CDF note 10035

A Measurement of Top Quark Width using Template Method in Lepton+Jets Channel with 4.3fb^{-1}

The CDF Collaboration
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We present a measurement of top quark width using 4.3 fb^{-1} of Tevatron's $p\bar{p}$ collisions collected by the CDF detector at Fermilab. We use a two dimensional template method to build the probability of signals and background in the lepton+jets decay topology. The observables are the reconstructed top quark mass from the minimization of a χ^2 for the overconstrained system, and the invariant mass of two jets from the hadronic W decays, which provides an *in situ* improvement in the determination of jet energy scale. We use a Feldman-Counsin (FC) construction method from Monte Carlo pseudo experiments to extract the top quark width from data at 95% Confidence Level(CL). We set an upper limit on the top quark width of $\Gamma_{top} < 7.5$ GeV at 95% CL, which corresponds to a lower limit on the top quark life time of $\tau_{top} > 8.7 \times 10^{-26}$ s at 95% CL. We also set central limits of top width at 68% CL: 0.4 GeV $< \Gamma_{top} <$ 4.4 GeV.

Preliminary Results of TMT 4.3 fb^{-1}

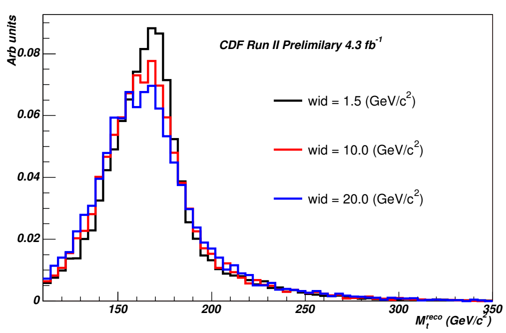
I. INTRODUCTION

This note describes a measurement of top quark width using $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV with the CDF detector at the Fermilab Tevatron. In Standard Model, a top quark decay is expected to be dominated by channel $t \rightarrow Wb$ according to CKM Quark-Mixing Matrix. The theoretical top decay width at next-to-leading order is[3]:

$$\Gamma_{top} = \frac{G_F m_t^3}{8\pi\sqrt{2}} \left(1 - \frac{M_W^2}{m^2)t}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \left[1 - \frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right] \tag{1}$$

which gives a short life time of $5 \times 10^{-25}s$ and makes top quark decay before top-flavored hadrons or $t\bar{t}$-quarkonium-bound states can form[4]. According to Heisenberg Uncertainty Principle $\tau = \hbar/\Gamma$, the predicted top quark decay width is 1.5 GeV, which is out of the reach of the sensitivity of current experiments, and [1] gives a upper limit of top width $\Gamma_{top} < 13.1$ GeV at 95% confidence level.

In this analysis, we use $t\bar{t}$ lepton+Jets channel and use a template method. We generate Monte Carlo (MC) samples using PYTHIA with dfferent input top widths ranging from 0.1GeV to 30GeV and all the samples have the same input top quark mass $M_{top} = 172.5GeV/c^2$. For each event in these samples an invariant top quark mass (m_t^{reco})and dijet mass of W boson (m_{jj}) are reconstructed, which form a two-dimentional template for each sample. The shape of m_t^{reco} will change as the input top width changes, as shown in Figure 1. By comparing the shapes (or distributions) of these two observables with that of the events drawn from samples (or data) with unknown top quark widths, we can extract the top quark width using maximum likelihood fit. We then perform Pseudo-Experiments (PE) for each MC sample, which enables us to apply Feldman-Cousins (FC) construction to build 95% confidence interval for top quark width. In the Feldman-Cousins construction, we take information from the maximum likelihood function and build an *ordering principle*,$\Delta\chi^2$ for each PE. Each MC sample, which has a set of PEs(3000), will finally have a *critical* value of $\Delta\chi^2$ called $\Delta\chi_c^2$ that is calculated from the $\Delta\chi^2$ of these PEs. In the end, we will use the $\Delta\chi_c^2$ of each sample together with the data fit information to find the limit(s) of top quark width. To incorporate systematic effects in to top quark width limits, we first convolute then shift the maximum likelihood function with and by a Gaussian function, which has a σ related to systematic effects. Thus a new maximum likelihood function with systematic effects considered is defined, and the same procedure as without systematic effects will be conducted afterwards to get top width limit(s).



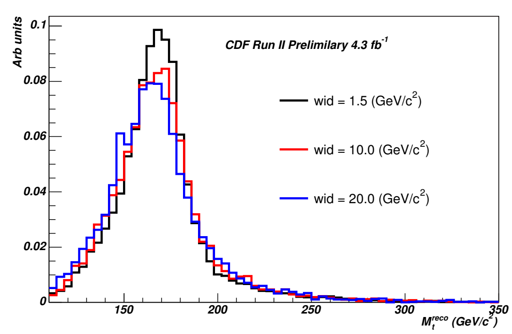


FIG. 1: Reconstructed top quark mass distributions of samples with different input top quark widths: 1.5 GeV, 10.0 GeV and 20.0 GeV.(1-btag on left plot and 2-btag on right plot)

II. DATA SAMPLE AND EVENT SELECTION

This Analysis is based on an intergrated luminosity of 4.3 fb^{-1} collected by CDF II detector between February 2002 and February 2009.

At trigger level, lepton+jets candidate events are selected by requiring a high-E_T electron (or high-P_T muon). Offline, the events are required to have a single energetic lepton, large missing E_T due to the escaping neutrino from the leptonic W decay, and at least four jets in the final state. Jets are reconstructed with JETCLU[6] cone

TABLE I: Event selection in the $t\bar{t}$ Lepton+Jets channel.

CDF Run II Preliminary, 4.3 fb^{-1}

	1-tag	2-tag
b-tags	$=1$	>1
Leading 3 jets E_T (GeV)	>20	>20
Missing E_T (GeV)	>20	>20
4th jet E_T (GeV)	>20	>12
Extra jets E_T (GeV)	<20	Any
χ^2 cut	<9	<9
m_t^{reco} boundary cut (GeV/c^2)	$110 < m_t^{reco} < 350$	$110 < m_t^{reco} < 350$
m_{jj} boundary cut (GeV/c^2)	$50 < m_{jj} < 115$	$50 < m_{jj} < 125$
Observed num of events	542	214
$t\bar{t}$ σ=7.4pb, $M_{top} = 172.5 GeV/c^2$	375 ± 50	187 ± 19
Expected background	120 ± 50	15 ± 5

algorithm using a cone radius of $R \equiv \sqrt{\eta^2 + \phi^2} = 0.4$. To improve the statistical power of the analysis, we divide the lepton+jets samples into two categories depending on the number of jets identified as arising from the hadronization and decay of b quarks. The SECVTX[7] algorithm uses the transverse decay length of tracks inside jets to tag jets as coming from b quarks. We require at least one tagged jet for lepton+jets events.

We also make a cut on the χ^2 out of the kinematic fitter which will be covered later, requiring it to be less than 9.0. In order to properly nomalize our probability density functions we define hard boundaries on the observables, that is, events in which observables with values falling outside of the boundaries are rejected. The summary of event selection criteria and χ^2 and boundary cuts are in Table I, as well as the observed num of events and expected background events.

III. JET ENERGY SCALE

We describe in this section the *a priori* determination of the jet energy scale uncertainty by CDF that is used later in this analysis. More information about JES, calibration and uncertainty can be found in [8]. There are many sources of uncertainties related to jet energy scale at CDF:

- Relative response of the calorimeters as a function of pseudorapidity
- Single particle response linearity in the calorimeters
- Fragmentation of jets
- Modeling of the underlying event energy
- Amount of energy deposited out of the jet cone

The uncertainty on each source is evaluated separately as a function of the jet p_T (and η for the first uncertainty in the list above). Their contributions are shown in Fig 2 for the region 0.2 ¡ η ¡ 0.6. The black lines show the sum in quadrature (σ_c) of all contributions. This $\pm\sigma_c$ total uncertainty is taken as a unit of jet energy scale miscalibration (Δ_{JES}) in this analysis.

A. Top Quark mass reconstruction

The reconstructed top quark mass (m_t^{reco}) in lepton+jets channel is determined by minimizing a χ^2 describing the overconstrained kinematics of the $t\bar{t}$ system. The reconstructed top mass is a number that distills all the kinematic information in each event into one variable that is a good estimator for the true top quark mass. The kinematic fitter uses knowledge of the lepton and jet four-vectors, b-tagging information and the measured missing E_T. The invariant masses of the lepton-neutrino pair and the dijet mass from the hadronic W decay are constrained to be near the well known W mass, and the two top quark masses per event are constrained to be equal within the narrow top width. The χ^2 (Eqn 2) is minimized for every jet-parton assignment consistent with b-tagging. The first sum constrains the p_T of the jets and lepton, within their uncertainties, to remain close to their measured values. The second term constrains the unclustered energy in the event to remain near its measured value, providing a handle on the neutrino 4-vector. The W boson has a small width, and the two W mass terms provide the most powerful constraints in the fit. The last two terms in the χ^2 constrain the three-body invariant masses of each top decay chain to remain close to a single top quark mass, m_t^{reco}. The single jet-parton assignment with the lowest χ^2 that is consistent with b-tagging gives the value of m_t^{reco} for the event. Events where the lowest χ^2 ¿ 9:0 are rejected..

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

Equation **??** shows the definition of χ^2 to estract m_t^{reco}. The first term constrains the p_t of the lepton and four leading jets to their measured values within their assigned uncertainties; the second term does the same for transverse components of unclustered energy; the third and fourth terms constrain the invariant mass of W boson to be pole mass of W 80.42 GeV/c^2; in the last two terms m_t^{reco} is the free parameter for the reconstructed top quark mass used in the minimization. The jet-quark assignment (and p_z^ν of neutrino) with the lowest χ^2 after minimization is selected for each event, and the requirement of $\chi^2 < 9$ is imposed.

IV. DIJET MASS OF W BOSON

The value of m_{jj} in each lepton+jets event can have an ambiguity due to not knowing which two jets came from a hadronic W decay. In 2-tag events, the value is chosen as the invariant mass of the two non-tagged jets in the leading 4 jets. In single-tag events, there are 3 dijet masses that can be formed from the 3 non-tagged jets among the 4 leading jets in the event. We choose the single dijet masses that is closest to the well know W mass..

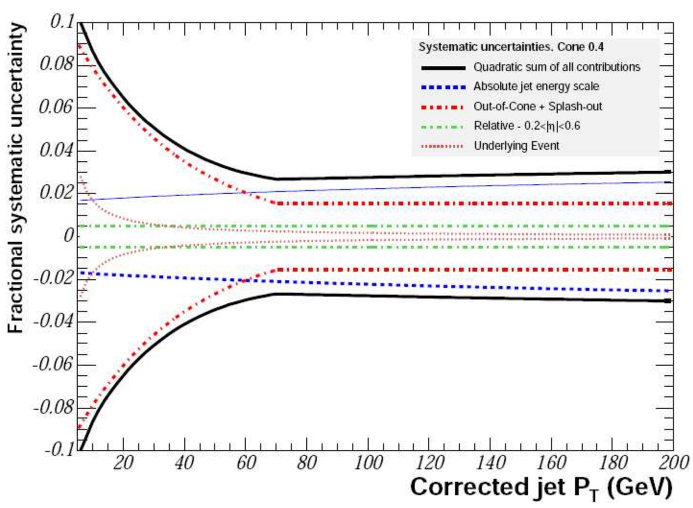


FIG. 2: Jet energy scale uncertainty as a function of the corrected jet p_T for the underlying event(dotted red), relative response (dashed green), out-of-cone energy (dashed red) and absolute response (dashed blue). The contribution of all sources are added in quadrature (full black) to form the total Δ_{JES} systematic σ_c.

TABLE II: The sources and expected numbers of background events in the Lepton+Jets channel(Numbers of total bkgd are rounded off).

CDF Run II Preliminary, 4.3 fb^{-1}		
Wbb	29.6±9.1	7.6 ± 2.3
W$c\bar{c}$/Wc	36.9±11.5	1.8 ± 0.6
W LF	19.1 ± 7.0	0.4 ± 0.1
single top	4.5 ± 0.4	1.8 ± 0.2
Diboson	5.7 ± 0.7	0.6 ± 0.1
QCD	24.5 ± 20.6	2.4 ± 1.8
Total bkgd	120.2 ± 49.5	14.6 ± 5.1

V. BACKGROUNDS

An *a priori* estimate for the Lepton+Jets background composition is used to derive background shapes for m_t^{reco} and m_{jj}. ALPGEN combined with PYTHIA is used to model W+jets. Contributions include Wbb,Wcc, Wc and W+light favor (LF) jets. Non-isolated leptons are used to model the QCD background. The relative fractions of the different W+jets samples are determined in MC, but the absolute normalization is derived from data. The MC are combined using their relative cross sections and acceptances, and we remove events overlapping in phase space and favor across different samples. MC and theoretical cross-sections are used to model the single-top and diboson backgrounds. The expected number of background from different sources is shown in Table II. The backgrounds are assumed to have no M_{top} dependence, but all MC-based backgrounds are allowed to have ΔJES dependence.

VI. KERNEL DENSITY ESTIMATION

To get the probability density function (p.d.f.) for signals and backgrounds we use Kernel Density Estimation (KDE) instead of simply fitting usual histograms. The (p.d.f.) in this analysis is a two-dimentional function of reconstructed top mass m_t^{reco} and dijet mass of W boson m_{jj}:

$$P(m_t^{reco}, m_{jj}|\Gamma_{top}, \Delta_{JES}) \tag{3}$$

For signal, there is one p.d.f. for each set of M_{top} and Δ_{JES}, while for background it only has one parameter Δ_{JES} since backgrounds do not depend on top quark mass. These p.d.f. will finally be needed for the maximum likelihood fit for any PE or data fit.

While histograms are a useful but limited way to estimate p.d.f., KDE supplies a better approach to estimate the underlying density of observed data. A KDE is in fact another histogram-like estimation. It associates to each data point a function (called a kernel function). The kernel histogram (properly normalized) is the sum of all these functions, which typically depend on a parameter called the *bandwidth* that significantly affects the roughness or smoothness of the kernel histogram that is ultimately generated. More details about KDE can be found in [16].

VII. LIKELIHOOD FIT

To extract the top quark width from the distribution of reconstructed top mass and dijet mass of W, we construct a likelihood term:

$$\begin{aligned} \mathcal{L}_{shape} &= \frac{(n_s+n_b)^N e^{-(n_s+n_b)}}{N!} \times e^{-\frac{(n_{b0}-n_b)^2}{2\sigma^2_{n_{b0}}}} \\ &\times \prod_{i=1}^{N} \frac{n_s P_s(m_t^{reco}, m_{jj}; \Gamma_{top}, \Delta_{JES}) + n_b P_b(m_t^{reco}, m_{jj}; \Delta_{JES})}{n_s+n_b} \end{aligned} \tag{4}$$

where n_s and n_b are expected number of signal and background events and N is the total number of events in the sample; P_s and P_b are the probability density function s for signal and background respectively. The first term is present in Equation 4 since this is an extended likelihood, meaning that the number of signal and background events obey Poisson statistics. The second term constrains the number of background events to predicted number n_{b0} within its uncertainty to improve sensitivity. Probability density functions P_s and P_b, which are obtained from

Kernel Density Estimation, are used to discern between signal and background event in order to extract top width, based on a minimization of the negative log likelihood.

VIII. A FELDMAN-COUSINS CONSTRUCTION

The key feature in constructing confidence intervals using Feldman-Cousins scheme is to define the *ordering principle*. In [12], an ordering principle is defined per Pesudo-Experiment as

$$R \equiv \Delta\chi^2 = \chi^2(\Gamma_{Input}) - \chi^2(\Gamma_{BestFit}) \tag{5}$$

where Γ_{Input} is the input top width of the MC sample, and $\Gamma_{BestFit}$ is the measured top width of a Pseudo Experiment; $\chi^2(\Gamma_{Input})$ is the χ^2 value at input top width, while $\chi^2(\Gamma_{BestFit})$ is the χ^2 value at the best fit top width of this single Pseudo-Experiment. We use the minimization of negative log-likilihood fit to get the best fit value of measured top width, but suppose the likihood function to be in Gaussian regime, $-2log(likelihood)$ should follow the χ^2 distribution. Therefore in Equation 5 we simply use

$$\chi^2 = -2\log L \tag{6}$$

where L is the likelihood function discribed in Section VII. There is a $\Delta\chi^2$ value for each Pseudo-Experiment. For a MC sample we run thousands of Pseudo-Experiments therefore there is a distribution of $\Delta\chi^2$ for this sample. With this distribution we need to find a critical $\Delta\chi^2$ value $\Delta\chi^2_c$ so that the interval $[0, \Delta\chi^2_c]$ covers 95% of the events. If the distribution is really a χ^2 distribution one would naively expect $\Delta\chi^2_c$ to be 3.84, as calculated from statistics. However, in reality $\Delta\chi^2_c$ could deviate from 3.84 for several reasons: a) Physical boundary effects; b) the deviation of likelihood function from Gaussian regime.
After we find the $\Delta\chi^2_c$ for each MC sample, we test the coverage by running another set of PEs of this sample. Note that we have two parameters when generating MC samples–M_{top} and Δ_{JES}, thus routinely a two-dimentional Feldman-Cousins construction should be performed. In our analysis, however, we fixed $\Delta_{JES} = 0$ and only M_{top} is used. Nevertheless, we can use the $\Delta\chi^2_c$ of samples of $\Delta JES = 0$ to test the coverage of samples of $\Delta_{JES} \neq 0$. If the coverage is fine (fluctuate around 95%) then we do not need to go to two-dimentional Feldman-Cousins construction. Figure 3 shows the coverage for both zero and none-zero Δ_{JES} samples, which does not show any obvious underestimation, therefore we think it is fine that we only use M_{top} to extract top width limits.

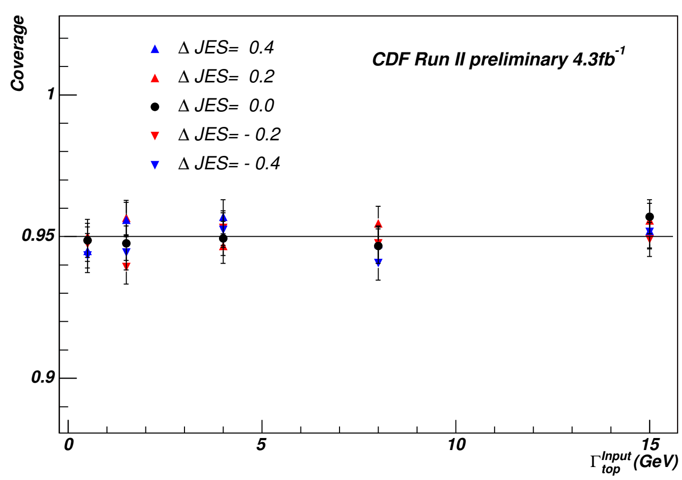


FIG. 3: Coverage of both zero and non-zero Δ_{JES} samples.

Since MC sample will have a $\Delta\chi^2_c$ value, now that we have 21 MC samples, we can draw a plot of $\Delta\chi^2_c$ vs input top width. From data fit, which is done by minimizing $\chi^2 = -2\log(likelihood)$, we get a plot of χ^2 vs input top width. In order to find the limit(s) of top width we overlap the stated two plots, and the point(s) at intersection of these two plots will give the top quark width limit(s) at 95% confidence level.

TABLE III: Summary of shift top width due to systematic effects. All numbers have units of GeV.

CDF Run II Preliminary, 4.3 fb^{-1}

Systematic (GeV)	$\Delta\Gamma_{top}$
Residual JES	0.3
Jet Resolution	1.1
Generator:	0.4
PDFs	0.3
b jet energy	0.2
Background shape	0.1
gg fraction	0.3
Radiation	0.2
Lepton energy	0.2
Multiple Hadron Interaction	0.3
Color Reconnection	0.9
Total Effect	1.6

IX. INCORPORATING SYSTEMATIC EFFECTS

Because we use the reconstructed top mass distributions to extract top width, any systematic that possibly alters the shape and location of the reconstructed top mass distribution will potentially change the fitted top width out of the likelihood fitter. We estimate each uncertainty by performing a series of pseudoexperiments with various systematic MC samples with top mass 172.5 GeV/c^2.

We examine a variety of effects that could systematically shift our top width measurement. As a single nuisance parameter, the JES that we measure does not fully capture the complexities of possible jet energy scale uncertainties, particularly those with different η and p_T dependence. Fitting for the global JES removes most of these effects, but not all of them. We apply variations within uncertainties to different JES calibrations for the separate known effects in both signal and background pseudodata and measure resulting shifts in top width Γ_{top} from pseudoexperiments, giving a residual JES uncertainty. Jet resolution can change the shape of reconstructed top mass distribution. While we cannot improve the jet resolution in our simulation, we can worsen it by smearing the jet resolution with a Gaussian function. We smear the jet resolution with a Gaussian probability density function with σ that is 5% of our default jet resolution. We also vary the energy of b jets, which have different fragmentation than light quarks jets, as well as semi-leptonic decays and different color flow, resulting in a b-JES systematic. Effects due to uncertain modeling of radiation including initial-state radiation (ISR) and nal-state radiation (FSR) are studied by extrapolating uncertainties in the p_T of Drell-Yan events to the $t\bar{t}$ mass region, resulting in a radiation systematics. Comparing pseudoexperiments generated with HERWIG and PYTHIA gives an estimate of the generator systematic. A systematic on different parton distribution functions is obtained by varying the independent eigenvector of the CTEQ6M set, comparing parton distribution functions with different values of QCD, and comparing CTEQ5L with MRST72. We also test the effect of reweighting MC to increase the fraction of tt events initiated by gg (vs qq) from the 6% in the leading order MC to 20%. Systematics due to lepton energy scales are estimated by propagating 1% shifts on electron and muon energies scales. Background composition systematics are obtained by varying the fraction of the different types of backgrounds in pseudoexperiments. For Lepton+Jets backgrounds, varying the uncertain Q^2 of background events results in a background shape systematic, and using a different model for QCD events gives an additional QCD modeling systematic. It has been suggested that Color Reconnection (CR) effects could cause a bias in the top quark mass measurement. We test this effect by generating MCs with and without CR and take the difference as systematics. The dependence of measured top width on input top mass could also contribute to systematic effects, but after performing some PEs with different input top masses we find that the measurement of top width is insensitive to top mass therefore we simply ignore its effect in this analysis.

The shift top width due to total systematic effects is 1.61 GeV. The summary of systematics is in Table III .

In order to incorporate these systematic effects into top width limit(s), we first use a convolution method for folding systematic uncertainties into likelihood function (CDF Note 5305[2]). That is, we convolute the original likelihood function $\mathcal{L}_0$(pure statistic) with a Gaussian function related to systematic effects to obtain a new likelihood function $\mathcal{L}$:

$$\mathcal{L}(\Gamma_{top}|x) = \int d\tilde{\Gamma}_{top}\mathcal{L}_0(\tilde{\Gamma}_{top}|x)\frac{e^{-\frac{1}{2}(\frac{\tilde{\Gamma}_{top}-\Gamma_{top}}{\sigma})^2}}{\sqrt{2\pi}\sigma} \tag{7}$$

where x represents data and σ is equal to the total top width shift(1.61 GeV) due to systematic effects. Second, we shift this new likelihood function horizontally by a random number according to a Gaussian distribution with $\sigma = 1.61$ GeV. In fact, with no boundary effect considered, the first step changes the shape of likelihood function while the second step changes the best fit top width of the likelihood function. Then we repeat what was done without systematics in Section VIII: 1),get the $\Delta\chi^2$ distribution for each MC sample and find the critical value $\Delta\chi^2_c$; 2), plot $\Delta\chi^2_c$ vs input top width; 3), overlap this plot with data fit and find the limit(s) of top quark width. Note that in the data fit the likelihood function should also be convoluted with the same Gaussian function.

X. RESULTS

We use dataset collected at CDF from period 0 upto period 23, corresponding to a total integrated luminosity of $4.3 fb^{-1}$.
Figure 4 and 5 show the distributions of reconstructed top mass and dijet mass for the dataset, overlaid with probability density functions from input $\Gamma_{top} = 1.5$ GeV and full lepton+jets backgrounds.

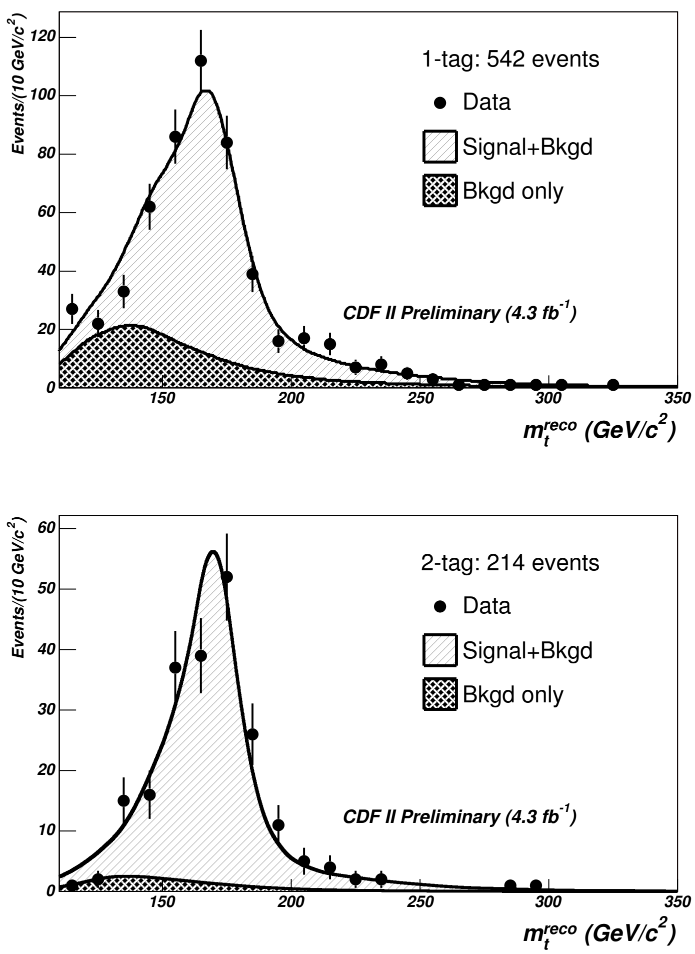


FIG. 4: Reconstructed top mass distributions of dataset, overlaid with probability density functions from input $\Gamma_{top} = 1.5$ GeV and full lepton+jets backgrounds. Top: 1-tag events of data; Bottom: 2-tag events of data.

After performing the log-likelihood fit of data, the best fit gives $\Gamma_{top}^{datameas} = 1.9^{+1.9}_{-1.5}$ GeV and $\Delta_{JES} = 0.07^{+0.20}_{-0.21}$, as shown in Figure 6. We project the 2D likelihood fit to 1D likelihood function with variable Γ_{top}, convert this function according to Equation 6. Then overlap the data fit plot and the plot of $\Delta\chi^2_c$ vs input top width, as is discribed in Section VIII. From the interception of the overlapped plots, as seen from Figure 7, we find an upper limit of top quark width $\Gamma_{top} < 7.5$ GeV at 95% Confidence Level.

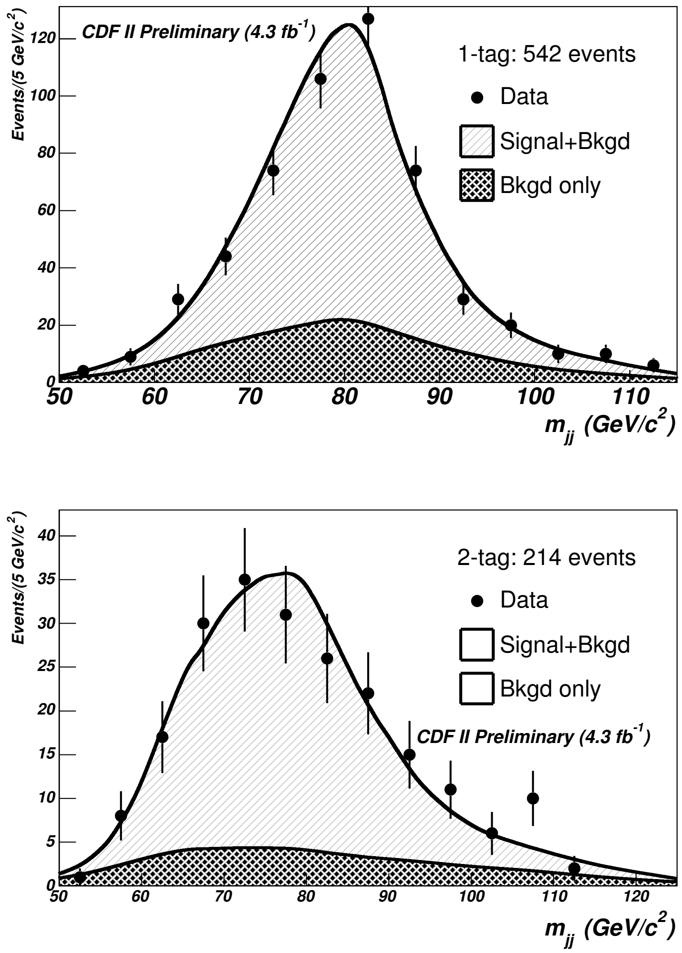


FIG. 5: Dijet mass of W boson distributions of dataset, overlaid with probability density functions from input $\Gamma_{top} = 1.5$ GeV and full lepton+jets backgrounds. Top: 1-tag events of data; Bottom: 2-tag events of data.

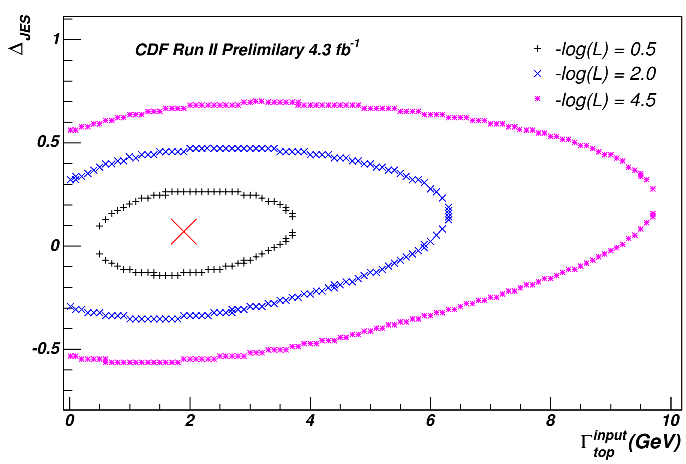


FIG. 6: 2D Log-likelihood fit of data, giving $\Gamma_{top}^{datameas} = 1.9^{+1.9}_{-1.5}$ GeV and $\Delta_{JES} = 0.07^{+0.20}_{-0.21}$.

We also measured top width at 68% confidence level, which is shown in Figure 8, and we have central limits of top quark width 0.4 GeV $< \Gamma_{top} <$ 4.4 GeV, with systematic effecs incorporated.

XI. CONCLUSIONS

We present a measurements of top quark width using 4.3 fb^{-1} of data. We set up two-dimentional templates–reconstructed top mass and dijet mass of W–from Monte Carlo samples generated by PYTHIA and extract top widths from these templates. Two-dimentional Kernel Density Estimation (KDE) is used to build the probability density function for both signals and backgrounds. By performing a series of Pseudo-Experiments (PEs) we define an ordering principle and build $\Delta\chi^2_c$ vs input top width distribution at 95% Confidence Level using Feldman-Cousins contruction. We incoporporate systematic effects into the bands by convoluting the likelihood function with a Gaussian probability density function of σ equal to shifted top width due to systematic effects. With the $4.3 fb^{-1}$ data in hand, we report an upper limit of top quark width $\Gamma_{top} <$ 7.5 GeV at 95% CL, corresponding to a lower limit on the top quark lifetime of $\tau_{top} > 8.7 \times 10^{-26}$ s. We also measure the central limit of top quark width at 68% CL: 0.4 GeV $< \Gamma_{top} <$ 4.4 GeV, after considering all systematic effects.

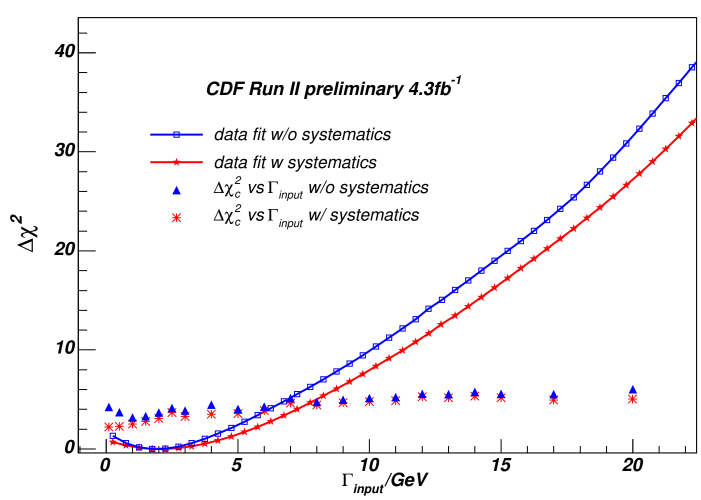


FIG. 7: Overlap of data fit and plot of $\Delta\chi^2_c$ vs input top width.

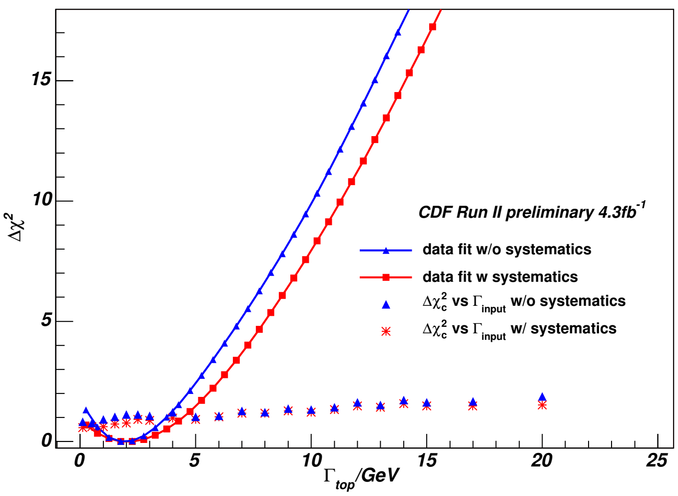


FIG. 8: Top quark width measurement at 68% CL.

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