PROCEEDINGS OF SCIENCE

Measurement of the top-quark mass from the b jet energy spectrum with the CMS detector

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A first measurement of the top-quark mass is presented based on the peak position of the energy spectrum of b jets produced from top-quark decays. This novel technique follows a recent theoretical proposal aiming to minimize systematic uncertainties related to the modeling of top quark production. The analysis is performed selecting top-antitop events with electron-muon final states in proton-proton collision data at $\sqrt{s} = 8$ TeV with the CMS detector, corresponding to an integrated luminosity of 19.7 fb^{-1}. The energy peak position is obtained by fitting the observed energy spectrum, and is translated to a top-quark mass estimation using relativistic kinematics, calibrated with Monte Carlo simulation.

38th International Conference on High Energy Physics
3-10 August 2016
Chicago, USA

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PoS(ICHEP2016)743

Discovered at Fermilab in 1995, the top quark is the heaviest fundamental particle of the Standard Model (SM) of particle physics. The crucial role of the top-quark mass ($\mathrm{m_t}$) in the electroweak theory demands its precise determination using standardised and alternative methods, to test the SM predictions and to set limits on scenarios of physics beyond the SM. This work discusses a new alternative measurement of the top-quark mass carried out using data collected by the CMS detector, described in [1]. This novel method is based on a determination of the peak position of the energy spectrum of b-tagged jets in dileptonic (electron-muon) top-antitop ($\mathrm{t\bar{t}}$) events [2].

1. Measuring the top-quark mass from the b jet energy peak position

The electroweak decay of the top quark mostly produces an on-shell W boson and a b quark. A modeling of this two-body decay using relativistic kinematics relates the value of the b-quark energy observed in the top-quark rest frame ($\mathrm{E_b^{Rest}}$) and the value of $\mathrm{m_t}$ by a simple equation: $\mathrm{m_t = E_b^{Rest} + \sqrt{E_b^{Rest\,2} + m_W{}^2 - m_b{}^2}}$. Assuming that top quarks produced via strong force are unpolarized, $\mathrm{E_b^{Rest}}$ is an observable independent of the top-quark boost in the laboratory frame, and therefore, corresponds to the peak position of the measured b quark energy distribution ($\mathrm{E_{peak}}$) [3].

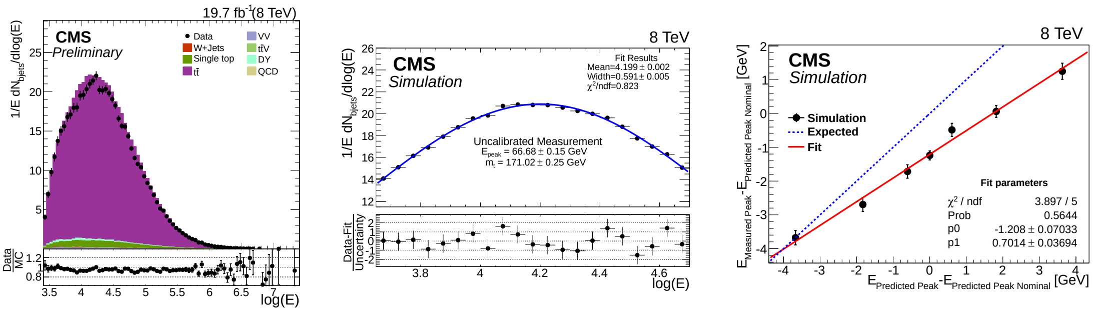
The analyzed data consists of proton-proton collisions at a center of mass energy of 8 TeV, corresponding to an integrated luminosity of 19.7 $\mathrm{fb^{-1}}$. Signal events are $\mathrm{t\bar{t}}$ production in which both W bosons decay into a charged lepton and a neutrino, such that the objects in the final state are two b jets (b-quarks hadronic state), an opposite charged electron-muon pair, and missing energy related to two undetected neutrinos. Signal and background events are simulated in Monte Carlo to develop a method to determine $\mathrm{E_{peak}}$ in the b jet energy spectrum observed in data, and consequently estimate the value of $\mathrm{m_t}$.

Event selection requires at least two jets with a minimum transverse momentum of 30 GeV. Moreover, it is considered optimal for this analysis to select events with one or two b jets identified by the loose working point of the b-tagging algorithm. Table 1 shows the event yields after the event selection cuts are applied. Complete descriptions regarding to the event reconstruction, simulation and selection are detailed in [2].

Sample	1 b-tagged jet	2 b-tagged jets
$\mathrm{t\bar{t}}$ (dileptonic)	13500±30	18710±40
W+jets	51.4±6.5	3.4±1.2
Diboson	308.7±4.6	53.6±1.9
Single Top	952.3±3.5	636.9±2.9
Drell-Yan	458.5±10.9	78.4±3.7
$\mathrm{t\bar{t}V}$ (V=W,Z)	43.2±1.1	51.6±1.2
Monte Carlo	15320±40	19540±40
Data	14336	18518

Table 1: Number of events in data and simulation.

The value of $\mathrm{E_{peak}}$ is determined from the energy distribution of all b-tagged jets in the selected events. The theoretical results suggest a symmetry of the linear energy distribution respect to its peak when is studied in a logarithmic scale [3]. This consideration is chosen to be optimal to get a straightforward extraction of E_{peak}. Given the change of variables $E \rightarrow \log(E)$ (where E represents units of energy in GeV), in order to obtain the correct distribution shape, the distribution $1/E\ dN_{bjets}/d\log(E)$ is used (Figure 1.a). Then, the value of E_{peak} is obtained by fitting the logarithmic energy distribution in a region near the peak using a Gaussian function because of its simple use and good performance observed in simulation. Thereafter, E_{peak} is determined by calculating e^{μ}, where μ is the fitted mean. Finally, E_{peak} is translated to an estimation of m_t using relativistic kinematics. Figure 1.b shows an example of this procedure using simulated $t\bar{t}$ events.



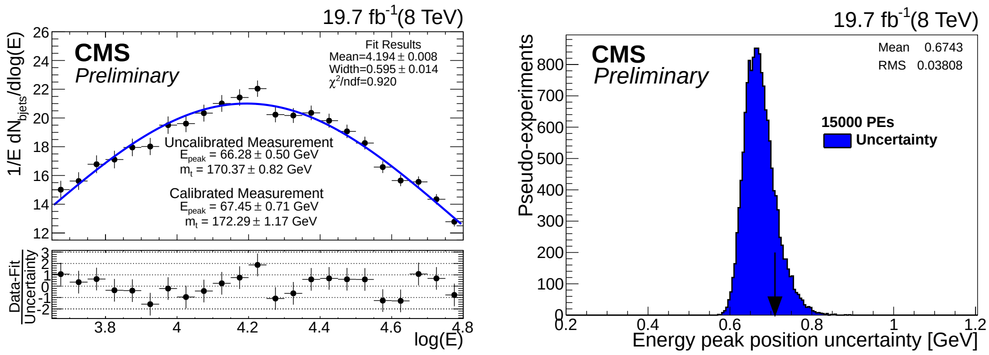
(a) Observed logarithmic energy distribution in data and simulation

(b) Energy peak position extraction in simulated signal events with $m_t = 172.5$ GeV (nominal mass)

(c) Calibration curve

Figure 1: Method development using simulated energy distributions of b-tagged jets.

A difference between the expected and measured position of the energy peak is observed in the simulation. This discrepancy is caused by bias effects associated to the event selection cuts, energy reconstruction, and misidentified b jets (including background events). To correct the peak position bias in data, a calibration curve is derived using generated pseudo-experiments corresponding to seven simulated templates with m_t ranging between 166.5 and 178.5 GeV (Figure 1.c). Furthermore, pseudo-experiments are computed to test the calibration procedure. This study shows that statistical uncertainties are overestimated up to 5%. However, given the small impact in the final result, no correction is applied.



(a) Fitted logarithmic energy distribution

(b) Measured energy peak position uncertainty in pseudo-experiments (blue) and data (arrow)

Figure 2: Determination of top-quark mass in CMS data.

As the final step, the logarithmic energy distribution is analyzed in collider data (Figure 2.a). The method estimates a calibrated value of $\mathrm{E_{peak}} = 67.45 \pm 0.71(\mathrm{stat.})$ GeV. The fitted statistical uncertainty agrees with the calculations using pseudo-experiments (Figure 2.b). Finally, the top-quark mass is determined to be $172.29 \pm 1.17(\mathrm{stat.})$ GeV using relativistic kinematics.

2. Systematic Uncertainties

The general procedure to calculate systematic uncertainties consists of comparing the values of $\mathrm{E_{peak}}$ and $\mathrm{m_t}$ measured in the nominal mass template, with the values obtained using modified templates in which a systematic variation is applied. The error values are calculated using simulated pseudo-experiments (See Table 2). More details on the uncertainty sources can be found in [2].

Source	$\delta\mathrm{E_{peak}}$ (GeV)	$\delta\mathrm{m_t}$ (GeV)
Jet energy scale	0.74	1.23
b jet energy scale	0.13	0.22
Jet energy resolution	0.18	0.30
Pile-up	0.02	0.03
b-tagging	0.12	0.20
Lepton selection efficiency	0.02	0.03
Fit calibration	0.14	0.24
Background events	0.21	0.34
Matrix-element generator	0.91	1.50
Renormalization and factorization scales	0.13	0.22
Parton-shower matching threshold	0.24	0.39
Top-quark transverse momentum	0.91	1.50
Parton distribution function	0.13	0.22
Underlying events	0.22	0.35
Color reconnection	0.38	0.62
Total	1.62	2.66

Table 2: Category breakdown of systematic uncertainties.

3. Conclusion

The first measurement of the top-quark mass based on the b jet energy peak position yields a value of $\mathrm{m_t} = 172.29 \pm 1.17\,(\mathrm{stat.}) \pm 2.66\,(\mathrm{syst.})$ GeV. This result is in agreement with the CMS Run I Legacy combination, and the 2014 World Average using measurements at the LHC and the Tevatron [2].

References

[1] CMS Collaboration, *The CMS experiment at the CERN LHC*, *JINST* **03** (2008) S0800.

[2] CMS Collaboration, *Measurement of the top-quark mass from the b jet energy spectrum*, CMS-PAS-TOP-15-002.

[3] K. Agashe, R. Franceschini, and D. Kim, *Simple invariance of two-body decay kinematics*, *Phys. Rev. D* **88** (2013) 057701.

PoS(ICHEP2016)743