PROCEEDINGS OF SCIENCE

Using the W as a standard candle to reach the top

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Precision measurements of the top quark mass at hadron colliders have been notoriously difficult. Energy-Energy Correlators (EECs) provide clean access to angular correlations in the hadronic energy flux, but their application to the precision mass measurements is less direct since they measure a dimensionless angular scale.

Inspired by the use of standard candles in cosmology, we will show that a single EEC-based observable can be constructed that reflects the characteristic angular scales of both the W boson and top quark masses. This gives direct access to the dimensionless quantity m_t/m_W, from which m_t can be extracted in a well-defined short-distance scheme as a function of the well-known m_W. We will demonstrate several remarkable properties of this observable as well as its statistical feasibility. This proposal provides a road map for a rich program for top mass determination at the LHC with record precision.

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1. Measurements of the top quark mass at the LHC

Top quark measurements at hadron colliders such as the LHC are cumbersome. Several processes including the proton structure, hard scattering, top quark decay, parton shower, hadronisation, multiple parton interactions, pileup, and colour reconnection span over many distinct energy scales and have to be considered in calculations and simulations. Thus, a variety of strategies have been developed to measure the top quark mass, m_t, that each comes with its limitations. The most precise extractions from the experimental side—often referred to as direct measurements—do not extract m_t by comparisons to analytic calculations but to distributions obtained with event generators. The relation of the top quark mass parameter in simulation and m_t in a field theory context remains a discussion point and comes with an uncertainty in the order of the hadronisation scale, which already exceeds the current measurement precision. Extractions from cross section measurements offer the possibility to extract m_t from calculations but are either less sensitive or often rely on the unphysical definition of a top quark particle state. Furthermore, the $\mathrm{t\bar{t}}$ threshold region, which offers high sensitivity to m_t, introduces non-trivial uncertainties connected to top quark bound states. To overcome this, a novel strategy using energy correlators was proposed in Ref. [1]. This strategy offers an extraction from a particle level cross section that is sensitive to m_t and remains in a regime with high theory control.

2. The triplet energy correlator

Energy correlators have already been proposed in the 1970s as tests of QCD [2] and have recently been used by the CMS Collaboration to extract α_S from jet substructure [3]. For a top quark mass measurement, the triplet energy correlator was found to be a suitable choice for an observable [1]. At the LHC, one targets the hadronic decay of top quarks, which are produced at high energies, such that their decay products merge into a single jet. The triplet correlator is constructed from all possible permutations of three particles inside the selected jet and is defined by the observable ζ and a weight w. The correlator can be interpreted as a triangle, which consists of the three angular distances between the constituents, where distances are further distinguished into the largest ΔR_l, medium ΔR_m, and smallest ΔR_s sides. We then define

$$\zeta = \frac{(\Delta R_l + \Delta R_m)^2}{2} \tag{1}$$

and

$$w = \frac{p_{\mathrm{T},1} p_{\mathrm{T},2} p_{\mathrm{T},3}}{p_{\mathrm{T,jet}}}, \tag{2}$$

where $p_{\mathrm{T},i}$ and $p_{\mathrm{T,jet}}$ are the transverse momenta of the i-th particle candidate in the triplet and the selected jet, respectively. As shown in Ref. [1], the distribution obtained from this variable is sensitive to the top quark mass if one selects triplets that form an equilateral triangle. In this configuration, the non-perturbative effects are well separated from the physics imprinted by the top quark mass. In Ref. [4] this strategy was further developed to also include a correlator configuration that is sensitive to the W boson decay. This can be achieved by requiring ΔR_s to be very small, such that the triangle consists of two long and a very short side. We additionally divide this correlator by the standard two-point correlator in order to cancel non-perturbative effects. This is not necessary for the top quark, because here the scale Γ_t already provides a natural cutoff that suppresses non-perturbative contributions in the peak region. The ratio of the correlators reconstructing the top quark and the W boson eliminates the dependence on $p_{T,jet}$ and allows to extract m_t in units of the well known W boson mass, m_W.

3. Feasibility study

With the dependence on $p_{T,jet}$ eliminated, several studies have been performed in a recent article [5], which highlights the feasibility of a top quark mass measurement using energy correlators at the LHC and planned HL-LHC. In order to estimate the size of statistical and systematic uncertainties as well as non-perturbative effects in the measurement, we use the following strategy. Since analytic calculations do not yet exist, which would allow to fit the correlator spectrum directly to predictions, we fit the peak of the W boson and top quark correlators with polynomial functions and extract the ratio of the peak positions. Using the nominal $t\bar{t}$ simulation obtained with Pythia 8.3 [6, 7], we translate the ratio of peak positions to a value of m_t. The statistical uncertainty in this fit procedure acts as an estimate of the statistical uncertainties in the measurement. Systematic uncertainties and non-perturbative effects are estimated by repeating the measurement with varied parameters in the simulation and accessing the shift in m_t by measuring the shift in the correlator peak ratio. Note that this method is a conservative estimate for all considered uncertainties since we only use the limited information of the peak positions and not the full correlator spectrum that would be available in a measurement and completed theory calculations.

We assess the statistical uncertainty by generating the same number of events as were selected in a measurement of the jet mass using boosted top quarks [8] that corresponds to an integrated luminosity of 138 fb^{-1}. For simplicity similar run conditions and centre-of-mass energies are assumed for all considered scenarios and only the number of generated events is scaled to the expected collected integrated luminosity. The statistical precision is estimated to be better than 1 GeV using the assumed 300 fb^{-1} of data available after LHC's Run 2 and Run 3. With the estimated 3000 fb^{-1} after the HL-LHC runs, we estimate an uncertainty of 0.3 GeV (see Fig. 1), which makes this measurement strategy already interesting with Run 3 data but can turn it into a precision extraction at the HL-LHC.

The uncertainties that dominate existing top quark mass measurements—such as uncertainties in the jet calibration or proton PDFs—have been estimated to not play a prominant role. For the estimation of the impact of this uncertainties, the CMS jet energy scale uncertainty [9, 10] was modelled (see Fig. 2 (left)). The extraction of m_t was then repeated with varied $p_{T,jet}$ according to the corresponding uncertainties. The effect of the variations is shown in Fig. 2 (right) and amounts to a few 100 MeV in each $p_{T,jet}$ bin, but is compatible with no shift within the statistical uncertainties in fitting the corresponding peak positions. Thus, we estimate the impact of the jet energy scale uncertainties to be negligible.

Furthermore, we have tested models for the uncertainty in the track reconstruction, even dependent on the original top decay parton flavour. These uncertainties remain small, in particular if the measurement is performed using only the tracks, thus omitting neutral particle candidates, as already suggested in Ref. [1].

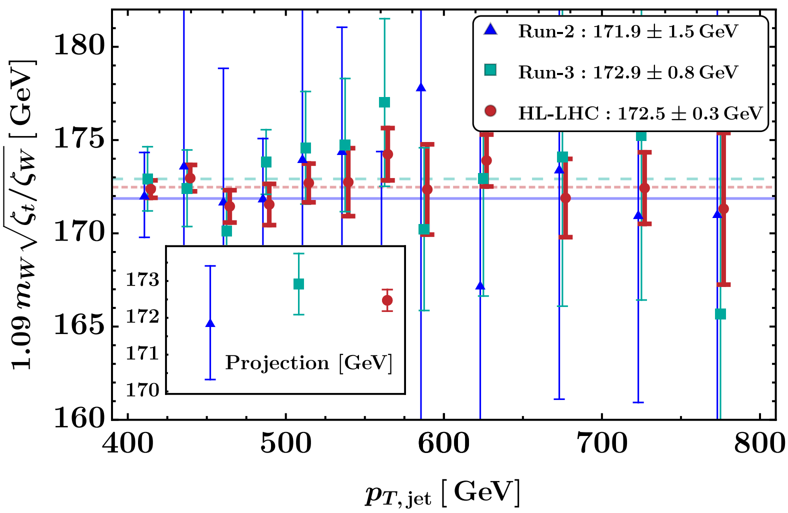

Figure 1: Estimated statistical uncertainties in the top quark mass extraction for three scenarios of collected data for LHC's Run 2, Run 3, and the estimated data set after the HL-LHC upgrade. Taken from [4].

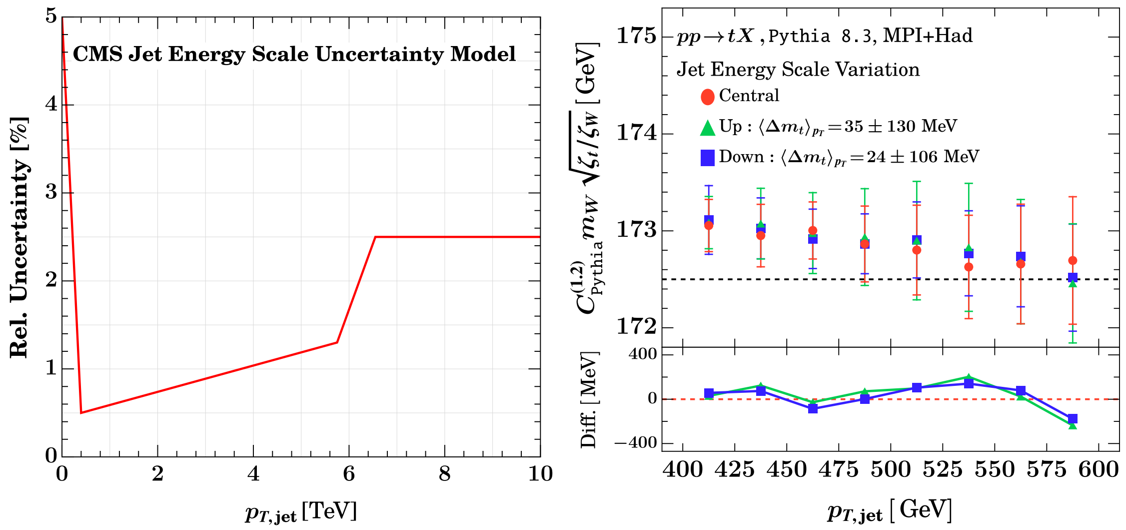

Figure 2: Model of the relative uncertainty in the jet energy scale at CMS (left). Shift in the extracted top quark mass due to the uncertainty in the jet energy scale (right). Taken from [5].

Many non-perturbative effects and effects of the modelling in the $t\bar{t}$ simulation were also studied in Ref. [5], although the calculations at higher order in QCD will supersede these results from simulation. However, these effects will enter the measurement through a potential bias in the simulation-based unfolding that is needed to correct for detector effects. Since the unfolding problem is not part of the presented studies, the effects due to modelling uncertainties estimated in Ref. [5] can be viewed as an upper limit. Thus, the small effects that were observed in studies of the modelling of initial state radiation, final state radiation, the underlying event, proton PDFs, colour reconnection, and b fragmentation do not show any particular limiting uncertainty.

Figure 3 shows the peak position ratio for various jet distance parameters between $R = 0.8$

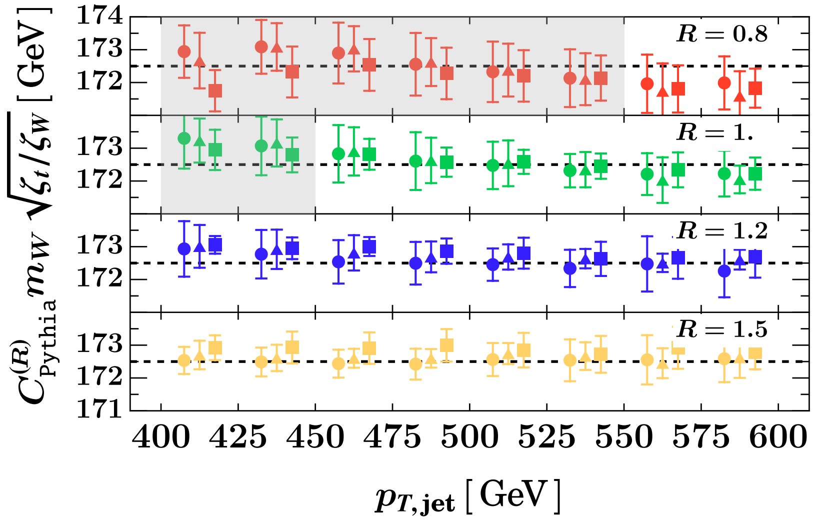

Figure 3: Ratio of peak positions of the top and W correlators for various jet distance parameters R. The grey area shows the region, $R \lesssim \sqrt{2\pi}\, m_t/p_{T,\mathrm{jet}}$, where the impact of the jet radius are non-negligible. Taken from [5].

and $R = 1.5$. As indicated in the plot, there exist regions for small R and small $p_{T,\mathrm{jet}}$ that show instabilities in the extracted ratio. In these regions, the jet covers a not sufficiently large area such that the top decay is fully included in the jet. For these cases, the correlator ratio is sensitive to the non-perturbative contributions such as the underlying event. However, for adequate choices of R and $p_{T,\mathrm{jet}}$, the ratio is very stable over the whole $p_{T,\mathrm{jet}}$ range.

4. Conclusions

We have presented a top quark mass measurement based on energy correlators that makes use of both the top quark and W boson decays in order to measure the top quark mass in units of the well known W boson mass. We show that systematic uncertainties that limit other top quark mass extraction only have negligible impact on the observable constructed from well-understood energy correlators. Already with LHC's Run 2 and Run 3 data, the statistical precision allows to perform a m_t extraction with sub-GeV precision, which can be turned into a record precision measurement with HL-LHC data.

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