Energy Correlators and Precision top quark mass

Aditya Pathak

SM@LHC, Durham, April 2025

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 [submitted to PRL]
2407.12900: J. Holguin, I. Moult, AP, M. Procura, R. Schöfbeck, D. Schwarz [accepted by JHEP]

Outline

- Theory challenges with current top mass measurements
- Energy Correlators for precision jet substructure
- A new proposal for top mass using EECs
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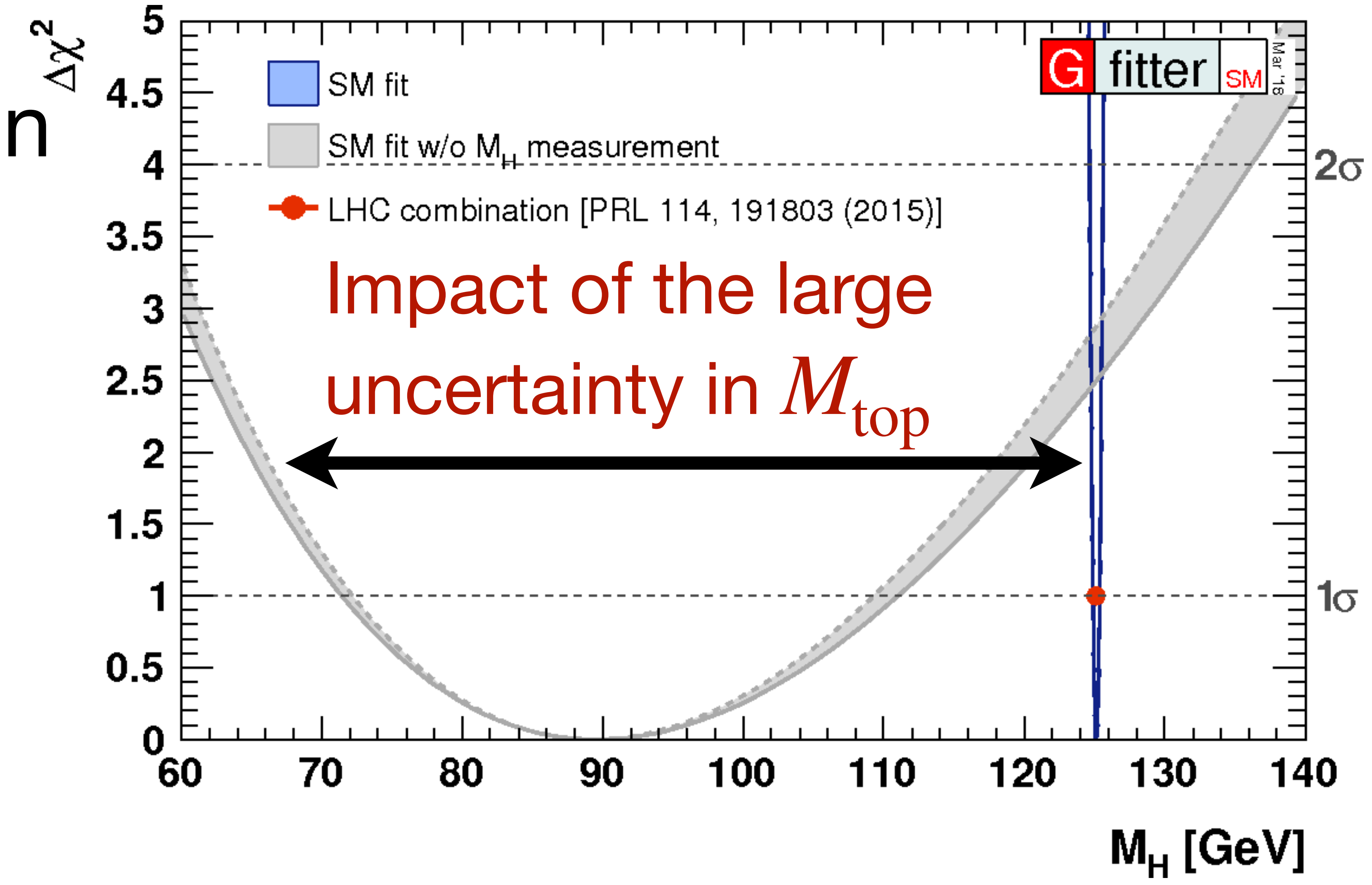
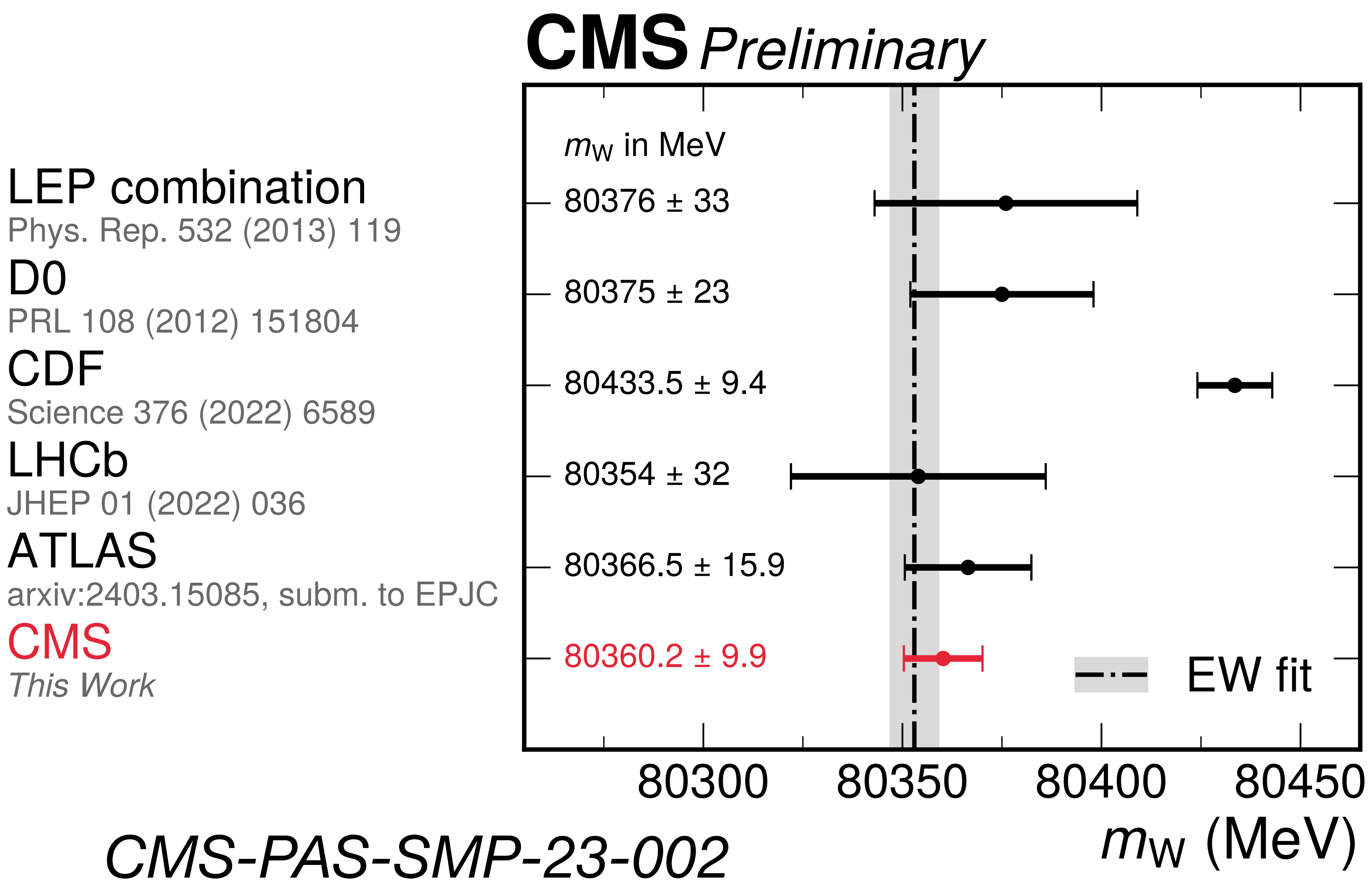
Precision Measurements: Key to new physics

- The masses of the Higgs, W and Z bosons known to < 0.2% precision
- The top mass (~172 GeV) is not as precise as you'd like it to be:
  - δM_t (~ 1 GeV) contributes the largest uncertainty $\delta M_W^{m_t} = 4\,\mathrm{MeV}$
  - A large 20 GeV uncertainty in the indirect M_H from δM_t
  - Crucial for EW Vacuum stability analysis





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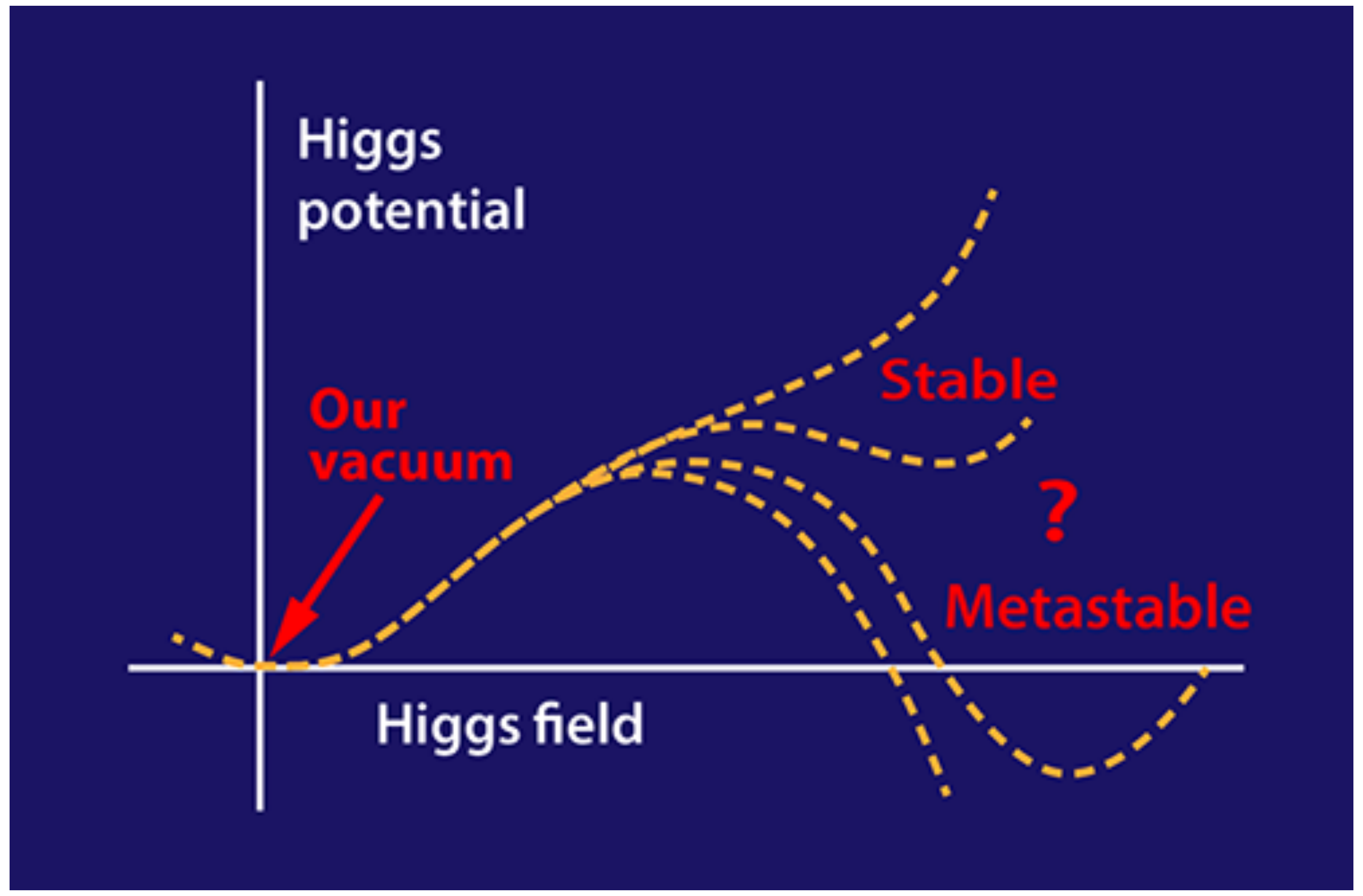
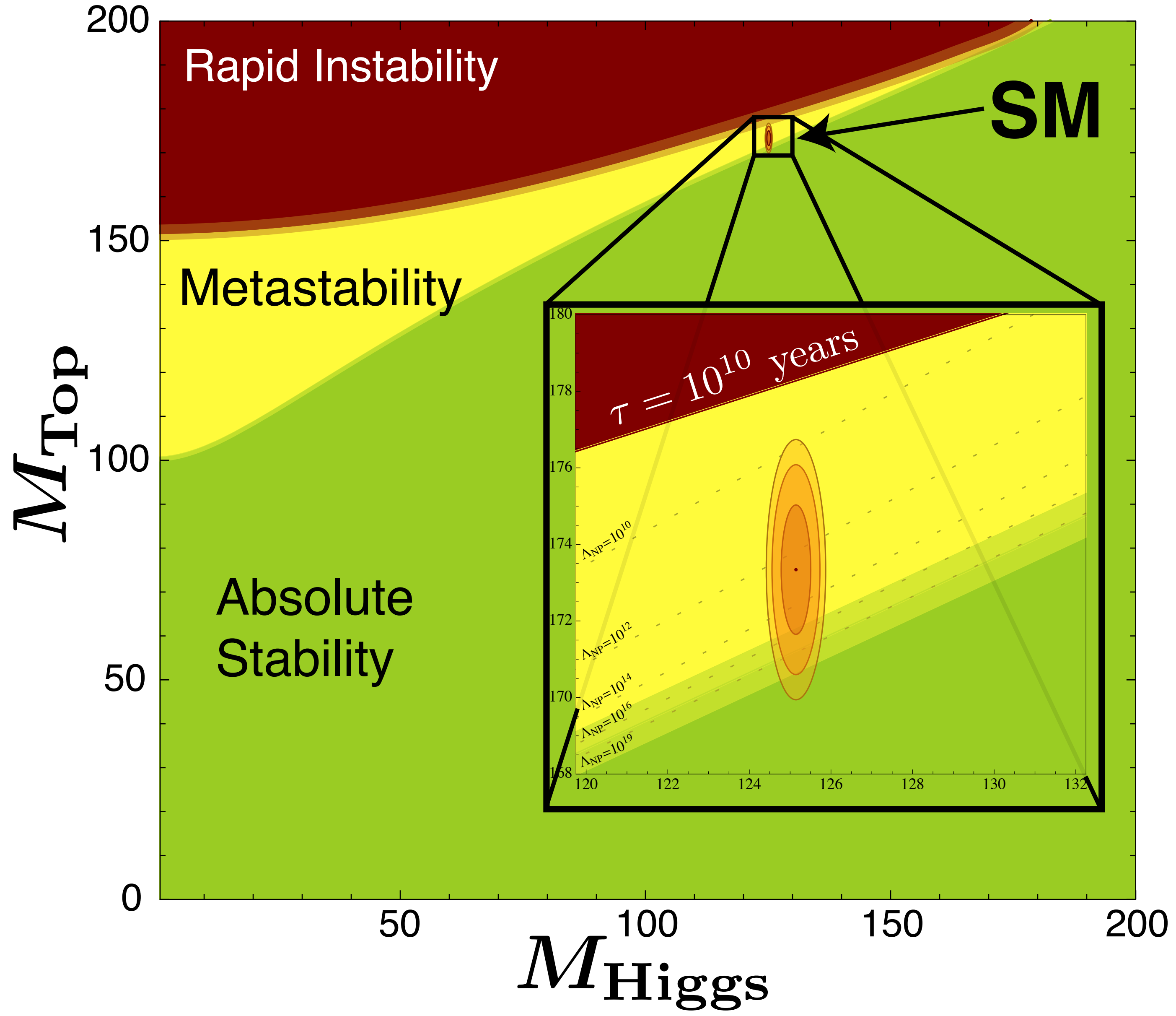
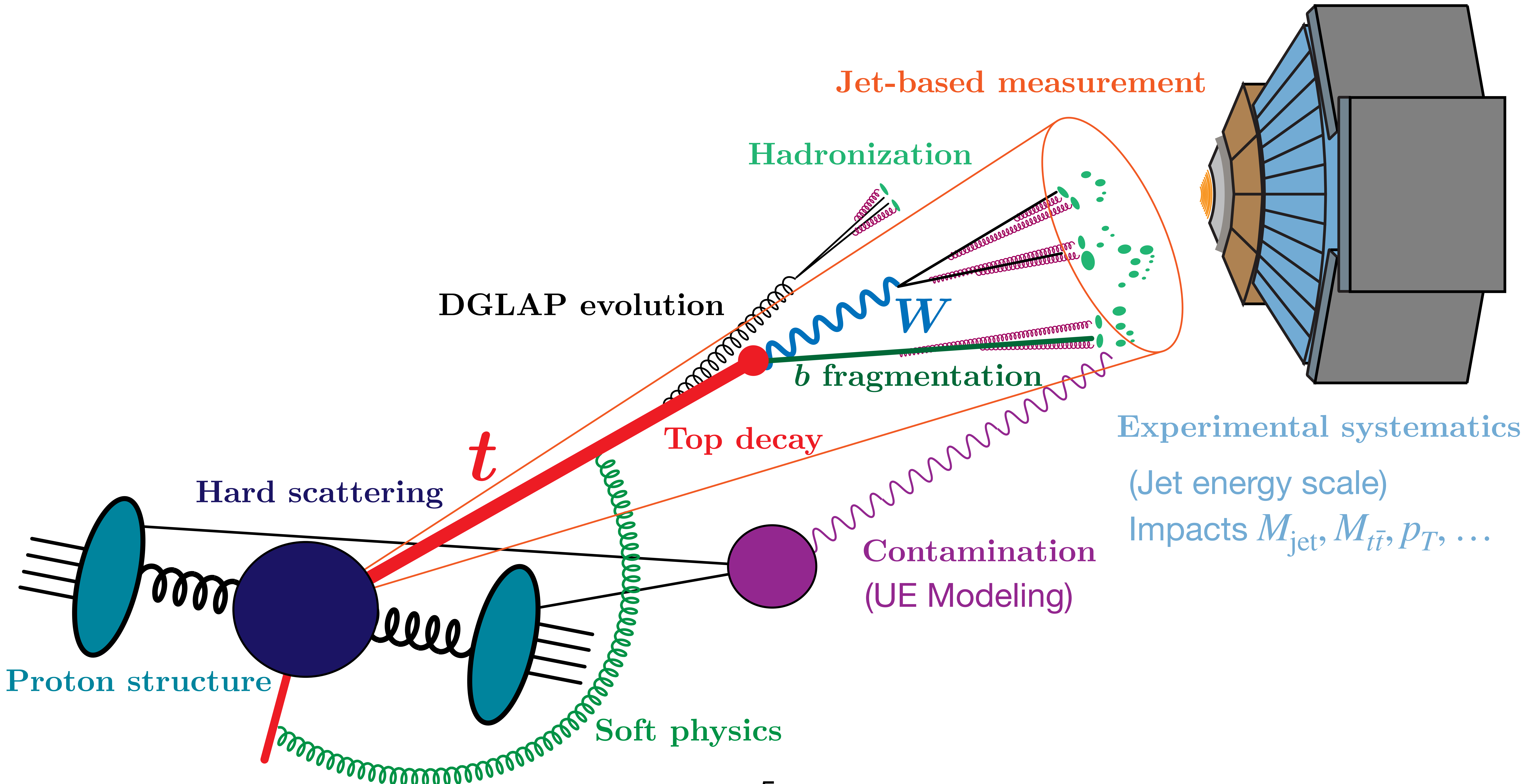




Andreassen, Frost, Schwartz 2014

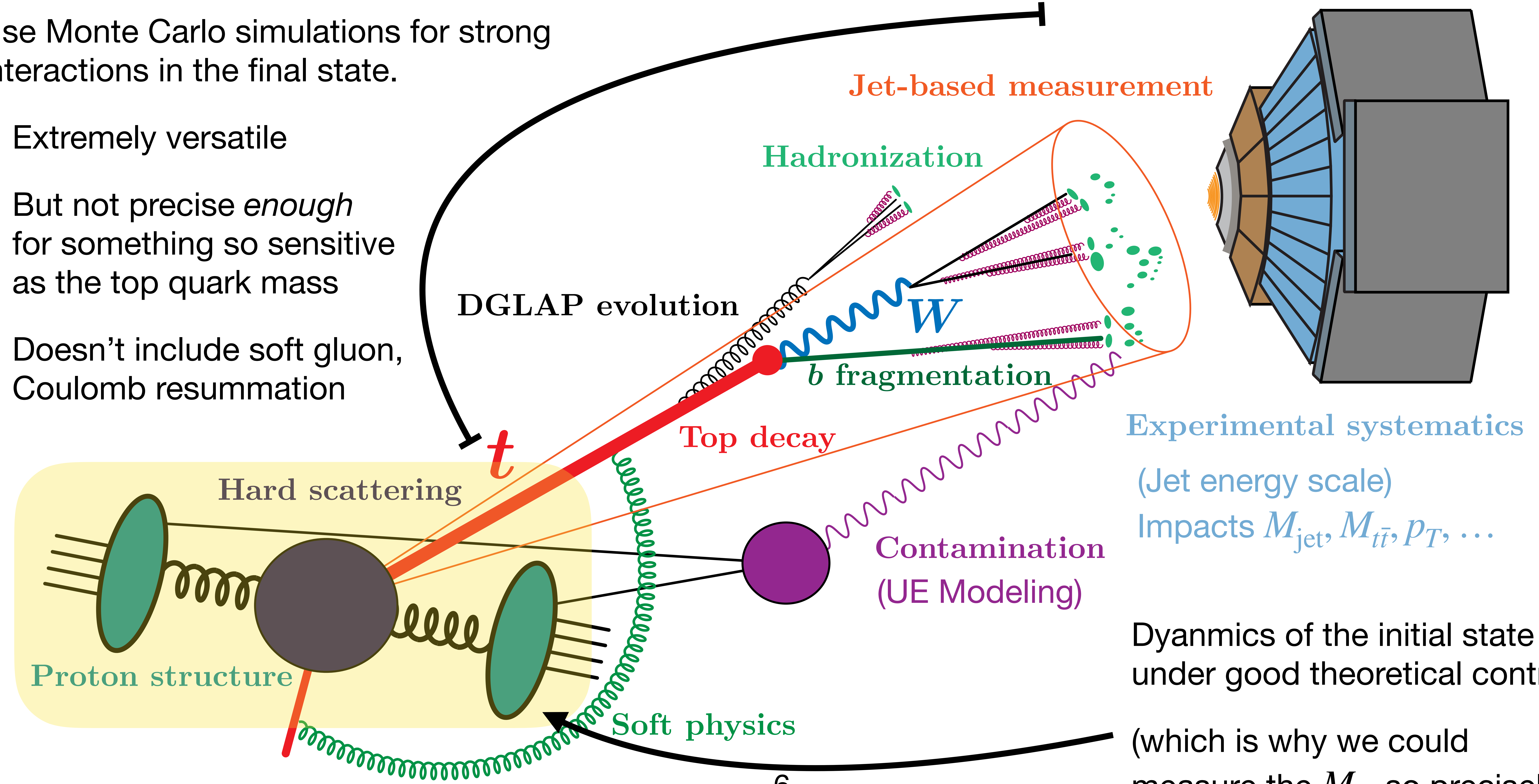
The current status of collider QCD predictions



The current status of collider QCD predictions

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

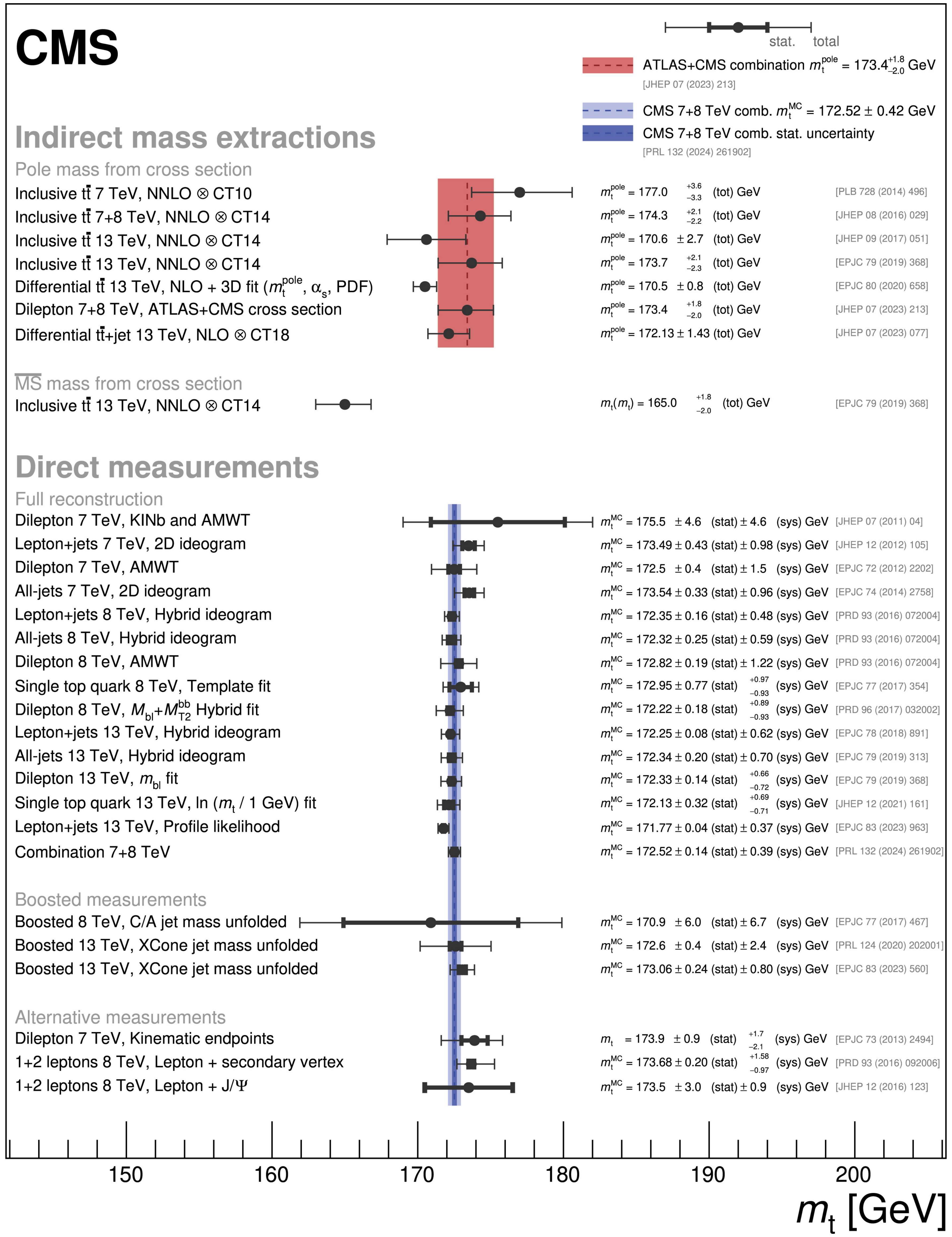
- Extremely versatile
- But not precise *enough* for something so sensitive as the top quark mass
- Doesn't include soft gluon, Coulomb resummation



Dyanmics of the initial state under good theoretical control

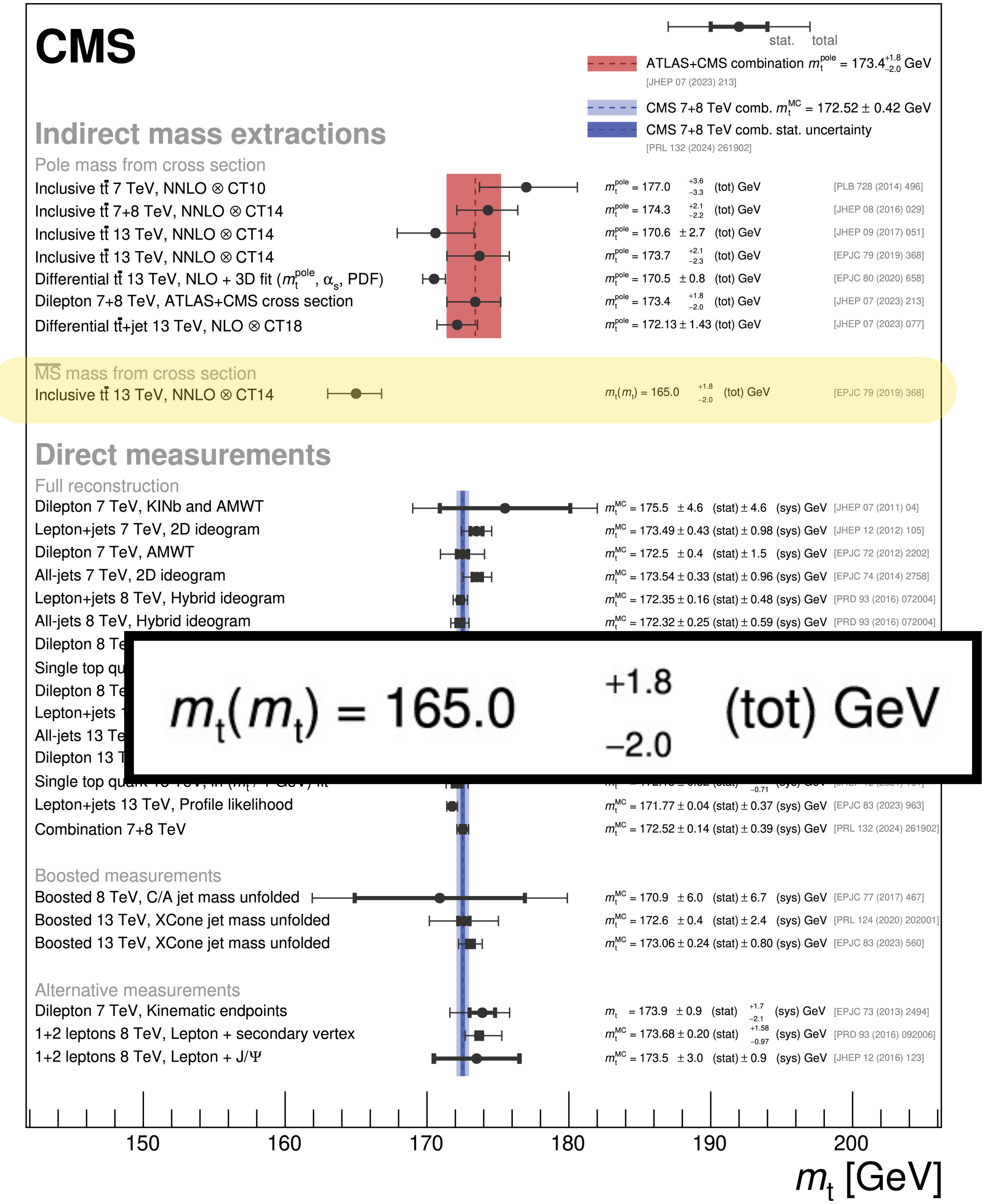
(which is why we could measure the M_W so precisely)

Existing top mass determinations



- A number of complementary techniques
- Excellent summary: Review of top quark mass measurements in CMS, Phys.Rept. 1115 (2025) 116-218

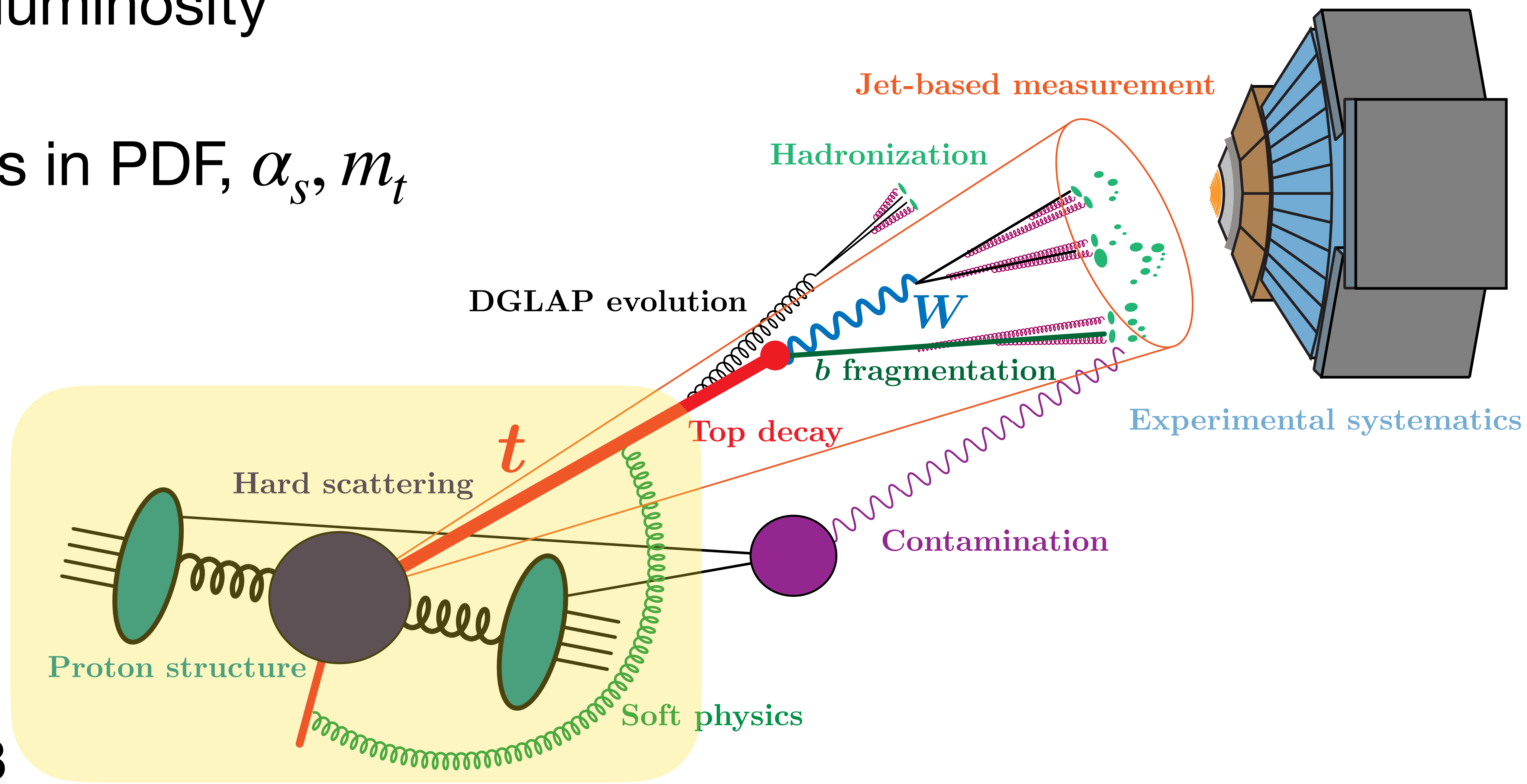
Top Mass from Total Cross Section



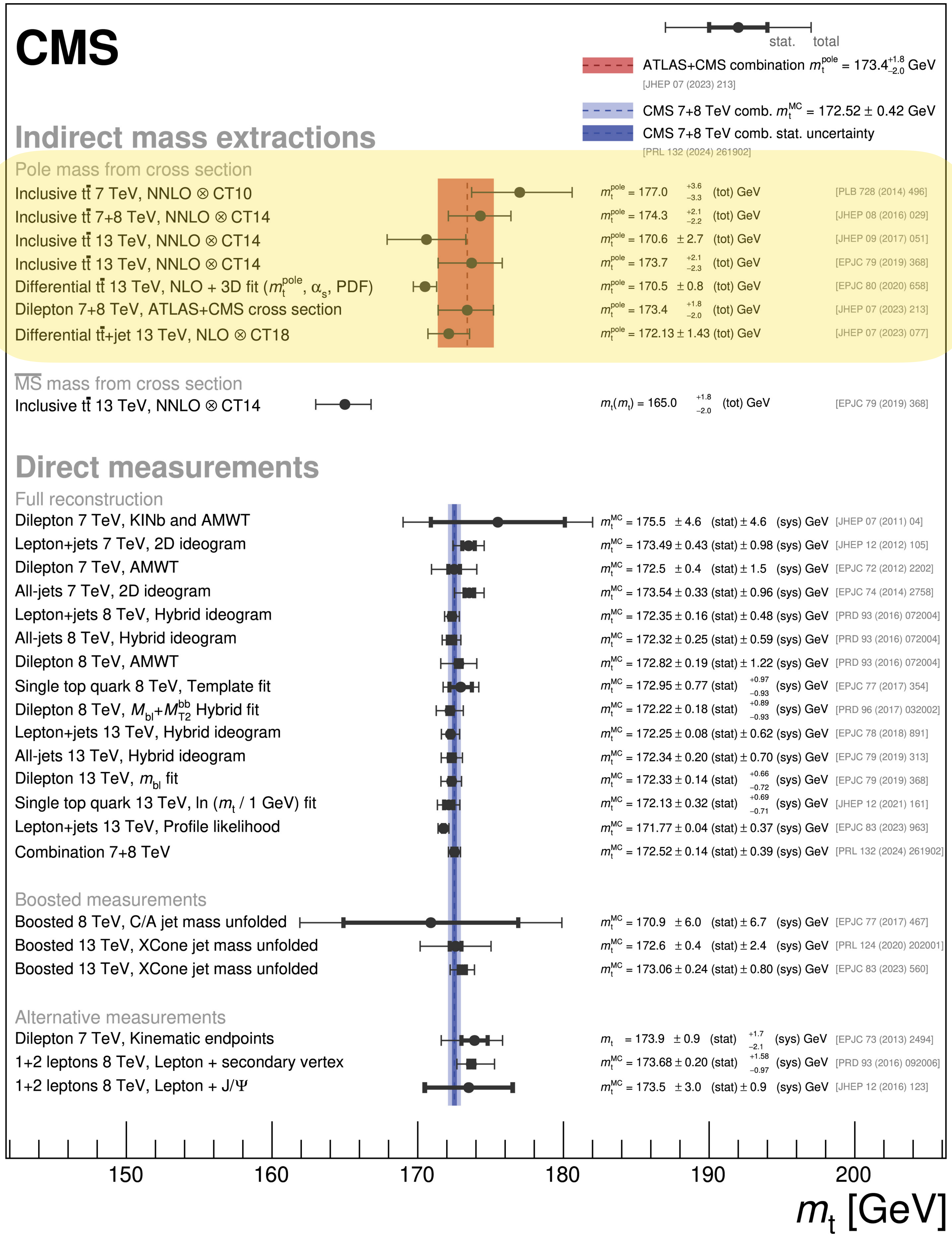
- Theoretically robust as it primarily depends on PDF and hard scattering
- Yields measurement in well defined $\overline{\text{MS}}$ scheme.
- Weak sensitivity to the top mass.

Main sources of uncertainty:

- Integrated luminosity
- Correlations in PDF, α_s, m_t

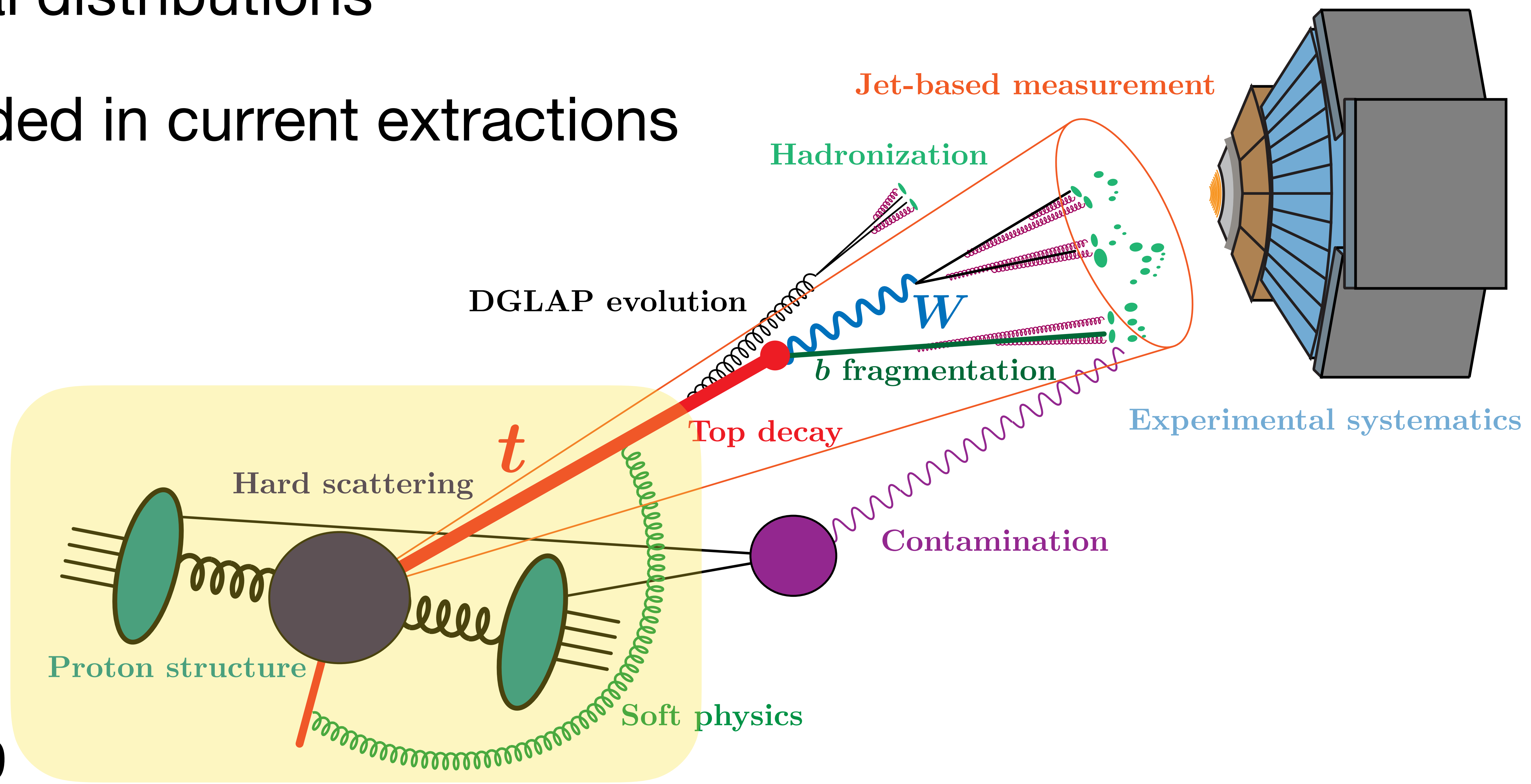


Pole Mass Measurements



- Gain more sensitivity by considering normalized multi-differential distributions: $m_{t\bar{t}}, y_{t\bar{t}}$

- The highest sensitivity in the $m_{t\bar{t}} \in (340,360)$ GeV region. Coulomb effects on quasi-bound $t\bar{t}$ state become important [See Maria Garzelli's talk]
  - Very hard to compute for differential distributions
  - Not included in current extractions



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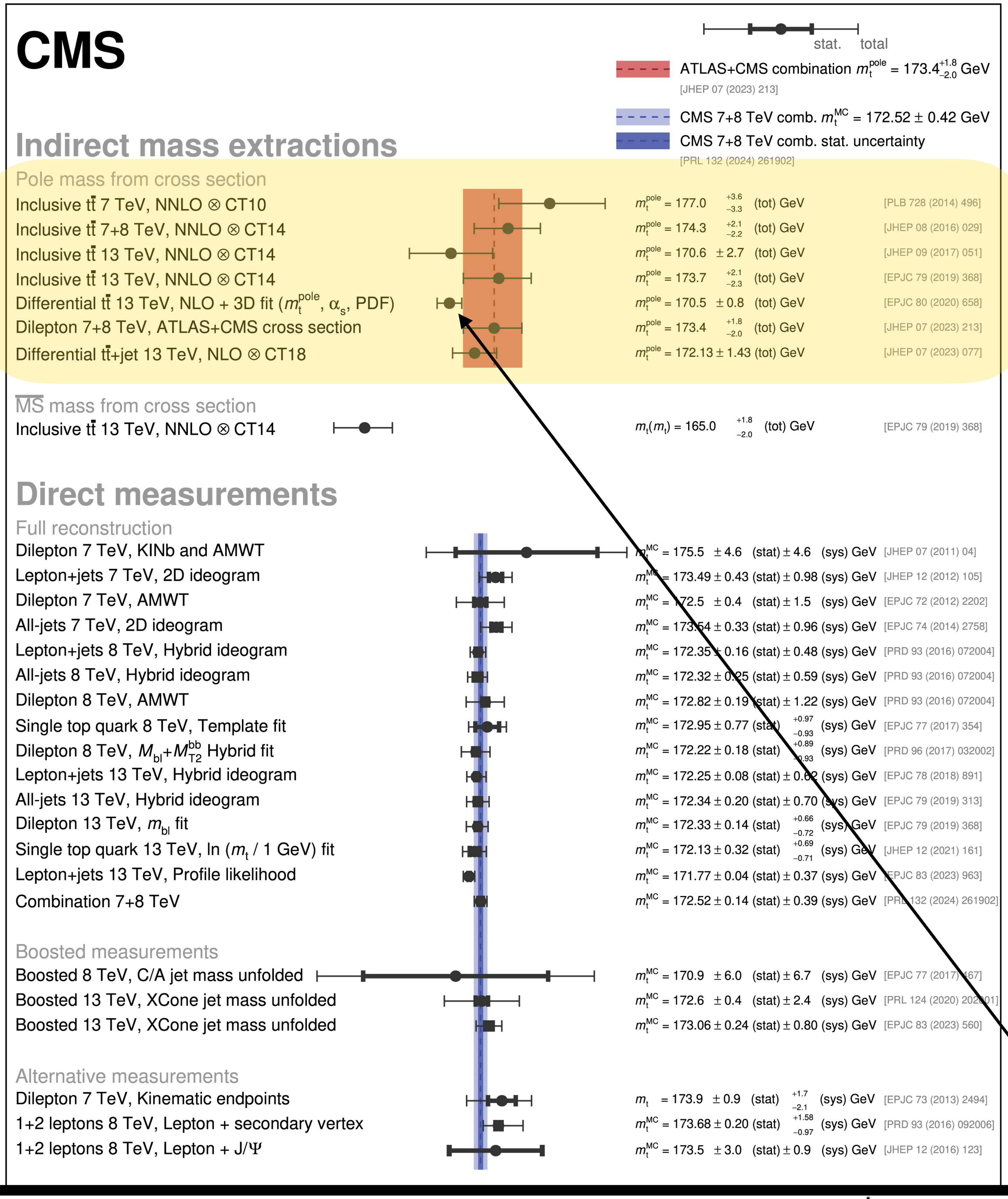

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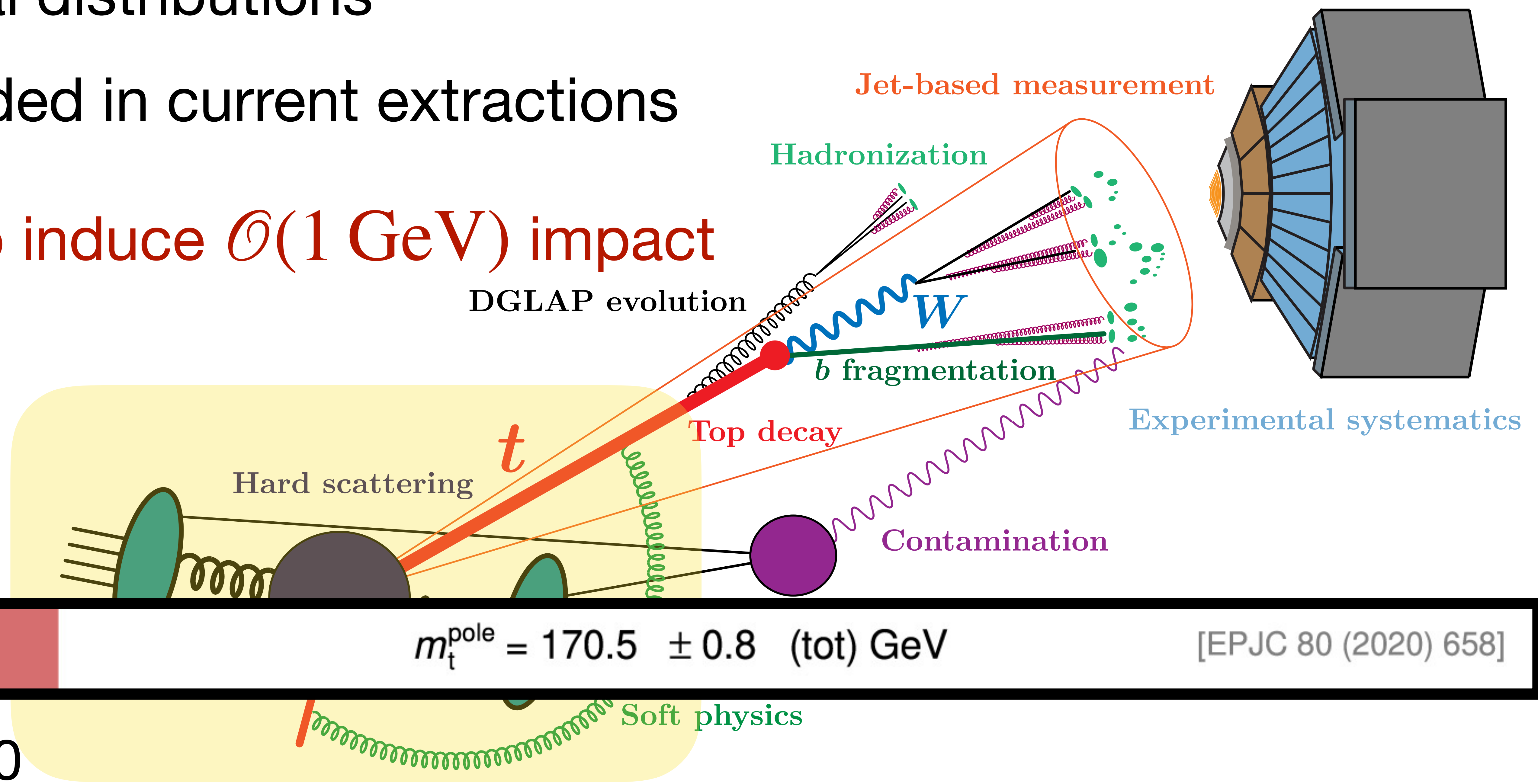
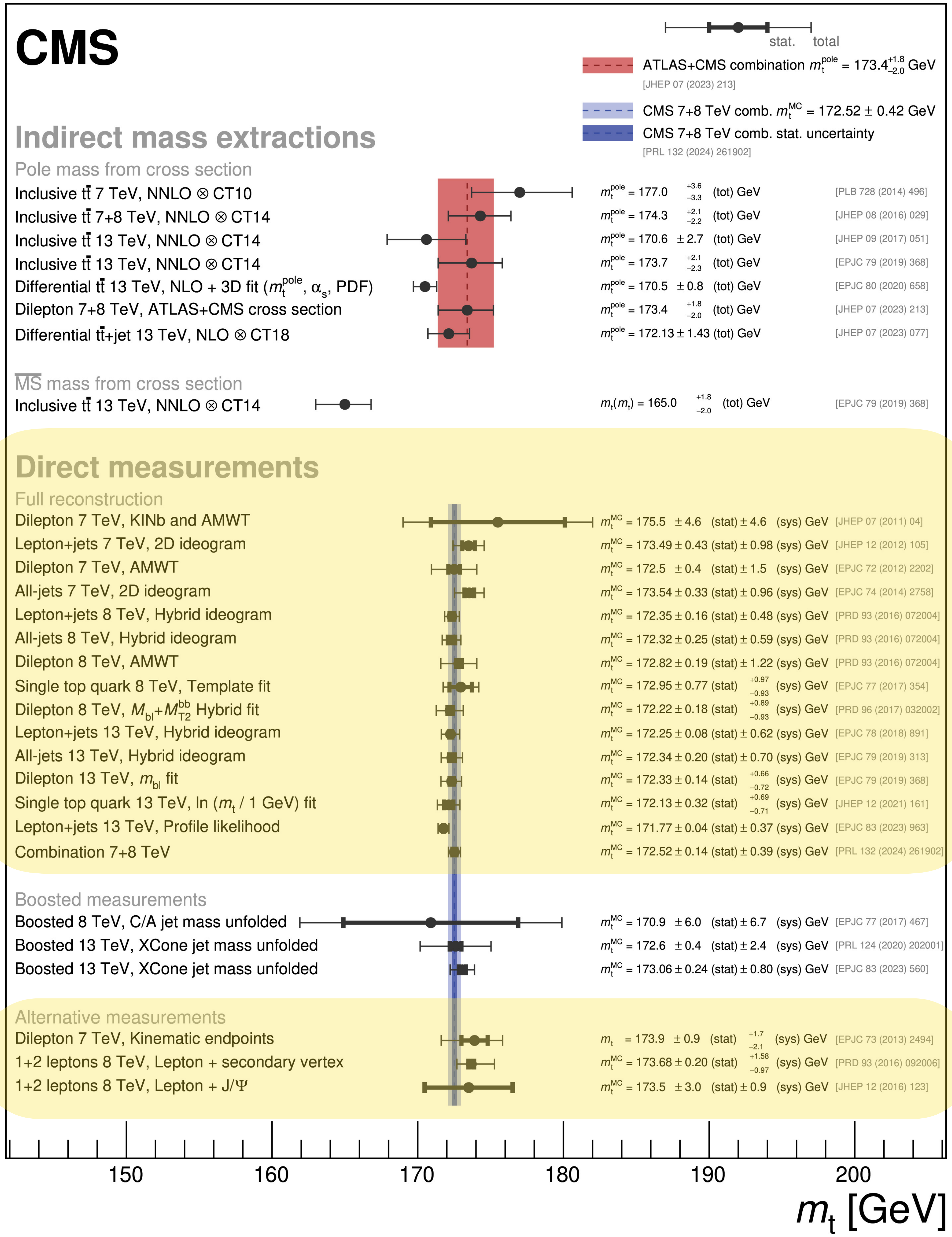
  - Very hard to compute for differential distributions
  - Not included in current extractions
  - Argued to induce $\mathcal{O}(1\ \text{GeV})$ impact

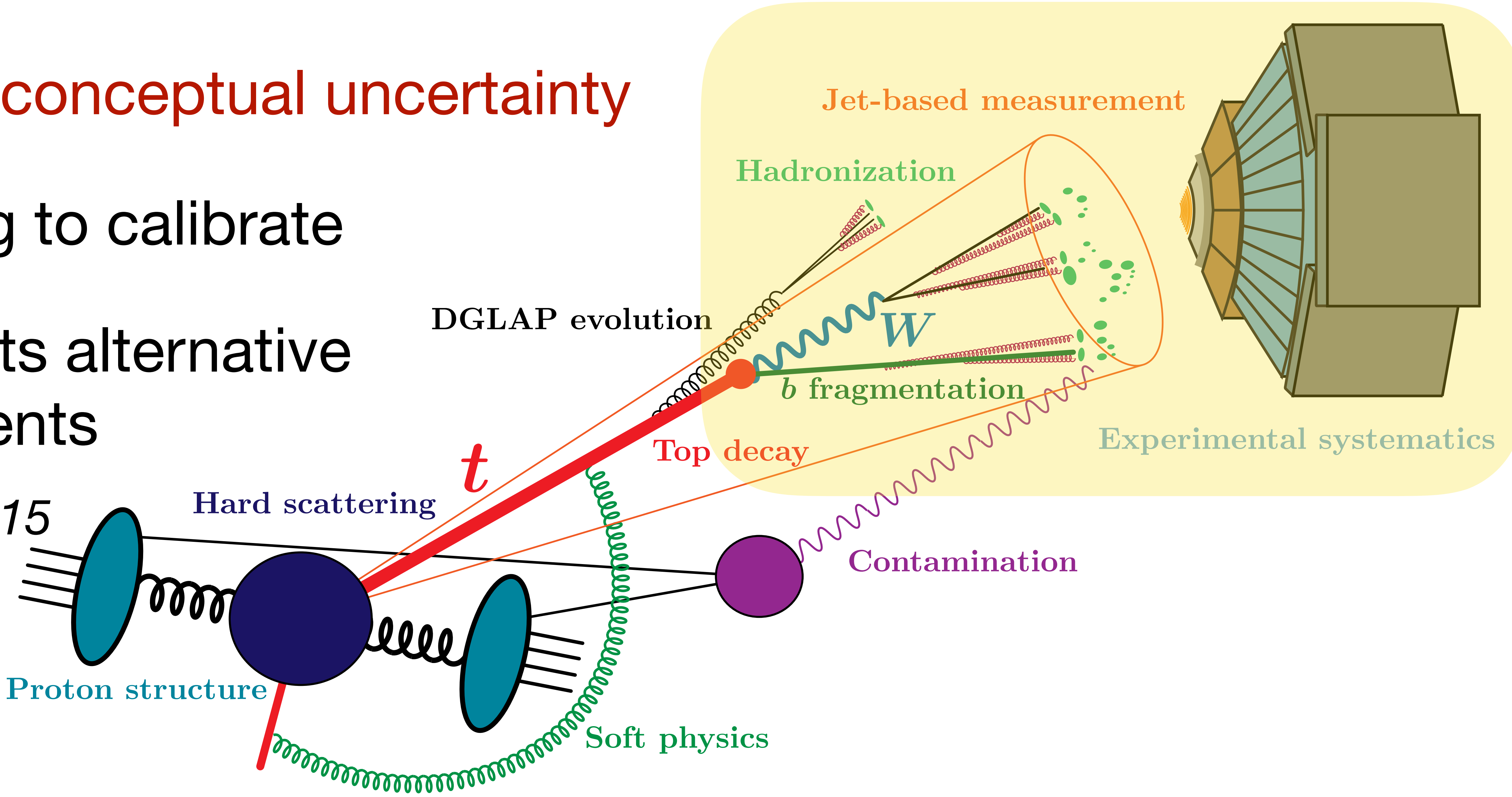


Direct Measurements

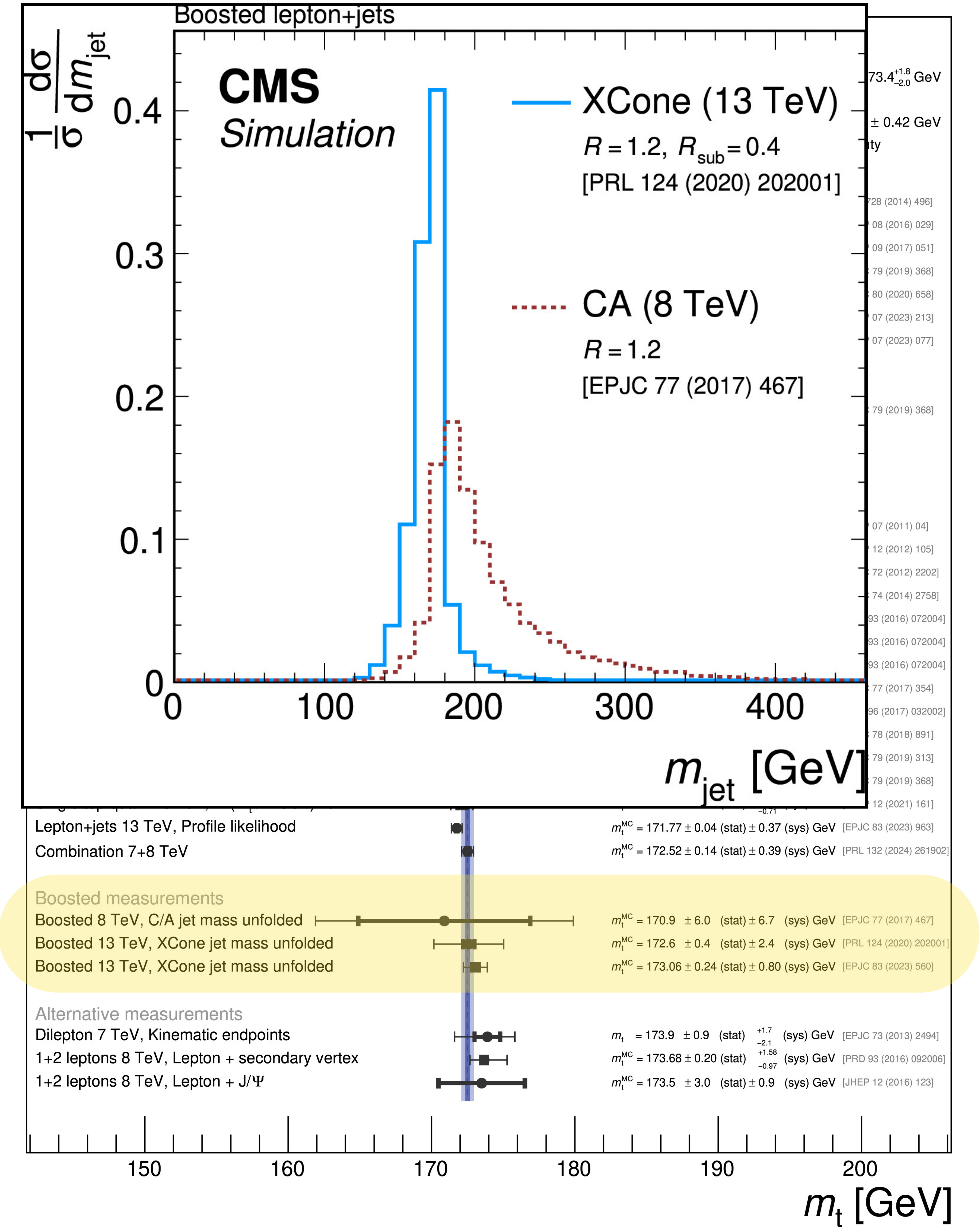


- Fit to data m_t-dependent Monte Carlo templates
- Main sources of uncertainty:
  - Experimental: JES, JER
  - Modelling: b jet, FSR, CR
- No well defined relation to a field-theoretic mass scheme:
  - $\mathcal{O}(1\,\mathrm{GeV})$ conceptual uncertainty
  - Challenging to calibrate
  - Also impacts alternative measurements

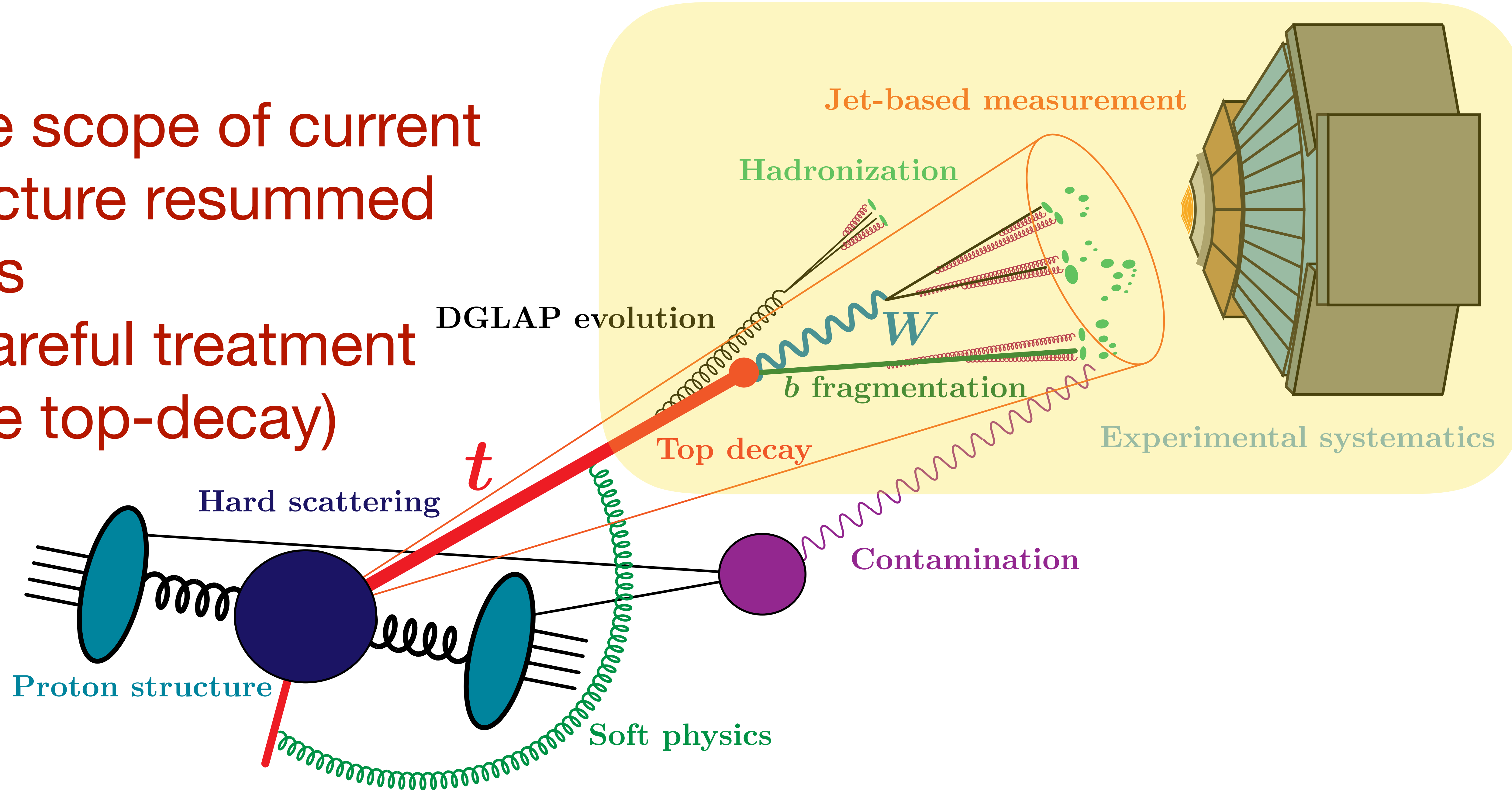
See Hoang 2004.12915



Boosted Jet Mass



- Boosted region amenable to precise, *hadron-level* (SCET-based) calculations.
- Unfold the distribution to enable comparison with the theory
- Plain jet mass yields large uncertainties
- Gaining higher sensitivity needs jet grooming or XCone clustering:
  - Beyond the scope of current jet substructure resummed calculations (requires careful treatment of exclusive top-decay)



Hadron-level predictions for boosted jet mass

- High-order analytical resummation using SCET and HQET of jet mass in the boosted region.

  Bachu, Hoang, Mateu, AP, Stewart Phys.Rev.D 104 (2021)

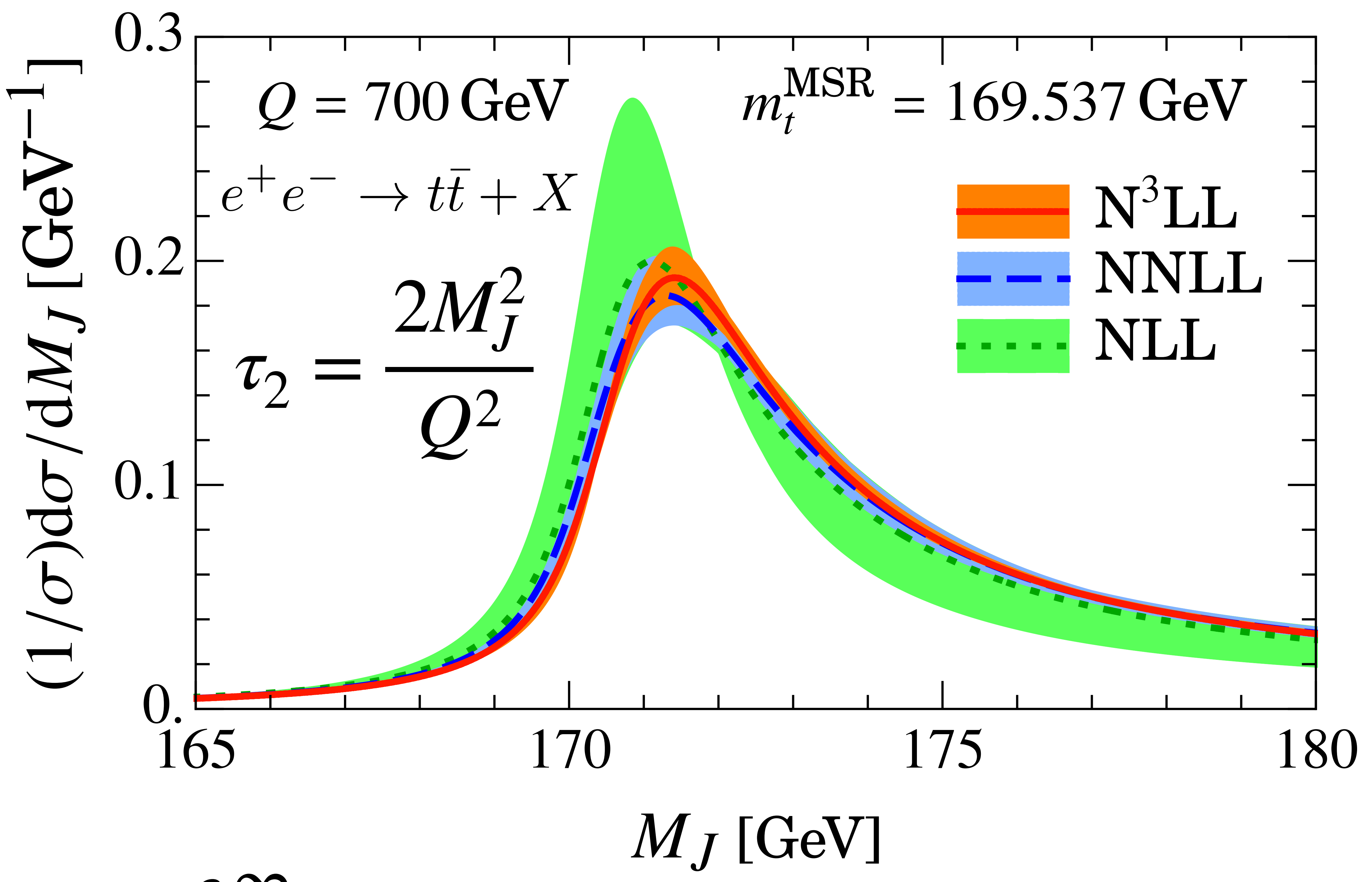
- Analytical, model-independent treatment of leading hadronization effects

  - Calibrate m_t^{MC} and hadronization models

    Dehnadi, Hoang, Jin, Mateu JHEP 12 (2023) 065
    Hoang, Jin, Plätzer, Samitz JHEP 10 (2018) 200
    Ferdinand, Lee, AP Phys.Rev.D 108 (2023) 11, L111501

  - Direct extraction using soft drop jet mass

    Hoang, Mantry, AP, Stewart Phys.Rev.D 100 (2019) 7, 074021



$$\frac{1}{\sigma_0}\frac{\text{d}\sigma}{\text{d}\tau_2} = m_t\, Q^2 H^{(5,6)}_{\text{evol}}(Q, m_t, \varrho, \mu; \mu_H, \mu_m)$$
$$\times \int \text{d}\ell\, \text{d}\hat{s}\, U_B^{(5)}(\hat{s}_\tau - \varrho\ell - \hat{s}, \mu, \mu_B)\, J^{(5)}_{B,\tau_2}(\hat{s}, \Gamma_t, \delta m, \mu_B)$$
$$\times \int \text{d}\ell'\text{d}k\, U_S^{(5)}(\ell - \ell', \mu, \mu_S)\hat{S}^{(5)}_{\tau_2}(\ell' - k, \bar{\delta}, \mu_S)F(k - 2\Delta)$$

$$\int_0^\infty \text{d}k\, k\, F(k) = \Omega_1 \sim \Lambda_{\text{QCD}}$$

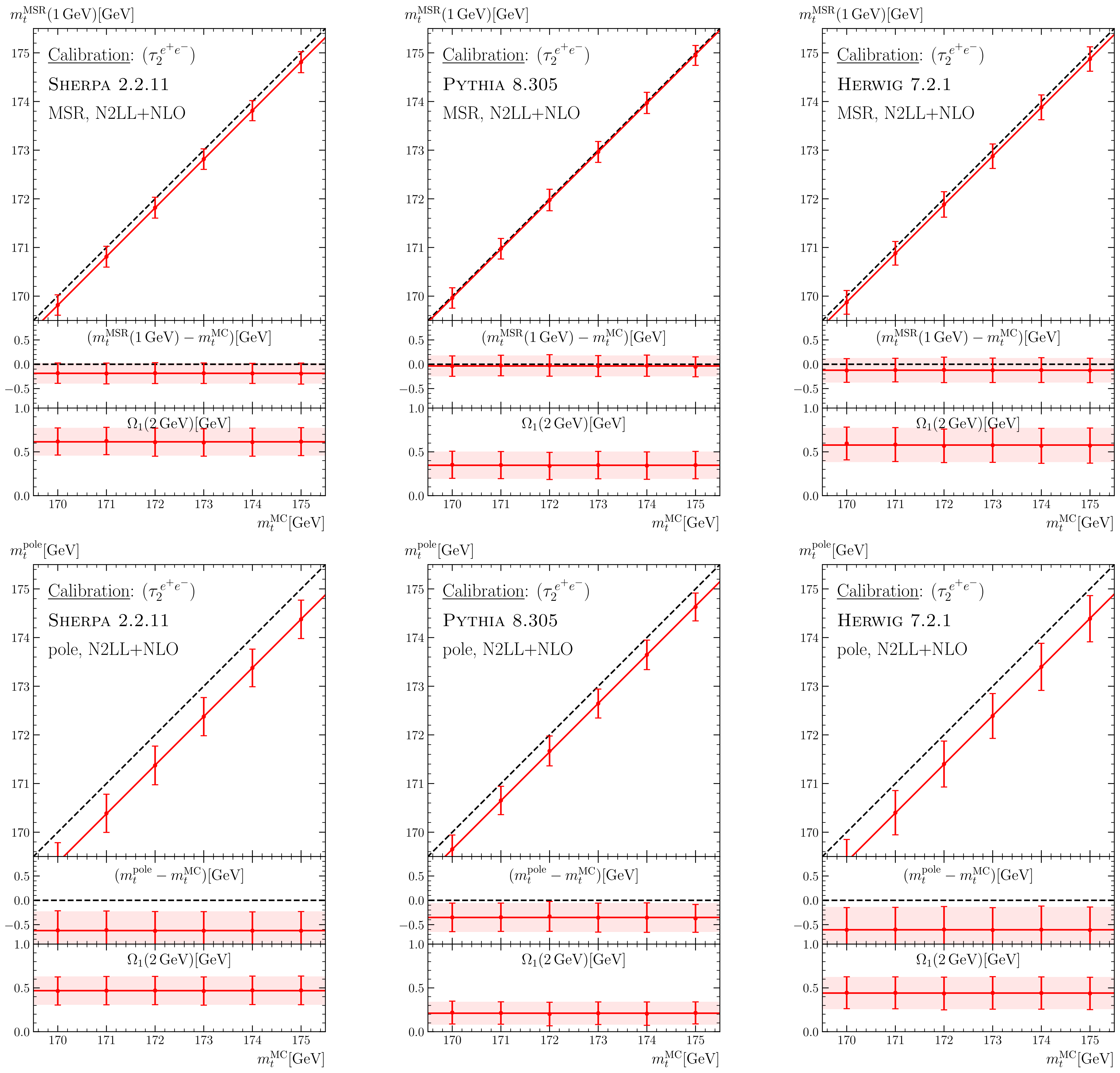
$$\Omega_1 \equiv \langle 0 \,|\, \text{tr} Y_{\bar{n}}^\dagger Y_n^\dagger \mathscr{E}_T(0) Y_n \overline{Y}_{\bar{n}} \,|\, 0 \rangle$$

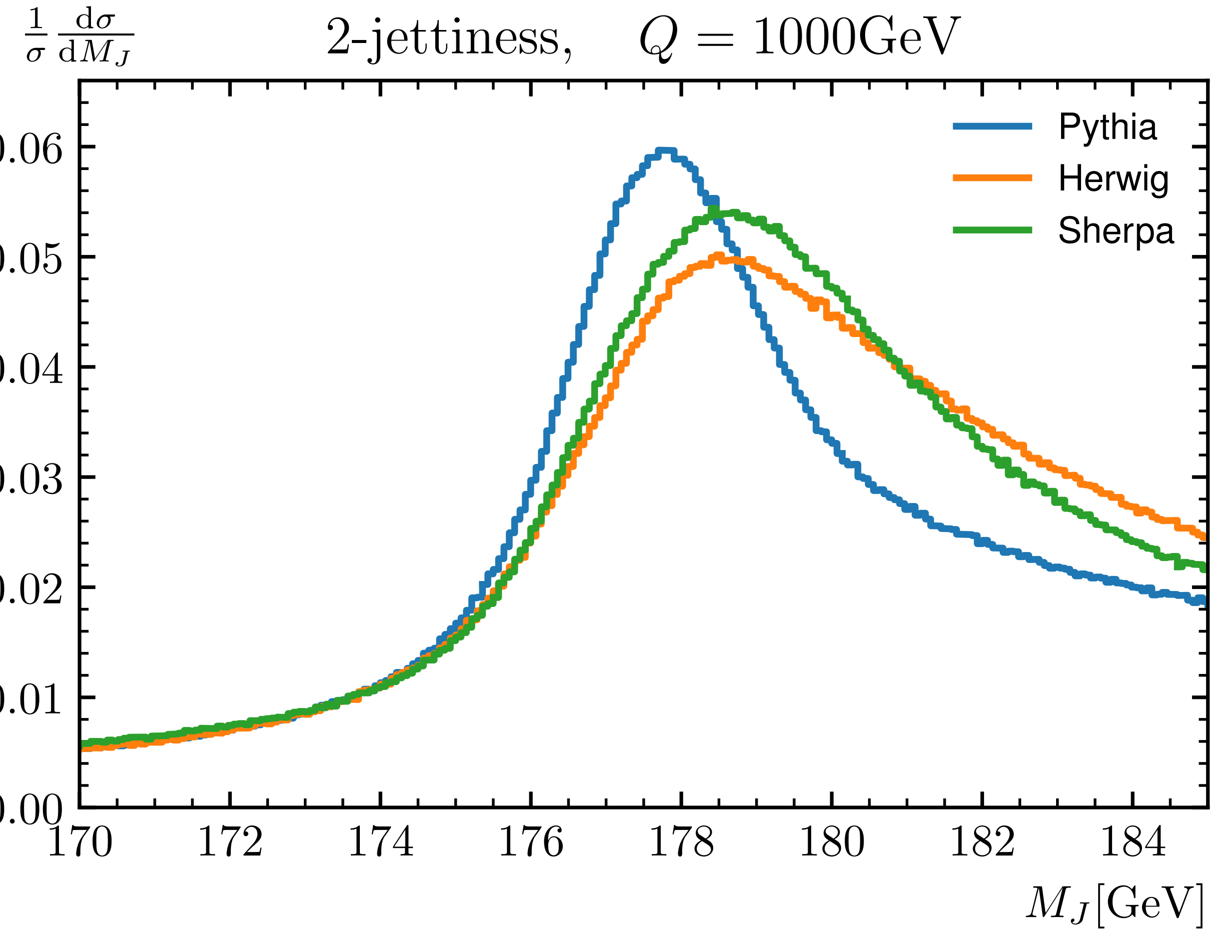
Lee, Sterman Phys.Rev. D 75, 014022 (2007)

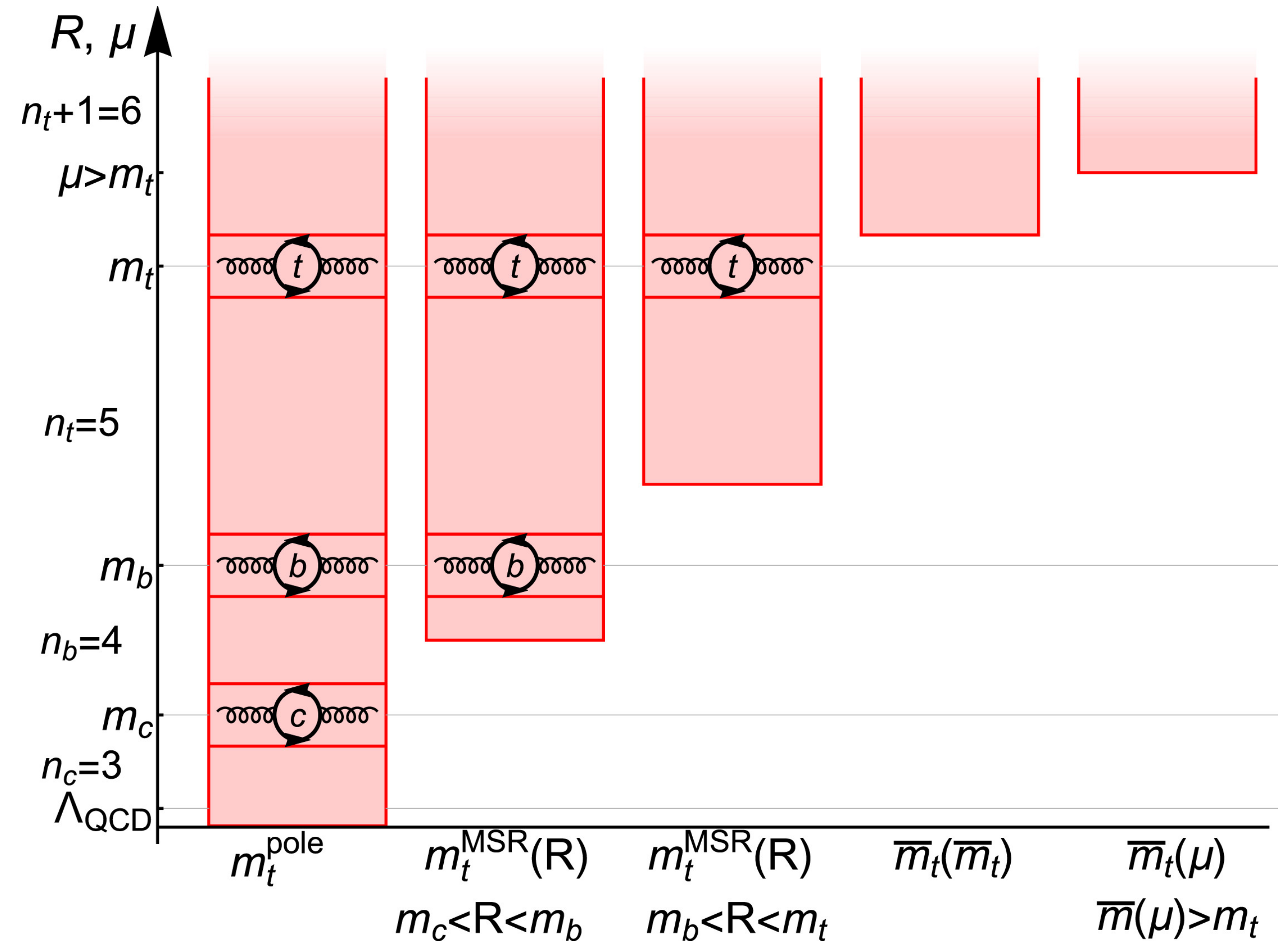
Ω_1 must be fitted for along with m_t

MC Top Mass Calibration

Dehnadi, Hoang, Jin, Mateu
JHEP 12 (2023) 065







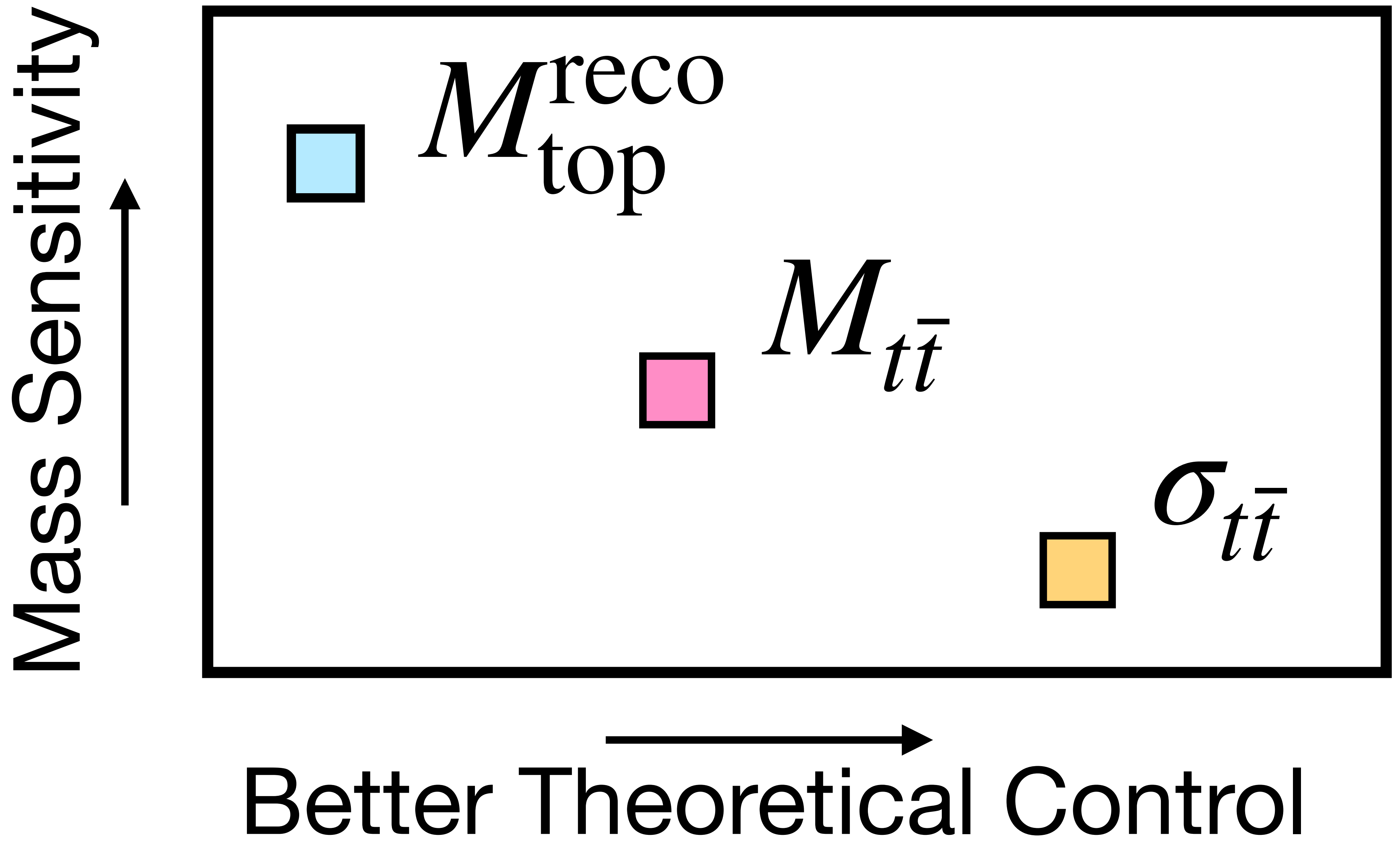
For Pythia v8.305:

$$m_t^{\rm MC} - m_t^{\rm pole} = 0.35 \pm 0.30\,{\rm GeV}$$
$$m_t^{\rm MC} - m_t^{\rm MSR}(1\,{\rm GeV}) = 0.03 \pm 0.21\,{\rm GeV}$$

- Use high precision NNLL+Ω_1 to calibrate $m_t^{\rm MC}$
- MC top mass consistent with MSR mass at 1 GeV
- Differences in the shape absorbed in $\Omega_1^{\rm MC}$
- Missing in this approach for pp ($\sim$ 0.5-1.0 GeV effects):
  - Interpretation for non-boosted tops
  - UE and initial state MPI
  - Non-universal power corrections (CR)

Problems with top mass measurements

Current Paradigm:



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

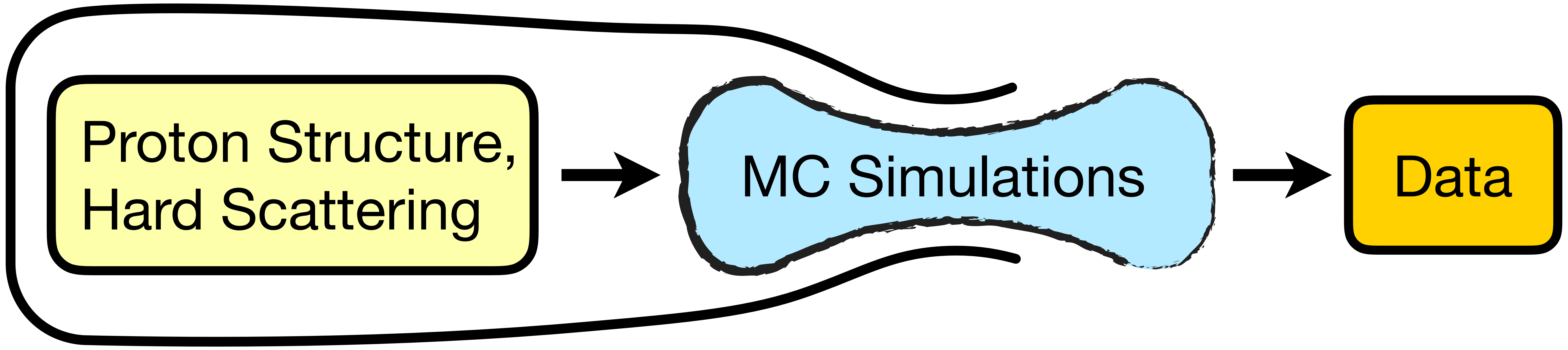
$$\Delta m_t^{\overline{\mathrm{MS}}} \sim \pm 2\,\mathrm{GeV}$$

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

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

The Standard Candle Approach

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



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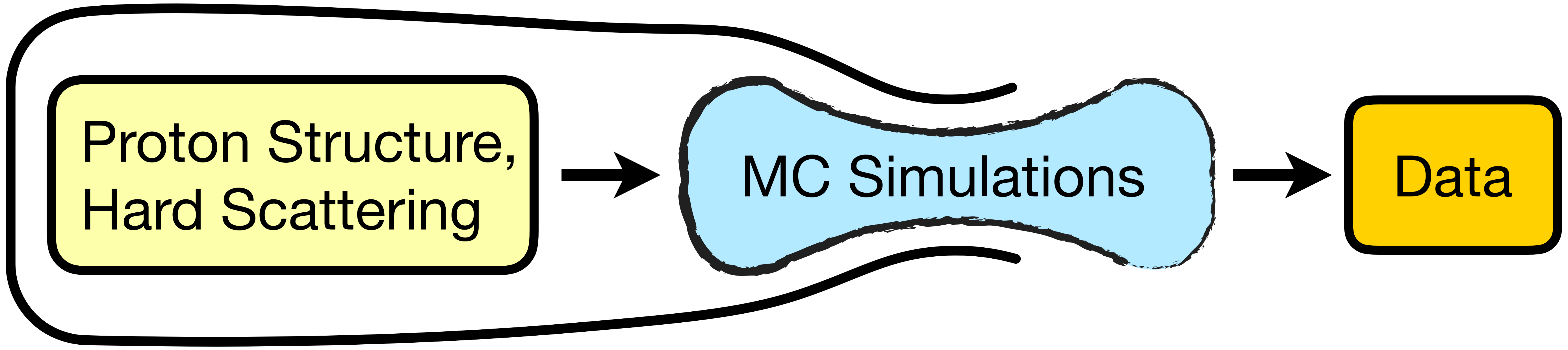
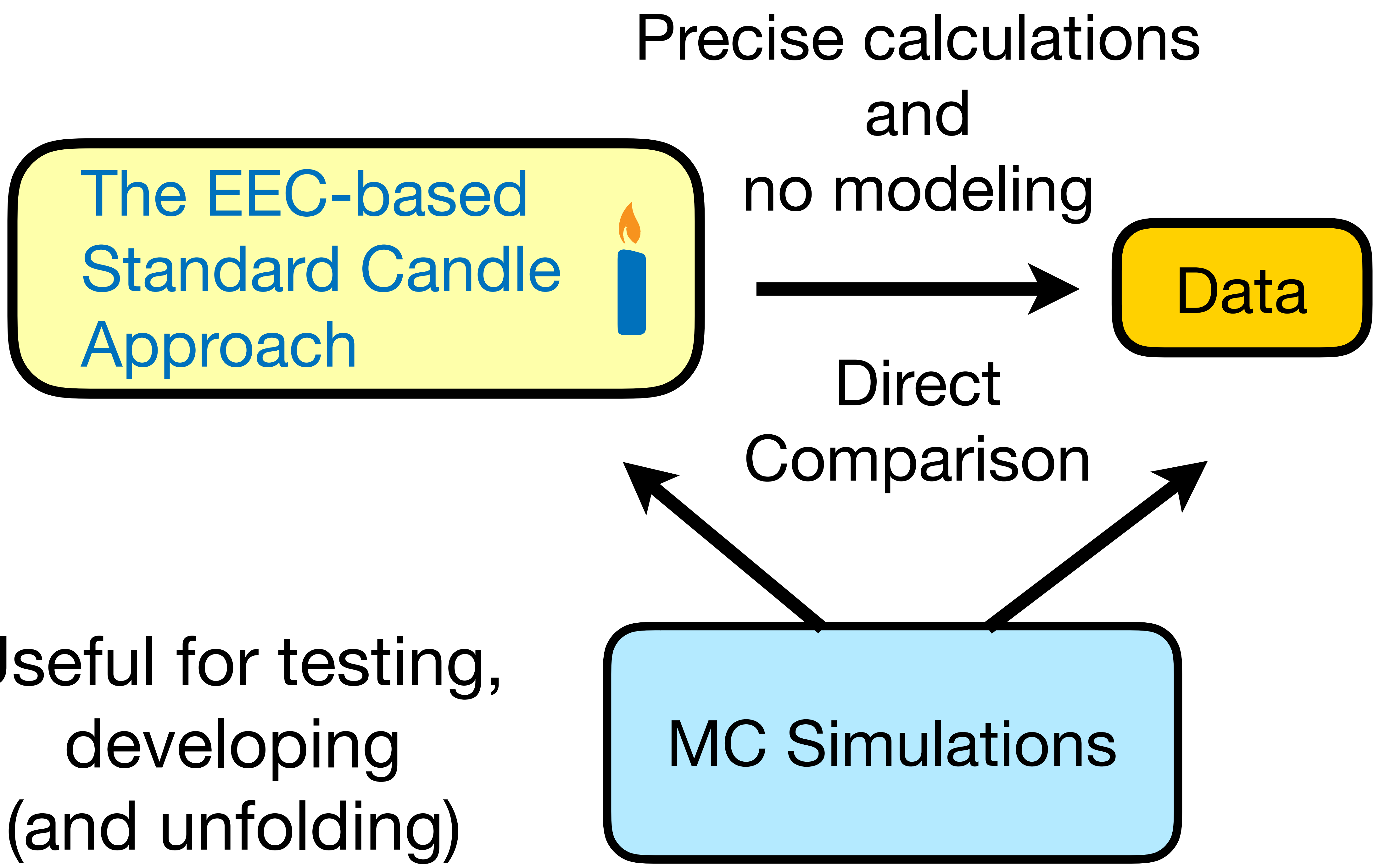


Proposal: A unique Energy Correlator-based “Standard-Candle” approach:



Useful for testing,
developing
(and unfolding)

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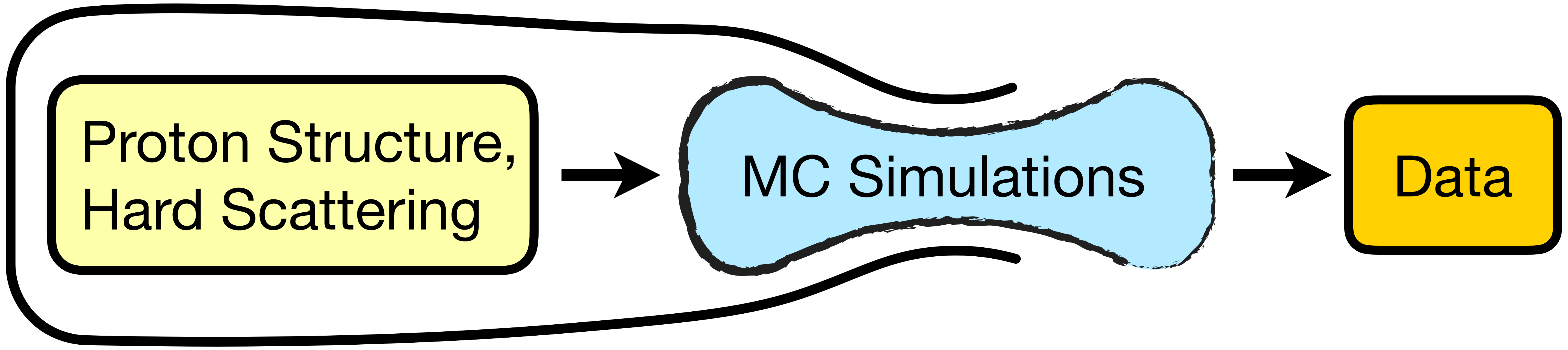

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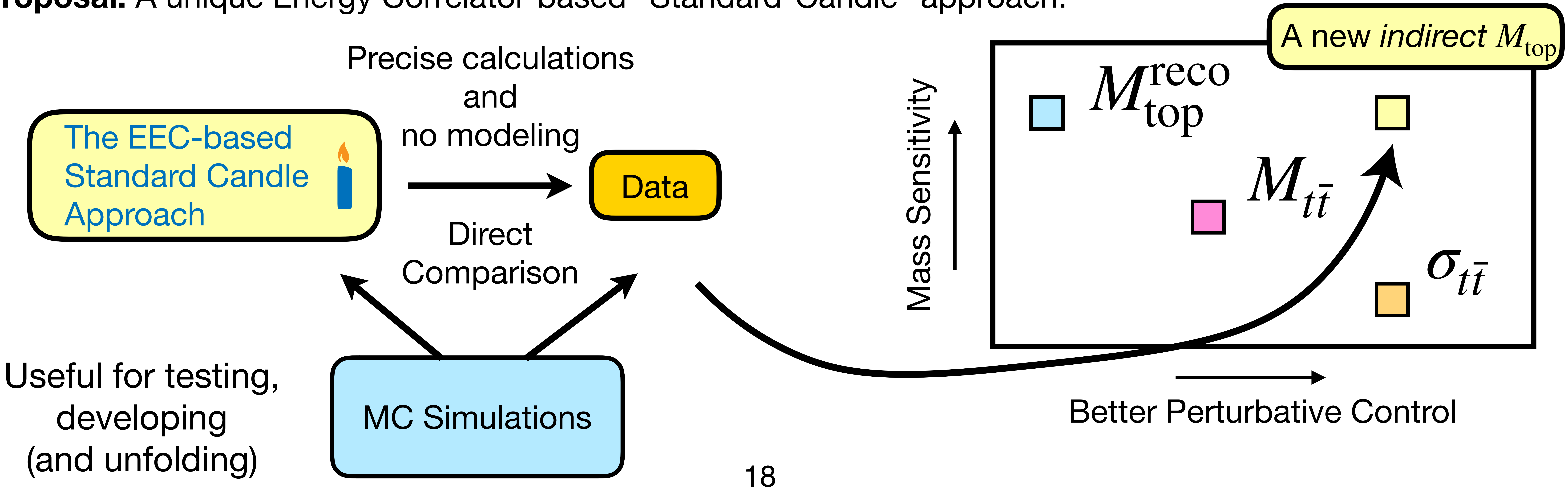

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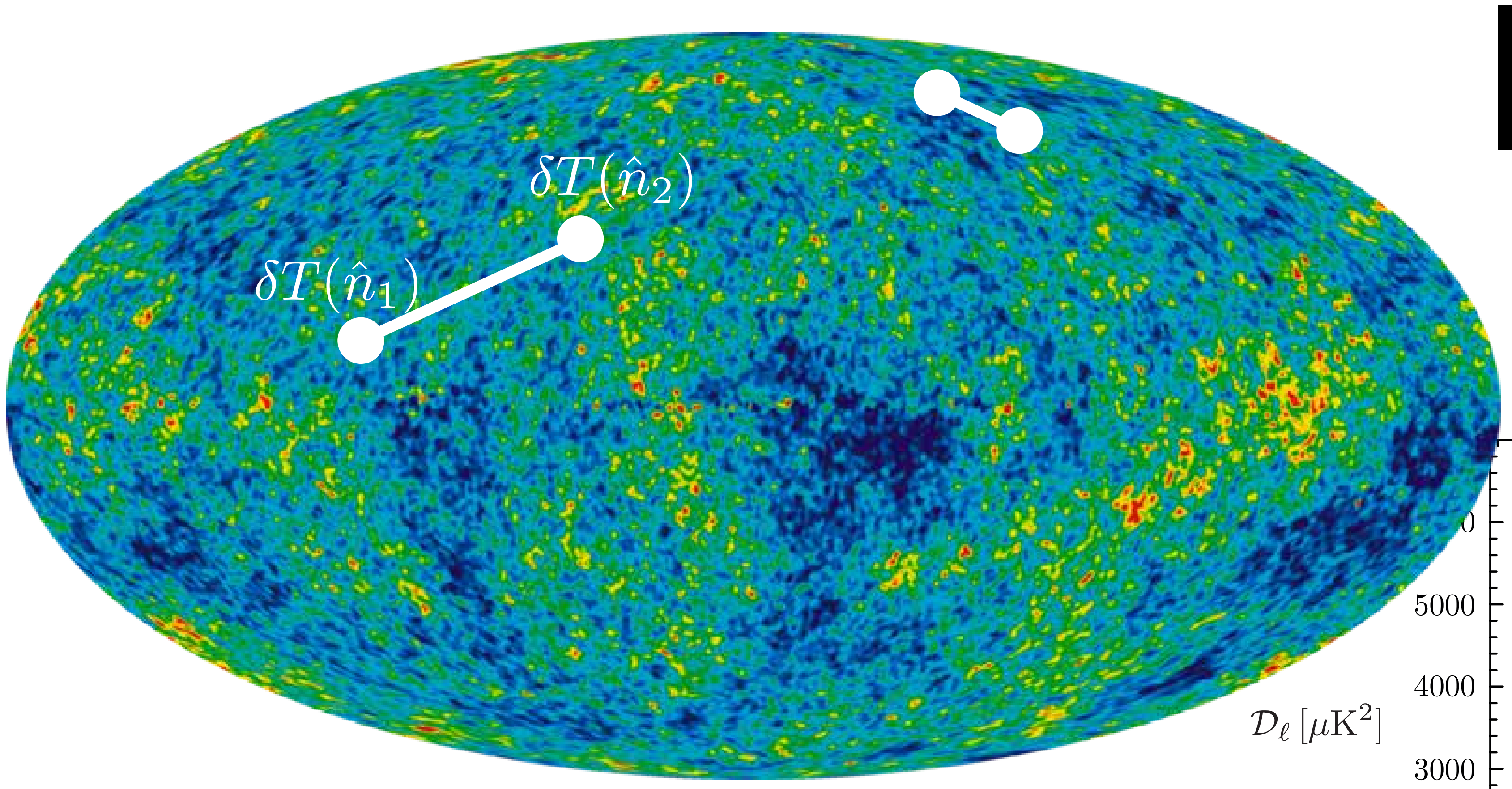
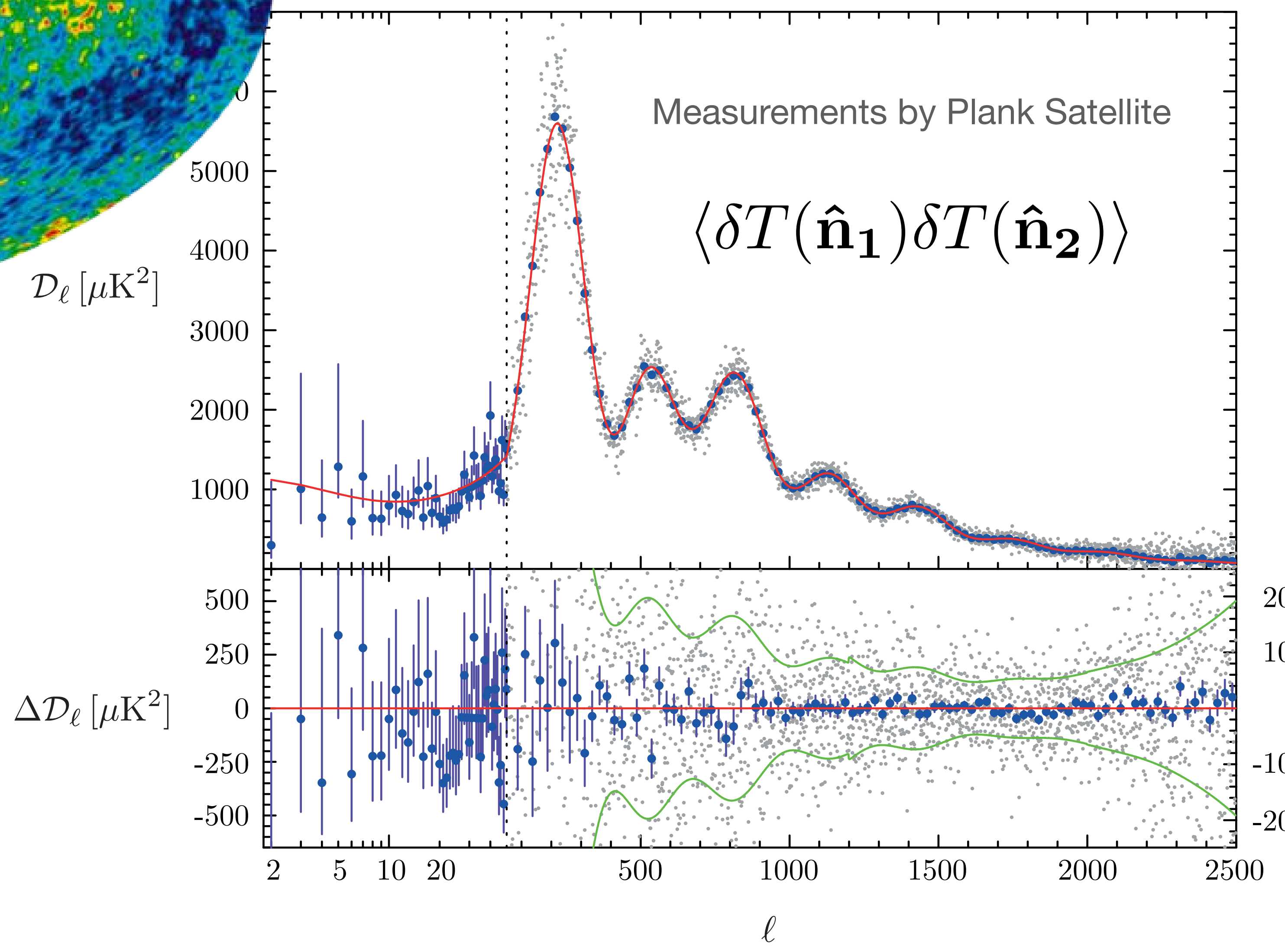
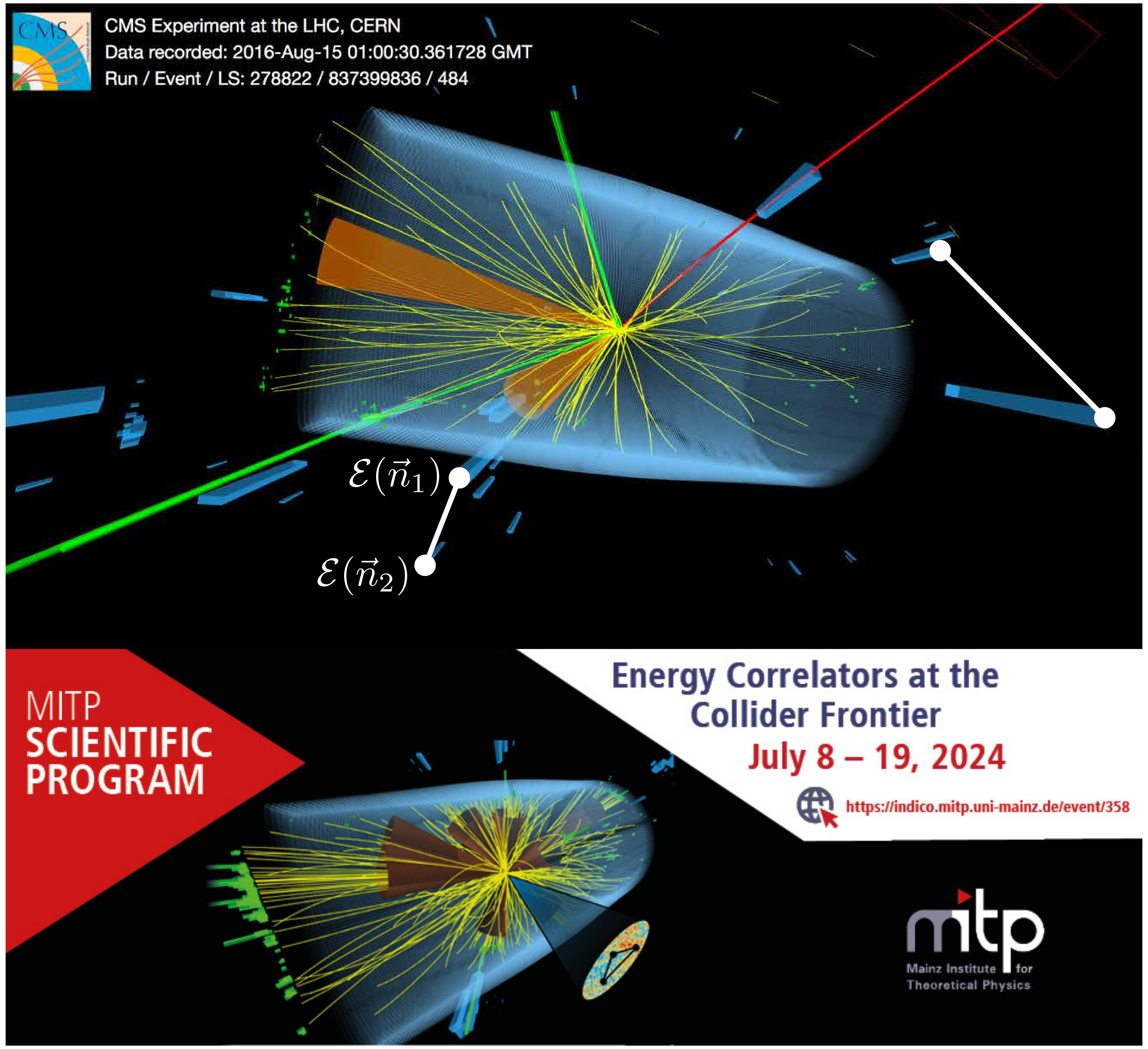
Energy Correlators







- Correlation functions are extremely powerful.
- An explosion of applications of Energy Correlators in collider QCD.
- First dedicated workshop on EECs at Mainz this year:
  - jet substructure, precision measurements, heavy ion, nuclear structure, light-ray operator product expansion, bootstrap, connections with celestial holography, …

The Energy Energy Correlator

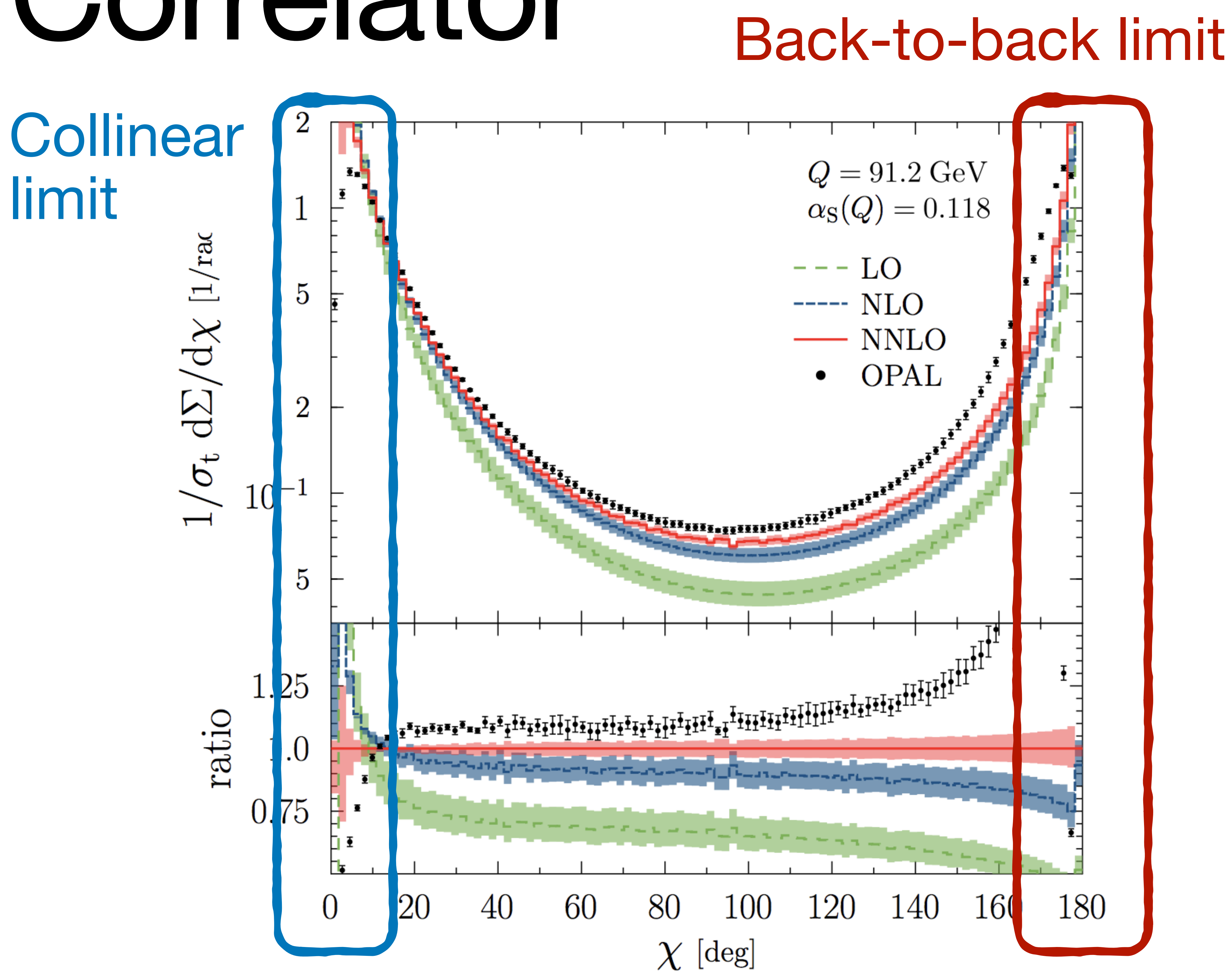
- One of the very first event shapes and a QCD correlation observable. *Basham et al. 1978*
- For $e^+e^- \to \gamma^*/Z \to q\bar{q} + X$:

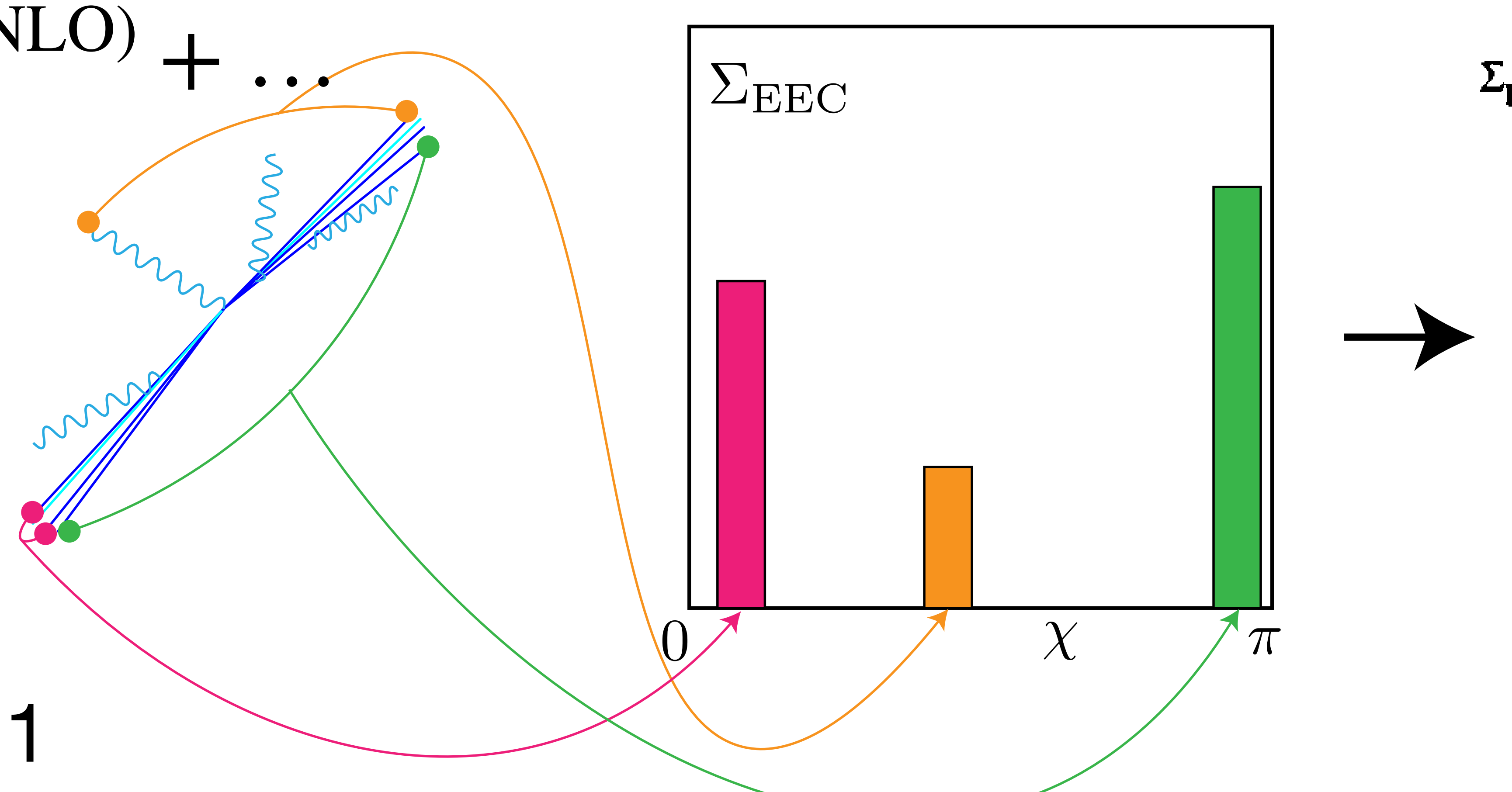
$$\frac{d\Sigma_{\mathrm{EEC}}}{d\cos\chi} = \sum_{ij}\int \frac{E_i E_j}{Q^2}\delta(\vec{n}_i \cdot \vec{n}_j - \cos\chi)\, d\sigma$$

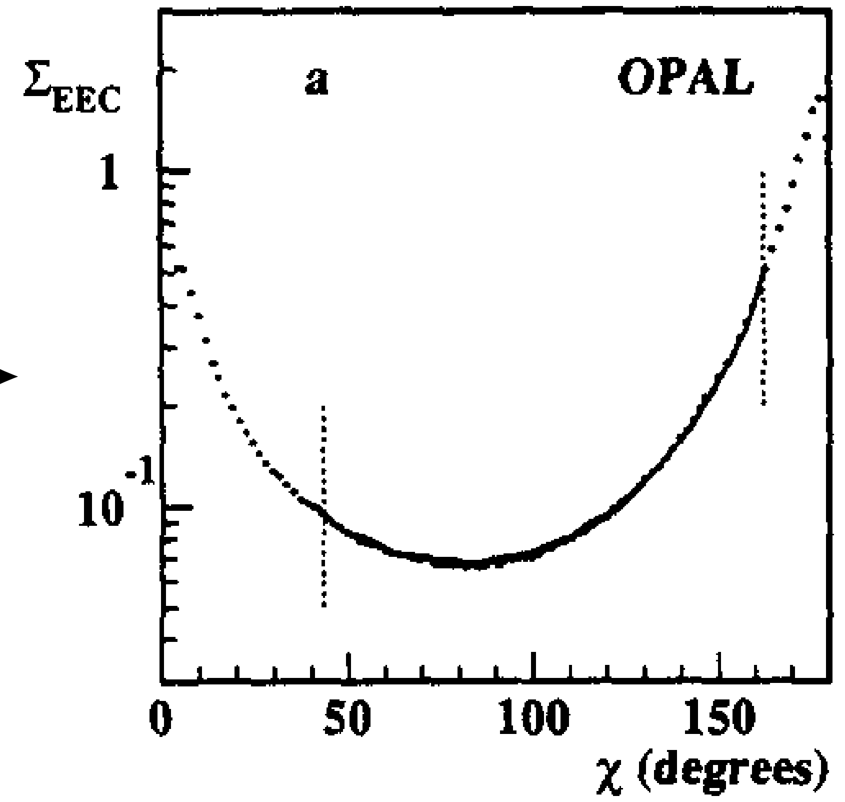
- Each event contributes to multiple bins, with the final distribution being an ensemble average over all events.
- In fixed order expansion:

$$d\Sigma_{\mathrm{EEC}} = \delta(1+\cos\chi) + \alpha_s d\Sigma^{(\mathrm{LO})} + \alpha_s^2 d\Sigma^{(\mathrm{NLO})} + \alpha_s^3 d\Sigma^{(\mathrm{NNLO})} + \ldots$$

- Two limits exhibiting a rich all-orders structure:
  - The Collinear limit: $\chi \to 0$
  - The back-to-back limit: $\chi \to \pi$







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

Universal behavior in the collinear limit

- In the collinear limit we find that the fixed order expansion breaks down for $z \to 0$:

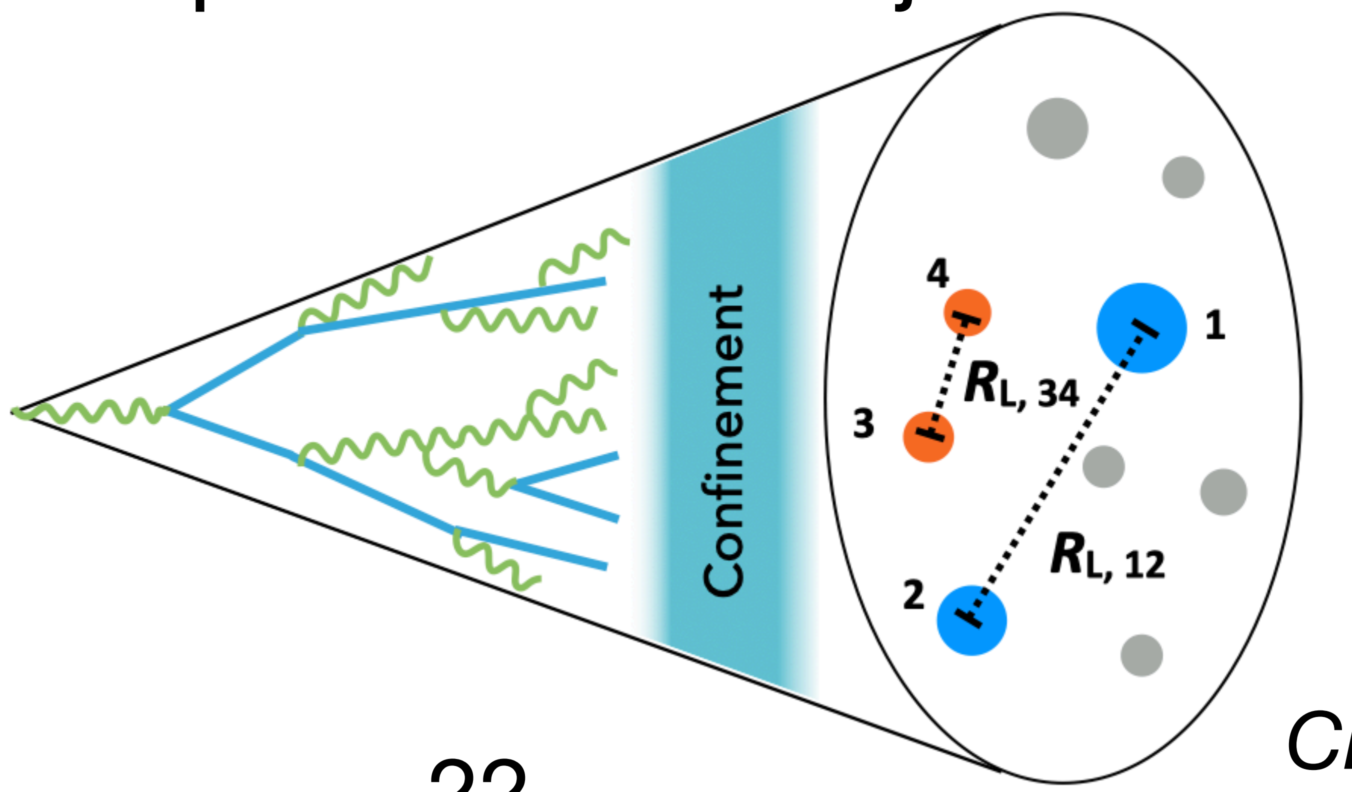
$$\lim_{z\to 0} \mathrm{d}\Sigma_{\mathrm{EEC}} \sim \frac{\alpha_s}{z}\left(1 + \alpha_s \ln z + (\alpha_s \ln z)^2 + \ldots\right), \qquad z \equiv \frac{1-\cos\chi}{2}$$

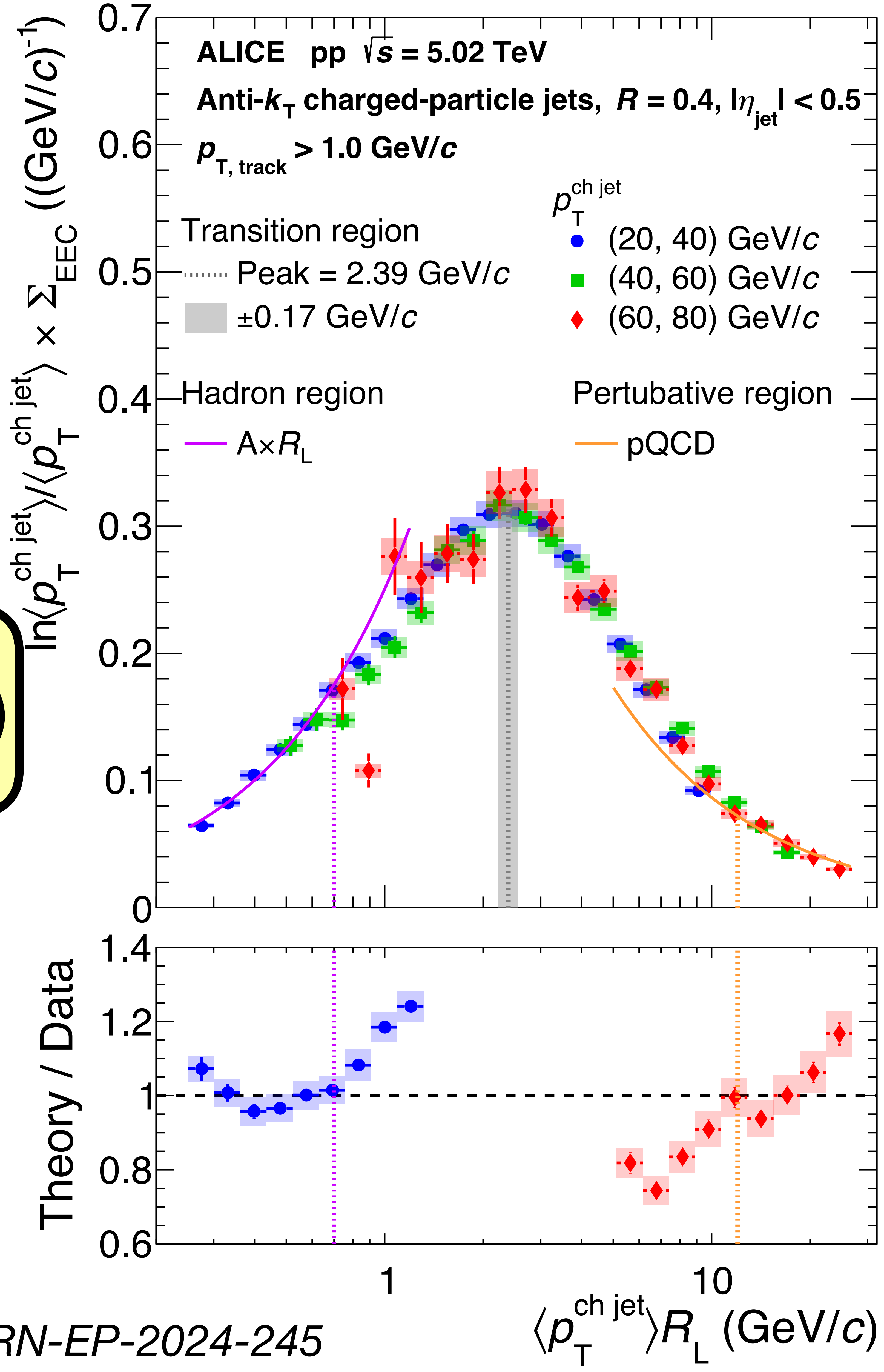
- In QCD a time-like factorization formula can be derived to resum large logs in the collinear limit:

Dixon, Moult, Zhu 2019

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

- For *pp* collisions we can measure the EEC on particles inside jets
  - Use $\Delta R_{ij} = \sqrt{\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2}$
  - $zQ^2 \to (p_T \Delta R)^2$





CERN-EP-2024-245

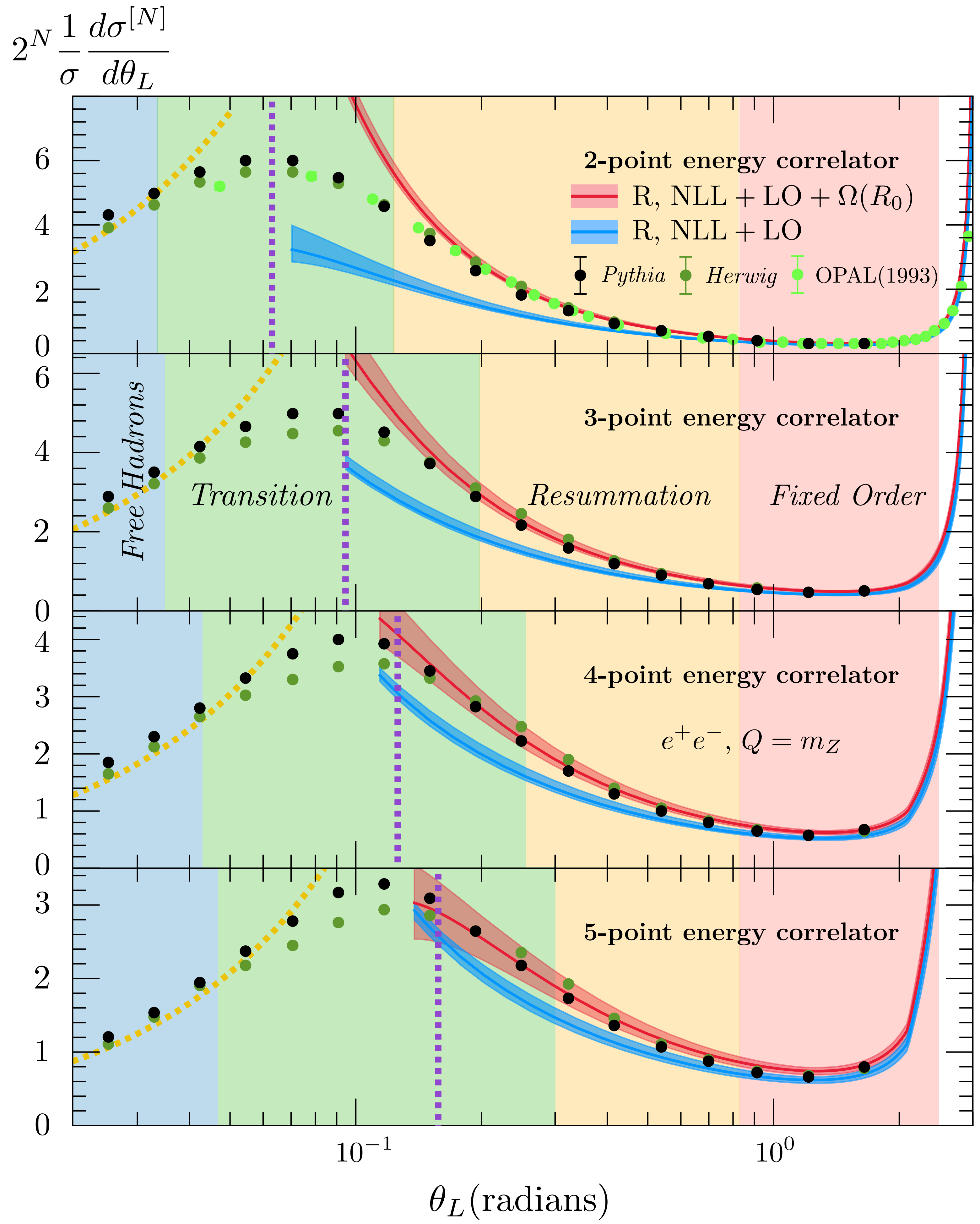
A model-independent treatment of hadronization

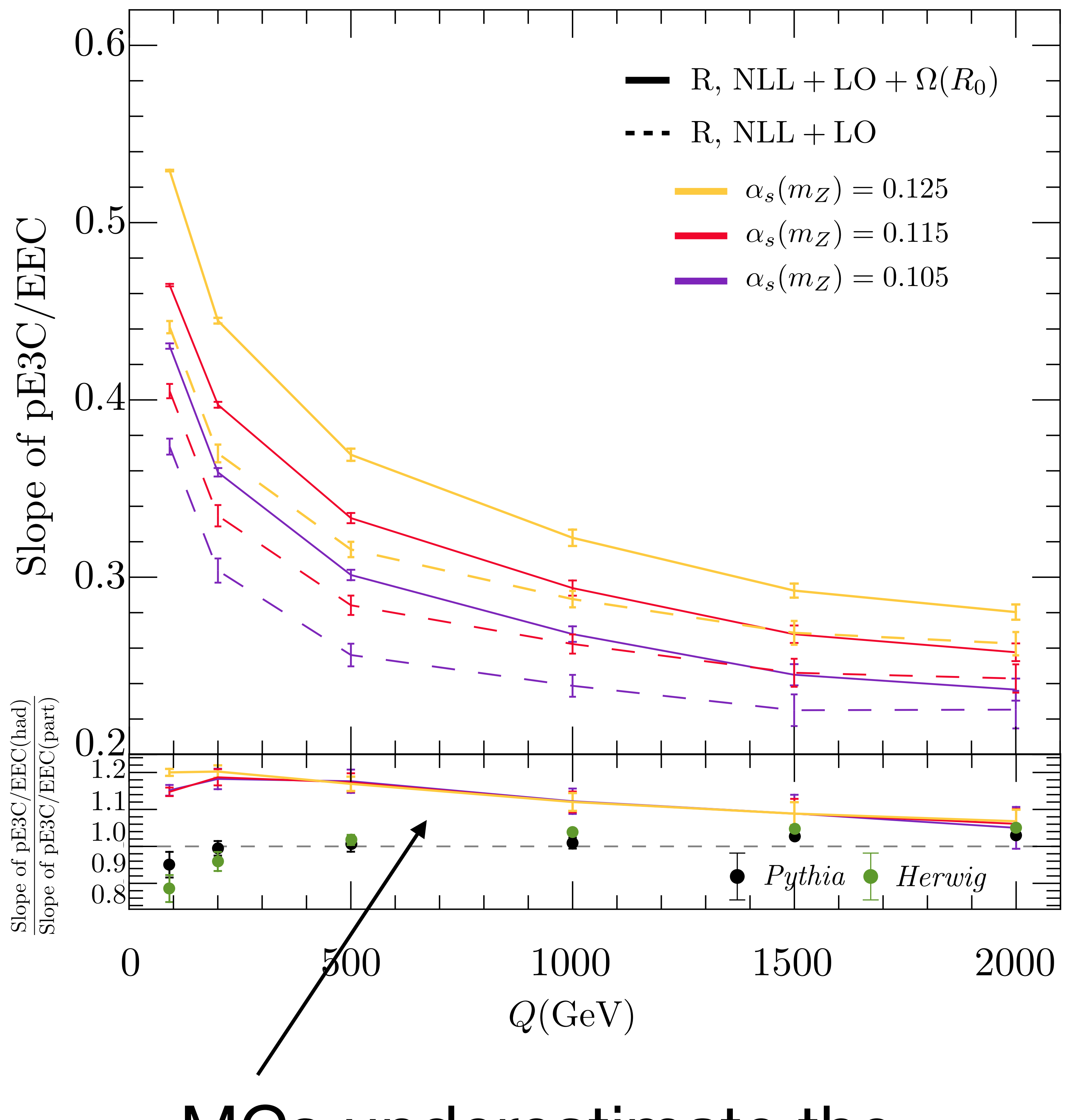
Lee, AP, Stewart, Sun arXiv:2405.19396 [Accepted by PRL]

- 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



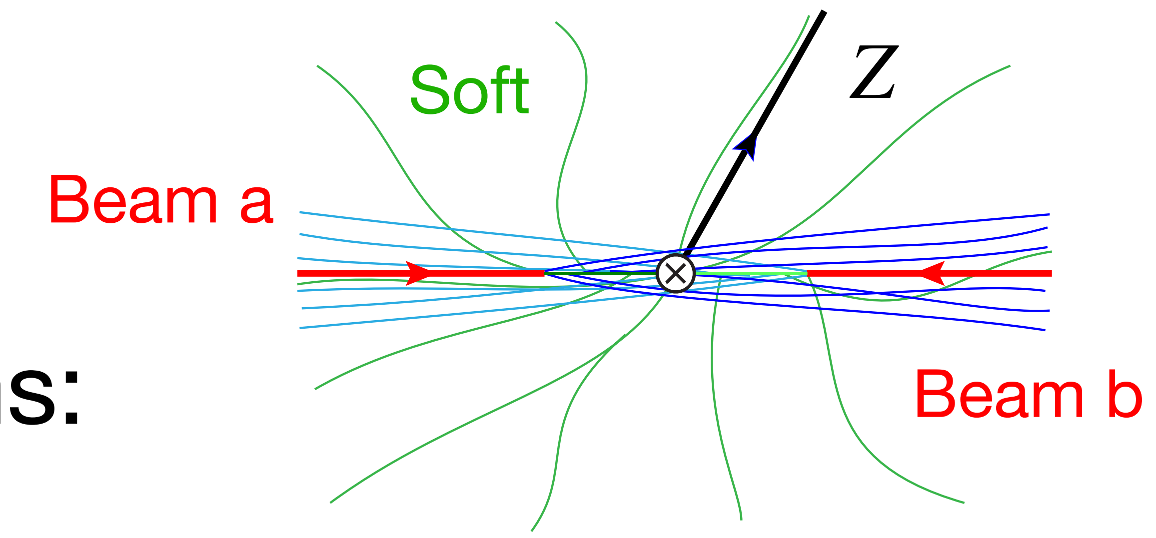


α_s MCs underestimate the size of hadronization in the collinear region!

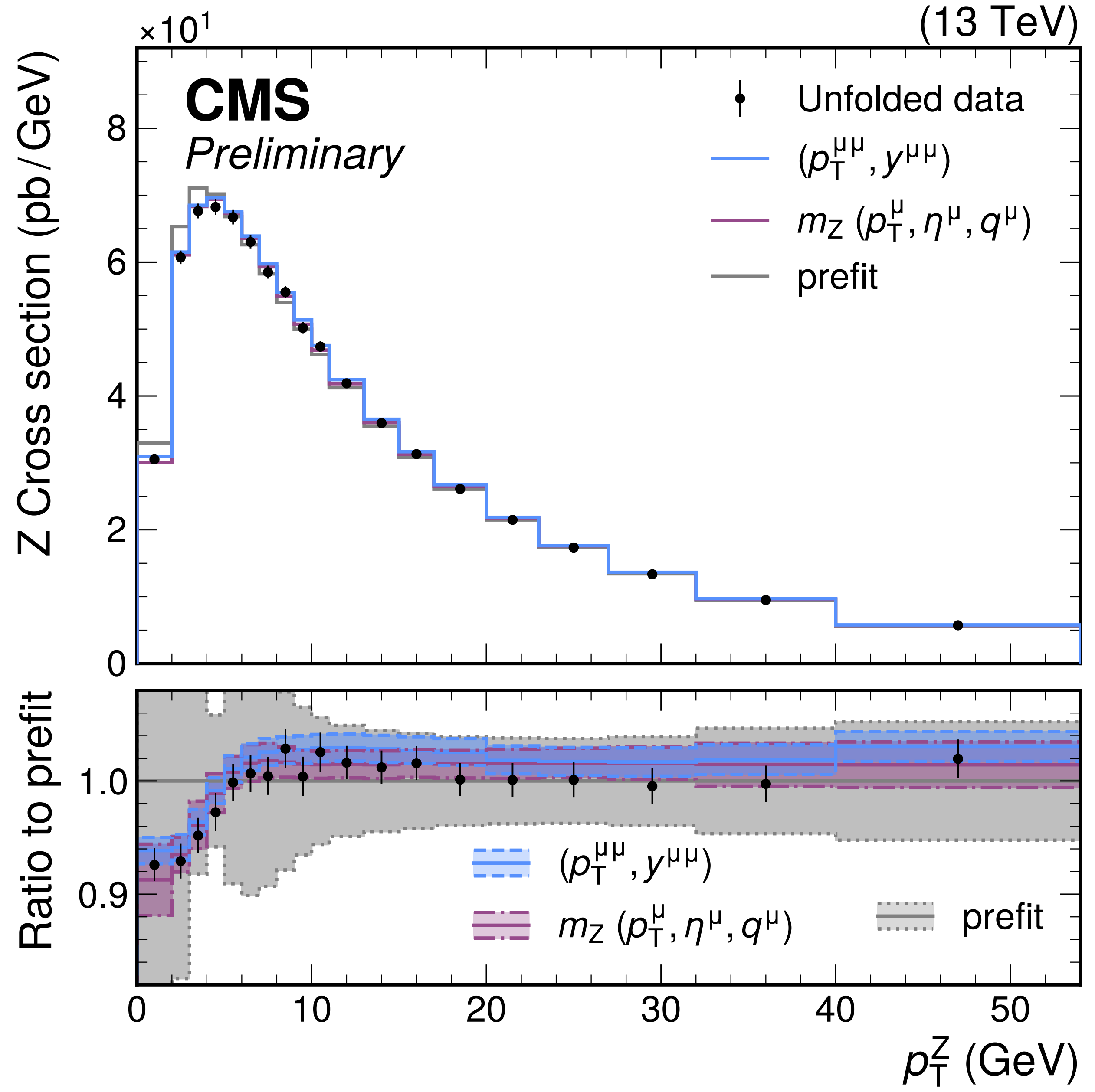
Also see Chen, Monni, Xu, Zhu 2046.06668

The back-to-back region of the EEC

- The shape of the Z boson p_T distribution has a rich all-orders structure for low p_T values: $\frac{1}{p_T^2}\alpha_s^n \log^{2n-1}\left(\frac{p_T^2}{Q^2}\right), \ldots$



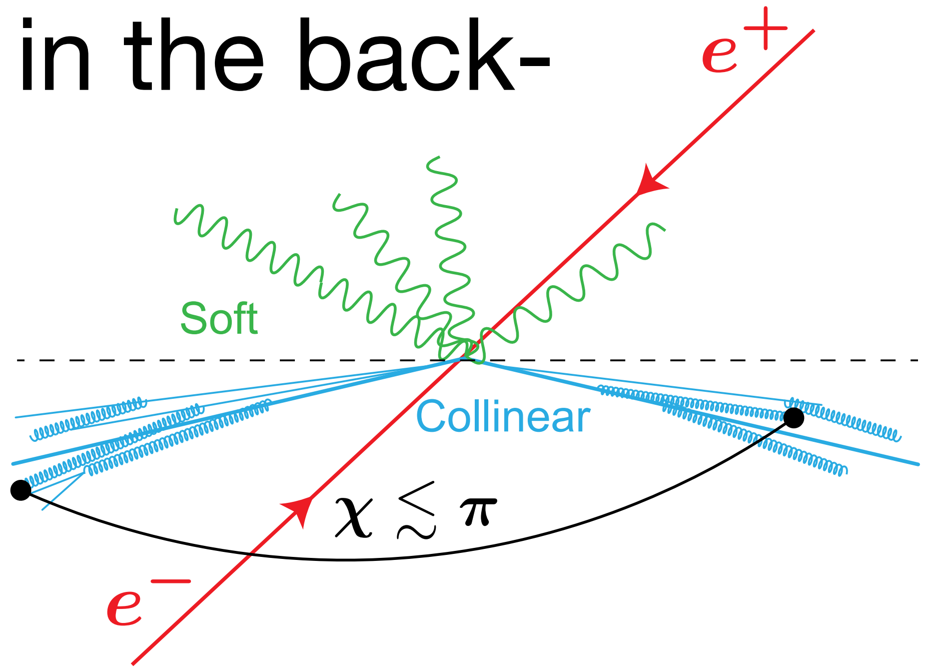
CMS-PAS-SMP-23-002



- The q_T-factorization formula resums these logarithms:

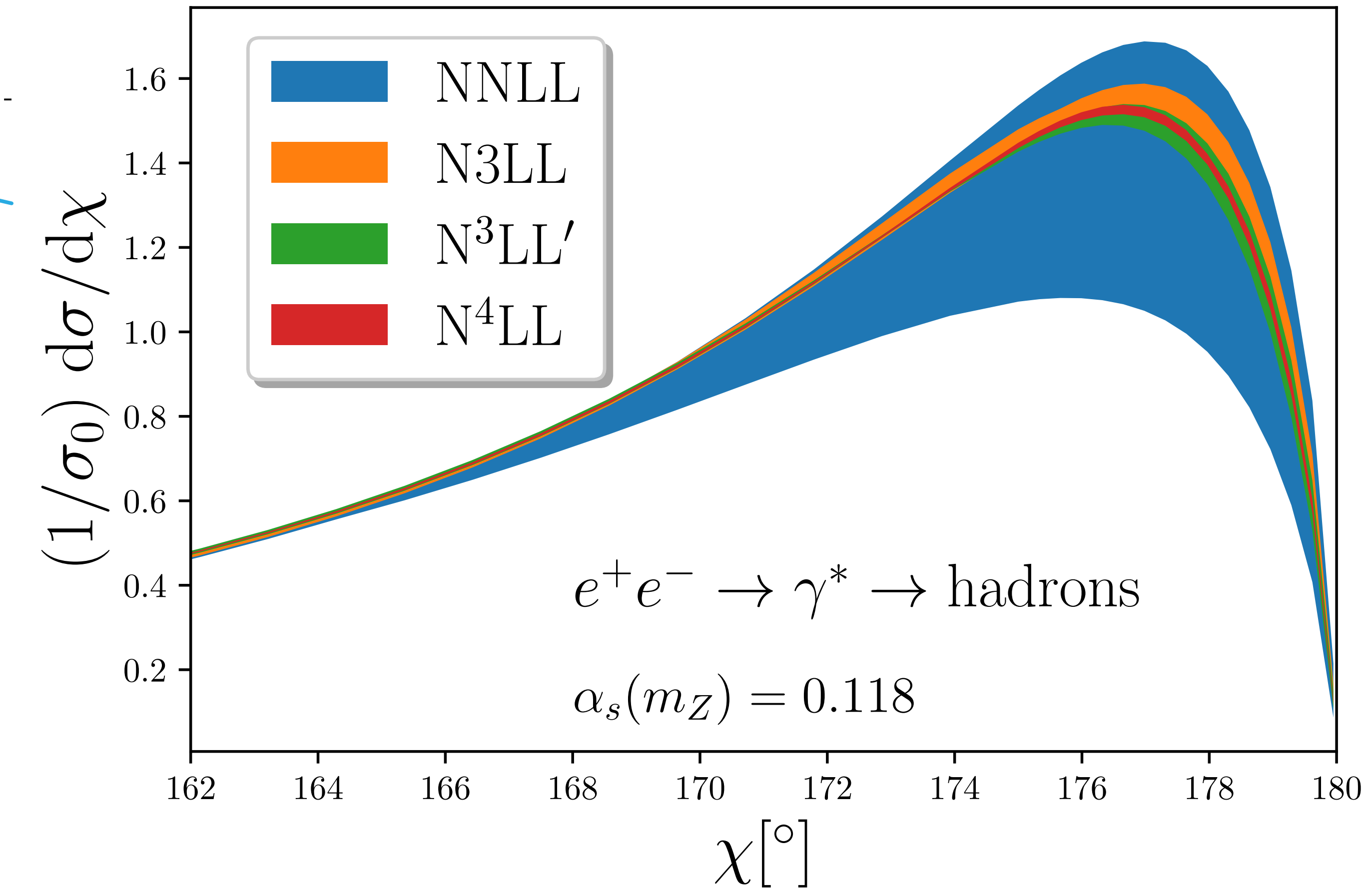
$$\frac{d\sigma}{dq_T} = \sum_{i,j} H_{\mathrm{DY}}^{ij}(Q,\mu) \int \frac{d\boldsymbol{b}_T}{(2\pi)^2}\, e^{-i\boldsymbol{b}_T\cdot\boldsymbol{q}_T}\, \mathscr{B}_{i/N_1}(x_1, b_\perp, \mu)\mathscr{B}_{j/N_2}(x_2, b_\perp, \mu) S_\perp(b_\perp, \mu, \nu)$$

- The same mechanism describes the structure of the EEC in the back-to-back region: $\frac{1}{1-z}\alpha_s^n \log^{2n-1}(1-z)$



- The b2b factorization has the same soft function:

$$\frac{d\Sigma_{\mathrm{EEC}}}{dz} = \frac{1}{4}\int d\boldsymbol{q}_T\, H_{e^+e^-}(Q,\mu) \int \frac{d\boldsymbol{b}_T}{(2\pi)^2}\, e^{-i\boldsymbol{b}_T\cdot\boldsymbol{q}_T}\, \delta\left(1 - z - \frac{q_T^2}{Q^2}\right) J_{\mathrm{EEC}}^{q}(b_\perp,\mu) J_{\mathrm{EEC}}^{\bar{q}}(b_\perp,\mu)\, S_\perp(b_\perp,\mu,\nu)$$

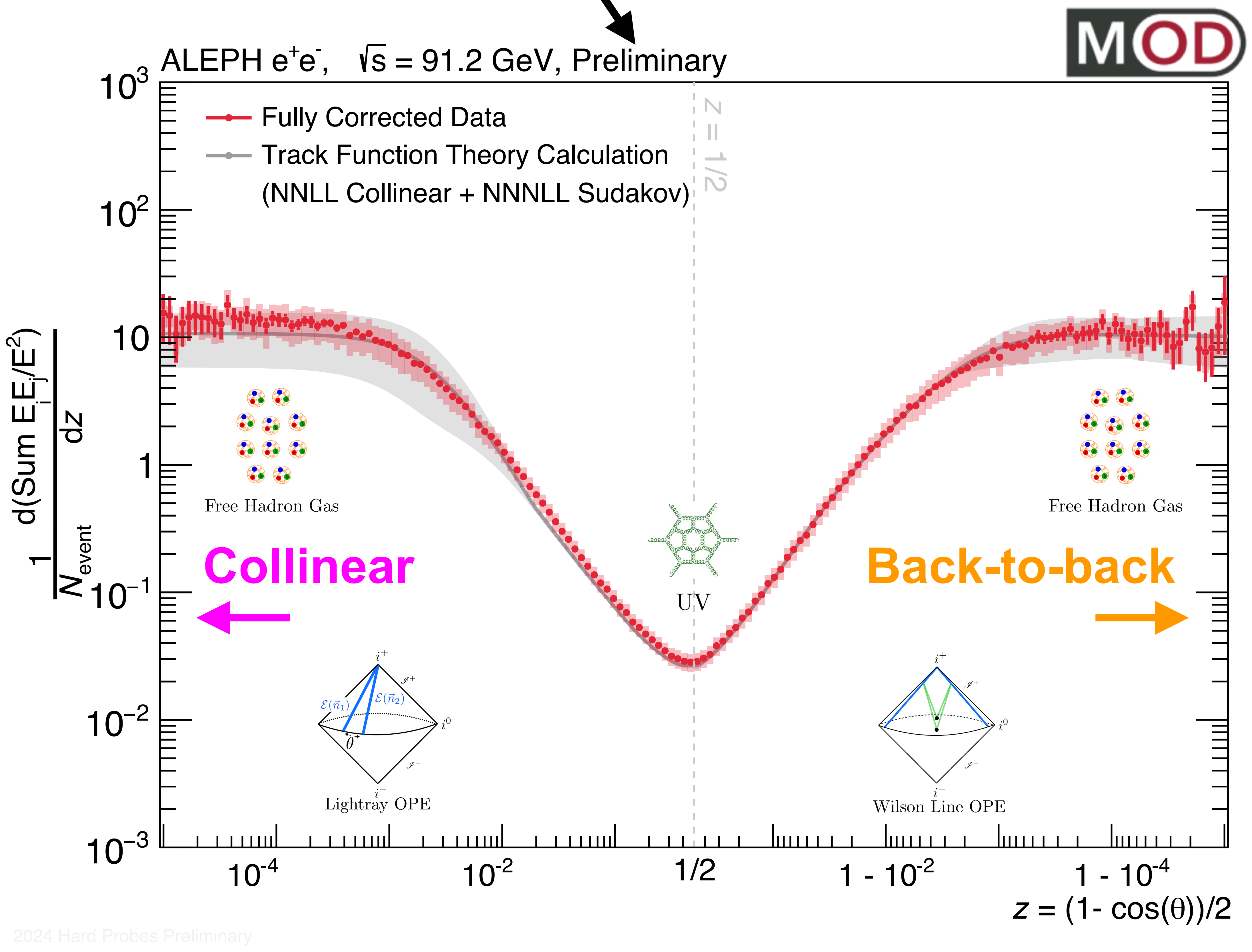


- The most precisely known event shape: N^{4}LL accuracy

Moult, Zhu 2018
Moult, Zhu, Zhu 2022
Duhr, Mistelberger, Vita 2022

Excellent agreement with e^+e^- data

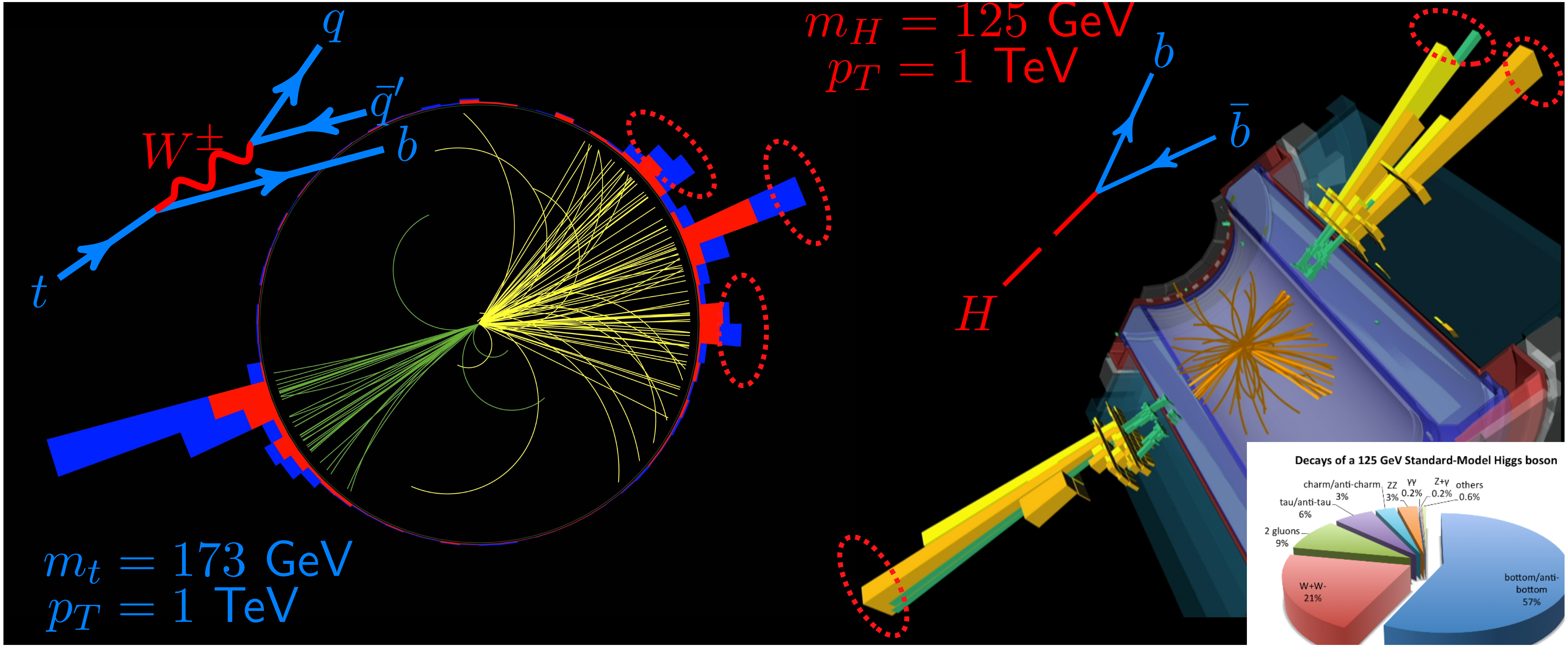
Uses Ω_{1q} from Thrust fits



- **First** highly-differential measurement of EEC(z) in e^+e^- with ALEPH from collinear to back-to-back limit with high statistical precision
- Excellent agreement between archived data and theory calculation
- Directly sensitive to theory parameters (ex: α_S)
- Constraining non-perturbative parameters in lattice QCD
- Stay tuned!

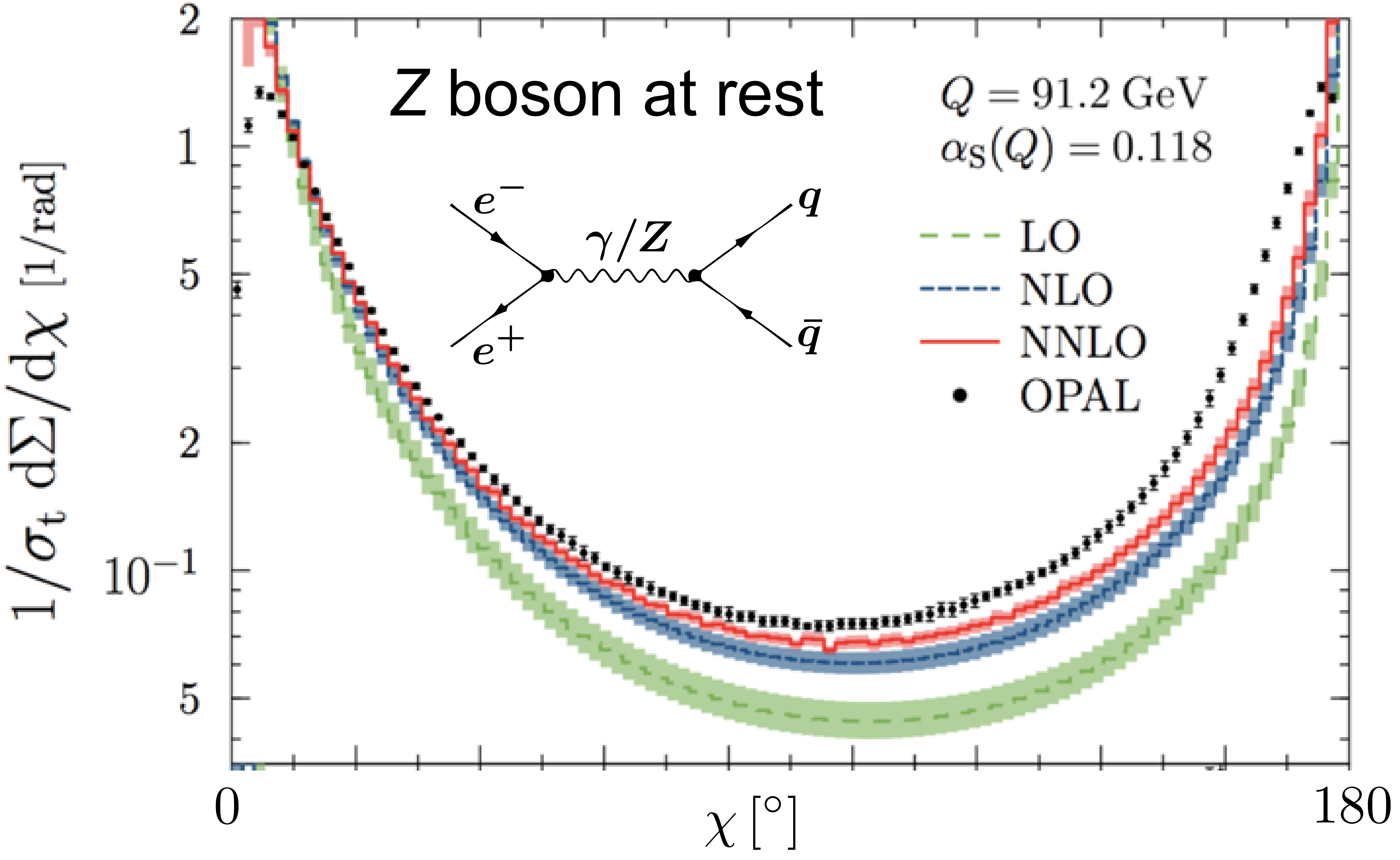
Is the e^+e^- example even relevant for the LHC?

At the LHC we can measure energy correlations on (fat) jets containing boosted boson/top quark decays.

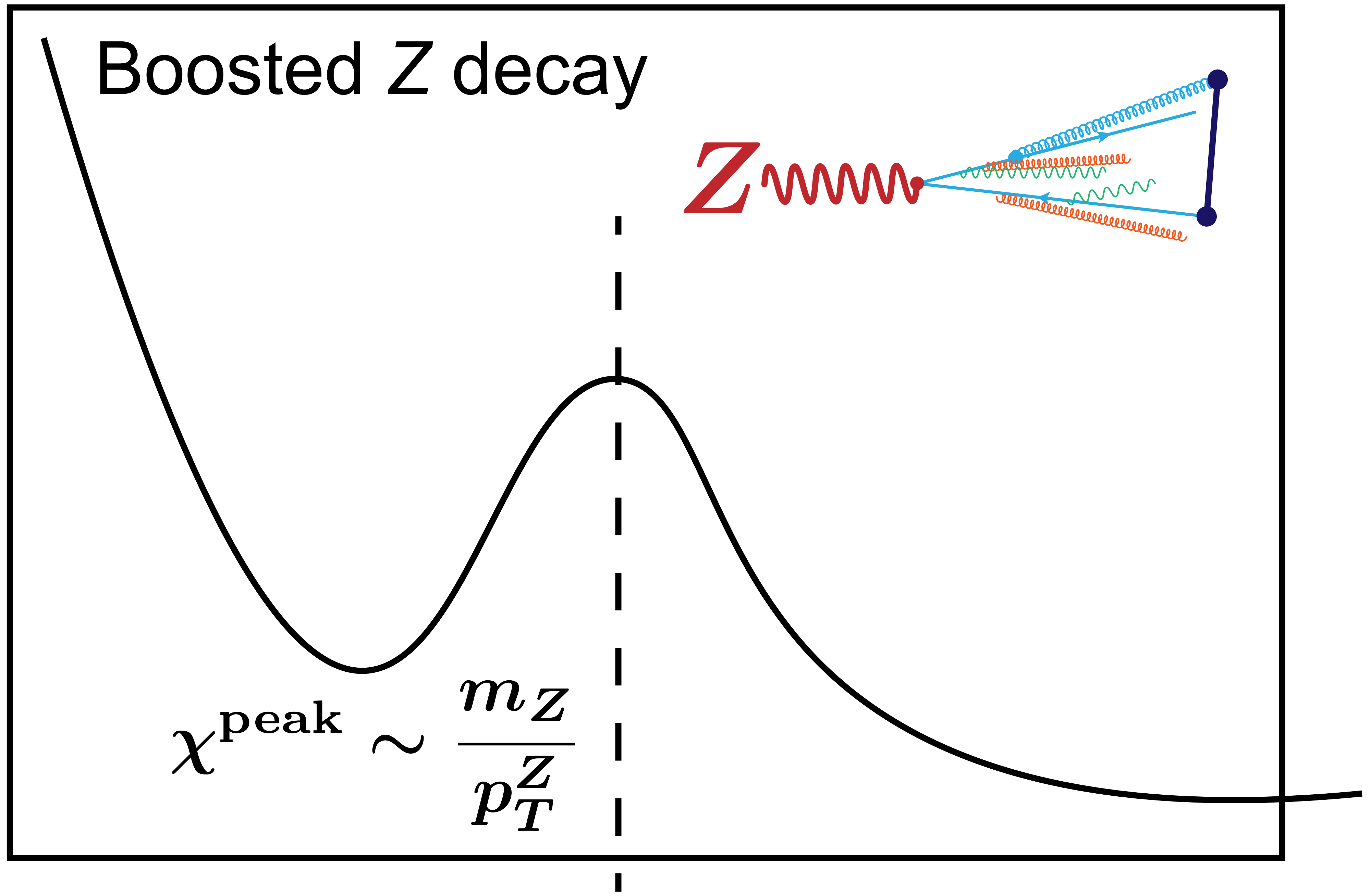


Is the e^+e^- example even relevant for the LHC?

The correlations in the e^+e^- with Z produced at rest is preserved in boosted electroweak Z decays!



Boost



Is the e^+e^- example even relevant for the LHC?

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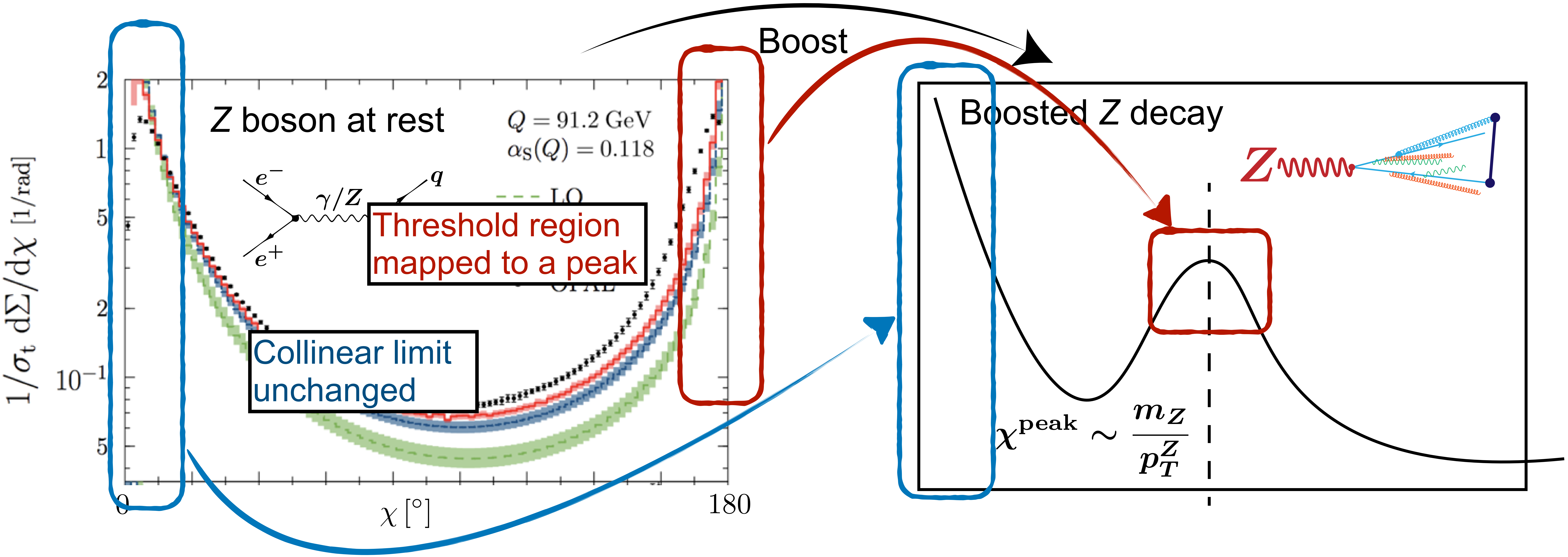


- The $\chi \to 0$ collinear limit probes the same quark/gluon collinear fragmentation dynamics
- The back-to-back region now appears as a peak corresponding to the opening angle of the boosted Z decay.

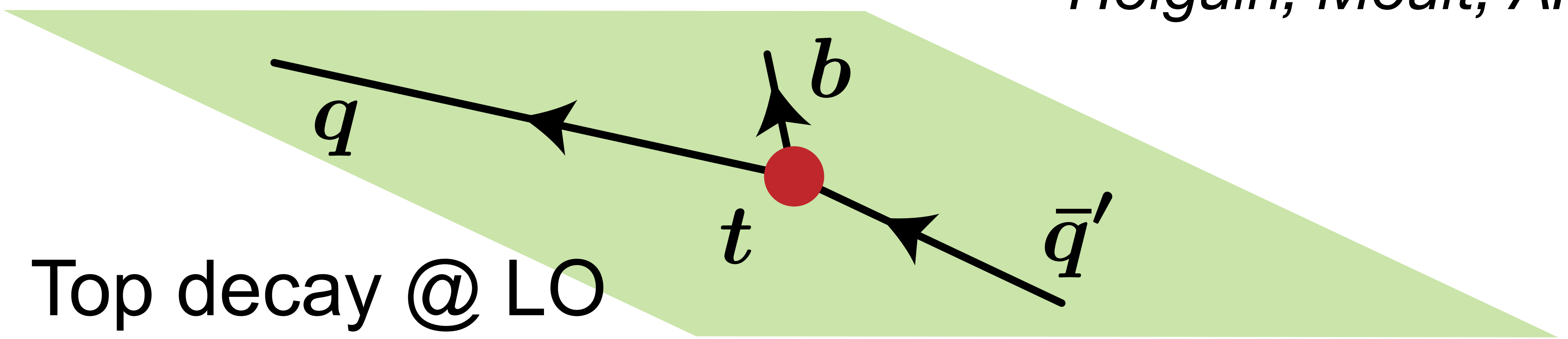
Outline

- Theory challenges with current top mass measurements
- Energy Correlators for precision jet substructure
- A new proposal for top mass using EECs
- Demonstrating robustness and experimental feasibility

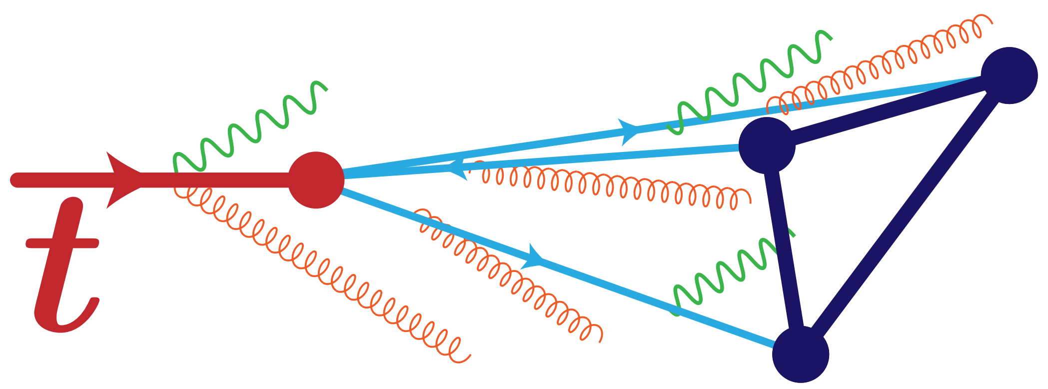
The “back-to-back” version for the *top*

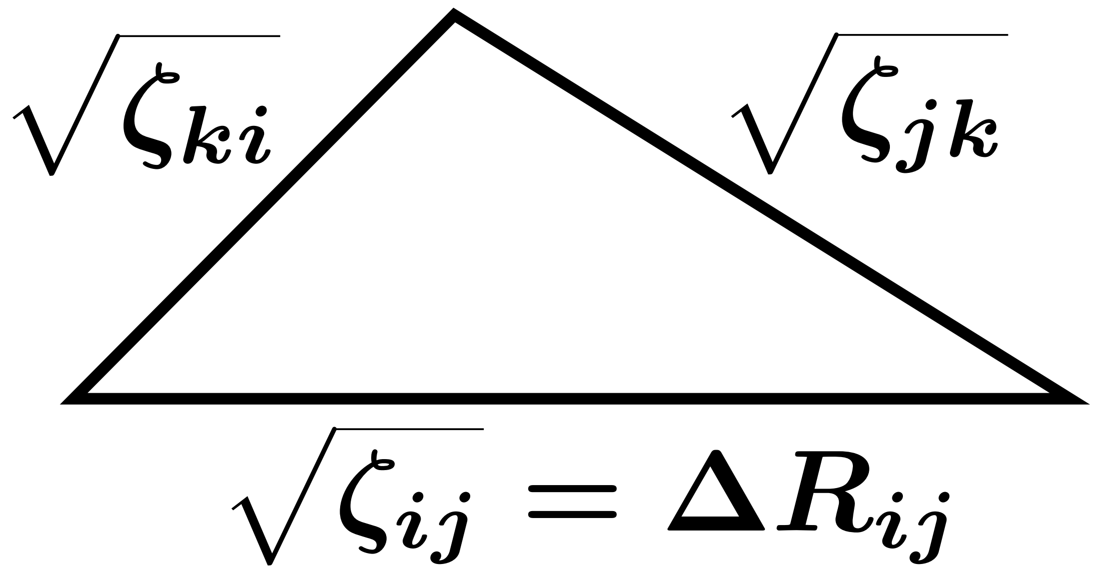
Holguin, Moult, AP, Procura 2022

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



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





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

$$\widehat{\mathscr{M}}^{(n)}(\zeta_{12},\zeta_{23},\zeta_{31}) = \sum_{ijk\in\text{jet}} \frac{p_{T,i}^n p_{T,j}^n p_{T,k}^n}{p_{T,\text{jet}}^{3n}} \delta(\zeta_{12}-\zeta_{ij})\delta(\zeta_{23}-\zeta_{ik})\delta(\zeta_{31}-\zeta_{jk})$$

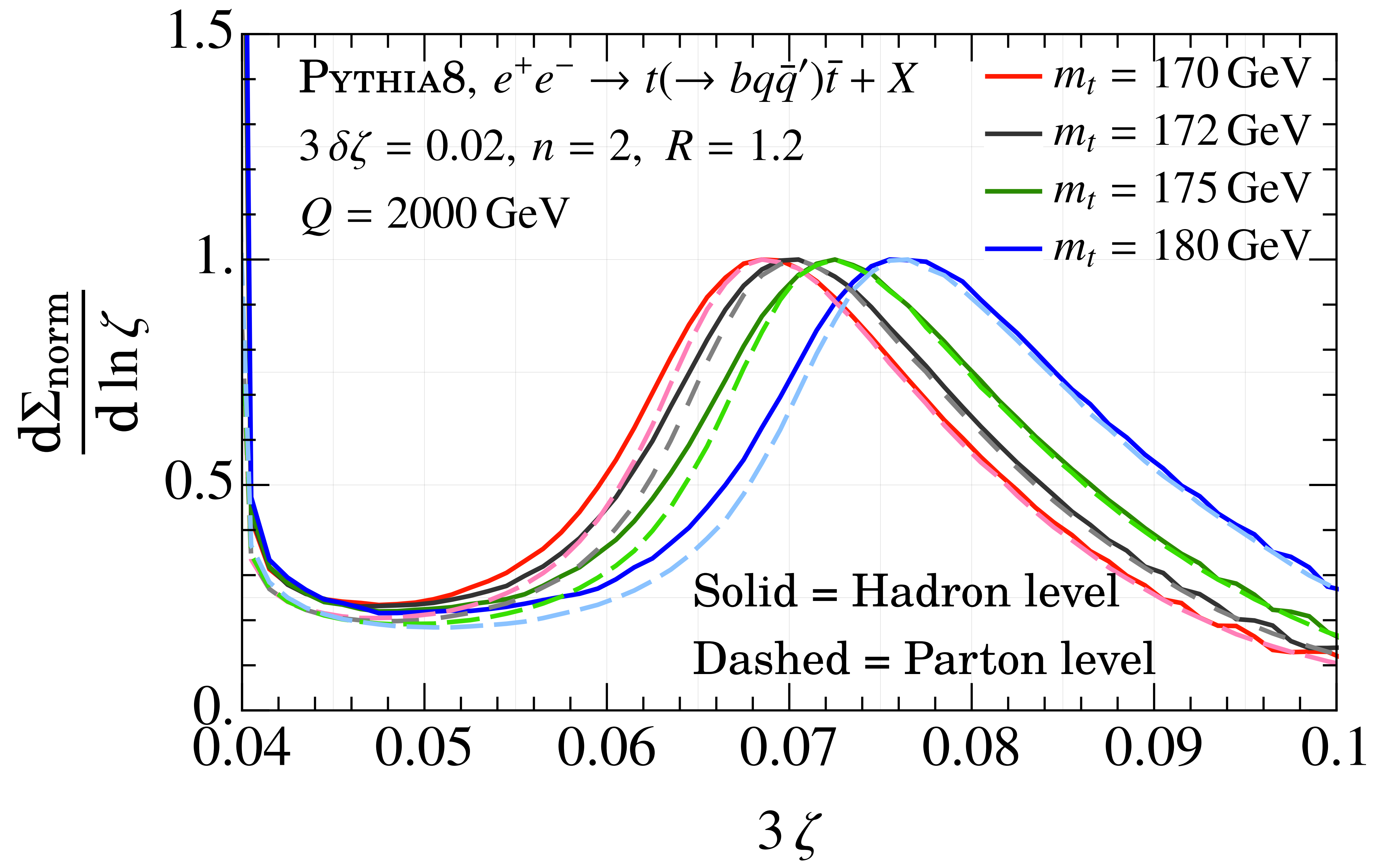
The correlator is sensitive to angles between the decay products. At LO:

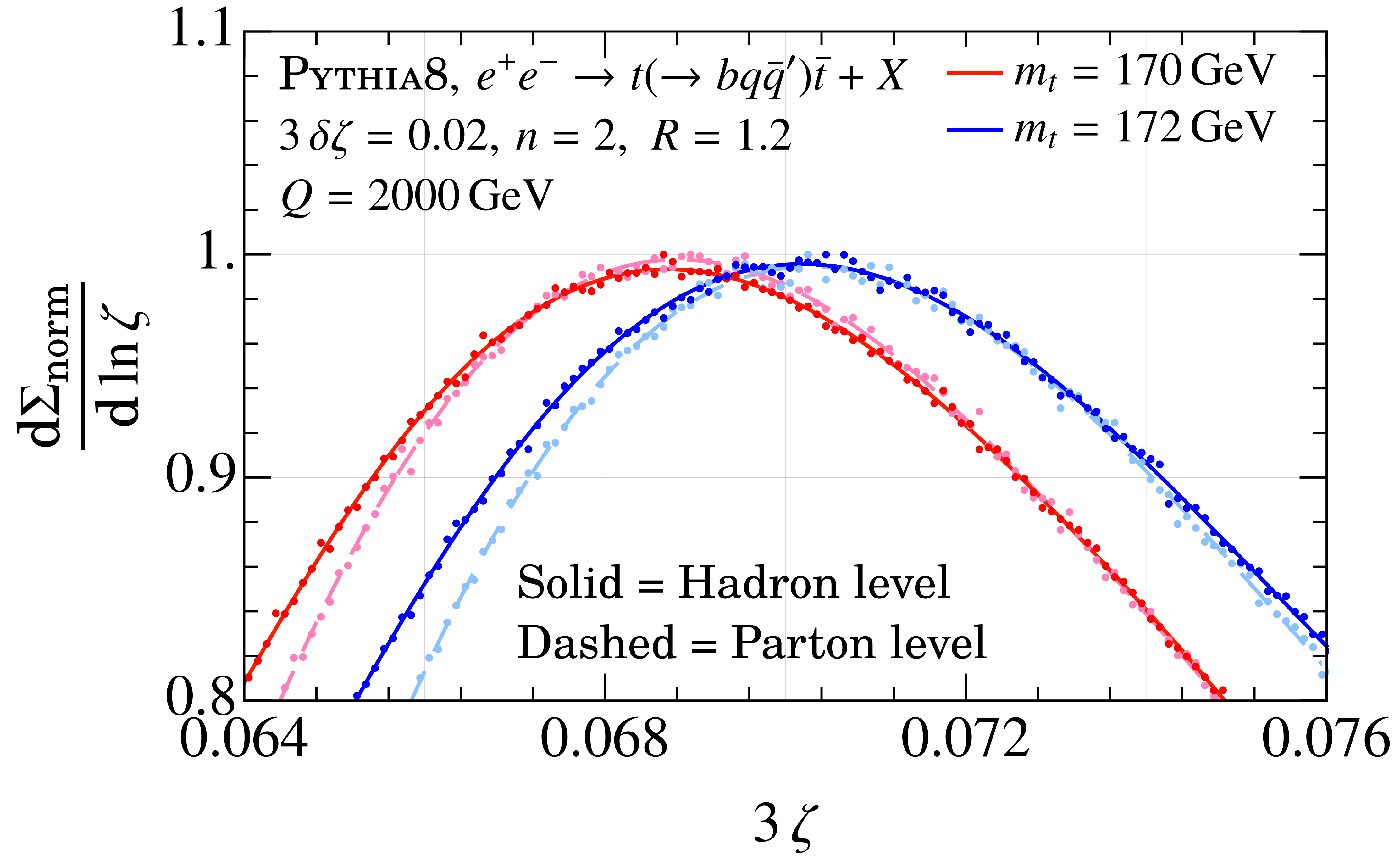
- Top rest frame : $\tilde{\zeta}_t = \tilde{\zeta}_{12} + \tilde{\zeta}_{23} + \tilde{\zeta}_{31} \in [2, 2.25]\,,$
- Lab frame (boosted): $\zeta_t \equiv \sum_{i<j} \zeta_{ij} \approx 3\left(\frac{m_t}{p_T}\right)^2 \sum_{i<j} \tilde{\zeta}_{ij}\,,$

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

Excellent top mass sensitivity and robustness to hadronization

Holguin, Moult, AP, Procura 2022



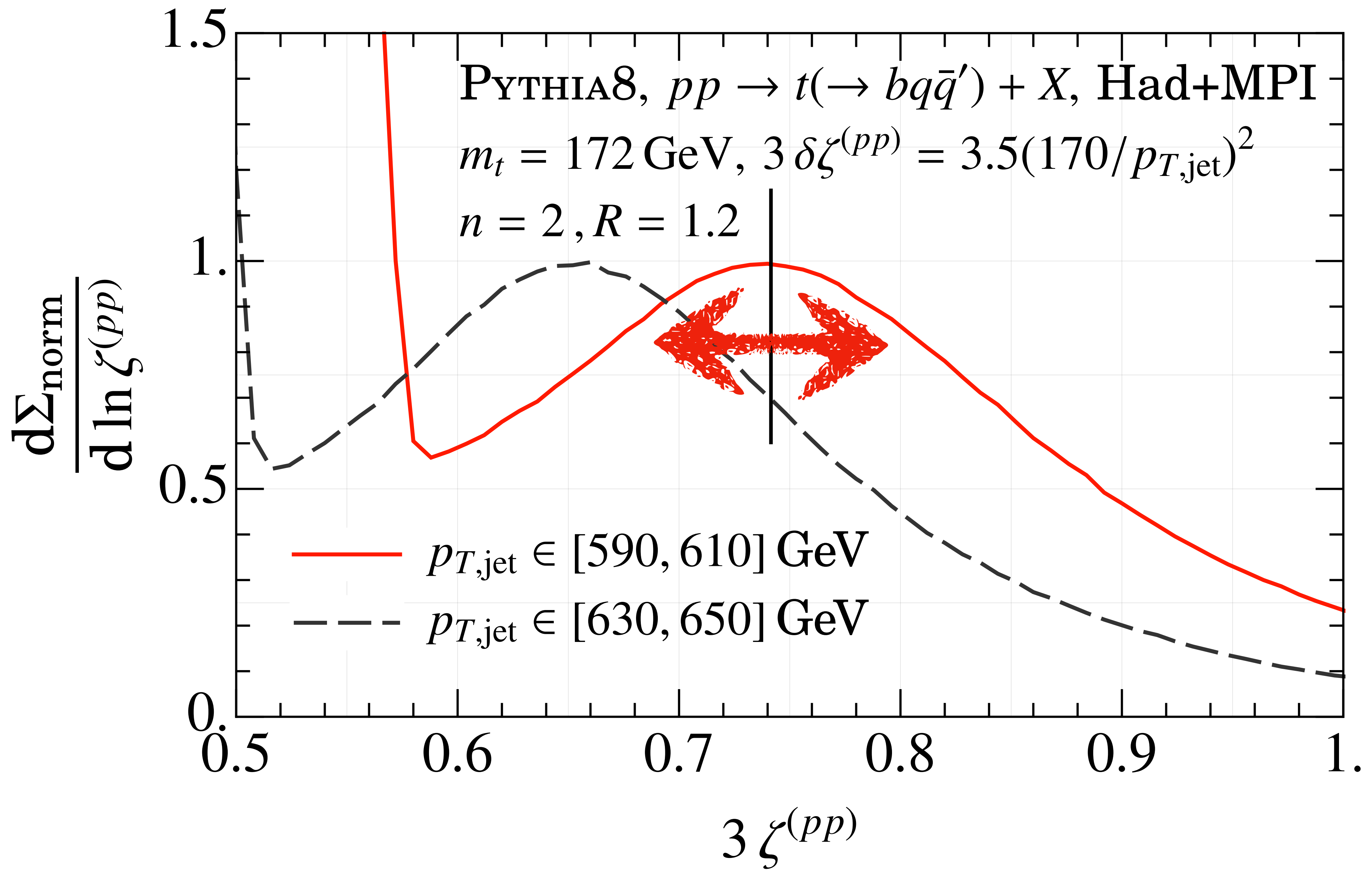


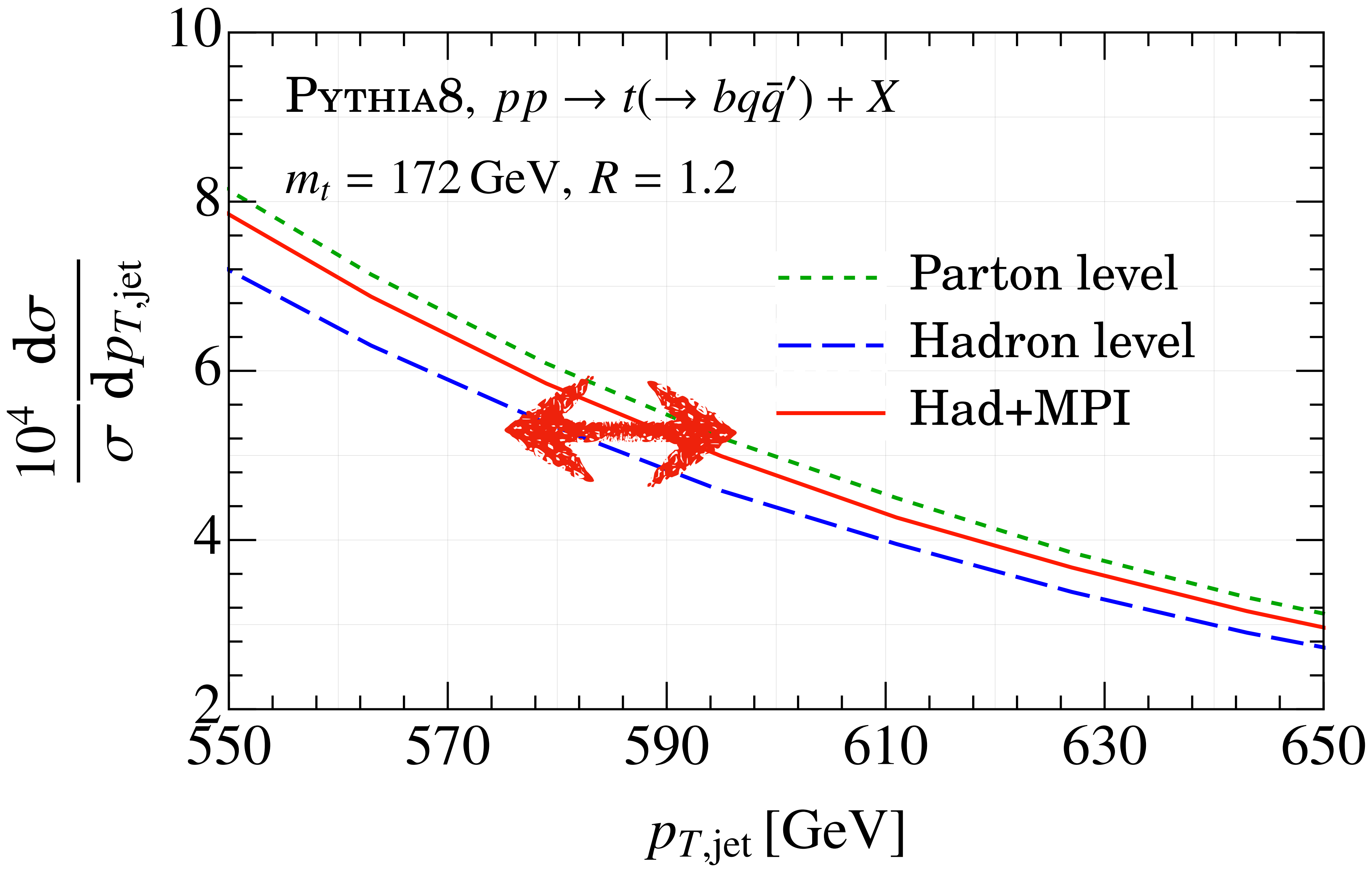
- The imprint of the top quark is extremely sensitive to the top quark mass
- Nonperturbative effects have a very small effect on the peak, $\Delta m_t^{\text{hadr.}} \approx 150 \pm 0.5\,\text{MeV}$
    - This is in a stark contrast to the jet mass with $\sim 1\,\text{GeV}$ shifts in the peak.

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:

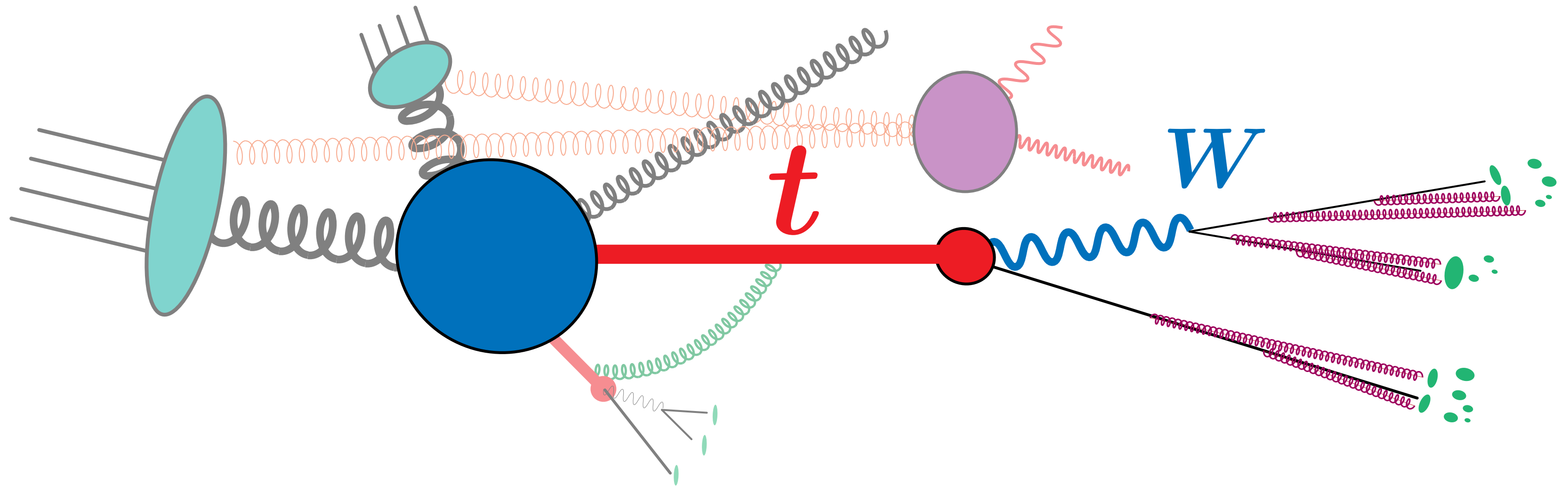


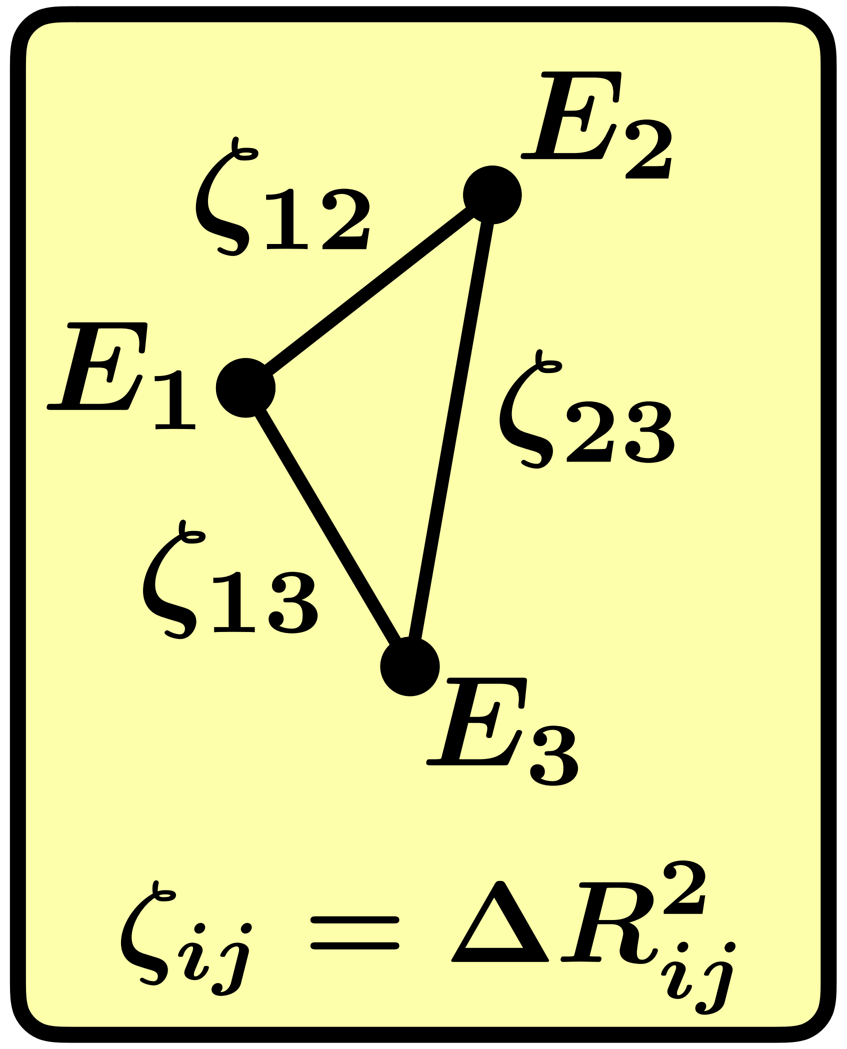


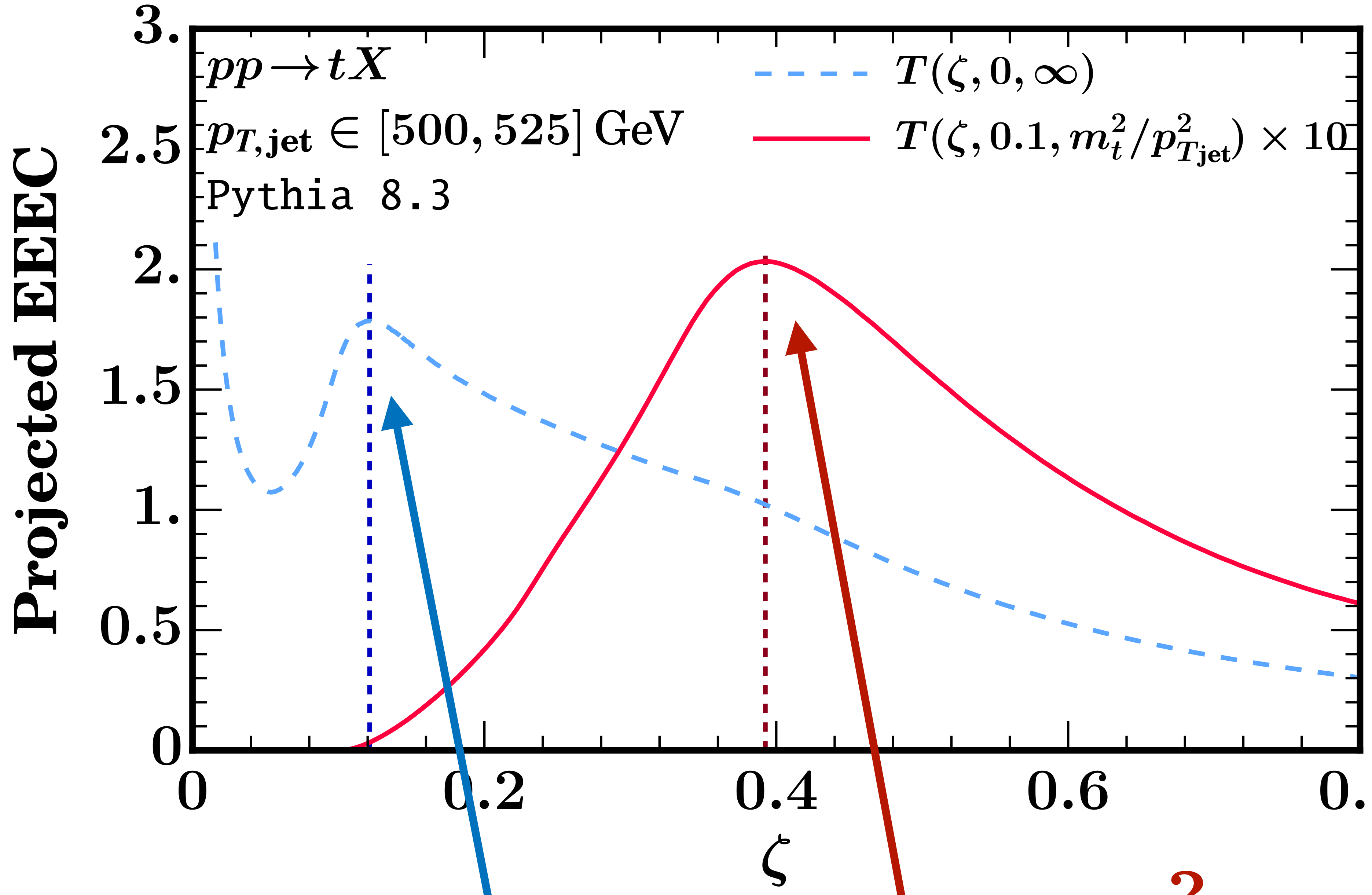
Problems:

- 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 $\zeta_t \sim m_t^2/p_{T,\mathrm{jet}}^2$.

The Standard Candle approach in nutshell







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

(squeezed limit)

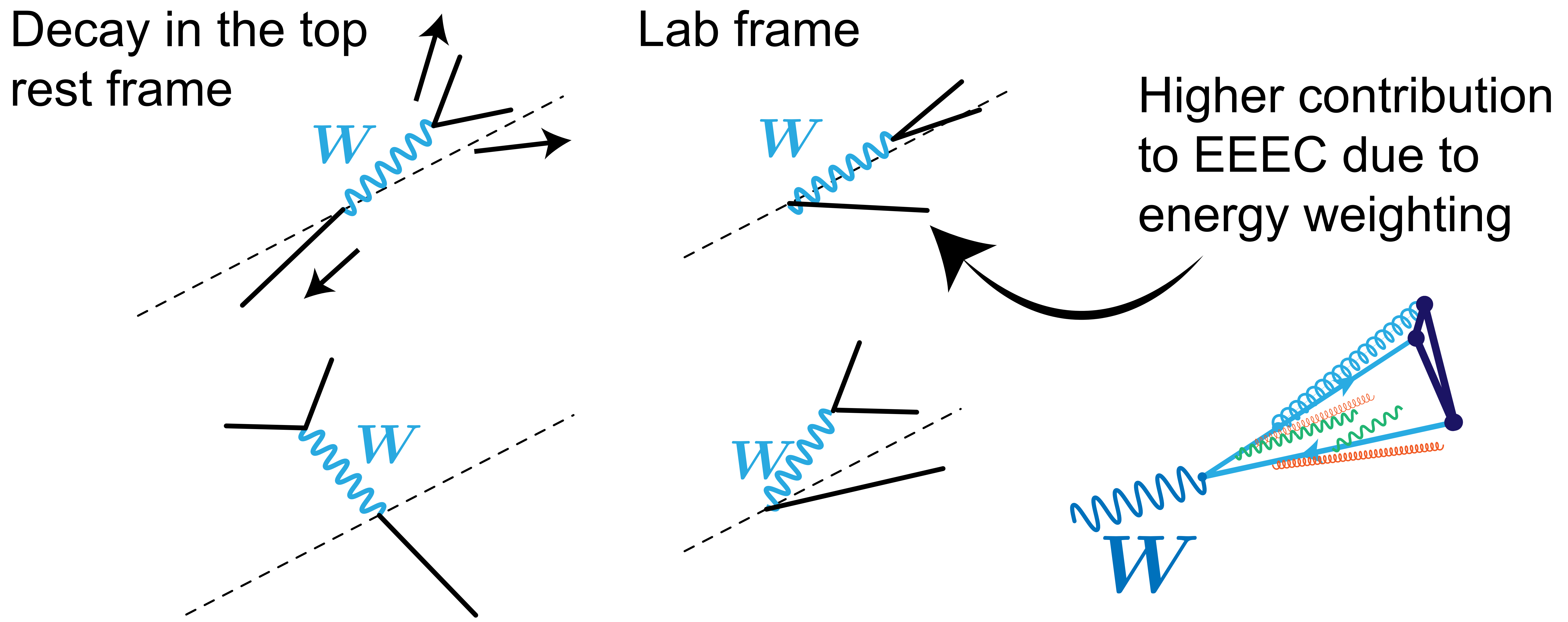
$$m_t \propto m_W \sqrt{\frac{\zeta_t}{\zeta_W}}$$

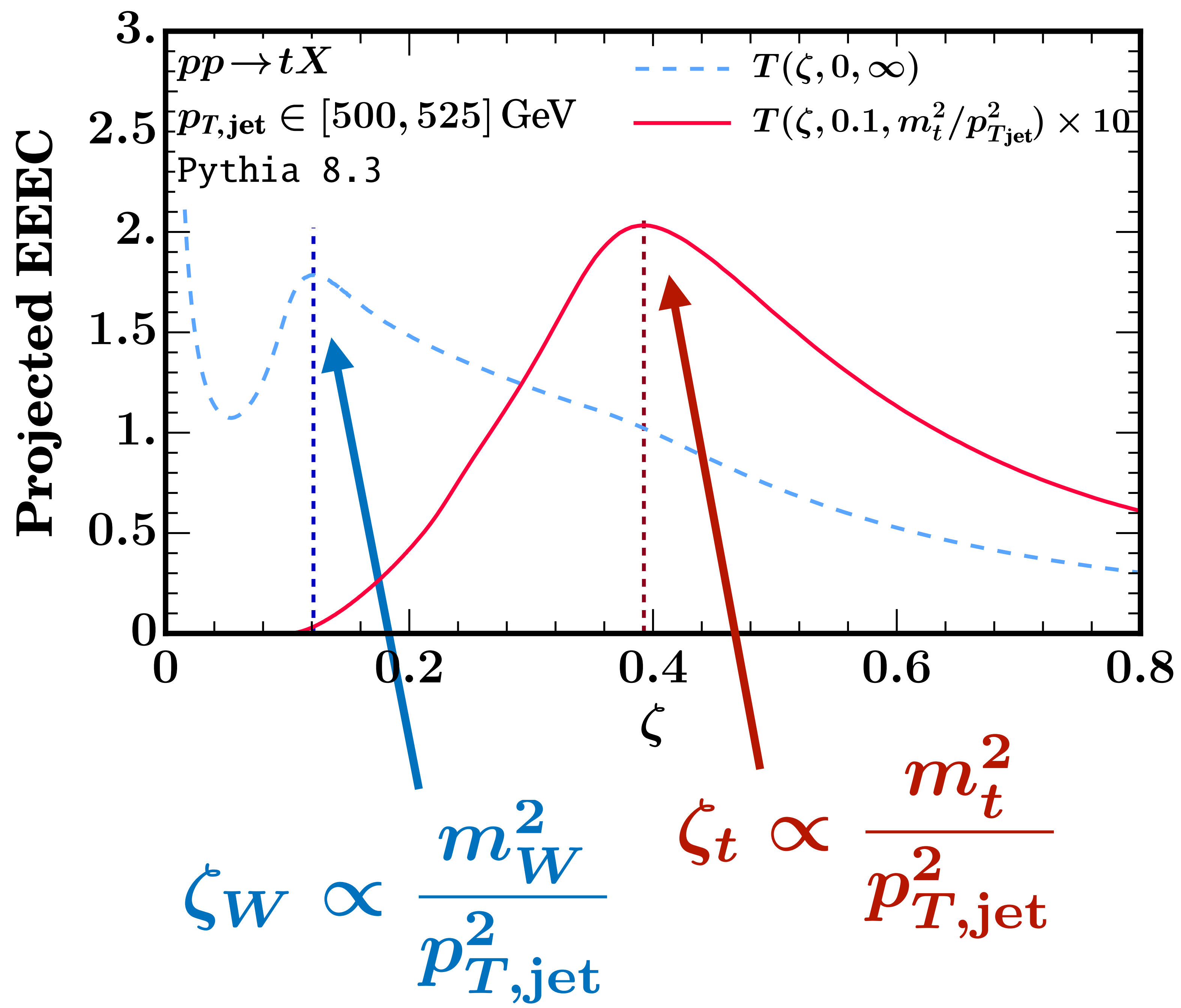
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2023-24

- 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

High degree of correlation of the two imprints

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





- The top quark and the W share a common boost defined by $p_{T,\mathrm{jet}}$
- 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.

Outline

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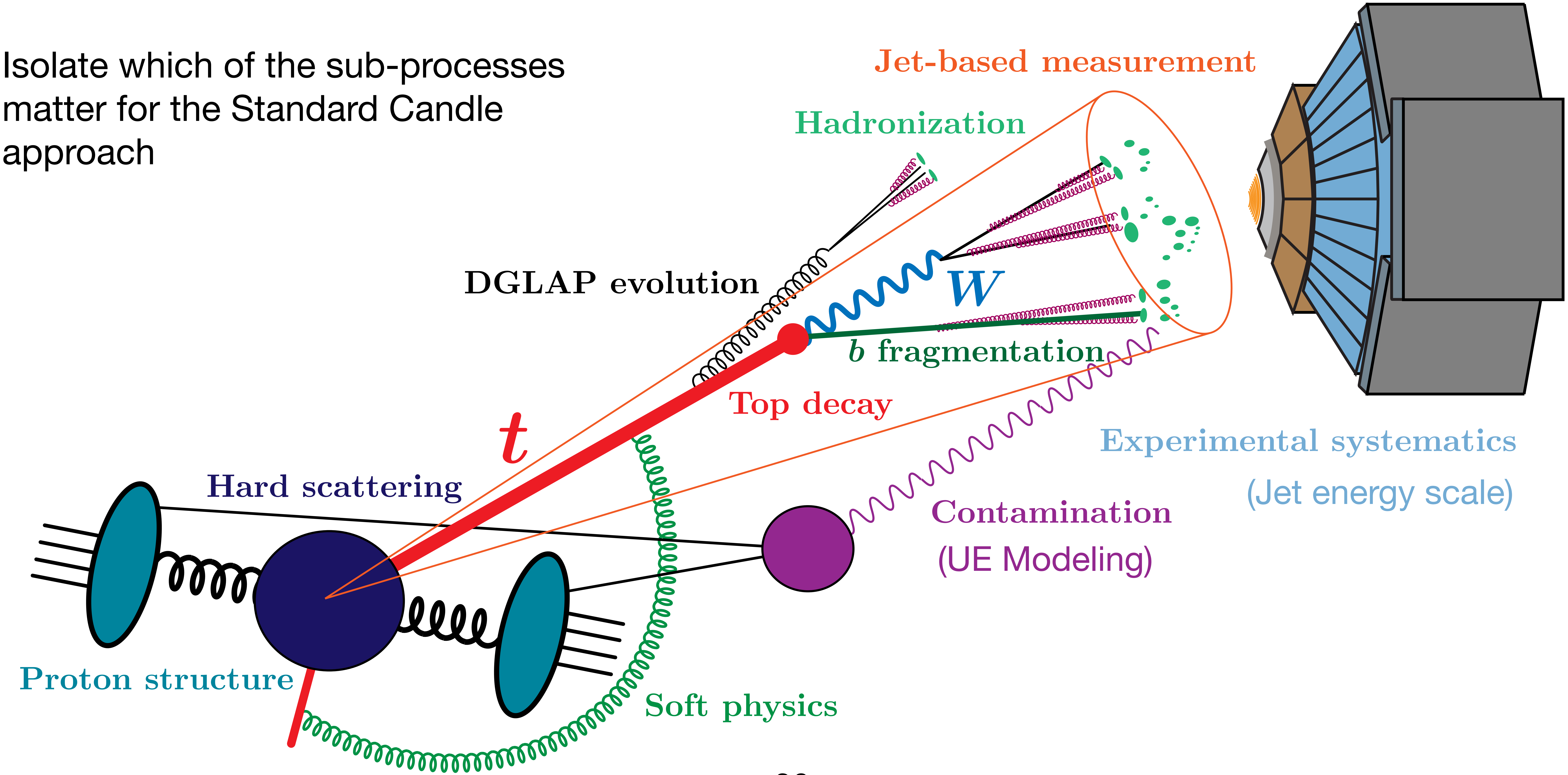
The task ahead

Isolate which of the sub-processes matter for the Standard Candle approach

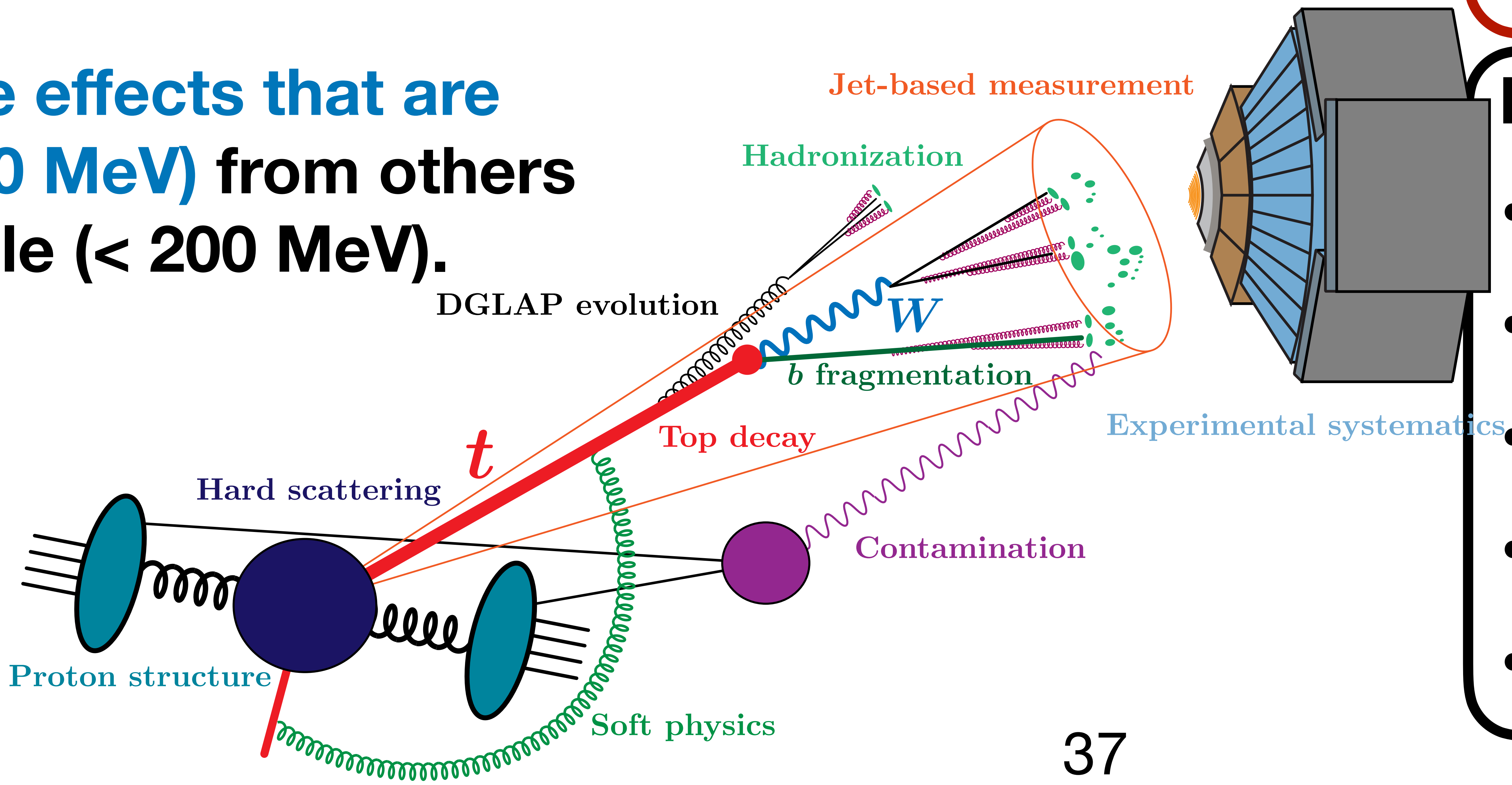


The checklist

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.

Goal is to isolate effects that are substantial (~500 MeV) from others that are negligible (< 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 ☐
- Tracks-based measurement ☐
- Heavy flavor dependence ☐

Calibrating the top mass

- 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:

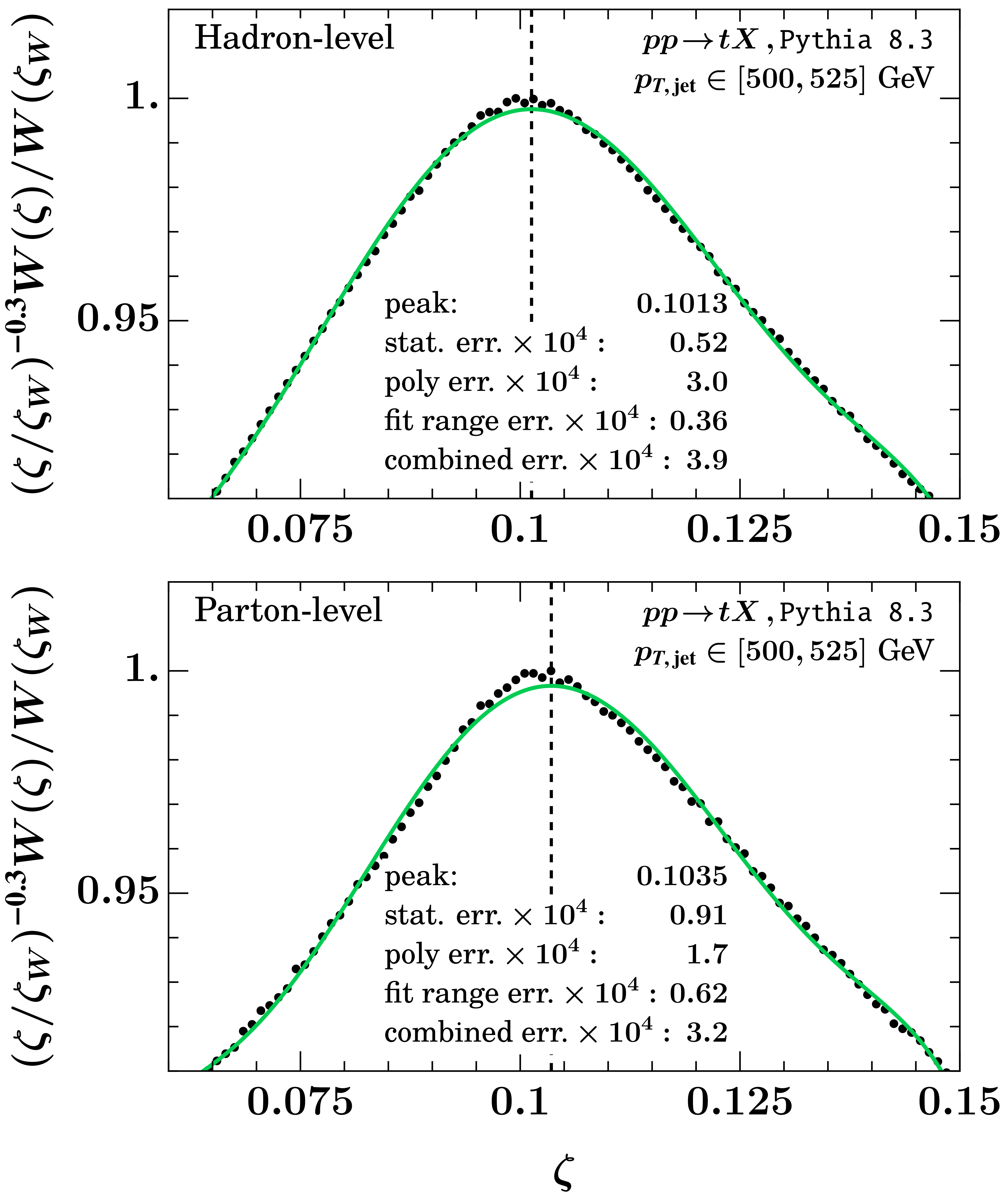
$$\left.\frac{\mathrm{d}T}{\mathrm{d}\zeta}\right|_{\zeta=\zeta_t} = 0\,, \qquad \left.\frac{\mathrm{d}W}{\mathrm{d}\zeta}\right|_{\zeta=\zeta_W} = 0$$

- In the large boost limit,

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

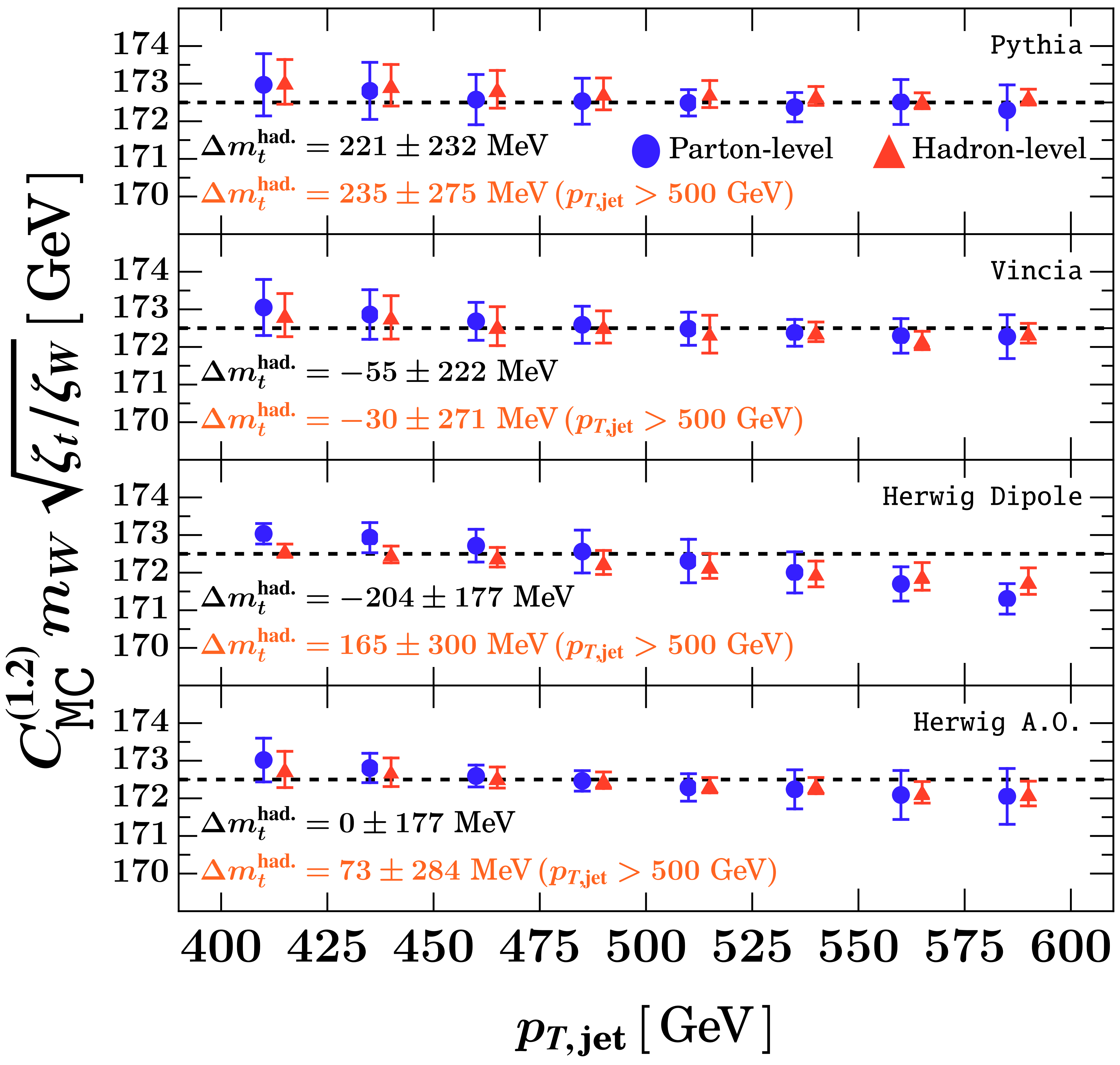
- The constant C is perturbatively calculable and R-dependent
- For now extract this from parton showers by averaging over $p_T \in [400{,}600]$ GeV.
- Primary error from varying the fit polynomial degree.

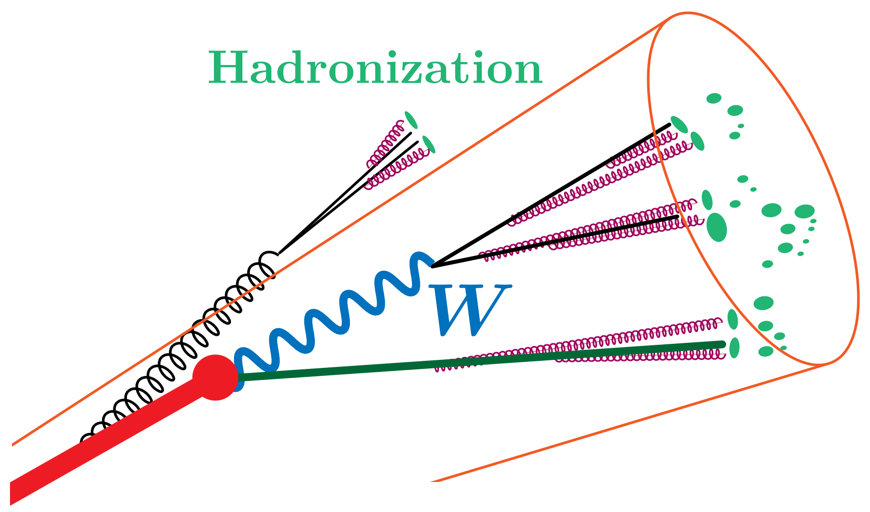
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 24



Hadronization effects

All the showers exhibit a cancellation of hadronization effects in the $p_{T,\text{jet}}$. Negligible shift $\lesssim 200$ MeV





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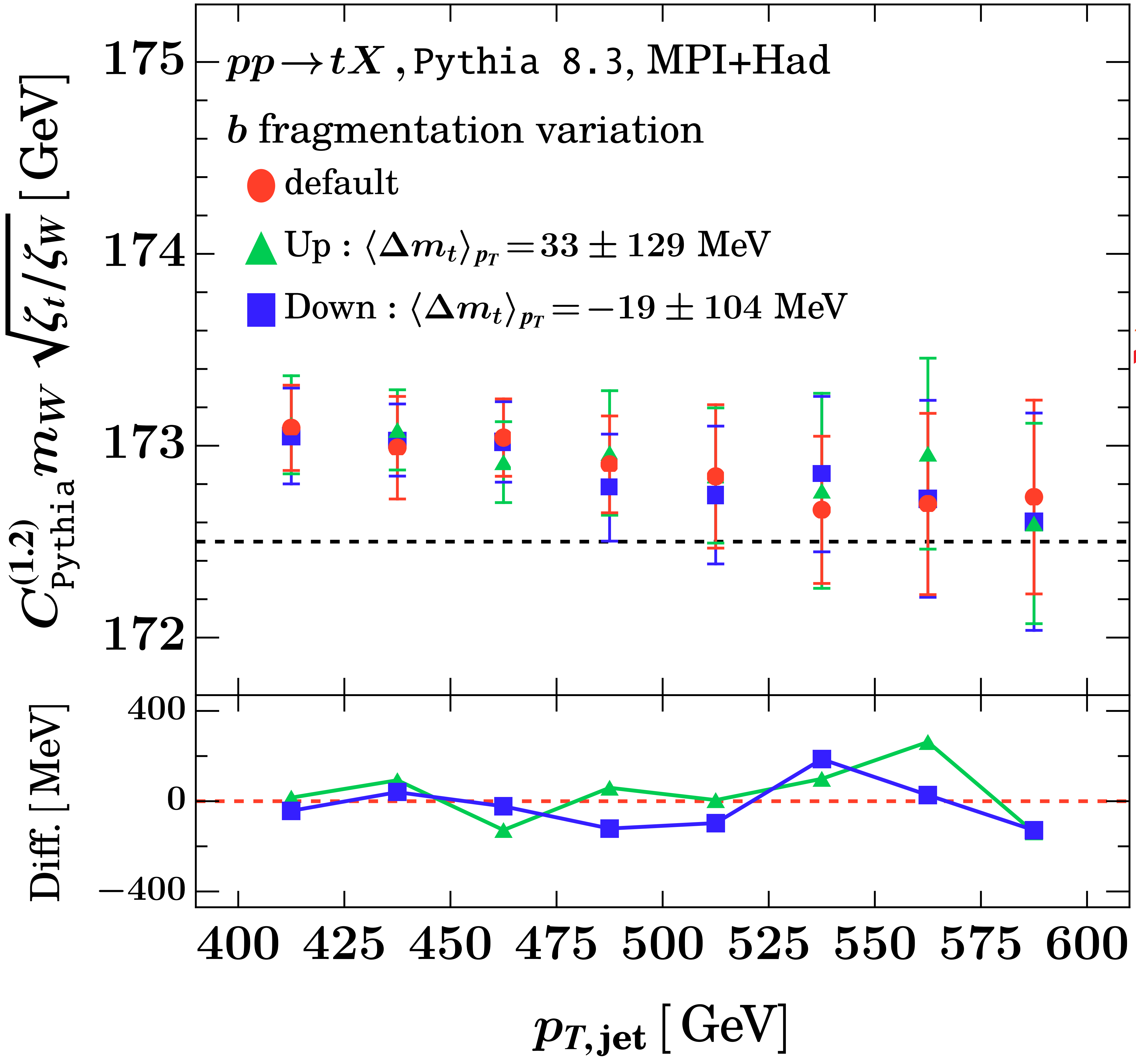
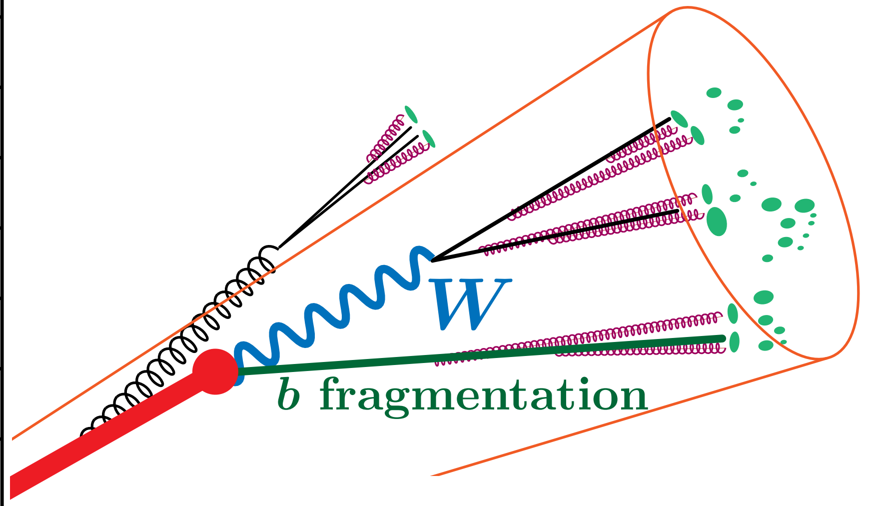
Hadronization effects

Negligible impact of *b* hadron fragmentation modeling:





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

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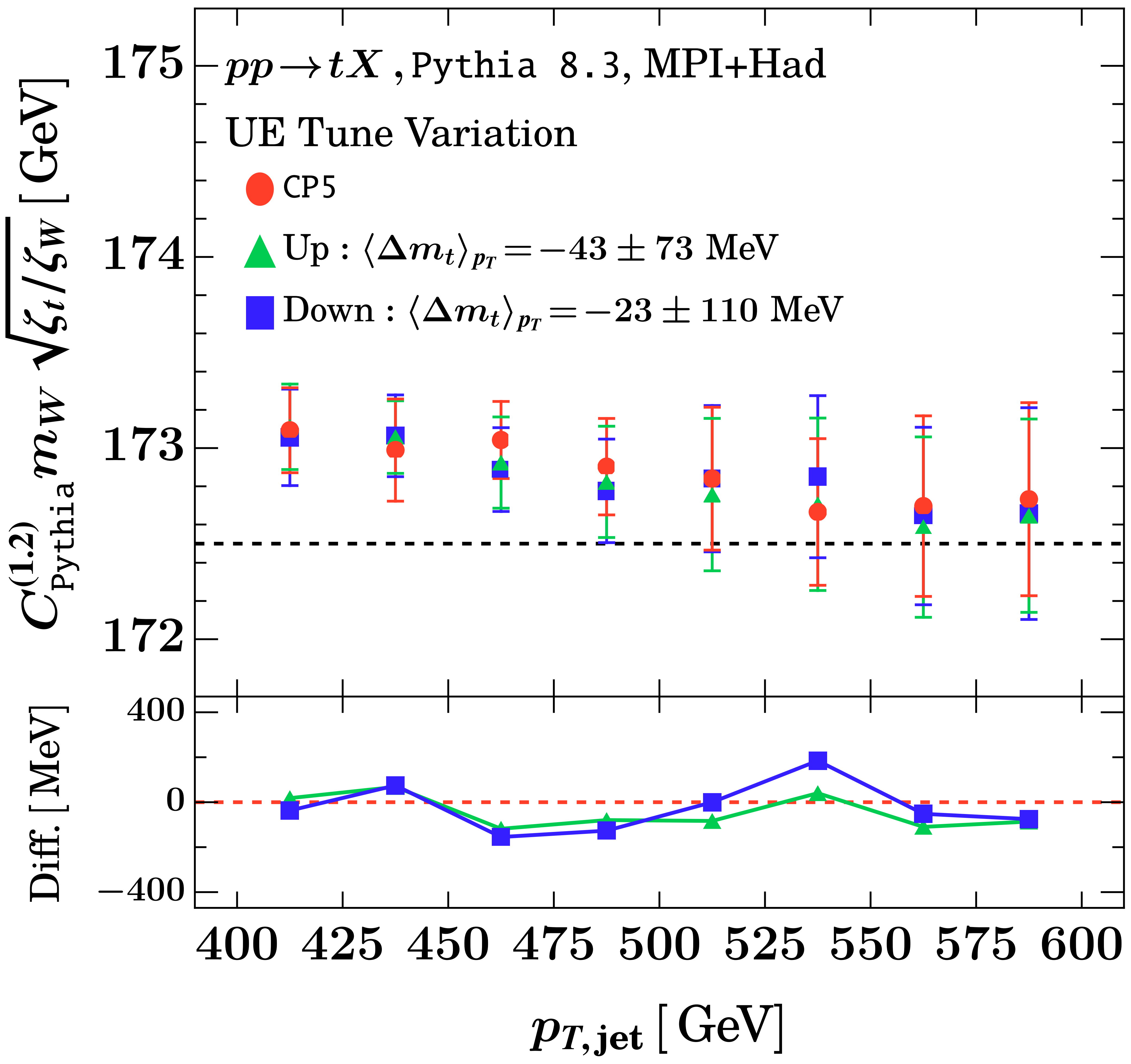
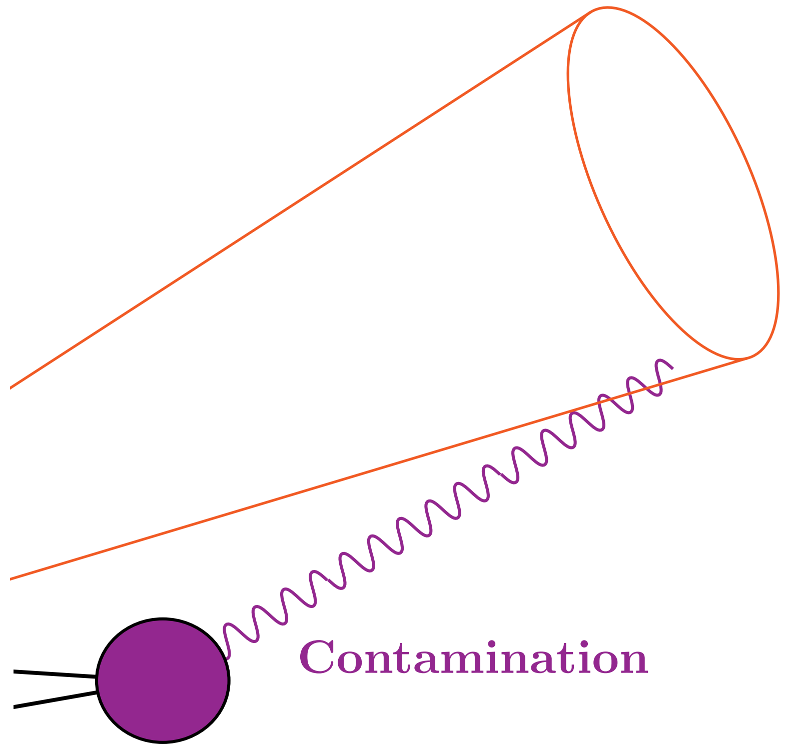
Effect of contamination

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





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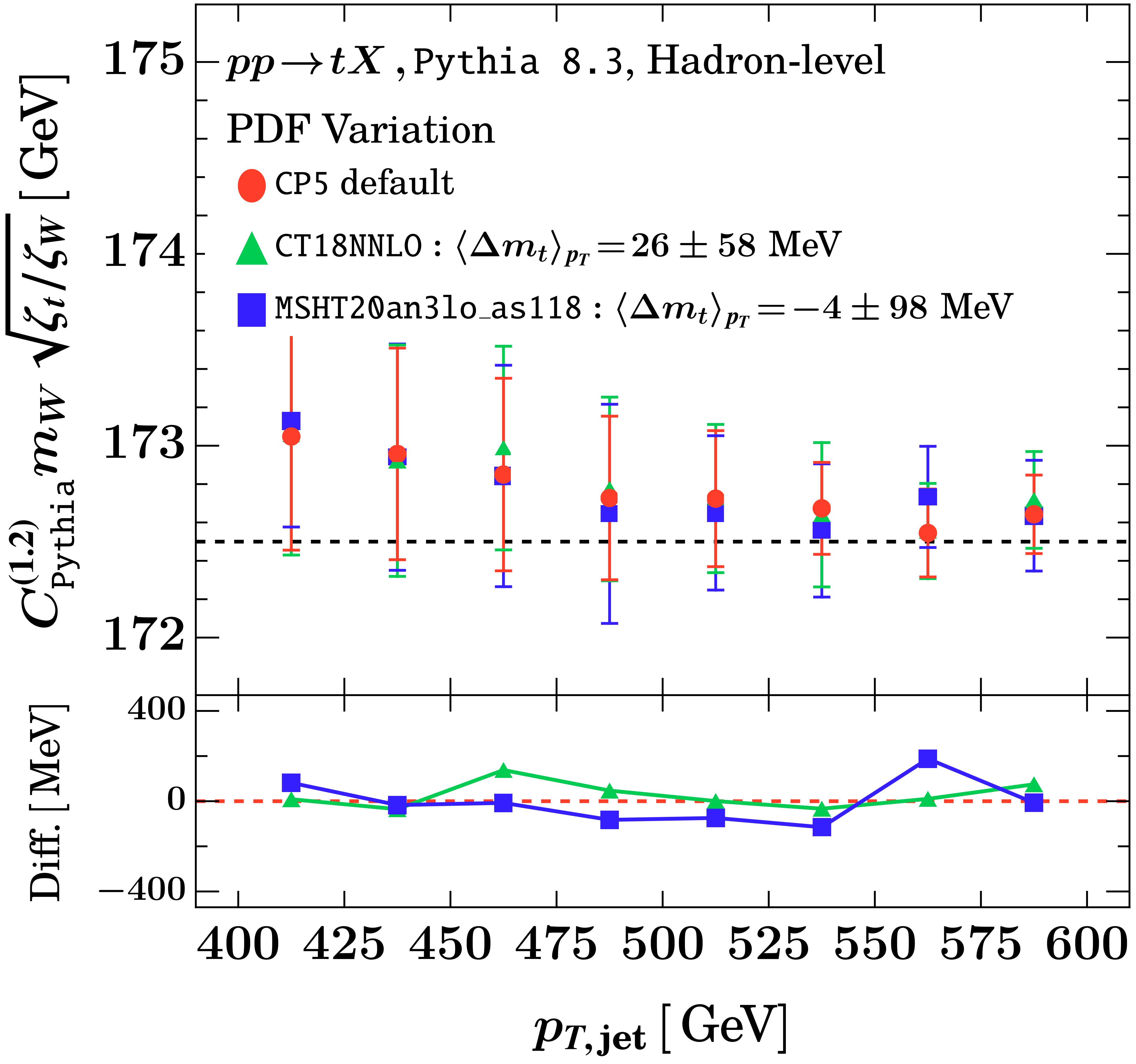
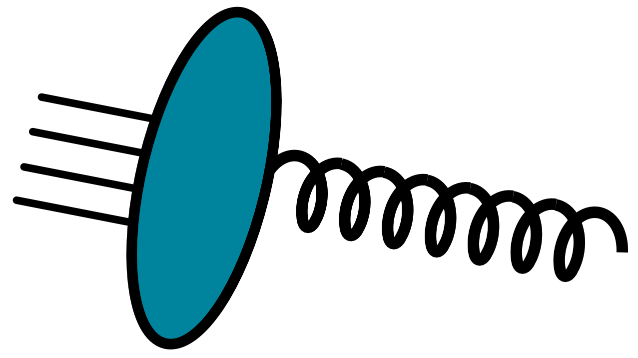
PDF variations

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):





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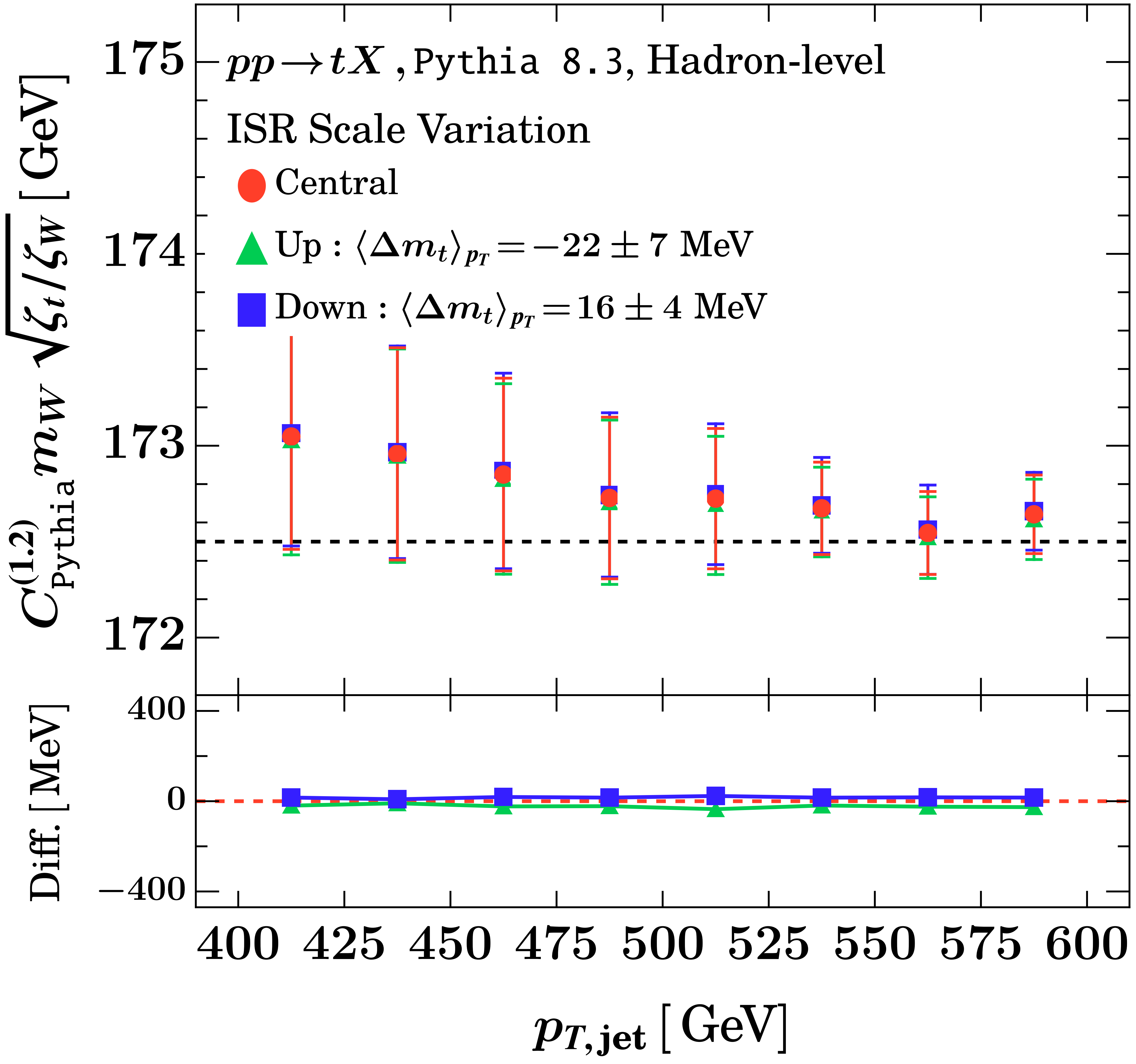
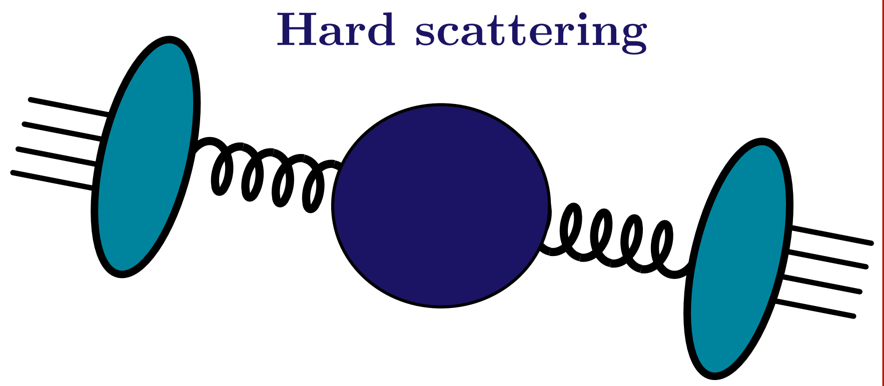
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2023, 2024

Hard scattering corrections

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





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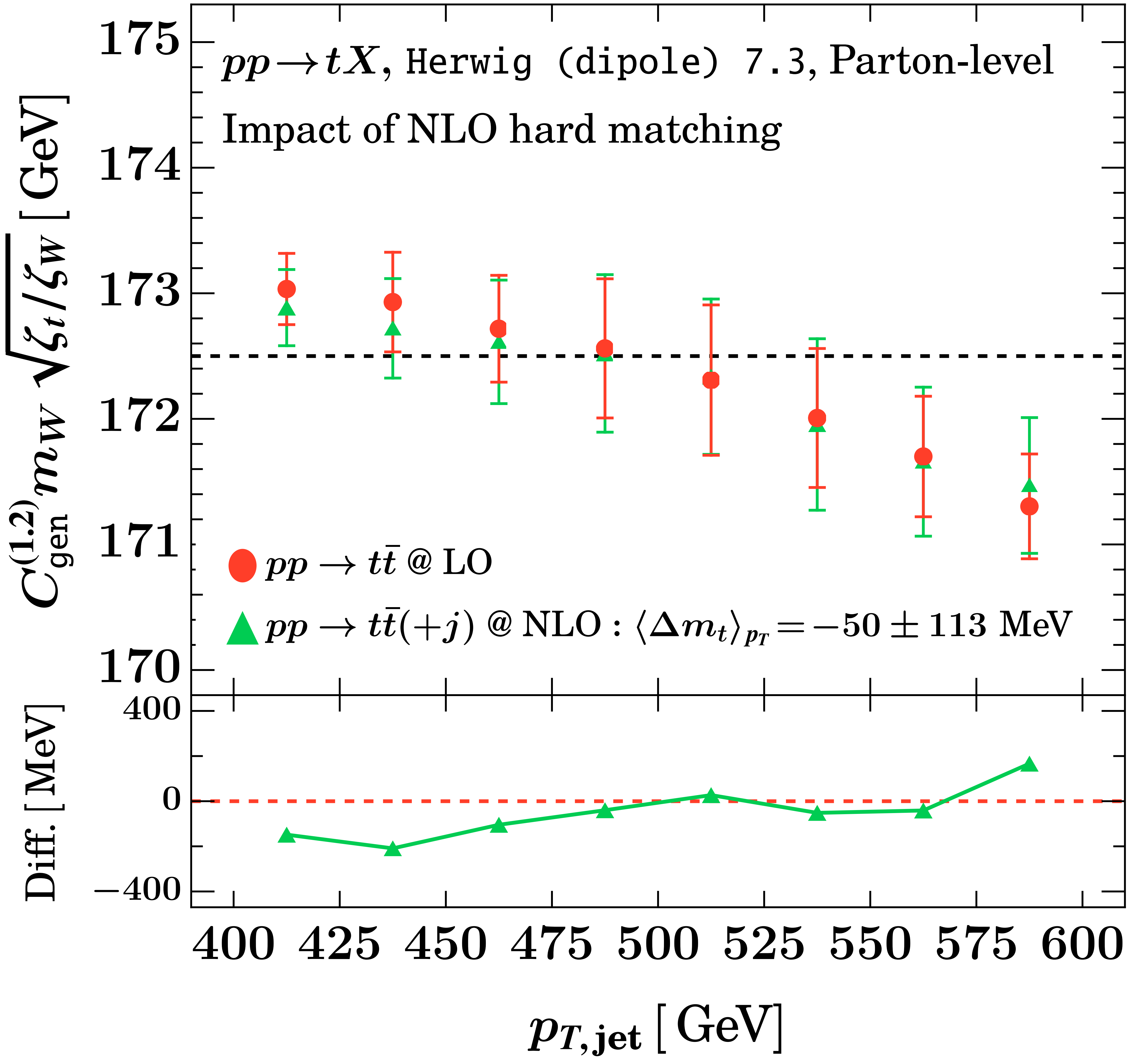
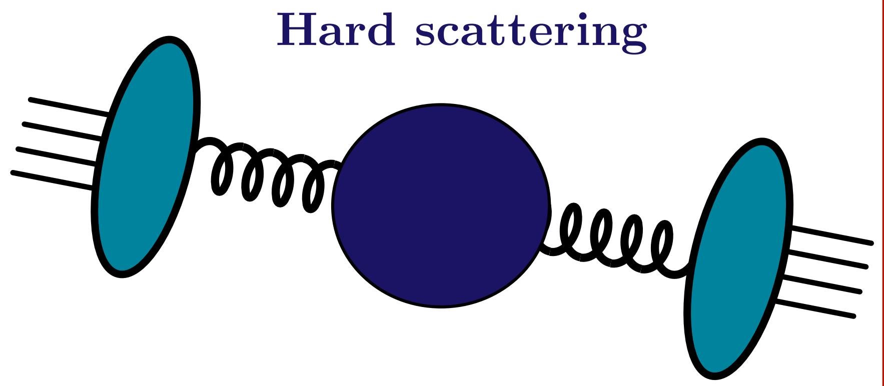
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2024

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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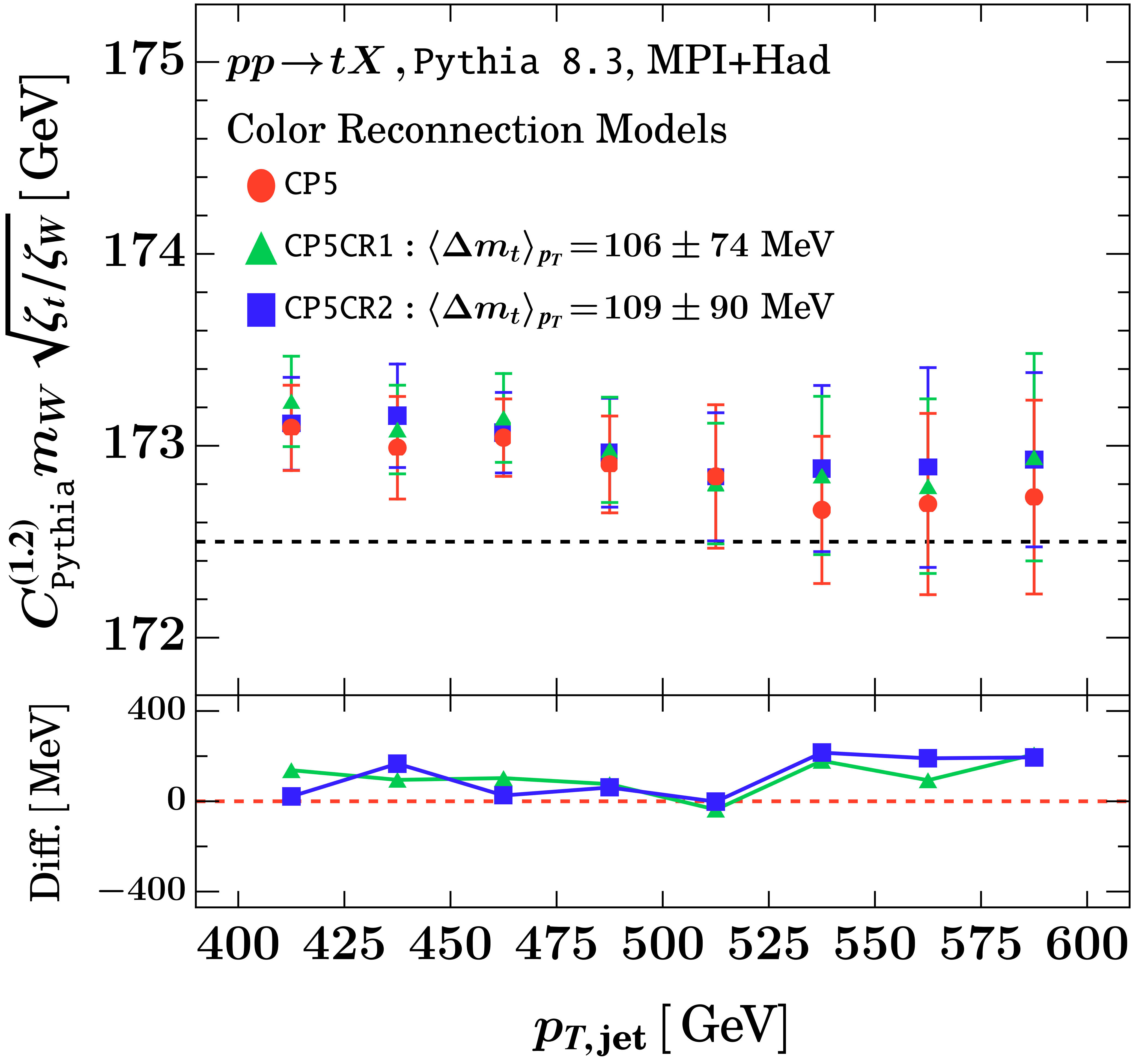
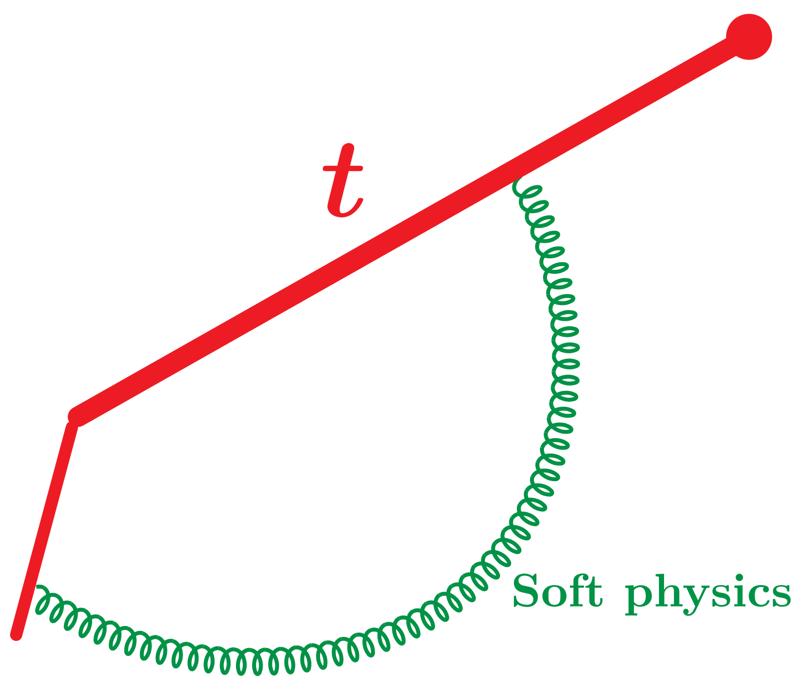
Wide angle soft physics

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





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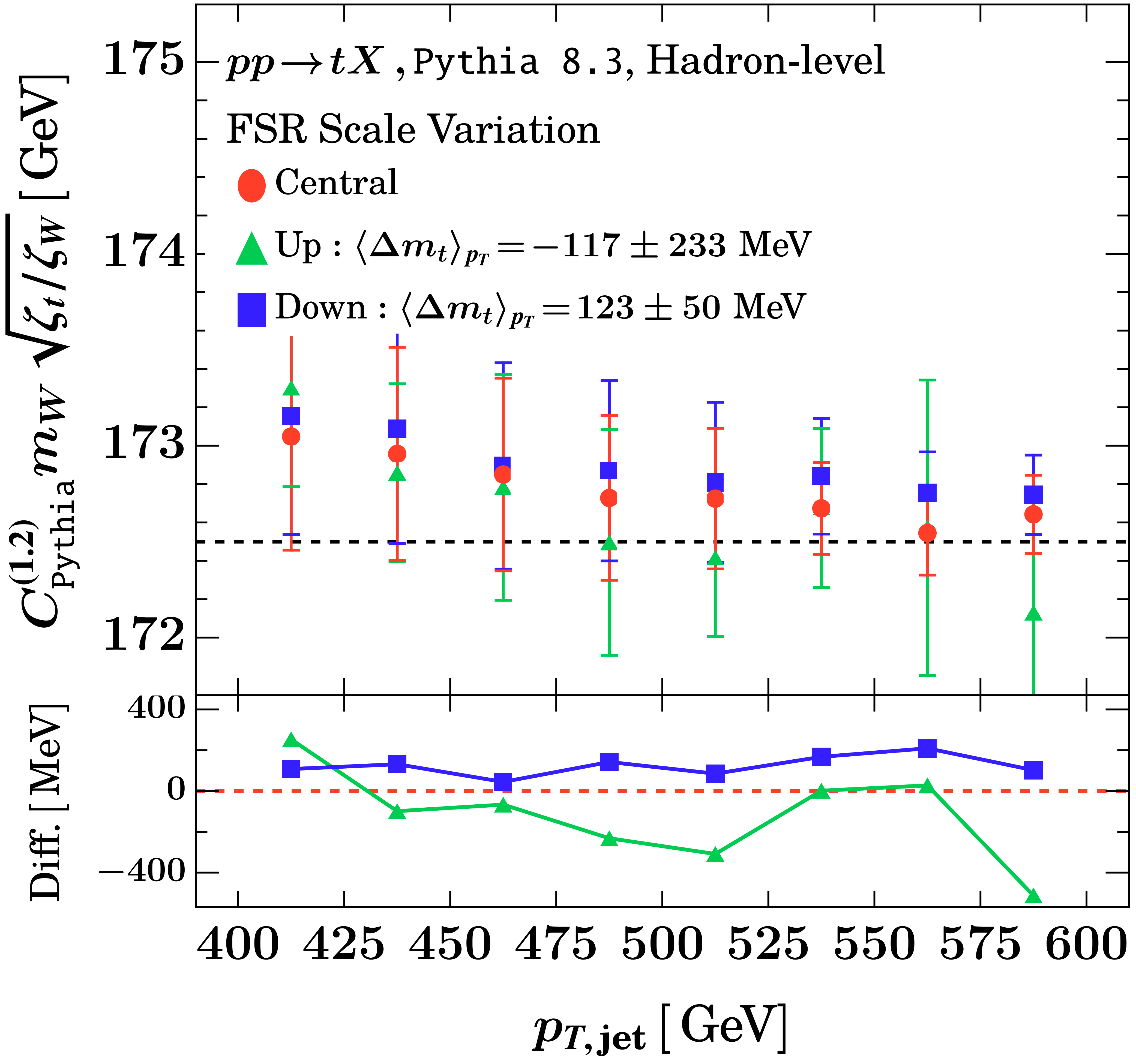
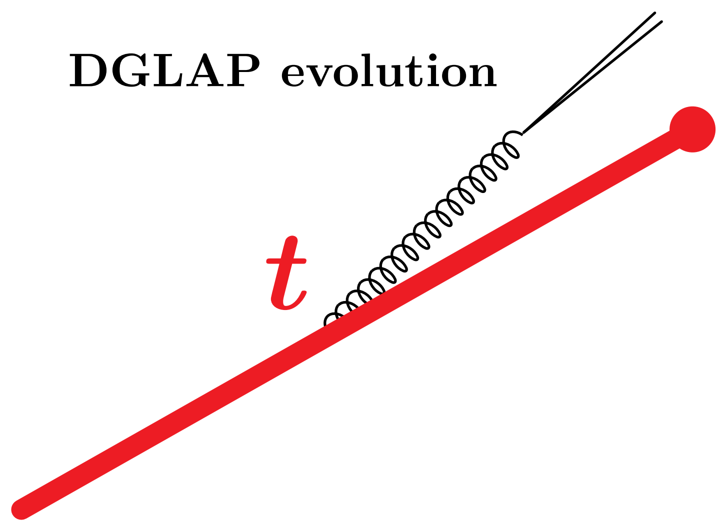
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2024

Shower Uncertainty

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





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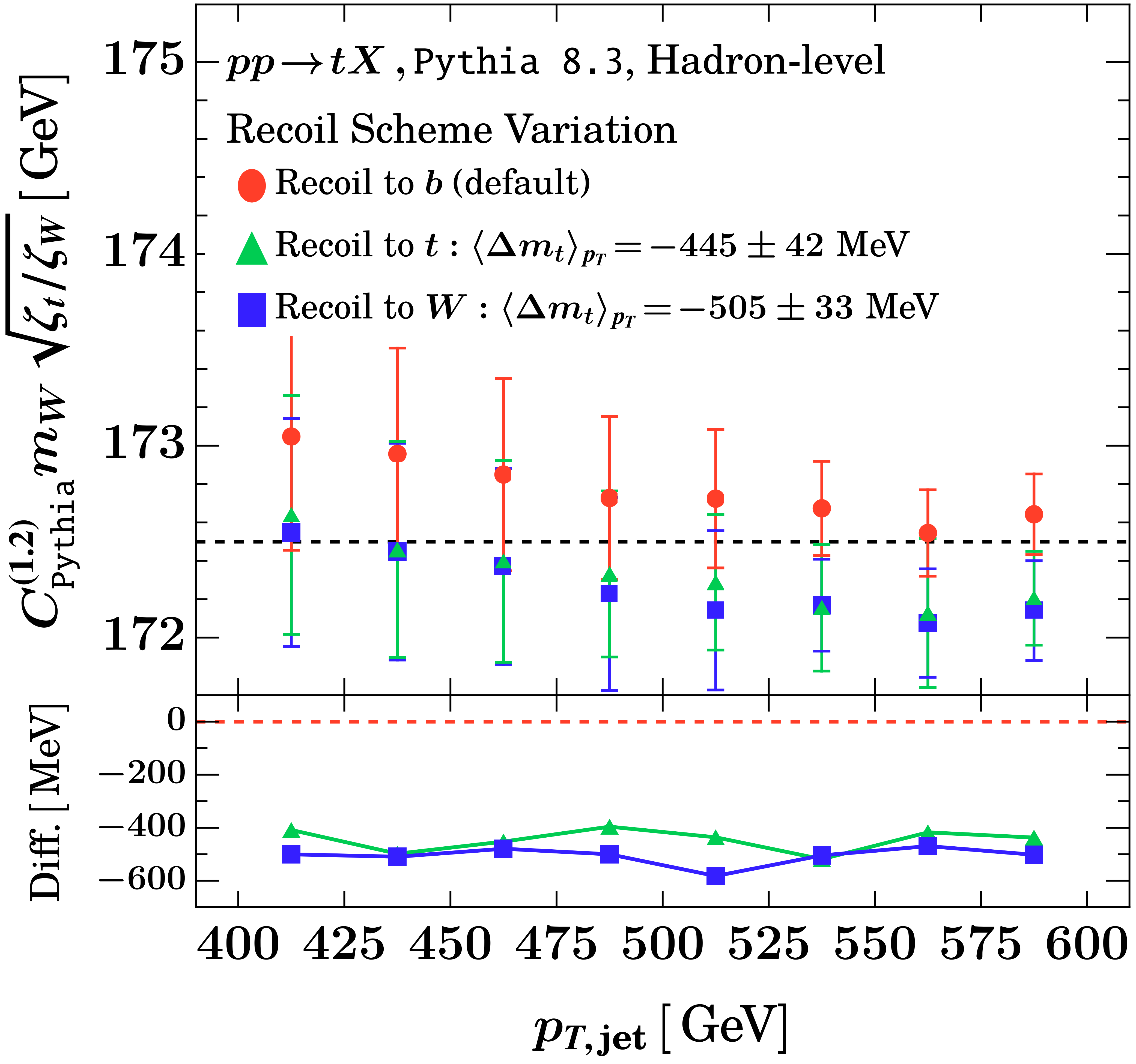
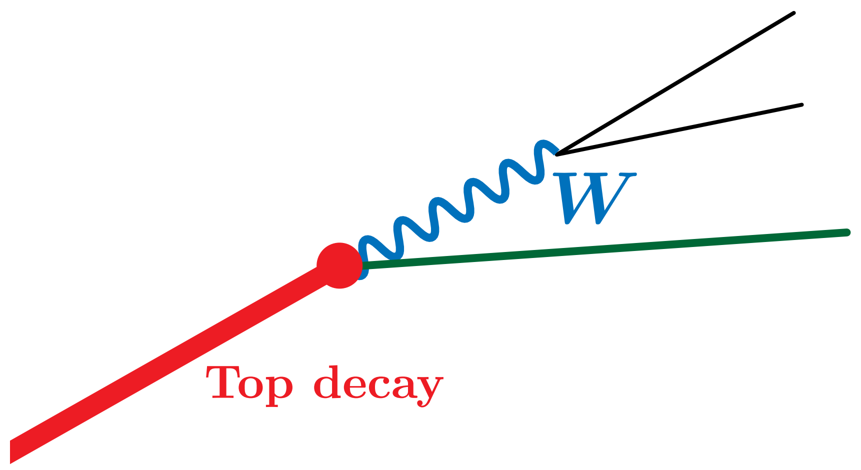
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2024

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 resummation in the peak





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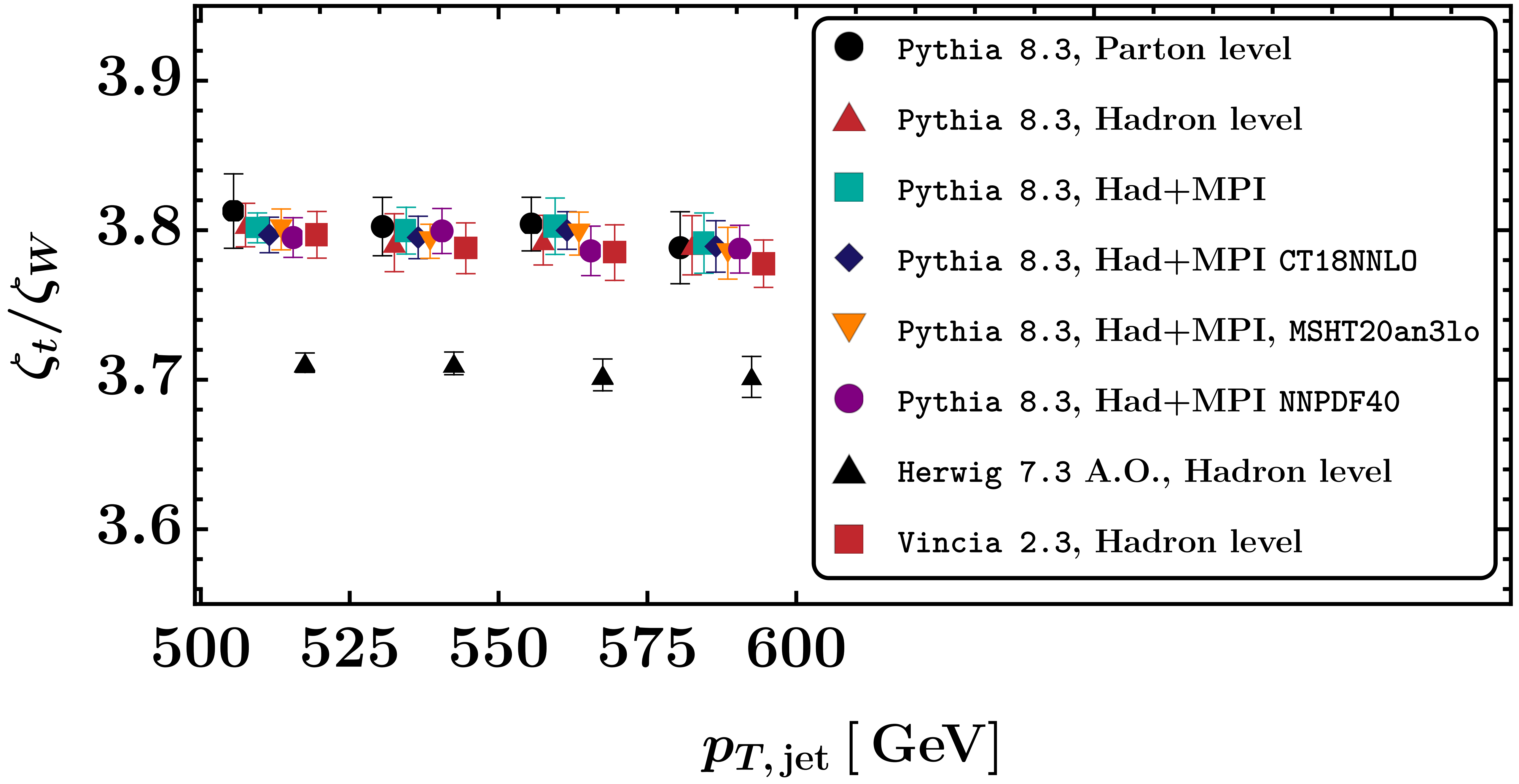
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2024

Differences between showers

Compare different showers without normalizing via C_{Gen}:

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



- Difference between Herwig A.O. and dipole showers due to different approximations of NLO top decay.
- Herwig angular-ordered shower differs by 3%: A proxy for LL uncertainty.

Production mechanism:

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Jet substructure:

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Experimental feasibility:

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- Jet energy scale ☐
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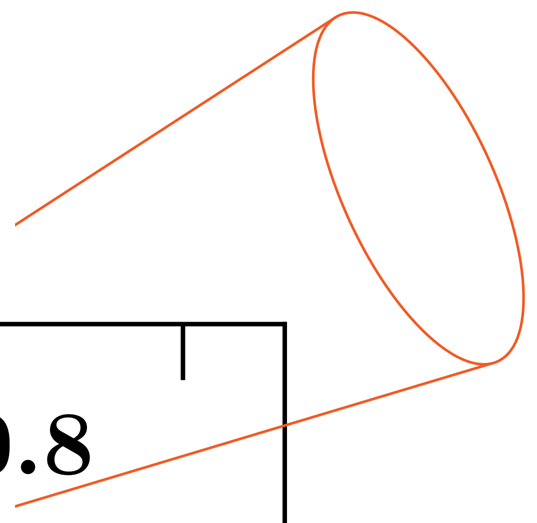
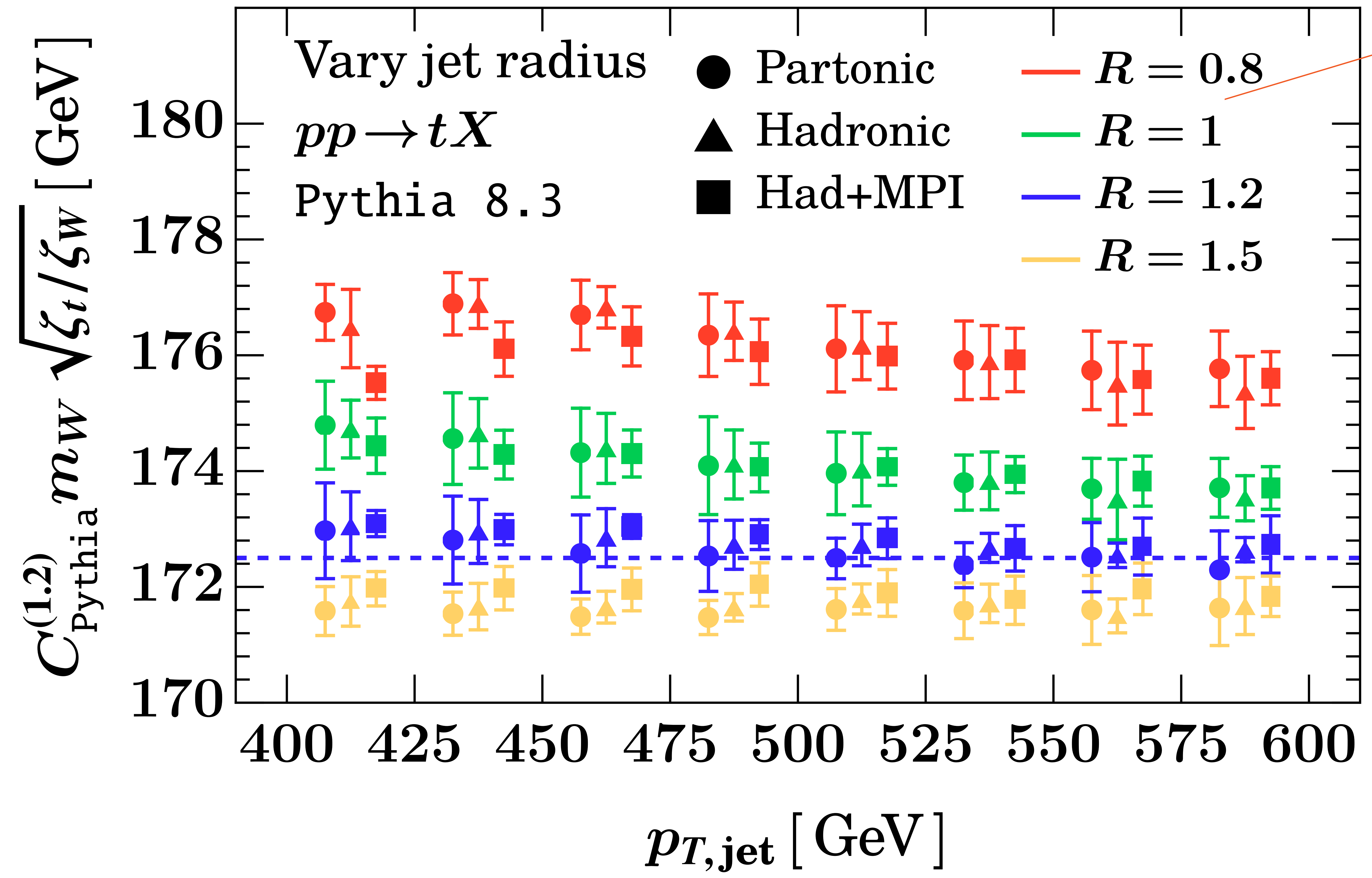
Jet radius dependence

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!

Jet-based measurement





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

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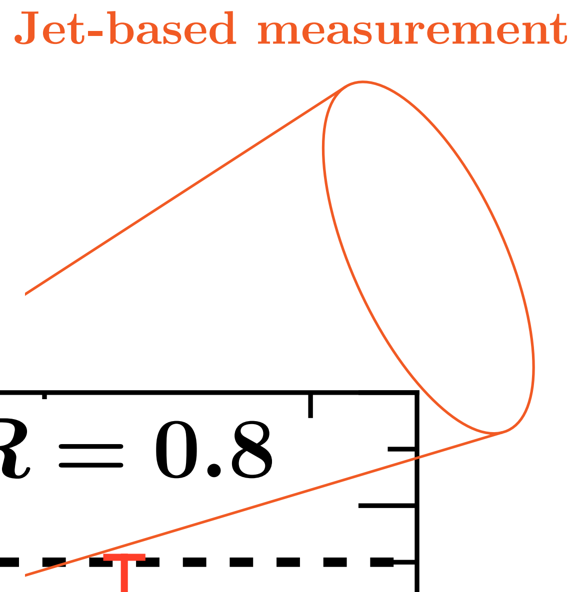
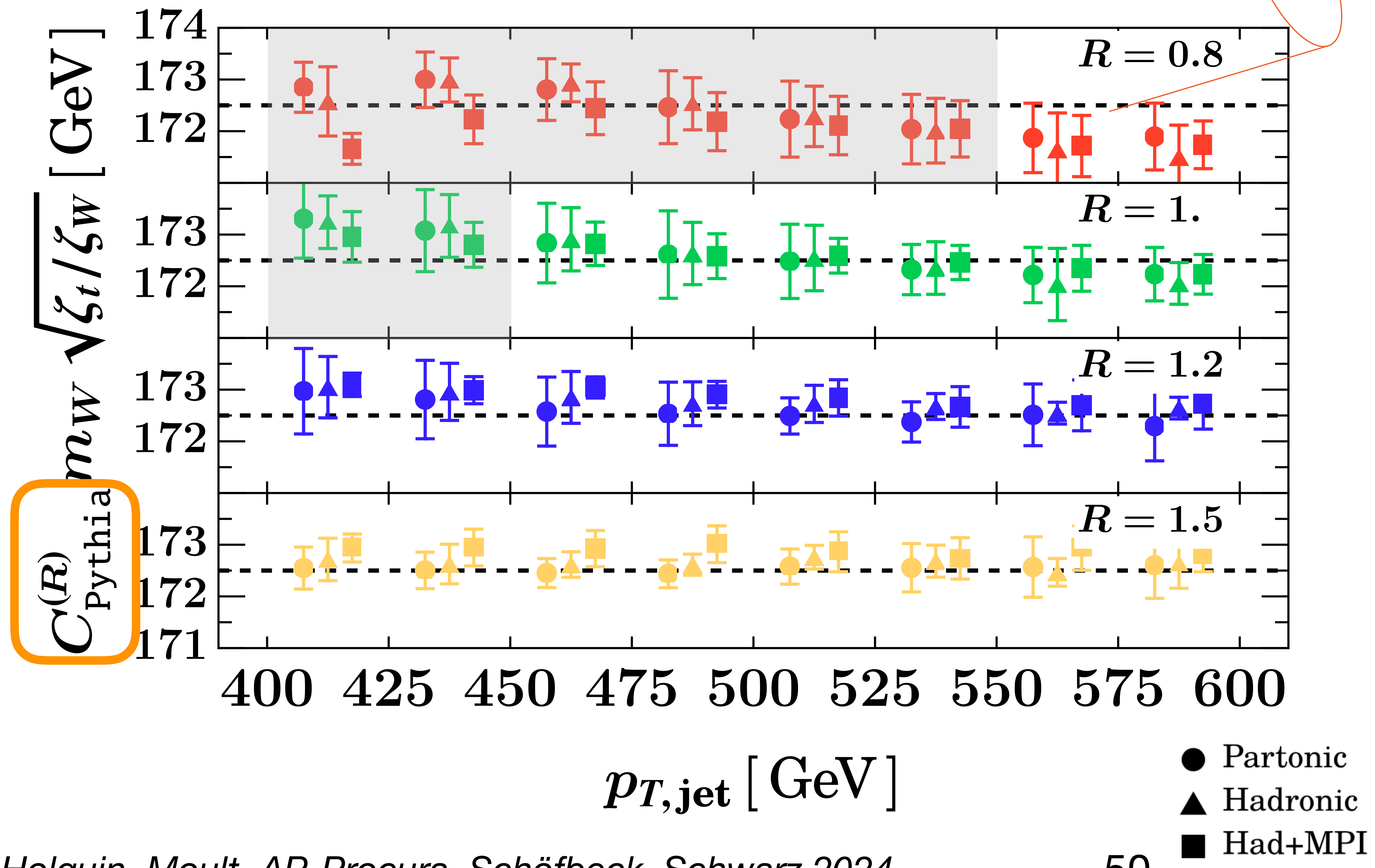
Shift from had/UE is ~ 200 MeV effect!





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

Production mechanism:

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- Hard scattering corrections ☑

Jet substructure:

- Jet radius dependence ☑
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- Impact of underlying event ☑
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- Perturbative uncertainty ☑

Experimental feasibility:

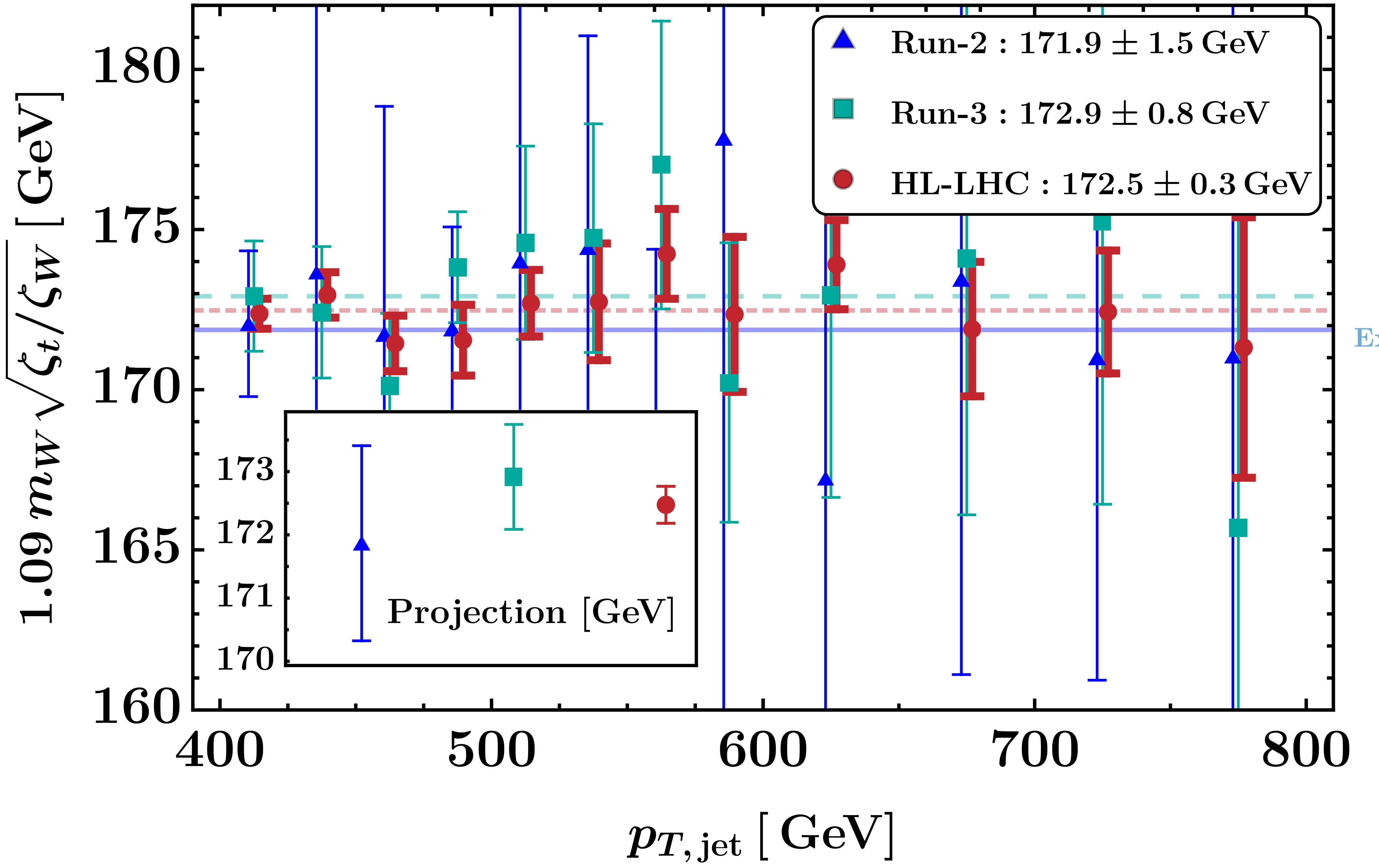
- Statistical sensitivity ☐
- Jet energy scale ☐
- Constituent energy scale ☐
- Tracks-based measurement ☐
- Heavy flavor dependence ☐

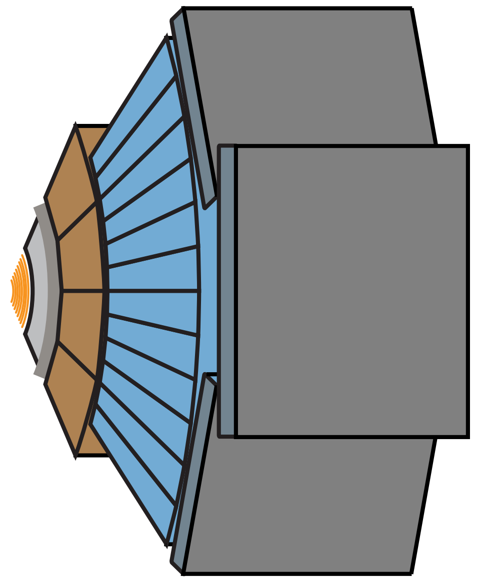
Outline

- Theory challenges with current top mass measurements
- Energy Correlators for precision jet substructure
- A new proposal for top mass using EECs
- Demonstrating robustness and experimental feasibility

Statistical sensitivity

Crucially, the measurement is statistically feasible at the LHC





Experimental systematics

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

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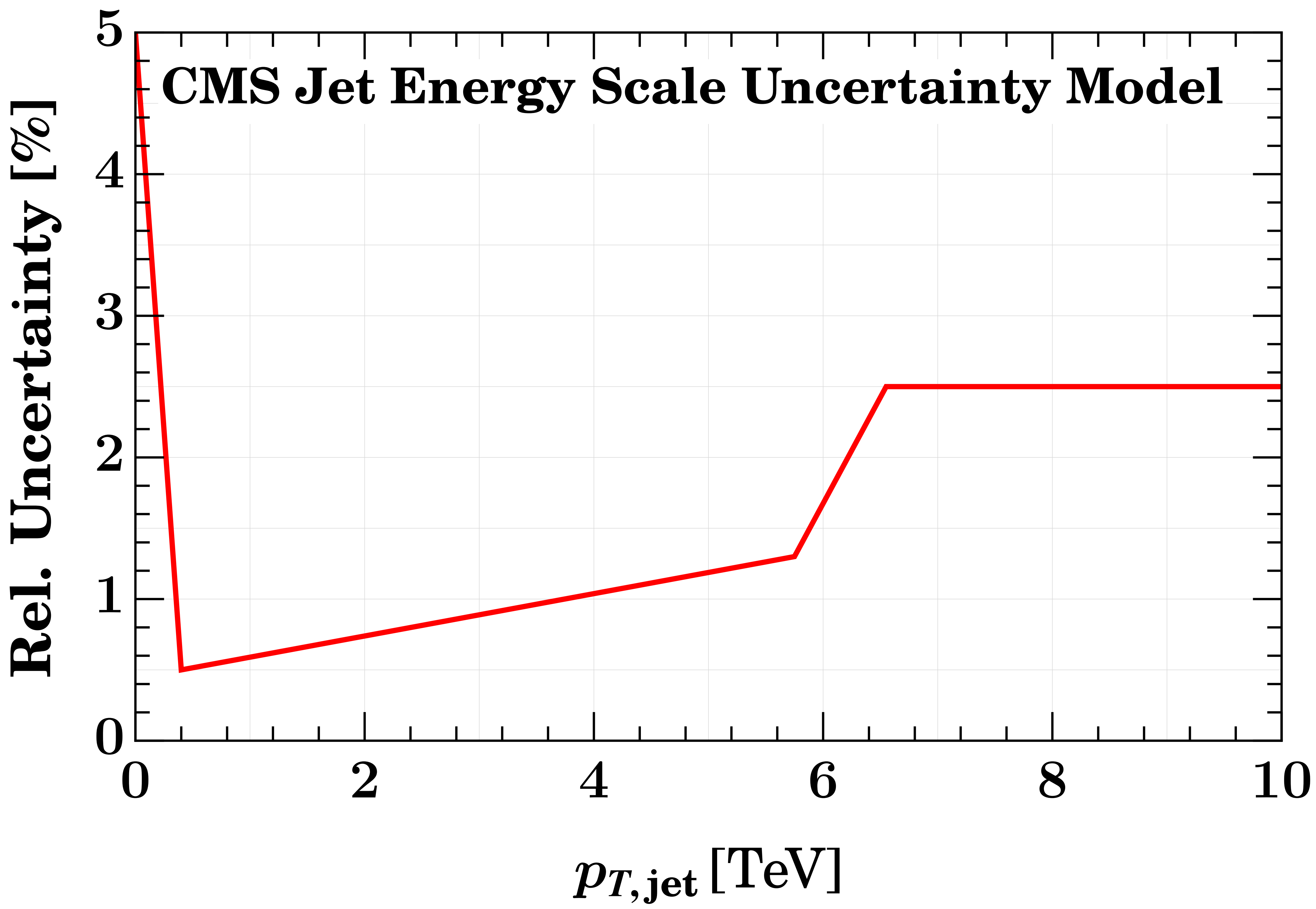
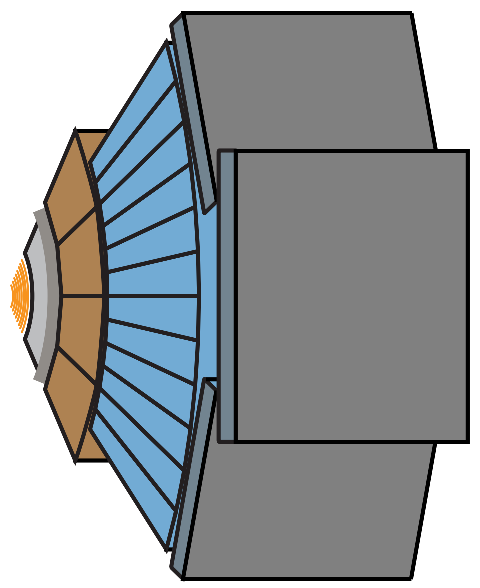
We model the CMS jet energy scale uncertainty and vary the $p_{T,\text{jet}}$





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

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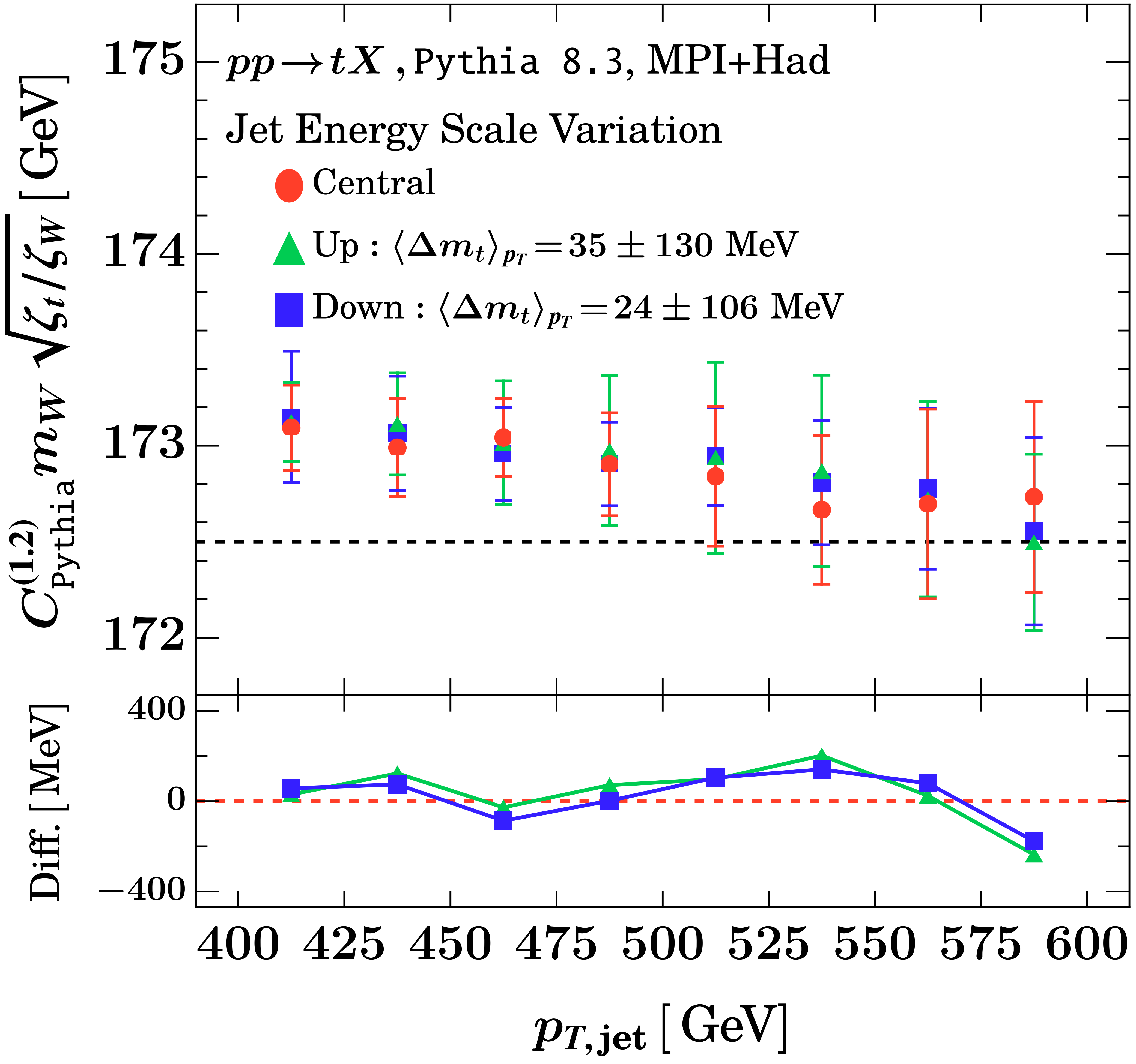
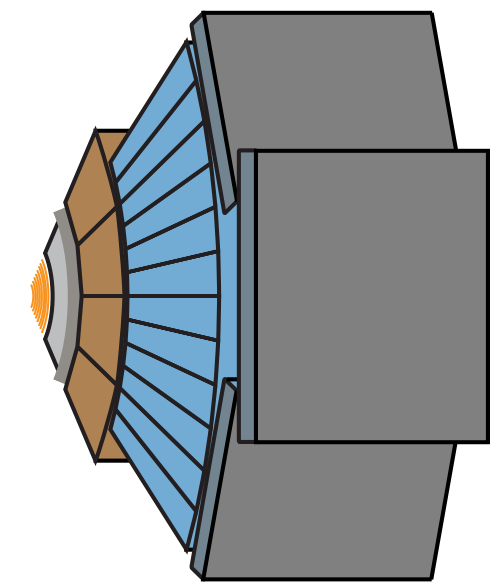
We model the CMS jet energy scale uncertainty and vary the $p_{T,\text{jet}}$: Negligible impact





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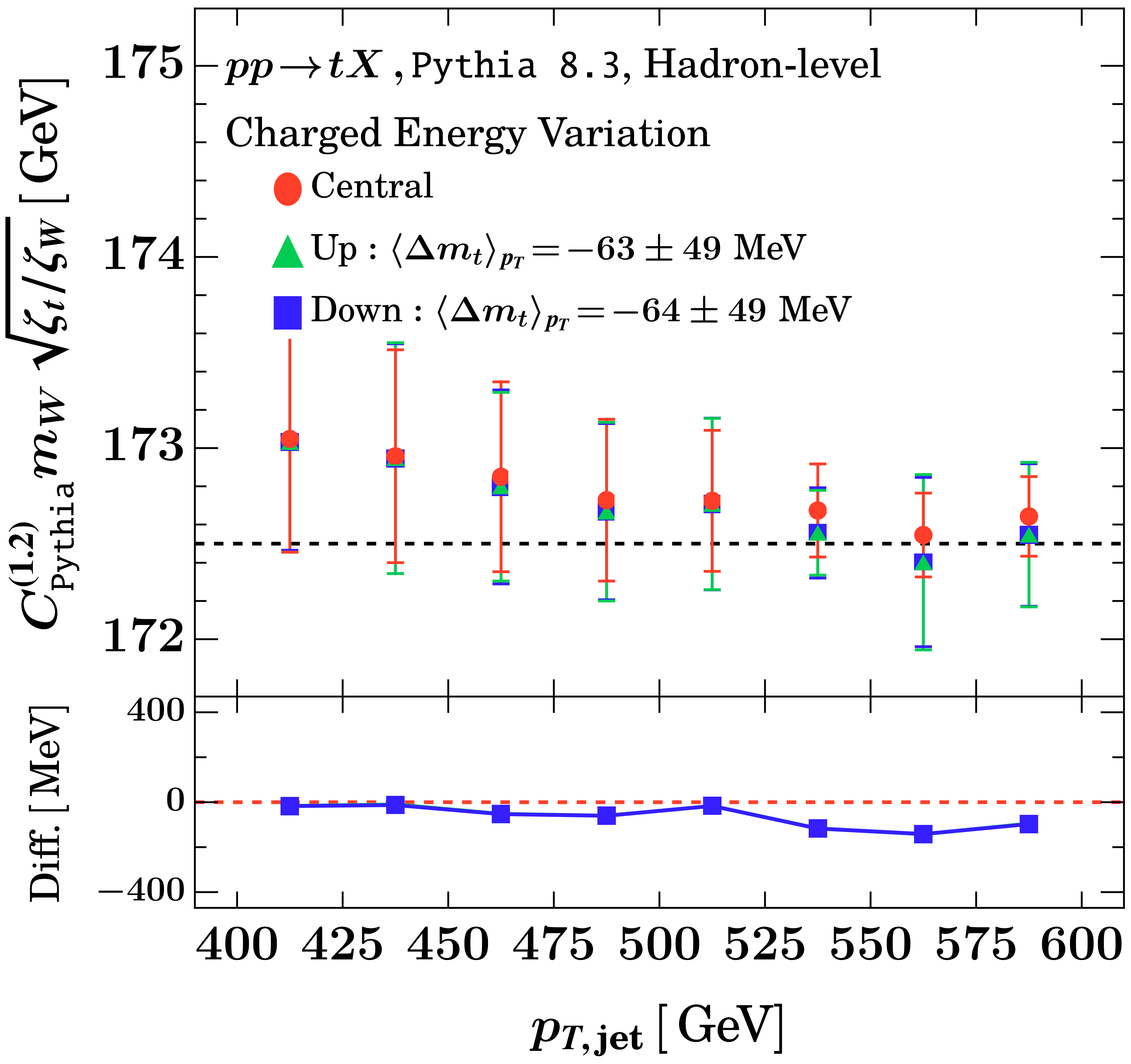
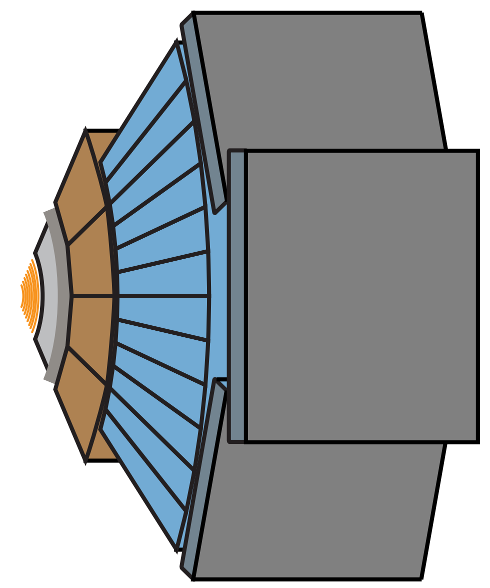
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2024

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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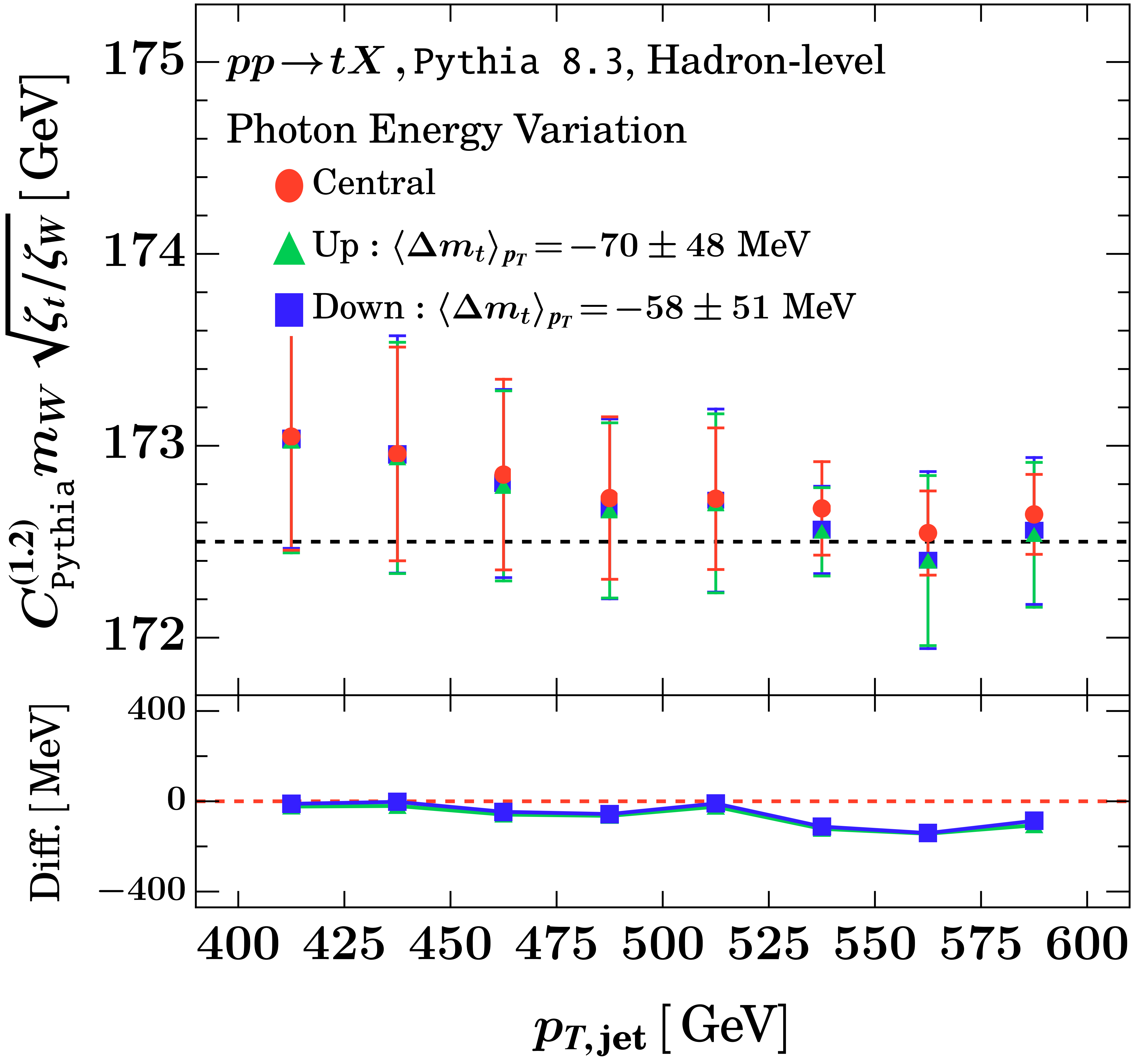

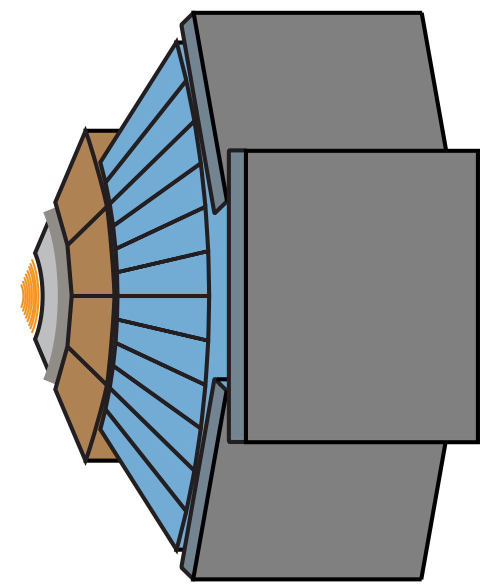

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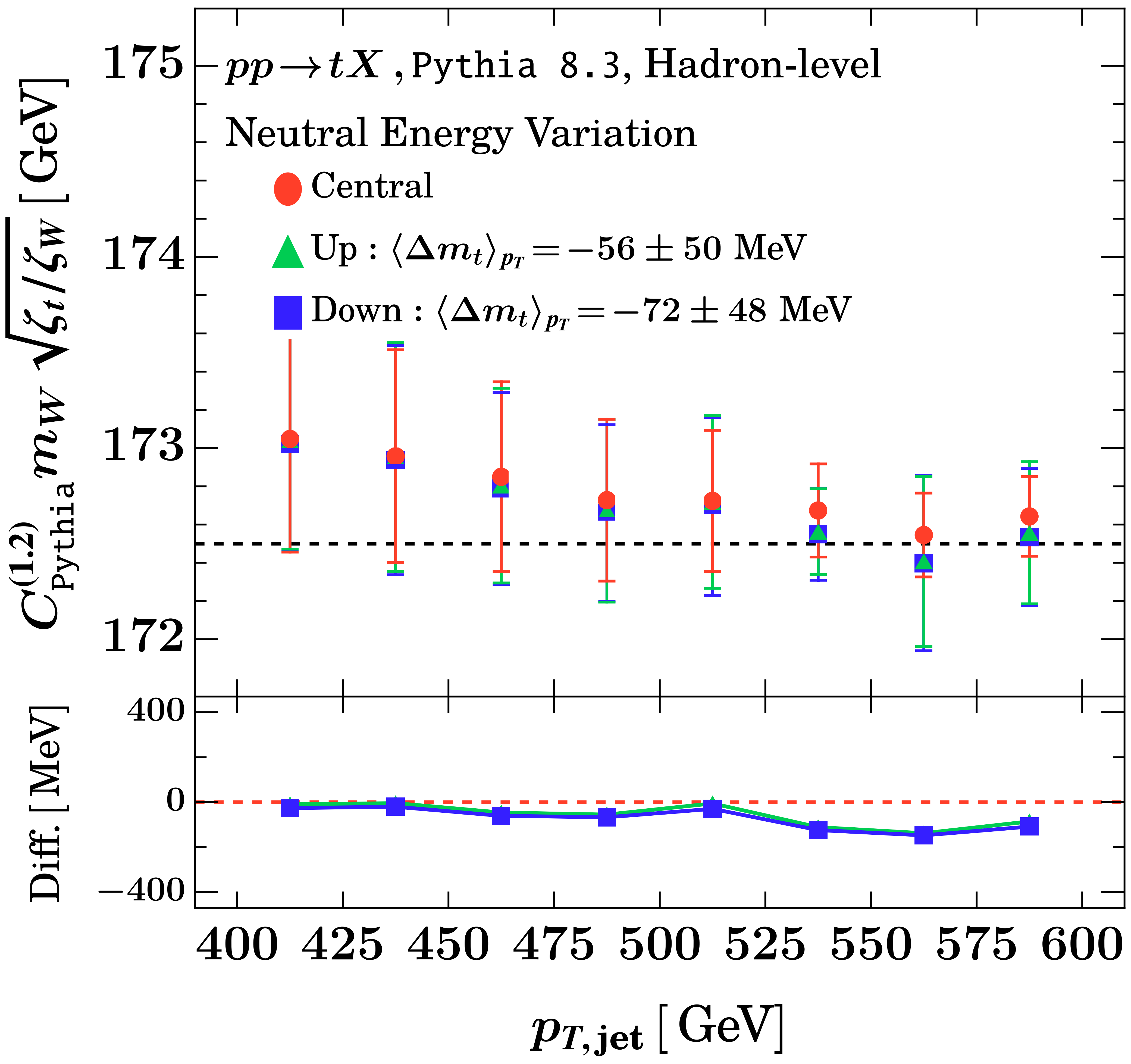

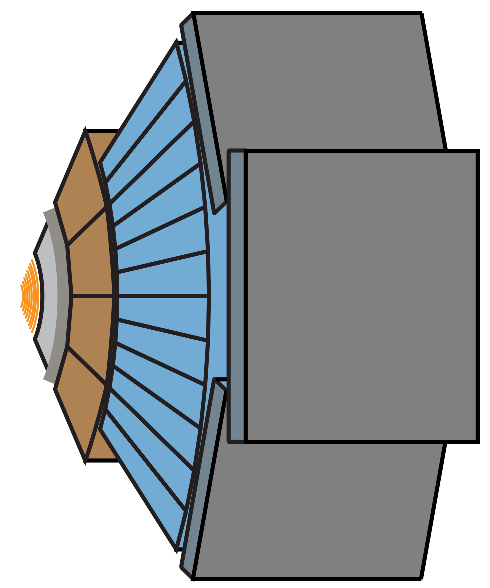

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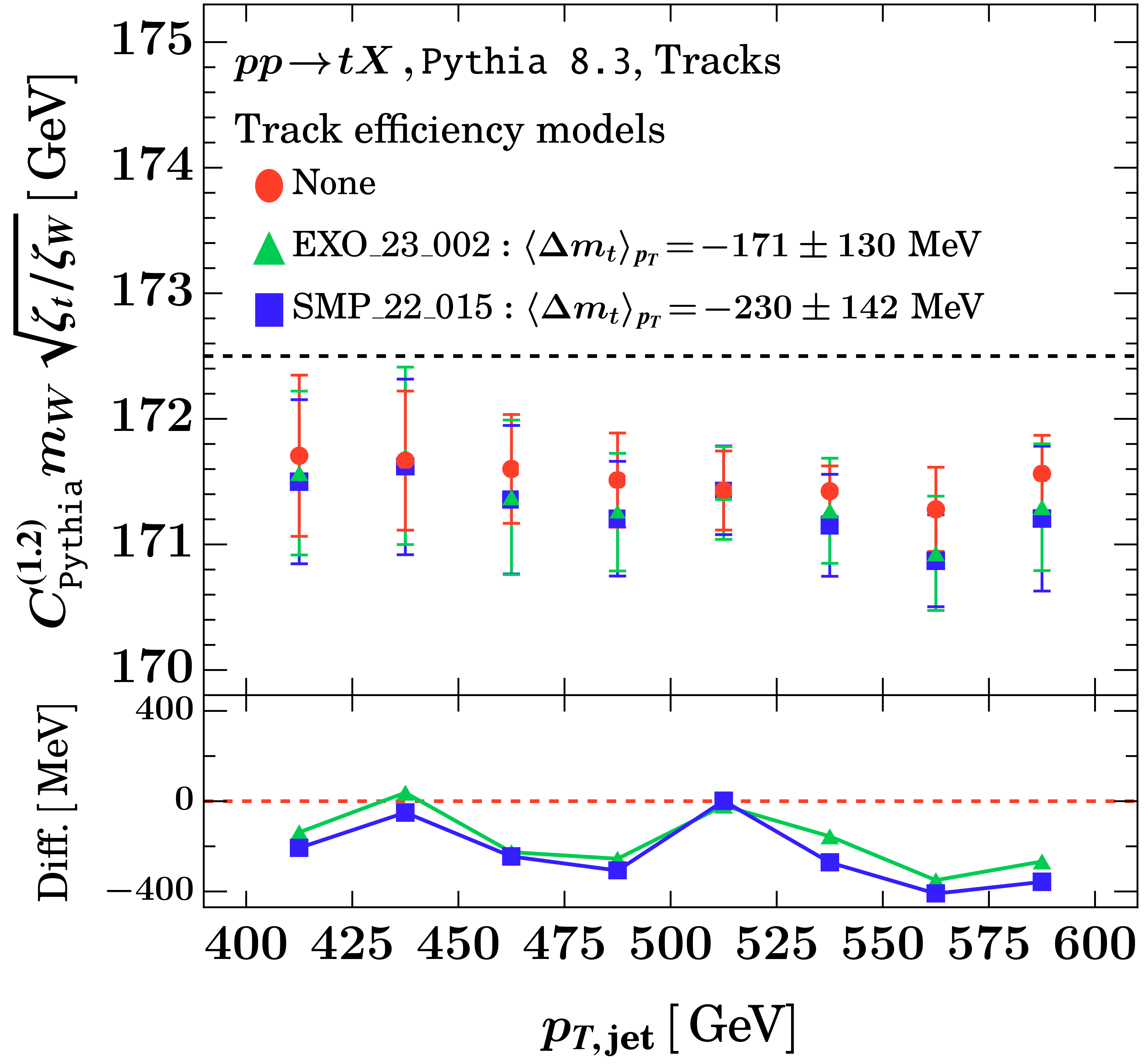
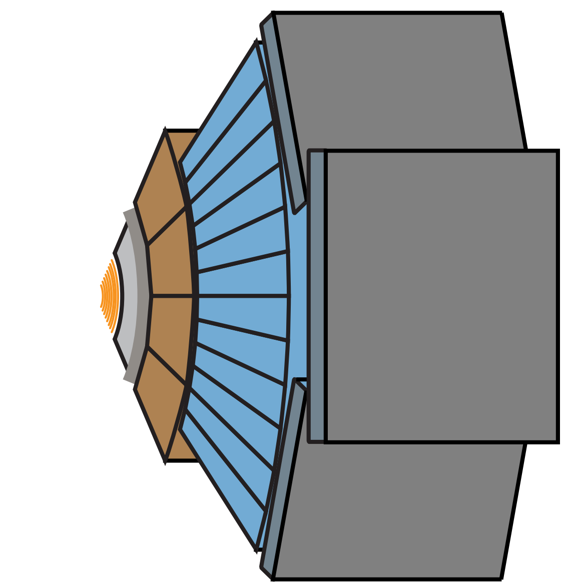
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2024

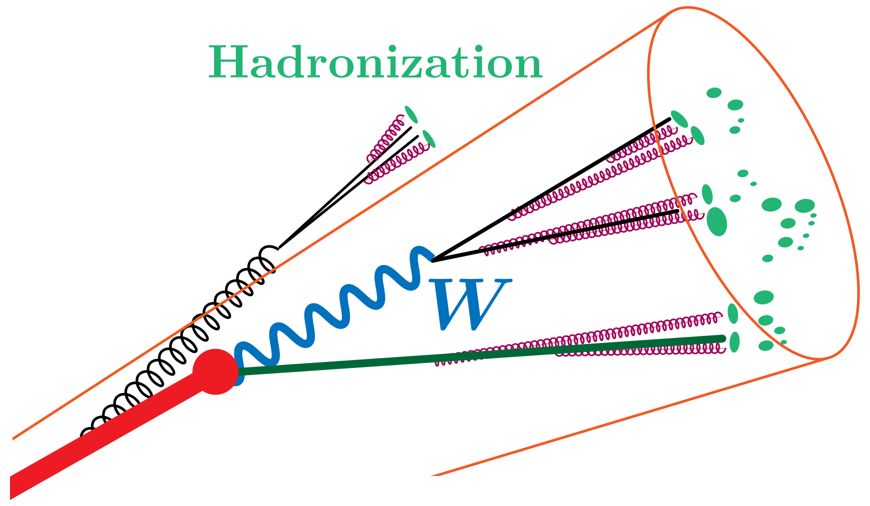
Track Efficiency

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.







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

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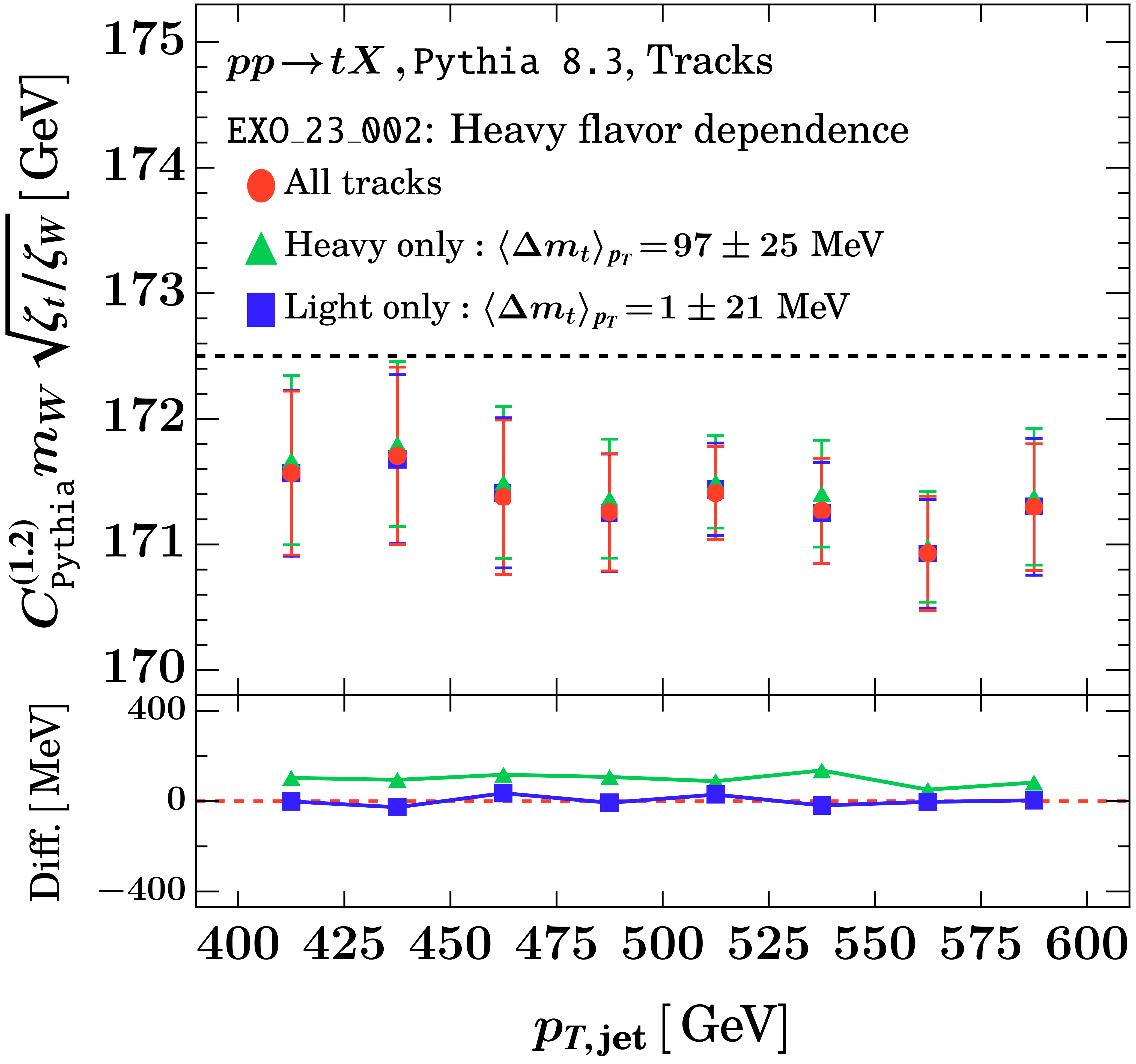
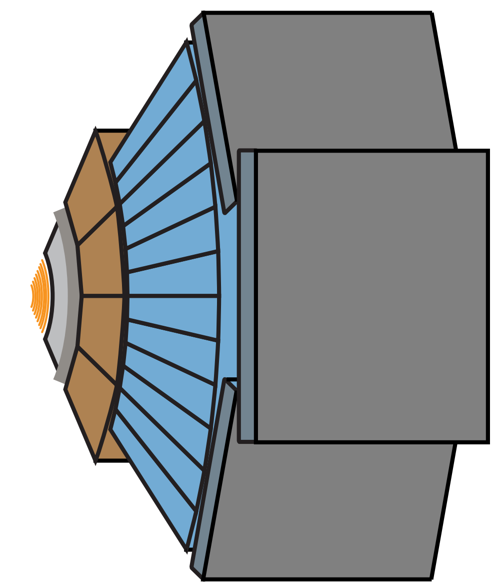
Heavy Flavor Dependence

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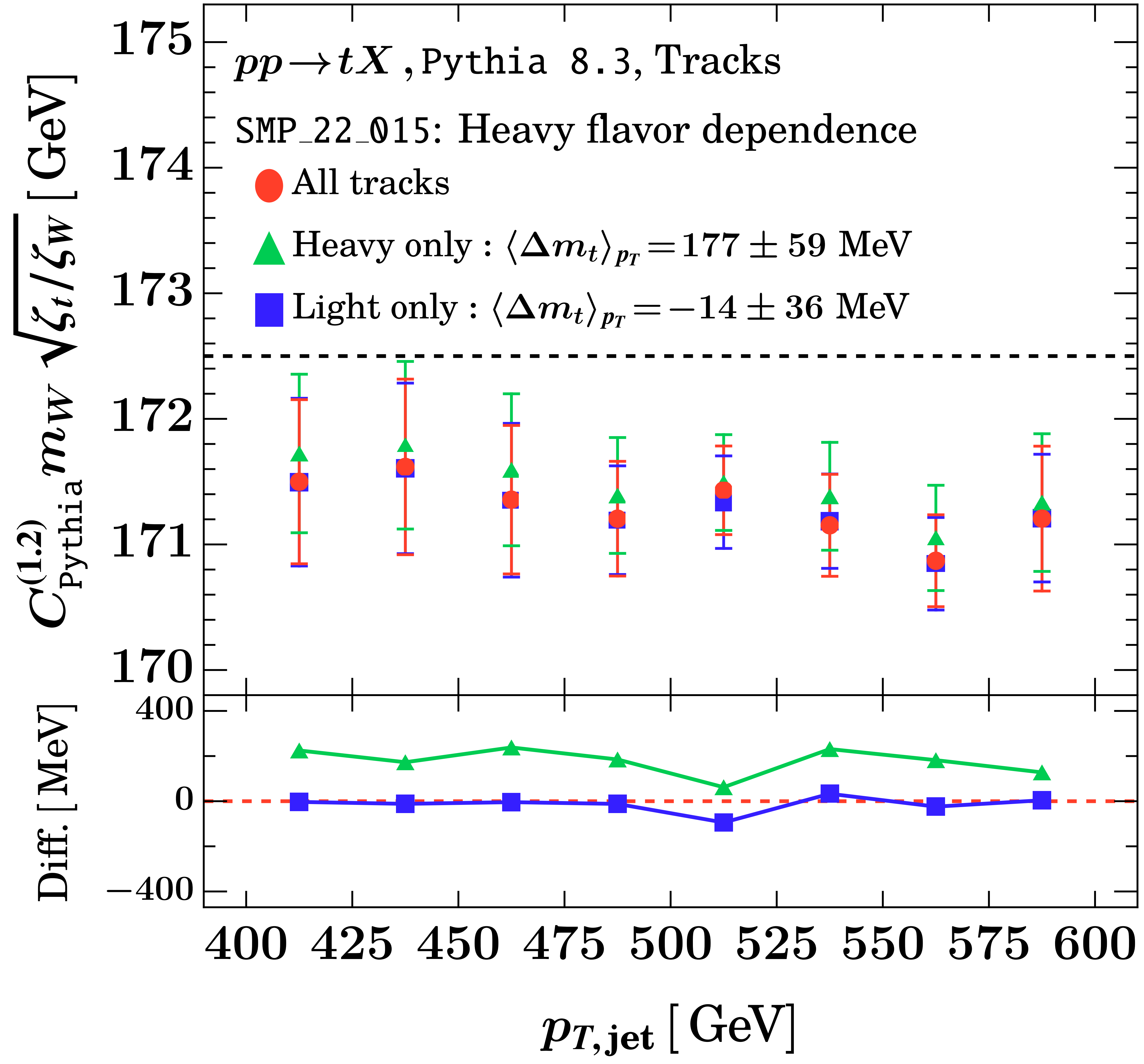
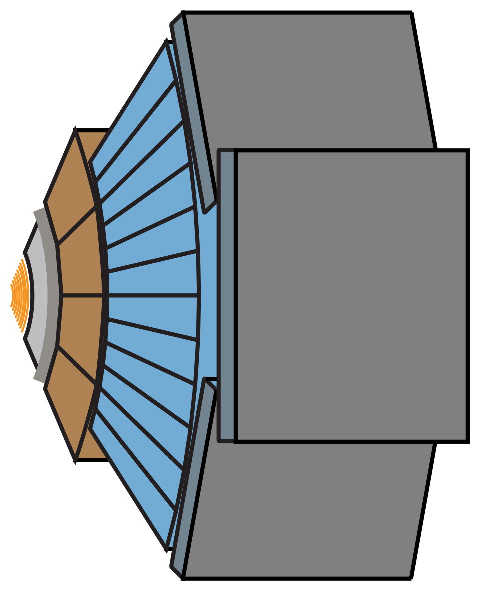
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2024

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.





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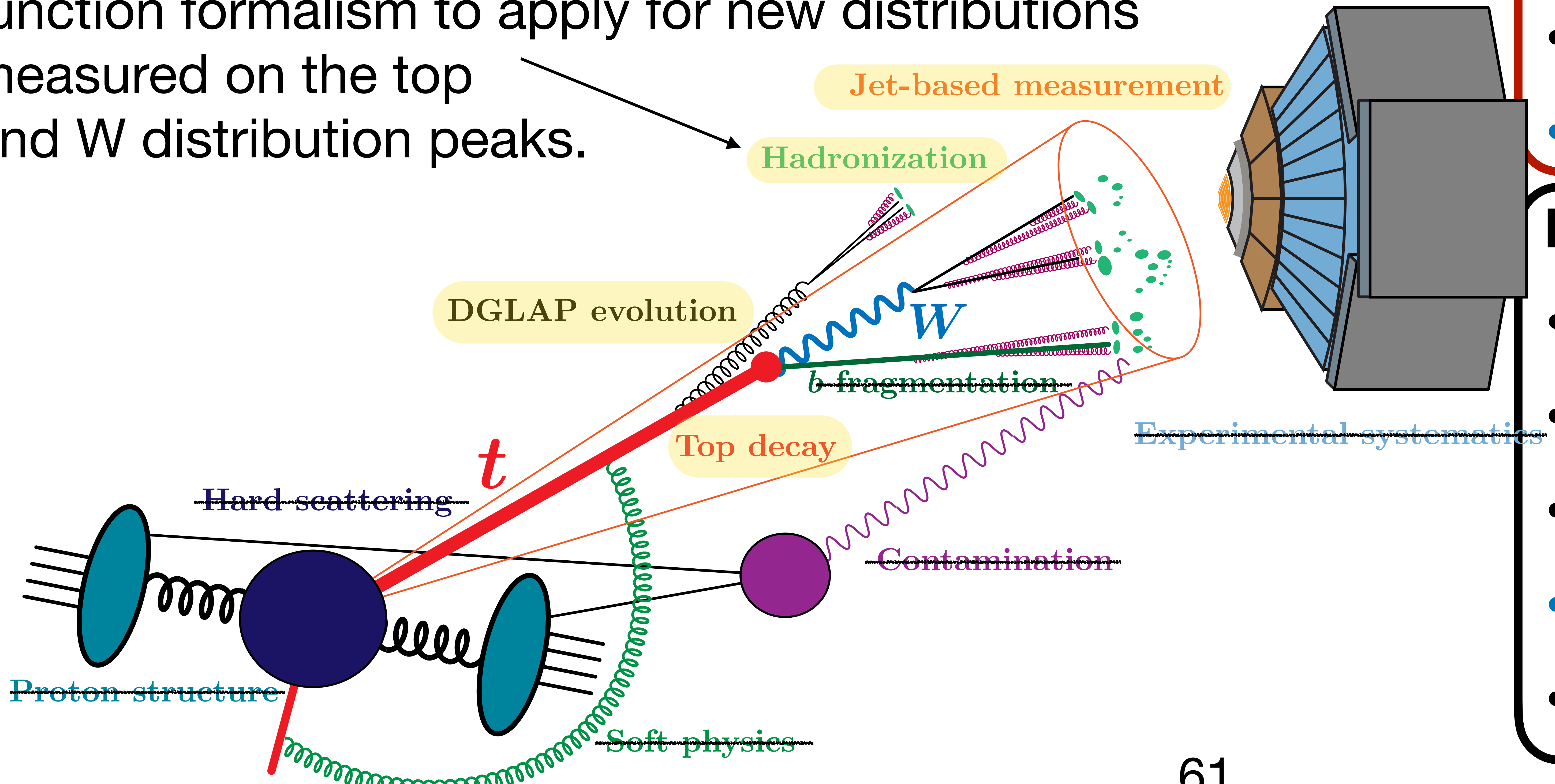
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2024

We are done …

Key relevant effects:

- **Jet radius dependence:** Found to be purely perturbative.
- **Perturbative uncertainty:** Key effects of NLO corrections to the top quark decay and Sudakov resummation in the peak
- **Track-based measurement:** Extending the track function formalism to apply for new distributions measured on the top and W distribution peaks.



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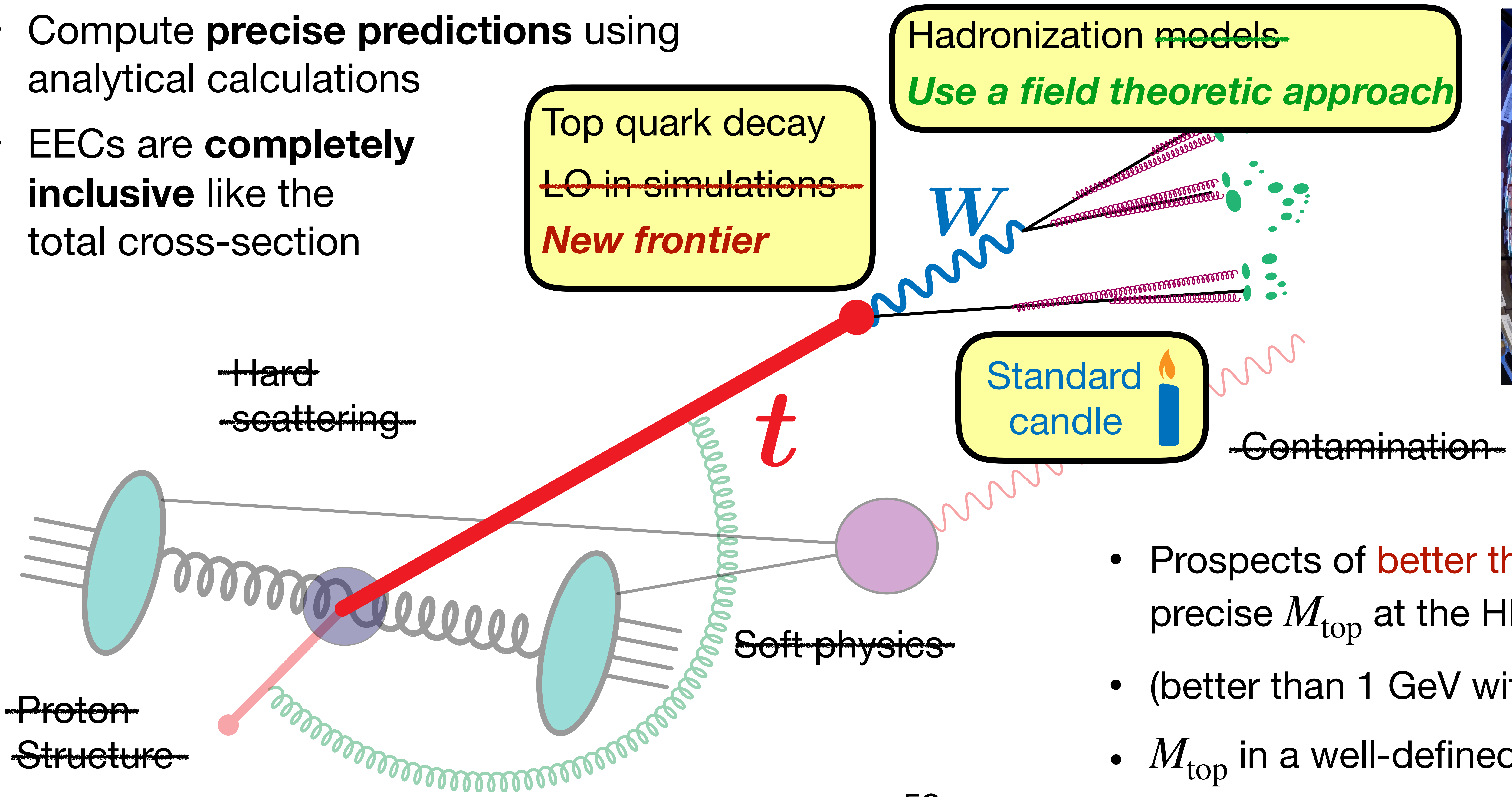
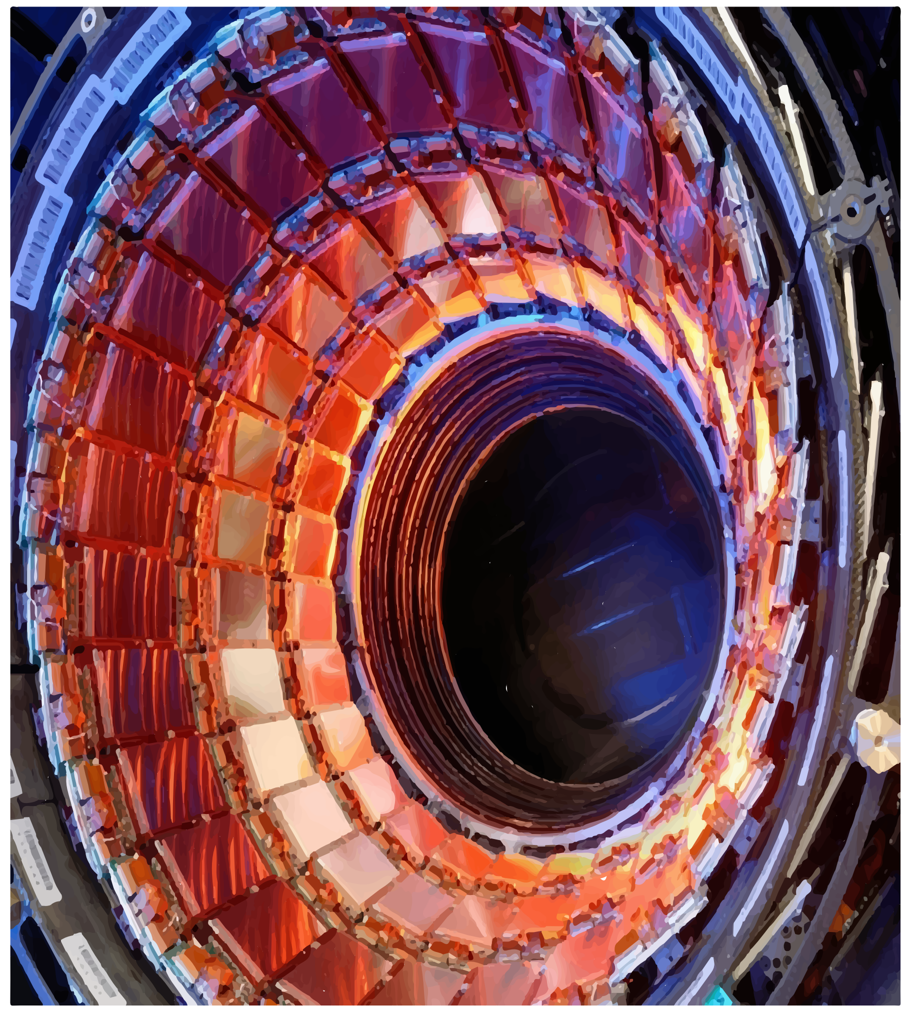
Looking ahead…

- 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





- Prospects of better than 500 MeV (0.3%) precise M_{top} at the HL-LHC
- (better than 1 GeV with Run 3)
- M_{top} in a well-defined mass scheme

Thank you!

Backup

Why care about the top mass? [EW Stability]

Important role in the analysis of electroweak vacuum stability

- Are we living in a true-vacuum or is there another global minimum or a bottomless abyss in the Higgs effective potential?

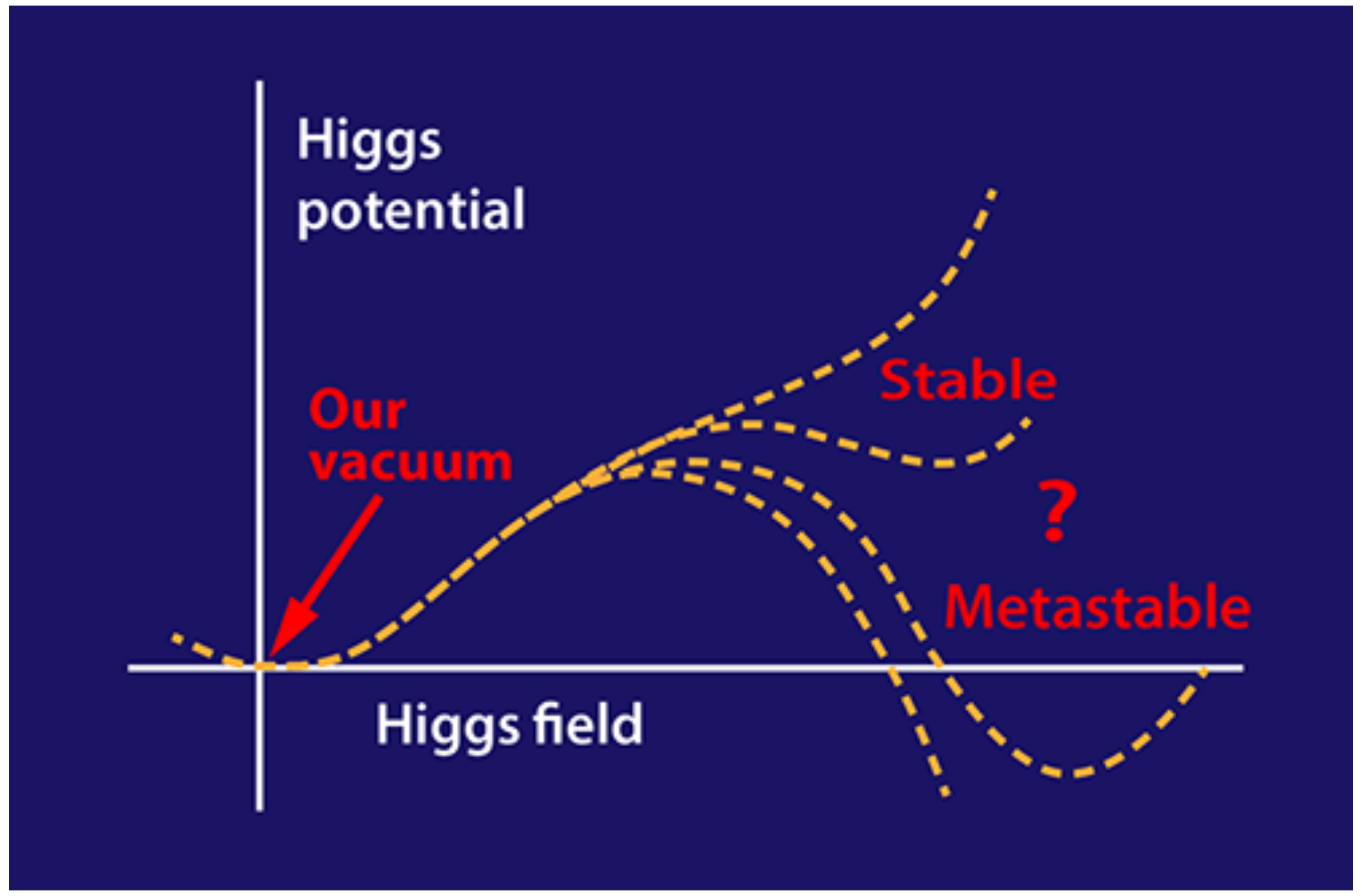
- The outcome of EW vacuum stability depends sensitively on the precision on the top quark mass.

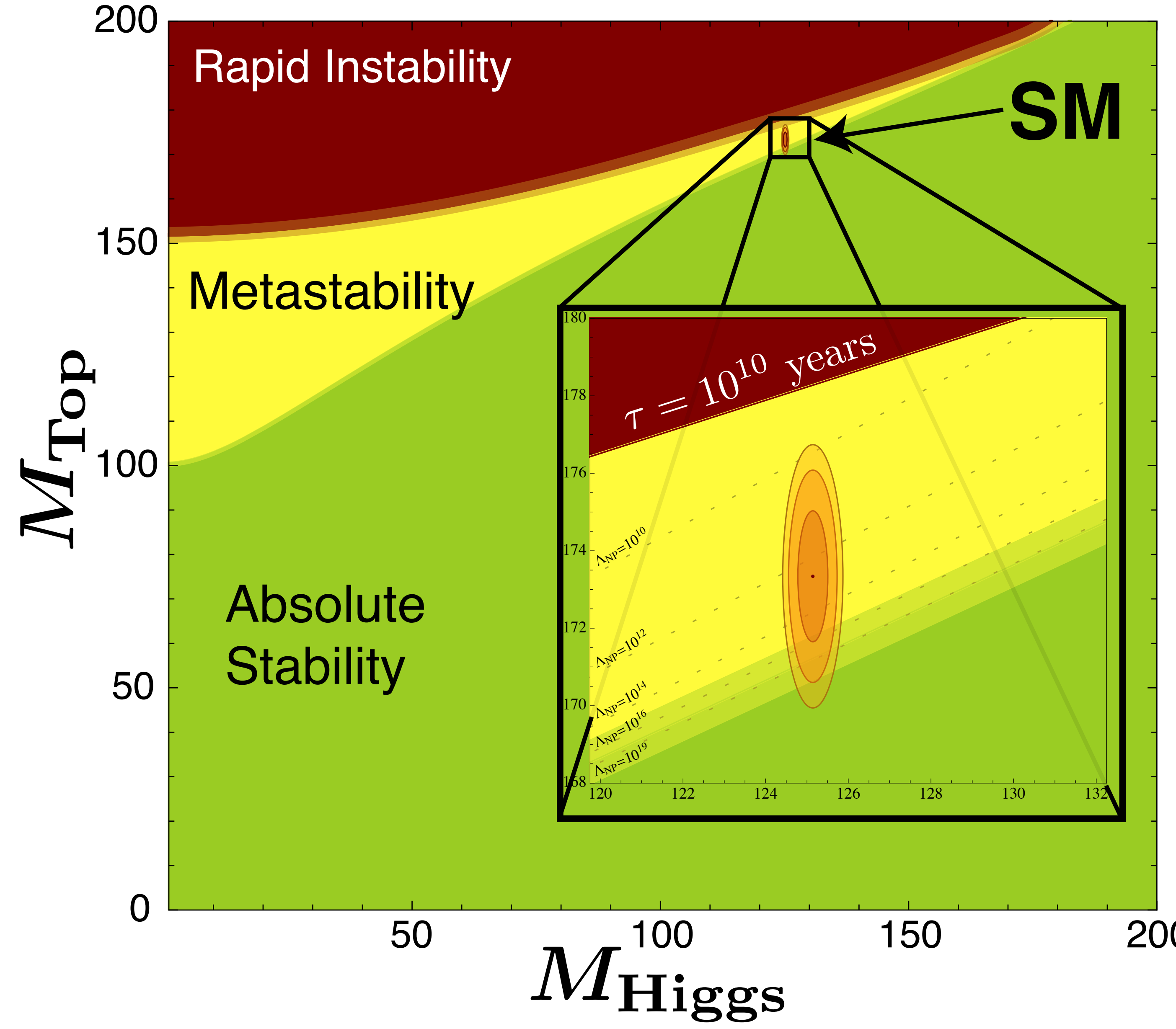
- Lifetime of our vacuum to decay through bubble nucleation (related to Higgs instability scale): *Khoury, Steingasser 2021-22*

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

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

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



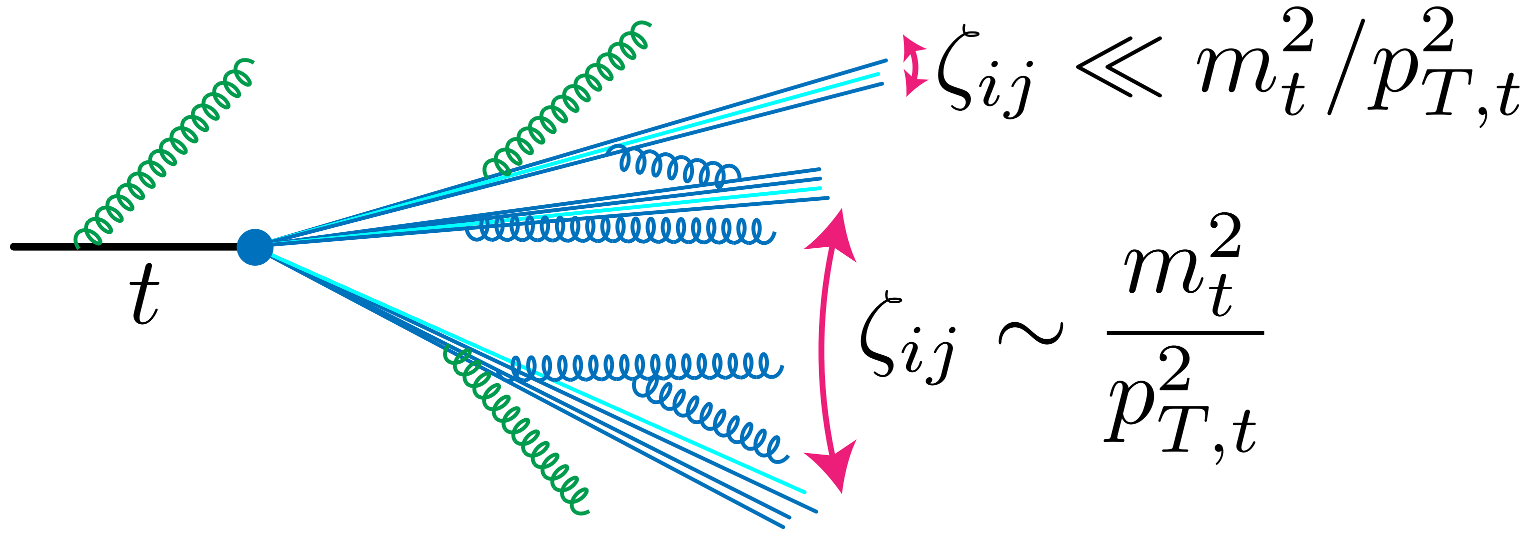


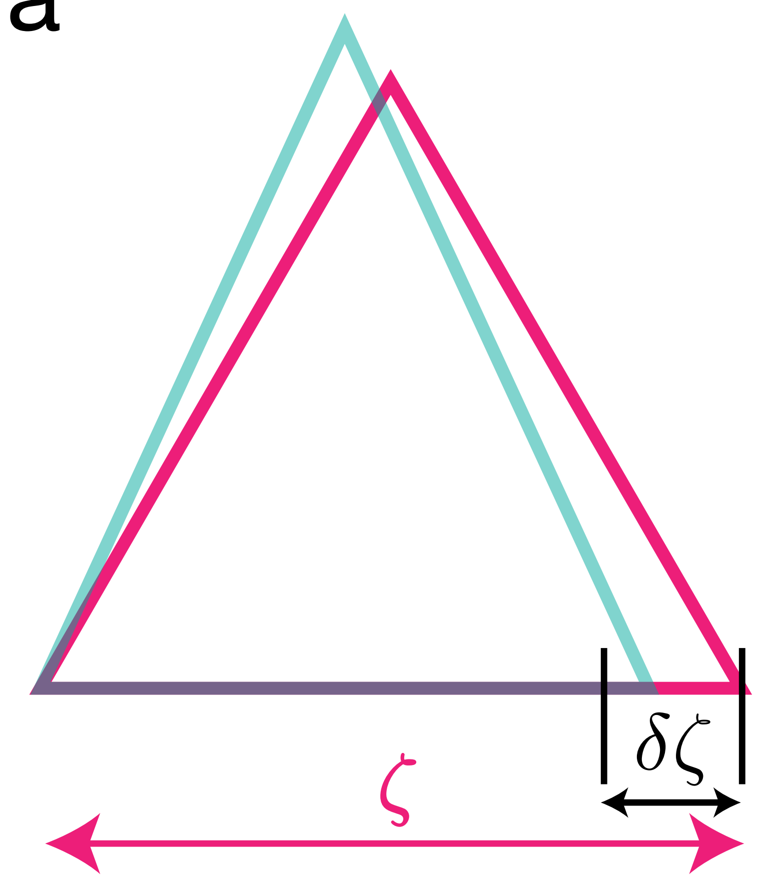
Andreassen, Frost, Schwartz 2014

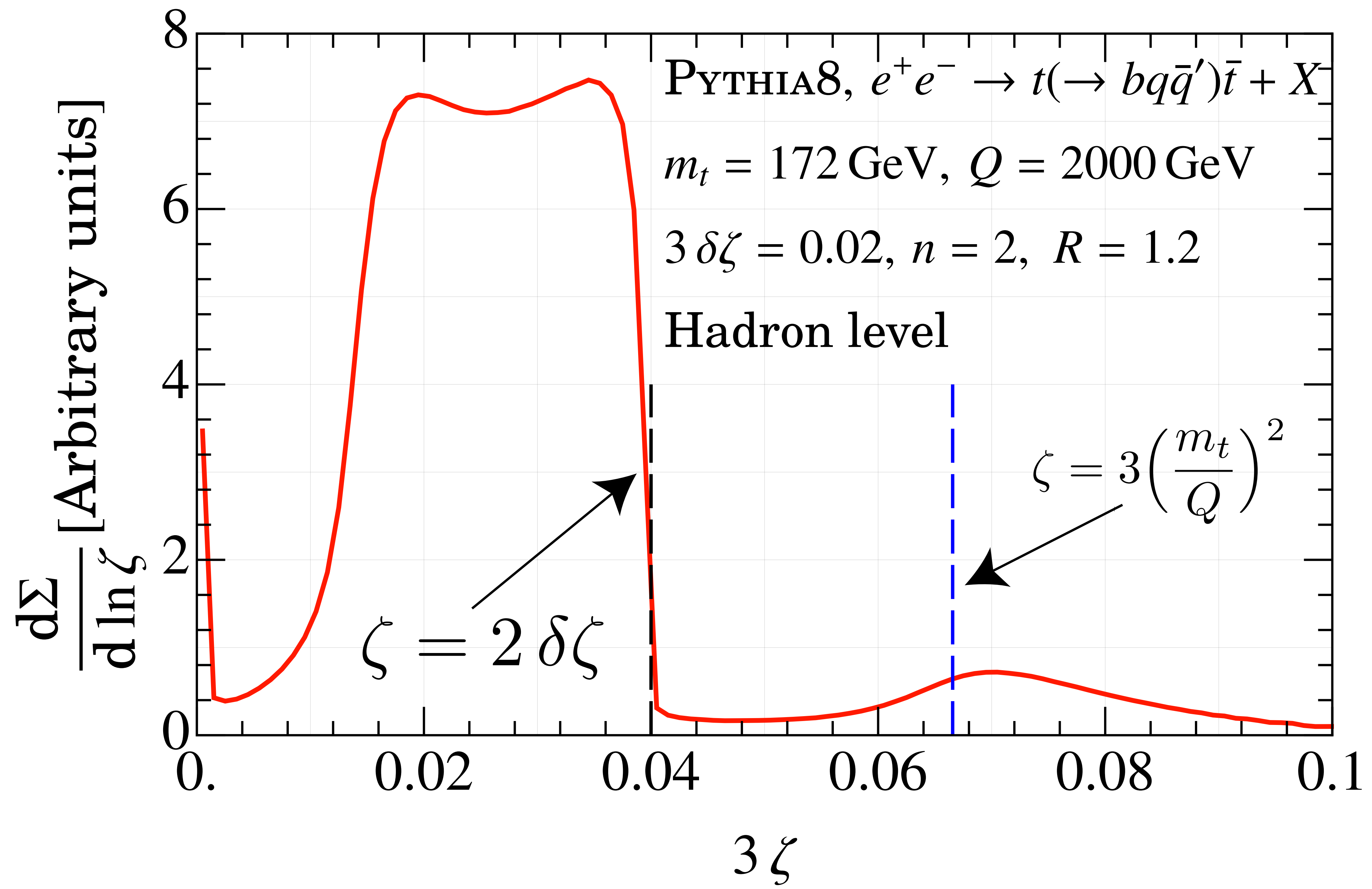
The top quark imprint in EEEC

Holguin, Moult, AP, Procura 2022

- A naive sum over the three angles picks up contributions from collinear splittings
- To capture the correlations among the three prongs we need to avoid such configurations
- Consider equilateral configurations with a asymmetry cut $\delta\zeta$.







- Distinct peak at $\zeta_t \sim 3(m_t/Q)^2$ for equilateral configuration: 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.

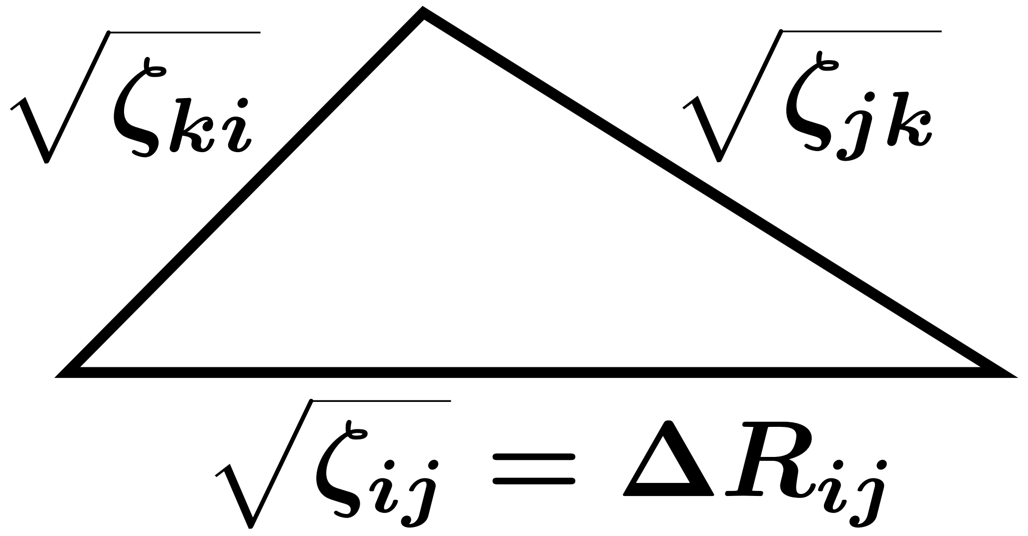
Imprint of the W in the EEEC distribution

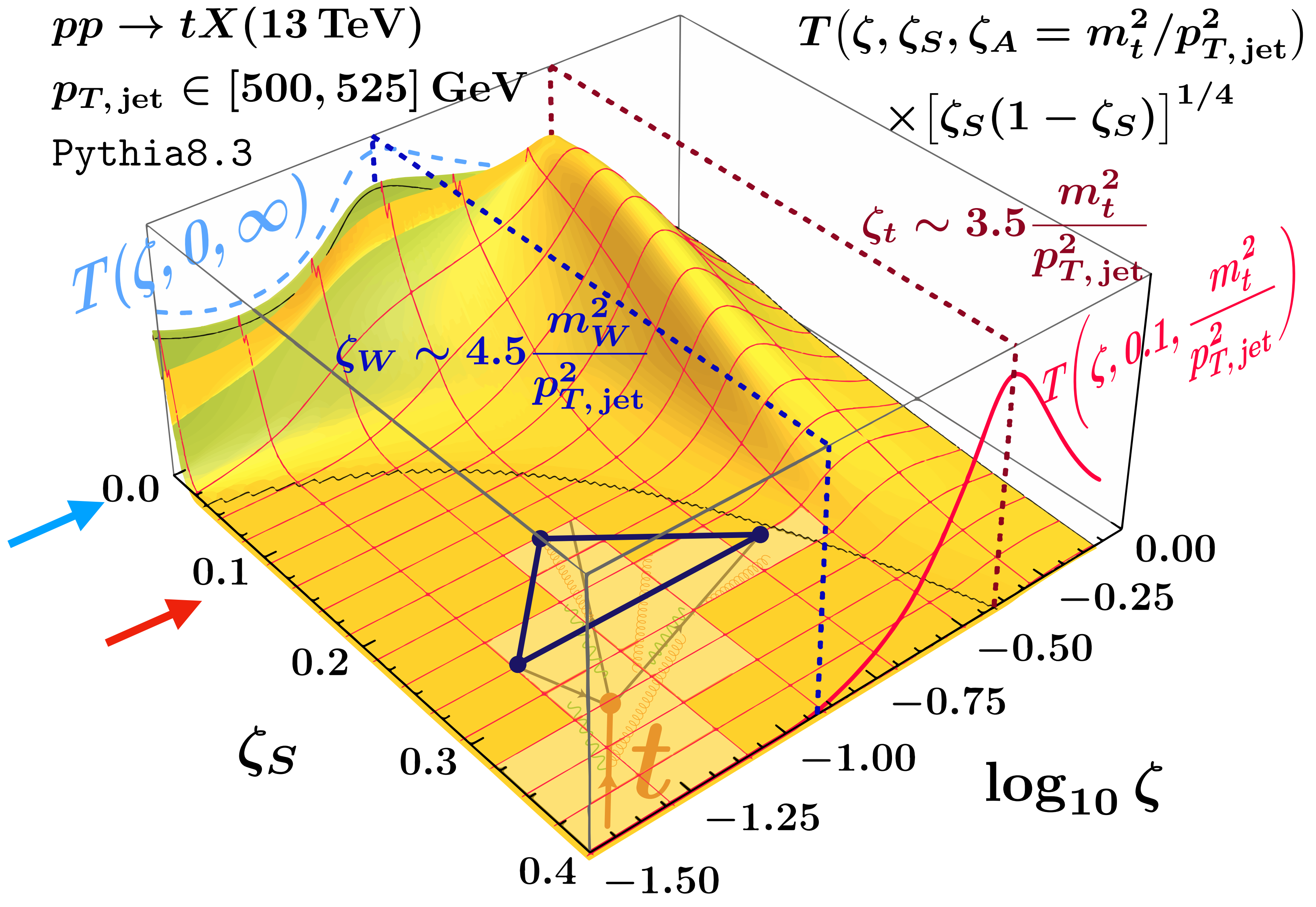
- The observable we define to extract the W-imprint:

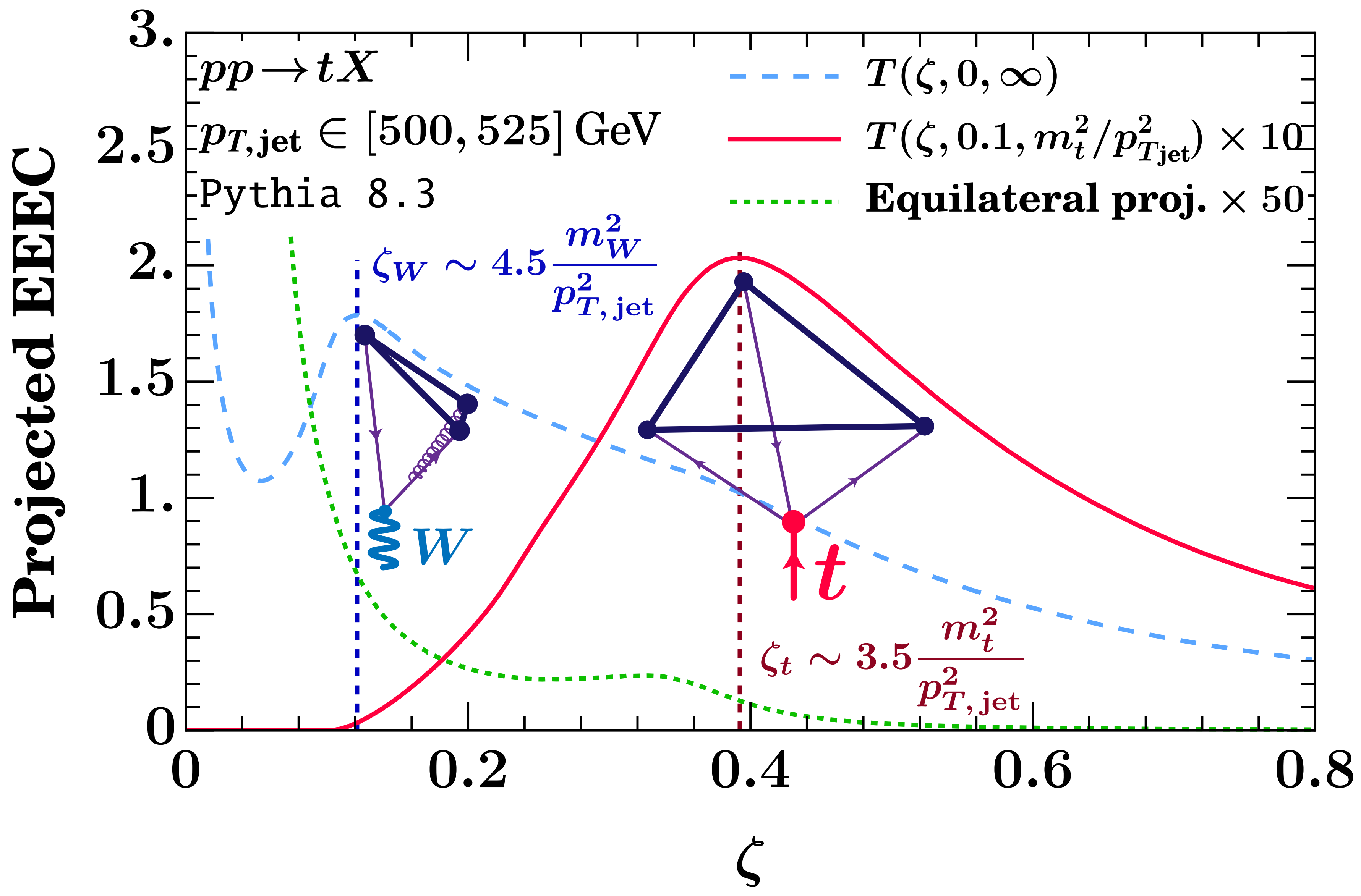
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2023

$$T(\zeta,\zeta_S,\zeta_A) \equiv \int \left(\prod \mathrm{d}\zeta_{ij}\right) \delta\!\left(\zeta - \left(\frac{\sqrt{\zeta_{ij}}+\sqrt{\zeta_{jk}}}{2}\right)^2\right) \Theta(\zeta_{ij} \geq \zeta_{jk} \geq \zeta_{ki} \geq \zeta_S)\, \Theta\!\left(\zeta_A - \left(\sqrt{\zeta_{ij}}-\sqrt{\zeta_{jk}}\right)^2\right) \widehat{\mathscr{M}}^{(1)}(\zeta_{ij},\zeta_{jk},\zeta_{ik})\, \mathrm{d}\sigma$$

- ζ: average of medium and long sides, ζ_S: Min cut on short side, ζ_A: Max allowed difference between the medium and long sides







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.

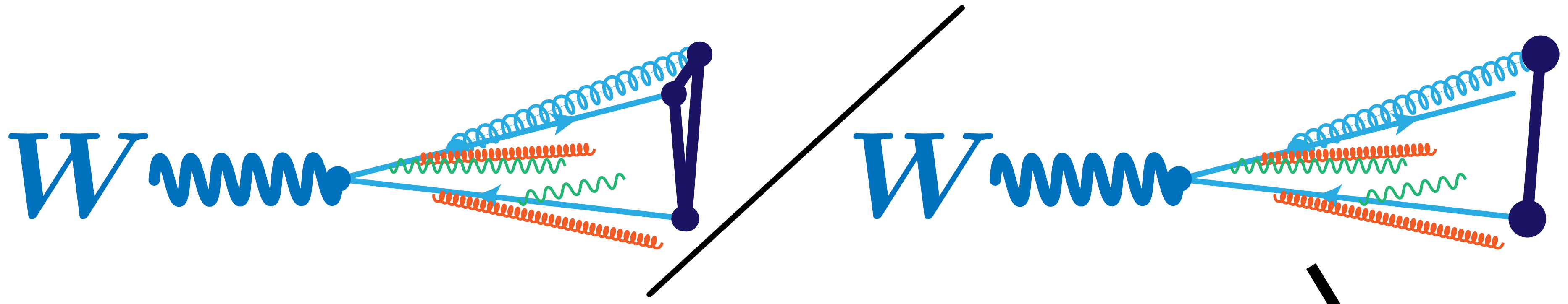
A robust m_W sensitive projection

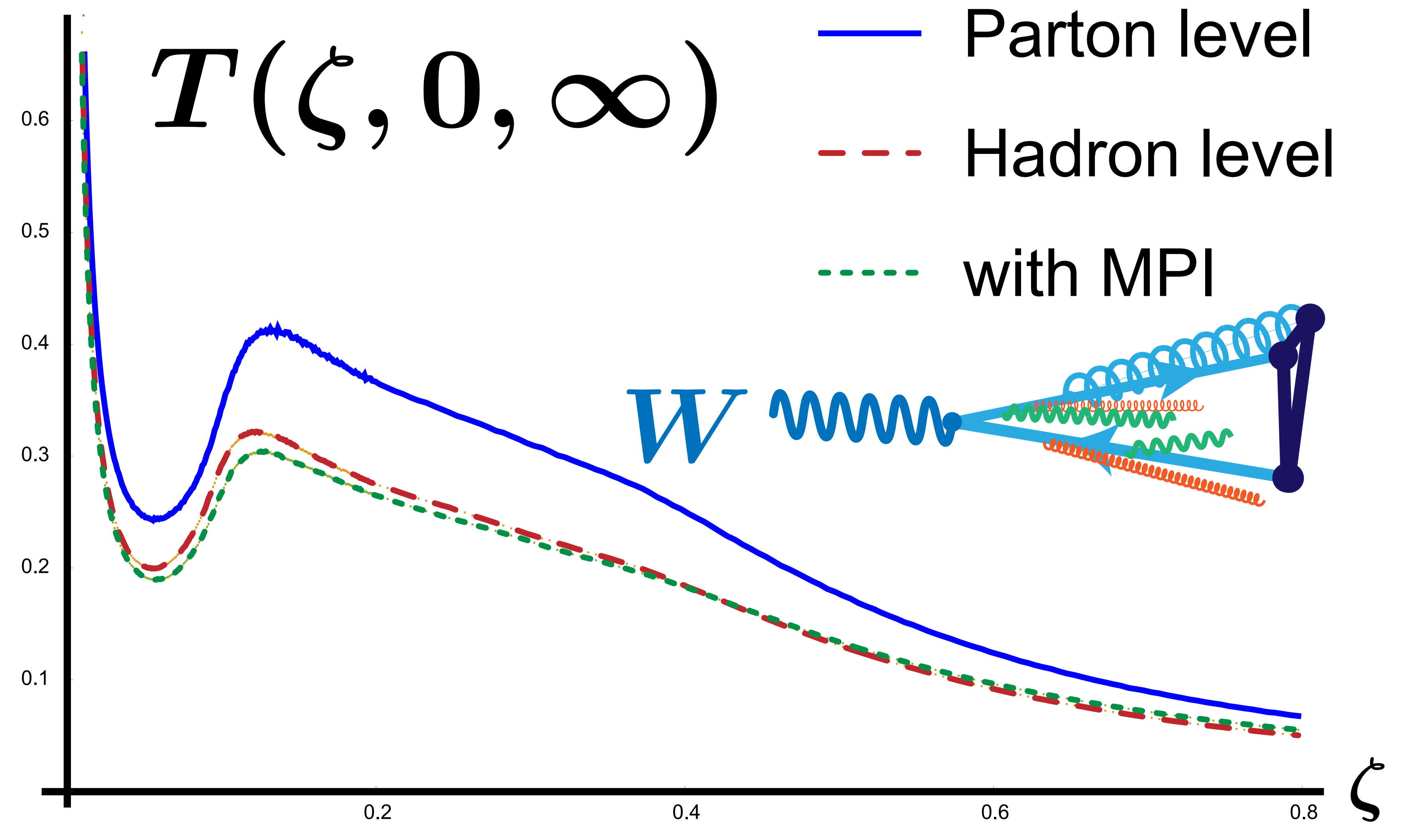
Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 2023

- The $T(\zeta,0,\infty)$ distribution is impacted by nonperturbative effects in back-to-back Sudakov.

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

$$W(\zeta) \equiv \frac{T(\zeta,0,\infty)}{\text{EEC}(\zeta)}$$

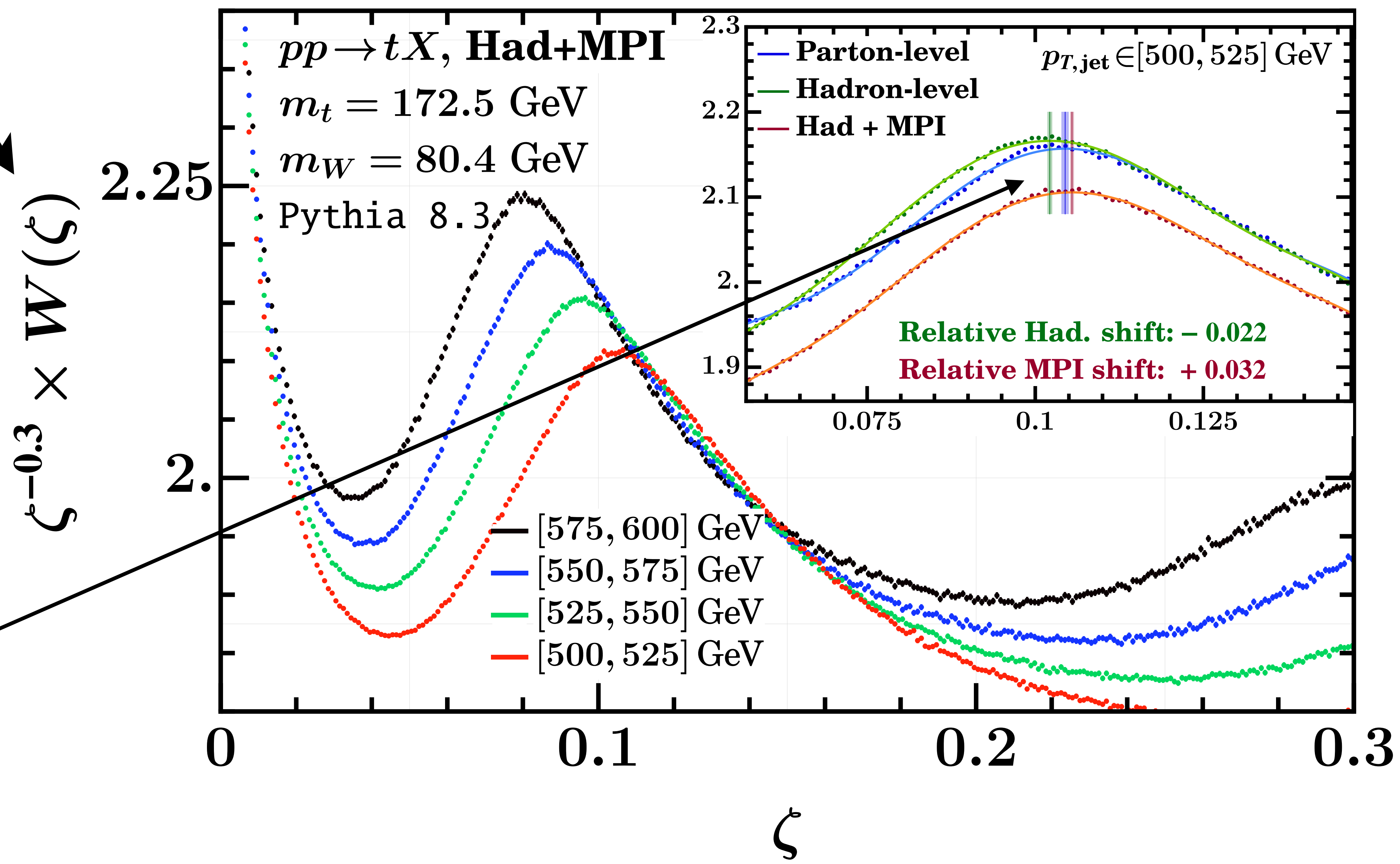




- This works because the same back-to-back soft function $S_\perp(b_\perp, \mu, \nu)$ appears in num and denom. Cancellation of leading nonperturbative effects: *Holguin, Lee, Moult, AP, Procura [in progress]*

$$\text{EEC}(\zeta) \sim J_{\text{EEC}} \otimes J_{\text{EEC}} \otimes S_\perp$$

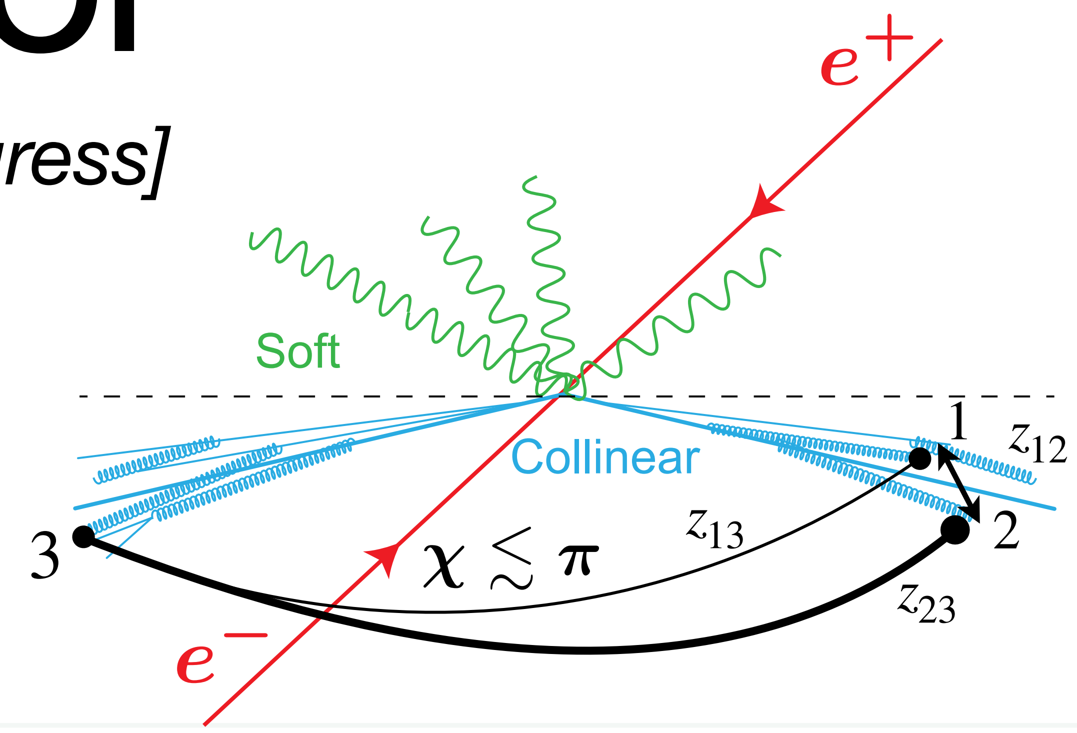
$$T(\zeta,0,\infty) \sim J_{\text{EEEC}} \otimes J_{\text{EEC}} \otimes S_\perp$$



- Remaining shifts in the $W(\zeta)$ primarily arise from the shifts in the $\langle p_{T,\text{jet}} \rangle$.

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:

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

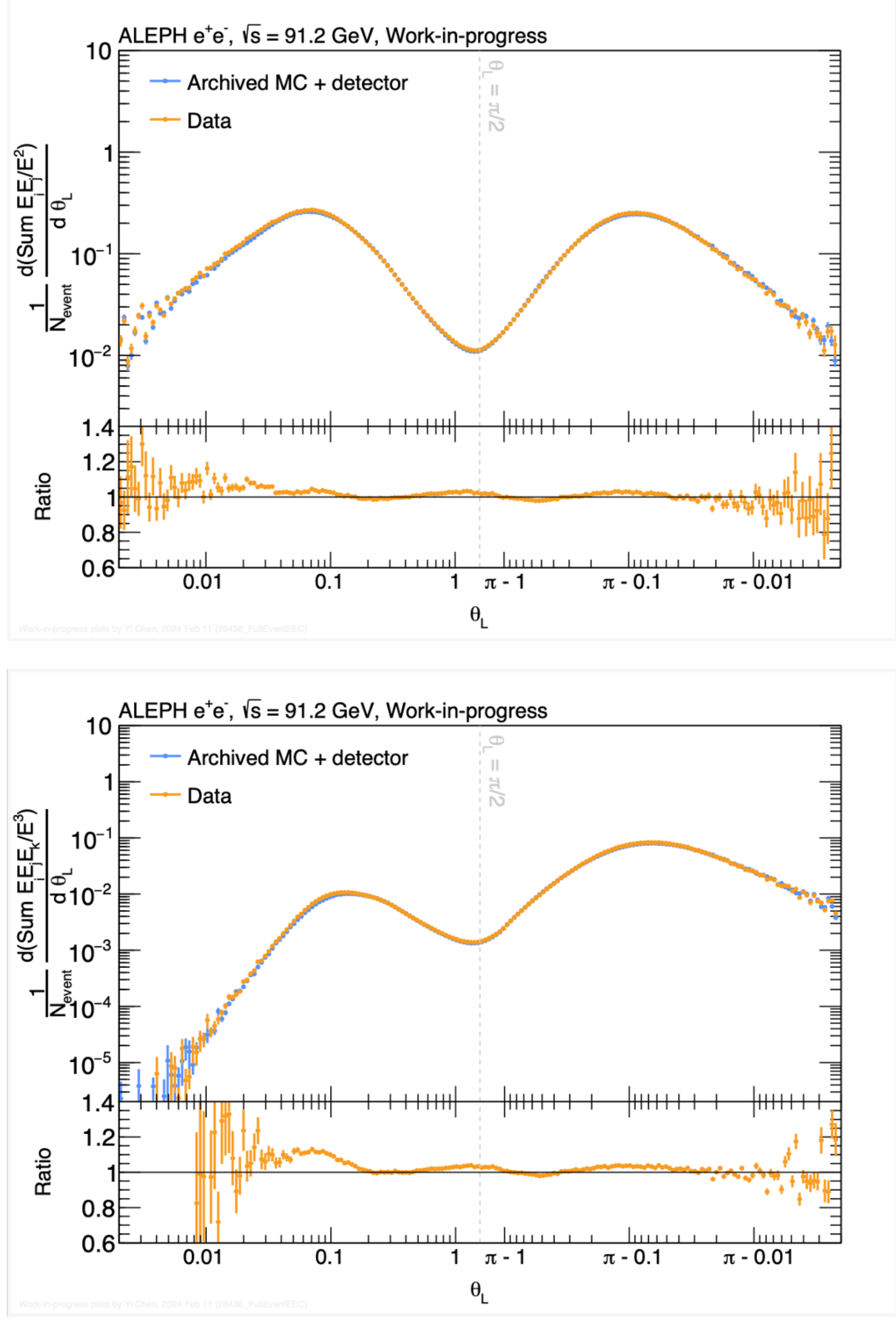
$$\mathcal{D}_{i/j}(z,b_\perp,\epsilon) \sim \frac{1}{z^2}$$

Key takeaways:

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

$$\int_0^1 \mathrm{d}z\, z^d\left[\mathcal{D}^{(1)}_{g/q}(z,b_\perp)+\mathcal{D}^{(1)}_{q/q}(z,b_\perp)\right] = C_F\left(\frac{3}{\epsilon}+3L_b-\frac{4\pi^2}{3}+10\right)+2C_FL_b\left(\frac{3}{2}-2\ln\frac{Q}{\nu}\right)$$

$$J^{(1)}_{f(12)} = C_F\left(-\frac{3}{\epsilon}-3\ln\frac{\mu^2}{Q^2}-\frac{37}{3}+2F^{(0)}_{x_2,z_{12}}(b_TQ)\right)\delta(z_{12})\delta(z_{23}-z_{13}) + C_F\left[\frac{F_{x_2}(b_TQ\sqrt{z_{12}},0)}{z_{12}}\right]_+\frac{\Theta(z_{12})}{\pi}\int \mathrm{d}\Omega^{(2)}_{d-2}\,\delta_{z_{23}}$$



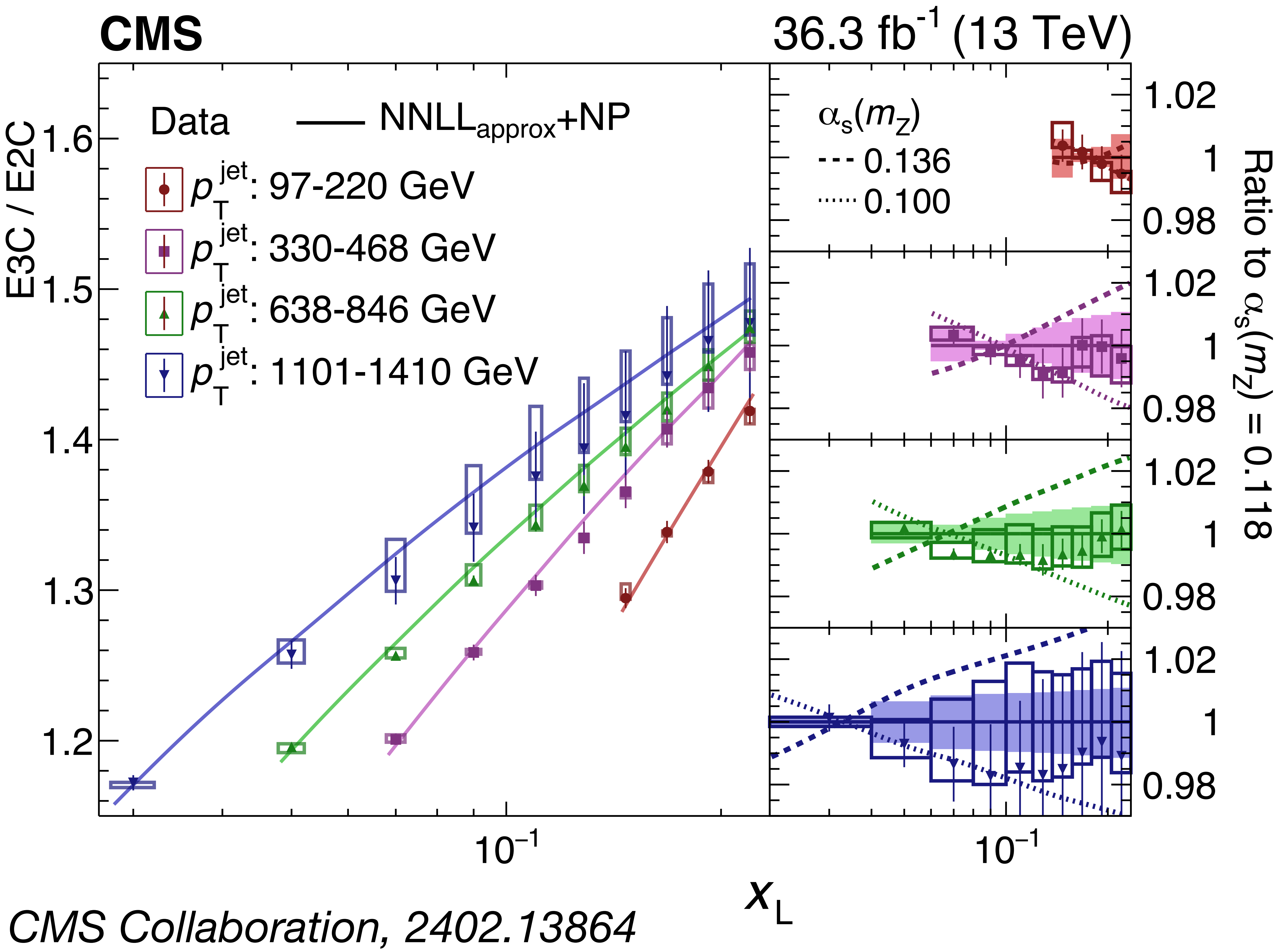
Plots from a talk by Yen-Jie Lee

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:

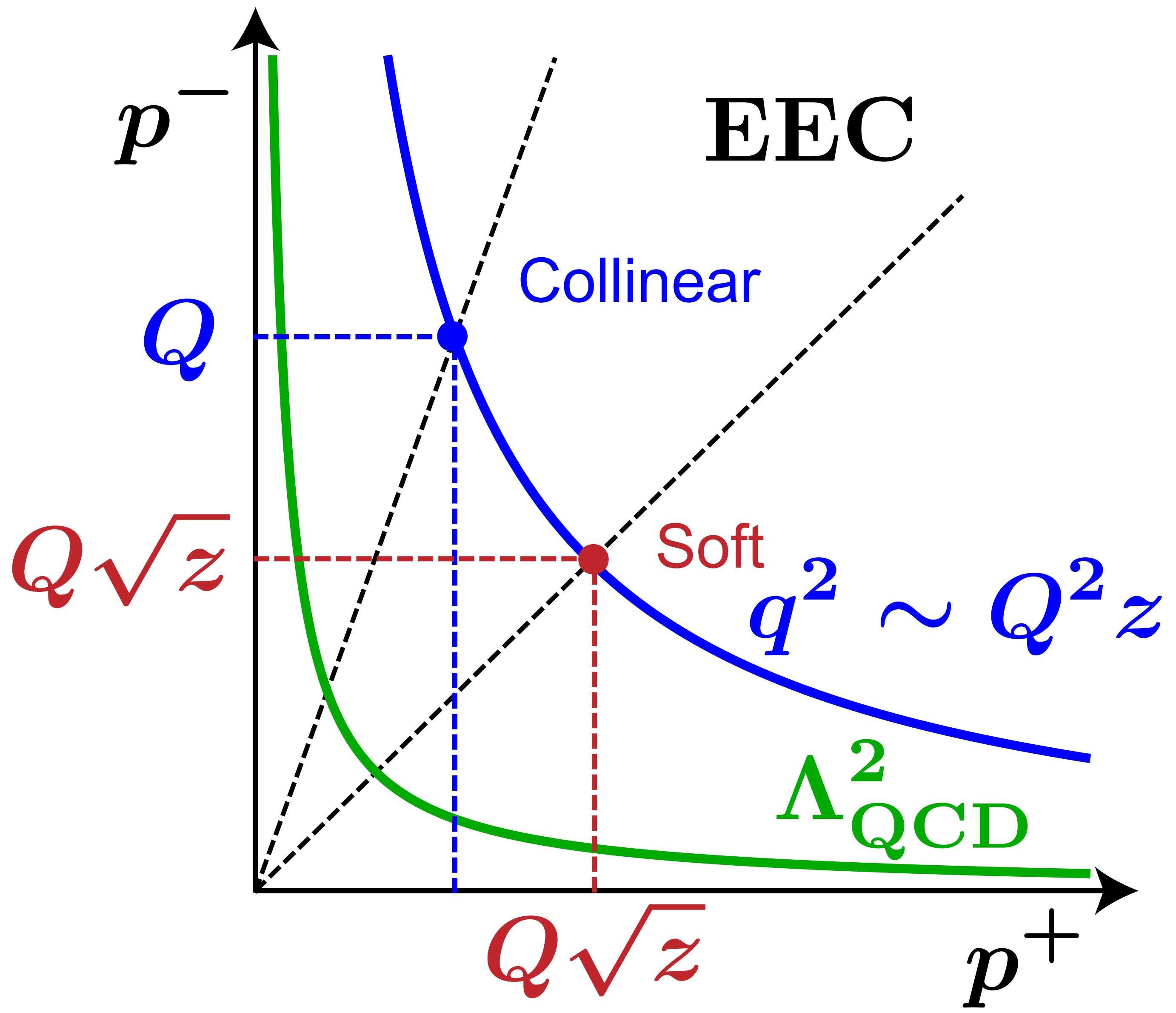
Same as thurst!

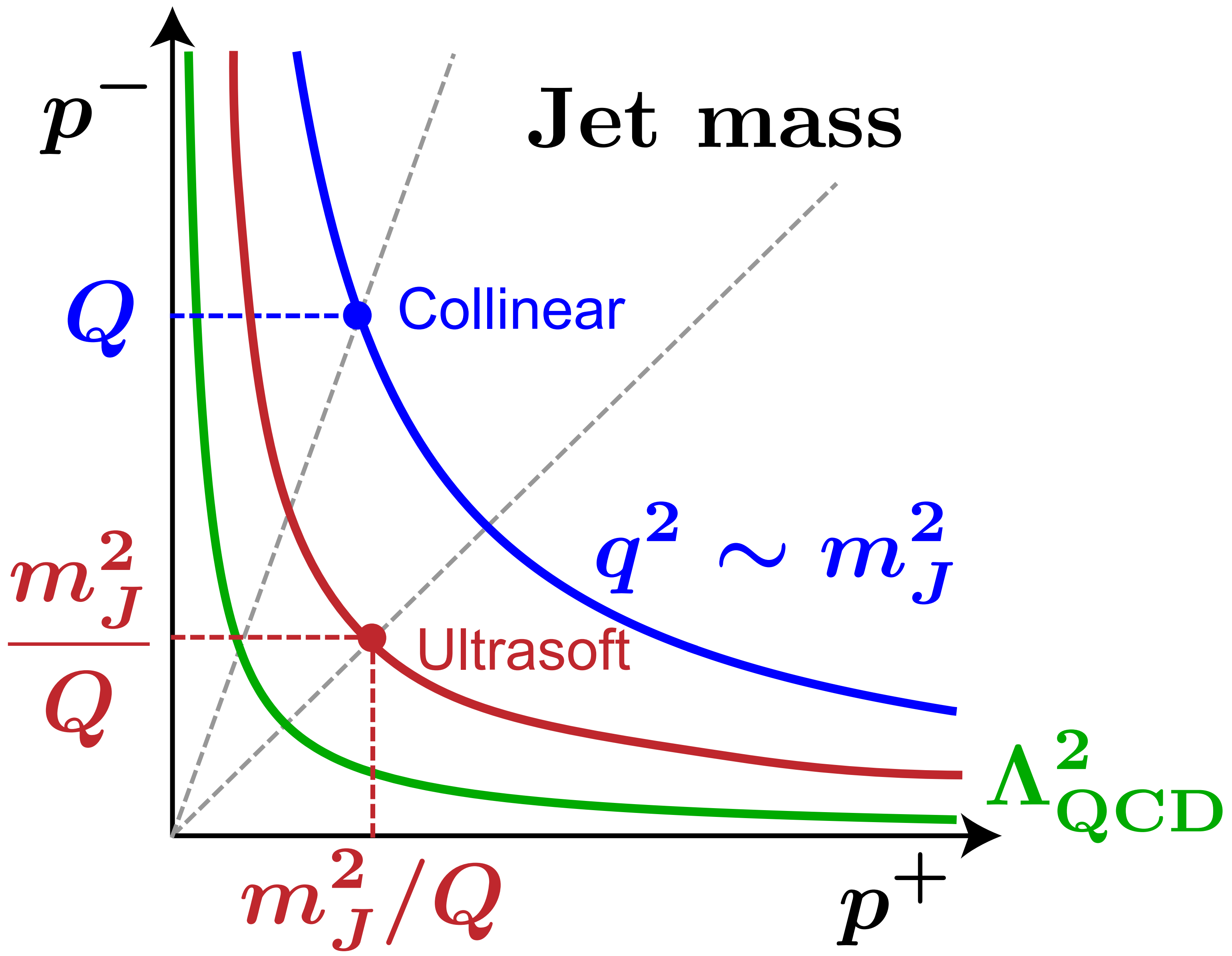
$$\frac{1}{\sigma}\frac{d\sigma^{[N]}}{dx_L} = \frac{1}{\sigma}\frac{d\hat{\sigma}^{[N]}}{dx_L} + \frac{N}{2^N}\frac{\overline{\Omega}_{1q}}{Q(x_L(1-x_L))^{3/2}}$$

Lee, AP, Stewart, Sun 2405.19396
[Accpeted by PRL]
(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

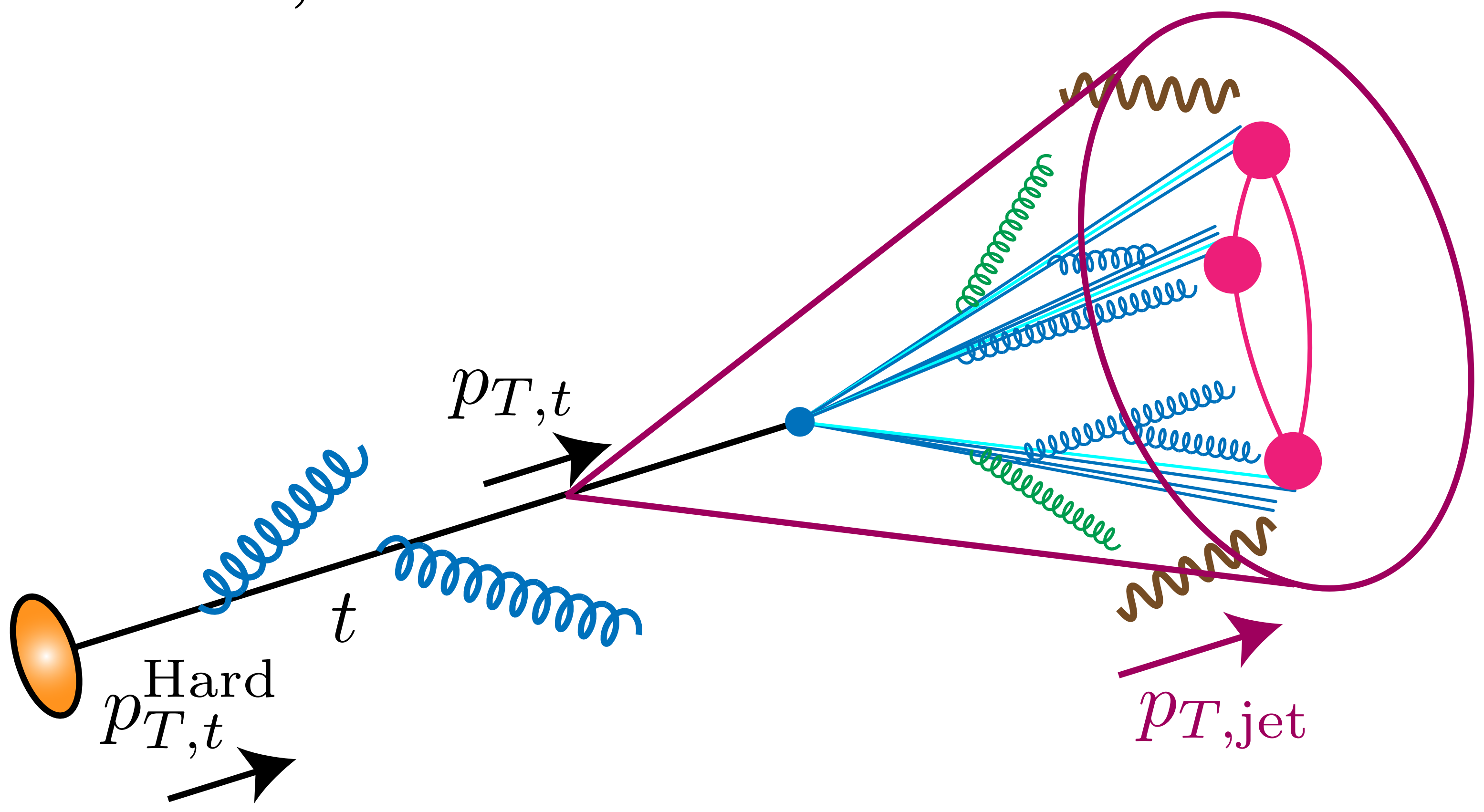
EECs are also insensitive to the contamination

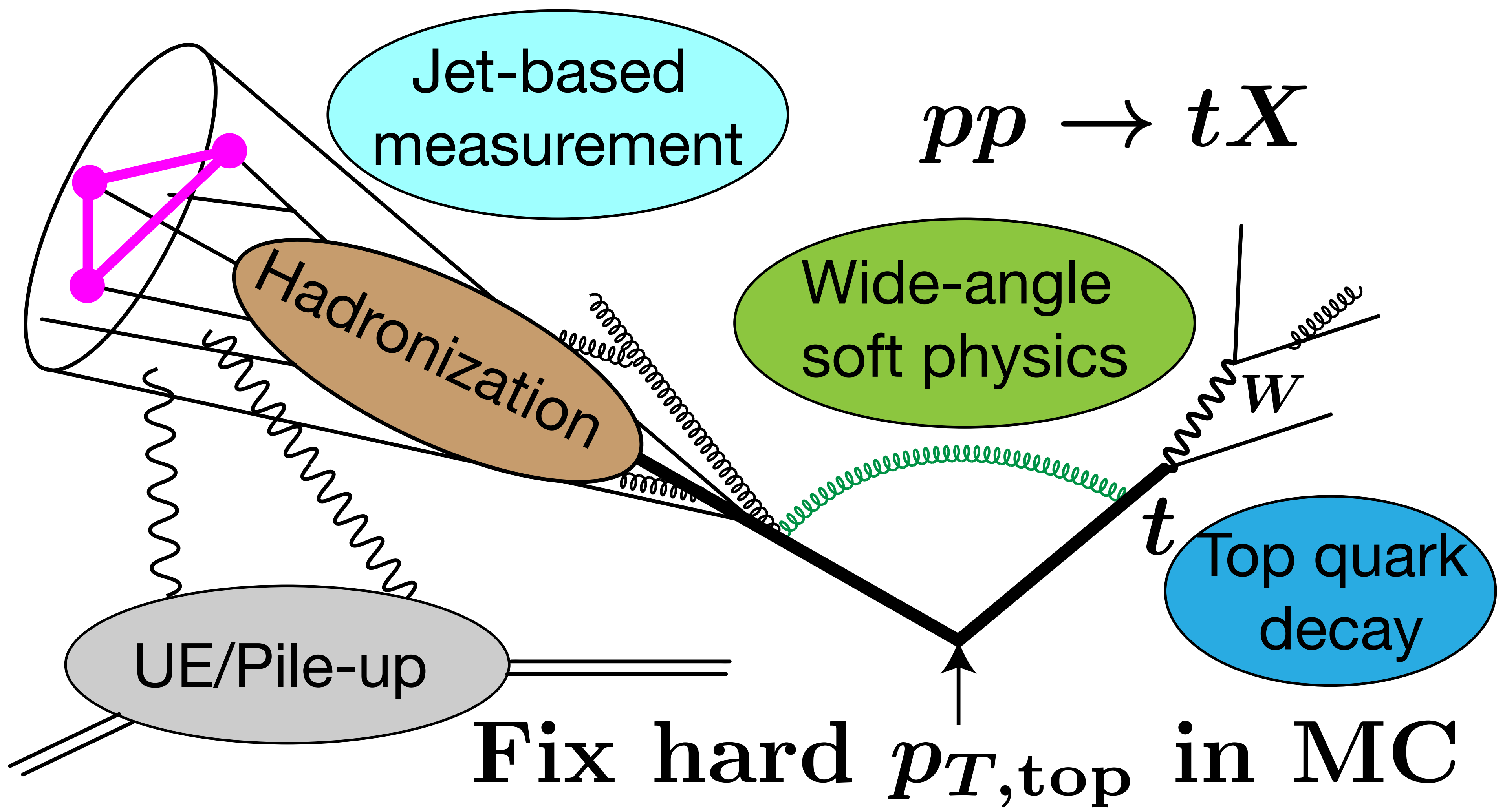
The correlator measurement can be expressed as

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

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:

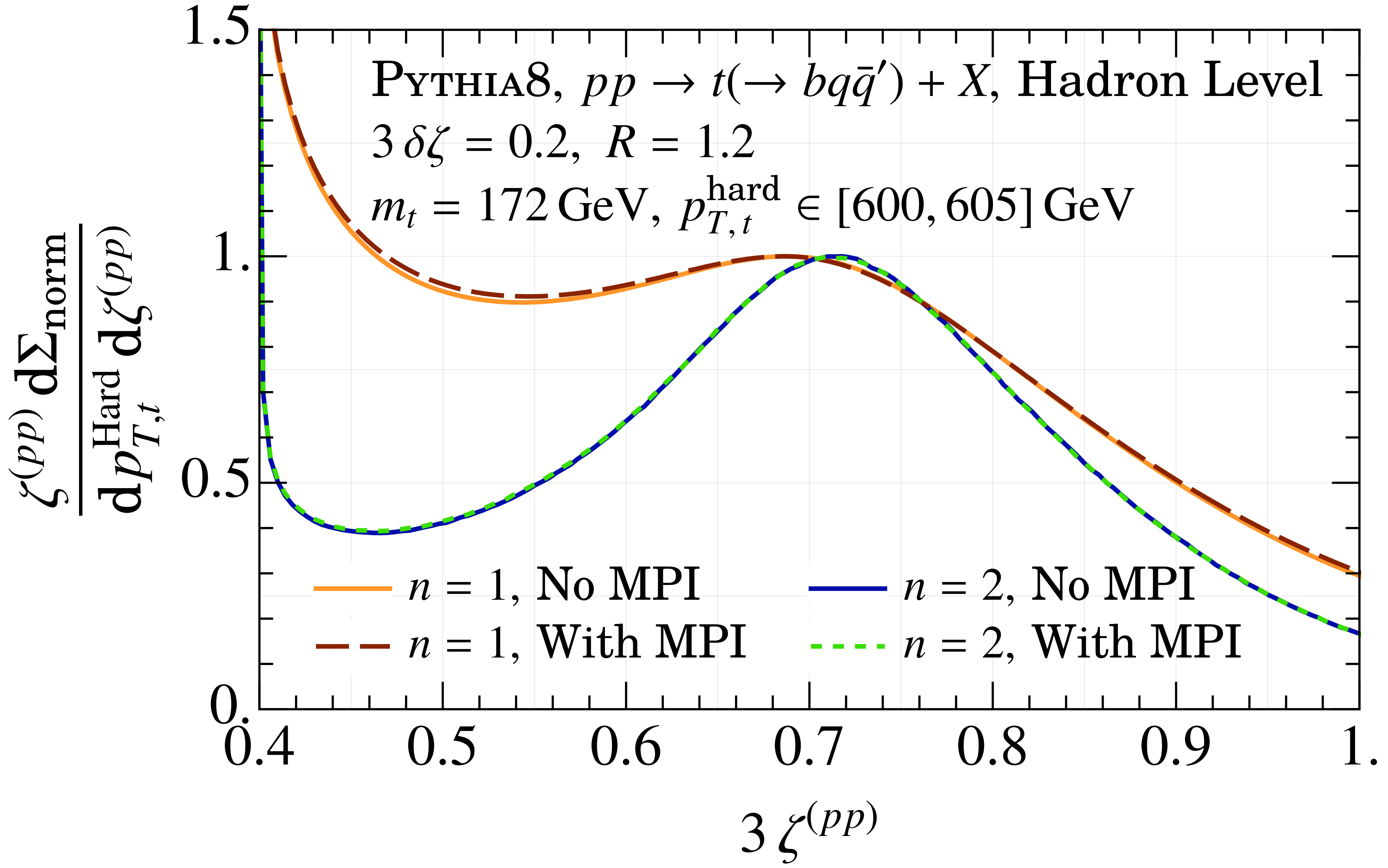
- Top quarks produced with a fixed hard p_T as in e^+e^- collisions.
- Can solely focus on the impact of the underlying event

EECs are also insensitive to the contamination

Holguin, Moult, AP, Procura 2022

The correlator measurement can be expressed as

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



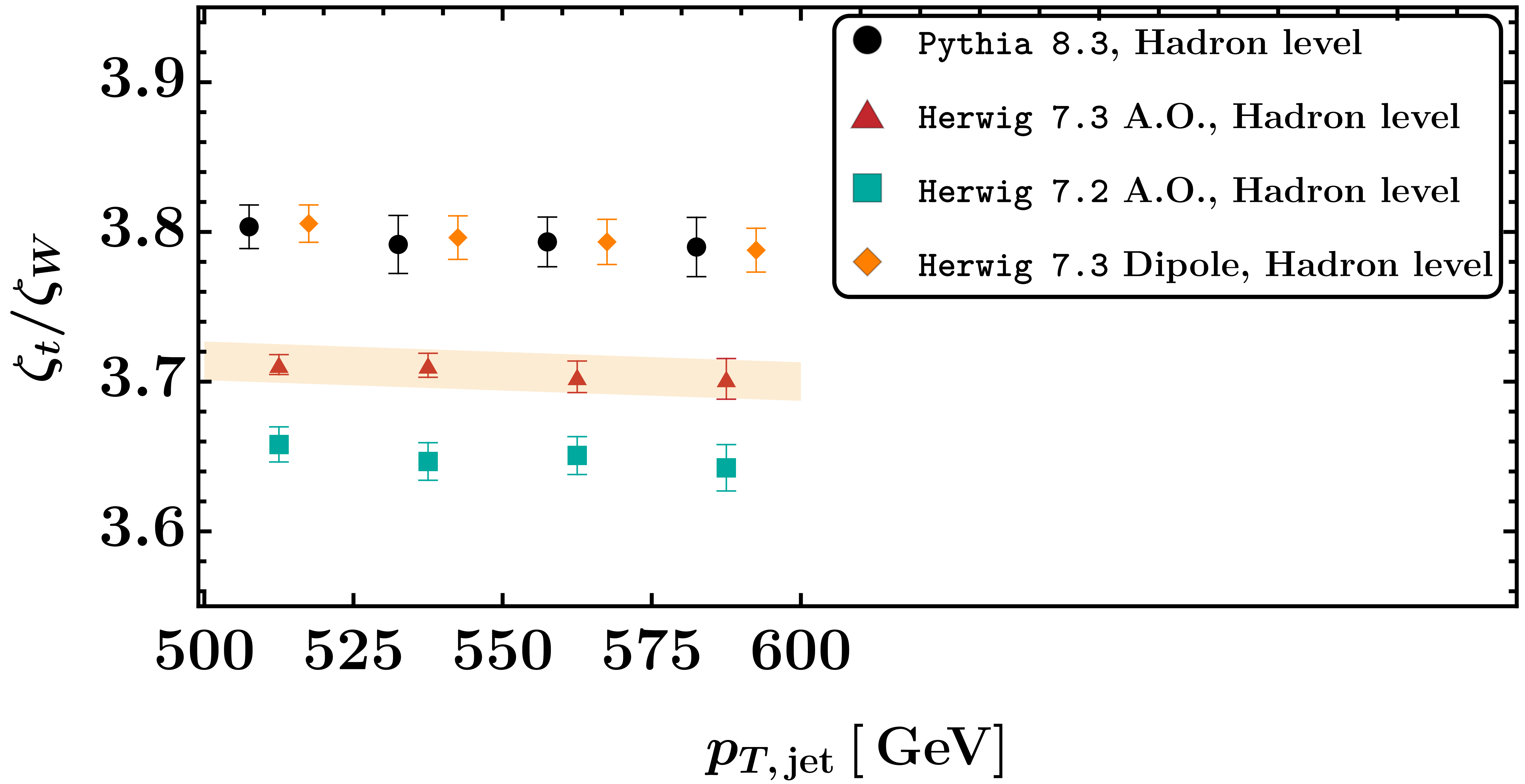
- The underlying event still impacts the jet p_T and adds contamination to the triplets sampled.
- The correlator measurement after normalization is however completely insensitive to the UE.

Calibrating the top mass

Holguin, Moult, AP, Procura, Schöfbeck, Schwarz 23-24

- Use the standard CP5 tune for Pythia and Vincia
- Herwig Angular ordered shower differs from the others by 3% due to different approximations to NLO top decay

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



Shower	$R = 0.8$	$R = 1$	$R = 1.2$	$R = 1.5$
Pythia 8.3	1.075 ± 0.001	1.090 ± 0.001	1.099 ± 0.001	1.105 ± 0.001
Vincia 2.3	1.078 ± 0.001	1.091 ± 0.002	1.101 ± 0.001	1.107 ± 0.001
Herwig 7.3 Dipole	1.078 ± 0.001	1.088 ± 0.001	1.098 ± 0.001	1.106 ± 0.001
Herwig 7.3 A.O.	1.092 ± 0.001	1.104 ± 0.001	1.113 ± 0.001	1.120 ± 0.001

A slope in p_T is not an issue

- There is a systematic procedure to incorporate power corrections in perturbative calculations which describe this p_T dependence.

- With the leading p_T-dependence canceled, any undesirable shifts are highly suppressed to < 100 MeV level.