

Using the W Boson as a Standard Candle to Reach the Top: Calibrating Energy-Correlator-Based Top Mass Measurements

Jack Holguin^{1,2}, Ian Moulton³, Aditya Pathak⁴, Massimiliano Procura⁵, Robert Schöfbeck⁶, and Dennis Schwarz⁶

¹*University of Manchester, School of Physics and Astronomy, Manchester M13 9PL, United Kingdom*

²*CPHT, CNRS, École polytechnique, Institut Polytechnique de Paris, 91120 Palaiseau, France*

³*Department of Physics, Yale University, New Haven, Connecticut 06511, USA*

⁴*Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany*

⁵*University of Vienna, Faculty of Physics, Boltzmannngasse 5, A-1090 Vienna, Austria*

⁶*Institute for High Energy Physics, Austrian Academy of Sciences, Nikolsdorfergasse 18, A-1050 Vienna, Austria*



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The top quark mass is a key parameter of the standard model, yet measuring it precisely at the Large Hadron Collider (LHC) is challenging. Inspired by the use of standard candles in cosmology, we propose a novel energy correlator-based observable, which directly accesses the dimensionless quantity m_t/m_W . We perform a Monte Carlo study to demonstrate the feasibility of the top mass extraction from Run 2, 3, and High-Luminosity LHC datasets. Our resulting m_t can be defined in a well-controlled short-distance mass scheme and exhibits remarkably small uncertainties from nonperturbative effects, as well as insensitivity to parton distribution functions, outlining a roadmap for a record precision measurement at the LHC.

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Introduction—The precise value of the top quark mass plays a crucial role in the standard model, both for testing its internal consistency [1,2] and for understanding its extrapolation to high energies for hints of what lies beyond [3–12]. However, the top can currently only be produced at hadron colliders, where precision measurements of its mass are notoriously difficult. While a large number of techniques have been proposed and used in precision measurements [13–16], they all suffer from difficulties, such as the lack of theoretical control over the observables' relation to the Lagrangian top mass parameter [17,18], or a high sensitivity to parton distribution functions (PDFs). With the High-Luminosity Large Hadron Collider (HL-LHC) era on the horizon, a renewed effort to develop qualitatively new approaches to extract the top mass is warranted.

A novel approach to studying complex final states in hadronic decays is jet substructure (e.g., Refs. [19–21] and references therein). Jet substructure enables the study of decaying heavy particles through their imprint in the correlations of hadronic energy flux within jets. As first shown in Ref. [22], this provides an opportunity to study inclusive decays of boosted top quarks at the LHC, which can be described with rigorous factorization theorems [23,24], enabling the top mass to be treated in short-distance mass

schemes [25,26], overcoming ambiguities in its definition present in other approaches.

So far, two observables have been put forward for precision extractions of the top mass from jet substructure: one dimensionful and one dimensionless. The first approach [22], further developed in Refs. [27,28], proposes to use the groomed [29,30] jet mass. This is directly sensitive to the dimensionful mass scale of the top. However, it is also sensitive to soft radiation and nonperturbative effects at scales parametrically lower than the top width, Γ_t . This can be ameliorated by grooming but at the expense of an increased theoretical complexity. While progress has been made in understanding the description of nonperturbative corrections for groomed jets [27,31,32], the distribution also receives a large contribution from the underlying event (UE) for the grooming proposed in Ref. [22], which is extremely challenging to model accurately. The second proposal [33] is to use energy correlators (EECs) [34–38], which have recently been introduced [39] as jet substructure observables. EECs were first measured in hadron colliders in Refs. [40–42]. Unlike the jet mass, EECs are sensitive to a dimensionless *angular scale*, with the mass scale being reconstructed from the jet p_T . Since soft radiation enters the energy correlators only via recoil, they are not sensitive to scales below Γ_t , making them naturally robust to both hadronization and UE. Despite the theoretical elegance of this approach, the jet p_T has large experimental uncertainties, making a precise determination of m_t challenging in practice. We thus believe that identifying a top-mass-sensitive observable that is simultaneously experimentally feasible at the LHC, robust to hadronization and UE, and

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calculable to high perturbative orders remains an important open problem.

In this *Letter*, we introduce an EEC-based observable for precision top quark mass measurements, which overcomes the previous experimental difficulties. Our observable is inspired by cosmology, where it is common that precisely measured observables, such as luminosity, are not directly related to quantities of interest, such as distances. The use of standard candles then plays a crucial role, providing a methodology for converting between two independent dimensional quantities. This is similar to the present case of extracting masses from measurements of high-multiplicity hadronic states: the dimensionless angular scales are robust observables, necessitating the development of standard candles to enable their use for precision mass measurements. Crucially, the top predominately decays into an electroweak scale particle whose mass has been measured with spectacular accuracy, the W boson. This particle provides the needed standard candle by introducing another dimensionless parameter, m_t/m_W , into the observable. In this *Letter*, we study a hadronization and UE insensitive standard candle constructed from EECs measured on the W boson, allowing us to build a distance ladder all the way back through the complicated QCD dynamics to the time scales of the top quark decay. The outcome is a measurement of the top mass in terms of the W mass and a purely angular measurement which are both independently robust experimental quantities. We emphasize that this approach is distinct from existing top mass extractions [43,44] wherein the W decay is reconstructed only to achieve a fine-grained calibration of the jet energy scale (JES). These methods are otherwise not *a priori* robust to experimental and modelling uncertainties. In contrast, our approach offers a higher potential for precision since we work with angular quantities that are already experimentally robust from the outset and are more amenable to theoretical calculations. This is supported by recent studies [45,46].

We here demonstrate the feasibility and properties of our approach at the LHC through a Monte Carlo study and lay out a roadmap for an experimental and theoretical program to achieve a record top mass measurement.

Energy correlators on top decays—There has been rapid progress in our understanding of multipoint energy correlators and their application to jet substructure (e.g. Refs. [33,47–62], as well as their structure for generic angles [63,64] and theoretical properties [65,66]. In Ref. [33], the three-point correlator was applied to detect the angular scale associated with the top decay. Since, at leading order, this is a hard three-body decay, it was proposed that this could be detected in an equilateral configuration for the correlator. However, the full three-point correlator on top decays is a rich function of three angles whose shape has not yet been explored.

The key object of our analysis is the following integrated EEC (weighted cross section). We express the angles

between the momenta of the correlated final state particles as $\zeta_{ij} = \Delta\eta_{ij}^2 + \Delta\phi_{ij}^2$ in terms of rapidity-azimuth coordinates. The observable we define is

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

Here the sum is over all (not necessarily distinct) triplets of hadrons (i, j, k) in the most energetic jets within each hemisphere of an identified top event. In the last equation, $p_{T,i}$ is the transverse momentum of particle i , which provides the energy weighting, and $d\zeta_{ijk} \equiv d\zeta_{ij}d\zeta_{jk}d\zeta_{ki}$. We find it convenient to trade the three angles of the correlator for an overall scale ζ , a cut on the smallest angle in the correlator, ζ_S , and a cut on the asymmetry between the longest two sides, ζ_A . This parametrization of the three-point correlator allows us to easily control the phase-space regions identified by the correlator. A plot of this distribution on boosted top quarks is shown in Fig. 1(a), revealing an interesting shape. For large values of ζ_S there is a single peak at the angular scale of the hard three-body decay of the top quark, $\zeta_t \sim m_t^2/p_{T,\text{jet}}^2$. As ζ_S is lowered, corresponding to the inclusion of more squeezed triangle configurations, a peak at the angular scale of the W , $\zeta_W \sim m_W^2/p_{T,\text{jet}}^2$ emerges in T and is clearly visible in the back wall of Fig. 1(a). In this work, ζ_S and ζ_A are fixed at the particular values $\zeta_S = 0.8(172 \text{ [GeV]}/p_{T,\text{jet}})^2$ and $\zeta_A = (172 \text{ [GeV]}/p_{T,\text{jet}})^2$ to cleanly isolate the top peak feature. The distributions with fixed ζ_S cuts are shown on the boundaries of the plot in Fig. 1(a) and separately in Fig. 1(b), which highlights the sharpness of the peaks, as well as the kinematic configurations that give rise to them. Figure 1(b) also highlights the substantial statistical gain of $T(\zeta, \zeta_S, \zeta_A)$ relative to the near equilateral projection previously used in the literature [33]. The topologies depicted in Fig. 1(b) are analogous to the “equilateral” and “squeezed” configurations for cosmological correlators [67,68]. This shows that we can simultaneously resolve the W and top inside a single jet without performing any reclustering, which is a remarkable feature of the EECs that are inclusively sensitive to all scales present in a given system. This property of the EECs was first applied in [69], where they were used to resolve both the b -quark mass scale and the length scale of the plasma in heavy-ion collisions.

The W as a standard candle—The identification of the angular scale of the W is the first key insight of this *Letter*,

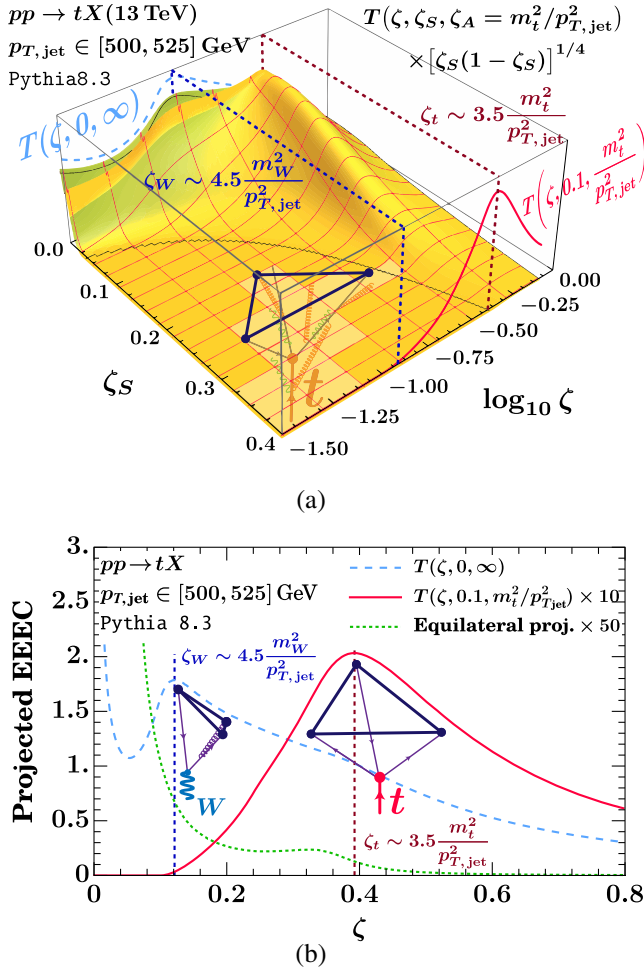


FIG. 1. Illustrative plots produced from PYTHIA showing the imprint of top and W on the 3-point EEC in Eq. (1). (a) The shape of the three-point correlator on boosted top jets, Eq. (1). A large value of ζ_S selects the hard top decay process, but by lowering ζ_S , the W peak emerges. Slices for specific values of ζ_S are shown on the boundaries of the plot. (b) Slices for specific values of ζ_S which emphasize the sharpness of the W and top peaks. The green line with the small bump corresponds to the equilateral projection considered in [33].

and opens the door to using m_W , which is known with a remarkable uncertainty of ± 12 MeV [70], to calibrate the mass scale of the top quark. The presence of the W introduces a dependence of the EEC distribution on the dimensionless scale m_t/m_W , which can be extracted from measurements of the shape of the distribution around the peak. In particular, the *ratio* of the location of its peaks is determined by m_t/m_W . This reflects the commonality between the rest frame of the top and the frame in which the W 's production is isotropic, and so their peak locations are determined by a single shared boost. The distribution in the peak region can be computed using rigorous factorization theorems and expressed in terms of the top mass in a short-distance mass scheme [25,26]. The known value of m_W then allows a conversion to a measurement of m_t in a

short-distance mass scheme. In this light, the complicated three-body decay of the top, via the intermediate W , is in fact a gift.

To exploit the presence of the W mass scale, we must develop a standard candle observable that is robust to hadronization and pileup effects and which can be calculated to high perturbative orders. Unlike for the top, where the scale Γ_t provides a natural cutoff suppressing nonperturbative contributions in the peak region, for the W there is no such cutoff. We must suppress nonperturbative effects in another fashion. One approach to obtaining EEC observables that are robust to hadronization is to take ratios that cancel leading nonperturbative effects. This was originally proposed in Ref. [39], and these ratios have since been calculated to high perturbative orders [54,57,71] and measured in collider experiments [47]. Here, we extend this approach to produce a robust standard candle from the W boson.

We define the ratio

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

where the denominator is the standard two-point EEC, while the numerator, $T(\zeta, 0, \infty)$, is the correlator of Eq. (1), with no cuts on the asymmetry ζ_A , or smallest angle, ζ_S . Note that this observable is nearly identical to the standard ratio of projected correlators [39], with the only difference being that we take ζ in the three-point EEC to be the average of the long and medium side, as compared to the longest side as done in Ref. [39], since we find that this is better behaved in the peak region. When defined in this way, the two- and the three-point EEC in $W(\zeta)$ have closely related leading nonperturbative corrections in the peak region. Specifically, these nonperturbative effects partly arise from the (boosted) Sudakov region involving the same soft function in the numerator and denominator of the $W(\zeta)$, such that they cancel at leading logarithmic accuracy [72]. Furthermore, the nonperturbative corrections of the kind that appear in the collinear limit of projected EECs cancel in the same way in the $W(\zeta)$ ratio as they do for massless jets [39]. Figure 2 shows this observable for different values of the jet p_T , illustrating the resulting peak structure. The inset shows shifts in the peak due to hadronization and the UE. We will show below that these shifts are highly correlated with those in the top quark peak, and arise solely due to shifts in the $p_{T,jet}$ distribution.

In addition to its robustness, this observable can be computed to high perturbative orders in the peak region using a factorization theorem building on Refs. [73,74], which we leave to future work. Combined, these features provide us with a well-calibrated standard candle in the complex LHC hadronic environment. To our knowledge, such an approach has not previously been used in precision

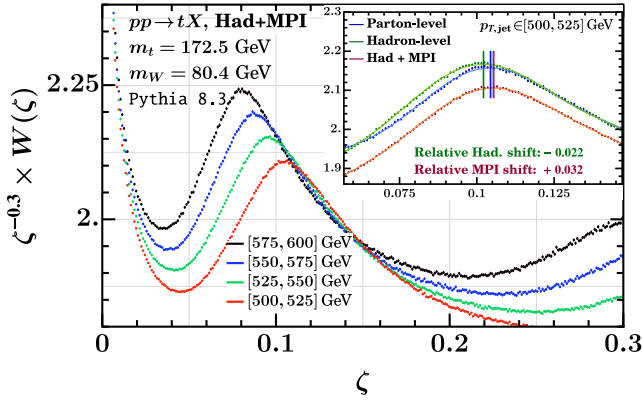


FIG. 2. The ratio of the three- to two-point correlator defined in Eq. (2) provides a robust standard candle identifying the angular scale of the W mass. The peak is shown for different values of the jet p_T , and the inset shows the robustness of the shape of the peak region to hadronization and UE effects. The factor of $\zeta^{-0.3} \approx \zeta^{-\gamma(4)+\gamma(3)}$, involving the relevant spin 4 and 3 anomalous dimensions, is included to reduce the tilt from universal small-angle physics making the peak easier to fit.

jet substructure measurements, and it would be interesting to explore if this could be applied in other situations.

Monte Carlo study—Having illustrated that EECs can be used to robustly identify the angular scales associated with the W and top masses, we now show that this allows us to precisely extract the value of the top mass in units of the known W mass. Crucially, we demonstrate that this calibration can be performed without needing to know the jet p_T , which has large experimental uncertainties, large nonperturbative corrections [75], and is sensitive to the parton distribution functions (PDFs).

The conversion should be performed using a full calculation of the observable. The formalism to achieve this will be presented in future work. Here, we show how this can be performed using a parton shower study where a polynomial is used to fit for the peak positions ζ_t and ζ_W . In the large boost limit of a top quark decay [45],

$$m_t = m_W \left[C(\alpha_s, R) \sqrt{\zeta_t/\zeta_W} + \mathcal{O}\left(\frac{m_W}{p_{T,jet}}, \frac{m_t}{p_{T,jet}}\right) \right], \quad (3)$$

where the coefficient C has a perturbative expansion and depends on the jet radius R , C 's magnitude is dominated by the relative boost of the W boson which is largely determined by the top decay at fixed order. The exact magnitude of C will differ between event generators which employ different approximations to the NLO top decay. We considered the HERWIG 7.3 [76–78], PYTHIA 8.3 [79], and VINCIA 2.3 [80] parton showers. We reconstruct anti- k_T [81] jets with radii $R = 1, 1.2, 1.5$ using FastJet [82]. We found the extraction of the top mass to be largely independent of R , and so we here focus on $R = 1.2$. We first illustrate that the ratio ζ_t/ζ_W extracted from the peak positions is

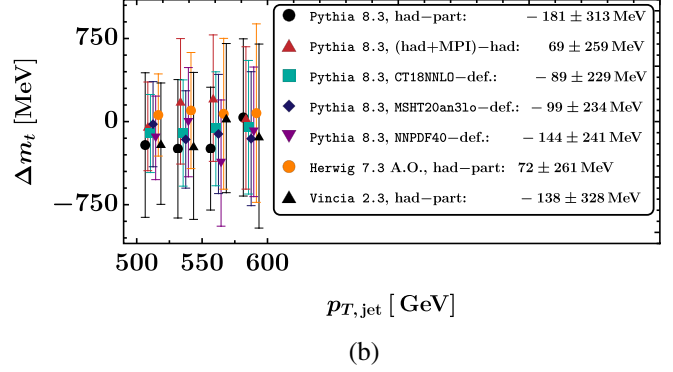
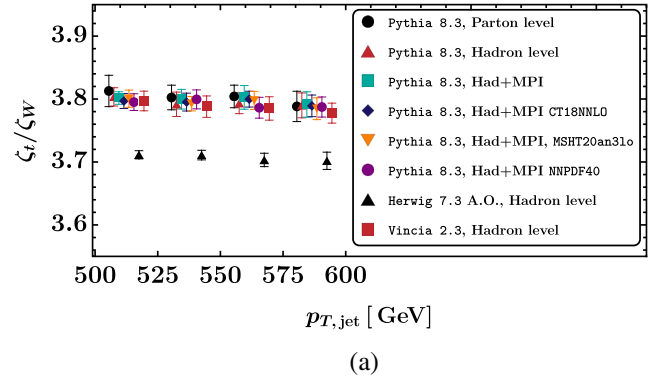


FIG. 3. The errors shown in panels (a) and (b) are conservatively computed from the cumulant of statistical errors, reasonable variation in the polynomial degree used for the peak fit, and variation of the peak fit range by $\pm 10\%$. Jet p_T is in 25 GeV bins. Horizontal clusters of points all share the same central value of $p_{T,jet}$. (a) The ratio ζ_t/ζ_W as a function of p_T , jet enabling the conversion between the standard candle and the top mass according to Eq. (3). While the ratio is virtually independent of the jet p_T , it is sensitive to m_t and m_W . (b) The shift in the extracted top mass from simulation due to hadronization, MPI effects, and modification of the PDFs. Simulations are performed with PYTHIA unless labeled otherwise. Variation of the PDF set is performed with hadronization and MPI. Averages across jet p_T bins are shown in the legend. This illustrates the resilience of the standard candle to nonperturbative and initial-state effects.

virtually independent of the jet p_T . We then show that this ratio is largely insensitive to nonperturbative effects.

In Fig. 3(a), we show the ratio of the W and top peaks, ζ_t/ζ_W at parton level, hadron level, and with MPI (PYTHIA model for UE) turned on, as well as for a variety of different PDFs. While perturbative corrections can be incorporated to further improve the conversion, Figure 3(a) shows that we have eliminated the dominant p_T scaling from the problem by using the standard candle approach. We emphasize that the location of the top and W peaks are themselves strongly dependent on the choice of the PDF set, which influences the jet p_T distribution. Still, this dependence cancels in the ratio to a remarkable degree. We note that HERWIG confirms the cancellation of the p_T dependence but differs by 3% from every other Monte Carlo in the perturbative constant dictating the

scale of the y axis, specifically C in Eq. (3). As elaborated in Supplemental Material [83], the difference is expected to originate from the absence of NLO top decays in PYTHIA 8.3 and HERWIG 7.3 [45] and is readily improvable [84–87]. In Fig. 3(b), we show the size of the shift in the extracted value of the top mass due to hadronization, MPI, and variation of the PDF set. All are observed to be $\lesssim 200$ MeV, and almost all are consistent within errors with no shift (see also [45]). This is very promising compared with shifts of the order of ~ 1 GeV due to MPI in the groomed jet mass [22], and illustrates the robustness of our observable. We stress that the magnitude of these shifts should not be taken as a source of uncertainty due to nonperturbative effects since we expect that the leading nonperturbative corrections can be understood field theoretically [88–91]. It should instead be taken as a demonstration of insensitivity to physics at and below the shower cutoff, illustrating that the observable is not sensitive to physics below Γ_t as desired.

Feasibility at the HL-LHC—Extracting the top mass from our proposed EEC-based observable will require the measurement of the distribution discussed above and an understanding of the associated experimental uncertainties, as well as a theoretical calculation expressing the distribution in terms of the parameter m_t . The goal of this Letter is to introduce an observable for precision top mass extractions and illustrate that it has the desired properties so as to motivate a dedicated experimental and theoretical effort. To do so, we will illustrate the statistical feasibility of our approach at the LHC and perform a parton-shower-based extraction of the top mass using polynomial fits of the peak positions. More details of the experimental aspects of this study are presented in a longer companion paper [45]. We performed an estimate of the statistical uncertainty at Run 2 and 3 of the LHC and at the HL-LHC using pseudodata from PYTHIA 8.3. For the Run 2 pseudodata set, we generated jets corresponding to the number of selected jets in the CMS Run 2 top jet mass measurement [43] (52000 top jets). For the Run 3 and HL-LHC pseudodata sets the number of jets is increased by factors of 300/138 and 3000/138, assuming integrated luminosities of 300 fb^{-1} and 3000 fb^{-1} , respectively. Our results forecast statistical precision on the top mass better than ~ 300 MeV for the HL-LHC, which is extremely promising. We also find that this measurement is statistically feasible with present LHC luminosities with about 1 GeV or better precision.

The observable we propose can also be computed on charged particles only (tracks) [57,92–97], which provide considerably better angular resolution. It will be interesting to study the interplay of the increased angular resolution against the reduced statistics by incorporating estimates of the tracking efficiency.

Outlook—We have focused on introducing our EEC-based observable and illustrating its desirable properties through parton-shower analyses. We believe that our results provide a strong motivation for its systematic theoretical

study. Here, we emphasize that resummation in the peak region, which is required for precise theory predictions, is achievable with high perturbative accuracy. As the observable in question is more complex than the jet mass, due to the fact that it involves the measurement of angular correlations on the radiation in the top decay at the scale Γ_t , the development of rigorous factorization theorems for EECs on unstable states is required. This can be achieved by combining HQET [98–100], SCET [101–103], and on-shell particle EFT [104–106] with the factorization theorems for the EECs in Refs. [73,74]. These give rise to a variety of interesting field theoretic structures, which will be explored in future work. Still, it is important to stress that many of the ingredients are already known to high perturbative orders. A key theoretical feature is that, in the peak region, the distributions we are interested in are described by SCET_{II}-type factorization theorems, with the lowest scale being the top width Γ_t . This is in contrast to the jet mass, which is described by a SCET_I framework, where the scale of soft radiation is parametrically lower than Γ_t . This also emphasizes the complementarity of the jet mass and EEC approaches.

Conclusions—In this Letter, we have introduced a top-mass-sensitive energy correlator (EEC) observable with desirable experimental and theoretical properties. The key to our proposal is to simultaneously extract the angular scales associated with m_W and m_t and to use the W mass as a standard candle to calibrate the top mass. This allows us to overcome previous issues of EEC-based approaches, which require the knowledge of the jet p_T to convert between angular and mass scales [33]. We performed a preliminary study using luminosity estimates for the LHC, finding promising results.

The discovery of a top-mass-sensitive observable with robust experimental and theoretical properties in a hadron collider environment is a crucial addition to the physics program of the LHC. Our proposed observable opens up a rich theoretical and experimental program, enabling a variety of new theoretical techniques to be applied to the phenomenology of heavy particle decays.

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