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RECENT TEVATRON RESULTS ON b QUARK PRODUCTION

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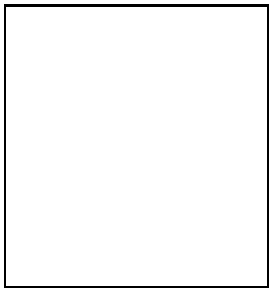

A number of recent B physics results from the CDF and DØ experiments at the Fermilab Tevatron Collider is reported. Measurements of open b quark production cross section in the central and forward rapidity regions in $p\bar{p}$ interactions at $\sqrt{s} = 1800$ GeV are presented. The measurements are used to evaluate the rapidity dependence of b quark production. We also report recent results on correlated $b\bar{b}$ production: a measurement of $b\bar{b}$ angular correlations using dimuon triggers (DØ) and the first direct measurement of $b\bar{b}$ rapidity correlations (CDF). The results from the various measurements are compared with the next-to-leading order QCD predictions. Finally, a measurement by CDF of the polarization of $\psi(2S)$ mesons is compared with the predictions of the Color Octet Model.

1 Introduction

Measurements of b quark production in high energy $p\bar{p}$ collisions have played a crucial role in testing the perturbative quantum chromodynamics (QCD) description of heavy quark production [1,2]. The b quark production cross section has been measured by the CDF and DØ experiments [3,4,5,6] at $\sqrt{s} =$ 1800 GeV using single and dimuon triggers, where muons come from semileptonic decay of b hadrons or from J/ψ decays. These results agree in the shape of the b quark transverse momentum (p_T^b) distribution with the next-to-leading order (NLO) QCD predictions but are generally higher than their central values.

In this paper, we present a new measurement (based on dimuon triggers) and a revised measurement (based on inclusive single muon triggers) of the b quark production cross section from DØ. They are compared with the previous CDF measurements and the NLO QCD predictions. The recent DØ measurement of the b produced muon cross section in the forward rapidity region is combined with the central muon cross section to evaluate the rapidity dependence of b quark production. As a further test of QCD, CDF and DØ have studied correlated $b\bar{b}$ production. The CDF direct measurement of $b\bar{b}$ rapidity correlations is in agreement with the strong correlation predicted by the theory. Furthermore, these correlations depend on the parton distribution functions (PDFs) inside the proton and can be used to assess the gluon distribution at large momentum fraction x. The DØ dimuon data

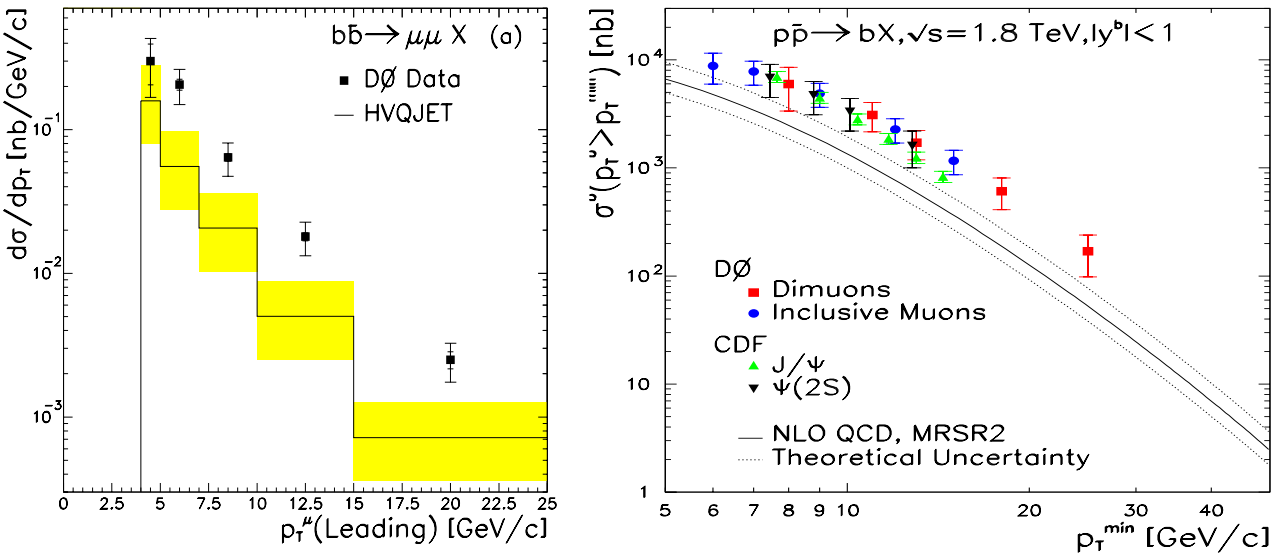

Figure 1: (Left) The leading muon p_T spectrum for $b\bar{b}$ production compared to the predicted spectrum. (Right) The CDF and DØ measurements of b quark production cross section compared with the NLO QCD prediction. The theoretical band shows the uncertainty associated with the factorization and renormalization scales and the b quark mass.

sample allows a direct measurement of $b\bar{b}$ angular correlations, which examines the different b quark production mechanisms. A relatively large contribution from the NLO gluon splitting processes, which give rise to 3-body topologies, is expected [1,2]. Finally, we report a recent measurement by CDF of the production polarization of $\psi(2S)$ mesons. This measurement is a sensitive test of the Color Octet Model [7], which has been proposed as an explanation for the unexpectedly large charmonium cross section in $p\bar{p}$ collisions.

2 Central and Forward Open b Quark Production

We start with b quark production in the central rapidity region. The DØ analysis uses the dimuon data sample ($\int \mathcal{L}dt = 6.5 \pm 0.4\ pb^{-1}$) collected in 1992-93. Kinematical and topological requirements are imposed to reduce backgrounds: two muons with $|\eta^\mu| < 0.8$, $4 < p_T^\mu < 25$ GeV/c, and $6 < m^{\mu\mu} < 35$ GeV/c^2. Each muon is also required to have an associated jet with $E_T > 12$ GeV within a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.8$. In addition to $b\bar{b}$ pairs, these dimuon events can also arise from $c\bar{c}$ pairs, events in which one or both of the muons are produced by in-flight decays of π or K mesons, Drell-Yan production, Υ decays, and cosmic rays. To extract the fraction of the dimuons coming from b quark decays, a maximum likelihood fit, which is primarily based on p_T^{rel} (transverse momentum of the muon with respect to the associated jet axis) of the leading and trailing muons, is performed.

Figure 1(Left) shows the unfolded leading muon (μ_1) p_T spectrum (preliminary) for $b\bar{b} \to \mu\mu$ with $4 < p_T^\mu < 25$ GeV/c, $|\eta^\mu| < 0.8$, and $6 < m^{\mu\mu} < 35$ GeV/c^2. The theoretical prediction is determined using the HVQJET [9] Monte Carlo, which is an implementation of the NLO calculation of Ref. [2] (MNR) for $b\bar{b}$ production. It uses the MNR parton level generator and a modified version of ISAJET [8] for hadronization, particle decays, and modeling of the underlying event. The particle decays are based on the ISAJET implementation of the CLEO decay tables. The prediction shown includes all four gg, gq, $g\overline{q}$ and $q\overline{q}$ initiated subprocesses with m_b(pole mass) = 4.75 GeV/c^2. The MRSR2 [10] PDFs are used with $\Lambda_5 = 237$ MeV. The shaded band shows the combined systematic and statistical error from the HVQJET prediction. This error ($^{+74}_{-50}\%$) is dominated by the uncertainty associated with the MNR prediction and is determined by varying the mass of the b quark between 4.5 and 5.0 GeV/c^2, and the factorization and renormalization scales, taken to be equal, between $\mu_0/2$ and $2\mu_0$, where $\mu_0^2 = m_b^2 + \langle p_T^b \rangle^2$.

The b quark cross section is calculated as

$$\sigma_b(p_T^b > p_T^{\rm min}) = \sigma_{b\bar{b}}^{\mu\mu}(p_T^{\mu_1}) \frac{\sigma_b^{\rm MC}}{\sigma_{b\bar{b}\to\mu\mu}^{\rm MC}}, \quad (1)$$

where $\sigma_{b\bar{b}}^{\mu\mu}(p_T^{\mu_1})$ is the measured dimuon cross section integrated over different intervals of $p_T^{\mu_1}$, $\sigma_b^{\rm MC}$ is the total Monte Carlo b quark cross section for $p_T^b > p_T^{\rm min}$ (where $|y^b| < 1.0$ and no cut on $y^{\bar{b}}$), and $\sigma_{b\bar{b}\to\mu\mu}^{\rm MC}$ is the Monte Carlo cross section for dimuon production with the same requirements used to select the data set. The $p_T^{\rm min}$ is defined as that value of the b quark p_T where 90% of the accepted events, after kinematic cuts, have b quark transverse momentum greater than $p_T^{\rm min}$.

Figure 1(Right) shows the b quark production cross section for the rapidity range $|y^b| < 1.0$ as a function of $p_T^{\rm min}$. The DØ measurement (preliminary) compares well with the previous CDF measurements. The NLO QCD prediction is computed using Ref.[2] with m_b(pole mass) = 4.75 GeV/c^2 and the MRSR2 PDFs. The theoretical uncertainty indicates the variation with the mass of the b quark and the factorization and renormalization scales as described above and is dominated by the variation of the scales. The ratio of the data to the central NLO QCD prediction is approximately three over the entire $p_T^{\rm min}$ range covered.

Also shown in Fig. 1(Right) is a revised result based on the previous inclusive single muon measurement from DØ[4]. In light of recent changes in B meson decay modes and of Monte Carlo improvements, the old measurement is re-evaluated. In addition, the high p_T inclusive muon data ($p_T^\mu > 12$ GeV/c) are excluded due to large uncertainties in the cosmic ray muon background subtraction. The re-evaluated cross section (preliminary), which supersedes that of Ref.[4], is in good agreement with the other measurements.

The DØ experiment has explored b production in the forward rapidity region using the inclusive single muon data sample ($\int \mathcal{L}dt = 82 \pm 7\ nb^{-1}$) collected during the 1994-1995 Tevatron run. The event selection required a muon in the rapidity range $2.4 < |y^\mu| < 3.2$, with momentum $p^\mu < 150$ GeV/c and $p_T^\mu > 2$ GeV/c. The differential muon cross section from b quark production and decay is calculated from the measured inclusive muon cross section, after subtracting the π/K contribution and correcting for the fraction of muons from b decays, both of which are determined using ISAJET. The result is shown in Fig. 2(Left), where it is compared with the NLO QCD prediction based on HVQJET. The theoretical uncertainty is determined by varying the b quark mass from 4.5 to 5.0 GeV/c^2 and the scales from $2\mu_0$ to $\mu_0/2$. Although the overall shape is in agreement, the predicted cross section is approximately a factor of four lower than the data.

The differential muon cross section as a function of rapidity, $d\sigma_b^\mu/d|y^\mu|$, is obtained by combining the DØ forward and central ($|\ y^\mu\ | < 0.8$) muon cross sections. Figure 2(Right) shows the results for $p_T^\mu > 5$ and 8 GeV/c. The rapidity dependence of the b produced muon cross section is not in agreement with the NLO QCD predictions; the ratio of data/theory is 2.5 ± 0.4 in the central region and increases to 3.6 ± 0.8 in the forward region. The uncertainty in these ratios reflects the experimental error only.

3 Correlated $b\bar{b}$ Production

In this section we report two results on correlated $b\bar{b}$ production at Tevatron. CDF[11] has conducted correlation studies in rapidity, measuring the $b\bar{b}$ production cross section with one quark produced in the forward region and the other in the central region. DØ reports a new measurement of $b\bar{b}$ angular correlations using the semileptonic decay of the b quark into a muon to tag the heavy quarks.

Using data ($\int \mathcal{L}dt = 77\ pb^{-1}$) from the 1994-1995 Tevatron run, CDF has measured the double differential cross section, $d^2\sigma/d|y_{b1}|d|y_{b2}|$, for two independent samples of b quarks, a central-central topology ($|y_{b1}| < 0.6$ and $|y_{b2}| < 1.5$), and a forward-central topology ($2.0 < |y_{b1}| < 2.6$ and $|y_{b2}| < 1.5$). In order to reduce the experimental uncertainties and the scale dependence of the theoretical prediction, CDF measures the ratio of the two cross sections. The event selection requires a b quark jet with a decay muon ($b1$). This jet, referred to as the trigger jet, has $E_T > 15$ GeV and the muon has $p_T^\mu > 6$ GeV/c. The selection also requires a central jet with $E_T > 26$ GeV and $|\eta^{jet}| < 1.5$ ($b2$). This

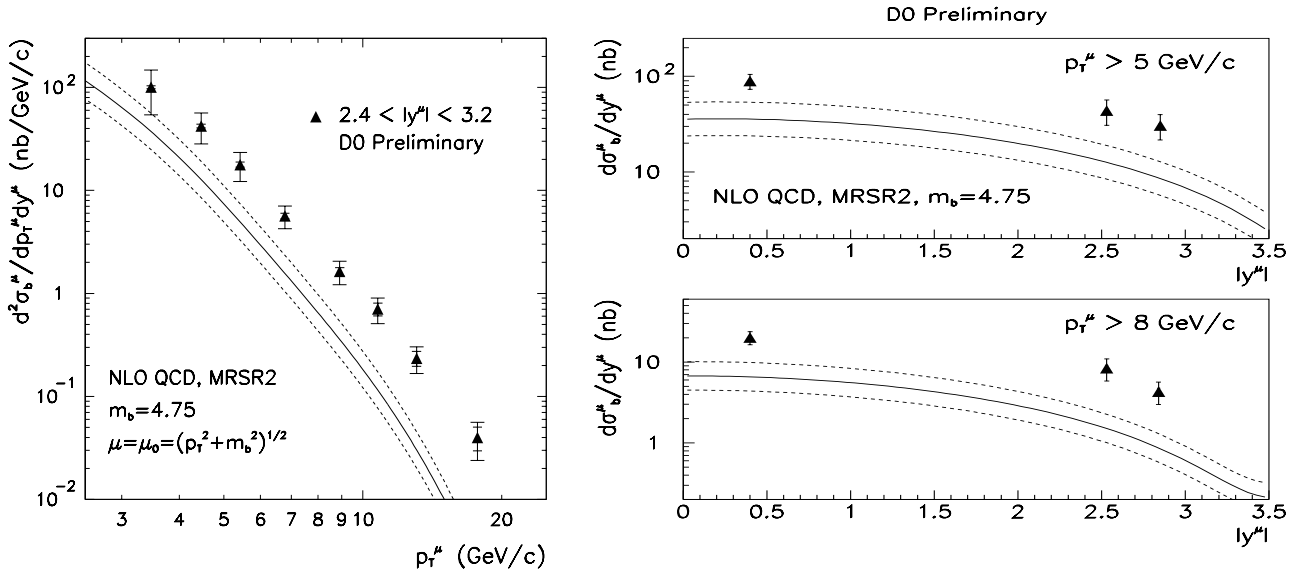

Figure 2: (Left) Differential muon cross section, per unit of rapidity, in the forward region from b quark production and decay as a function of p_T^{μ}. The solid curve is the NLO QCD predictions of HVQJET with the dashed curves representing the theoretical uncertainties. (Right) Differential muon cross sections from b production and decay as a function of $|y^{\mu}|$.

jet is identified as a b quark jet through a secondary vertex tag. The event is then classified as being either central-central or forward-central depending on the muon pseudorapidity range, $|\eta^{\mu}| < 0.6$ or $2.0 < |\eta^{\mu}| < 2.6$, respectively. To extract the $b\bar{b}$ signal fraction from each data sample, the p_T^{rel} of the muon and the pseudo-ct of $b2$ jet are simultaneously fitted, where pseudo-ct is the transverse proper decay length of the secondary vertex. The cross section ratio is calculated from the following relation:

$$R = \frac{\sigma(p\bar{p} \rightarrow b_1 b_2 X;\ 2.0 <\mid y_{b1} \mid < 2.6)}{\sigma(p\bar{p} \rightarrow b_1 b_2 X;\ \mid y_{b1} \mid < 0.6)}, \tag{2}$$

where $p_T(b1, b2) > 25$ GeV/c, $|y_{b2}| < 1.5$, and $\Delta\phi(b1, b2) > 60^{\circ}$. Taking into account the efficiencies for the central-central and forward-central events, the result is $R_{\rm expt} = 0.361 \pm 0.033({\rm stat})^{+0.015}_{-0.031}({\rm syst})$ in agreement with the NLO QCD prediction $R_{\rm thry} = 0.338^{+0.014}_{-0.097}$, obtained using the MRSA$'$[12] PDFs. The uncertainty on $R_{\rm thry}$ arise from changing the scale between $2\mu_0$ and $\mu_0/2$. The evolution of the cross section ratio with the rapidity of the trigger jet ($b1$) is shown in Fig. 3(Left). The measurement is in agreement with the QCD predictions, which exhibit a strong $b\bar{b}$ rapidity correlation.

We note that this cross section ratio is sensitive to the gluon distribution in the proton at high x values. Figure 3(Right) shows a comparison of the $R_{\rm expt}$ with the $R_{\rm thry}$ values obtained using various PDFs, as a function of the rapidity of the trigger jet. The data point and theory curves are normalized to that from MRSA$'$ PDFs. We observe good agreement between data and QCD using the MRSR2 PDFs, while the CTEQ4HJ [13] and MRST [14] PDFs are disfavored.

DØ using the dimuon data sample described in Sec. 2 has studied angular correlations in $b\bar{b}$ production by measuring the azimuthal opening angle between the muons from the b quark decays. The differential cross section, $d\sigma^{\mu\mu}_{b\bar{b}}/d\Delta\phi^{\mu\mu}$, allows us to differentiate between the contributing QCD production mechanisms, which are the leading order (LO) subprocess (flavor creation) and the NLO subprocesses (gluon splitting, flavor excitation and gluon radiation). Figure 4(Left) shows the measured $\Delta\phi^{\mu\mu}$ distribution (preliminary). Also shown are the LO and NLO QCD predictions which are determined using HVQJET and include all four gg, gq, $g\overline{q}$ and $q\overline{q}$ initiated subprocesses. The grey band around the NLO prediction shows the combined statistical and systematic errors associated with the prediction, which is $^{+74}_{-50}\%$ as detailed in Sec. 2. The LO prediction shows the statistical error only. The data again show an excess above the NLO QCD prediction but agree with the overall shape. The agreement in shape is a clear indication for the presence of NLO subprocesses; the LO prediction, which contains the $b \rightarrow \mu$ smearing, does not describe the data.

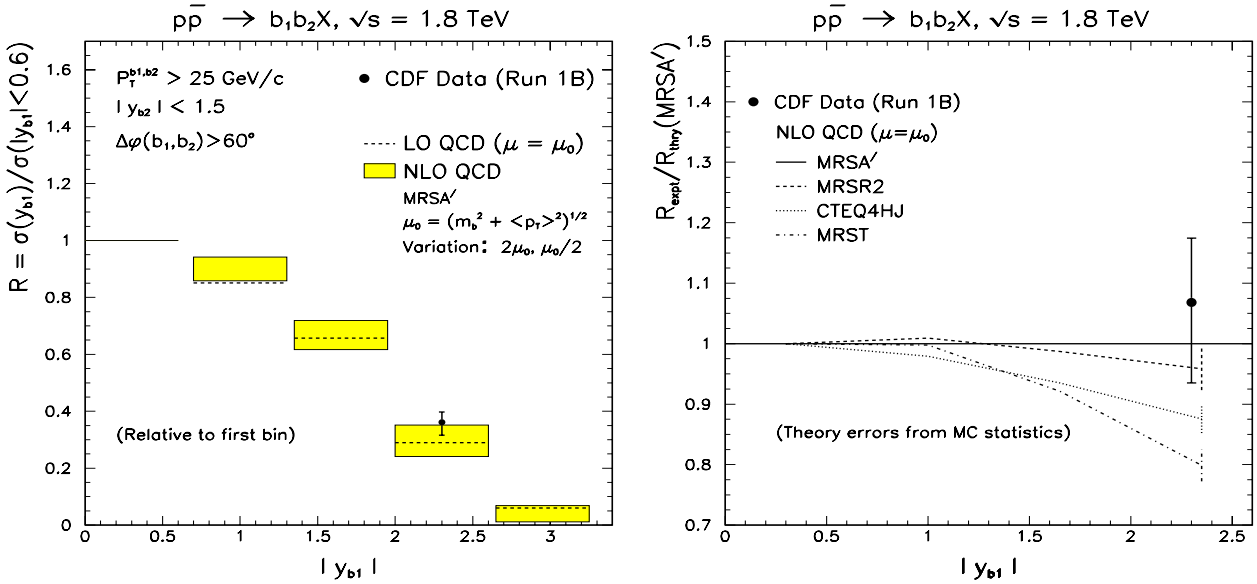

Figure 3: (Left) The normalized rapidity distribution of the trigger b jet. The bands are the predictions for each bin taking into account variations in the scale. (Right) Comparison of the ratio R between data and theory using MRSA′ PDFs. Theory curves for the other PDFs are divided by that from MRSA′ and normalized to unity in the first bin.

4 $\psi(2S)$ Polarization

Measurements of direct (prompt) $\psi(2S)$ production cross section[15] are about 50 times larger than the Color Singlet Model predictions[16]. A theoretical model proposed to explain this anomalous production is the Color Octet Model (COM)[7]. The model describes the large cross section by including color-octet $c\bar{c}$ states in the gluon fragmentation process. As a consequence, COM predicts that at high p_T ($p_T \gg m_c$) direct $\psi(2S)$ production should approach 100% transverse polarization. The angular distribution in $\psi(2S) \to \mu^+\mu^-$ is given by[17] $w(\theta) = 3(1 + \alpha\ cos^2\theta)/2(\alpha + 3)$, where θ denotes the angle between the μ^+ momentum in the $\psi(2S)$ rest frame and the $\psi(2S)$ momentum in the laboratory frame. The polarization, α, is $+1$ (-1) for fully transverse (longitudinal) polarization.

The analysis is based on a sample of low p_T dimuon triggers ($\int \mathcal{L}dt = 110\ pb^{-1}$) collected by CDF during 1992-95. Both muons are required to have $p_T^\mu > 2$ GeV/c and $p_T^{\mu\mu} > 5.5$ GeV/c. The reconstructed dimuon invariant mass distribution is fitted with a gaussian plus linear background which gives a total of 1776 ± 62 signal $\psi(2S)$ candidates. To extract the polarization and study its p_T dependence, this data sample is subdivided into bins of $\psi(2S)$ p_T and ct. The ct is related to the transverse decay length and allows separation of prompt and B decay $\psi(2S)$. Then, the prompt and B decay production polarizations are extracted from the $cos\ \theta$ distributions of the $\psi(2S)$ candidates by simultaneously fitting the two ct regions. Figure 4(Right) shows the measured prompt $\psi(2S)$ polarization as a function of $\psi(2S)$ p_T. A theoretical calculation based on COM is also shown. Although the measurement has large statistical uncertainties, $\alpha(9 < p_T^\psi < 20\ \text{GeV}/c) = -0.76 \pm 0.49 \pm 0.06$, it does not appear to support the COM prediction.

5 Summary

Several different CDF and DØ data sets give consistent measurements of the b quark production cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1800$ GeV. The NLO QCD calculations describe the p_T^b shape but underestimate b quark production by a factor of about three. The rapidity dependence of the b produced muon cross section is not in agreement with the NLO QCD predictions, which underestimate the data by a factor of 2.5 ± 0.4 in the central rapidity region and 3.6 ± 0.8 in the forward region. CDF reports the first direct measurement of $b\bar{b}$ rapidity correlations. The ratio of forward to central $b\bar{b}$ production, $R = 0.361 \pm 0.033^{+0.015}_{-0.031}$, is in agreement with the strong correlation predicted by theory. The results by DØ on $b\bar{b}$ angular correlations show that the shape of $d\sigma/d\Delta\phi^{\mu\mu}$ is described by the NLO QCD, indicating a sizeable contribution from the NLO subprocesses to $b\bar{b}$ production.

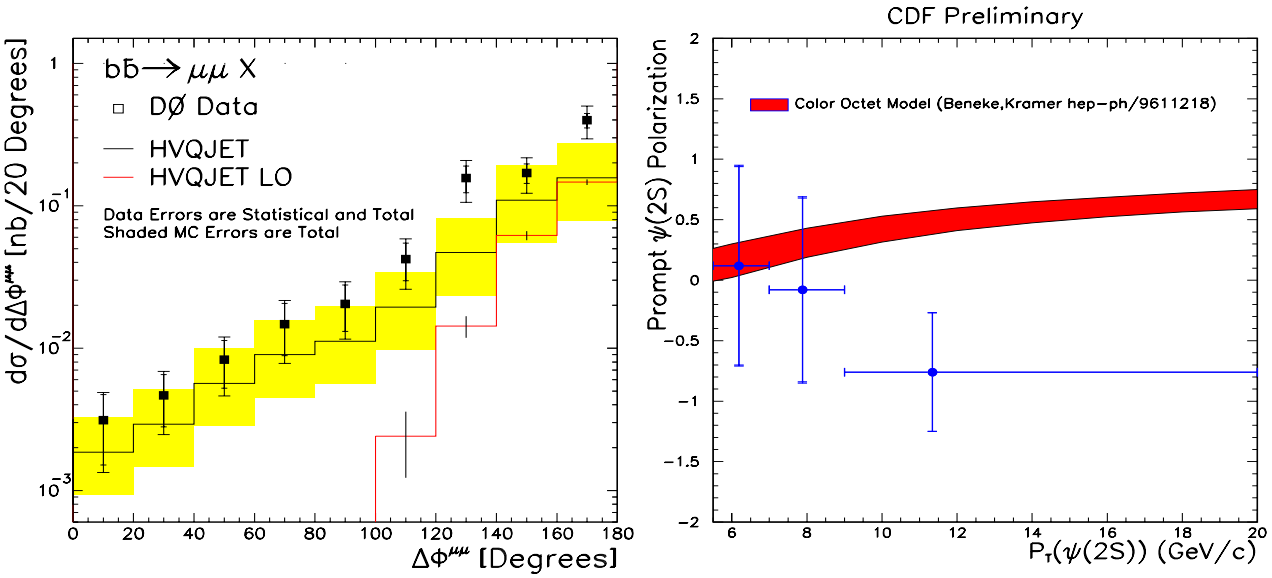

Figure 4: (Left) The $\Delta\phi^{\mu\mu}$ spectrum for $b\bar{b}$ production compared to the HVQJET prediction. The errors on the data are statistical and total. The solid histogram shows the NLO prediction with the grey band indicating the total uncertainty. (Right) The measured prompt $\psi(2S)$ polarization as a function of its p_T, compared with the COM prediction.

A preliminary measurement by CDF of prompt $\psi(2S)$ polarization gives $\alpha(9 < p_T^{\psi} < 20 \text{ GeV}/c) = -0.76 \pm 0.49 \pm 0.06$, which does not support the Color Octet Model prediction that $\psi(2S)$ is produced transversely polarized.

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