Weighing the top with energy correlators

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Outline

- Intro: indirect and direct measurements of the top quark mass at the LHC
- Novel proposal: extract the top mass from correlators of energy flow operators
- First results of an analysis based on Monte Carlo simulations of a 3-point correlator
- Summary and outlook

Jack Holguin, Ian Moult, Aditya Pathak, MP: arXiv 2201.08393

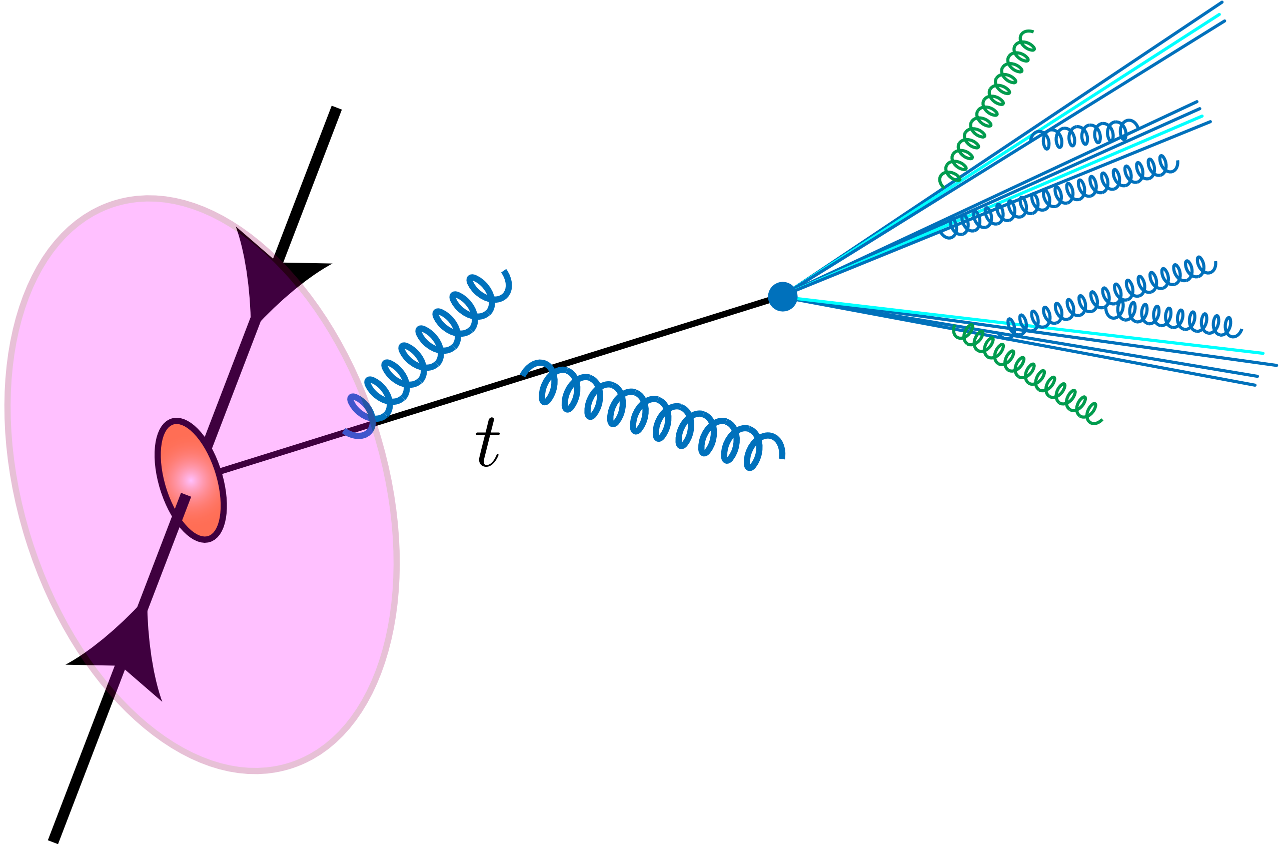
The top quark mass: indirect measurements

- The top quark mass is a SM parameter of fundamental importance in high-energy physics: EW precision tests, vacuum stability, … Precision is a key goal!

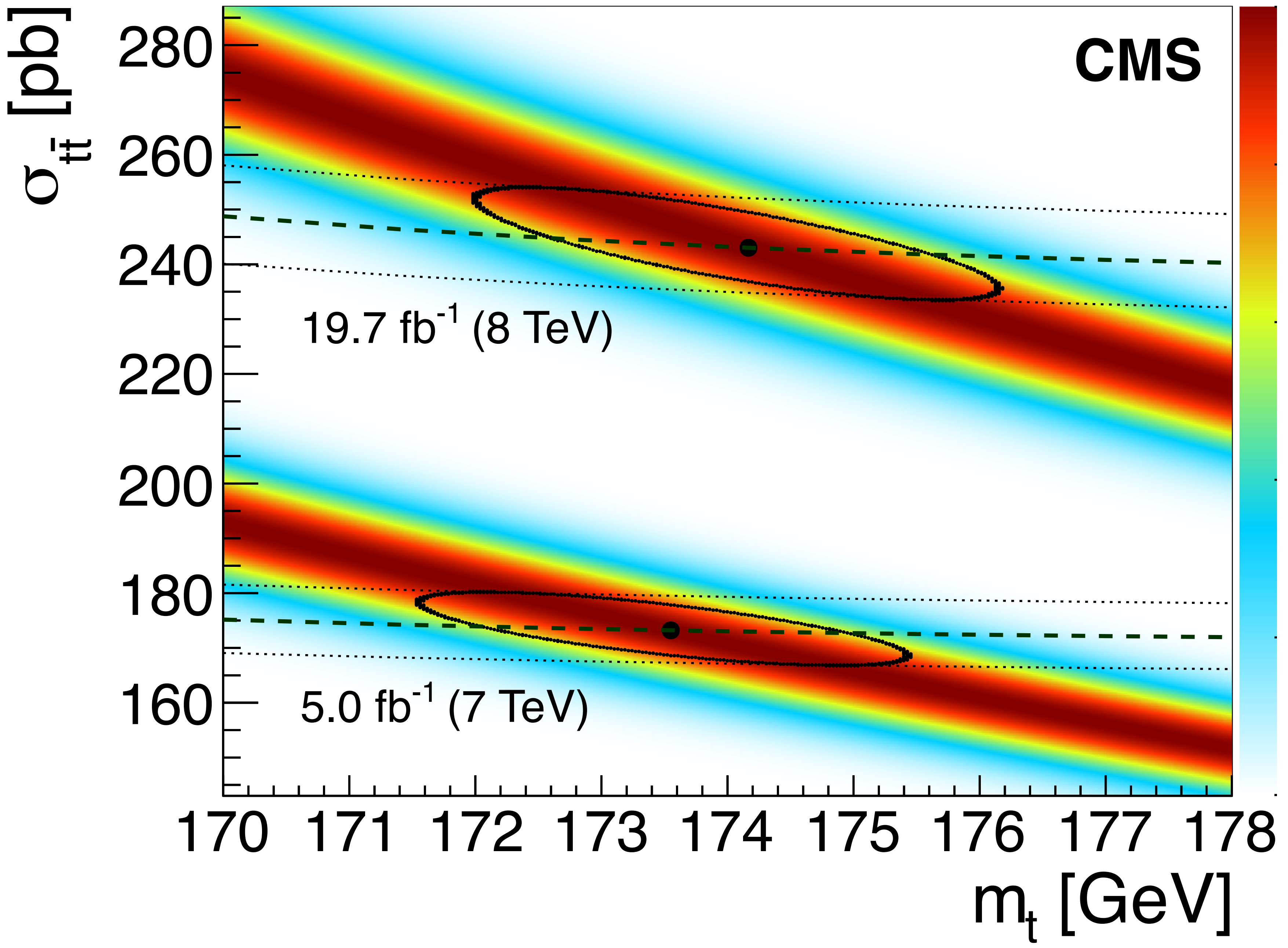
- Extracted by comparing theory vs data for collider observables, whose perturbative calculable contributions are evaluated in a renormalization scheme

- Good theoretical control achieved by measuring the inclusive $t\bar{t}$ cross section (indirect top mass sensitivity, tied to hard interaction)

  Parton-level results for $\sigma(t\bar{t}+X)$ to NNLO+NNLL accuracy (1112.5675) used by ATLAS and CMS to extract m_t in the pole-mass scheme



The top quark mass: indirect measurements



$$m_t^{\text{pole}} = 172.9^{+2.5}_{-2.6}\ \text{GeV}$$ ATLAS, 1406.5375

$$m_t^{\text{pole}} = 172.7^{+2.4}_{-2.7}\ \text{GeV}$$ CMS, 1701.06228

(Large contribution from normalization uncertainties in the inclusive cross section)

More sensitivity to the top mass at LHC gained by exploiting information from the final-state top decay products

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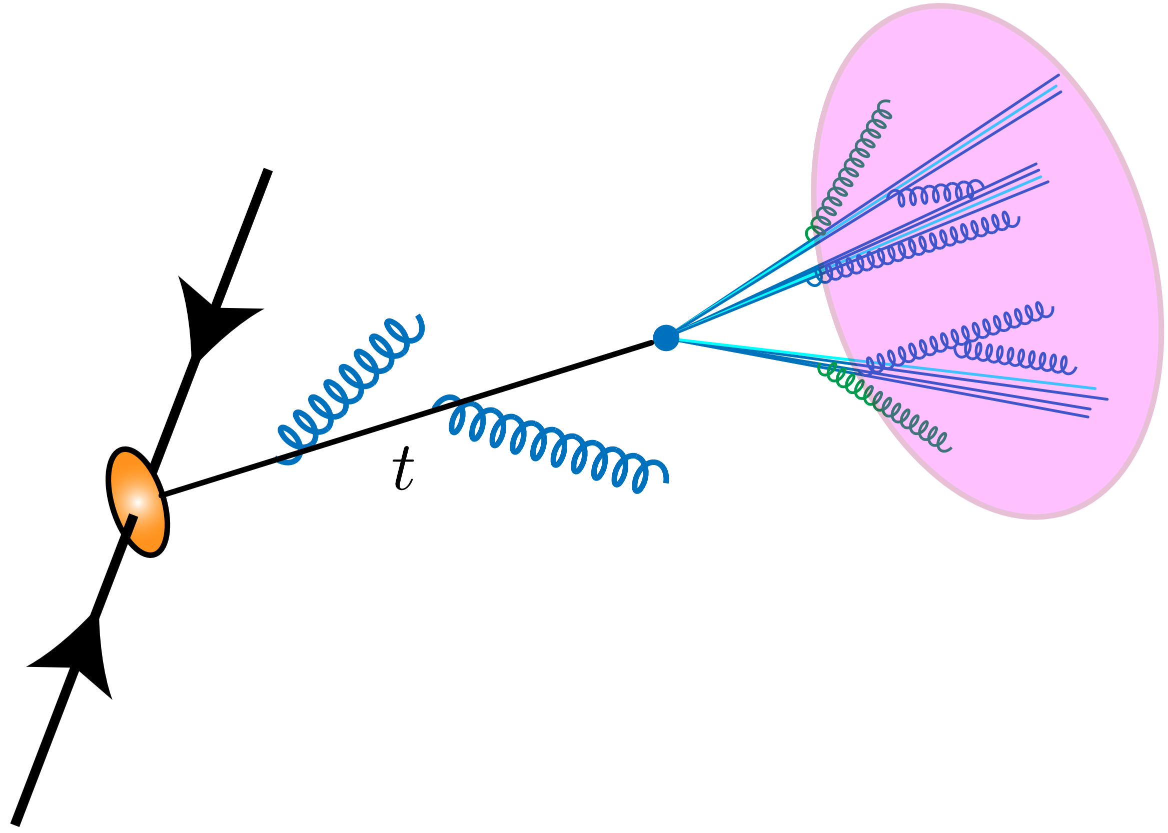


The top quark mass: direct measurements

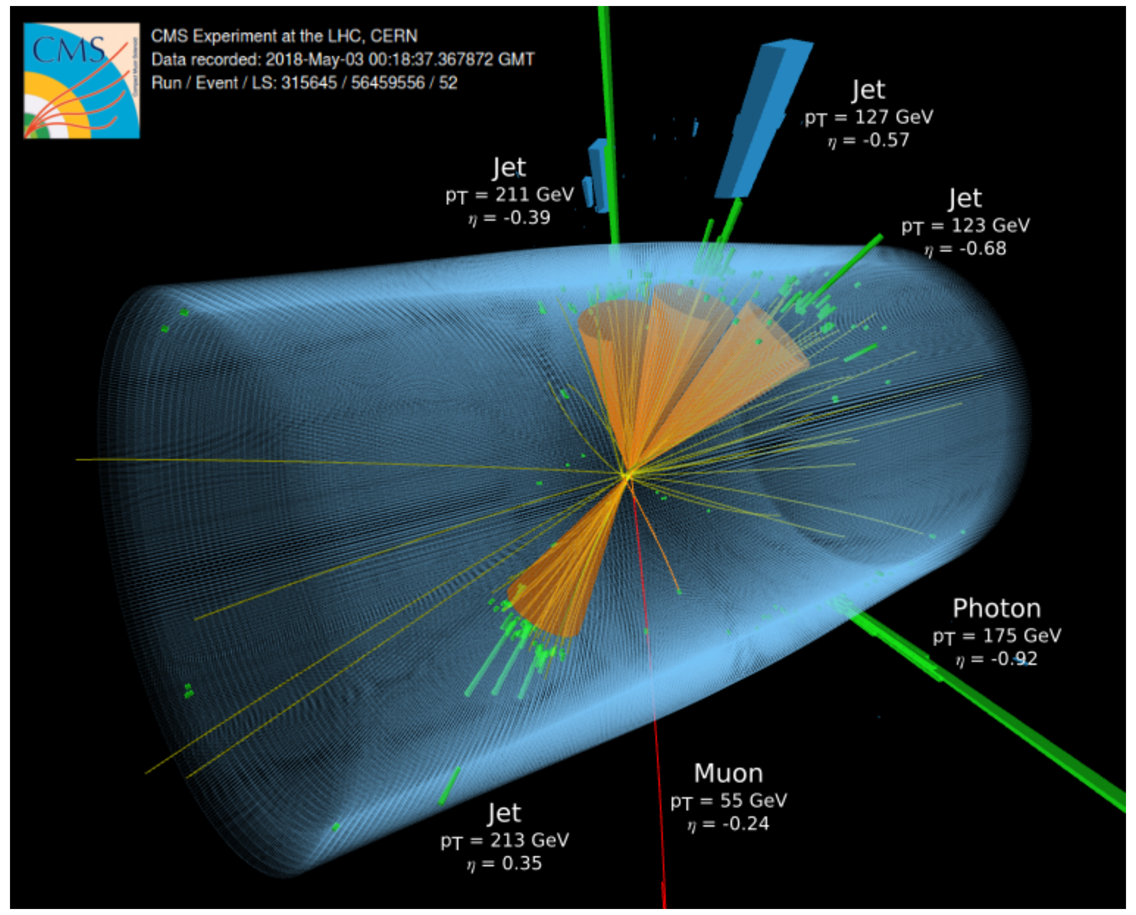
- Analysis of kinematic observables built out of reconstructed top decay products ($\mathrm{d}\sigma/\mathrm{d}m_t^{\mathrm{reco}}$, $\mathrm{d}\sigma/\mathrm{d}M_{bl}$ ...) has yielded

$$m_t^{\mathrm{MC}} = 172.69 \pm 0.48\,\mathrm{GeV}$$

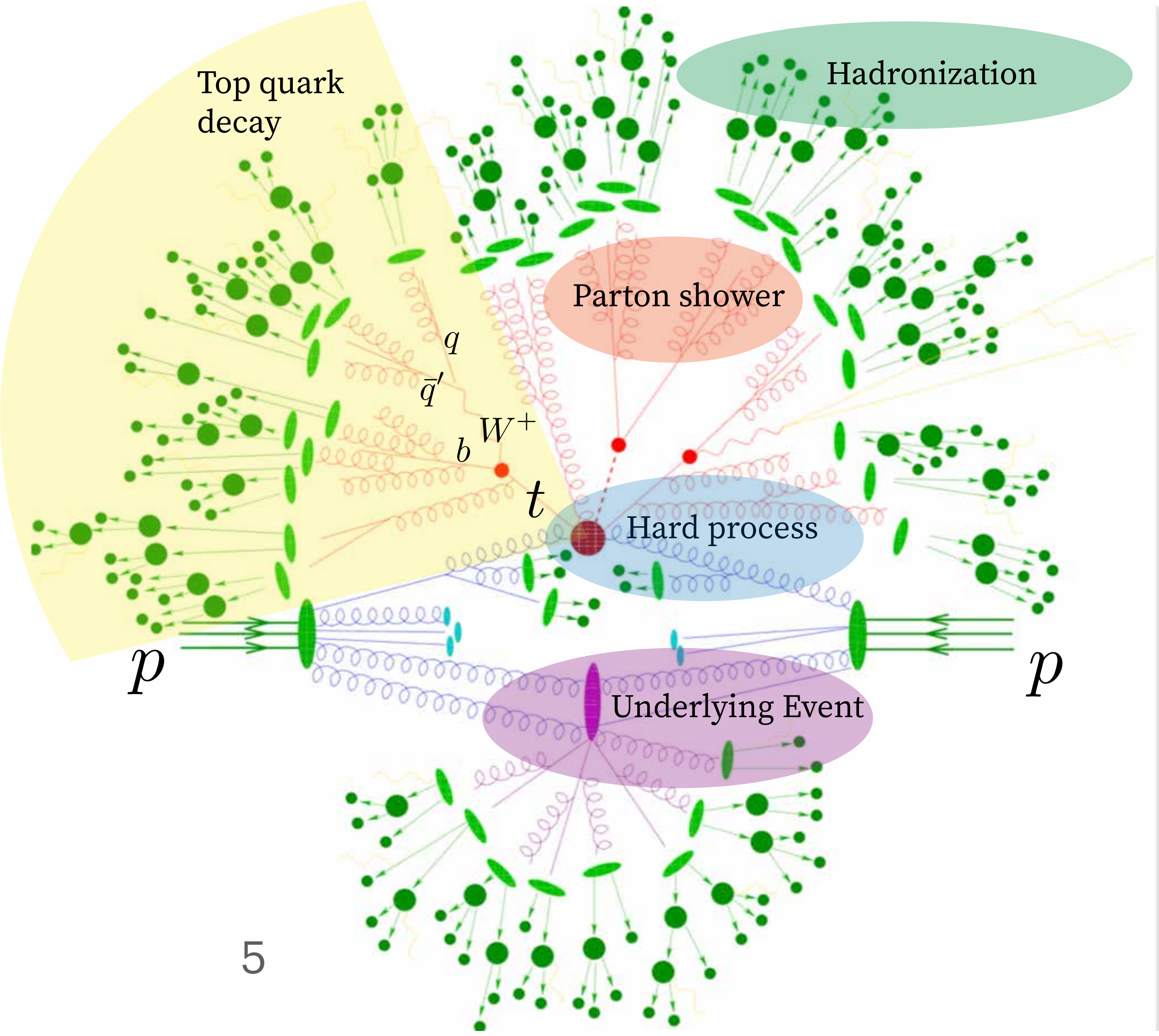
ATLAS, 1810.01772

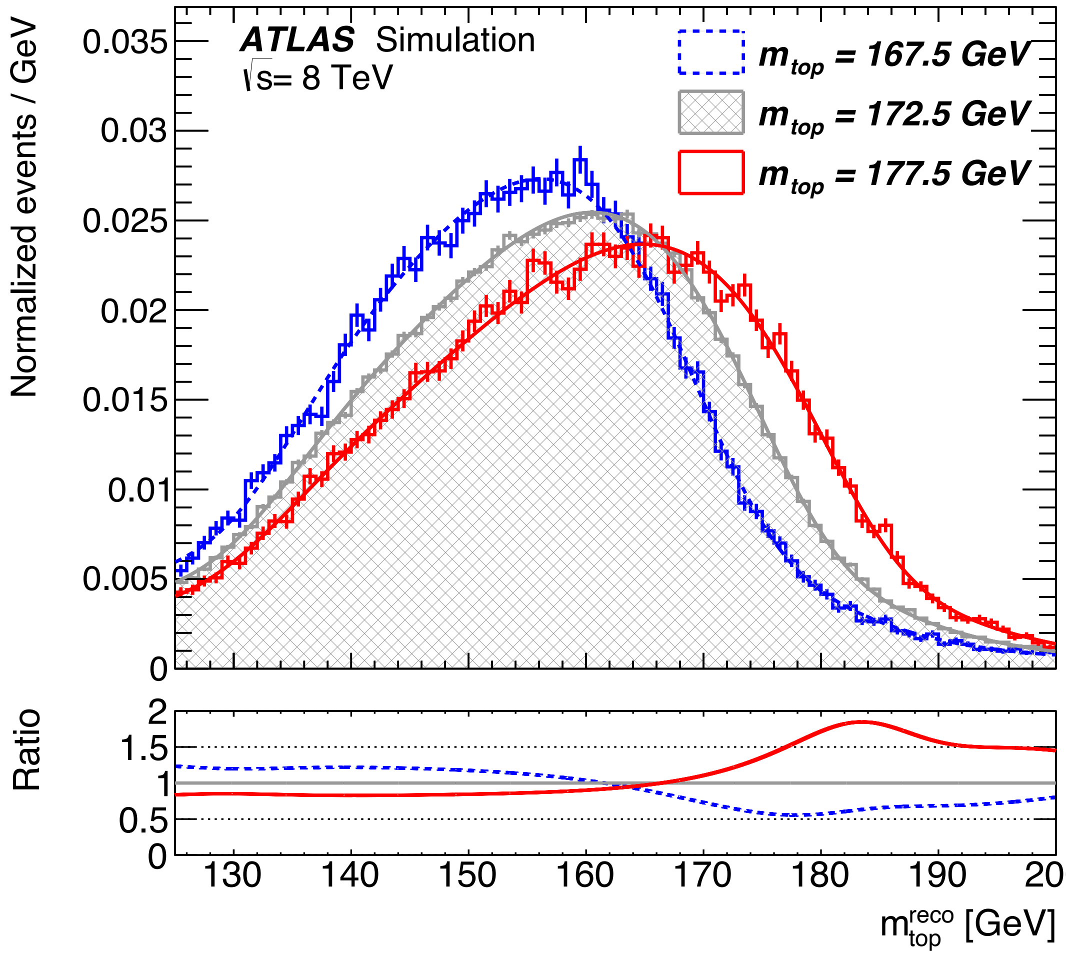
$$m_t^{\mathrm{MC}} = 172.26 \pm 0.61\,\mathrm{GeV}$$

CMS, 1812.06489



- Approach relies entirely on parton shower and models of hadronization and UE in Monte Carlo event generators: Theory uncertainty?

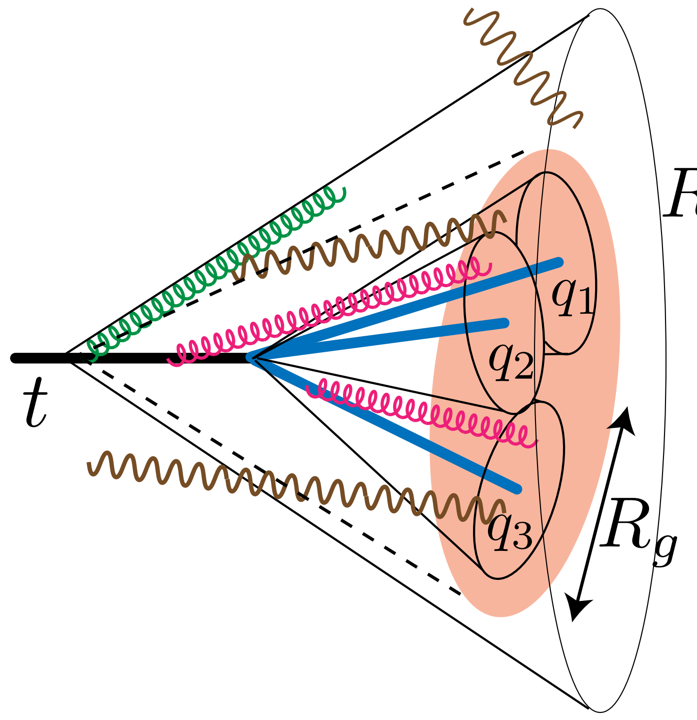


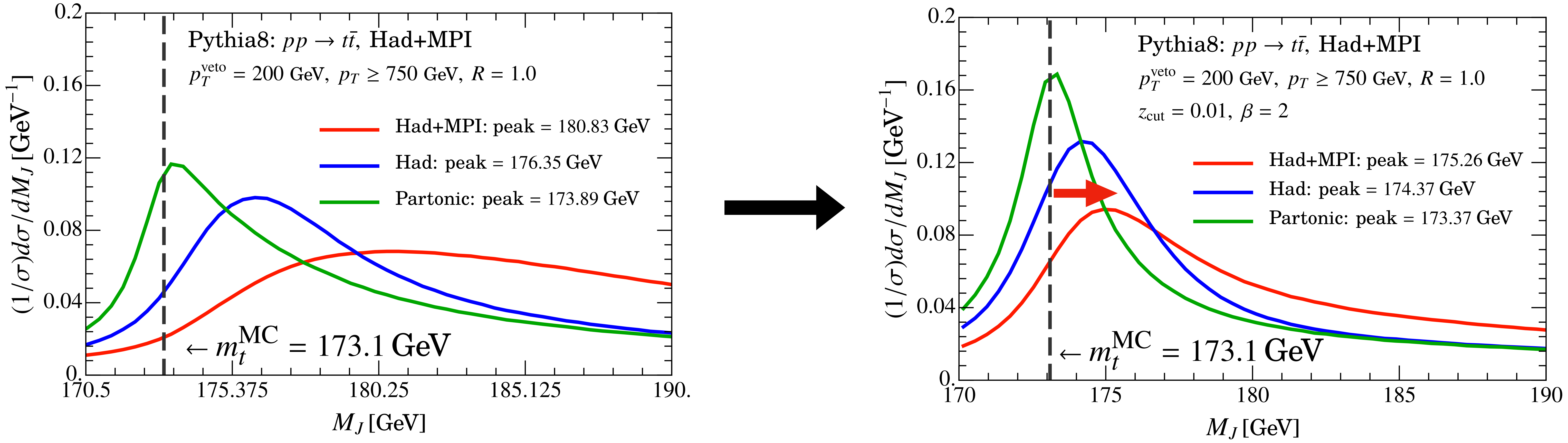


The top quark mass: groomed jet mass

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

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



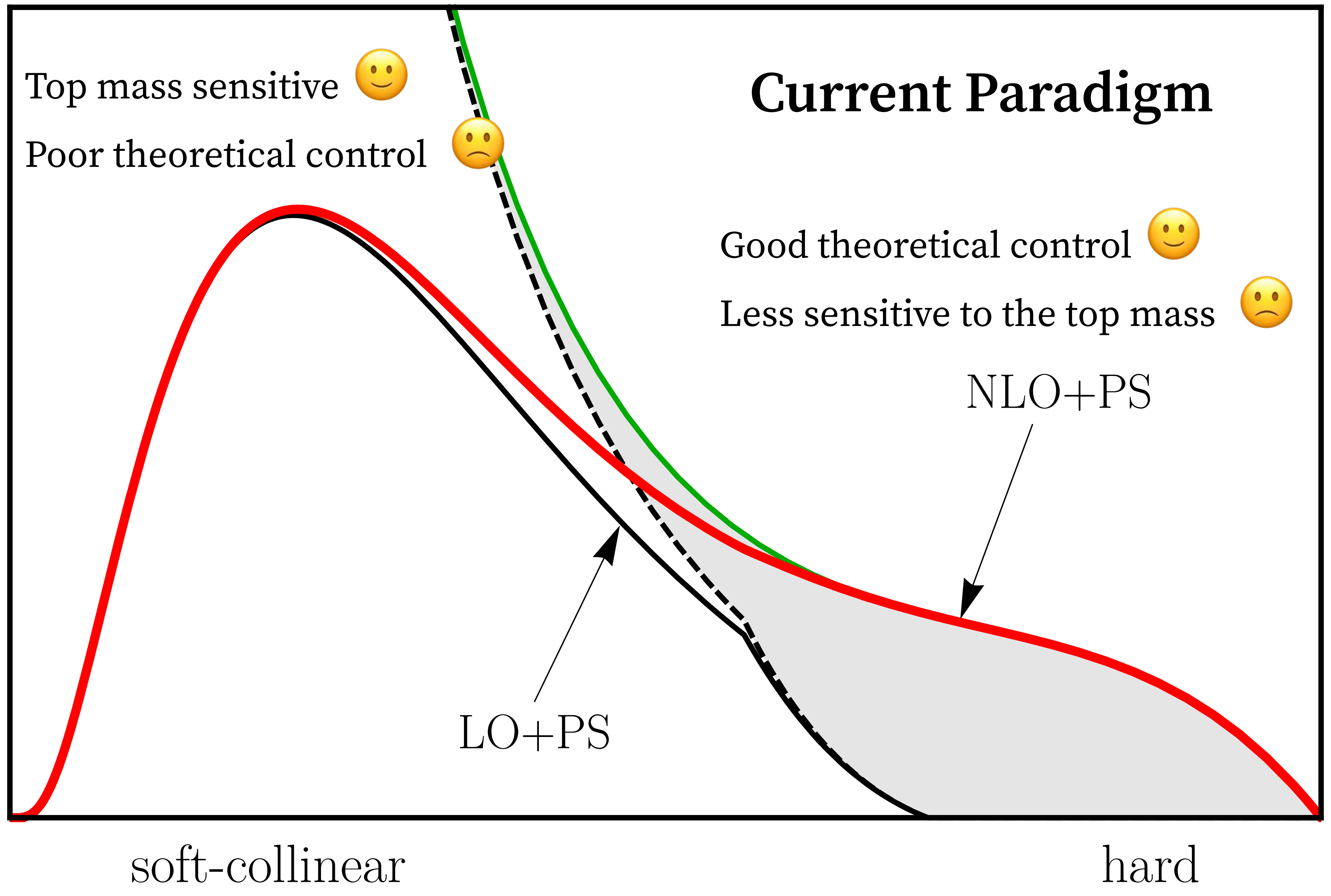


Even after grooming one needs to account for residual O(1 GeV) shifts

(1708.02586, 1906.11843, 2012.15568)

Summary of challenges in the current paradigm

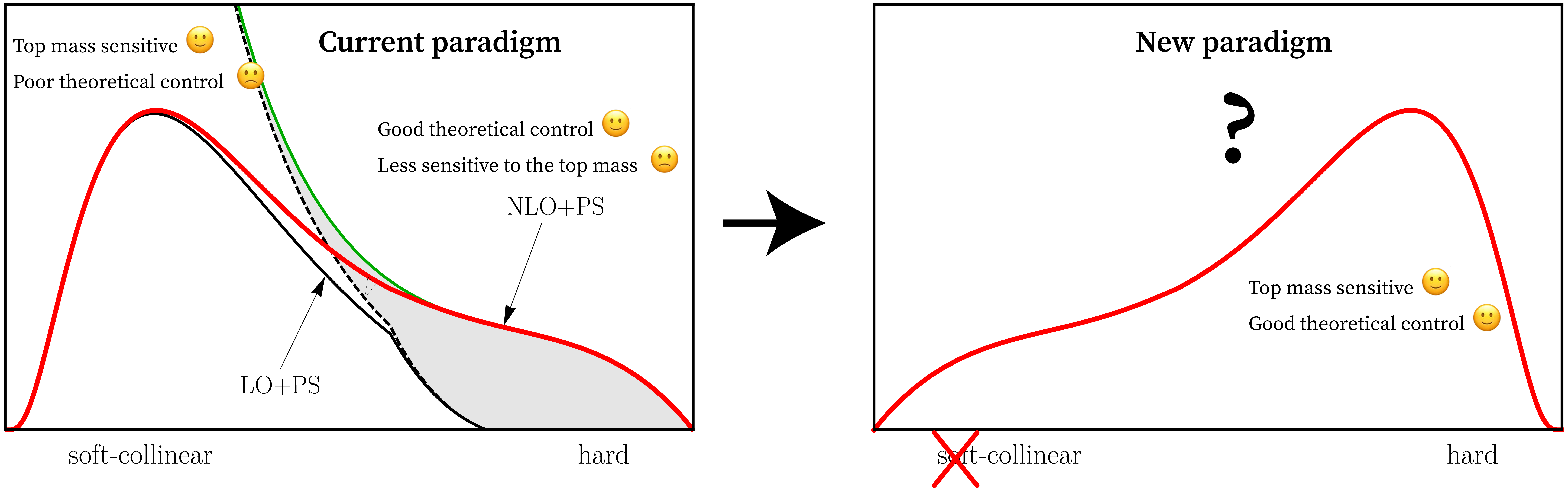
Generic kinematic distribution with a top-mass sensitive threshold structure:



2004.12915

Non-trivial task to improve the situation in the current paradigm!

New paradigm ?



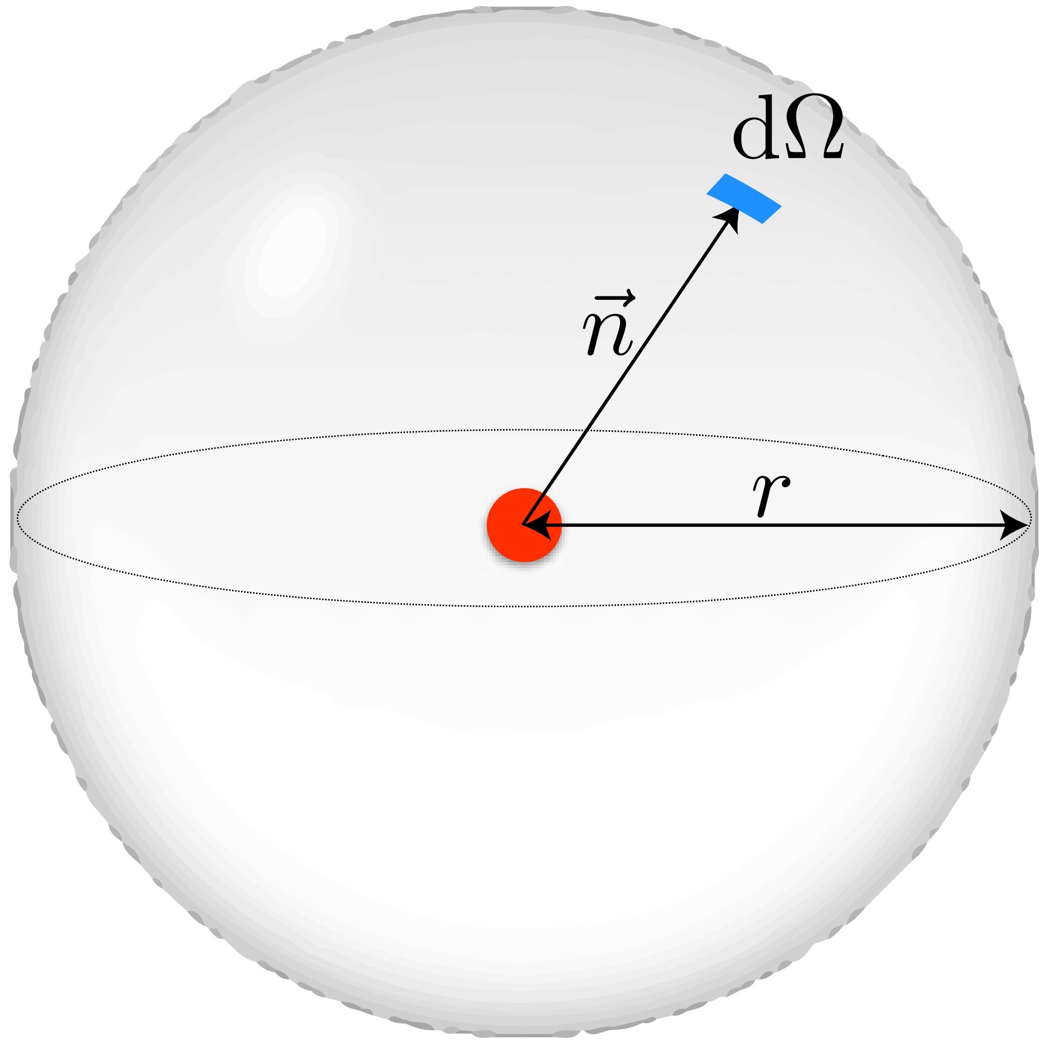
We explore the possibility to extract the top quark mass from the measurement of energy-weighted angular correlations of boosted top decay products

Energy flow operators and correlators

- Energy flow operator:

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

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



hep-ph/9512370, 0803.1467, 1309.0769, 1309.1424

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

Energy-energy correlator in e+e- collisions

PRL 41 (1978), PRD 19 (1979)

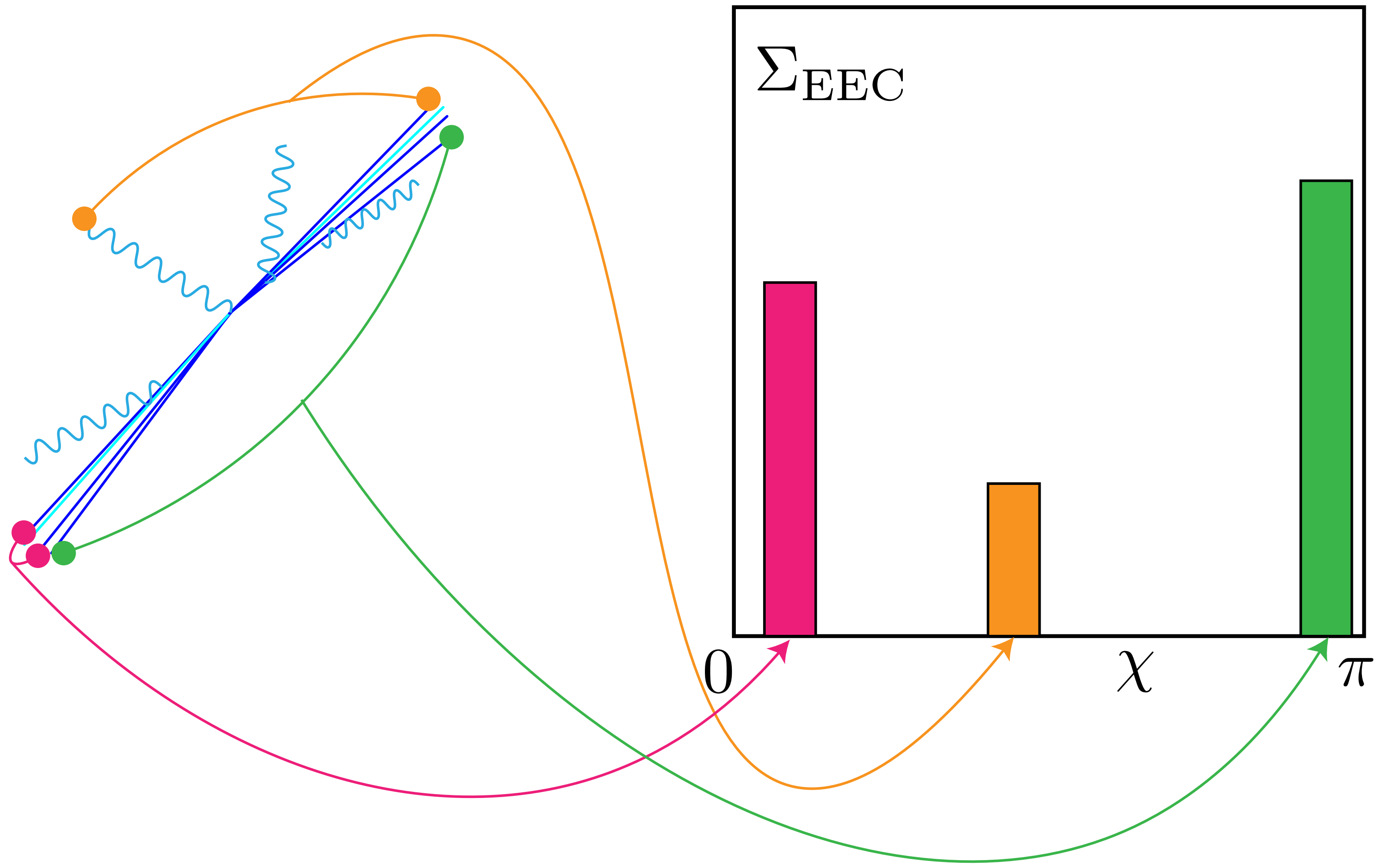
$$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle = \sum_{ij}\int \frac{\mathrm{d}\sigma_{ij}}{\mathrm{d}^2\vec{n}_i\mathrm{d}^2\vec{n}_j} E_i E_j \delta^2(\vec{n}_1-\vec{n}_i)\delta^2(\vec{n}_2-\vec{n}_j)$$

← two-particle inclusive QCD cross section

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

(weighted cross section)

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



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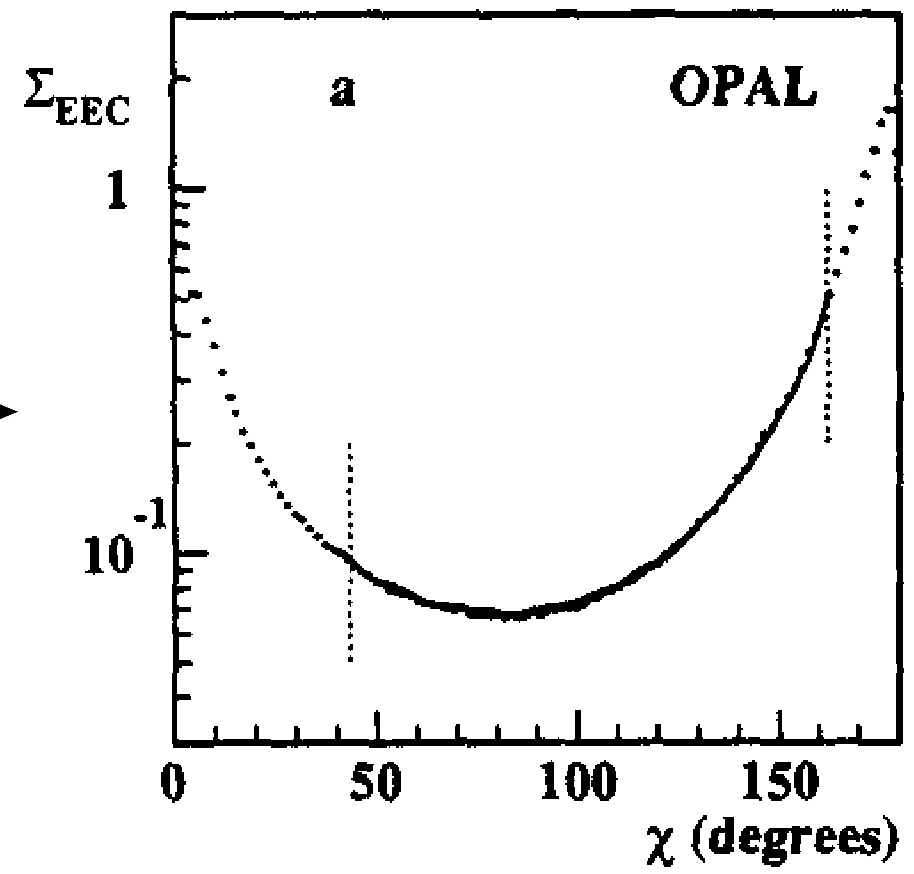


[Opal collboration, Z. Phys. C59 (1993) 21]

Strong coupling determination: 1804.09146, 1902.08158

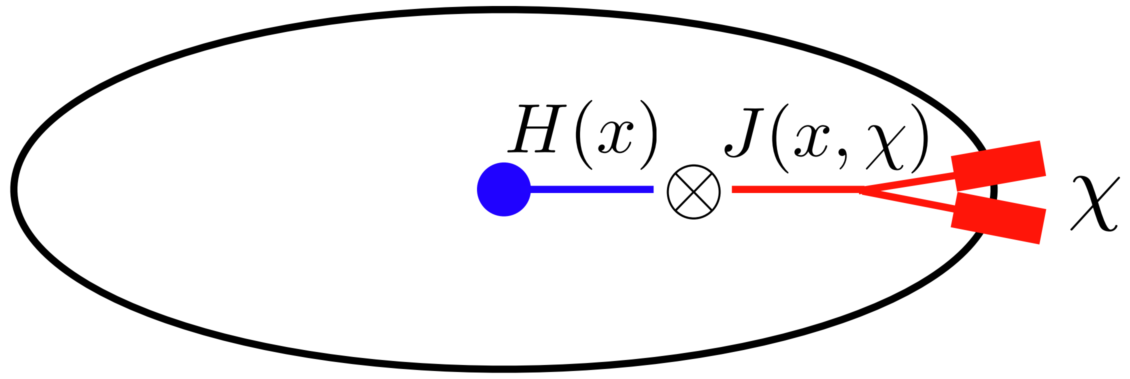
Energy correlators for jet substructure

- N-point energy correlators on jets: energy weighting naturally suppresses soft radiation without grooming, enabling novel precision calculations of LHC observables

2004.11381, 2011.02492, 2201.07800, 2205.03414

- Leading-power factorization theorems in the collinear limit

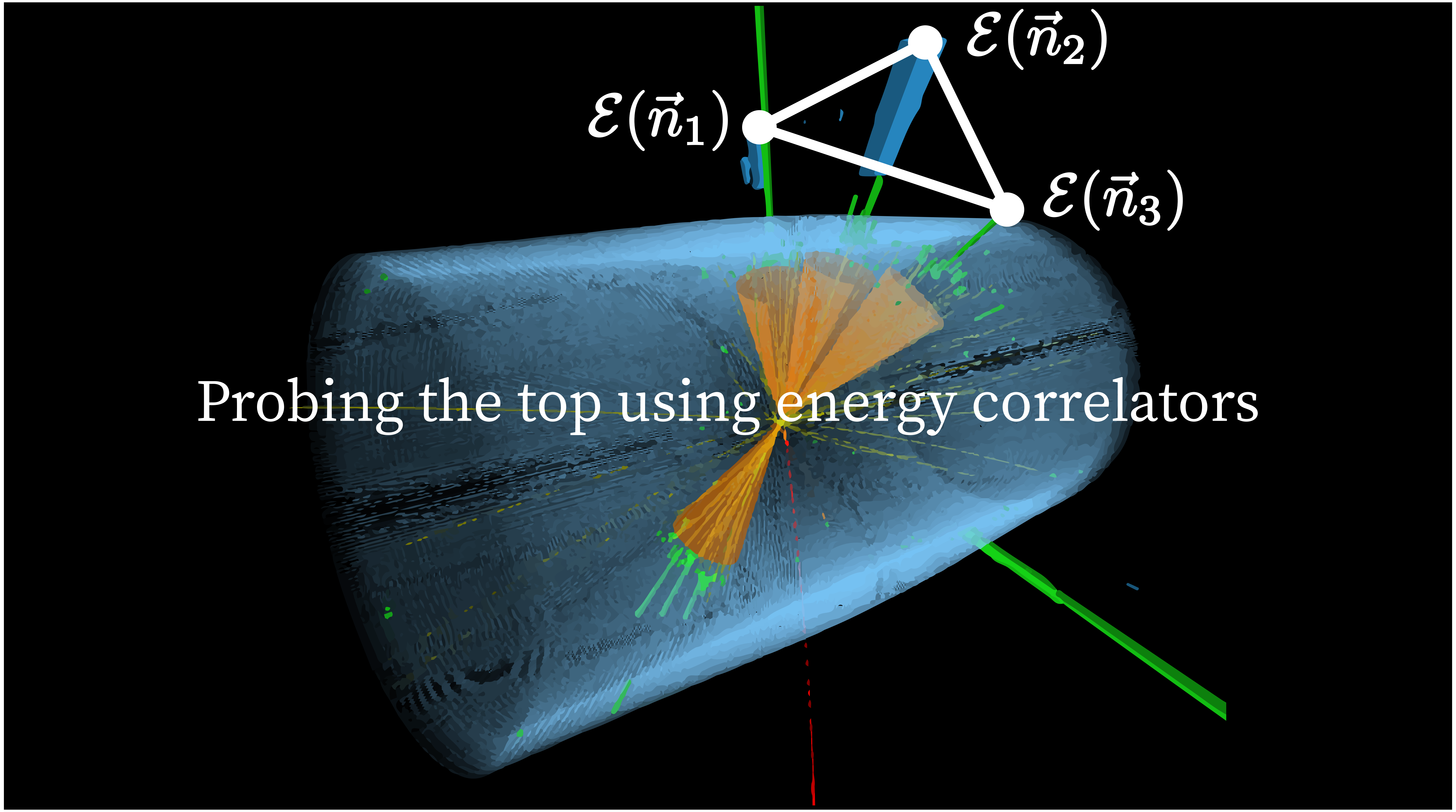
EEC observable:



1905.01310

- Straightforward to compute these observables on charged particles only and exploit the fine angular resolution of tracking detectors (energy weights get rescaled by moments of track functions 1303.6637, 1306.6630)

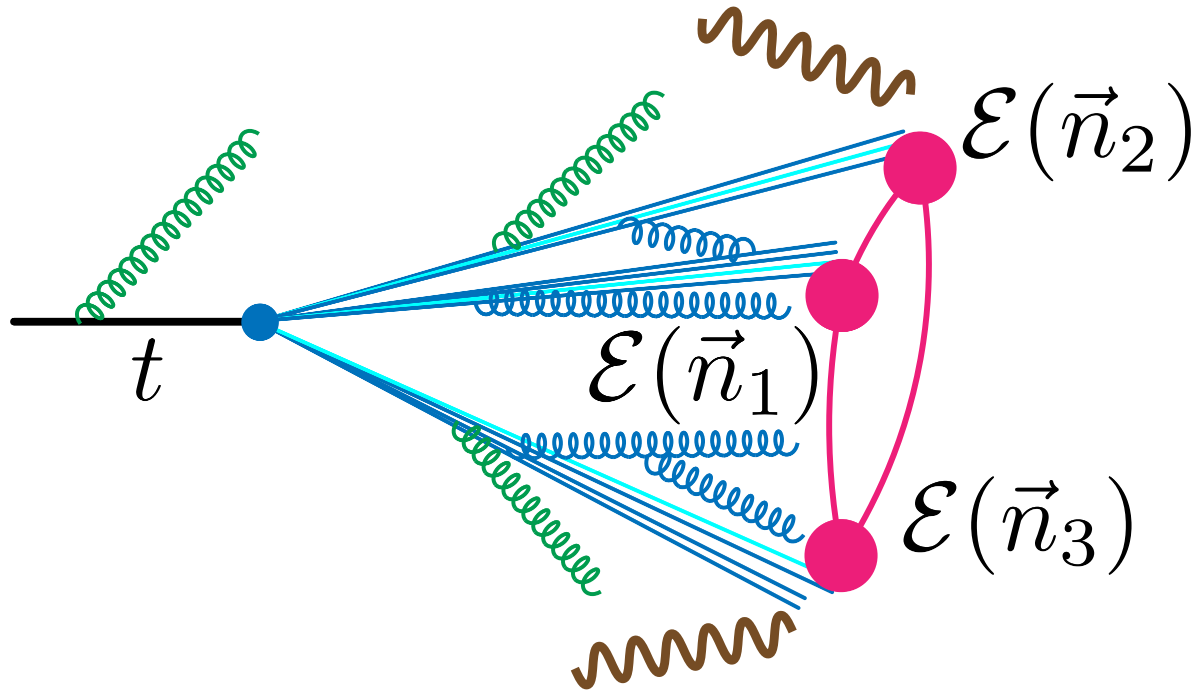
2108.01674, 2201.05166



Probing the top using energy correlators

EEC sensitivity to the top mass

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



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

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

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

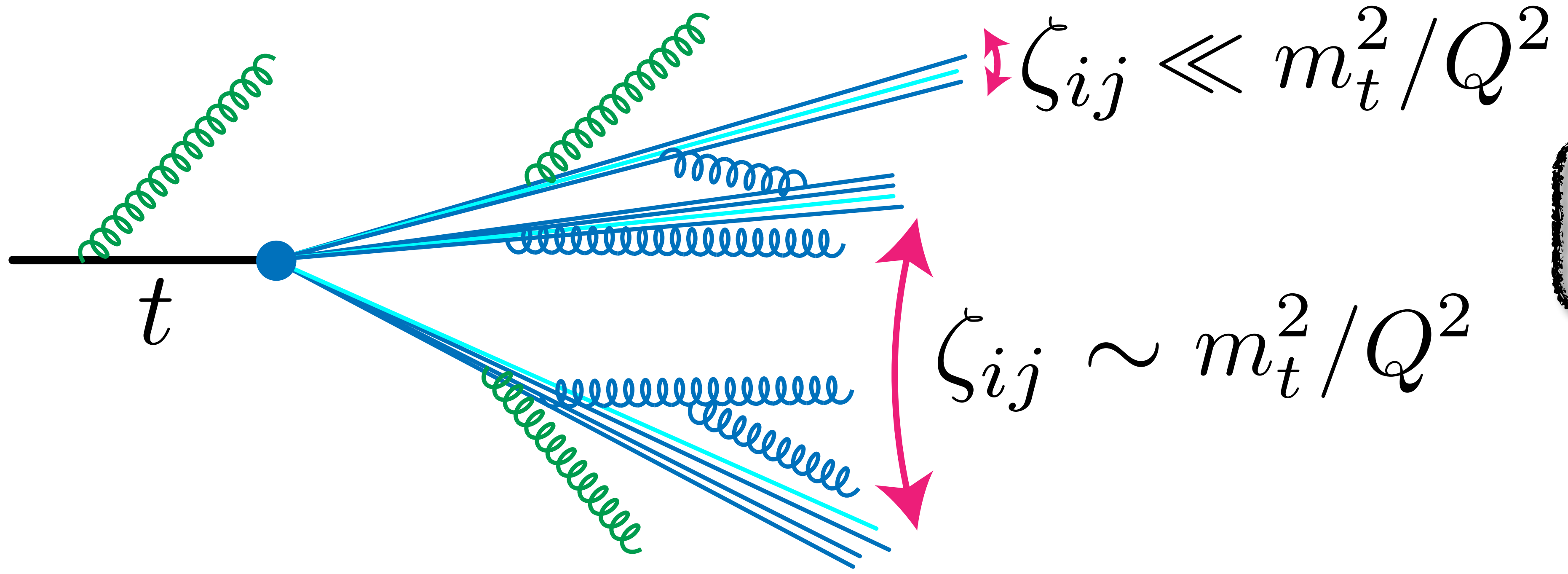
EEEC sensitivity to the top mass

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

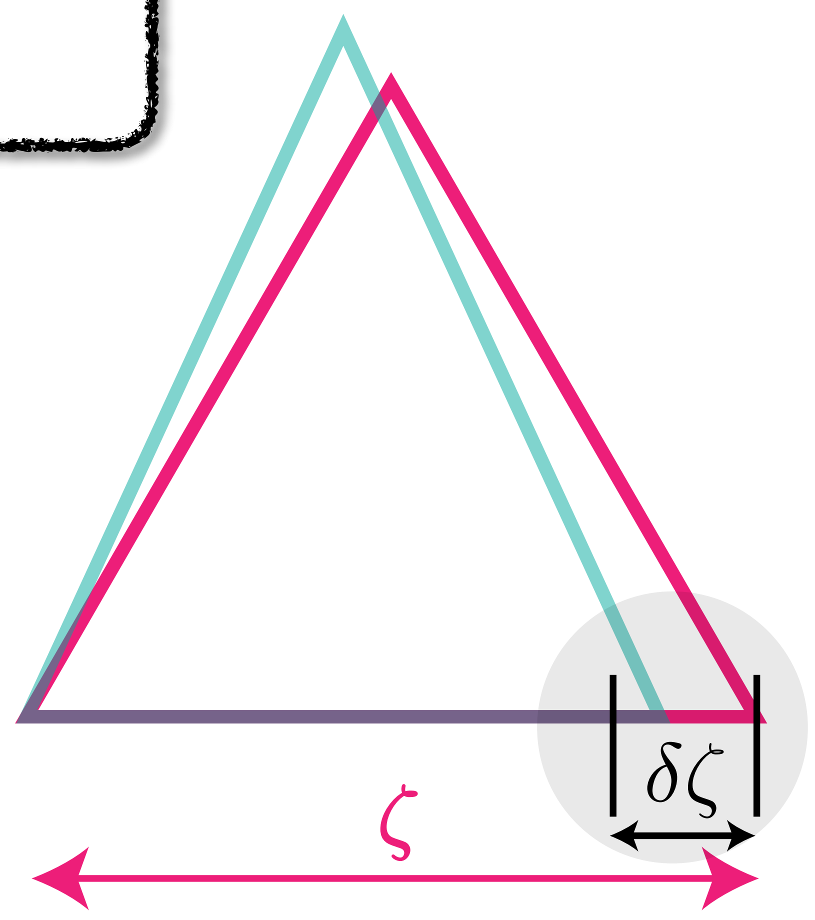
$$\frac{\mathrm{d}\Sigma(\delta\zeta)}{\mathrm{d}Q\mathrm{d}\zeta} = \int \mathrm{d}\zeta_{12}\mathrm{d}\zeta_{23}\mathrm{d}\zeta_{31} \int \mathrm{d}\sigma \widehat{\mathcal{M}}^{(n)}_{\triangle}(\zeta_{12},\zeta_{23},\zeta_{31},\zeta,\delta\zeta)$$

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

$$\times\ \delta(3\zeta-\zeta_{12}-\zeta_{23}-\zeta_{31}) \prod_{l,m,n\in\{1,2,3\}} \Theta(\delta\zeta-|\zeta_{lm}-\zeta_{mn}|)$$

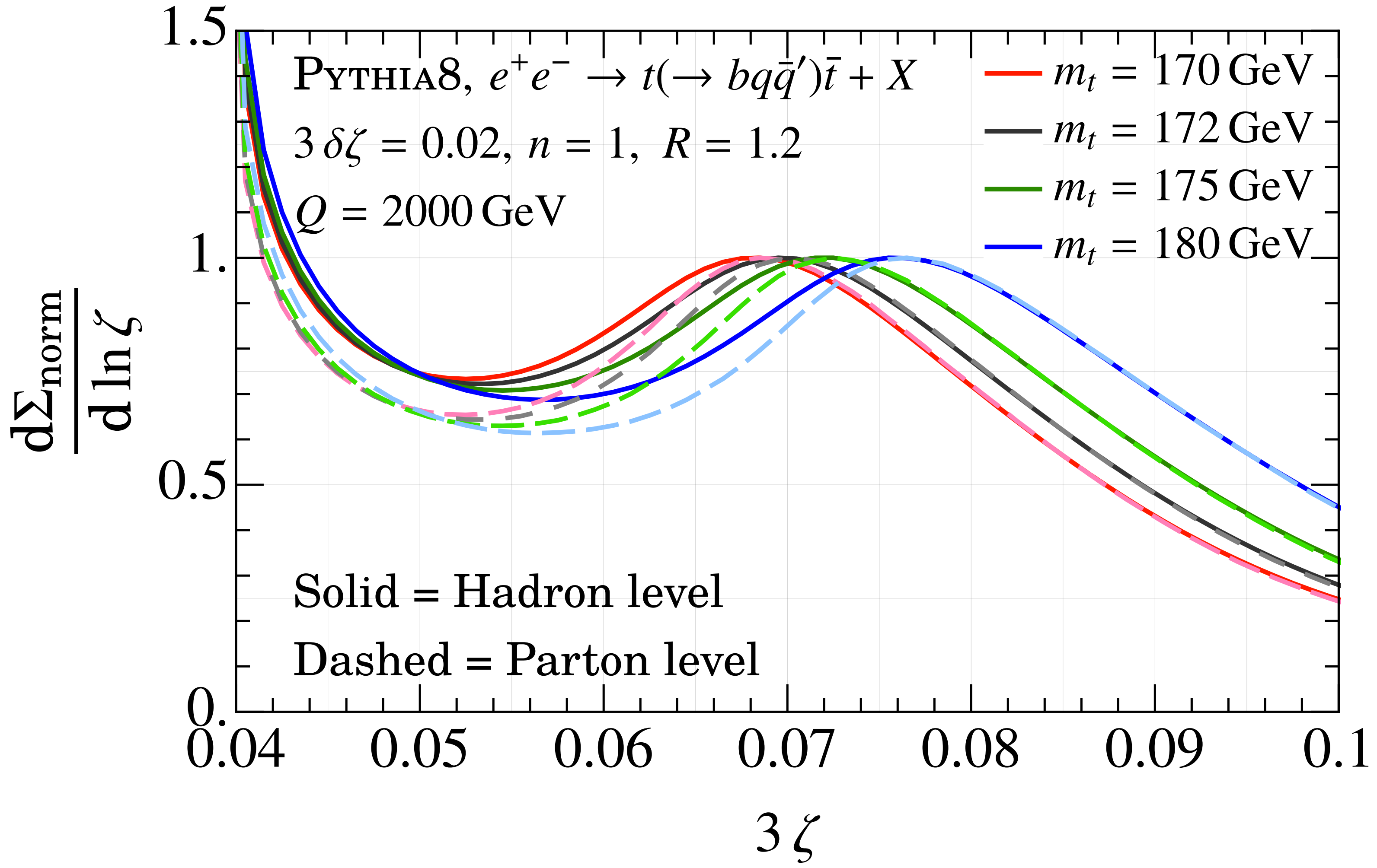


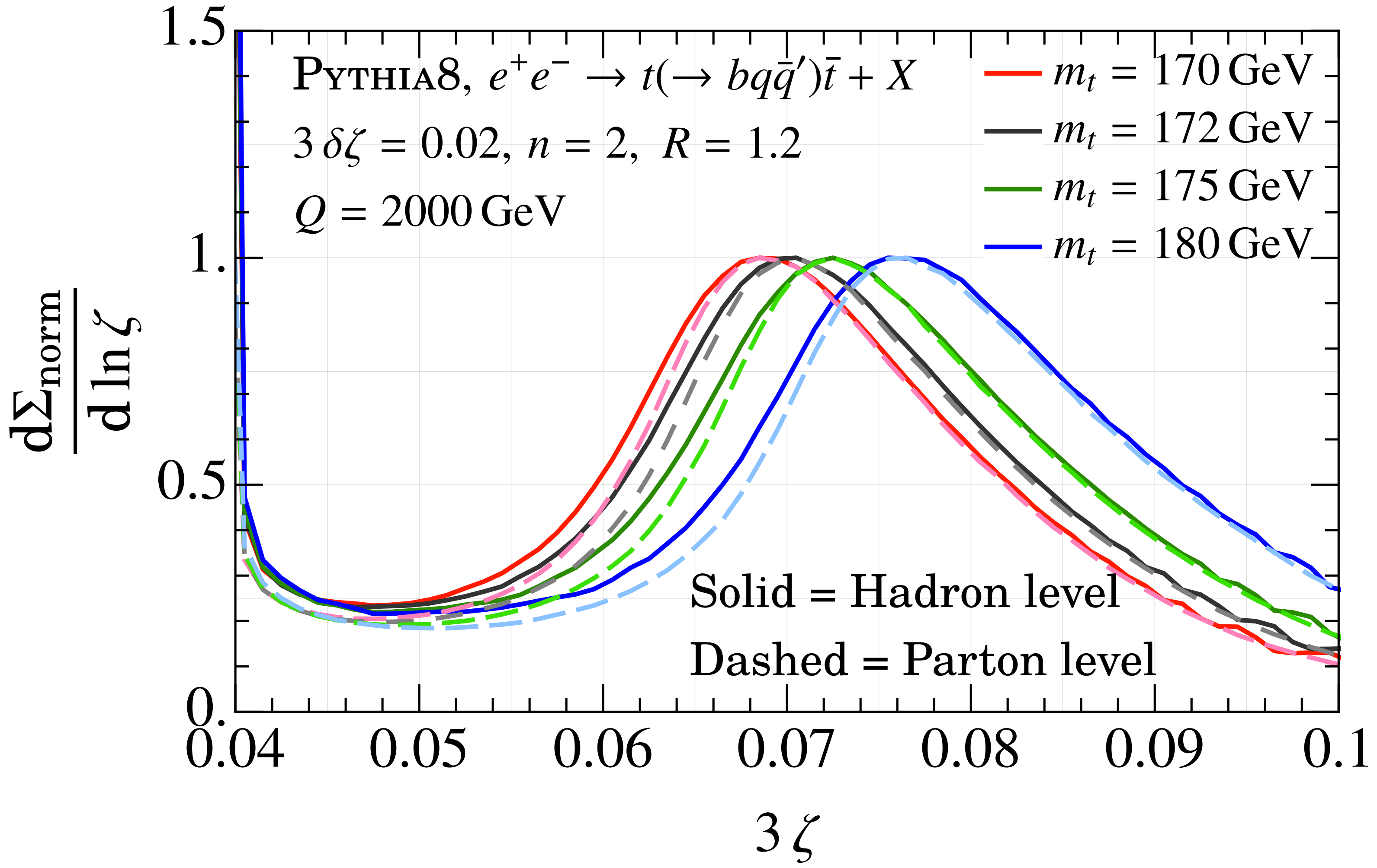
3-body hard kinematics: $\zeta_{\mathrm{peak}} \approx 3m_t^2/Q^2$

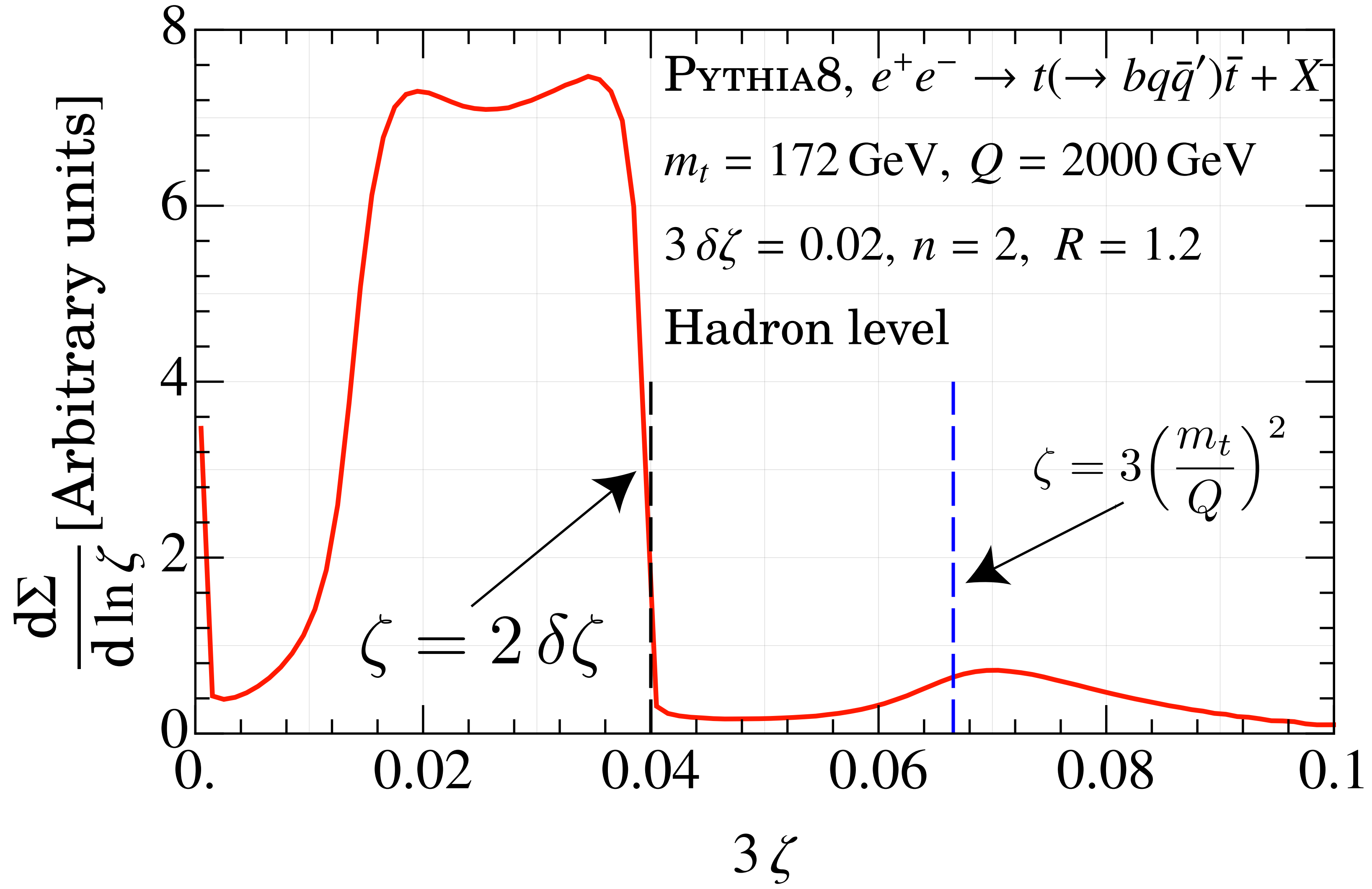


Top mass from EEEC in e+e- collisions (PYTHIA8)

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





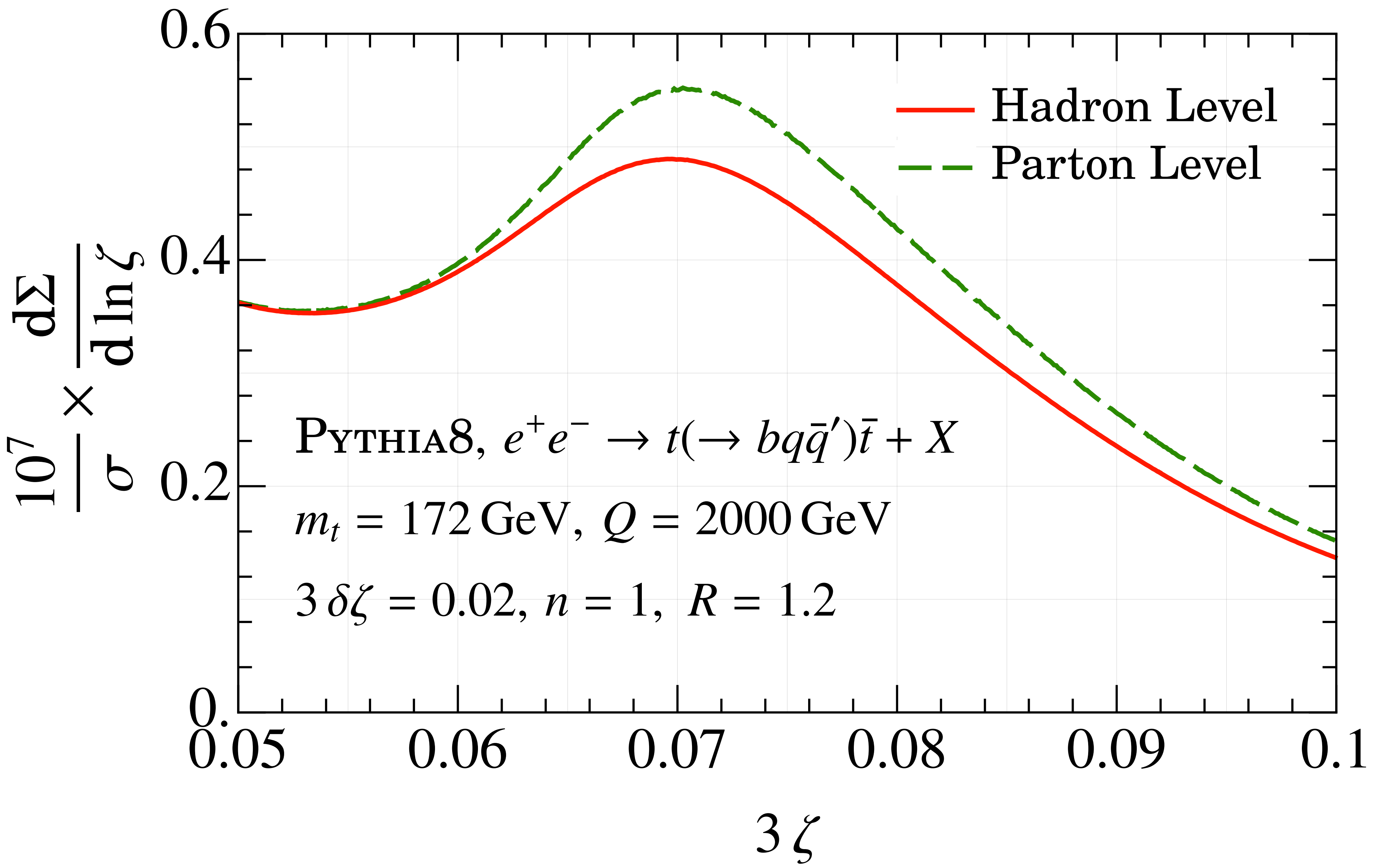


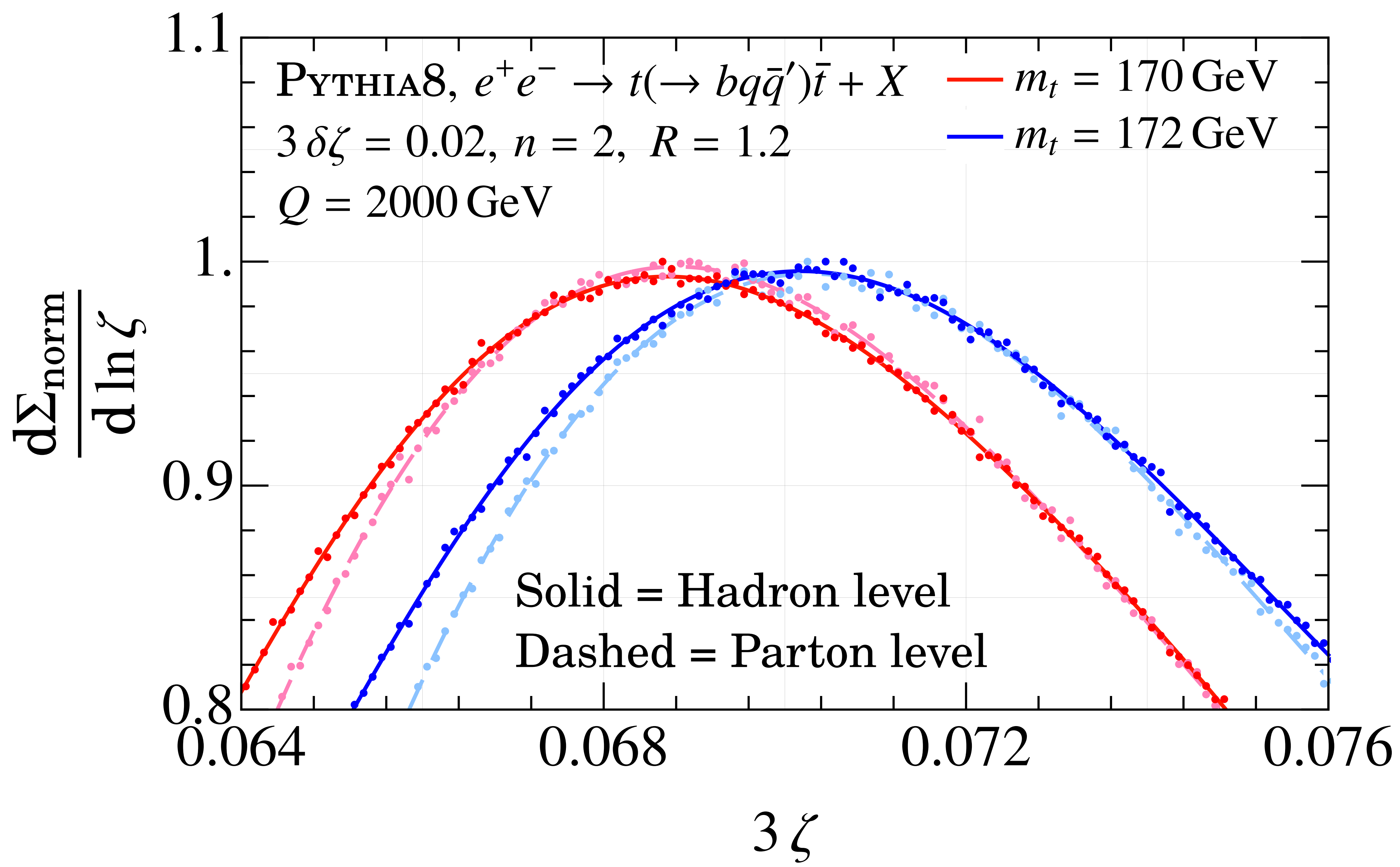
- Peak position dominantly determined by the hard process

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

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

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





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

Top mass from EEEC in pp collisions

- Boost-invariant measurement operator on a boosted top quark jet:

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

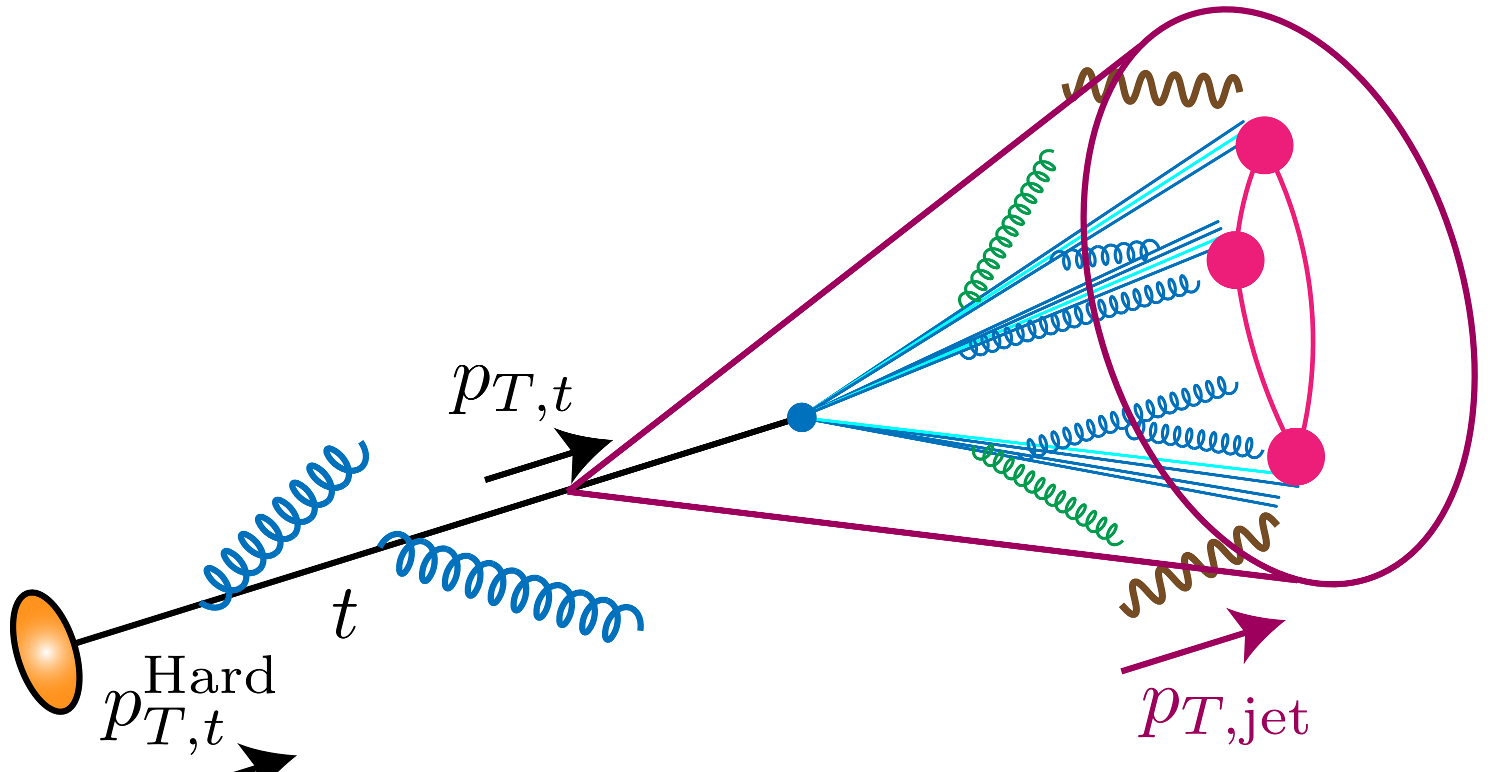
$$\hat{\zeta}^{(pp)}_{ij} = R_{ij} = \sqrt{\Delta\eta^2_{ij} + \Delta\phi^2_{ij}}$$

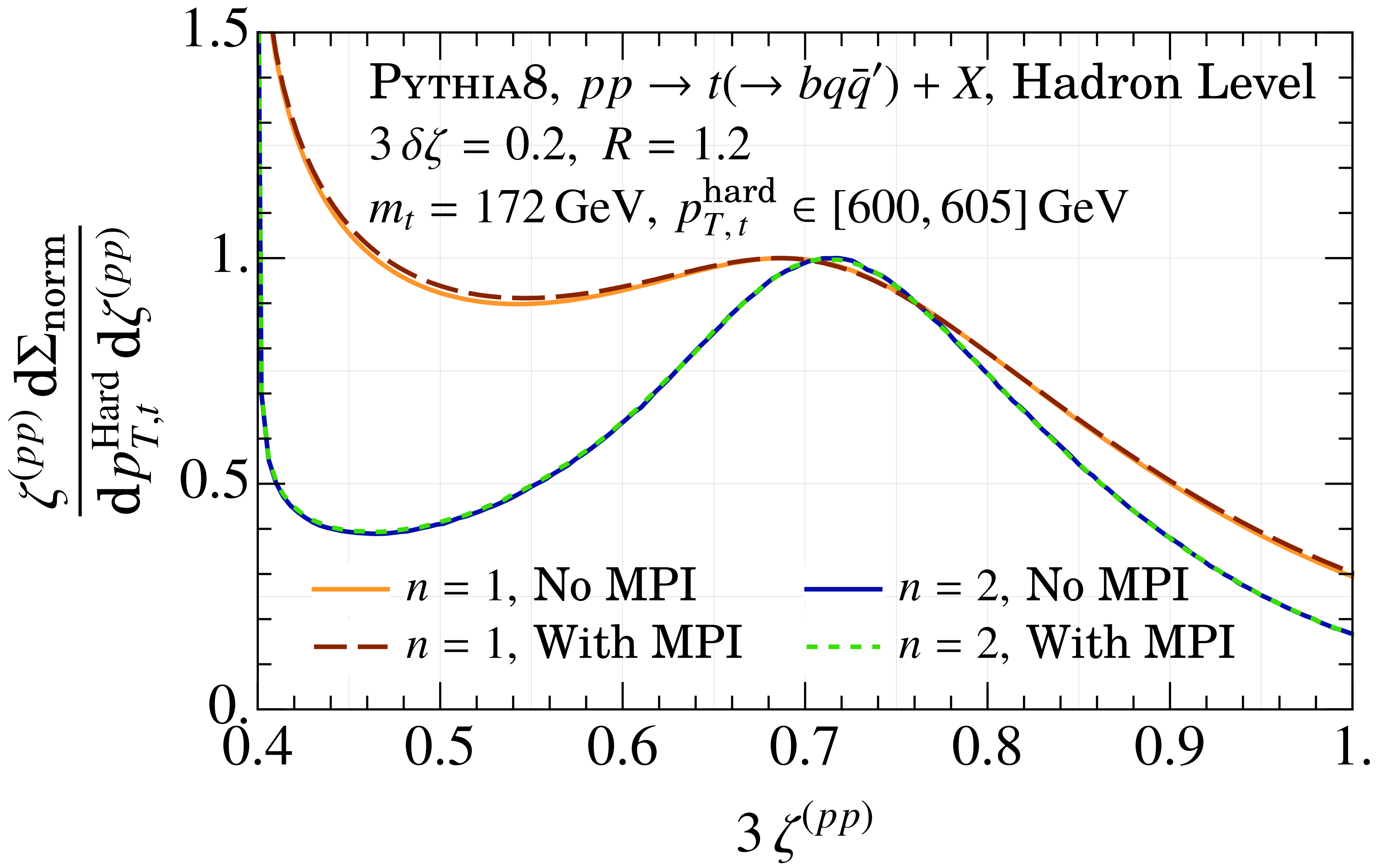
- The peak from hard kinematics is now at $\zeta^{(pp)}_{\text{peak}} \approx 3m_t^2/p_{T,t}^2$

- Performed a proof-of-concept analysis to show how the characterization of the top-jet pT-spectrum could allow us to extract the top mass

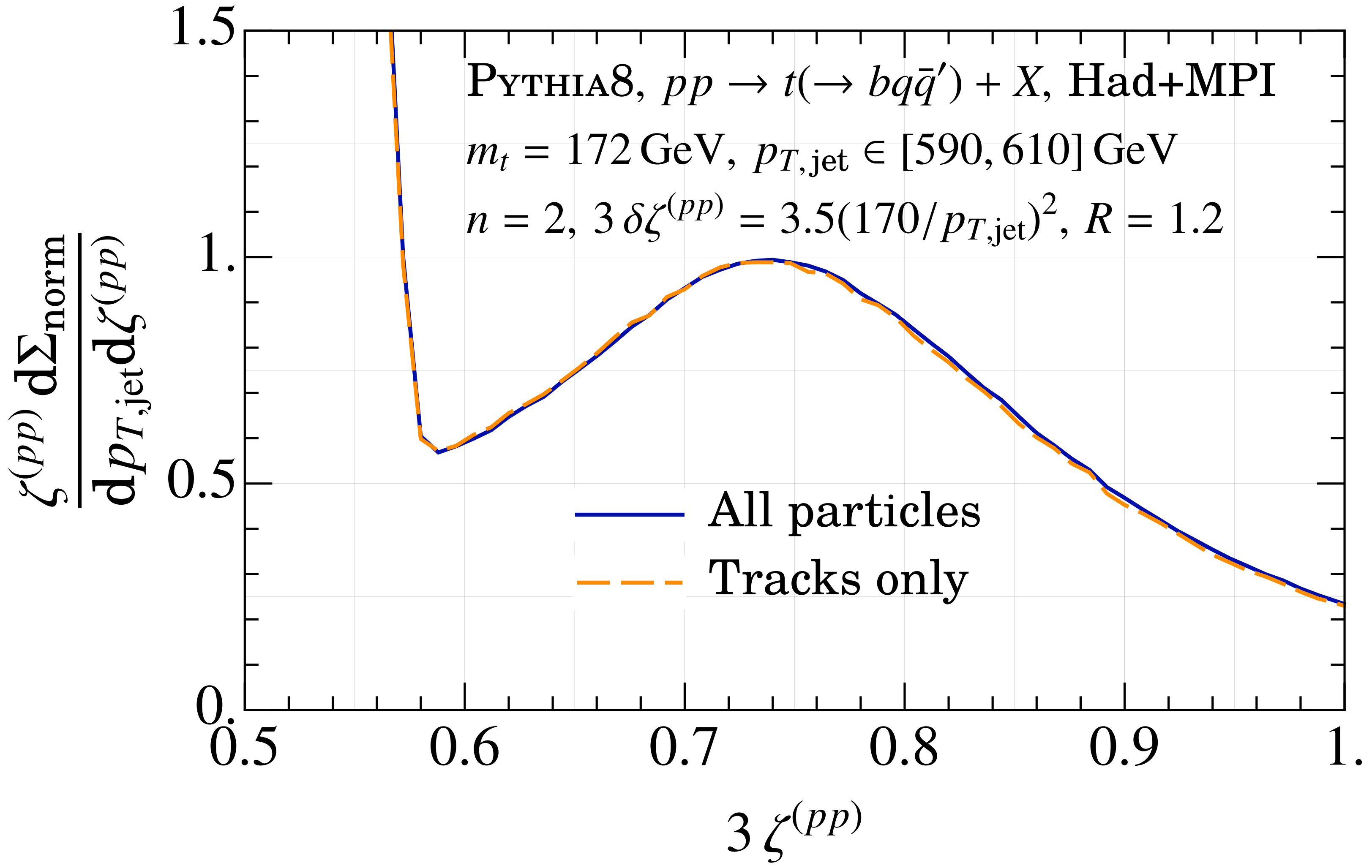
Top mass from EEEC in pp collisions: UE and tracks

- Measuring EEECs on top quarks with a fixed hard pT: insensitivity to UE contamination, even without grooming





- EEEC is also insensitive to the use of tracks:

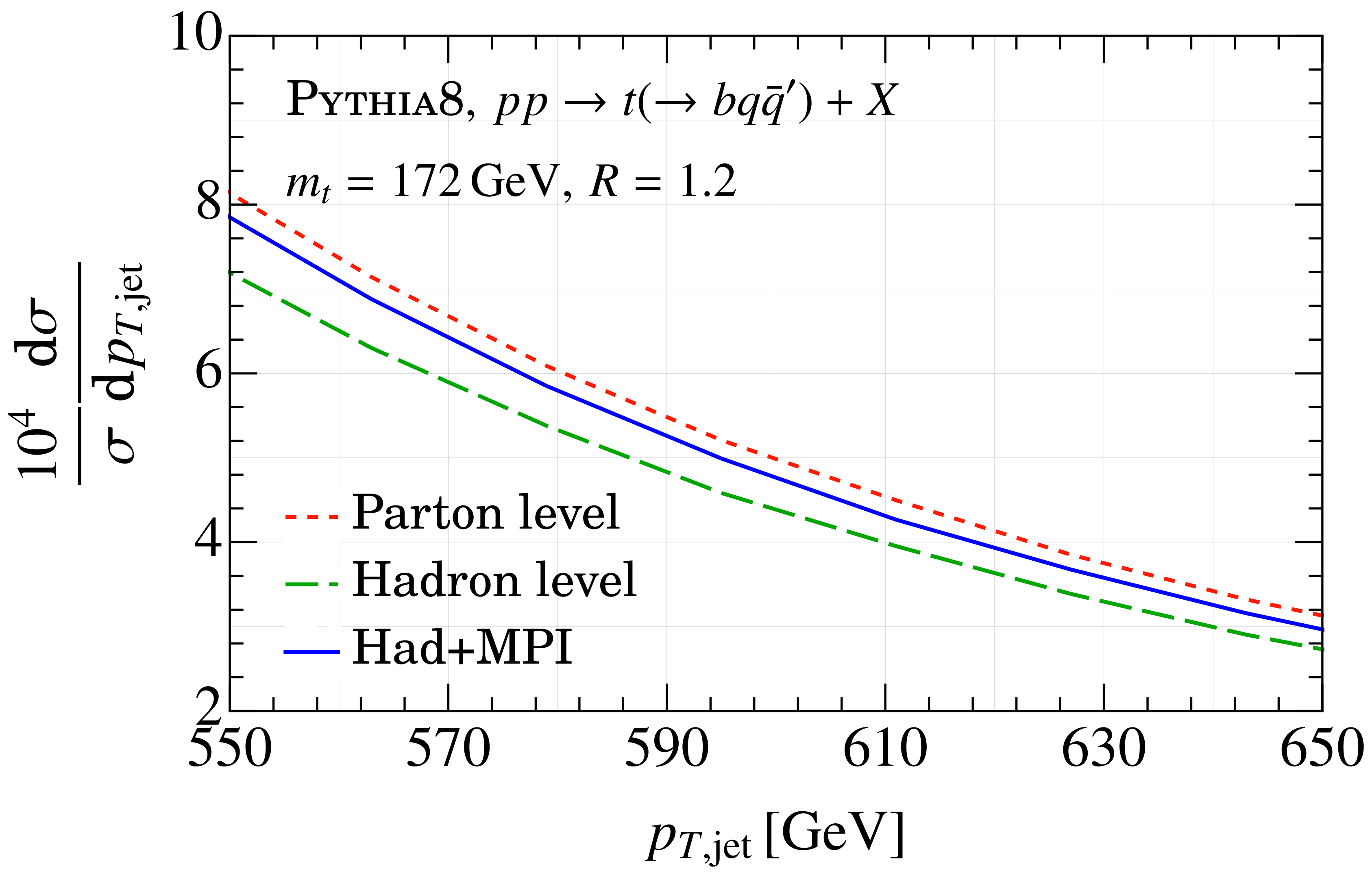


Top mass from EEEC in pp collisions: top-jet pT-spectrum

The peak position is parameterized by $\zeta_{\text{peak}}^{(pp)} = \dfrac{3F_{\text{pert}}(m_t, p_{T,\text{jet}}, \alpha_s, R)}{(p_{T,\text{jet}} + \Delta_{\text{NP}}(R) + \Delta_{\text{MPI}}(R))^2}$.

At leading order, $F_{\text{pert}} = m_t^2$.

We first determined the shifts due to hadronization and UE from an independent measurement of the top-jet pT-distribution using PYTHIA8:



shift due to hadronization $\approx 12\,\text{GeV}$

shift due to hadronization + UE $\approx 4\,\text{GeV}$

Top mass from EEEC in pp collisions: top-jet pT-spectrum

The peak position is parameterized by $\zeta^{(pp)}_{\text{peak}} = \dfrac{3F_{\text{pert}}(m_t, p_{T,\text{jet}}, \alpha_s, R)}{(p_{T,\text{jet}} + \Delta_{\text{NP}}(R) + \Delta_{\text{MPI}}(R))^2}$.

At leading order, $F_{\text{pert}} = m_t^2$.

We then determined $\sqrt{F_{\text{pert}}}$ from a fit looking at the peak positions $\zeta^{(pp)}_{\text{peak}}$ in different $p_{T,\text{jet}}$ bins. As a proxy for a perturbative calculations we used parton-level data to extract $\sqrt{F_{\text{pert}}}$

PYTHIA8 m_t	Parton $\sqrt{F_{\text{pert}}}$	Hadron + MPI $\sqrt{F_{\text{pert}}}$
172 GeV	172.6 ± 0.3 GeV	$172.3 \pm 0.2 \pm 0.4$ GeV
173 GeV	173.5 ± 0.3 GeV	$173.6 \pm 0.2 \pm 0.4$ GeV
175 GeV	175.5 ± 0.4 GeV	$175.1 \pm 0.3 \pm 0.4$ GeV
$173 - 172$	0.9 ± 0.4 GeV	1.3 ± 0.6 GeV
$175 - 172$	2.9 ± 0.5 GeV	2.8 ± 0.6 GeV

Consistency between the two approaches with differences smaller than/about 1 GeV

Future improvements

- Factorization theorem:

$$\frac{\mathrm{d}\Sigma}{\mathrm{d}p_{T,\mathrm{jet}}\mathrm{d}\eta\,\mathrm{d}\zeta} = f_i \otimes f_j \otimes H_{i,j\to t}\left(z_J; p_{T,t} = \frac{p_{T,\mathrm{jet}}}{z_J}, \eta\right) \otimes J_{t\to t}(z_J, z_h; R) \otimes J_{\mathrm{EEEC}}^{[\mathrm{tracks}]}(n, z_h, \zeta; m_t; \Gamma_t)$$

- Using the equilateral configuration we projected onto the top peak. However, also the W mass imprints itself in the correlator, in a different region of parameter space. Goal: trade the dependence of the EEEC measurement on the top-jet pT-spectrum for the dependence on the W mass

Summary

- Triple correlators of energy flow operators measured on boosted top jets: enhanced top-mass sensitivity in the hard region and natural suppression of soft radiation effects, hadronization and UE contamination

- Our first analysis based on simulations using PYTHIA8 motivates further studies to optimize EC-based strategy for top mass extraction with improved theoretical control

Goal: