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STATUS OF THE TOP QUARK: TOP PRODUCTION CROSS SECTION AND TOP PROPERTIES

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Abstract

This report describes the latest cross section and property measurements associated with the top quark at the Tevatron Run II. The largest data sample used is 760 pb^{-1} of integrated luminosity. Due to its large mass, the top quark might be involved in the process of electroweak symmetry breaking, making it a useful probe for signs of new physics.

1 Introduction

During the summer of 2005, FNAL celebrated the 10^{th} anniversary of the discovery of the top quark by the CDF and DØ collaborations. Discovering the top quark was not a big surprise since it had been predicted within the Standard Model (SM) in order to complete the quark sector. Ten years later, the field of top physics is one of discovery still, in terms of observing the single top production for example, or studying the properties of the top quark. The field of top physics has also entered a new era of precision measurements since we can now measure the top cross section with an uncertainty of only 12% and the top mass with an uncertainty of less than 2%.

The big surprise associated with the top quark was its mass. There are a number of implications for a large top mass. For example it means that the top Higgs Yukawa coupling is close to unity implying that it is the largest contribution to the problematic divergent radiative contribution of the Higgs mass in the SM. The top mass also contributes to the largest radiative correction to the W mass. These observations are possible hints that the top quark might be related with the electroweak symmetry breaking mechanism. A large top mass also implies a large width which means it is not possible to have top hadrons or a $t\bar{t}$ quarkonium, the top decays right away and transfer its spin information to its decay products. This is a unique case among all the quarks.

2 Top physics at the Tevatron

At the Tevatron top pairs are produced from quark annhiliation 85% of the time and gluon annihilation 15% of the time. This ratio is reversed at the LHC. At the Tevatron energy, there is 1 $\mathrm{t\bar{t}}$ pair produced in 10^{10} events. At the LHC energy the cross section is a factor 100 larger than at the Tevatron energy. Measuring the top production cross section is crucial: it is a window into possible scenarios of new physics which would impact different channels differently, it is also the starting point for all properties analyses. Finally, since $t\bar{t}$ events are a background for various particle searches, knowing the cross section of this process is very important. The theoretical value of the top cross section is $6.7 \pm 0.8pb$ for a top mass of 175 GeV/c^2 [1].

Since the top mass is larger than the W and b quark mass, the dominant decay of the top quark is to a W and a b jet. This branching fraction has been measured to be close to 100%. The different types of $\mathrm{t\bar{t}}$ events are labeled according to the way the W decays in the event. If both W decay into lepton pairs, this is called a dilepton event, happens about 5% of the times and has very low backgrounds; if one W decays leptonically and the other one hadronically, this is called a lepton+jets event, happens about 30% of the times and has moderate backgrounds; if both W decay hadronically, this is called the all hadronic channel, happens about 44% of the times and has very high backgrounds. The rest of the branching fraction is when one or both W decay into a tau lepton.

3 Production cross section measurements

3.1 Dilepton channel

The event selection for the standard dilepton analysis is to request two leptons with $E_T > 20GeV$ and with opposite sign and at least 2 jets with $E_T > 15GeV$. There should also be some missing transverse energy ($> 25GeV$) coming from the elusive neutrinos and also the total energy in the event ($H_T = \sum p_{Tlep} + E_{Tjet} + ME_T > 200GeV$) should be high. The backgrounds are from physics processes involving the production of dibosons and also a Z decaying to a pair of tau leptons, where the taus decayed leptonically. There is also instrumental background coming from a jet faking a lepton. The latest result from the CDF collaboration uses 750 pb^{-1} of data and finds a cross section value of 8.3 $\pm$ 1.5 (stat.) $\pm$ 1.0 (syst.) + 0.5 (lumi.) pb [2].

Another analysis performed using the dilepton channel is where we try to be as inclusive as possible to get high statistical power at the cost of less purity compared to counting experiments. The general idea is to look at the missing transverse energy vs jet multiplicity plane and realize that the region where $t\bar{t}$ events show up (high jet multipliciy and high missing transverse energy) is well separated from other backgrounds (low jet multiplicity, various missing transverse energies). This plane also allows to distinguish between the region populated by WW events (high missing transverse energy) and the region populated by Z decaying to a pair of tau leptons (low missing transverse energy). Since the Drell-Yan background is very large in the ee and $\mu\mu$ channels, there is an additional cut on the significance of the transverse missing energy ($ME_T^{sig} = \frac{ME_T}{\sqrt{\Sigma E_T}} > 2.0$) in that channel. This CDF analysis obtains, using 360 pb^{-1} of data, the following values for the different cross sections: for the $ee + e\mu + \mu\mu$ fit: $\sigma(t\bar{t}) = 8.4^{+2.5}_{-2.1}$(stat. + acc. syst.)$^{+0.7}_{-0.3}$(shape syst.)$pb$ and $\sigma(WW) = 16.1^{+5.0}_{-4.3}$(stat. + acc. syst.)$^{+0.8}_{-0.2}$(shape syst.)$pb$, and for the $e\mu$ fit: $\sigma(Z \to \tau\tau) = 293^{+49}_{-45}$(stat.+acc. syst.)$^{+6}_{-3}$(shape syst.)$pb$ [3]. The WW and $Z \to \tau\tau$ cross sections are in agreement with other analyses and the statistical uncertainty is reduced. The next step for this analysis will be to use this method to look for new physics, which could show up at high jet multiplicity.

3.2 Lepton+jets channel

The first lepton+jets channel analysis discussed makes use of the kinematics of the event. The main ingredients of the event selection are requiring one lepton with $p_T > 20GeV/c$ and at least three jets with $E_T > 15GeV$. The backgrounds are W production associated with jets and also QCD events where the lepton came from a jet faking a lepton or a semileptonic decay. The way to discriminate between signal and background is to use kinematic variables in a neural net since $t\bar{t}$ events tend to be energetic, central and spherical for example. CDF uses seven carefully chosen kinematic variables. A fit is performed on the neural net output. The result using 760 pb^{-1} of data is $\sigma(t\bar{t}) = 6.0 \pm 0.6(\text{stat.}) \pm 0.9(\text{syst.})pb$ [4]. We note that this measurement is now systematically dominated. The dominant systematics are the jet energy scale and the W+jet Q^2 scale.

The second lepton+jets channel analysis discussed is one that requests the b jet to be tagged in order to discriminate between signal and background. However the b jet efficiency is also the dominant systematic. At CDF, the tagging efficiency for b jets is about 40%, for c jets is less than 10% and for light quark jets is less than 0.05%. These efficiencies vary with the jet E_T. The results obtained, using 695 pb^{-1} of data, are: in the single b tag case: $\sigma(t\bar{t}) = 8.2 \pm 0.6(\text{stat.}) \pm 1.0(\text{syst.})pb$ and in the double tagged case: $\sigma(t\bar{t}) = 8.8^{+1.2}_{-1.1}(\text{stat.})^{+2.0}_{-1.3}(\text{syst.})pb$ [5].

3.3 All hadronic channel

In the all hadronic channel, the event selection of the DØ collaboration requires at least six jets with $p_T > 15GeV/c$, at least one tagged b jet and a neural net discriminant value greater than 0.9. The neural net is used to discriminate between signal events and the overwhelming QCD background. There are six kinematic variables in the neural net. The result for this cross section, using 349 pb^{-1} of data is $\sigma(t\bar{t}) = 5.2^{+2.6}_{-2.5}(\text{stat.})^{+1.5}_{-1.0}(\text{syst.}) \pm 0.3(\text{lumi.})pb$ [6].

3.4 Summary of top pair production cross sections

In figures 1 and 2 we show the summary of all recent top pair production cross sections for both CDF and DØ. The CDF plot also shows the combination of recent measurements, the combined cross section is $\sigma(t\bar{t}) = 7.3 \pm 0.5(\text{stat.}) \pm 0.6(\text{syst.}) \pm 0.4(\text{lumi.})pb$ [7]. We can see that given the uncertainties of the measurements we can already test the theory estimates. We can also see that soon it will be possible to compare the various channels and see how statistically compatible the cross sections are.

3.5 Single top production

Single top production proceeds via the electroweak interaction according to either an s-channel diagram with a predicted cross section of $\sigma_s = 0.88 \pm 0.07pb$

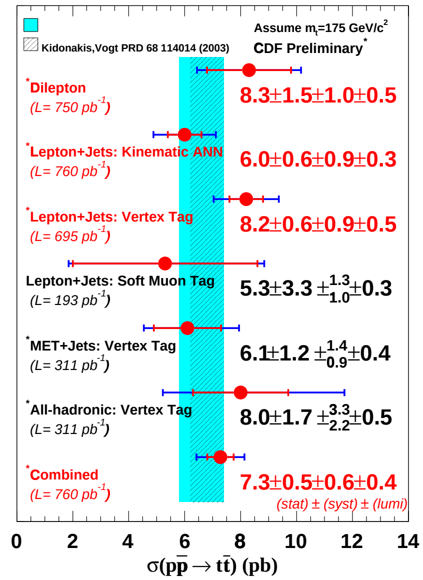

Figure 1: *A Summary of recent top quark pair production cross section measurements from CDF.*

or a t-channel diagram with a predicted cross section of $\sigma_t = 1.98 \pm 0.21pb$. Since the two diagrams are sensitive to different kind of new physics it is important to eventually distinguish between the two. A measurement of the single top production cross section could show hint of new physics in terms of new resonances or flavor changing neutral current processes. Observation of single top interaction could also lead to a measurement of the CKM element $|V_{tb}|$ and of a possible anomalous Wtb coupling. The event selection is the same as the lepton+jets channel described earlier but with a lower jet multiplicity (at least two jets) and b tagging information is also used. Since there is an overwhelming amount of background coming from $W + jets$ and $t\bar{t}$ processes, sophisticated methods are used for discriminating the signal: likelihood discriminants, neural nets, decision trees, etc.

The DØ collaboration uses a likelihood discriminant analysis which has different filters: single top vs $t\bar{t}$, single top vs $W + jets$, electron vs muon and also single b tag (mostly t-channel) vs double b tag (mostly s-channel). There are a total of 16 variables that enter the distriminant. The 95% upper limits observed are $5.0pb$ for the s-channel and $4.4pb$ for the t-channel, while the expected limits are $3.3pb$ and $4.3pb$ respectively using $370pb^{-1}$ of data [8]. It is expected that a 3 sigma significance will be reached for single top quark observation with less than $2fb^{-1}$ of data.

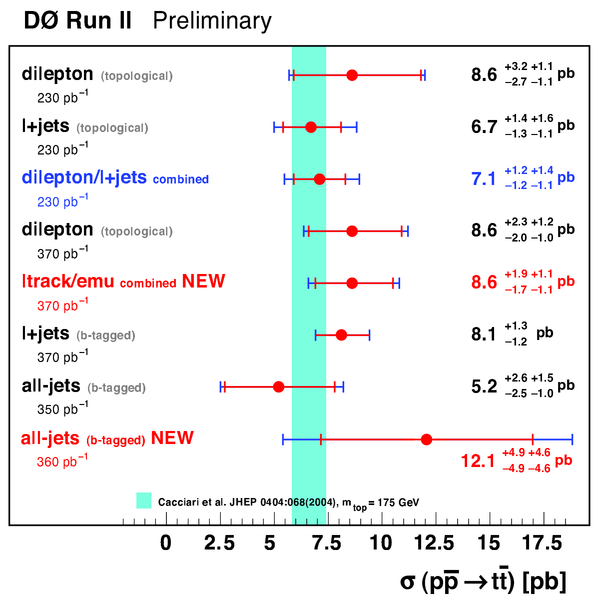

Figure 2: *A Summary of recent top quark pair production cross section measurements from DØ.*

4 Top quark properties

4.1 Search for a heavy quark t'

There are several theoretical scenarios that predict a heavy fourth generation quark still consistent with electroweak data [9), 10)]. To search for such a quark the CDF collaboration uses the lepton+jets data sample and performs a two-dimensional fit in H_T, the total transverse energy of the event, and M_{reco} the reconstructed quark mass coming from the χ^2 kinematic mass fit. The observed limit is extracted using a binned likelihood fit and a Bayesian limit. The measurement rules out at 95% confidence level a t' quark with $196GeV/c^2 < m(t') < 206GeV/c^2$ using 347 pb^{-1} of data, as shown in figure 3 [11)].

4.2 Measurement of $B(t \to Wb)/B(t \to Wq)$

In the SM, the branching fraction $B(t \to Wb)$ is expected to be close to unity. If it is measured to be less than one, this could imply new physics in either top decays or top backgrounds. While single top process can measure this branching fraction directly, $t\bar{t}$ process is sensitive to the ratio R of branching fractions: $B(t \to Wb)/B(t \to Wq)$. If one assumes the SM, then this ratio

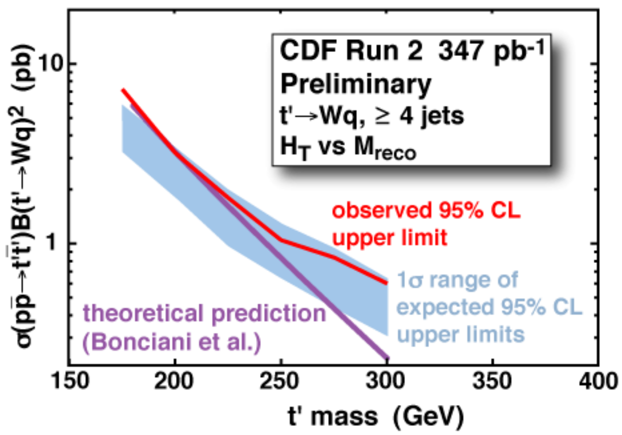

Figure 3: *Upper limit, at 95% CL, on the production rate for t' as a function of t' mass (red). The purple curve is a theoretical cross section. The blue band represents +/-1 standard deviation expectation limit.*

is also equal to $|V_{tb}|^2$. The DØ collaboration makes use of the lepton+jets data sample requesting either 3 or $\geq$ 4 jets and fits the number of 0, 1 and $\geq$ 2 b tagged events. In the case of the $\geq$ 4 jets with 0 tagged b they use a 4 variable discriminant. They measure a ratio of branching fractions equal to $R = 1.03^{+0.19}_{-0.17}$ which they turn into a 95% confidence limit of $R > 0.61$. They also extract a $|V_{tb}|$ limit assuming the SM: $|V_{tb}| > 0.78$ at 95% confidence level 12).

4.3 Search for charged Higgs

A charged Higgs boson is predicted in models with 2 Higgs doublets, leading to five Higgs bosons. The direct production of a charged Higgs has a small production rate and a difficult signature. A charged Higgs could also be indirectly produced in association with a top quark. For example if the mass of the charged Higgs is less than the difference between the top mass and the b quark mass, then the decay $t \to H^{\pm}b$ could compete with the decay $t \to Wb$. Depending on values of $tan(\beta)$ (the ratio of vacuum expectation value of the two Higgs fields) this branching fraction could be large and there is a clean signature for it. In the CDF analysis, the following four decay channels for the charged Higgs are considered: $H^{\pm} \to c\bar{s}$, $H^{\pm} \to \tau\nu$, $H^{\pm} \to t^{*}\bar{b}$ and $H^{\pm} \to Wh^0 \to Wb\bar{b}$.

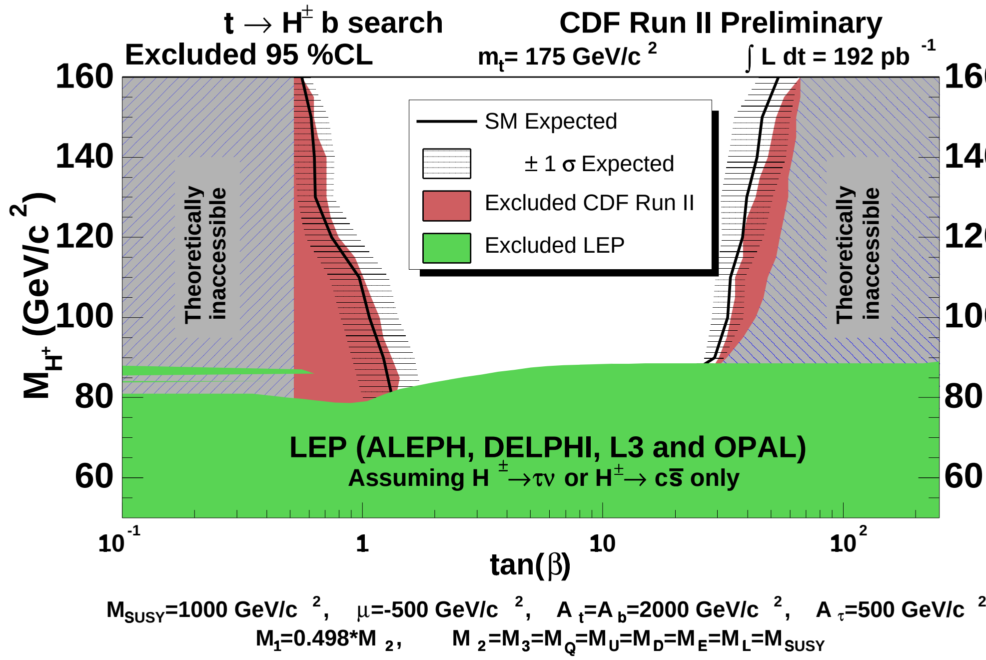

Figure 4: *95% confidence limit on the mass of the Charged Higgs vs tan(β) by CDF, the SUSY parameters used are shown below the plot.*

Those various charged Higgs decays affect differently the top pair cross section in the different channels, so the idea is to make use of the cross section results to look for an imbalance that could be explained by a charged Higgs hypothesis. The cross sections considered are the dilepton channel, the lepton+jets channel in the single b tag and the double b tag cases and also the lepton+τ channel. The results are 95% confidence level limits in the charged Higgs mass vs $tan(\beta)$ plane. There are different sets of limits depending on the various parameters associated with different models of the Higgs doublets. In figure 4 we show an example of such a limit obtained with 192 pb^{-1} of data [13].

4.4 Top charge

Although we have observed that the top quark decays to a W and a b quark, we actually don't know if it decays to W^+b, as predicted by the SM top with charge $+2/3e$ or W^-b, which would correspond to an exotic quark with charge $-4/3e$. There are hypothesis that allow for such an exotic quark, and which predict the true top quark to have a mass at about 270 GeV/c^2 [15]. The DØ collaboration uses the sample of lepton+jets with 2 b tags. It uses the top mass χ^2 kinematic fit to get which of the 2 b jets is associated with the lepton. It also makes use of an algorithm called Jet Charge to decide whether the b jet is a b or $\bar{b}$. The Jet Charge algorithm sums up the charge of each track in a cone

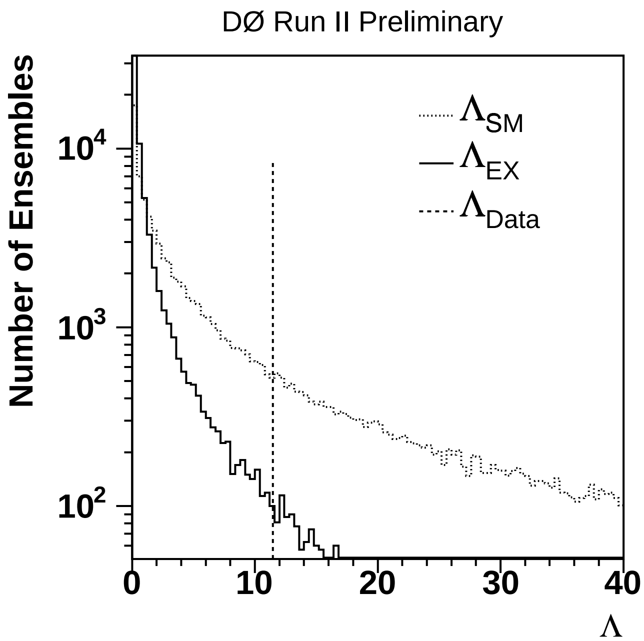

Figure 5: *Expected and Observed distribution of* Λ *for each hypothesis of top quark charge by DØ.*

around the b jet axis and weight this charge by the $p_T^{0.6}$ of the track. To get the confidence limit exclusion value, they build a likelihood ratio test (Λ), where the numerator is the product over all the events of the probability that the event follows the $+2/3e$ hypothesis, and the denominator is the product over all the events of the probability that the event follows the $-4/3e$ hypothesis. The distribution of Λ expected for each hypothesis is shown in figure 5. The vertical line is the value obtained from the data using a sample of 370 pb^{-1} of data: $\Lambda_{data} = 11.5$. This translates into an exclusion of the $-4/3e$ hypothesis to 94% confidence level using pseudo-experiments [16].

4.5 Top lifetime

In the SM the top quark has a lifetime of about $10^{-24}s$, which is too small to be measured experimentally, however if one measures a significant lifetime, this could come from a new production mechanism involving long lived particles. The CDF collaboration uses the lepton+jets data sample with one of the b jets tagged. The lifetime is obtained by looking at the lepton impact parameter. The backgrounds are classified according to whether they are prompt: this is the case for $W+jets$, Drell-Yan and diboson, or whether they have a displaced lepton: this is the case for $W(Z)$ boson decaying to a τ, for semileptonic b, or c decays and for photon conversion that failed the conversion filter. A calibration

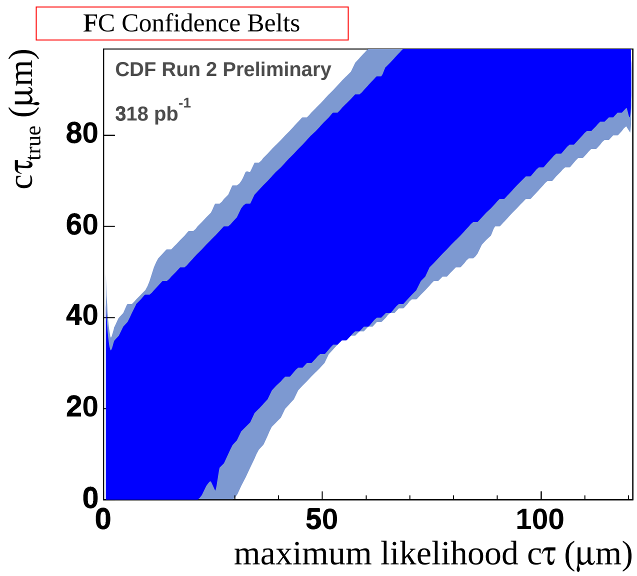

Figure 6: *Feldman-Cousins 90% (dark color) and 95% (light color) confidence limits for the top quark $c\tau$ from CDF.*

sample using Drell-Yan events near the Z resonance is used to get the lepton impact parameter resolution. A template fit is performed using the signal shape and the expected background shapes. The resulting $c\tau$ limit is extracted as shown in figure 6. The limit at 95% confidence level is $c\tau_t < 52.5\mu m(\tau < 1.75 \times 10^{-13}s)$ [14].

4.6 W helicity

In the SM, the $V - A$ coupling of the tWb vertex only allows for two helicities for the W boson: the left-handed helicity ($f_- \sim 0.3$) and the longitudinal helicity ($f_0 \sim 0.7$), while the right-handed polarization is not allowed ($f_+ = 0$). Measuring the helicity of the W coming from the top quark decay allows to test the $V - A$ structure of the tWb vertex and consequently whether the top quark is the SM top quark. The DØ collaboration uses both the $cos(\theta^*)$ in the lepton+jets sample and the lepton p_T in the dilepton as observables that can discriminate between the various helicities. $cos(\theta^*)$ is the angle between the lepton direction and the top direction in the W rest frame. For the lepton+jets analysis (using $230pb^{-1}$ of data), there are two template analyses using either b tagging information or topological variables. The χ^2 kinematic fit is used to match the lepton with the right b jet. The dilepon analysis uses $370pb^{-1}$ of data. The combined result gives $f_+ = 0.04 \pm 0.11(\text{stat.}) \pm 0.06(\text{syst.})$ and

$0.0 < f_+ < 0.25$ as the 95% confidence limit [17]. This is obtained while f_0 is fixed.

5 Conclusion

I have reported on recent measurements on the top quark pair production cross section. These measurements are starting to be systematically limited and the level of precision allows for comparison with the theoretical calculations. Soon comparison among the different channels will be possible. I have also reported on recent limit of the single top pair production. It is expected that with about 2 fb^{-1} of data the Tevatron experiments will be able to make the first observation of single top production. Finally I have reported on several top properties measurements. So far they are all supporting the hypothesis of a SM top quark. More stringent tests will be possible with the significant data sample already available and expected in the coming year.

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