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Top Mass Measurements with Energy Correlators

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Based on arXiv:2311.02157, Phys.Rev.D.107.114002 (2022),
and upcoming work

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   Our wheel can survive off-road in the experimental environment.

Why a new top mass observable?

Current world average (High-lumi projection $\sim$ 200 MeV) [Gro+20]

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

But the is a conceptual problem. **What is m_t^{MC}?**

Simulating the top quark as a particle with a definite mass ignores $\mathrm{O}(1\ \mathrm{GeV})$ theoretical ambiguities due to long distance effects.

The only quark with three masses in PDG [Gro+20]

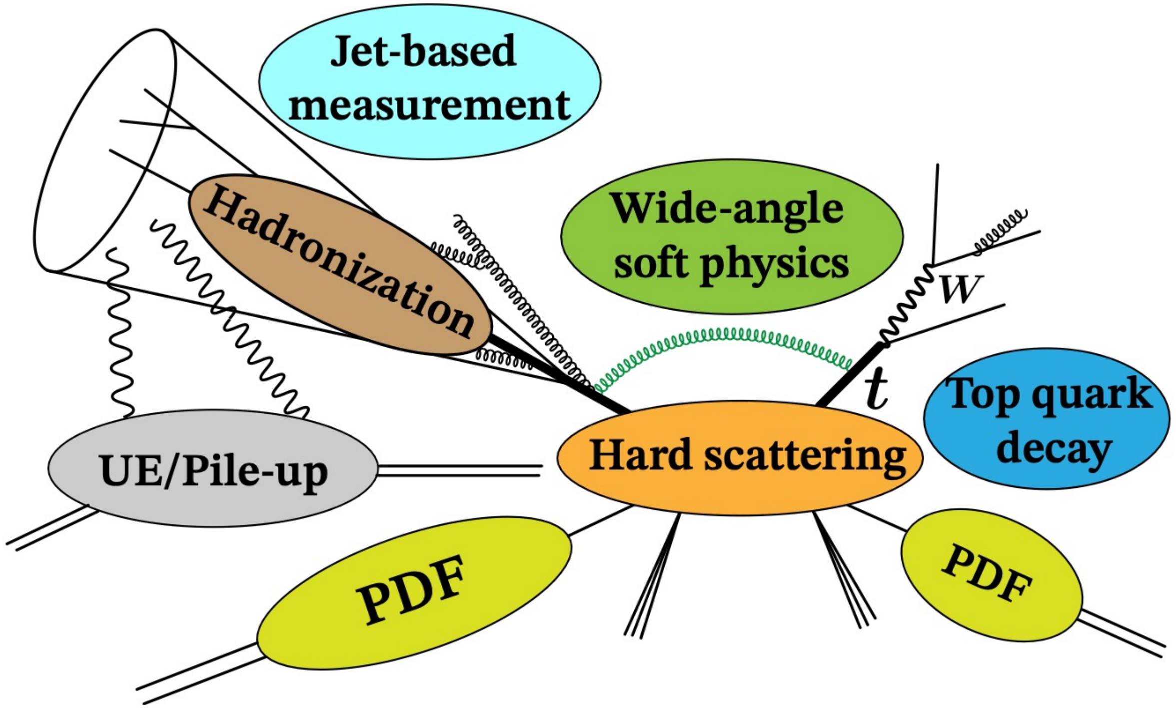
Direct measurements: $m_t^{\mathrm{MC}} = 172.69 \pm 0.3\ \mathrm{GeV}$

cross-section measurements: $m_t^{\overline{\mathrm{MS}}} = 162.5 + 2.1\ \mathrm{GeV}$

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

Why a new top mass observable?

Why are measurements so difficult? -Measurements depend on many hard to describe processes.



Why a new top mass observable?

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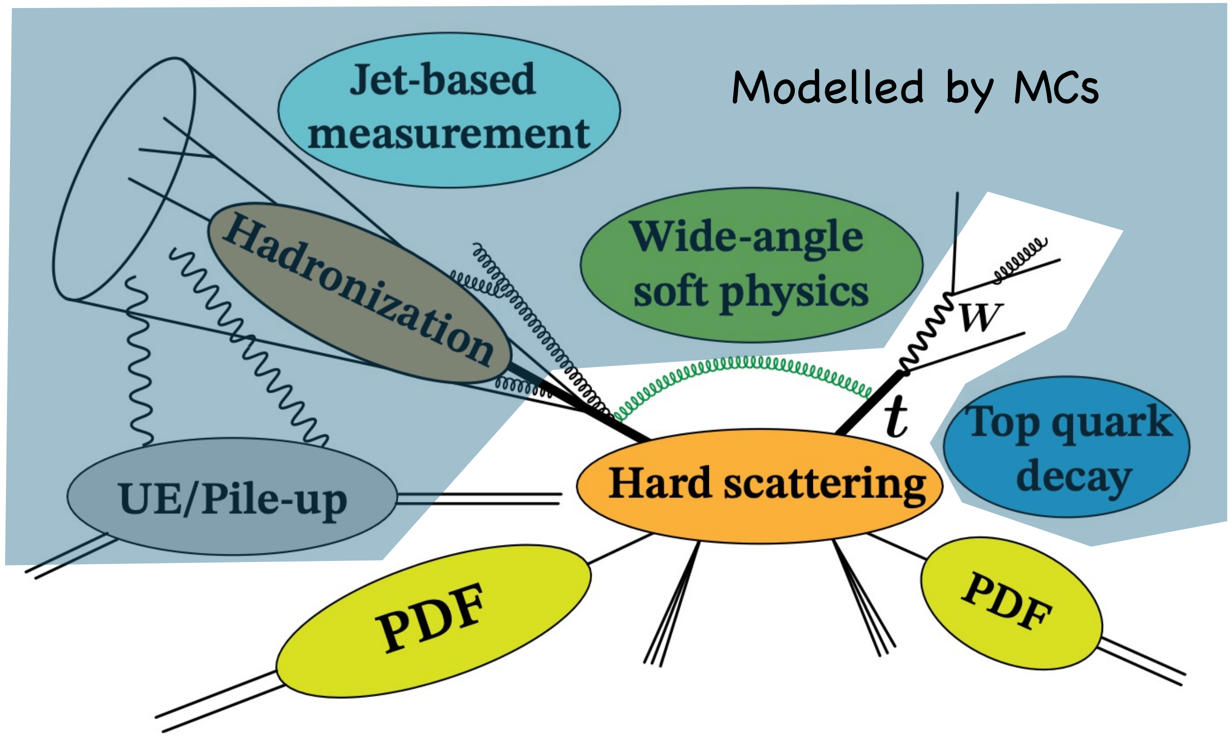


We want an observable which can be expressed theoretically in a well-defined short distance mass scheme and that largely removes the MC dependence.

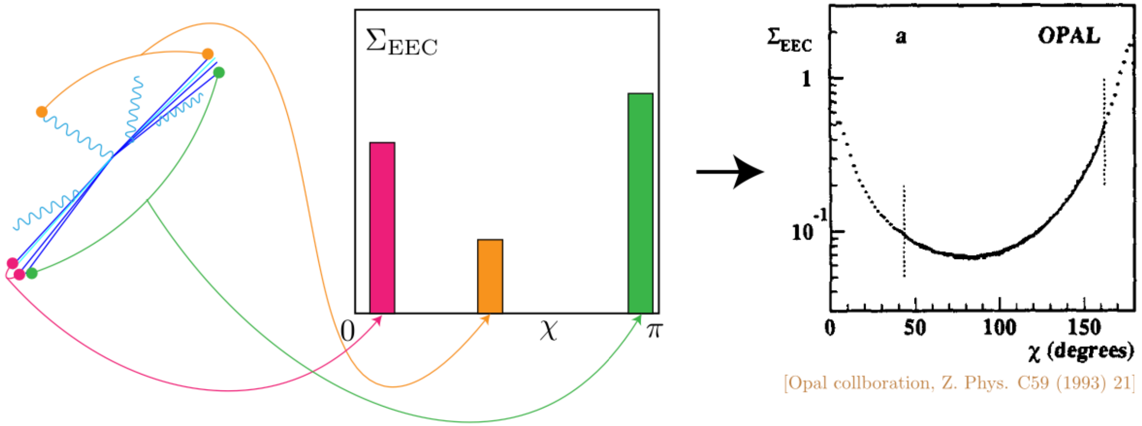
The energy correlator approach from theory.

The two-point energy correlator in e^+e^-:

[Bas+78] $$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle = \sum_{ij} \int \frac{\mathrm{d}\sigma_{ij}}{\mathrm{d}^2\vec{n}_i \mathrm{d}^2\vec{n}_j} E_i E_j \, \delta^2(\vec{n}_1 - \vec{n}_i)\delta^2(\vec{n}_2 - \vec{n}_j) \, .$$

We integrate out isometries and normalise to make the distribution dimensionless:

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



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

Not even by event

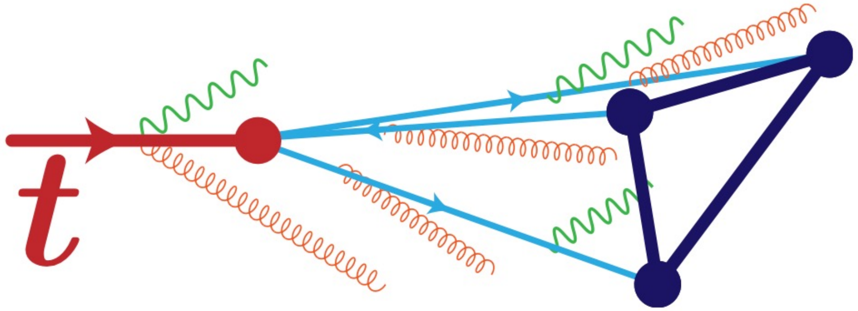
The energy correlator approach from theory.

The top mass EEC. [Hol+23]

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.

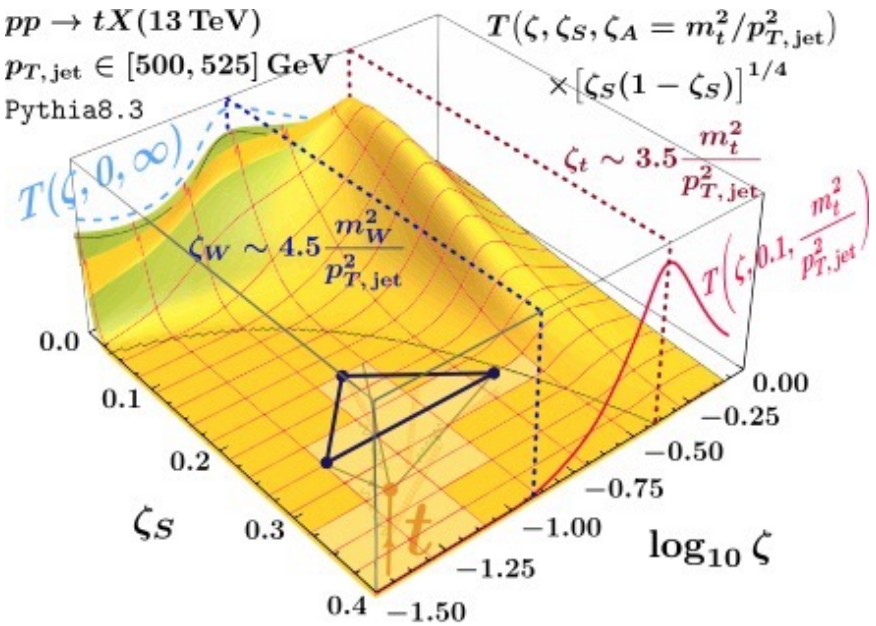
$$E_i \to p_{T,i}$$
$$\text{angles} \to \text{rapidity differences}$$

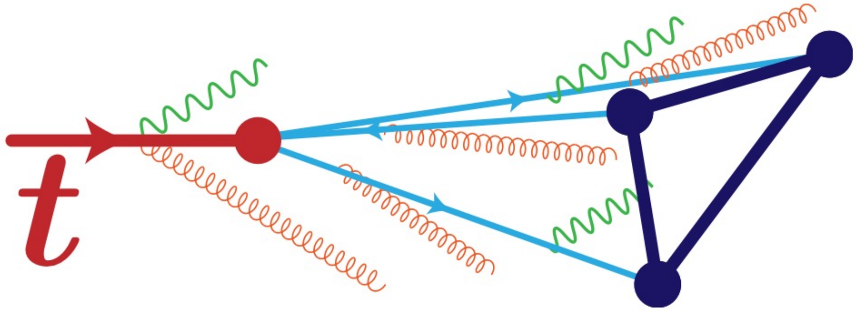


The energy correlator approach from theory.

Definition:

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

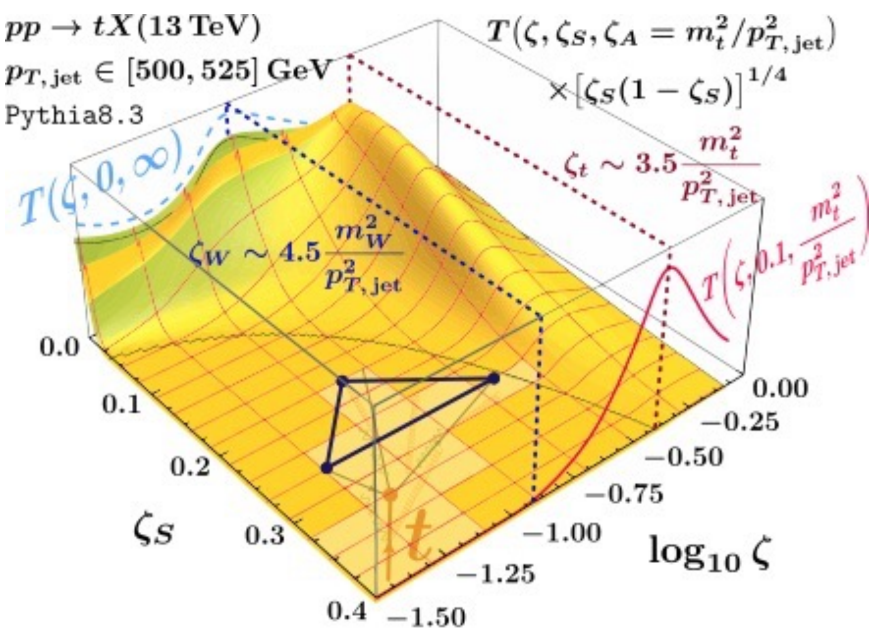


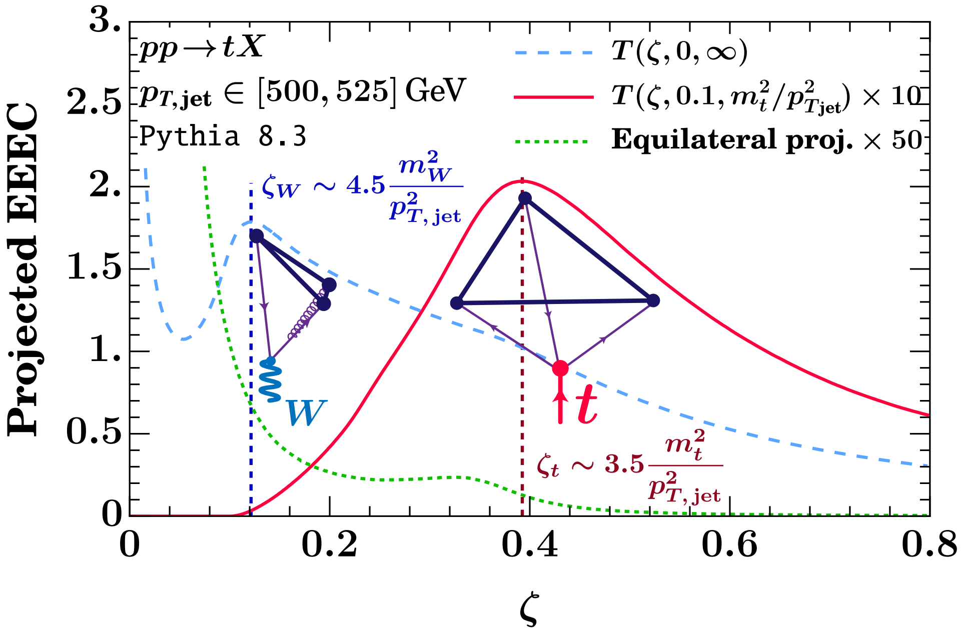


The energy correlator approach from theory.

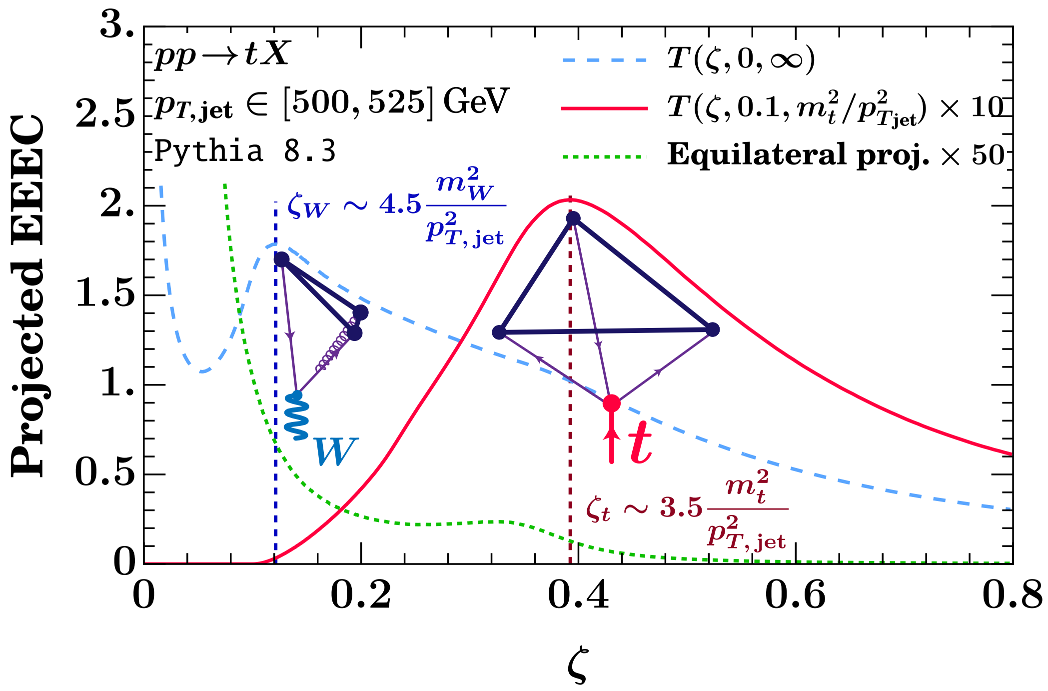
The top mass EEC:

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





The energy correlator approach from theory.

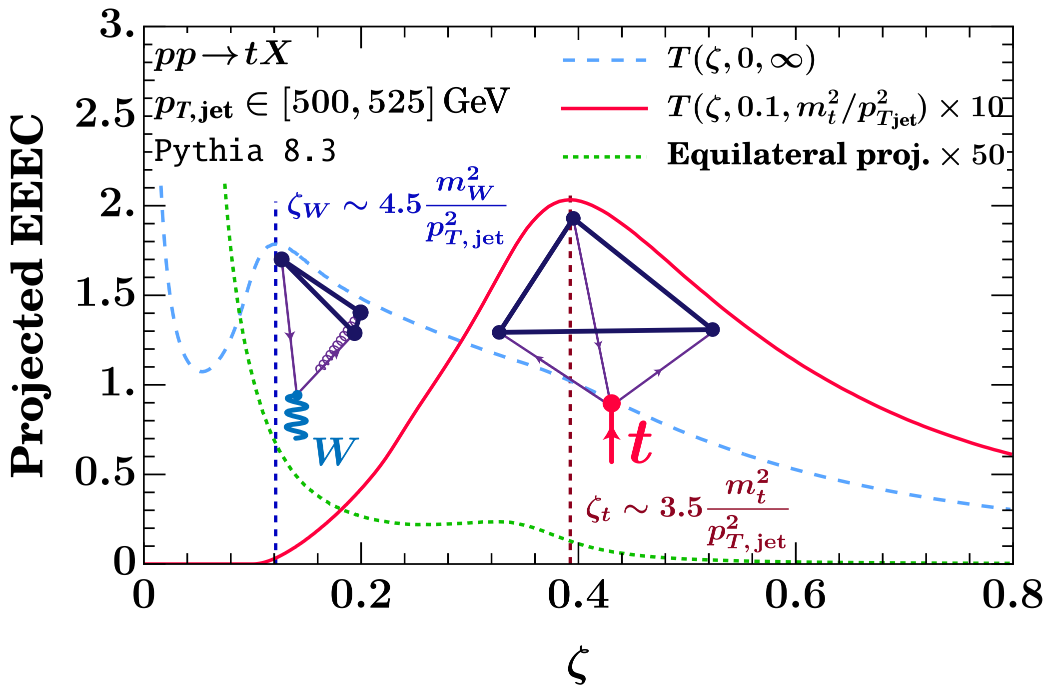


The top peak is very sensitive to the top mass (in a well-defined short distance scheme).

However, it is equally sensitive to the jet p_T.

For 1GeV accuracy on the top mass, within a 500GeV jet, the jet p_T needs to be known with 5GeV precision, *very tough*.

The energy correlator approach from theory.



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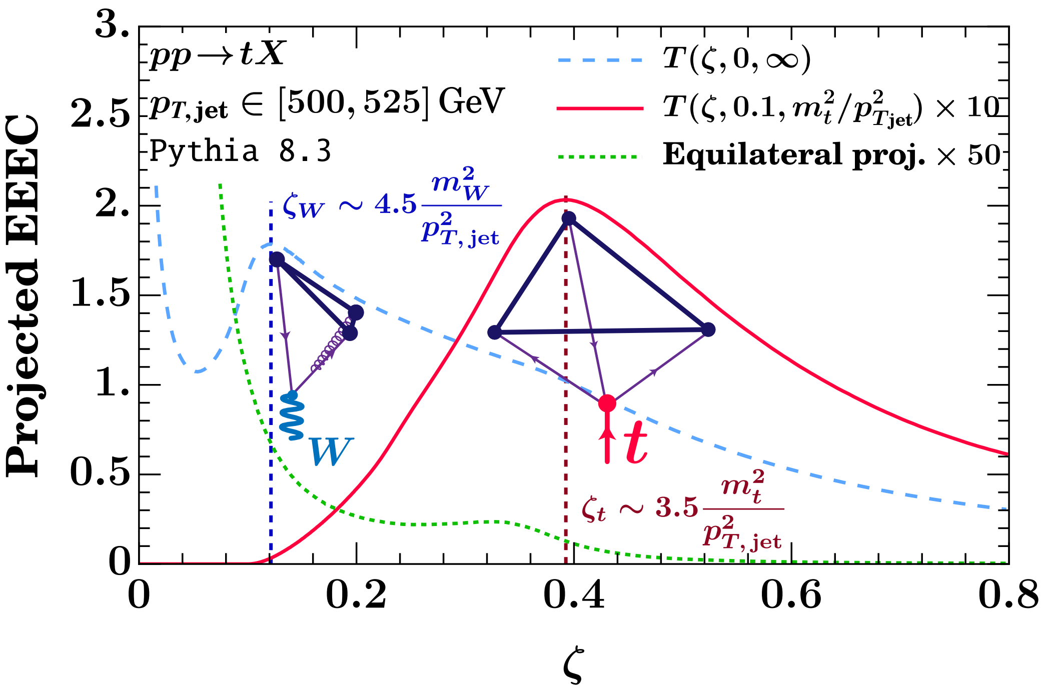
For 1GeV accuracy on the top mass, within a 500GeV jet, the jet p_T needs to be known with 5GeV precision, *very tough*.

BUT the W depends on the exact same jet p_T!
(Up to small power corrections from the decay)

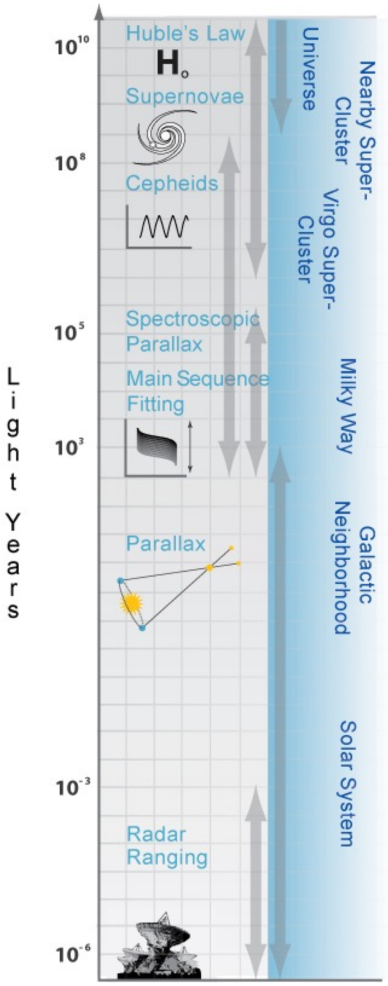
The energy correlator approach from theory.



Measuring the ratio between the position of the W peak and the top peak should entirely remove the jet p_T dependence.

This measurement can be done cross multiple p_T 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 energy correlator approach from theory.



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).

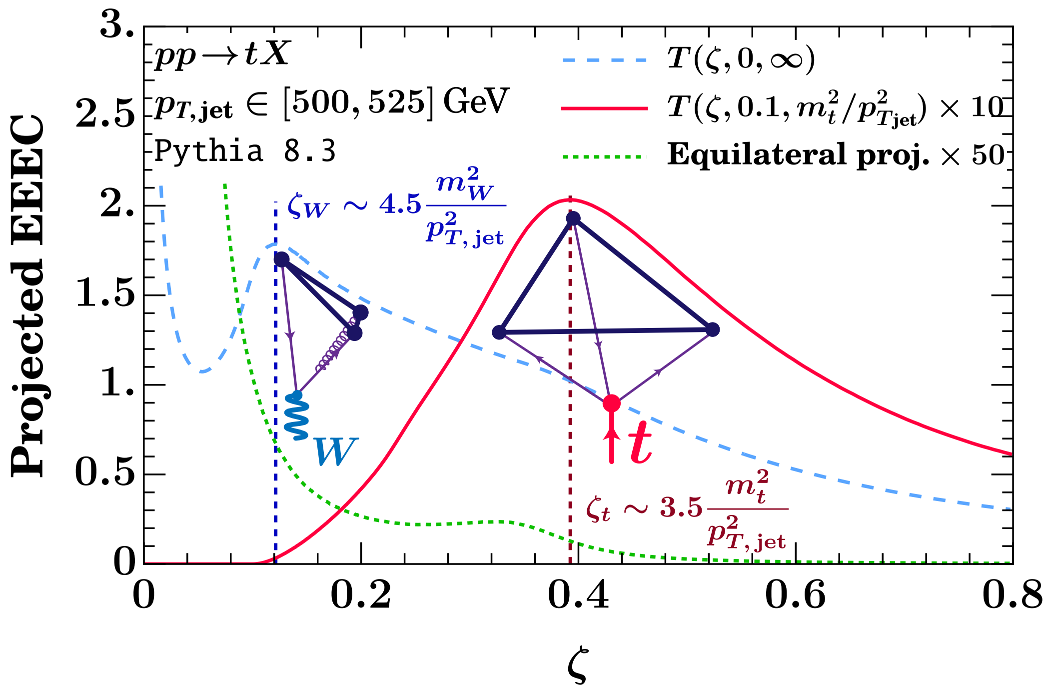
The energy correlator top mass measurement converts a top decay angle to a top mass with the W mass (which replaces the p_T) and with knowledge of the W boson's boost from the top decay rest frame.

$m_t^{\overline{\mathrm{MSR}}} \sim 173 \text{ GeV}$

$m_W = 80.377 \pm 0.012\text{GeV}$

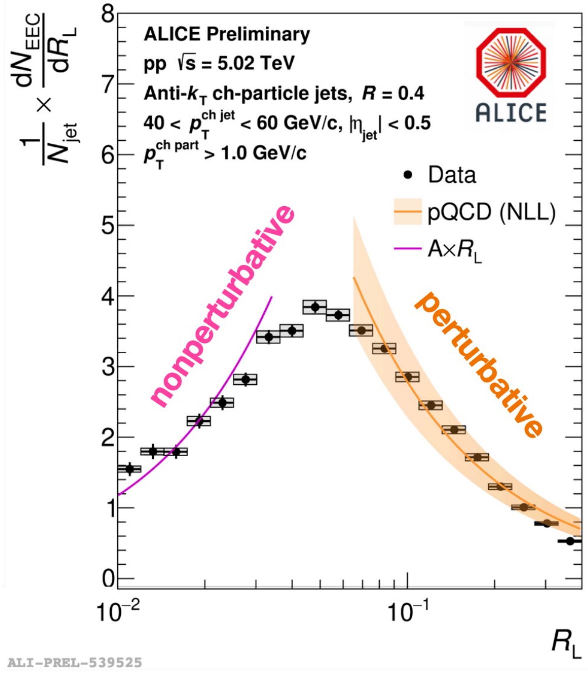
[Gro+20]

The energy correlator approach from theory.



BUT there is a second problem!

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

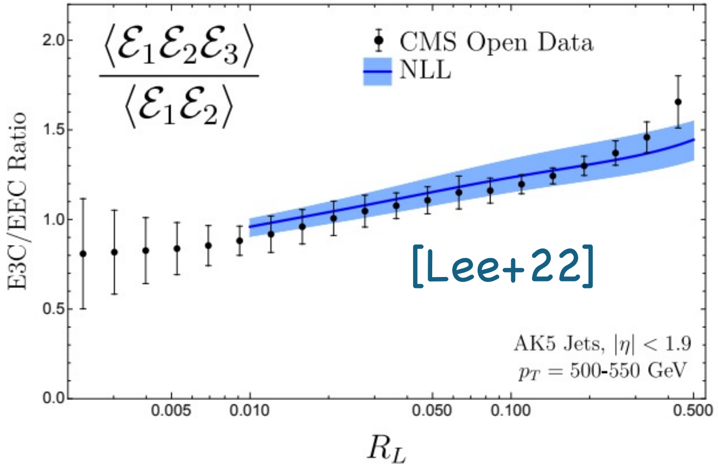


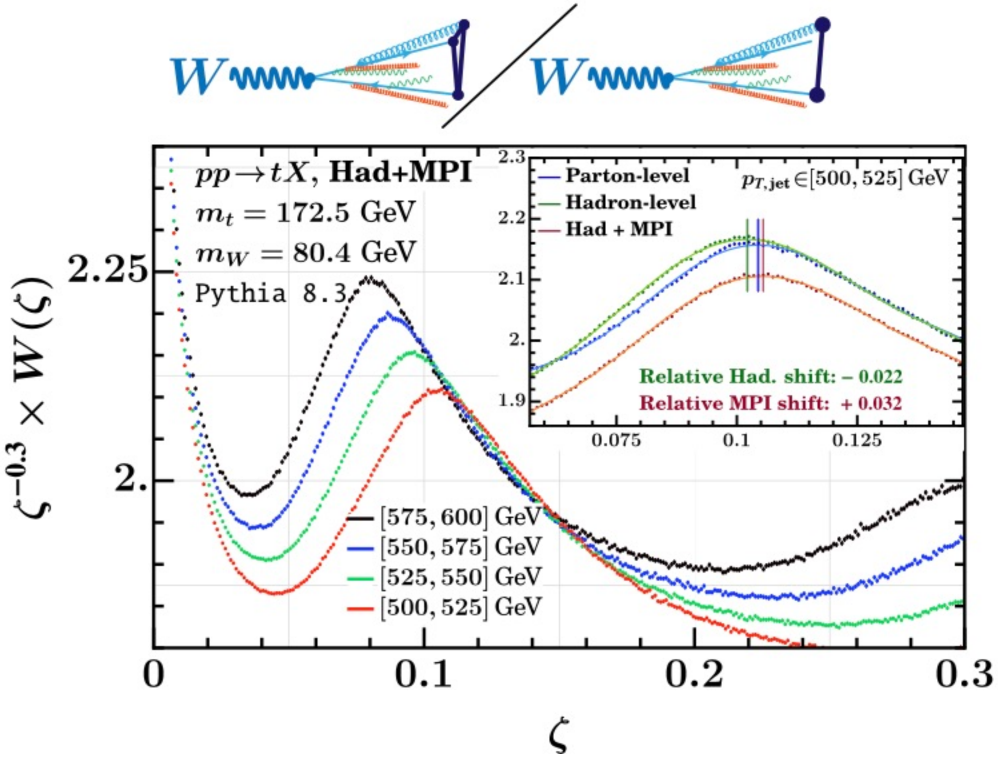
The energy correlator approach from theory.

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

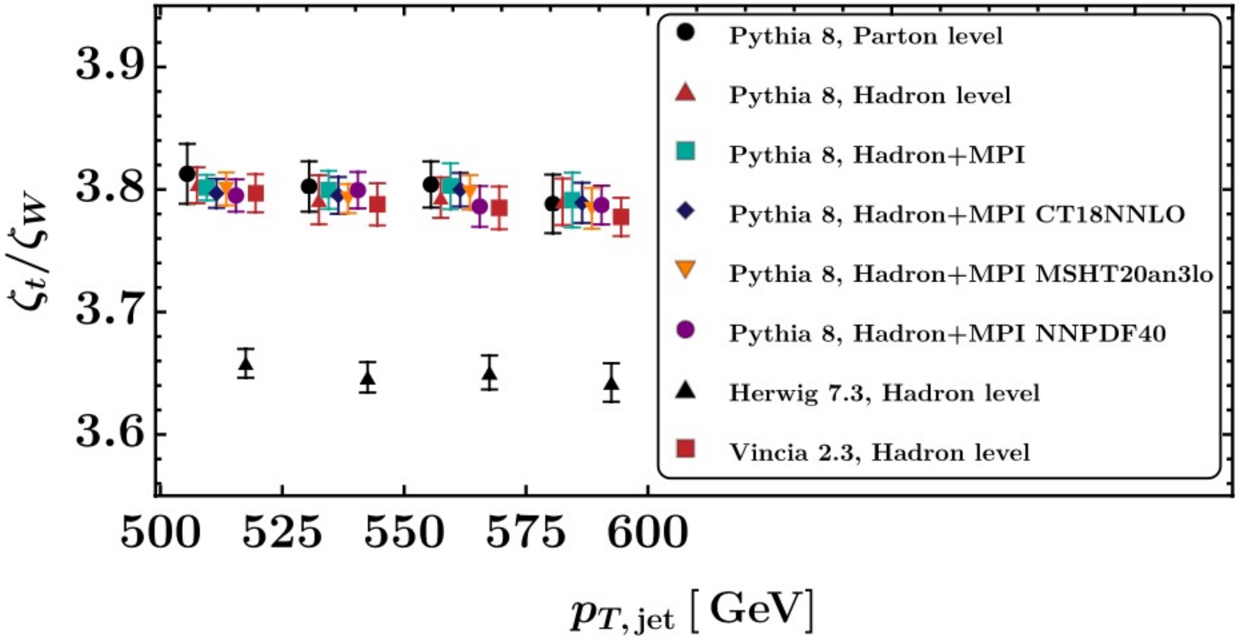
BUT there is a second Solution!

It is well understood that the hadronisation corrections between the squeezed limit of the 3-point correlator are correlated with the 2-point correlator.





Simulation of the observable.

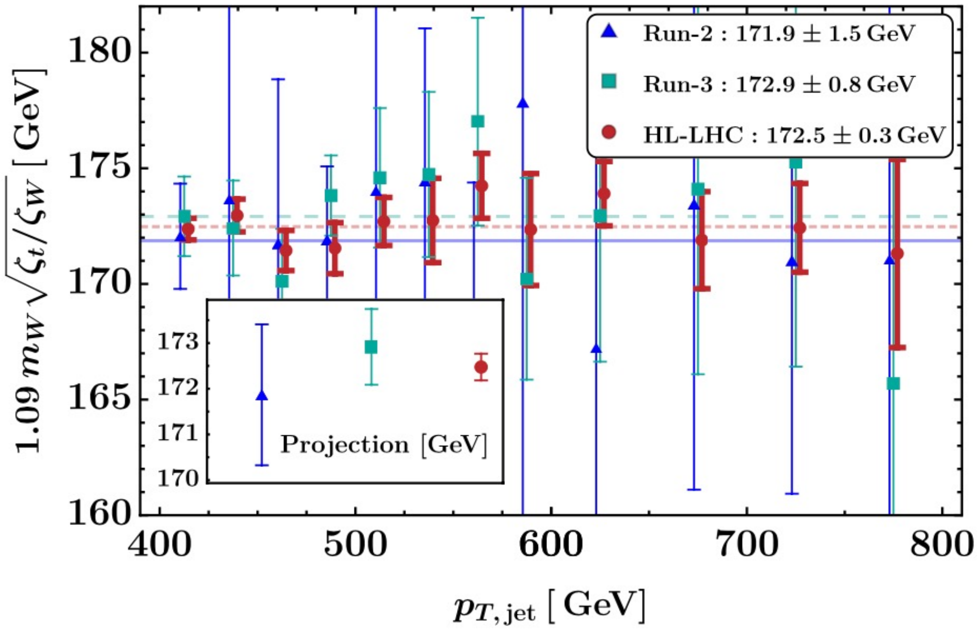


The jet p_T dependence does cancel!

Herwig is lower than all other generators, which means it would give a different top mass if the same constant from the top decay were used. The effect is about 1.5%.

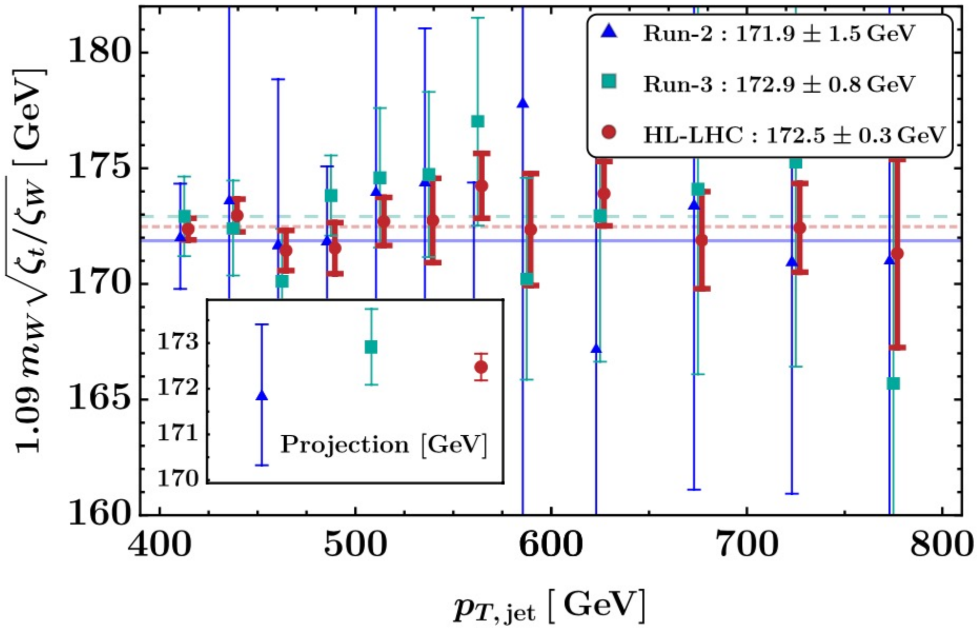
This is because the NLO correction to the top decay is handled only approximately by the parton shower and is different between the MCs.

Simulation of the observable.



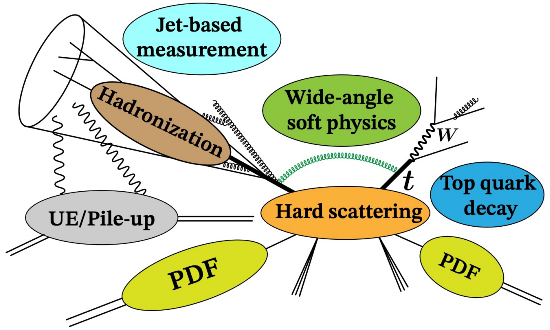
And a reliable top measurement does seem feasible!

Simulation of the observable.



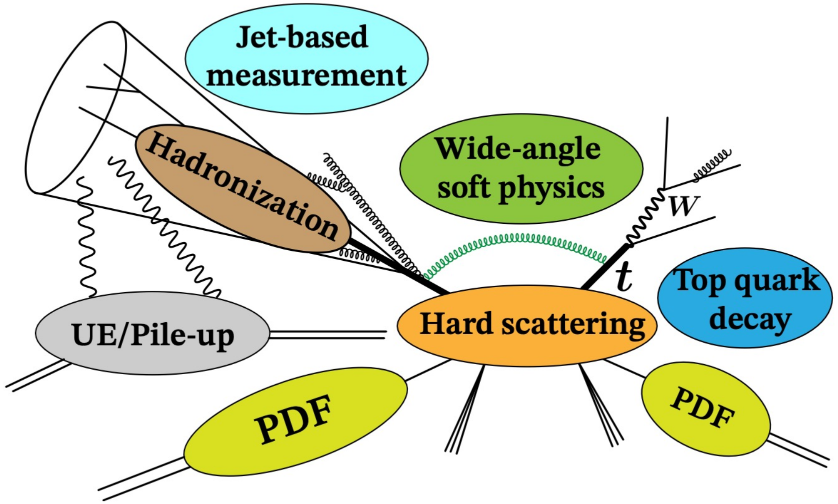
And a reliable top measurement does seem feasible!

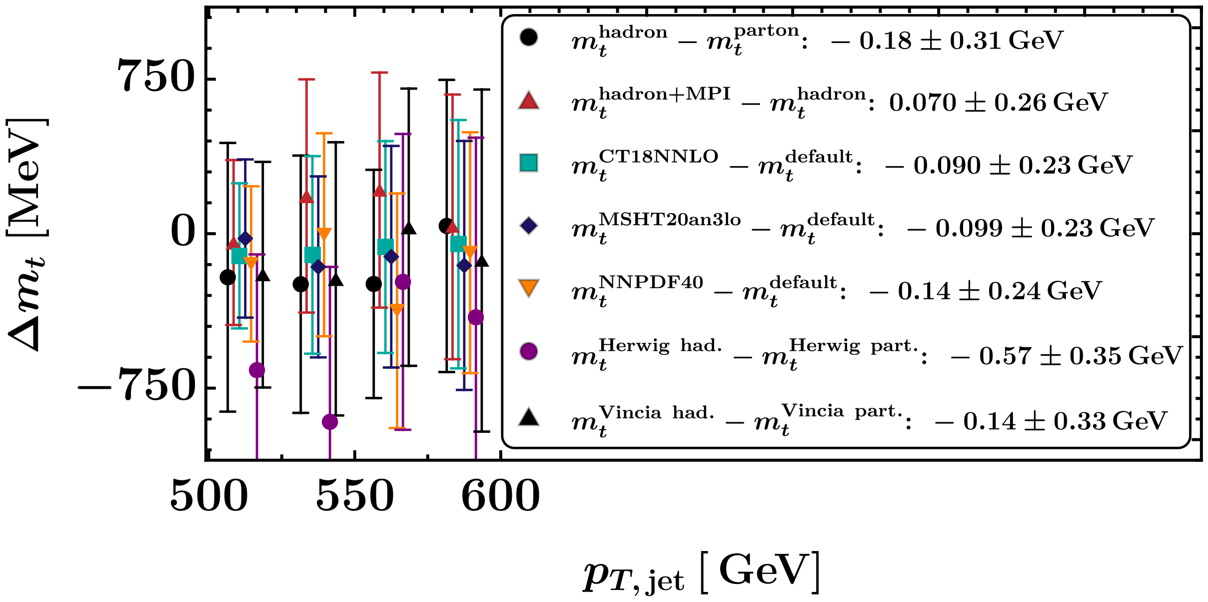
However, I'm sure you are not convinced by just two nice plots.



What about the whole messy environment!?

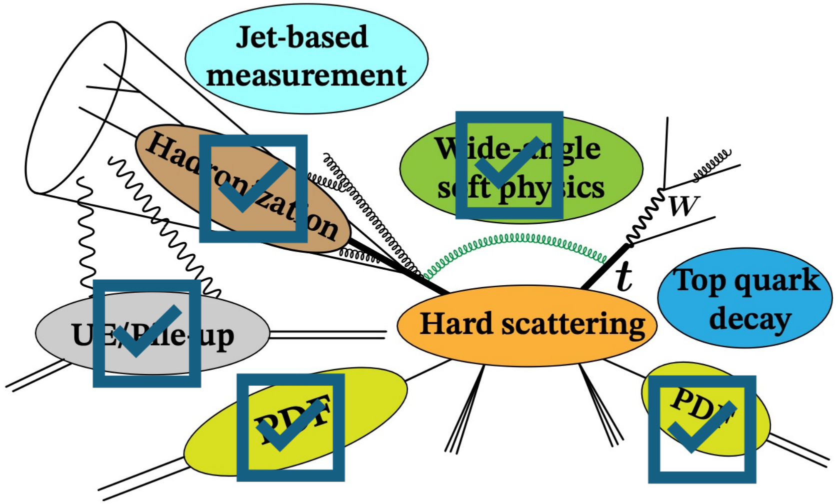
Plots Plots Plots

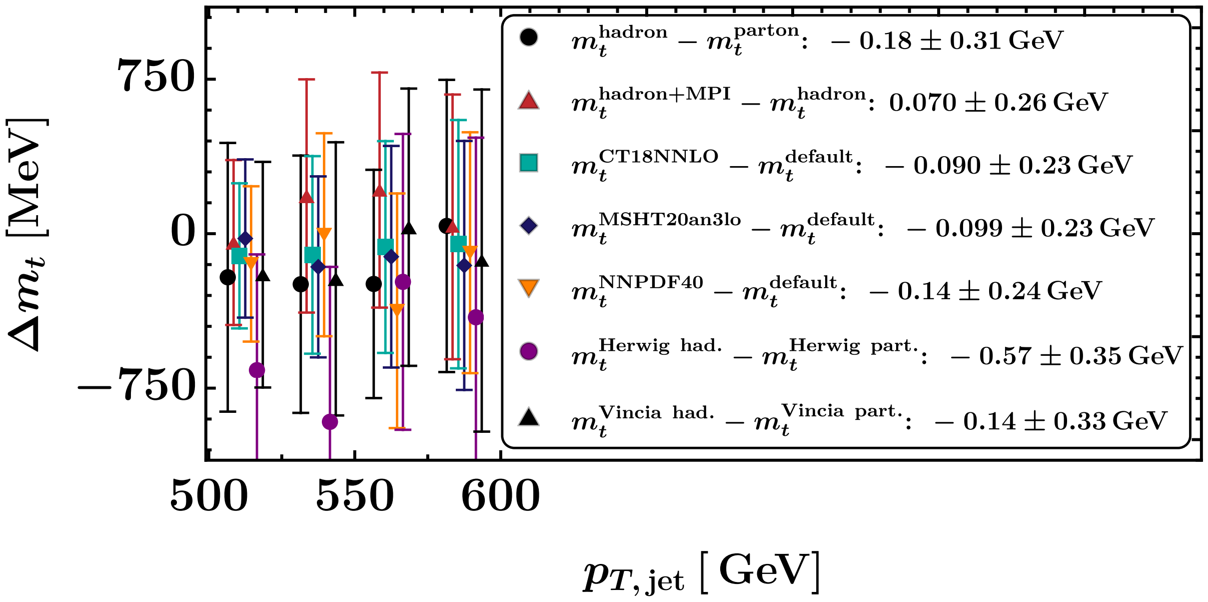




Here is a third nice plot.

Plots Plots Plots





Here is a third nice plot.

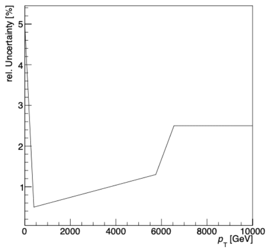
What about the realistic environment!?

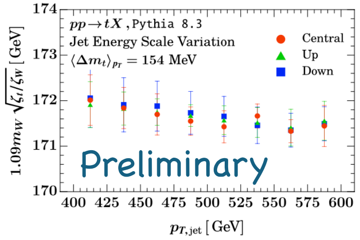
Plots Plots Plots

Vary jet 4-momentum $p_{\text{new}} = p_{\text{old}} \pm u(p_T) \cdot p_{\text{old}}$ with

$$u(p_T) = \begin{cases} 0.05 - p_T(0.05 - 0.005)/400 & \text{for } p_T < 400 \\ 0.005 + (p_T - 400)(0.013 - 0.005)/(5750 - 400) & \text{for } 400 < p_T < 5750 \\ 0.013 + (p_T - 5750)(0.025 - 0.013)/(6550 - 5750) & \text{for } 5750 < p_T < 6550 \\ 0.025 & \text{for } p_T > 6550. \end{cases}$$

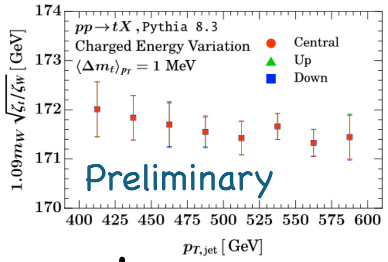
Simulate 100 million events:

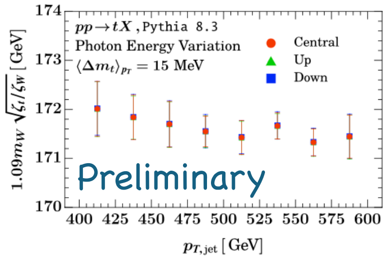


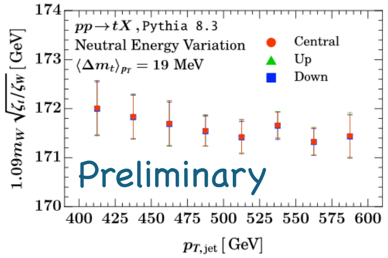


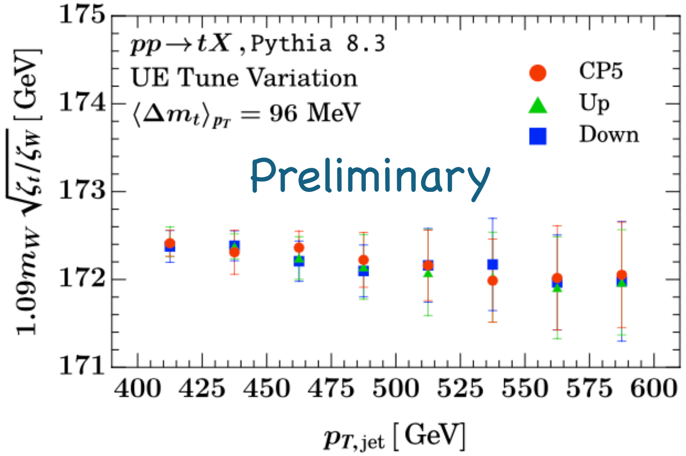
Coming soon…

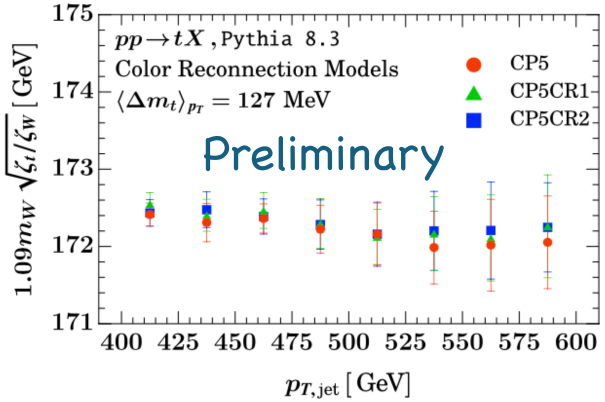
The experimental environment











Conclusions

Top mass measurements from EECs are very promising and have the potential to address long standing problems. [Hol+23]

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 [Cam+12] 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.

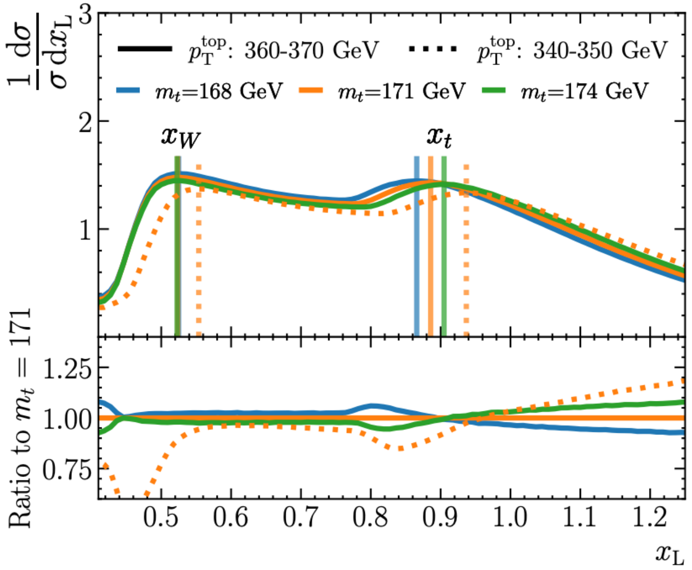
A MC driven approach to this observable may also be fruitful and achievable on a shorter time-scale that a complete theory calculation. However, great care should be taken for the previously stated reason!

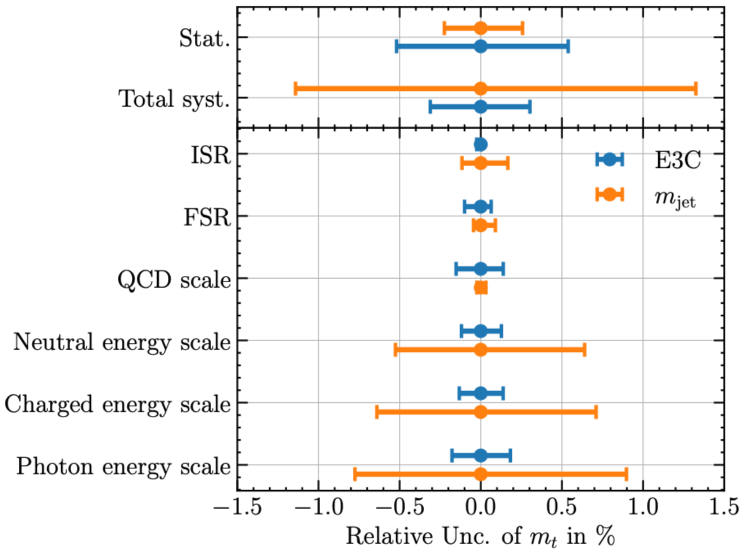
Conclusions

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!

Very recent work [Xia+24]

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…





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