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# $\Upsilon$ Production at CDF

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The CDF Collaboration

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We report on preliminary measurements of the $\Upsilon$(1S), $\Upsilon$(2S) and $\Upsilon$(3S) differential and integrated cross sections in $p\bar{p}$ collisions at $\sqrt{s} =$ 1.8 TeV using a sample of 16.6 $\pm$ 0.6 pb$^{-1}$ collected by the Collider Detector at Fermilab. The three resonances were reconstructed through the decay $\Upsilon \rightarrow \mu^+\mu^-$ in the rapidity region $|y| < 0.4$. The cross section results are compared to theoretical models of direct bottomonium production.

We report a study of the reaction $p\bar{p} \rightarrow \Upsilon X \rightarrow \mu^+\mu^- X$ at $\sqrt{s} = 1.8$ TeV. This study yields the transverse momentum ($P_t$) dependence of the production cross sections for the $\Upsilon$(1S), $\Upsilon$(2S), and $\Upsilon$(3S) states as well as the integrated cross sections. These results represent the first measurements of the individual $\Upsilon$ cross sections at a hadron collider, and are important for the investigation of bottomonium (a $b\bar{b}$ bound state) production mechanisms in $p\bar{p}$ collisions [1–5]. The $\Upsilon$ resonances are produced directly or from the decay of higher mass $\chi_b$ states. Using information from our silicon vertex detector, we have determined that the $\Upsilon$ particles are produced with zero lifetime [6]. Since our measurements of prompt charmonia production for the $J/\psi$ and $\psi$(2S) states are higher than the theoretical predictions [7], it is important to determine if the same is true for the $\Upsilon$ particles. Additionally, the $\Upsilon$ states allow exploration of the low $P_t$ region inaccessible to the charmonia measurements, which do not extend below 4 GeV/c due to triggering constraints.

The data were collected in 1992-93 by the Collider Detector at Fermilab. The CDF detector has been described in detail elsewhere [8]. The components relevant to this analysis are briefly described here. The central tracking chamber (CTC) is in a 1.4 T axial magnetic field and has a resolution of $\delta P_t/P_t = \sqrt{(0.0011 P_t)^2 + (0.0066)^2}$ for beam constrained tracks. The central muon chambers (CMU), at a radius of 3.5 m from the beam axis, are located behind 5 interaction lengths of calorimeter and provide muon identification in the region of pseudorapidity $|\eta^\mu| < 0.6$, where $\eta = -ln[tan(\theta/2)]$ and $\theta$ is the polar angle with respect to the beam axis. These chambers are complemented by the central muon upgrade system (CMP) which consists of four layers of drift chambers behind a total of 8 interaction lengths. Use of the CMP considerably reduces hadronic punch-through backgrounds.

The measurements reported here are based on a 16.6 $\pm$ 0.6 pb$^{-1}$ data sample of muon pairs collected with a three level online trigger. The level 1 trigger required two charged track segments in the central muon chambers. The efficiency for this trigger is 90% at $P_t$ = 3.1 GeV/c and has a plateau of 94%. At level 2 at least one muon segment was required to match a CTC track found by a hardware track processor. The level 2 trigger is 90% efficient at $P_t$ = 3.1 GeV/c and has a plateau of 93%. The level 3 trigger used online track reconstruction software which required a pair of fully reconstructed tracks matched to hits in the muon chambers. Both muons were required to have $P_t$ greater than 2.0 GeV/c, with at least one muon having $P_t$ greater than 2.5 GeV/c.

Additional requirements were placed offline to isolate the $\Upsilon$ resonances. Both muons from the $\Upsilon \to \mu^+\mu^-$ decay were required to be identified by the CMU system and at least one muon had to be identified by the CMP system. To reduce the sensitivity to the trigger thresholds, the $P_t$ of both muons was required to be greater than 2.2 GeV/c and at least one muon had to have $P_t$ greater than 2.8 GeV/c. A difference of less than $3\sigma$ in the x position and $3.5\sigma$ in the z position between each muon chamber track and its associated CTC track were required, where $\sigma$ is the calculated uncertainty due to multiple scattering, energy loss, and measurement uncertainties. The muons were required to have opposite sign and the rapidity of the reconstructed pair had to be in the region $|y| < 0.4$. The resulting mass distribution of dimuon pairs, shown in Figure 1, is well described by a fit to three gaussians and a quadratic background.

The differential cross section times the branching ratio for $\Upsilon \to \mu^+\mu^-$ is calculated according to the equation

$$\frac{d\sigma(\Upsilon)}{dP_t} Br(\Upsilon \to \mu^+\mu^-) = \frac{N - B}{A \cdot \int \mathcal{L}dt \cdot \Delta P_t \cdot \epsilon_{l1l2} \cdot \epsilon_{l3} \cdot \epsilon_{trk} \cdot \epsilon_{\mu}}$$

where $N$ ($B$) is the number of $\Upsilon$ candidate (background) events in each $P_t$ bin, $A$ is the geometric and kinematic acceptance, $\int \mathcal{L}dt$ is the integrated luminosity, and $\Delta P_t$ is the width of the $P_t$ bin. The various efficiency corrections include the combined level 1 and level 2 trigger efficiency, $\epsilon_{l1l2}$, the level 3 trigger efficiency, $\epsilon_{l3}$, the efficiency for reconstructing offline both tracks in the CTC, $\epsilon_{trk}$, and the efficiency for reconstructing both muon track segments and associating them with extrapolated CTC tracks, $\epsilon_\mu$.

A binned likelihood fit was performed on the dimuon mass distribution for each $P_t$ bin to determine the number of signal events $(N - B)$. For the $\Upsilon$(1S) the region between 8.7 and 9.8 GeV/c$^2$ was fit to a gaussian plus quadratic background. The values for the $\Upsilon$(2S) and $\Upsilon$(3S) were obtained by fitting all three resonances simultaneously to three gaussians with a quadratic background. The relative widths of the resonances in each $P_t$ bin were constrained to values determined from Monte Carlo simulation. No excess of events was observed in the $\Upsilon$(2S) and $\Upsilon$(3S) resonances below $P_t$ 1 GeV/c, and therefore no results are given below this value.

The geometric and kinematic acceptances for $\Upsilon$(1S),$\Upsilon$(2S), $\Upsilon$(3S) $\rightarrow \mu^+\mu^-$ were calculated with a Monte Carlo simulation. The event generator produces $\Upsilon$ particles with flat $P_t$ and $y$ distributions. Since the polarization of the $\Upsilon$ resonances is not known, the states were assumed to decay isotropically. The generated events were processed with a full detector simulation, and with the same reconstruction criteria that were imposed on the data. The integrated acceptance $A$ was computed for each $P_t$ bin, and has a typical value of 19%.

The events were corrected on an event by event basis for the level 1 and level 2 trigger efficiency, $\epsilon_{l1l2}$, which is typically 87% for each $P_t$ bin. The values of the $P_t$ independent efficiencies are $\epsilon_{l3}$ = (92$\pm$ 2)%, $\epsilon_{trk}$ = (97.8 $\pm$ 2)% and $\epsilon_\mu$ = (95.0 $\pm$ 0.8)%.

Systematic uncertainties arise from the level 1 and level 2 trigger efficiency corrections (4%), the fitting procedure (6% for $\Upsilon$(1S) and 10% for the $\Upsilon$(2S) and $\Upsilon$(3S)), the luminosity determination (3.6%) and the reconstruction efficiencies (3%). The systematic uncertainty associated with the acceptance model (7%) was determined by recalculating the acceptances using a parton level generator [9] which provides the four momentum of all known bottomonium states which decay to the $\Upsilon$ resonances. A $P_t$ dependent systematic uncertainty arises from the unknown $\Upsilon$ polarization. This uncertainty was determined by recomputing the cross section assuming that the muons from the $\Upsilon$ decay have an angular distribution proportional to $1+\alpha cos^2\theta$ with $\alpha = \pm 1$.

The differential cross section results are displayed in Figures 2–4 where the vertical error bars include the statistical uncertainty added in quadrature with the polarization, fitting procedure and acceptance model systematic uncertainties. There is an additional common systematic of 6% which is not included.

Theoretical predictions from Ref. [5] are also shown in Figures 2–4. These curves include only color-singlet terms and are not reliable below 2 GeV/c. The calculation for the $\Upsilon$(1S) includes contributions from direct production and $\chi_b$(1P) and $\chi_b$(2P) decay. (Contributions from $\Upsilon$(2S) and $\Upsilon$(3S) decay are neglected.) The theoretical prediction for the $\Upsilon$(2S) includes direct production and $\chi_b$(2P) decay. Two theoretical curves are shown for the $\Upsilon$(3S) cross section. One corresponds to the direct $\Upsilon$(3S) production contribution [10] and the other to the sum of the contributions from the direct $\Upsilon$(3S) production and the decay of the unobserved $\chi_b$(3P) state. Recently, attempts have been made to explain the discrepancies in both the shape and normalization between the theoretical and measured distributions. These include the inclusion of $k_T$ effects [4] and novel color-octet production mechanisms [5,11]. These calculations more adequately describe the shape of the $P_t$ distributions, however questions regarding the overall normalization still remain.

The integrated cross section results are:

$$\sigma(\overline{p}p \to \Upsilon(1S), |y|<0.4, 0<P_t<16\ \mathrm{GeV/c}) Br(\Upsilon(1S) \to \mu^+\mu^-) = 560 \pm 21\,(\mathrm{stat}) \pm 53\,(\mathrm{sys})\ \mathrm{pb}$$

$$\sigma(\overline{p}p \to \Upsilon(2S), |y|<0.4, 1<P_t<10\ \mathrm{GeV/c}) Br(\Upsilon(2S) \to \mu^+\mu^-) = 137 \pm 13\,(\mathrm{stat}) \pm 18\,(\mathrm{sys})\ \mathrm{pb}$$

$$\sigma(\overline{p}p \to \Upsilon(3S), |y|<0.4, 1<P_t<10\ \mathrm{GeV/c}) Br(\Upsilon(3S) \to \mu^+\mu^-) = 75 \pm 11\,(\mathrm{stat}) \pm 10\,(\mathrm{sys})\ \mathrm{pb}.$$

The polarization model systematic uncertainties for the integrated cross sections are 2%, 5%, and 5% for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ respectively. The uncertainty from the acceptance model is estimated to be 3%. The uncertainty from the fitting procedure is conservatively taken to be the same as that used for the differential cross section values. The uncertainties from the luminosity determination and the reconstruction and trigger efficiencies are also the same.

The ratios of the integrated cross sections results can also be computed in the range $1 < P_t < 10$ for $|y| < 0.4$. The results are $\sigma Br(\Upsilon(2S))/\sigma Br(\Upsilon(1S)) = 0.281 \pm 0.030(\mathrm{stat}) \pm 0.038(\mathrm{sys})$ and $\sigma Br(\Upsilon(3S))/\sigma Br(\Upsilon(1S)) = 0.155 \pm 0.024(\mathrm{stat}) \pm 0.021\,(\mathrm{sys})$. These production ratios are consistent with the results from experiments at lower energies [3,12].

In conclusion we have measured both the integrated and differential cross sections for the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$. The rate of $\Upsilon$ production was generally found to be higher than leading order color-singlet QCD predictions. Inclusion of additional production mechanisms helps to explain some of the discrepancies and work is ongoing to understand the impact of these mechanisms.

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## Figure Captions

1) Invariant mass distribution for $\Upsilon$(1S), $\Upsilon$(2S), $\Upsilon$(3S) for $|y| < 0.4$. The histogram corresponds to the data and the solid curve is a fit to three Gaussians plus a quadratic background.

2) The product $\left(\frac{d\sigma}{dP_t}\right) \times Br$ vs. $P_t$ for $\Upsilon(1S) \rightarrow \mu^+\mu^-$ for $|y| < 0.4$. The vertical error bars include the statistical uncertainty added in quadrature with the polarization, fitting procedure and acceptance model systematics. There is an additional common systematic of 6% not shown. The color-singlet calculation from Ref. [5], multiplied by Br($\Upsilon(1S) \rightarrow \mu^+\mu^-$) = 2.48% [13], is also shown. The theoretical prediction includes contributions from direct $\Upsilon$(1S) production and $\chi_b$(1P) and $\chi_b$(2P) decay.

3) The product $\left(\frac{d\sigma}{dP_t}\right) \times Br$ vs. $P_t$ for $\Upsilon(2S) \rightarrow \mu^+\mu^-$ for $|y| < 0.4$. The vertical error bars include the statistical uncertainty added in quadrature with the polarization, fitting procedure and acceptance model systematics. There is an additional common systematic of 6% not shown. The color-singlet calculation from Ref. [5], multiplied by Br($\Upsilon(2S) \rightarrow \mu^+\mu^-$) = 1.31% [13], is also shown. The theoretical prediction includes contributions from direct $\Upsilon$(2S) production and $\chi_b$(2P) decay.

4) The product $\left(\frac{d\sigma}{dP_t}\right) \times Br$ vs. $P_t$ for $\Upsilon(3S) \rightarrow \mu^+\mu^-$ for $|y| < 0.4$. The vertical error bars include the statistical uncertainty added in quadrature with the polarization, fitting procedure and acceptance model systematics. There is an additional common systematic of 6% not shown. The color-singlet calculation

from Ref. [5], multiplied by Br($\Upsilon(3S) \rightarrow \mu^+\mu^-$) = 1.81% [13], is also shown. The dashed line corresponds to the direct $\Upsilon$(3S) production contribution and the solid line corresponds to the sum of the contributions from the direct $\Upsilon$(3S) production and the decay of the unobserved $\chi_b$(3P) state.

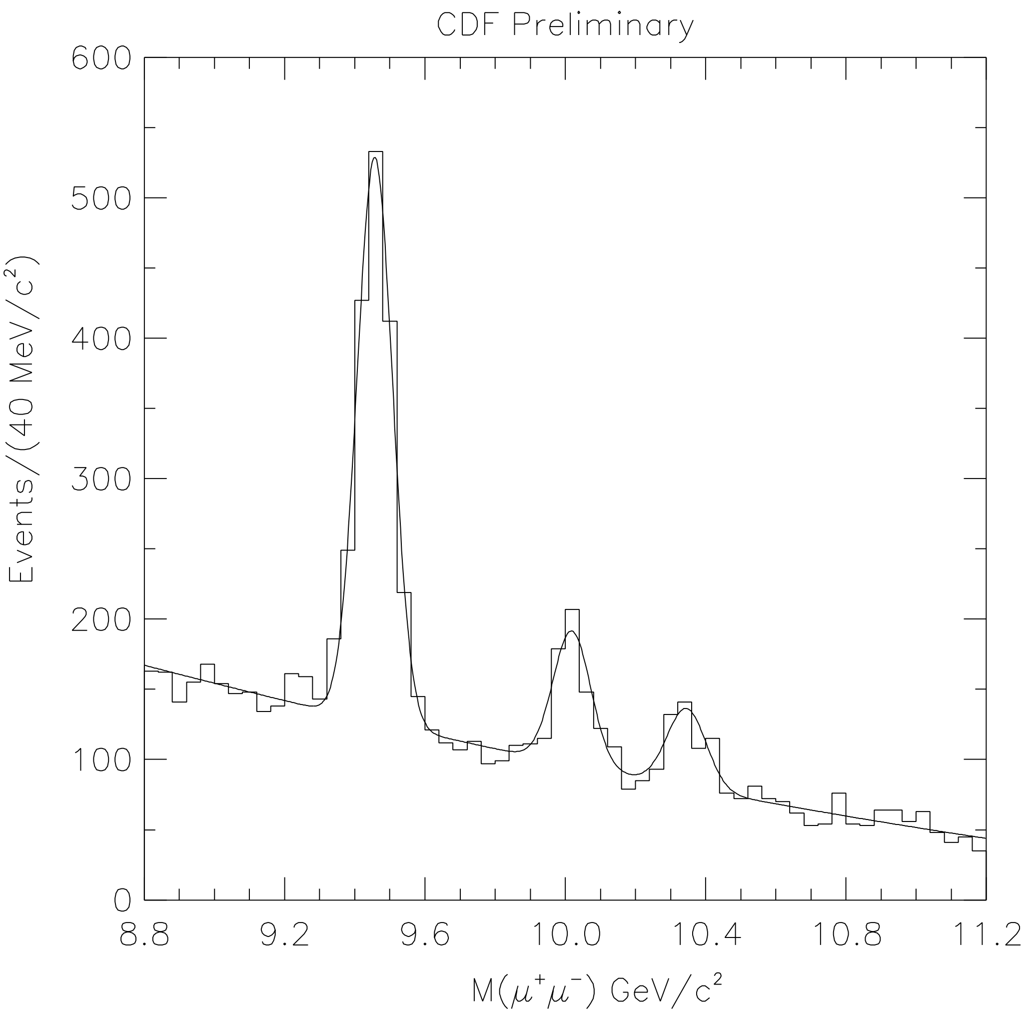

CDF Preliminary
600
500
400
300
200
100
0
Events/(40 MeV/c²)
8.8
9.2
9.6
10.0
10.4
10.8
11.2
M(μ⁺μ⁻) GeV/c²

**FIG. 1.**

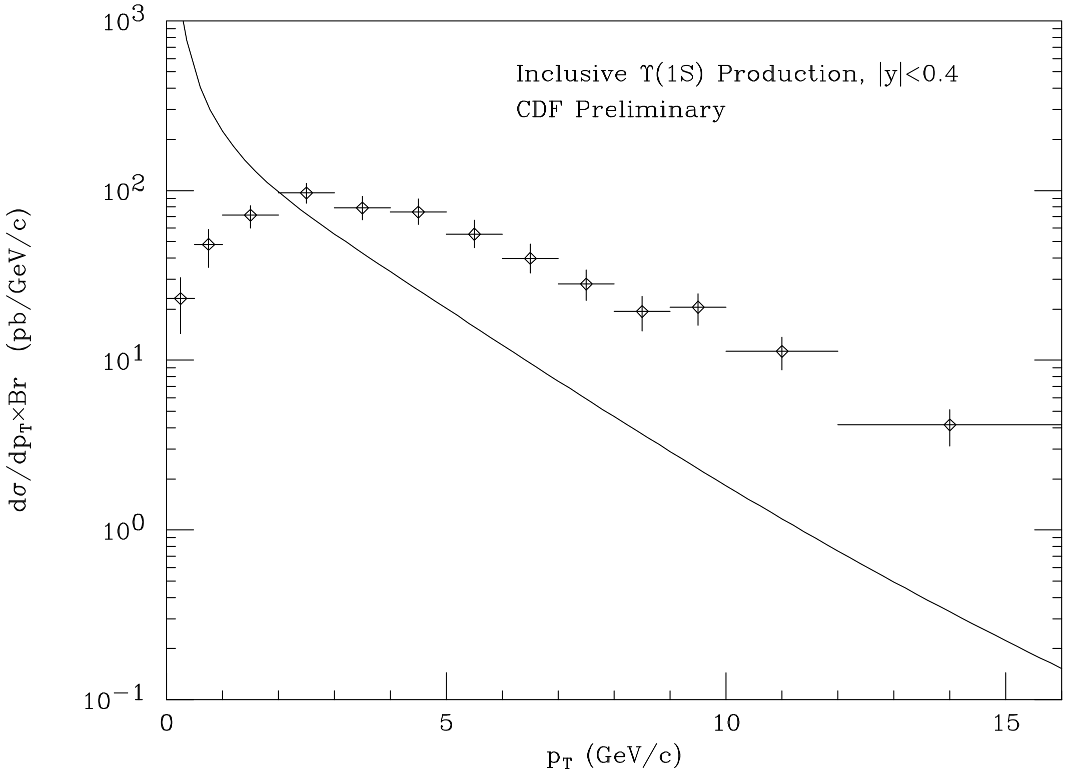
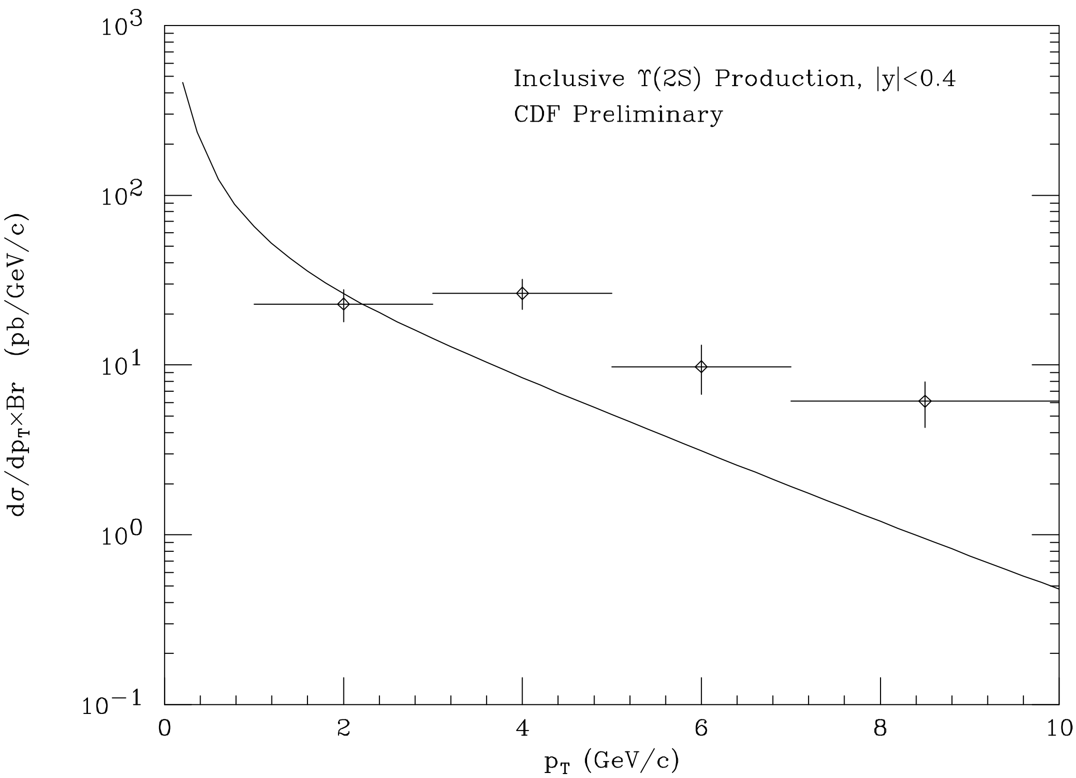

Inclusive Υ(1S) Production, |y|<0.4
CDF Preliminary
10^3
10^2
10^1
10^0
10^-1
0
5
10
15
dσ/dp_T×Br (pb/GeV/c)
p_T (GeV/c)

FIG. 2.



Inclusive Υ(2S) Production, |y|<0.4
CDF Preliminary
dσ/dp_T×Br (pb/GeV/c)
p_T (GeV/c)
10^3
10^2
10^1
10^0
10^-1
0
2
4
6
8
10


FIG. 3.

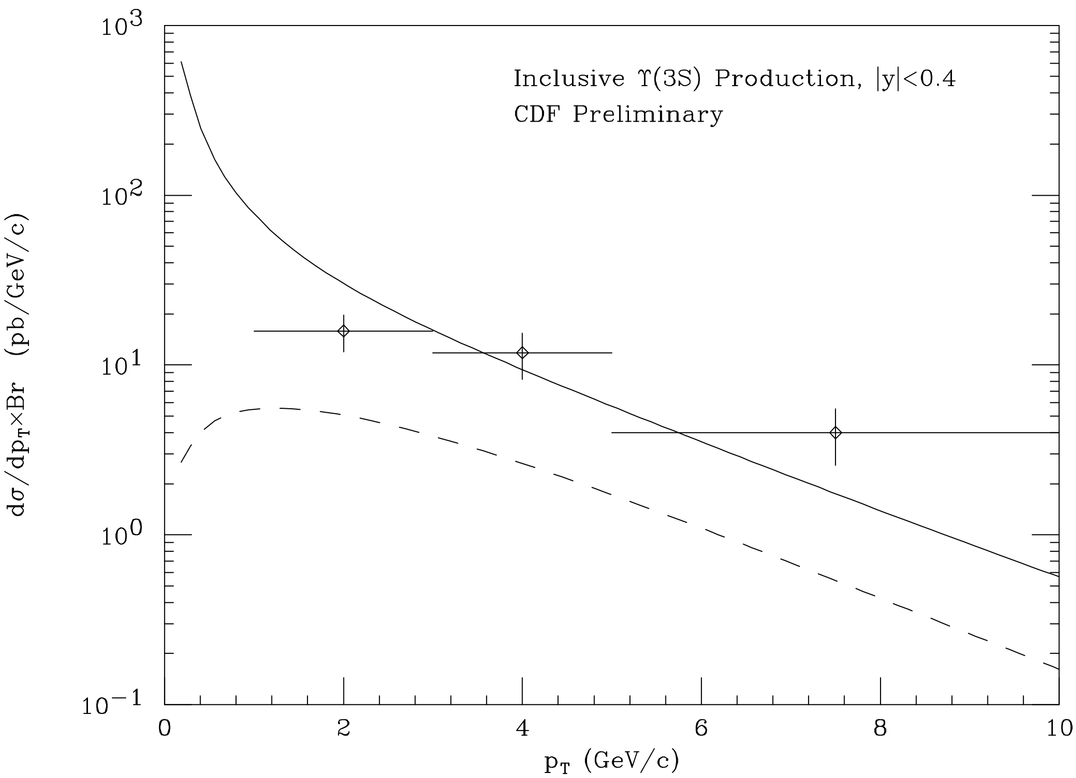

Inclusive Υ(3S) Production, |y|<0.4
CDF Preliminary
dσ/dp_T×Br (pb/GeV/c)
p_T (GeV/c)
10^3
10^2
10^1
10^0
10^-1
0
2
4
6
8
10

FIG. 4.