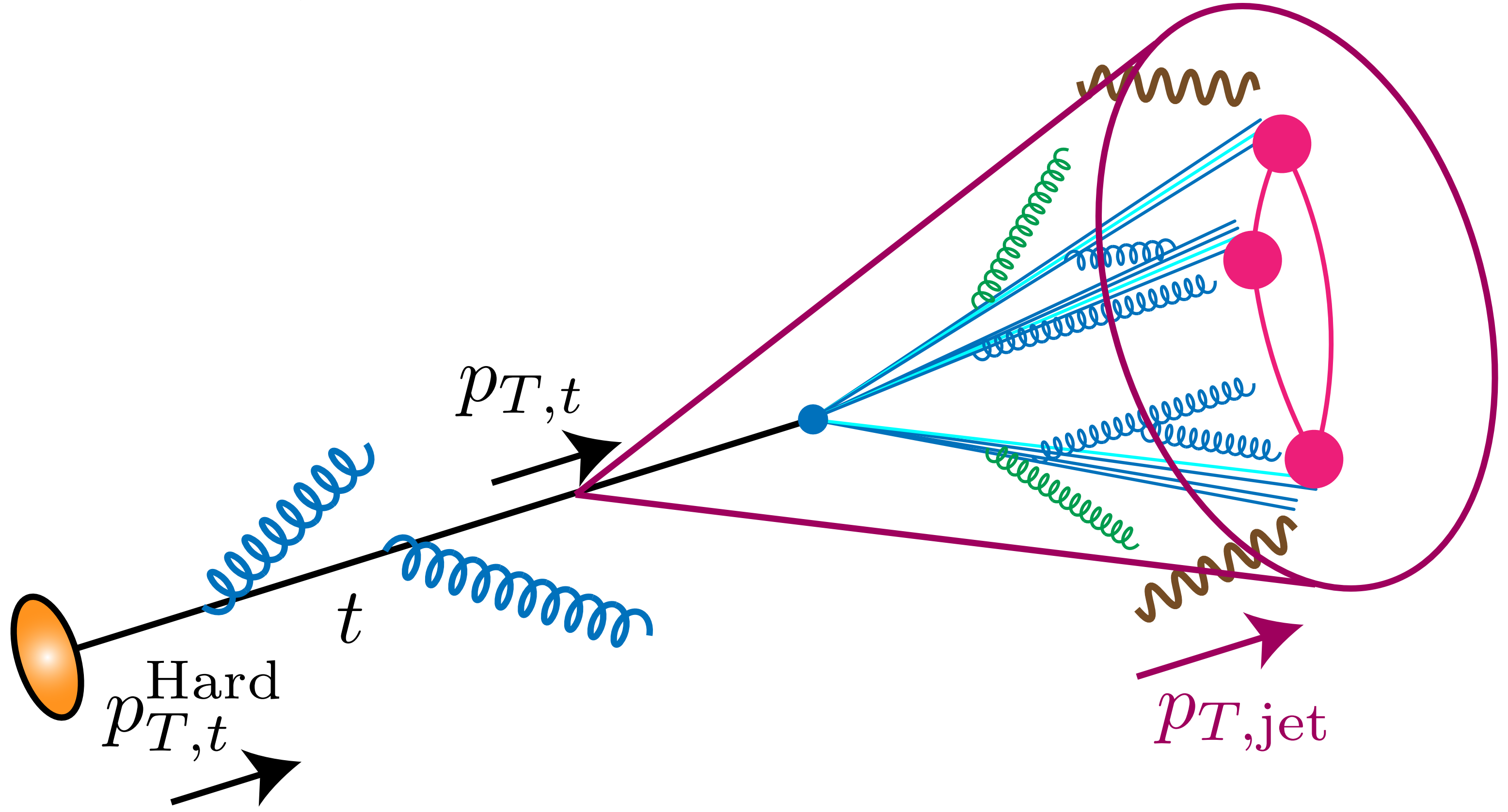
EECs are also insensitive to the contamination

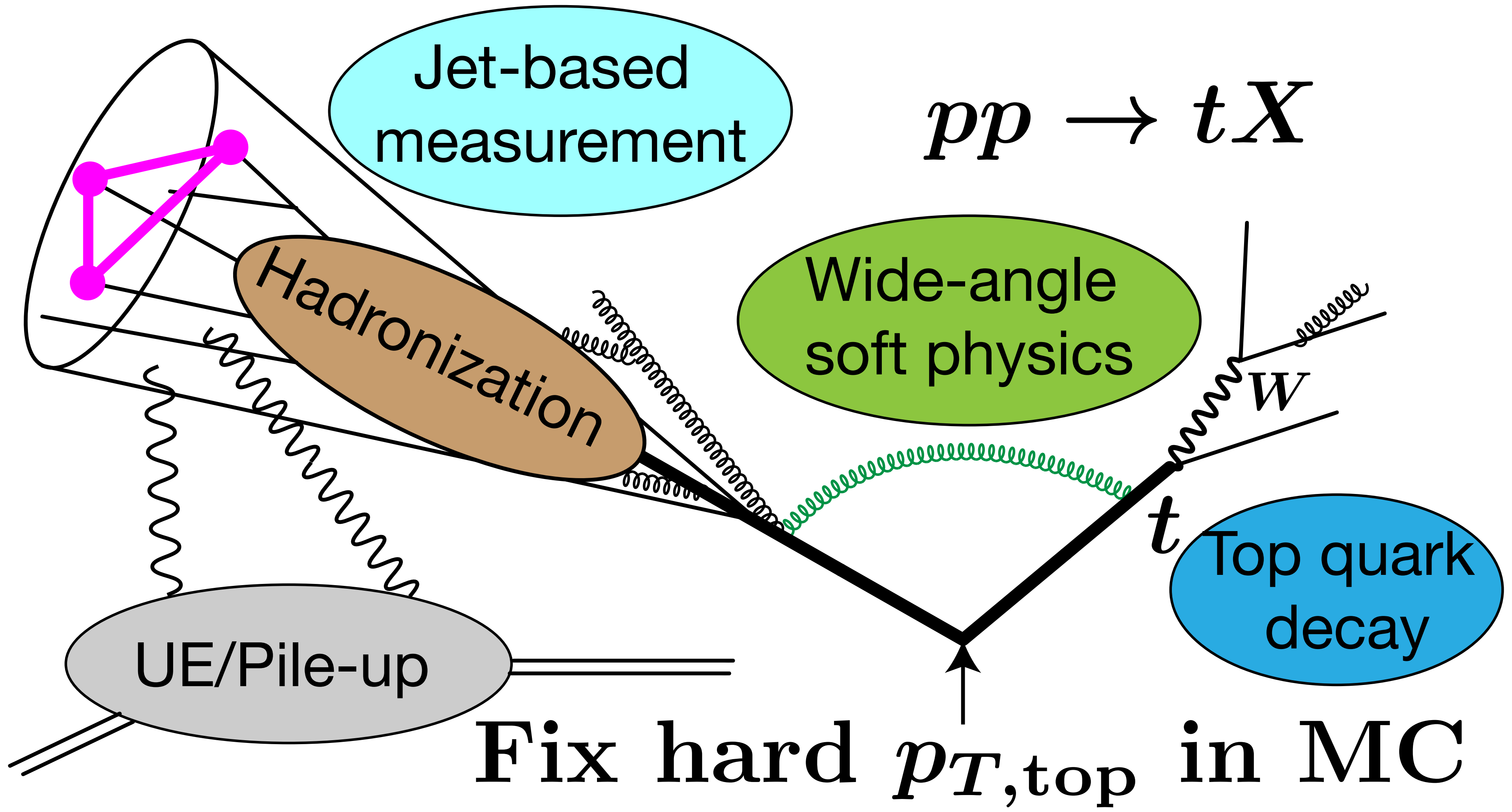
The correlator measurement can be expressed as

$$\frac{\mathrm{d}\Sigma(\delta\zeta)}{\mathrm{d}p_{T,\mathrm{jet}}\mathrm{d}\zeta} = \frac{\mathrm{d}\Sigma(\delta\zeta)}{\mathrm{d}p_{T,t}\mathrm{d}\zeta}\frac{\mathrm{d}p_{T,t}}{\mathrm{d}p_{T,\mathrm{jet}}}$$

The $p_{T,t}$ determines the opening angle but can only be accessed via the jet p_T.

- For now fix the hard $p_{T,t}$ in MC by hand:





Simplifications:

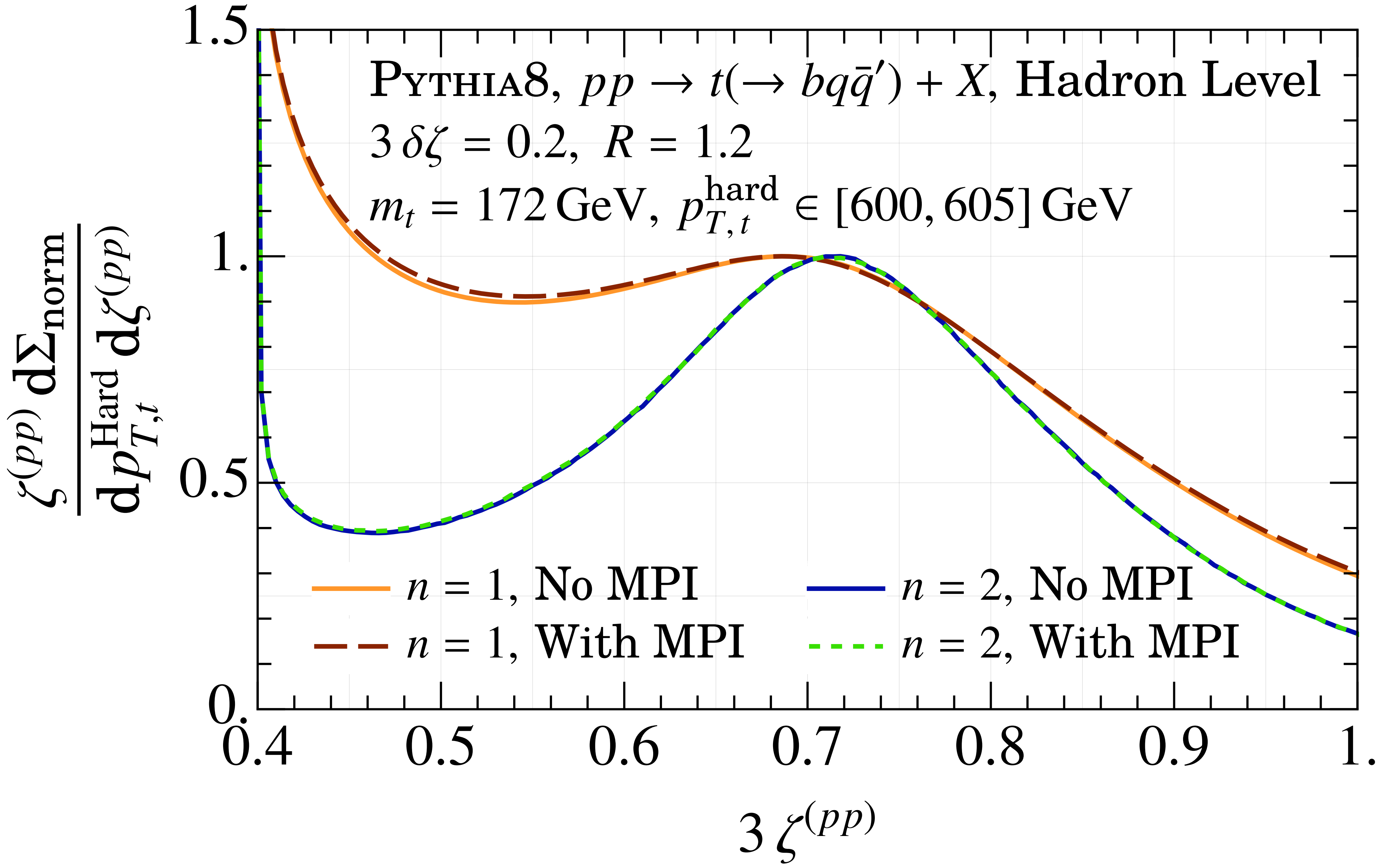
- Top quarks produced with a fixed hard p_T as in e^+e^- collisions.
- Can solely focus on the impact of the underlying event

EECs are also insensitive to the contamination

Holguin, Moult, AP, Procura 2022

The correlator measurement can be expressed as

$$\frac{\mathrm{d}\Sigma(\delta\zeta)}{\mathrm{d}p_{T,\mathrm{jet}}\mathrm{d}\zeta} = \frac{\mathrm{d}\Sigma(\delta\zeta)}{\mathrm{d}p_{T,t}\mathrm{d}\zeta}\frac{\mathrm{d}p_{T,t}}{\mathrm{d}p_{T,\mathrm{jet}}}$$

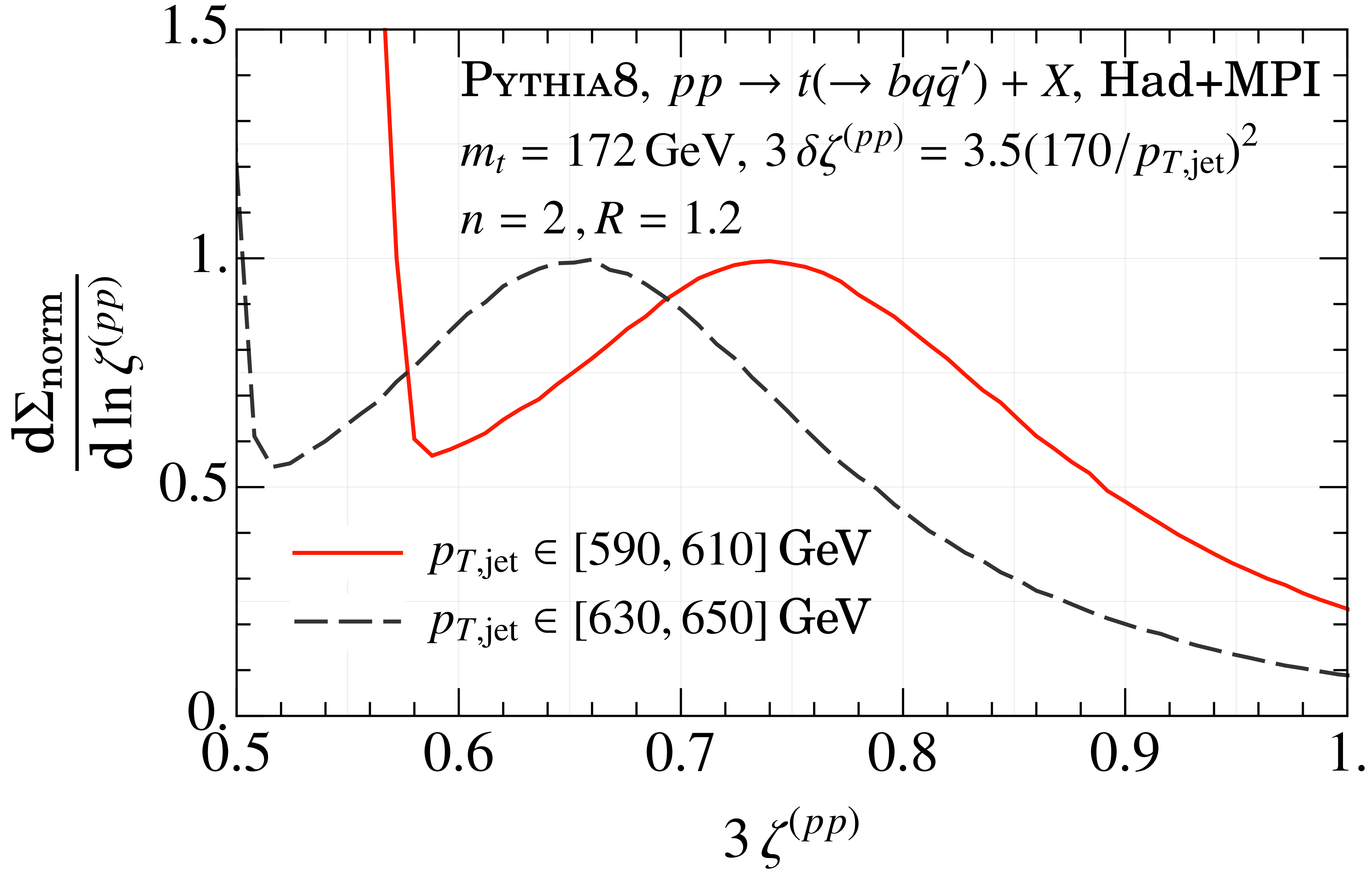


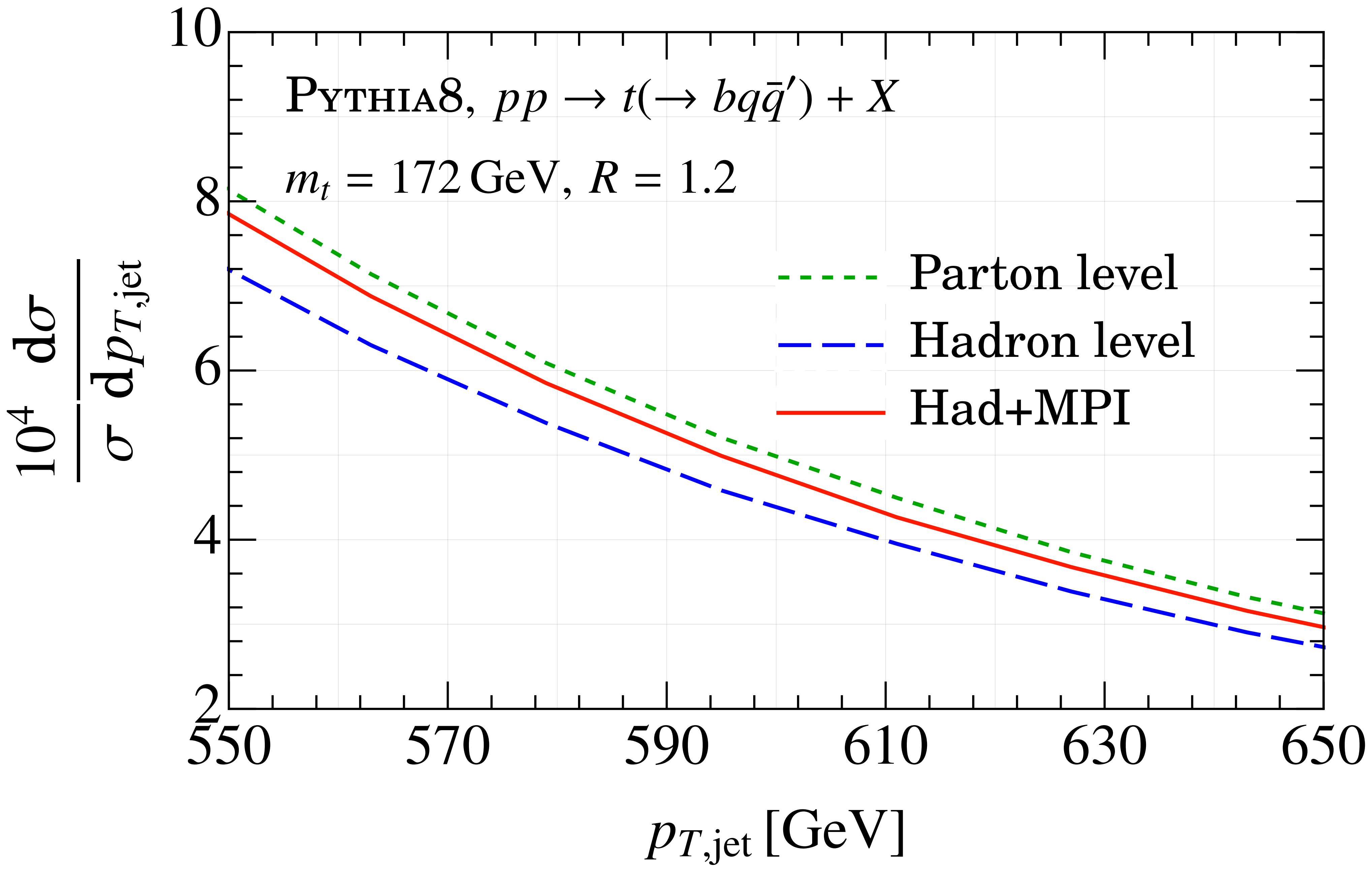
- The underlying event still impacts the jet p_T and adds contamination to the triplets sampled.
- The correlator measurement after normalization is however completely insensitive to the UE.

But the jet p_T spoils the elegance ...

Holguin, Moult, AP, Procura 2022

The need for a clean jet p_T measurement however spoils the theoretical elegance of this approach:





Problems:

- Challenging to unfold the jet p_T to $\sim 5\,\mathrm{GeV}$ precision!
- Shifts due to hadronization and MPI in the jet p_T spectrum induce large $\sim 1\,\mathrm{GeV}$ shifts in the extracted top mass from $\zeta_t \sim m_t^2/p_{T,\mathrm{jet}}^2$.

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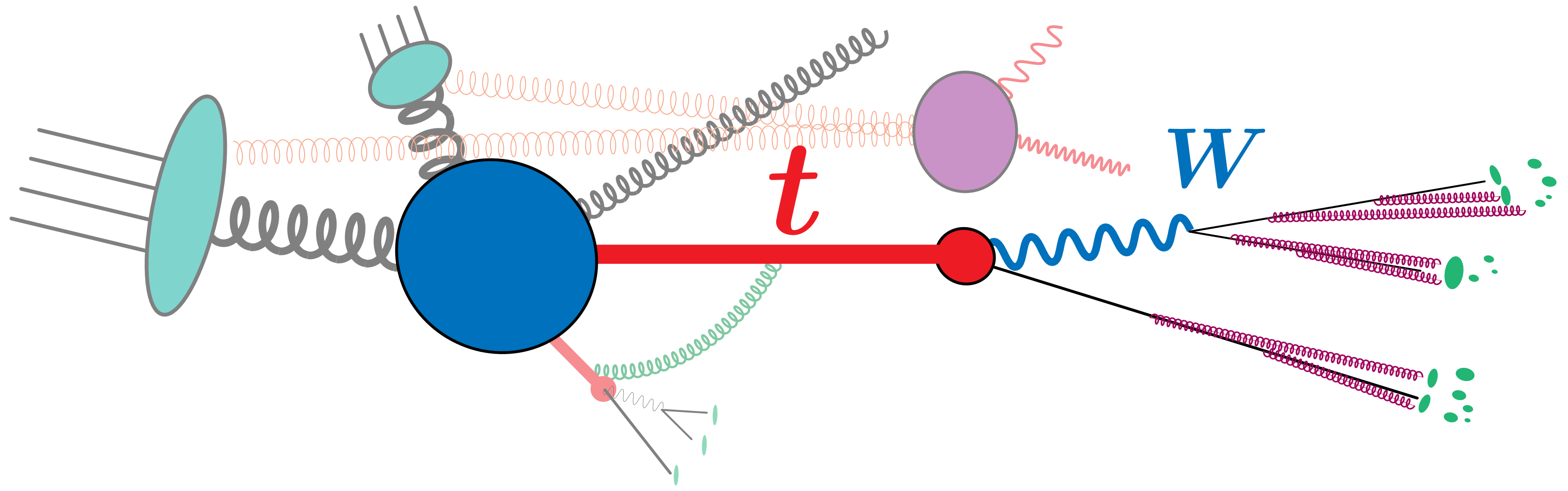
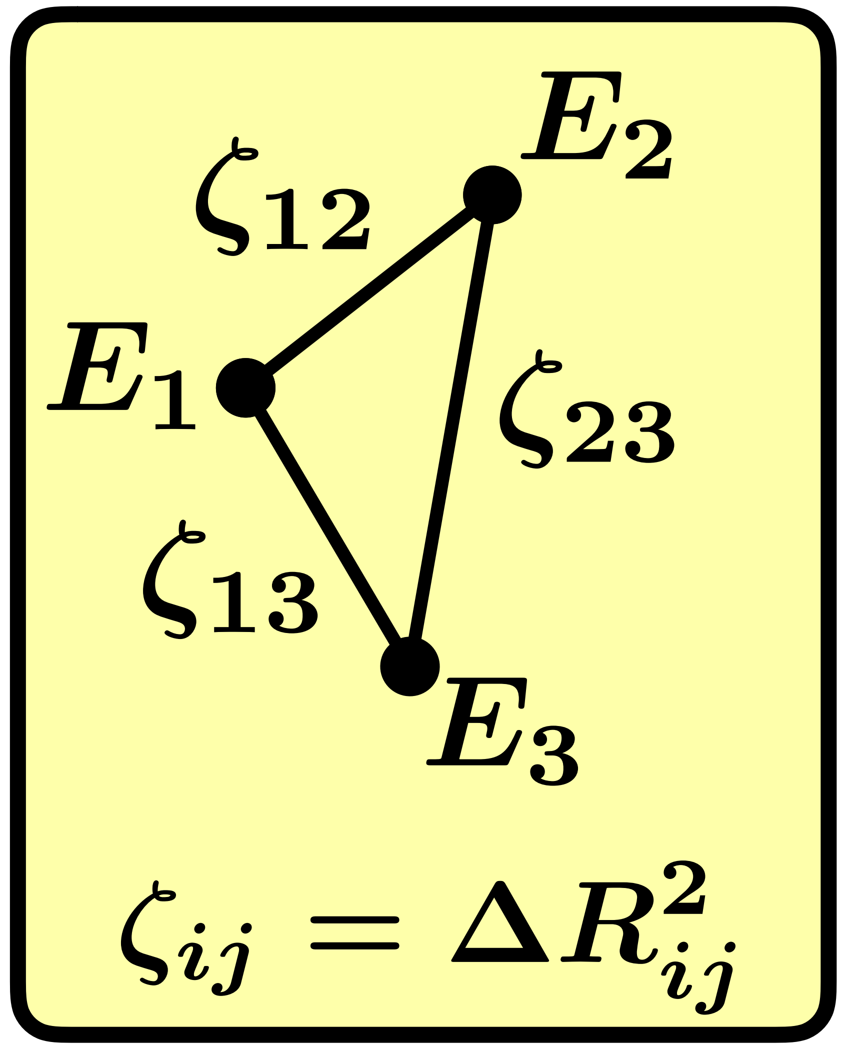
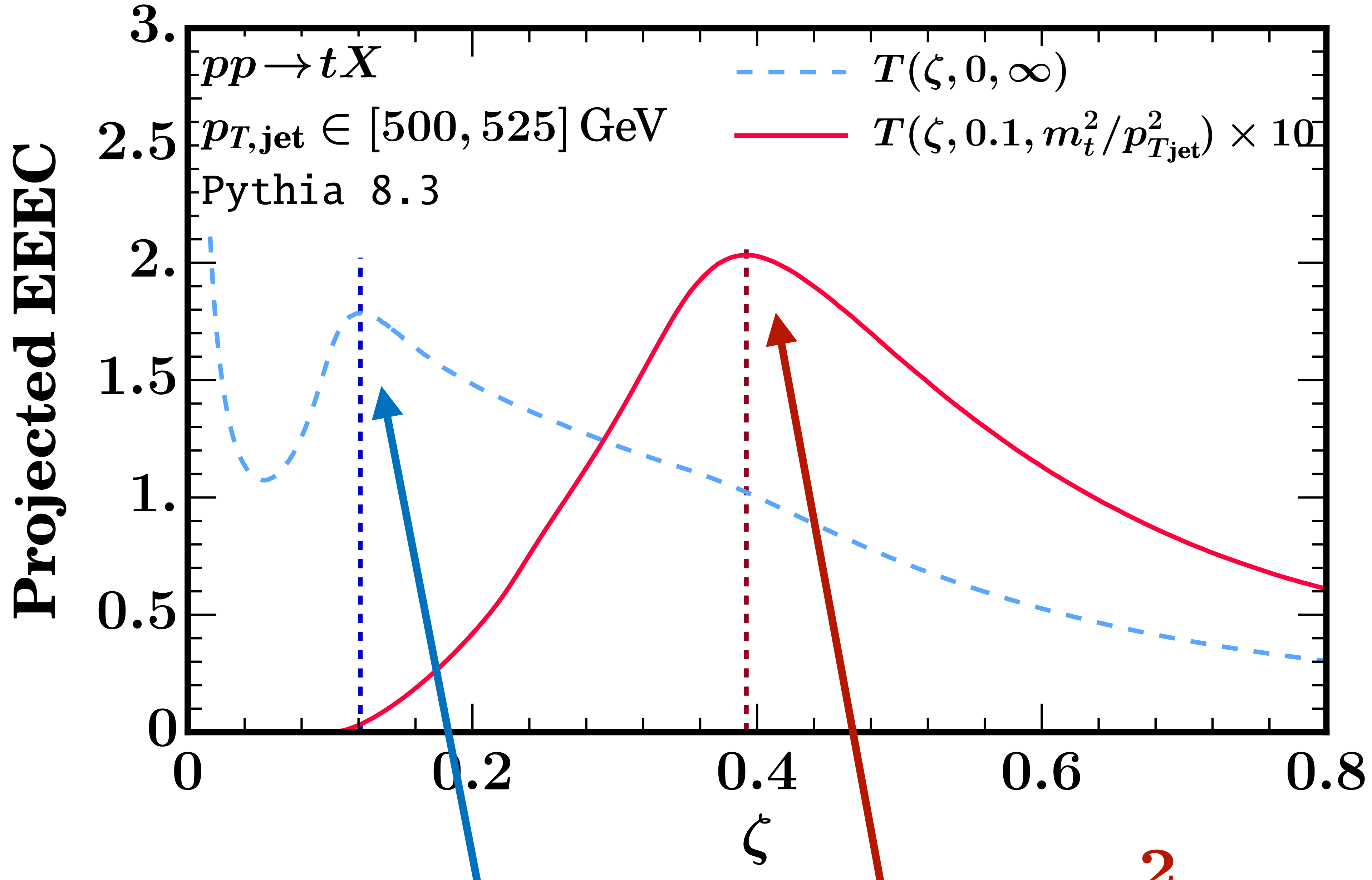
The Standard Candle approach in nutshell





$$\zeta_{ij} = \Delta R_{ij}^2$$



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

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

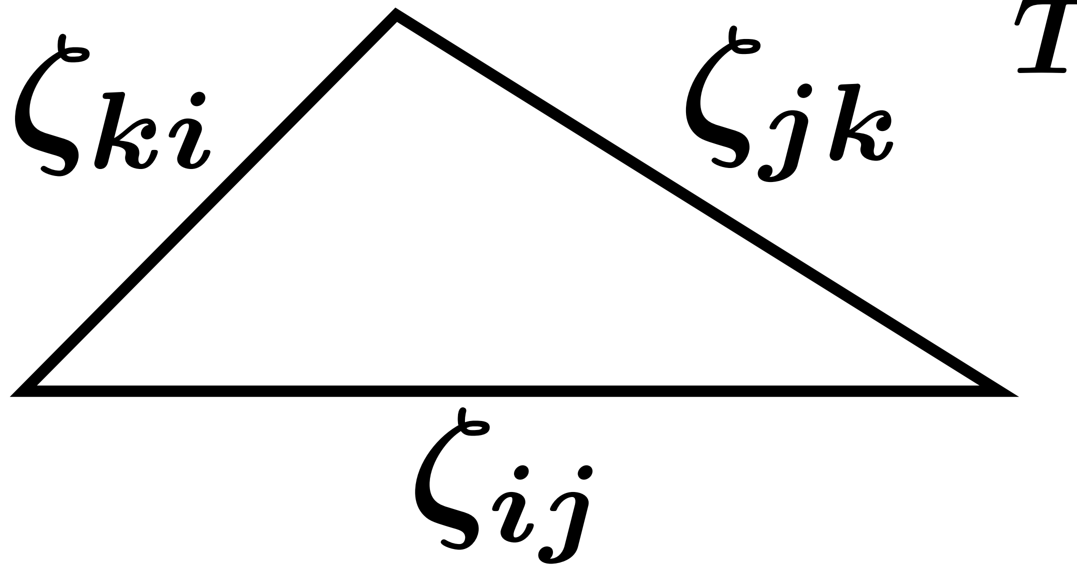
Holguin, Moult, AP, Procura
+ Schöfbeck, Schwarz 2023-24

- Remove the shared energy scale
- Calibrate M_{top} using the W mass : $m_W = 80.377 \pm 0.012\,\mathrm{GeV}$
- Exploit the W inside the top jets as a standard candle

Imprint of the W in the EEEC distribution

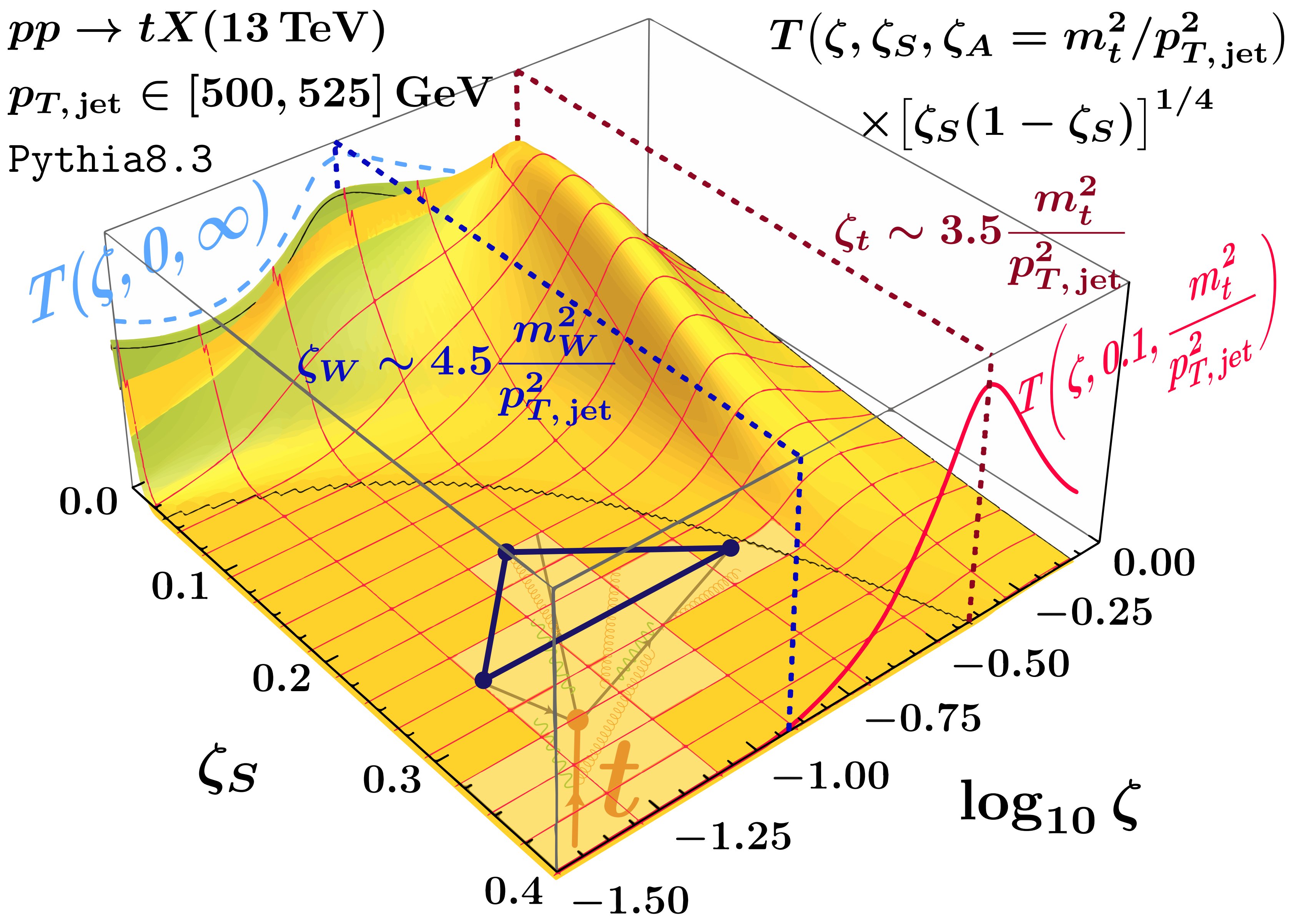
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2023

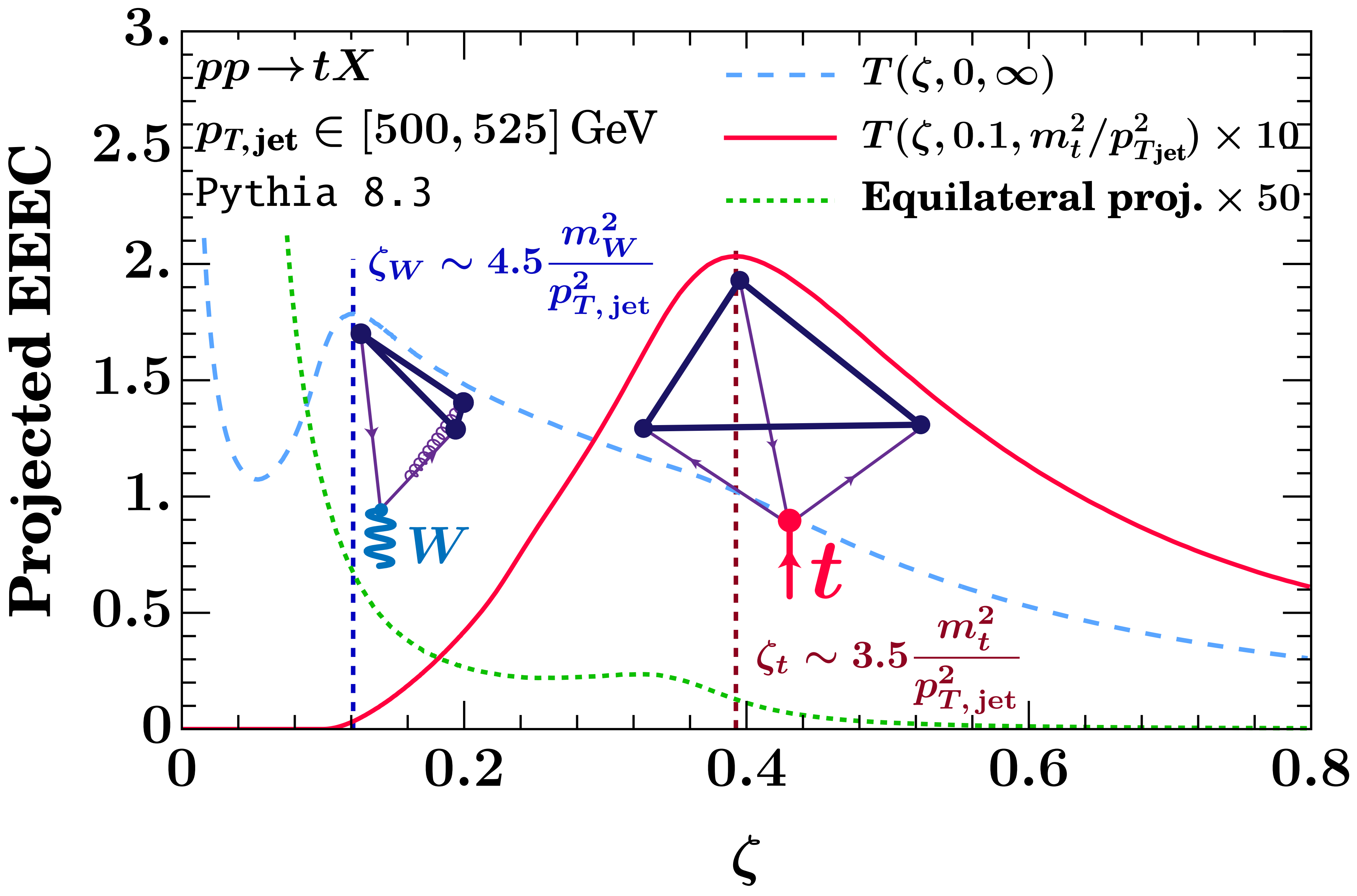
The observable we define to extract the W-imprint:



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

$$\Theta(\zeta_{ij} \geq \zeta_{jk} \geq \zeta_{ki} \geq \zeta_S)\ \Theta\left(\zeta_A > (\sqrt{\zeta_{ij}}-\sqrt{\zeta_{jk}})^2\right)$$

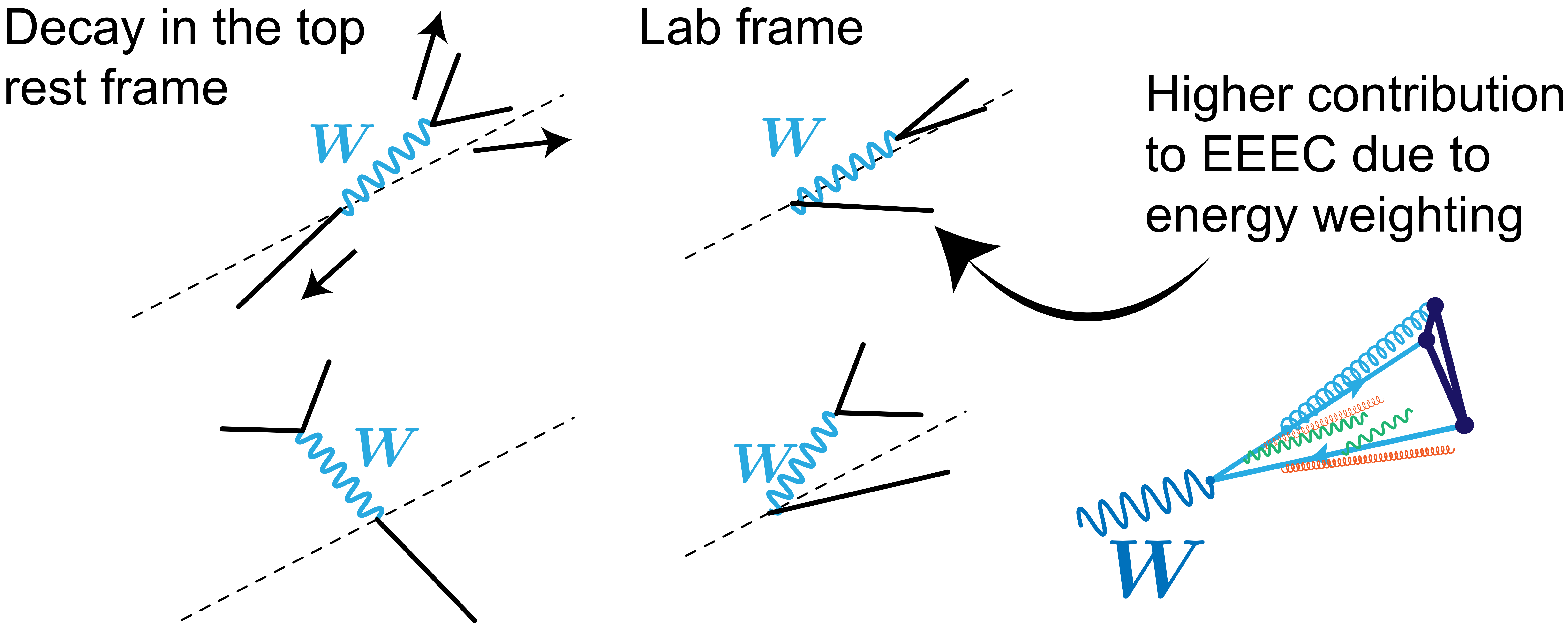




As ζ_S is lowered we allow for more squeezed configuration and see the peak at $\zeta_W \sim m_W^2/p_T^2$ emerging.

High degree of correlation of the two imprints

The ratio of top and W peaks are more correlated than you'd naively think …



Decay in the top rest frame

Lab frame

Higher contribution to EEEC due to energy weighting

- The top quark and the W share a common boost defined by $p_{T,\text{jet}}$
- While the orientation of the W is largely uncorrelated with top boost axis in the rest frame, the EEEC preferentially picks out the Ws aligned with the top in the lab frame.

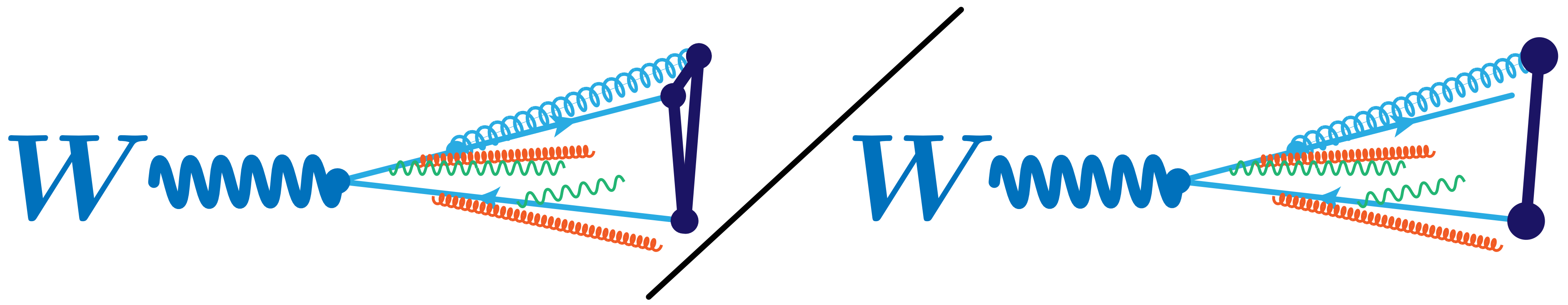
A robust m_W sensitive projection

Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2023

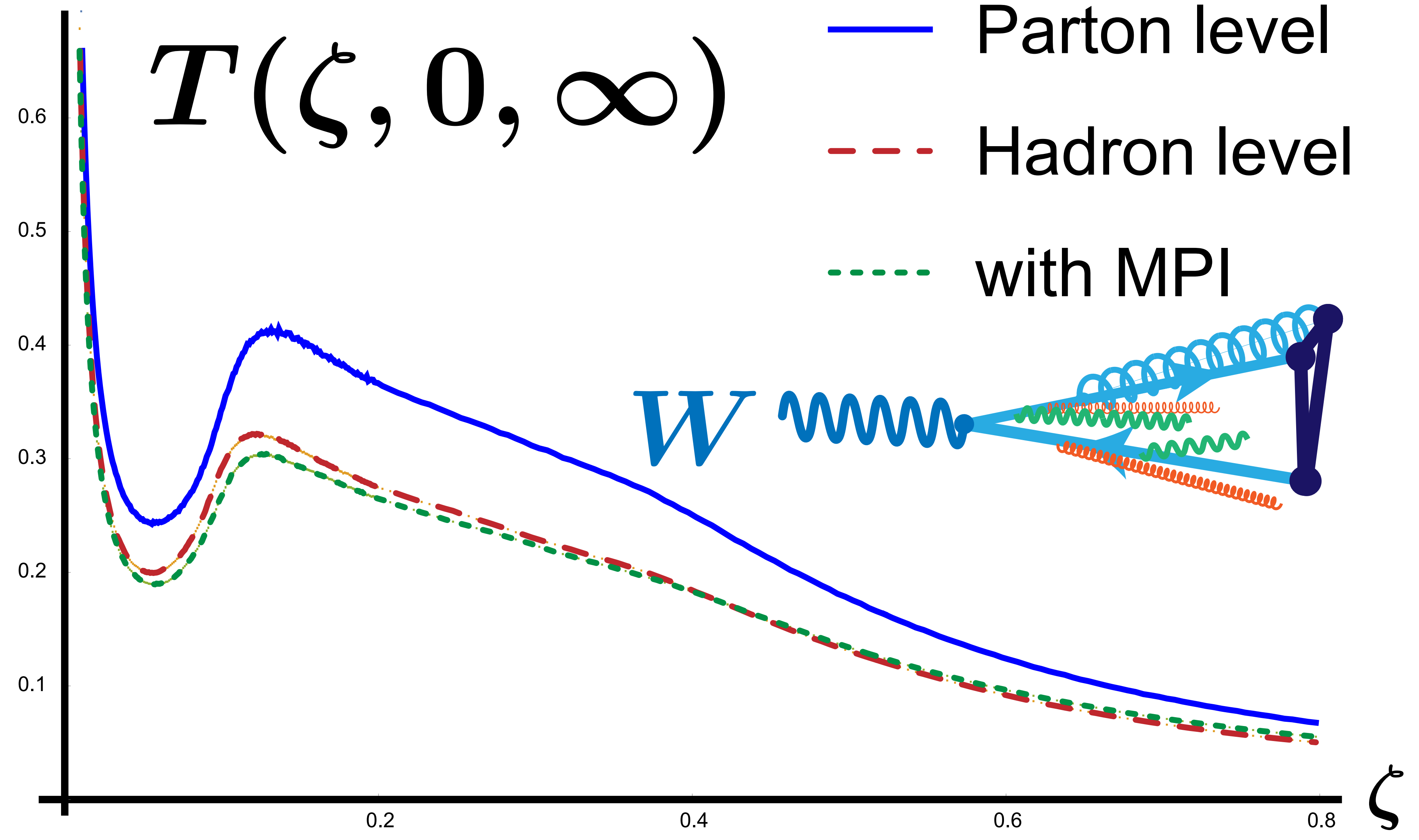
Unlike the top, the Γ_W does nothing to protect the distribution from sensitivity to the Λ_{QCD} scale

- Consider the ratio against two-point correlator for robustness against hadronization effects:

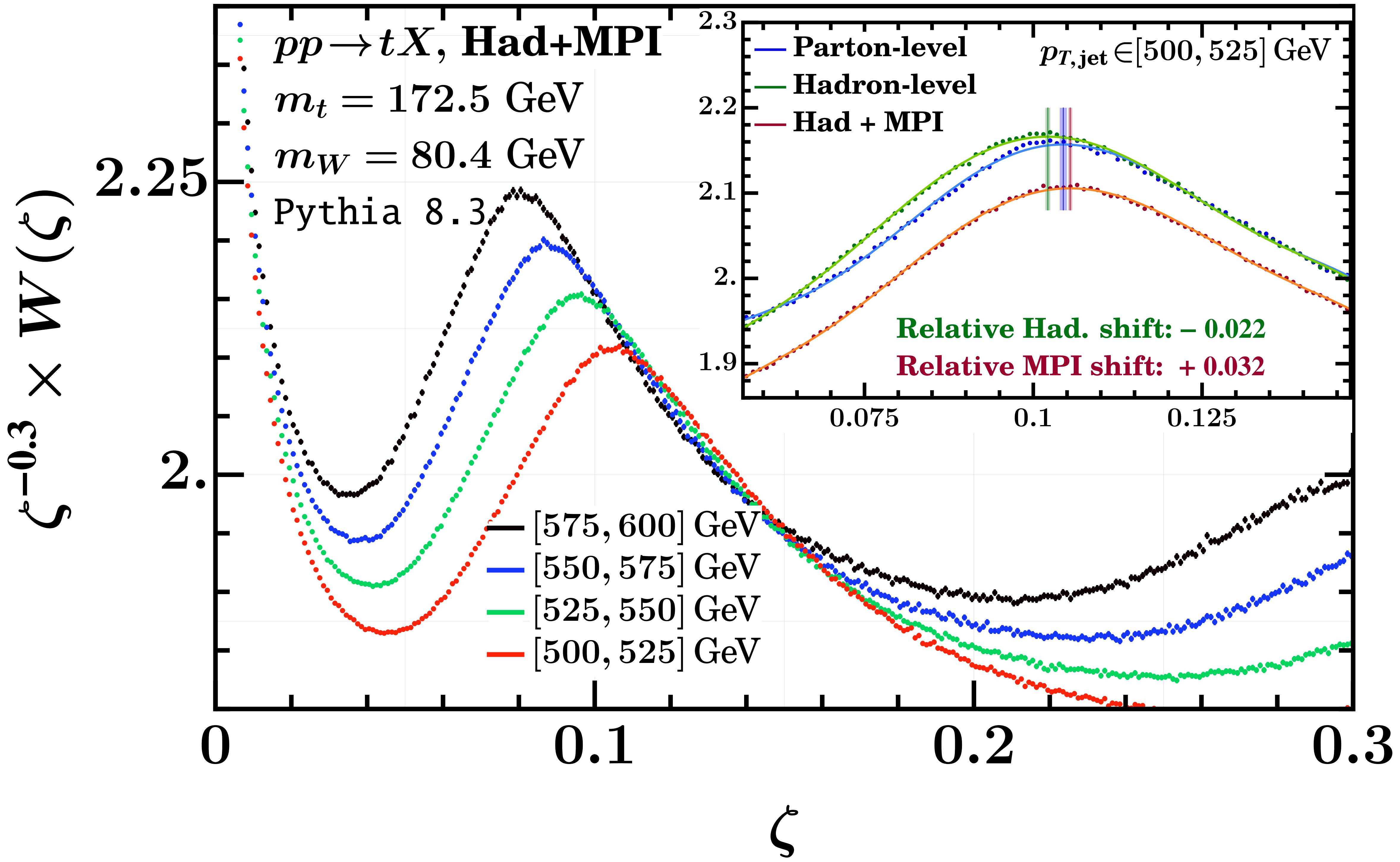
$$\boldsymbol{W(\zeta) \equiv T(\zeta, 0, \infty) \left(\sum_{\substack{\text{hadrons} \\ i,j}} \int \mathrm{d}\zeta_{ij} \, \frac{p_{T,i}\, p_{T,j}}{(p_{T,\text{jet}})^2} \, \frac{\mathrm{d}\sigma_{i,j}}{\mathrm{d}\zeta_{ij}} \, \delta(\zeta - \zeta_{ij}) \right)^{-1}}$$



- This works because of the *same* b2b soft function.



→



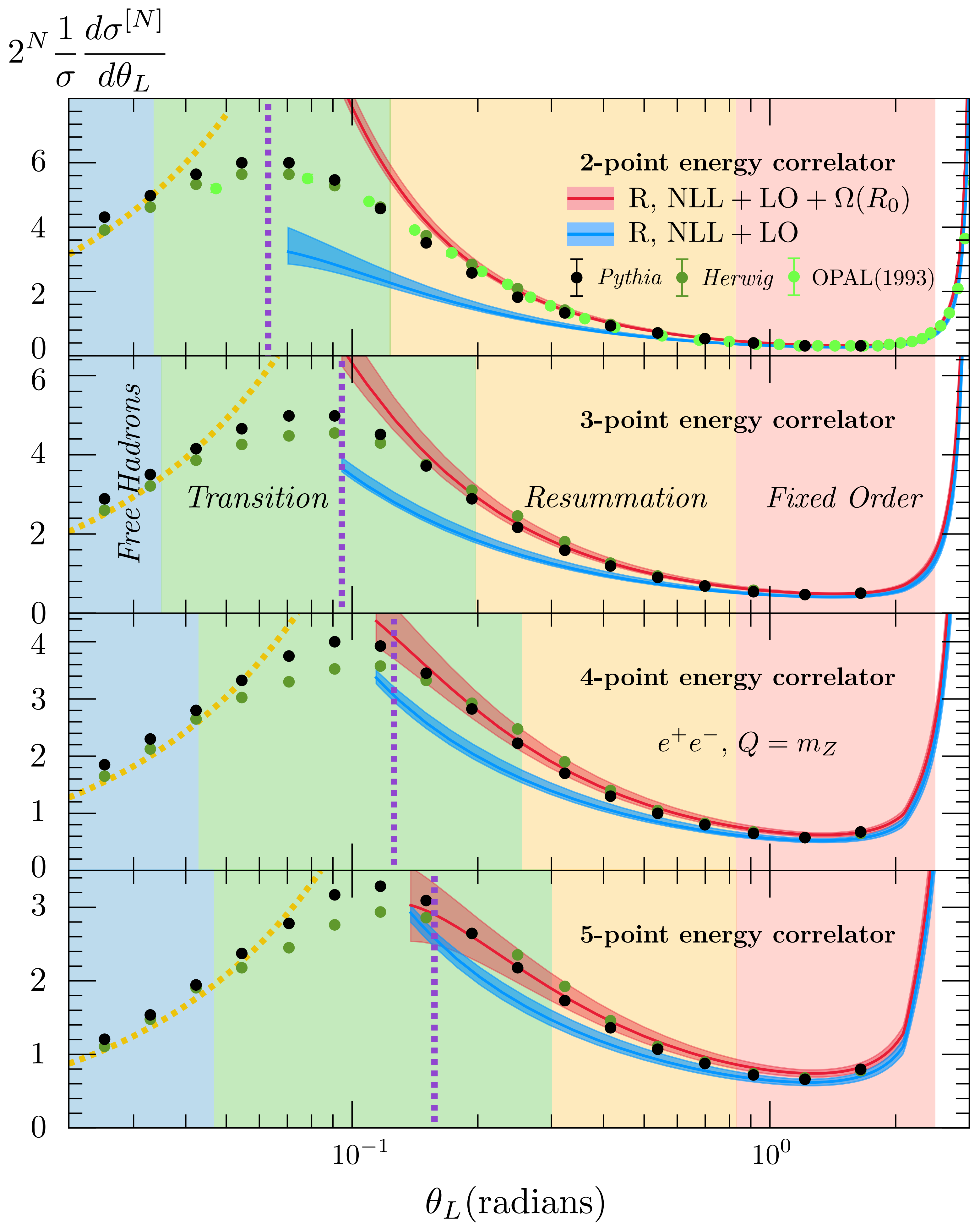
Aside: Hadronization in the collinear limit

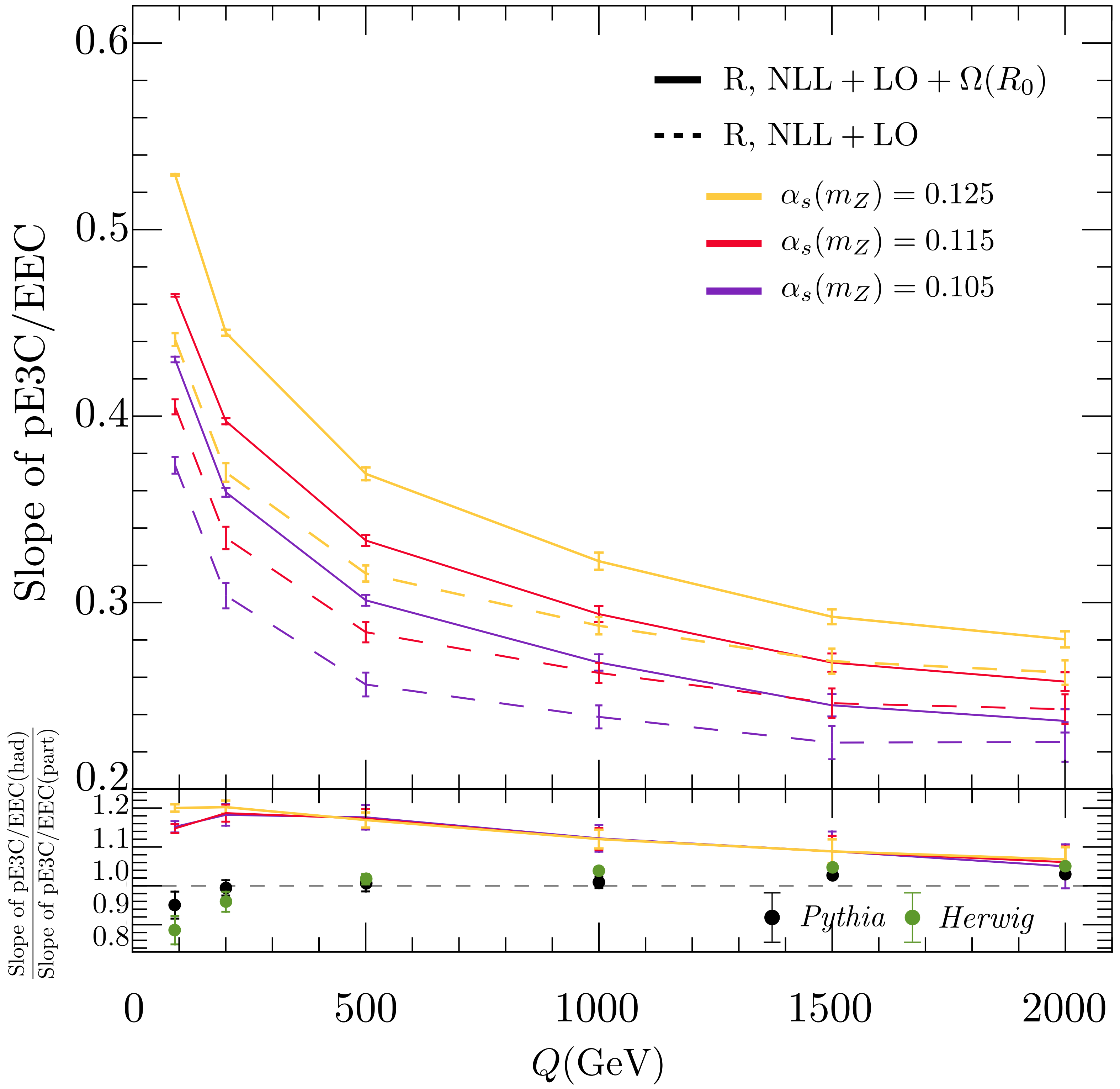
Lee, AP, Stewart, Sun arXiv:2405.19396

- EECs enable a field-theoretic analysis of hadronization effects.
- Use renormalon calculus to tame the leading hadronization correction.

$$\frac{1}{\sigma}\frac{d\sigma^{[N]}}{dx_L} = \frac{1}{\sigma}\frac{d\hat{\sigma}^{[N]}}{dx_L} + \frac{N}{2^N}\frac{\overline{\Omega}_{1q}}{Q(x_L(1-x_L))^{3/2}}$$

- Enable a model-independent assessment of hadronization effects in α_s measurement





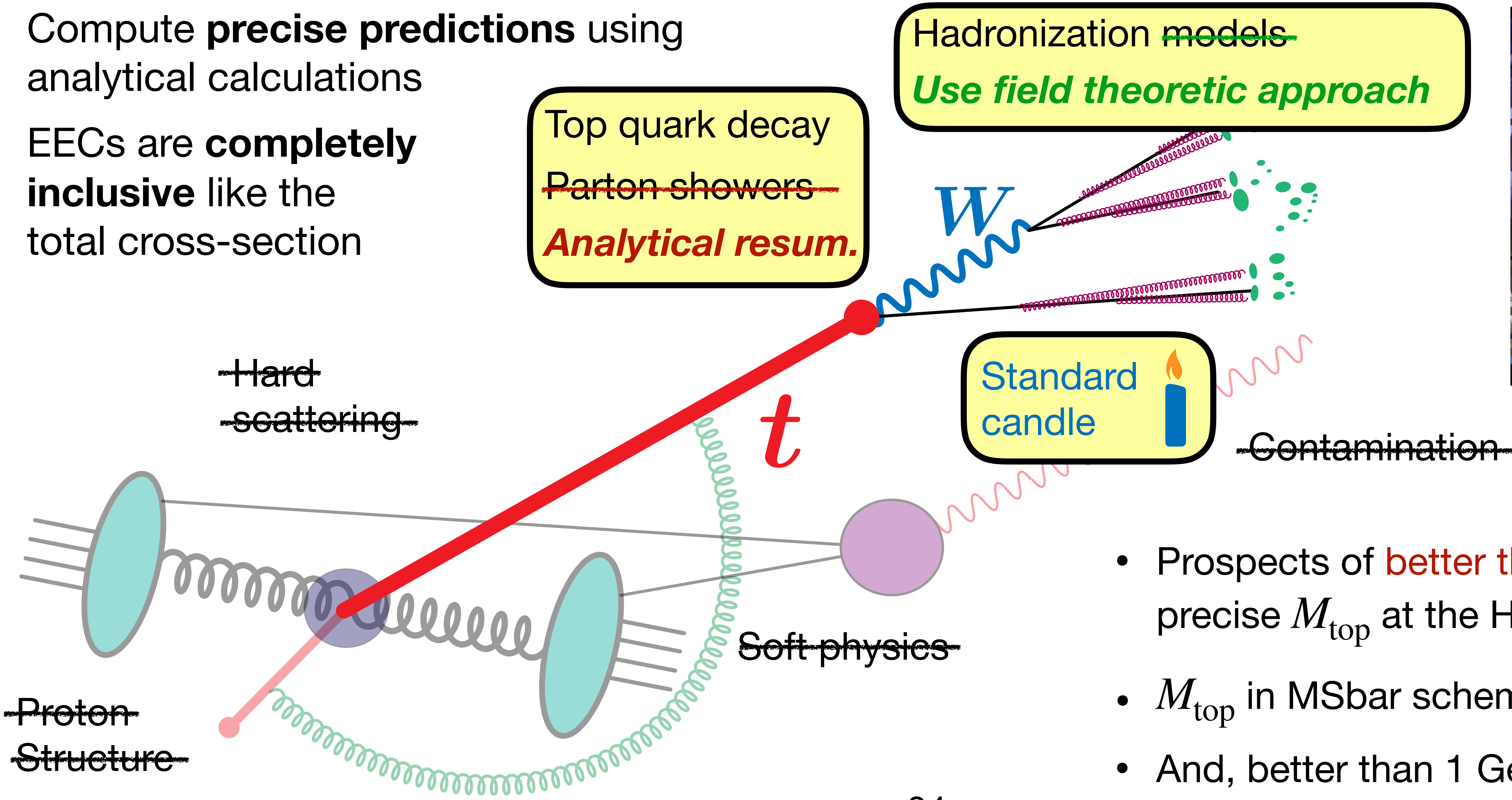
See talks by Zhiquan and Hua-Xing tomorrow.

The promise of the standard candle approach

- Demonstrate **robustness** using simulations.
- Compute **precise predictions** using analytical calculations
- EECs are **completely inclusive** like the total cross-section

~~Energy scale uncertainty~~

Exploit the excellent angular resolution of the tracker



Hadronization ~~models~~

Use field theoretic approach

Top quark decay

~~Parton showers~~

Analytical resum.

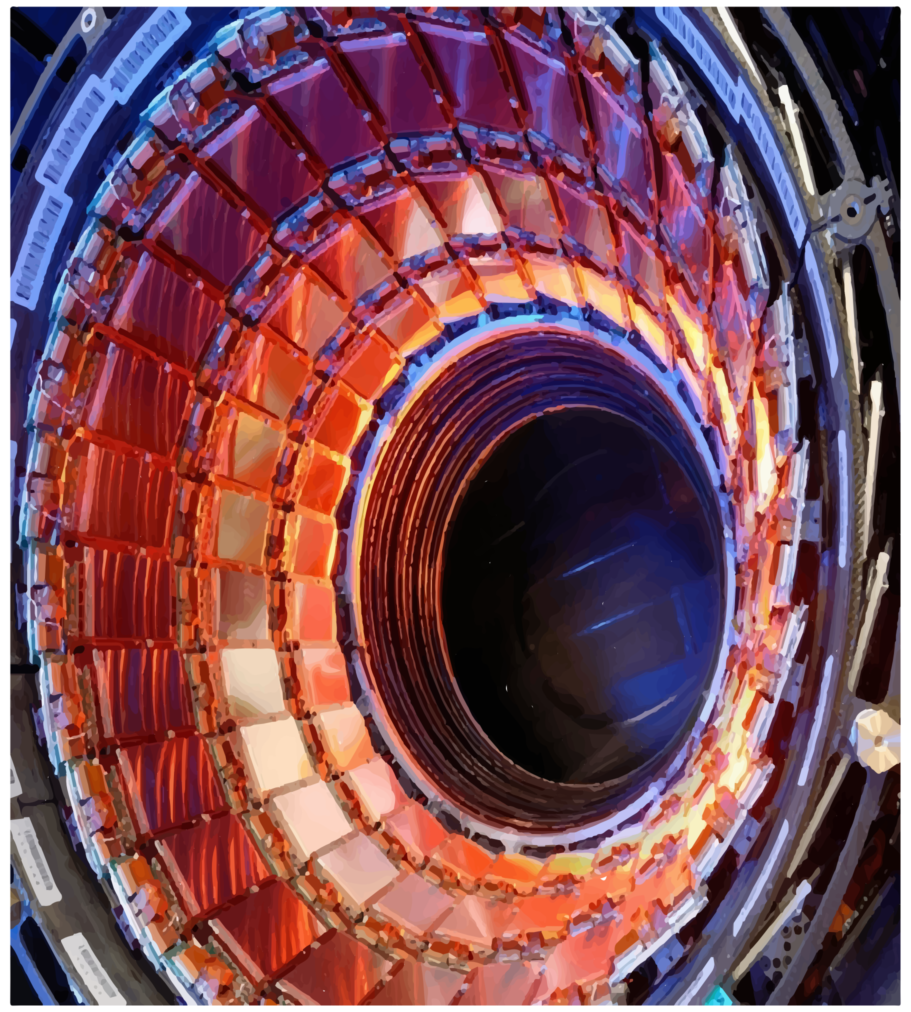
Standard candle

~~Hard scattering~~

~~Contamination~~

~~Soft physics~~

~~Proton Structure~~



- Prospects of better than 500 MeV (0.3%) precise M_{top} at the HL-LHC!
- M_{top} in MSbar scheme
- And, better than 1 GeV with Run 3

Outline

- Motivation
- EECs on boosted top quarks
- The Standard Candle approach
- Demonstrating Robustness and Experimental Feasibility

Calibrating the top mass

Holguin, Moult, AP, Procura, Schöfbeck, Schwarz

The strategy is to simply take the ratio of the peaks of the $T(\zeta)$ and the $W(\zeta)$ distributions. The resulting ratio is proportional to top mass:

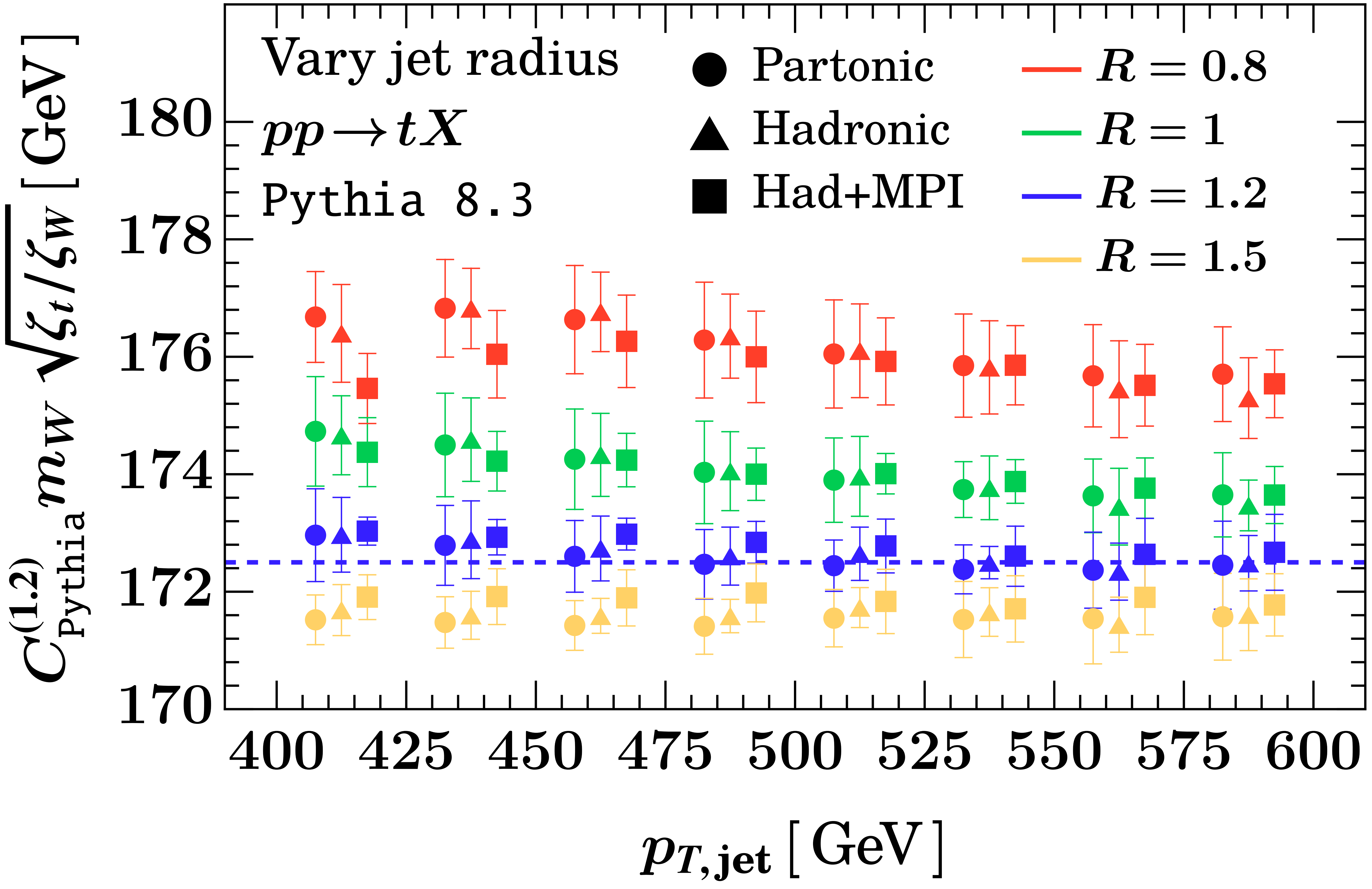
$$\boxed{m_t = C\, m_W \sqrt{\zeta_t/\zeta_W}}$$

The constant C depends on the jet radius and is perturbatively computable. For now extract this from parton showers (error bar is stat + polynomial peak fit):

Shower	$R = 0.8$	$R = 1.0$	$R = 1.2$	$R = 1.5$
Pythia 8.3	1.076 ± 0.002	1.090 ± 0.001	1.099 ± 0.001	1.105 ± 0.001
Vincia 8.3	1.079 ± 0.002	1.091 ± 0.002	1.100 ± 0.002	1.107 ± 0.002
Herwig 7.2 Dipole	1.071 ± 0.002	1.082 ± 0.001	1.091 ± 0.001	1.100 ± 0.002
Herwig 7.2 A.O.	1.094 ± 0.001	1.106 ± 0.001	1.116 ± 0.001	1.125 ± 0.001

Jet radius dependence

Varying the jet radius impacts the sampled top and W boosts via the $p_{T,\text{jet}}$



Production mechanism:

- PDF uncertainty ☐
- Hard scattering corrections ☐

Jet substructure:

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

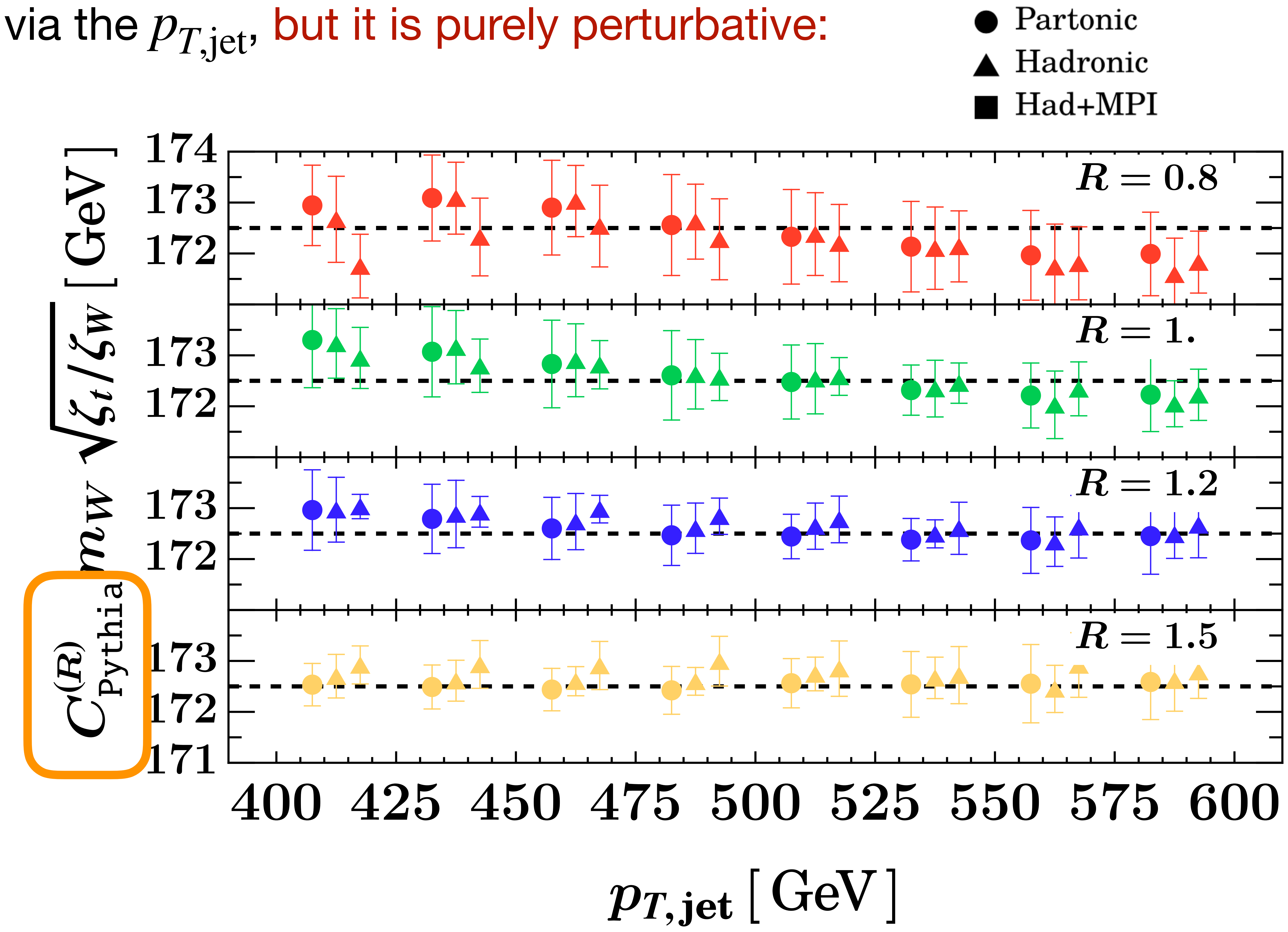
Experimental feasibility:

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

Holguin, Moult, AP, Procura, Schöfbeck, Schwarz

Jet radius dependence

Varying the jet radius impacts the sampled top and W boosts via the $p_{T,\mathrm{jet}}$, but it is purely perturbative:



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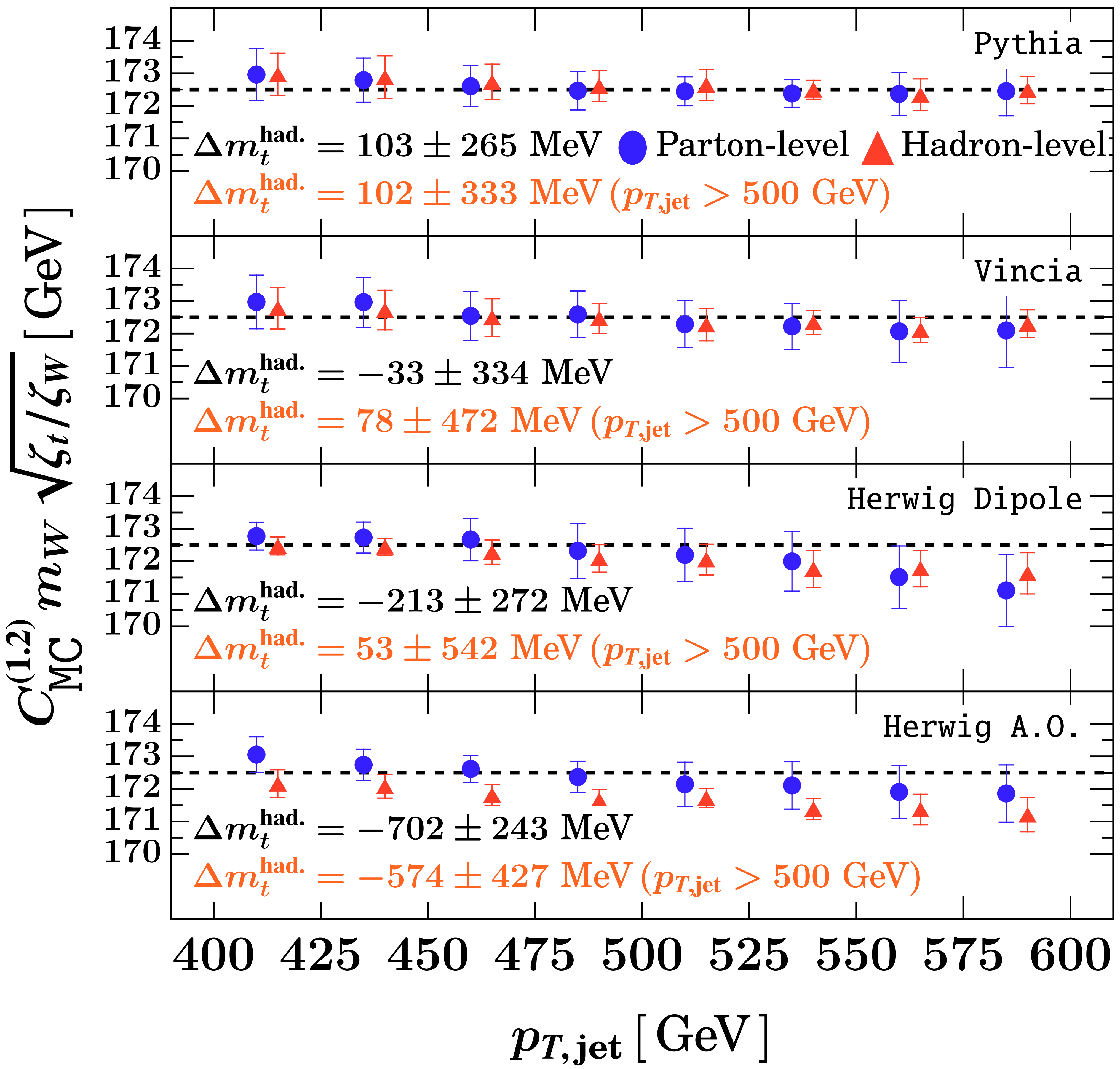
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz

Hadronization effects

Except for Herwig angular ordered shower, all the showers exhibit an excellent cancellation of hadronization effects in the $p_{T,\mathrm{jet}}$ (error bar is stat + polynomial peak fit)



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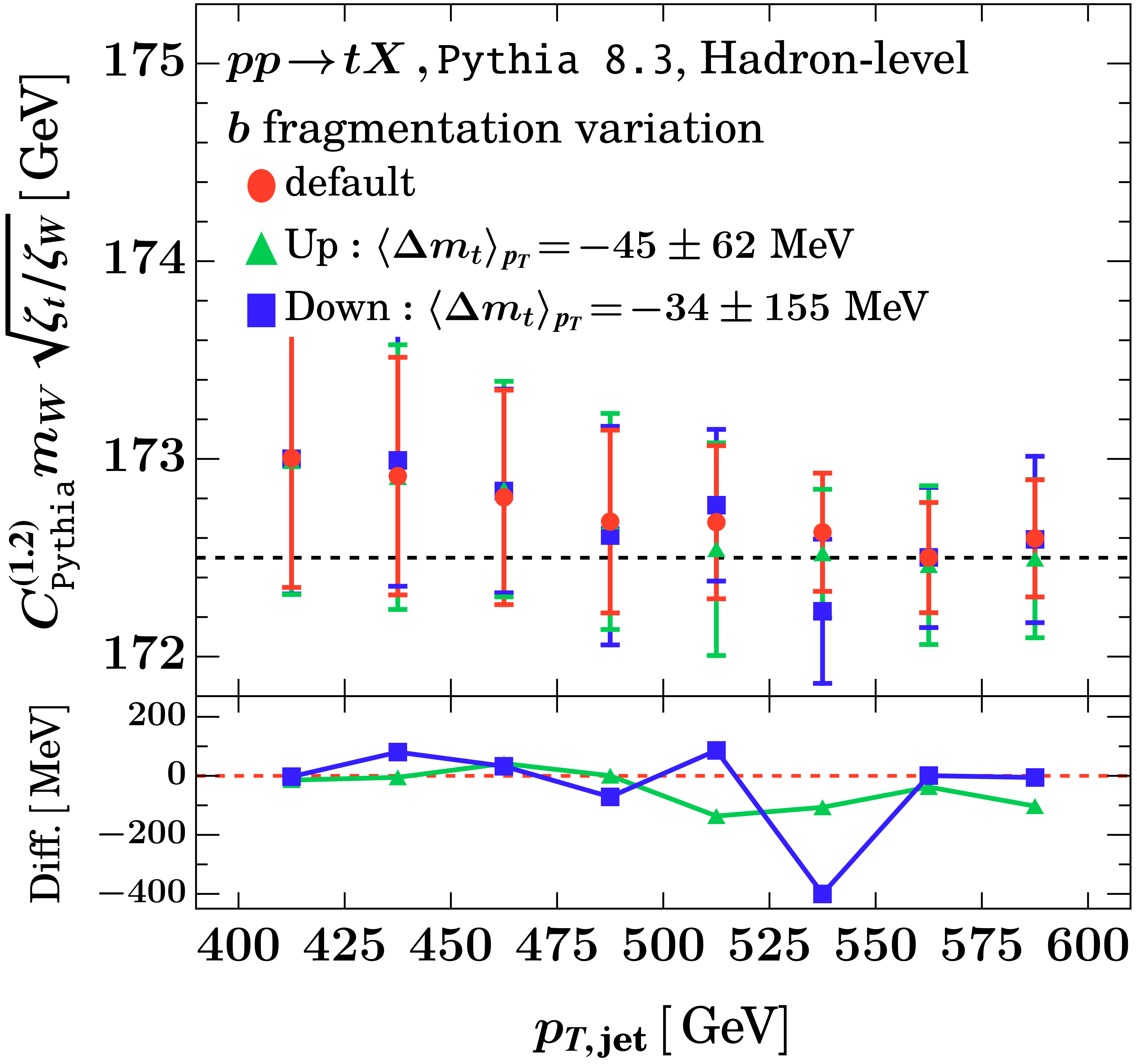
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz

Hadronization effects

Negligible impact of *b* hadron fragmentation modeling:



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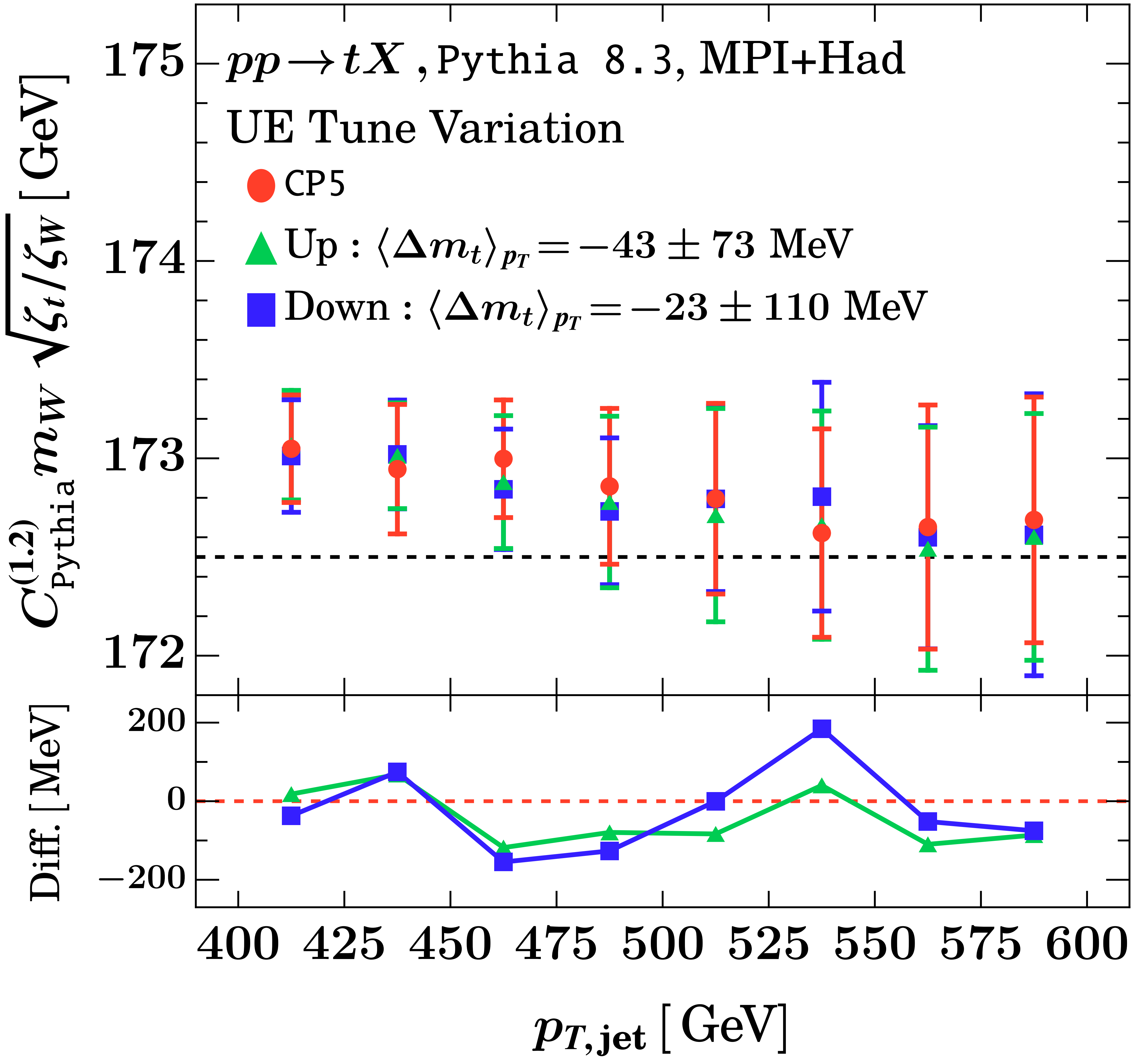
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz

Effect of contamination

We work with standard CMS CP5 tune and consider UE tune variation and find negligible impact



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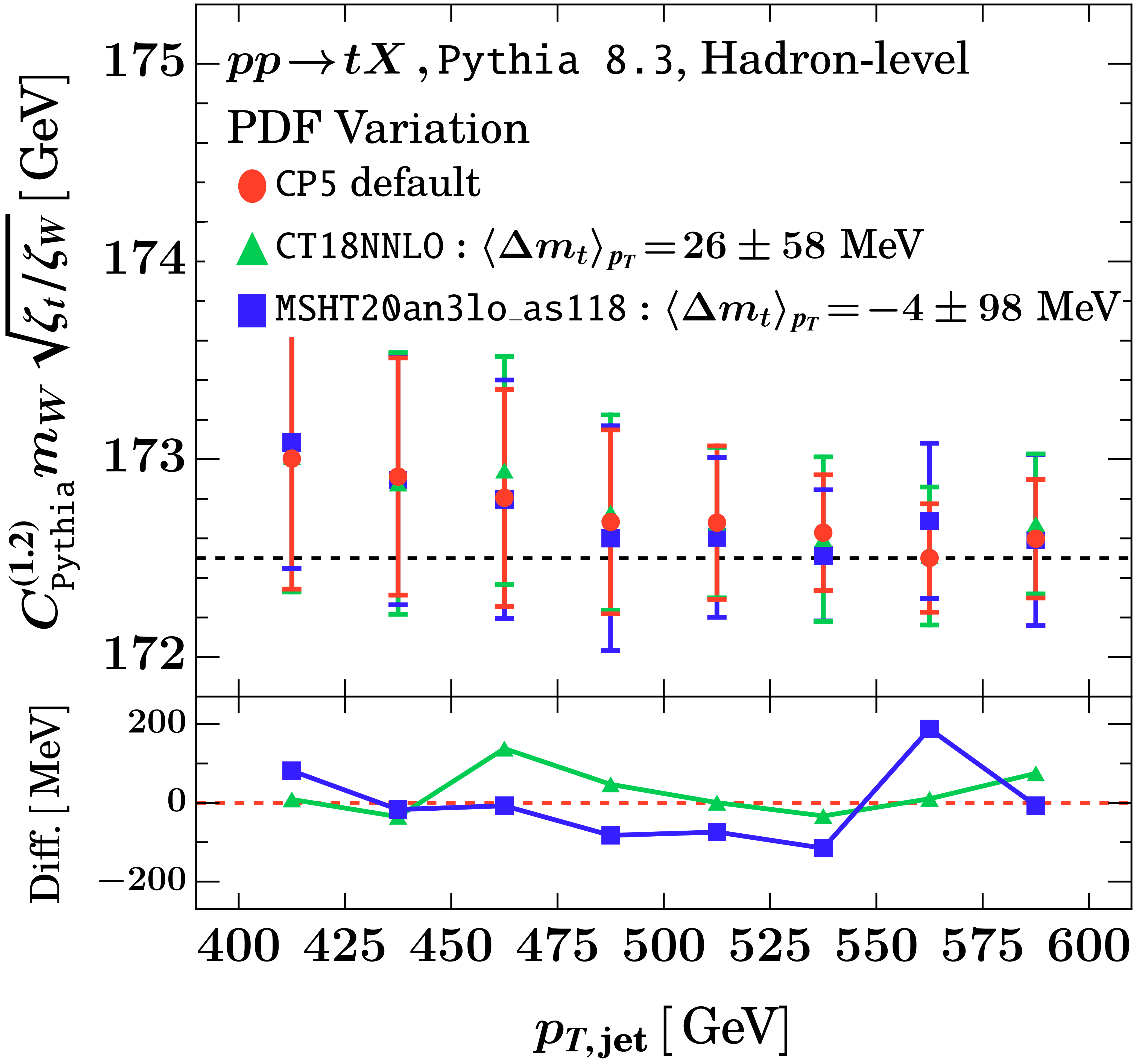
PDF variations

Variations in PDFs lead to significant shifts and induce substantial uncertainties in the $p_{T,\text{jet}}$ distribution but the ratio of the peaks is extremely robust (consistent with no shift):



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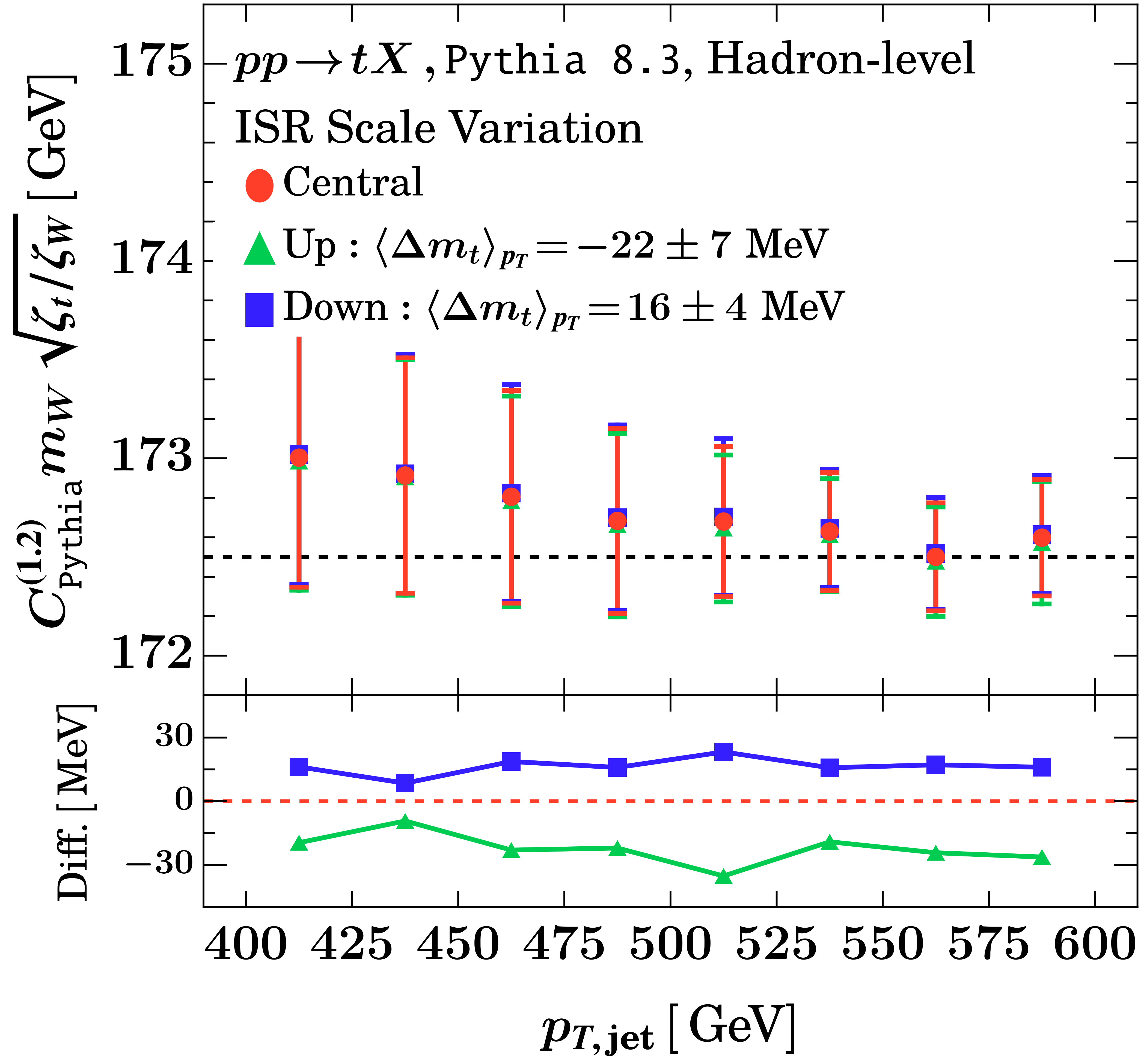
Hard scattering corrections

Probe variations in the physics at the hard scale via scale variation in the ISR: Negligible impact.



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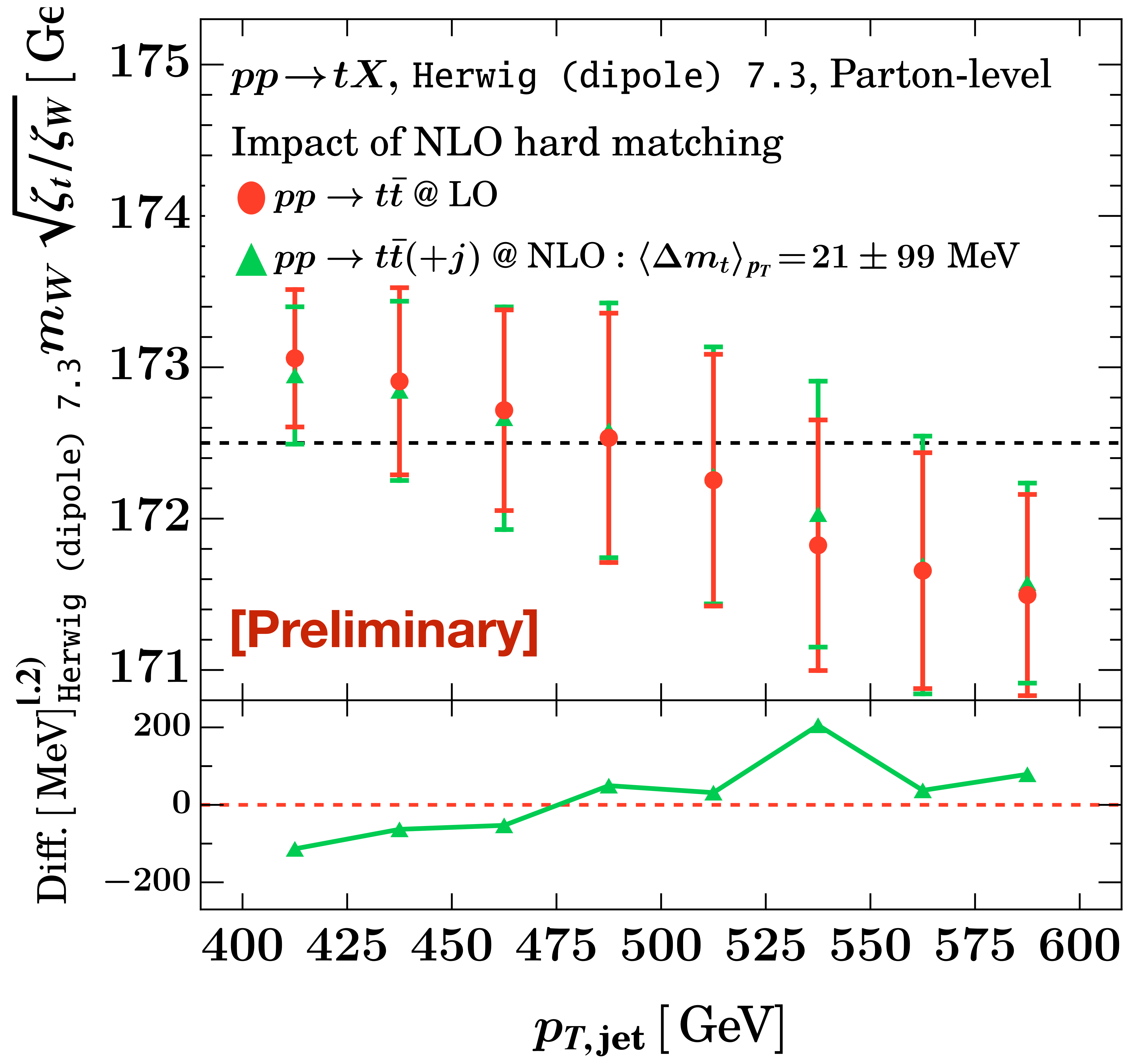
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz

Hard scattering corrections

Probe variations in the physics at the hard scale via NLO matching to $t\bar{t}+j$ process: Negligible impact.



Holguin, Moult, AP, Procura, Schöfbeck, Schwarz

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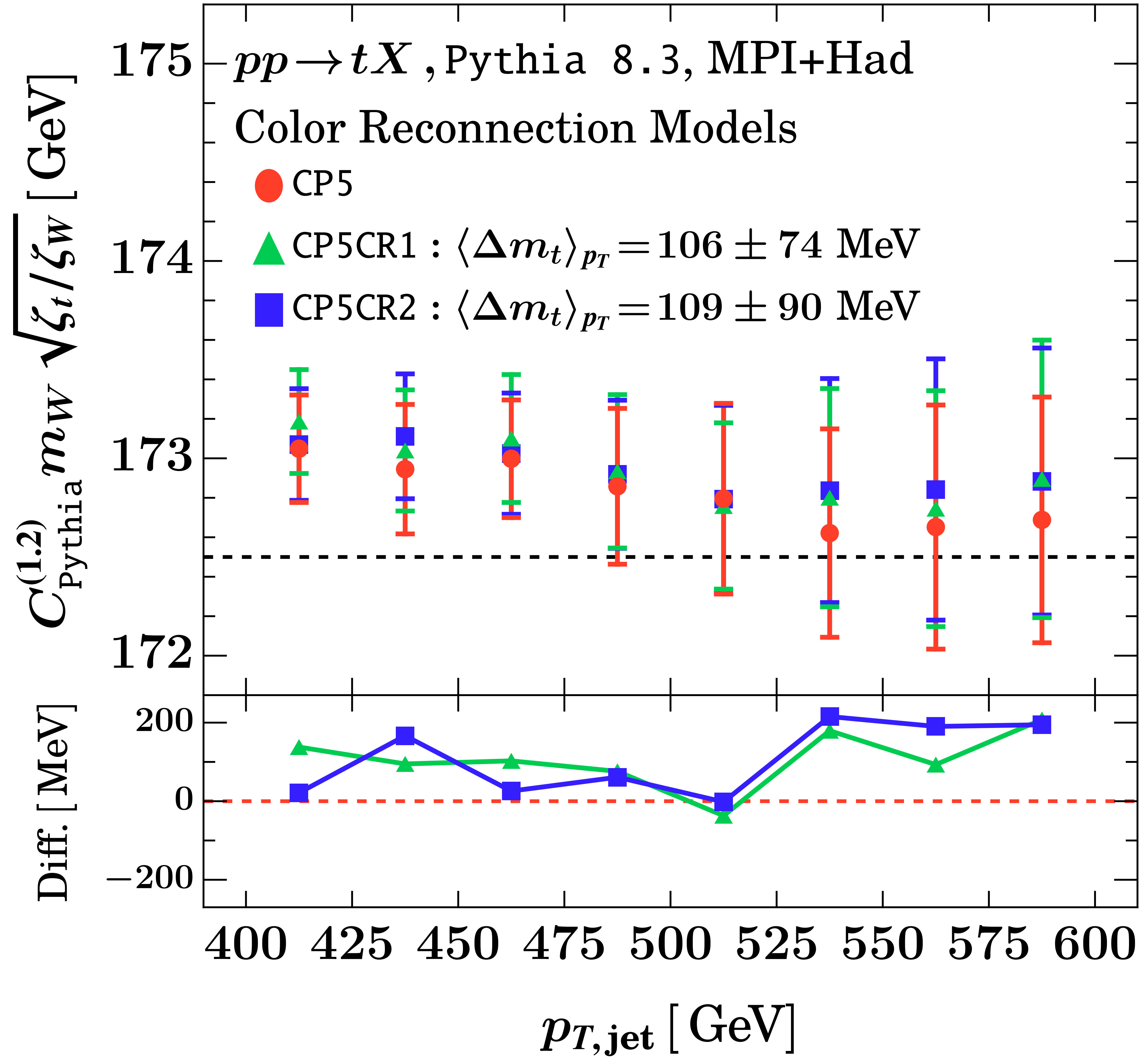
Wide angle soft physics

Color reconnection models probe the soft wide angle effects at the nonperturbative scale: Negligible impact



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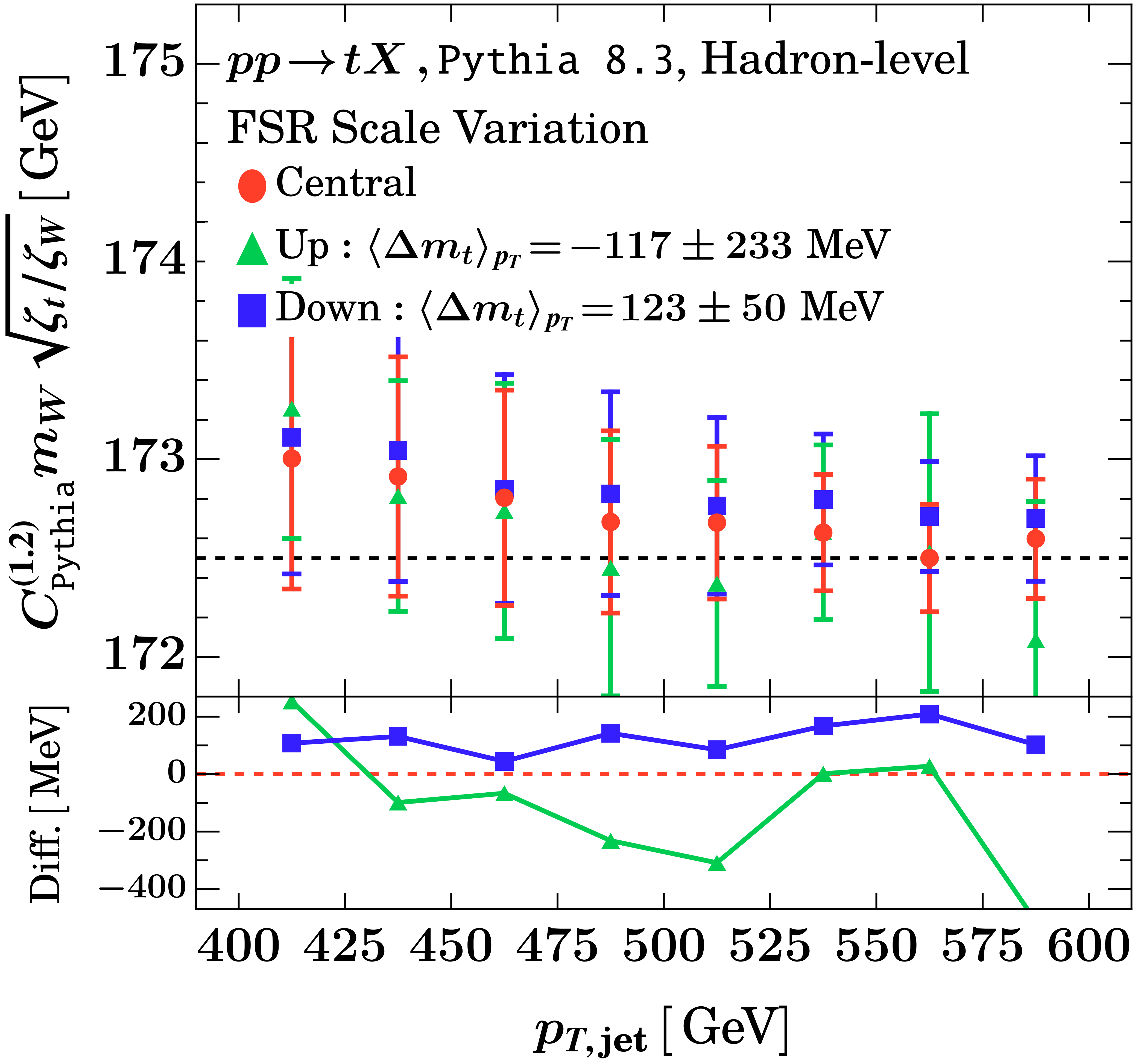
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz

Shower Uncertainty

Shower uncertainty results from LL showers + LO description of the top decay: Negligible impact of FSR scale variation



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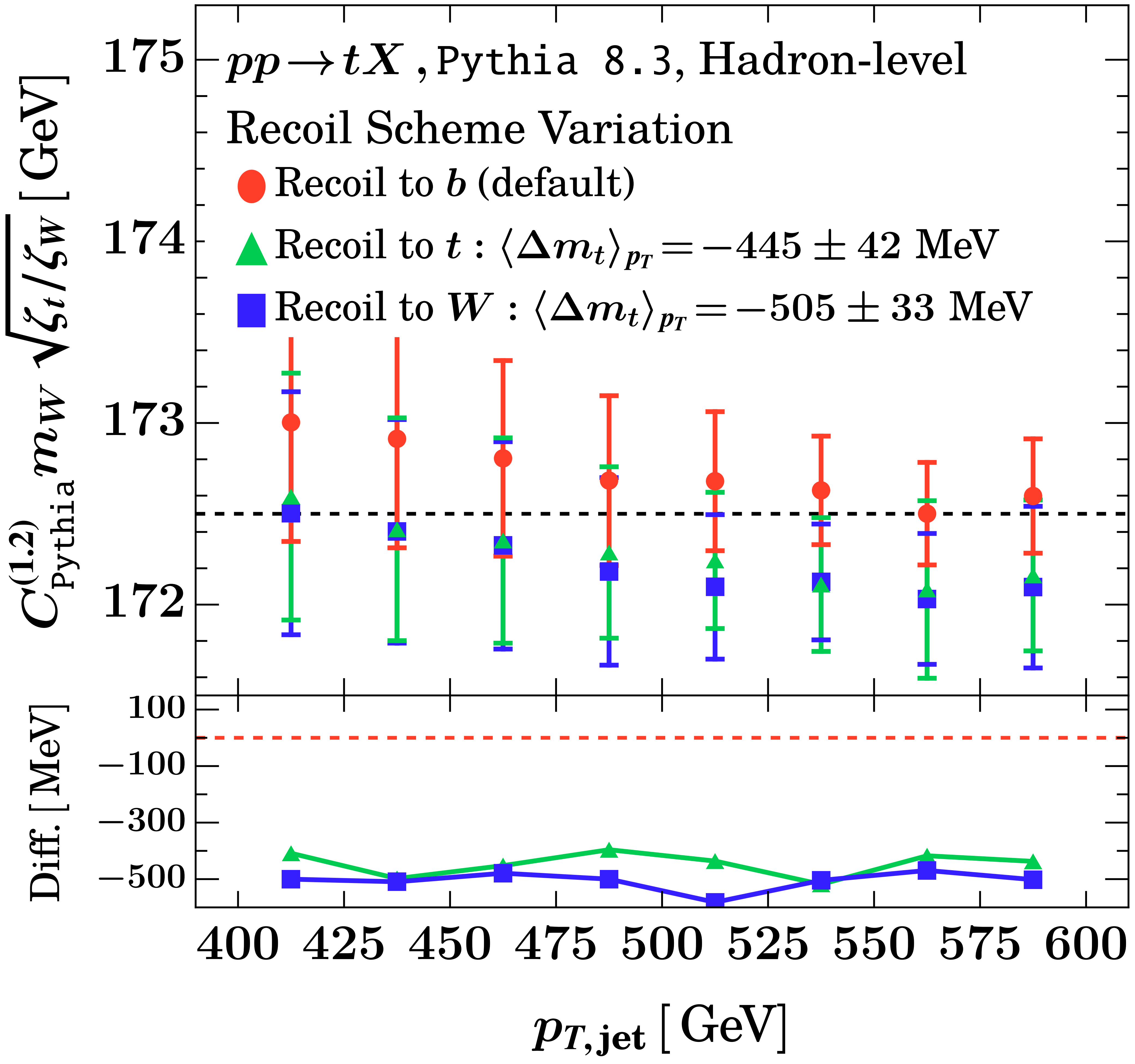
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz

Shower Uncertainty

Shower uncertainty results from LL showers + LO description of the top decay: Expect significant improvement with the top decay description at NLO



Holguin, Moult, AP, Procura, Schöfbeck, Schwarz

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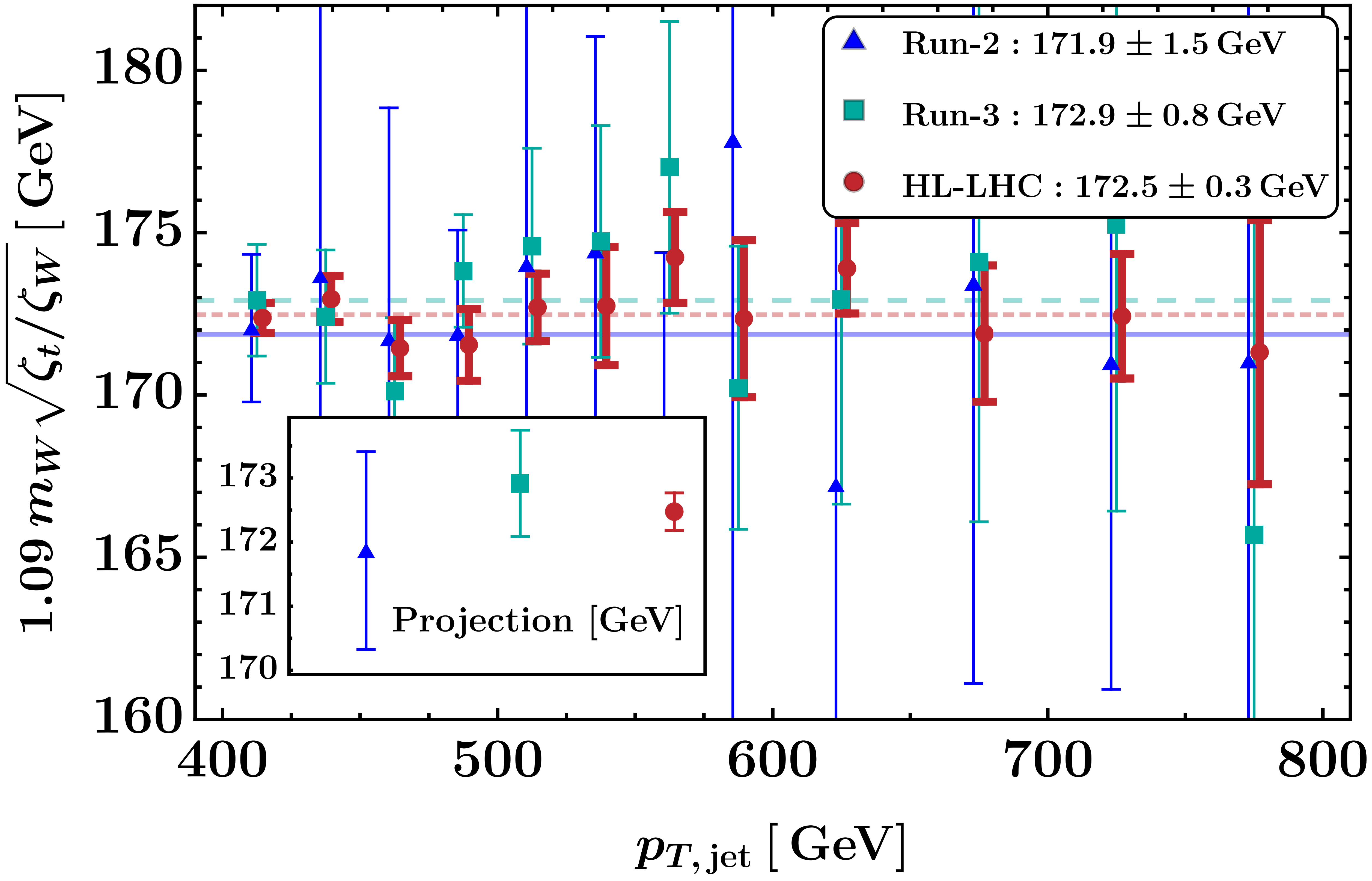
Statistical sensitivity

Crucially, the measurement is statistically feasible at the LHC



Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2023

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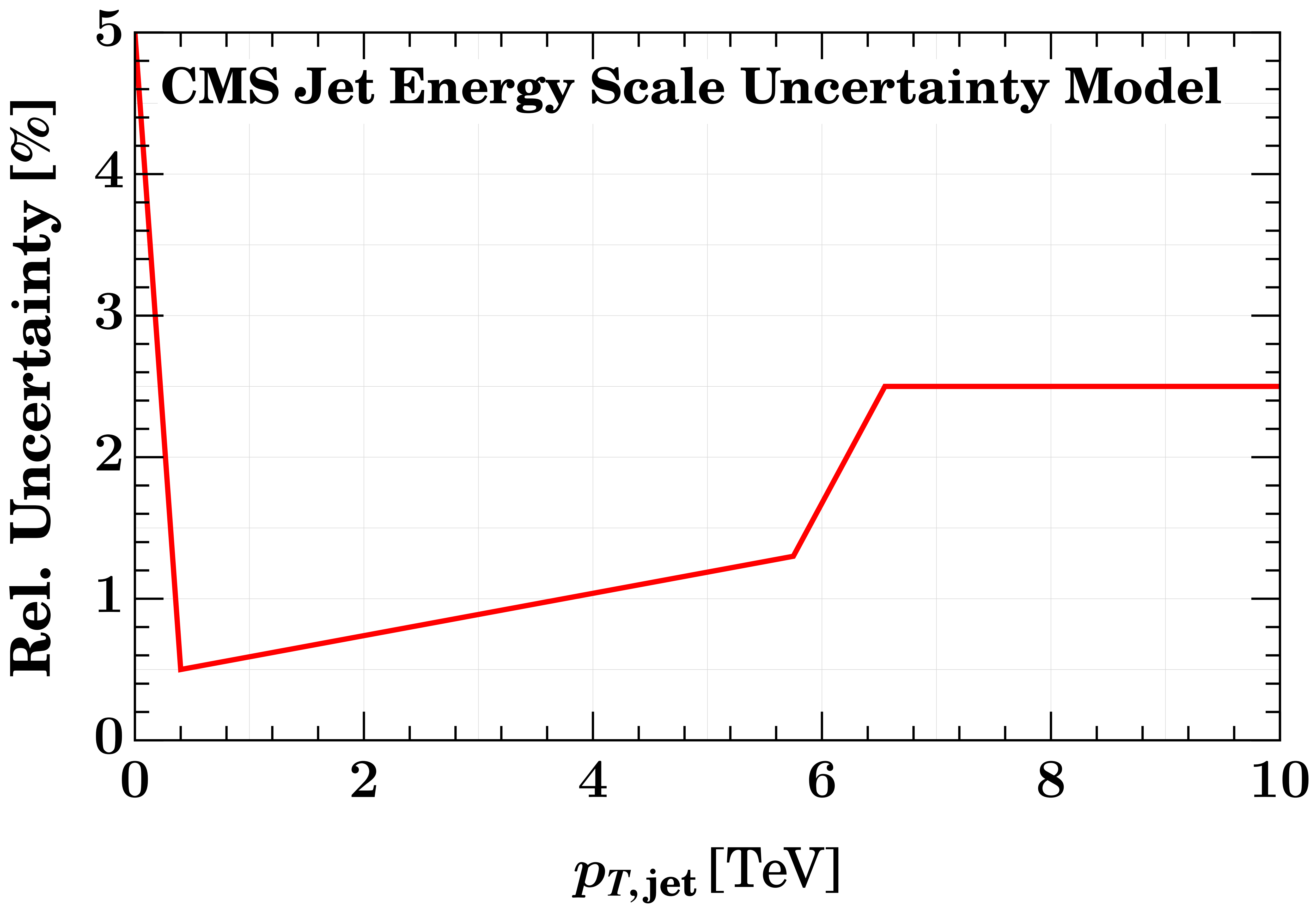
Jet energy scale

We model the CMS jet energy scale uncertainty and vary the $p_{T,\mathrm{jet}}$



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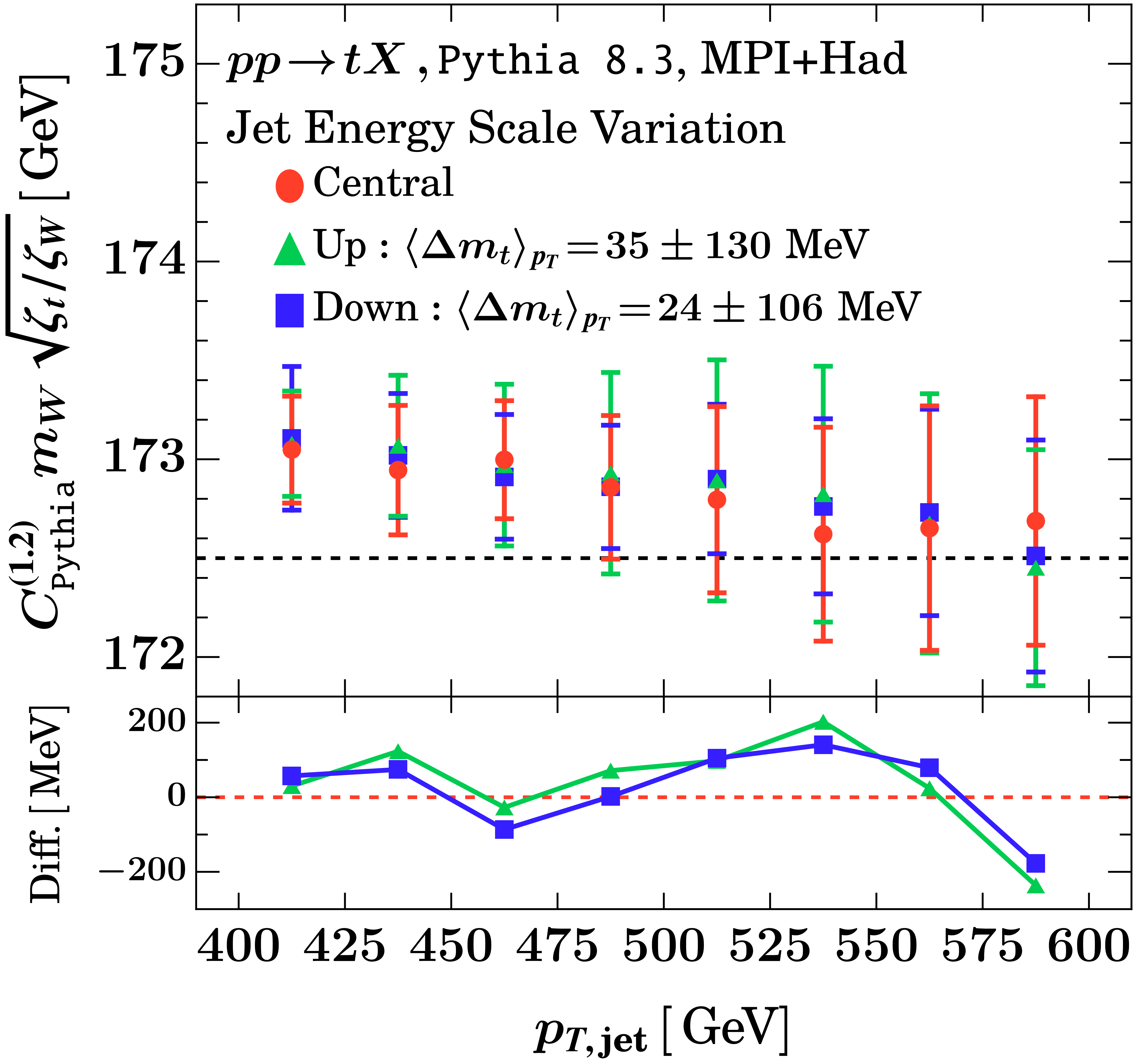
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz

Jet energy scale

We model the CMS jet energy scale uncertainty and vary the $p_{T,\text{jet}}$: Negligible impact



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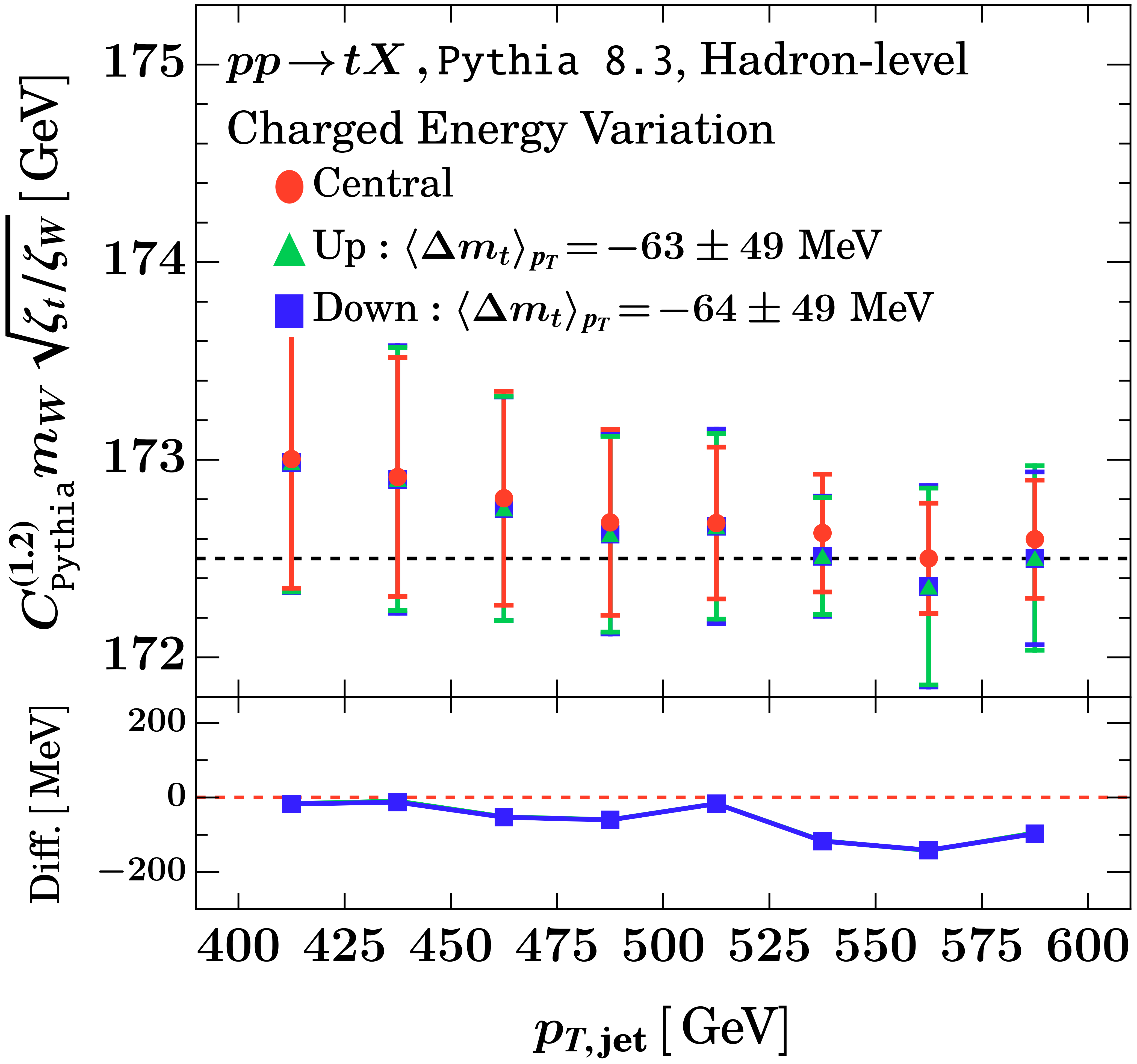
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz

Constituent Energy Scale

Study the effect of varying the constituent momenta: 1% for charged, 3% for photons and 5% for neutrals: Negligible impact



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Holguin, Moult, AP, Procura, Schöfbeck, Schwarz

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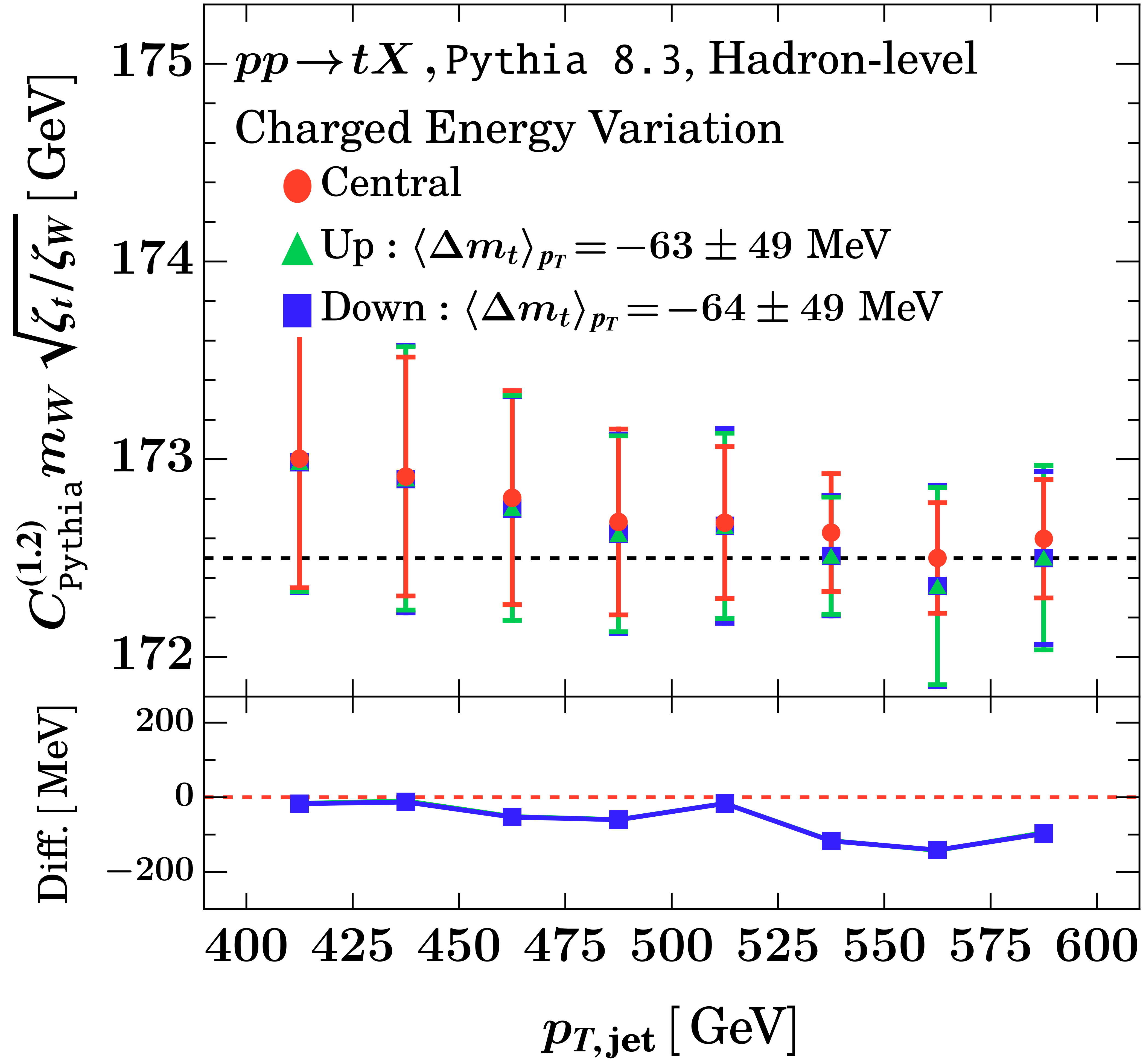

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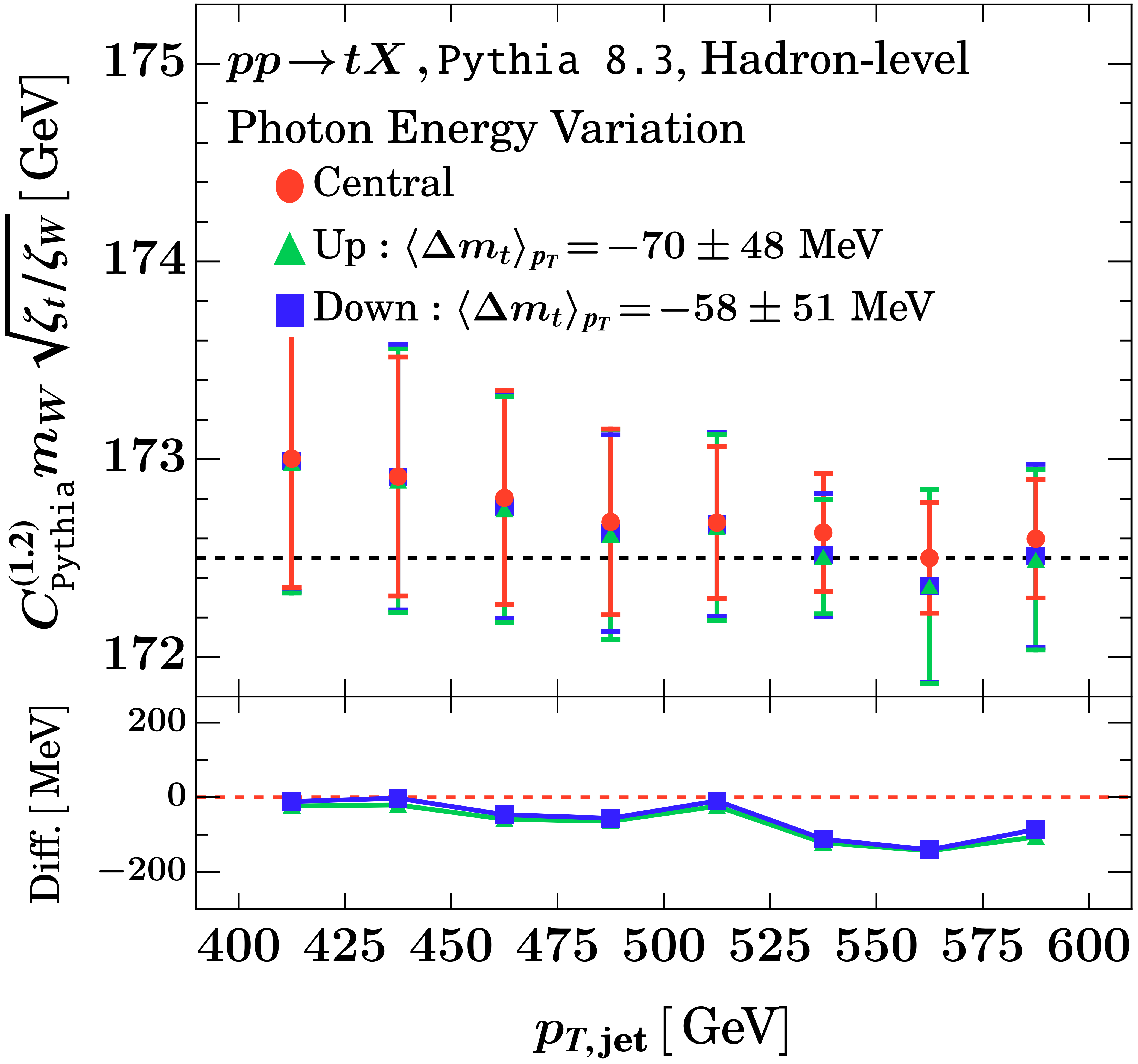

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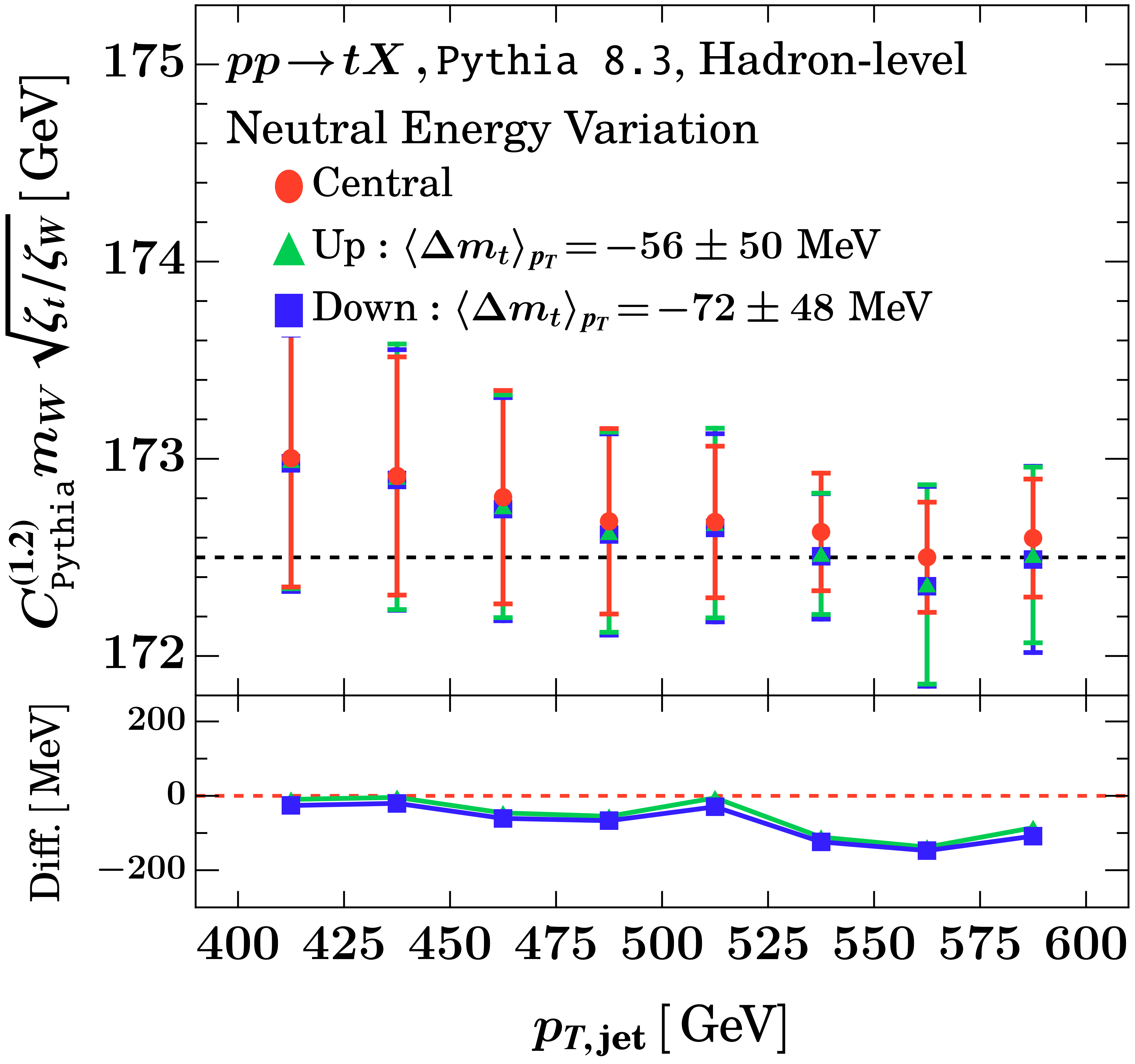

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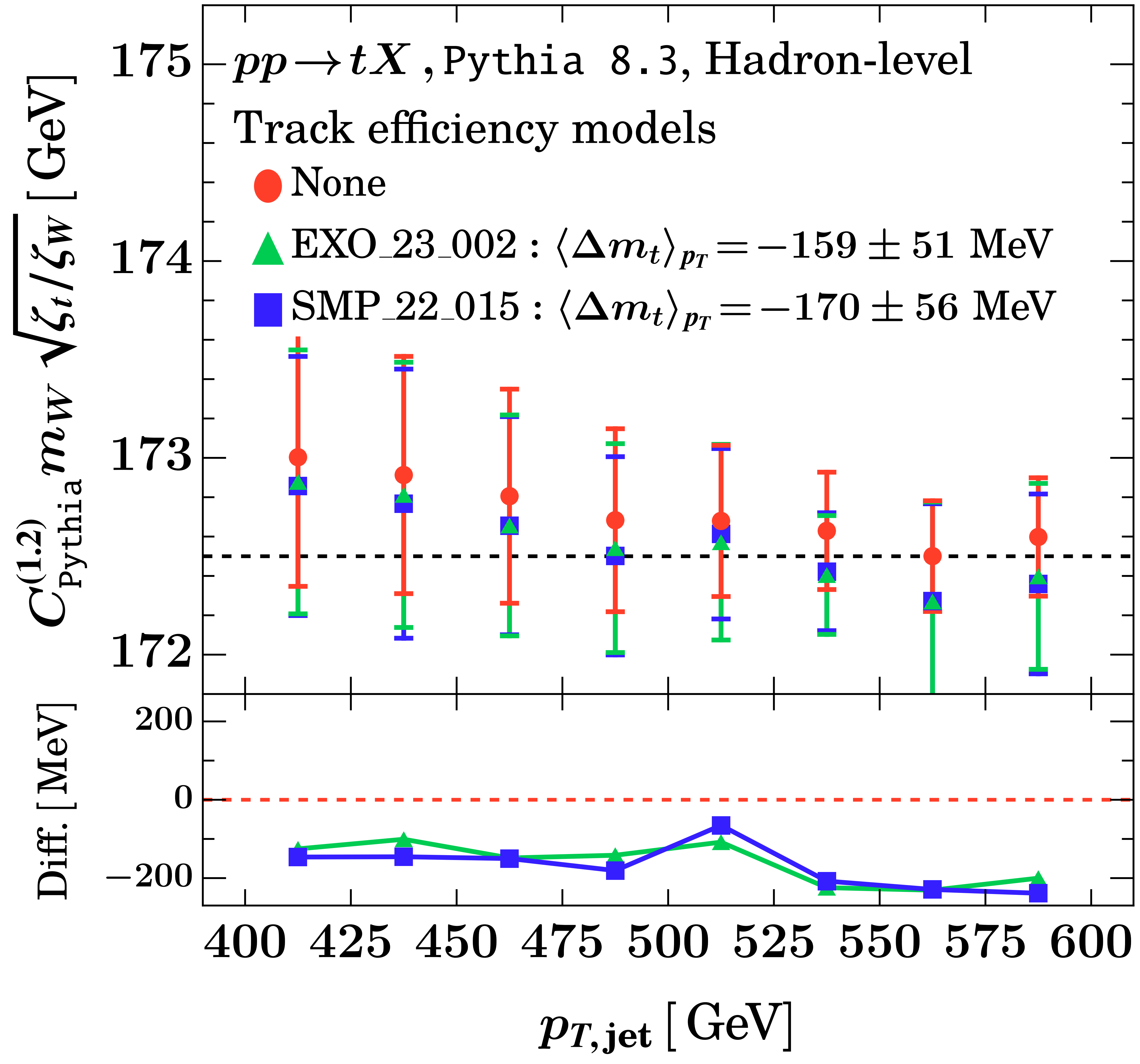
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz

Track Efficiency

Investigate two CMS track efficiency models: Negligible impact of track efficiency profile (SMP_22_015 includes track p_T dependence).



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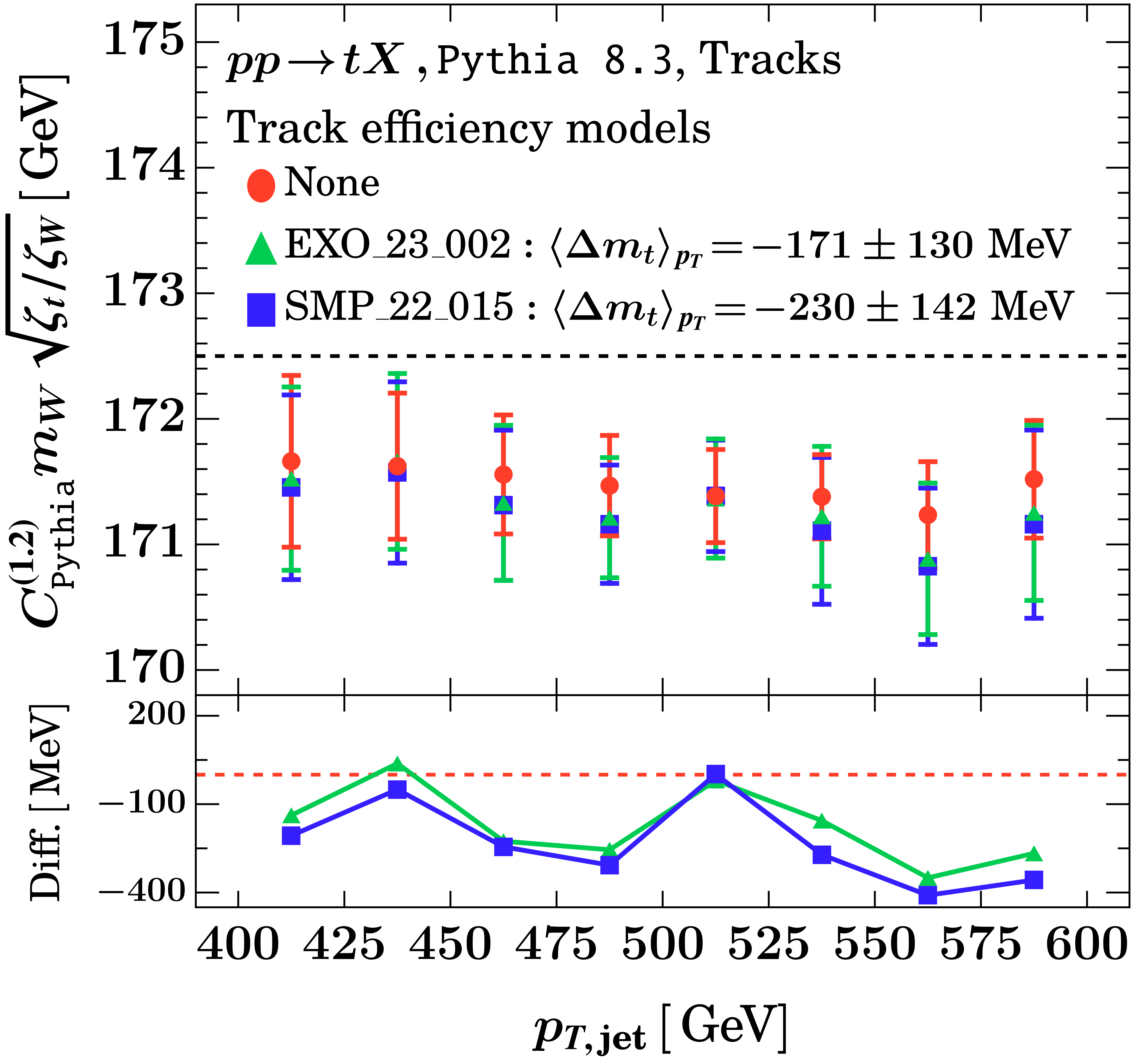
Track Efficiency

The restriction to tracks is a small effect to the energy correlator spectrum. Primary shift in the W distribution: Only 10% accuracy of track function moments required.



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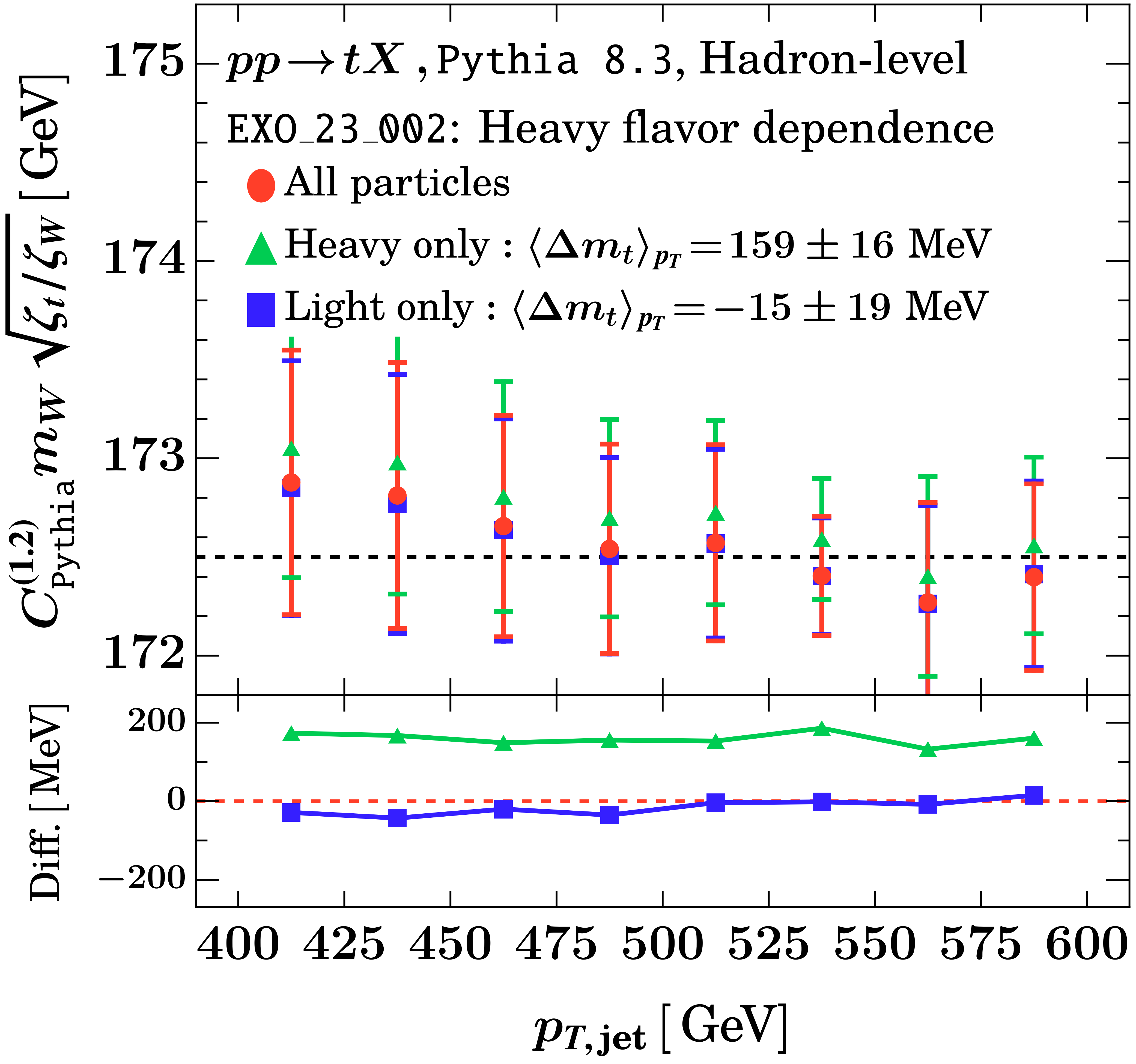
Heavy Flavor Dependence

A known effect in detectors is the different jet response depending on the origin of a jet. Test the effect separately for particles that originate from a heavy flavor bottom quark or from a light quark.



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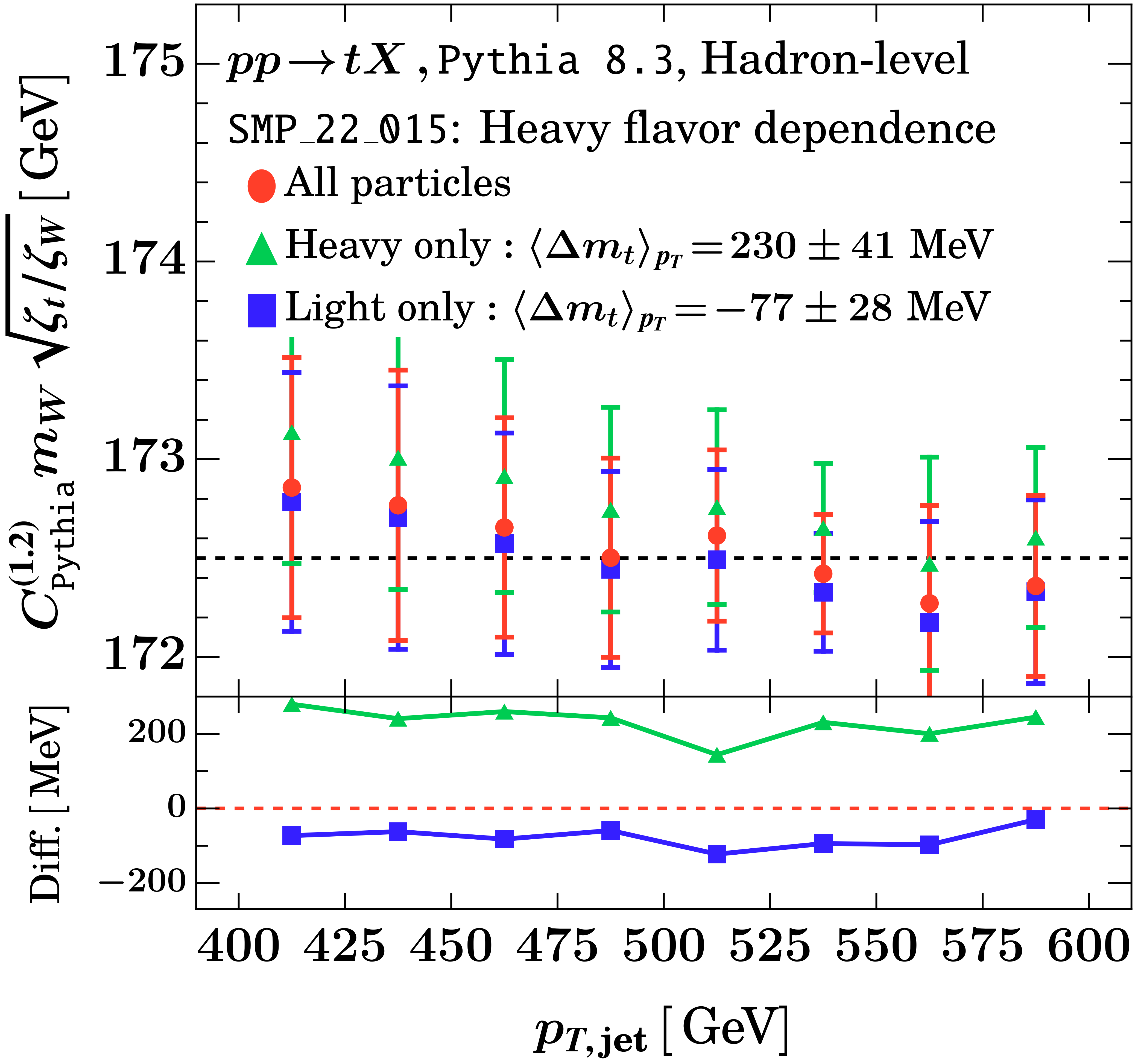

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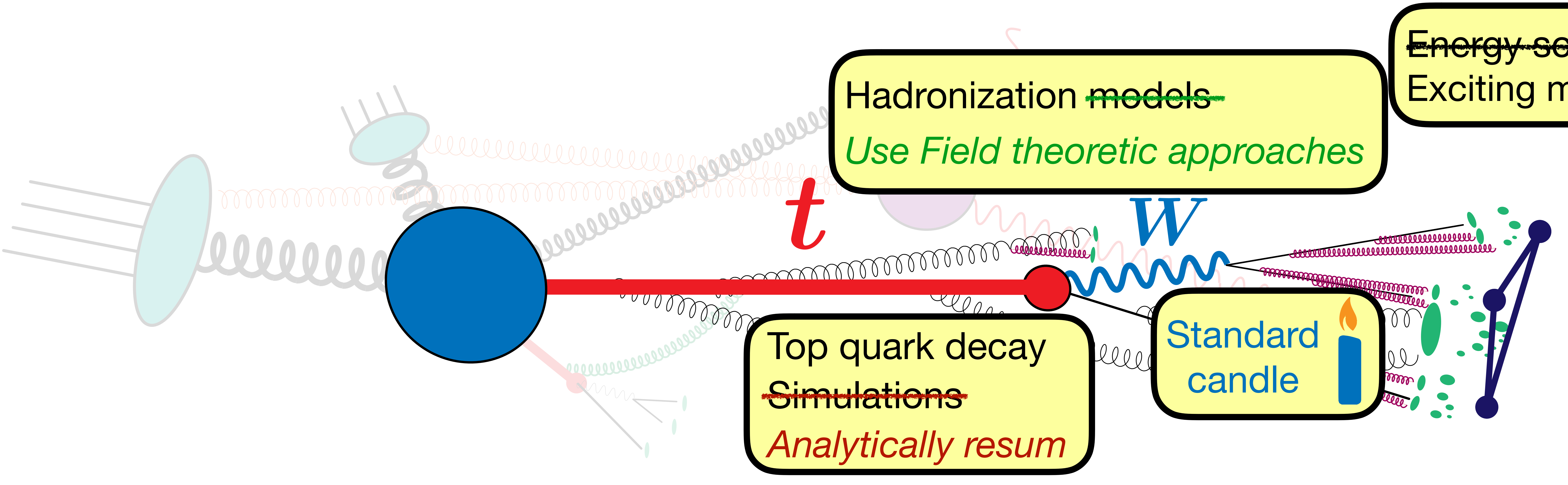
High-precision top mass becoming a reality

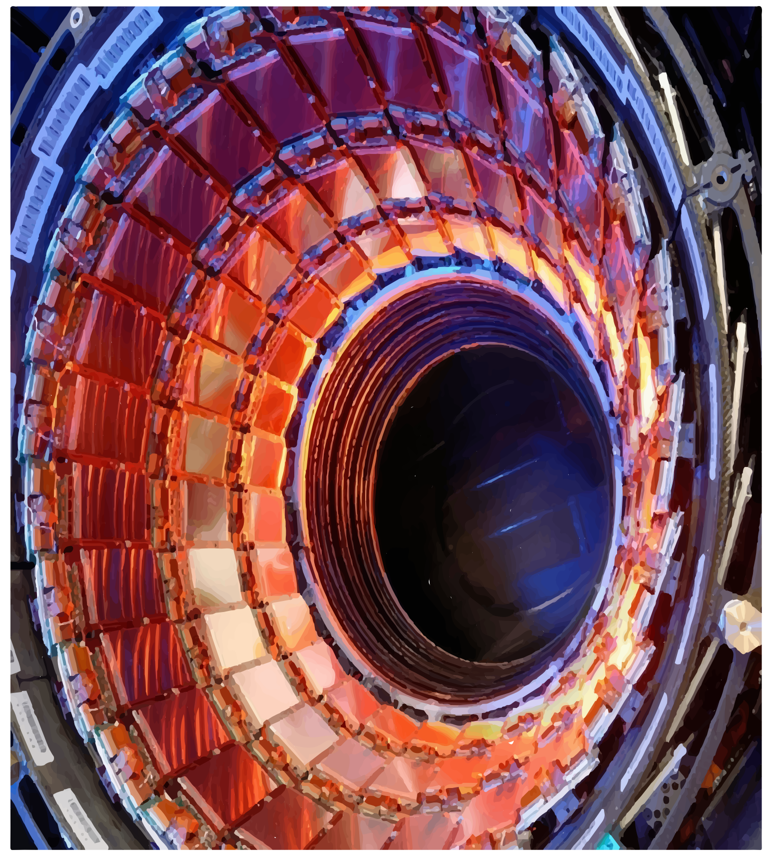


Hadronization ~~models~~
Use Field theoretic approaches

~~Energy scale uncertainty~~
Exciting measurement prospects

Top quark decay
~~Simulations~~
Analytically resum

Standard candle



Conclusions

- Enable complete calibration mechanism with the W as a standard candle: can directly measure the top mass in a well-defined short distance scheme in terms of m_W better than 500 MeV.
- Wealth of exciting directions for phenomenology, calculations and measurements with EECs
- Measurement is robust against the environment and is statistically feasible.

Thank you!