CDF note 9322

A search for charged Higgs in lepton + jets $t\bar{t}$ events using 2.2 fb^{-1} of CDF data

The CDF Collaboration
URL http://www-cdf.fnal.gov
(Dated: May 12, 2008)

We describe a search for charged Higgs(H^+) in top decays using 2.2 fb^{-1} of data collected by Collider Detector at Fermilab(CDF). Considering the Minimal Super-symmetric Standard Model, H^+ could be found in top decays if it has a smaller mass than a top quark's mass. The H^+ is predicted to decay into $c\bar{s}$ in low $\tan\beta$ plane and is reconstructed via its di-jet decay channel like the W^+ but with a higher invariant mass. Based on H^+ and W^+ mass templates and pseudo experiments, we develop a binned likelihood fit to distinguish H^+ from W^+. Looking into the data, we see no significant access of H^+ in di-jet mass in lepton+jets top decays, and set upper limit branching ratio at 95% C.L. for H^+ mass of 90 GeV/c^2 to 150 GeV/c^2 .

Preliminary Results for Summer 2008 Conferences

I. INTRODUCTION

The SUSY particle search is one of the major goals at the Large Hadron Collider (LHC) at CERN. Prior to that, it will be very exciting to have a clue of SUSY particles at Tevatron. However, its direct production cross-section is too small to separate it from the Standard Model (SM) processes at the Tevatron. Therefore, searching for SUSY particles in the decays of SM particles could be a solution. If the charged Higgs (H^+), introduced in the Minimal Super-symmetric Standard Model (MSSM) [2], is lighter than top quark mass, the H^+ can be involved in top quark decays. The same searches have been performed several times by the CDF [1] and *DØ* collaborations since top was discovered. In FIG. 1, the latest CDF result [3] shows the MSSM parameter limits, and there is a room to discover H^+ in the low $\tan\beta$ region above the W^+ mass. FIG. 2 shows the MSSM predicted branching ratio as a function of $\tan\beta$ for a charged Higgs mass of 120 GeV/c^2 . According to the branching ratio plot, a charged Higgs is predicted to decay into $\tau\nu$ regardless of $\tan\beta$. However, it is experimentally difficult to reconstruct τ decay. Here we focus on the low $\tan\beta \sim 1$, where the H^+ decays into $c\bar{s}$.

As seen in the FIG. 3, we expect to see same signal final state as the SM lepton + jets channel $t\bar{t}$ decays, one W^+ decays into $e/\mu + \nu$ and the other decays into di-jets, but higher di-jet invariant mass for H^+ . We develop a binned likelihood fit to distinguish H^+ from W^+ using di-jet mass templates. We use Pythia [5] Monte Carlo for W^+ and H^+ mass template, and Alpgen [6] with Pythia showering for non-$t\bar{t}$ background mass template. The charged Higgs Monte Carlos are generated with H^+ mass of 90 GeV/c^2 , 100 GeV/c^2 , and up to 150 GeV/c^2 . The likelihood fit on the di-jet mass gives us measured branching ratio of top decaying into H^+ and b. The upper limit of $Br(t \rightarrow H^+ b)$ from pseudo experiments is compared to the fit result from data later.

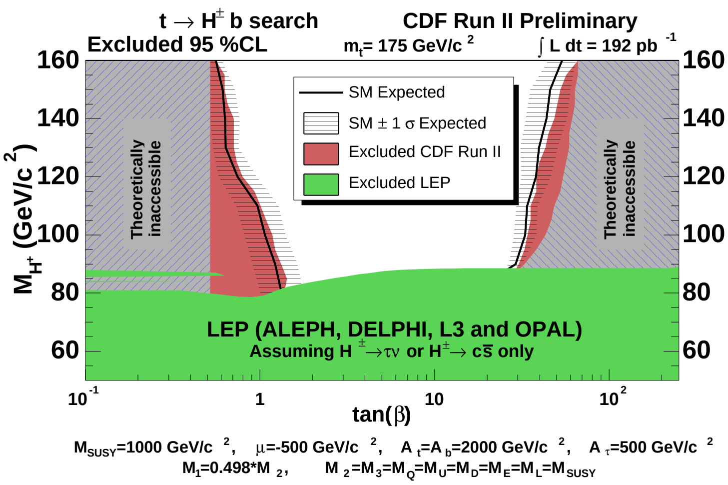

FIG. 1: The MSSM results obtained with 192 pb^{-1} at CDF. The SM-expected exclusion limits are indicated by black solid lines. The darkest solid region represents the area excluded at 95% C.L. The solid lower region is the direct searches at LEP. For these limits, the MSSM parameters are set to: $M_{SUSY} = 1000 GeV/c^2$, $\mu = -500 GeV/c^2$, $A_t = A_b = 2000 GeV/c^2$, $A_\tau = 500 GeV/c^2$, $M_2 = M_3 = M_Q = M_U = M_D = M_E = M_L = M_{SUSY}$, and $M_1 = 0.498 M_2$.

II. EVENT SELECTION

The event selection criteria are listed below.

- An isolated electron (muon) with $E_T > 20$ GeV ($p_T > 20$ GeV/c). The isolation requires the additional calorimeter energy in a cone of $\Delta R < 0.4$ around electron cluster to be less than 10% of the cluster energy.
- Missing transverse energy > 20 GeV. This is due to the neutrino, which traverses the CDF detector without interacting. The vector sum of all visible energy in the detector in the transverse plane will have an imbalance due to the missing neutrino energy.
- At least 4 jets with $E_T > 20$ GeV and $|\eta| < 2.0$ (called leading jets).

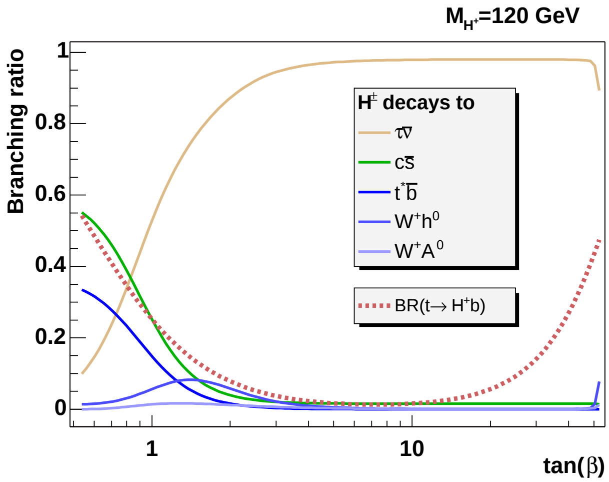

FIG. 2: Branching ratios as a function of $\tan\beta$ in the MSSM. Here, Higgs mass is assumed as 120 GeV/c^2 . This plot is made using CP$_{\rm SUPER}$H [4]

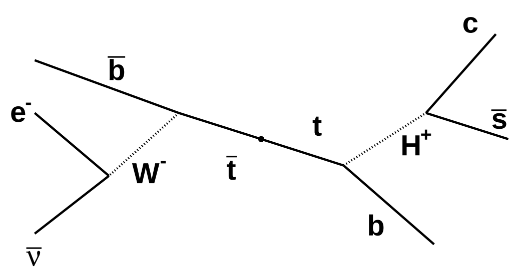

FIG. 3: A H^+ is assumed to decay into $c\bar{s}$ in low $\tan\beta$. The final state appears same as the Standard Model $t\bar{t}$ lepton+jets channel.

- At least two of leading 4 jets should be tagged as b-jets by requiring secondary vertex (SecVtx) in the jet. The b-quark hadron is long lived and travels a measurable distance from the $p\bar{p}$ interaction vertex. Thus, it appears as having a secondary vertex in the jet.

All jets are reconstructed using particles detected within cone size ($\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$) of 0.4 and only jets directed within detector pseudo-rapidity ($\eta = -ln(\tan\theta/2)$) less than 2.4 are considered for analysis. The θ and ϕ are polar and azimuthal angles with respect to the z (beam axis), which is defined to be along the direction of the proton. For the leading jets, $|\eta|$ is required to be less than 2.0. The four leading jets are supposed to be from final state quarks in $t\bar{t}$ events, and are used to reconstruct $t\bar{t}$ events in the kinematic fitter. We also allow additional jets with $E_T > 12$ GeV and $|\eta| < 2.4$ present in selected events. With about 50% chance we see one or two extra jets in $t\bar{t}$ events, and they are supposed to be from initial state or final state radiation. In case of 5^{th} energetic jet being nearby any of leading jets, we consider adding it to the the closest leading jet for better di-jet mass resolution. This is dicussed in sect. III A.

III. MASS RECONSTRUCTION

A $t\bar{t}$ event is reconstructed from all the final state particles and jets using a kinematic fitter, Eqn. 1. The fitter picks the most probable jet-parton assignments based on the smallest χ^2 from a *Minuit* [8] fit. In the lepton + jets channel, the leading 4 jets are supposed to be 2 b-jets (b-quark jets) and 2 h-jets (Higgs jets). Since we require two SecVtx tagged jets, only non-tagged 2 jets are assigned as 2 h-jets.

The χ^2 is formed as

$$\chi^2 = \sum_{i=l,4jets} \frac{(\mathrm{p_T}^{\mathrm{i,fit}} - \mathrm{p_T}^{\mathrm{i,meas}})^2}{\sigma_i{}^2} + \sum_{j=x,y} \frac{(p_j{}^{UE,fit} - p_j{}^{UE,meas})^2}{\sigma_{UE}{}^2}$$
$$+ \frac{(M_{l\nu} - M_W)^2}{\Gamma_W{}^2} + \frac{(M_{jj} - M_H{}^{reco})^2}{\Gamma_H{}^2} + \frac{(M_{bl\nu} - M_t)^2}{\Gamma_t{}^2} + \frac{(M_{bjj} - M_t)^2}{\Gamma_t{}^2}. \qquad (1)$$

The W^+ mass in the leptonic decaying side of top, sum of lepton and neutrino 4-vector, is constrained to 80.4 GeV/c^2 . The $t(\bar{t})$ quark mass, the 4-vector sum of H^+/W^+ +b (W^-/H^- + $\bar{b}$), is constrained to 175 GeV/c^2 . The tagged b-jets are assigned to each $t(\bar{t})$ quark as to minimize the χ^2.

A. Di-jet Mass Improvement

Di-jet invariant mass of H^+ in top decays is compared to the W^+ in the SM $t\bar{t}$ events in FIG. 4. The H^+ has a significant amount of events in the low mass region. We focus on the low mass tail and that 50% of $t\bar{t}$ events have one or more extra jets as mentioned earlier. The extra jet could be a final state radiation jet from Higgs. We realized that we can recover some of low mass Higgs by adding extra jet to the closest leading jet if ΔR between them is less than 1.0. FIG. 5 shows improved mass after adding 5th jet to the closest leading jet. The mean of histogram is increased from 113.4 GeV/c^2 to 115.3 GeV/c^2 for true mass of 120 GeV/c^2 in FIG. 5. However, di-jet mass of W^+ is not much affected by adding extra jet.

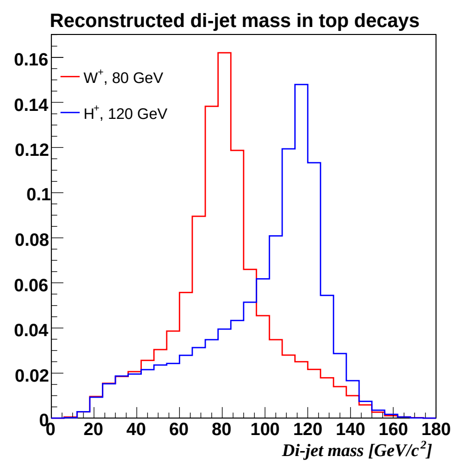

FIG. 4: Di-jet invariant mass for the H^+ (generated mass of 120 GeV/c^2) and W^+ in SM $t\bar{t}$ events. The number of events in both samples is normalized by the area.

IV. BACKGROUNDS

We assume that the lepton+jets data sample consists of electroweak, single top, $t\bar{t}$, QCD (non-W), and W+jets processes. In the sense of charged Higgs search, the biggest background is the SM $t\bar{t}$ events in the lepton+jets channel, which takes about 92% of all the backgrounds. Considering that both of W^+ and H^+ belongs to the $t\bar{t}$ events, we will concentrate on the non-$t\bar{t}$ background in this section.

The non-$t\bar{t}$ backgrounds are estimated in two ways, data-driven background and MC-driven background. The SM predicted backgrounds are theoretically is very well-proven, so we can estimate the shape and cross-section from Monte Carlo. The MC-based backgrounds are di-boson, Z to $\tau\tau$ + multi-jets, and s-channel/t-channel single top processes. On the other hand, simulation is not perfectly matched to the multi-jet processes in data, therefore the background normalization of those backgrounds rely heavily on data. In the case of multi-jet productions assiciated with a real W^+ (W+jets background), it can fake a signal with missing E_T and lepton from real W^+ , and multiple jets. This

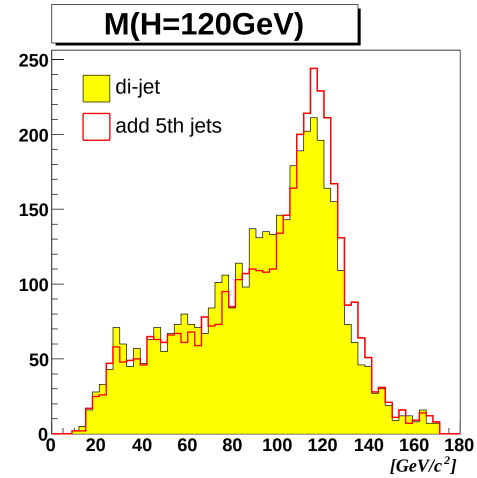

FIG. 5: Improved di-jet mass resolution after adding extra jet nearby a leading jet.

W+jets background is a dominant non-$t\bar{t}$ background. Other than W+jets background, there exist multi-jet events with faked W^+ (conversion electron or semi-leptonic B decays), non-W background. A large uncertainty is assigned to this least understood non-W background.

First, the well-estimated MC-driven background including SM $t\bar{t}$ events are subtracted from lepton+jets data. Then, we estimate non-W background by fitting the missing E_T with electron-like objects which fail the final electron selection cuts. From the missing E_T fit, we can estimate the fracton of non-W background out of selected sample. Now the data remained after subtracting non-W background is considered only W+jets backgdound. In the tagged sample, W+jets is broken into W+heavy flavored jets or W+light flavored jets. For the prior, we select SecVtx tagged events and then apply a data-corrected heavy flavor fraction and a SecVtx tagging efficiency. Then, we isolate the number of W+light flavored jets sample. To estimate the light-flavor contribution to the SecVtx tagging, we apply the parameterized generic jet tag rate (mistags), which is driven from data, to the jets before SecVtx tagging required.

In this manner, the number of backgrounds are estimated using cross-section of 6.7 pb for $t\bar{t}$ events as in TABLE. I.

Process	$\geq$ 4 tight jets	fraction(%)
di-boson(WW/ZZ/WZ)	0.7 $\pm$ 0.1	0.4
s-channel single Top	1.0 $\pm$ 0.1	0.5
t-channel single Top	0.8 $\pm$ 0.1	0.5
Z+lf	0.5 $\pm$ 0.1	0.3
W+bb	5.6 $\pm$ 2.3	3.4
W+cc/W+c	1.9 $\pm$ 0.8	1.1
W+lf	1.9 $\pm$ 0.6	1.1
non-W	1.6 $\pm$ 3.3	0.9
non-$t\bar{t}$	13.9 $\pm$ 7.5	8.4
$t\bar{t}$ (6.7pb)	152.6 $\pm$ 25.0	91.6
Total Prediction	166.5 $\pm$ 32.4	100
Observed	200	

TABLE I: Expected number background events in 2.2 fb^{-1} data after two b-jets are required. In the background calculation, $t\bar{t}$ production cross-section is assumed 6.7 pb.

V. LIKELIHOOD FIT

This section describes how to extract Br($t \rightarrow H^+$ b) from di-jet mass in top decays. Using templates, we know how probable H^+ ,W^+ , and non-$t\bar{t}$ backgrounds would exist in each bin. In the following sub sections, we will describe the binned likelihood function construction using mass templates, branching ratio uncertainty due to shape systematic, and likelihood function marginalization with systemtic uncertainties.

A. Binned Maximum Likelihood construction

A binned likelihood fitter is constructed as

$$\begin{aligned} LH &= \prod \frac{\nu_i^{n_i} \times e^{-\nu_i}}{n_i!} \bigotimes G(N_{bkg}, \sigma_{bkg}), \\ \text{where } \nu_i &= N_{t\bar{t}} \times (1 - Br(t \to \mathrm{H^+ b})) \times \mathrm{Br(W^+ \to e/\mu/\tau + \nu)} \times 2.0 \times \mathrm{Br(t \to H^+ b)} \\ &\times A_h \times P_i^{\mathrm{H^+}} + N_{t\bar{t}} \times (1 - Br(t \to \mathrm{H^+ b}))^2 \times \mathrm{A_w} \times \mathrm{P_i^{W^+}} \\ &+ N_{bkg} \times P_i^{bkg} \end{aligned} \quad (2)$$

, where $\mathrm{N_{t\bar{t}}}$, Br(t → $\mathrm{H^+}$ b), and $\mathrm{N_{bkg}}$ are fit parameters. Br(t → $\mathrm{H^+}$ b) is the most interesting parameter that we concern. $\mathrm{N_{t\bar{t}}}$ is number of produced $t\bar{t}$ events, and $\mathrm{N_{bkg}}$ is number of background in the histogram. We assume that we know very well about the backgrounds, so we make Gaussian constraints on the number of background in the fitter. The probabilities of $\mathrm{W^+}$ ($P_i^{\mathrm{W^+}}$), $\mathrm{H^+}$ ($P_i^{\mathrm{H^+}}$), and non-$t\bar{t}$ (P_i^{bkg}) backgrounds are obtained from the template distributions as shown in the FIG. 6. Here, the acceptances of $\mathrm{W^+}$ and $\mathrm{H^+}$, A_w and A_h, are calculated using Monte Carlo events.

Once data (magenta dot) comes into the fitter, the fitter finds the maximum likelihood value and gives us the fit output, Br(t → $\mathrm{H^+}$ b), number of $t\bar{t}$ ($\mathrm{W^+}$ + $\mathrm{H^+}$), and number of backgrounds.

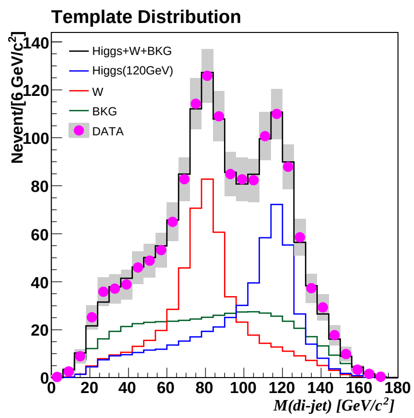

FIG. 6: A template consists of di-jet mass of Higgs, W, and non-$t\bar{t}$ background. Higgs mass of 120 GeV/c^2 template is shown as an example.

B. Systematic Uncertainties

Since this analysis mostly relys on template shapes, any variation which can make change on di-jet mass is to be checked. The way of measuring uncertainties is common to all kind of systematics. At first, we make new di-jet mass distribution (shifted di-jet mass) of $\mathrm{W^+}$ and $\mathrm{H^+}$ by varying systematic conditions. Then, a pseudo experiments set (shifted pseudo experiments) is generated using the shifted di-jet mass distribution. The next step is to fit shifted pseudo experiments with un-shifted di-jet mass template. Finally, we compare the output branching ratio from shifted pseudo experiments to the expected branching ratio from non-shifted pseudo experiments. The difference of branching ratio is set to the systematic uncertainty for each kind of variance. The systematics in consideration are listed as below. Each systematic uncertainty is shown in linear function of input branching ratio in the FIG. 7.

- **Jet Energy Scale Uncertainty** : A jet energy scale uncertainty is a dominant systematic uncertainty because the jet energy shift directly affects invariant mass. We vary $\pm 1\sigma$ of jet energy corrections and take averaged absolute difference of output branching ratio as uncertainty.

- **Initial State Radiation (ISR)/Final state Radiation (FSR)** : Using the ISR enhanced/reduced Pythia Monte Carlo for 120/150 GeV/c^2 Higgs, we calculate averaged absoute difference of output branching ratione.

For the Higgs mass templates which do not have ISR samples, we extrapolate the uncertainties linearly. If any extrapolated value is less than measured one, we take the measured one as the uncertainty in the mass bin. FSR systematic samples are available for 120/150 GeV/c^2 Higgs only, so we calculate systematic uncertainty in the same way as done for ISR uncertainty.

- **Monte Carlo Generator** : $t\bar{t}$ sample generated by Herwig [7] for W^+ di-jet mass shape changes. There is no Herwig Higgs sample, therefore we shifted di-jet mass of W^+ only for the uncertainty calculation.

- **Background** Q^2 **scale changes** : The W+multi-jets background generated with different Q^2 affects the overall background shape. We have W+multi-jet Monte Carlo sample with Q^2 of 0.5 and 2.0. After having shifted background shape from samples we take the averaged absolute difference of output branching ratio.

- **b-tagging scale factor** : The b-tagging scale factor of data to Monte Carlo is 0.95 ± 0.05 for SecVtx tagging method. We shift the scale factor by $\pm 1\sigma$ and check the branching ratio differences.

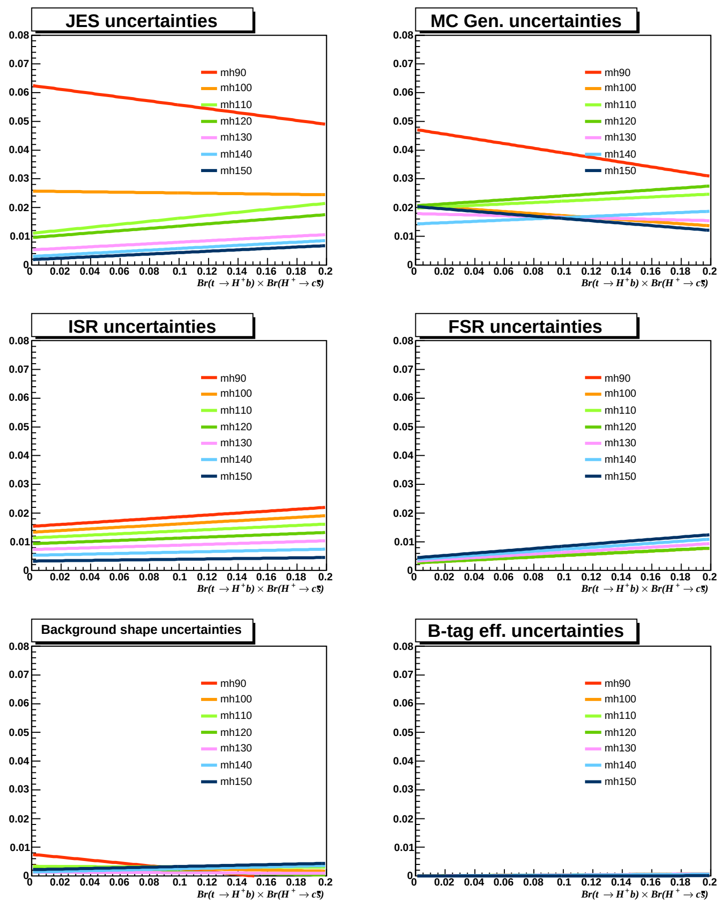

FIG. 7: Branching ratio uncertainty($\Delta Br(t \to H^+b)$) as a linear function of input branching ratio. Square-root-sum of all these uncertainties is put into the width of likelihood marginalization.

C. Marginalization Method

The effect of systematic uncertainty is convoluted to the likelihood function as Gaussian distribution for null-Higgs signal. The output branching ratio shift due to systematic uncertainty is parameterized as a function of $Br(t \to H^+b)$ and is put into the likelihood convolution as below :

$$LH'(x') = \int_0^1 LH(x) \times \frac{1}{\Delta(x')\sqrt{2\pi}}\ exp(-\frac{1}{2}(\frac{x'-x}{\Delta(x')})^2)dx \quad (3)$$

, where x is the input branching ratio ($Br(t \rightarrow \mathrm{H}^+\mathrm{b})$), and $\Delta(\mathrm{x}')$ is parameterized branching ratio shift at x'. Through this marginalization process, the likelihood function is smeared out as shown in the FIG. 8.

The upper limit branching ratio is calculated by integration of positive (physical) likelihood function up to 95% of total area. The projection on to the branching ratio is the upper limit, which is represented by an arrow on the FIG. 8. That upper limit increases according to the likelihood function smearing out. Final upper limit from the pseudo experiments, whose size corresponds to 10 fb^{-1} of data, with null-Higgs hypothesis is compared with upper limit from data in the FIG. 10.

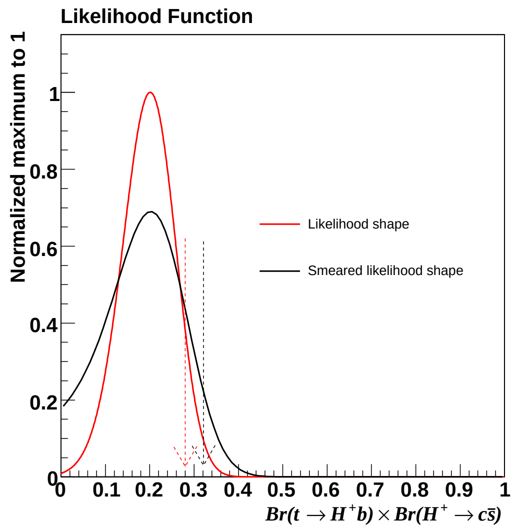

FIG. 8: Likelihood function before (red) and after (black) marginalization. According to the likelihood shape changes, the area integration up to 95% of total area also changes.

VI. RESULTS

We use 2.2 fb^{-1} data to search for a charged Higgs decaying into di-jet in $\mathrm{t\bar{t}}$ lepton+jets decays. The di-jet mass distrbution of 2.2 fb^{-1} $\mathrm{t\bar{t}}$ events is validated with Monte Carlo in the FIG. 9, where the MC normalization is done by likelihood fit (sect. V) forcing $\mathrm{Br(t \rightarrow H^+\ B)}$ to be 0. This is a promissing search if $\tan\beta$, one of MSSM parameter, is small around unity. As seen in the FIG. 10, the upper limit branching ratio from data fit agrees with result of pseudo experiments with null-Higgs hypothesis. We have no significant access of charged Higgs in top decays of 2.2 fb^{-1}.

Acknowledgments

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium fuer Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Particle Physics and Astronomy Research Council and the Royal Society, UK; the Russian Foundation for Basic

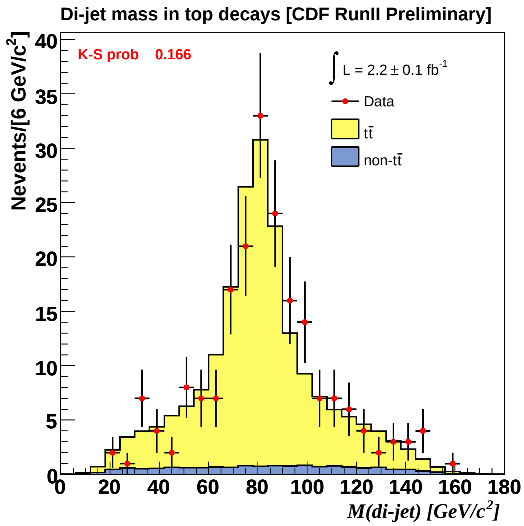

FIG. 9: Di-jet mass in top decays in 2.2 fb^{-1} data and expected background distribution. The background normalization is from likelihood fit result forcing br(t $\rightarrow$ H^+ b) = 0.

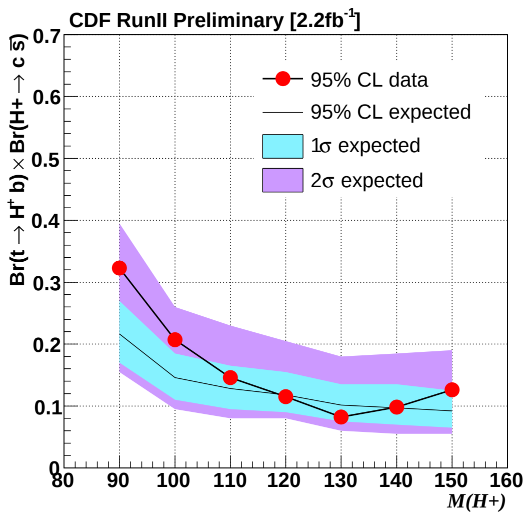

FIG. 10: The upper limit branching ratio, Br(t $\rightarrow$ H^+ b), at 95% C.L. from data likelihood fit is compared to the upper limit from pseudo experiments with null-Higgs hypothesis. That upper limit is set to Higgs mass of 90 GeV/c^2 to 150 GeV/c^2 .

Research; the Comision Interministerial de Ciencia y Tecnologia, Spain; and in part by the European Community's Human Potential Programme under contract HPRN-CT-20002, Probe for New Physics.

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