PROCEEDINGS OF SCIENCE

Top-quark mass measurements with CMS

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Measurements of the top-quark mass are presented, obtained from CMS data collected in proton proton collisions at the LHC at centre-of-mass energies of 7 TeV and 8 TeV. The mass of the top quark is measured using several methods and channels, including the reconstructed invariant mass distribution of the top quark, an analysis of endpoint spectra as well as measurements from shapes of top-quark decay distributions. The dependence of the mass measurement on the kinematic phase space is investigated. The results of the various channels are combined and compared to the world average. The top-quark mass and also α_s are extracted from the top-pair cross section measured at CMS.

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1. Introduction

The top-quark mass plays a key role in the prediction of many observables either directly or via electroweak radiative corrections. It is also a key input to electroweak fits [1], which enable comparisons between experimental results and predictions within and beyond the Standard Model. The top-quark mass being correlated to a high Yukawa coupling to the Higgs boson, it can be used as a probe for the stability of the electroweak vacuum and Higgs boson properties. For all these reasons and so many others, the top-quark mass is a fundamental parameter, and subject of several analyses.

Experimentally, the top-quark mass is reconstructed through either invariant mass or kinematic distributions. Using Monte Carlo simulations, the measured distributions are related to a top-quark mass parameter. The latter is believed to be close to the pole mass at the level of less than 500 MeV/c^2 [2]. One way to get the pole mass is to use the $t\bar{t}$ production cross section measurement. Since the top quark is a colored object, a theoretical uncertainty of Λ_{QCD} surrounds the pole mass.

In order to reduce the experimental precision on the top-quark mass, alternative methods are developed. Using Lorentz-invariant quantities, experimental measurements are usually limited by jet energy scale and b-jet response uncertainties. In alternative measurements, other observables with more indirect sensitivity to the jet energy scale and the top-quark decay modes are used, such that systematic uncertainties are more and more orthogonal to the standard ones and the combined uncertainty is reduced.

2. Standard methods

Standard measurements using the reconstructed invariant mass of the decay products of the top quark have been performed for all three $t\bar{t}$ decay channels using the data at a centre-of-mass energy of 7 TeV [3, 4, 5]. Here, only the most recent measurement is presented. The analysis makes use of $t\bar{t}$ events in the semi-leptonic channel recorded at $\sqrt{s} = 8$ TeV.

2.1 Top-quark mass in the ℓ+jets channel

For this measurement, as represented in figure 1, events with one isolated lepton (e or μ) and at least four jets (of which two are b-tagged jets) among $\sqrt{s} = 8$ TeV data are selected (19.7 fb^{-1}). A kinematic fit [6] is performed in order to check the compatibility of each event with the $t\bar{t}$ hypothesis and thus improve the resolution. During this procedure, b-tagged and light jets are associated to quarks: two permutations are possible. The jet energy scale factor (JSF) and the top-quark mass are simultaneously determined through a joint likelihood fit of the W-boson and top-quark mass distributions, the W-boson mass distribution being prior to the kinematic fit unlike the top-quark mass one. For the correct permutations, the convolution of Breit-Wigner and Gaussian functions is used, while a Crystal Ball function replaces the Gaussian one in the other cases. The result, presented in figure 2, is

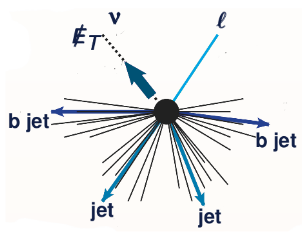

Figure 1: Semi-leptonic $t\bar{t}$ event.

$m_{\text{top}} = 172.04 \pm 0.19(\text{stat.+JSF}) \pm 0.75(\text{syst.})$ GeV/c^2 [7]. Systematic uncertainties are mainly related to the pileup treatment, the jet energy resolution, and the flavor dependency of the jet energy scale factor.

2.2 Combination of the standard measurements

The Best Linear Unbiased Estimate (BLUE) method [8] is used to combine all the results of the standard analyses. Each measurement provides an unbiased estimate of the top-quark mass under some uncertainties. In order to be able to take into account correlations between the uncertainties of the different measurements, they are classified in four main categories: experimental uncertainties, modeling of hadronization, modeling of the hard scattering process, modeling of non-perturbative processes. The linear combination of the individual estimates that has the minimum possible variance is retained. The latest combination of the CMS measurements summarized in figure 3 yields a mass of $m_{\text{top}} = 172.2 \pm 0.1(\text{stat.}) \pm 0.7(\text{syst.})$ GeV/c^2 [7].

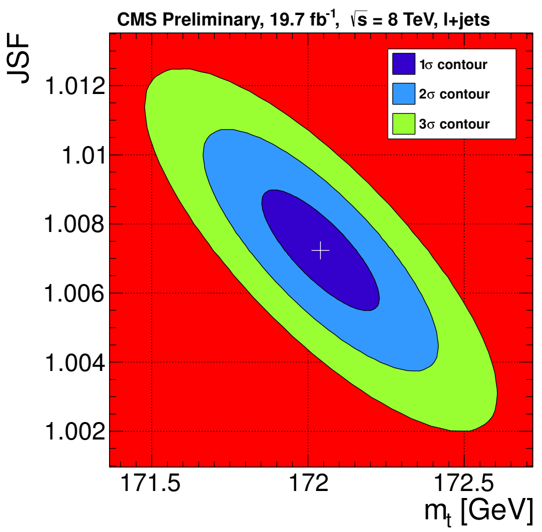

Figure 2: Result of the 2D likelihood fit in the semileptonic channel.

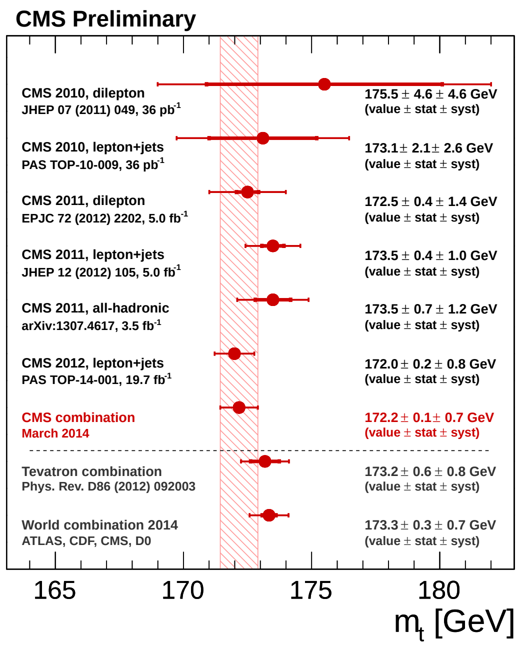

Figure 3: Overview of the CMS standard top-quark mass measurements, their combination, and the Tevatron and world averages.

3. Alternative methods

Three alternative analyses have been brought to fruition and are presented here. Several others are currently ongoing, but only one is introduced in the following.

3.1 Top-quark pole mass from the $t\bar{t}$ production cross section

The $t\bar{t}$ production cross section has been derived as a function of the top-quark pole mass from data collected in the dileptonic decay channel at $\sqrt{s} = 7$ TeV (2.3 fb^{-1}) [9]. The expected

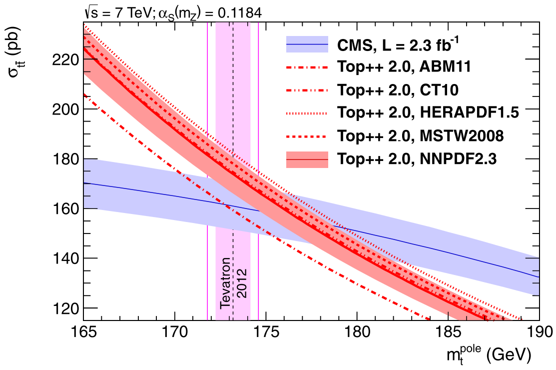

Figure 4: Predicted $t\bar{t}$ cross section at NNLO+NNLL as a function of the top-quark pole mass, using 5 different NNLO PDF sets, compared to the cross section measured by CMS assuming $m_{\text{top}} = m_{\text{top}}^{\text{pole}}$.

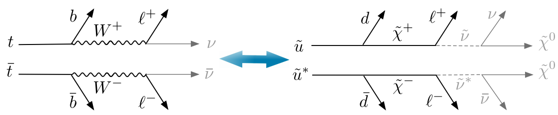

Figure 5: Topological resemblance between a dileptonic $t\bar{t}$ event and a beyond-Standard Model physics event.

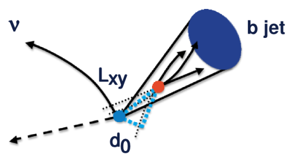

Figure 6: Decay cascade of a b quark in the rest frame of a leptonically decaying top-quark mass.

cross section is calculated to NNLO using the program TOP++ 2.0, soft-gluon resummation being performed at NNLL accuracy, and parametrized as a function of the top-quark pole mass. Both experimental and theoretical cross sections are presented in figure 4 with respect to $m_{\text{top}}^{\text{pole}}$. A Bayesian prior is then constructed. A translation of 1 GeV/c^2 is allowed for the experimental cross section, in order to take into account theoretical uncertainties around Monte Carlo parameters. Constraining the strong coupling at the scale of the Z boson mass to the current world average $\alpha_S(m_Z) = 0.1184$, the result, under the assumption that the measured cross section is not affected by non-Standard Model physics, is $m_{\text{top}}^{\text{pole}} = 176.7^{+3.8}_{-3.4}$ GeV/c^2 [10].

3.2 Kinematic endpoint method

The kinematic endpoint method is used on dileptonic $t\bar{t}$ events. Not only the invariant mass $M_{\text{b}\ell}$ is reconstructed, but also μ_{bb}, a variable designed for this analysis and weakly correlated to $M_{\text{b}\ell}$. The endpoints of the two distributions are correlated to the top-quark mass. As these correlations can be derived analytically, no Monte Carlo calibration is needed. The neutrino and W boson masses are respectively constrained to 0 and 80.4 GeV/c^2, in order to fully constrain the kinematic system. Using $\sqrt{s} = 7$ TeV data (5.0 fb^{-1}), this leads to a mass of $m_{\text{top}} = 173.9 \pm 0.9(\text{stat.})^{+1.7}_{-2.1}(\text{syst.})$ GeV/c^2 [11].

This mass determination method can also be used in physics scenarios beyond the Standard Model. Indeed, there is a topological resemblance, shown in figure 5, between both situations, where two cascade decays end in invisible particles. Nevertheless, in a non-Standard Model analysis, no assumption is added to constrain the kinematic system, but the endpoint of one more mass distribution is used.

3.3 B hadron lifetime technique

In the rest frame of the top quark, its decay products momenta are correlated to m_{top}. Considering that most of the energy of the b quark is transferred to the B hadron, the B hadron transverse decay length L_{xy}, sketched in figure 6, is analogously correlated to the top-quark mass. In practice, the secondary vertex with the largest L_{xy} is selected for each event. The linear dependency of the median of the L_{xy} distribution on the top-quark mass is calibrated through Monte Carlo samples simulated for several top-quark mass hypotheses. As the mass extracted from L_{xy} depends directly on the modeling of the production process, a good understanding of B hadron fragmentation and top-quark p_T is required in this analysis. Nevertheless, the result does not rely on the jet energy scale. Using leptonic $t\bar{t}$ events recorded at $\sqrt{s} = 8$ TeV, the top-quark mass is estimated to be $m_{\text{top}} = 173.5 \pm 1.5(\text{stat.}) \pm 1.3(\text{syst.}) \pm 2.6(p_T(\text{t}))$ GeV/c^2 [12].

3.4 Comparison to the standard measurements and outlook

For now, the precision of these three alternative measurements, summarized in figure 7, does not reach the precision of the standard ones [13]. Nevertheless, according to the projection presented in figure 8, based on 5 fb^{-1} data at $\sqrt{s} = 7$ TeV, they could have a significant impact in the future [14].

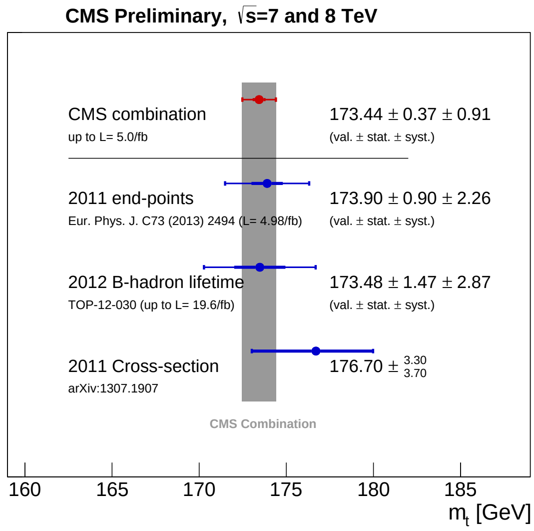

Figure 7: Comparison of the previous CMS top-quark mass combination and measurements obtained using alternative analysis techniques.

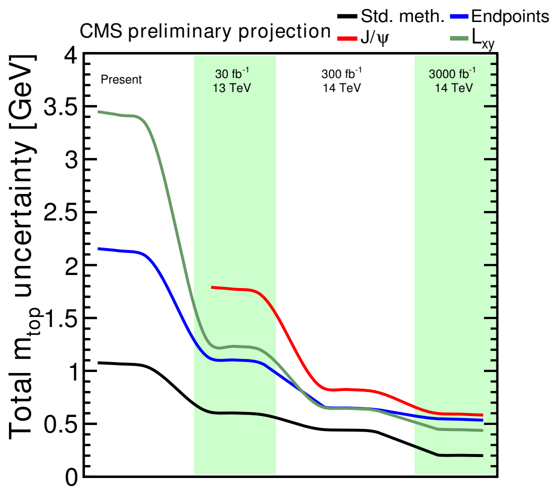

Figure 8: Projection of the top-quark mass precision obtained with different measurement methods, for various integrated luminosity.

3.5 Leptonic final state with $\mathbf{b \to J/\psi + X \to \mu^+\mu^- + X}$

The idea is to select a J/ψ and a lepton (e or μ) produced in the disintegration of a top quark. As shown in figure 9, the J/ψ comes from the B hadron fragmentation and the lepton from the W boson. So far, leptonic $t\bar{t}$ events with a J/ψ decaying into an opposite-sign di-muon pair in the final state have been selected using $\sqrt{s} = 8$ TeV data (19.8 fb^{-1}) [15]. The next step will be to use the correlation between the top-quark mass and the invariant mass of the combination of the J/ψ and the lepton. The systematic uncertainties should be mainly imputable to B hadron fragmentation.

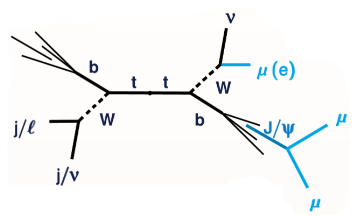

Figure 9: Leptonic $t\bar{t}$ event with a J/ψ in the final state.

4. Conclusion

A lot of efforts are being made in order to improve the experimental uncertainty on the top-quark mass; from the harmonization of systematic uncertainties to ease combinations, to the multiplication of alternative measurements with orthogonal uncertainties. In the future, NLO-multileg generators should provide a finer description, while the theoretical modeling, especially of b-JES and soft QCD, is expected to be better constrained by data. Kinematic dependencies and color (re)connection effects are also studied with the aim to improve the precision further.

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