FACULTY OF SCIENCES

Using the W as a Standard Candle to Reach the Top:

Calibrating Energy Correlator Based Top Mass Measurements

stop me if I go to fast, slides are dense at times

also

my choice of pizza is expertly hidden in the presentation, congrats if you can find it!

David Marckx
23/02/2024
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CMS

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overview

1. why we care about the top mass
   EW vacuum stability
2. why it’s hard to measure at the LHC
3. jet substructure methods
   jet grooming and EECs
4. the new method
5. feasibility and conclusions

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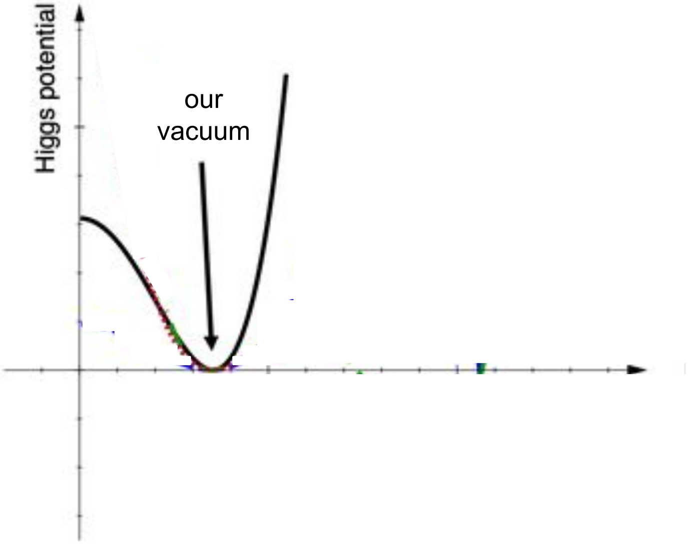
Why care about top mass: stability of the EW vacuum

- We have our Higgs potential
- completely related:



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(one can think of more reasons but let's focus on the one the authors focus on)

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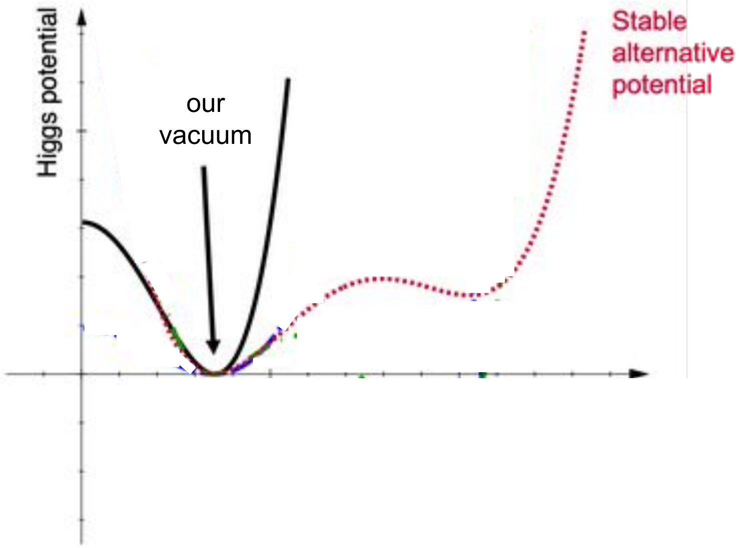
Top mass: the stability of the EW vacuum

- We have our Higgs potential

- But if you look at higher scales, the effective potential changes
  - depends on all parameters of the SM
  - **Higgs self-interaction (λ)** and **top mass**
  - **BSM physics**



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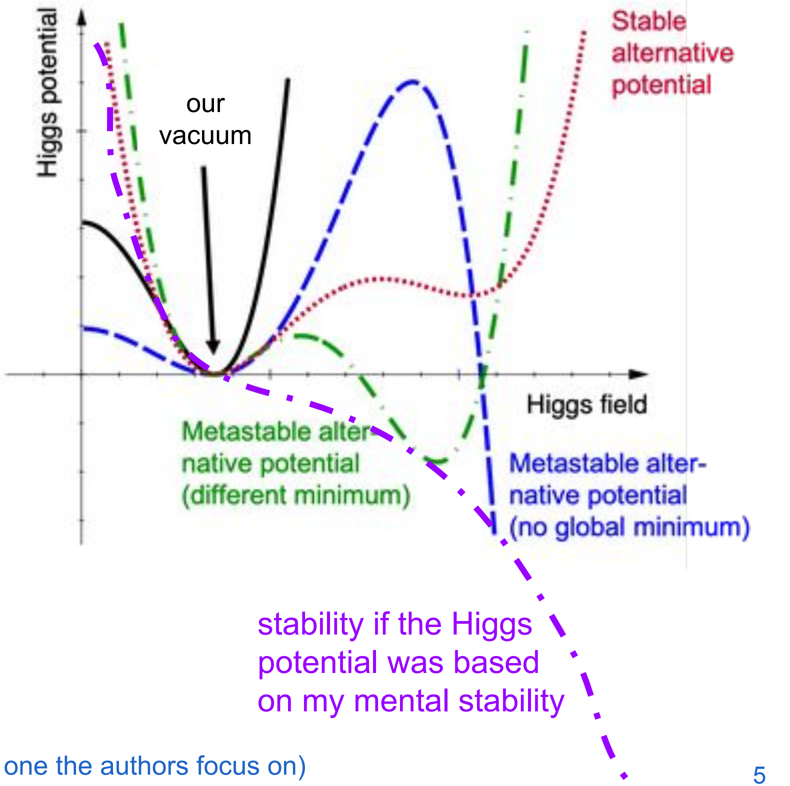
- Current measurements indicate we are **metastable at higher scales**



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Top mass: the stability of the EW vacuum

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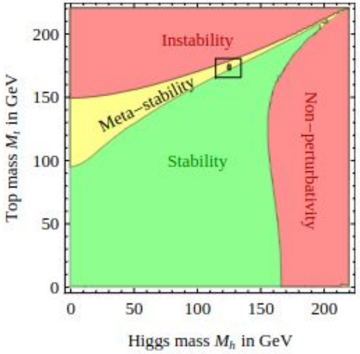
- Current measurements indicate we are **metastable at higher scales**

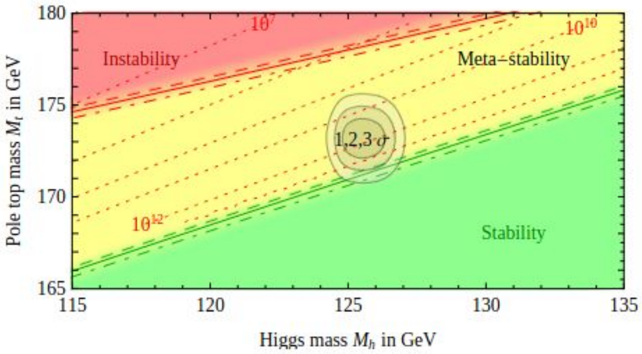
- Vacuum has to remain stable until new physics scale is reached (otherwise cosmologists become very, very sad)
  - High Hubble rates during **inflation** and high temperatures during **reheating**: why did we not end in the real vacuum?
  - Universe would be a ticking timebomb eh!

Top mass: the stability of the EW vacuum

- so we don't want to be metastable
- measuring top mass = measuring upper bound of scale of new physics
  - red lines = scale of breakdown (GeV)
- many other reasons

light top





heavy top

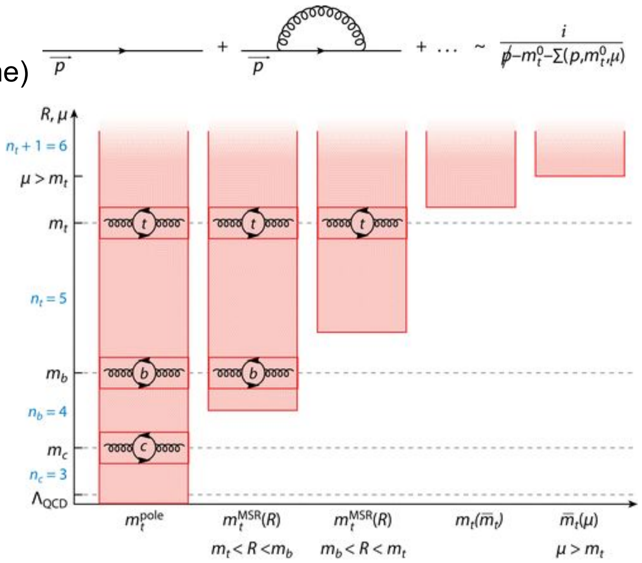
so how do we measure the top mass?

(one can think of more reasons but let's focus on the one the authors focus on)

Top mass: measuring at a ee collider

click here to read from someone who does know what this all means

- not a physically observable particle, what even is the top mass?
  - m_t^{MC} is assumed to describe the pole mass (mass from renormalization scheme)
    - mass of “free” top quark with all self energies absorbed (parton level)
    - already point of discussion

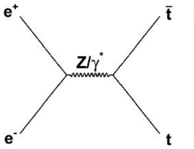


- every QCD observable σ however also has nonperturbative corrections:

$$\sigma^{\rm exp} = \hat{\sigma}(Q, m_t^X, \alpha_s(\mu), \mu; \delta m^X) + \sigma^{\rm NP}(Q, \Lambda_{\rm QCD}).$$

↘ dependence only disappears for infinite order

- for ee, top mass can be extracted from e.g. top pair production xsec in ee annihilation
  - color-singlet (no difficult color neutralization)
  - no QCD ISR
  - almost no corrections due to width



- non-perturbative QCD corrections are minimal
  - so m_t^{MC} and the experimental observable should describe the pole mass well with minimal non-perturbative corrections

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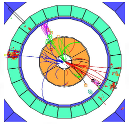
Top mass: measuring at a pp collider

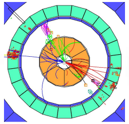
click here to read from someone who does know what this all means

- for pp collider very difficult
  - UE
  - protons give nonsinglet color configurations
  - non perturbative effects, collinear splitting and IR radiation
    - not perfectly modeled until now

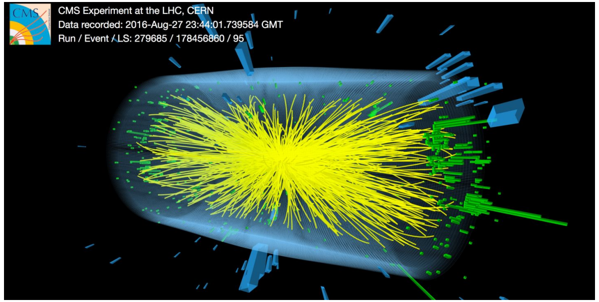
$$\sigma^{\exp} = \hat{\sigma}(Q, m_t^X, \alpha_s(\mu), \mu; \delta m^X) + \sigma^{NP}(Q, \Lambda_{QCD}).$$

this is a much bigger issue here

Me : mom can we have  ?

Mom : no, we have  at home

at home :



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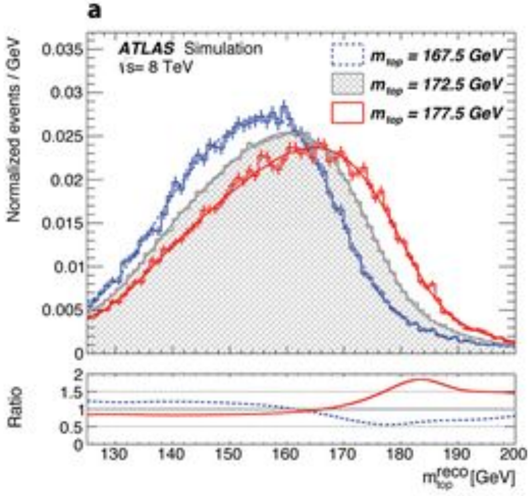
  - effects of QCD and electroweak quantum fluctuations
    have to be covered by PS

    (probably not safe to assume that this is well done)

  - Can we find a measurement method that is less affected
    by the non-pert. part and can be used to infer the pole mass with <u>less uncertainties</u>?

e.g. non-pert. corrections are huge for jet masses



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  - effects of QCD and electroweak quantum fluctuations have to be covered by PS

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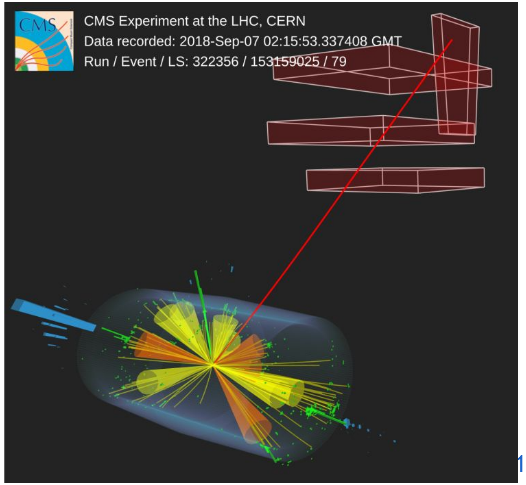
  - Can we find a measurement method that is less affected by the non-pert. part and can be used to infer the pole mass?
    - two examples using jet substructure, 4 tops is not one of them

4 tops:

Let's just add the 4-vectors!



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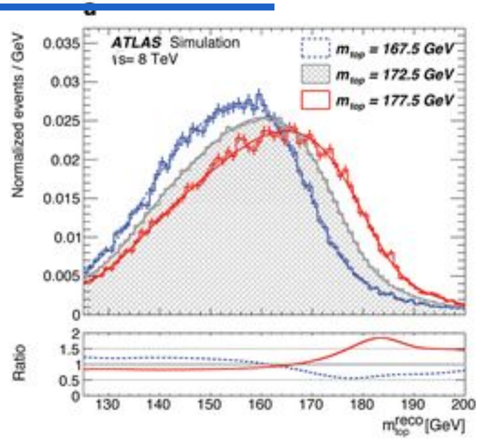
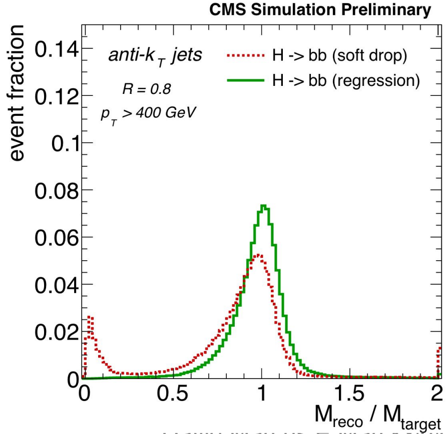
Top mass using jet substructure: groomed mass

- using jet masses is a bad idea
    - not IRC safe
    - UE
    - doesn't match parton level at all, swamped by non-pert. QCD
- jet grooming
    - soft drop or PN regressor
    - not perfectly non-pert. safe, UE is still background
- understanding the description of non-perturbative corrections for groomed jets. [26, 30, 31]





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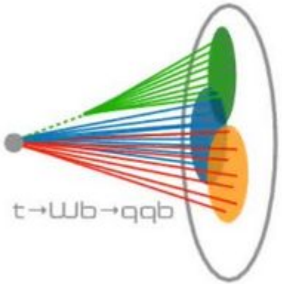
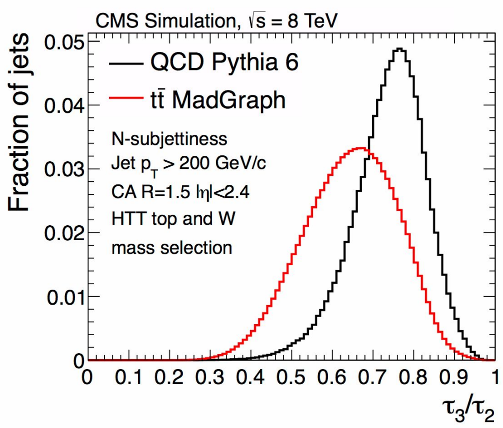
Top mass using jet substructure: energy correlators

- boosted top jet: 3 body decay, collinear radiation
  - define three-point correlator (EEEC)
  - ζ_{ij} is "angle" between PF candidates in jet, $\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2$ / $(1-\cos(\theta_{ij}))/2$, $\zeta_{12/23/31}$ are specific angles you choose
  - you scan a triangle over the jet and see how well the energy profile matches that triangle
  - n controls the weight you put on soft PFs





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

where

$$\widehat{\mathcal{M}}^{(n)}(\zeta_{12}, \zeta_{23}, \zeta_{31}) = \sum_{i,j,k} \frac{E_i^n E_j^n E_k^n}{Q^{3n}} \delta\left(\zeta_{12} - \hat{\zeta}_{ij}\right) \delta\left(\zeta_{23} - \hat{\zeta}_{ik}\right) \delta\left(\zeta_{31} - \hat{\zeta}_{jk}\right). \qquad (2)$$

$$\zeta_{\text{peak}} \approx 3m_t^2/Q^2$$

(assume 3 equal decays)

we look ensemble basis (not per event)

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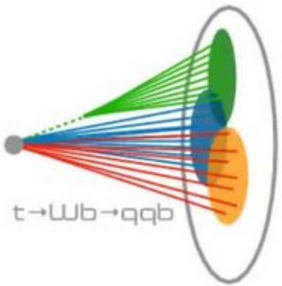
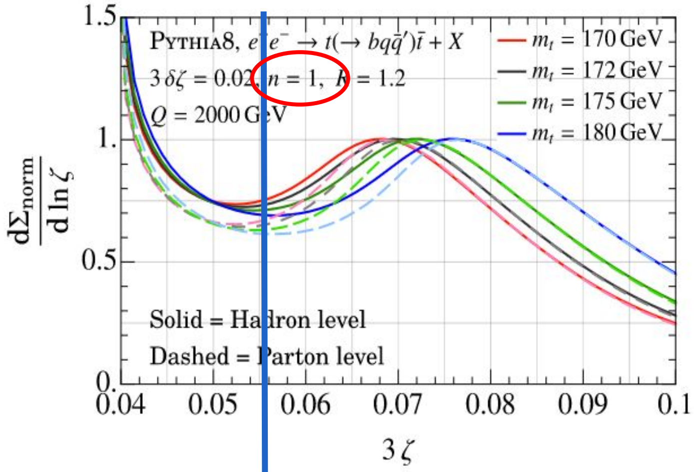
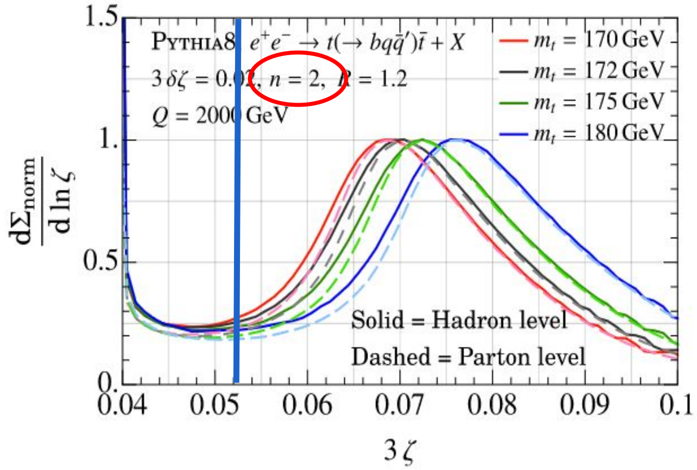
Top mass using jet substructure: energy correlators

- 3 body decay, collinear and soft radiation
  - here we take ζ = ζ12 = ζ23 = ζ13 (assume perfect triangular decay)
  - to reduce sensitivity to non-pert. part, we can **focus on hard decay angles (not collinear)**
  - and look at **higher powers of n (harder radiation)**
  - "size sensitive subjettiness scan", how big is triangle? (**important for later**: can also be shape sensitive if $\zeta_{12} \neq \zeta_{23} \neq \zeta_{13}$)
  - sensitive to the top mass





QCD | **larger scale substructure**



further lowers non-pert. QCD sensitivity

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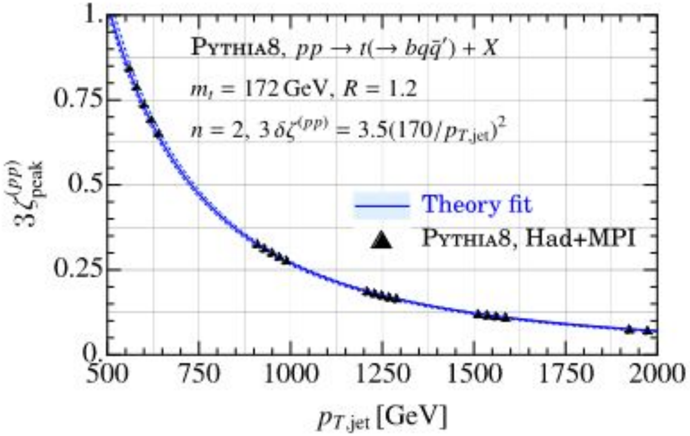
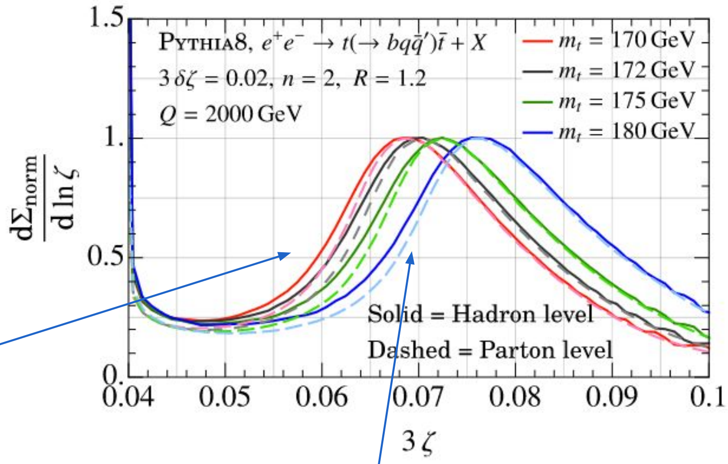
energy correlators (EECs)





assumes a jet pt distribution!!!

- **Problem**: location of peak also depends on pt of the jets
  - you need a perfect jet pt description to extract the top mass
  - sensitive to PDFs, large experimental uncertainties, large non-pert. corrections…
  - **can we do better**? Maybe we can use the W in the top decay to calibrate our method

use the W as a standard candle: first goal

- since W is not a QCD object, we know its mass very precisely from l nu decays
  - if we can extract W angles and top angles at the same time, we can calculate ζ_t/ζ_W
    - maybe from this we can extract m_t/m_W without need for jet pt info?
  - we define a new observable similar to EECs:

$$T(\zeta,\zeta_S,\zeta_A) \equiv \sum_{\substack{\text{hadrons}\\ i,j,k}} \int \mathrm{d}\zeta_{ijk} \frac{p_{T,i}\, p_{T,j}\, p_{T,k}}{(p_{T,\text{jet}})^3} \frac{\mathrm{d}^3\sigma_{i,j,k}}{\mathrm{d}\zeta_{ijk}} \times \Theta(\zeta_{ij} \geq \zeta_{jk} \geq \zeta_{ki} > \zeta_S)\, \delta\left(\zeta - \frac{(\sqrt{\zeta_{ij}}+\sqrt{\zeta_{jk}})^2}{2}\right) \times \Theta\left(\zeta_A > (\sqrt{\zeta_{ij}}-\sqrt{\zeta_{jk}})^2\right). \quad (1)$$

- ζ, ζ_S and ζ_A are reparametrisations of the angles (overall scale, smallest allowed “angle”, max asymmetry between two largest “angles”)
- pt’s act as energy weighting (IR safety)
- small ζ_S basically gives 2-point-like correlator, larger ζ_S becomes very similar to original symmetric EEC
- Heavisides, less delta functions!

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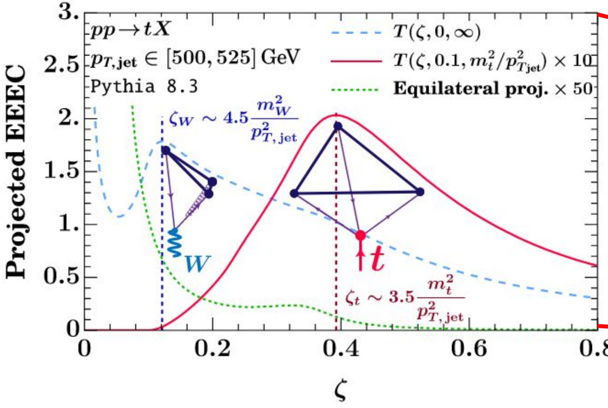
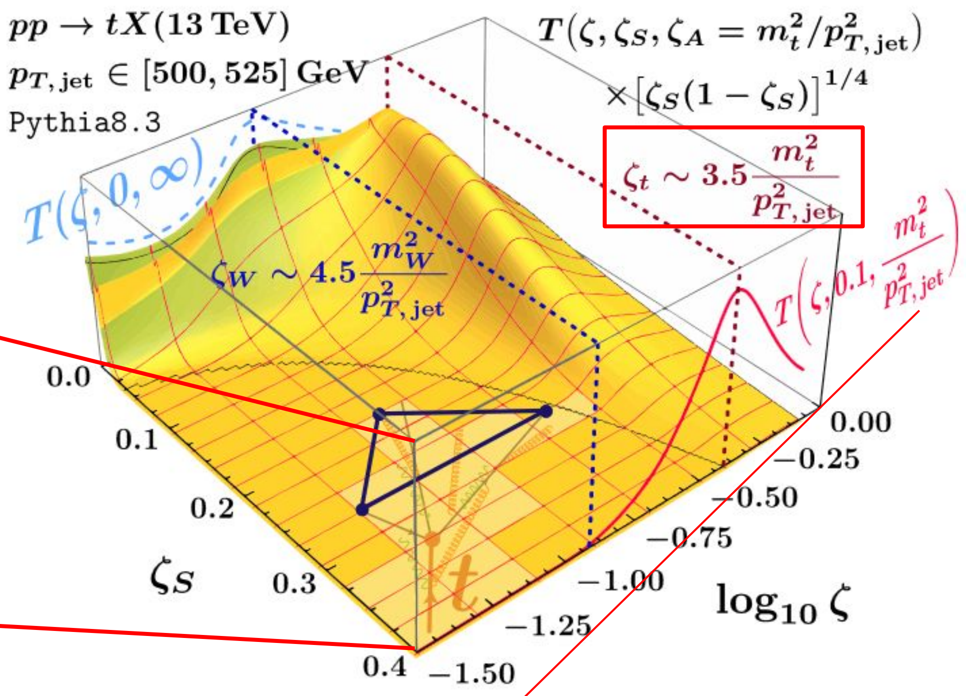
use the W as a standard candle: first goal

- large ζ_S peak for angular scale of top decay

significantly better stats than equilat. case!



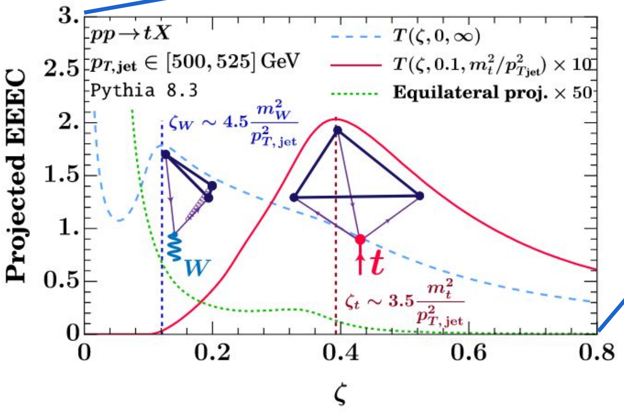


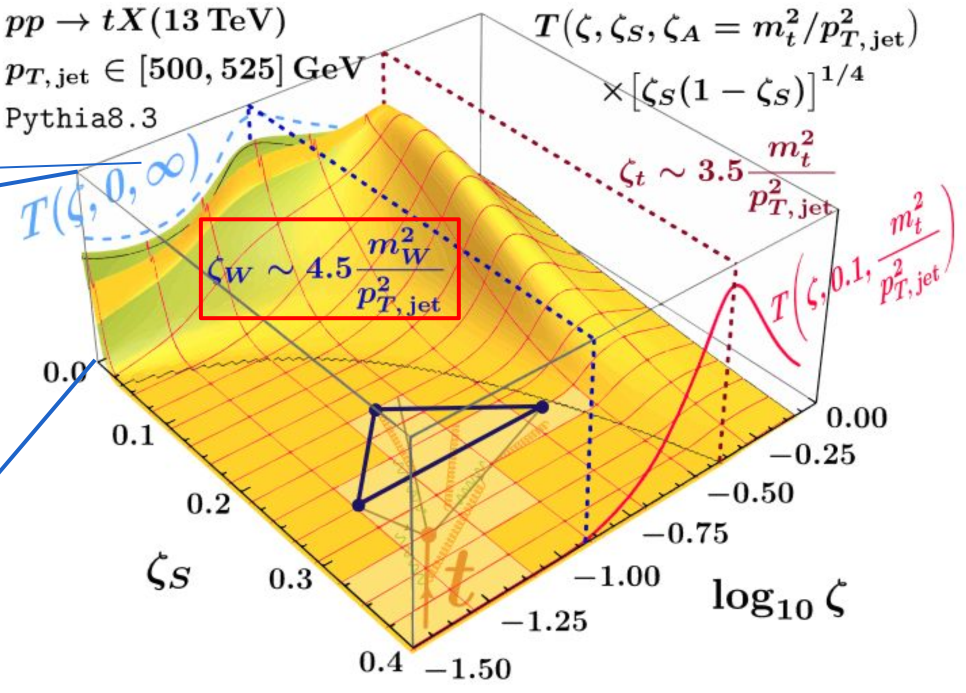
correlation can’t be too asymmetric because we want a top decay structure

use the W as a standard candle: first goal

- large ζ_S peak for angular scale of top decay
- low ζ_S a peak at the angular scale of the W

all asymmetries are allowed because the third particle is not relevant





simultaneously resolve the W and top inside a single jet without performing any reclustering!!!

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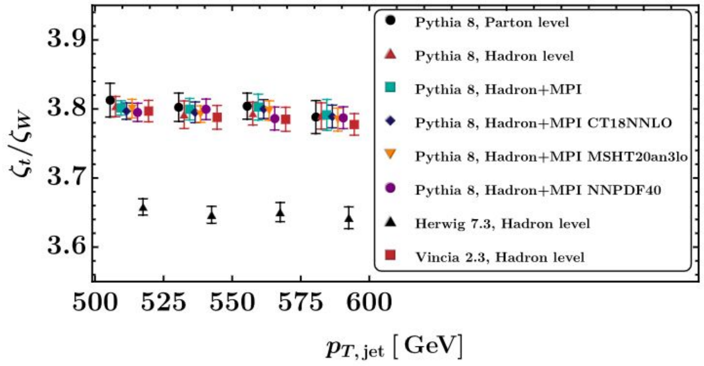
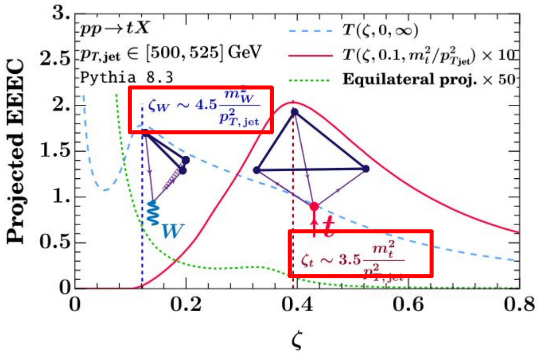
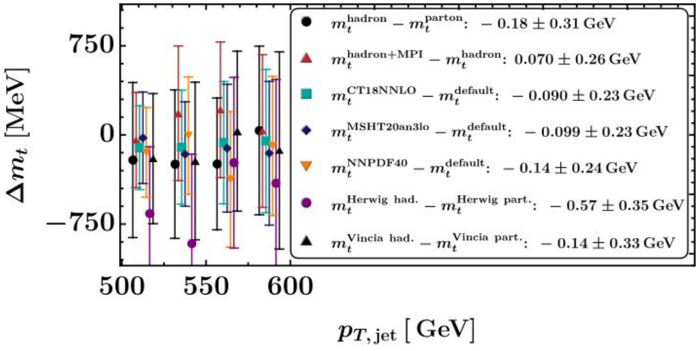
use the W as a standard candle: second goal

- So we can extract ζ_t/ζ_W at the same time
- how do we extract the mass ratio from this any better?
  - jet pt boosts top and W angular scale the same way
    - no jet pt sensitivity
  - parton level, hadron level, MPI, PDF effects
- **ratio cancels a lot of the sensitivity to this modeling!**
- we can safely use the peaks to extract the mass ratio!





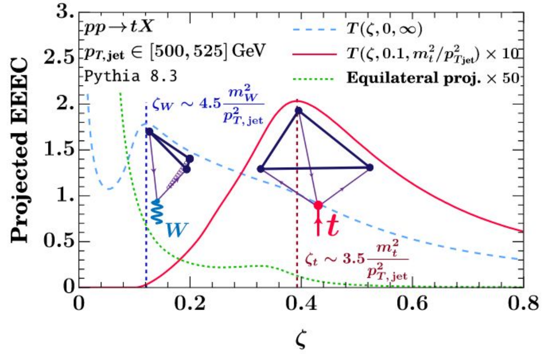


~100MeV compared to 1GeV for groomed jet mass

use the W as a standard candle: last hurdle

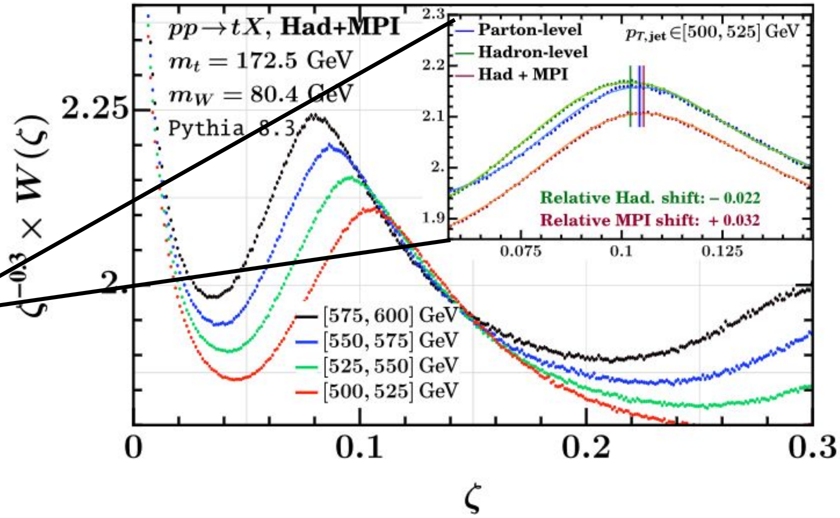
- extracting ζ_W is difficult
  - unlike top, the width doesn't protect from non-pert. corrections
  - how do we deal with non-pert. corrections?

Let's divide again!



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

- divide by standard two-point EEC
  - both sensitive to same effects
  - cancels leading non-perturbative effects
  - peak agrees well for non-perturbative effects
  - peak you get here is still ζ_W
  - still same pt dependence



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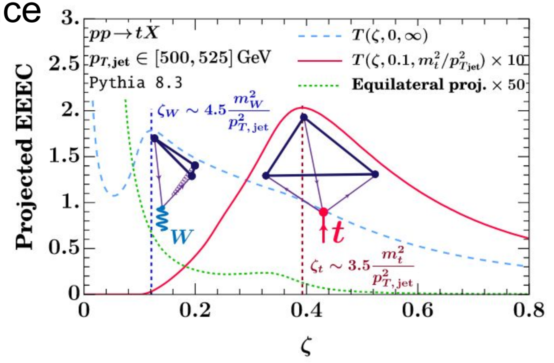
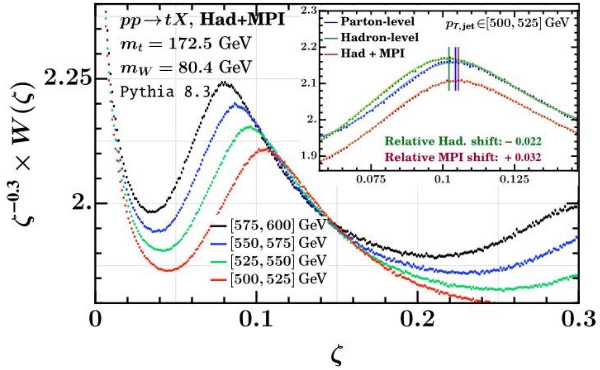
use the W as a standard candle: gameplan

1. measure $T(\zeta, \zeta_S, \zeta_A)$ for top region to extract ζ_t, but this has pt dependence
2. measure $W(\zeta)$ to extract ζ_W with minimal non-pert. uncertainties
3. define the ratio ζ_t/ζ_W, without pt dependence
4. extract from this m_t/m_W without any need for jet pt
5. we know m_W so we know m_t!!!
6. commit tax fraud (covered in next presentation)





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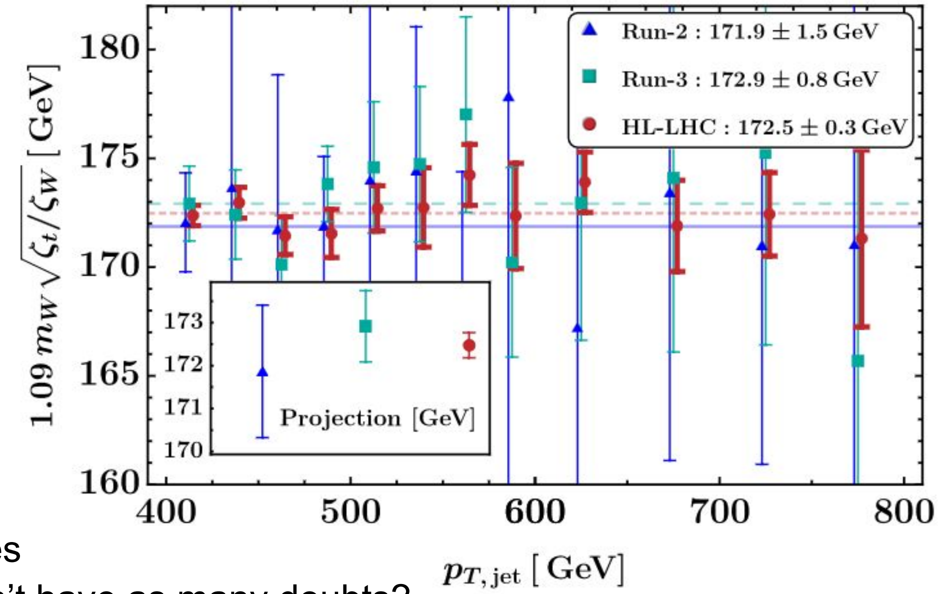
Feasibility and conclusions

more details in companion paper to come
small feasibility study:

- stats from CMS Run 2 top mass measurement
- 300 and 3000fb^{-1} assumed
- cumulant of statistical errors
- reasonable variation in the polynomial degree
- variation of the peak fit range by ± 10%



conclusions

- complex scheme to bypass several non-pert. issues
- uncertainty seems not super competitive but doesn't have as many doubts?
- investigate using charged particles only to calculate EECs? lower stats, higher angular accuracy

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