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Top pair production distributions at the Tevatron

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Abstract. At the Tevatron, the top quark is mainly produced in pairs through the strong interaction and decays before forming hadrons. Thus the kinematical distributions at top pair production possess rich information on the $t\bar{t}$ production vertex including polarizations of top and anti-top quarks. In this article, recent measurements on top quark pair production distributions at Tevatron (CDF and D0) are presented.

1 Introduction

The top quark is the heaviest known elementary particle today with a mass of about 173 GeV/c^2 [1], which is one of the most noteworthy features of the top quark. Due to its heavier mass than the W boson, the top quark decays via the parity-violating (V-A) weak interaction in a much shorter time than hadronization by quantum chromodynamics (QCD). The top quark decay properties are well measured at Tevatron [2] as well as LHC [3], and V-A structure at top decay vertex is experimentally well-established. The total width of the top quark is expected to be approximately $\Gamma_t = 1.3$ GeV [4, 5]. This means the top quark decays retaining the momentum as well as spin polarization as a bare quark at its production, and their information can be extracted from the momenta of the top quark decay products. This property makes the top quark the only quark that can provide us an opportunity to probe a heavy-quark production vertex directly.

At the Tevatron, $p\bar{p}$ collider at $\sqrt{s} = 1.96$ TeV, the $t\bar{t}$ pair is expected to be produced dominantly through $q\bar{q}$ annihilation, while about 15% contribution comes through gg fusion [6], which is dominant process of $t\bar{t}$ production at LHC. Therefore, the Tevatron is suitable especially to the study of $q\bar{q}$ annihilation process in the $t\bar{t}$ productions.

Measurements of differential cross sections in the $t\bar{t}$ system, consequently, test perturbative QCD (pQCD) for heavy-quark production, and thus, can constrain potential physics beyond the Standard Model (SM) [7].

2 Differential cross-section measurements

2.1 $d\sigma/dp_T^t$

The transverse momentum (p_T) of top quarks in $t\bar{t}$ production provides a strict test [7]. D0 performed a measurement of the inclusive $d\sigma/dp_T$ of top quark in $t\bar{t}$ production [8].

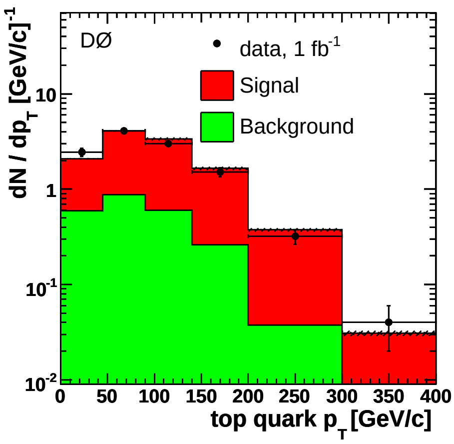

Figure 1. The reconstructed p_T of top in $t\bar{t}$ obtained from ℓ+jet channel at D0 in 1 fb^{-1} data, compared with the signal and background expectation.

Figure 1 shows the reconstructed p_T of top in $t\bar{t}$ obtained from ℓ+jet channel at D0 in 1 fb^{-1} data. The distribution is affected by detector acceptance, resolution, and backgrounds. Using a regularized unfolding technique [9] after subtracting the expected background contribution, we correct the distribution to the parton level, that can be directly compared with the theoretical prediction of the distribution. Fig. 2 shows the resulting inclusive $d\sigma/dp_T$ for $t\bar{t}$ production. The parton level p_T of top distribution shows good agreement with NLO and NNLO predictions in its normalization and shape. It shows an agreement with the prediction from PYTHIA and ALPGEN in its shape, but not in its normalization.

2.2 $d\sigma/dM_{t\bar{t}}$

The $t\bar{t}$ invariant mass spectrum is sensitive to a variety of exotic particles decaying into $t\bar{t}$ pairs [10]. CDF performed

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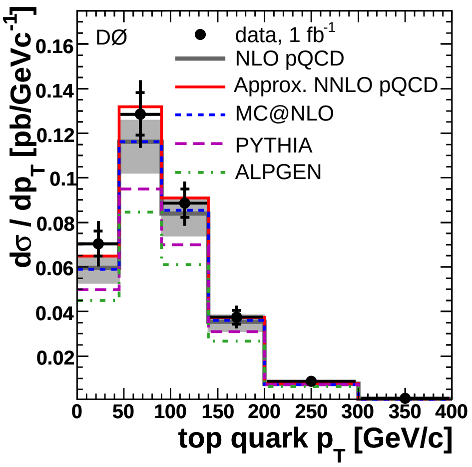

Figure 2. Inclusive $d\sigma/dp_T$ of top quark for $t\bar{t}$ production obtained from D0 1 fb^{-1} data using an unfolding technique, compared with expectations from NLO pQCD, from an approximate NNLO pQCD calculation (solid lines) and from MC@NLO (dotted line), PYTHIA (dashed line), ALPGEN (dot-dashed lines).

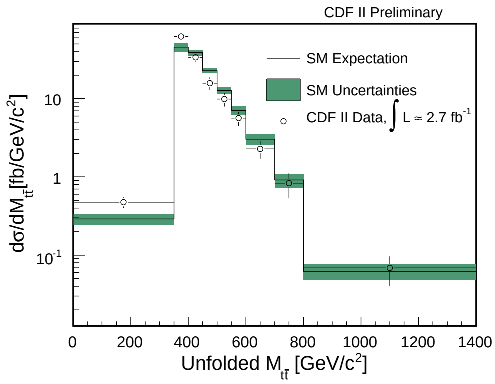

Figure 3. $d\sigma/dM_{t\bar{t}}$ measured with CDF data of 2.7 fb^{-1} of integrated luminosity, obtained from the reconstructed $M_{t\bar{t}}$ in ℓ+jet channel using an unfolding technique, compared with the prediction.

a measurement of the $t\bar{t}$ differential cross section with respect to the $t\bar{t}$ invariant mass, $d\sigma/dM_{t\bar{t}}$ [11].

Figure 3 shows $d\sigma/dM_{t\bar{t}}$ measured with CDF data of 2.7 fb^{-1} of integrated luminosity. The distribution is obtained from the reconstructed $M_{t\bar{t}}$ in ℓ+jet channel using an unfolding technique. We have no evidence beyond the SM. The result is consistent with the prediction from PYTHIA with CTEQ5L parton distribution functions. The result, for example, gives the restriction on the parameter of a RS graviton [12] decaying $t\bar{t}$, yielding $\kappa/M_{pl} > 0.16$ (95% CL) for $G \to t\bar{t}$ ($M_1 = 600$ GeV).

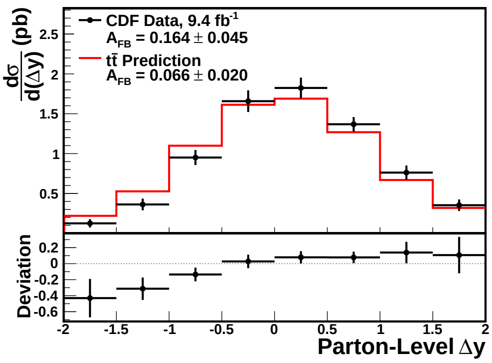

Figure 4. The differential cross section $d\sigma/d\Delta y$ as measured in the CDF data of 9.4 fb^{-1} after correction to the parton level using an unfolding technique, compared to the SM prediction.

3 Forward backward asymmetry

3.1 $d\sigma/d\Delta y$, $d^2\sigma/d\Delta y \cdot dM_{t\bar{t}}$

CDF presented new measurements of the inclusive forward-backward $t\bar{t}$ production asymmetry, $A_{\rm FB}$ [13]. The measurements are performed with the full Tevatron data set in CDF, which corresponds to an integrated luminosity of 9.4 fb^{-1}.

The inclusive differential cross section with respect to rapidity difference $\Delta y = y_t - y_{\bar{t}}$ is measured from the reconstructed Δy distribution in ℓ+jet channel, using an unfolding technique. Fig. 4 shows the resulting $d\sigma/d\Delta y$, compared to the SM NLO prediction. The distribution yields an inclusive asymmetry of 0.164±0.045 (stat + syst), while the NLO model predicts 0.066 ± 0.020. The result also show a linear dependence of $A_{\rm FB}$ on the $|\Delta y|$. Fig. 5 shows the parton-level forward-backward asymmetry as a function of $|\Delta y|$ with a best-fit line, compared to the SM prediction. The shaded region represents the theoretical uncertainty on the slope of the prediction. The measured slope is found to be greater than the predicted slope at 2.2 σ significance level.

The inclusive differential cross section with respect to to the $t\bar{t}$ invariant mass as well as Δy is measured, using an unfolding technique in two dimensional binning of $M_{t\bar{t}}$ and Δy. In the analysis we measured $d\sigma/dM_{t\bar{t}}$ separately for $\Delta y > 0$ and $\Delta y < 0$, and this yield the parton-level forward-backward asymmetry as a function of $M_{t\bar{t}}$. The result also show a linear dependence of $A_{\rm FB}$ on the $M_{t\bar{t}}$ as shown in Fig. 6. The measured slope is found to be greater than the predicted slope at 2.4 σ significance level.

3.2 Other $A_{\rm FB}$ measurements at Tevatron

We also has $A_{\rm FB}$ measurements in 5.4 fb^{-1} data in D0 ℓ+jet channel [14], in 5.4 fb^{-1} in D0 dilepton channel [15] and in 5.1 fb^{-1} in CDF dilepton channel [16]. The results in D0 ℓ+jet and CDF dilepton indicate larger asymmetries than the prediction at 2 ~ 3 σ significance level, while lepton asymmetries in D0 dilepton are consistent with the prediction.

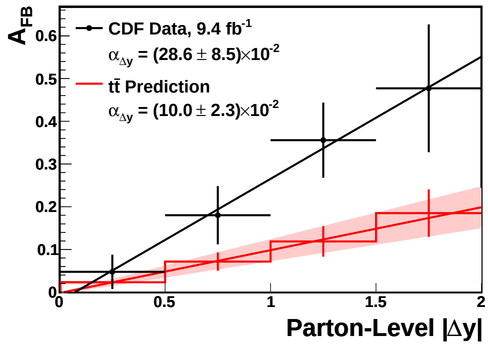

Figure 5. The parton-level forward-backward asymmetry as a function of $|\Delta y|$ with a best-fit line, compared to the SM prediction. The shaded region represents the theoretical uncertainty on the slope of the prediction.

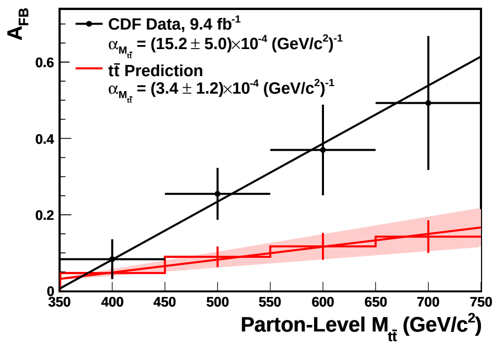

Figure 6. The parton-level forward-backward asymmetry as a function of $M_{t\bar{t}}$ with a best-fit line, compared to the SM prediction. The shaded region represents the theoretical uncertainty on the slope of the prediction.

4 Top polarization and correlations

We have handy tools to investigate what happen at $t\bar{t}$ production. They are top polarization and their correlations. Because top quark decays before losing polarization, top quark and anti-top quark polarizations and their correlation can be measured as angular distributions of decay products from $t\bar{t}$ decays. The spin correlations are described by the differential cross section $d^2\sigma/d\cos\theta_+ d\cos\theta_- \propto 1 + C\cos\theta_+\cos\theta_-$ using a correlation coefficient C [17], where $\theta_\pm$ indicates the angle of the flight direction of decay products in the parent top (anti-top) quark rest frame. The correlation coefficient is depending on the $t\bar{t}$ production process and its quantization basis. We have different spin configurations, for example, for $q\bar{q}$ annihilation and gg fusions. Therefore, more sensitive to $t\bar{t}$ production mechanism than other kinematic variables, and might gives a hint on $t\bar{t}$ forward-backward asymmetry.

4.1 $t\bar{t}$ spin correlations

CDF performed the measurements of C in the so-called beam-line basis [18] as the quantization axis using dilepton channel $t\bar{t}$ candidates in 5.1 fb^{-1} of data, and ℓ+jet channel in 5.3 fb^{-1} of data, and yields $C = 0.04 \pm 0.56$ (stat+syst) and $C = 0.72 \pm 0.64_{\text{stat}} \pm 0.26_{\text{syst}}$, respectively [19, 20], while SM NLO calculation predicts $C \sim 0.78$ for the beam-line basis [18]. The measured results are consistent with the prediction, but they are statistically limited and also consistent with null correlation case ($C = 0$).

D0 also performed the measurements of C in beam-line basis using dilepton and ℓ+jet channel in 5.4 fb^{-1} of data, and yield $C = 0.66 \pm 023$ (stat+syst) [21]. This result implies no-correlation hypothesis is excluded at 3.1 σ significance level.

4.2 Top polarization in $t\bar{t}$ production

As we mentioned above, the top quark polarization at $t\bar{t}$ production can be measured by the angular distribution of flight direction of the decay products. D0 and CDF performed the measurements of the distribution of the flight direction of charged lepton from the top quark decay [15], [19, 20]. Fig. 7 shows the reconstructed distribution of $\cos\theta$ of lepton flight direction in the helicity basis in the top (anti-top) rest frame in $t\bar{t}$ production of the dilepton and ℓ+jet channel in D0 5.4 fb^{-1} data. The distributions are compared to the SM predictions and $t\bar{t}$ production via a hypothetical Z' boson. The results indicate the measured distributions are consistent with the SM predictions. Fig. 8 shows the reconstructed distribution of $\cos\theta$ of lepton flight direction in the beam-line basis in the top (anti-top) rest frame in $t\bar{t}$ production of the dilepton and ℓ+jet channel in CDF 5.1 fb^{-1} and 5.3 fb^{-1} (ℓ+jet) data, respectively. The results also indicate the measured distributions are consistent with the SM predictions.

5 Summary

Tevatron gives unique opportunity to study $q\bar{q} \to t\bar{t}$ production process for detail. Kinematical distributions of $t\bar{t}$ and the differential cross-section imply more information than the inclusive cross-section measurement. The measurements of $t\bar{t}$ forward-backward asymmetry at Tevatron suggest a contribution from new physics. Thanks to top quark short life-time, we can probe top quark polarization at $t\bar{t}$ production as well. This might give more information on $t\bar{t}$ forward-backward asymmetry.

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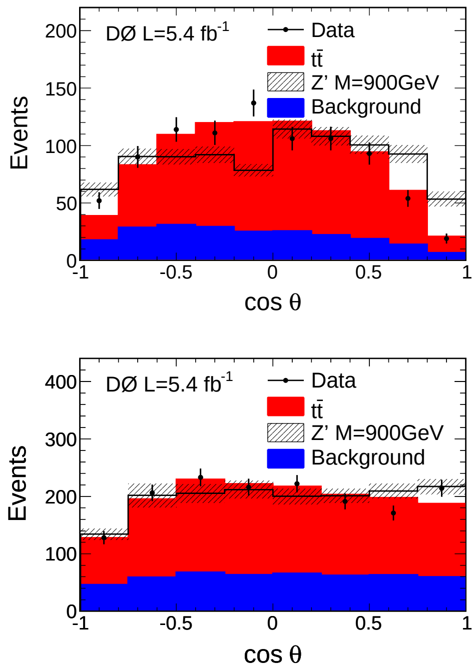

Figure 7. The reconstructed distribution of $\cos\theta$ of lepton flight direction in the helicity basis in the top (anti-top) rest frame in $t\bar{t}$ production of the dilepton (upper) and ℓ+jet channel (lower) in D0 5.4 fb^{-1} data, compared to the SM predictions and $t\bar{t}$ production via a hypothetical Z' boson.

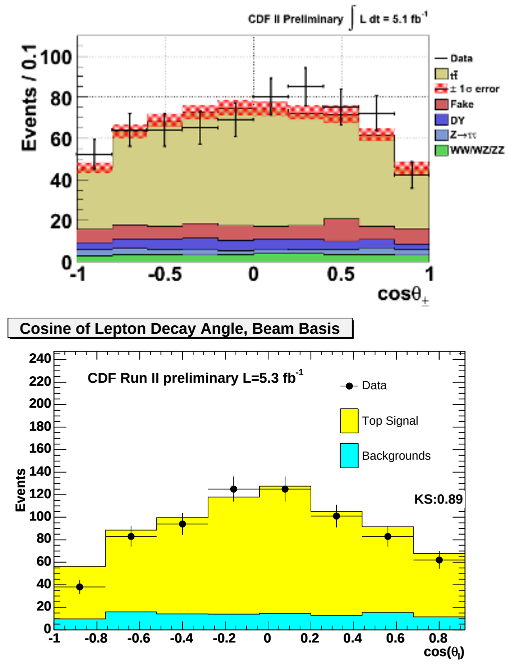

Figure 8. The reconstructed distribution of $\cos\theta$ of lepton flight direction in the beam-line basis in the top (anti-top) rest frame in $t\bar{t}$ production of the dilepton (upper) and ℓ+jet channel (lower) in CDF 5.1 fb^{-1} (dilepton) and 5.3 fb^{-1} (ℓ+jet) data, compared to the SM predictions.

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