TOP MASS AND PROPERTIES

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The top quark was discovered in 1995. The top quark mass is now well measured at the Tevatron, with uncertainty getting below 1% of the top mass. The world average from last year was 170.9 ± 1.8 GeV/c^2. The new CDF measurement is 172 ± 1.2 (stat) ± 1.5 (sys) GeV/c^2, and D0 will soon present a new measurement. The top quark mass is an important parameter in the Standard Model, and should be measured as precisely as possible. To learn more about the top quark observed and study possible new physics, other properties also should be measured. At the Tevatron, the charge of the top quark can be measured directly. Examples of other properties studied and reported in this presentation are W helicity, top decay branching ratio to b (R_b), searches for $t \to Hb$ and for flavor changing neutral current (FCNC). The results are all consistent with the Standard Model within current statistics. With significantly more data being collected at the Tevatron, precision measurements of the top properties are just starting.

1 Introduction

Top quarks are produced at the Tevatron mainly in top anti-top pairs, $P\bar{P} \to t\bar{t}$, through quark anti-quark annihilation and gluon gluon fusion. The t ($\bar{t}$) quark subsequently decays into a $W^+(W^-)$ boson and a $b(\bar{b})$ quark, $t \to Wb$, with a branching ratio close to 1. From the b's and the final products of the W decays, the mass and other properties of the top quark can be measured.

The $P\bar{P} \to t\bar{t} \to W^+bW^-\bar{b}$ production cross section and event selection have been reported in a previous talk at this Conference. Based on how the W's decay, three analysis channels are identified: the di-lepton channel (DIL) for both W's decaying leptonically, the lepton plus jet channel (LJ) for only one W decaying leptonically, and the all hadron channel for both W's decaying hadronically. (In this article we consider the final leptons being electron or muon only. The case of $W \to \tau\nu$ has to be handled differently due to the nature of tau decay.) Each channel has its own challenges and strengths. Some common methods are developed and used when applicable.

2 top mass measurement

Mass is a fundamental property of a particle. While the top has been discovered for more than ten years, we have many interesting questions about the top quark. Are we seeing the same particle in all three analysis channels (DIL, LJ and all hardon)? Precise measurement of the top mass in these three channels could provide some insight to this question. If this particle seen as top quark is truly the one of the SM, then since its mass strongly correlates with the mass of Higgs particle, precise measurement of the top mass can help the search of the Higgs particle, and will also enable stringent constraints for electroweak tests and new physics.

The three channels, DIL, LJ and all hadron, have their own challenges and methods. In the DIL channel, each event has two neutrinos that are not measured directly, with only the missing transverse energy providing partial information for these two neutrinos. The system is under-constrained. Additional assumption is used to further constrain the system to be able to reconstruct the top mass. Also, various top mass could be used as input to obtain a probability density function to determine the most probable value for top mass.

A general issue with all three channels is: which lepton and jet(s) in each $t\bar{t}$ event are decay products of the top quark and which are from the anti-top? One could try all possible combinations and select one based on reconstruction probability or simple kinematic information, such as the invariant mass of the top and anti-top system. Alternatively, one could use all possible solutions and assign weights based on the some relevant quantities, such as a weight defined by comparing missing Et from the reconstruction to that from what is measured in each event. These techniques are also generally applied in studying properties of the top quark.

2.1 The methods

One common issue with all channels is the jet energy calibration. In prior analysis jet energy calibration was based on predefined cone sizes. In an event where at least one W decays hadronically, the known W boson mass can be used as input to further fine tune the two jets associated with this W. This is called the in-situ jet energy calibration. In top mass measurement, this W mass constraint is applied to the final events selected to find the average shift to the nominal jet energy calibration. The shift is applied to all jets including the b jets. This procedure significantly improves the determination of the uncertainty in the top mass measurement.

The Template Method is one of the main methods used to obtain the top mass. In this method, top mass is reconstructed from the kinematic information available in the event. Templates are formed based on Monte Carlo with different top mass input. Comparing these templates with the observed events reconstructed in the same way reveals the top mass. In each DIL channel event, the system is under-constrained. Additional reasonable assumption has to be made, such as taking P_z of top anti-top system from observed events [1], or weighting on the ϕ angle of the neutrino [2], etc. In the LJ channel, the assumption is made that the missing energy is due to the neutrino being not detected. A top mass fitter is used to find the most probable top mass, taking into account the resolution of p_t and jet energy measured. In-situ jet energy calibration is commonly applied to improve the uncertainty. In each all hadronic event, there are two W's decaying hadronically. In-situ jet energy calibration is generally applied to the jets which form the W's. In the Template Method with 2-dimensional fit (TMT2D) [3] analysis in CDF, all possible jet pairing combinations are tried but only the one with best $\chi 2$ is kept.

The Matrix Element Method is based on theory. This takes into account all the kinematics information contained in an event, which are top mass dependent. A conditional probability

Table 1: top mass measurement at the Tevatron

Analysis	Samples	Result
ME+NN (CDF) [6]	DIL, 2 fb^{-1}	$171.2 \pm 2.7(stat) \pm 2.9(sys)$ GeV/c^2
TMP+NN (CDF) [3]	Had., 1.9 fb^{-1}	$177.0 \pm 3.7(stat + JES) \pm 1.6(sys)$ GeV/c^2
ME+NN (CDF) [4]	LJ, 1.9 fb^{-1}	$172.7 \pm 1.2(stat) \pm 1.3(JES) \pm 1.2(sys)$ GeV/c^2
MW (D0) [7]	DIL, 1 fb^{-1}	$175.2 \pm 6.1(stat) \pm 3.4(sys)$ GeV/c^2
NW (D0) [8]	DIL, 1 fb^{-1}	$172.5 \pm 5.8(stat) \pm 3.5(sys)$ GeV/c^2

can be formed for a given top mass. In DIL, this probability can be expressed as

$$P(\mathbf{x}|M_t) = \frac{1}{N} \int d\Phi_8 |\mathcal{M}_{t\bar{t}}(p; M_t)|^2 \prod_{jets} W(p,j) f_{PDF}(q_1) f_{PDF}(q_2), \qquad (1)$$

where M_t is the top mass, $\mathbf{x}$ contains the lepton and jet energy measurement, $\mathcal{M}_{t\bar{t}}(p; M_t)$ is the $t\bar{t}$ production matrix [5], q is the vector of incoming parton-level quantities, p is the vector of resulting parton-level quantities: lepton and quark momenta, $W(p,j)$ is the transfer function which gives the probability to observe a jet with energy j given a parton energy p, and finally, f_{PDF} the parton distribution functions of the two quarks from the proton and anti-proton. The integral is over the entire six-particle phase space. Scanning through the top mass, the most probable point reveals the mass of the top quark. An example of applying such method for top mass measurement is performed at CDF using DIL samples [6].

This method "Matrix Weighting" is different from the "Matrix Element" method described previously. This method is applied to DIL samples, where the system is under-constrained due to missing neutrinos. For a given top mass, one could try to resolve for $t\bar{t}$ momentum. A weight is calculated for each solution found by comparing the missing energy calculated with the one observed in observed events. The top mass is determined from a scan through a range of top mass to find a maximum weight and the extremum of likelihood. This is described in D0's public conference note [7].

"Neutrino weighting" is a method applied in D0. Using DIL samples, for a given top mass η was thrown based on Monte Carlo simulation for each ν. Then the set of energy-momentum conservation equations can be resolved for ν momentums. For each event a weight template was derived based on missing energy expected and observed at each given top mass. A maximum likelihood is formed, combining all events, and the extremum of this distribution reveals the top mass. This is described in D0's public conference note [8].

At the Tevatron, many techniques have been developed to measure the top mass. Progress has been made to improve the uncertainty. Some of the methods have not been mentioned in this presentation. A single variable that has a distribution being sensitive to the top mass can be used to do the measurement. One such variable is the Lxy, which is the closet distance of the secondary vertex to the primary vertex in the transverse plan of the detector. may have a distribution which is sensitive to the top mass. The top mass measurement from the top production cross section is discussed by Marc Besancon at this Conference. All of the methods provide additional info, and could help in improving uncertainty of the combined top mass.

2.2 The results

The results on the top mass measurement at Tevatron given at this conference are listed in Table 1. All individual top mass measurement from all three channels show consistent results. There is no indication of seeing different particles in different channels.

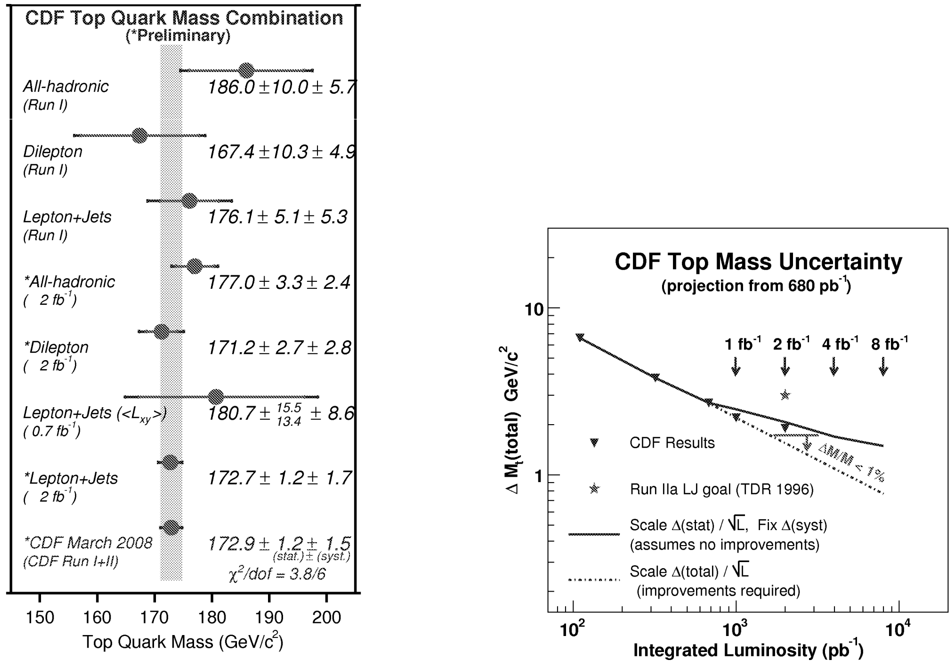

Figure 1: The combined measurement of top mass from CDF. The plot on the right shows the improvement of uncertainty with respect to the integrated luminosity. The dark blue points are the reality, compared to the projection based on including more data only (blue line) or further improving the analysis methods (dashed line). The improvement based better methods is hard to predict. The dashed line is the most optimistic case. The new results are between the two lines. CDF alone is at the same level as CDF and D0 combined last year. Combining effort from CDF and D0, the uncertainty of top mass should be less than 1% of the measured top mass.

At the moment of this presentation, CDF has already a combined result using various results from all hadronic, DIL and LJ channels. This yields $172.9 \pm 1.2(stat) \pm 1.5(sys)$ GeV/c^2 and is shown in Figure 1. This result is approaching an uncertainty of 1% of the top mass, which is similar to CDF and D0 combined result for the year 2007. Together with the updated D0 measurement, the new combined result would have an uncertainty below 1%. (This happened right after the Moriond EW 2008 conference.[9].) CDF and D0 are working together on common systematic issues to improve uncertainty at the Tevatron for the high precision era of top mass measurement.

3 Top property studies

The SM top quark has spin (1/2), charge (+2/3), and other definite properties which should be measured. In contrast, the top mass is a free parameter in SM. Any significant deviation of the top quark properties from SM would indicate new physics. The top charge is among the fundamental properties of the top quark most accessible at Tevatron. Other properties, such as top spin, lifetime, decay width, either need significantly more data or are far beyond our capability to measure with our given detector resolution. Studies from the top deccay include the helicity of W boson from top decay, measurement of branching ratio, search for charged Higgs, search for flavor changing neutral current, etc.

3.1 The charge of top quark

In the SM, the charge of top quark is +2/3. An alternative possibility suggested by an exotic model (XM)[11] is −4/3. In this model, it is claimed that the particle seen at Tevatron may be an exotic top of charge −4/3, which decays into W^- and b, unlike in the SM where the top quark decays into W^+ and b. The two key elements in the study are then to identify the source of a jet being b or $\bar{b}$, and how the b and $\bar{b}$ jets are paired with the two W's.

The identification of a jet being from b or $\bar{b}$ is done via calculating the jet charge, which is sum of jet-track charges weighted by the track momentum amplitude and how close the track is to the jet axis. For true b jets this method has 60% probability of identifying b or $\bar{b}$ correctly.

The pairing can be done by taking the measured top mass as input and check which pairing is more probable. In DIL channel, events can be selected based on the square of invariant mass of the paired lepton and jet $m_{lb}2$ to improve the purity. In each event there are two possible ways of pairing and four possible $m_{lb}2$ values. The pairing having the maximum $m_{lb}2$ does not always provide the correct pairing. In the events with the maximum $m_{lb}2$ is greater than certain value, this method can be almost 100% correct. However cutting too tight would lose too much in statistics. The best point for making such cut is 21000, assuming that SM is true and top mass is 175 GeV/c^2. With this selection, 94% of pairing purity can be reached with efficiency of 39%.

The charge of the top quark was first studied by D0. With 0.37 fb^{-1} of data, the result prefers the SM instead of XM [10]. In CDF, the study has been done with data up to 1.5 fb^{-1}. The result [12] up to date support SM over XM, and the XM is rejected at 87% confidence level (CL). Combining DIL and LJ, among 225 top or anti-top quark decays 124 decays support SM and 101 support XM. Correcting for purity of the analysis, the measured true fraction of SM over total is 0.87, which based on our sensitivity gives a p value of 0.31. An additional way of showing this is the Bayes Factor (BF), which is defined as $P(N_+|SM)/P(N_+|XM)$, i.e. the probability of observed events happening assuming SM is true over the one of XM. A common way to utilize BF is the quantity $L = 2 * Ln(BF)$. For L in the ranges (0-2), (2-6), (6-10), (>10), the result is uncertain, positive, strongly supporting SM, or very strongly supporting SM, respectively. Our result from CDF data is 12.01, thus very strongly support SM over XM. With more data, we will determine more precisely the top charge.

3.2 W helicity

In the SM, V-A rules the weak decay. The W boson from top quark decay is thus polarized. The SM predicts that the W helicity in this case should have 70% longitudinal (f_0) and 30% left-handed (f_-). The component of right-handed (f_+) is very small, 3.6×10^{-4}. Significant deviation of f_+ would indicate new physics.

The study of W helicity can be performed via looking at the $cos\theta^*$ distribution, where θ^* is the angle of the electron or muon in the W rest frame with respect to the anti-direction of top quark in this frame. The analysis can be performed in LJ and DIL channels. In case of LJ the missing energy is assumed to be due to the missing neutrino. Events can be reconstructed using top mass as input and lepton angle in W rest frame can be calculated. The top mass used is generally 175 GeV/c^2. In case of DIL there are two missing neutrinos. Using top mass as input one can figure out which jet is paired with which lepton and resolve for the neutrino momenta. Lepton angle in the W rest frame can be obtained in this way. CDF does this analysis, using 1.9 fb^{-1} data, in the LJ channel. In a 2 dimensional fit where both f_0 and f_+ are fitted at the same time the result shows $f_0 = 0.65 \pm 0.19(stat) \pm 0.03(sys)$ and $f_+ = -0.03 \pm 0.07(stat) \pm 0.03(sys)$. If f_0 is fixed to the SM value CDF obtains $f_+ = -0.04 \pm 0.04(stat) \pm 0.03(sys)$ and sets upper limit for f_+ at 0.07 at 95% CL [13]. D0 collaboration does the analysis in both LJ and DIL channels. A 2-D fit of f_0 and f_+ reveals $0.425 \pm 0.166(stat) \pm 0.102(sys)$ and $0.119 \pm 0.0090(stat) \pm 0.053(sys)$ respectively. Fixing f_0 to the SM value gives $f_+ = -0.002 \pm 0.047(stat) \pm 0.047(sys)$. An upper limit of 0.13 at 95% CL is set [14].

3.3 Study of R_b

A study on the $R_b = Br(t \to Wb)/Br(t \to Wq)$, where q represents all possible quarks allowed in the decay, is performed at D0. R_b is correlated with the top pair production. Noting that D0 does simultaneous fit to both values, using LJ channel from 0.9 fb^{-1} data [15]. The result is $R_b = 0.97^{+0.09}_{-0.08}(stat + sys)$. A lower limit of R_b is set at 0.79 at 95% CL. From this a lower limit on $|V_{tb}|$ is set at 0.89 at 95% CL. From the same fit the resulted production cross section is $\sigma_{t\bar{t}} = 8.18^{+0.90}_{-0.84}(stat + sys) \pm 0.50(lumi)$ pb, which is consistent with the direct measurement.

3.4 Search for $t \to Hb$

It is interesting to search for charged Higgs in the top quark decay. D0 collaboration did this analysis by comparing the production cross section of top pair from the LJ channel against the one from the DIL channel. If there were charged Higgs in the top decay, it would mostly contribute to the LJ channel but much less in the DIL channel. The ratio of the two production cross sections is $R = 1.21^{+0.27}_{-0.26}(stat+sys)$, based on the assumption that $R_b = 1$. Extracting the branching ratio of $t \to Hb$ from this cross section ratio, D0 obtains $Br = 0.13^{+0.12}_{-0.11}(stat + sys)$. An upper limit is set at 0.35 at 95% CL [16].

3.5 Search for FCNC

At CDF an analysis to study FCNC is to search for $t \to Zq$ in the top quark decay. The SM predicts a branching ratio at the order of $O(10^{-14})$. However beyond SM up to $O(10^{-4})$ is possible. At CDF events having two high p_t leptons with at least 4 jets were selected with constraint on masses of top, Z and W. Comparing the data (1.9 fb^{-1}) with expectation, no excess is seen. An upper limit is set at 3.7% at 95% CL [17].

4 Summary and Future Prospects

The top quark mass has been well measured at the Tevatron, with uncertainty getting below 1% of the top mass. The top quark mass is an important parameter in the Standard Model, and should be measured as precisely as possible. Other properties of the top quark also should be measured, to learn more about the top quark and study possible new physics. Examples of other top studies at the Tevatron are the charge of the top quark, W helicity, top decay branching ratio to b (R_b), searches for $t \to Hb$ and for flavor changing neutral current (FCNC). The results are all consistent with the Standard Model within current statistics. With significantly more data being collected at the Tevatron, precision measurements of the top properties are just starting.

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