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Top quark results at CDF

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Summary. — A selection of the most recent CDF analyses on the top quark physics is reported. The reviewed results are based on the Tevatron Run II data. An emphasis is put on comparison of experimental results to the latest theoretical models and on the first observation of the single top production at Tevatron.

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1. – Introduction

At the Tevatron collider at Fermilab, in $p\bar{p}$ collisions at the center-of-mass energy of $\sqrt{s} = 1.96\,\text{TeV}$ Standard Model (SM) top quarks are primarily produced in pairs through strong interaction, at first order via the processes $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$.

Electroweak mechanisms allow the single top quark production, and the establishment of its presence in $p\bar{p}$ collisions is an important goal of the Tevatron program.

The SM decay $t \to Wb$ of the top quark provides a $t\bar{t}$ decay signature of two W bosons and two bottom quarks. The three decay channels are dilepton, lepton+jets and hadronic, where, respectively, both W decay leptonically, one W decays leptonically and one W decays to $q\bar{q}$, both the W bosons decay in to $q\bar{q}$. The lepton+jets channel is the best compromise between a fair background-to-signal ratio and an acceptable complexity in kinematic reconstruction of the full event. The experimental observed rate in top quark production or decay signatures could be altered by new processes beyond the SM. Therefore measurements of top properties provide powerful tests of the SM predictions.

A test of QCD production mechanism is provided by the cross-section measurement for top quark pair. The contribution from different primary partons to the production cross-section is difficult to estimate. The SM predicts that the $t\bar{t}$ production processes $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$ occur at Tevatron (Fermilab) with relative fractions of $\sim 85\%$ and $\sim 15\%$ respectively, having significantly different kinematic properties. A measurement of this fraction tests the SM prediction and our understanding of gluon parton distribution functions (PDFs) in the proton. A possible signature for new production processes can also be a forward-backward asymmetry larger than the QCD prediction. Latest measurements of top quark pair production cross-section, fraction of $t\bar{t}$ production and the forward-backward asymmetry at CDF will be described in the following sections.

Descriptions of the most recent results on top quark mass measurements will be also provided, concluding with the first observation of the single top quark production.

2. – $t\bar{t}$ pair production cross-section

CDF performed many measurements of the $t\bar{t}$ production cross-section. The most powerful measurements use lepton+jets or dilepton decay channels.

The combination of latest experimental measurements use a data sample with an integrated luminosity of up to $2.8\,\text{fb}^{-1}$. Among measurements, those carring most of the weight in the combination use Secondary Vertex (SecVtx) *b-tagging* or artificially neural network (NN) method. The SecVtx *b-tagging* method is traditionally used at CDF, it exploits displaced secondary vertices as evidence of bottom quark decays. Analyses exploiting this method are based on lepton identification and jets "tagged" with SecVtx algorithm. The selected sample shows a favorable signal-to-background ratio, despite the loss in signal efficiency. The NN technique is a kinematic method implemented to test the modeling of signal and background processes with higher statistics. It maximizes the discriminating power from kinematic and topological variables with a sensitivity comparable to the secondary vertex b-tag method.

The result of the combination is $\sigma(p\bar{p} \to t\bar{t}) = 7.02 \pm 0.30_{(\text{stat})} \pm 0.38_{(\text{syst})} \pm 0.41_{(\text{lumi})}$ pb for $m_{\text{top}} = 175\,\text{GeV}/c^2$ [1]. The third uncertainty number comes from the 6% uncertainty in the luminosity measurement. The total uncertainty is 0.63 pb. Recent theoretical calculations constrain the top pair production cross-section to $6.73^{+0.71}_{-0.79}$ pb from [2], and $6.90^{+0.46}_{-0.64}$ pb from [3]. The result is in good agreement with the theoretical prediction.

3. – Top gg and qq production

At CDF, measurements of the relative fraction of $t\bar{t}$ production through gluon fusion F_{gg} have been performed. This quantity yields information about the contribution from different primary partons to the $t\bar{t}$ pair production cross-section.

A $t\bar{t}$ pair produced via gluon fusion has different spin state from one via $q\bar{q}$ annihilation. This difference can be identified with azimuthal correlation between l^+ and l^- in the dilepton decay channel. Flight direction of leptons is correlated with the top spin.

The latest F_{gg} measurement exploits the difference between $\Delta\phi$ distributions for the two production processes. CDF measured this quantity in the dilepton sample in $2\,\text{fb}^{-1}$ of data using a maximum likelihood fit to the gg fraction and the number of $t\bar{t}$ events, with the result: $F_{gg} = 0.53^{+0.36}_{-0.38}(^{+0.35}_{-0.37}(\text{stat.})^{+0.07}_{-0.08}(\text{syst.}))$ [4]. However, the best result still remains the measurement using data sample with an integrated luminosity of $955\,\text{pb}^{-1}$. It is a combination between two analyses using, respectively, an artificially neural network (NN) and the low-p_T track multiplicity in lepton+jet channel [5]. The average number of low-p_T tracks scales with the gluon content of the sample, because of the higher probability for a primary gluon, compared to a quark, to radiate a low-energy gluon in the production process. The combination results is $F_{gg} = 0.07^{+0.15}_{-0.07}$ yielding the most stringent measurement [6].

4. – Forward-backward asymmetry A_{fb} measurement

The forward-backward asymmetry A_{fb} gives information about the top preferentially decaying forward or backward. Therefore the angle between the proton beam direction and top momentum is an indicator of the A_{fb} value. In LO QCD the top quark production angle is symmetric with respect to beam direction, while NLO processes contribute to a known asymmetry ($A_{\rm fb} = 0.050 \pm 0.015$) in the SM.

CDF presented the latest $A_{\rm fb}$ result as an update to the measurement published in [7]. $3.2\,{\rm fb}^{-1}$ of data has been used and t (or $\bar{t}$) rapidity $y_{\rm had}$ distributions have been considered in $p\bar{p}$ frame. The rapidity of the hadronically decaying t (or $\bar{t}$) system has been studied since its direction is better reconstructed than the leptonic one, which is complicated by the missing energy of the neutrino. Assuming CP invariance, $N_{\bar{t}}(p) = N_t(\bar{p})$, the charge asymmetry is equivalent to a forward-backward asymmetry. To know which of the quarks in the $t\bar{t}$ pair decayed leptonically, the charge information has been tagged with the lepton sign Q_l from the leptonically decaying system.

The latest measurement computed the asymmetry in $-Q \cdot y_{\rm had}$. The total background shape has been substracted off and the farward-backward asymmetry has been measured as: $A_{\rm fb} = 0.193 \pm 0.065 \pm 0.024$ [8].

5. – Top quark mass measurement

The top quark mass is an important parameter of the SM. Precise knowledge of the top mass places significant constraints on the mass of particles, including the unobserved Higgs boson. CDF measured this quantity in all the decay channels. Template and Matrix Element Methods are the standard analysis techniques used at CDF. The most precise single measurement to date has been obtained in the lepton+jets decay channel using a Matrix Element Method. A neural network was constructed to distinguish between signal and background events. The top mass measurement was dominated by systematic uncertainties, out of which the jet energy scale (JES) was the dominant one. A recent technique to deal with this uncertainty consists to use jets originating from the W boson to calibrate the JES directly on an event-by-event basis. Introducing the JES as parameter sensitive to the true top mass m_t, most of the systematic uncertainty on the jet energy scale are included in the statistical uncertainty of the result. This technique has proven to significantly reduce the total error due to the JES.

The latest top mass measurements at CDF use a data sample with an integrated luminosity of up to $3.2\,{\rm fb}^{-1}$, reaching a top mass knowledge with 0.8% of precision. The most precise measured top quark mass in $3.2\,{\rm fb}^{-1}$ is: $m_t = 172.1 \pm 0.9({\rm stat.}) \pm 0.7({\rm JES}) \pm 1.1({\rm syst.})\ {\rm GeV}/c^2$ [9].

Combining results from Run-I (1992-1996) with the most recent Run-II (2001-present) measurements the CDF average mass of top quark is: $m_t = 172.6 \pm 0.9({\rm stat.}) \pm 1.2({\rm syst.})\,{\rm GeV}/c^2$ [10].

6. – Single top production

The single top quark production is one of the most important topics in the top physics at Fermilab. Both CDF and DØ have observed this process [11]. Measuring the cross-section for electroweak single top production places direct experimental constraints on the value of the magnitude of the CKM matrix element $|V_{tb}|$. The expected cross-section for the electroweak production of single top quarks is $\sigma_{st} \sim 2.9\,{\rm pb}$, much smaller than those of competitive background processes. Since trigger and topological selections are not enough to discriminate between signal and background, multivariate techniques have been developed. There are currently six separate CDF searches for single top production, using different multivariate analyses: boosted decision tree, neural network, multivariate likelihood function, or matrix element. All those analyses use $3.2\,{\rm fb}^{-1}$ of CDF Run II

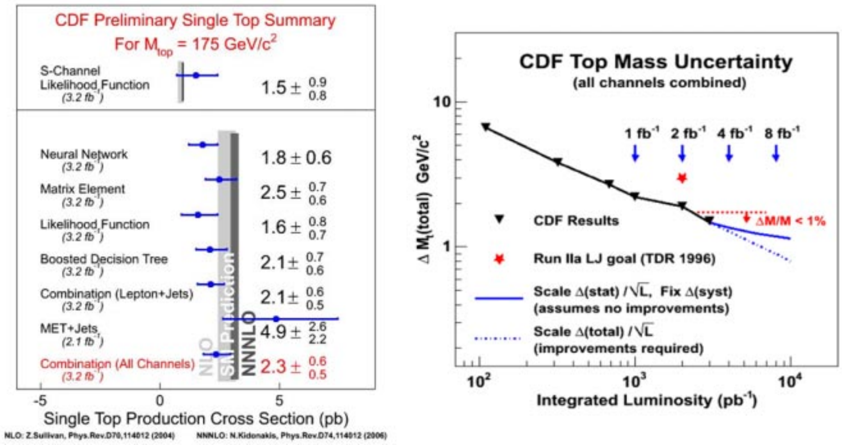

Fig. 1. – (a) Summary of CDF's $3.2\,\mathrm{fb}^{-1}$ results on single top production (left). (b) Future projection on CDF top mass measurement precision (right).

data [12]. Results from each analysis can be found in fig. 1(a). Discriminant outputs from these analyses are combined into a single more powerful super discriminant (SD) using neural networks. A combined single top s- and t-channel cross-section of $\sigma_{ts} = 2.3^{+0.6}_{-0.5}$ pb has been observed. The observed signal has a significance of 5.0σ, which is sufficient for observation. From the cross-section measurement we extract a value for $|V_{tb}|$ of $0.91 \pm 0.11(\exp.) \pm 0.07(\text{theory})$ [12].

7. – Conclusion

CDF has a broad program on top quark physics. Measurements of top properties are consistent with Standard Model and the top quark mass is measured to 0.8% precision. Projection about how precisely CDF can measure the top quark mass as a function of integrated luminosity upholds a precision below 1% (see fig. 1(b)). Substantial progress has been made in single top search too, providing a solid anchor to test the analysis techniques that are now also used in Higgs boson searches.

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