Energy correlators for boosted tops and bosons

Dennis Schwarz

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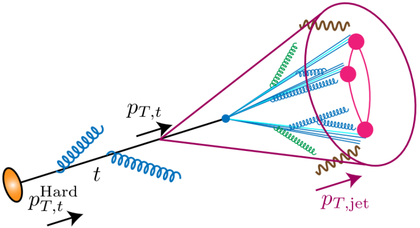
Energy correlators

- Fundamental object in field theory: energy flow operator

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

→ "Flow of energy through idealized calorimeter cell located at infinity"

- Jet substructure: study the correlation functions of energy flow operators

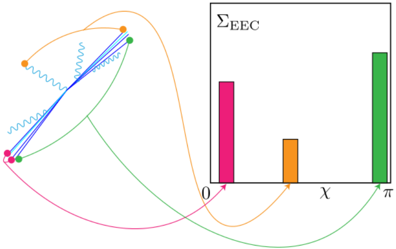


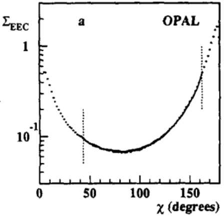
Energy-Energy Correlator: One of the very first event shapes and a QCD correlation observable:

Basham et al. 1978

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

Multiple entries per event!





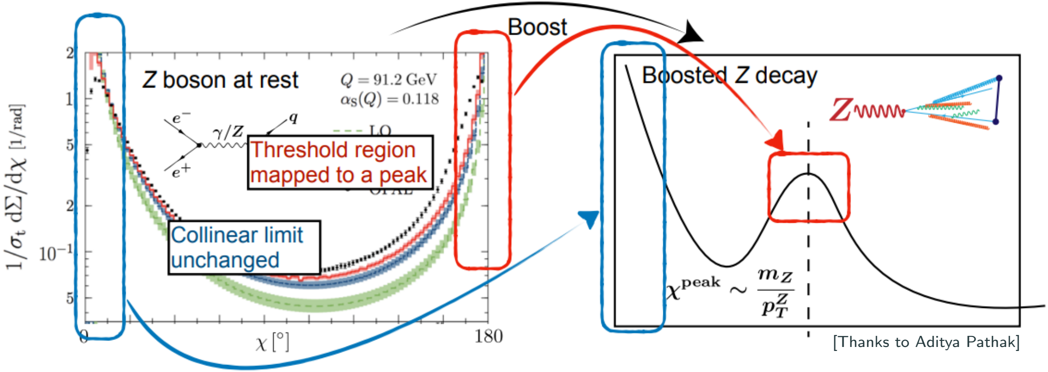
[Opal collboration, Z. Phys. C59 (1993) 21]

Well explored field

[Basham, Brown, Ellis, Love, PRL 41, 1585 (1978)], [Schindler, Stewart, Sun, arXiv:2305.19311], [Lee, Pathak, Stewart, Sun, arXiv:2405.19396], ...

Fundamental test of QCD!

Relevance at the LHC



- Back-to-back limit at large χ for boson at rest

$\rightarrow$ Peak after boost

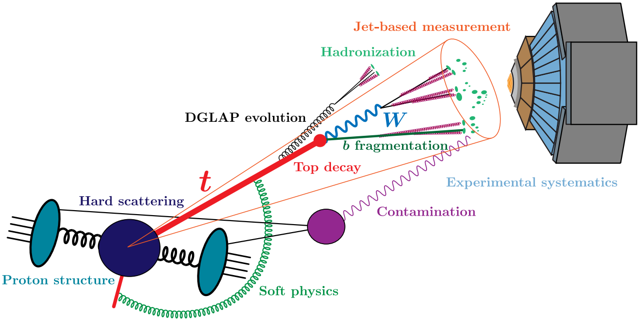
- Observable sensitive to particle boost

Energy correlators for m_t

Energy correlators for m_t

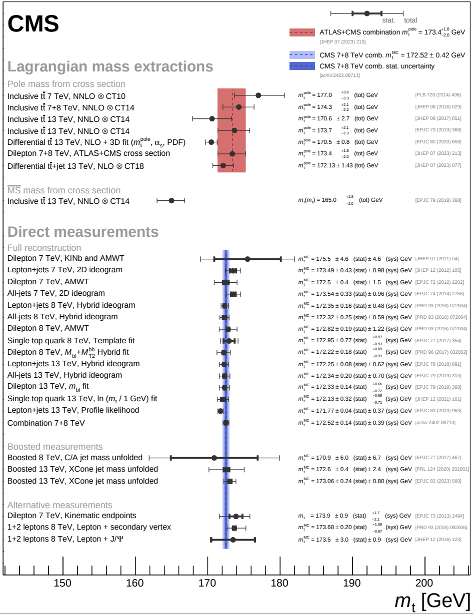
Why use it for m_t?

- Top quark measurements at hadron colliders are complicated!
- Hadronic initial states, pileup, underlying event, soft QCD, parton shower, hadronization
- Correlators can provide theoretically clean predictions!



Challenges in top quark mass measurements

[CMS, arXiv:2403.01313]



Multiple strategies to measure the top quark mass:

- **Direct** measurements: very precise but ambiguities in m_t^{MC}
- Extractions from **cross sections**: Less precise, often depend on definition of a stable top quark particle, $t\bar{t}$ threshold sensitive to non-trivial corrections
- **Boosted** measurements: defined at level of stable particles, high sensitivity to m_t, but theory and experimental phase space not compatible yet

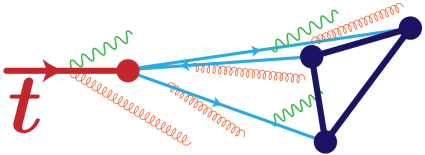
Energy correlators in the top decay

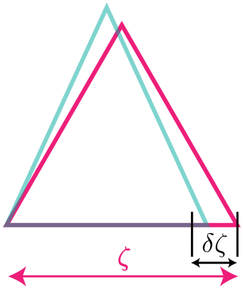
- Triplet energy correlator captures opening angle of top decay

$\rightarrow$ Sensitivity to boost (p_T) and mass m_t

1. Find all triplets of particles
2. For each triplet: entry at $\zeta = \frac{\sum \Delta R_{ij}^2}{3}$ with weight $w = \frac{(p_{T,1} p_{T,2} p_{T,3})^n}{p_{T,\text{jet}}^n}$ (n: exponent of choice)

- Equilateral triangle configuration suppresses collinear contributions

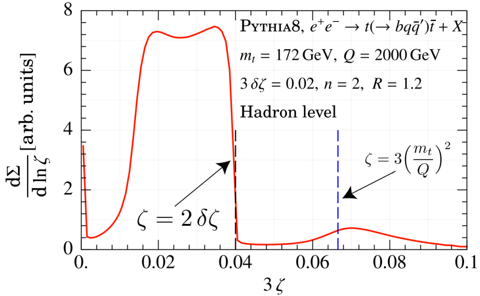


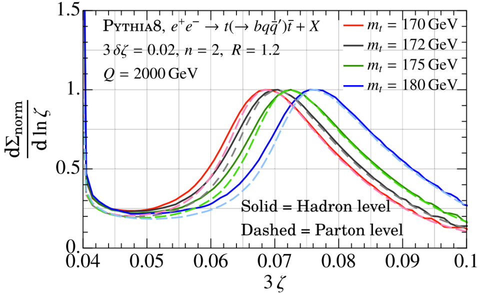


Example in ee collisions

[Holguin, Moult, Pathak, Procura, Phys. Rev. D 107, 114002]

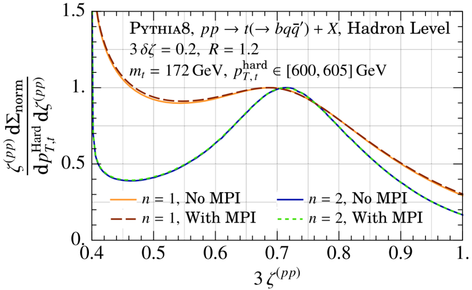
- Example in ee $\rightarrow t\bar{t}$
- Here, replace $p_{\mathrm{T,jet}}$ with $Q = \sqrt{s}$
- Peak at $\zeta \sim 3\left(\frac{m_t}{Q}\right)^2$
- Non-perturbative effects in the peak very small
- Sensitivity to m_t

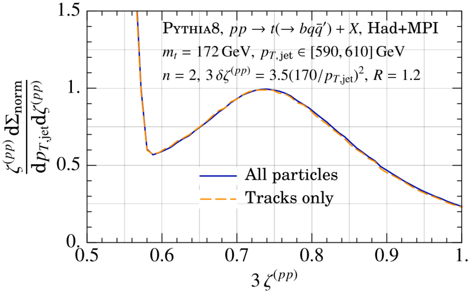




Energy correlator in pp collisions

[Holguin, Moult, Pathak, Procura, Phys. Rev. D 107, 114002]



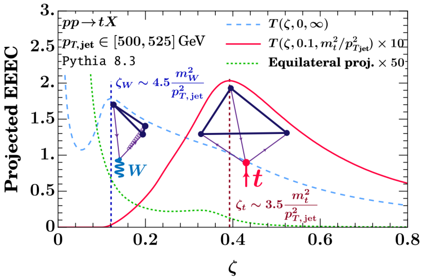


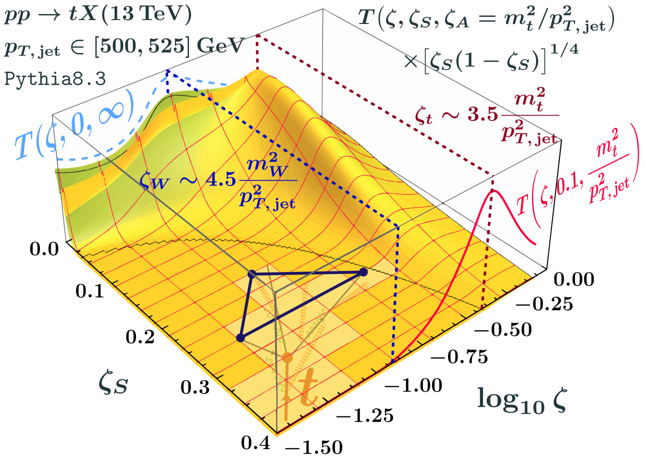
- In pp use top decays reconstructed in a single jet
- Energy scale is now jet p_T
- Robust against MPI
- Measurement can be performed using tracks only!
- But peak position still depends on jet p_T, which results in large uncertainties due to jet calibration

The W as a standard candle

[Holguin, Moult, Pathak, Procura, Schöfbeck, Schwarz, arXiv:2311.02157]

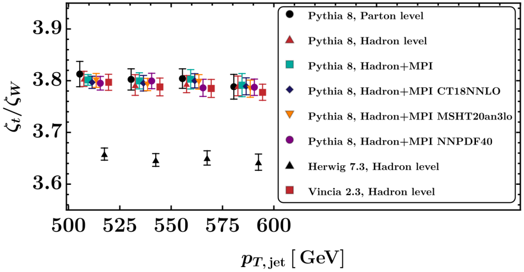
- If we allow the shortest side of the triangle to be small, a W peak emerges
- Similar p_T dependence in W and top peaks → cancellation





Ratio of top and W

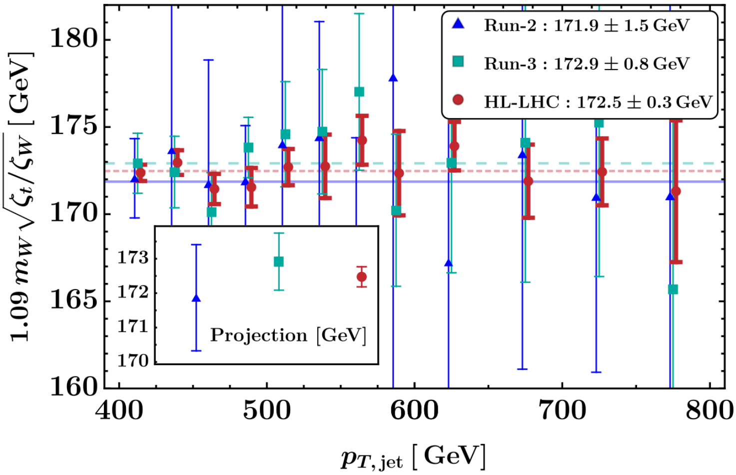
[Holguin, Moult, Pathak, Procura, Schöfbeck, Schwarz, arXiv:2311.02157]



- For now, measure ratio of peak positions (with calculations available, the measurement would be performed using the full distributions)
- Jet p_T dependence eliminated in top to W ratio
- Non-perturbative effects very small
- Precise value of the ratio can be calculated. Here it differs between Pythia and Herwig because of different showers

Statistical feasibility

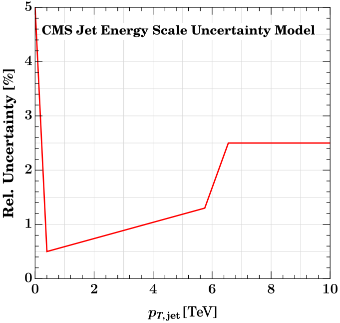
[Holguin, Moult, Pathak, Procura, Schöfbeck, Schwarz, arXiv:2311.02157]

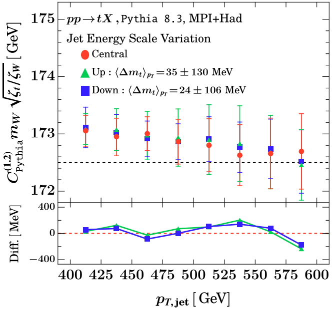


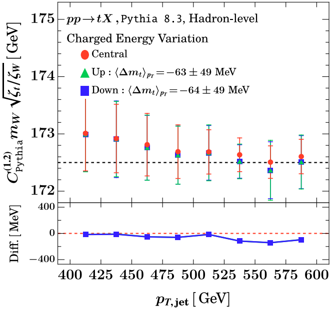
- Measurement experimentally feasible at HL-LHC!
- Statistical uncertainty < 1 GeV already with Run 3

Systematic uncertainties - Jet energy scale

[Holguin, Moult, Pathak, Procura, Schöfbeck, Schwarz, arXiv:2407.12900]



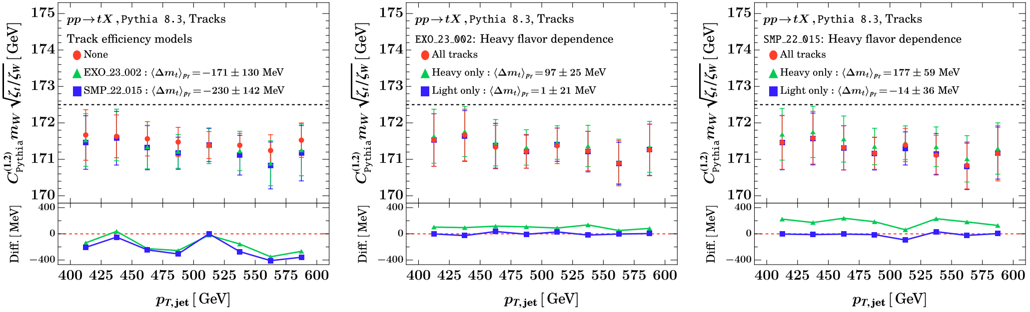




- Variations of jet p_{T} (oriented at CMS jet energy uncertainty) and constituent p_{T} lead to shifts well below 200 MeV

Systematic uncertainties - Track efficiency

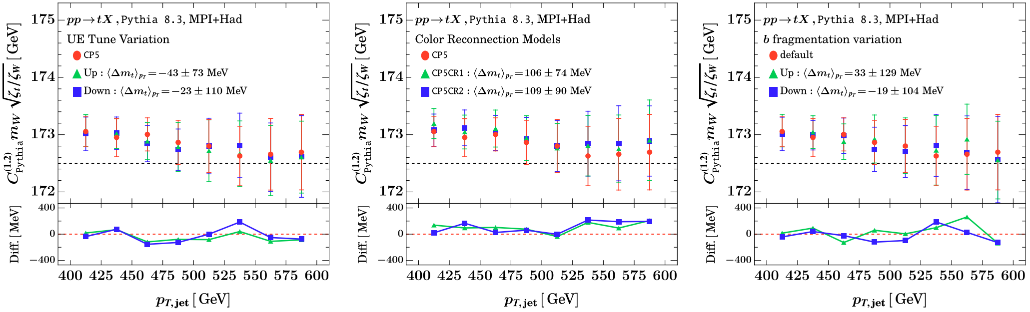
[Holguin, Moult, Pathak, Procura, Schöfbeck, Schwarz, arXiv:2407.12900]



- Vary tracking efficiency (constant 3% or p_{T}-dependent)
- Second model where we only vary the light/heavy tracking efficiency
- Estimates have larger uncertainties, still small effect

Systematic uncertainties - Modelling

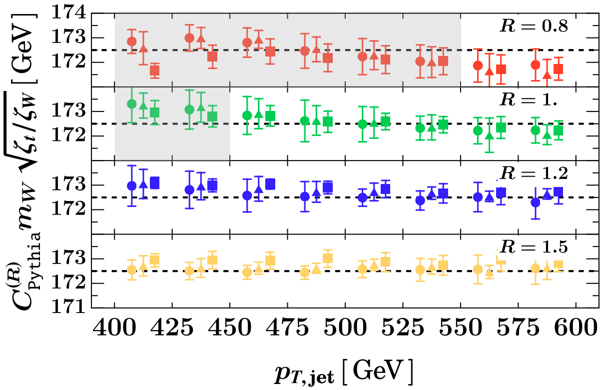
[Holguin, Moult, Pathak, Procura, Schöfbeck, Schwarz, arXiv:2407.12900]



- Also studied modelling parameters that enter via (simulation-based) unfolding
- Variations of UE tune, color reconnection, b fragmentation
- All smaller than 200 MeV

Stability against jet radius

[Holguin, Moult, Pathak, Procura, Schöfbeck, Schwarz, arXiv:2407.12900]

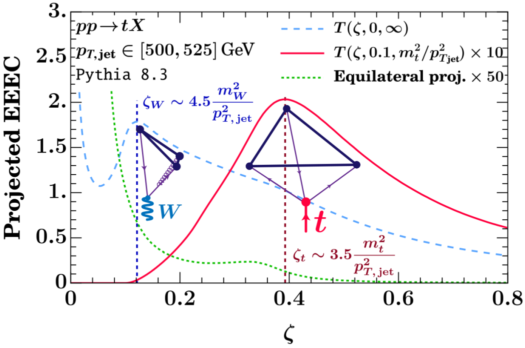


- Stable for suitable jet R
- If boost too small for chosen R: edge effects

Energy correlator for m_t

In summary:

- Novel idea to extract m_t using correlators
- Sensitivity to m_t ✓
- Robust against uncertainties ✓
- Theoretical control ✓



Energy correlators in diboson

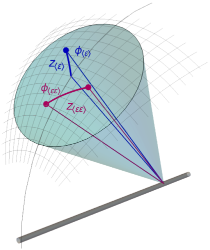
[Ricci, Riembau, Phys. Rev. D 106, 114010]

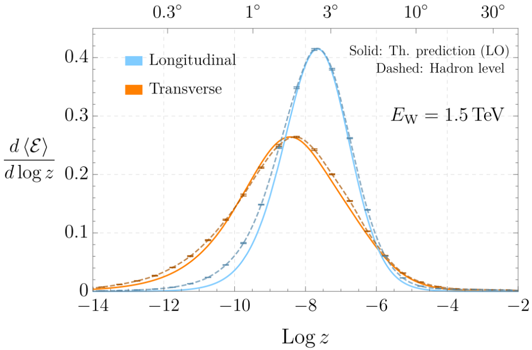
Energy correlators in diboson

[Ricci, Riembau, Phys. Rev. D 106, 114010]

- One-point correlator in boosted W/Z→qq
- Distance to jet axis as measure
- Smaller distances in configurations where quarks are emitted in/against boson direction

→ Sensitivity to polarization!

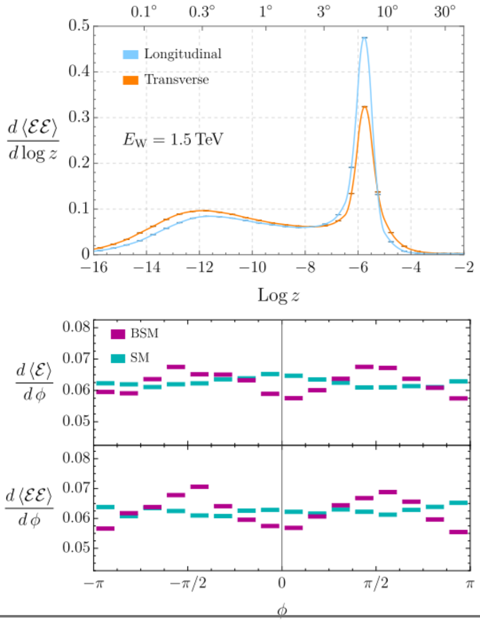




Energy correlators in diboson

[Ricci, Riembau, Phys. Rev. D 106, 114010]

- Now look at two-point correlator
- Two-point correlator peaks at similar position because quark-quark distance is not changed
- But: Interference effects visible in both E1C and E2C with respect to angle ϕ (azimuthal angle relative to scattering plane)
- Sensitive to EFT!



Energy correlators for α_S

[CMS, PRL 133 (2024) 071903]

Energy correlators for α_S

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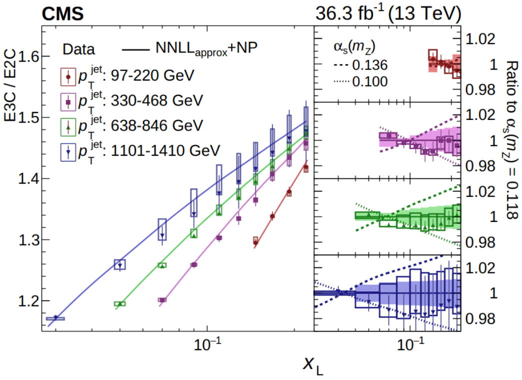

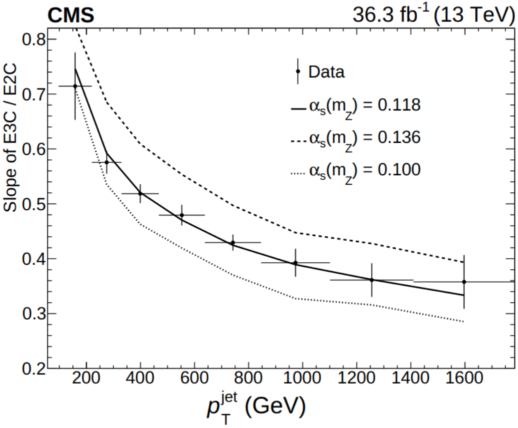

- Measurement of α_S inside jets
- Sensitivity from ratio of two-point to three-point correlators
- Most precise α_S measurement using jet substructure

Summary

- Energy correlators provide clean predictions from theory
- Various configurations for different physics questions
- Proposal for precision measurement of m_t
- Applications also in boosted bosons
- Related idea: Learn EFT effects from PF candidates inside jets

  [Chatterjee, Cruz, Schöfbeck, Schwarz, Phys. Rev. D 109, 076012]
- Most precise α_S measurement already published
- Promising field at the LHC!