DØ note 5466-CONF

Measurement of the Cross Section Ratio $\sigma(\mathbf{p\bar{p}} \to \mathbf{t\bar{t}})_{\ell+\text{jets}}/\sigma(\mathbf{p\bar{p}} \to \mathbf{t\bar{t}})_{\ell\ell}$ with the DØ Detector at $\sqrt{s} = 1.96$ TeV in the Run II Data

The DØ Collaboration

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The DØ results for the measurement of the top pair production cross sections in the ℓ+jets and dilepton channels are used to derive their ratio. The result found is:

$$R_\sigma = \sigma(\mathrm{p\bar{p}} \to \mathrm{t\bar{t}})_{\ell+\mathrm{jets}}/\sigma(\mathrm{p\bar{p}} \to \mathrm{t\bar{t}})_{\ell\ell} = 1.21^{+0.27}_{-0.26} \text{ (stat+syst)}$$

in agreement with the Standard Model expectation of $R_\sigma = 1$. This result can be interpreted into an upper limit on the branching ratio $B(t \to Xb)$ due to a top decay into any other particle X in addition to the decay into the W boson. As an example, in a simplified model assuming the existence of a charged Higgs boson $H^\pm$ with a mass close to the W boson and decaying exclusively into $H^+ \to c\bar{s}$ and $H^- \to \bar{c}s$, respectively, a branching ratio of

$$B(t \to Hb) < 0.35 \text{ at } 95\% \text{ C.L.}$$

is derived. Such a scenario can be realized, for instance, in a general multi-Higgs-doublet model.

Supplement to: Preliminary Results for Summer 2007 Conferences

I. INTRODUCTION

Let us define

$$R_\sigma \equiv \frac{\sigma(t\bar{t})_{\ell+\text{jets}}}{\sigma(t\bar{t})_{\text{dilepton}}} \tag{1}$$

to be the ratio of the $t\bar{t}$ cross sections measured using ℓ+jets events to that measured using dilepton events under the assumption that the top quarks decay only via Standard Model (SM) processes. If the measured R_σ differs from the SM prediction $R_\sigma = 1$, then it will imply new physics that will allow the top quark to decay without a W boson in the final state. It is thus sensitive to the disappearance of the W boson due to any non-vanishing branching ratio $B(t \to Xb)$.

An example for such a scenario could be a decay into a charged Higgs boson $t \to Hb$ which, under particular conditions, could be competitive with the SM decay $t \to Wb$ [1]. In the case of the branching ratio $B(H^+ \to c\bar{s})$ being dominant this would lead to an increase of the ℓ+jets cross section while the dilepton cross section would remain unchanged. Thus, it would lead to an enhancement of R_σ. In the limit of small admixture from charged Higgs, $1/R_\sigma = B(t \to Wb)$.

In general, the branching fraction $B(t \to Wb)$ is an important parameter to measure since a future measurement of the total top decay width given by $\Gamma_t = \Gamma(t \to Wb)/B(t \to Wb)$ would rely on it. Here $\Gamma(t \to Wb)$ is the partial decay width which can be measured in single top production.

This note reports the interpretation of two analyses using data collected by the DØ detector in Run II of the Tevatron at a center of mass energy of $\sqrt{s} = 1.96$ TeV. One analysis is the measurement of the ℓ+jets cross section using data samples which correspond to an integrated luminosity of 0.91 fb^{-1} in the e+jets channel and 0.87 fb^{-1} in the μ+jets channel [2]. The results of this analysis are used assuming SM top decays. The other is the cross section measurement in the dilepton channel using data samples which correspond to an integrated luminosity of 1.04 fb^{-1}, 1.05 fb^{-1} and 1.05 fb^{-1} in the e^+e^-, $e^\pm\mu^\mp$ and $\mu^+\mu^-$ channels, respectively [3]. The ratio of these cross sections R_σ is calculated using a frequentist approach.

There is a Run I measurement of $1/R_\sigma$ using 125 pb^{-1} of data by DØ which was never published [4]. CDF has reported a measurement of the ratio $1/R_\sigma = 1.45^{+0.83}_{-0.55}$ and the limit $0.46 < 1/R_\sigma < 4.45$ at 95% C.L. with a 200 pb^{-1} data set [5]. Based on the ratio, CDF sets a limit on the $t \to Xb$ decay, where X decays exclusively hadronically, of less than 0.46 at 95% C.L. under the assumption that the standard and non-standard hadronic decay is detected with the same efficiency.

II. CROSS SECTIONS AND ENSEMBLE TESTING

To derive the cross section ratio R_σ we use the cross section measurement in the $\ell +$ jets channel [2] which gave the following result:

$$\sigma(t\bar{t})_{\ell+\text{jets}} = 8.27^{+0.96}_{-0.95}\ \text{(stat+syst)} \pm 0.51\ \text{(lumi) pb} .$$

In the dilepton channel we use the cross section measurement [3] which gave

$$\sigma(t\bar{t})_{\text{dilepton}} = 6.8^{+1.2}_{-1.1}\ \text{(stat)}^{+0.9}_{-0.8}\ \text{(syst)} \pm 0.4\ \text{(lumi) pb} .$$

Ensemble tests were performed to derive the expected statistical and systematic errors in the measurement of R_σ. We have taken into account properly the correlations between systematic uncertainties affecting the ℓ+jets and the dilepton channels. In particular, the uncertainties on the lepton and primary vertex identification, muon trigger, jet energy calibration, jet identification and resolution and diboson background normalization (based on the theoretical NLO cross section) were taken as 100% correlated. Other uncertainties affecting only one of the two channels were taken as uncorrelated. The uncertainties due to the luminosity measurement were assumed to cancel in the ratio.

The method to generate the ensembles in the ℓ+jets channel is identical to the one to generate the ensembles used in the likelihood for the cross section measurement [2]. For these ensembles the ratio $R_b = B(t \to Wb)/B(t \to Wq)$ was set equal to 1. However, since the contribution of dilepton events to the ℓ+jets channel cannot be neglected in general, we restrict ourselves to the subchannels where at least 4 jets are required. The contribution from dilepton events is then only at the per cent level.

In the dilepton channel ensembles were generated for each subchannel (ee, $e\mu$, $\mu\mu$). The background yield and the number of observed events in each channel were allowed to fluctuate according to a Poisson distribution. The mean value of the cross sections in each channel was then smeared by a Gaussian distribution to take the systematic uncertainties into account. Then the ensembles of the different subchannels were combined as for the combined cross section measurement.

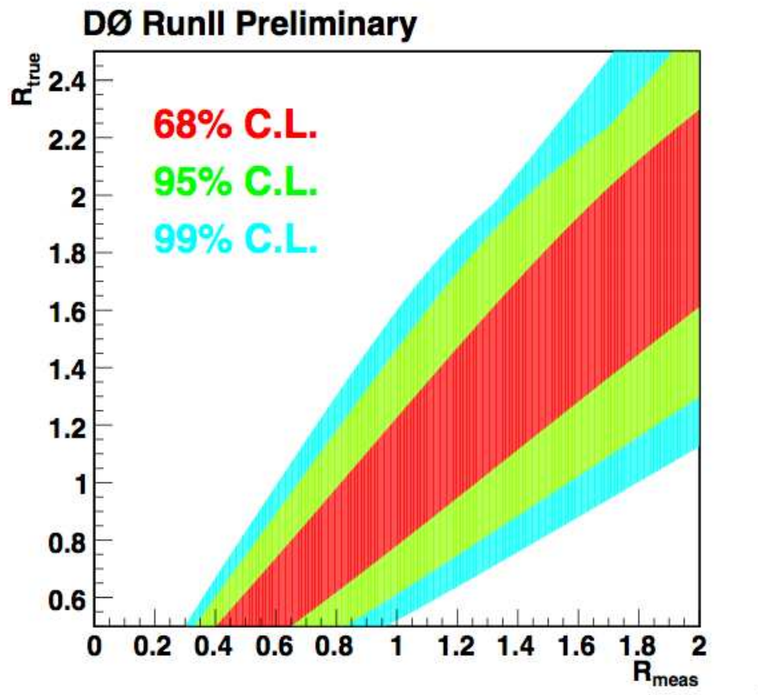

FIG. 1: Confidence intervals as function of measured and generated cross section ratios R_σ.

III. RESULTS IN THE MEASUREMENT OF R_σ

For the calculation of confidence intervals as function of the measured and generated cross section ratios we generate different ensembles for R_σ varying $\sigma(t\bar{t})_{\ell+\text{jets}}$ in steps of 0.5 pb between 6 pb and 15 pb and using the measured value for $\sigma(t\bar{t})_{\text{dilepton}}$. For each generated R_σ value 10,000 ensembles are generated. For each R_σ the set of ensembles is fitted by a Gamma distribution.

After having parameterized all distributions for different generated R_σ by the fits using the Gamma distribution and after having interpolated between the fit parameters for different generated R_σ one can calculate continuous confidence intervals as a function of the measured R_σ and the generated R_σ using the method of Cousins and Feldman [7]. The results for the 68%, 95% and 99% C.L. are shown in Fig. 1.

Using this approach we calculate the interval that contains the generated values for R_σ 68% of the time. This interval is our total uncertainty. As final result we calibrate the measured R_σ to the true value and derive

$$R_\sigma = 1.21^{+0.27}_{-0.26} \text{ (stat+syst)}$$

IV. TRANSLATION INTO THE CHARGED HIGGS BRANCHING FRACTION B

A cross-section ratio $R_\sigma \neq 1$ could be explained by a top quark decaying into something other than $t \to Wb$. In particular, a value $R_\sigma > 1$ could be generated by a top decay into a non SM particle which leads to a larger contribution to the ℓ+jets channel than to the dilepton channel. To illustrate this the value of R_σ from Sec. III is interpreted in a model where the top quark could decay to a charged Higgs boson $t \to H^\pm b$ with $H^\pm \to cs$, $H^\pm \to \tau\nu$ or $H^\pm \to W^\pm b\bar{b}$. The favored decay mode of the charged Higgs depends on $\tan\beta$, the ratio of the Higgs vacuum expectation values.

Here we investigate a model with a 100% branching ratio of the charged Higgs to cs. This decay would lead to a different ratio between the ℓ+jets and the dilepton cross sections. We explore this model for a charged Higgs mass of 80 GeV so that the event kinematics, as e.g. the invariant dijet mass, is expected to be similar for $t \to Hb$ and $t \to Wb$. Furthermore, we assume that there is no separation power due to the different spin.

A scenario where the charged Higgs boson decays into jets with a 100% branching fraction can be realised, for instance, in a general multi-Higgs-doublet model (MHDM) [8]. It was demonstrated that such a leptophobic charged

Higgs boson with a mass of 80 GeV could lead to noticeable effects at the Tevatron if $\tan\beta \leq 3.5$. [9].

But even within the MSSM, large radiative corrections from SUSY-breaking effects can lead to a suppression of $H^\pm \to \tau\nu$ compared to $H^\pm \to cs$ [10].

The measured cross section in the ℓ+jets channel is given by

$$\sigma_{\ell+\mathrm{jets}} = \frac{N_{\ell+\mathrm{jets}}}{\mathcal{L}_{\ell+\mathrm{jets}}\,\varepsilon_{sm}(\ell+\mathrm{jets})} = \sigma(t\bar{t})_{\ell+\mathrm{jets}}\,B_{sm}(\ell+\mathrm{jets})\ , \tag{2}$$

where $\sigma(t\bar{t})_{\ell+\mathrm{jets}}$ is the top pair production cross section measured in the ℓ+jets channel, $\varepsilon_{sm}(\ell+\mathrm{jets})$ is the efficiency of the $t\bar{t}$ event selection obtained using MC events generated by assuming a standard model production mechanism, $B_{sm}(\ell+\mathrm{jets})$ is the corresponding branching fraction in the Standard Model. By $N_{\ell+\mathrm{jets}}$ we denote the number of top pair events events with a $\ell+$jets final state and by $\mathcal{L}_{\ell+\mathrm{jets}}$ the integrated luminosity.

Similarly, the measured cross section in the dilepton channel is given by

$$\sigma_{\ell\ell} = \frac{N_{\ell\ell}}{\mathcal{L}_{\ell\ell}\,\varepsilon_{sm}(\ell\ell)} = \sigma(t\bar{t})_{\ell\ell}\,B_{sm}(\ell\ell)\ , \tag{3}$$

where $\sigma(t\bar{t})_{\ell\ell}$ is the top pair production cross section measured in the dilepton channel, $\varepsilon_{sm}(\ell\ell)$ is the efficiency of the $t\bar{t}$ event selection obtained using MC events generated by assuming a standard model production mechanism, $B_{sm}(\ell\ell)$ is the corresponding branching fraction in the Standard Model. By $N_{\ell\ell}$ we denote the number of top pair events events with a dilepton final state and by $\mathcal{L}_{\ell\ell}$ the integrated luminosity.

In the following we assume that all the selection efficiencies are the same for the SM and the analysis presented here ($\varepsilon_{sm} = \varepsilon$). That this assumption is valid has been checked with a signal MC sample including a charged Higgs boson with a mass of 80 GeV.

Now we assume the branching ratios to be identical for the decay of a particle and its anti-particle:

$$B(t \to H^+b) = B(\bar{t} \to H^-\bar{b}) \equiv B(t \to Hb) \tag{4}$$
$$B(t \to W^+b) = B(\bar{t} \to W^-\bar{b}) \equiv B(t \to Wb) \tag{5}$$
$$B(H^+ \to c\bar{s}) = B(H^- \to \bar{c}s) \equiv B(H \to cs) = 1 \tag{6}$$
$$B(W^+ \to q\bar{q}') = B(W^- \to \bar{q}q') \equiv B(W \to qq) \tag{7}$$
$$B(W^+ \to \ell^+\nu) = B(W^- \to \ell^-\bar{\nu}) \equiv B(W \to \ell\nu) \tag{8}$$

For the last we define

$$B(W \to \ell\nu) = B(W \to e) + B(W \to \mu) + B(W \to \tau \to e) + B(W \to \tau \to \mu)\,. \tag{9}$$

The total top decay branching ratio is given in this model by

$$B(t \to Wb) + B(t \to Hb) = 1\,. \tag{10}$$

We define furthermore

$$B(t \to Hb) \equiv B\ , \tag{11}$$
$$B(t \to Wb) = 1 - B\,. \tag{12}$$

Including a non-vanishing contribution from the dilepton channel to the ℓ+jets cross section we expect

$$\sigma_{\ell+\mathrm{jets}} = \sigma(t\bar{t})\ \cdot \tag{13}$$
$$\Big\{ 2\,B(t \to Wb)\,B(W \to \ell\nu)\big[\,B(t \to Wb)\,B(W \to qq) + B(t \to Hb)\,\big] + k \cdot B^2(t \to Wb)\,\big[\,1 - B(W \to qq)\,\big]^2 \Big\}\ ,$$

where $k = \varepsilon(\ell\ell\ell j)/\varepsilon(\ell j\ell j)$. Here $\varepsilon(\ell\mathrm{j}\ell\mathrm{j}) = \varepsilon_{\mathrm{sm}}(\ell+\mathrm{jets})$ is the selection efficiency in the ℓ+jets channel for $t\bar{t}$ ℓ+jets events and $\varepsilon(\ell\ell\ell\mathrm{j})$ is the selection efficiency in the ℓ+jets channel for $t\bar{t}$ dilepton events, and

$$1 - B(W \to qq) = B(W \to e) + B(W \to \mu) + B(W \to \tau)\ . \tag{14}$$

Note that $1 - B(W \to qq)$ is not equal to $B(W \to \ell\nu)$ from equation (9) due to the fact that the efficiency for dilepton $t\bar{t}$ events was calculated in the ℓ+jets channel with respect to the full inclusive dilepton sample, while for ℓ+jets events it was calculated with respect to ℓ+jets events containing electrons and muons from W or τ decays at the Monte Carlo truth level.

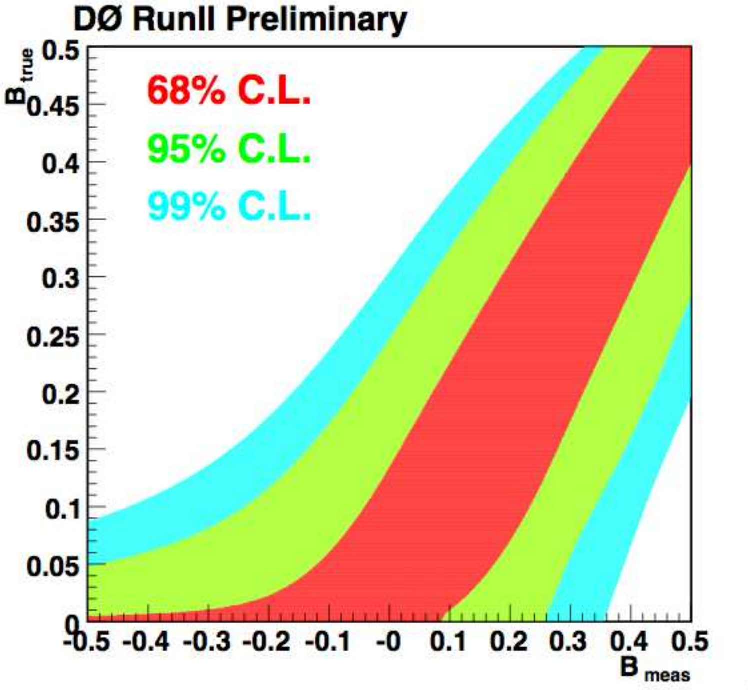

FIG. 2: Confidence intervals as function of measured and generated branching fractions B.

For the dilepton cross section we expect

$$\sigma_{\ell\ell} = \sigma(t\bar{t})\, B^2(t \to Wb)\, B^2(W \to \ell\nu)\ . \tag{15}$$

Comparing the measured cross section ratio of Eq. 2 over Eq. 3 with what we would expect in our model, which is given by the ratio of Eq. 13 over Eq. 15, we get for the ratio of the measured top pair production cross sections

$$R_\sigma = \frac{\sigma(t\bar{t})_{\ell+\mathrm{jets}}}{\sigma(t\bar{t})_{\mathrm{dilepton}}} = 1 + \frac{B}{1-B} \cdot \frac{1}{B(W \to qq) + 1/2 \cdot k \cdot A}\ , \tag{16}$$

where

$$A = \left[\, 1 - B(W \to qq) \,\right]^2 / B(W \to \ell\nu)\ . \tag{17}$$

The selection efficiencies for ℓ+jets events yield $\varepsilon(\ell j \ell j) = 0.1116$ for e+jets and $\varepsilon(\ell j \ell j) = 0.0984$ for μ+jets. The corresponding dilepton selection efficiencies are $\varepsilon(\ell\ell\ell j) = 0.0072$ for e+jets and $\varepsilon(\ell\ell\ell j) = 0.0062$ for μ+jets. After averaging over e+jets and μ+jets channels we obtain $k = 0.064$.

We use the branching fraction $B(W \to qq) = 0.676$, the branching fraction squared for the dilepton final state $\left[\, 1 - B(W \to qq) \,\right]^2 = 0.1061$ and $B(W \to \ell\nu) = 0.25$ yielding $A = 0.4244$. Defining $W = B(W \to qq) + 1/2 \cdot k \cdot A$ with $W = 0.69$ we obtain:

$$B = B(t \to Hb) = W \cdot (R_\sigma - 1)/(1 + W \cdot (R_\sigma - 1))\ . \tag{18}$$

To derive the limit we generate 10,000 ensembles for different B by variation of $\sigma(t\bar{t})_{\ell+\mathrm{jets}}$ using the same procedure as described for R_σ. We fit an asymmetric Gaussian to every distribution. The confidence intervals as a function of the measured B and the generated B for the 68%, 95% and 99% C.L. are shown in Fig. 2.

The branching ratio B calculated using Eqs. 18 and 16 with the dilepton contribution taken into account yields

$$B \ = \ 0.13^{+0.12}_{-0.11} \ \text{(stat+syst)}.$$

We derive two different limits for B (Eq. 18): using R_σ according to Eq. 16 but setting $k = 0$ and according to Eq. 16. We quote the limit we get with Eq. 16 as our main result.

Using Eq. 16 and setting $k = 0$ we derive an upper limit of

$$B(t \to Hb) < 0.34 \text{ at } 95\% \text{ C.L.}.$$

Figure 2 shows the Feldman Cousins limit plot when using the dilepton correction factor (Eq. 16). We derive an upper limit of

$$B(t \to Hb) < 0.35 \text{ at } 95\% \text{ C.L.}.$$

The upper limit expected for a measured branching ratio of $B(t \to Hb) = 0$ is

$$B(t \to Hb)_{\mathrm{SM}} < 0.25 \text{ at } 95\% \text{ C.L.}.$$

V. SUMMARY

We have derived the ratio $R_\sigma = \sigma(t\bar{t})_{\ell+\mathrm{jets}}/\sigma(t\bar{t})_{\mathrm{dilepton}}$ using the ℓ+jets and dilepton cross section measurements:

$$R_\sigma \;=\; 1.21^{+0.27}_{-0.26} \text{ (stat+syst)}\,.$$

Using a simplified model we translated R_σ into the branching fraction of a 80 GeV charged Higgs boson decaying exclusively hadronically:

$$B \;=\; 0.13^{+0.12}_{-0.11} \text{ (stat+syst)}$$

leading to an upper limit of

$$B(t \to Hb) < 0.35 \text{ at } 95\% \text{ C.L.}$$

with an expectation in the SM of

$$B(t \to Hb)_{\mathrm{SM}} < 0.25 \text{ at } 95\% \text{ C.L.}$$

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