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Precision Top Mass Measurements via Energy Correlators

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Based on arXiv:2311.02157, arXiv: 2407.12900 and arXiv:25xx.xxxxx

Milano Bicocca 13/01/25

Outline

(1) Why study the top mass?

(2) Energy correlators on boosted top jets.

(3) The standard candle.

(4) Experimental feasibility and event generator studies.

(5) A test case: energy correlators on boosted Z-jets.

Why study the top mass?

The current world average quoted in the PDG is [1]

$$m_t^{\mathrm{MC}} = 172.69 \pm 0.3 \ \mathrm{GeV}.$$

The high-lumi projection is for the uncertainty to be reduced to $\sim 0.2 \ \mathrm{GeV}$.

This is impressively accurate! Yet, the top mass is still a limiting factor for many studies, from SM vacuum stability to BSM fits.

A part of this issue is a conceptual problem. What is m_t^{MC} ?

Simulating the top as an on-shell particle with a definite mass and a PS cut-off can mishandle long-distance effects Hoang '20 [2]. There are debates over the size of an additional uncertainty this should introduce.

Why study the top mass?

Demonstrating this ambiguity, the top is the only quark with 3 quoted masses in the PDG [1]:

Cross section measurements: $m_t^{\overline{\mathrm{MS}}} = 162.5 \pm 2.1\ \mathrm{GeV}$

Direct measurements: $m_t^{\mathrm{MC}} = 172.69 \pm 0.3\ \mathrm{GeV}$

Pole measurements: $m_t^{\mathrm{pole}} = 172.5 \pm 0.7\ \mathrm{GeV}$

At its core, the problem reduces to picking a suitable renormalisation scheme for the mass measurement.

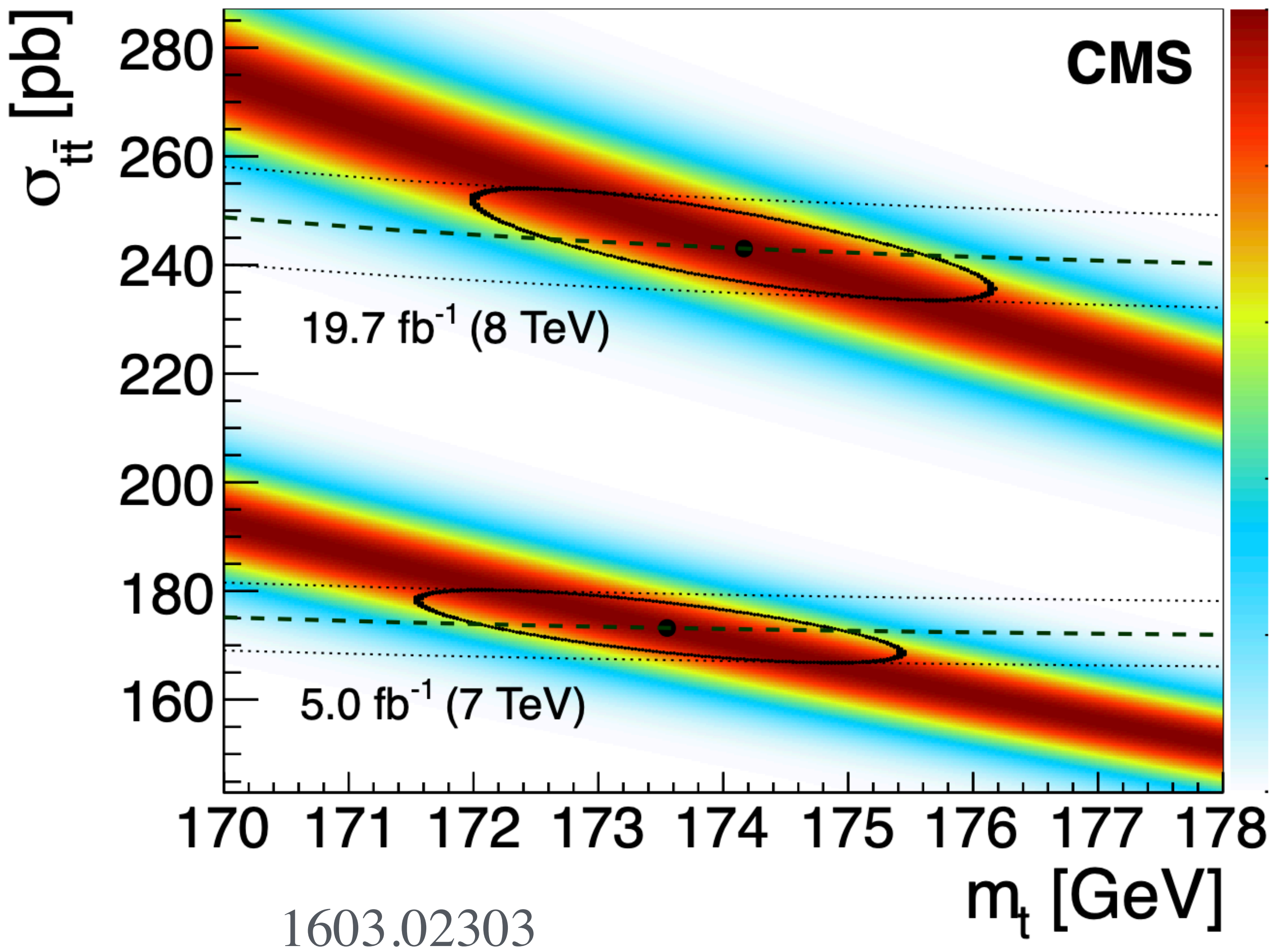
The Lagrangian mass should be defined in a sensible perturbative scheme, such as $\overline{\mathrm{MS}}$ or an MSR scheme. However, the at low scales the top mass suffers a non-perturbative (renormalon) ambiguity [2]. This ambiguity introduces an inherent theoretical uncertainty into the Pole/MC mass measurements.

Why study the top mass?

Cross section measurements

Under the best theoretical control are cross section measurements. These can be computed at high accuracy (for instance NNLO+NNLL, M. Czakon, A. Mitov [3]) and, depending on the approach taken, a suitable renormalisation scheme can be used ($\overline{\mathbf{MS}}$, $\mathbf{MSR}$ or Pole).

However, these are indirect measurements, with no explicit feature to fit.



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$\Delta m_t^{\text{Cross section}} \sim 2\ \mathbf{GeV}$ CMS '18, ATLAS '19 [4]

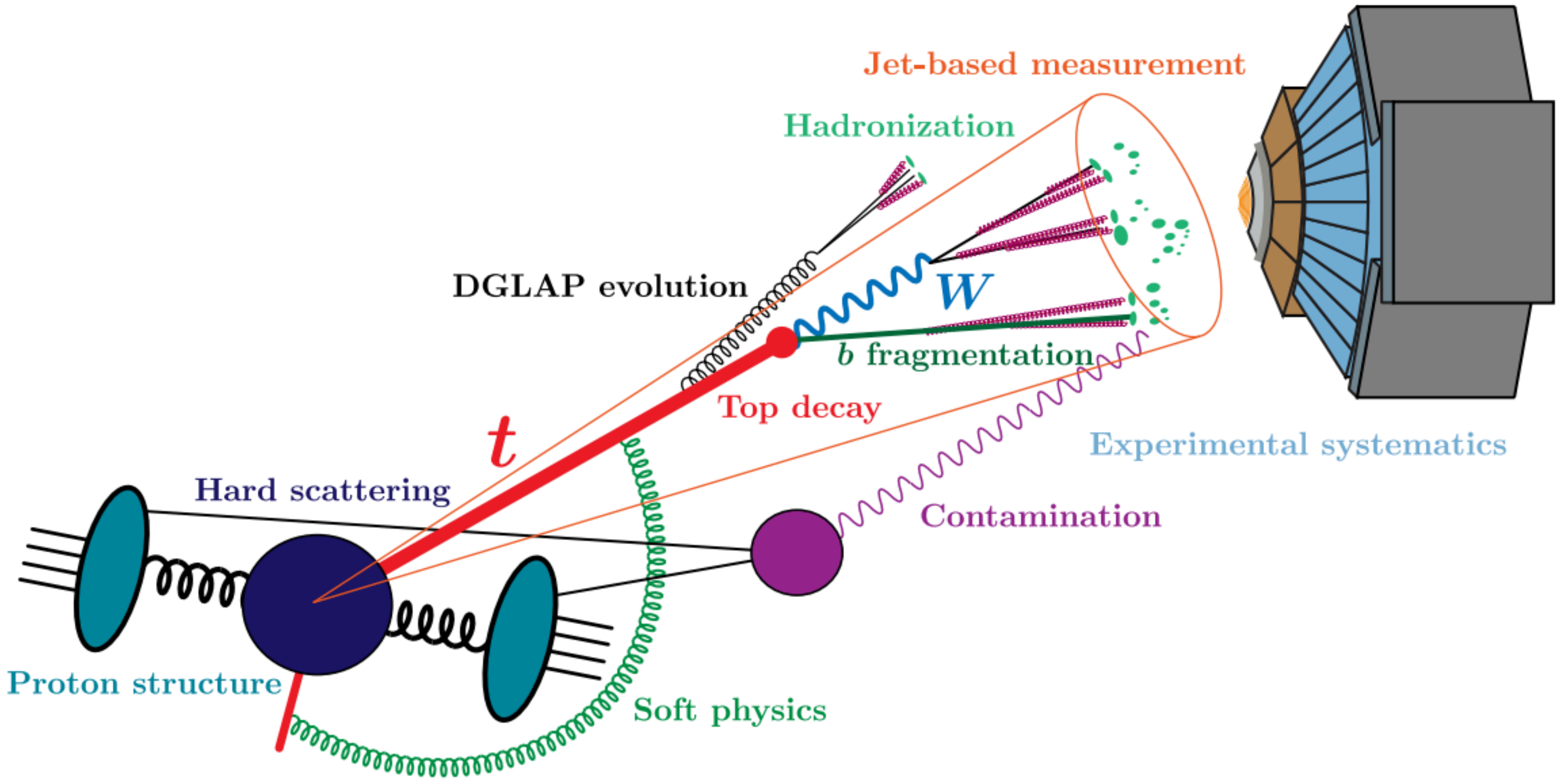
Uncertainties dominated by PDFs.

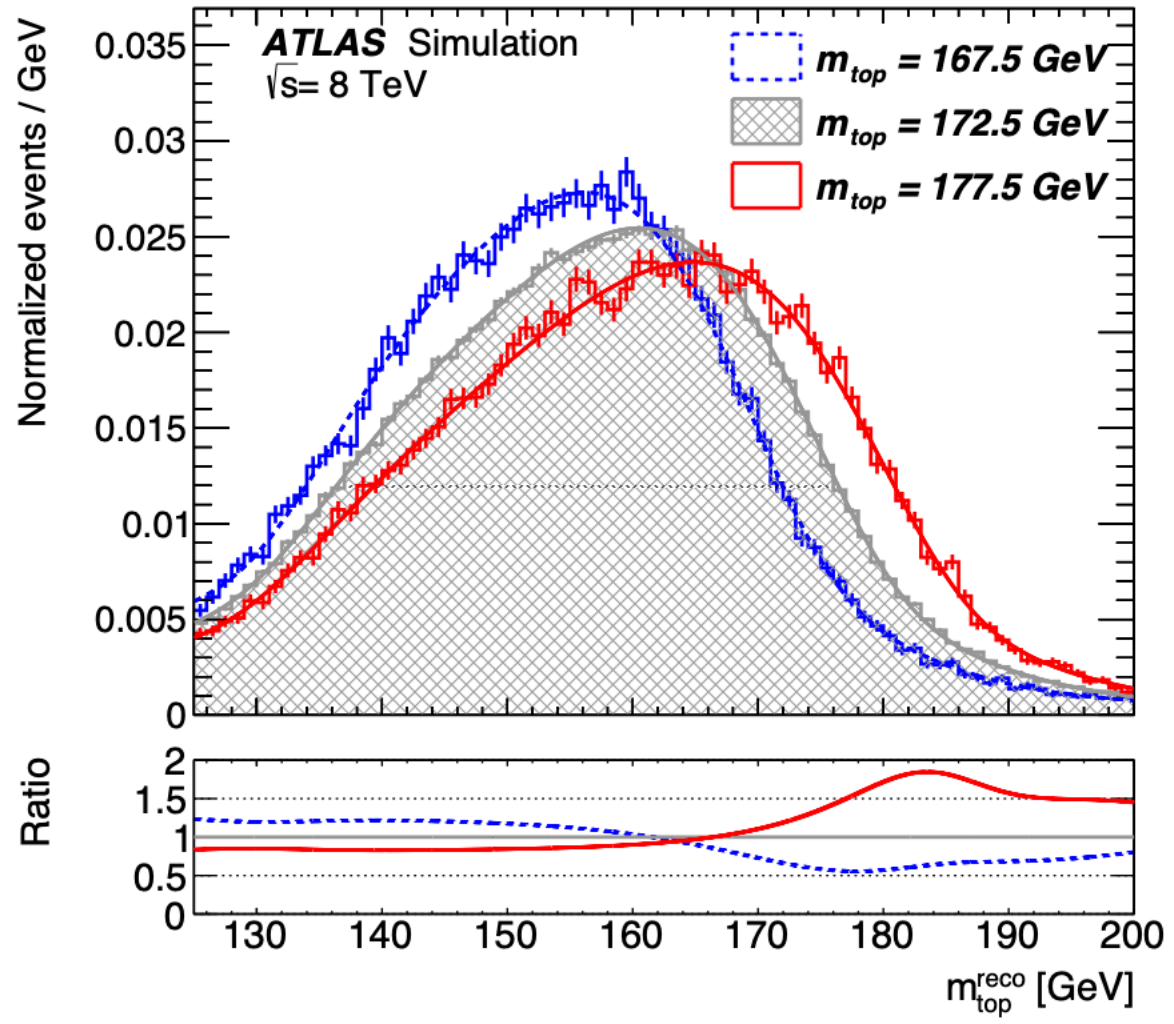
Why study the top mass?

Direct measurements

Under much better experimental control are direct measurements, i.e. $m_t^{\mathrm{MC}} = 171.77 \pm 0.37\ \mathrm{GeV}$ CMS '23 [5]. These use the top decay kinematics to reconstruct the top resonance or threshold giving experimentally robust features to fit.

They intrinsically rely on Event generators due to the extreme complexity of the measurement.





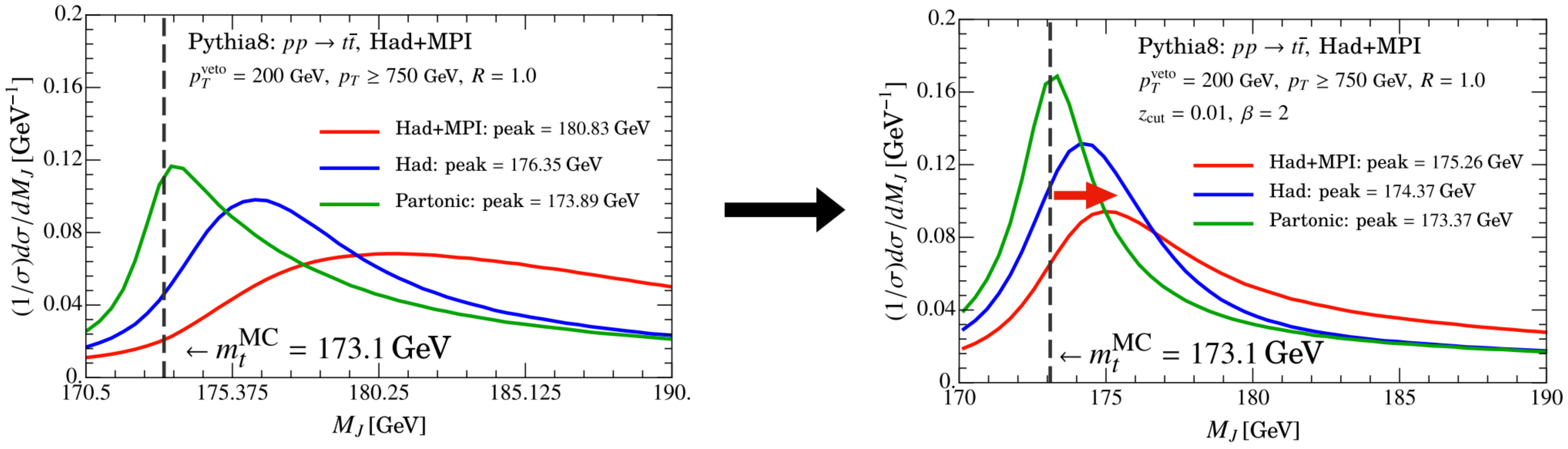
Why study the top mass?

The groomed jet mass

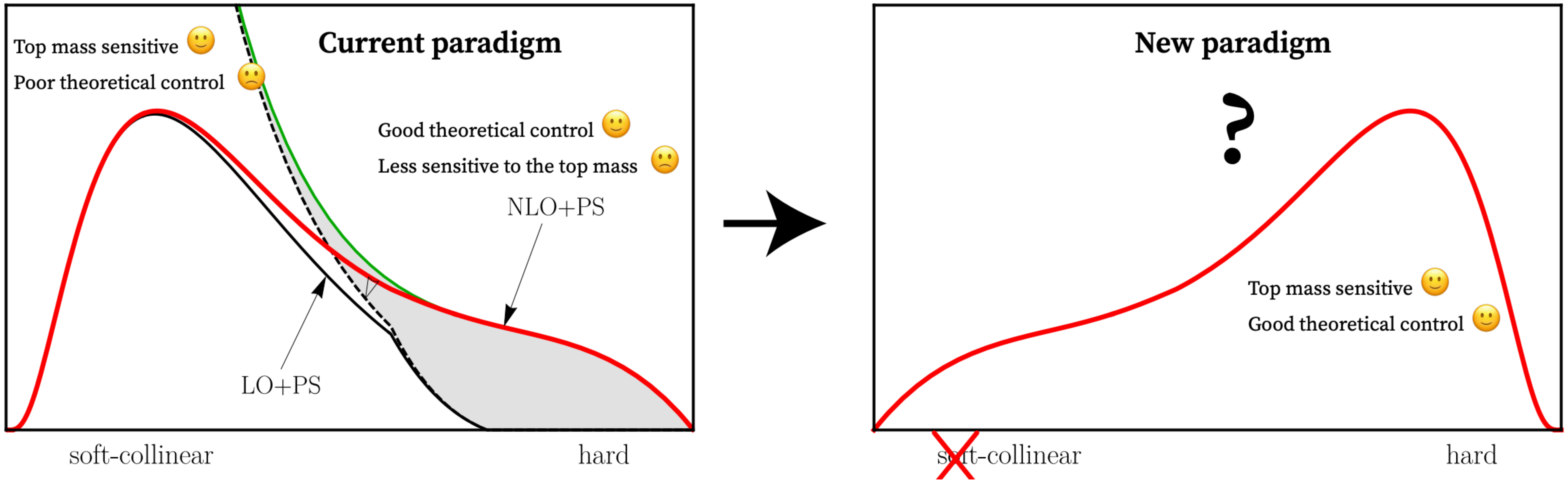
What would be extremely useful is a "semi-direct" measurement that is under theoretical control, i.e. an observable that is computable, but also has a feature with one-to-one correspondence with the mass.

The jet mass was the first observable of this kind studied in detail and with high precision (Hoang, Mantry, Pathak, Stewart, et al '17-'20 [6]).

Grooming was used to remove the NP/soft physics which is not under good theoretical control. However, $\sim 1\ \mathrm{GeV}$ NP effects still need accounting for. This presents a soft ceiling to the achievable accuracy.



Why study the top mass?



Overall, these approaches are summarised in this schematic by A. Hoang [2].

This talk reviews work attempting to find a observable in the "new paradigm" using energy correlators.

Energy correlators on boosted top jets

Reviewing energy correlators

Most of this presentation will focus on the 3-point correlator:

$$\langle \mathscr{E}\mathscr{E}\mathscr{E} \rangle(R_L, R_M, R_s) = \frac{1}{\sigma} \sum_{i,j,k} \int \mathrm{d}\sigma_{ijk} \frac{E_i E_j E_k}{Q^2} \, \delta\left(R_L - \Delta R_{ij}\right) \delta\left(R_M - \Delta R_{ik}\right) \delta\left(R_S - \Delta R_{jk}\right) \Theta(R_L \geq R_M \geq R_S).$$

I'll also make use of the 2-point correlator:

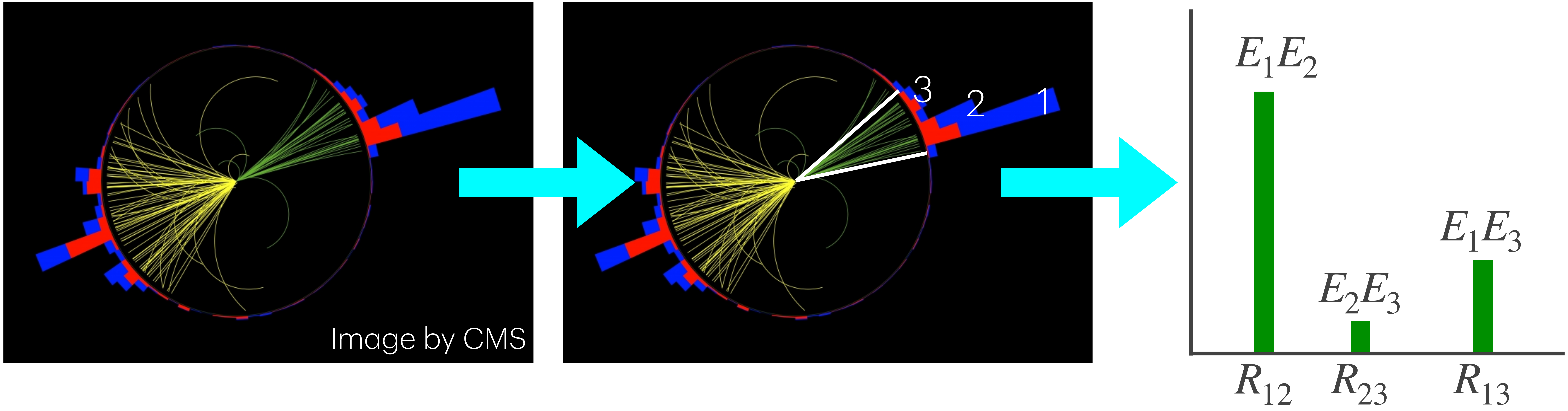
$$\langle \mathscr{E}\mathscr{E} \rangle(R_L) = \frac{1}{\sigma} \sum_{i,j} \int \mathrm{d}\sigma_{ij} \frac{E_i E_j}{Q^2} \, \delta\left(R_L - \Delta R_{ij}\right).$$

Here I have given the often quoted e^+e^- definitions. I'll shortly give the LHC appropriate definitions we employ.

Energy correlators on boosted top jets

Reviewing energy correlators

$$\langle \mathcal{E}\mathcal{E} \rangle (R_L) = \frac{1}{\sigma} \sum_{i,j} \int \mathrm{d}\sigma_{ij} \frac{E_i E_j}{Q^2} \, \delta\left(R_L - \Delta R_{ij}\right)$$



Energy correlators on boosted top jets

Reviewing energy correlators

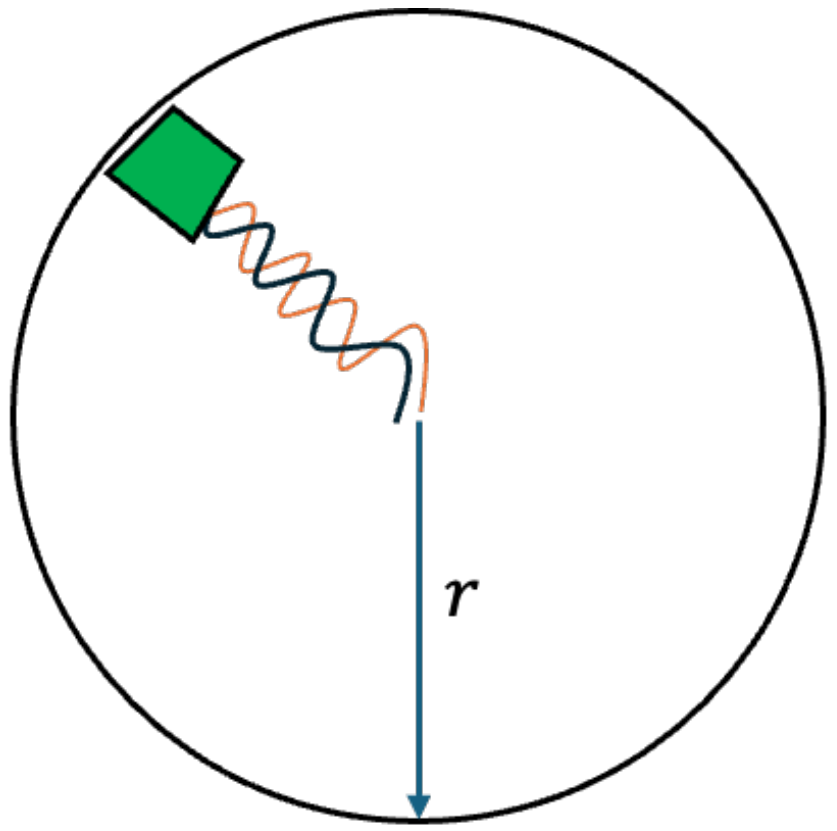
These correlators benefit from a dual description in terms of the ANE operator:

$$\langle \mathscr{E}\mathscr{E} \rangle (R_L) = \frac{1}{\sigma} \sum_{i,j} \int \mathrm{d}\sigma_{ij} \frac{E_i E_j}{Q^2} \, \delta\left(R_L - \Delta R_{ij}\right) \equiv \frac{1}{\langle \Psi | \Psi \rangle \, Q^2} \int \mathrm{d}\Omega_{1,2} \left\langle \Psi \,|\, \mathscr{E}(n_1) \mathscr{E}(n_2) \,|\, \Psi \right\rangle \delta\left(R(n_1, n_2) - R_L\right).$$

The energy-flow (ANE) operators $\mathscr{E}(n)$ are local 'calorimeters` on the celestial sphere.

$$\mathscr{E}(n) = \lim_{r \to \infty} r^2 \int_0^\infty \mathrm{d}t \;\, n_i \, T^{0i}(t, r\vec{n}),$$

$$\mathcal{E}(n) = \lim_{r \to \infty} r^2 \int_{-\infty}^{\infty} dt$$



This will be utilised later when studying the Z boson.

Energy correlators on boosted top jets

Reviewing energy correlators

It is the dual description in terms of ANE operators which has led to a huge quantity of research into energy correlators as jet substructure observables in recent years.
Focusing only on vacuum QCD:

	$\langle \mathcal{E}(\vec{n}_1) \rangle$	$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2) \rangle$	$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\mathcal{E}(\vec{n}_3) \rangle$	$\langle \mathcal{E}(\vec{n}_1) \dots \mathcal{E}(\vec{n}_i) \rangle$
Fixed order	Effectively as accurate as cross-section calculations	Complete NLO (2-loops) for colour singlet Dixon, Luo, Shtabovenko, Yang, Zhu arXiv:1801.03219	Complete LO (1-loop) for colour singlet Yang, Zhang arXiv:2402.05174	Tree-level
Resummation	N/A	Small angle NNLL & NNNLL Dixon, Moult, Zhu arXiv:1905.01310 Gao, Li, Moult, Zhu arXiv:2312.16408	Small angle NLL Cheng, Moult, Zhu arXiv:2011.02492	Small angle NLL Cheng, Moult, Zhu arXiv:2011.02492
Pheno	Extracting EW density matrices	Measuring α_s Komiske, Moult, Thaler, Zhu arXiv:2201.07800	Measuring α_s Komiske, Moult, Thaler, Zhu arXiv:2201.07800	Measuring α_s Komiske, Moult, Thaler, Zhu arXiv:2201.07800
Pheno	Small x proton structure Liu, Zhu arXiv:2209.02080	Extracting EW density matrices Ricci, Riembau arXiv:2207.03511	Measuring m_t JH, Moult, Pathak, Procura arXiv:2201.08393	
Pheno		Detecting the deadcone Craft, Lee, Meçaj, Moult arXiv:2210.09311	Measuring spin correlations Cheng, Moult, Zhu arXiv:2011.02492 Karlberg, Salam, Scyboz, Verheyen arXiv:2103.16526	

*These are some highlights focusing on the small angle limit QCD. There is a lot more literature away from that limit.

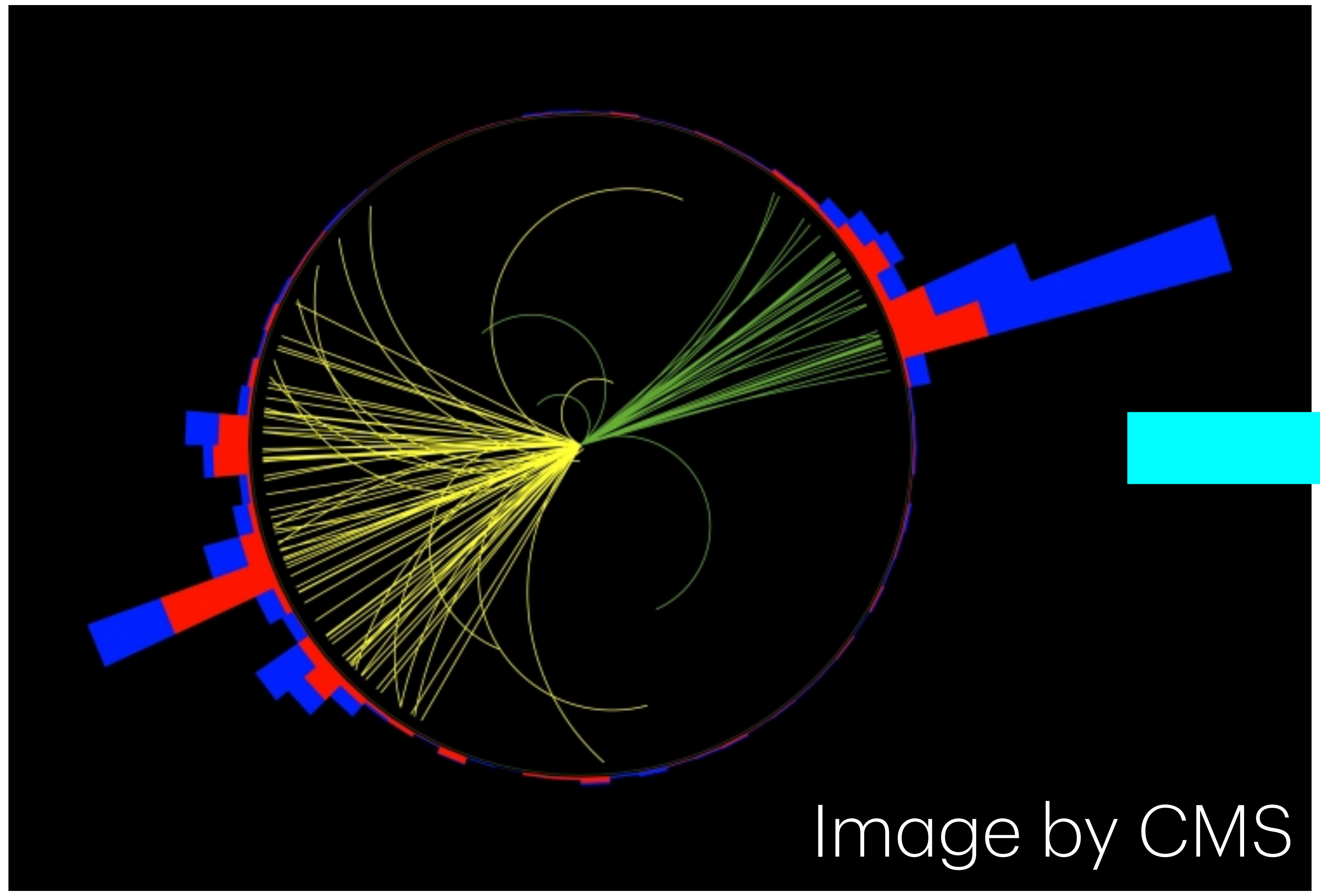
This is from a slide I made 1 year ago. Already much more could be added, including more "N"s in the computations.

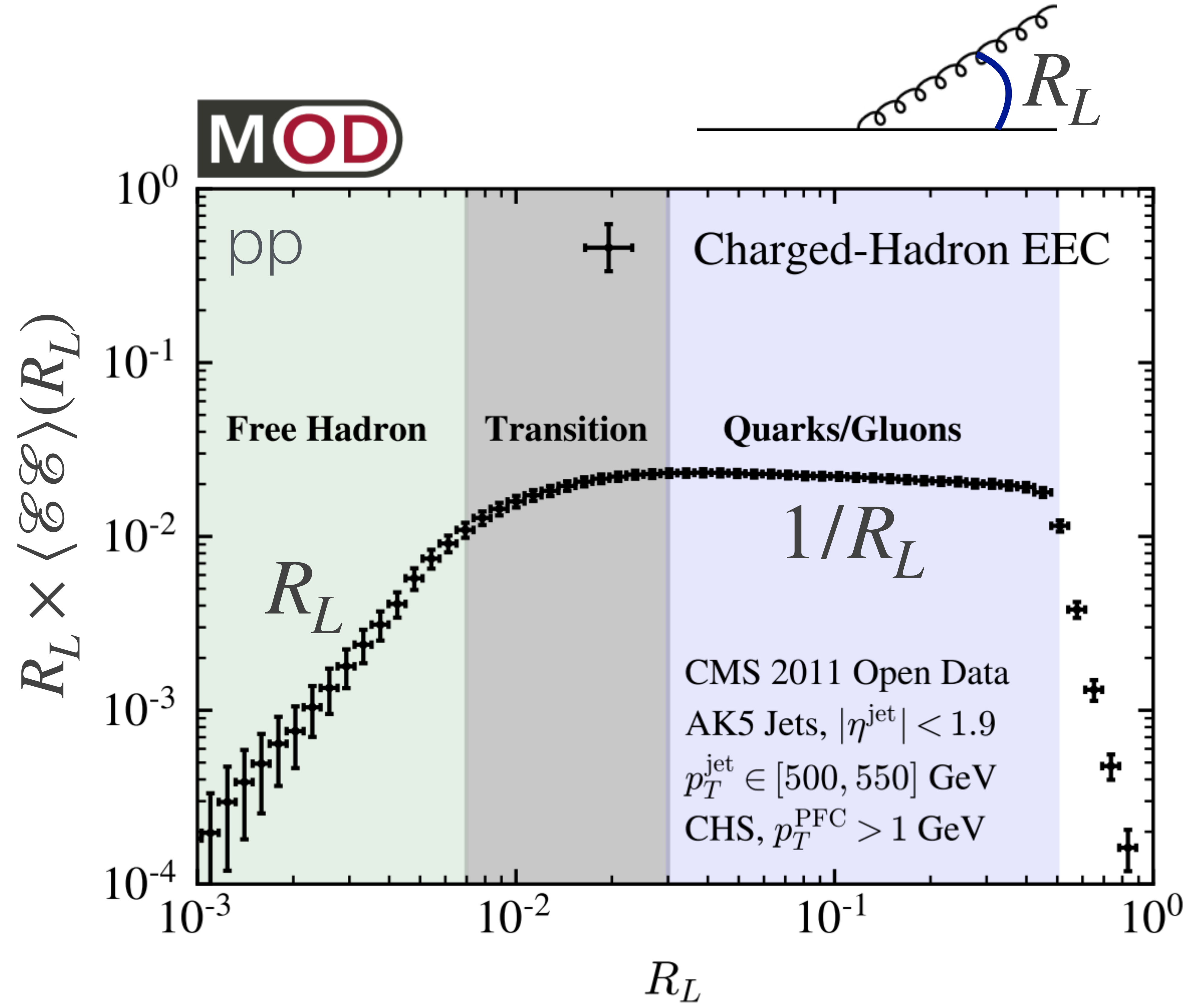
Energy correlators on boosted top jets

Reviewing energy correlators

What does an energy correlator look like on a massless-vacuum QCD jet?

$$\langle \mathcal{E}\mathcal{E} \rangle (R_L) = \frac{1}{\sigma} \sum_{i,j} \int \mathrm{d}\sigma_{ij} \frac{E_i E_j}{Q^2} \, \delta\left(R_L - \Delta R_{ij}\right)$$





Energy correlators on boosted top jets

Reviewing energy correlators

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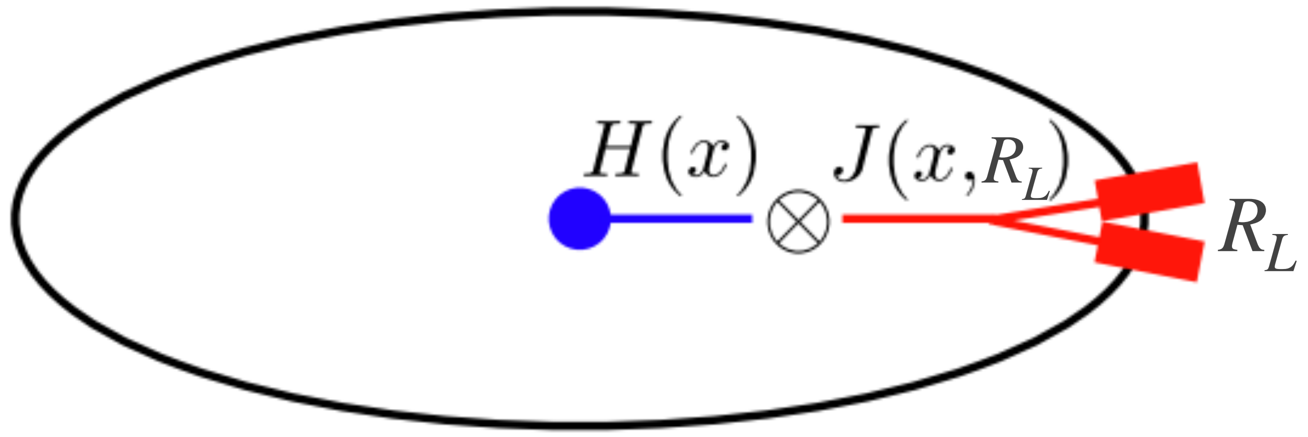
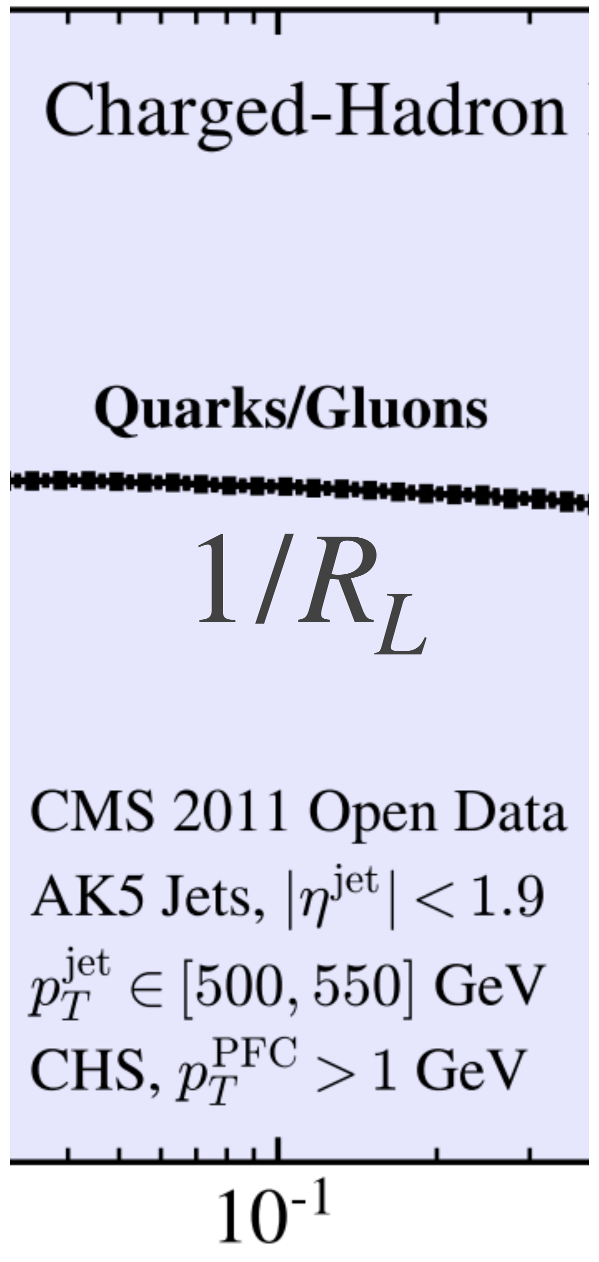
$$\langle \mathscr{E}\mathscr{E} \rangle (R_L) = \frac{1}{\sigma} \sum_{i,j} \int \mathrm{d}\sigma_{ij} \frac{E_i E_j}{Q^2} \, \delta\left(R_L - \Delta R_{ij}\right)$$

At leading power the EEC has a very simple factorisation theorem.

$$\langle \mathscr{E}\mathscr{E} \rangle (R_L) = \int_0^1 \mathrm{d}x \; x^2 \vec{J}_{\mathrm{EEC}} \left(\ln \frac{x R_L Q}{\mu}, \mu^2 \right) \cdot \vec{H}\left(x, \frac{Q^2}{\mu^2}, \mu^2 \right).$$

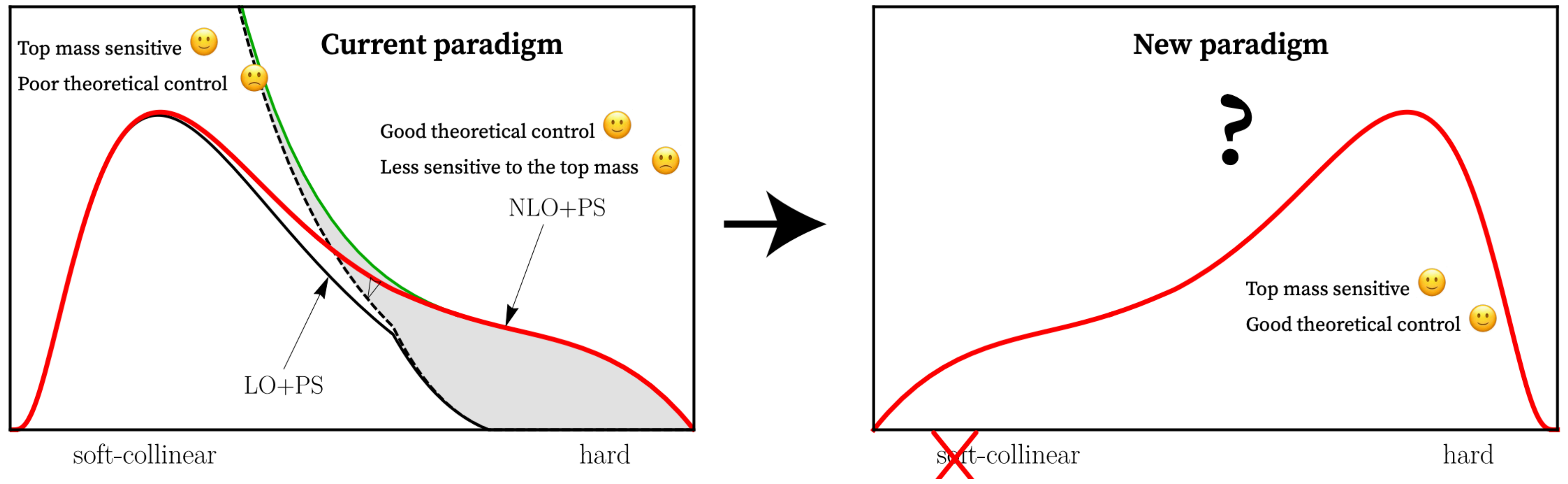




Energy correlators on boosted top jets

Why EECs for top measurements?

Think back to the paradigm outlined by Hoang '20 [2]. EECs have several features which seem to naturally address the present issues.



- They are collinear-sensitive observables when used for jet substructure. The soft physics (such as UE and Hadronisation) which hinders the jet mass is naturally suppressed, even without grooming.

- They can be defined in terms of low multiplicity inclusive cross sections. These are the objects which are under good theoretical control and are typically dominated by hard physics, away from thresholds.

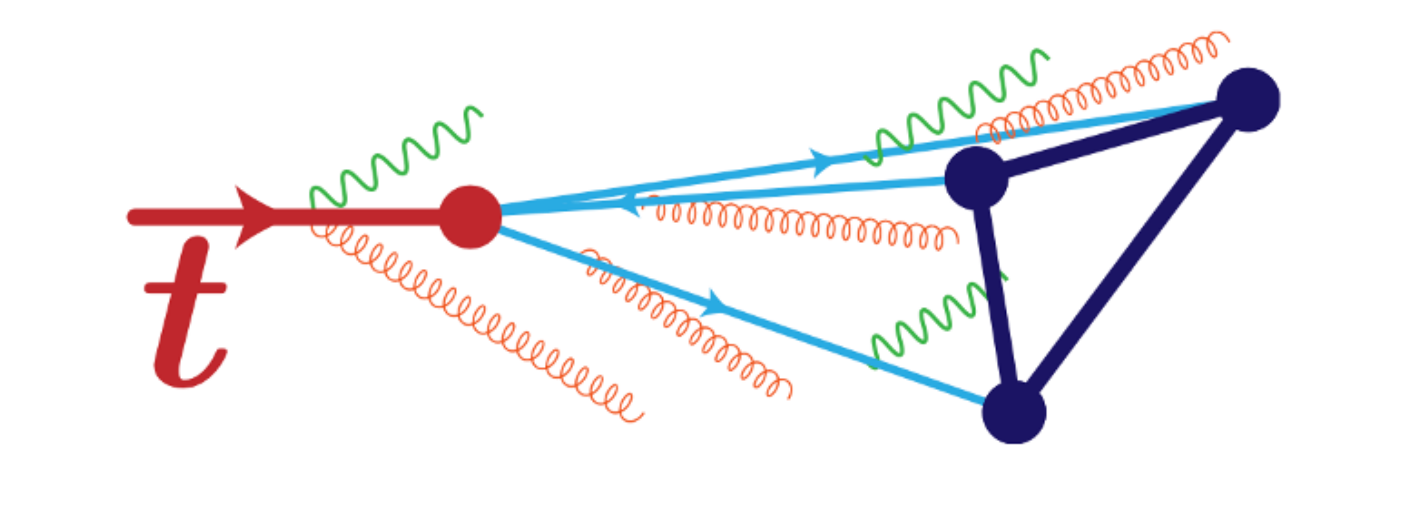
- They are a SCET-II type observable. I wont discuss this in detail but this renders them much more resilient to NP physics than, for instance, the jet mass which is SCET-I.

Energy correlators on boosted top jets

Energy correlators on top quarks

The top mass EEC was introduced in JH, I. Moult, A. Pathak, M. Procura '22 [8].

The top has a 3-body decay (at LO). Therefore, it is naturally studied with a 3-point correlator.



We study the top in the LHC, so we need hadron collider variables.

$$E_i \to p_{T,i}$$

angles → rapidities

The observable is (JH, I. Moult, A. Pathak, M. Procura, R. Schöfbeck, D. Schwarz '23 [9]):

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

Energy correlators on boosted top jets

Energy correlators on top quarks

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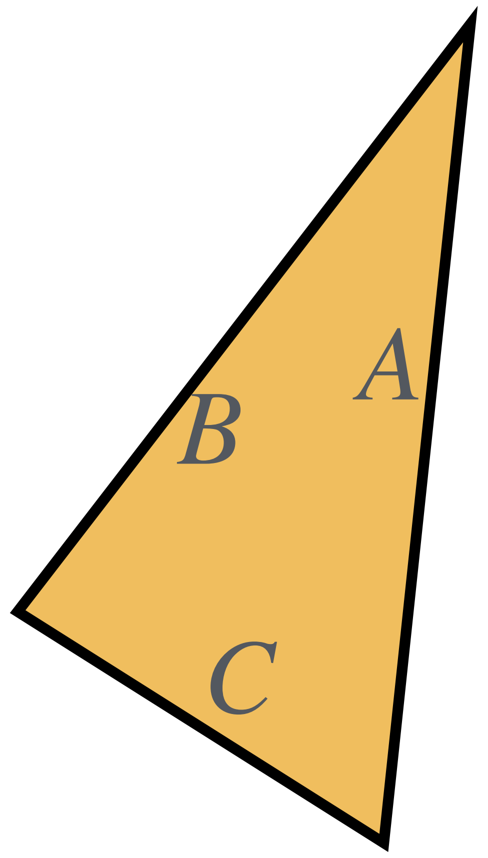
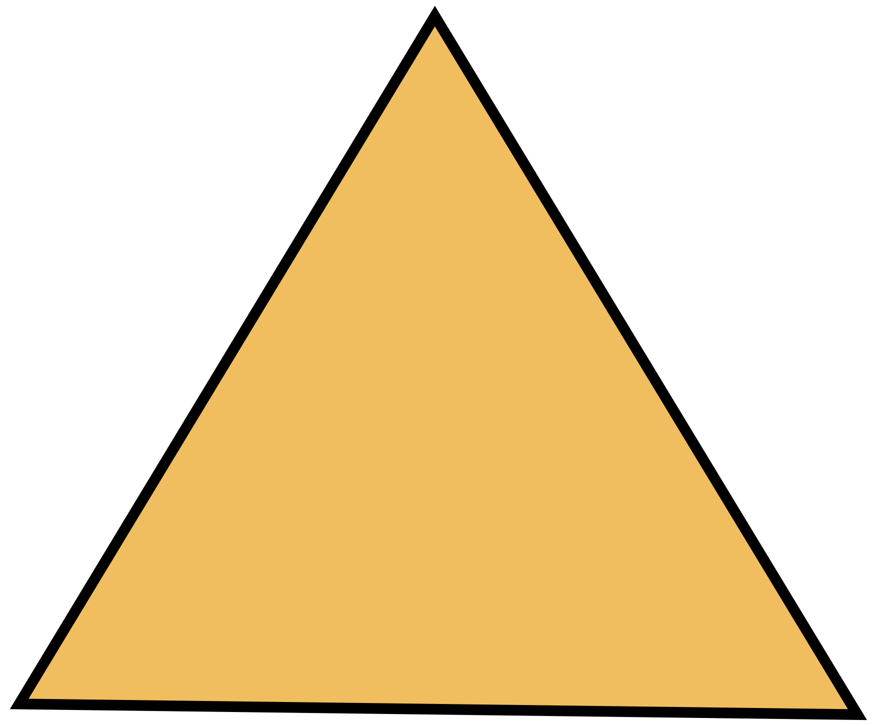


$\zeta \sim (A+B)/2$

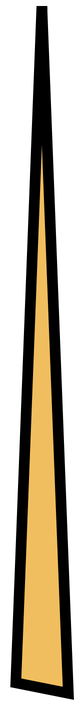
$\zeta_A \sim A - B$

$\zeta_S \sim C$



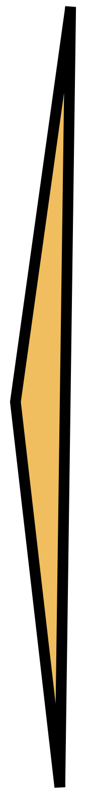
$\zeta_A \sim 0$

$\zeta_S \gg 0$



$\zeta_A \sim 0$

$\zeta_S \sim 0$



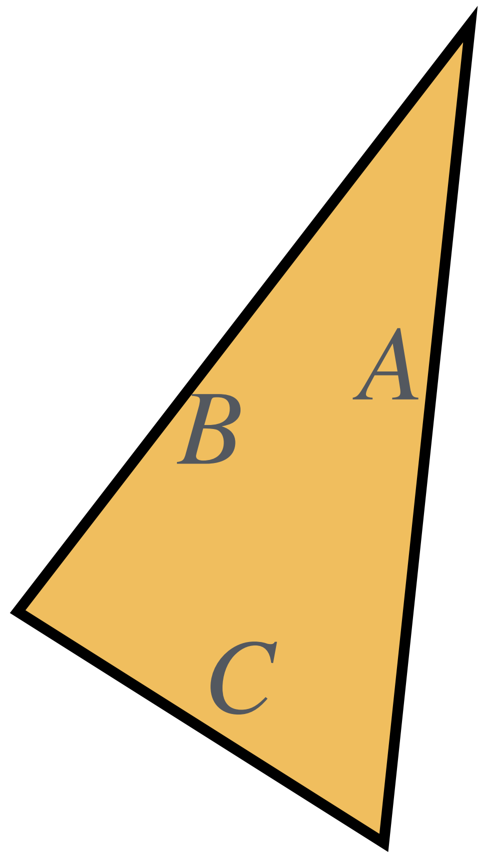
$\zeta_A \sim \zeta$

Energy correlators on boosted top jets

Energy correlators on top quarks

The observable is:

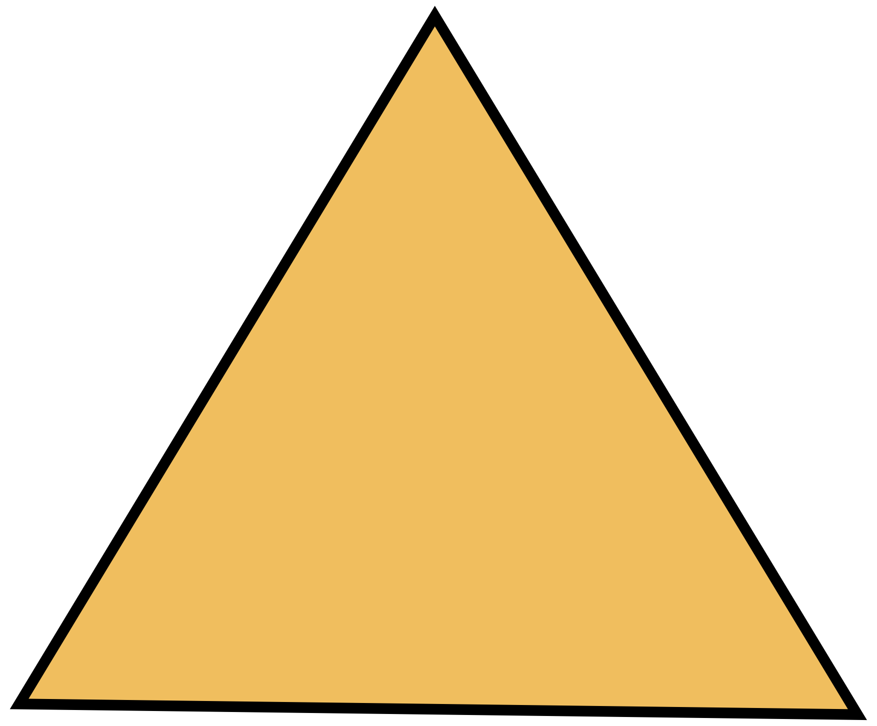
$$T(\zeta,\zeta_S,\zeta_A) \equiv \sum_{\substack{\text{hadrons}\\ i,j,k}} \int \mathrm{d}\zeta_{ijk} \frac{p_{T,i}\, p_{T,j}\, p_{T,k}}{(p_{T,\mathrm{jet}})^3} \frac{\mathrm{d}^3\sigma_{i,j,k}}{\mathrm{d}\zeta_{ijk}} \Theta(\zeta_{ij} \geq \zeta_{jk} \geq \zeta_{ki} \geq \zeta_S)\, \delta\left(\zeta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



$\zeta \sim (A+B)/2$

$\zeta_A \sim A - B$

$\zeta_S \sim C$

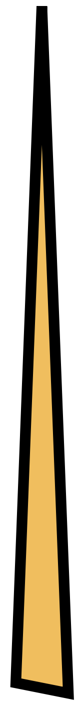


$\zeta \sim m_t^2/p_{T\,\mathrm{jet}}^2$

$\zeta_A \sim 0$

$\zeta_S \gg 0$

Top decay sensitive

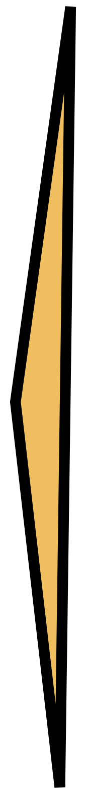


$\zeta \sim m_W^2/p_{T\,\mathrm{jet}}^2$

$\zeta_A \sim 0$

$\zeta_S \sim 0$

W decay sensitive



$\zeta_A \sim \zeta$

Intra-jet radiation sensitive

Energy correlators on boosted top jets

Energy correlators on top quarks

The observable is:

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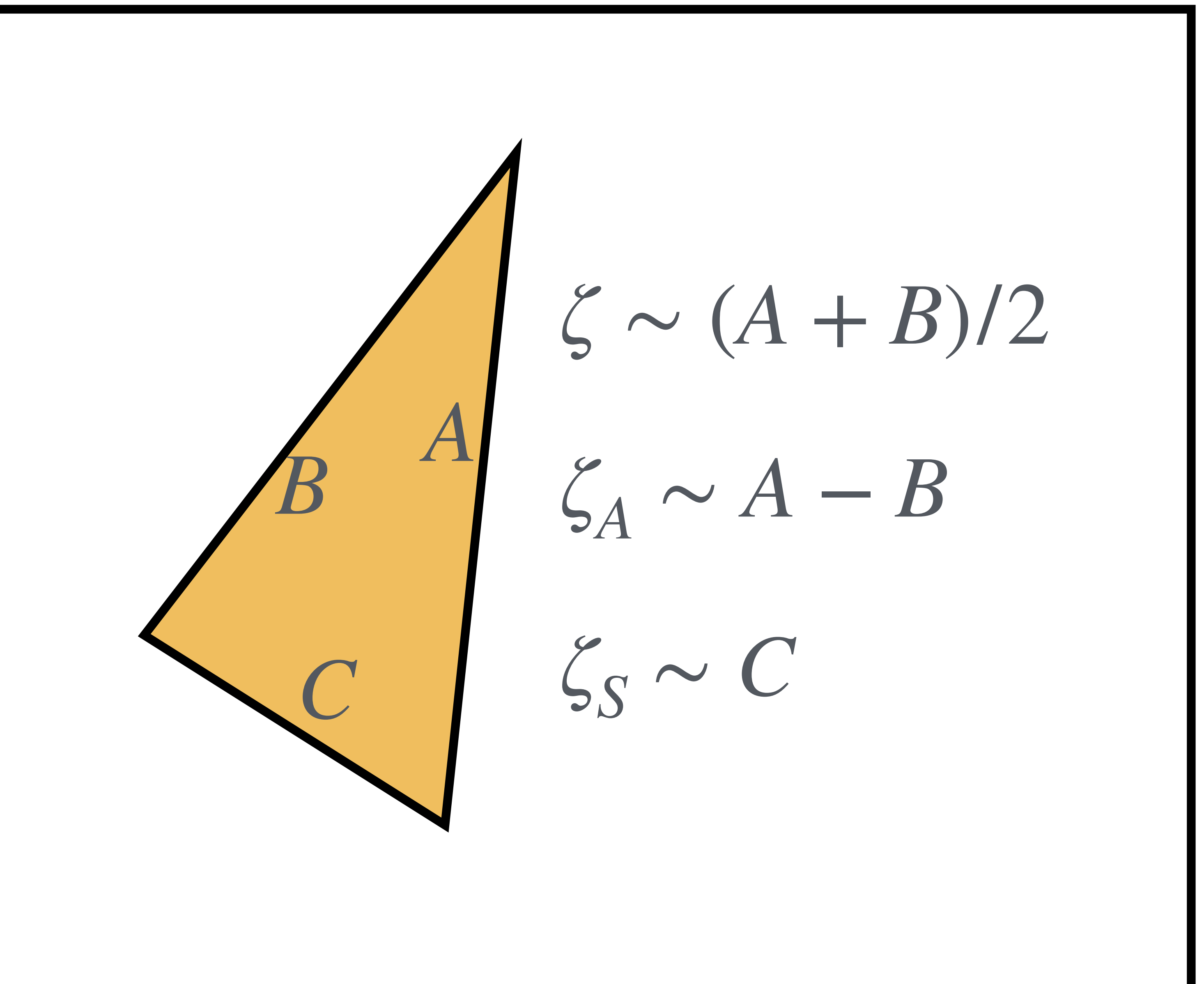
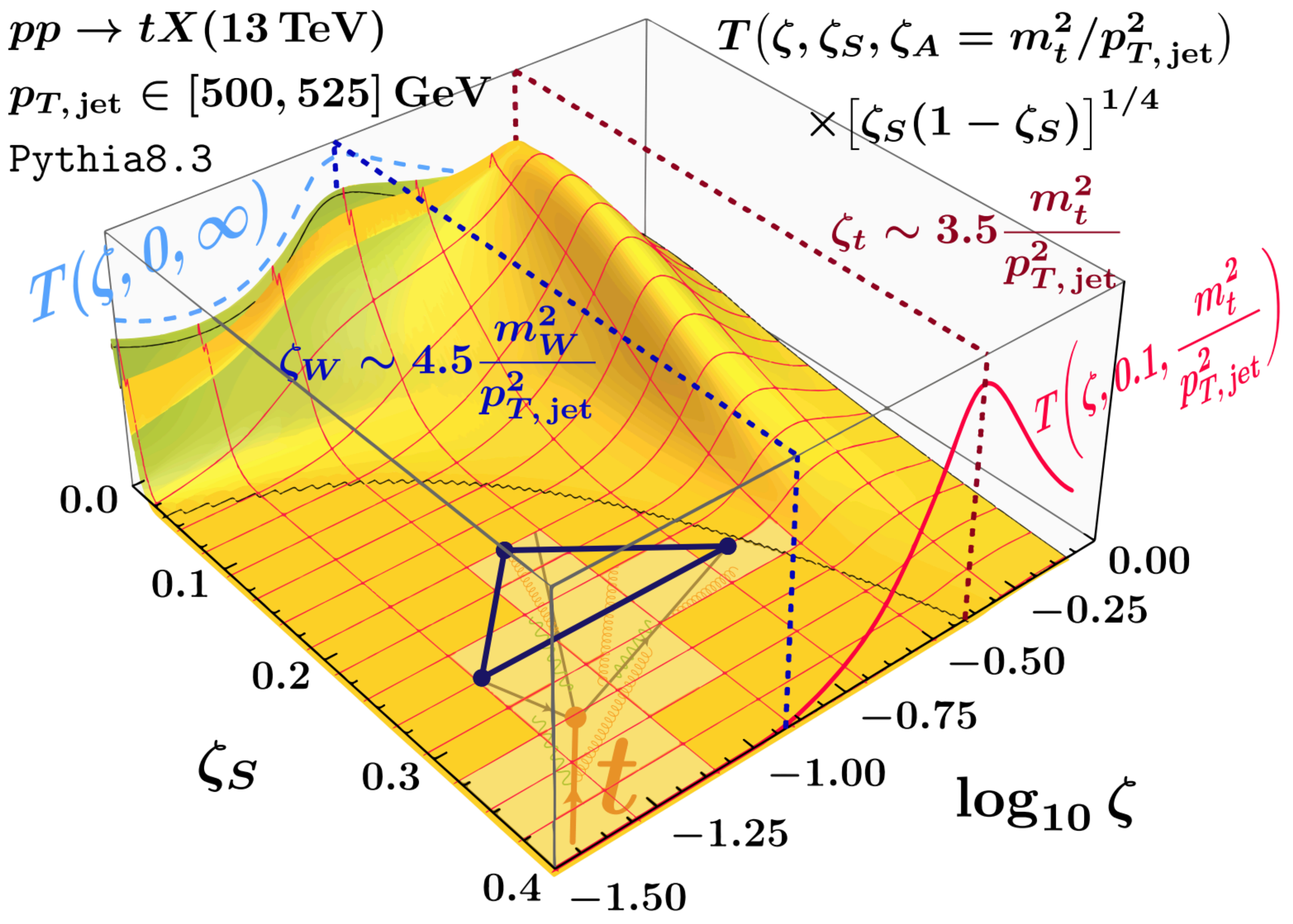
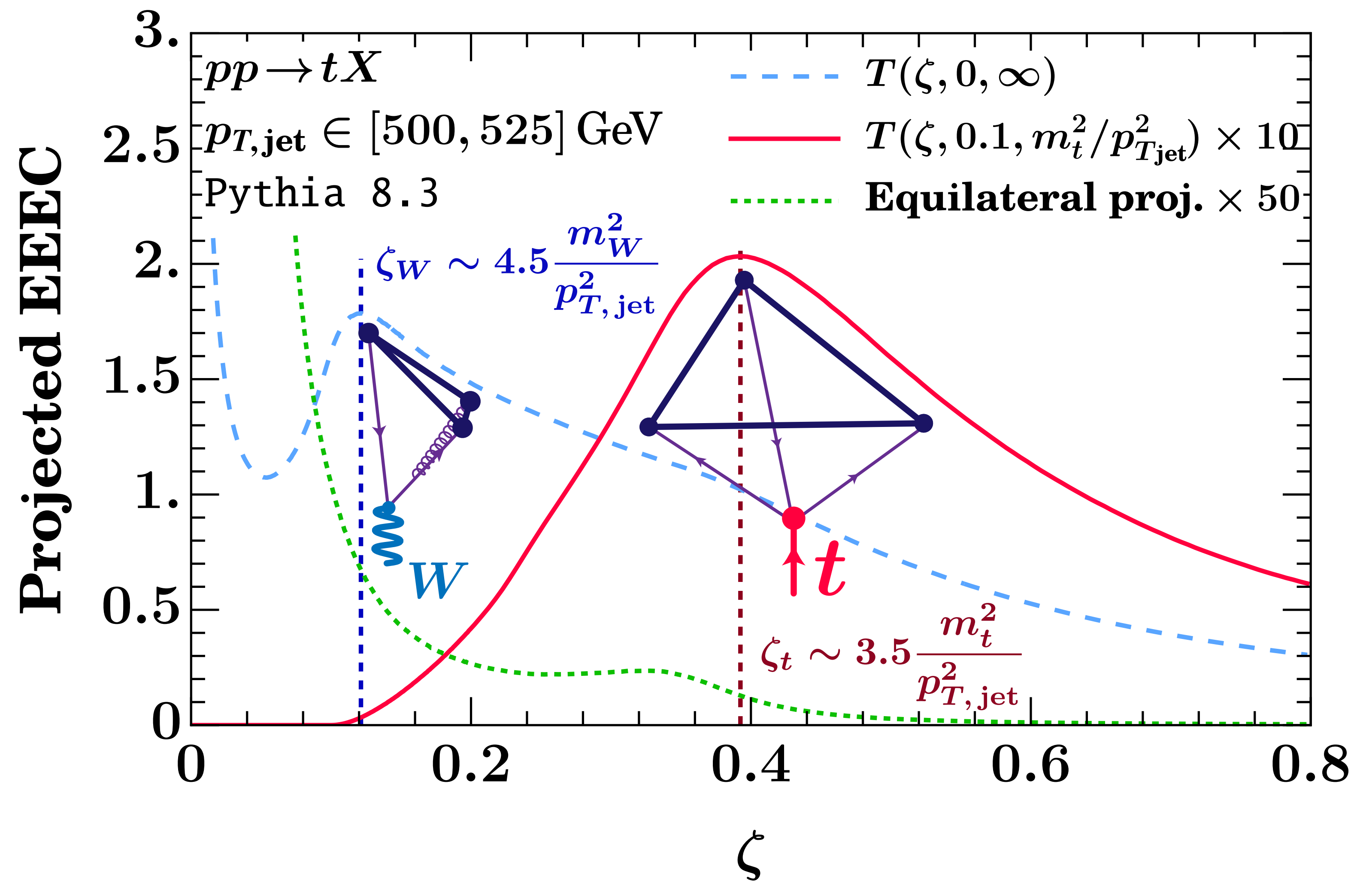




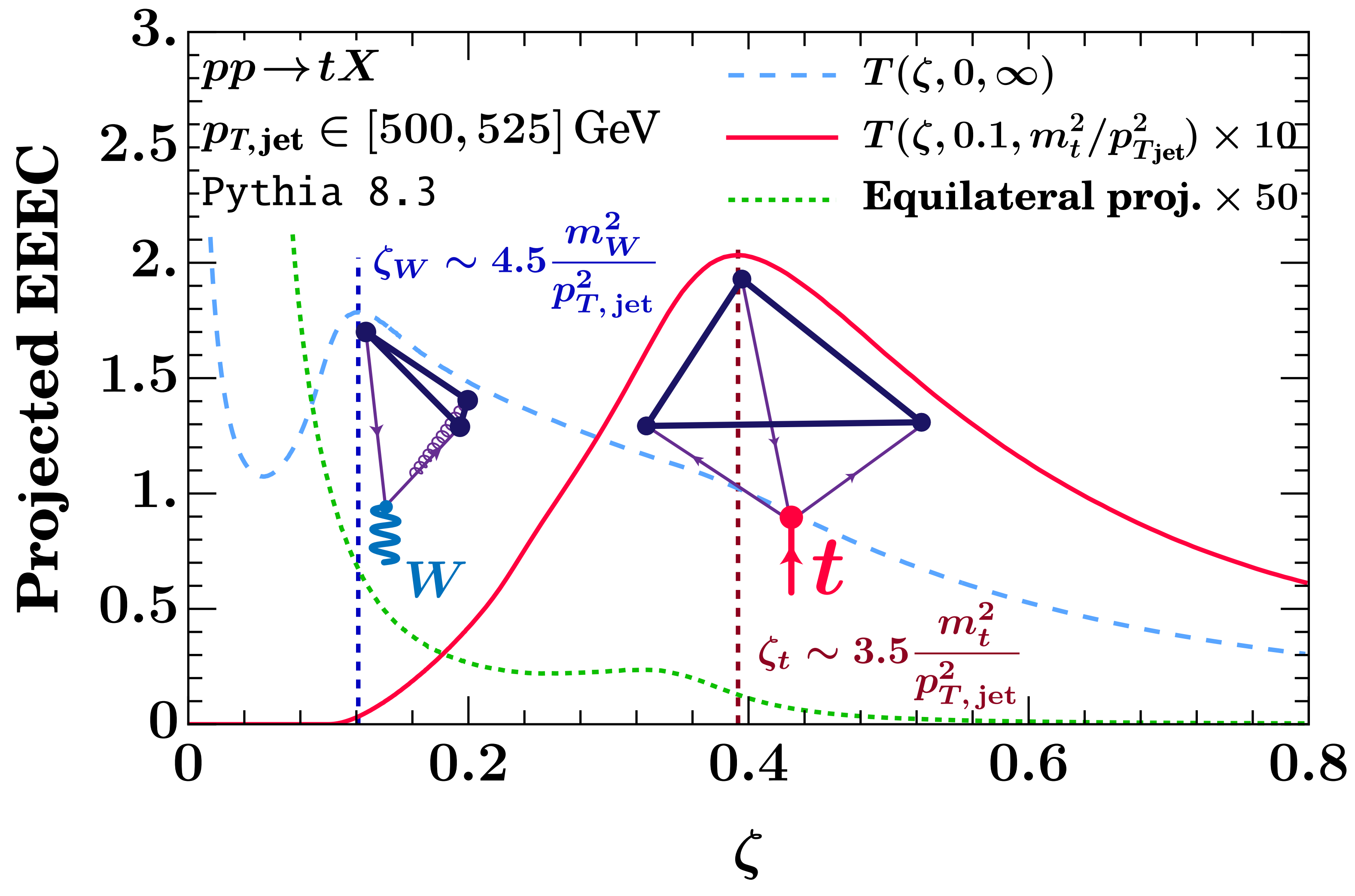


Energy correlators on boosted top jets

Energy correlators on top quarks

The top peak is very sensitive to the top mass (in a well-defined short distance scheme).

The peak itself is highly resilient to NP and soft physics [8] (I'll show this more later). It would seem we've solved the problem...



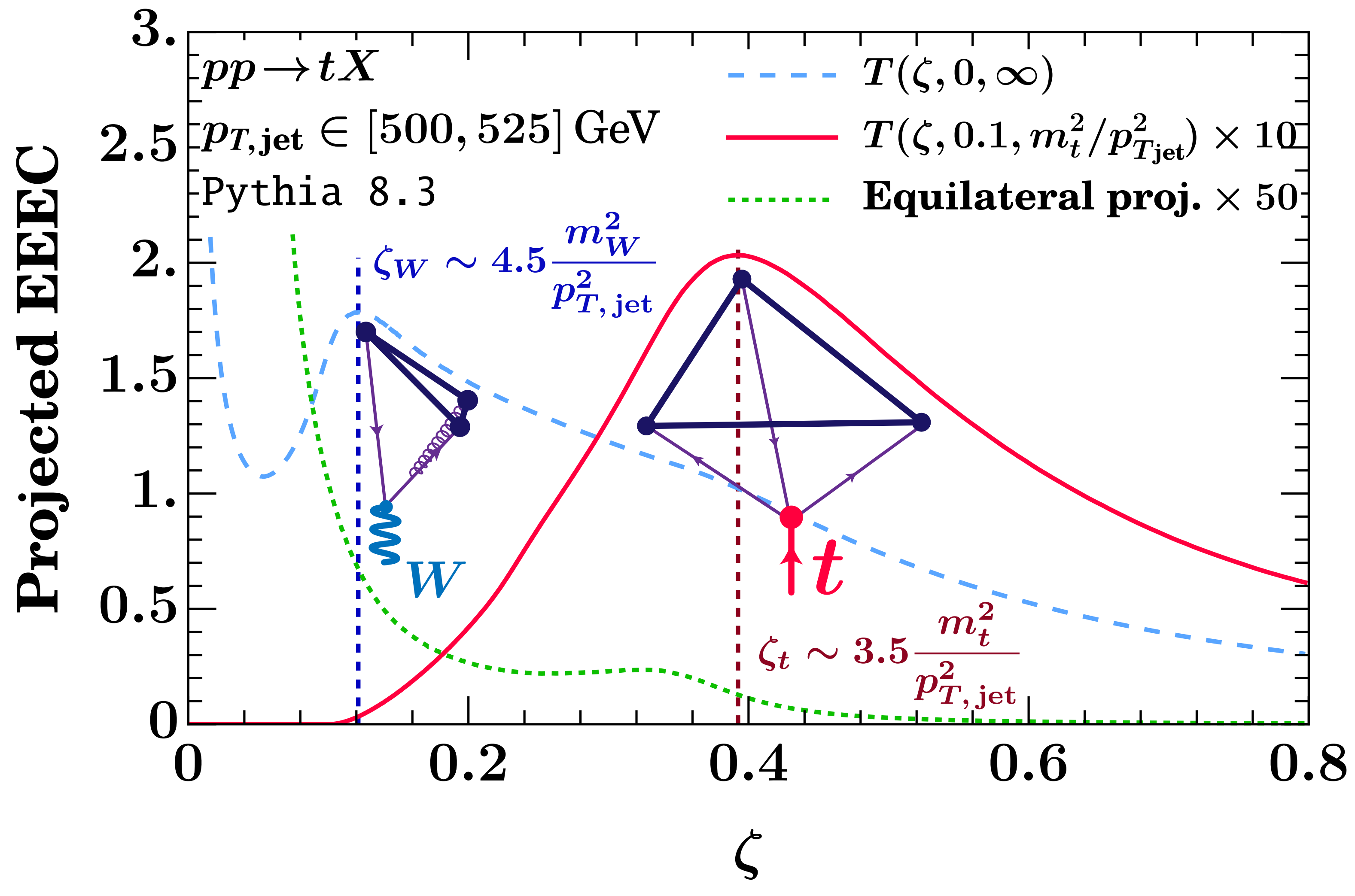
Energy correlators on boosted top jets

Energy correlators on top quarks

The top peak is very sensitive to the top mass (in a well-defined short distance scheme).

However, it is equally sensitive to the jet $p_{T\,\mathrm{jet}}$.

For $1\;\mathrm{GeV}$ accuracy on the top mass, measured with a $500\;\mathrm{GeV}$ jet, the $p_{T\,\mathrm{jet}}$ needs to be known with $5\;\mathrm{GeV}$ precision, *very tough*.



Energy correlators on boosted top jets

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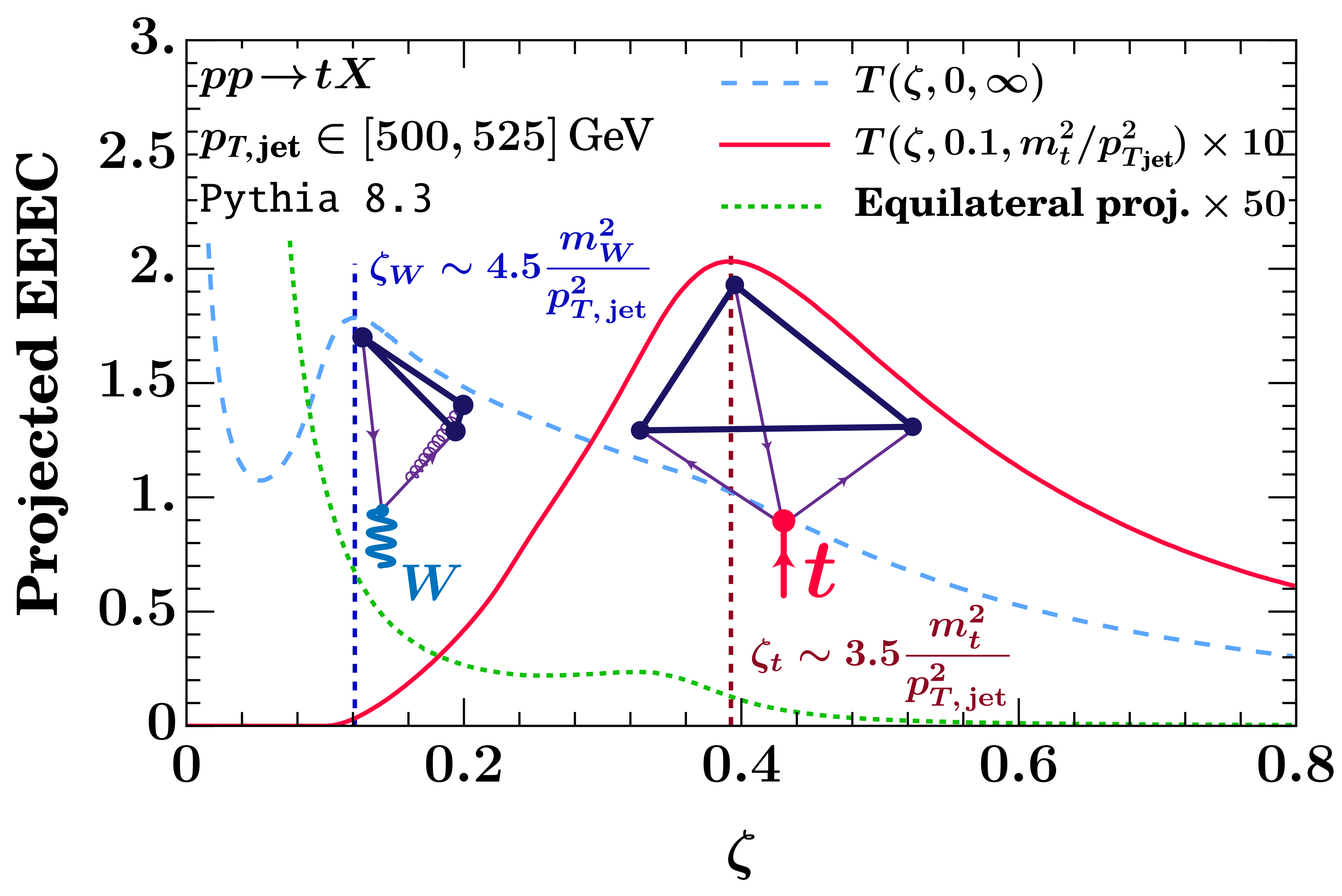
For $1\ \text{GeV}$ accuracy on the top mass, measured with a $500\ \text{GeV}$ jet, the $p_{T\,\text{jet}}$ needs to be known with $5\ \text{GeV}$ precision, *very tough*.

BUT the W peak depends on the exact same $p_{T\,\text{jet}}$!



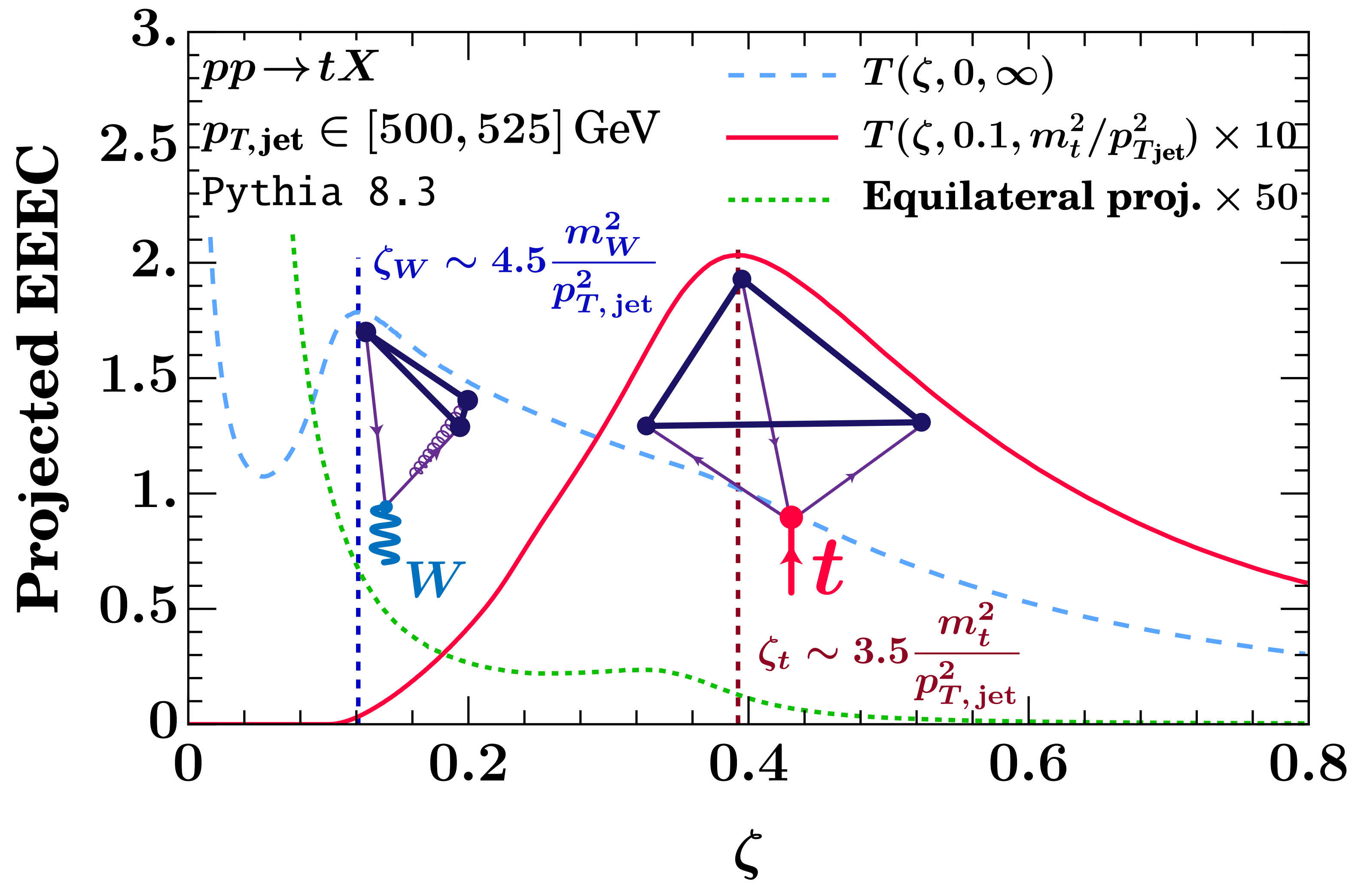
Energy correlators on boosted top jets

Energy correlators on top quarks

Measuring the ratio between the position of the W peak and the top peak should removes the leading $p_{T\,\text{jet}}$ dependence.

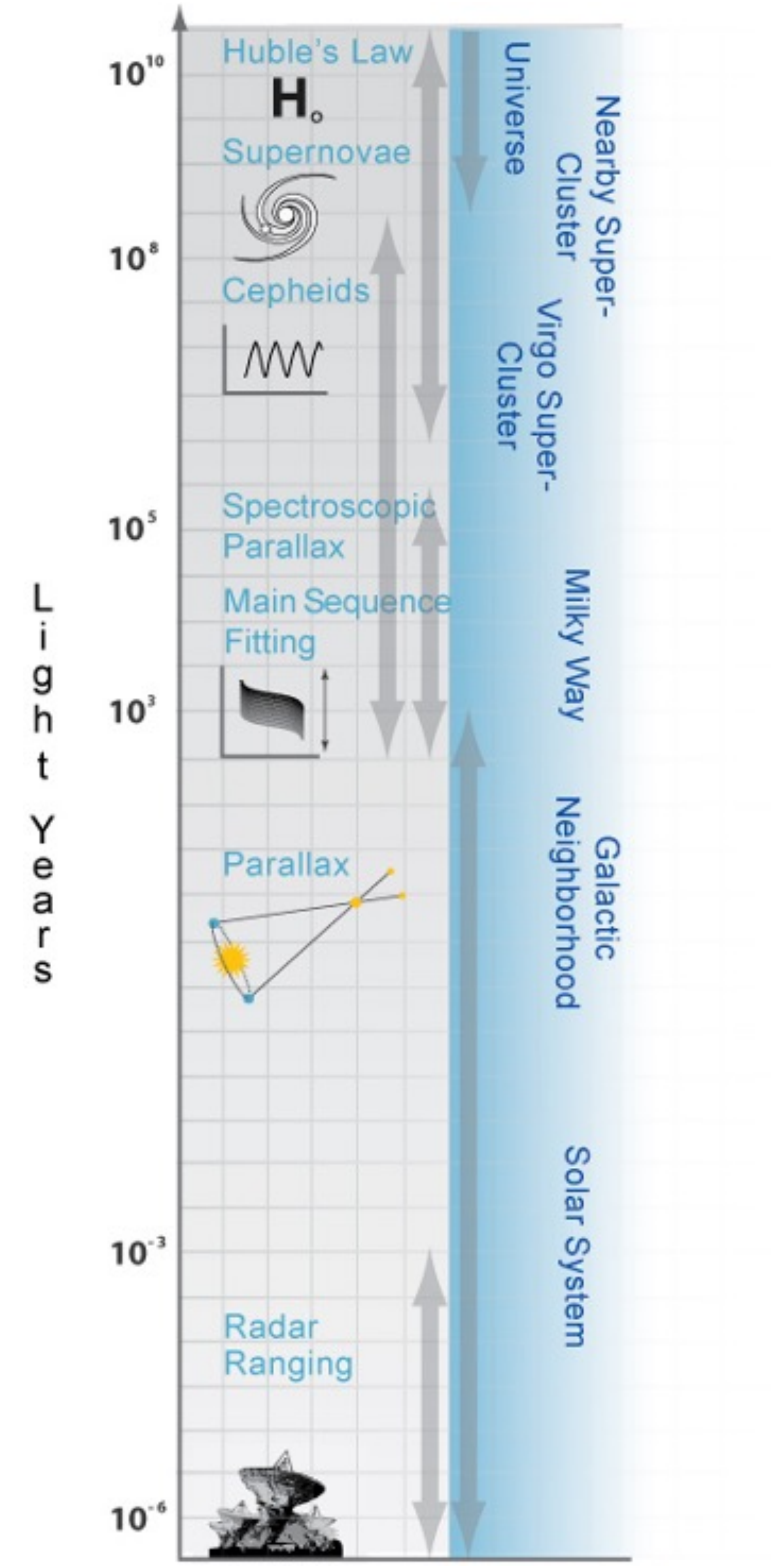
Fitting both the spectra completely allows for a complete elimination of the $p_{T\,\text{jet}}$ dependence.

This measurement can be done cross multiple $p_{T\,\text{jet}}$ bins and will return the top mass in terms of the W mass multiplied by a constant determined by the dynamics of the top decay.



The standard candle

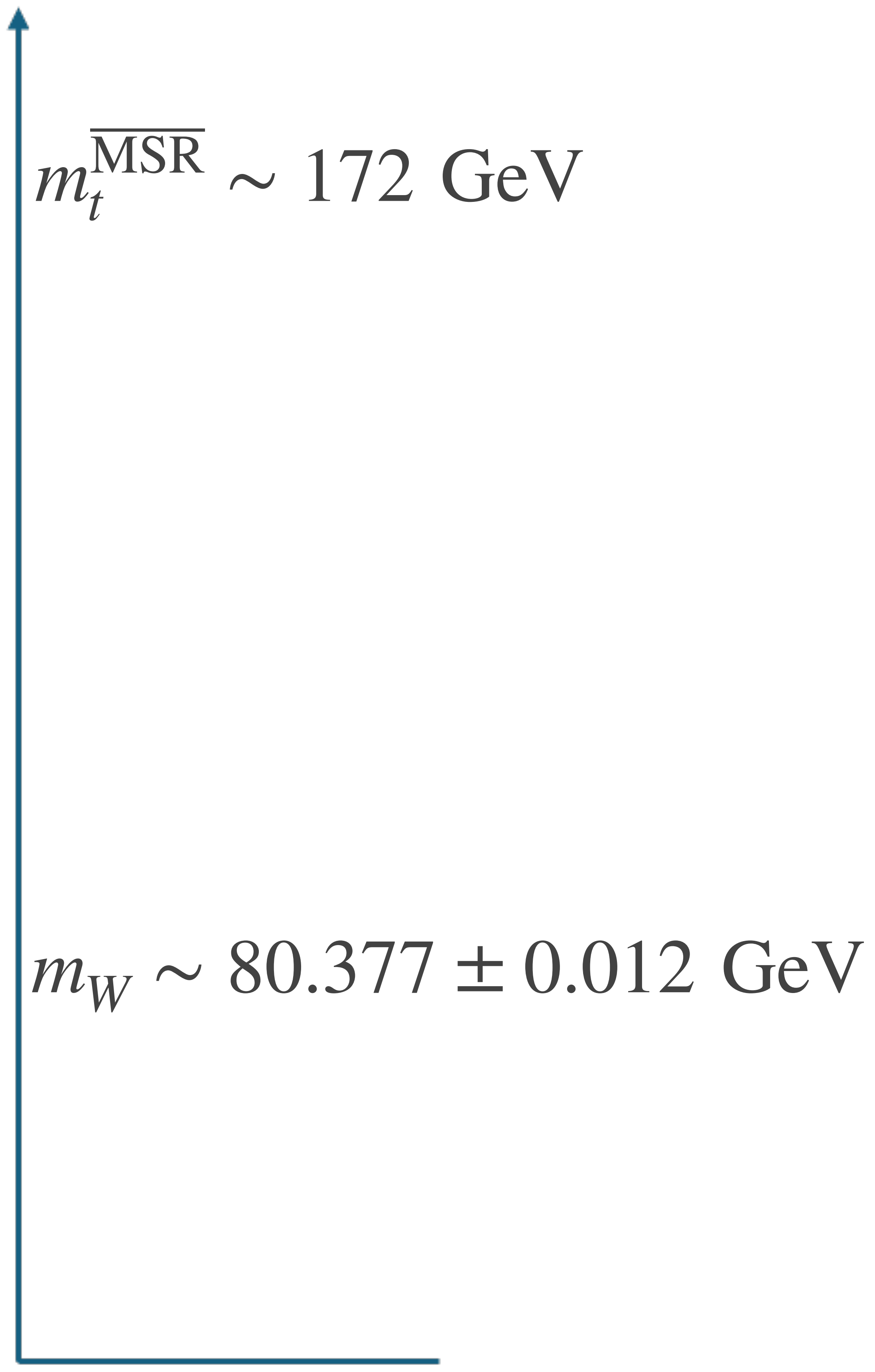
The analogy



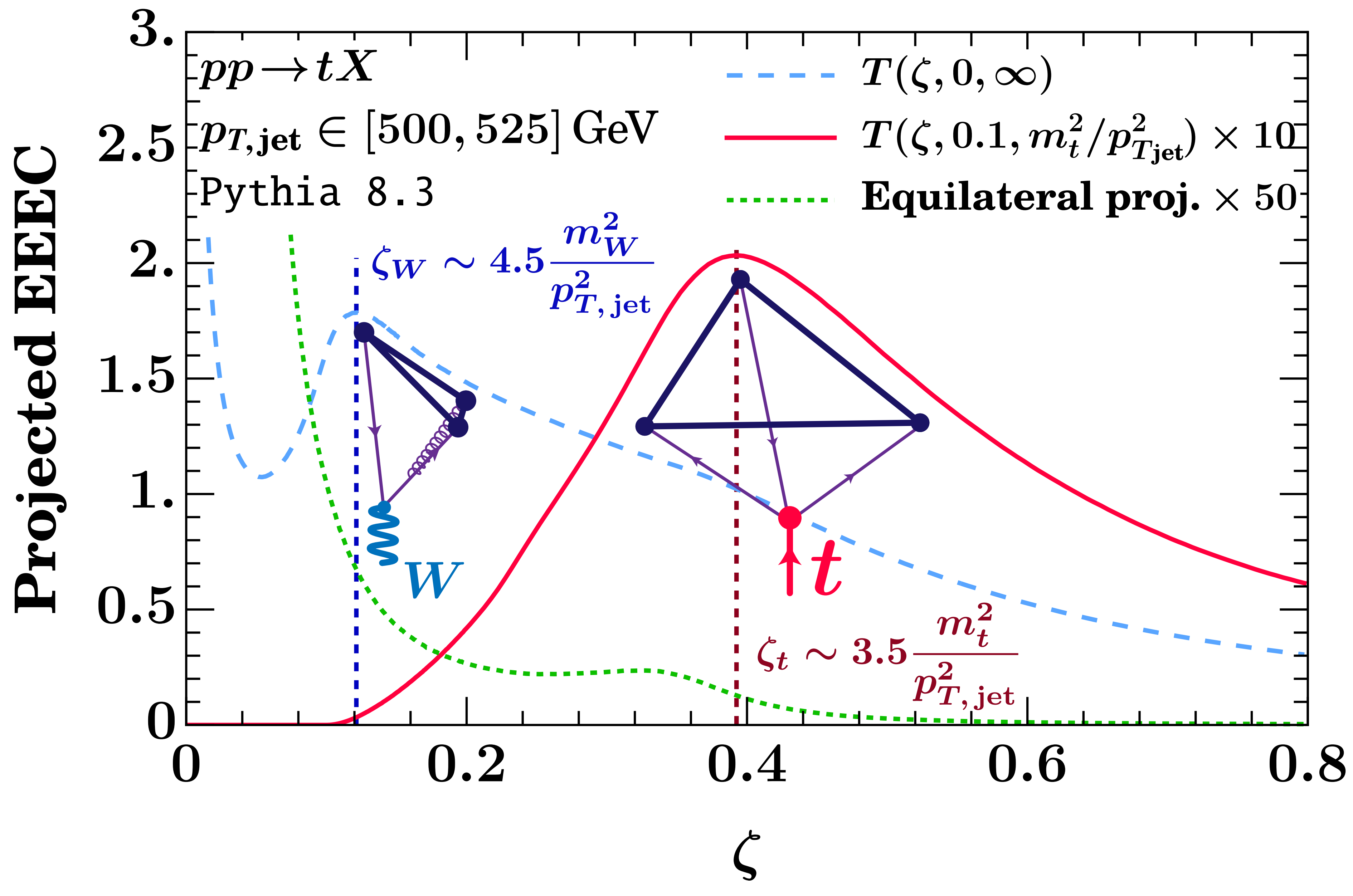
Very similar in approach to the cosmological distance ladder.

In cosmology a dimensionful quantity which can be measured (perceived luminosity) is converted to a differently dimensioned quantity (distance) by including the dynamics of a process that can be computed in terms of either quantity (i.e. the cepheid period to luminosity relationship).

The energy correlator top mass measurement converts a top decay angle to a top mass with the W mass (which replaces the $p_{T\,\text{jet}}$) and with knowledge of the W boson's boost from the top decay rest frame.

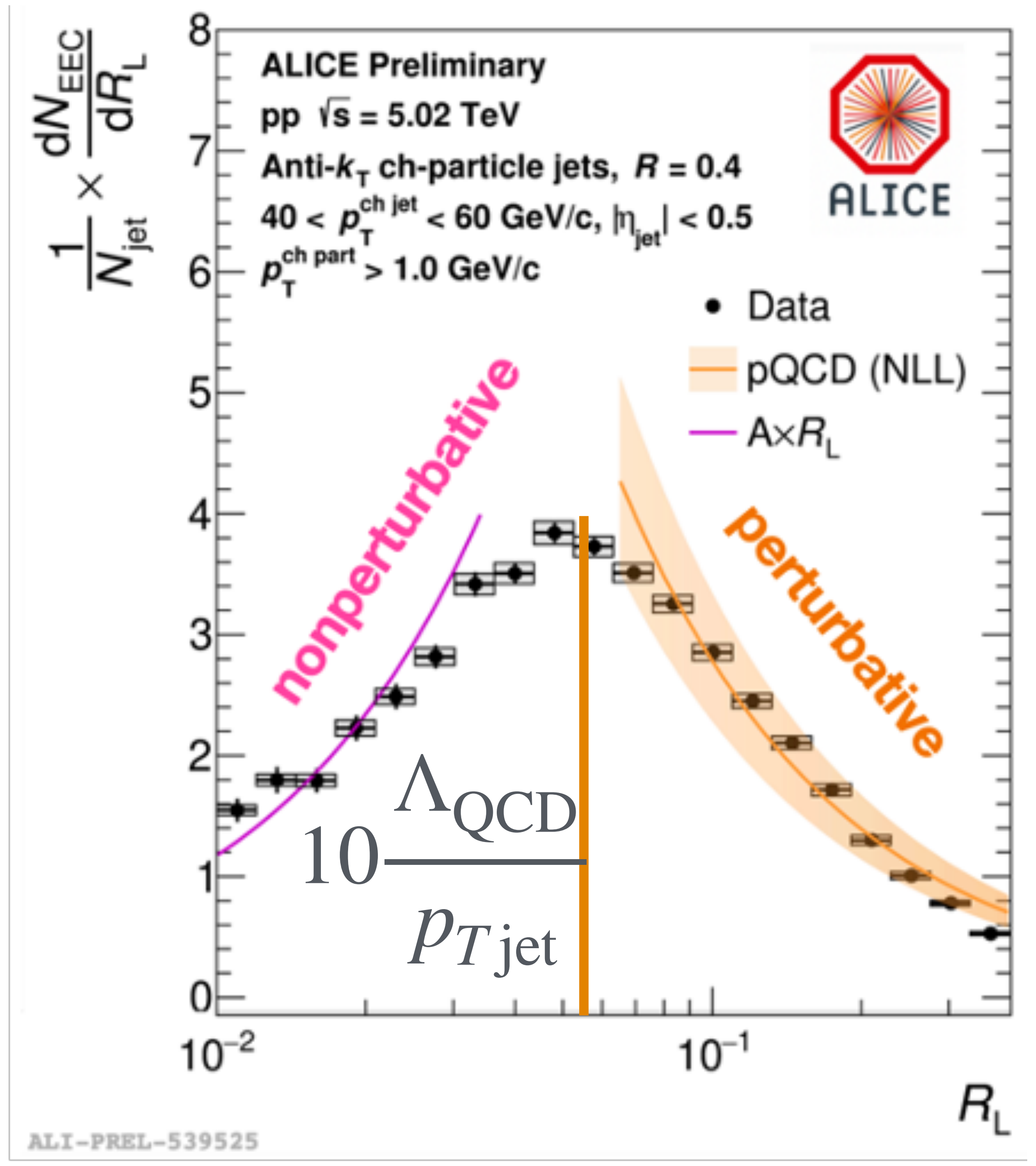


The standard candle



BUT there is a second problem!

The W appears at much smaller angles that the top decay.



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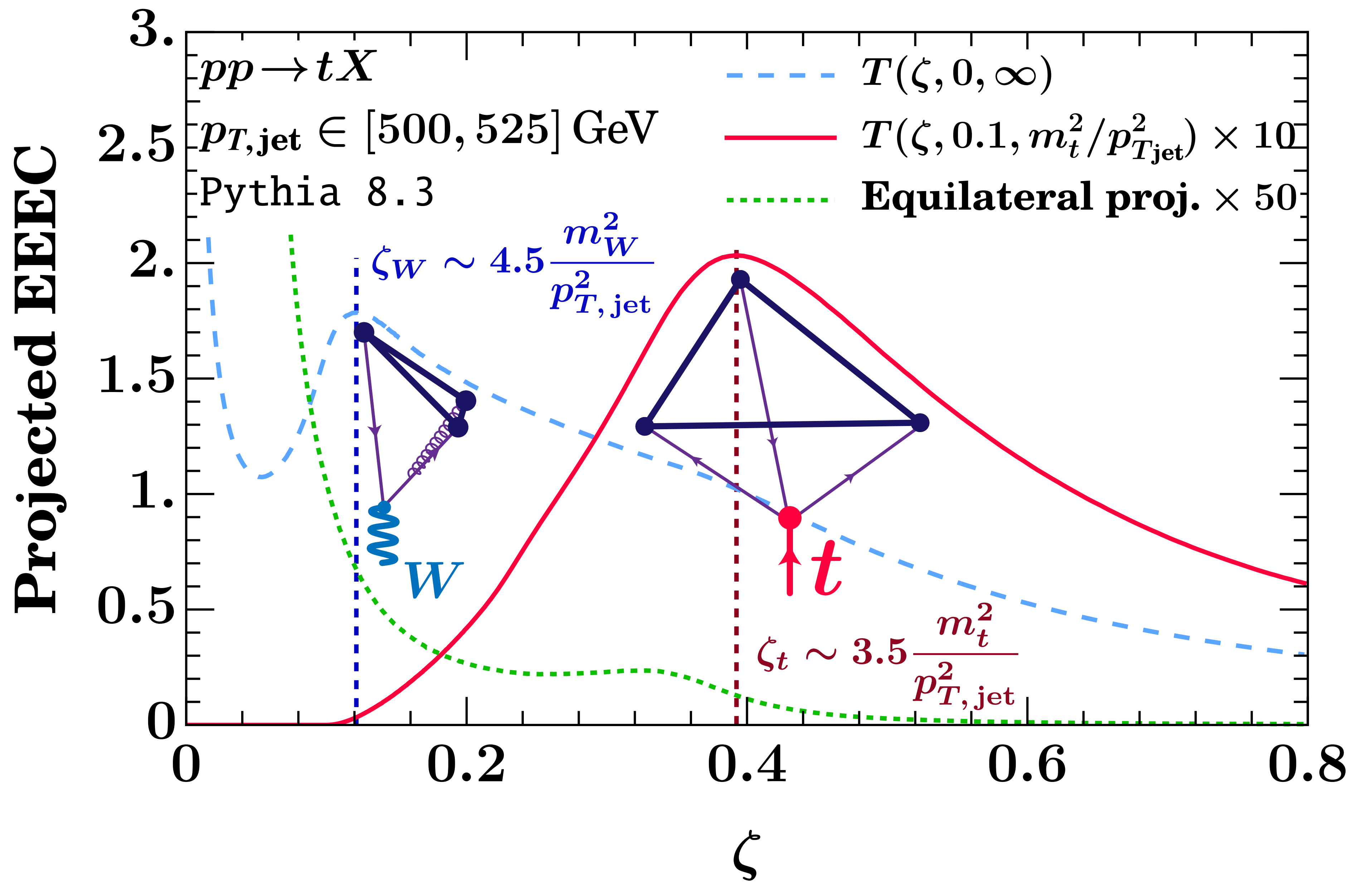


BUT there is a second problem!

The W appears at much smaller angles that the top decay.

The W appears still at angles much larger than the hadronisation transition

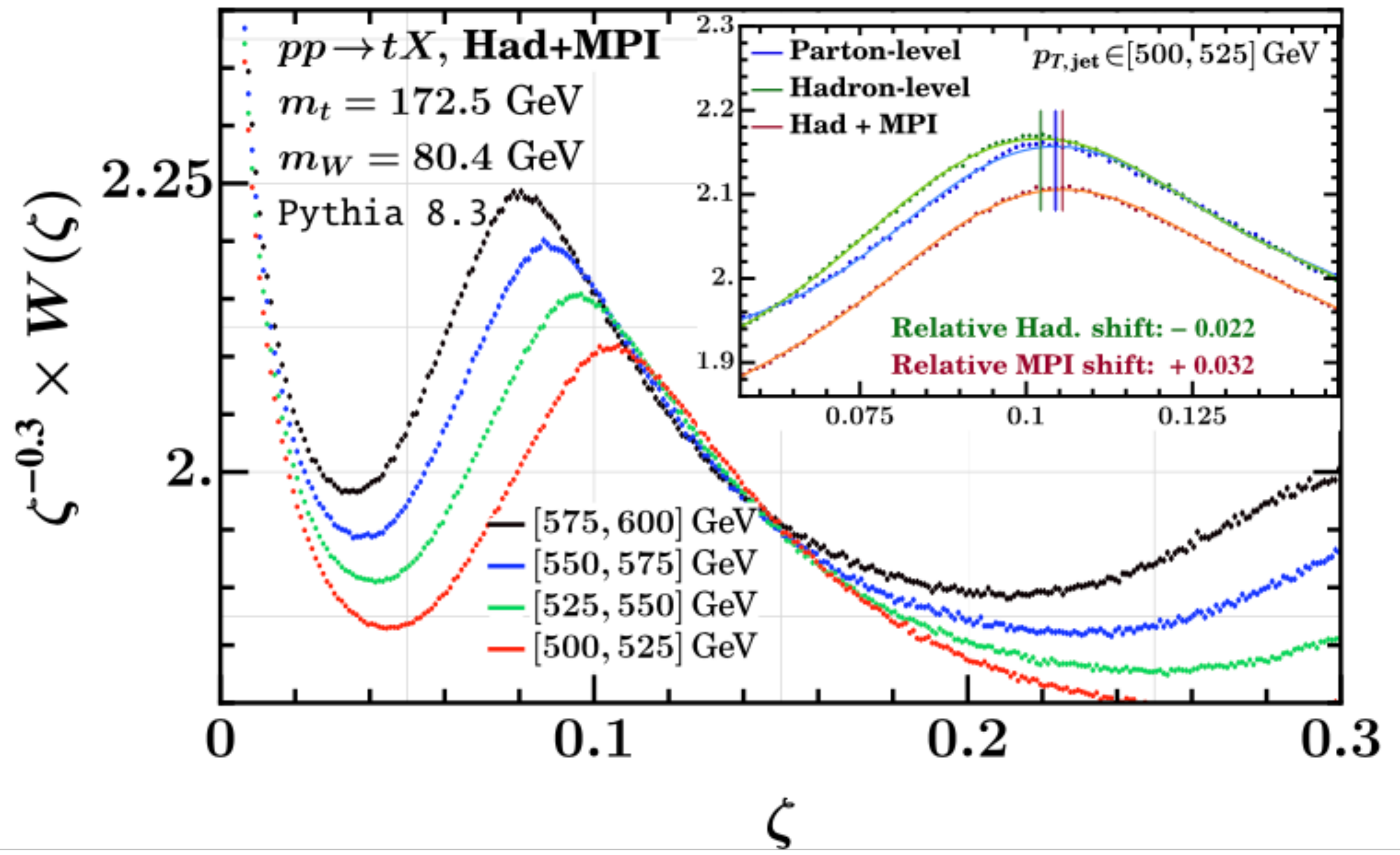
$$m_W/p_{T\,\text{jet}} \gg 10\,\Lambda_{\text{QCD}}/p_{T\,\text{jet}}.$$

But non-perturbative effects in the perturbative region grow as

$$\Lambda_{\text{QCD}}/(\zeta p_{T\,\text{jet}}).$$

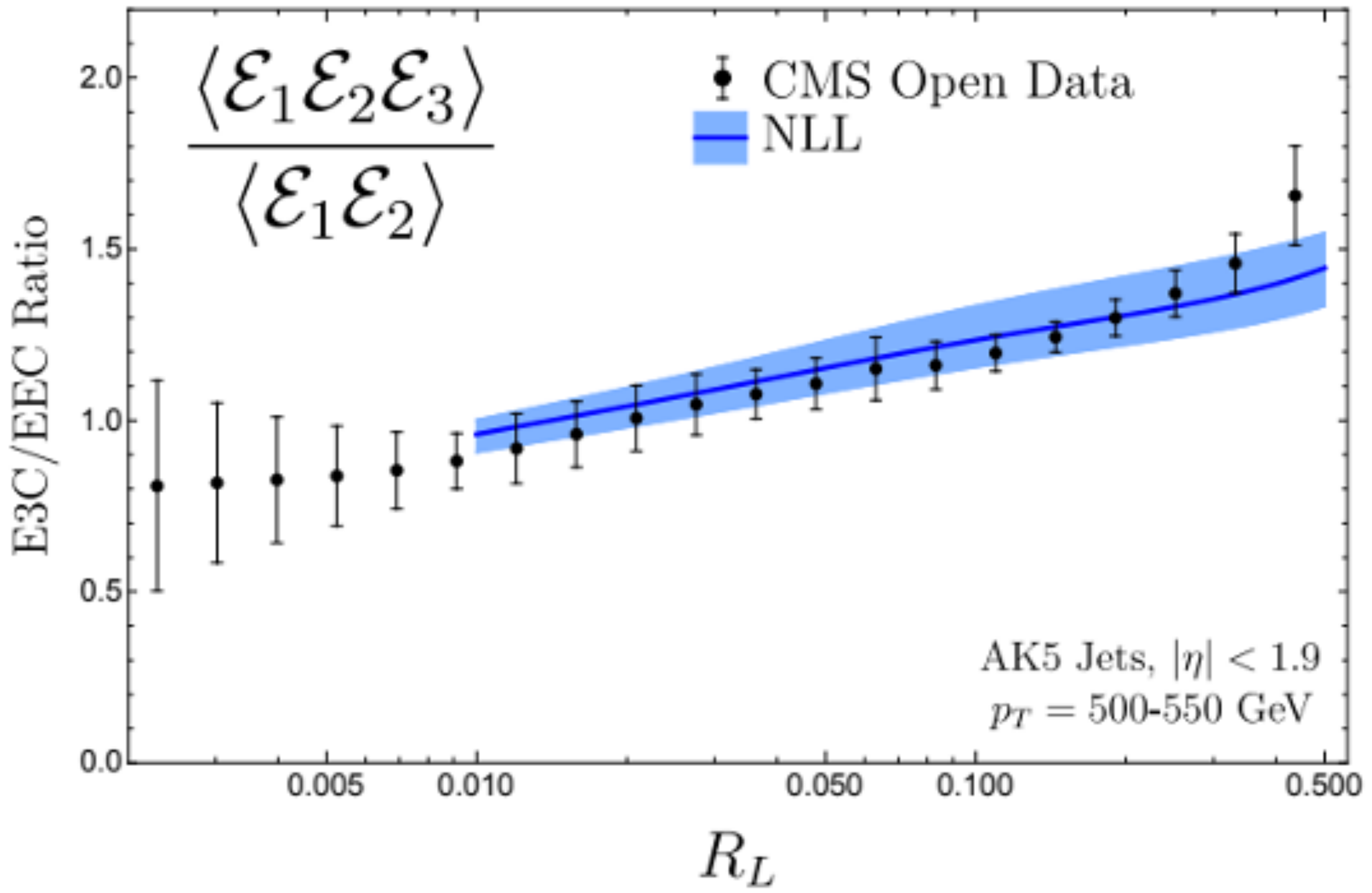
The standard candle

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



BUT there is a second Solution! Phew

It is well understood that on massless jets the hadronisation corrections between the squeezed limit of the 3-point correlator are correlated those in with the 2-point correlator K. Lee, B. Meçaj, I. Moult '22 [10]. This should also hold on massive jets...



The standard candle

The proposed measurement

The Proposed procedure is:

1. Measure the distributions:

$$W(\zeta) \text{ and } T\left(\zeta, 0.8\left(\frac{172[\text{GeV}]}{p_{T\,\text{jet}}}\right)^2, \left(\frac{172[\text{GeV}]}{p_{T\,\text{jet}}}\right)^2\right).$$

2. Simultaneously fit predictions for the spectra in terms of m_t and $p_{T\,\text{jet}}$ using prior measurements of m_W. This is an over-constrained system which allows m_t to be determined.

   i. Whilst we lack theory predictions, we instead find the peak positions (ζ_t, ζ_W) in the spectra. This is a constrained system in terms of m_t and $p_{T\,\text{jet}}$ using prior measurements of m_W.

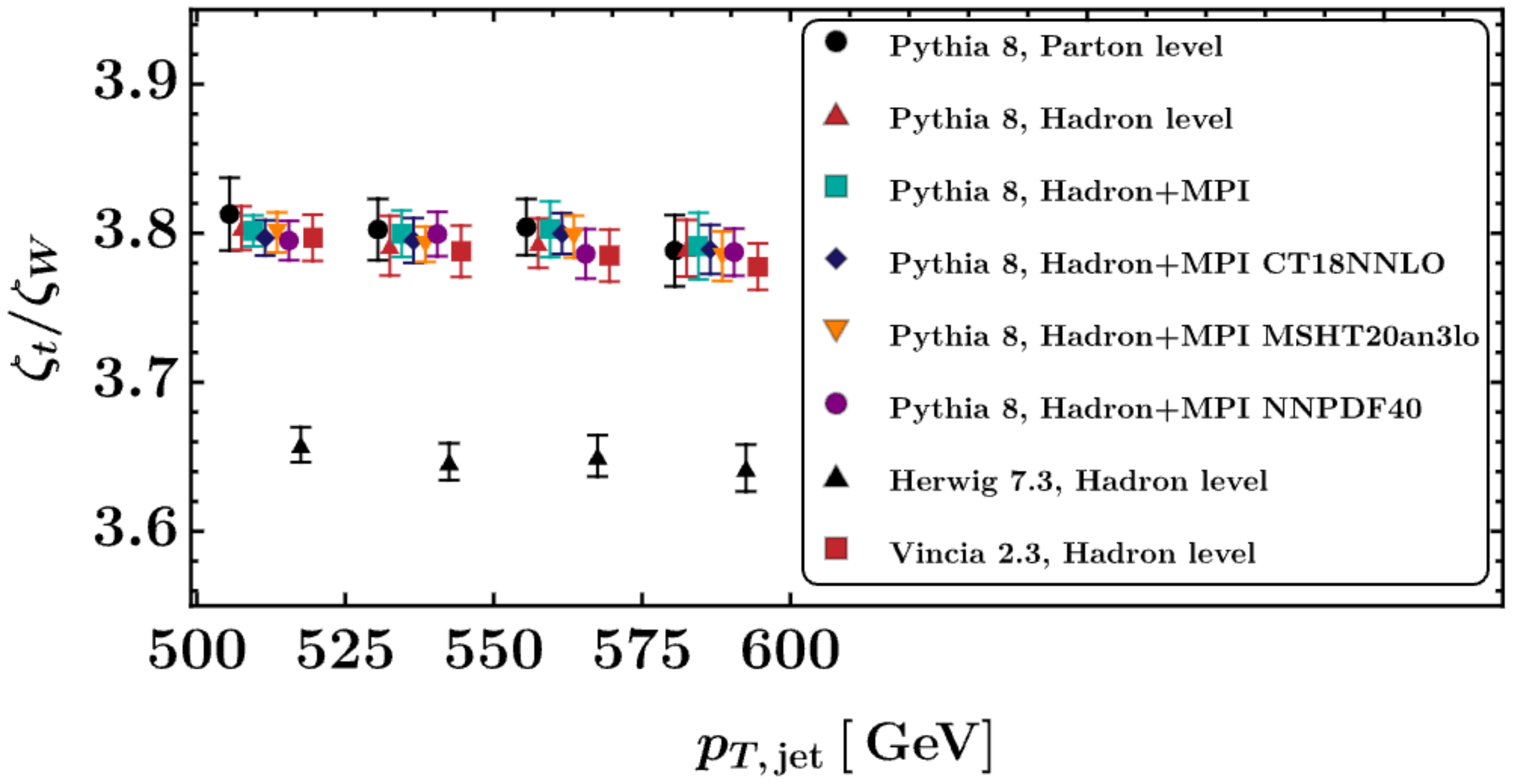
   ii. The top mass determined by $m_t = m_W\left(C(\alpha_s, R_{\text{jet}})\sqrt{\zeta_t/\zeta_W} + \mathcal{O}\left(\frac{m_t}{p_{T\,\text{jet}}}, \frac{m_W}{p_{T\,\text{jet}}}\right)\right)$.

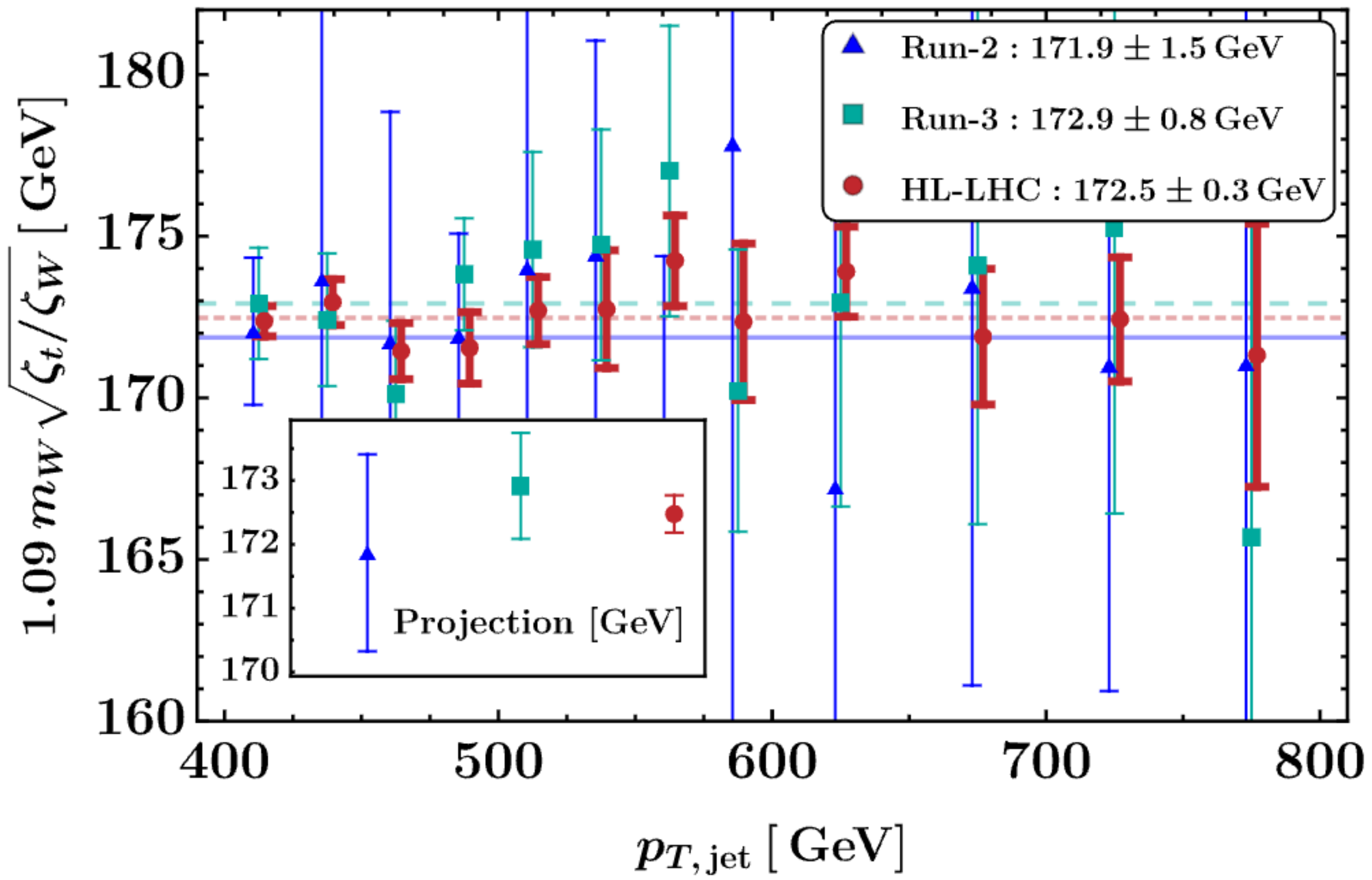
Experimental feasibility and event generator studies

Feasibility

Before going into the details of a full generator study, firstly, is it feasible?

Predicted sensitivity with current LHC data sets in ~800 MeV. With the HL-LHC, it is predicted that this can be improved to ~300 MeV. This is becoming competitive with direct measurements which are becoming systematically limited rather than statistically limited.



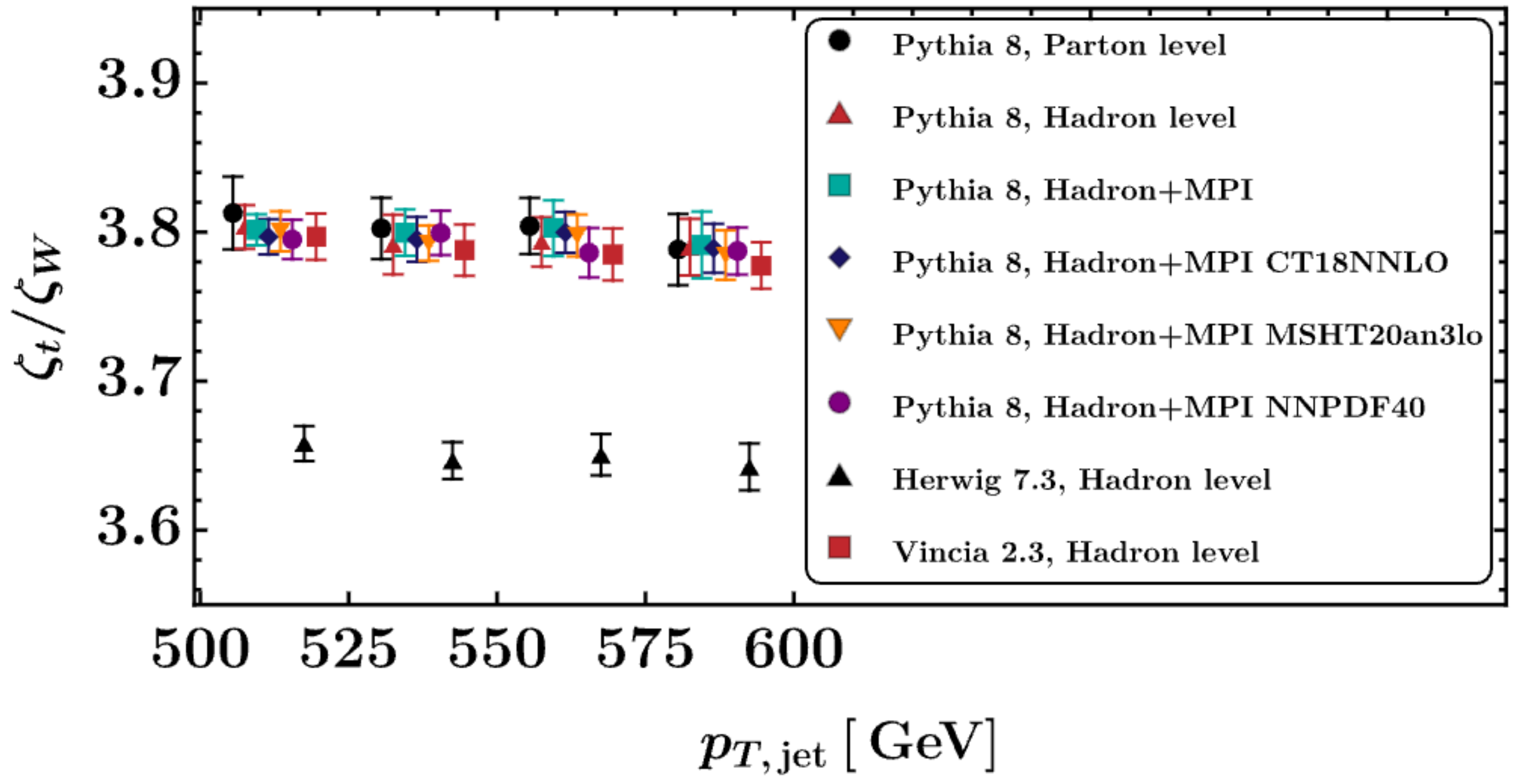


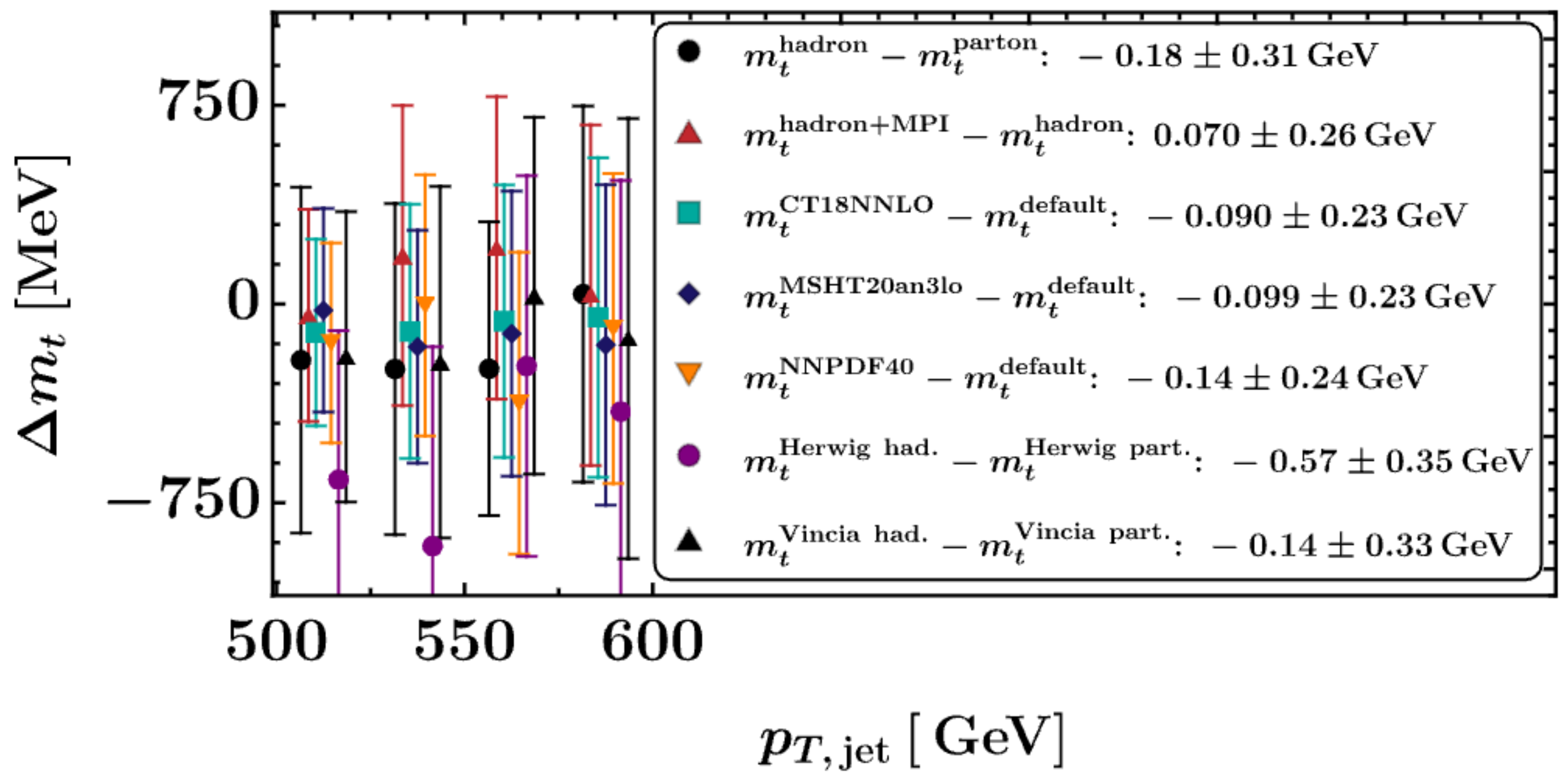
Experimental feasibility and event generator studies

More detail from a basic study:

A basic study finds that the proposed measurement is extremely robust again NP physics, including PDF uncertainties.

Herwig is lower than all other generators originating from a shift in the parton level prediction. The effect is about 1%. It occurs because the NLO correction to the top decay is handled only approximately by the parton shower and is different between the MCs, particularly between the angular ordered and dipole showers. This results in the showers predicting different values of $C(\alpha_s, R_{\rm jet})$.



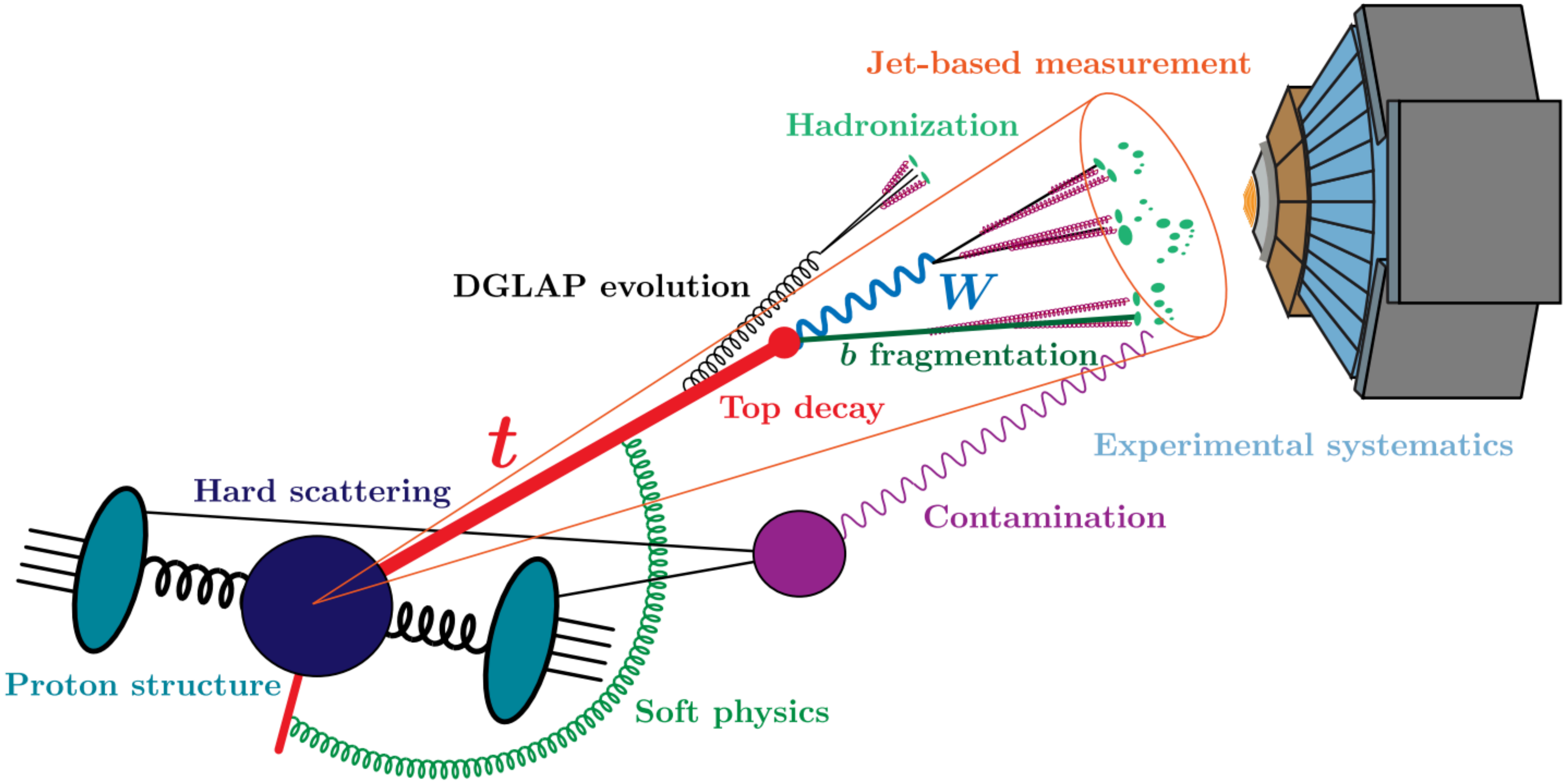


Experimental feasibility and event generator studies

A thorough study:

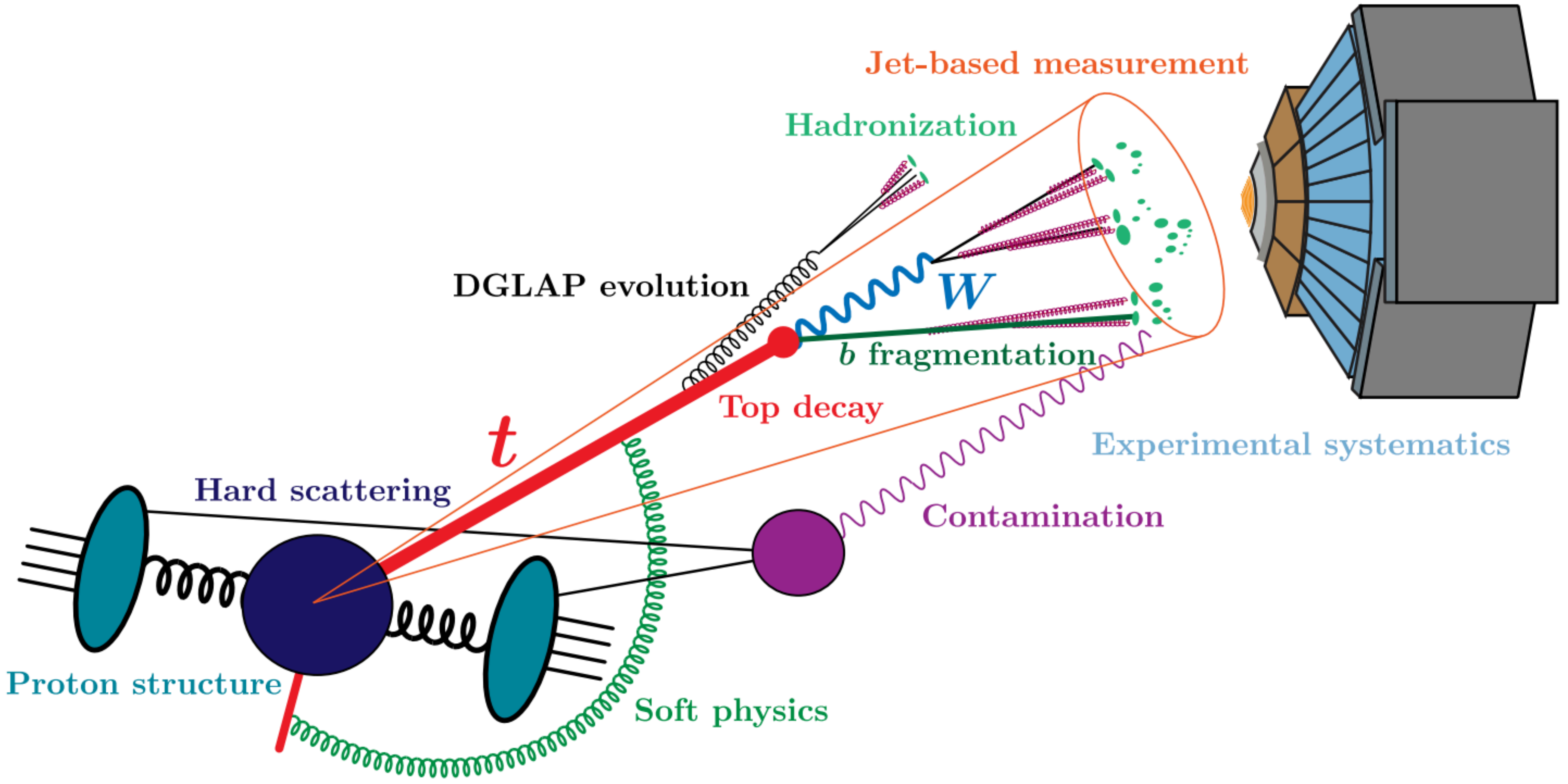
The basic study motivates that the measurement is possible and should be looked at seriously, with an eye towards anything that will hinder the maximum achievable precision.

The complete Event Generator study involves systematically studying the effect of each sub-process on the proposed measurement. We are looking for two things, to see resilience to the generator modelling (needed for unfolding), and minimal sensitivity to subprocesses which lack precise analytic control.



Experimental feasibility and event generator studies

A thorough study:



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

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

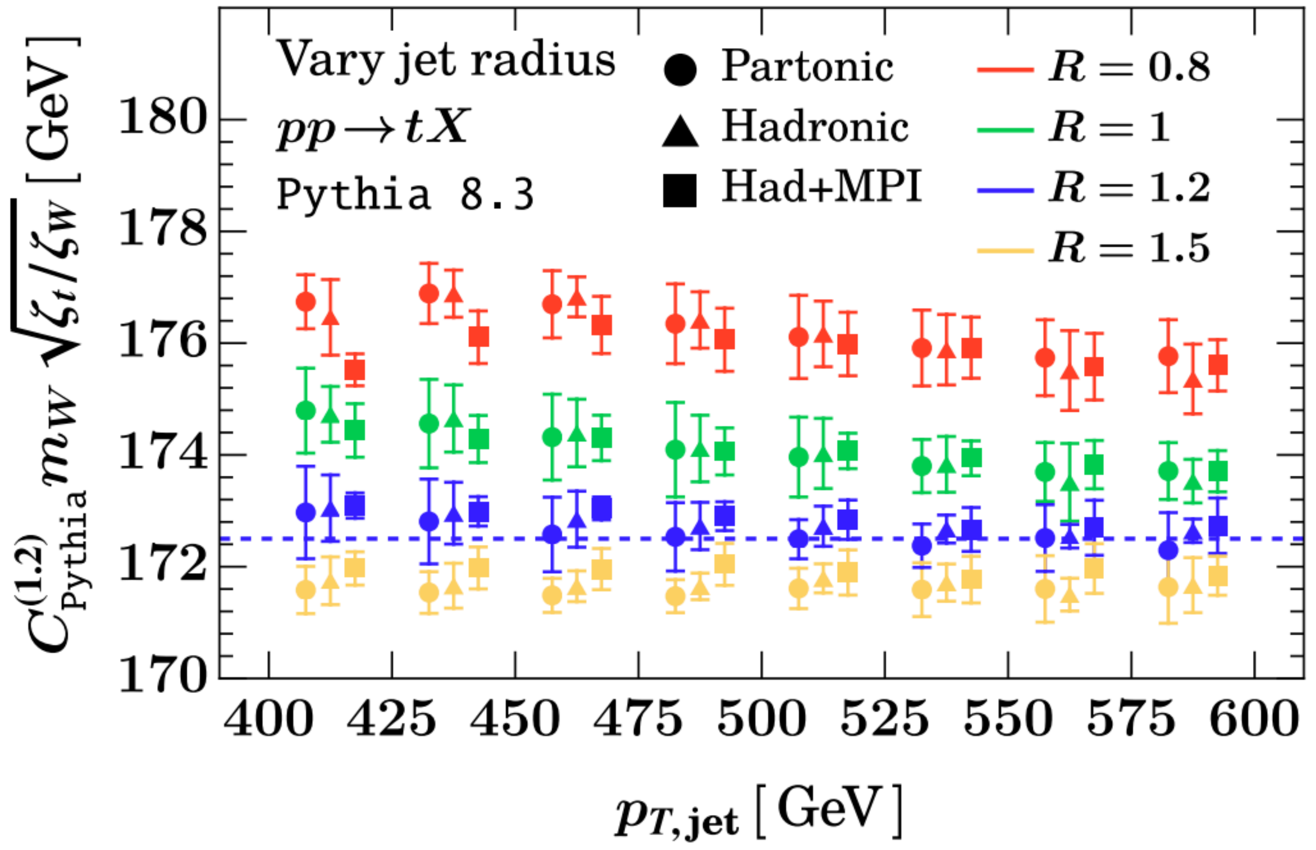
Experimental feasibility:
- Statistical sensitivity ☐
- Jet energy scale ☐
- Constituent energy scale ☐
- Track efficiency ☐
- Heavy flavor dependence ☐

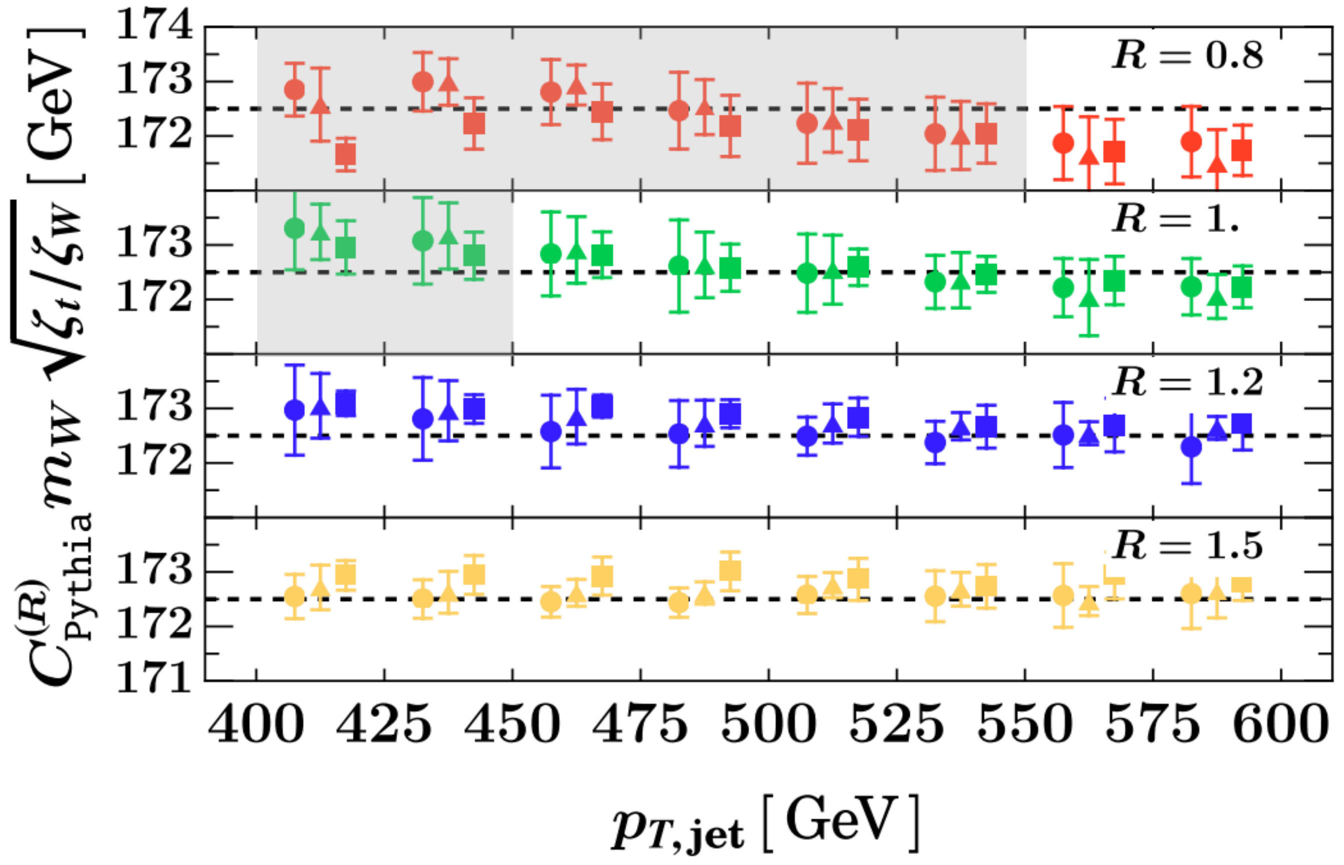
Experimental feasibility and event generator studies

Jet radius dependence:

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

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





The radius dependence is almost entirely perturbative

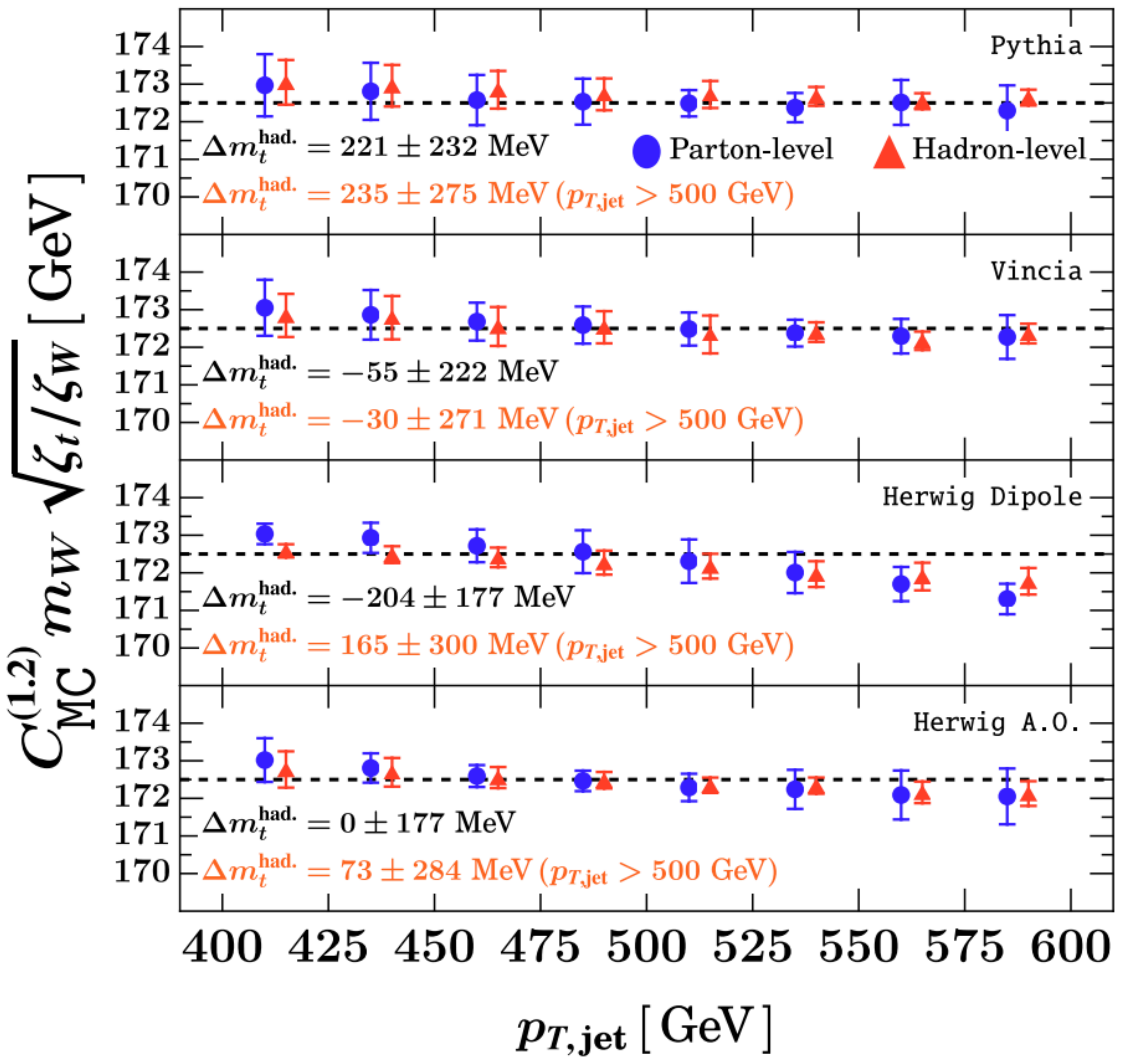
Production mechanism:
- PDF uncertainty ☐
- Hard scattering corrections ☐

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

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

Experimental feasibility and event generator studies

Hadronisation corrections:



Minimal sensitivity to hadronisation

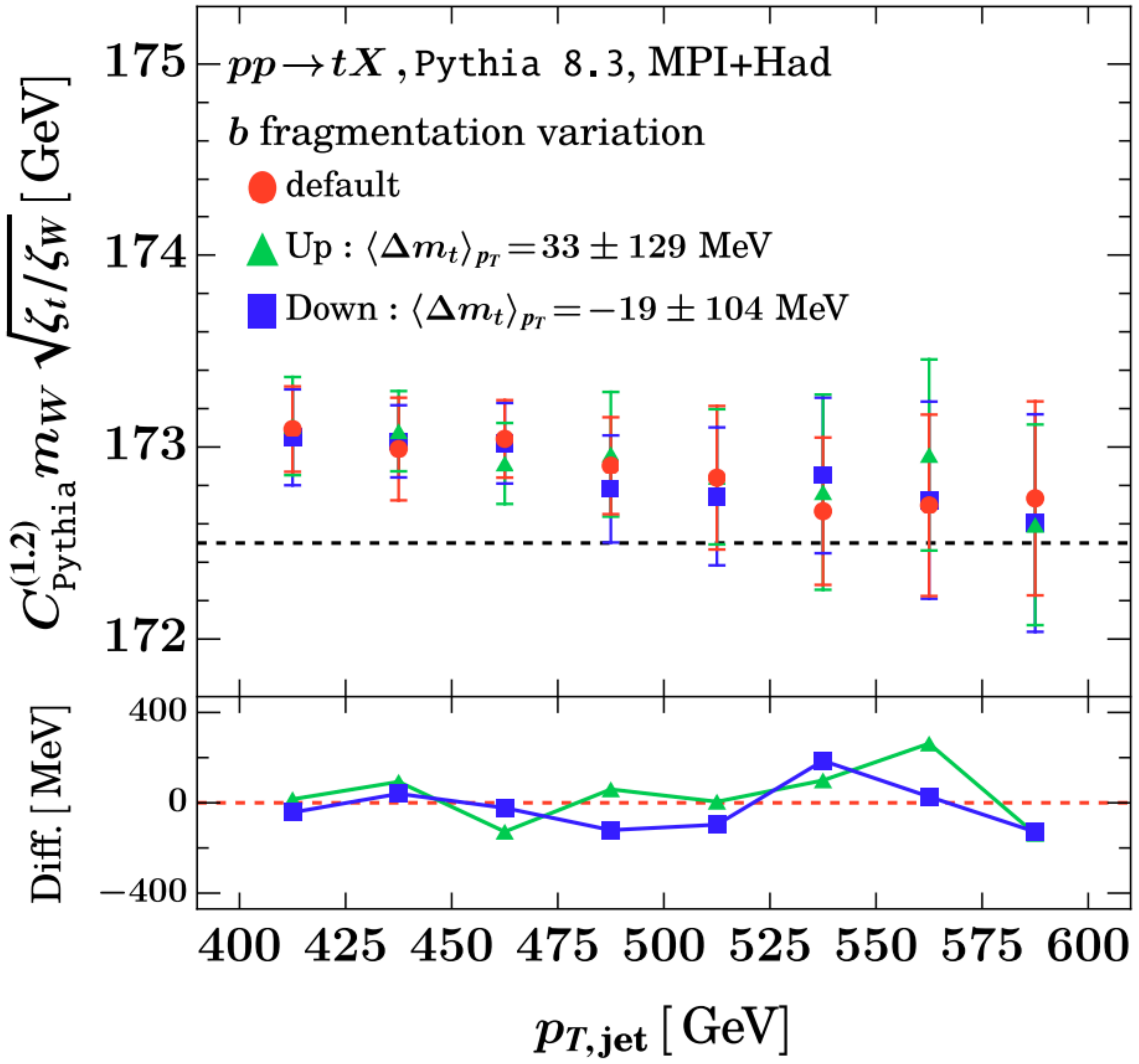
Production mechanism:
- PDF uncertainty ☐
- Hard scattering corrections ☐

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 ☐

Experimental feasibility and event generator studies

b fragmentation:



Virtually no effect from b fragmentation

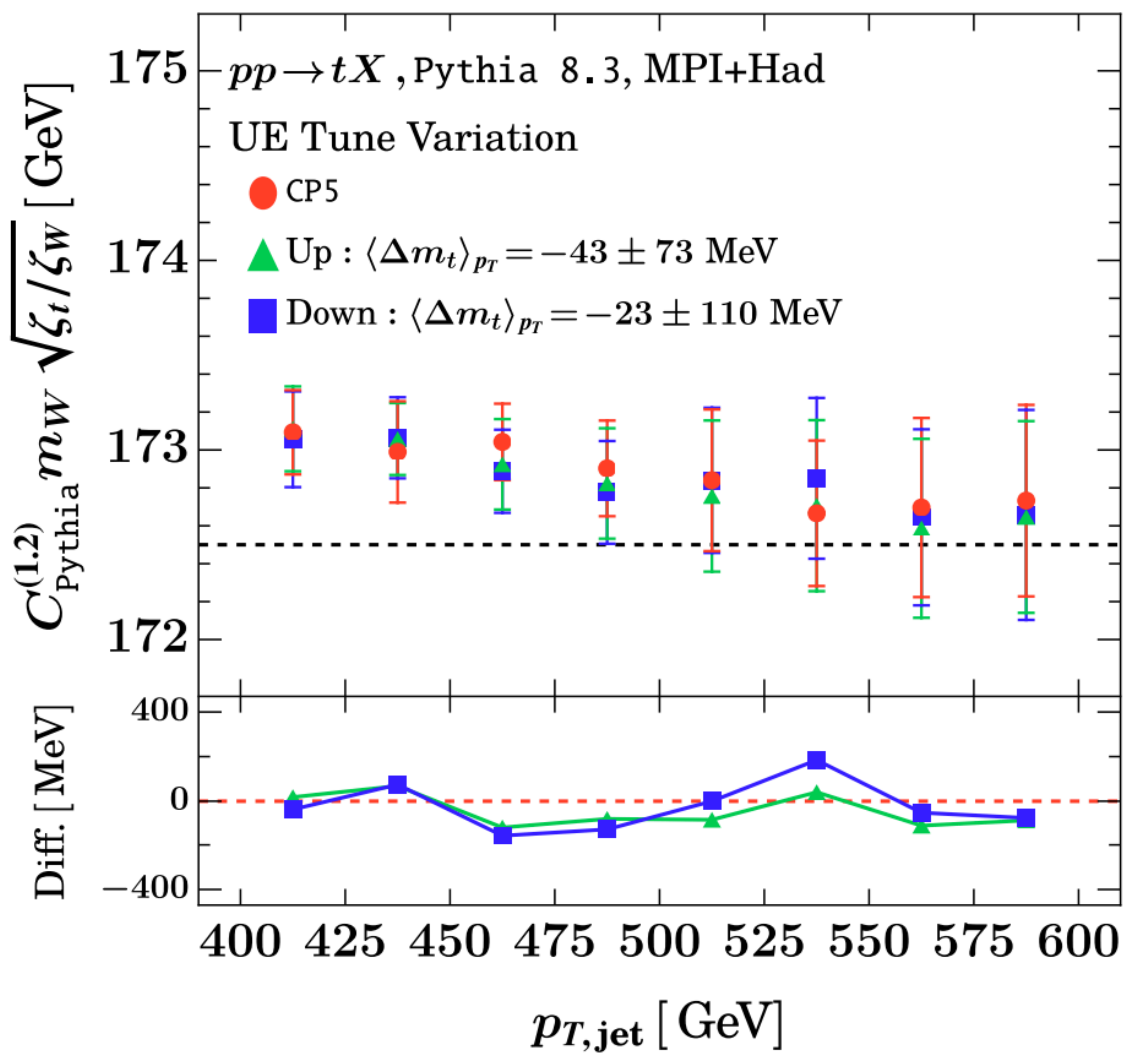
Production mechanism:
- PDF uncertainty ☐
- Hard scattering corrections ☐

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 ☐

Experimental feasibility and event generator studies

Underlying event:



Virtually no effect from underlying event

Production mechanism:

- PDF uncertainty ☐
- Hard scattering corrections ☐

Jet substructure:

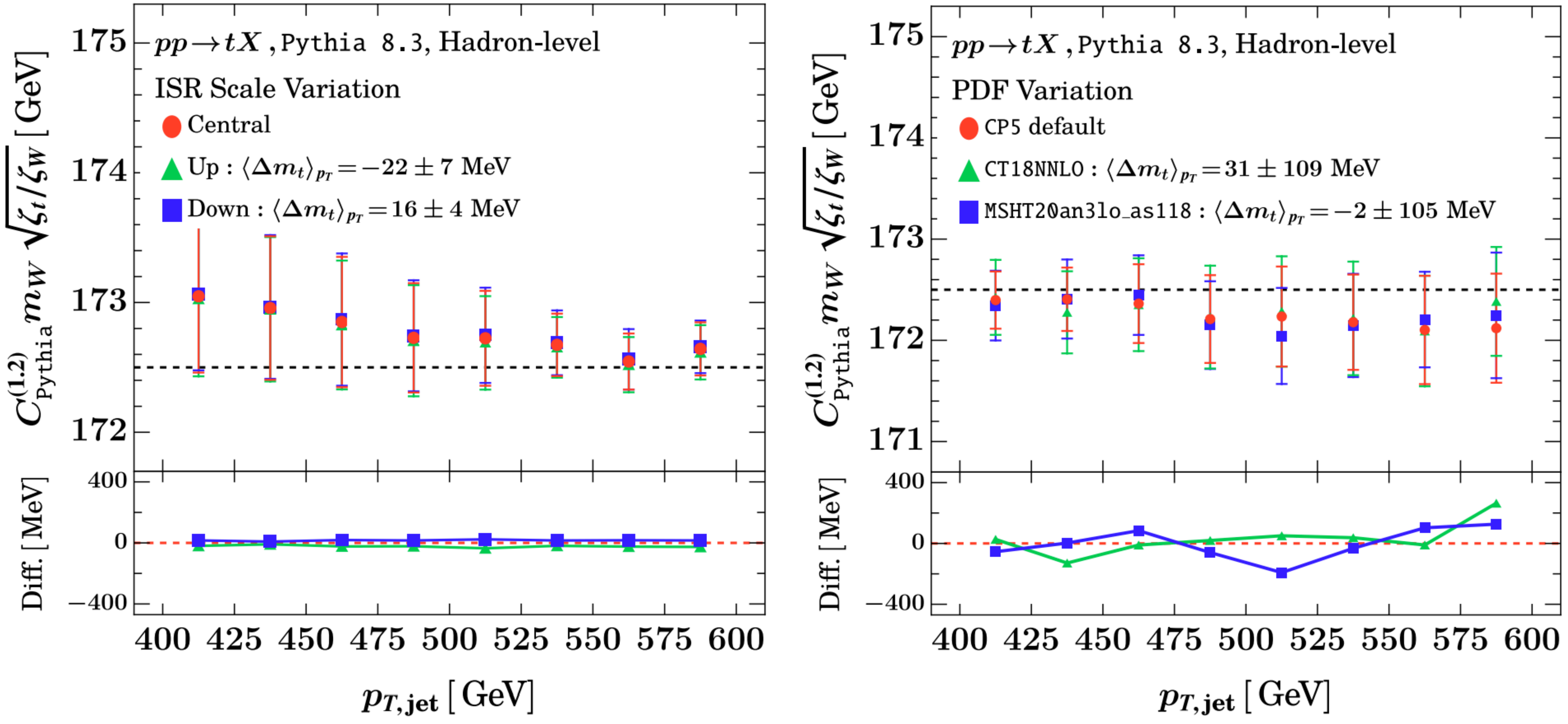
- Jet radius dependence ☑
- Hadronization effects ☑
- Impact of underlying event ☑
- Wide angle soft physics ☐
- Perturbative uncertainty ☐

Experimental feasibility:

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

Experimental feasibility and event generator studies

PDF and ISR uncertainty:



Virtually no effect from PDF or ISR variations

Production mechanism:

- PDF uncertainty ☑
- Hard scattering corrections ☐

Jet substructure:

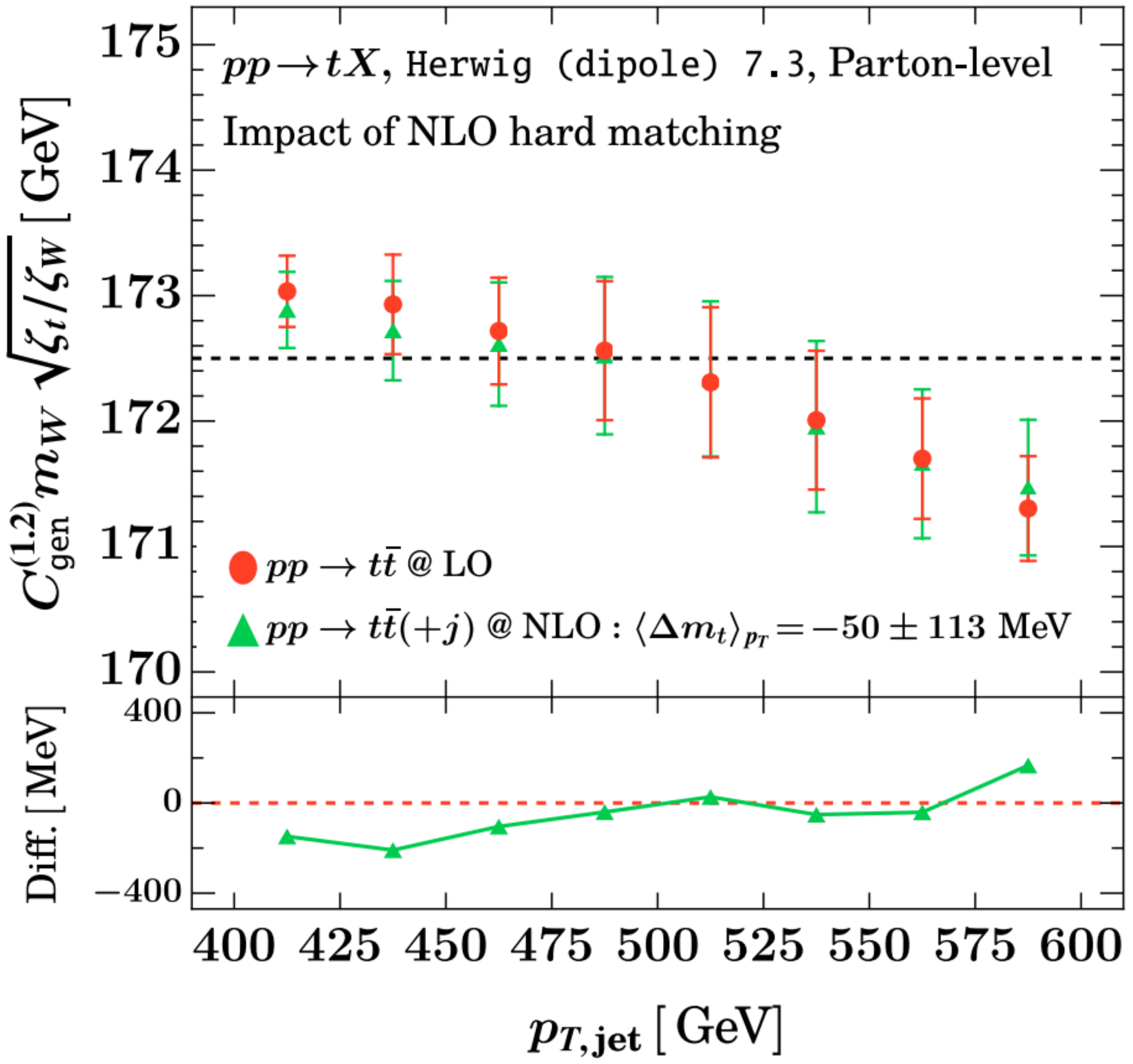
- Jet radius dependence ☑
- Hadronization effects ☑
- Impact of underlying event ☑
- Wide angle soft physics ☐
- Perturbative uncertainty ☐

Experimental feasibility:

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

Experimental feasibility and event generator studies

Hard process corrections:



Virtually no effect from Hard process corrections

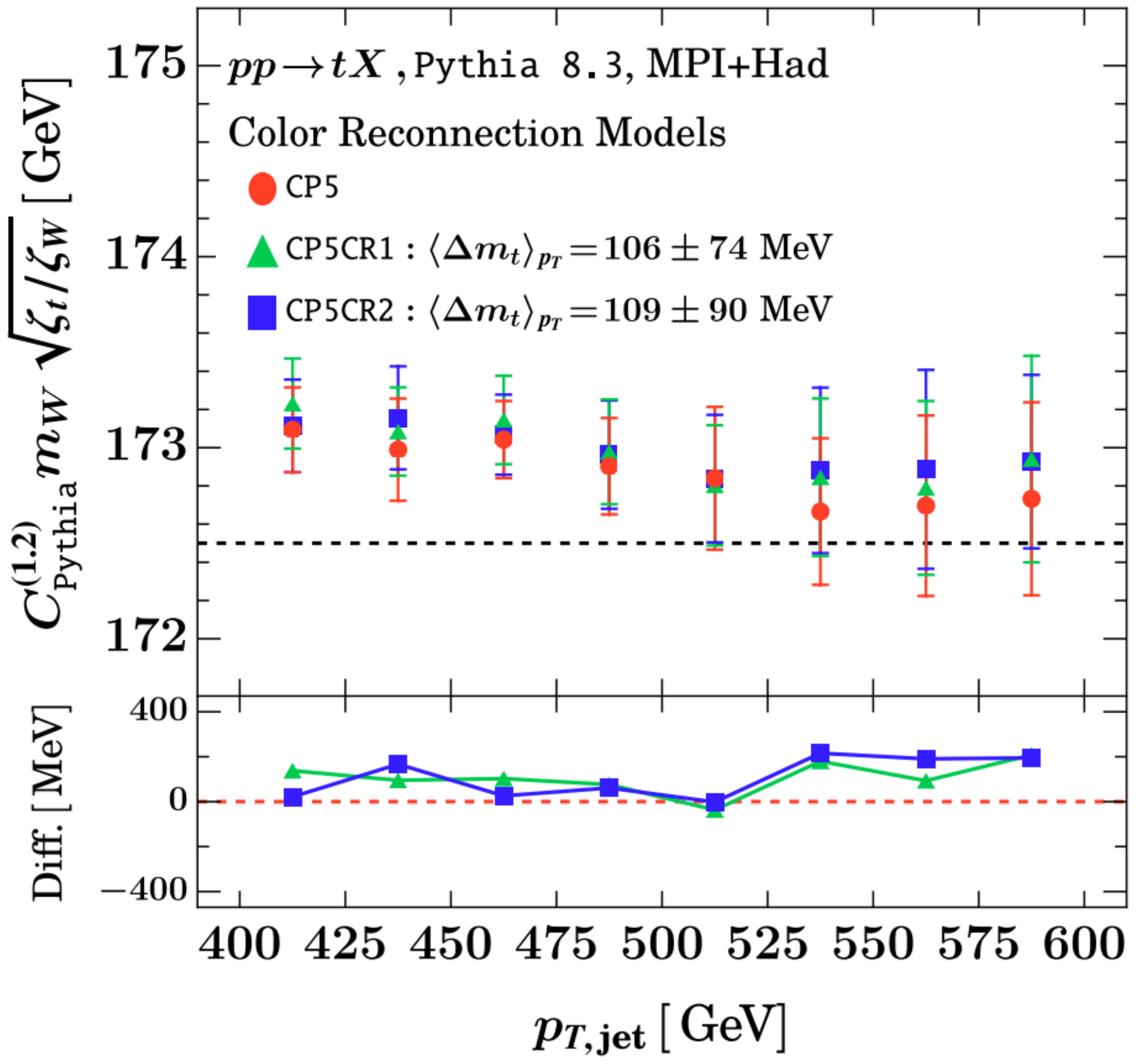
Production mechanism:
- PDF uncertainty ☑
- Hard scattering corrections ☑

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 ☐

Experimental feasibility and event generator studies

Colour reconnection:



Colour reconnection models simulate the effects of wide angle physics at non-perturbative scales. This impact here is again small.

Production mechanism:

- PDF uncertainty ☑
- Hard scattering corrections ☑

Jet substructure:

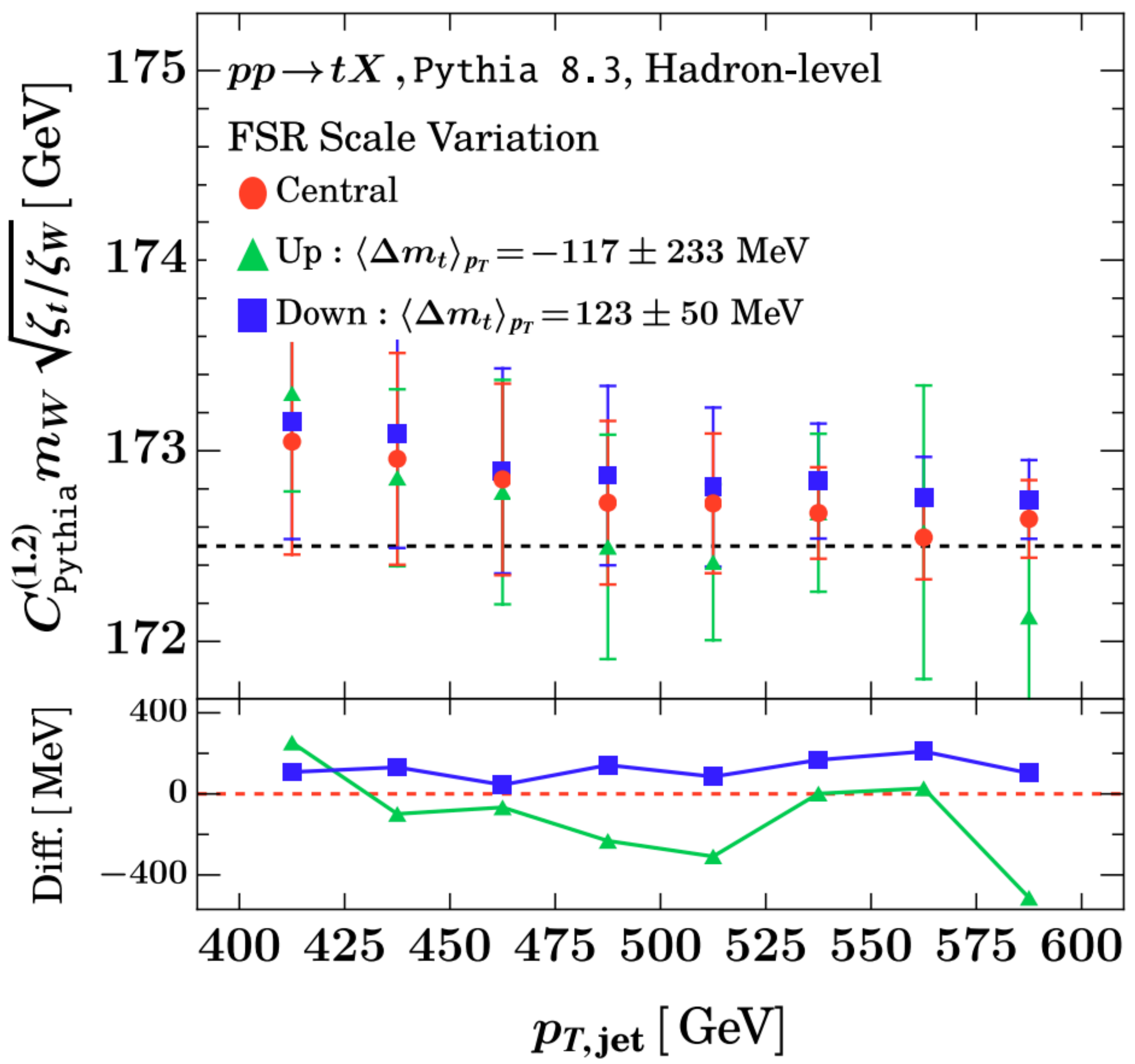
- Jet radius dependence ☑
- Hadronization effects ☑
- Impact of underlying event ☑
- Wide angle soft physics ☑
- Perturbative uncertainty ☐

Experimental feasibility:

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

Experimental feasibility and event generator studies

FSR scale variation:



FSR scaling variation approximates an error from the resummations performed in the parton shower. It is again small.

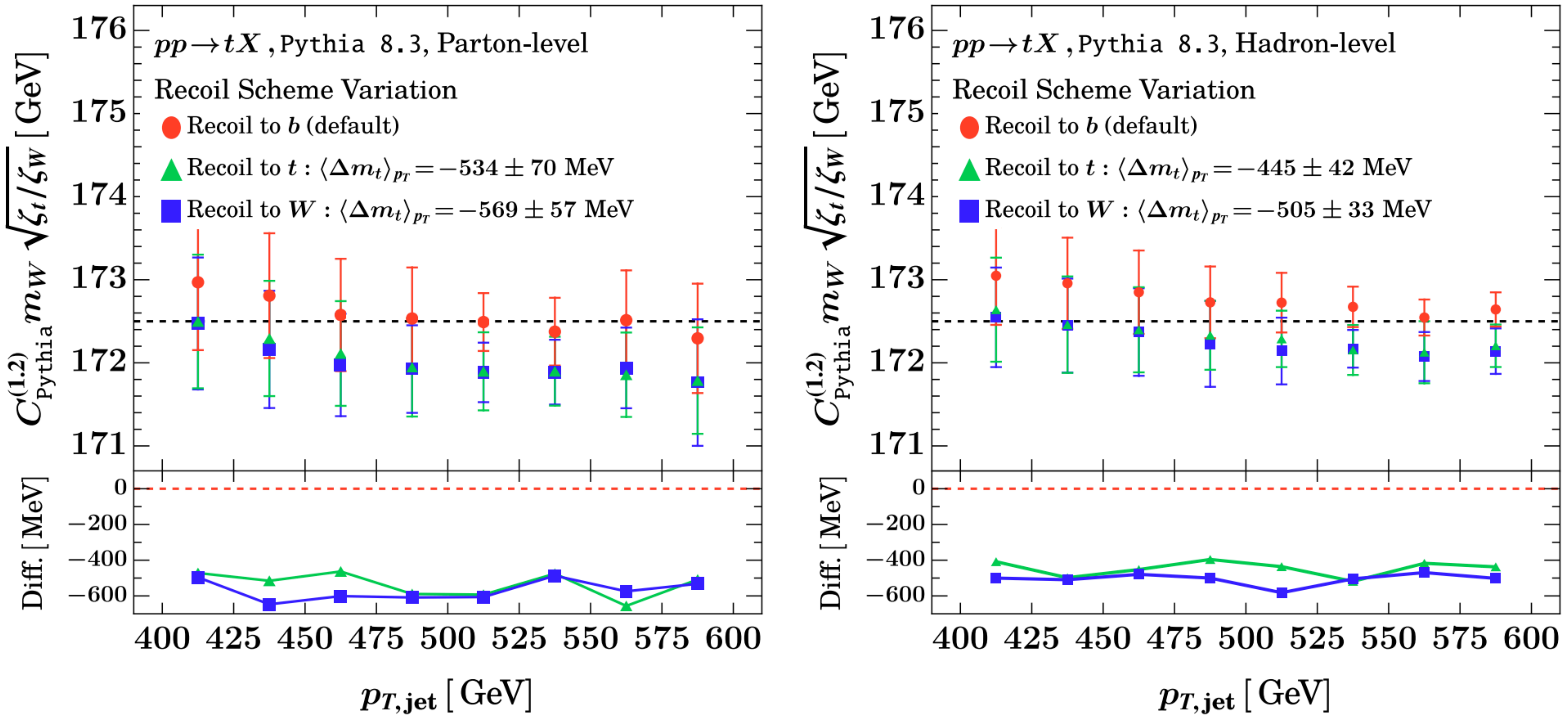
Production mechanism:
- PDF uncertainty ☑
- Hard scattering corrections ☑

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 ☐

Experimental feasibility and event generator studies

Recoil to the top:



Recoil to the top approximates the NLO effects of momentum conservation in the top decay. Here effects are sizeable but purely perturbative. I'll come back to this very shortly…

Production mechanism:

- PDF uncertainty ☑
- Hard scattering corrections ☑

Jet substructure:

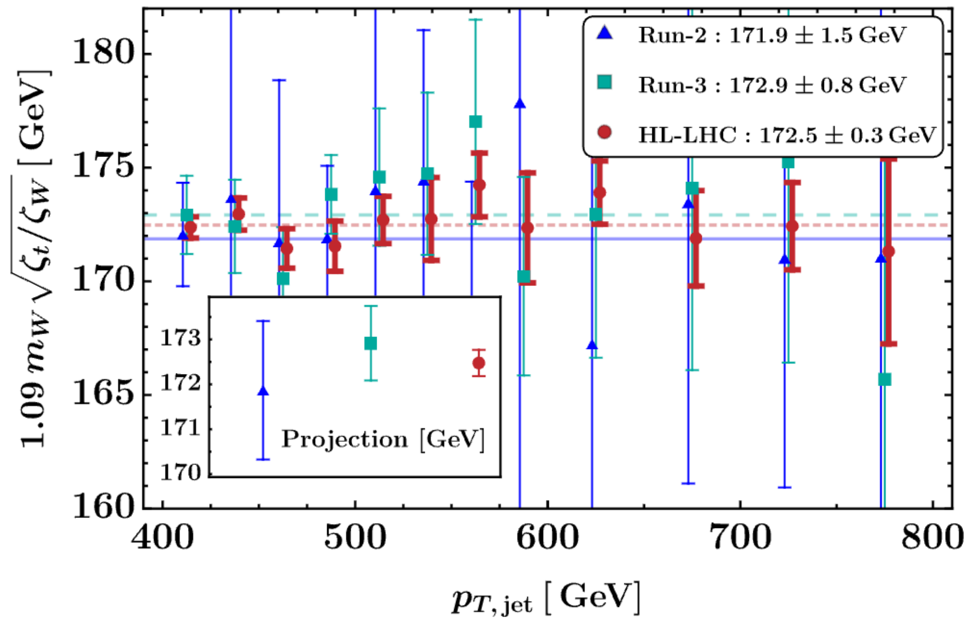
- Jet radius dependence ☑
- Hadronization effects ☑
- Impact of underlying event ☑
- Wide angle soft physics ☑
- Perturbative uncertainty ☑

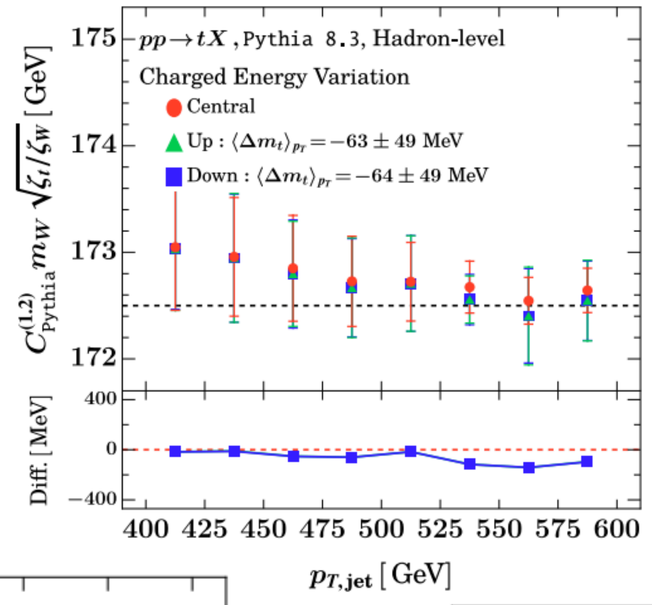
Experimental feasibility:

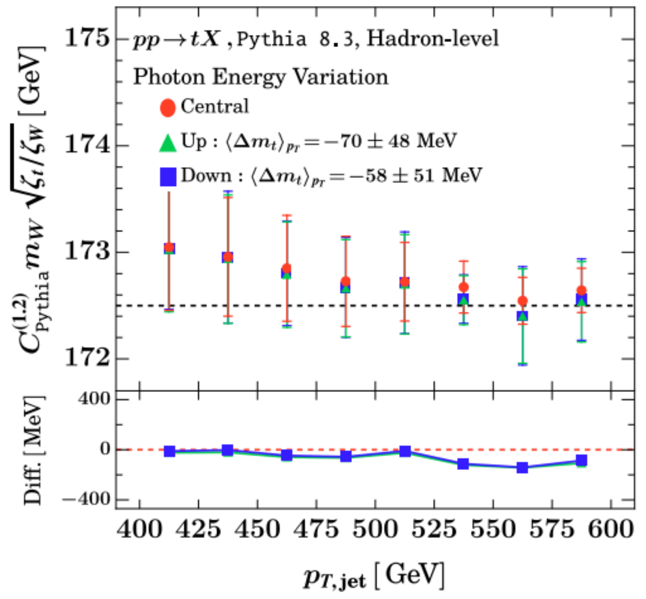
- Statistical sensitivity ☐
- Jet energy scale ☐
- Constituent energy scale ☐
- Track efficiency ☐
- Heavy flavor dependence ☐

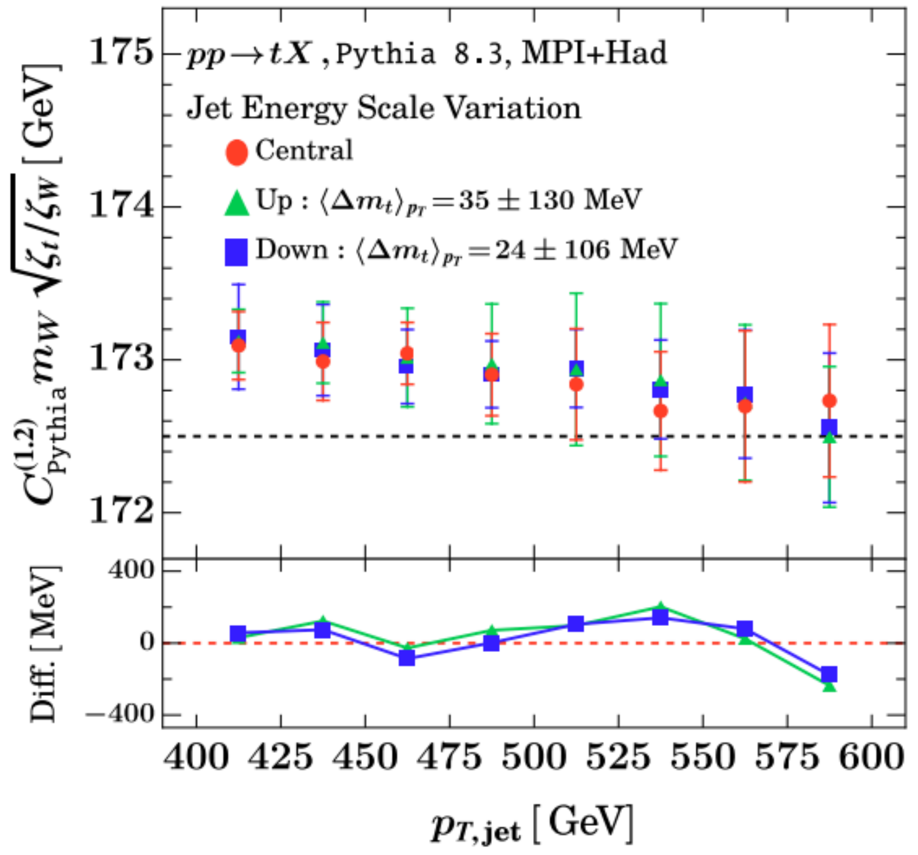
Experimental feasibility and event generator studies

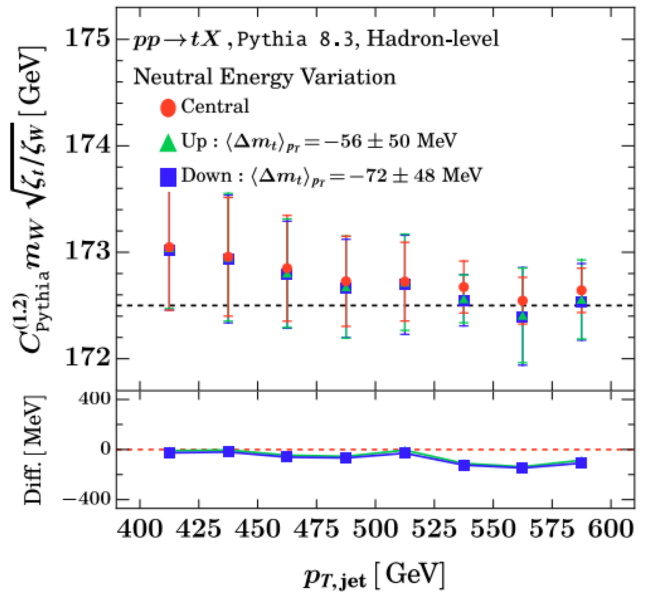
Experimental effects:

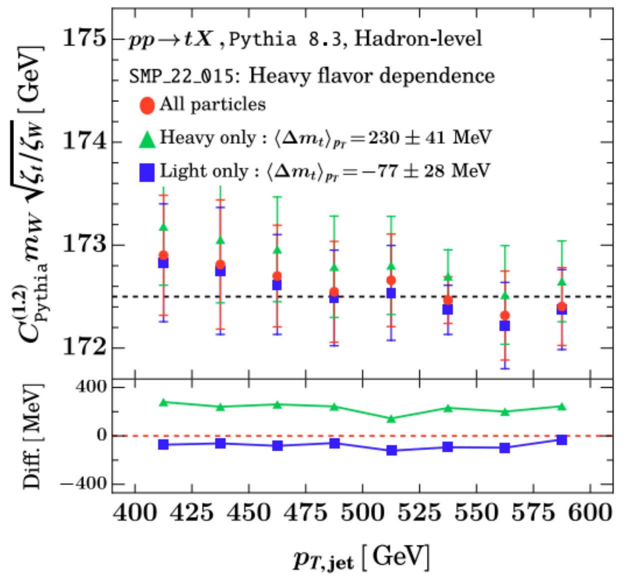


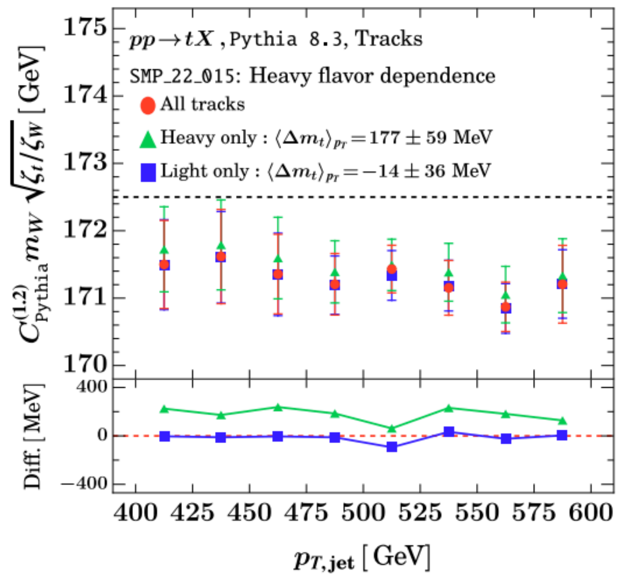


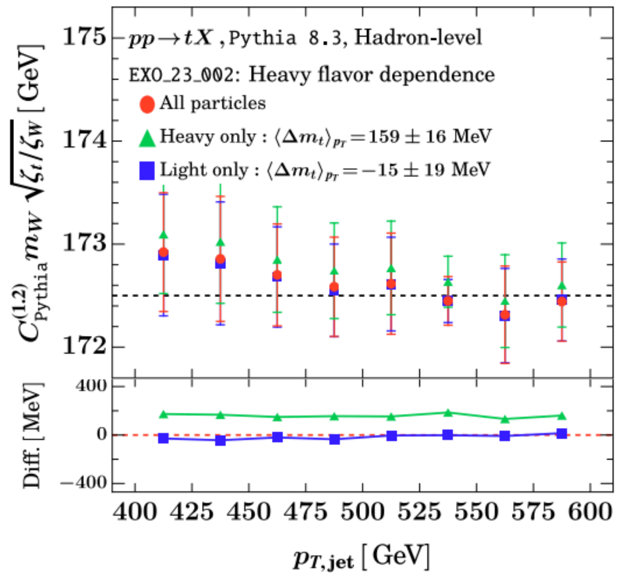


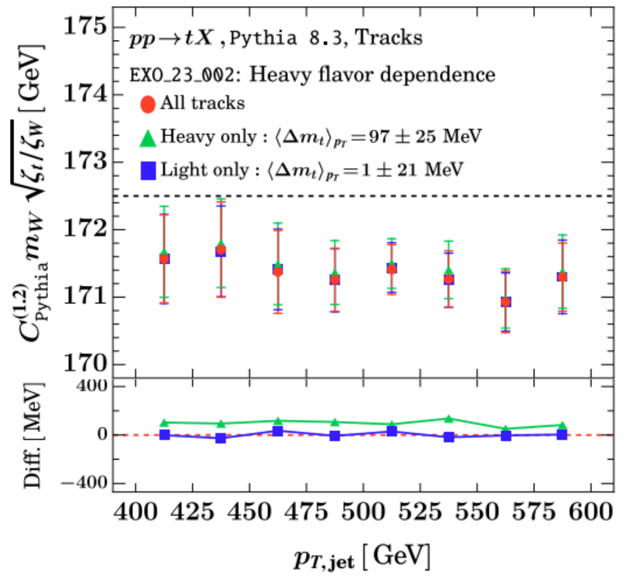


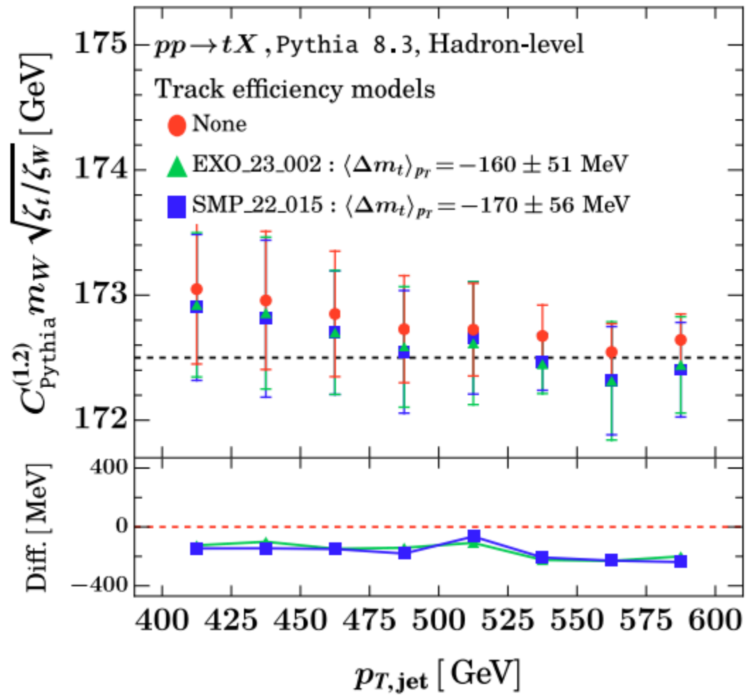


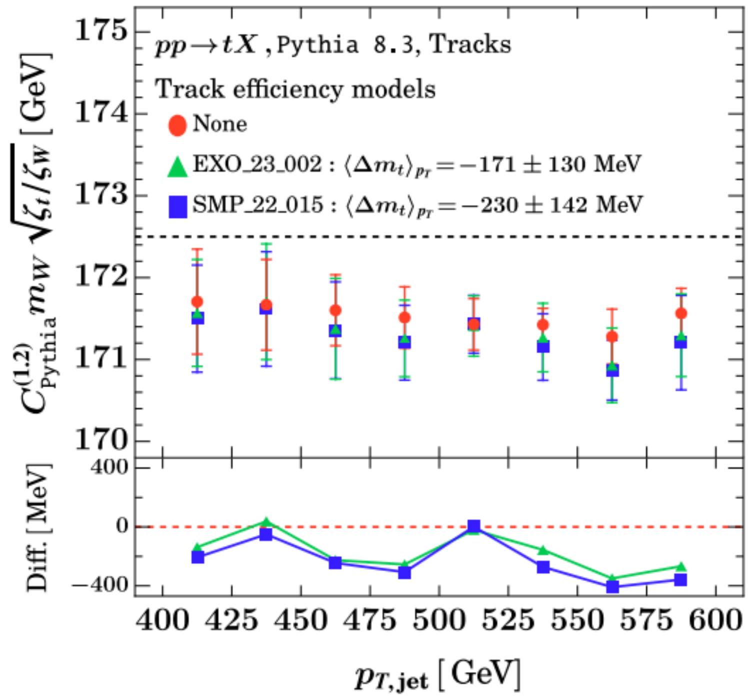












Production mechanism:

- 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 ☑

Experimental feasibility and event generator studies

Returning to perturbative uncertainty...

We have observed two key sub-processes that do strongly influence the predicted top mass:

1. The parton shower ordering variable (dipole-k_t vs angular ordered).

2. Recoil schemes for radiation from the top decay in the parton shower.

Do these have a common source?

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 ☑

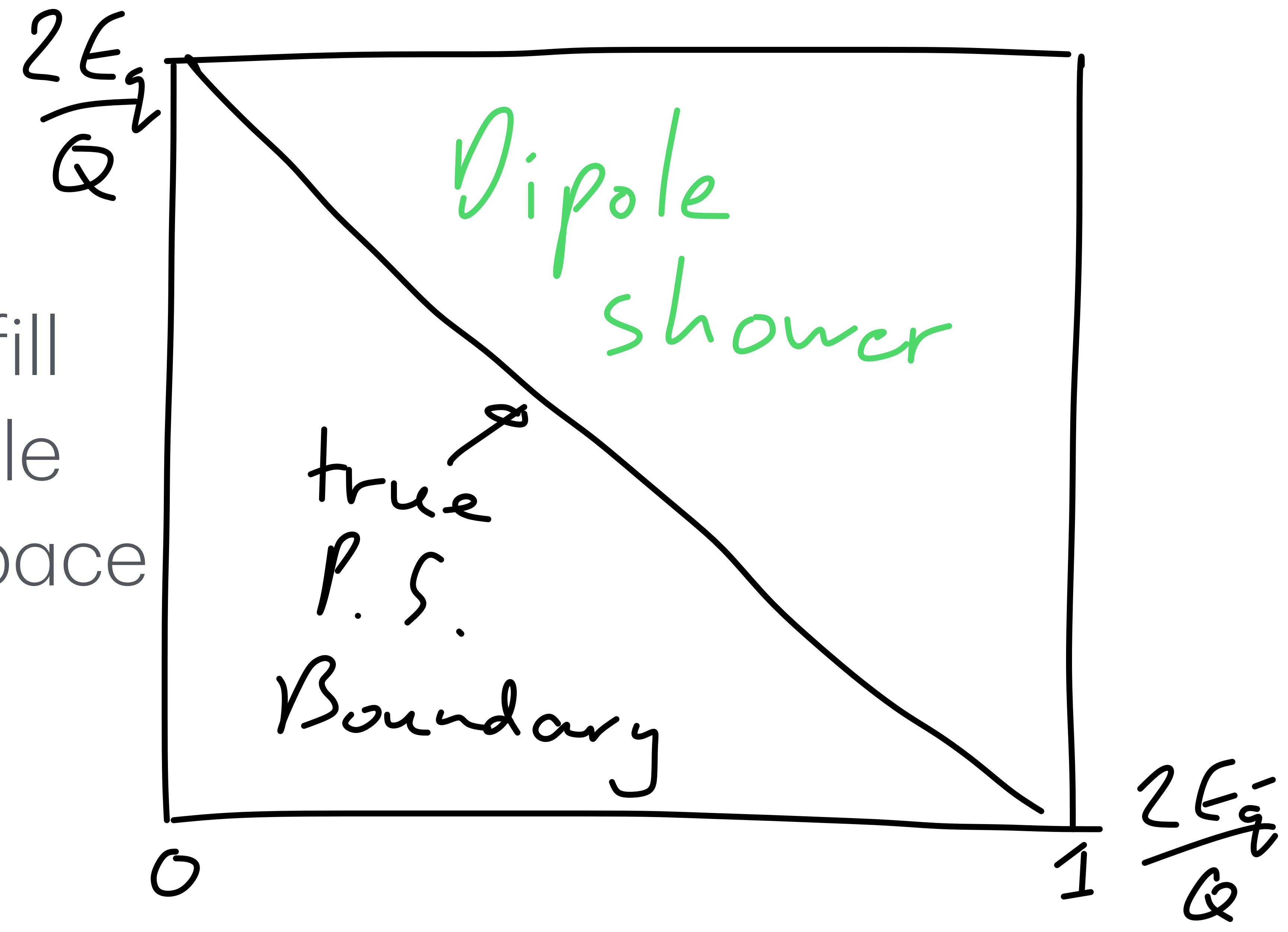
Experimental feasibility and event generator studies

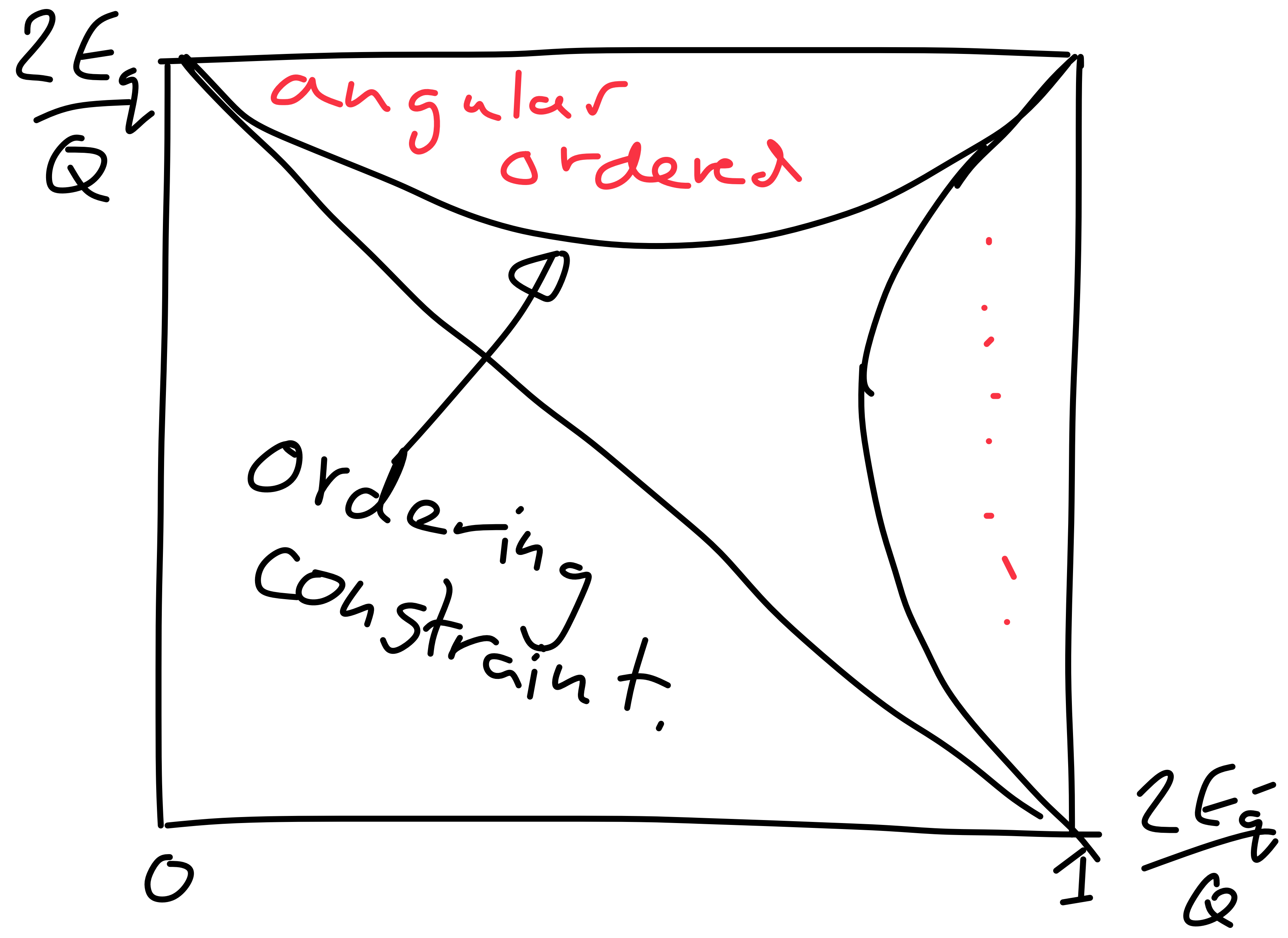
Returning to perturbative uncertainty...

1. The parton shower ordering variable (dipole-k_t vs angular ordered).

In a collinear dominated observable, the logarithmic accuracy of a well constructed dipole-k_t shower and an angular ordered shower should be equivalent. Where they differ drastically is in the non-logarithmic regions of the phase-space, particularly the phase-space of the first emission.

Consider $e^+e^- \to q\bar{q}g$
Angular ordering does not fill the NLO phase space. Dipole showers do fill the phase space but with incorrect matrix elements away from the divergent boundaries.



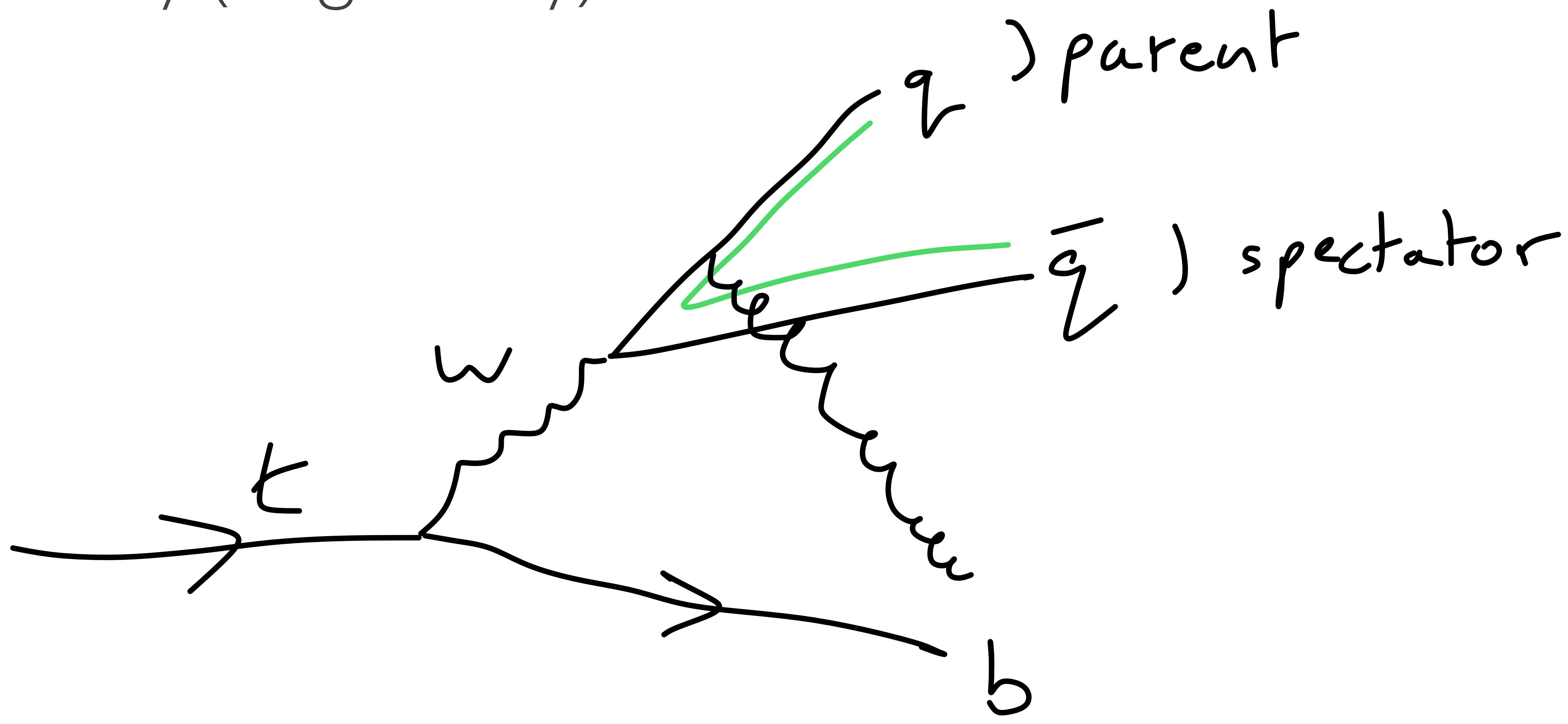


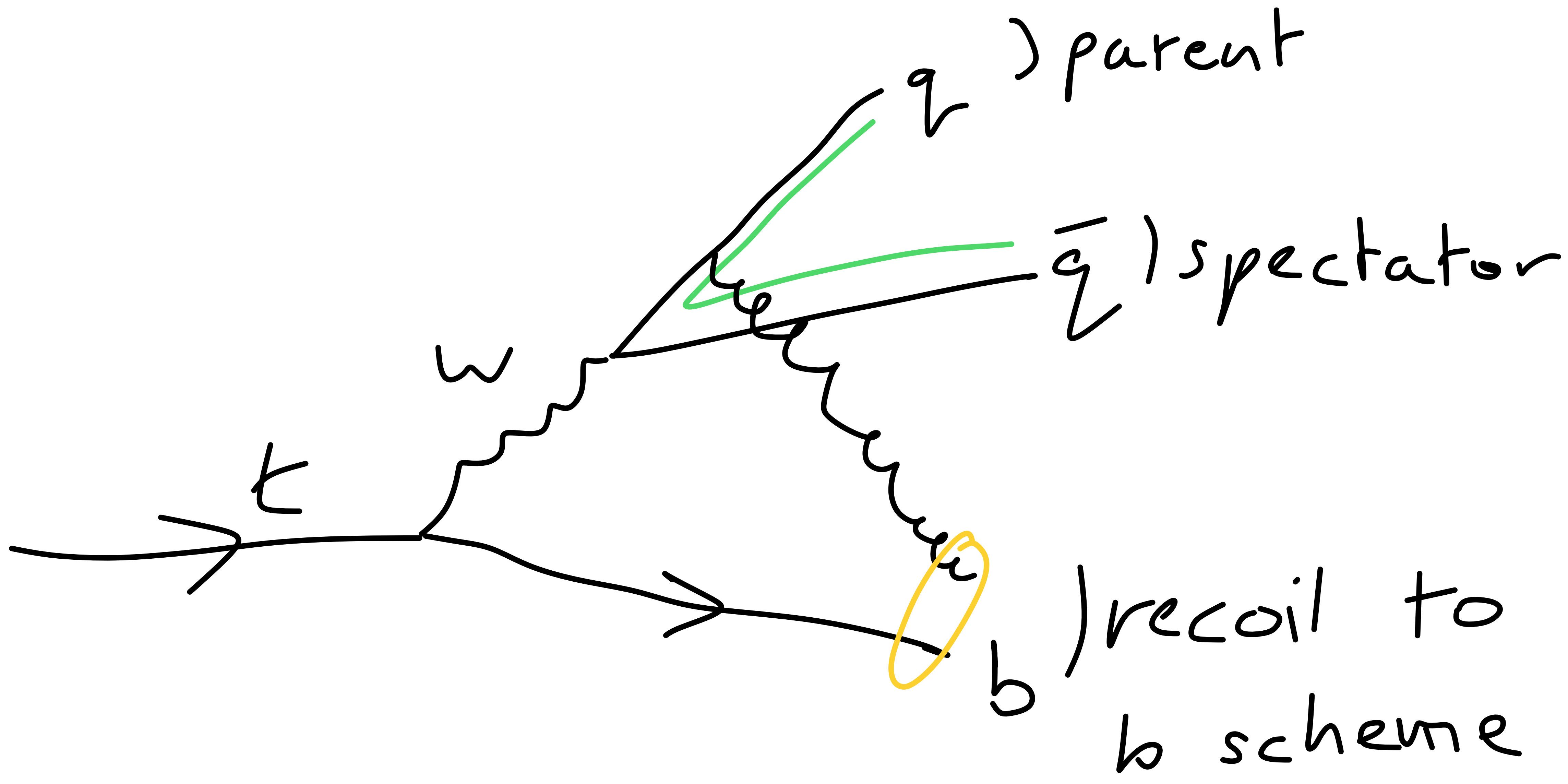
Experimental feasibility and event generator studies

Returning to perturbative uncertainty...

2. Recoil schemes for radiation from the top decay in the parton shower.

As I have already mentioned, this attempts to model the NLO phase-space of a top decay by sharing the momentum conservation across the decay products rather than completely locally (or globally).





Experimental feasibility and event generator studies

In summary:

The proposed EEC top mass measurement is exceptionally resilient to experimental systematics. It also is resilient to backgrounds, soft and non-perturbative physics.

However, it is crucially sensitive to the perturbative top decay! Presently, out-the-box generators only handle this at LO. Every significant discrepancy in the Event Generator analysis can be traced back to this.

However, high accuracy calculations (up to NNLO [11]) of the top decay are available and can be implemented into analytical predictions.

We expect the largest effect originates at NLO. We are doing an angular measurement and NLO is the first order where the angles in the decay are not completely constrained by momentum conservation.

A test case: energy correlators on boosted Z-jets

As I've repeated illustrated, top jets are exceedingly complex objects. Whilst computing the proposed observable with high accuracy is definitely achievable within modern methods (factorisation, HQET, SCET), it is not an easy calculation.

Before going straight to the top quark, let us consider a simpler test case. To this end, we consider Z-jets. Z bosons are colour neutral and have a simple 2-body LO decay. Nevertheless, they can teach the core mechanisms behind given features in the EEC spectrum on a boosted massive jet.

To start with we will consider measurements of the 2-point correlator on inclusive Z-jets in e^+e^-.

A test case: energy correlators on boosted Z-jets

Schematic Factorisation of the 2-point correlator:

Substructure on boosted Z jets obey exceptionally simple factorisation properties. The inclusive Z-jets cross-section (with radius R) at leading power is:

$$\Sigma(R) = \int_0^1 \mathrm{d}y \, J_{\mathrm{jet}}\left(\frac{x}{y}, \ln\frac{y^2R^2Q^2}{\mu^2}\right) H\left(y, \frac{Q^2}{\mu^2}, \mu\right)\left(1 + \mathcal{O}(R^2) + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{RQ}\right) + \mathcal{O}\left(\frac{M_Z^2}{Q^2}\right)\right).$$

K. Lee, I. Moult, X. Zhang '24 [12]

Which re-factorises as a inclusive substructure EEC measurement as

$$\frac{\mathrm{d}\Sigma(R)}{\mathrm{d}\theta} = \int_0^1 \mathrm{d}x\mathrm{d}y \; x^2 J_{\mathrm{EEC}}(x, \mu^2, \theta^2, Q^2, M_Z)\, J_{\mathrm{jet}}\left(\frac{x}{y}, \ln\frac{y^2R^2Q^2}{\mu^2}\right) H\left(y, \frac{Q^2}{\mu^2}, \mu\right)\left(1 + \text{subleading power}\right).$$

A test case: energy correlators on boosted Z-jets

Schematic Factorisation of the 2-point correlator:

At leading order in α_{EW} the convolutions fully collapse and J_{jet} becomes trivial so that:

$$\frac{\mathrm{d}\Sigma(R)}{\mathrm{d}\theta} = J_{\mathrm{EEC}}(1,\mu^2,\theta^2,Q^2,M_Z)\, H\left(1,\frac{Q^2}{\mu^2},\mu\right)\left(1 + \text{subleading power}\right),$$

where $E_Z = Q/2$ and

$$J_{\mathrm{EEC}} = \int \mathrm{d}^2\Omega_Z \sum_{i,j} \int \mathrm{d}^4x\; e^{ix\cdot P_Z} \left| \left\langle p_i\, p_j + X \middle| E_i E_j\, O_{\mathrm{EM}}(x) \middle| 0 \right\rangle \right|^2 \delta(\cos\theta - \cos\theta_{ij}).$$

Where O_{EM} is the EM current contracted with polarisation vectors for the Z-boson.

A test case: energy correlators on boosted Z-jets

The covariant 2-point correlator:

We can re-write J_{EEC} using the operator definition of the EEC:

$$J_{\mathrm{EEC}} = \int \mathrm{d}^2\Omega_Z \int \mathrm{d}^2 n_{1,2} \int \mathrm{d}^4 x \; e^{ix\cdot P_Z} \left\langle 0 \middle| O^\dagger_{\mathrm{EM}}(x)\mathscr{E}(n_1)\mathscr{E}(n_2)\, O_{\mathrm{EM}}(x) \middle| 0 \right\rangle \delta\left(1 - \cos\theta - \frac{n_1\cdot n_2\, P_Z^2}{n_1\cdot \Lambda_Z P_Z \; n_2 \cdot \Lambda_Z P_Z}\right).$$

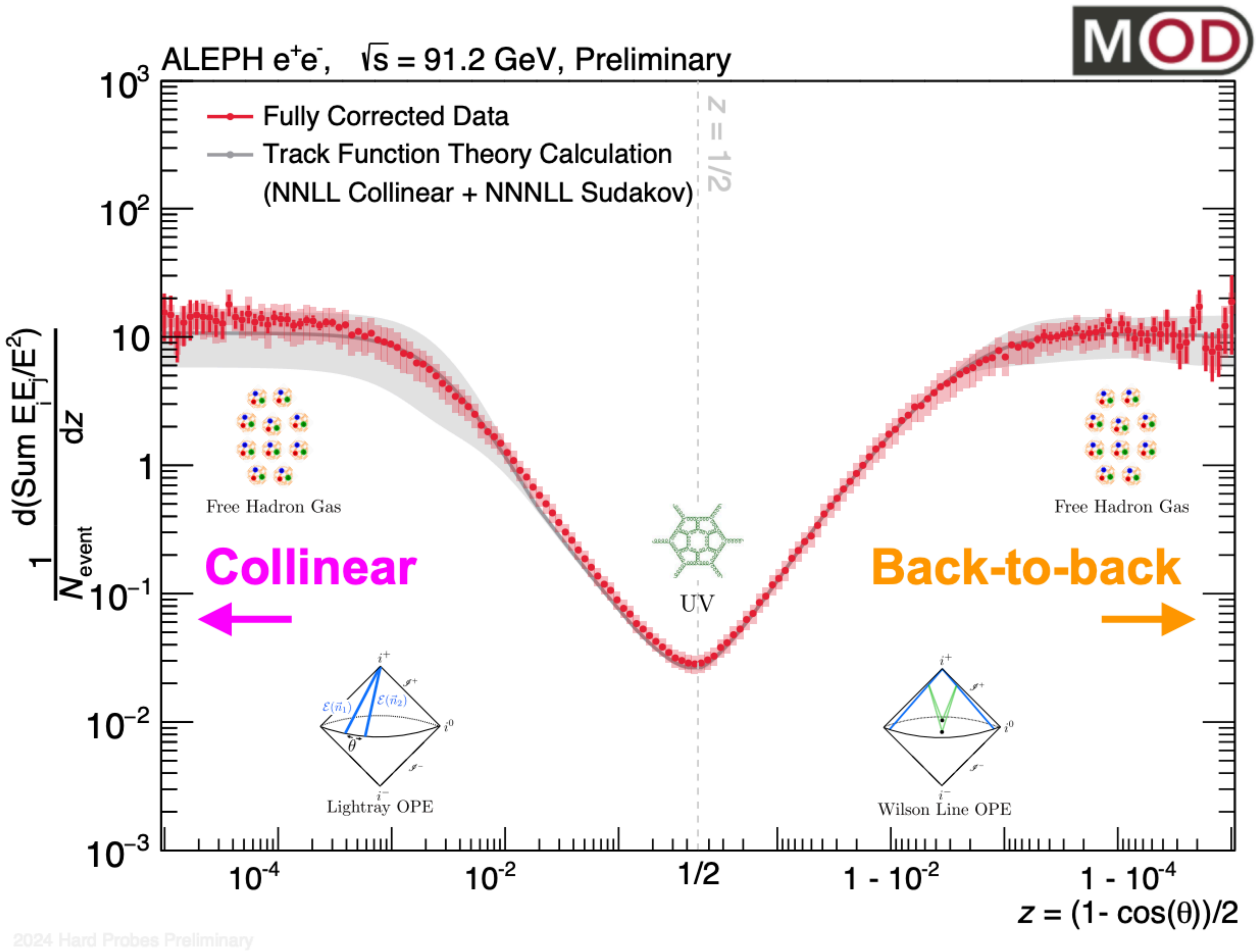
This form is entirely Lorentz covariant. ANE operators have simple, understood transformations under the Lorentz group and the rest of the expression is explicitly Lorentz covariant.

We can therefore compute J_{EEC} in the Z rest frame. The Z rest frame spectrum can be simply determined from the extremely precisely understood e^+e^- 2-point correlator.

A test case: energy correlators on boosted Z-jets

The full e^+e^- 2-point correlator:

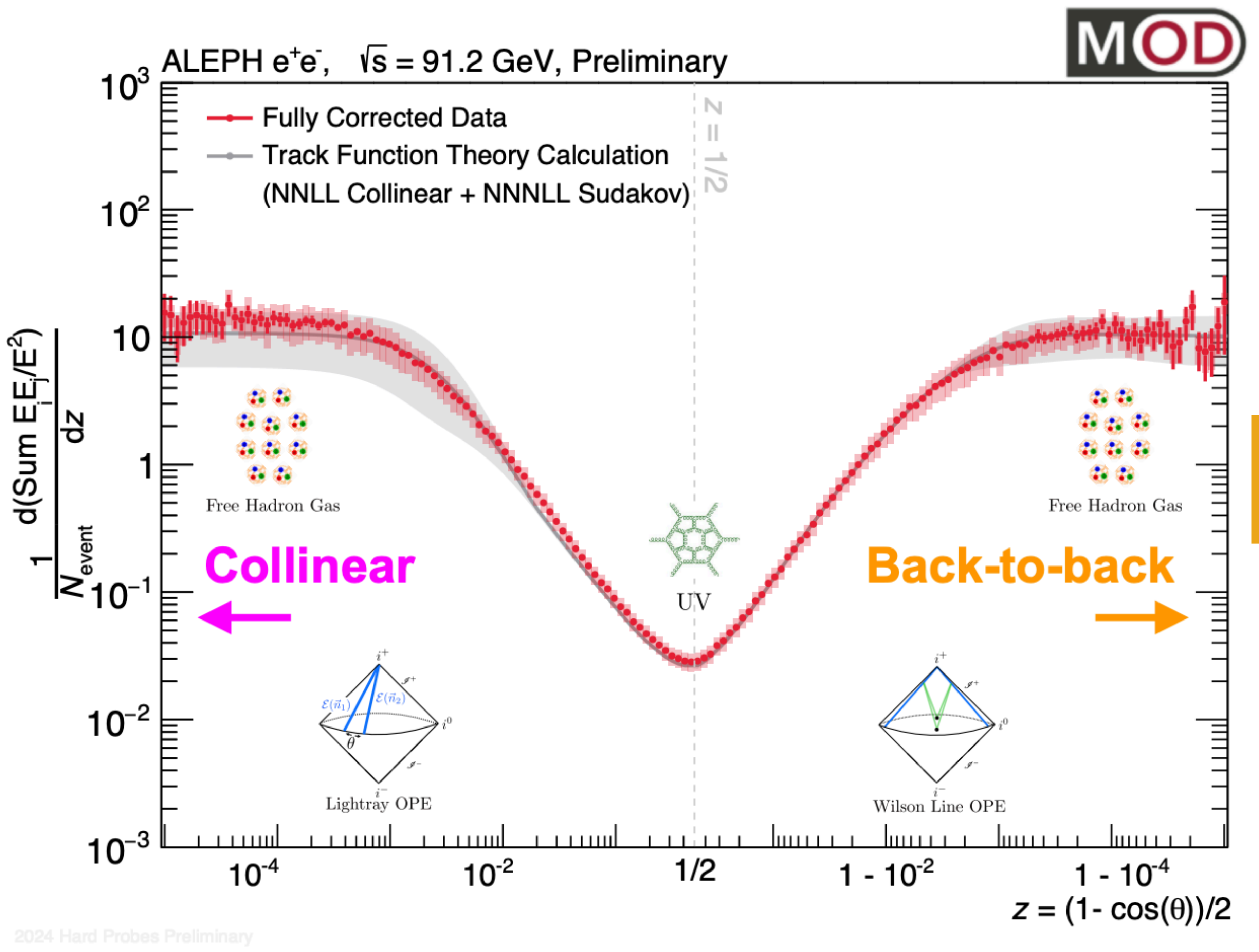
$$\frac{d\Sigma}{dz} \sim J_{\text{EEC}} \otimes H$$



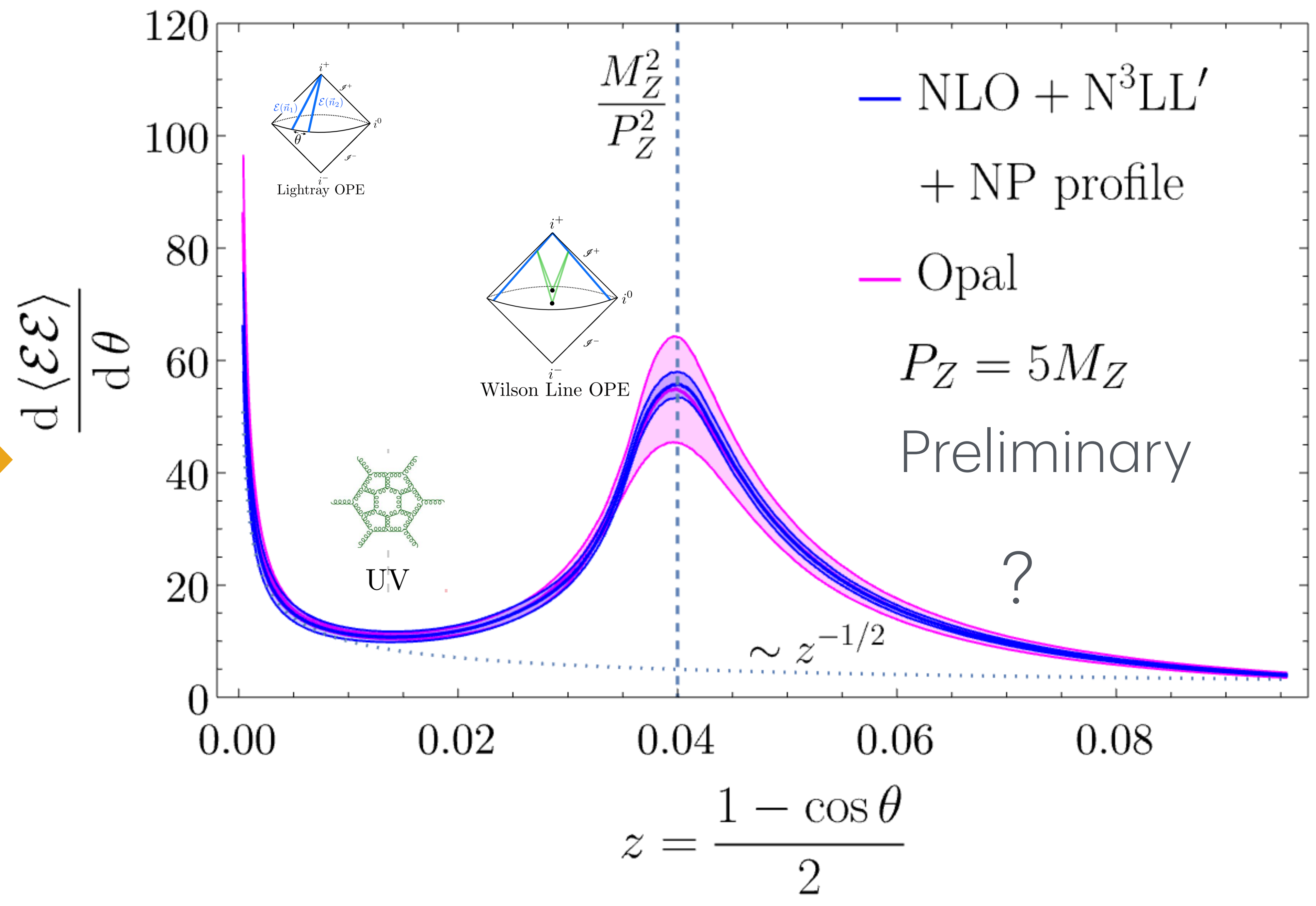
$$\frac{d\Sigma}{dz} \sim J_{\text{EEC}} \otimes J_{\text{EEC}} \otimes S \times H$$

A test case: energy correlators on boosted Z-jets

Boosting the e^+e^- 2-point correlator to a Z-jet:



Boost!



The peak is built from the back-to back Sudakov physics in the rest frame.

A test case: energy correlators on boosted Z-jets

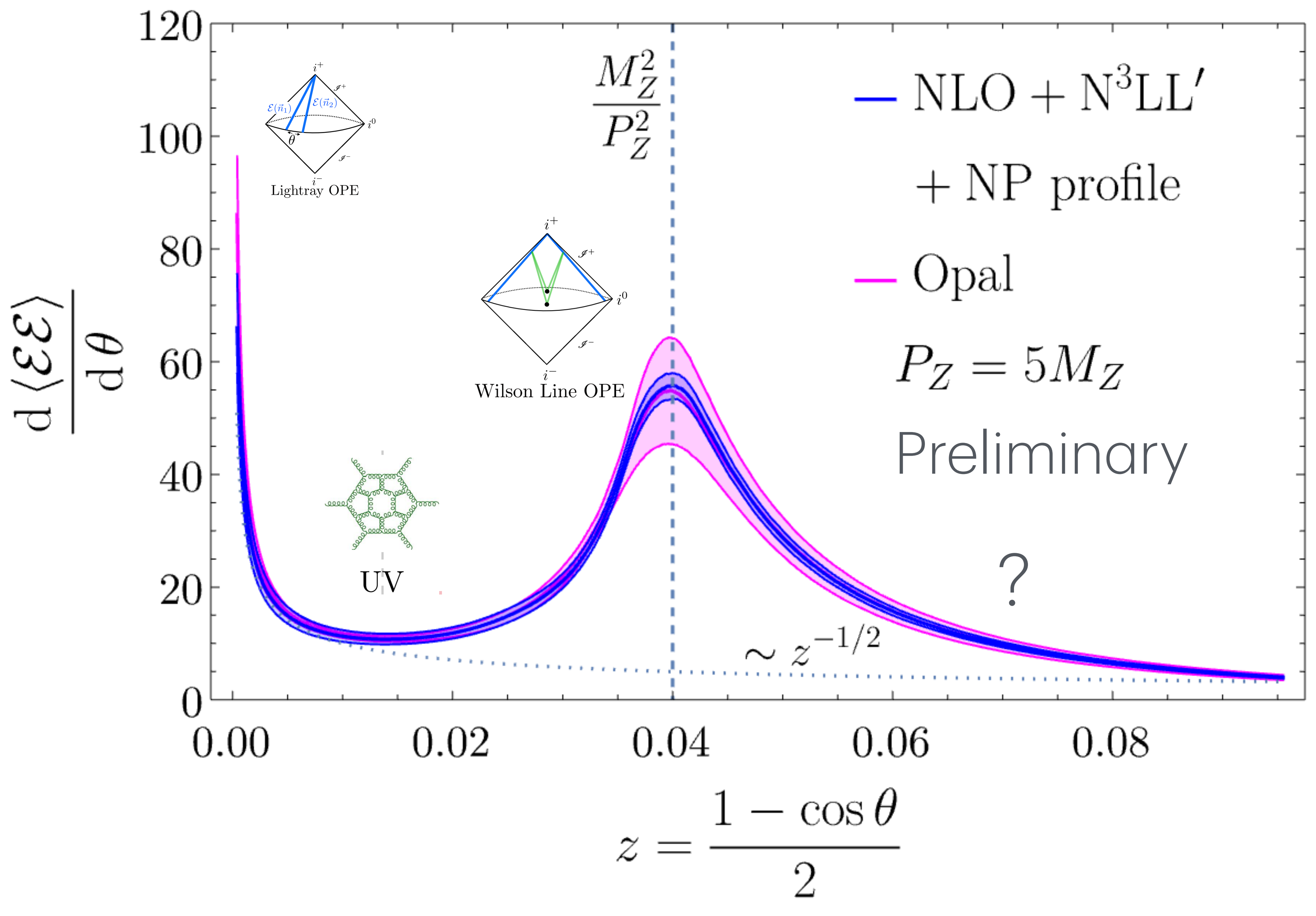
What do we learn?

The peak features in a correlator measured on a massive resonance can be associated with the Sudakov region of the EEC in the decay rest frame.

Usually the collinear limit of an EEC is a single-log observable. However, on a massive decay it is Sudakov observable.

The leading NP contributions to a the back-to-back Sudakov are universal between the 2-point and 3-point correlator (both coming from a double Wilson line soft function). This is why the cancellation works in the W ratio.

The peak width is determined by the Sudakov, not the decay width as would be the case for a resonance. Instead, a narrow decay width is a small smearing on this feature.



Conclusions

Top mass measurements from EECs are very promising and could provide novel insight on the top mass!

The 'standard candle' approach uses the W boson to almost completely eliminate dependence on parts of the process which we cannot control theoretically.

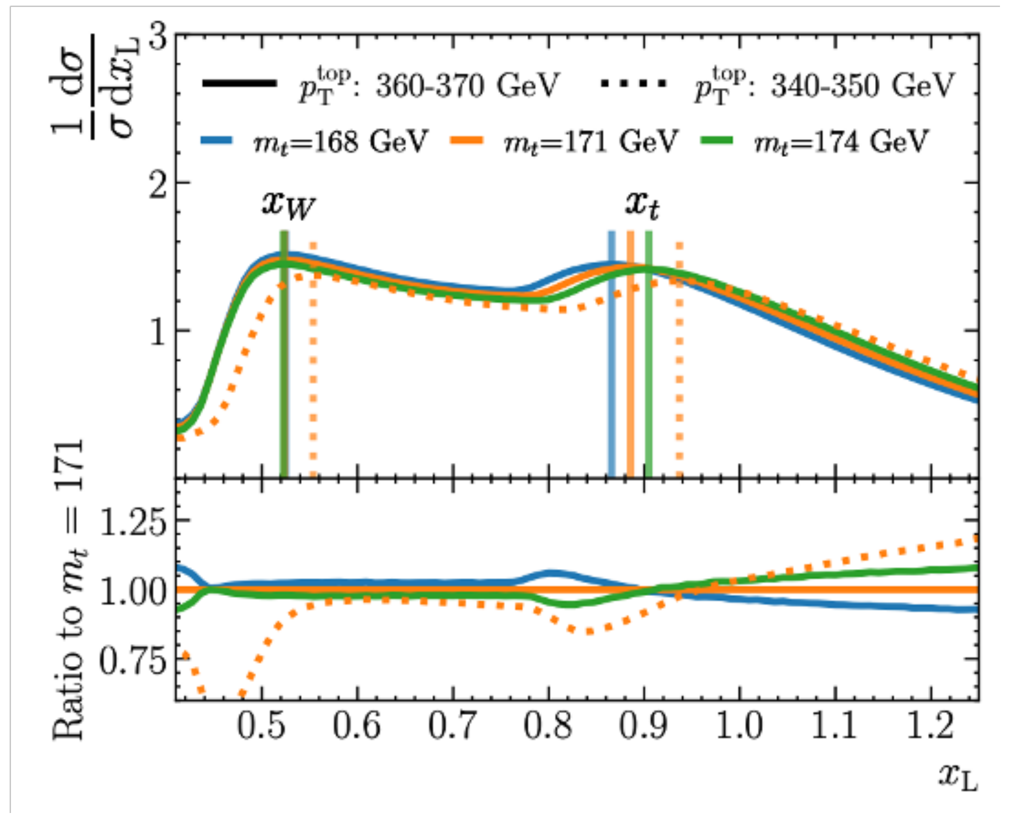
Resultantly, this observable can be computed directly, with analytical precision potentially much higher than can be achieved with MCs. The theory calculations could be compared against data.

However, the observable is sensitive to the description of the top decay. This has been computed to high precision in the literature [11] but is only included at LO in MC generators. The discrepancies between how generators handle the top decay can explain the differences between the generators.

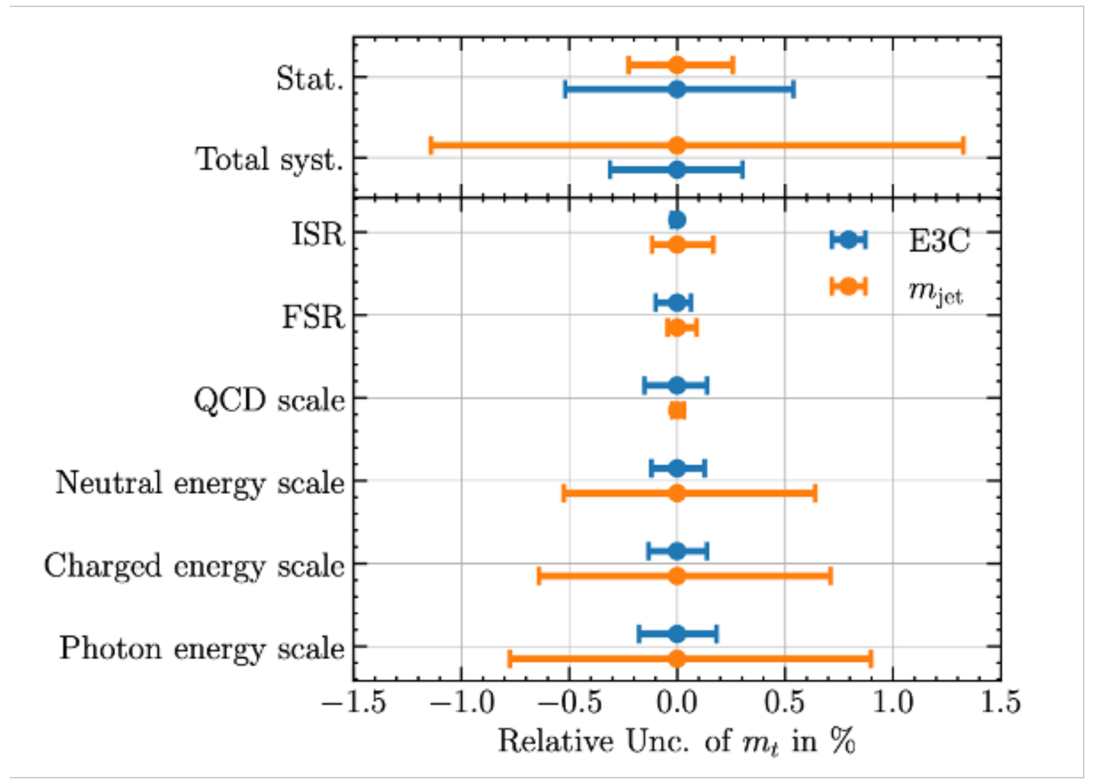
A MC driven approach to this observable may also be fruitful and achievable on a shorter time-scale that a complete theory calculation. However, great care should be taken for the previously stated reason!

Conclusions

A MC driven approach to this observable may also be fruitful and achievable on a shorter time-scale that a complete theory calculation. However, great care should be taken for the previously stated reason!



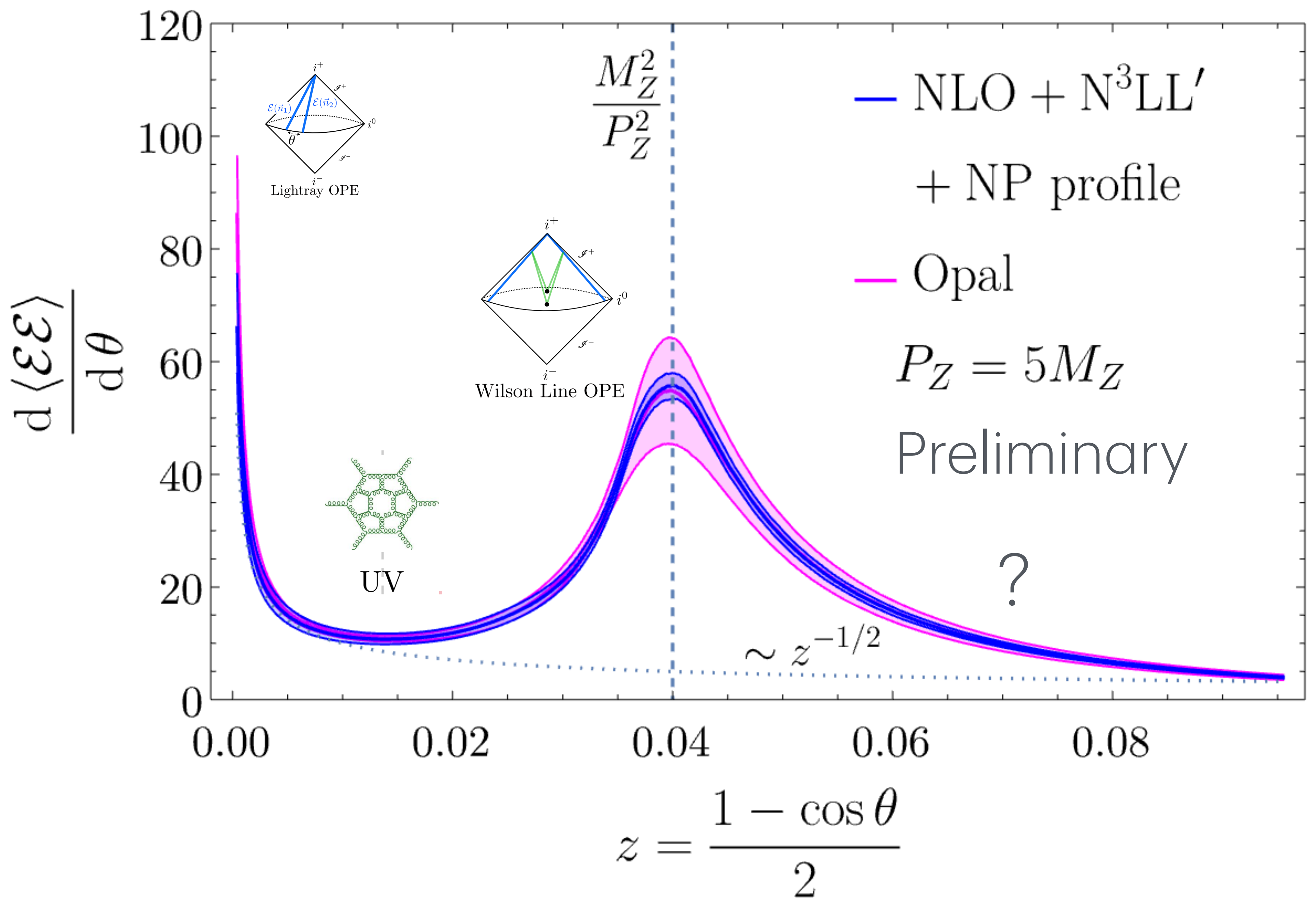
Recent work (M. Xiao, Y. Ye, X. Zhu '24 [13]) introduces an alternative approach to the MC mass based on the EEC standard candle approach. Looks promising and might have reduced the modelling dependence in the MC mass. Merits further investigation...



Conclusions

A full treatment from theory is under development and is proceeding well.

An early test case of implementing the measurement on Z decays will be realised soon and shows the unique potential this approach has for high precision.



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