Precision Top Mass Using Energy Correlators

Aditya Pathak

QCD@LHC, Freiburg, Oct 24

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
2407.12900: J. Holguin, I. Moult, AP, M. Procura, R. Schöfbeck, D. Schwarz
[In progress] J. Holguin, K. Lee, I. Moult, AP, M. Procura

Outline

- Precision Top Mass: A notorious challenge
- The collinear and back-to-back limits of EEC
- EECs on boosted top quarks
- The Standard Candle approach
- Demonstrating Robustness and Experimental Feasibility

A longstanding problem

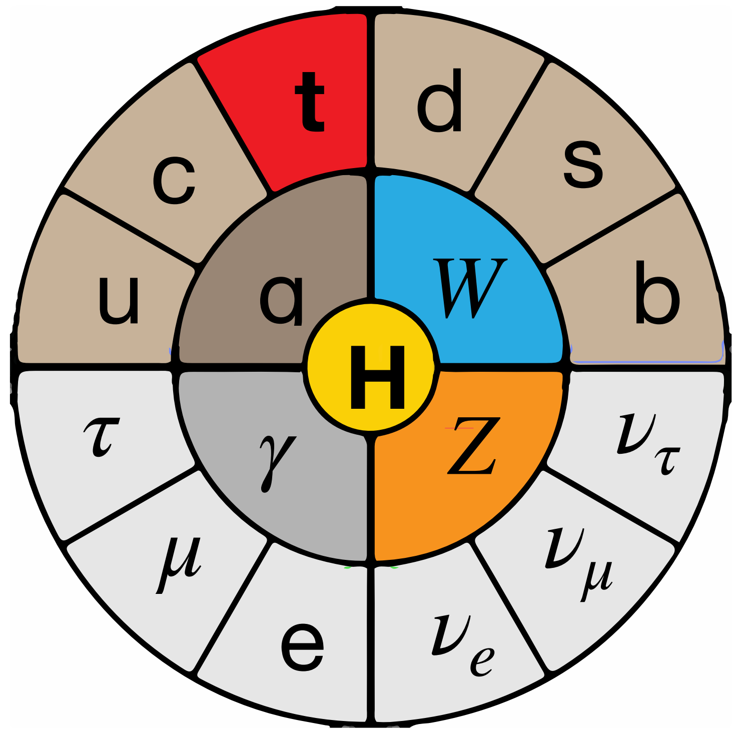
- **Key to new physics:** Precision measurements and consistency tests via *indirect* predictions.

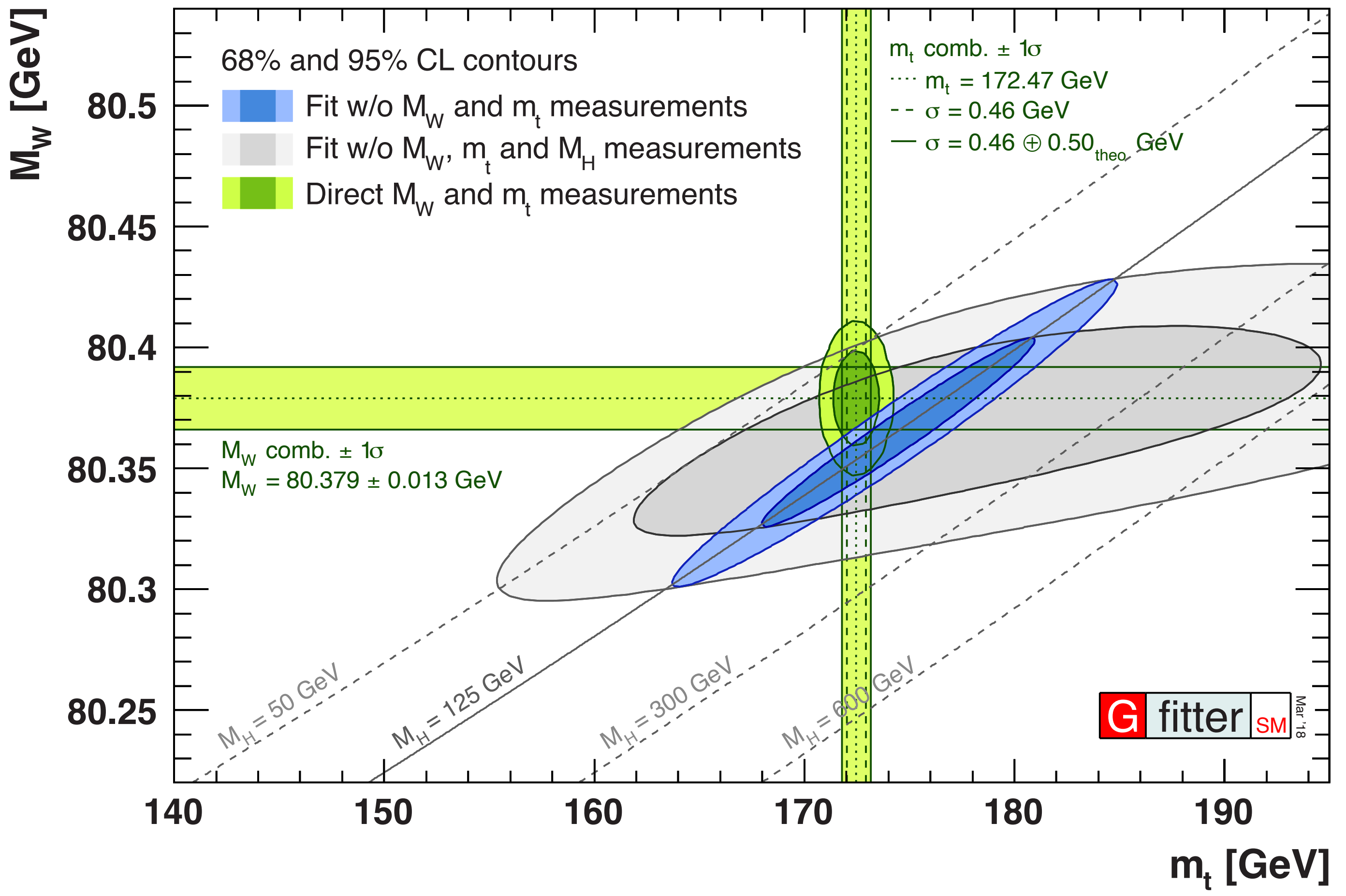
- The masses of the Higgs, W and Z bosons known to < 0.2% precision, but …

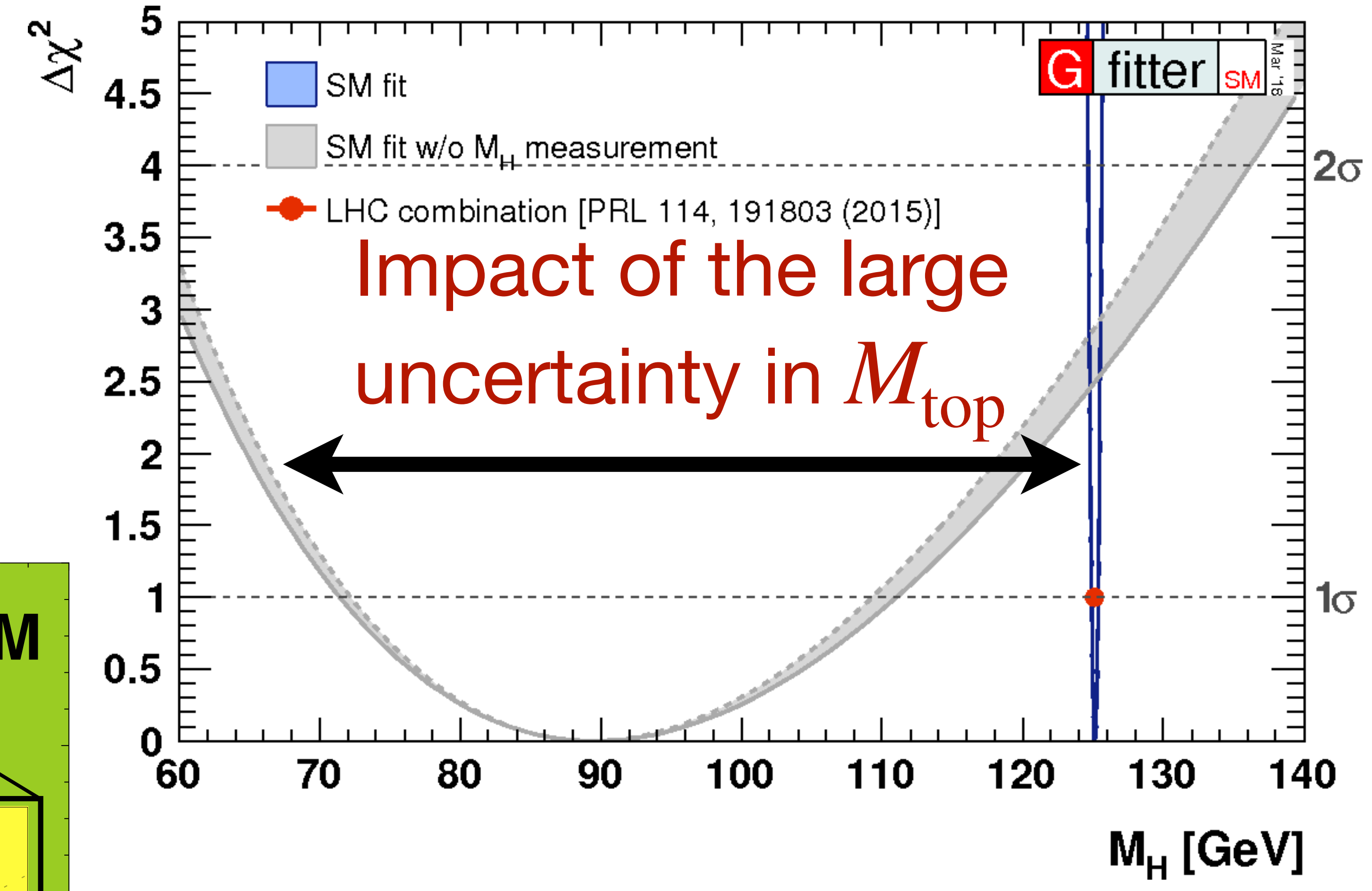
- **Top mass is not as precise as you'd like it to be:**
  - Largest uncertainty $\delta M_W^{m_t} = 4\,\mathrm{MeV}$ from δM_t
  - 20 GeV uncertainty in the indirect M_H from δM_t

- Top mass precision is critical for EW vacuum stability analyses.
  - Need sub-percent ($< 1\,\mathrm{GeV}$) M_{top}: a longstanding problem for two decades.

- **What is halting the progress?**

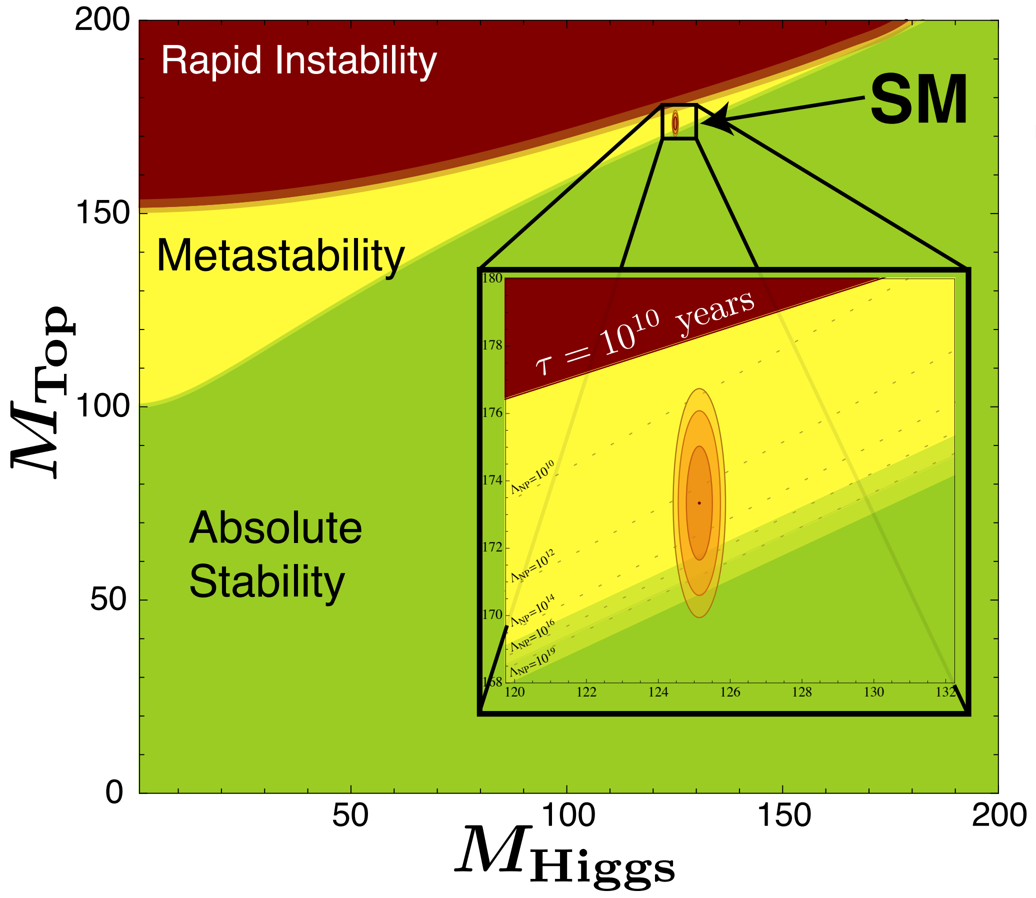






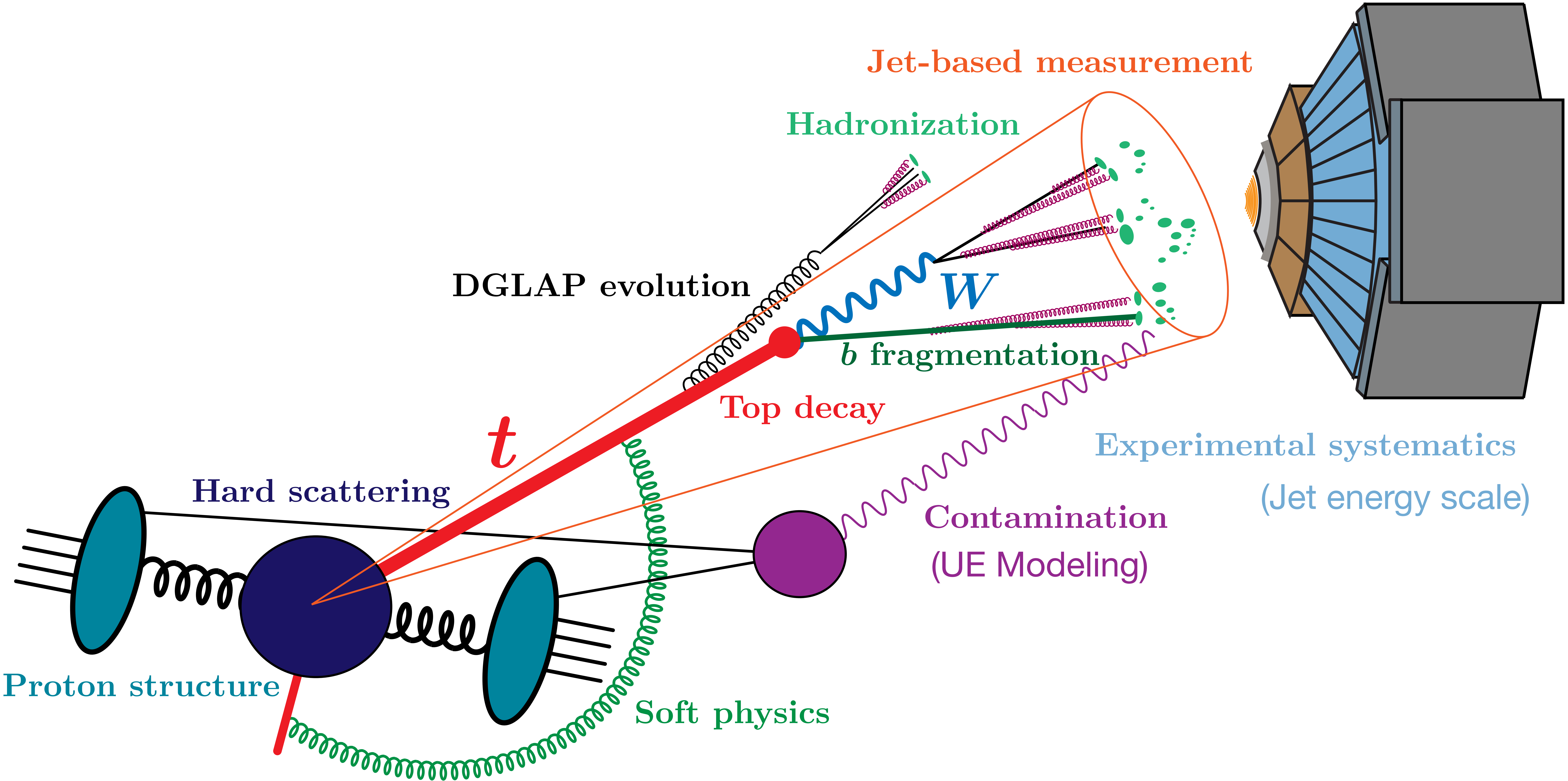
Impact of the large uncertainty in M_{top}

GFitter group



Andreassen, Frost, Schwartz 2014

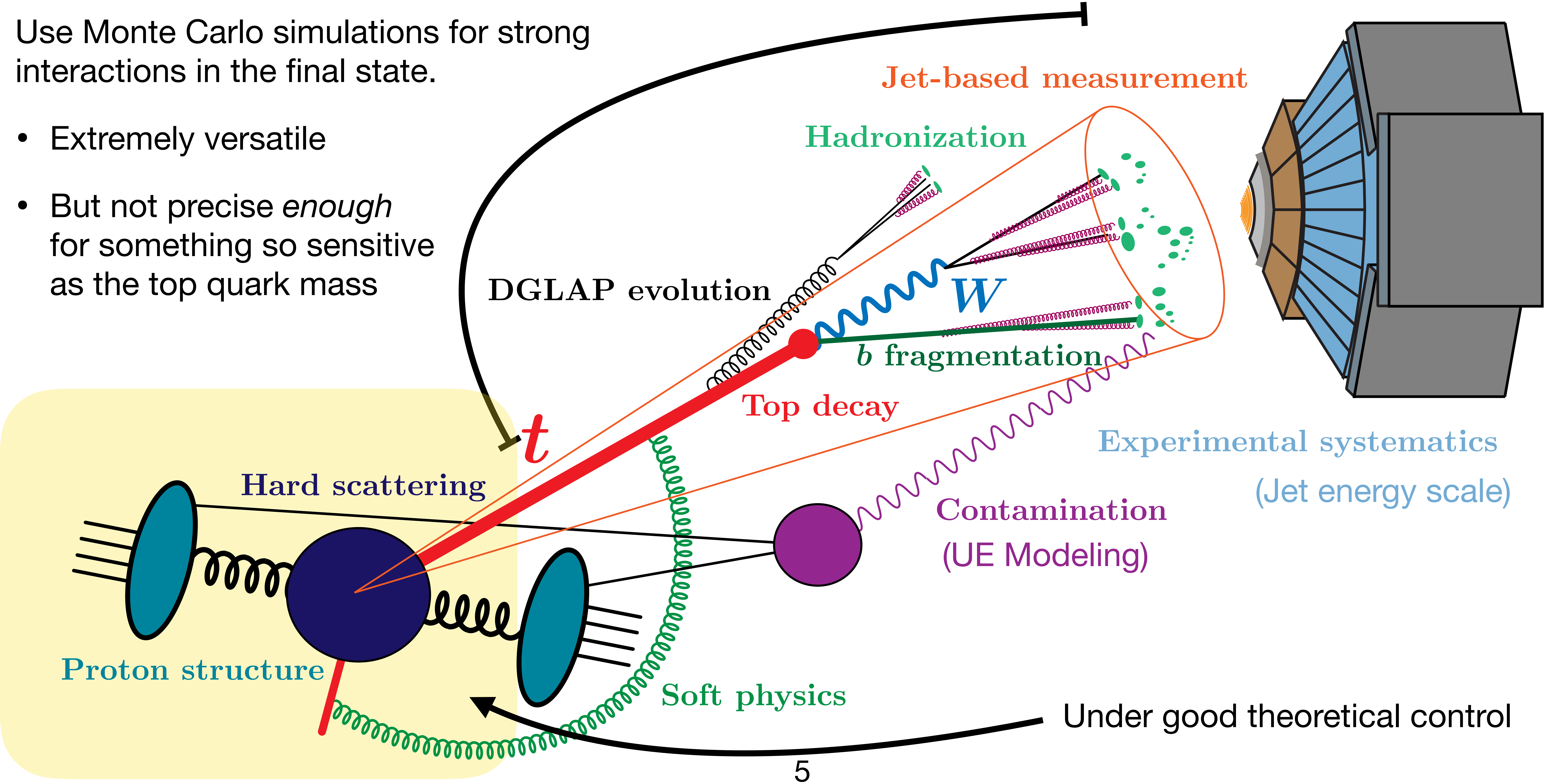
The current status of collider QCD



The current status of collider QCD

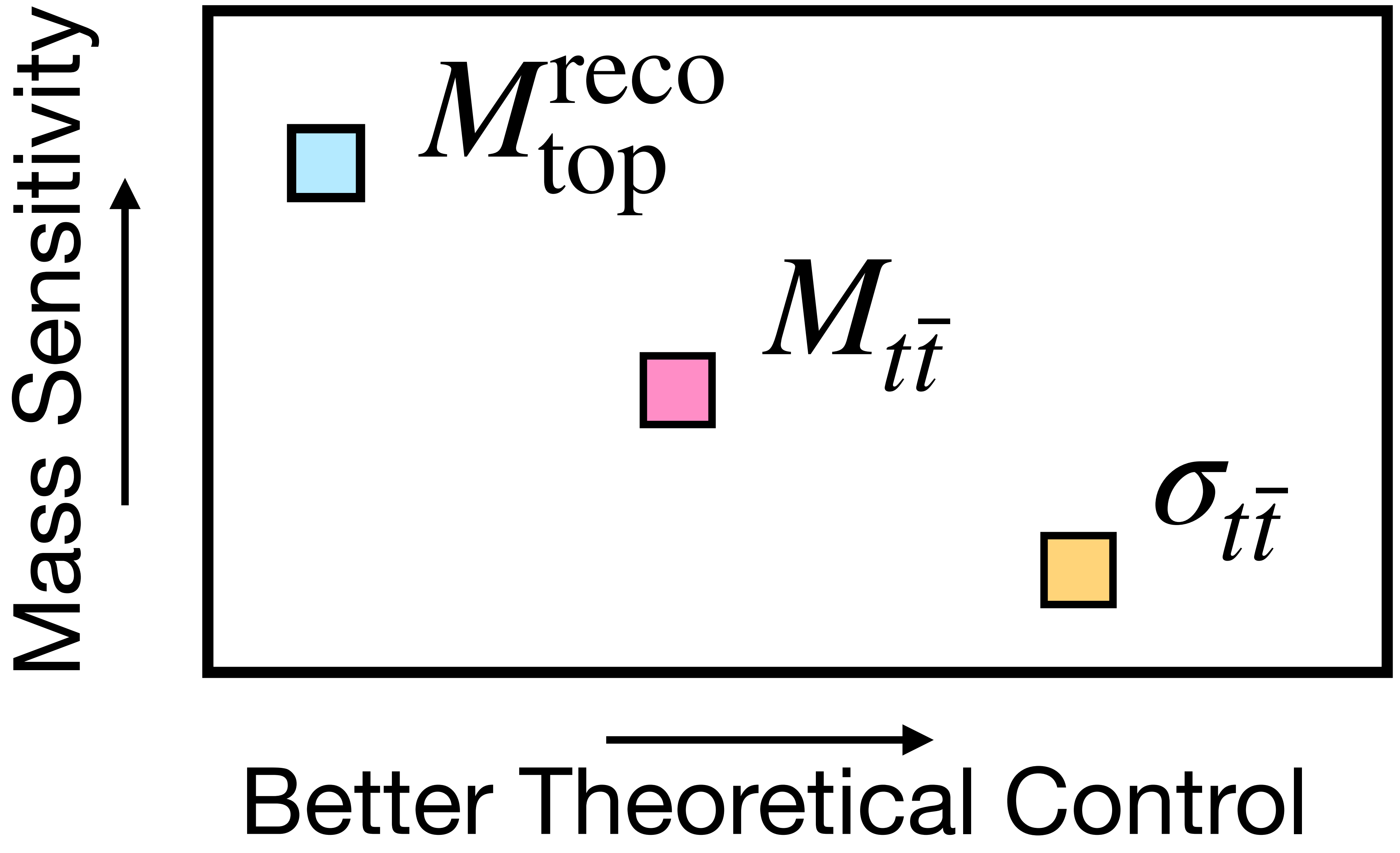
Use Monte Carlo simulations for strong interactions in the final state.

- Extremely versatile
- But not precise *enough* for something so sensitive as the top quark mass



Problems with top mass measurements

Current Paradigm:



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

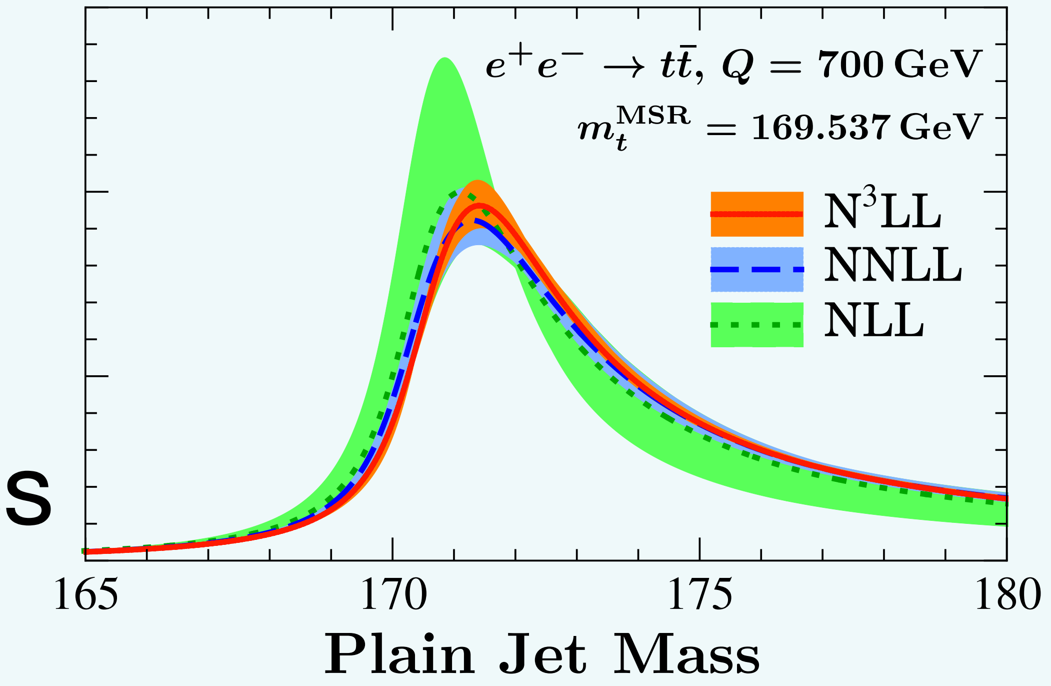
$$\Delta m_t^{\text{pole}} = \pm 0.7\,\text{GeV}$$
$$+\mathcal{O}(1\,\text{GeV})$$ (soft physics)

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

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

Recent progress*

Direct top mass using jet substructure:



- High-order analytical resummation of jet mass in the boosted region.

Bachu, Hoang, Mateu, AP, Stewart 2012.12304

- Calibrate m_t^{MC} and hadronization models

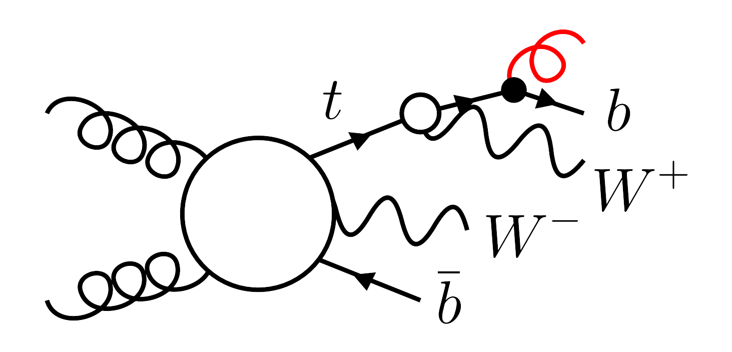
Dehnadi, Hoang, Jin, Mateu 2309.00547
Hoang, Jin, Plätzer, Samitz 2404.09856
Ferdinand, Lee, AP 2301.03605

- Direct extraction using soft drop jet mass

Hoang, Mantry, AP, Stewart 1708.02586

Fixed order matching:

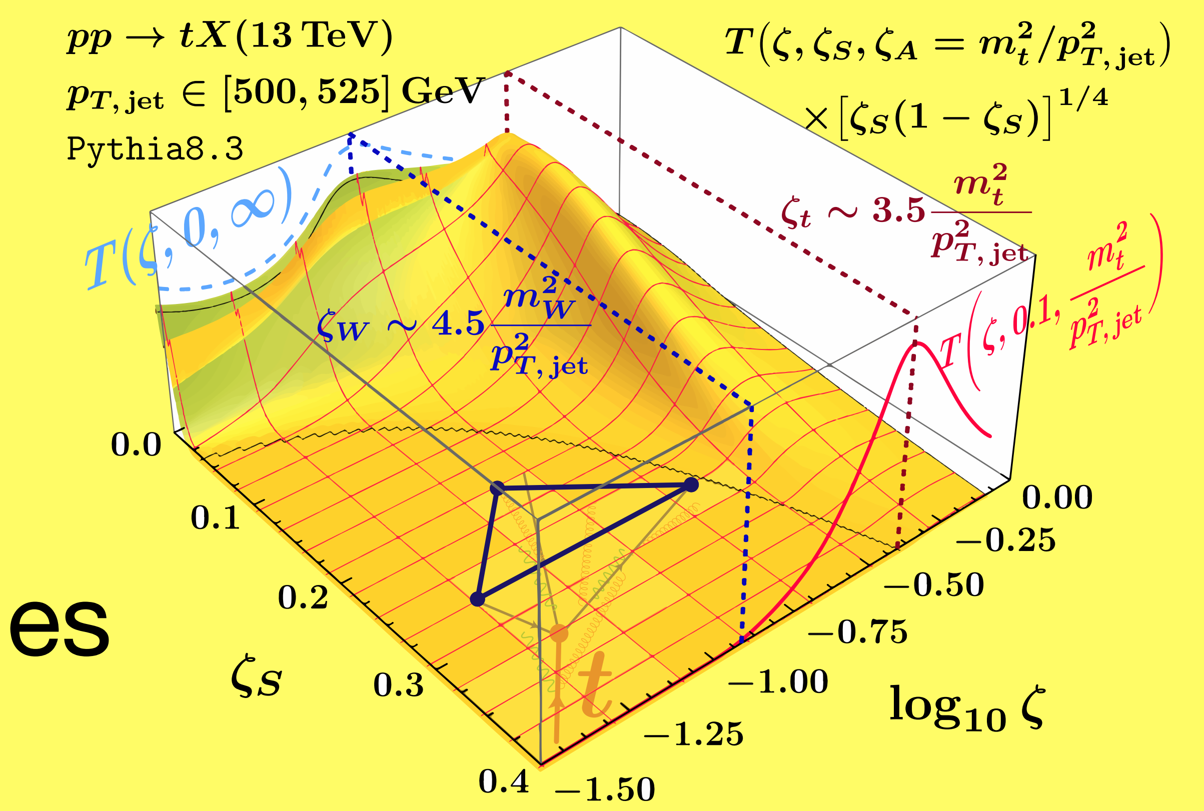
- Consistent treatment of width effects
- Non-resonant Wb final state



Ježo, Lindert, Pozzorini 2307.15653

Top mass determination using EECs (this talk):

- A new indirect top mass measurement proposal
- Motivating new Energy Correlators-based observables



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

"Pole Mass" measurements:

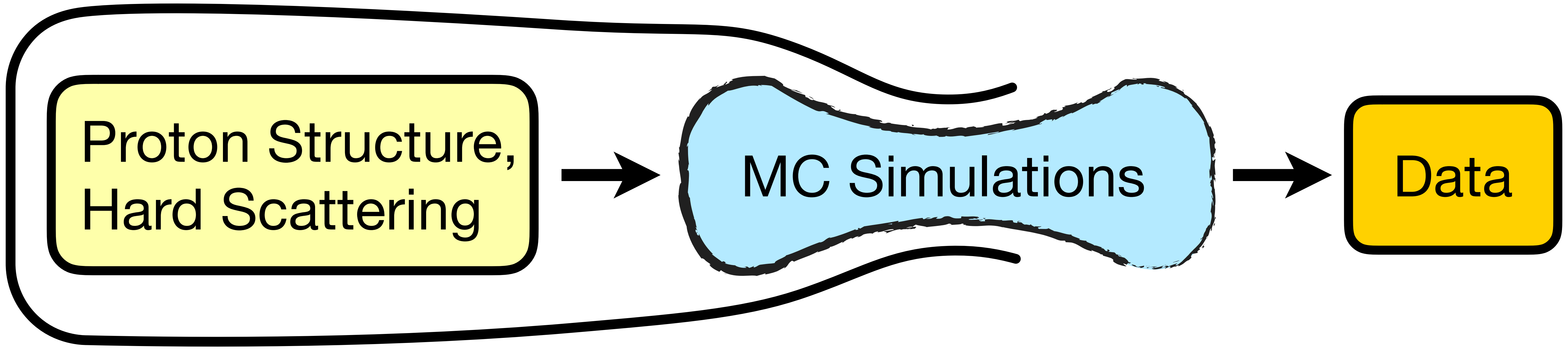
- Running mass scheme for kinematic distributions

Mäkelä, Hoang, Lipka, Moch 2341.03546

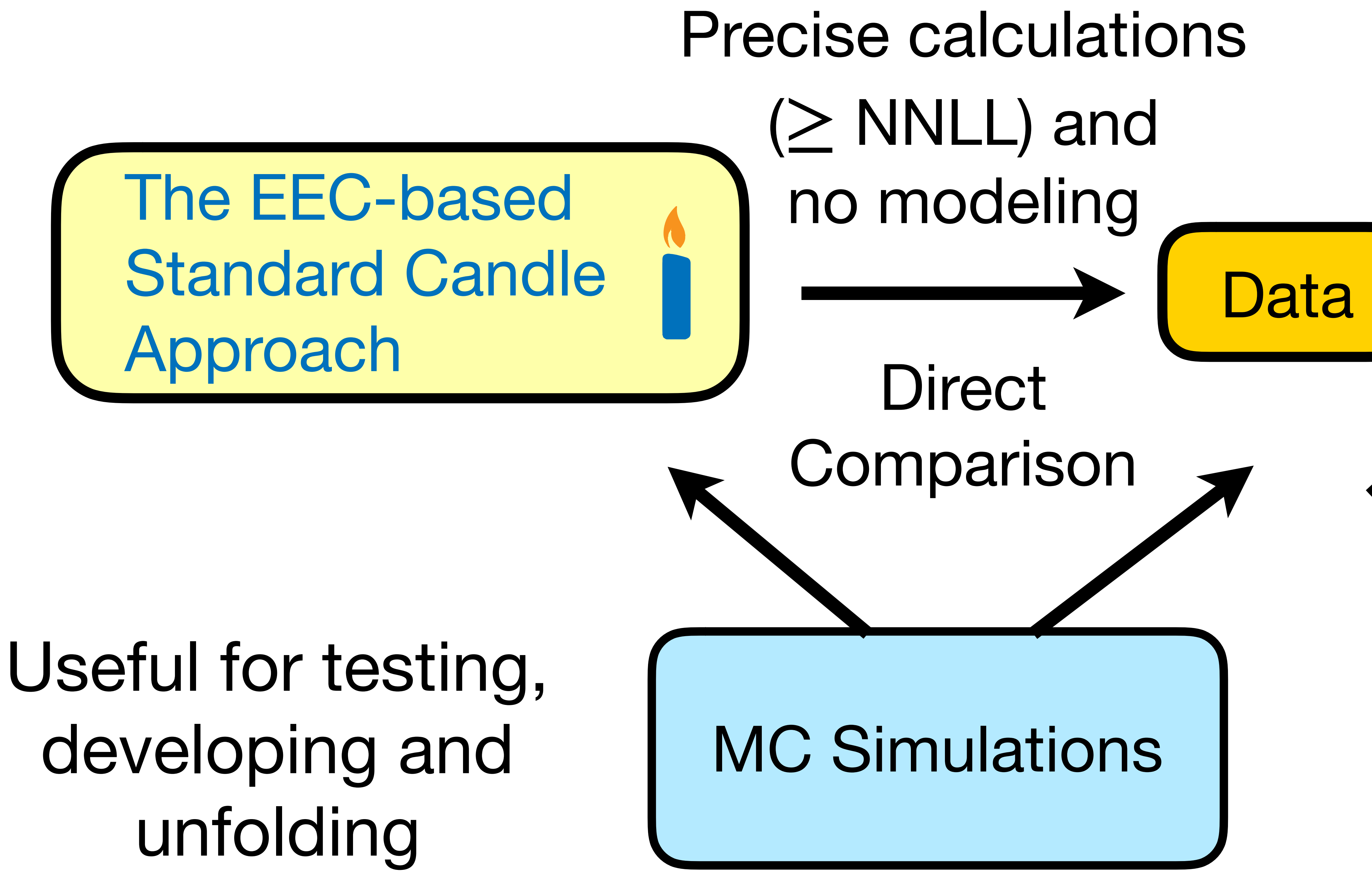
*By no means an exhaustive list!

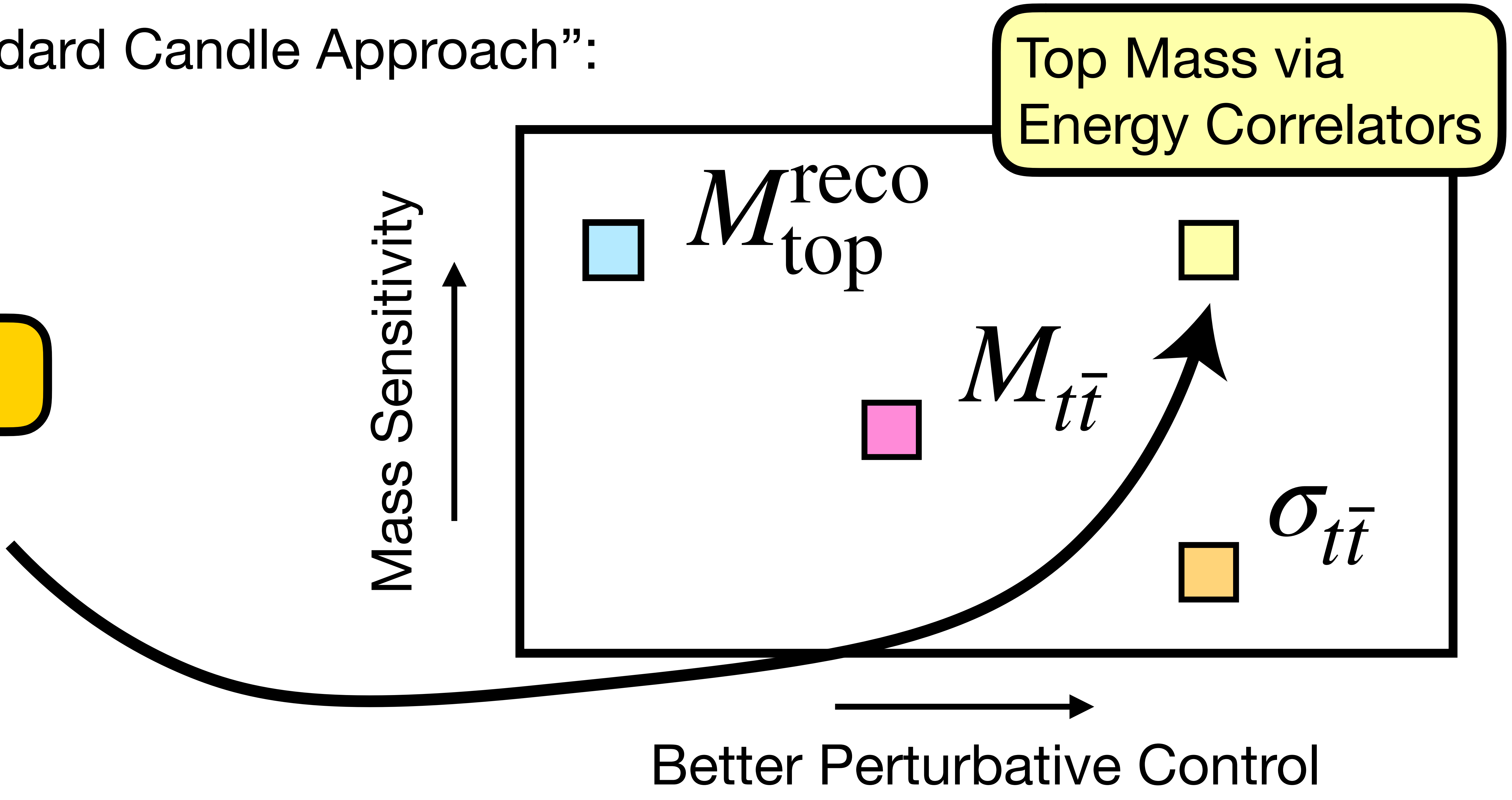
The Standard Candle Approach

The over-reliance of current approaches on MC simulations presents a bottleneck that limits precision.



Proposal: A new energy correlators-based “Standard Candle Approach”:





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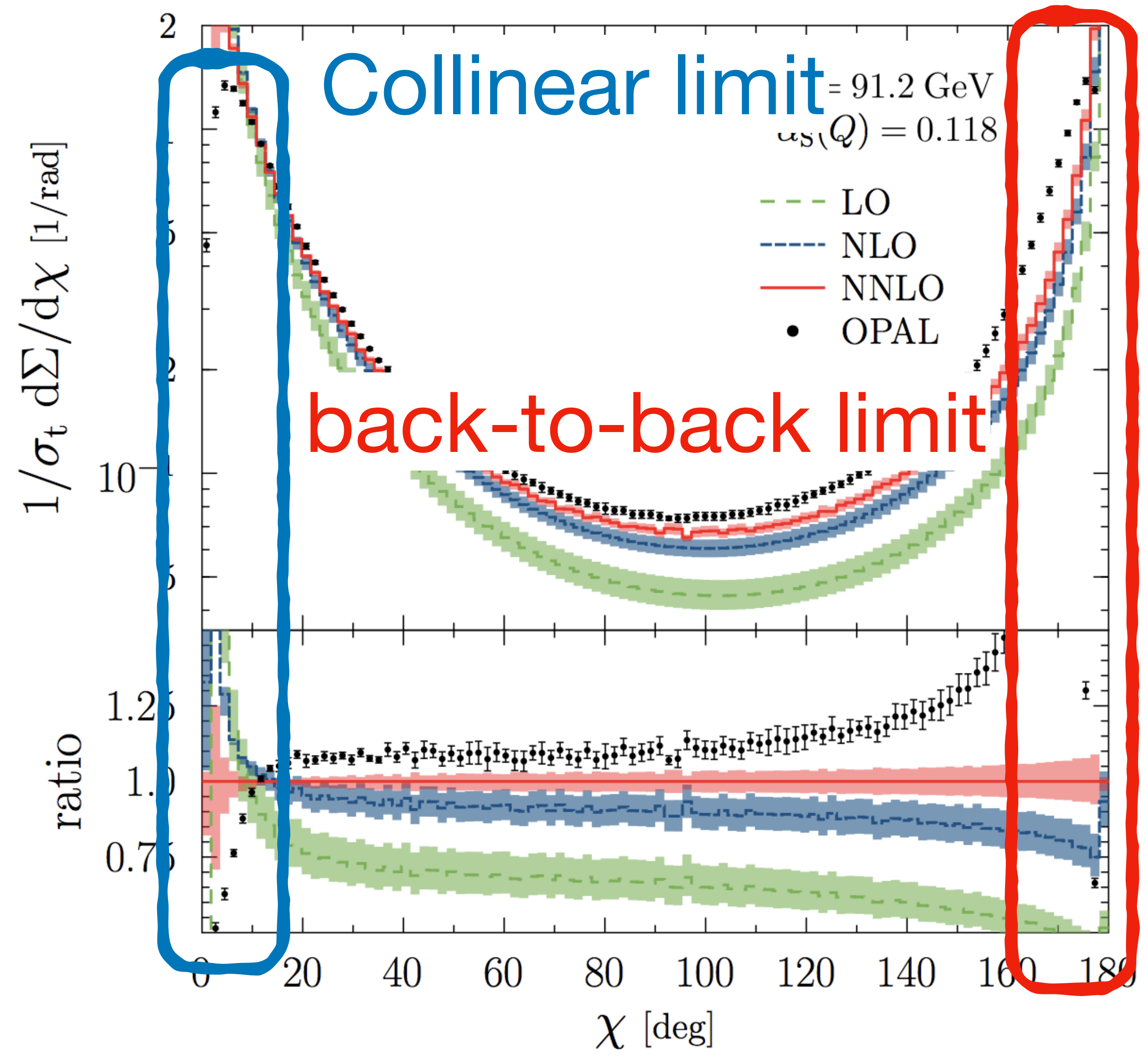
Jet substructure as correlation functions

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

Basham et al. 1978

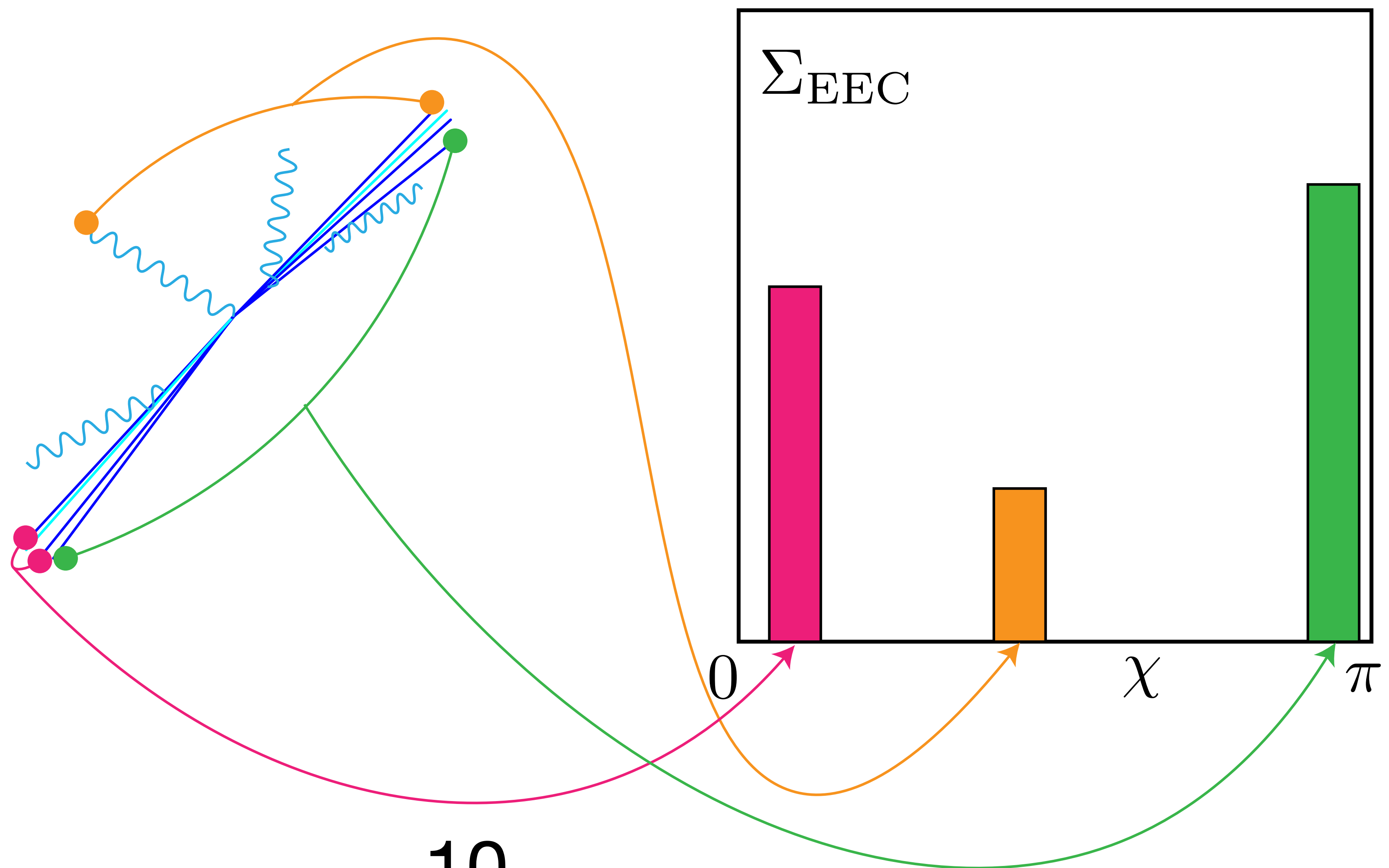
$$\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\chi} = \sum_{ij}\int \frac{E_i E_j}{Q^2}\delta(\vec{n}_i\cdot\vec{n}_j - \cos\chi)\mathrm{d}\sigma$$



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:



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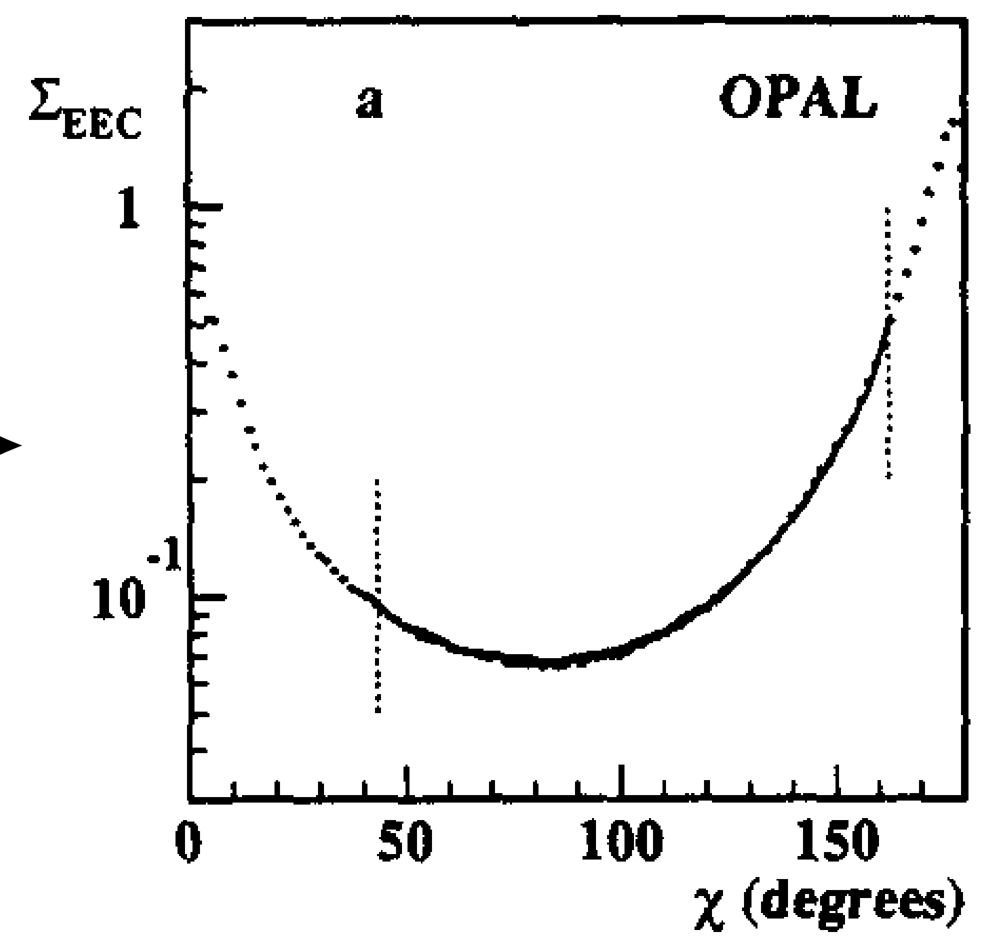


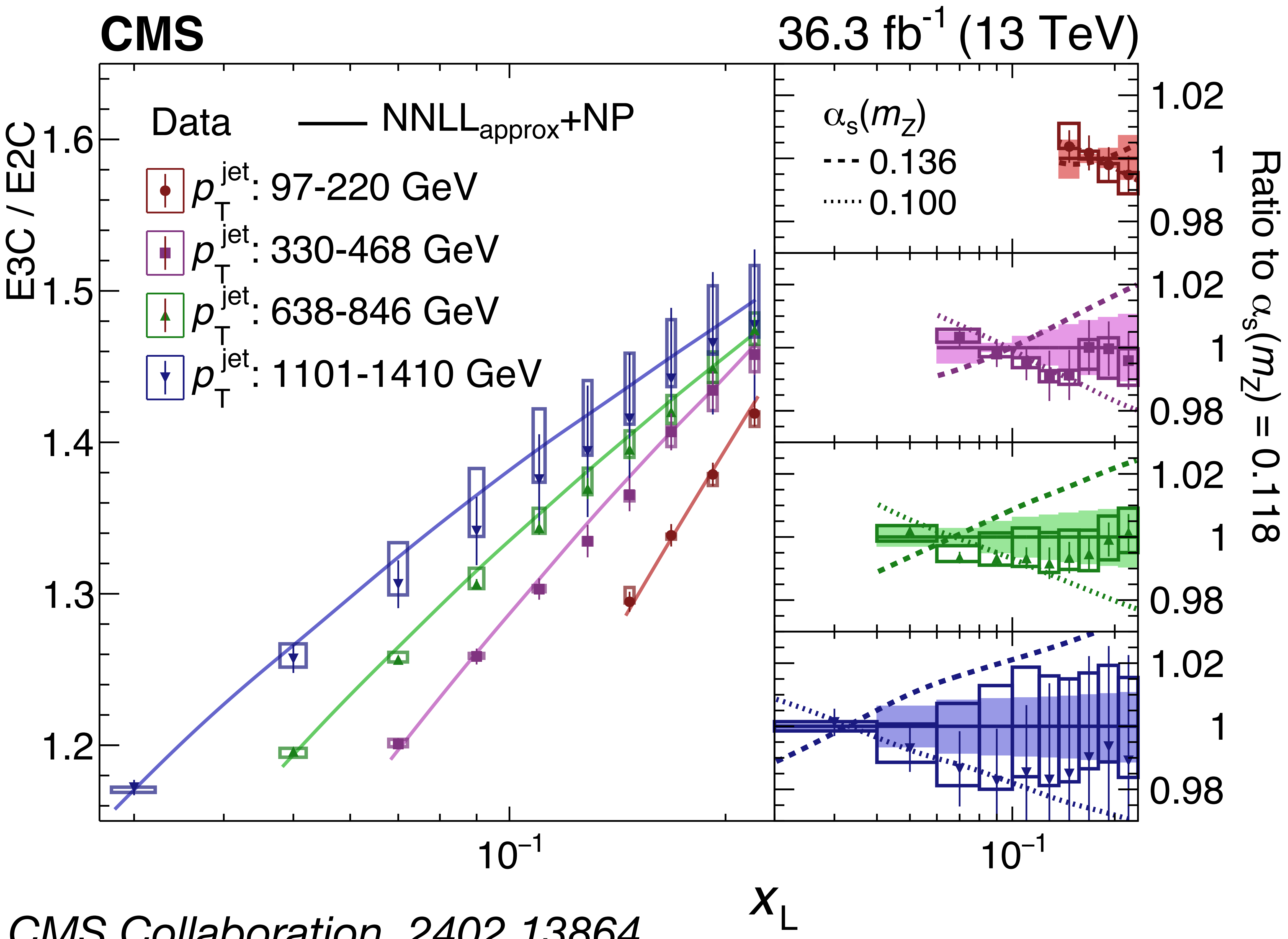
[Opal collboration, Z. Phys. C59 (1993) 21]

Universal behavior in the collinear limit

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

Dixon, Moult, Zhu 2019

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



CMS Collaboration, 2402.13864

Strong coupling determination:

- 4% precise (the best jet substructure-based) α_s extraction from E3C/E2C ratio by CMS
- EECs enable a field-theoretic analysis of hadronization effects:

Same as thurst!

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

Lee, AP, Stewart, Sun 2405.19396
(Also see Chen, Monni, Xu, Zhu 2046.06668)

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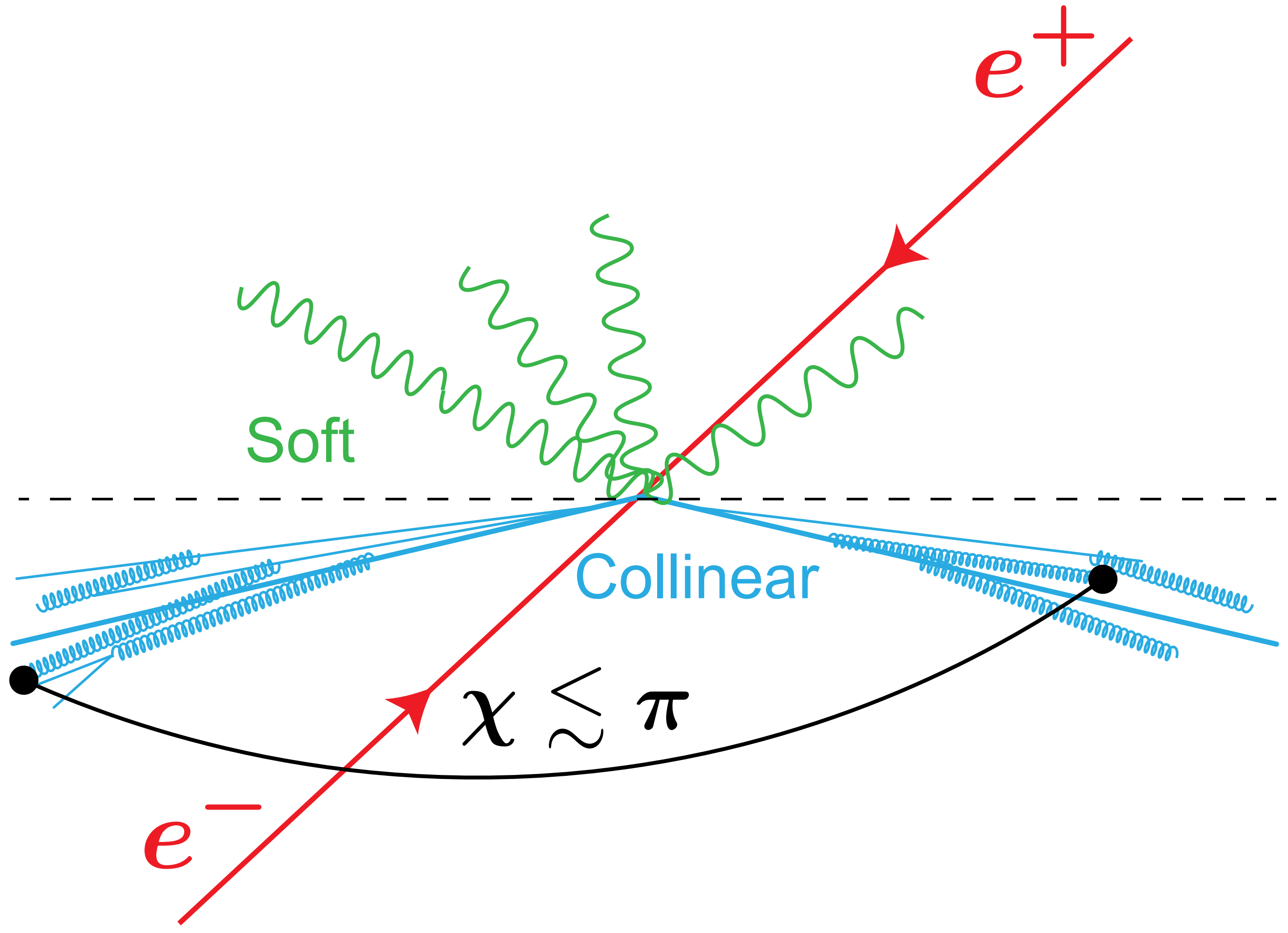
The back-to-back region of EEC

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:

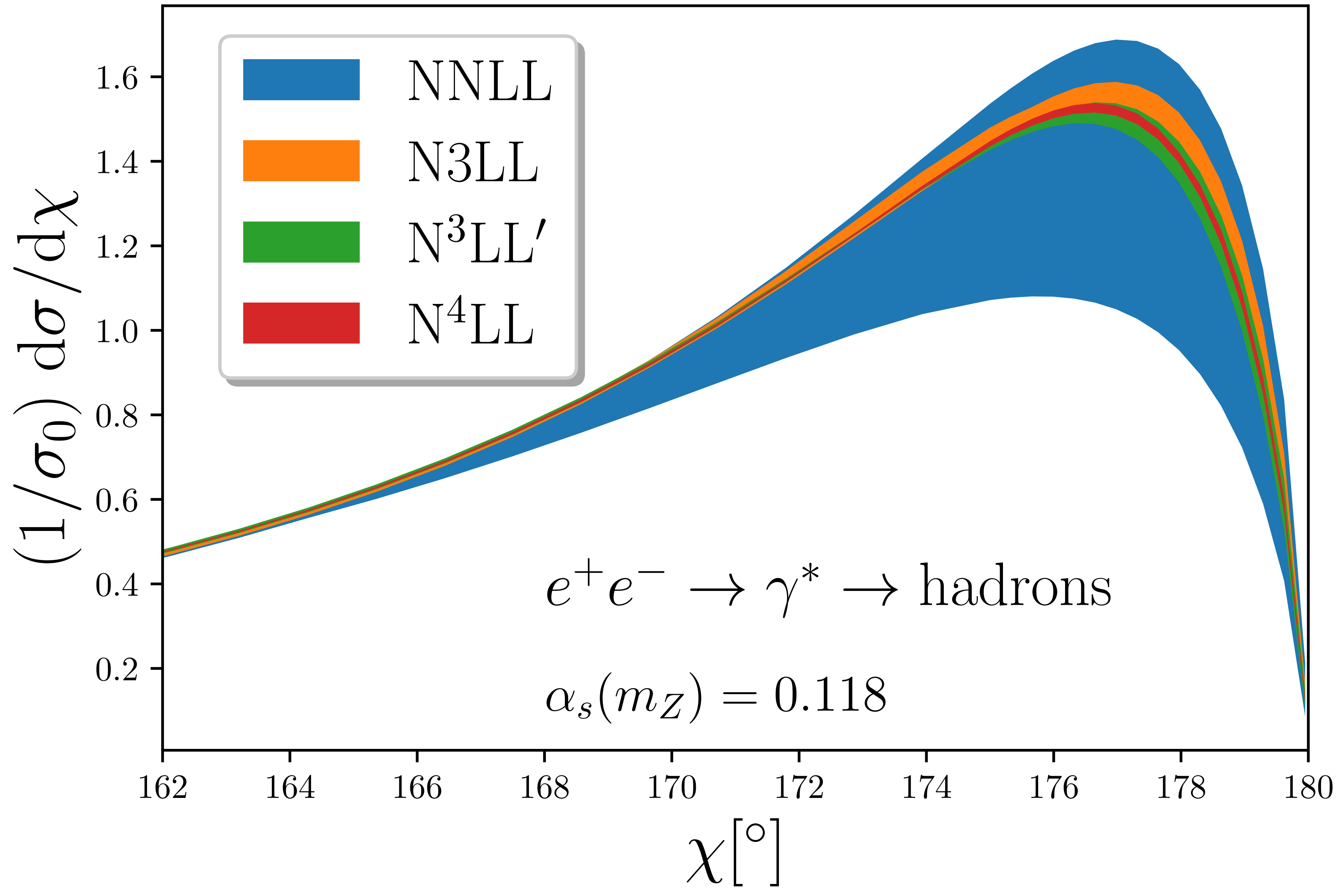
Moult, Zhu 2018

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

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



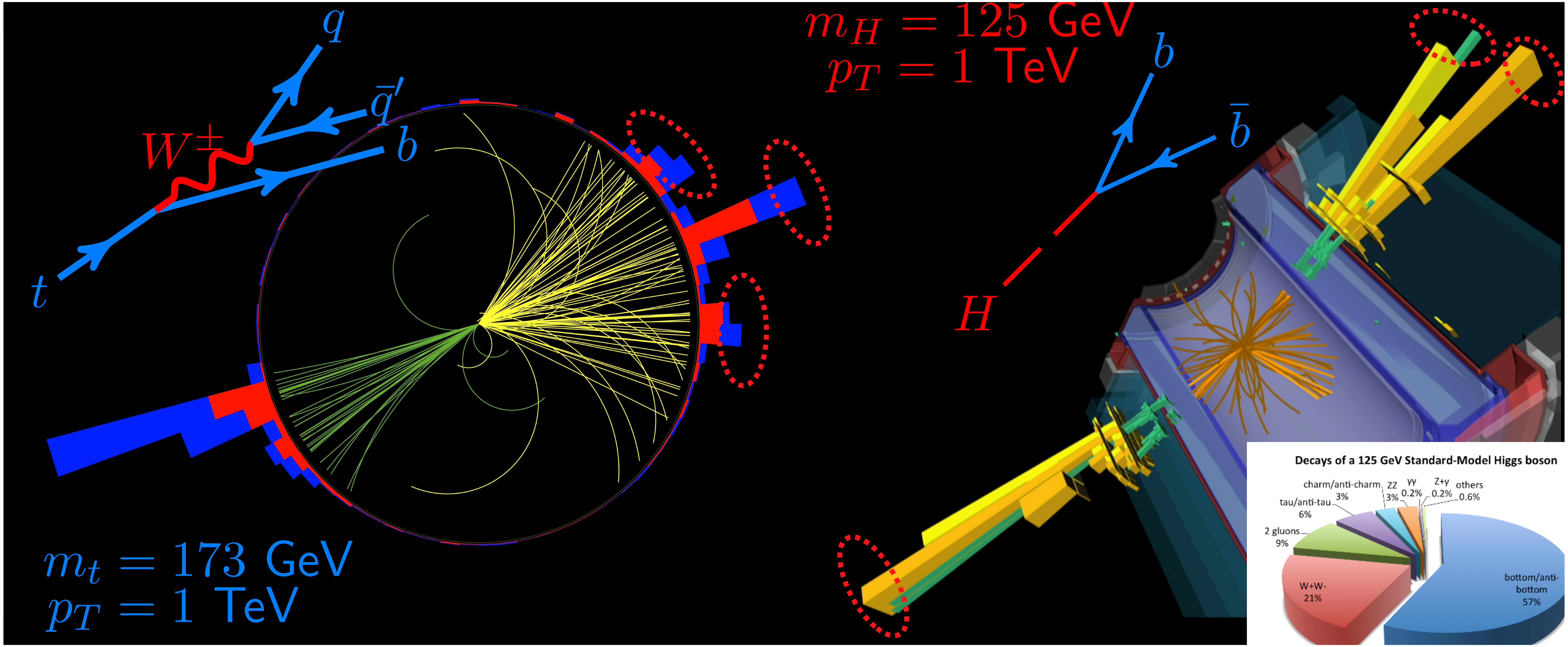
Moult, Zhu, Zhu 2022
Duhr, Mistelberger, Vita 2022



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

Is the 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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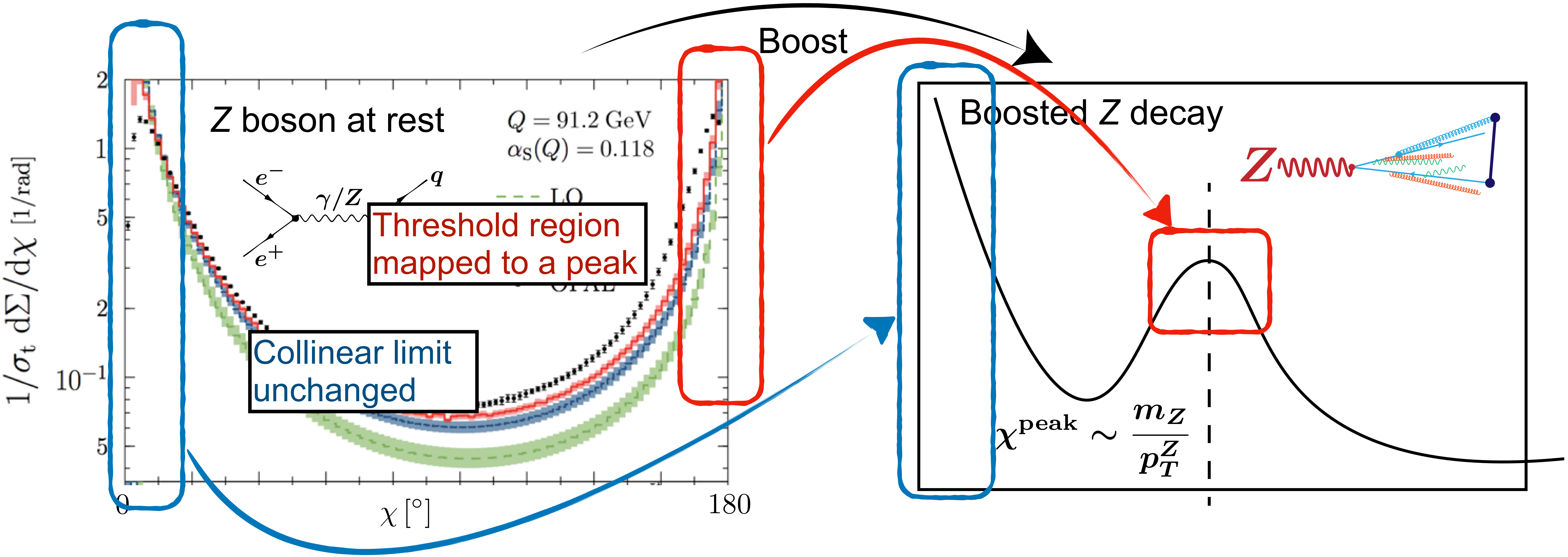

Threshold region mapped to a peak

Collinear limit unchanged

- 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.

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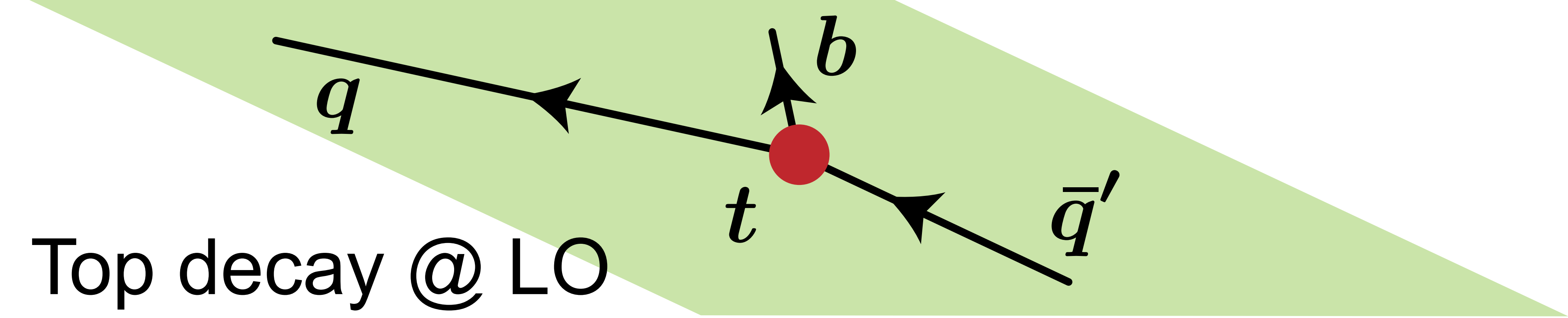
The “back-to-back” version for the *top*

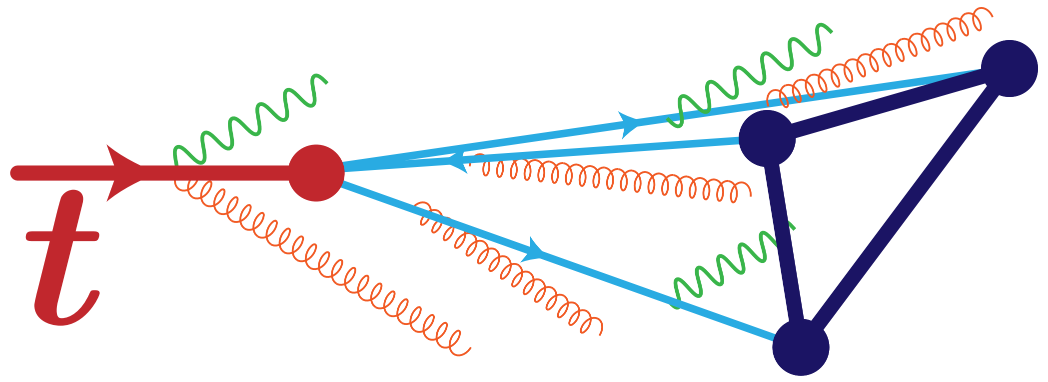
Holguin, Moult, AP, Procura 2022

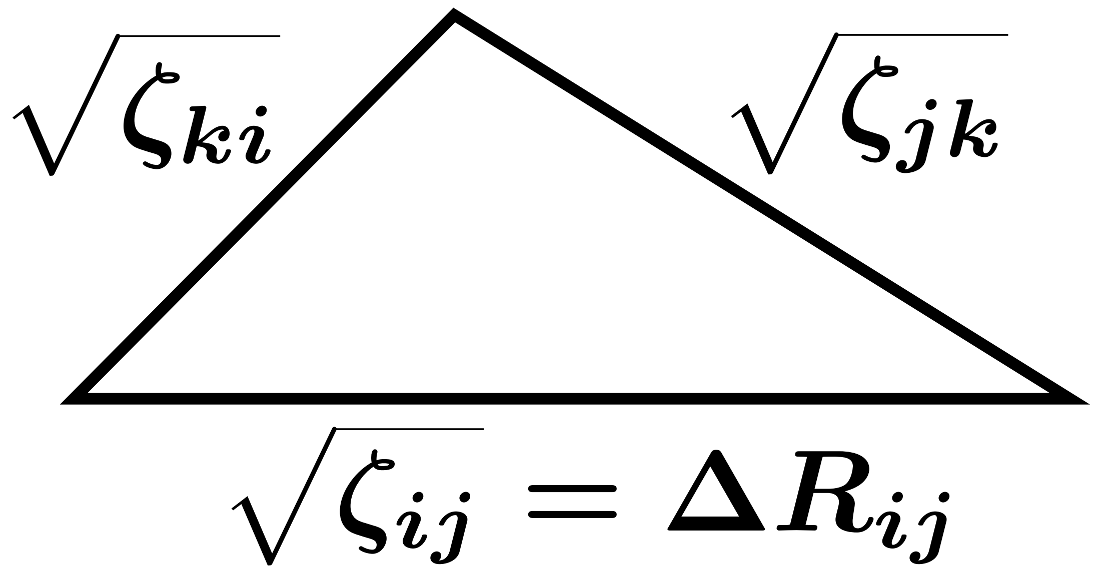
Threshold limit for the top: At leading order the top quark exhibits a near planar decay:



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): $\zeta_t \equiv \sum_{i<j} \zeta_{ij} \approx \left(\frac{m_t}{p_T}\right)^2 \sum_{i<j} \tilde{\zeta}_{ij}$,

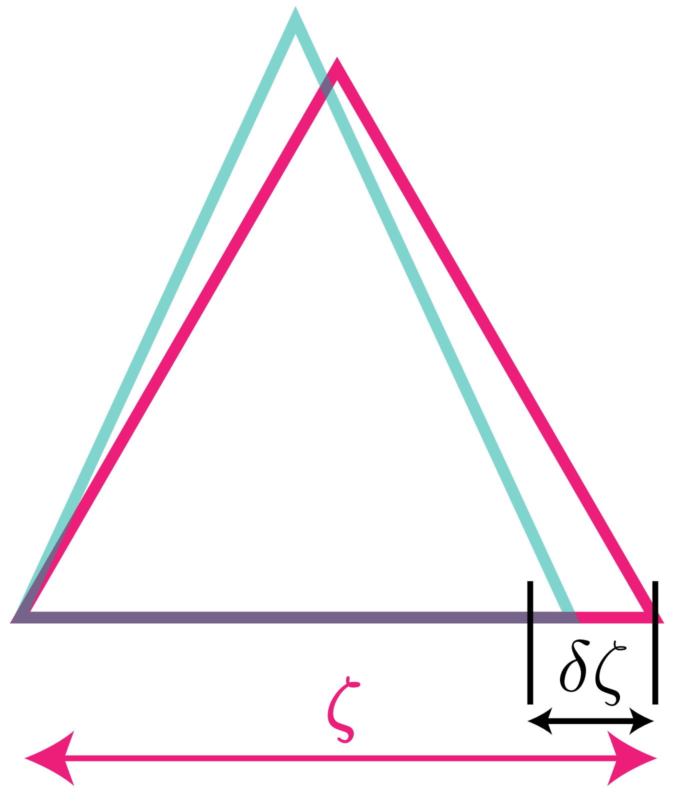
→

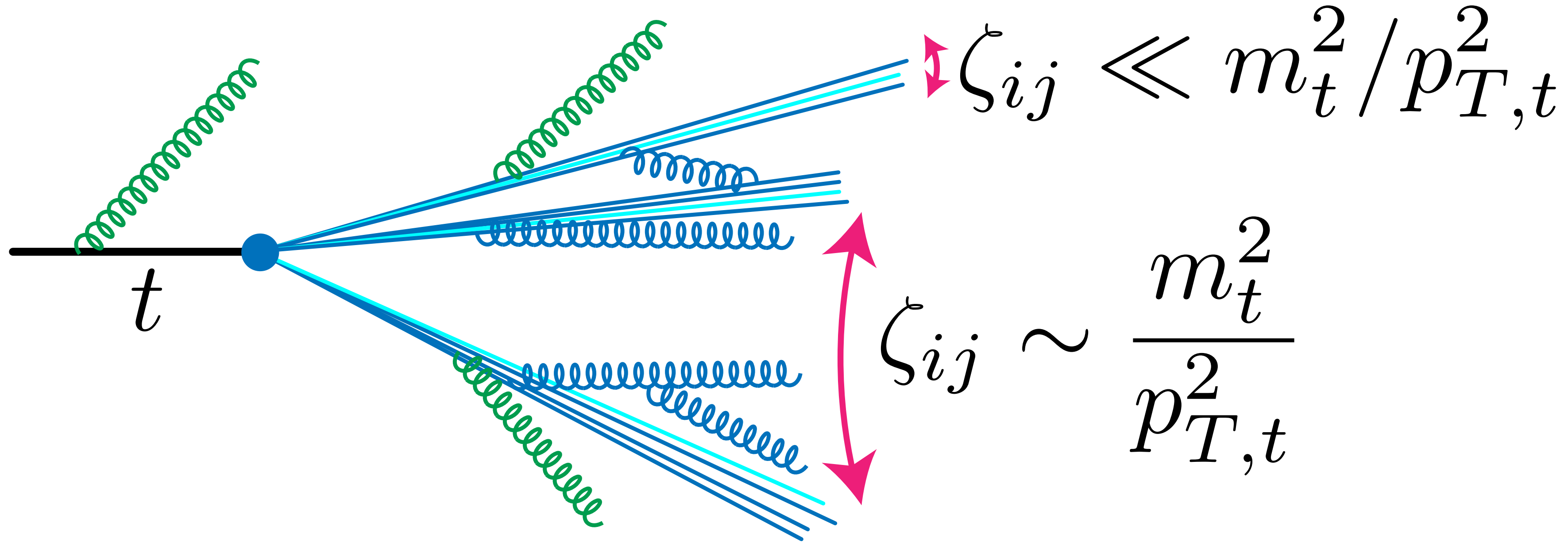
A feature at the characteristic angle $\langle \zeta_t \rangle \approx 3m_t^2/p_T^2$.

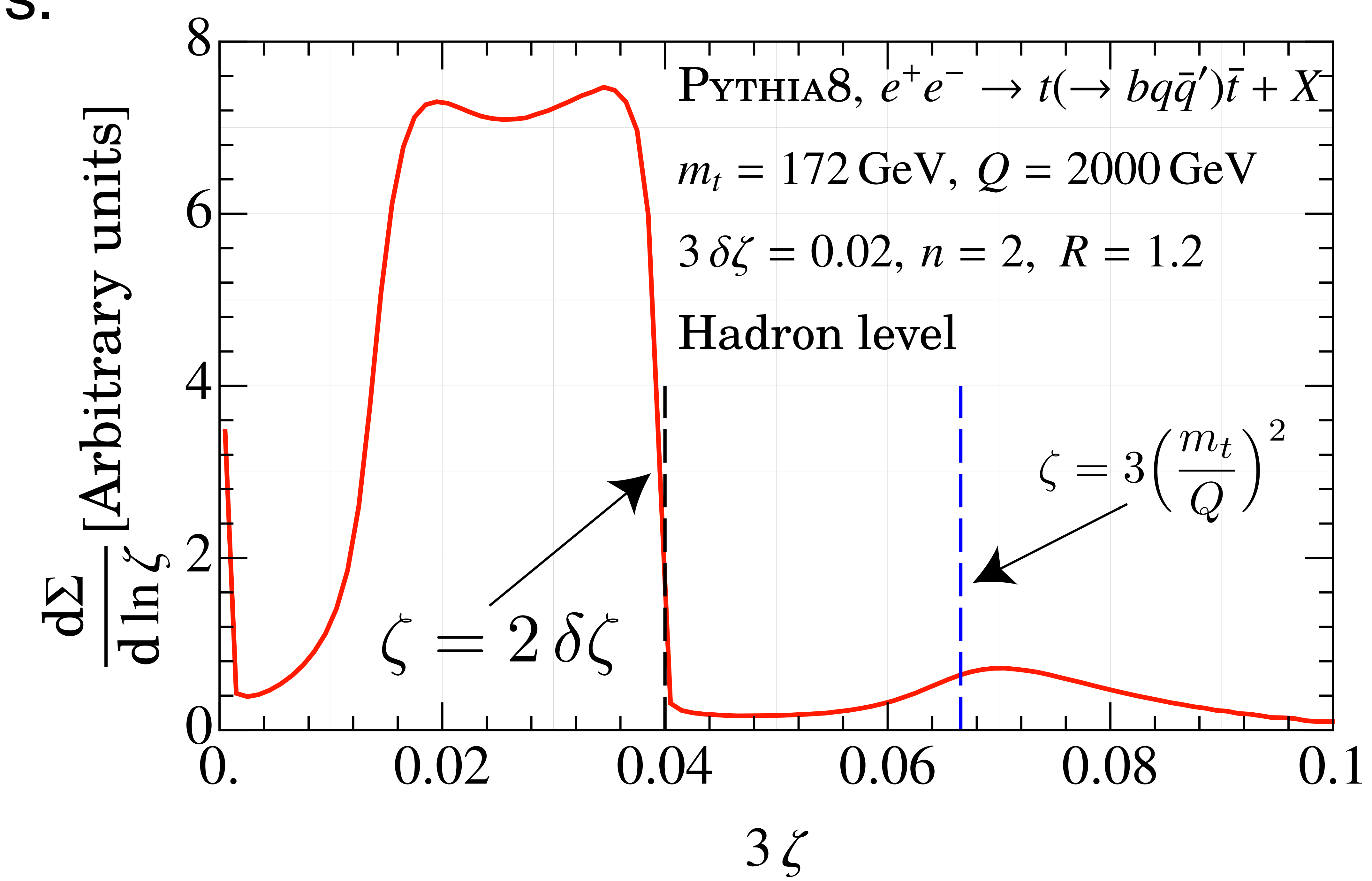
The top quark imprint in EEEC

Holguin, Moult, AP, Procura 2022

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



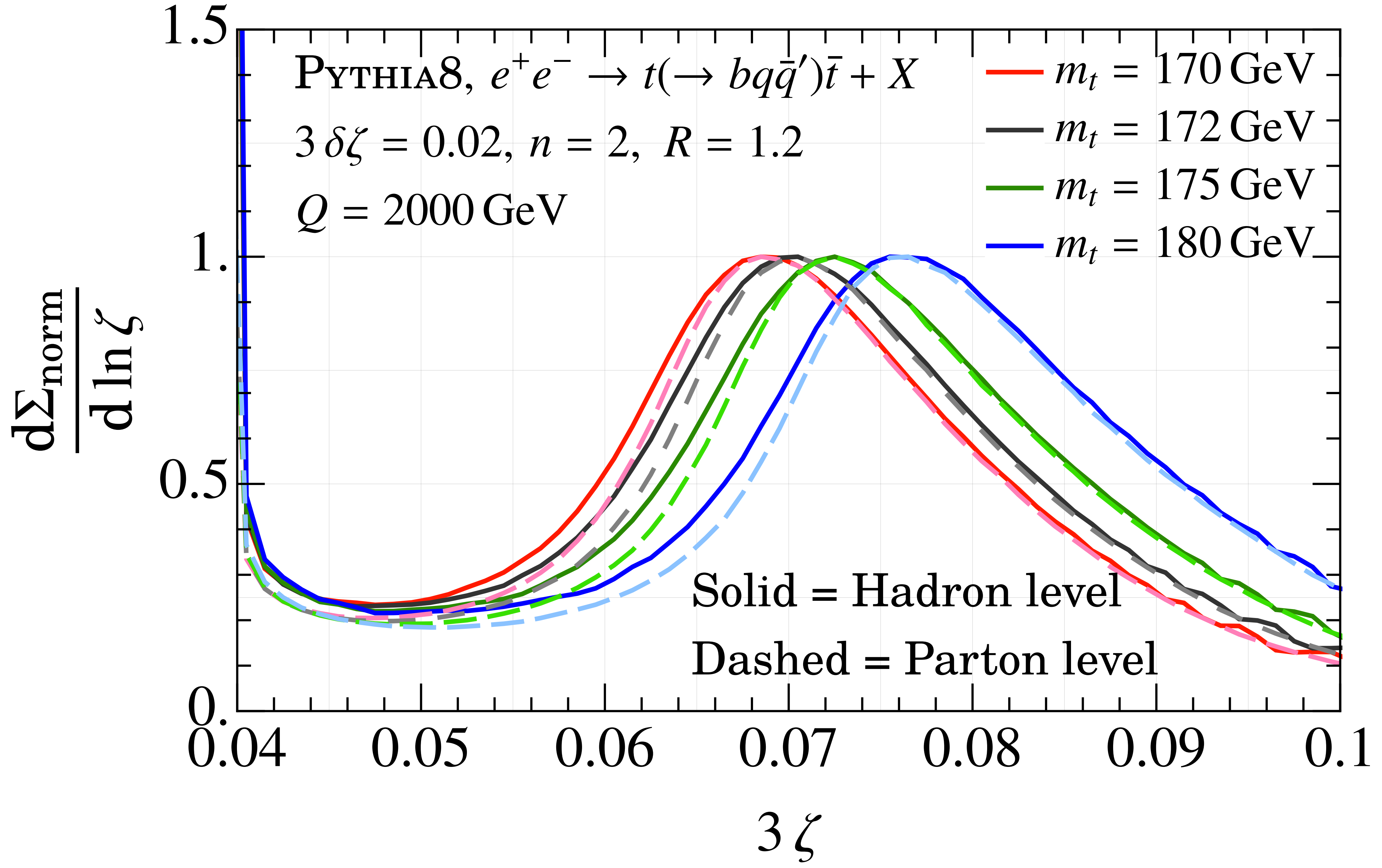


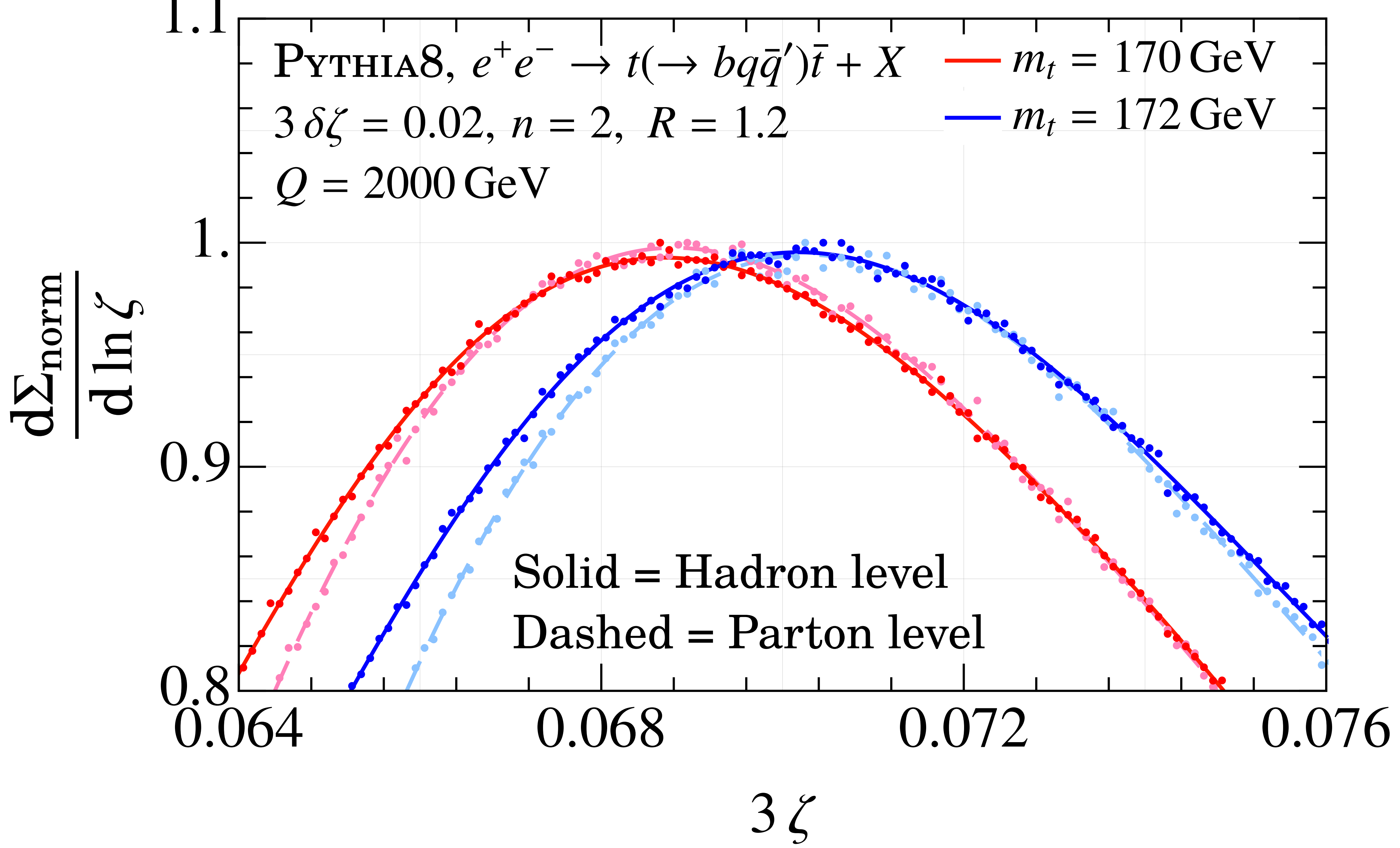


- Distinct peak at $\zeta_t \sim 3(m_t/Q)^2$: peak dominated by hard decay of the top
- Appears at relatively larger angles: Resilient to collinear radiation, $\alpha_s \ln \zeta_t^{\text{peak}} < 1$
- The asymmetry cut $\delta\zeta < m_t^2/p_T^2$ eliminates the otherwise overwhelming contribution of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

Excellent top mass sensitivity and robustness to hadronization

Holguin, Moult, AP, Procura 2022



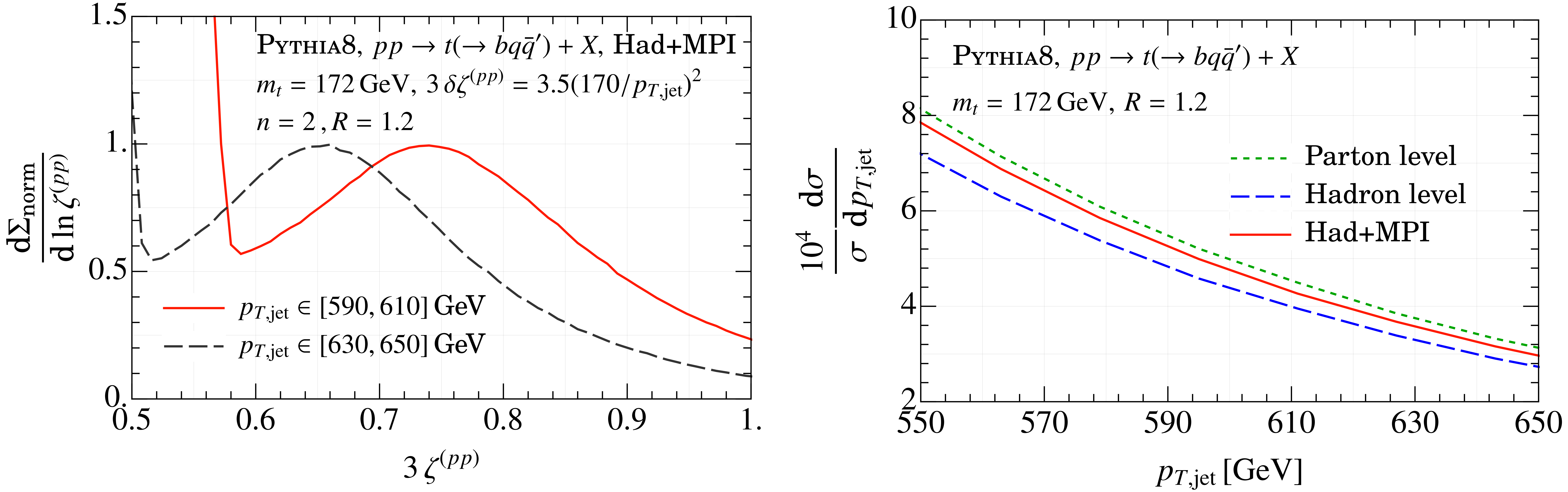


- The imprint of the top quark is extremely sensitive to the top quark mass
- Nonperturbative effects have a very small effect on the peak, $\Delta m_t^{\text{hadr.}} \approx 150 \pm 0.5\,\text{MeV}$
  - This is in a stark contrast to the jet mass with $\sim 1\,\text{GeV}$ shifts in the peak.

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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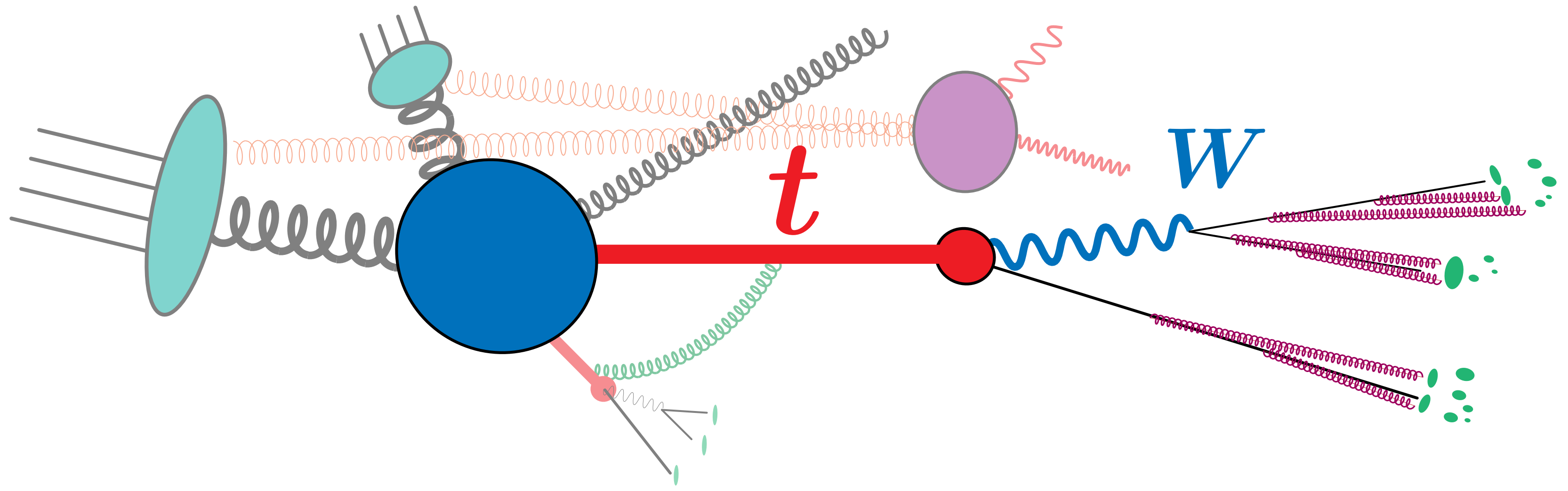
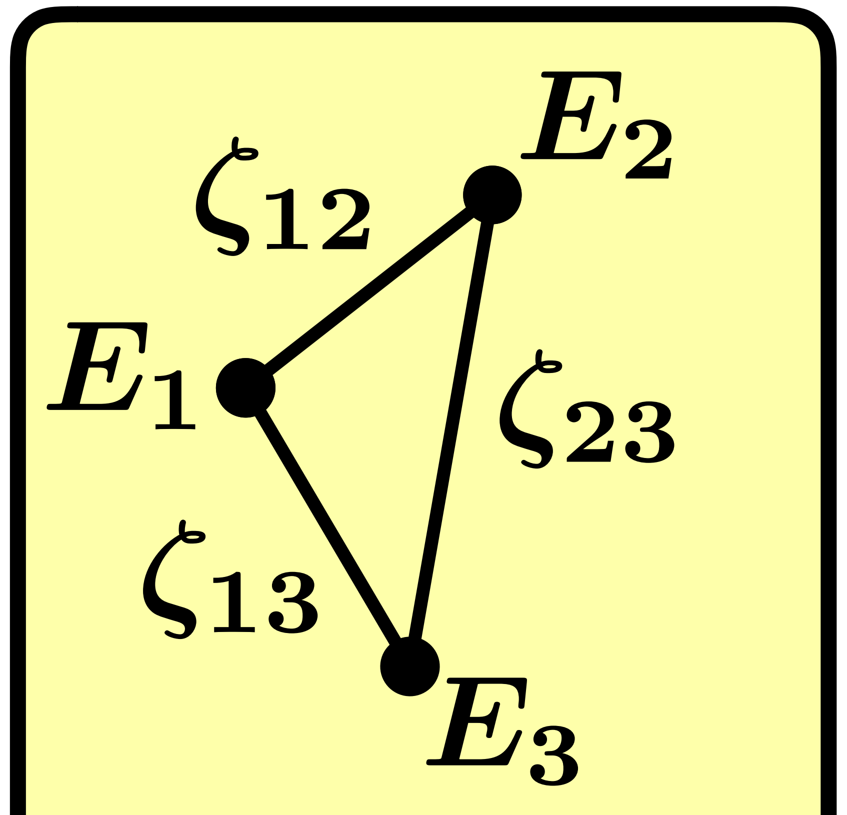
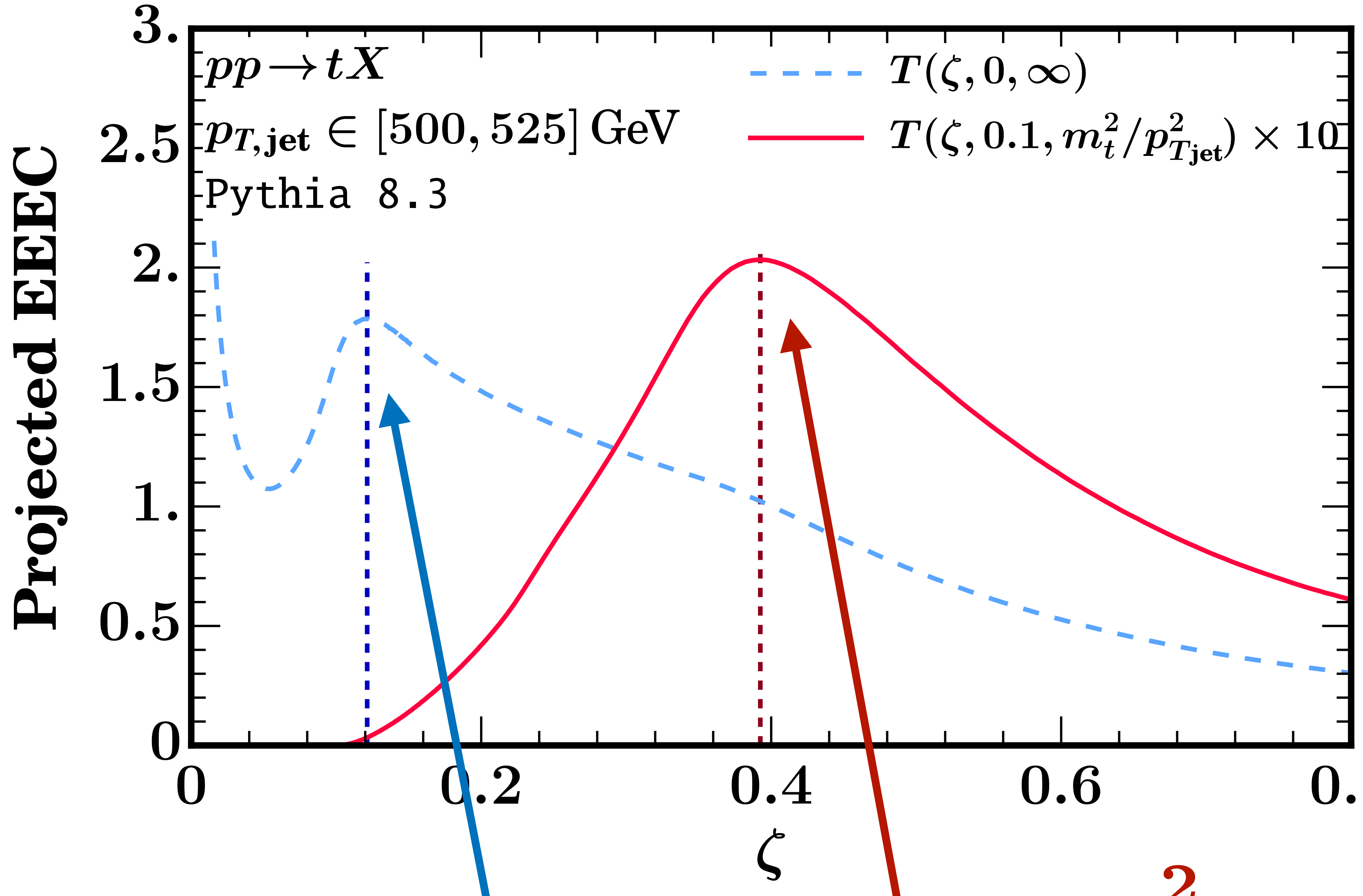
The Standard Candle approach in nutshell





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



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

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

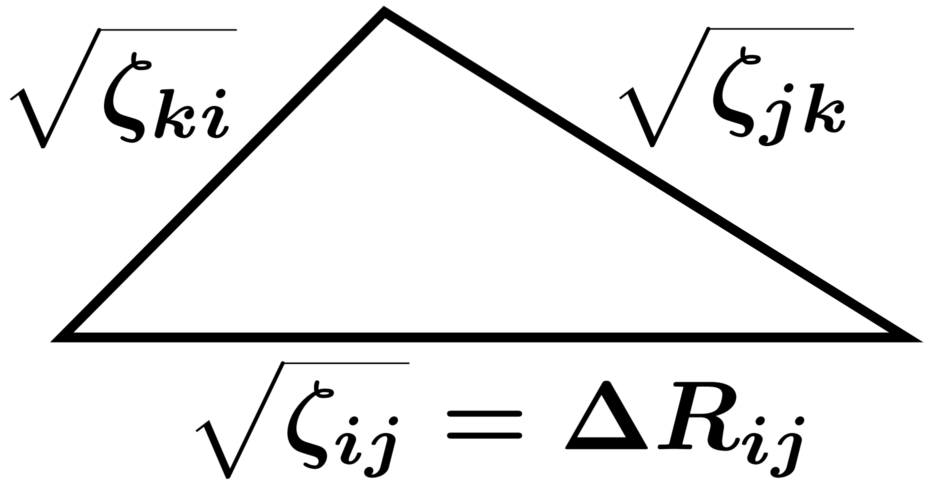
- Remove the shared energy scale
- Calibrate M_{top} using the W mass : $m_W = 80.377 \pm 0.012\,\mathrm{GeV}$
- Exploit the W inside the top jets as a standard candle

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

Imprint of the W in the EEEC distribution

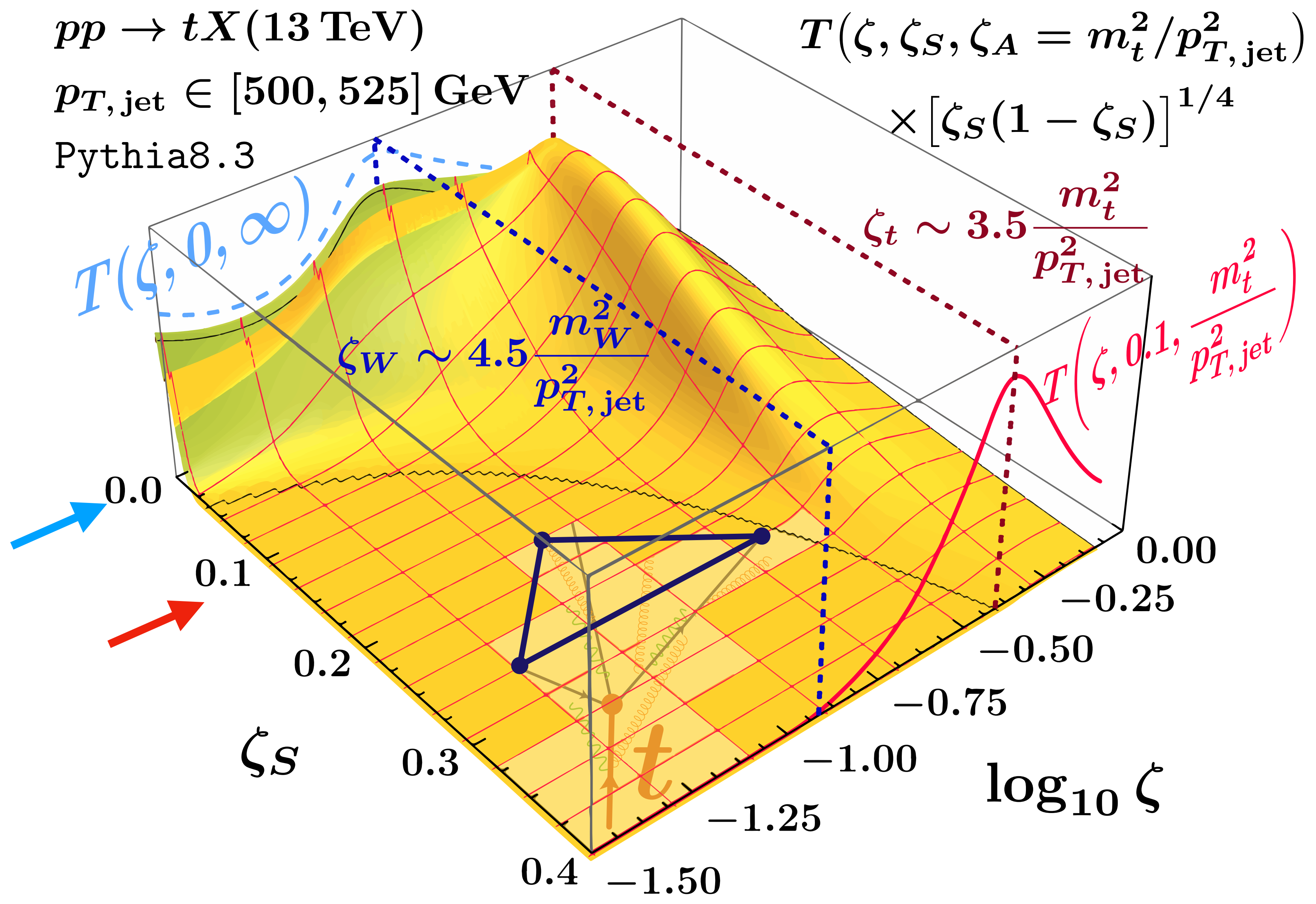
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2023

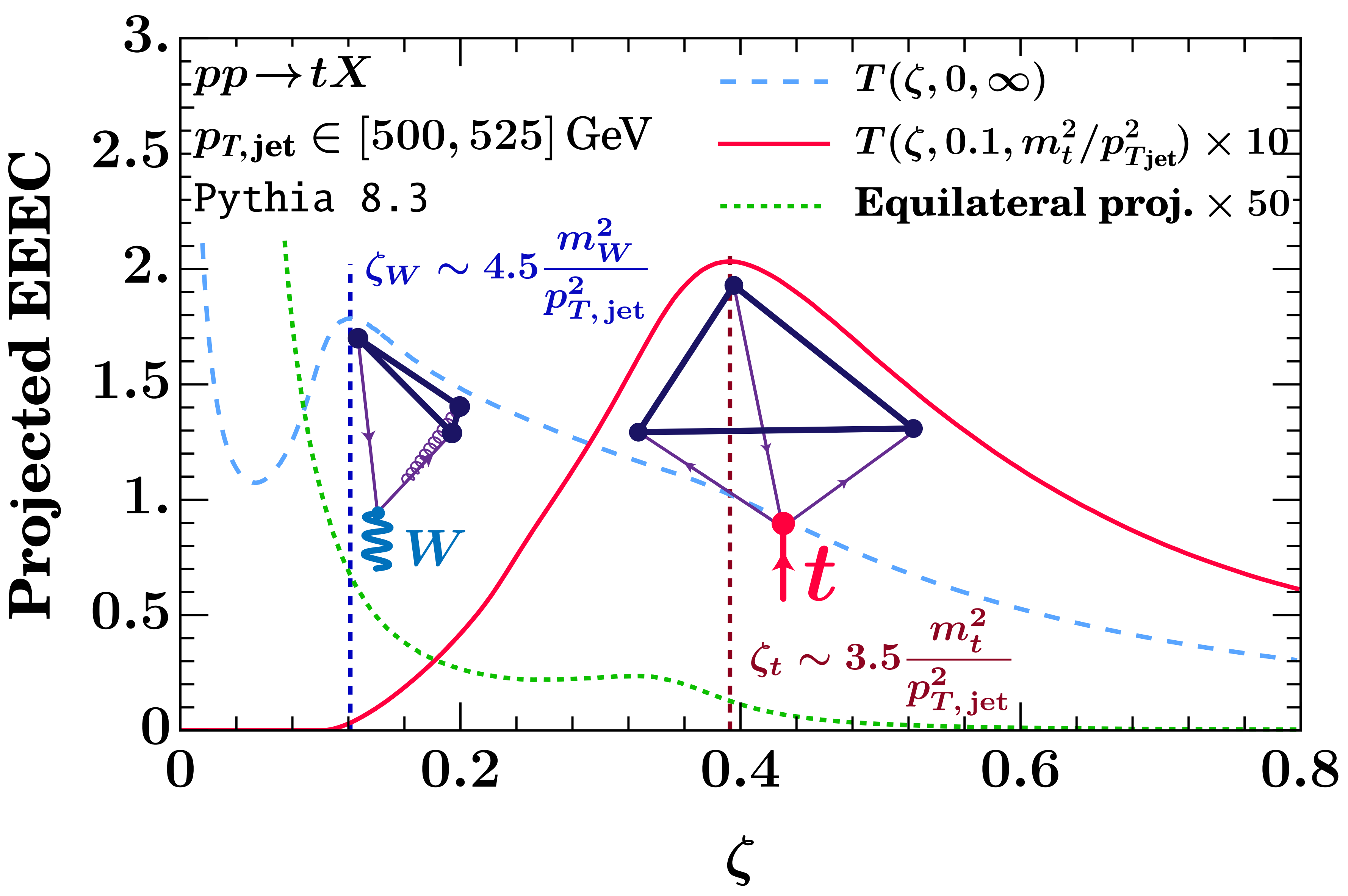
The observable we define to extract the W-imprint:



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

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

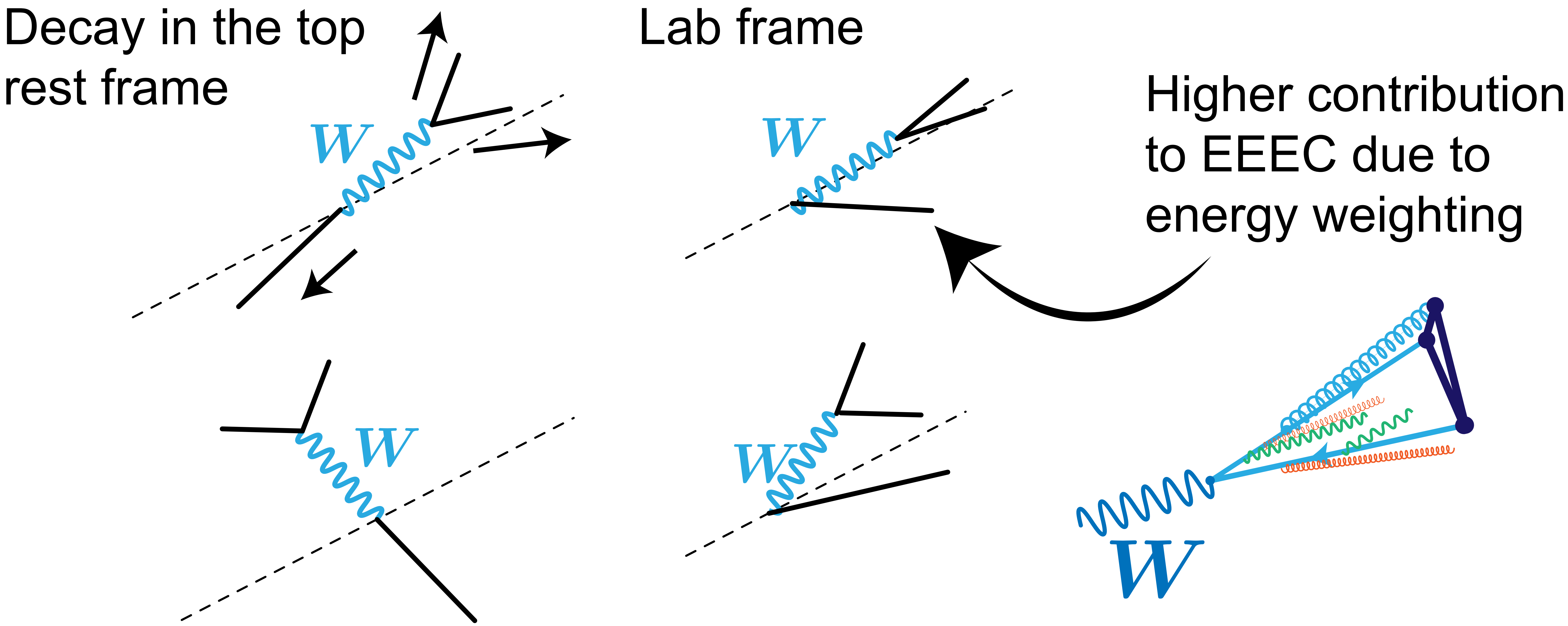




As ζ_S is lowered we allow for more squeezed configuration and see the peak at $\zeta_W \sim m_W^2/p_T^2$ emerging.

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

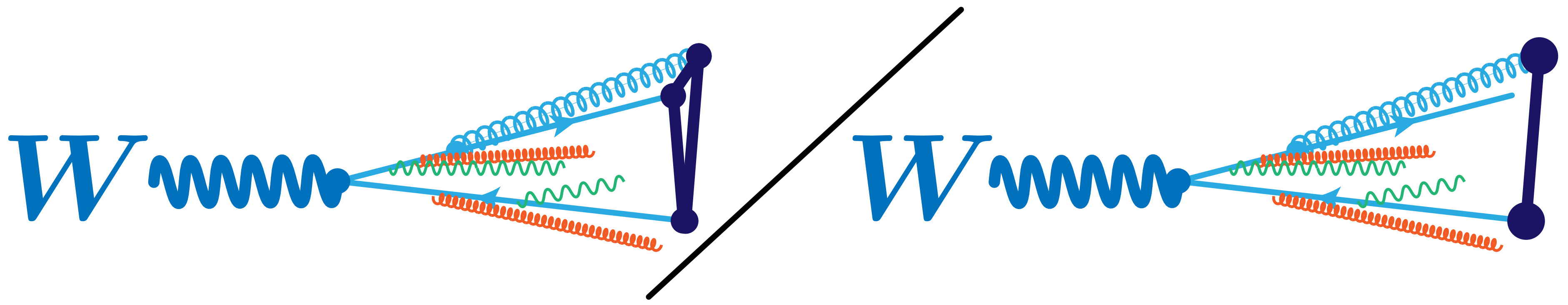
- The top quark and the W share a common boost defined by $p_{T,\text{jet}}$
- While the orientation of the W is largely uncorrelated with top boost axis in the rest frame, the EEEC preferentially picks out the Ws aligned with the top in the lab frame.

A robust m_W sensitive projection

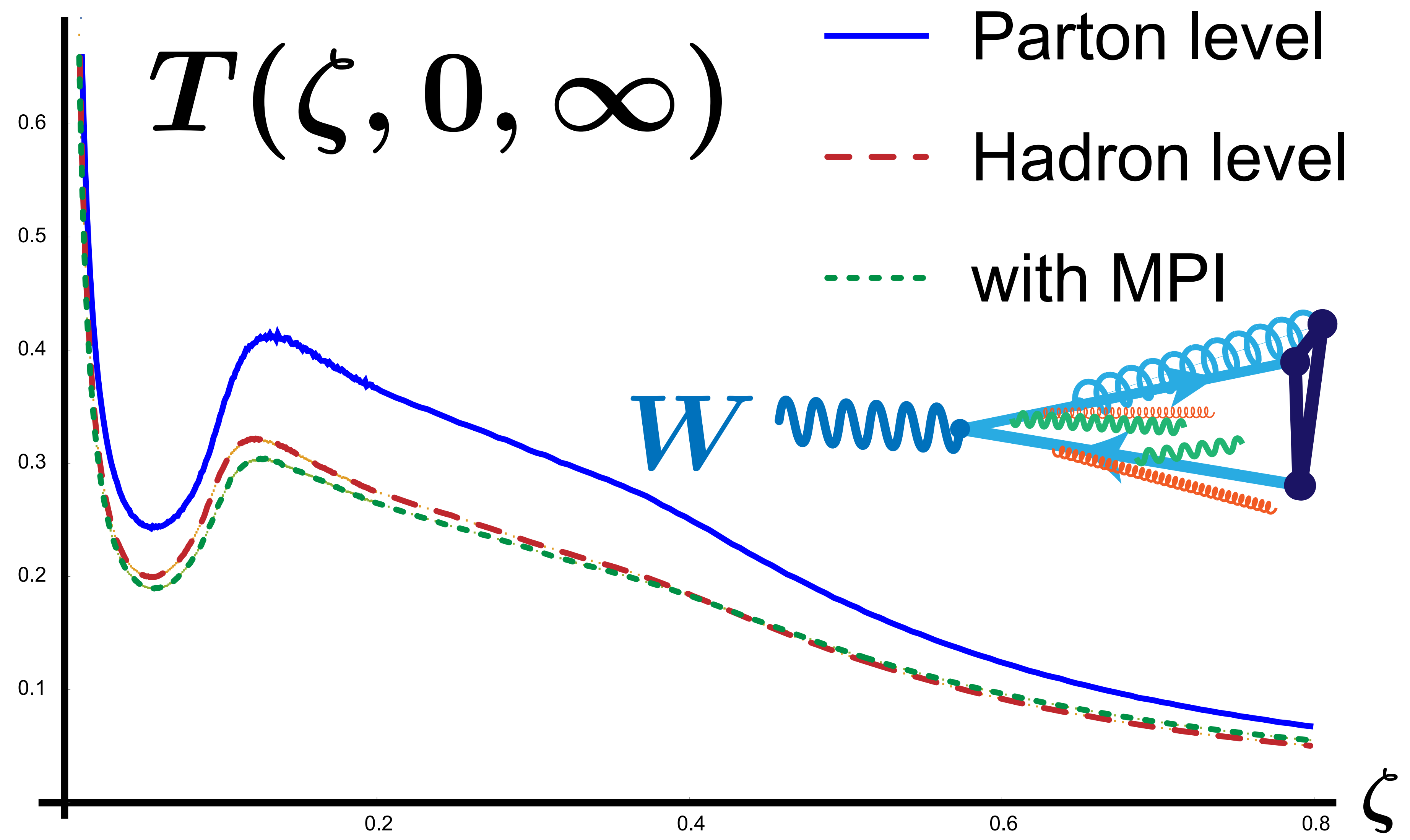
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2023

The ratio against 2-point correlator is robust against both collinear and b2b hadronization effects

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



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



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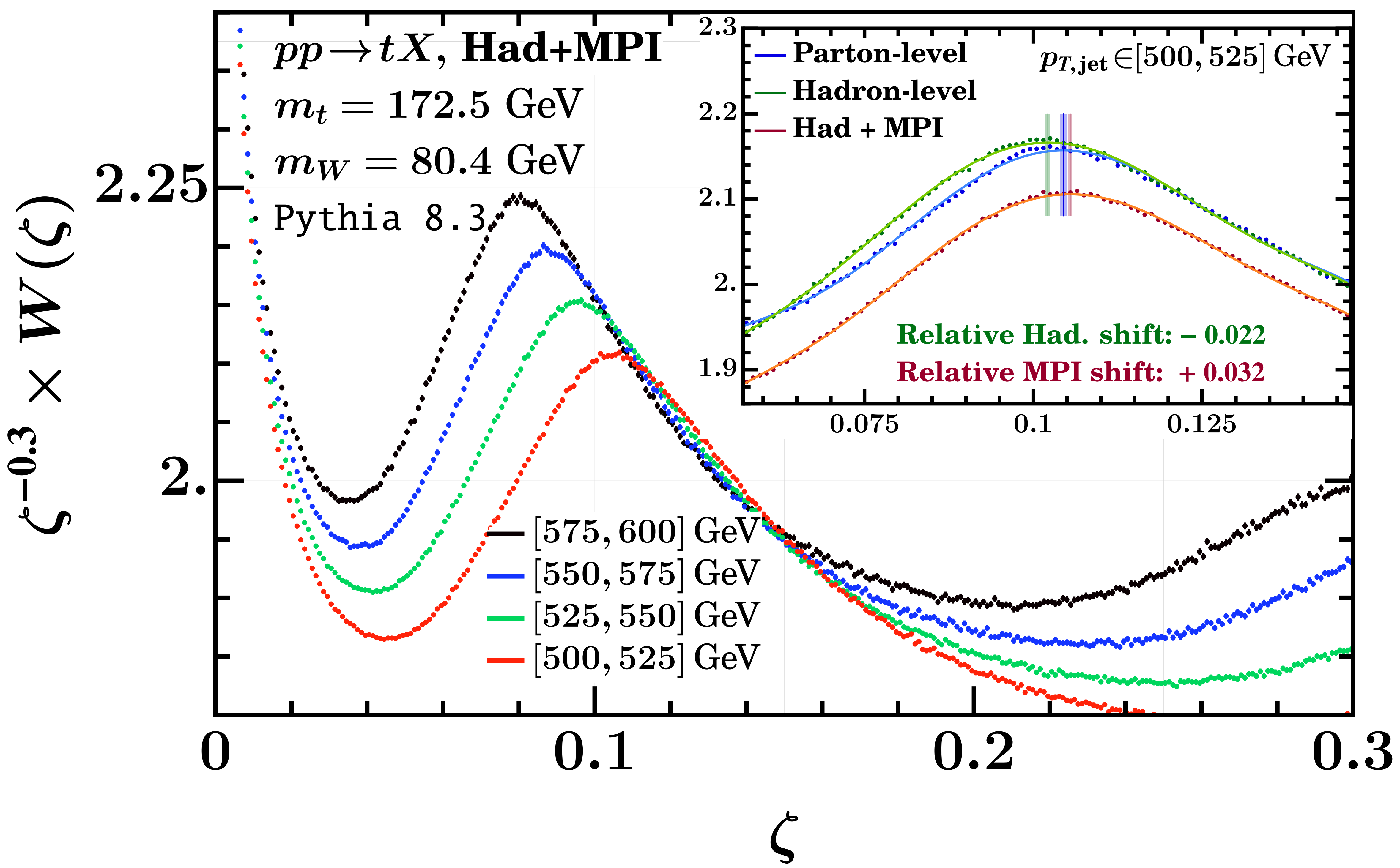
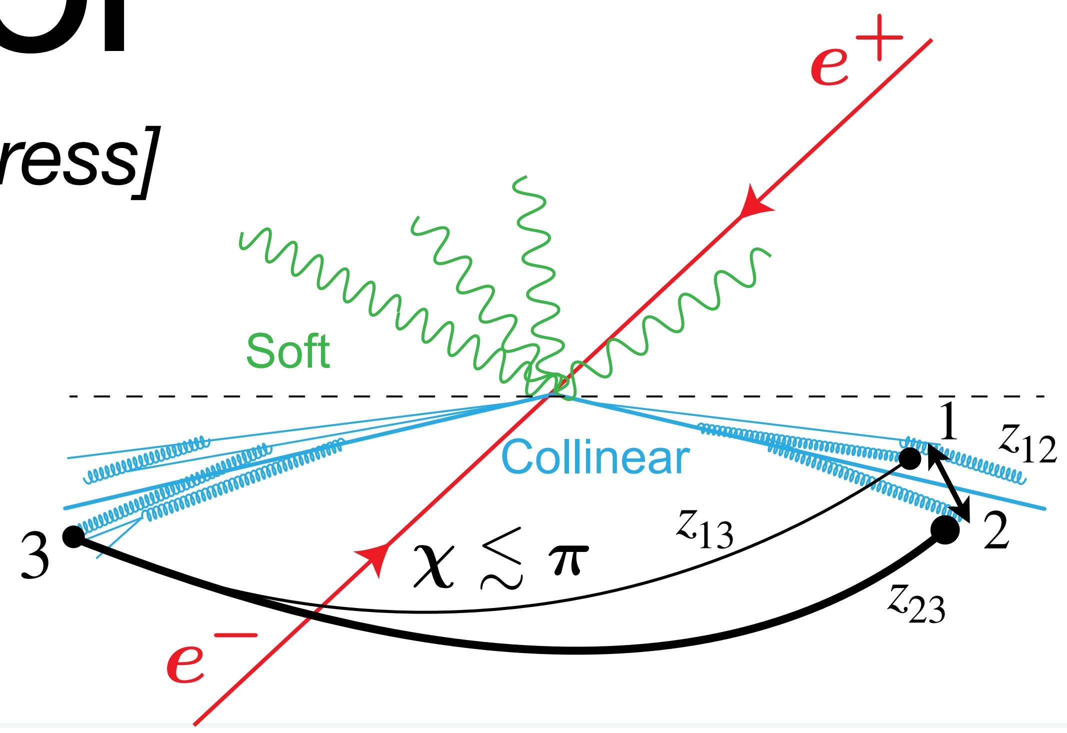


Squeezed b2b 3-point Correlator

Holguin, Lee, Moult, AP, Procura [in progress]



Squeezed EEEC region: $\sqrt{z_{12}} \sim \sqrt{1-z_{13}} \sim \sqrt{1-z_{23}} \sim \lambda \ll 1$

We derive a new factorization formula:

$$\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma_{\mathrm{EEEC}}}{\mathrm{d}z_{13}\mathrm{d}z_{12}\mathrm{d}z_{23}} = \frac{1}{8}\int \mathrm{d}^2\boldsymbol{q}_T\, \delta\left(1-z_{13}-\frac{\boldsymbol{q}_T^2}{Q^2}\right)\int \text{đ}^2\boldsymbol{b}_T\, e^{-\mathrm{i}\boldsymbol{b}_T\cdot\boldsymbol{q}_T}$$
$$\times \sum_f H_f(Q,\mu) J^f_{\mathrm{EEEC}}(Qb_T,\{z_{ij}\},L_b,L_\nu) J^{\bar{f}}_{\mathrm{EEC}}(L_b,L_\nu) S_\perp(b_T,\mu,\nu)$$

The squeezed EEEC jet function involves dihadron TMD + contact term:

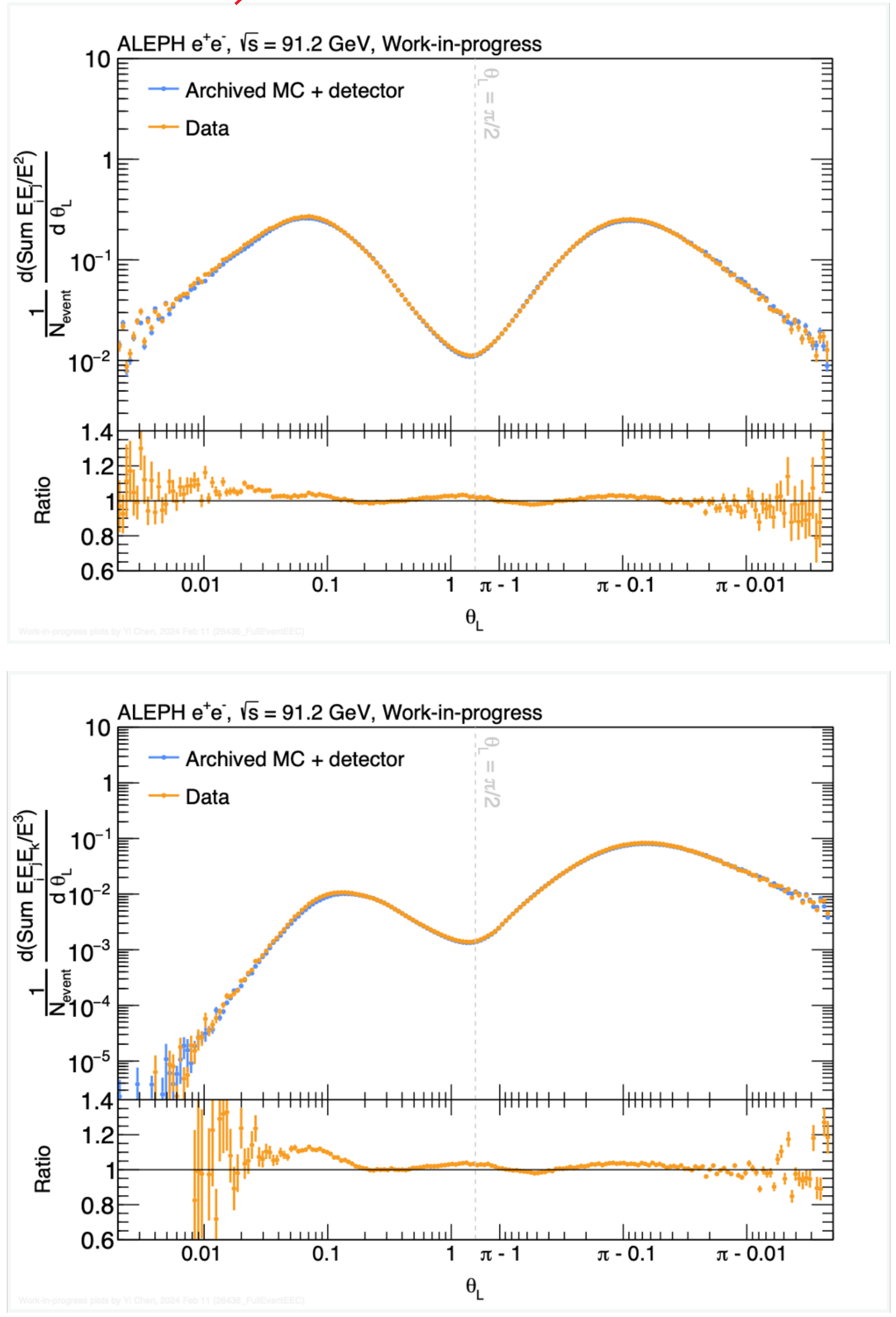
$$J^{f(1)}_{\mathrm{EEEC}} \equiv J^{(1)}_{f(12)}(b_T Q,\{z_{ij}\},\epsilon)$$
$$+\,\delta(z_{12})\delta(z_{23}-z_{13})\int_0^1 \mathrm{d}z\, z^d\left[\mathcal{D}^{(1)}_{g/q}(z,b_\perp,\epsilon)+\mathcal{D}^{(1)}_{q/q}(z,b_\perp,\epsilon)\right]$$

$$\mathcal{D}_{i/j}(z,b_\perp,\epsilon) \sim \frac{1}{z^2}$$

Key takeaways:

- Rapidity divergence only in the contact term
- Non-trivial cancellation of IR poles

$$\int_0^1 \mathrm{d}z\, z^d\left[\mathcal{D}^{(1)}_{g/q}(z,b_\perp)+\mathcal{D}^{(1)}_{q/q}(z,b_\perp)\right]$$
$$= C_F\left(\frac{3}{\epsilon}+3L_b-\frac{4\pi^2}{3}+10\right)+2C_F L_b\left(\frac{3}{2}-2\ln\frac{Q}{\nu}\right)$$
$$J^{(1)}_{f(12)} = C_F\left(-\frac{3}{\epsilon}-3\ln\frac{\mu^2}{Q^2}-\frac{37}{3}+2F^{(0)}_{x_2,z_{12}}(b_T Q)\right)\delta(z_{12})\delta(z_{23}-z_{13})$$
$$+\,C_F\left[\frac{F_{x_2}(b_T Q\sqrt{z_{12}},0)}{z_{12}}\right]_+\frac{\Theta(z_{12})}{\pi}\int \mathrm{d}\Omega^{(2)}_{d-2}\,\delta_{z_{23}}$$



Plots from a talk by Yen-Jie Lee

Outline

- Precision Top Mass: A notorious challenge
- The collinear and back-to-back limits of EEC
- EECs on boosted top quarks
- The Standard Candle approach
- Demonstrating Robustness and Experimental Feasibility

Calibrating the top mass

Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 24

The strategy for now 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:

$$\left.\frac{\mathrm{d}T}{\mathrm{d}\zeta}\right|_{\zeta=\zeta_t} = 0, \qquad \left.\frac{\mathrm{d}W}{\mathrm{d}\zeta}\right|_{\zeta=\zeta_W} = 0$$

In the large boost limit,

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

The constant C is perturbatively calculable and depends on the jet radius.

- Later fit for the entire shape in the peak region when a calculation becomes available.

Calibrating the top mass

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The resulting ratio is proportional to top mass:

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

For now extract this from parton showers (error bar is stat + polynomial peak fit) by averaging over $p_T \in [400{,}600]$ GeV.

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

Use the standard CP5 tune for Pythia and Vincia

The checklist

For a robust experimental strategy for precision top mass we need to ensure

1. The distribution is resilient to experimental systematics,
2. Robust against modeling of hadronization and UE
3. All non-universal and power suppressed effects have a negligible impact
4. The key effects will be perturbatively calculable.

What is NOT included here:

1. Detector simulation
2. Impact of event generator modeling through unfolding (expect to be small for a track-based measurement)

Production mechanism:

- PDF uncertainty ☐
- Hard scattering corrections ☐

Jet substructure:

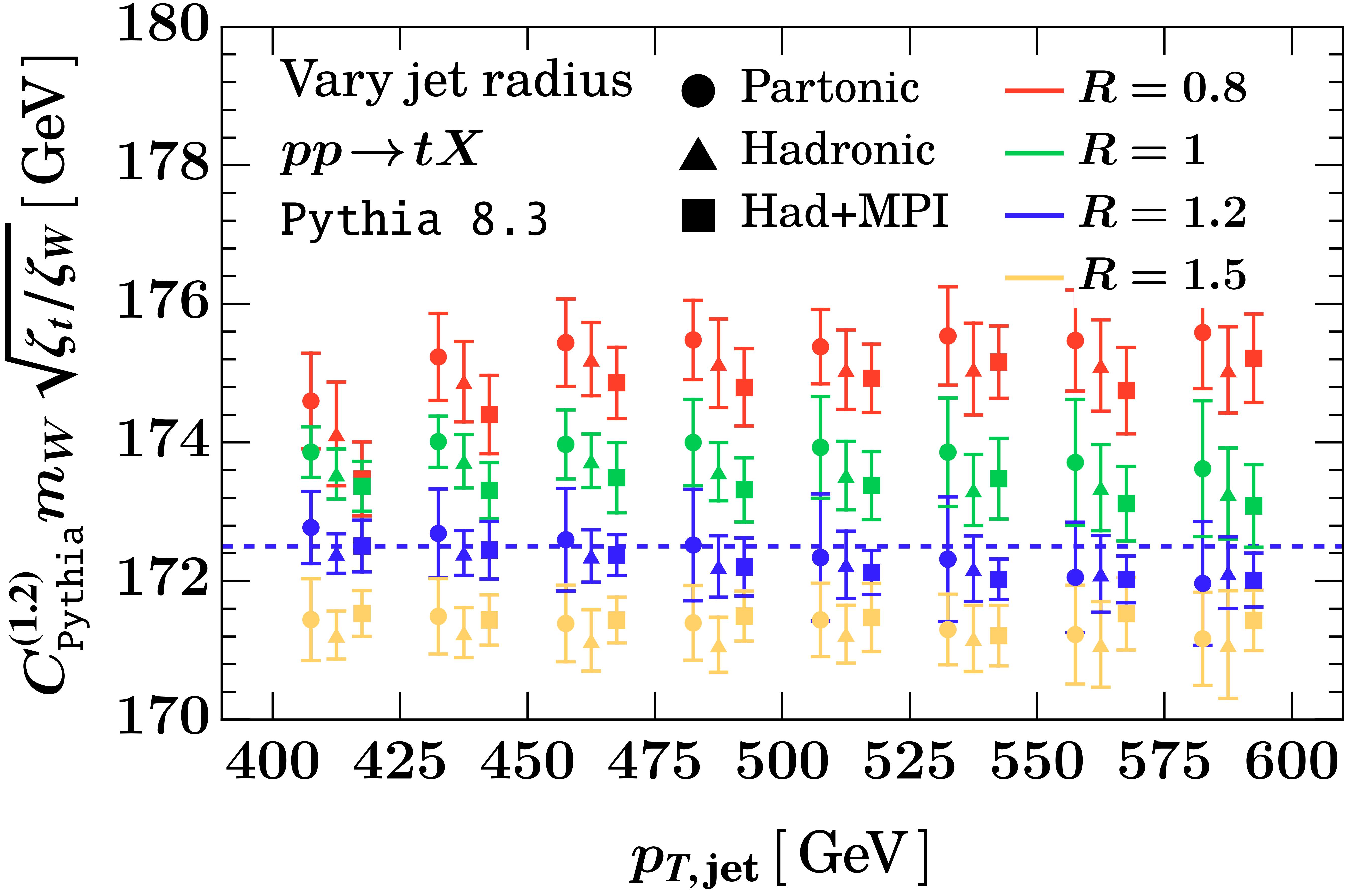
- Jet radius dependence ☐
- Hadronization effects ☐
- Impact of underlying event ☐
- Wide angle soft physics ☐
- Perturbative uncertainty ☐

Experimental feasibility:

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

Jet radius dependence

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



Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2024

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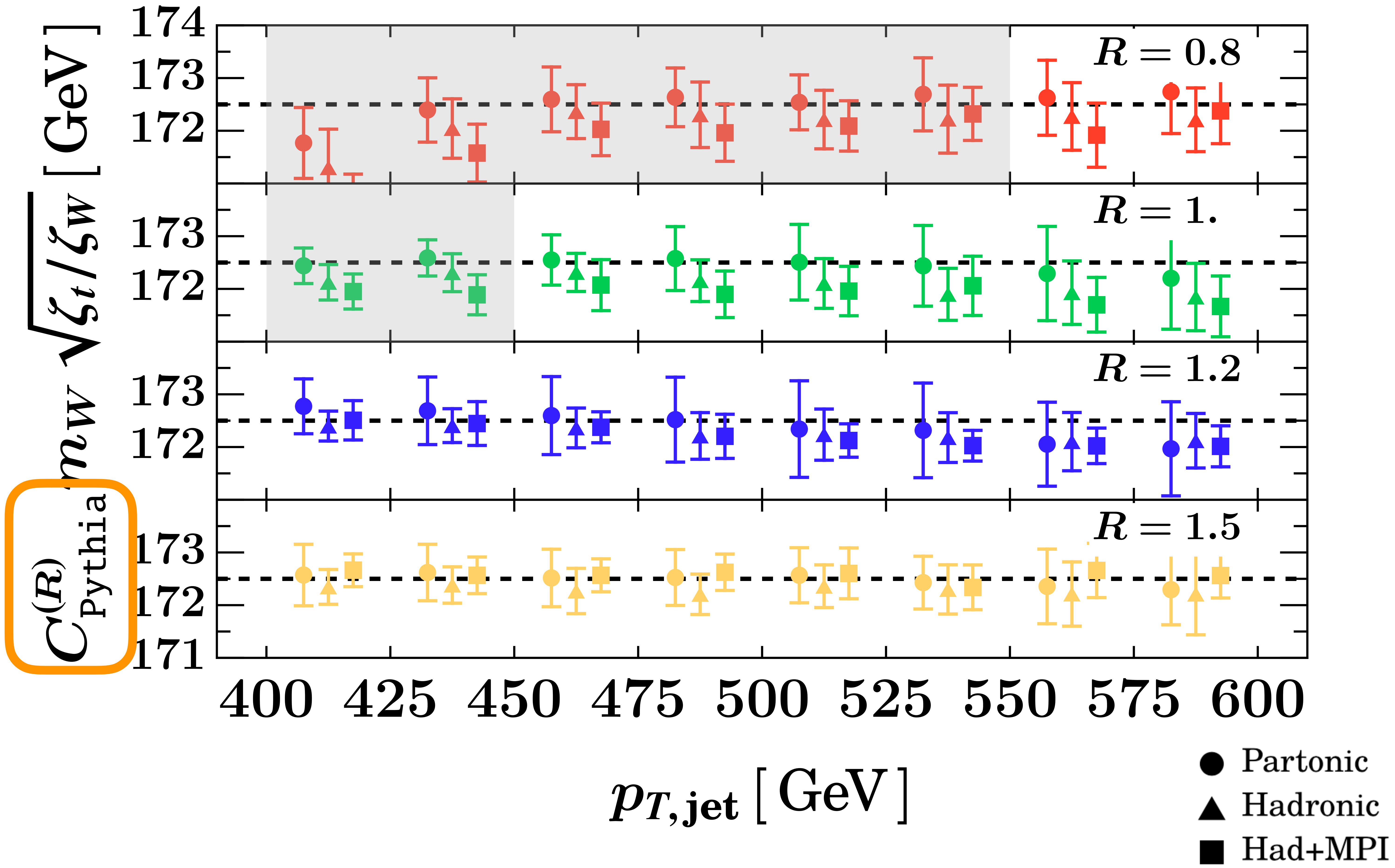
Jet radius dependence

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

Shift from had/UE is ~ 200 MeV effect!



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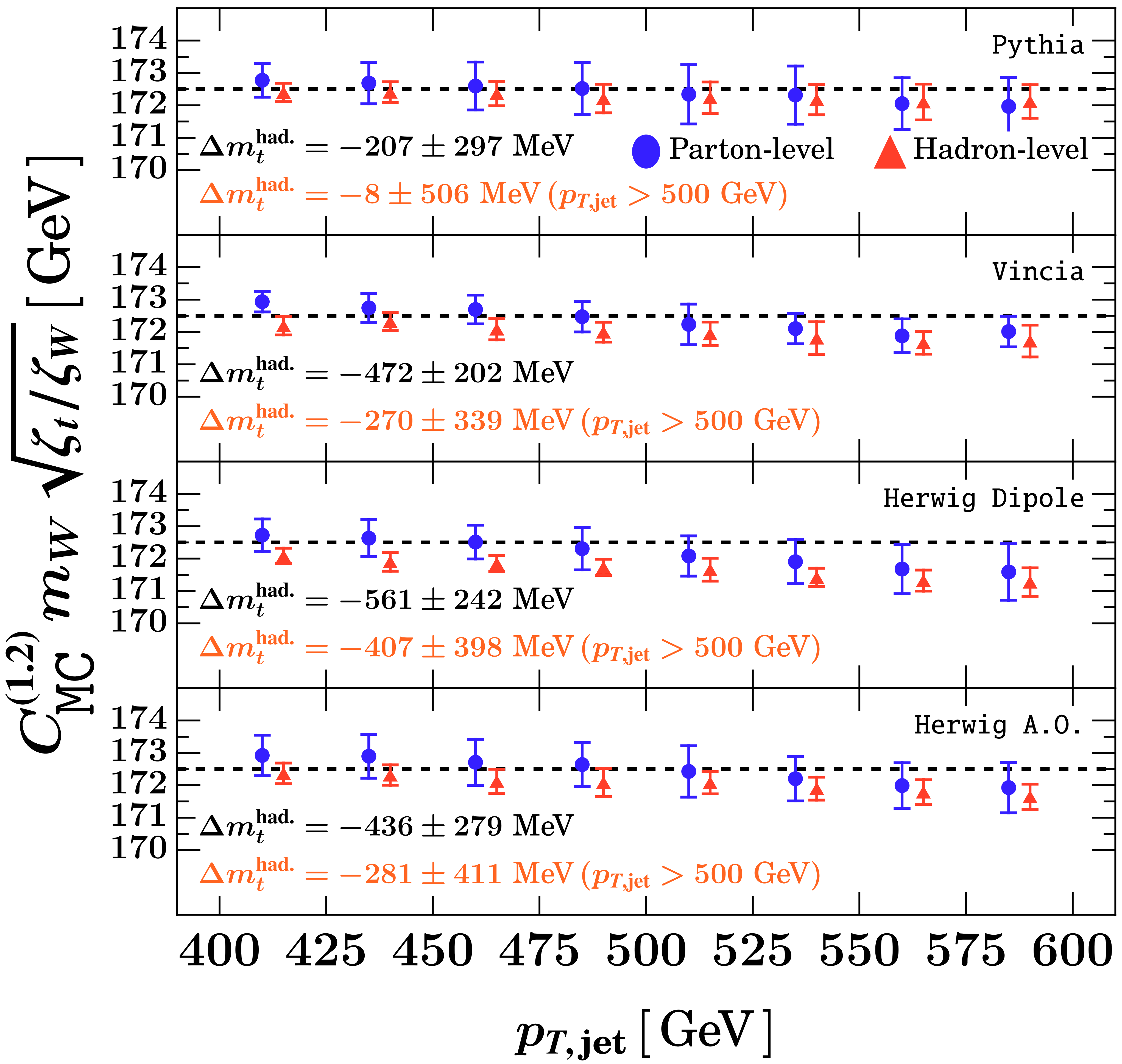
Hadronization effects

All the showers exhibit a cancellation of hadronization effects in the $p_{T,\mathrm{jet}}$ up to 500 MeV. Primarily shifts in the W distribution.
(error bar is stat + polynomial peak fit)



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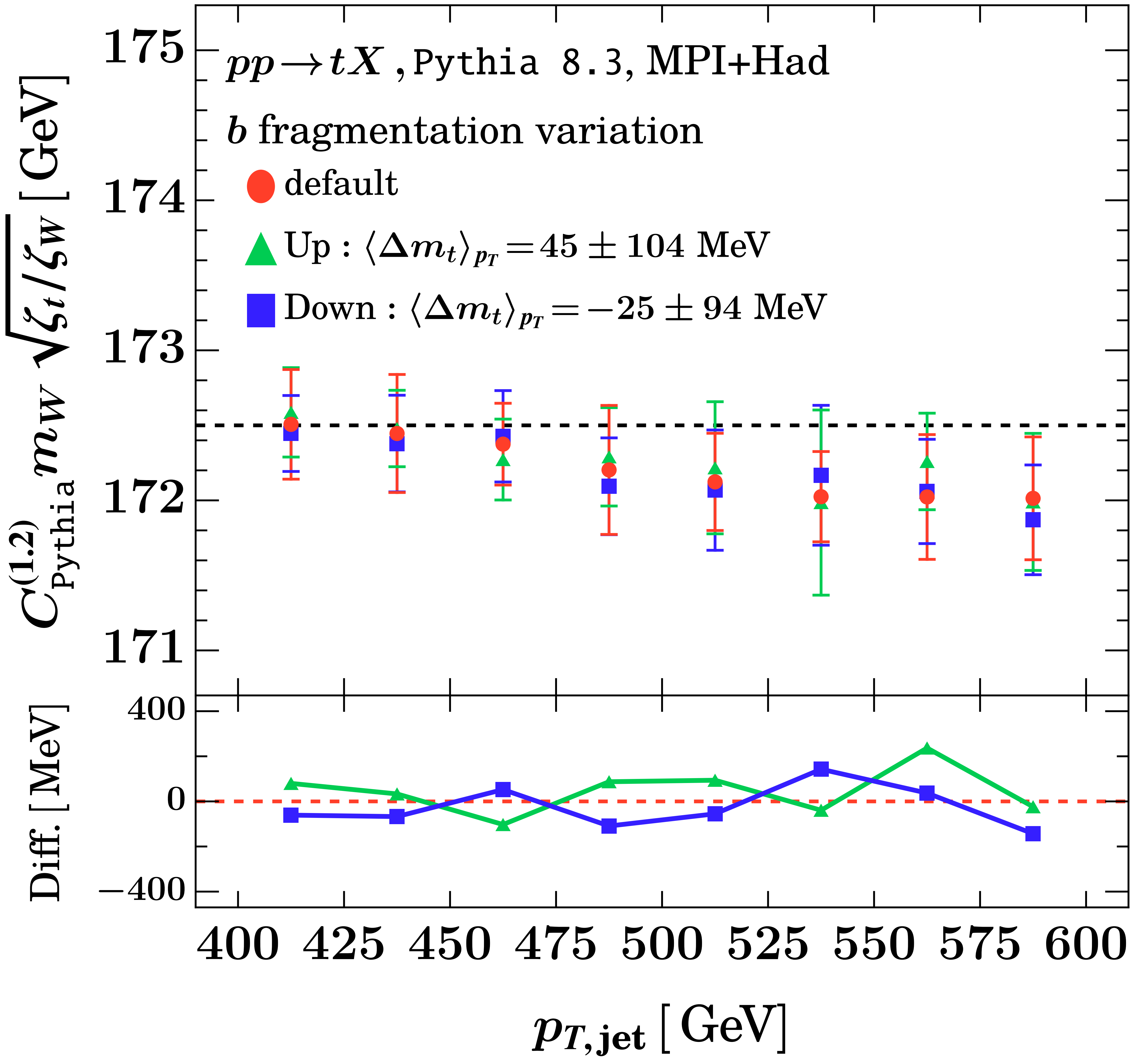
Hadronization effects

Negligible impact of *b* hadron fragmentation modeling:



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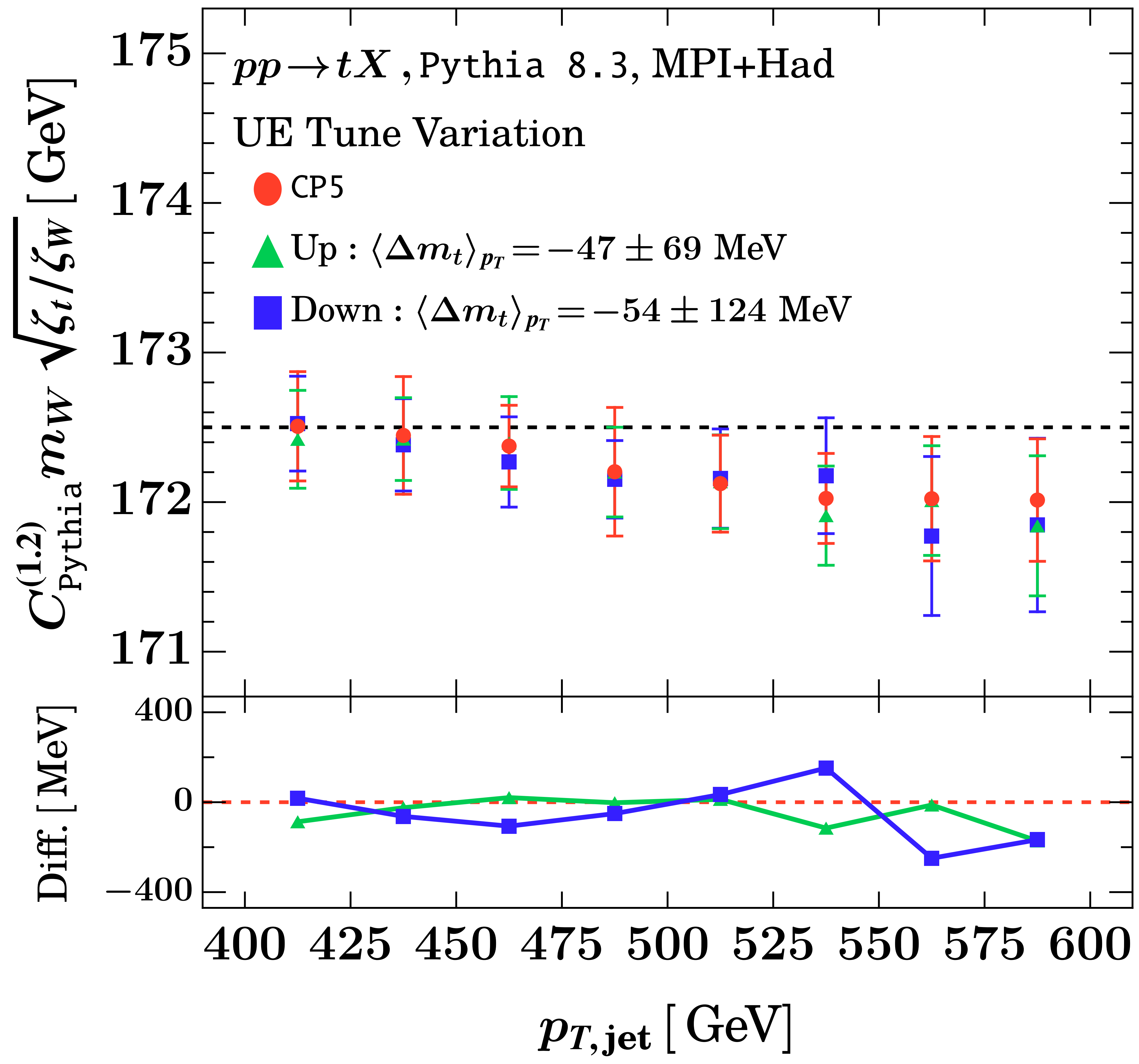
Effect of contamination

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



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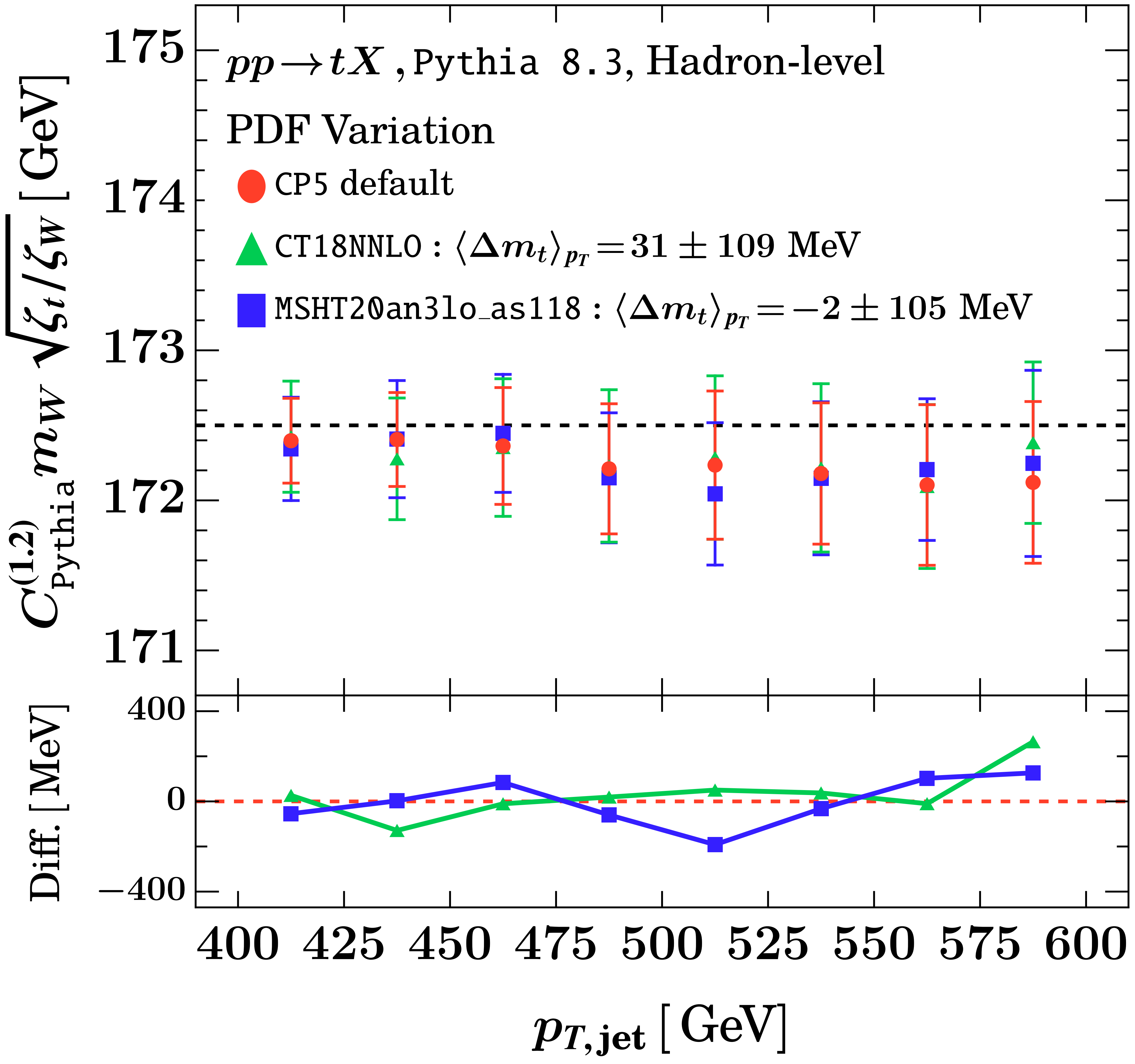
PDF variations

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



Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2023, 2024

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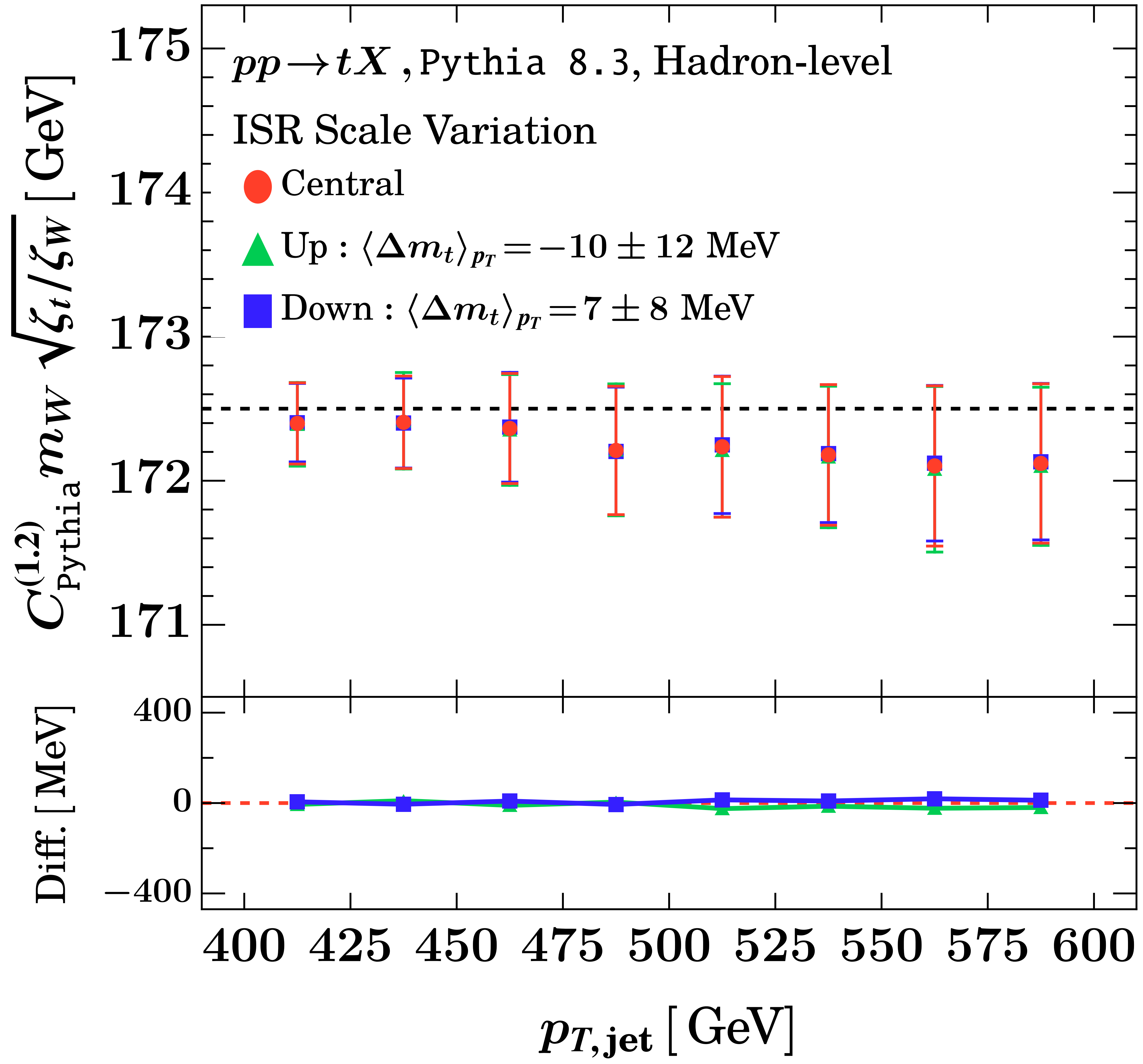
Hard scattering corrections

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



Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2024

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Experimental feasibility:

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- Jet energy scale ☐
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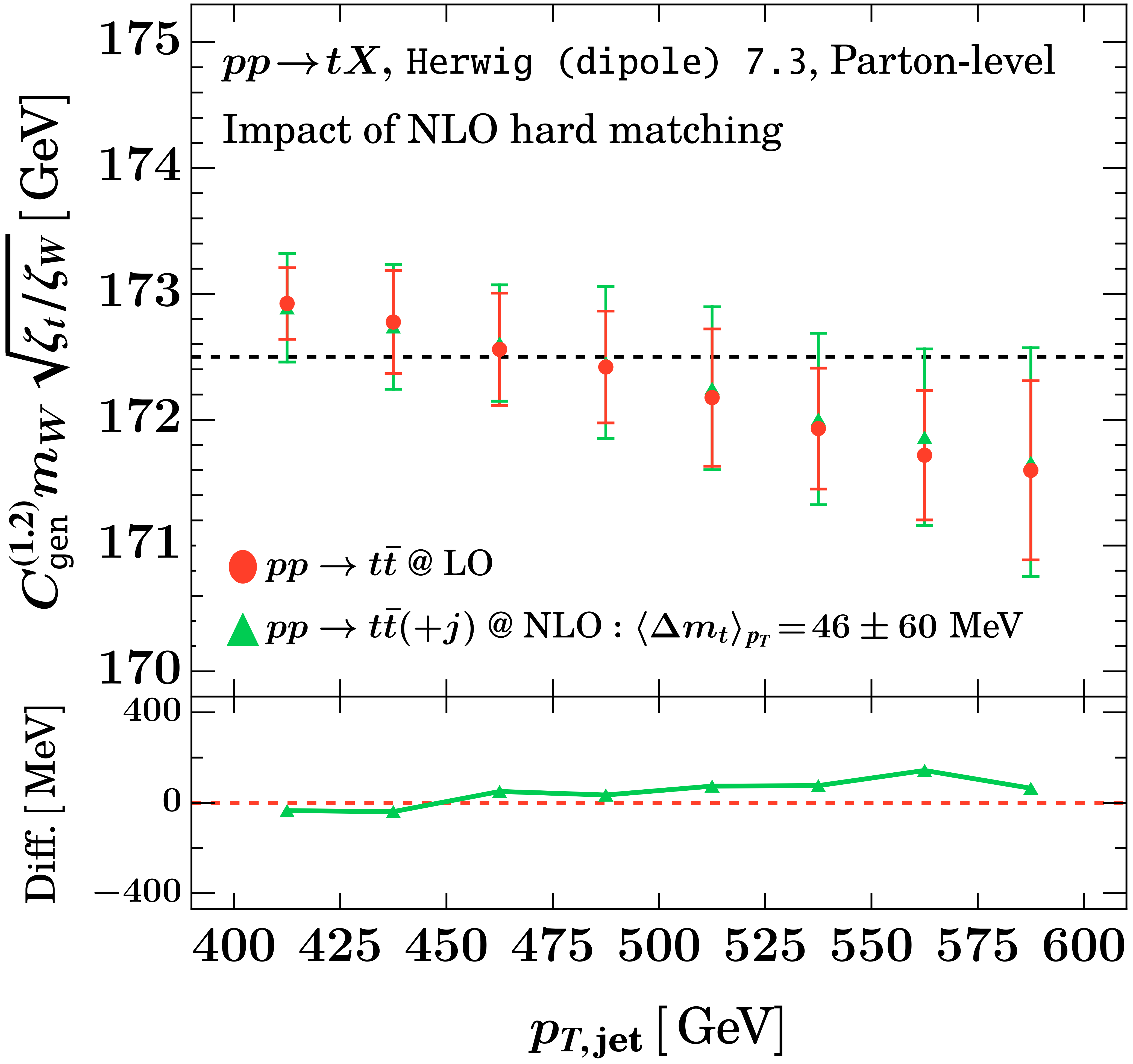
- Heavy flavor dependence ☐

Hard scattering corrections

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



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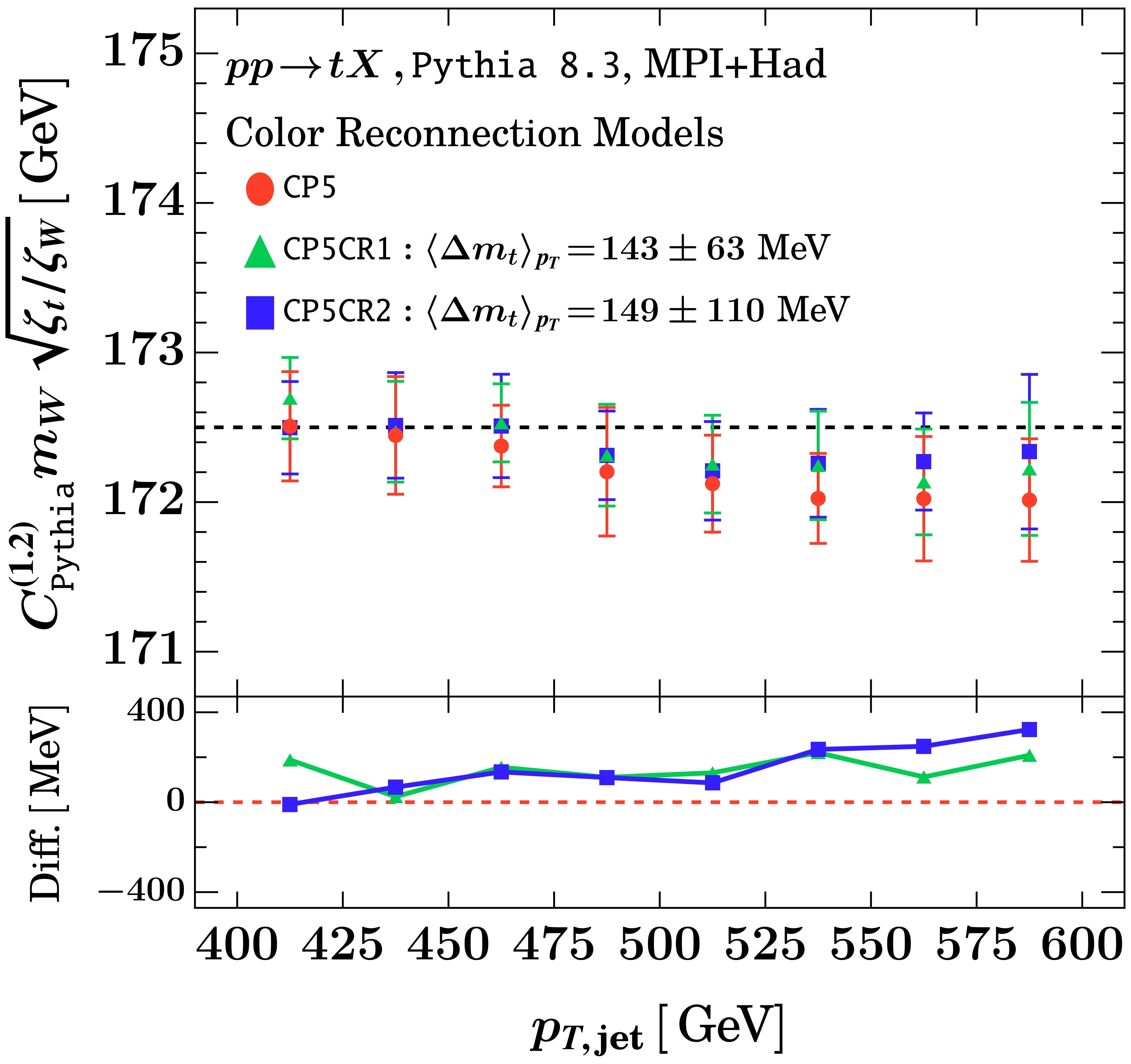
Wide angle soft physics

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



Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2024

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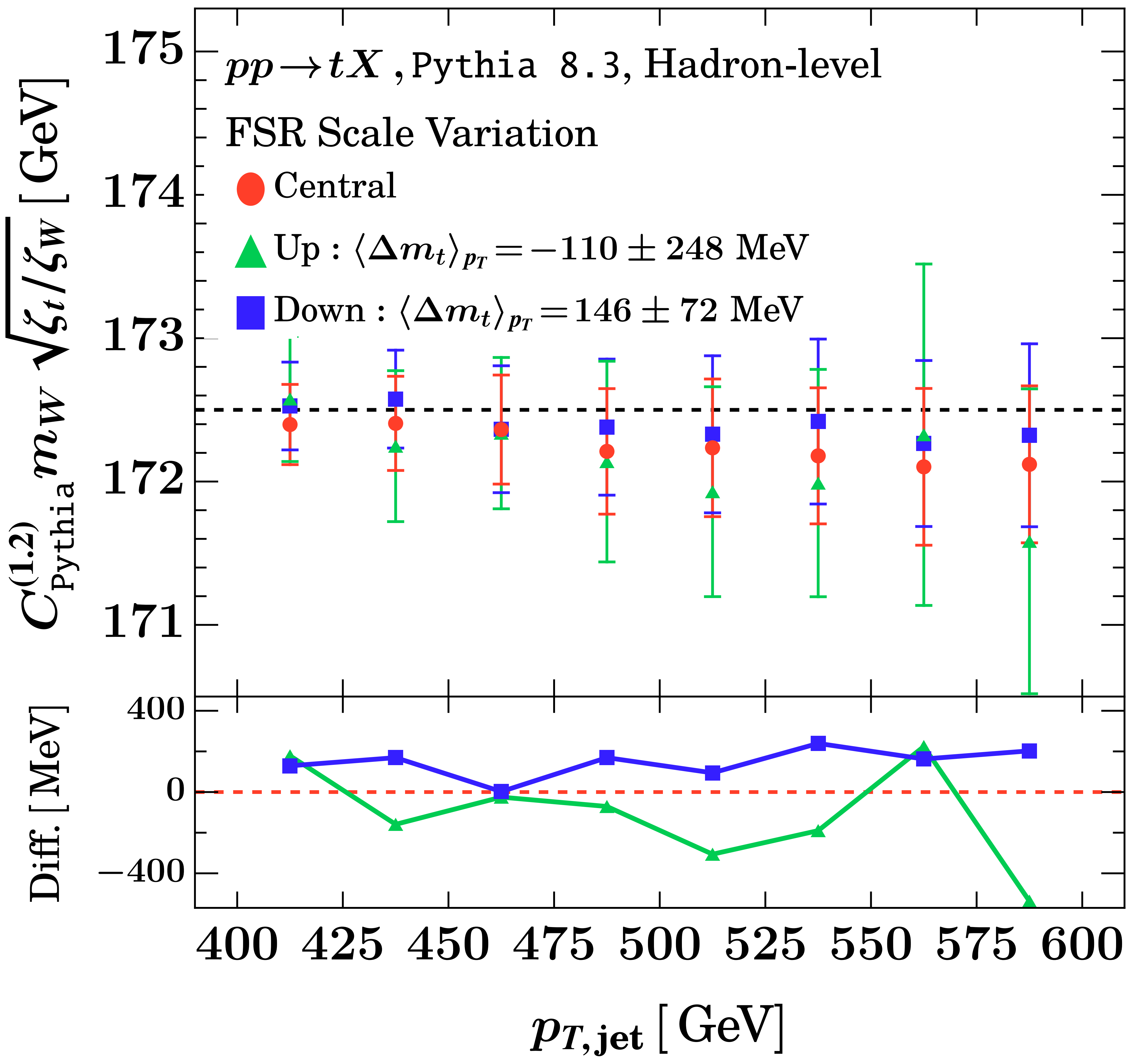
Shower Uncertainty

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



Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2024

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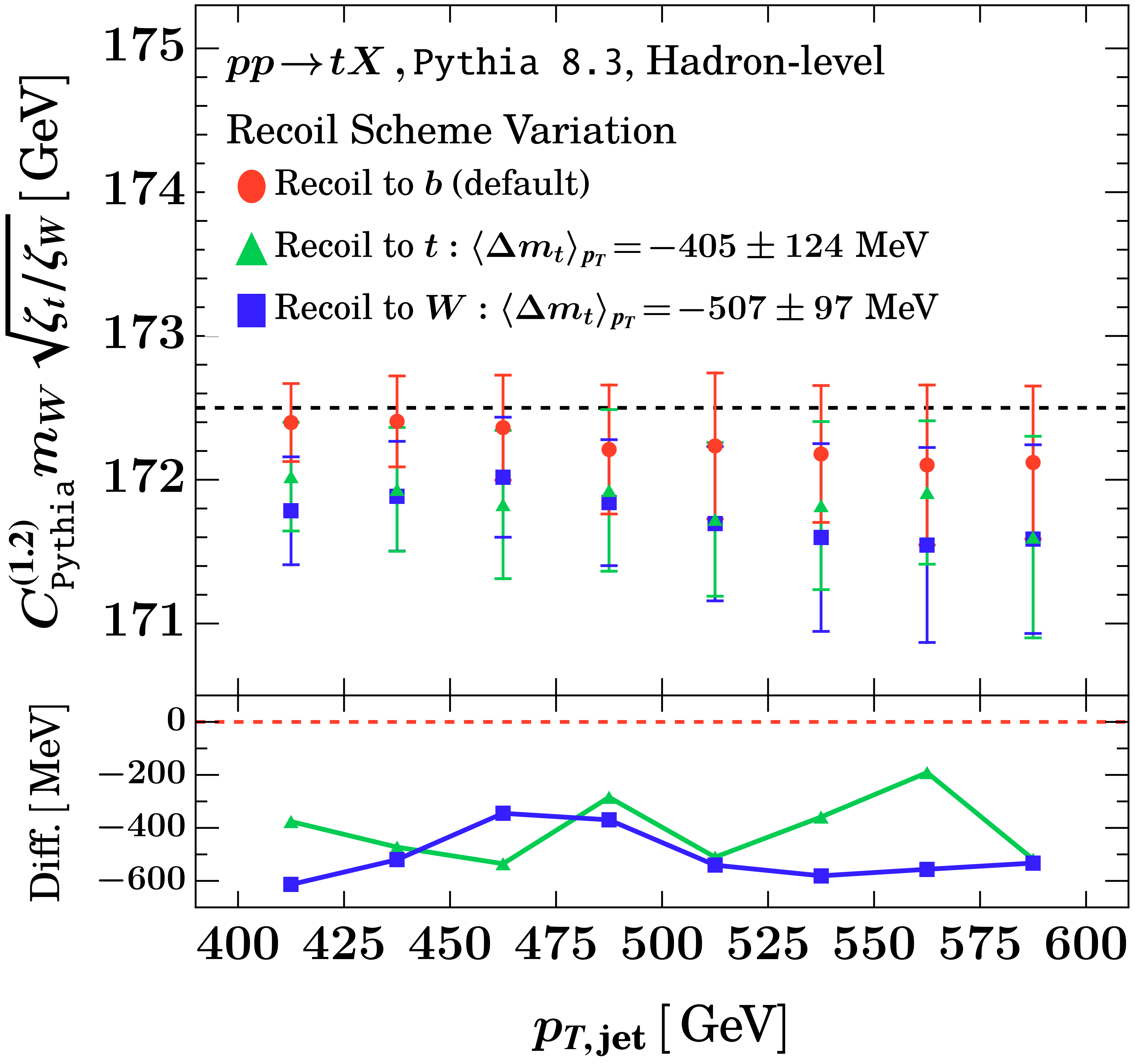
Shower Uncertainty

Shower uncertainty results from LL showers + LO description of the top decay: Expect significant improvement with the top decay description at NLO + Sudakov “b2b” resummation



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Outline

- Precision Top Mass: A notorious challenge
- The collinear and back-to-back limits of EEC
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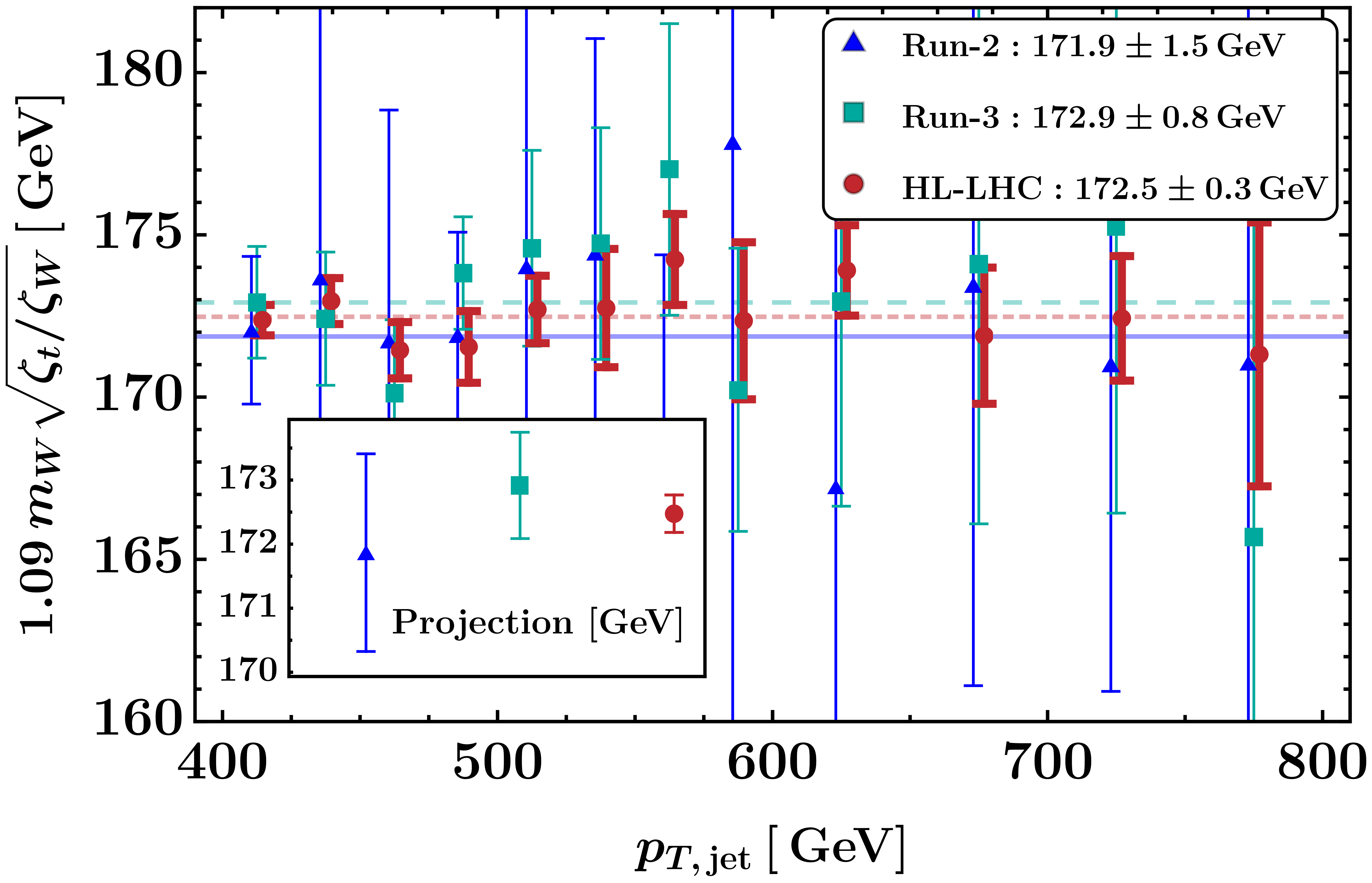
- The Standard Candle approach
- Demonstrating Robustness and Experimental Feasibility

Statistical sensitivity

Crucially, the measurement is statistically feasible at the LHC



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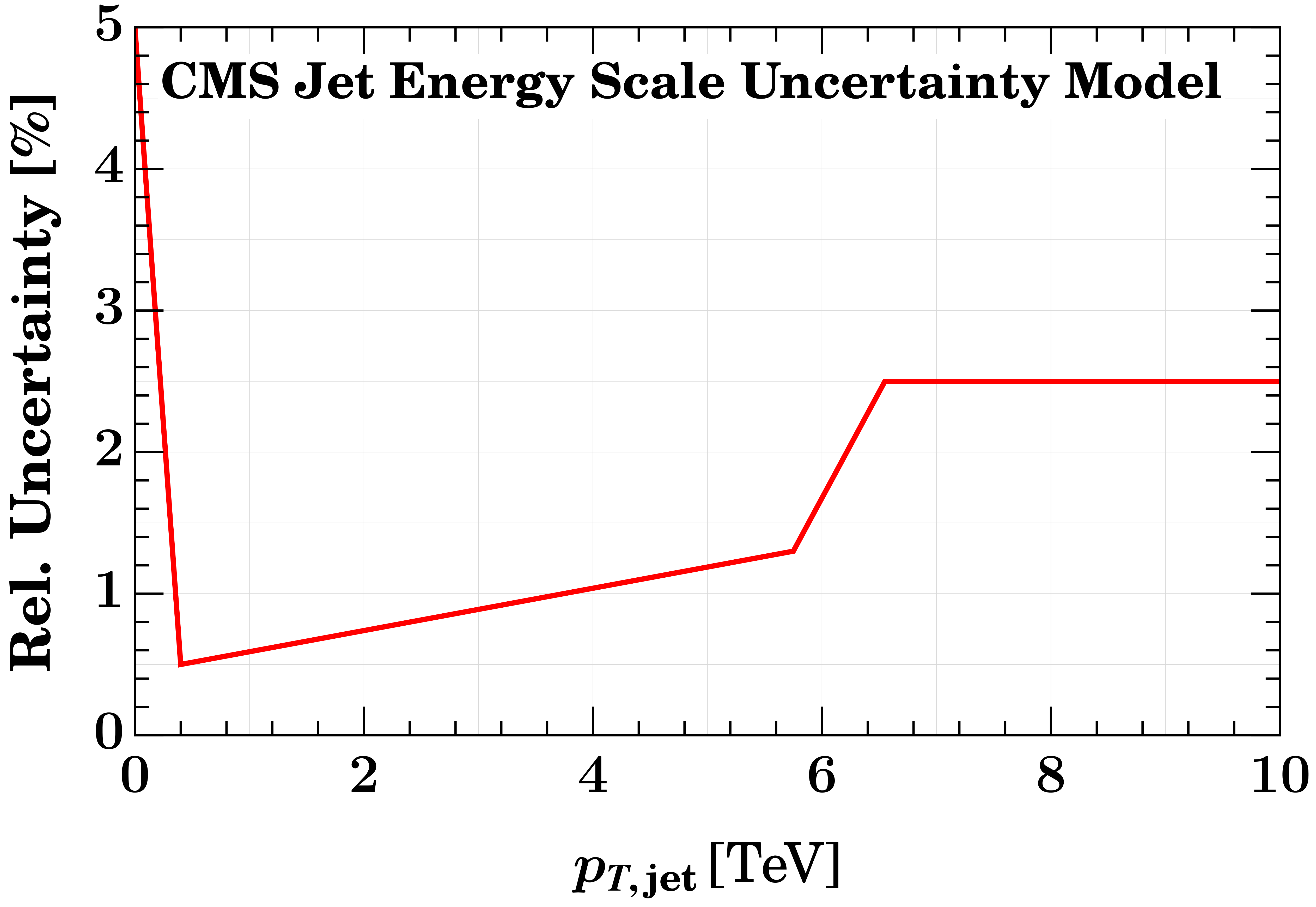
Jet energy scale

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



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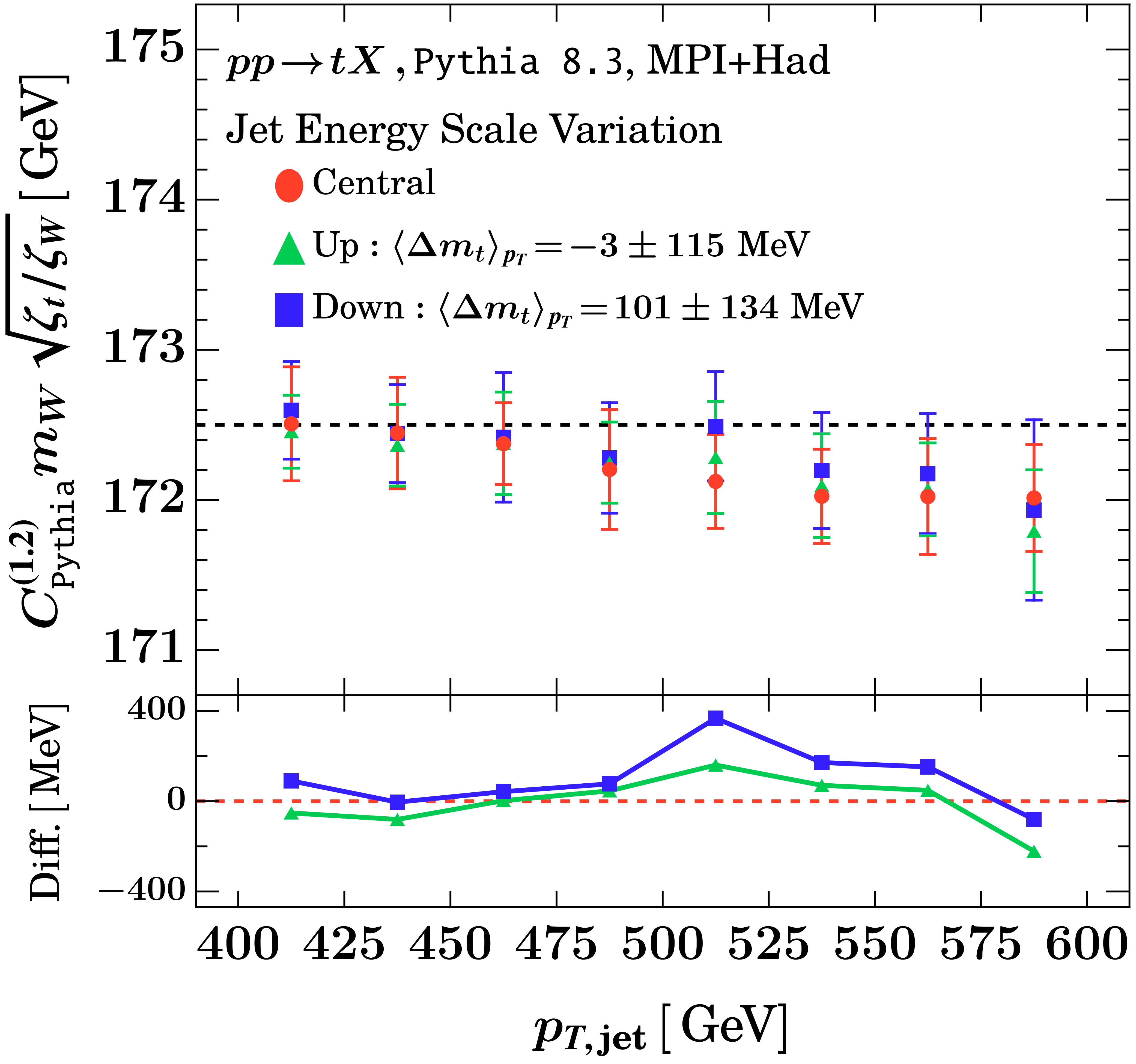
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2024

Jet energy scale

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



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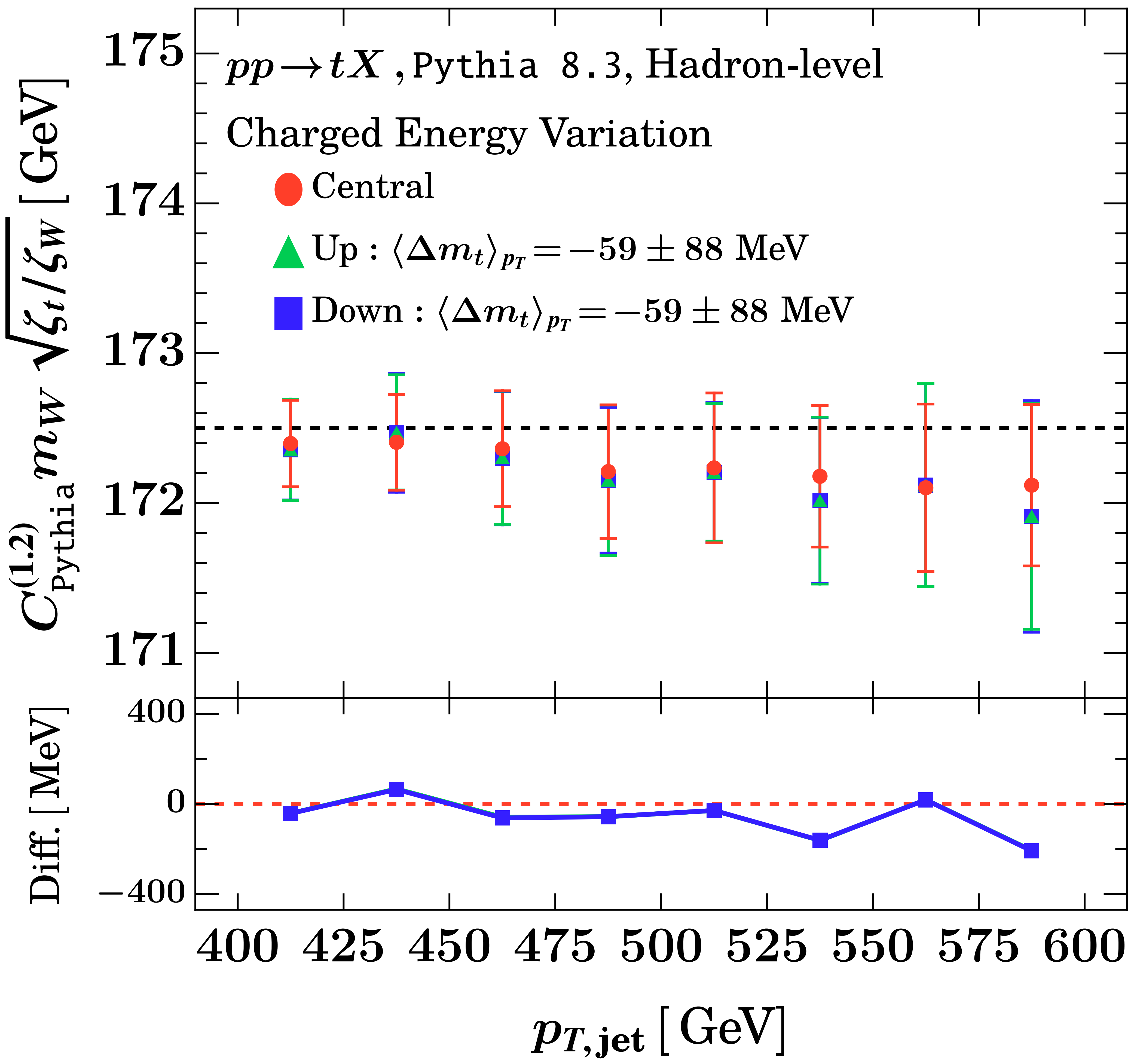
Constituent Energy Scale

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



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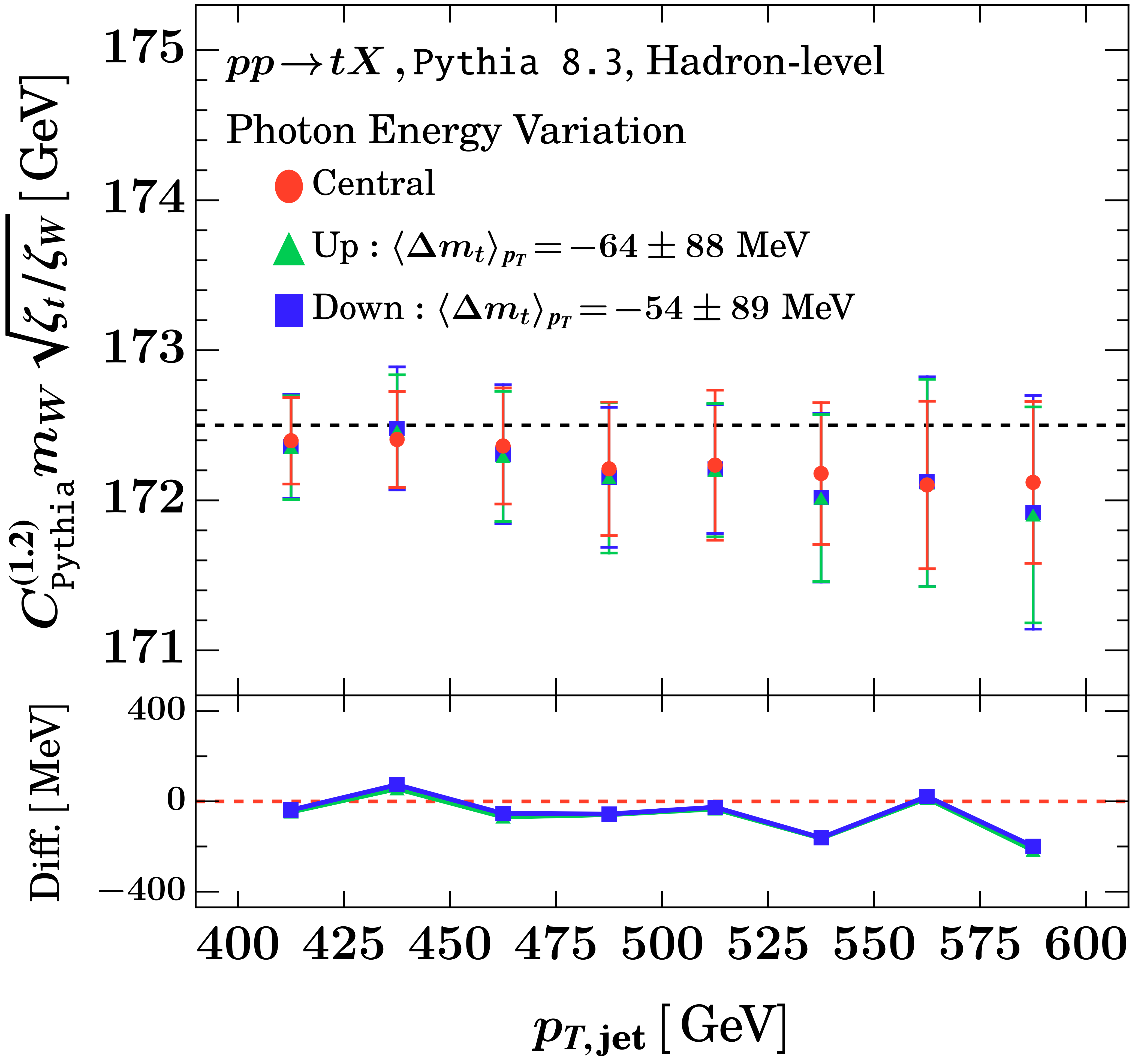

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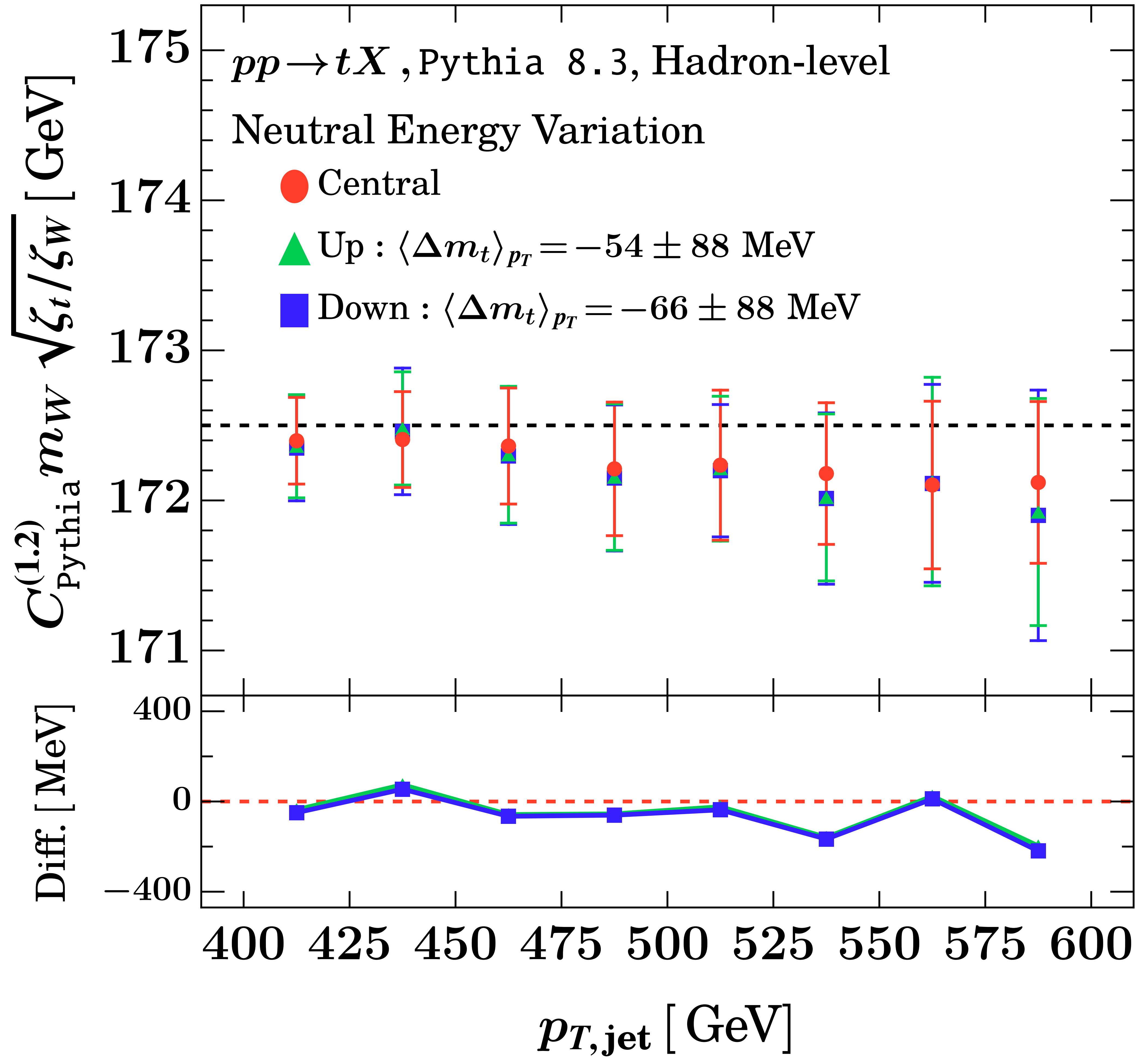
Study the effect of varying the constituent momenta: 1% for charged, 3% for photons and 5% for neutrals: Negligible impact



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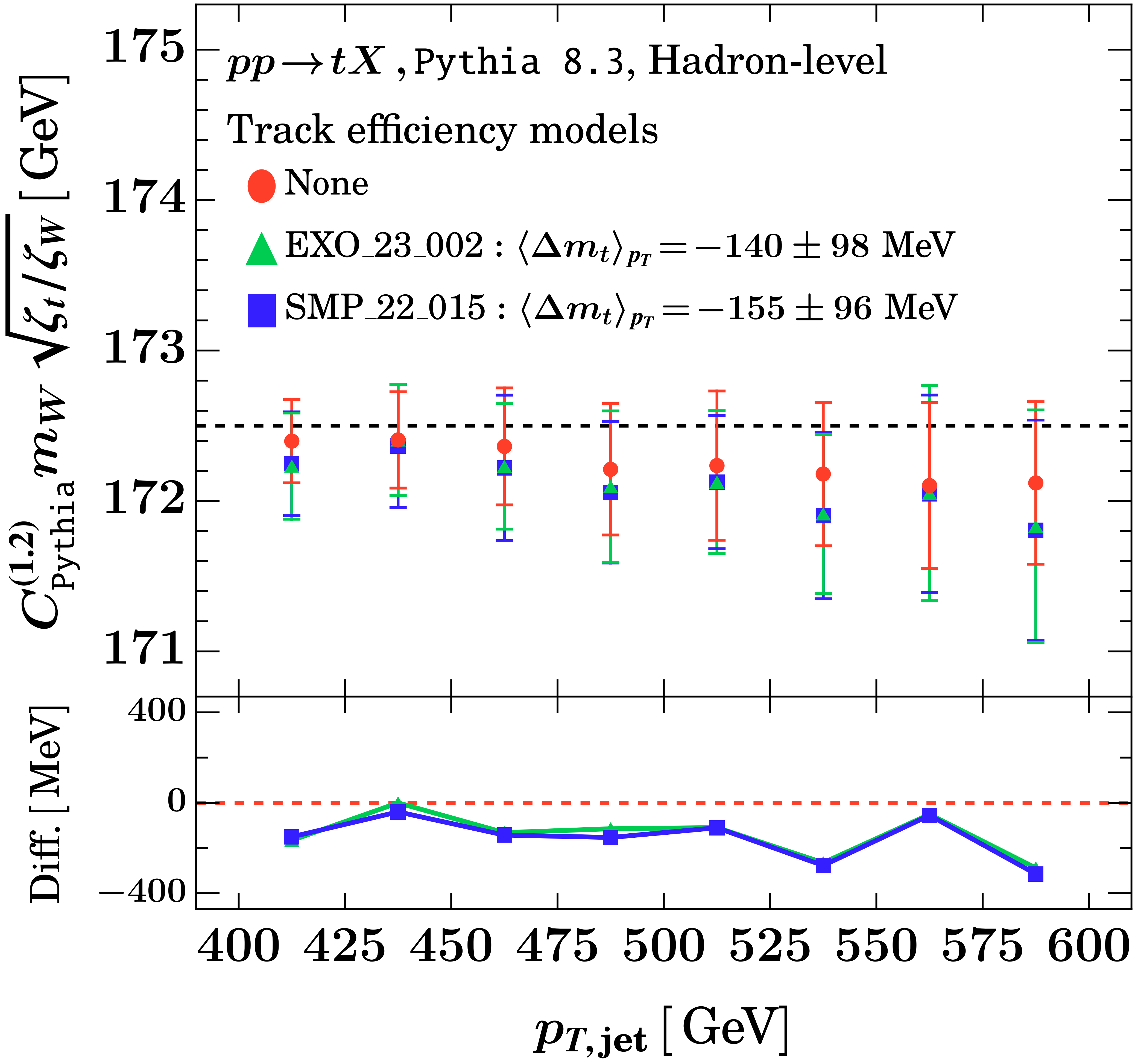
Track Efficiency

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



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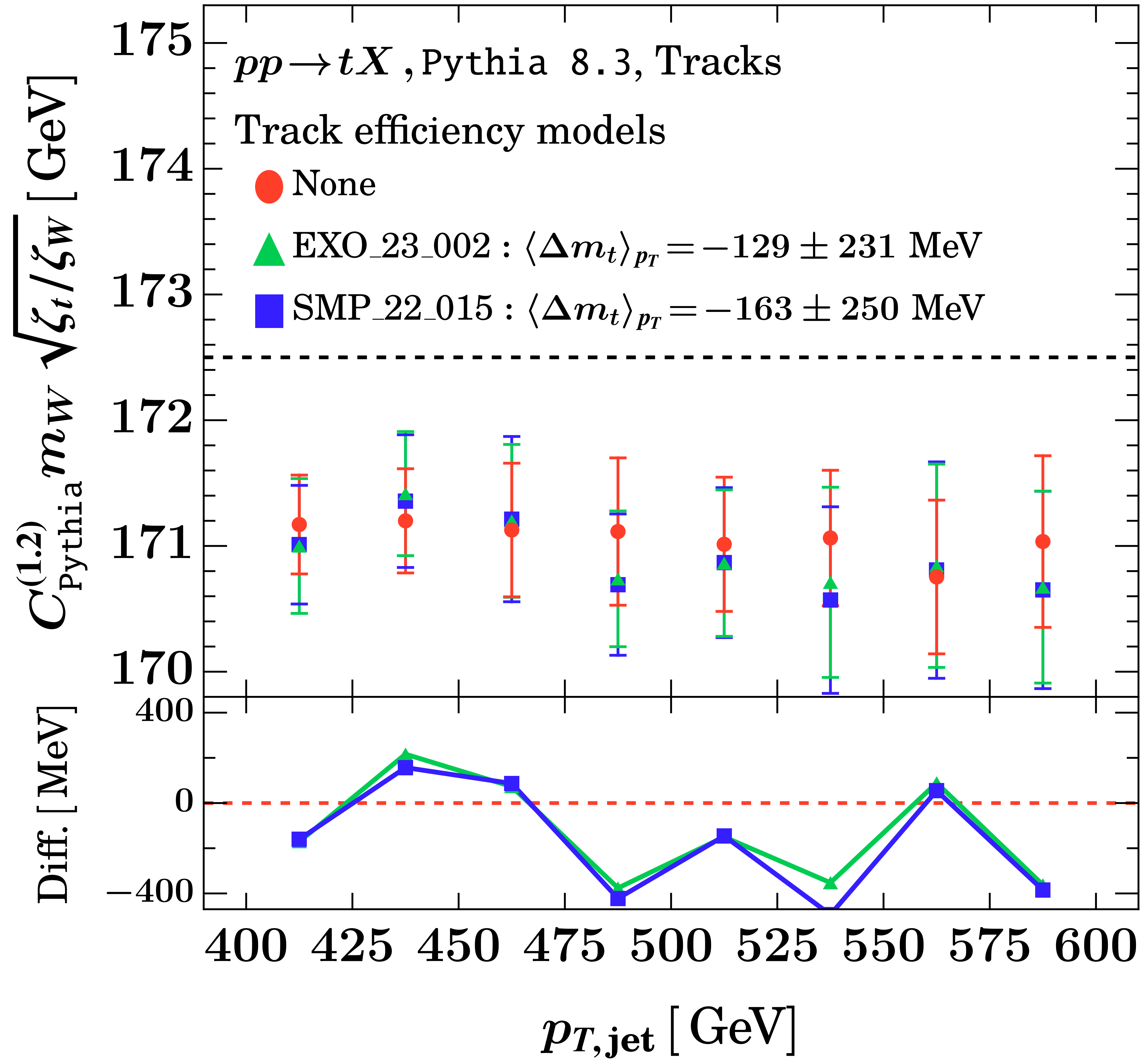
Track Efficiency

The restriction to tracks is a small effect to the EEC spectrum.

Primary shift in the W distribution: Only 10% accuracy of track function moments required.



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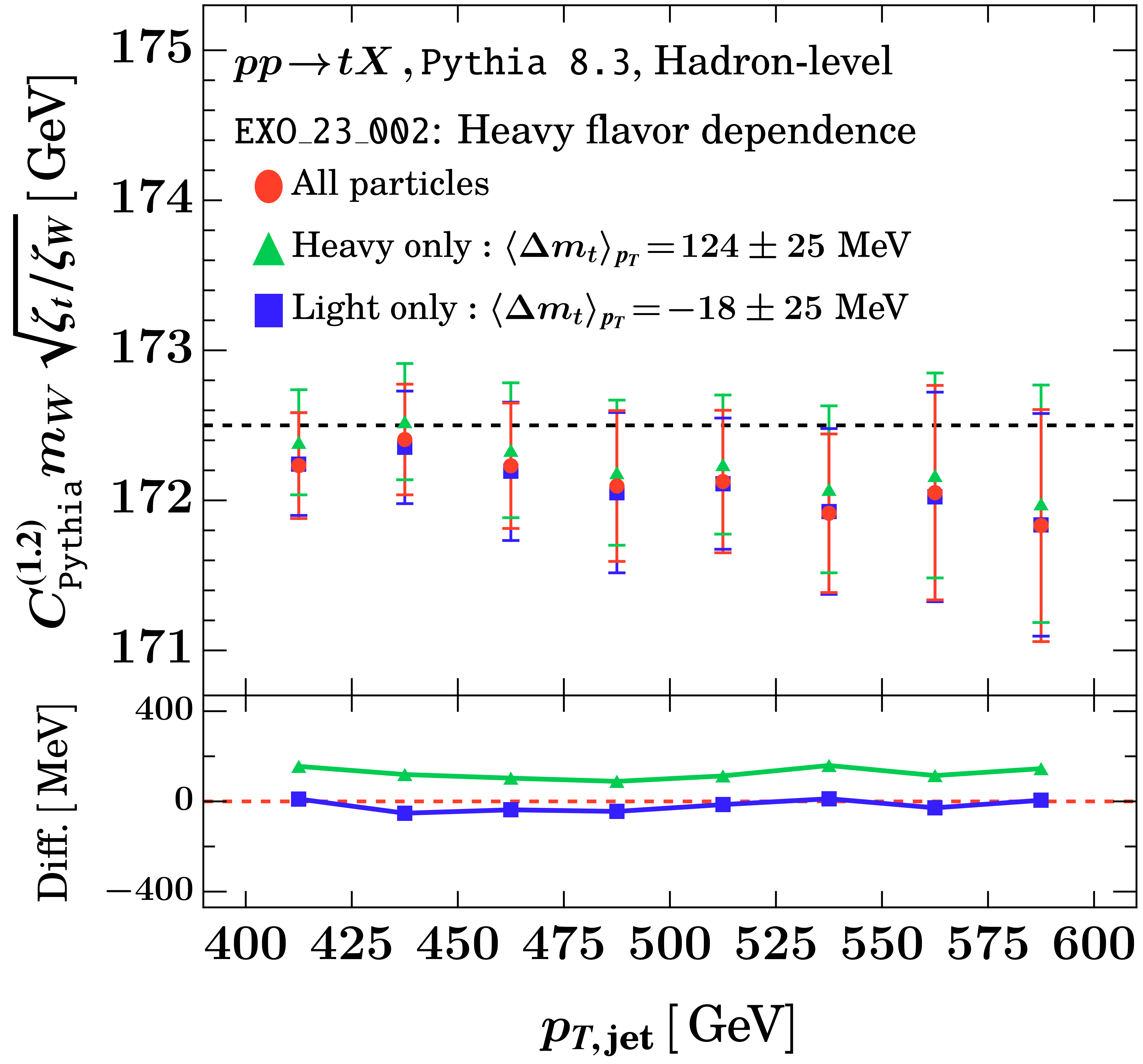
Heavy Flavor Dependence

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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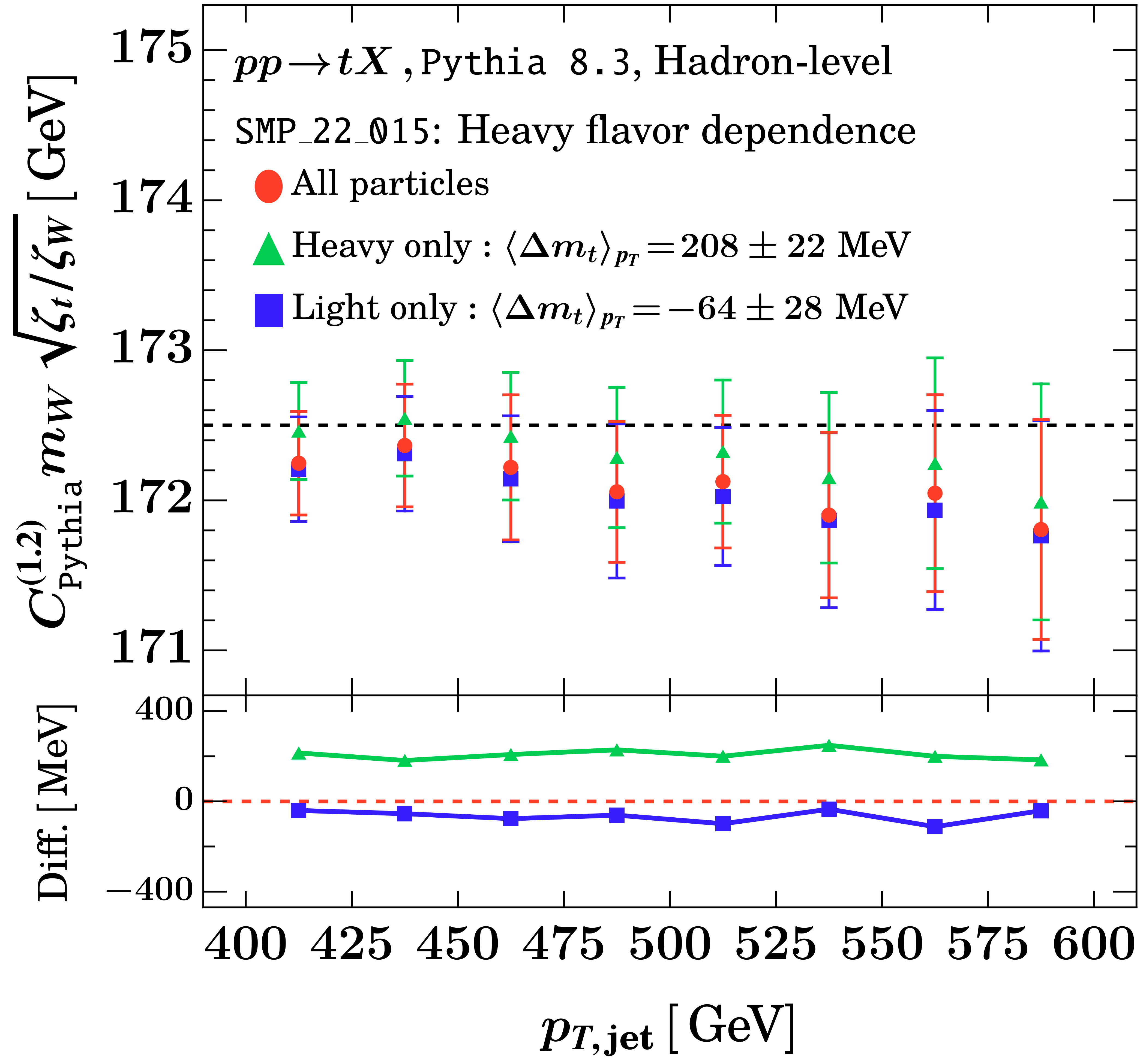

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Heavy Flavor Dependence

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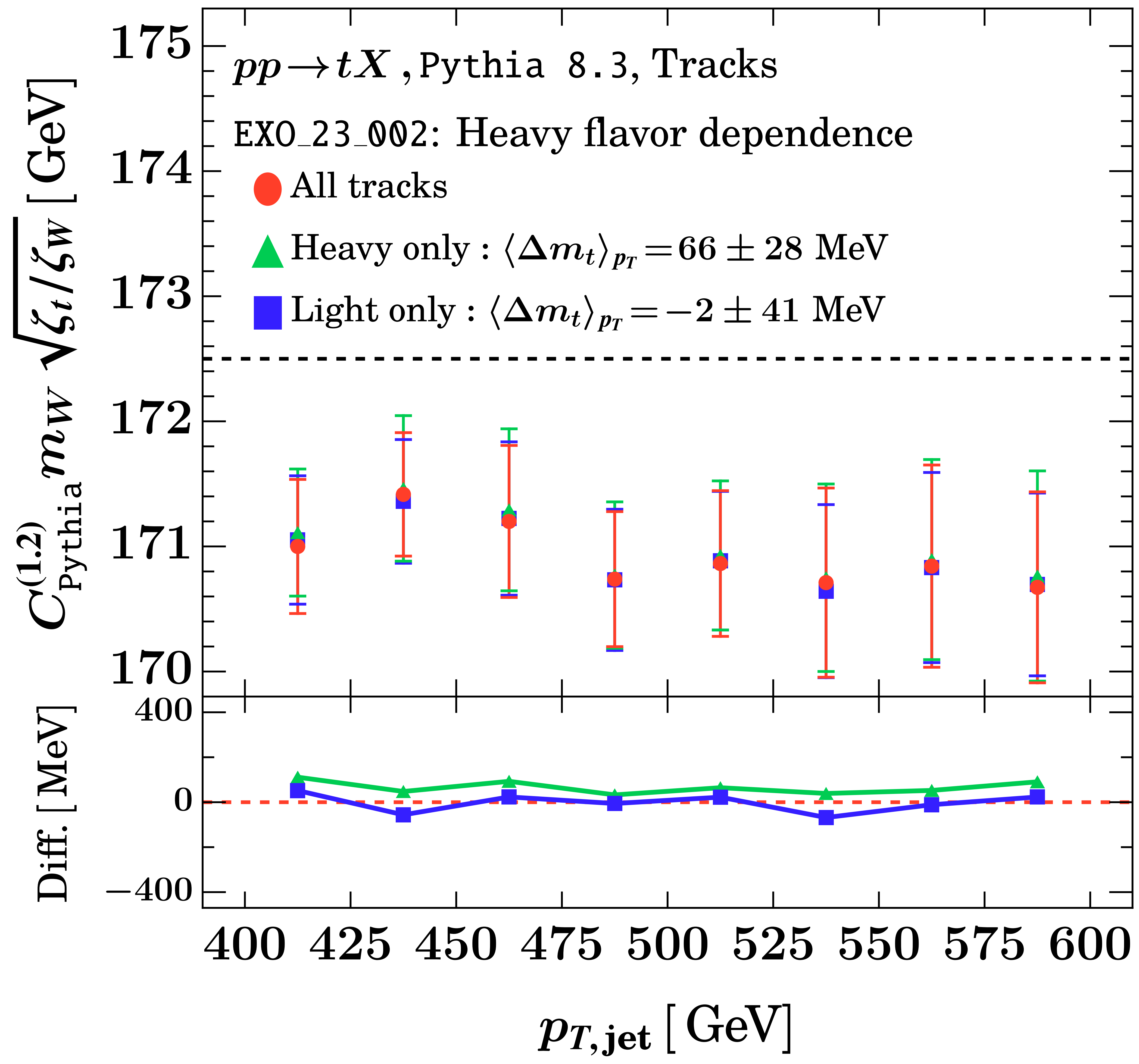

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- Jet radius dependence ☑
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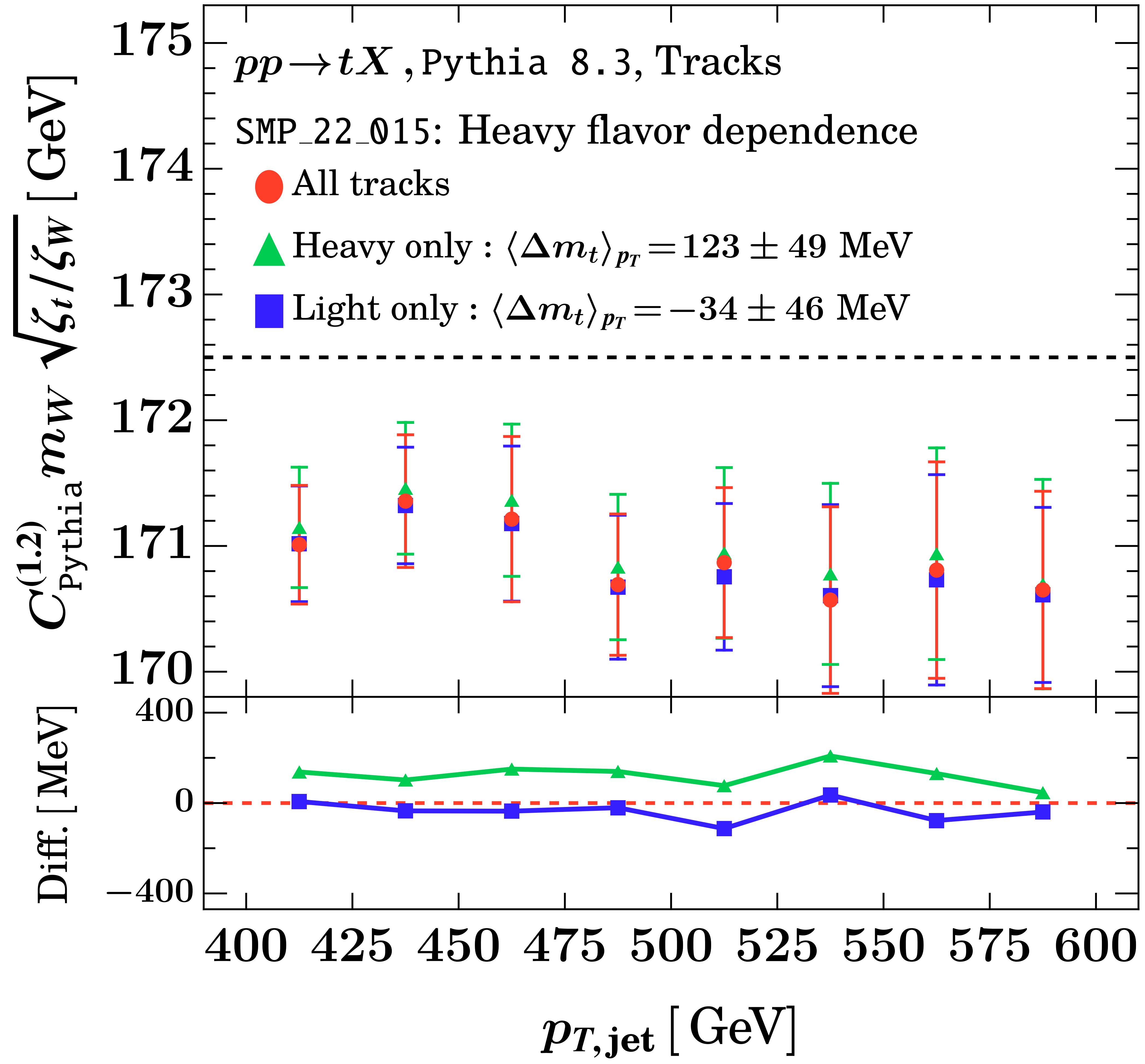
- Impact of underlying event ☑
- Wide angle soft physics ☑
- Perturbative uncertainty ☑

Experimental feasibility:

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

Heavy Flavor Dependence

A known effect in detectors is the different jet response depending on the origin of a jet. Smaller effect for track-based EEC.



Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2024

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 ☑

We are done …

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:

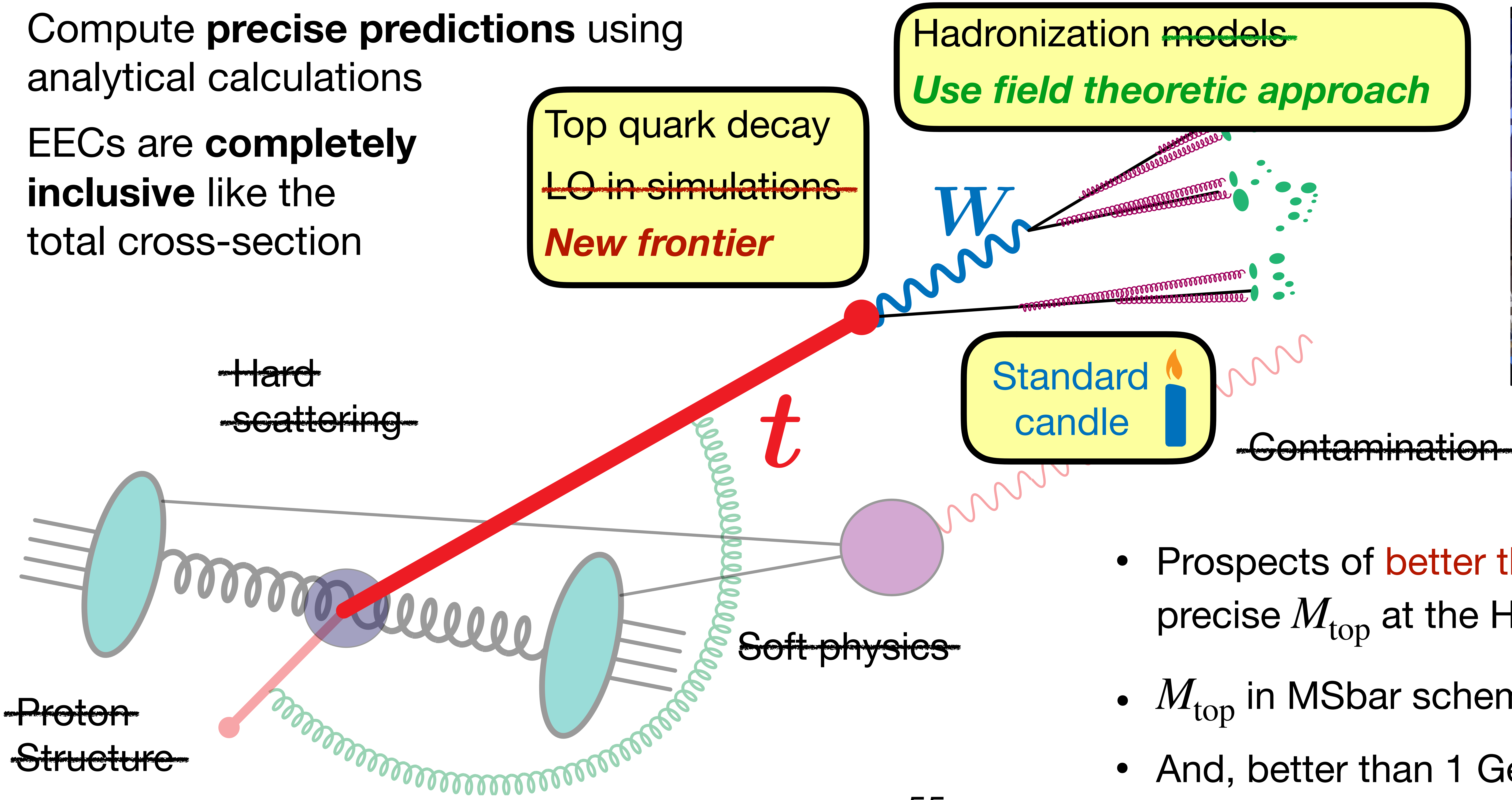
- Statistical sensitivity ☑
- Jet energy scale ☑
- Constituent energy scale ☑
- Track efficiency ☑
- Heavy flavor dependence ☑

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

~~LO in simulations~~

New frontier

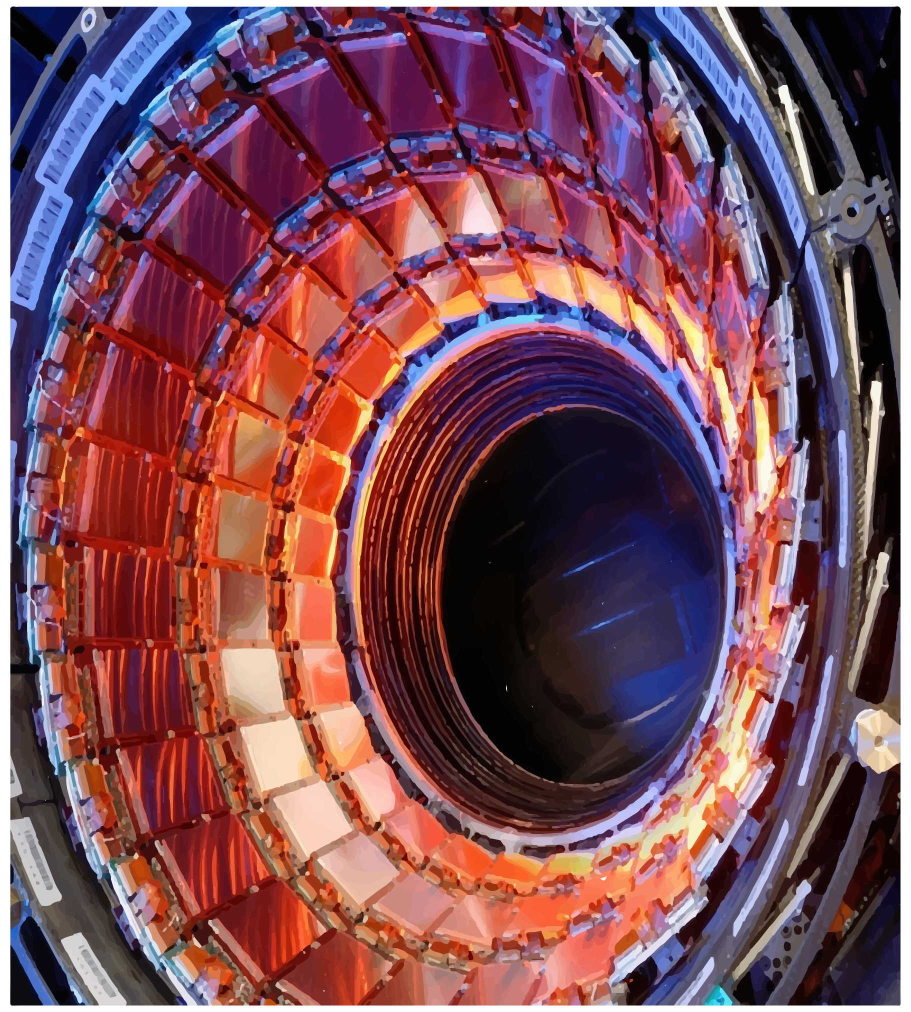
Standard candle

~~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

Conclusions

Hadronization ~~models~~
Use Field theoretic approaches

~~Energy scale uncertainty~~
Exciting measurement prospects

Top quark decay
~~LO in Simulations~~
New frontier

Standard candle

- 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.
  - Hadronization effects in EEC can be described without modeling.
- Measurement is robust against the environment and is statistically feasible.
- A wealth of exciting directions for phenomenology, calculations, and measurements with EECs:
  - Motivates studying new interesting EEC-based observables

Thank you!

Backup

Why care about the top mass? [EW Stability]

Important role in the analysis of electroweak vacuum stability

- The outcome of EW vacuum stability depends sensitively on the precision on the top quark mass.
- Lifetime of our vacuum to decay through bubble nucleation (related to Higgs instability scale):

Khoury, Steingasser 2021-22

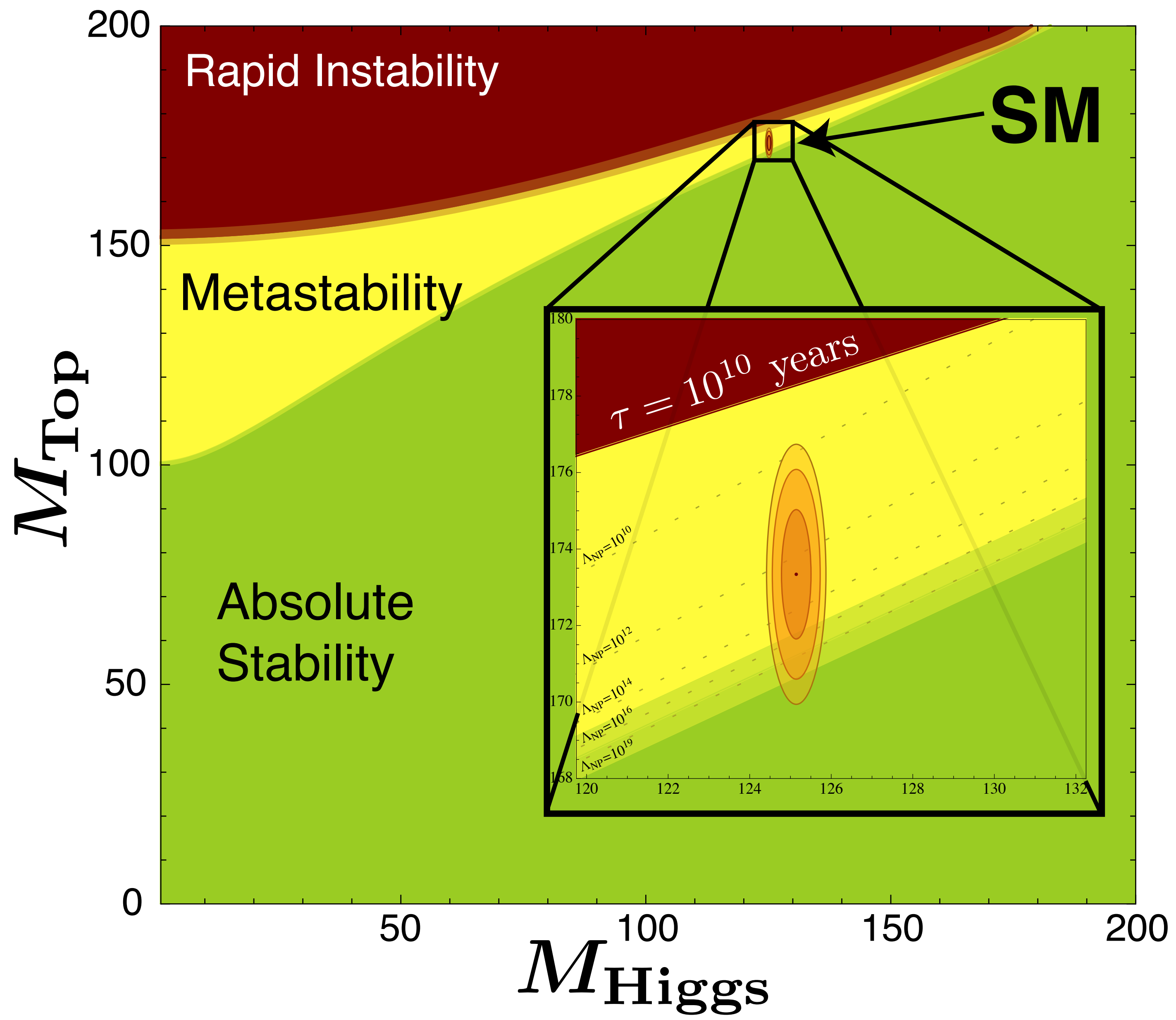
$$\tau_{\mathrm{EW}} \sim 10^{983^{+1410}_{-430}} \ \mathrm{years}$$

The enormous error stretching 2000 orders of magnitude results from the top mass precision!

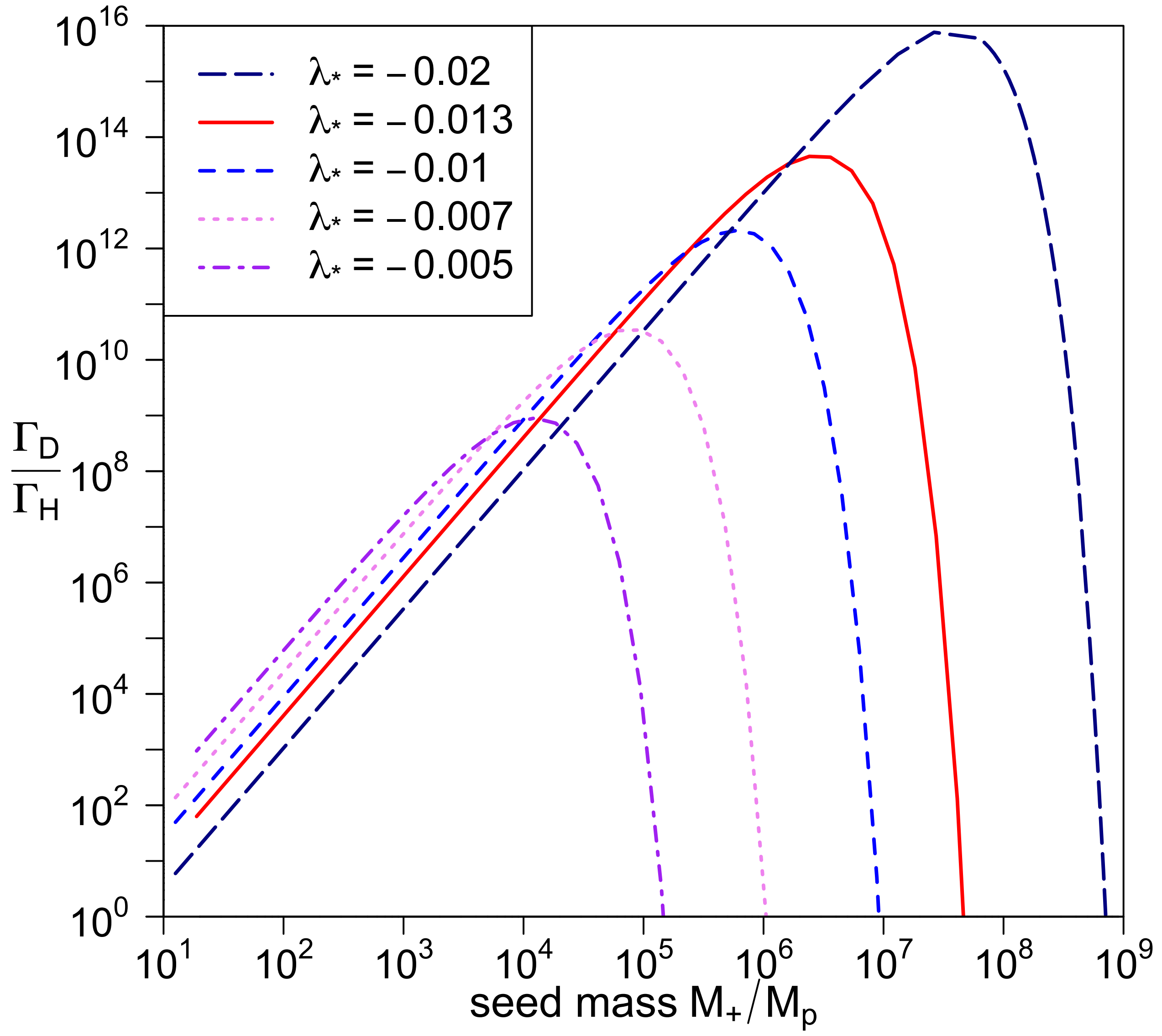
- [*Aside:* Primordial black holes can further seed and accelerate vacuum decay.
  - A single primordial black hole with mass $< 4.5 \times 10^{14}\, g$ can trigger decay if there is no BSM.]

Burda, Gregory, Moss 2015-16

- Need sub-percent ($< 1\,\mathrm{GeV}$) M_{top} to answer these questions: a longstanding problem for three decades.

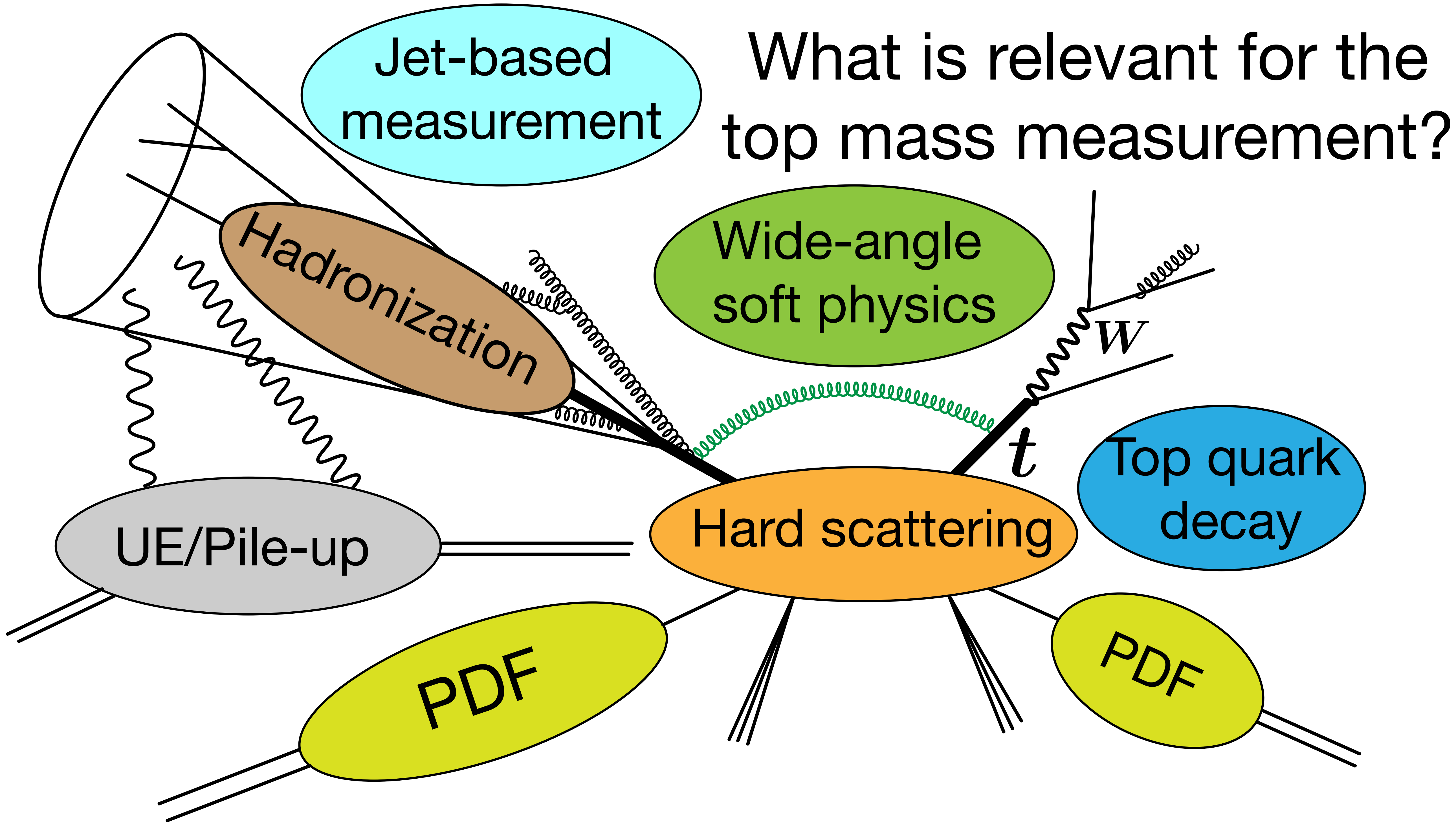


Andreassen, Frost, Schwartz 2014



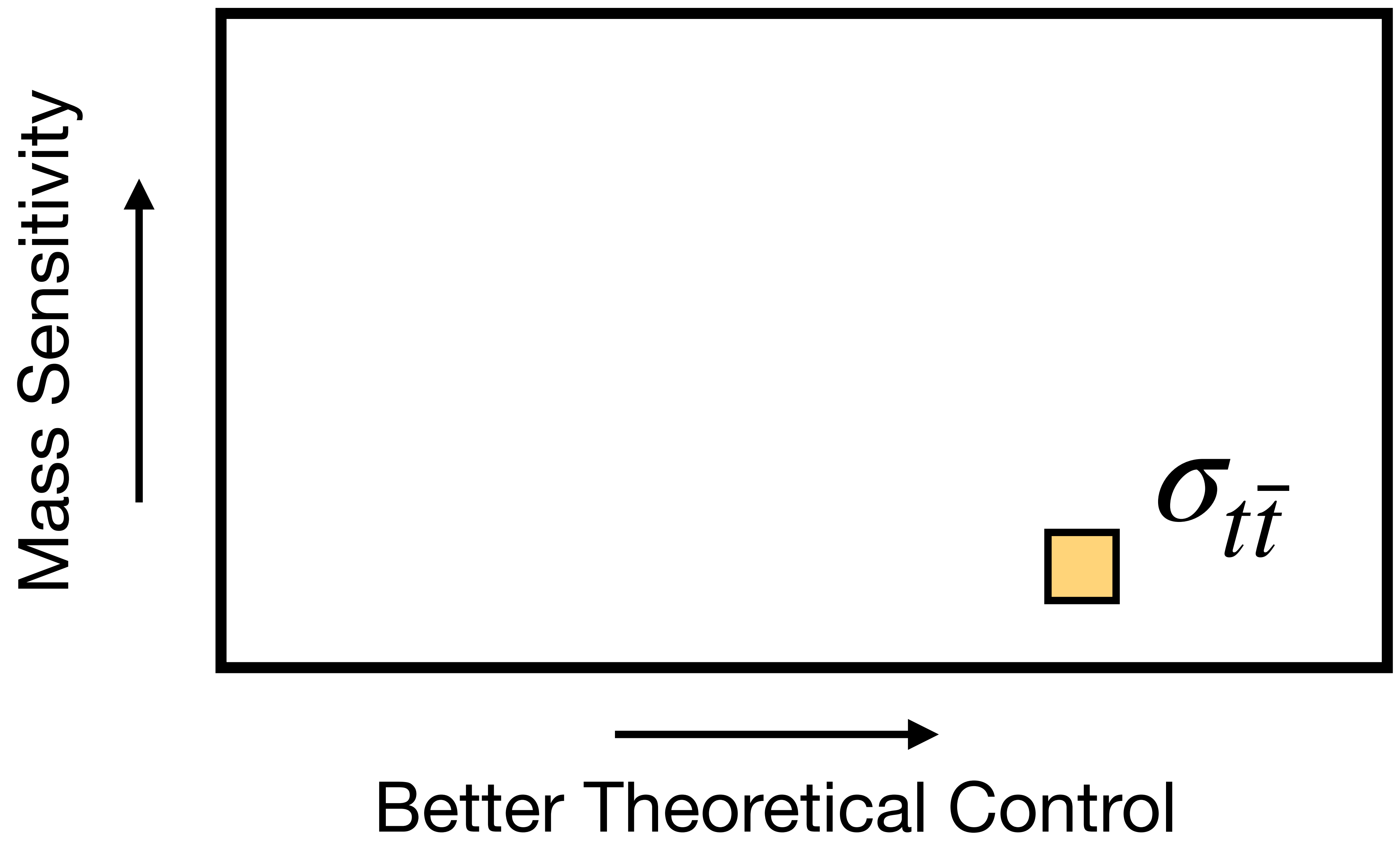
Why is the top mass measurement hard?

A **sub-GeV precise** top mass measurement **requires excellent control over a range of physical effects** at widely separated energy scales:



Total cross section

Current Paradigm:

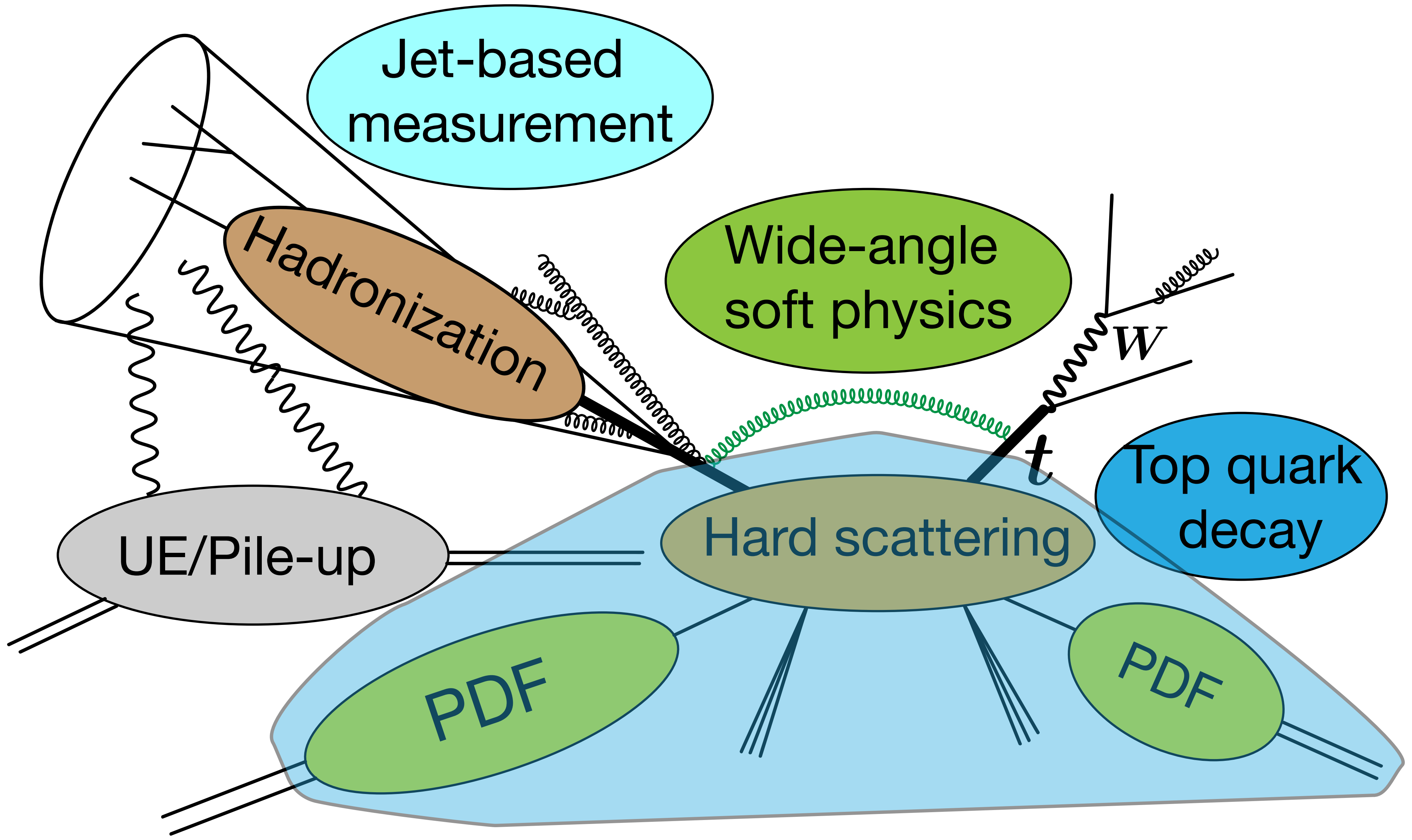


$$\boxed{m_t^{\overline{\text{MS}}} = 162.5^{+2.1}_{-1.5}\,\text{GeV}}$$

PDG

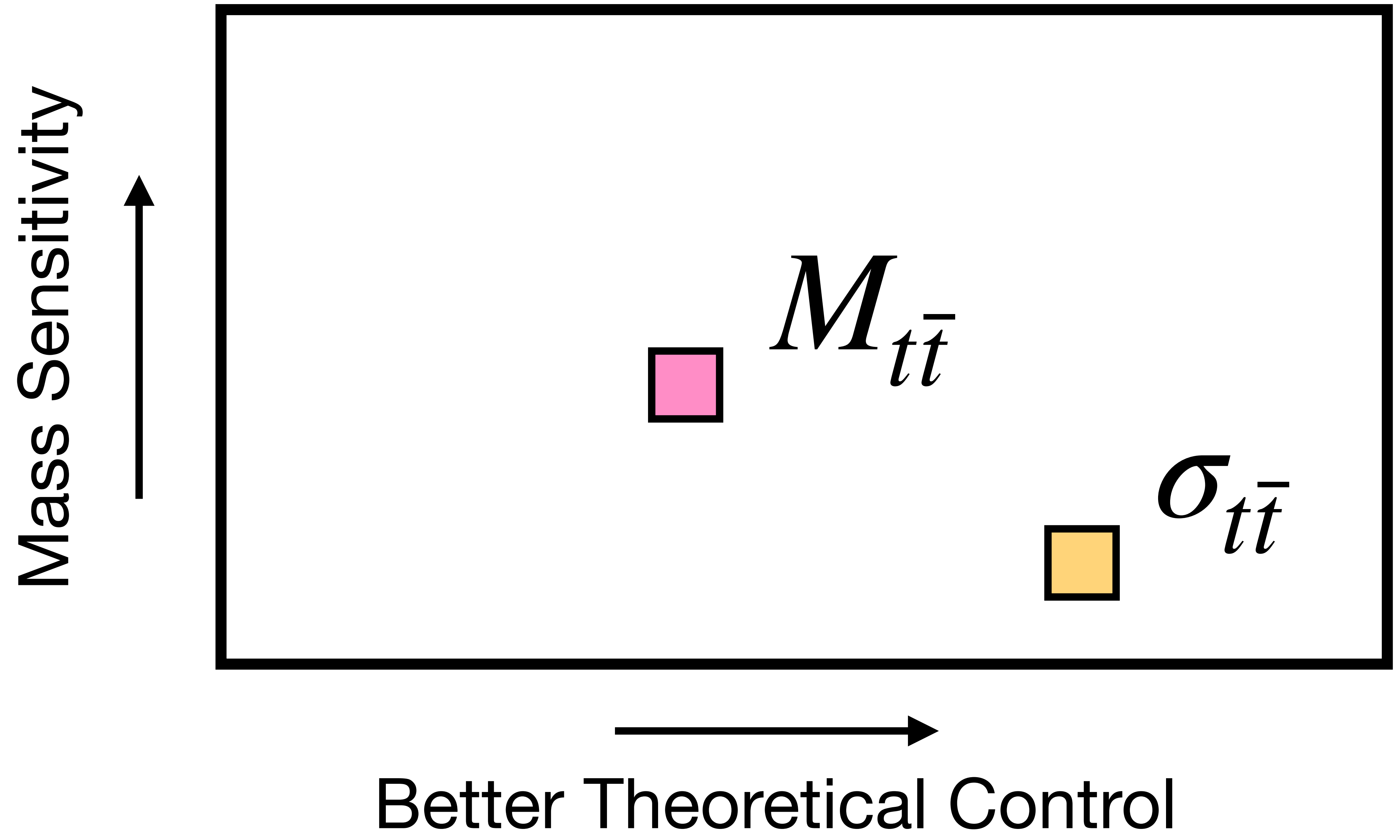
Total $t\bar{t}$ cross section:

- Theoretically robust as it primarily depends on PDF and hard scattering
- Yields measurement in well defined $\overline{\text{MS}}$ scheme.
- Weak sensitivity to the top mass.



Subtleties with m_t^{pole} measurements

Current Paradigm:

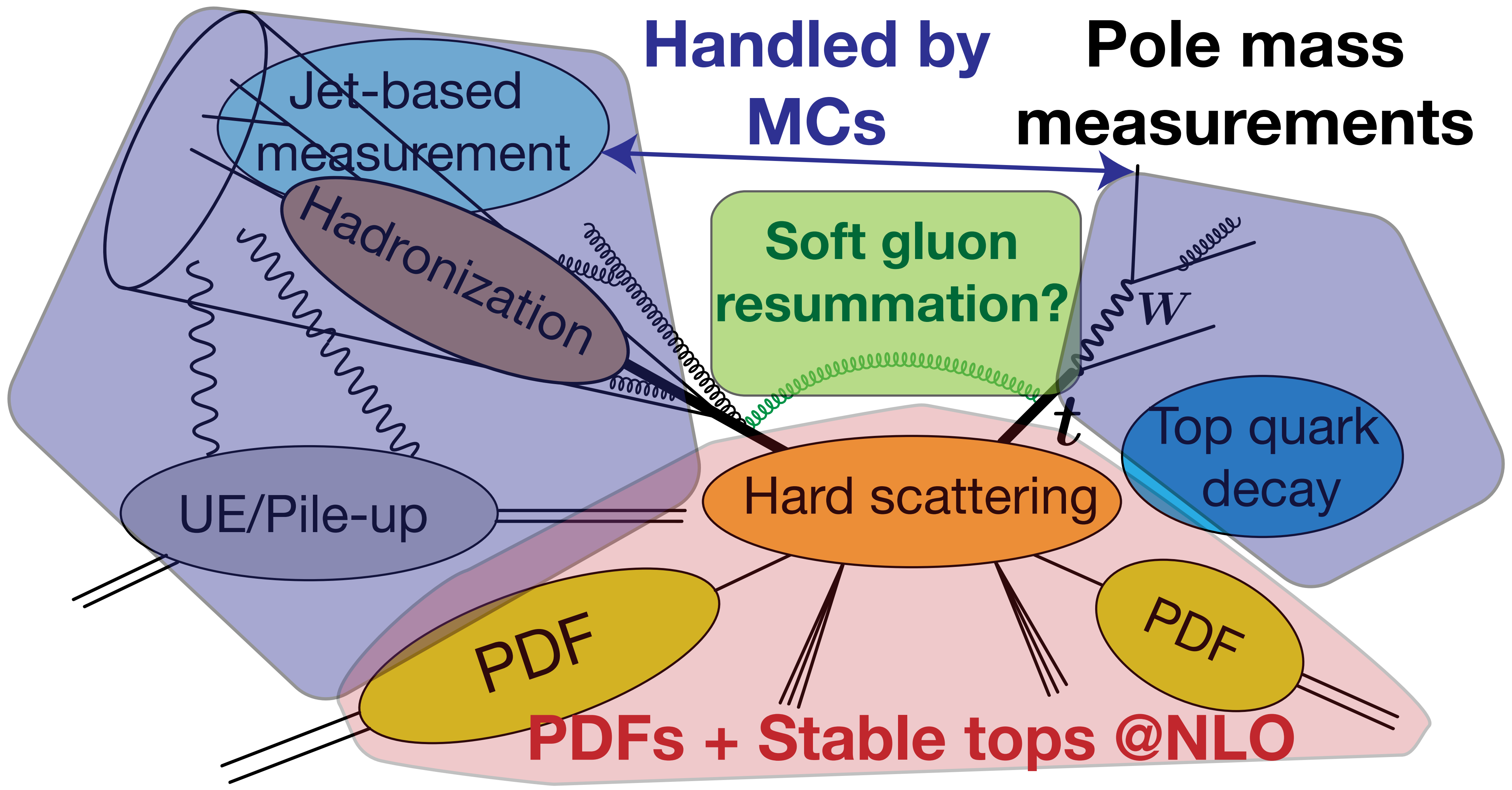


$$m_t^{\text{pole}} = 172.5 \pm 0.7\,\text{GeV}$$
$$\pm\mathcal{O}(1\,\text{GeV})\ \text{(soft physics)}$$

PDG

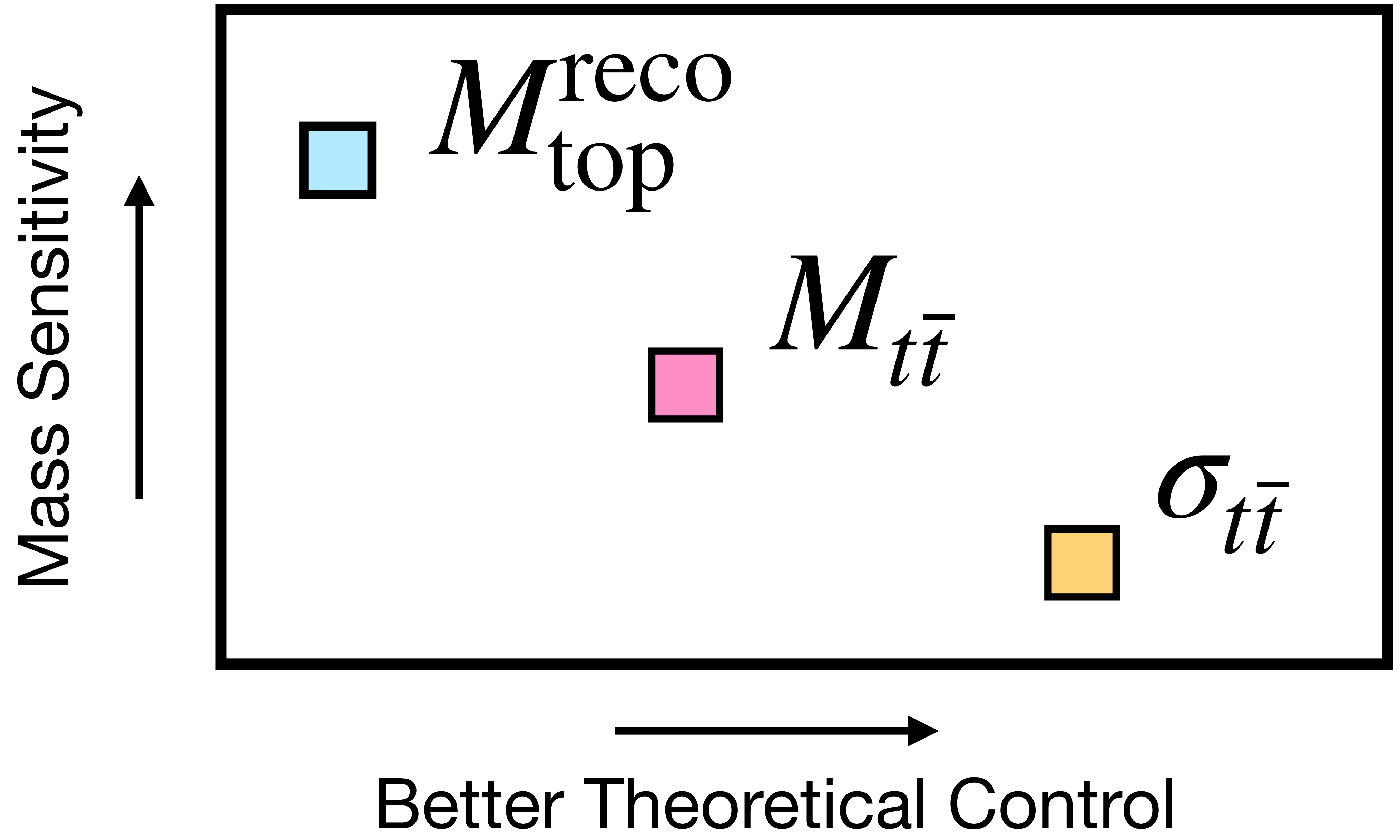
- The core NLO calculation assumes stable top quarks.
- The highest sensitivity comes from the low $m_{t\bar{t}}$ region. Coulomb and soft gluon resummation effects important and not included.
  - Argued to induce $\mathcal{O}(1\,\text{GeV})$ effects

CMS 1904.05237, Piclum Schwinn 2018



What mass is m_t^{MC}?

Current Paradigm:



$$m_t^{\text{MC}} = 172.69 \pm 0.3\,\text{GeV}$$
$$\pm\,\mathcal{O}(1\,\text{GeV})$$

(Modeling hadronization)

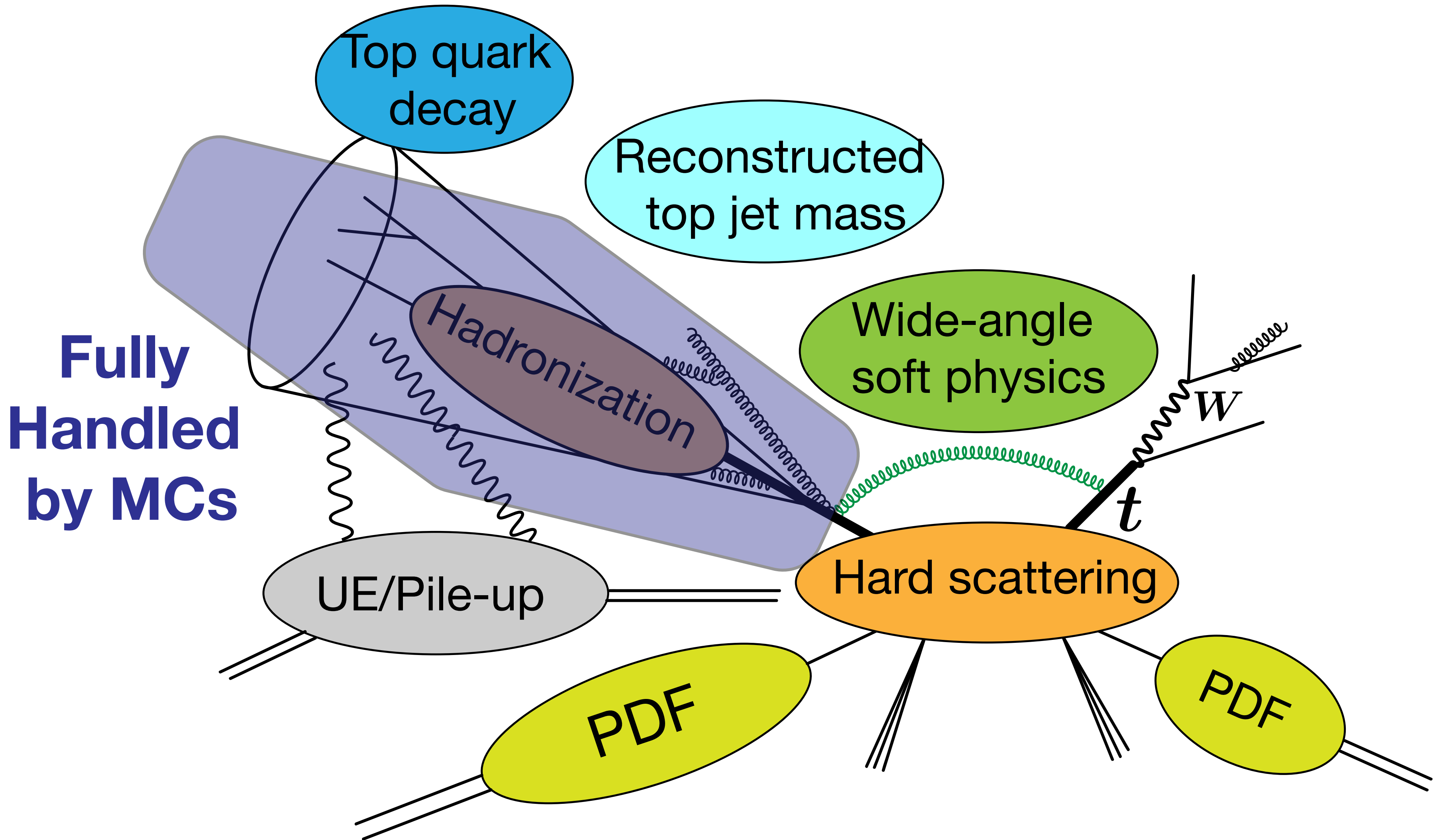
PDG

Top Mass measurement via simulations:

- Simulating the top quark as a particle with a definite mass ignores $\mathcal{O}(1\,\text{GeV})$ long-distance effects

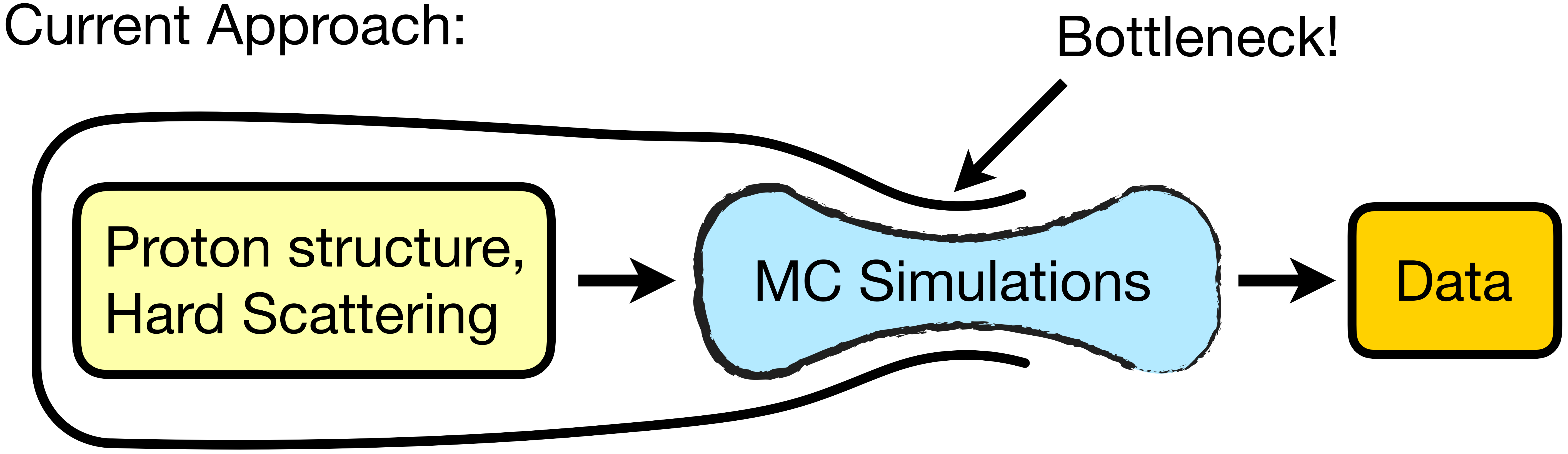
See Hoang 2004.12915

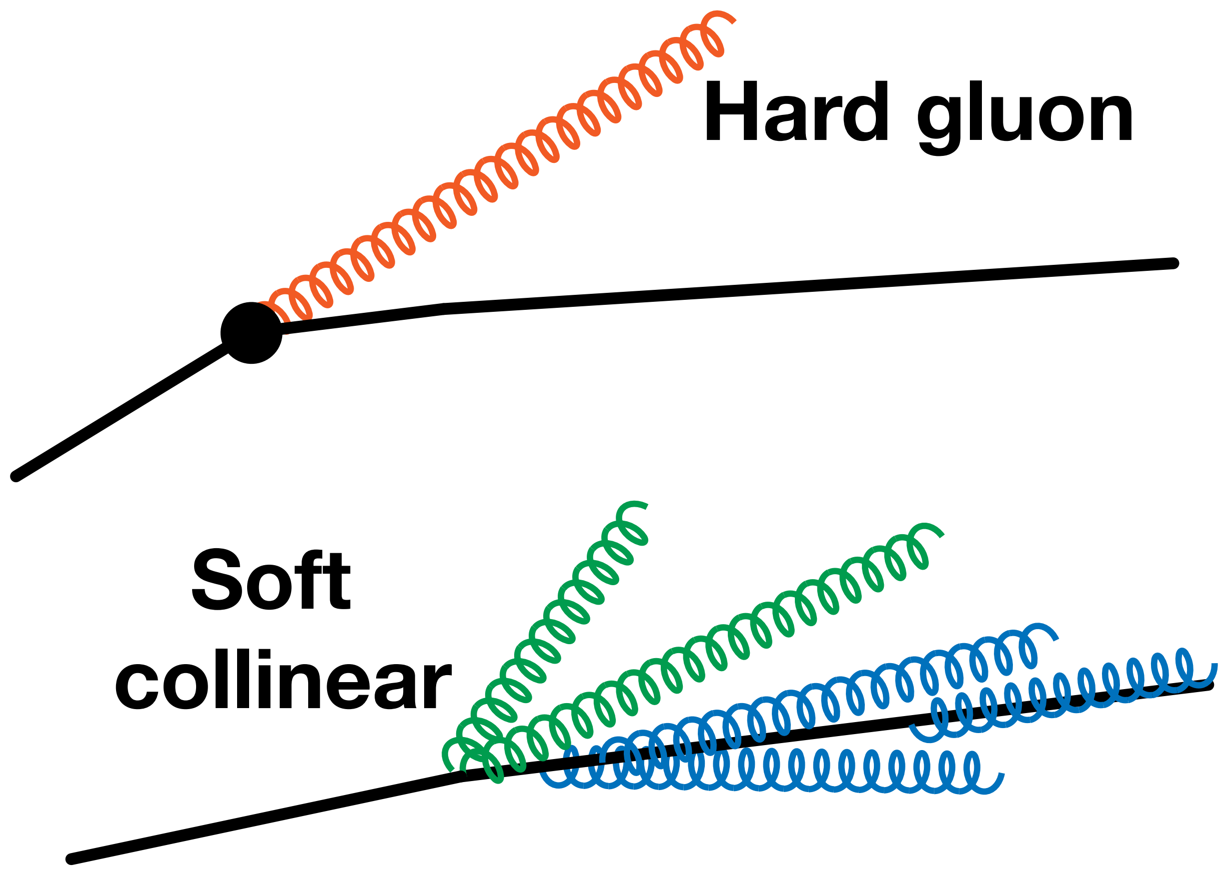
- Complicated interface with parton shower and hadronization modeling.
  - No well defined relation to a field theoretic mass scheme



Problems in the current paradigm

Current Approach:





- 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.

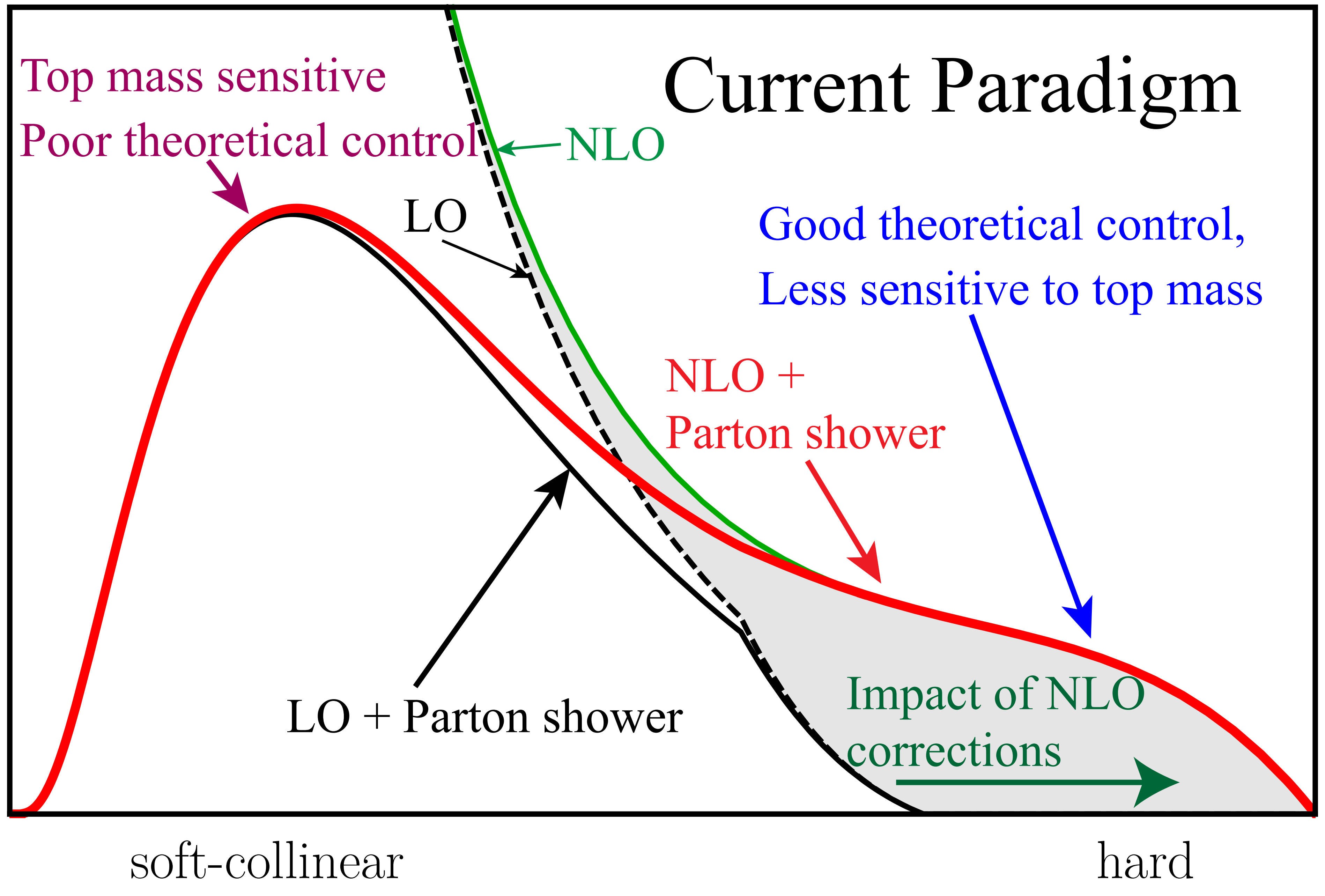


Figure adapted from Hoang 2004.12915

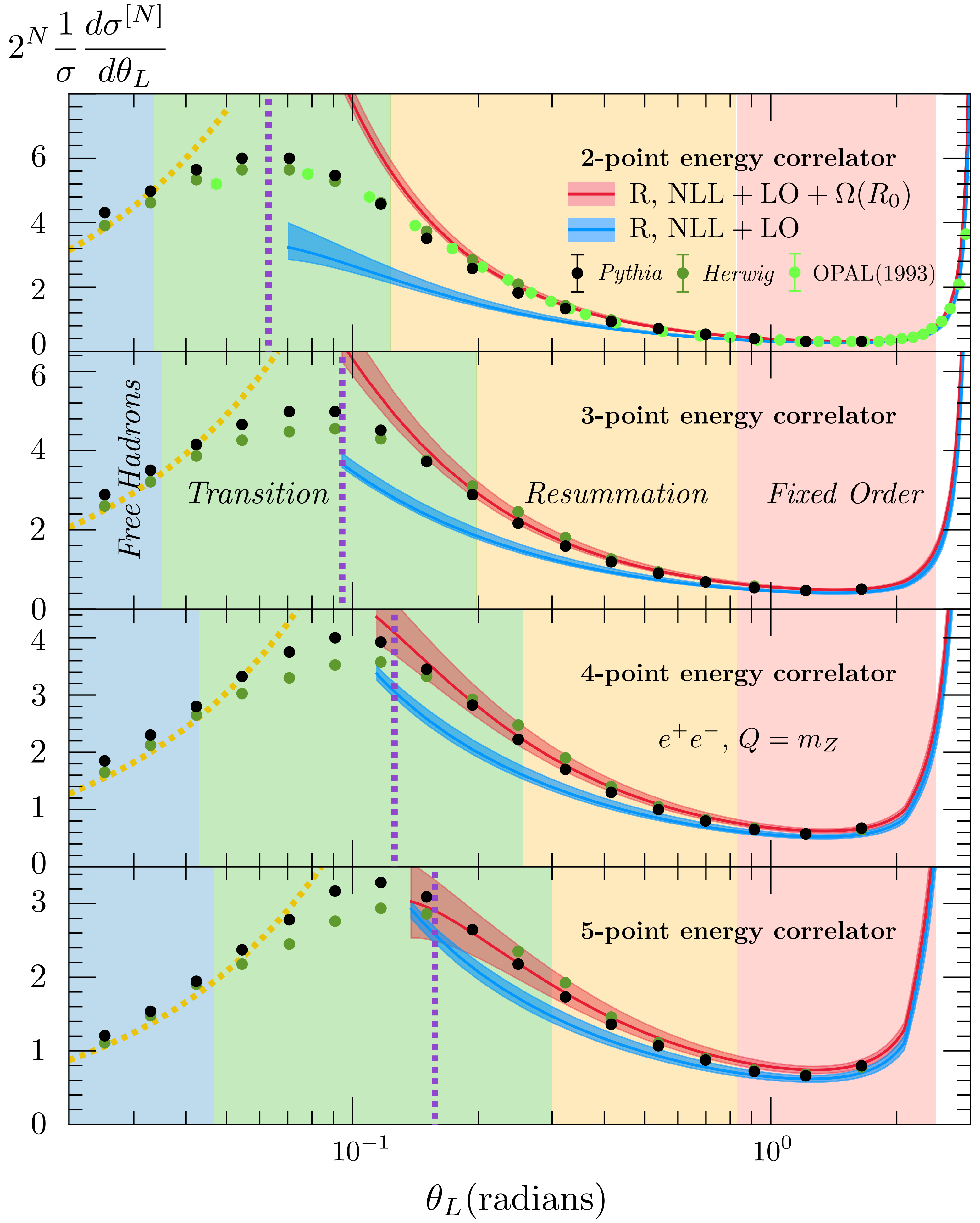
A model-independent treatment of hadronization

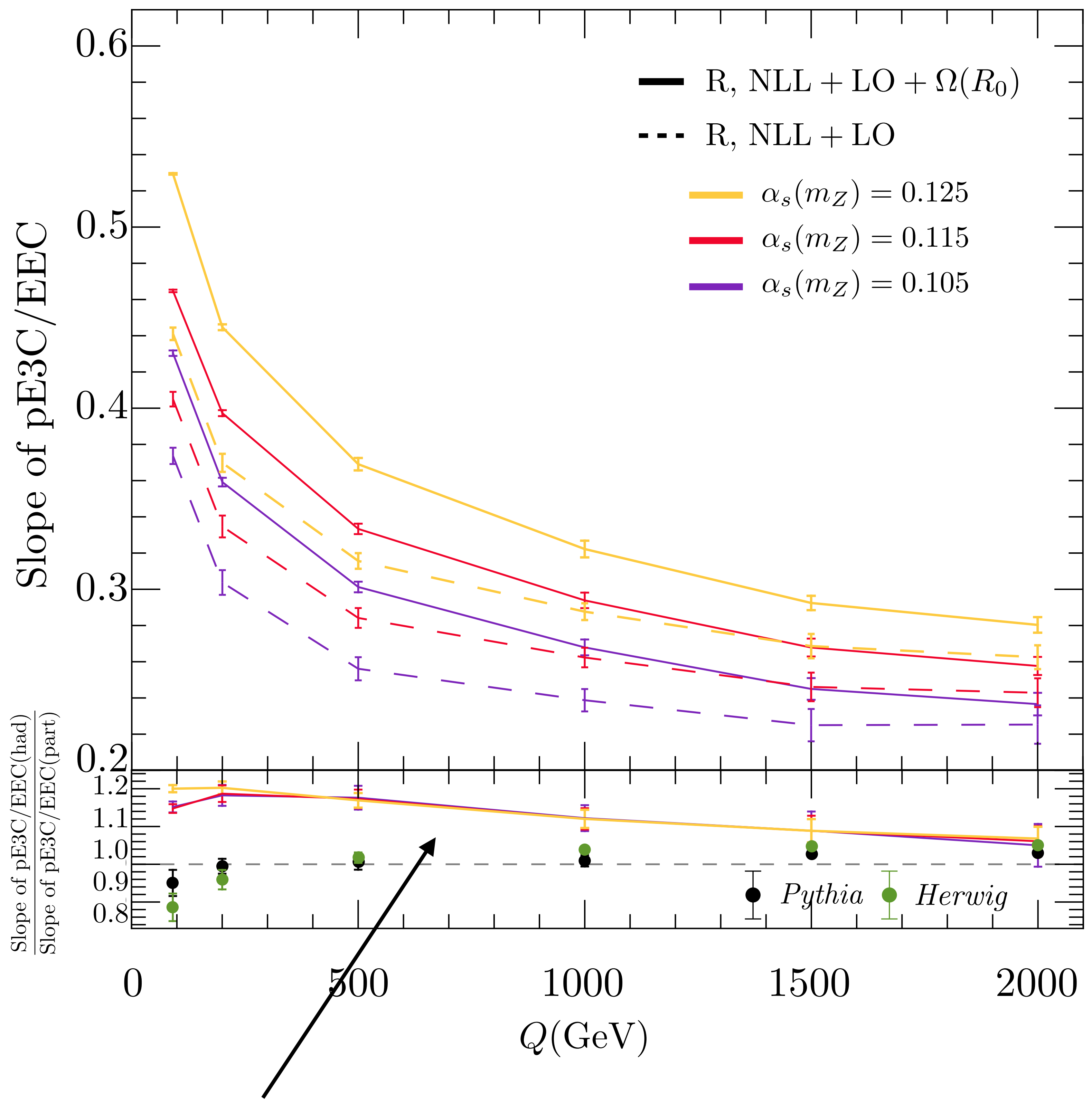
Lee, AP, Stewart, Sun arXiv:2405.19396

- EECs enable a field-theoretic analysis of hadronization effects.
- A *field-theoretic* statement about the leading nonperturbative correction:

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

- This $\overline{\Omega}_{1q}$ is universal with dijet event shapes in e^+e^- collisions.
- Enables a model-independent assessment of hadronization effects in α_s measurement



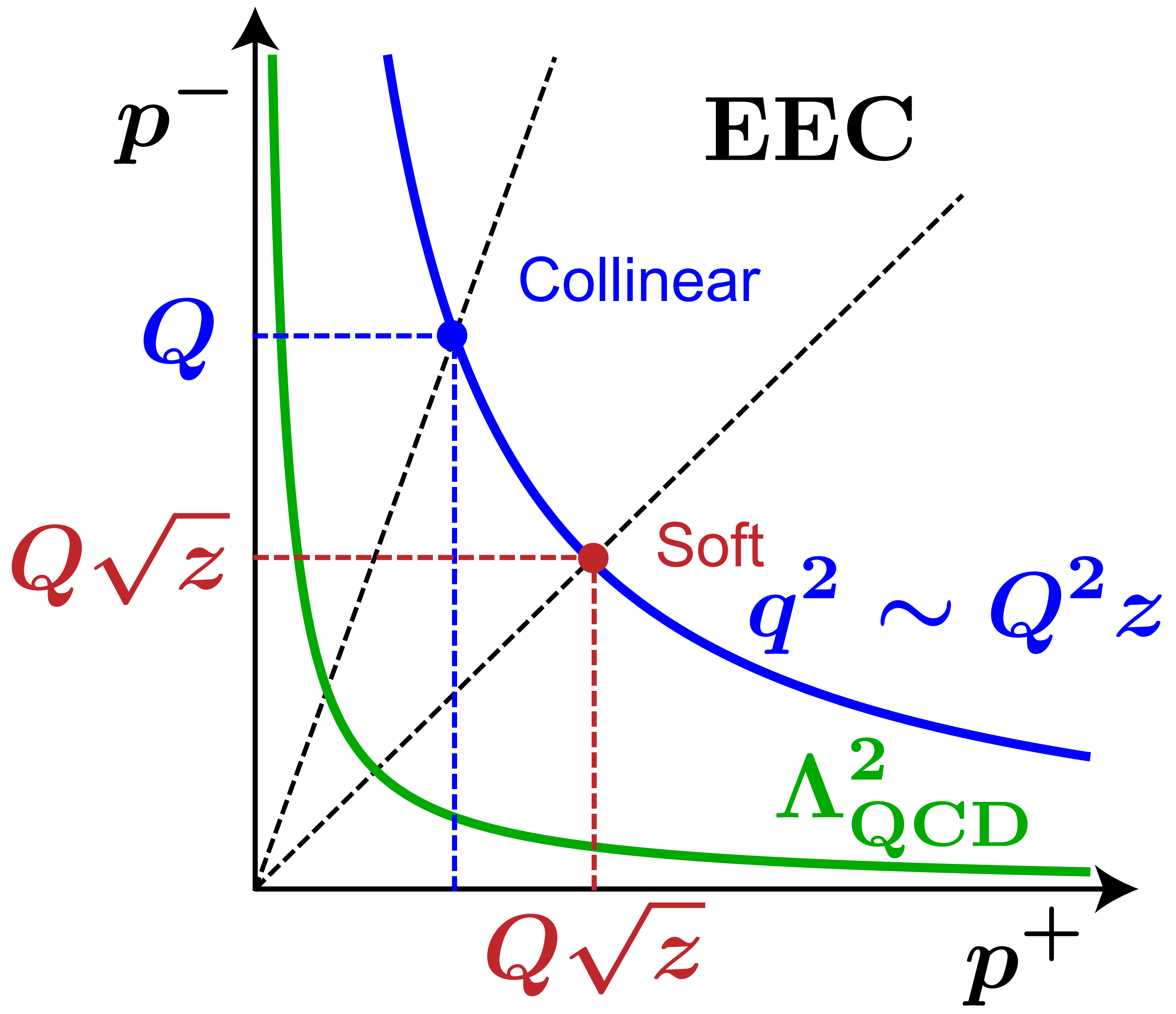


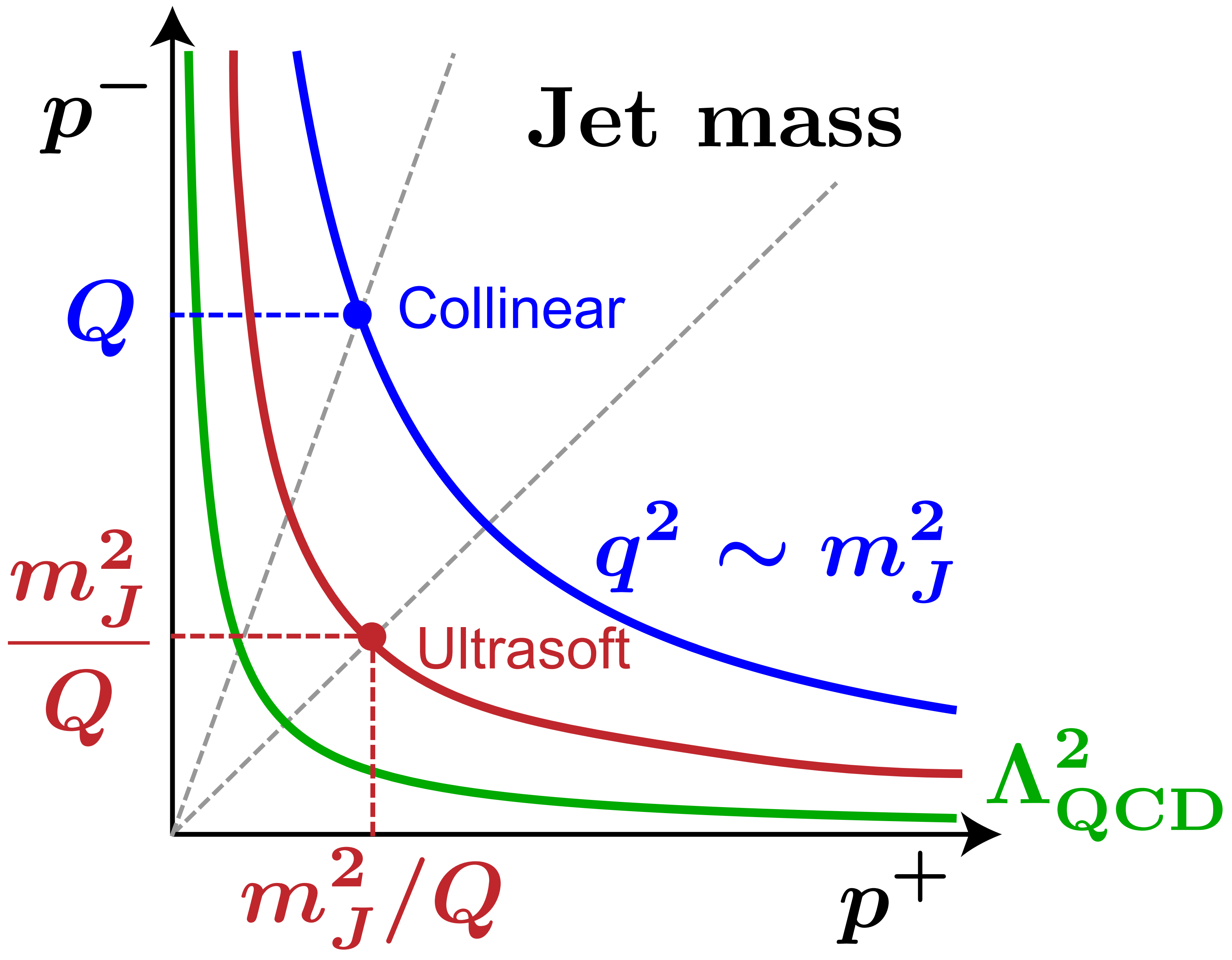
α_s MCs underestimate the size of hadronization in the collinear region!

Also see Chen, Monni, Xu, Zhu 2046.06668

Why is EEC robust against hadronization?

Unlike the jet mass, the EEC is a $\mathrm{SCET}_{\mathrm{II}}$ 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

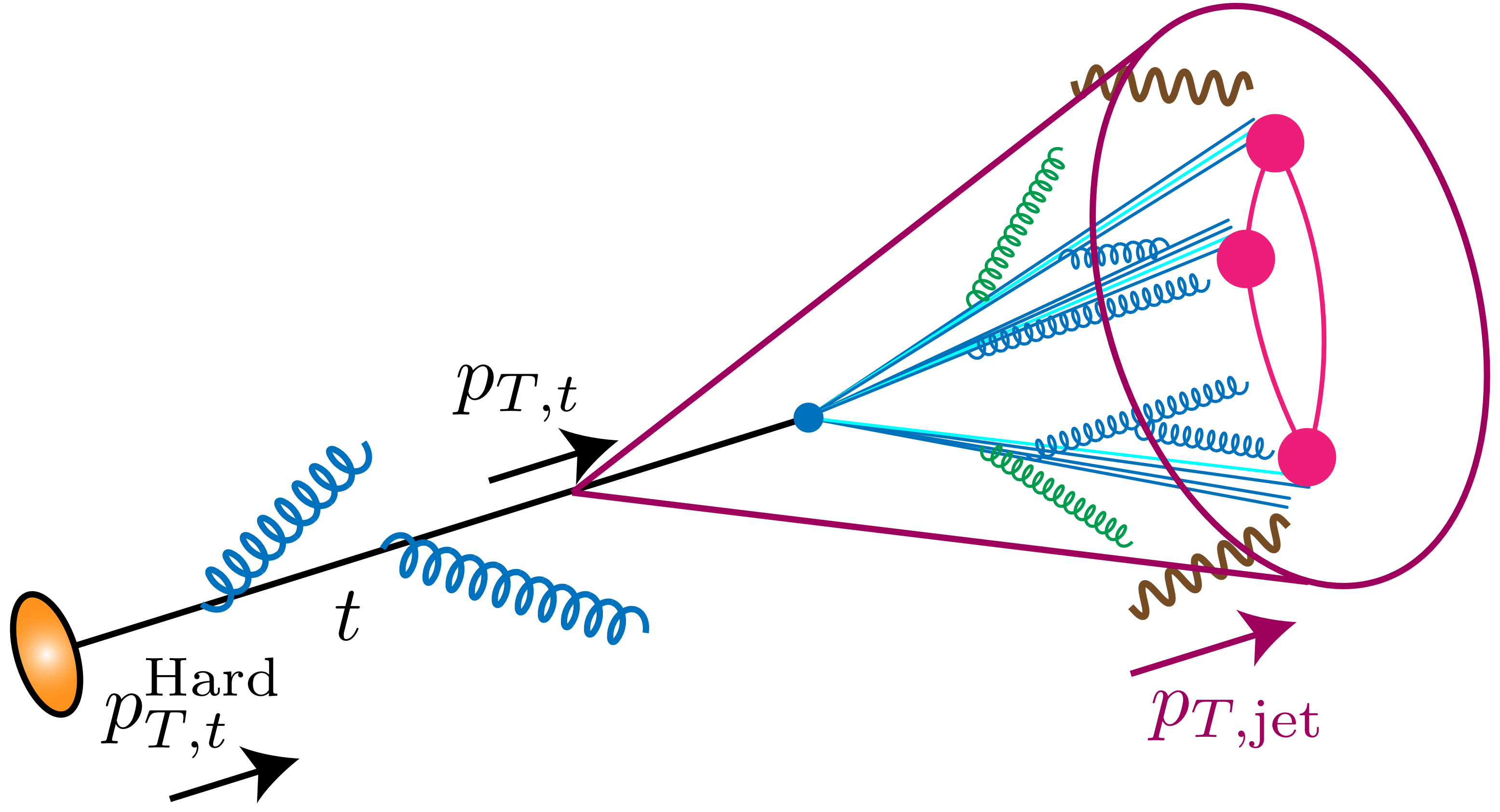
EECs are also insensitive to the contamination

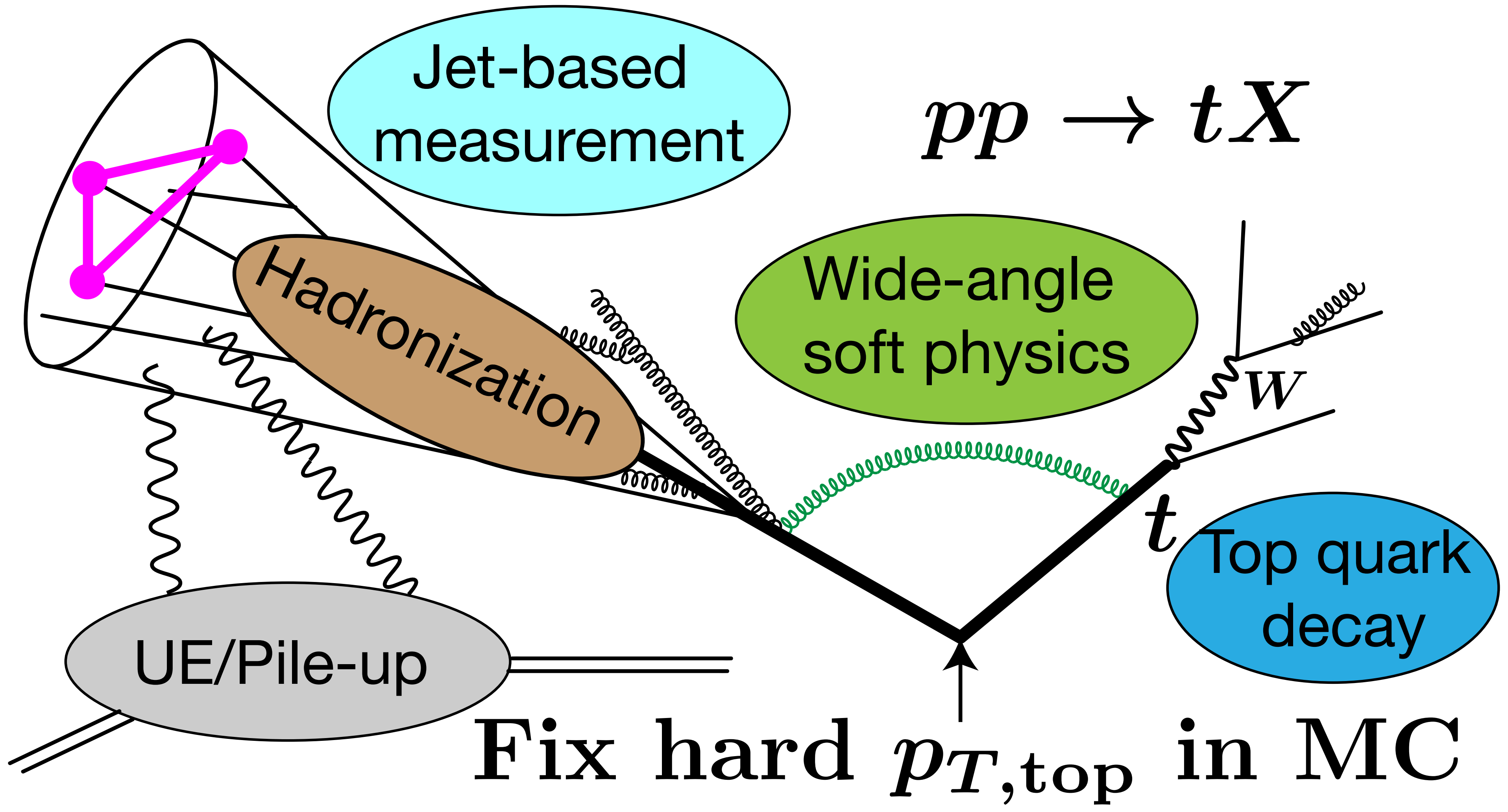
The correlator measurement can be expressed as

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

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:

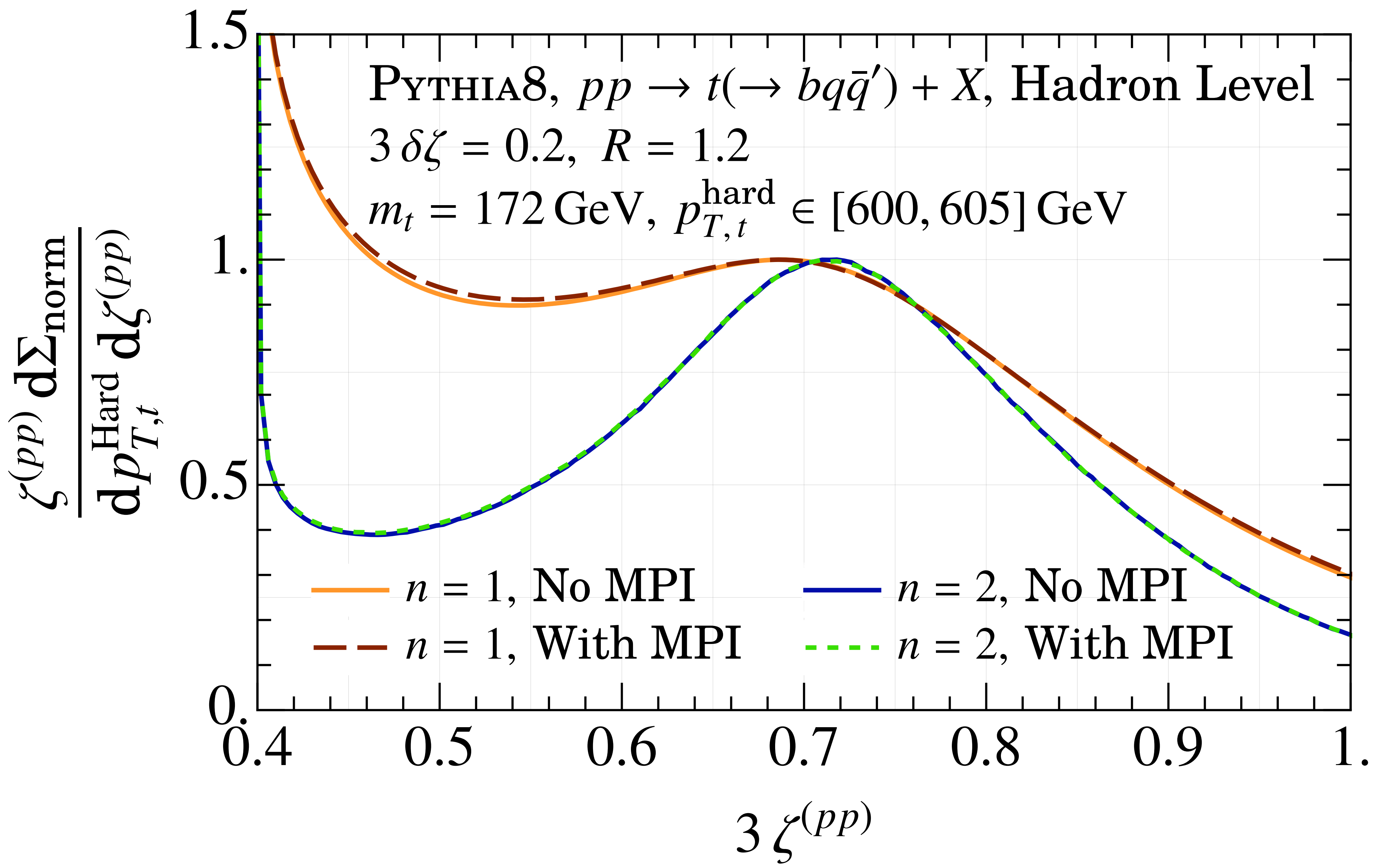
- Top quarks produced with a fixed hard p_T as in e^+e^- collisions.
- Can solely focus on the impact of the underlying event

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.