

Tevatron Top-Quark Combinations and World Top-Quark Mass Combination

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Abstract. Almost 20 years after its discovery, the top quark is still an interesting particle, undergoing precise investigation of its properties. For many years, the Tevatron proton antiproton collider at Fermilab was the only place to study top quarks in detail, while with the recent start of the LHC proton proton collider a top quark factory has opened. An important ingredient for the full understanding of the top quark is the combination of measurements from the individual experiments. In particular, the Tevatron combinations of single top-quark cross sections, the $t\bar{t}$ production cross section, the W helicity in top-quark decays as well as the Tevatron and the world combination of the top-quark mass are discussed.

1. Introduction

Since its discovery in 1995 by the CDF and D0 experiments at the Fermilab Tevatron proton antiproton collider [1][2], the top quark has been studied in detail by four different experiments: CDF and D0 at the Tevatron, and since 2009 also by the ATLAS [3] and CMS [4] experiments at the LHC proton proton collider at CERN. While each collaboration performs their measurements independent of the other experiments, an important step for the full understanding of the top quark is the combination of the acquired measurements between experiments at the same collider, as well as experiments at the two different colliders for those properties that are independent of collision energy or type.

In the following I present the combinations of top-quark measurements between CDF and D0 as well as the first world combination of the top-quark mass. The Tevatron combinations are the recent combination of single top-quark measurements, the top quark-antiquark ($t\bar{t}$) production cross section, the W helicity and the top-quark mass.

2. Tevatron Combinations

Since the discovery of the top quark, intense programs to study the heaviest known elementary particle have been undergone at both experiments, CDF and D0, and are partially still going on today. The Tevatron Runs in which top quarks were studied were Run I and Run II. Run I lasted from 1992 to 1996, providing about 120 pb^{-1} of $p\bar{p}$ collisions at an energy of 1.8 TeV. In Run II $p\bar{p}$ collisions at an energy of 1.96 TeV took place (starting 2001 and ending September 30th, 2011), providing about 10.5 fb^{-1} of integrated luminosity for each of the D0 and CDF experiments. Several analyses used in the combination are based on the full Run II data sample.

2.1. Single Top Cross Section Combinations

The two top-quark production mechanisms are production in pairs via the strong interaction, or singly via the electroweak interaction. The latter occurs via s -channel, t -channel and Wt -channel production. While the Wt channel has a negligible production cross section at the Tevatron, the other two channels have now all been observed at the Tevatron. In particular, the observation of s -channel single top production was only possible via the combination of the CDF and D0 analyses. The measurement of single top quark production is very challenging, as the main background from W +jets events looks very similar to the single top signature. Various multivariate techniques have been employed to distinguish the signal from the large background. For the observation of s -channel single top, events with one isolated, high-transverse-momentum (p_T) electron or muon, large missing transverse energy from the not-detected neutrino and two (or two and three for D0) high- p_T jets, of which one or two have to be identified as b -jets, are considered in both collaborations. In addition, CDF also performs an analysis, where events with a missing transverse energy plus jet signature are used, adding events to the sample in which the lepton is not directly reconstructed. A multivariate discriminant is built to separate s -channel signal from background. The combined cross section is then extracted by performing a Bayesian statistical analysis, where the likelihoods of the analyses from both collaborations are combined. The systematic uncertainties are categorised in classes, taking into account the correlations of different sources between the analyses and between the experiments. The central result is taken as the maximum of the posterior probability. In this analysis, the t -channel single top production cross section was set to its standard model (SM) value. The combined analysis results in a cross section of $\sigma_s = 1.29_{-0.24}^{+0.26}$ pb [5], which deviates with more than 6.3 standard deviations from zero and is consistent with the SM prediction.

The same methods and input analyses have also been used for a combination of the t -channel and $s+t$ -channel cross section. For the $s+t$ -channel combinations, the multivariate discriminants were trained separately on s -channel and t -channel as signal, and both discriminants were used simultaneously. A 2D posterior probability density of σ_s versus σ_t was then constructed for the $s+t$ -channel measurement. For the extraction of σ_{s+t} , the t -channel is then integrated out. The resulting cross sections are $\sigma_t = 2.25_{-0.31}^{+0.29}$ pb and $\sigma_{s+t} = 3.30_{-0.40}^{+0.52}$ pb [6]. Figure 1 (left) shows an overview of all Tevatron combinations of single top quark processes.

Using the same discriminants, also the square of the CKM-matrix element, $|V_{tb}|^2$, can be extracted. In this case the Bayesian posterior probability density is formed for $|V_{tb}|^2$, using a flat prior in $|V_{tb}|^2$. The result yields $|V_{tb}|^2 = 1.04_{-0.10}^{+0.12}$ [6].

2.2. $t\bar{t}$ Cross Section Combinations

At the Tevatron, the production of top-quark pairs is dominated by $q\bar{q}$ annihilation with a fraction of approximately 85%, while gluon-gluon fusion contributes with about 15%. The Tevatron combination of the $t\bar{t}$ cross section uses as input four analyses by CDF and two by D0. In particular, the CDF analyses are: a counting-method in dileptonic final states, where events with at least one identified b -jet are considered; an analysis in the semileptonic final state, where a neural-network discriminant is built based on various kinematic variables; another analysis in semileptonic events, where events with at least one identified b -jet are counted; and an analysis in all-hadronic events, where a fit to the reconstructed top-quark mass is performed on events with six to eight jets of which one or more than one are identified as b -jets. In a first step, these CDF analyses are combined using the BLUE method [7], taking into account correlations between analyses and systematic uncertainties. Since the systematic uncertainty on the selection efficiency is directly proportional to the measured cross section, three iterations of BLUE are performed in order to remove any potential bias.

Furthermore, the two analyses by D0 are also first combined experiment-internally, where the combination is done by a likelihood fit, treating the systematic uncertainties as nuisance

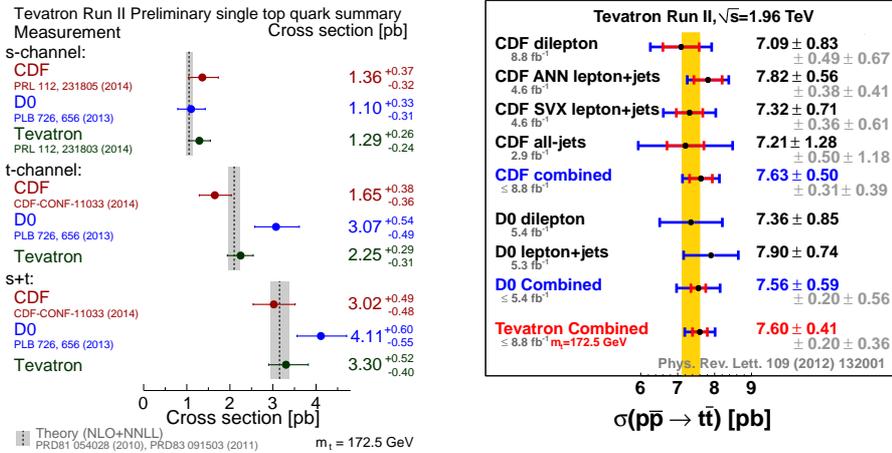


Figure 1. Recent Tevatron combination of single top quark production cross sections (left) [6] and $t\bar{t}$ production cross sections (right) [8].

parameters. The two analyses are one in the dilepton final state, where a fit to the discriminant based on the neural network b -jet identification algorithm is performed, and an analysis in the semileptonic final state, in which events with three or more than three jets, split into samples of zero, one or at least two identified b -jets, are either counted or used to build a random forest discriminant. The two D0 and CDF combinations are then further combined using BLUE, with a more rough classification of the systematic uncertainties. The final combined cross section is $\sigma_{t\bar{t}} = 7.60 \pm 0.41$ pb [8], which is consistent with the standard model (SM) prediction. The compatibility between the cross sections by CDF and D0 is 17%. Figure 1 (right) shows the $t\bar{t}$ cross section combination and all individual inputs.

2.3. W -Helicity Combination

The very first Tevatron combination of a top-quark property has been the combination of the W -helicity measurements in $t\bar{t}$ events, using up to 5.4 fb^{-1} . Since W bosons couple purely left-handedly to fermions in the SM, the relative orientation of the spin of the b -quark and the W boson from the top-quark decay are constrained. The fractions of negative (f_-), zero (f_0) and positive (f_+) helicity of the W boson are predicted to be $f_- = 0.685 \pm 0.005$, $f_0 = 0.311 \pm 0.005$ and $f_+ = 0.0017 \pm 0.0001$ at next-to-next-to-leading order (NNLO) QCD [9].

The combination of the W -helicity includes two measurements from CDF and one analysis from D0. In particular, one of the input analyses performed by CDF uses the Matrix Element method in semileptonic $t\bar{t}$ events. In this method, matrix elements for different assumptions of f_0 and f_+ are calculated, integrated with parton distribution functions and transfer functions, that map the true momenta of the particles used in the matrix element to the measured quantities, and are then compared to data. The second input analysis by CDF is based on a template method, where templates in the cosine of the angle θ^* between the down-type decay product of the W boson and the top quark in the W boson rest frame are formed for the different helicity states and fitted to data. The analysis is performed on semileptonic events. The D0 analysis uses the same strategy of a template fit, which is done in dileptonic and semileptonic events. All analyses are performed by fitting the fractions f_0 and f_+ simultaneously, only constraining the sum of all three fractions to be one. Using this model independent approach, the combination yields $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$ and $f_+ = -0.039 \pm 0.034(\text{stat}) \pm 0.030(\text{syst})$ [10], in good agreement with the SM prediction.

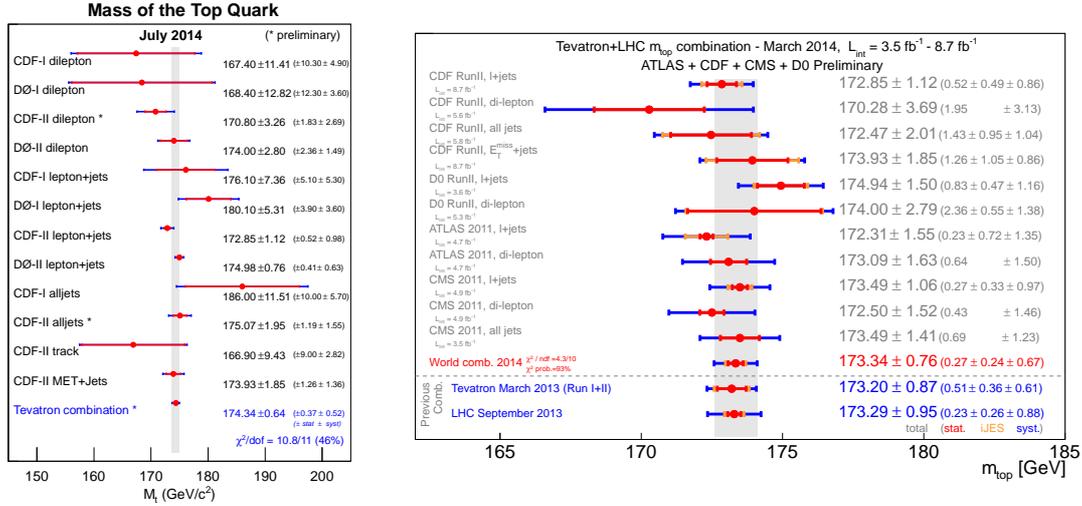


Figure 2. Recent Tevatron combination of the top-quark mass (left) [12] and world top-quark mass combination (right) [14].

2.4. Top Quark Mass Combination

The mass of the top quark is an important free parameter of the SM. In order to get the most precise value, combinations of the different analyses within each experiment, and between the experiments are necessary. The main challenge for the combination is the proper handling of the correlations between the systematic uncertainties, given that the total uncertainty on the top-quark mass measurements is often dominated by the systematic uncertainty. For the latest Tevatron combination, five measurements from Tevatron Run I are used, as well as five published analyses from Run II and two preliminary results by the CDF collaboration. A first published Tevatron combination, where only published results were used as inputs, was released in 2012 [11], using up to 5.8 fb^{-1} . Since then CDF updated their analyses in the dileptonic and fully hadronic final states, while DØ performed an updated analysis in the semileptonic final state, using the full Run II data sample. The procedure follows that of the published combination: The tool used for the combination is BLUE; the systematic uncertainties are categorised in classes according to a common source and correlations. The new Tevatron top-quark mass combination, using up to 9.7 fb^{-1} of data, yields $m_{\text{top}} = 174.34 \pm 0.37(\text{stat}) \pm 0.52(\text{syst}) \text{ GeV}$ [12]. The main contributions to the systematic uncertainty arise from signal modelling and the uncertainty on the in-situ light-jet calibration. Figure 2 (left) shows the Tevatron top-quark mass combination and all the individual input measurements.

3. World Top Quark Mass Combination

Once that LHC [13] and Tevatron had performed separate combinations of the top-quark mass measurements, the next natural step was to perform the first world combination of the top-quark mass, which happened in March 2014. In order to ease the treatment of correlations, the inputs to the combination are the respective best measurement per channel per experiment. Based on this principle, the combination uses six measurements from the Tevatron and five from LHC as input. In particular, from CDF a measurement using a template method in the semileptonic and a measurement based on neutrino weighting in the dileptonic channels are used. From DØ, a measurement using the Matrix Element method in semileptonic and also a neutrino weighting technique in the dileptonic final state are used, where the in-situ jet energy scale calibration from the measurement in the semileptonic channel is transferred to the measurement in dileptonic

events. The inputs contributed by ATLAS are a 3D template method in semileptonic events and a measurement based on an $m_{\ell b}$ observable in dileptonic events, while from CMS an analysis in the semileptonic and the fully hadronic final state, using the ideogram method, are used as input, as well as an analysis in dileptonic events based on analytic matrix weighting. All analyses by the ATLAS and CMS collaboration are based on the $\sqrt{s} = 7$ TeV data.

In the same light as for the Tevatron mass combination, the main challenge for the world combination is the treatment of systematic uncertainties. Given that the four experiments have different methods to estimate their systematic uncertainty, the situation is even more complicated and a proper classification and estimation of the correlations is crucial. The current solution to this problem is to classify the systematics into logical classes with the same correlation, determine the central result for this choice, and then vary the correlations to check the stability of the result. Several of these checks have been done, where either a global scale is applied on all correlation coefficients of experiment-only, LHC-only, Tevatron-only, collider-only or all-experiments correlation factors, or where for individual classes the correlation values are varied, and the impact on m_{top} or the uncertainty on m_{top} are checked. It turns out that the size of the effect of these different choices is quite small, and thus no additional uncertainty is assigned for the choice of correlations. The combined world top-quark mass is $m_{top} = 173.34 \pm 0.27(\text{stat}) \pm 0.71(\text{syst})$ GeV [14]. In Figure 2 (right) the world mass combination and the inputs from all experiments are listed. This result does not include the latest results from Tevatron and LHC, which will reduce the uncertainty even further, but also require even more care to be taken on the treatment of systematic uncertainties and correlations.

4. Conclusion

Several Tevatron top-quark combinations have been performed, as well as the first world combination. Especially the observation of s -channel single top-quark production, which was only possible by combining the CDF and D0 analyses, shows the value of combining results from different experiments. At both colliders, further combinations of top-quark properties are planned, and will help to understand the heaviest known elementary particle as precise as possible.

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