CDF note 8953

A Limit on the Top Quark Width and the Lifetime using the Template Method in the Lepton plus Jets Channel at CDF II

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We present the first direct upper limit on the top quark width in the lepton plus jets channel of $t\bar{t}$ events from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. This analysis uses a dataset with integrated luminoity of 1 fb^{-1}, containing 253 $t\bar{t}$ candidates. Reconstructed top mass distributions of the data are compared to those of Monte Carlo samples with various input top widths using a maximum likelihood fit. The Feldman-Cousins prescription is employed to set a limit. For $\mathrm{M_{top}} = 175$ GeV/c^2, the upper limit on the width is $\Gamma_{\mathrm{top}} < 12.7$ GeV and a lower limit on the lifetime is $\tau_{\mathrm{top}} > 5.2 \times 10^{-26}$ s at 95% confidence level.

Preliminary Results for Summer 2007 Conferences

I. INTRODUCTION

The lifetime (τ) of the top quark is related to the decay width (Γ) through the Heisenberg Uncertainty Principle, $\tau = \hbar/\Gamma$ [1]. The extremely short lifetime of $\tau \sim 4 \times 10^{-25}$ s is predicted in the Standard Model and corresponds to the top quark width of 1.5 GeV. The current experimental upper limit on the lifetime of the top quark is $\tau < 1.75 \times 10^{-15}$ s at 95% confidence level [2]. Since a precise measurement of the lifetime is difficult, this analysis sets an upper limit on the total width and consequently a lower limit on the lifetime of the top quark.

At the Tevatron, top quarks are produced primarily as $t\bar{t}$ pairs and decay to W bosons and b quarks nearly 100% of the time within the Standard Model. The W bosons can decay into lepton-neutrino ($l\nu$) or quark pairs (qq'). In this analysis, we use the "lepton + jets" channel of $t\bar{t}$ candidates in which only one of two W bosons decays to $l\nu$ while the other decays to qq'.

II. DATA SAMPLE & EVENT SELECTION

This analysis is based on an integrated luminosity of 1 fb^{-1} collected with the CDF II detector between March 2002 and February 2006.

The lepton + jets events are selected by requiring one well-identified electron or muon, large $\not\!\!E_T$ due to the neutrino from the W decay and at least four jets in the final state.

Electron candiates are identified as a high-momentum track in the tracking system matched to an electromagnetic cluster reconstructed in the calorimeters with $E_T > 20$ GeV. The ratio of hadronic to electromagnetic energy deposition in the cluster is required to be low to ensure validity of the electron hypothesis. We also require that energy shared by the towers surrounding the cluster is low. Muon candidates are reconstructed as high-momentum tracks with $p_T > 20$ GeV/c matching hits in the muon chambers. Energy deposited in the calorimeter is required to be consistent with a minimum ionizing particle.

The missing transverse energy is measured by the imbalance in the calorimeter transverse energy and is required to be greater than 20 GeV.

Jets are reconstructed with the JETCLU cone algorithm with a radius $R = \sqrt{\eta^2 + \phi^2} = 0.4$. At least 4 jets are required with the jet E_T requirement depending on the event category as described below (Table I).

For the top quark mass reconstruction, the lepton+jets sample is divided into two subsamples based on the number of jets that are b-tagged in the event. The SECVTX algorithm [3] based on the identification of secondary vertices inside jets is used to tag b-jets. Events with 1-tag and 2-tag are considered separately. Events with 2-tag have better mass resolution and lower background contamination than those with 1-tag.

Category	1-tag	2-tag
leading 3 jets E_T	> 15 GeV	> 15 GeV
4th jet E_T	> 15 GeV	> 8 GeV
Expected S:B	3.7:1	10.6:1
Observed number of events	171	82

TABLE I: Jet E_T cut and b-tagging requirement for the 2 event categories. Also shown is the expected signal to background ratio (S:B) for each subsample as well as the number of events observed in data.

III. TOP QUARK MASS RECONSTRUCTION

For each lepton+jets event, an invariant mass of the top quark is reconstructed from the top decay products (lepton candidate, four highest E_T jets and missing transverse energy) using a χ^2 kinematic fit. A more detailed description of χ^2 kinematic fitter used in this analysis can be found in [4].

The reconstructed top quark mass distributions are produced using PYTHIA Monte Carlo events for various true top quark width for $\mathrm{M_{top}} = 175$ GeV. These distributions are called the templates.

The purpose of the χ^2 kinematic fit is to extract a single good estimator of the true top quark mass from all information available in the event. Inputs to the fitter include lepton and jet four-vectors (together with the b-tagging information) as well as the unclustered energy. The χ^2 as presented in Eqn. 1 is minimized for all jet-to-parton assignments consistent with the b-tagging information. For each such combination two neutrino p_z solutions consistent with the W mass on the leptonic side exist. The fit is performed with both p_z solutions taken as an initial condition (neutrino p_z is a free parameter in the fit). The precise definition of χ^2 is:

$$\begin{aligned}\chi^2 \;=\; & \Sigma_{i=l,4jets}\frac{(p_T^{\text{i, fit}}-p_T^{\text{i, meas}})^2}{\sigma_i^2}+\Sigma_{j=x,y}\frac{(p_j^{\text{UE, fit}}-p_j^{\text{UE, meas}})^2}{\sigma_j^2}\\ & +\frac{(M_{l\nu}-M_W)^2}{\Gamma_W^2}+\frac{(M_{jj}-M_W)^2}{\Gamma_W^2}\\ & +\frac{(M_{bl\nu}-m_t^{\text{reco}})^2}{\Gamma_t^2}+\frac{(M_{bjj}-m_t^{\text{reco}})^2}{\Gamma_t^2}. \end{aligned} \quad (1)$$

In this equation, $\sigma_l, \sigma_j, \sigma_{x,y}$ are the uncertainties on the lepton, jets and the unclustered energy respectively. The first two terms constrain the fitted lepton and jet momenta and components of unclustered energy to their measured values. The third and fourth terms provide the most powerful constraint in the fit: the invariant mass of neutrino and lepton and the invariant mass of light quark jets are constrained to the measured mass of W boson. The last two terms enforce the requirement that the reconstructed top mass m_t^{reco} is the same on the leptonic and hadronic legs of the decay (see Section III A for further discussion).

Templates for $\Gamma_{\text{t}}^{\text{input}} = 1.5$, 30, and 50 GeV are shown in Figure 1.

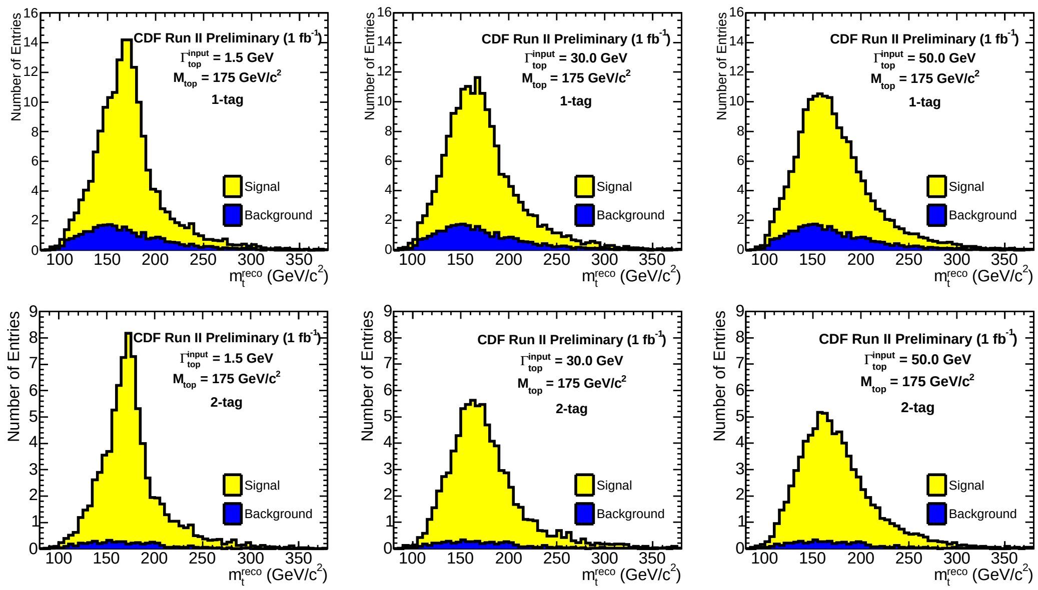

FIG. 1: Reconstructed top mass distributions for $\Gamma_{\text{t}}^{\text{input}} = 1.5$, 30, and 50 GeV Monte Carlo samples. Background events are shown in blue. (Top: 1-tag sample, Bottom: 2-tag sample)

A. Comment on the Reconstructed Top Mass Constraint

The kinematic fitter constrains the reconstructed top mass and anti-top mass to be equal ($m_t^{\text{reco}} = m_{\bar{t}}^{\text{reco}}$) within 1.5 GeV. We have studied removing this constraint since the top mass and anti-top mass can be very different if the top quark has a large width. However, we found that our sensitivity to the top width is slightly better with the constraint. We believe that when we remove the $m_t^{\text{reco}} = m_{\bar{t}}^{\text{reco}}$ constraint, the number of incorrect jet to parton assignment in the kinematic fitter increases due to the extra degree of freedom, resulting in a loss of sensitivity to the top width. Therefore, we apply the $m_t^{\text{reco}} = m_{\bar{t}}^{\text{reco}}$ constraint in our top mass reconstruction.

IV. SIGNAL TEMPLATE PARAMETRIZATION

Monte Carlo samples are available only at discrete values of true $\Gamma_{\rm t}^{\rm input}$. We parameterize the $m_t^{\rm reco}$ distributions as a function of $\Gamma_{\rm t}^{\rm input}$ to obtain a probability density function $P_s(m_t^{\rm reco};\Gamma_{\rm t}^{\rm input})$ that depend on $\Gamma_{\rm t}^{\rm input}$. Examples of the parameterization is shown in Figure 2.

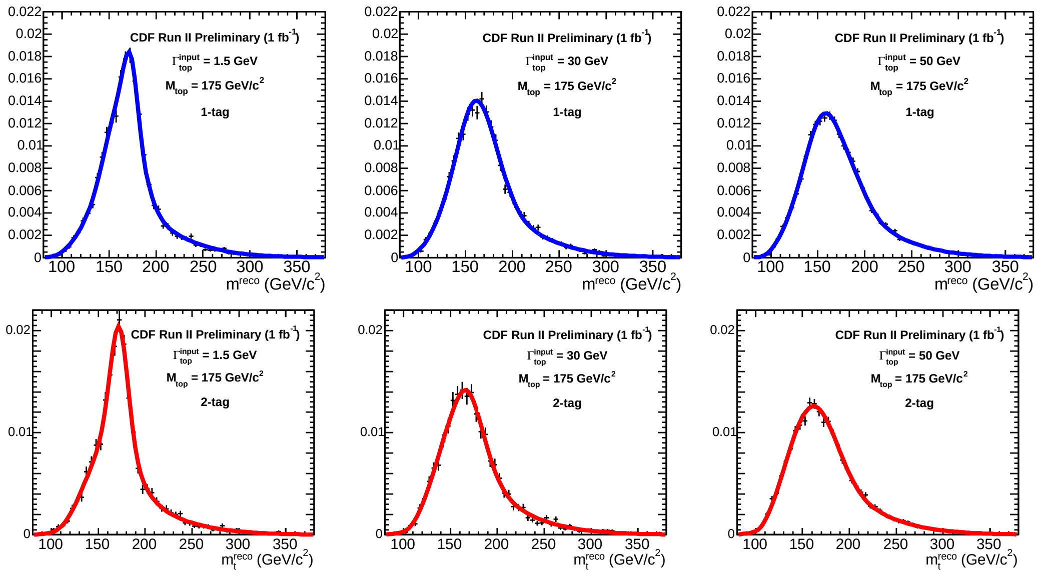

FIG. 2: Parameterization fits to the reconstructed top mass distributions for $\Gamma_{\rm t}^{\rm input}$ of 1.5, 30, and 50 GeV. (Top: 1-tag sample, Bottom: 2-tag sample)

V. BACKGROUND TEMPLATES

An *a priori* estimate for background composition is used to obtain $m_t^{\rm reco}$ shapes for background. We use Wbb + *2 partons* Monte Carlo samples generated by HERWIG and ALPGEN to model all W + *heavy flavour*. The QCD background is modeled with W + *light flavour* samples. The single top and dibozon backgrounds are modeled with *Single Top t-channel* and *s-channel* MadEvent samples.

VI. LIKELIHOOD FIT

The reconstructed top mass distributions from data are compared to the signal and background templates using unbinned likelihood fit. The likelihood fits for the expectation values of the number of signal and background events in each sample. For each subsample, the likelihood is given by the following:

$$\mathcal{L} = \mathcal{L}_{\rm shape} \times \mathcal{L}_{\rm bg} \tag{2}$$

$$\mathcal{L}_{\rm shape} = \frac{e^{-(n_s+n_b)}(n_s+n_b)^N}{N!}\Pi_{i=1}^{N}\frac{n_s P_{sig}(m_i;\Gamma_{top}) + n_b P_b(m_i)}{n_s+n_b} \tag{3}$$

$$-ln(\mathcal{L}_{\rm bg}) = \frac{(n_b - n_b^{exp})^2}{2\sigma_{n_b}^2}. \tag{4}$$

In this equation, n_s, n_b are expected number of signal and background events, N is the observed number of events with reconstructed top mass m_i. The likelihood $\mathcal{L}_{\rm shape}$ is the joint probability density for a sample of N reconstructed mass, m_i, with a background fraction of $n_b/(n_s+n_b)$. The likelihood $\mathcal{L}_{\rm bg}$ constrains the number of background events to the predicted number $n_b^{\rm exp}$ within its uncertainty σ_{n_b}.

The probabilities $P_{\rm sig}(m_i;\Gamma_{\rm top})$ and $P_{\rm bg}(m_i)$ come from parameterizations of the signal and background templates, respectively. This allows us to compare the shapes of the reconstructed top mass distributions in our data to the parameterized function with the likelihood fit to see which true input top width is the most likely the parent distribution. Examples of the fitted width distributions for various $\Gamma_t^{\rm input}$ are shown in Figure 3.

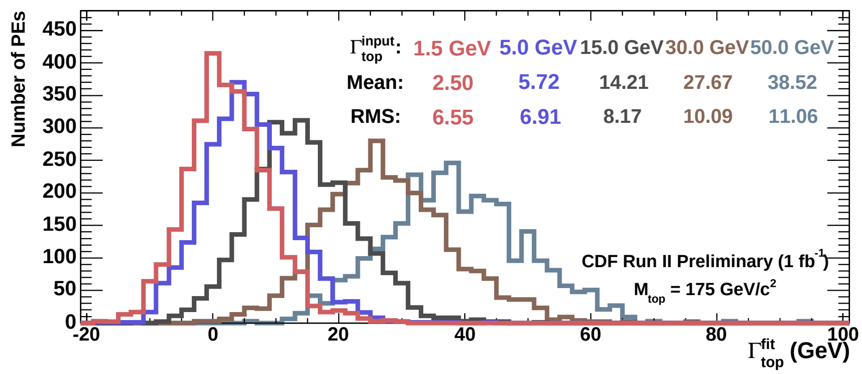

FIG. 3: Fitted width distributions for 3000 pseudoexperiments using Monte Carlo samples with various $\Gamma_t^{\rm input}$.

VII. FELDMAN-COUSINS CONFIDENCE BANDS

Once the width is extracted from the reconstructed top mass distribution, we employ the Feldman-Cousins prescription to set a limit. When the expected limit on the width is close to a non-physical result (i.e. $\Gamma \leq 0$), the Feldman-Cousins prescription guarantees a physically meaningful result and tells us how to smoothly transition from one-sided to two-sided limit. The Feldman-Cousins prescription is described in detail in [5]. In the Feldman-Cousins prescription, we use a likelihood ratio as an ordering principle for selecting the acceptance region and creating the confidence bands. The likelihood ratio is defined as the following:

$$R(x) = \frac{P(x|\Gamma_0)}{P(x|\Gamma_{\rm max})} \tag{5}$$

where $R(x)$ is a likelihood ratio at x for a given width, Γ_0, and $\Gamma_{\rm max}$ is the width that yields the maximum likelihood among all the possible width.

After the confidence bands are created, the coverage at all input top width are studied using the fitted width out of the likelihood pseudoexperiments. The coverages are plotted in Figure 4. The error bars in this plot are calculated using a bootstrap method for an input top width of 1.5 GeV sample and used for all the widths. Overall, the coverage fluctuates around 95%, suggesting that the limit-setting method is working properly.

VIII. SYSTEMATIC UNCERTAINTIES

Because we use the reconstructed top mass distributions to extract the top width, any systematic that possibly alters the shape and location of the reconstructed top mass distributions will potentially change the fitted width out of the likelihood fitter. We estimate each uncertainty by performaing a series of pseudoexperiments with various systematic Monte Carlo samples for the top mass of 175 GeV/c^2.

The $\Delta\Gamma$ due to jet energy scale, jet resolution, ISR, and FSR are studied as functions of the systematic. Since these systematics do not exhibit linear dependence of $\Delta\Gamma$ on the systematic shift, probability density functions for the $\Delta\Gamma$ are created individually.

The $\Delta\Gamma$ from background shape, parton distribution functions, Monte Carlo generator, Monte Carlo acceptance, and Monte Carlo statistics are assumed to depend linearly on the systematics. In this case, the probability density functions for the $\Delta\Gamma$ are Gaussian and have σ that correspond to the systematic uncertainties.

The systematic uncertainties are incorporated to the confidence bands by convoluting probability density function of $\Delta\Gamma$ due to systematics with the fitted width function. The new width function is used to create the confidence bands with systematics.

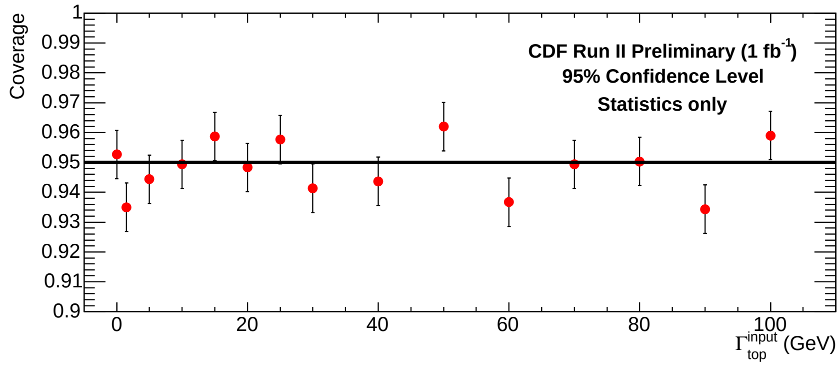

FIG. 4: Coverage of the limits for the different input top width samples.

IX. RESULTS

Separate likelihood fits to the 1-tag and 2-tag reconstructed top mass distributions from the data are shown in Figure 5, and the combined likelihood is shown in Figure 6. The combined likelihood fit yields the following fitted top width:

$$\Gamma_t^{\rm fit} = -4.86 \text{ GeV}.$$

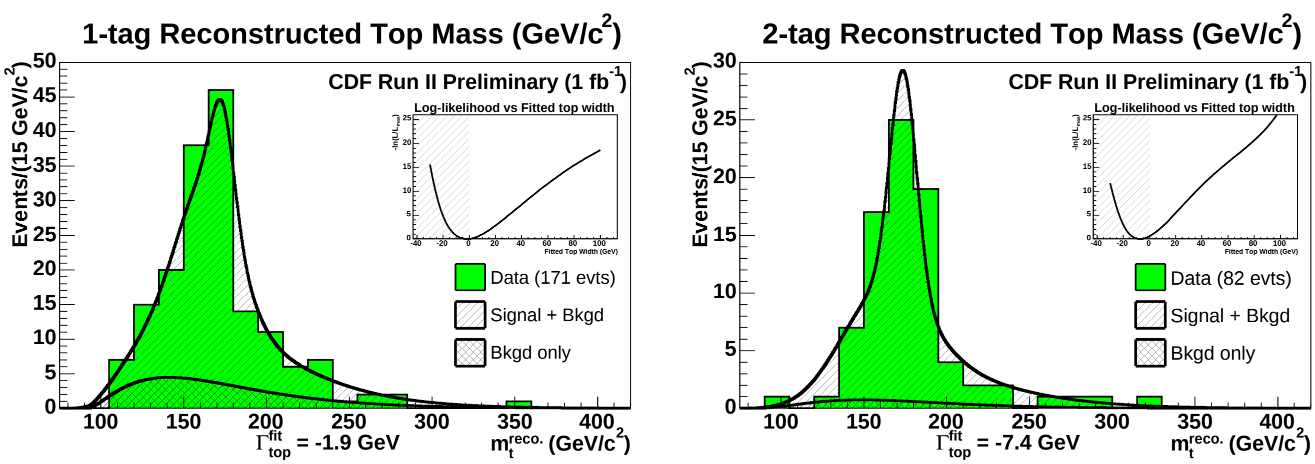

FIG. 5: Likelihood fit to reconstructed top mass distributions of the data.

Based on the confidence band with the systematics, $\Gamma_t^{\rm fit}$ for the data yields an upper limit on the top quark width:

$$\Gamma_{\rm top} < 12.7 \text{ GeVat } 95\% \text{ confidence level.}$$

The confidence bands including systematics are shown in Figure 7; our measurement is indicated by an arrow.

X. CONCLUSIONS

For a top quark mass of 175 GeV/c^2, we have set an upper limit on the to quark width to be 12.7 GeV and the lower limit on the top quark lifetime to be 5.2×10^{-26} s at 95% confidence level. Based on our study of the top quark mass dependence, the upper limit on the top quark width would be smaller by a few GeV for a top quark mass close to the current world average of $\sim$ 171 GeV.

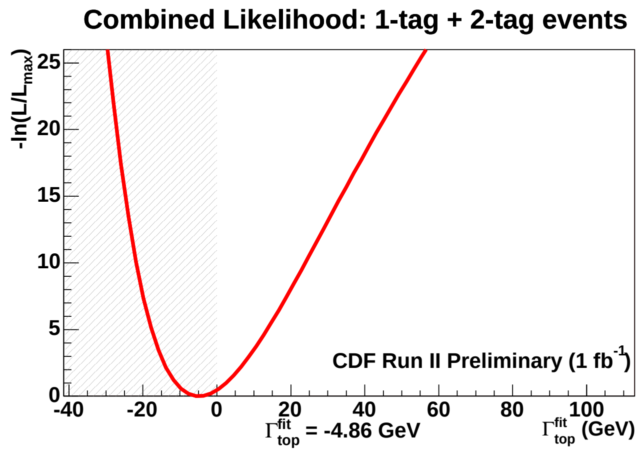

FIG. 6: Combined likelihood of 1-tag and 2-tag samples in the data.

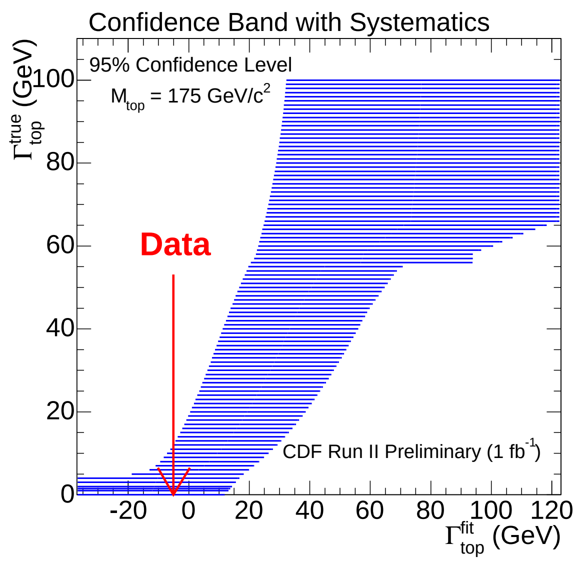

FIG. 7: Confidence band with systematics. The data is indicated with a red arrow.

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[1]

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