Quarkonia Production at $p\bar{p}$ Colliders

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Confronting QCD with Experiment; Puzzles and Challenges
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Outline of the Talk

- **Overview**
- **$\psi(2S)$'s**
- **J/ψ's**
- **χ_c's**
- **Υ's**
- **Conclusions**
- **Prospects**

MOTIVATION

) The study of quarkonia has yielded valuabl insight into the nature of strong interaction since the discovery of J/ψ in 1974.

- As far as the strong interactions are concerne heavy quarkonia are the next simplest partic (probes) after leptons and electroweak gauge boso

- They provide a window in the boundary region between perturbative and non-perturbative QC

- The charmonium and bottomonium systems exhit a rich spectrum of orbital + angular excitations
  → potentially more information than leptons and electroweak gauge bosons

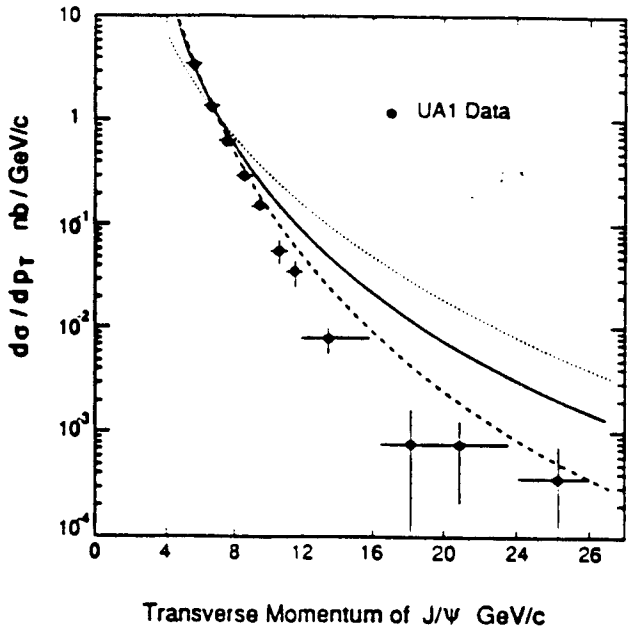
- They play fundamental role in B physics studies

- Recent investigations of charmonia and botto uncovered some striking surprises

HISTORY

$p\bar{p}$ Collider at $\sqrt{s}$ = 630 GeV

$d\sigma/dp_T \cdot Br \quad F\bar{F} \to J/\psi X$



UA1, 1991
C. Albajar et al.
P.L. B 256, 112

$4.7\ pb^{-1}$
$|y|<2$

B decays → (69 − 31)%
χ decays (χ) (B)

$F_B^{\psi} = 0.31 \pm 0.02 \pm 0.1$
stat sy

Fig. 2. The differential cross-section $BR(J/\psi \to \mu^+\mu^-)d\sigma/dp_T$, for $p\bar{p} \to J/\psi$ in the region $|y| < 2.0$. The curves show the Monte Carlo predictions described in the text and normalized to the data for $p_T > 5.0$ GeV/c: χ decays (dashed line), beauty decays (dotted line), (69–31)% mixture of χ and beauty decays (solid line).

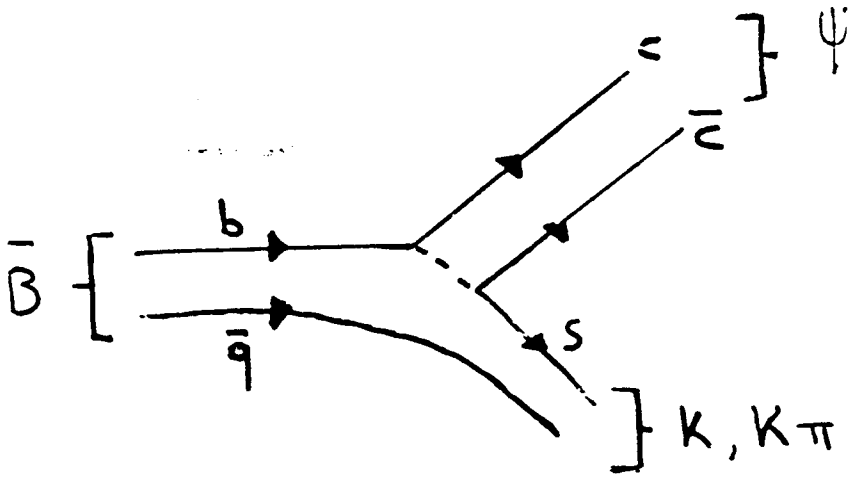
" Since beauty production as a function of P_T is well understood [16], we conclude that our Monte Carlo predic for the P_T slope of the χ process does not agree with t data"

" The predictions for direct charmonium production cross section include a K-factor of 2 which is also needed to reproduce data from the ISR"

" The observed production rate for ψ' is consistent within errors with the expectation for ψ' production from beauty decays alone"

Where do ψ's come from?

B decays

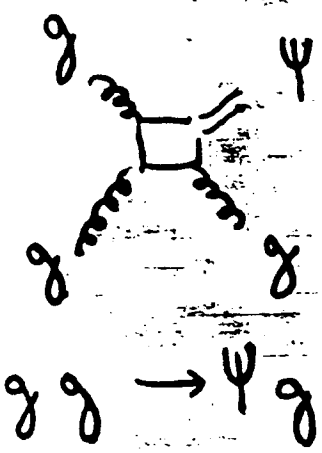


$gg, q\bar{q} \to b\bar{b}\{g\}$

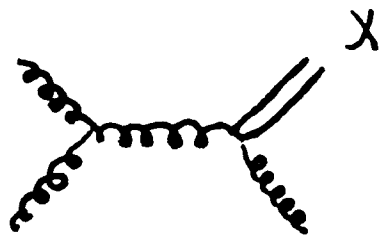
$gq \to b\bar{b}q$

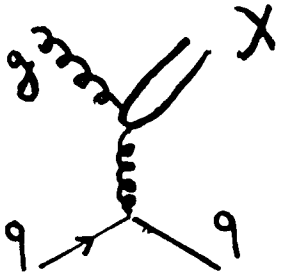
$b \to \bar{B} \to \psi X$

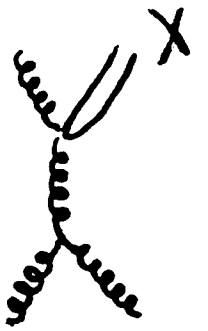
Direct production

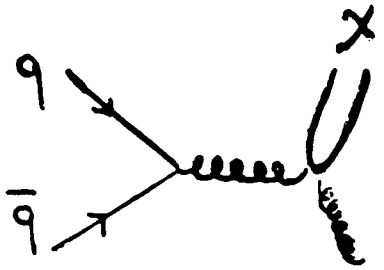


$gg \to \psi g$









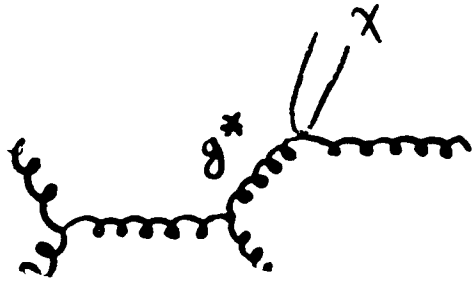
$gg, q\bar{q} \to X$

$gq \to X$

$X \to \psi$

Fragmentation

$gg \to gg^*$



HISTORY

$p\bar{p}$ Collider at $\sqrt{s} = 1.8$ TeV

◉ **1992 :** CDF published J/ψ, $\psi(2S)$ differential cross section measurements, which disagree with theory by big factors

which model is wrong/inadequate ?

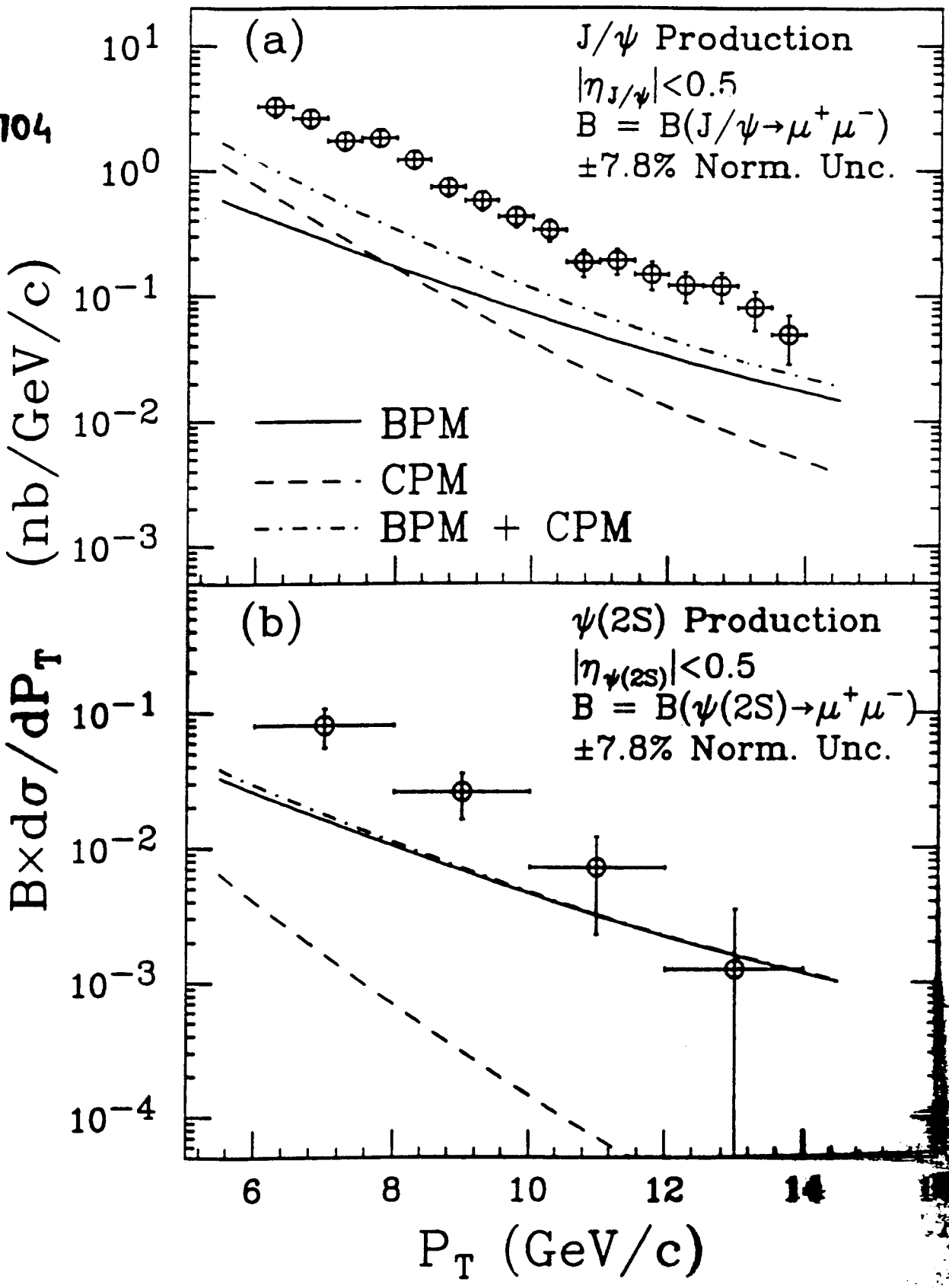
B decay ? | Prompt production (parton fusion) ? | Both ?

◉ **1993 :** Braaten and Yuan (PRL 71 (1993) 1673) point out that fragmentation processes will dominate at large P_T (parton fragmentation)

◉ **1994 :** CDF distinguished between J/ψ ($\psi(2S)$) from B or prompt and found big discrepancy especially with the prompt prod model, which included now parton fragment in the color singlet model
($\psi(2S) \sim 50\times$ discrepancy)

BPM: [illegible] production model

(Glover et al.) CPM: charmonium production mod



[illegible], 3704 (1992)

BPM: $Q^2 = M^2 + P_T^2$, DFLM structure [illegible]

CPM: $Q^2 = (M^2 + P_T^2)/4$, D_1 structure [illegible]

more studies from CDF

more studies from DØ

more -onia investigated

more on Theory front

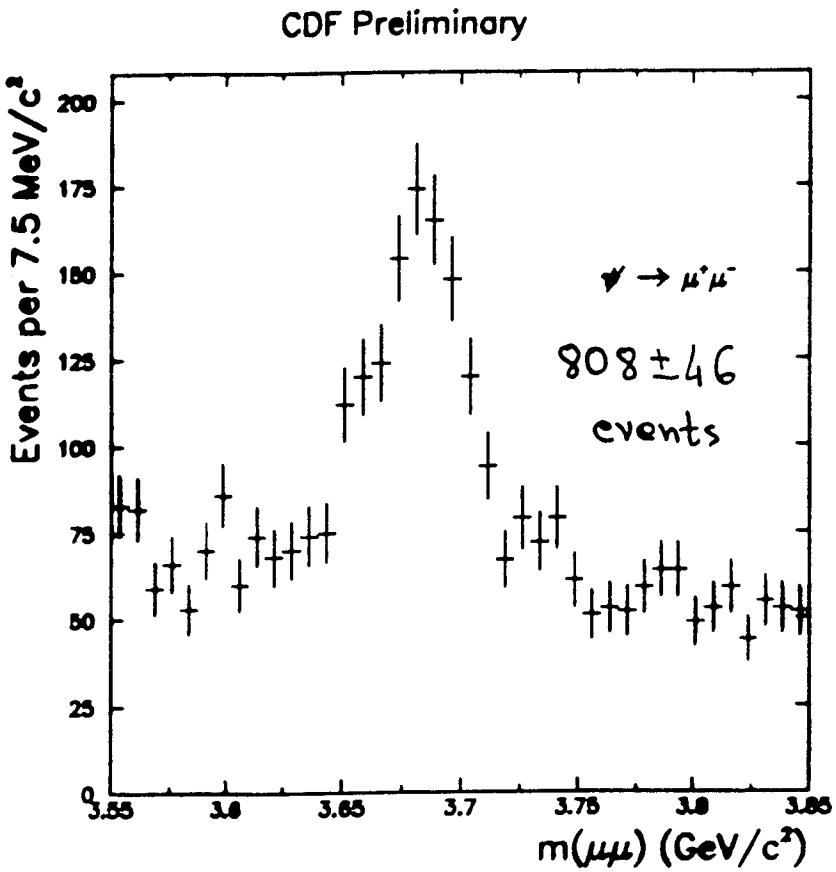
	CDF$_c$	DØ$_c$	Theory$_c$	CDF$_c$	DØ$_{Forw.}$
$\psi(2s)$	1				
J/ψ	3	2	6		8
χ_c	5	4		7 χ_{c_1}, χ_{c_2}	
Υ	10	9	11		

$\psi(2S) \rightarrow \mu^+\mu^-$

$17.8\ pb^{-1}$

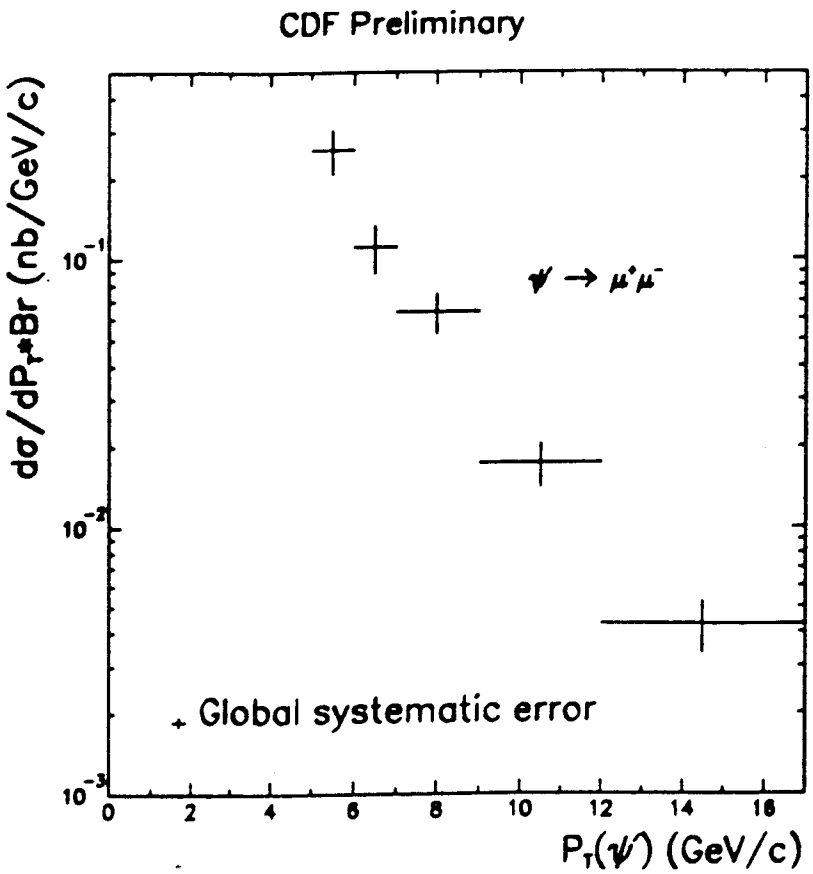
$P_T > 5\ GeV/c$

$|\eta| < 0.6$



$P_T^{\mu}(min) > 2.0\ GeV/c$

$P_T^{\mu}(max) > 2.8\ GeV/c$



$\sigma(p\bar{p} \rightarrow \psi' X) \cdot Br(\psi' \rightarrow \mu^+\mu^-)$

$= 0.571 \pm 0.036\ ^{+0.082}_{-0.089}$

(stat) (sys)

Measuring the fraction from B's

- Use SVX to identify displaced $\mu^+\mu^-$ vertex
- Measure L_{xy}, decay length in the transverse plane

$$L_{xy} = \vec{R} \cdot \vec{P}_t / P_t$$

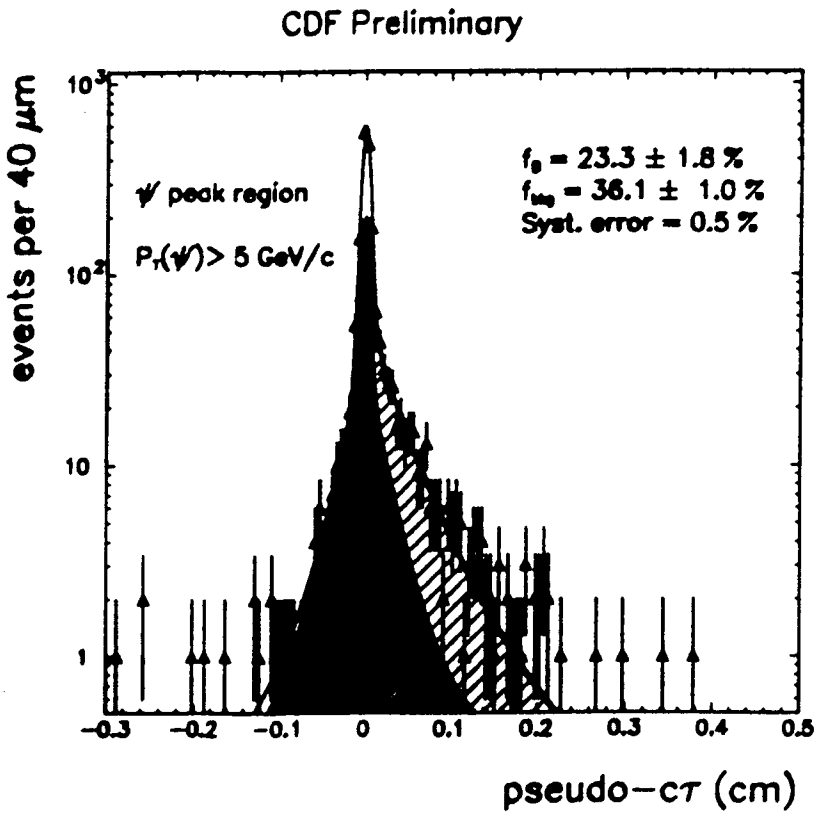
- Fit $c\tau_{pseudo}$ distribution

$$c\tau_{pseudo} = \frac{L_{xy}}{(P_t/M) \cdot F_{corr}}$$

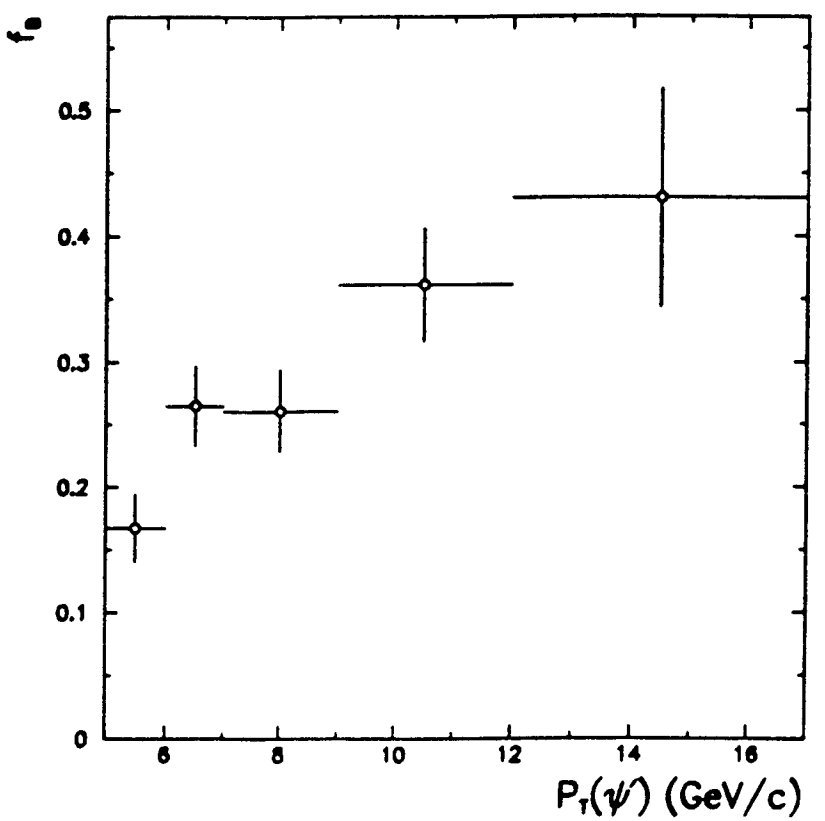
  - Prompt component
  - Long lived component from B's
  - Background component
  - F_{corr} correction factor from MC $(\beta\gamma)_\psi \rightarrow (\beta\gamma)_B$

$\psi(2S) \rightarrow \mu^+\mu^-$

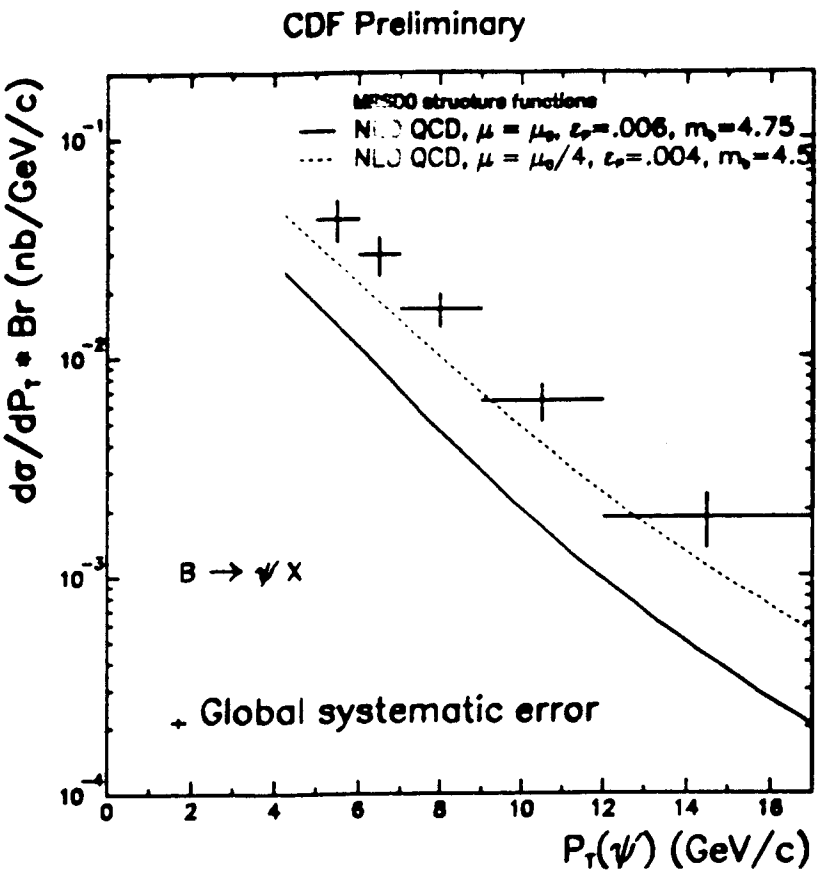
$\sim 110\ pb^{-1}$

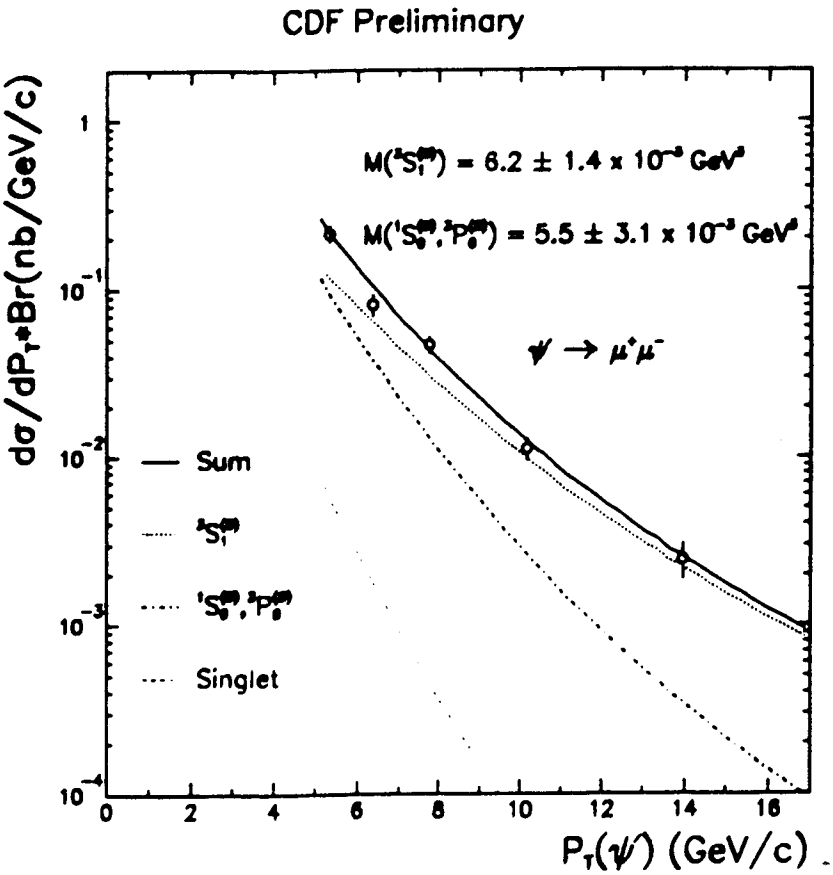


$$c\tau_{PS} = \frac{L_{xy}}{\left(\frac{P_T^{\mu\psi}}{m^{\psi'}}\right) \cdot F_{corr}(P_T^{\mu}}$$



$\psi(2S) \rightarrow \mu^+\mu^-$





WHAT IS THE SOURCE OF THIS EXCESS?

- Uncertainty in the determination of wave-function parameters; choice of scale $\sim$ 2-3 factc
- states above $D\bar{D}$ threshold whose deca to DD, $D^*\bar{D}$ is suppressed

(eg. $2^3P_{0,1,2}$. $Br(\chi'_{c2} \to \psi(2S)+\gamma) \approx 5-10\%$ needed to enhance $\psi(2S)$ production by an order of magnitude.)

- $c\bar{c}g$ hybrids

NRQCD

- subleading Fock components in $\psi(2S)$ wavefunctio

$$|\psi(2S)\rangle = O(1)|c\bar{c}[^3S_1^{(1)}]\rangle + O(v)|c\bar{c}[^3P_J^{(8)}]g\rangle +$$
$$O(v^2)|c\bar{c}[^3D_J^{(1,8)}]gg\rangle + O(v^2)|c\bar{c}[^1S_0^{(8)}]g\rangle +$$
$$O(v^2)|c\bar{c}[^3S_1^{(1,8)}]gg\rangle + \cdots$$

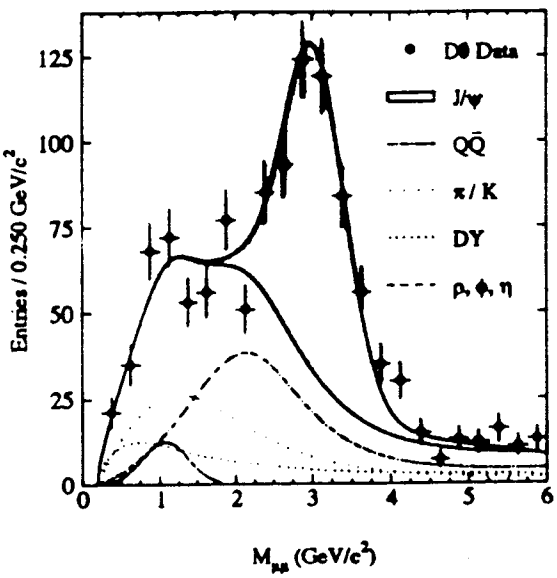
Inclusive $J/\psi, \psi(2S)$ Production at D0

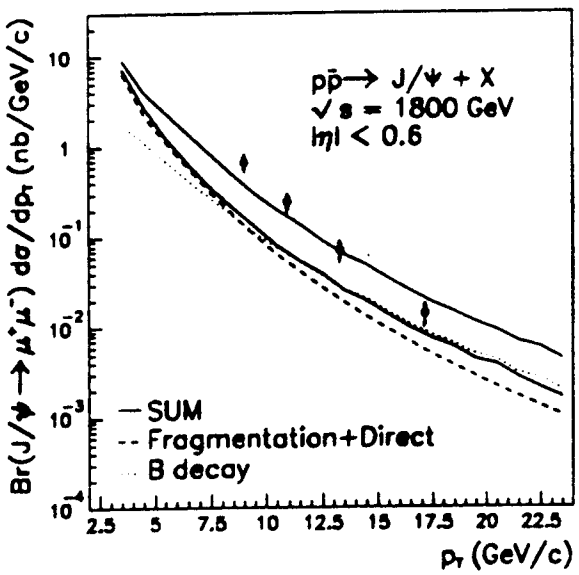
$J/\psi, \psi(2S) \rightarrow \mu^+\mu^-$

Dimuon Invariant Mass

$P_T^{\mu\mu} > 8GeV,\ c,\ |\eta^{\mu\mu}| < 0.6$

- To determine relative contributions use: $M_{\mu\mu}$, p_T^{rel} of dimuon to jet axis and the muon isolation parameter, I_μ
- In 6.6 pb^{-1} D0 has: 407 ± 28 (stat) $\pm$ 55 (sys) $J/\psi, \psi(2S)$ events





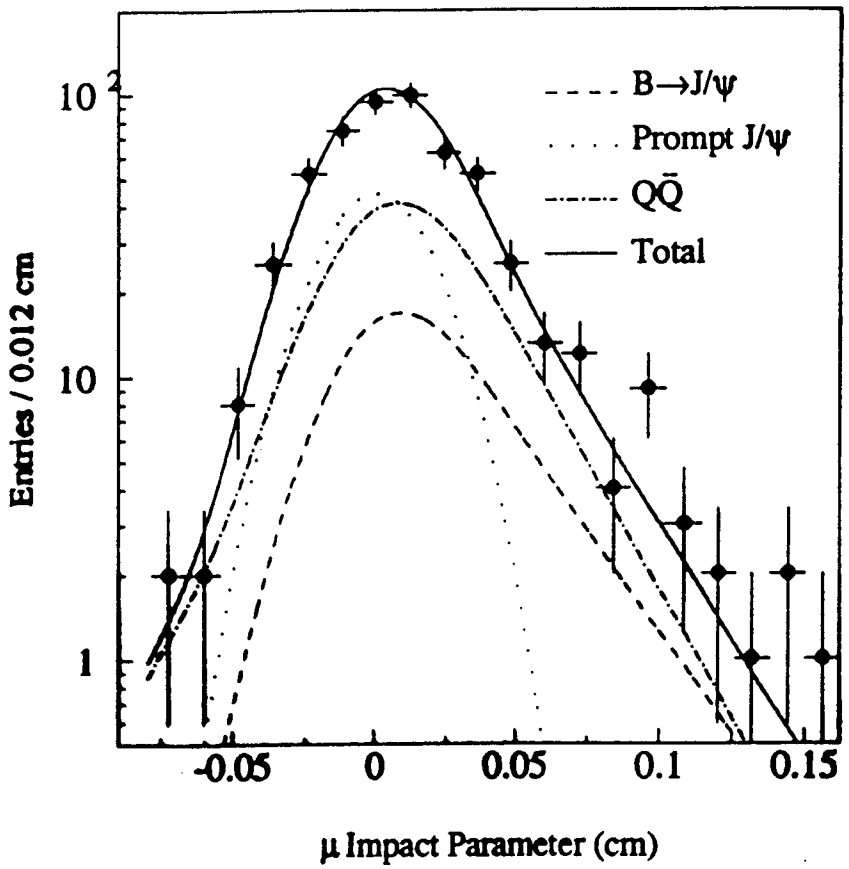
$\sigma(\bar{p}p \rightarrow J/\psi X) \times Br(J/\psi \rightarrow \mu^+\mu^-) =$
$2.08 \pm 0.17(stat) \pm 0.46(syst)$ nb
$P_T^{\mu\mu} > 8$ GeV/c. $|\eta^{\mu\mu}| < 0.6$

$\pm \sim 20\%$ error due to polarization

J/ψ Production from B Meson Decays

Examine the impact parameter of muons relative to the event vertex in the transverse plane

- Require **muons** to have matching tracks in the central **drift chamber** and in the inner vertex chamber
- **2.0** $< M_{\mu\mu} <$ 4.4 GeV/c^2
- **impact** parameter: $-0.08 <$ Imp $<$ 0.16 **cm**



- **Simultaneous** $M_{\mu\mu}$ **and Imp fit**

$$f_b = 0.35 \pm 0.09\,(\text{stat}) \pm 0.10\,(\text{sys})$$

$P_T^{J/\psi} > 8$ GeV

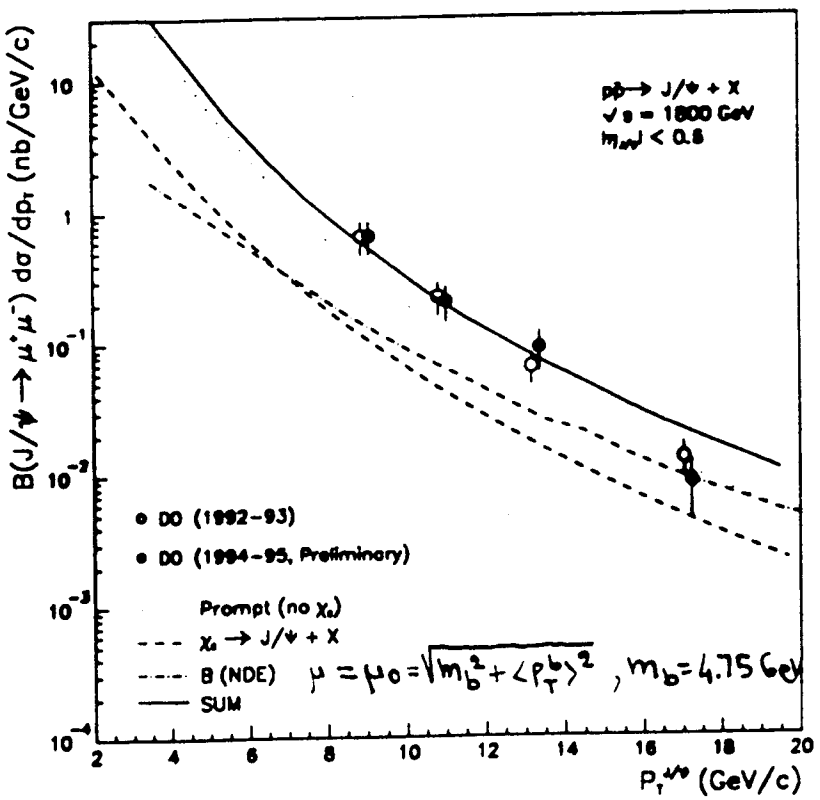
Inclusive J/ψ Production at D0

$$J/\psi \to \mu^+\mu^-$$

Production Cross section as a function of J/ψ P_T

$$P_T^{\mu\mu} > 8GeV/c,\ |\eta^{\mu\mu}| < 0.6$$

8.6 pb^{-1} from 1994-95 data



$$\sigma(\bar{p}p \to J/\psi X) \times Br(J/\psi \to \mu^+\mu^-) =$$

$$1.96 \pm 0.16(stat) \pm 0.63(syst)\ \text{nb}$$

$J/\psi \to \mu^+\mu^-$

CDF

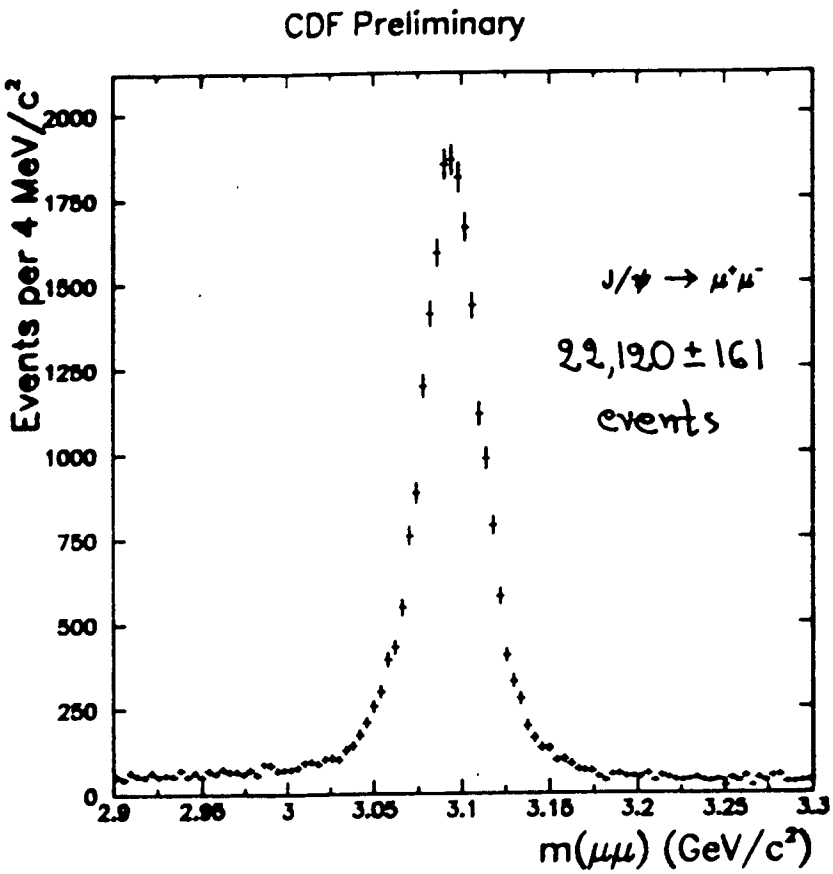
15.4 pb^{-1}

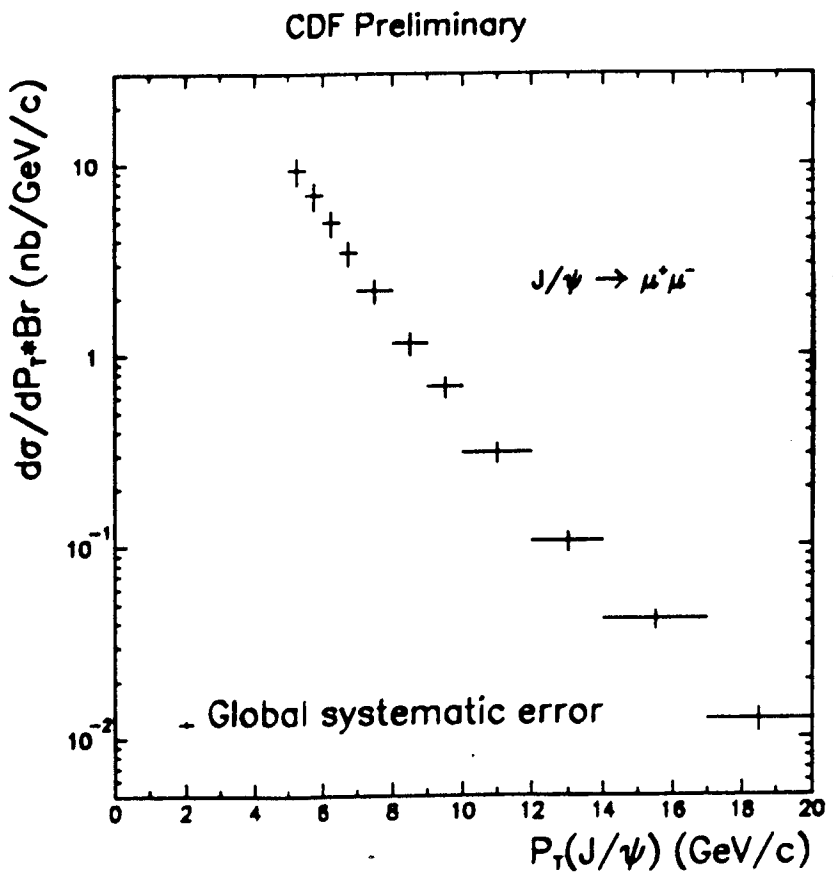
$P_T > 5$ GeV/c

$|\eta| < 0.6$

$P_T^{\mu}(min) > 2.0$ GeV/c

$P_T^{\mu}(max) > 2.8$ GeV/c





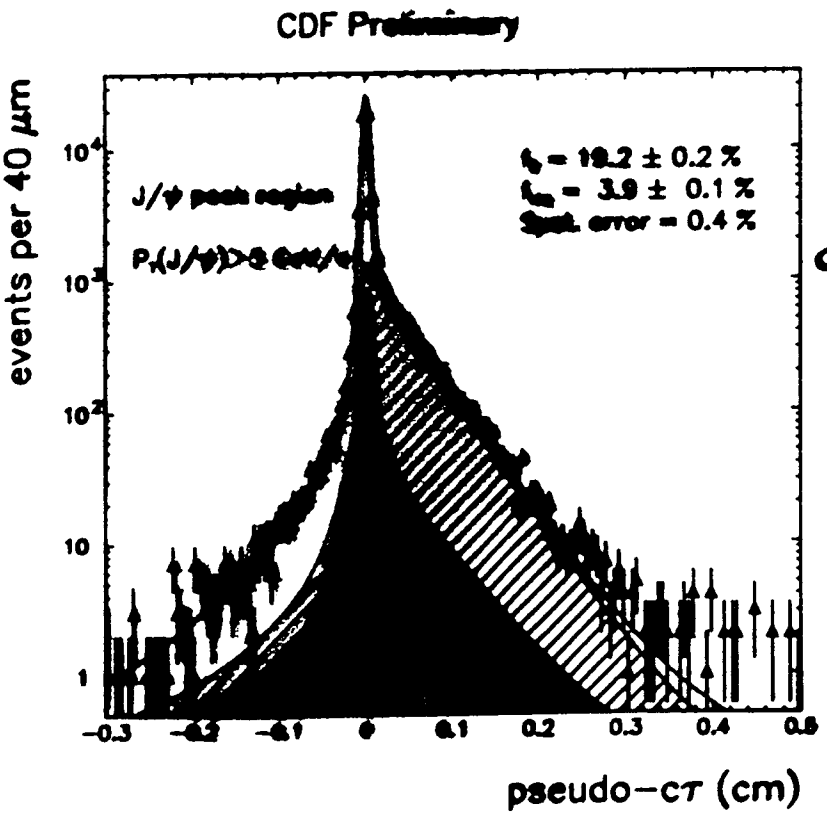
$\sigma(p\bar{p} \to J/\psi X) \cdot Br(J/\psi \to$

$= 17.35 \pm 0.14\ ^{+2.59}_{-2.79}$ nb

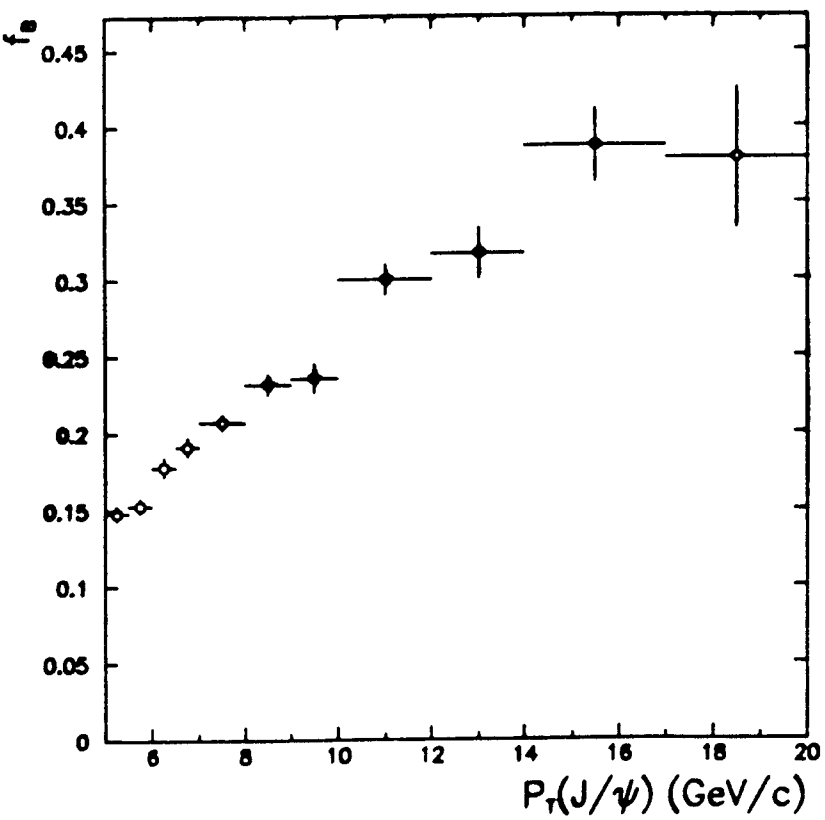
(stat) (sys)

$J/\psi \rightarrow \mu^+\mu^-$

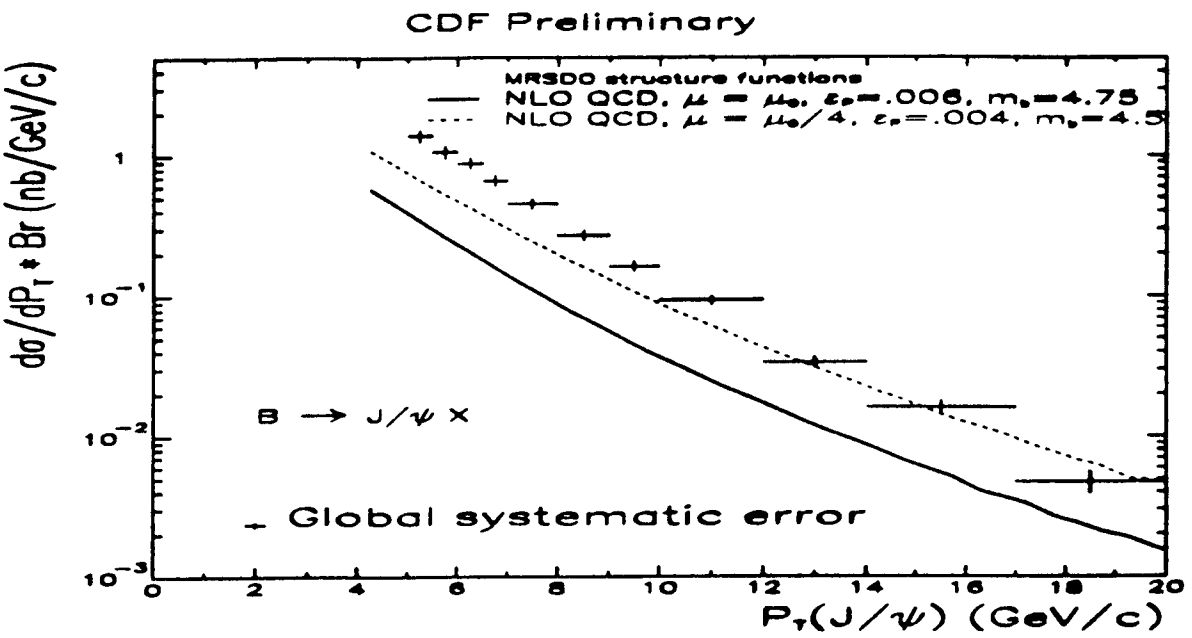
$\sim 110\ pb^{-1}$



$$c\tau_{ps} = \frac{L_{xy}}{\left(\frac{P_T^{\mu\mu}}{m^{J/\psi}}\right) F_{corr}(P_T^{\mu\mu})}$$



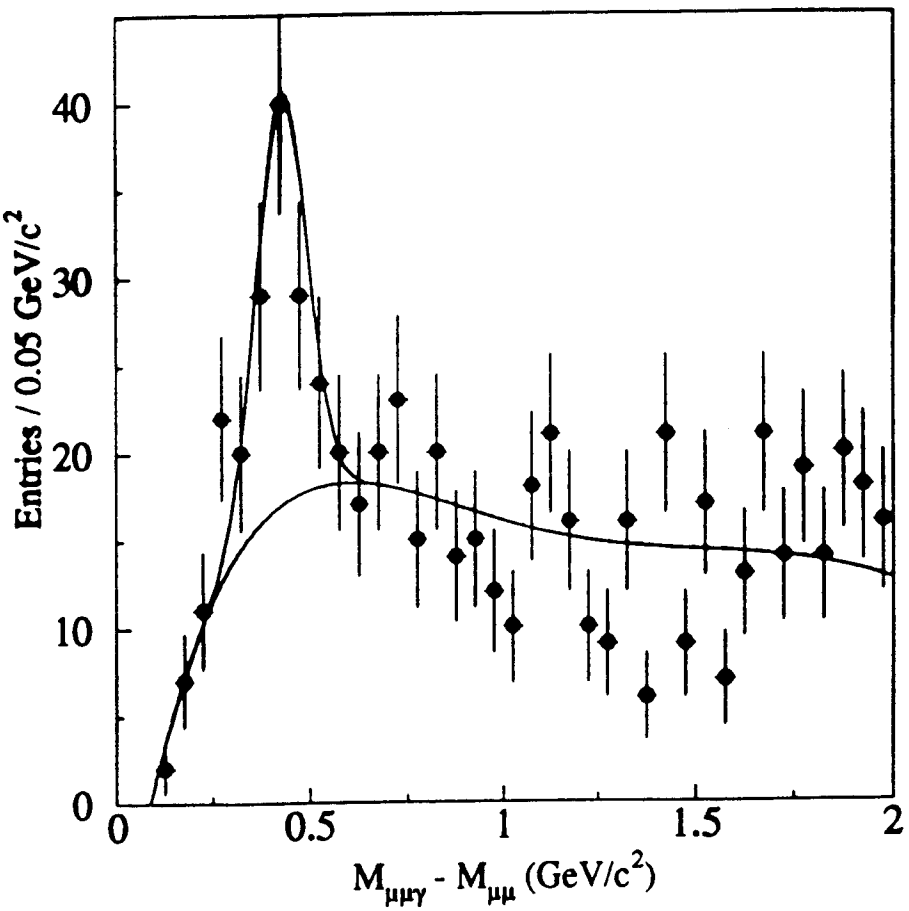
J/ψ cross section



- Fraction from B's is also about right
- Most prompt J/ψ are expected to come from χ_c
- We have to account for direct J/ψ and feed down from χ_c
- $\Rightarrow$ Measure fraction of J/ψ from $\chi_c \rightarrow J/\psi\ \gamma$

$\chi_c \to J/\psi\,\gamma$ (DØ)

- $E_\gamma > 1$ **GeV**
- **Plot** $M_{\mu\mu\gamma} - M_{\mu\mu}$ **in** J/ψ **signal region**



$$N_\chi = 70 \pm 15(\text{stat}) \pm 15(\textbf{sys})$$

$$F_\chi = 0.32 \pm 0.07(\text{stat}) \pm 0.07(\textbf{sys})$$

- **Accounting for contribution from** $B \to \chi_c$, **find** 0.41 ± 0.17 **of** J/ψ **not from** B **or** χ_c

Prompt J/ψ production is not dominated by χ_c

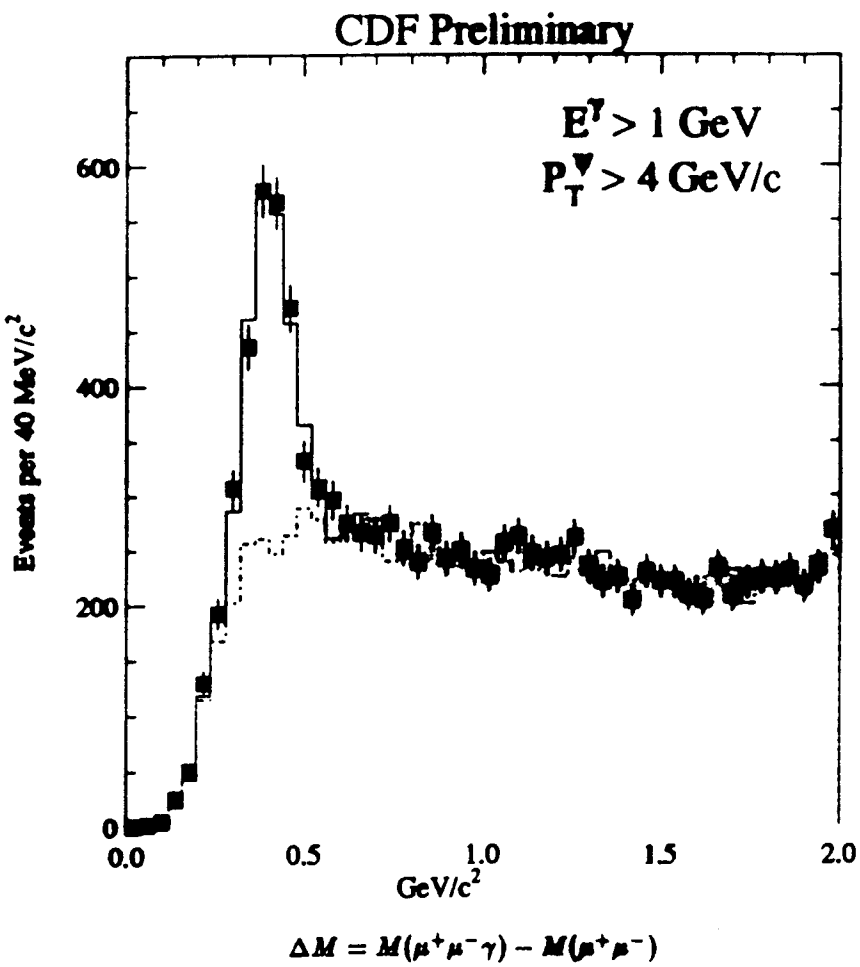
$\chi_c \to J/\psi\gamma,\ J/\psi \to \mu^+\mu^-$ (CDF)

$\int \mathcal{L}dt \sim 18\,\mathrm{pb}^{-1}$

- Identify photon by demanding central E.M. calorimeter energy deposition, $E^\gamma > 1.0\ GeV$, and a cluster in the central E.M. strip chambers
- No charged track pointing to calor. tower

1230 ± 71 events

$(\varepsilon \cdot A)^{\gamma}_{\psi}$ = 15.9%



$M(\chi_{c2}) - M(\chi_c$

= 45.7 Mel

Too close to be resolv with this me

Background Model

- Use charged tracks in real J/ψ events
- Call each track π^0, η or K_s
- Decay particles into γ's and simulate detector response
- Combine γ's with J/ψ and plot ΔM

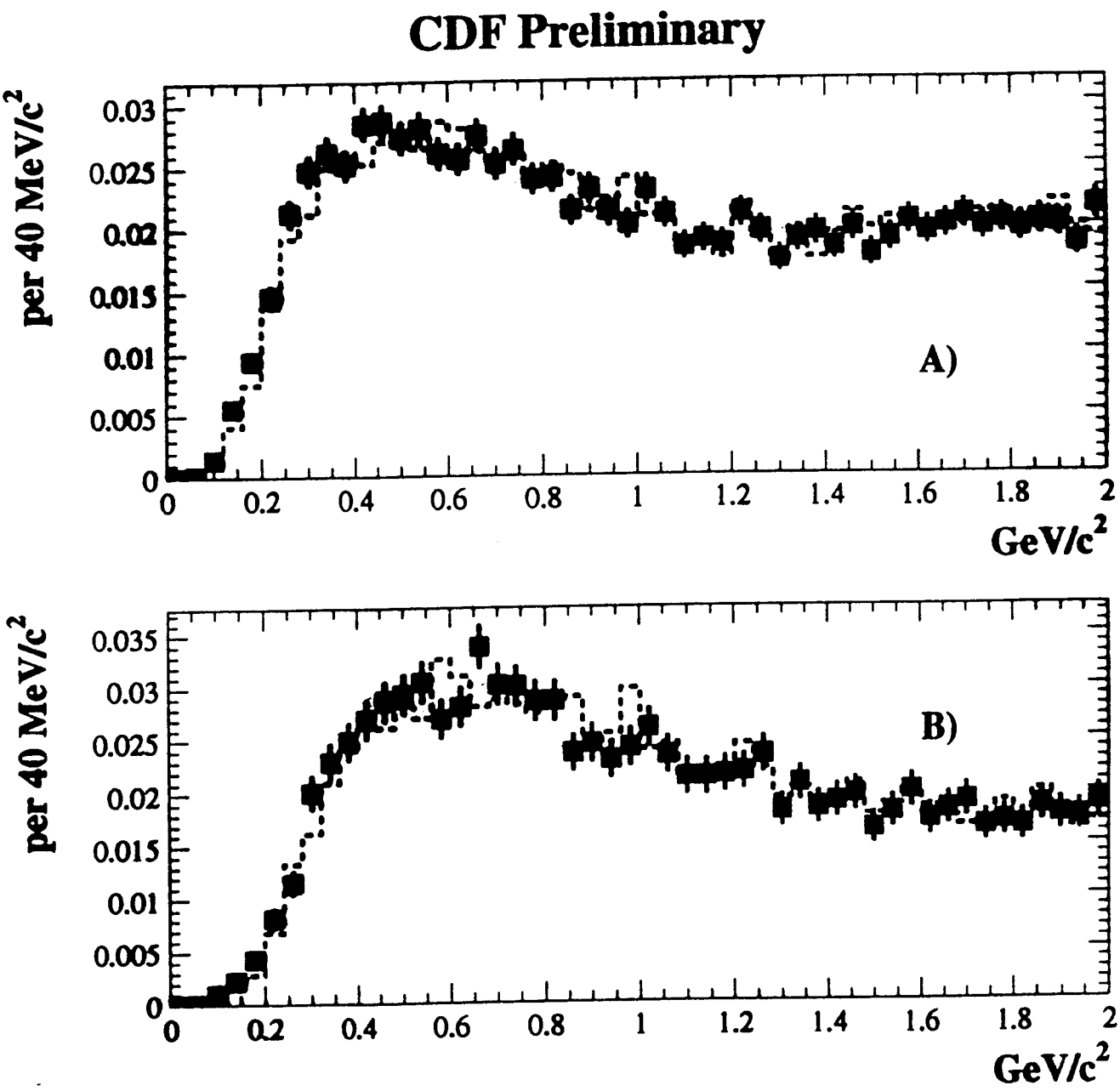
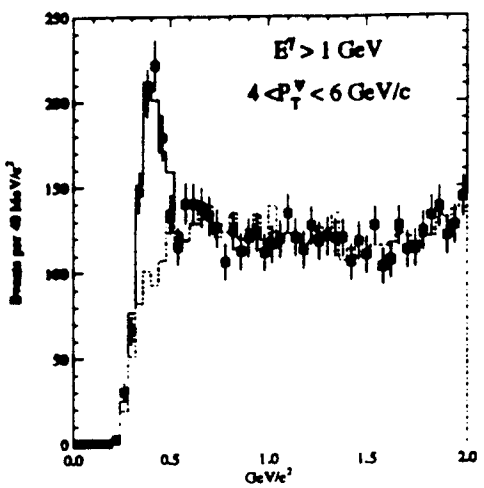
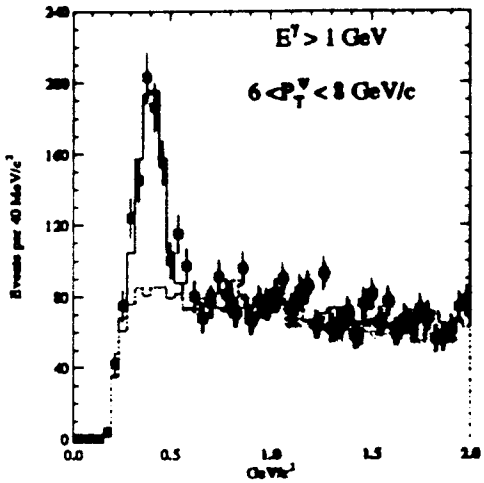


Figure 1: Mass difference $M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$ for the ψ sidebands in 40 MeV/c^2 bins. The points show the data histogram and the dashed line is the shape predicted by our background Monte Carlo. Both histograms are normalized to unit area. A) $E^\gamma > 0.7$ GeV and $p_T^{J/\psi} > 4$ GeV, B) $E^\gamma > 1.0$ GeV and $p_T^{J/\psi} > 4$ GeV

CDF Preliminary

13 ± 34 events

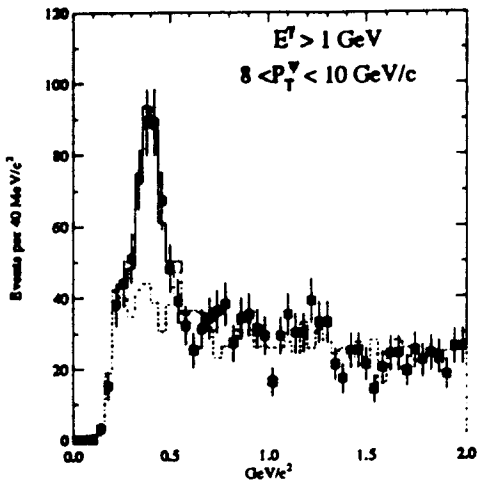


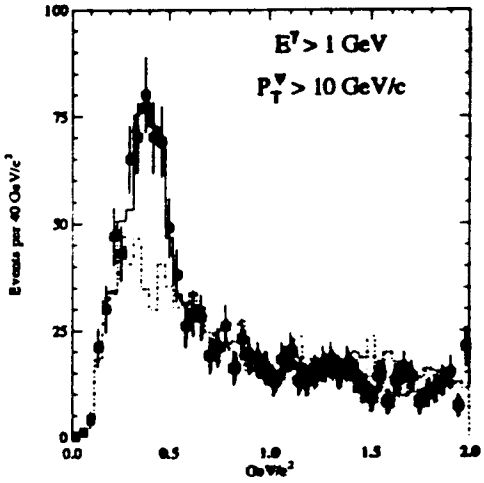


432 ± 34 events

$[M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)]$ GeV/c^2

195 ± 23 events

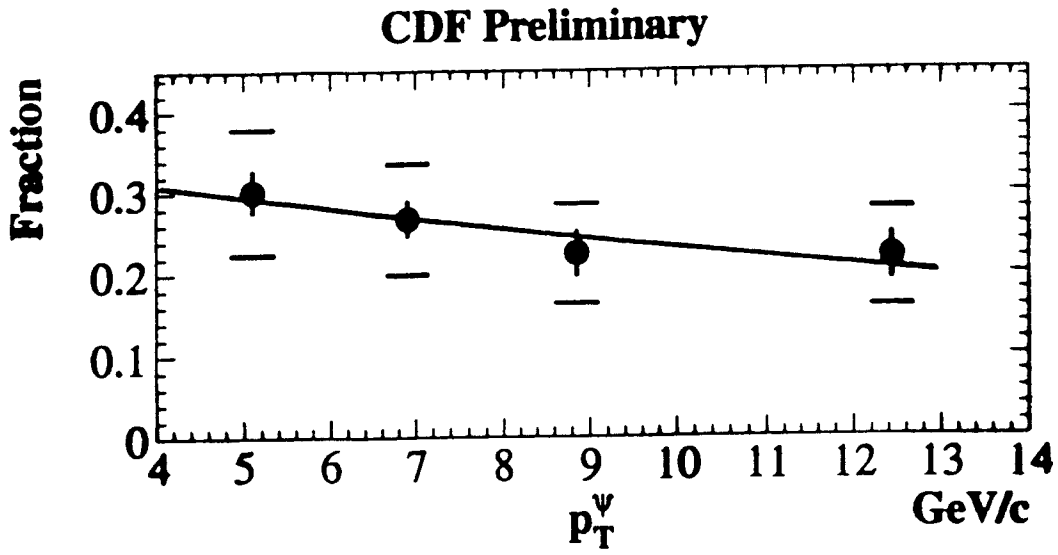




175 ± 22 events

$[M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)]$ GeV/c^2

Figure 1: Mass difference $M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$ for the ψ signal region in 40 MeV/c^2 bins. The points show the data histogram, the shaded histogram is the background shape predicted by our background Monte Carlo. The solid line is the fit to the data of a gaussian signal plus the background histogram.



Systematic error $(P_T^\psi) = 0.24\times$ fraction(P_T^ψ)

Fraction of J/ψ from χ_c vs $p_T^{J/\psi}$

$P_T^\psi > 4.0\,GeV/c$	$0.283 \pm 0.0^{\cdot}6 \pm 0.068$
$4.0 < P_T^\psi < 6.0\,GeV/c$	$0.302 \pm 0.026 \pm 0.072$
$6.0 < P_T^\psi < 8.0\,GeV/c$	$0.268 \pm 0.022 \pm 0.064$
$8.0 < P_T^\psi < 10.0\,GeV/c$	$0.224 \pm 0.028 \pm 0.054$
$P_T^\psi > 10.0\,GeV/c$	$0.220 \pm 0.029 \pm 0.053$

Figure 1: Fraction of J/ψ from χ_c as function of the J/ψ p_T . The contribution from b's is not removed.

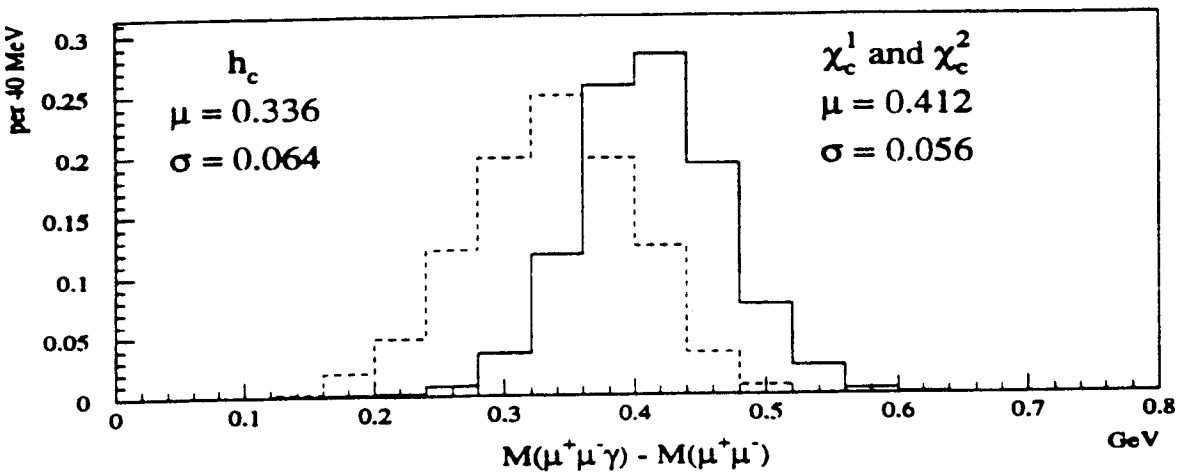
Systematic Uncertainties

photon electron difference	± 0.16
(CES requirement removed, known diff. in detector response not applied)	
χ_c production and decay model	± 0.11
(power law exponent (10%), angular variations (5%))	
background shape	± 0.10
(Fitting uncertainties (± 3%), Varry π^0, η, K_s composition (± 5%), Other physics processes* (-10%))	
ϵ^γ	± 0.05
total	± 0.224

* $h_c \to J/\psi\pi^0$
$\psi(2S) \to J/\psi\pi^0\pi^0$, $\psi(2S) \to J/\psi\eta$, $\psi(2S) \to J/\psi\pi^0$,
$\psi(2S) \to \chi_c\gamma$

$h_c \longrightarrow J/\psi\,\pi^0$

$\uparrow_{3526\ MeV/c^2}$



- 76 MeV lower than χ_c peak
- 2.8 times lower probability to pass analysis cuts

no peak at low mass, below χ_c peak.

2 gaussian fit $\Rightarrow$ ~10% contribution

Figure 22: Mass difference $M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$ distribution for χ_c^1 and χ_c^2 (solid) compared with $h_c \rightarrow J/\psi\,\pi^0$ (dashed) obtained from the Monte Carlo simulation in 40 MeV/c^2 bins. The photon is required to have $E^\gamma > 1.0$ GeV.

2 gaussian fit (fixed distance, fixed width from Monte Ca
allowed to float together)

1109 ± 91 χ_c $\quad$ 136 ± 102 h_c

Removing $B \rightarrow J/\psi\, X$ and $B \rightarrow \chi_c\, X$

We use only J/ψ reconstructed in the SVX and:

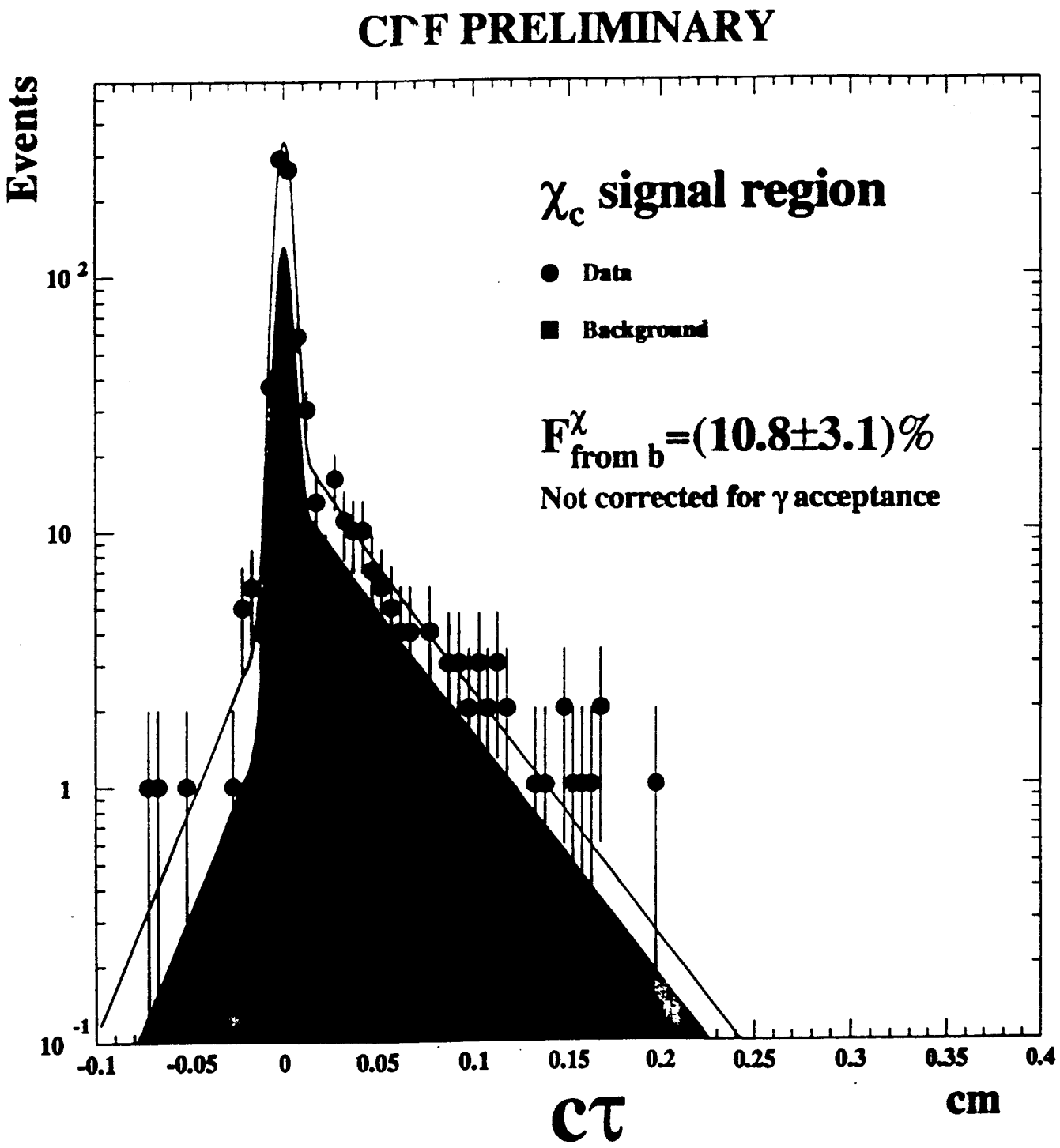
measure fraction of χ_c from $B \rightarrow J/\psi\, X$
and the fraction of J/ψ from B's

$$F(No\ b)^{\psi}_{\chi} = F^{\psi}_{\chi} \cdot \frac{1 - F^{\chi}_{b}}{1 - F^{\psi}_{b}} = F^{\psi}_{\chi} \cdot (1.085 \pm 0.04)$$

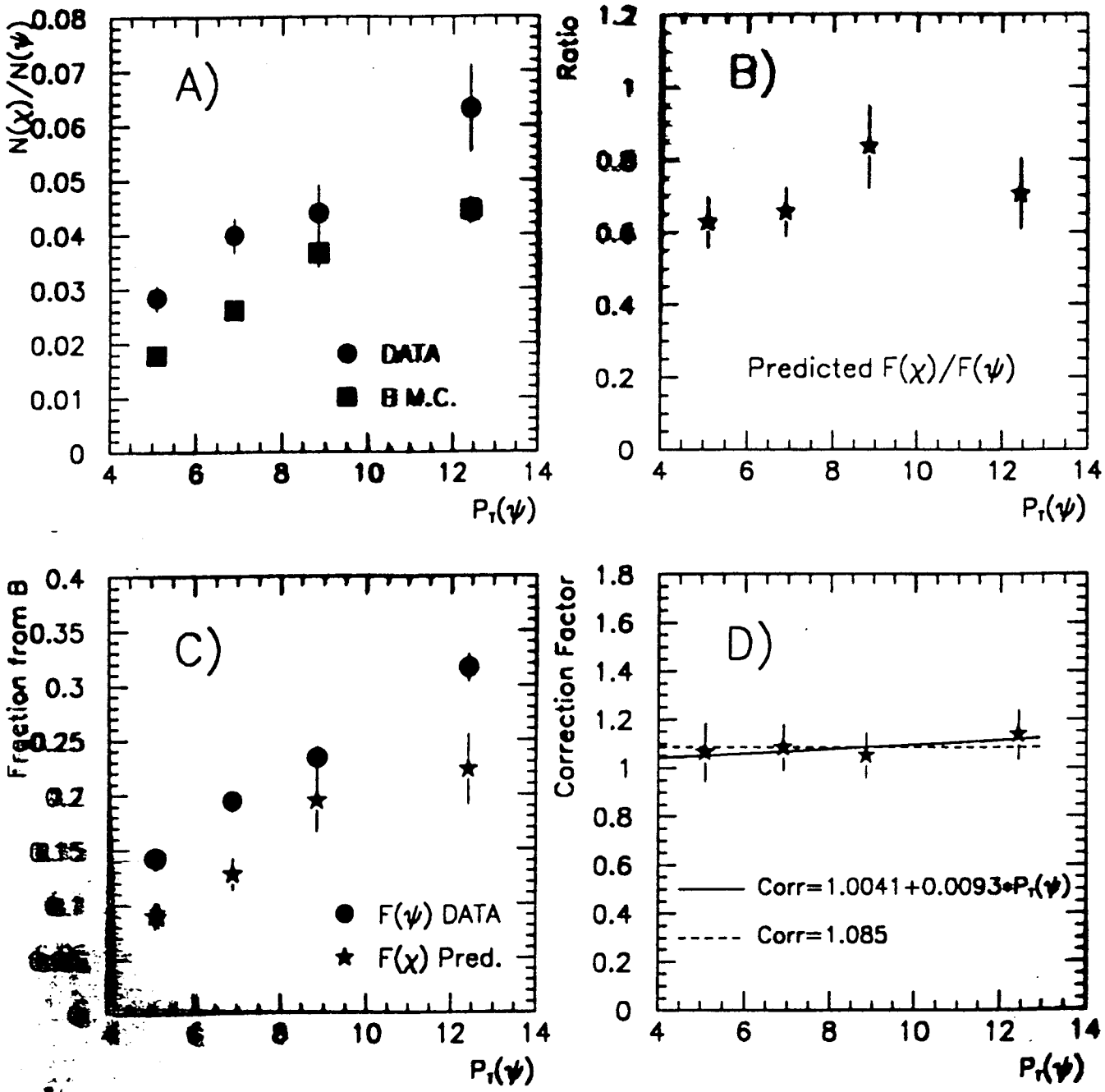
$$F(N_o b)^{\psi}_{\chi} = \frac{N^{\chi_c} - N^{\chi_c}_{\text{from } b}}{(N^{\psi} - N^{\psi}_{\text{from } b}) \cdot A^{\gamma}_{\psi} \cdot \varepsilon^{\gamma}} = F^{\psi}_{\chi} \cdot \frac{1 - F^{\chi}_{b}}{1 - F^{\psi}_{b}}$$

$F_b^{\psi} = 17.8 \pm 0.2 \pm 0.4\,\%$ $\quad P_T^{\psi} > 4$ GeV/c

$F_b^{\chi} = (10.8 \pm 3.0)\,\%$ $\quad P_T^{\psi} > 4$ GeV/c


CDF PRELIMINARY
Events
χ_c signal region
Data
Background
$F^{\chi}_{\text{from b}}=(10.8\pm3.1)\%$
Not corrected for γ acceptance
10^2
10
1
10^{-1}
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
$c\tau$
cm

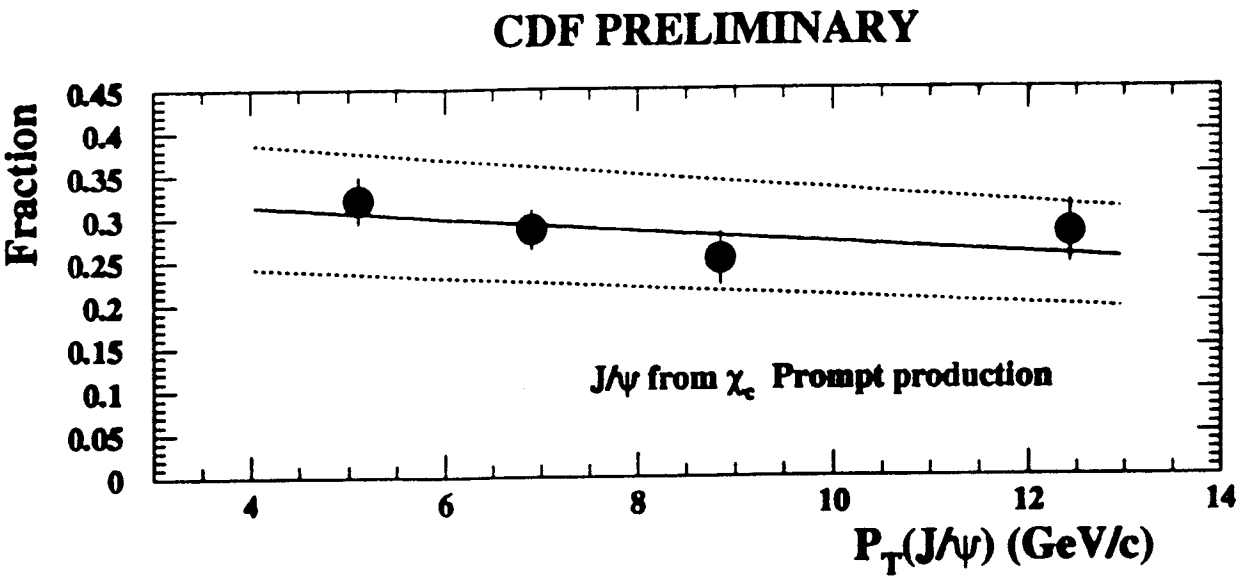
correction factor: $\dfrac{1-F_b^{\chi}}{1-F_b^{\psi}}$



We [illegible] F_b^{ψ} as a function of $P_T^{3/\psi}$ (measurement)

we can predict F_b^{χ} as a function of $P_T^{3/\psi}$

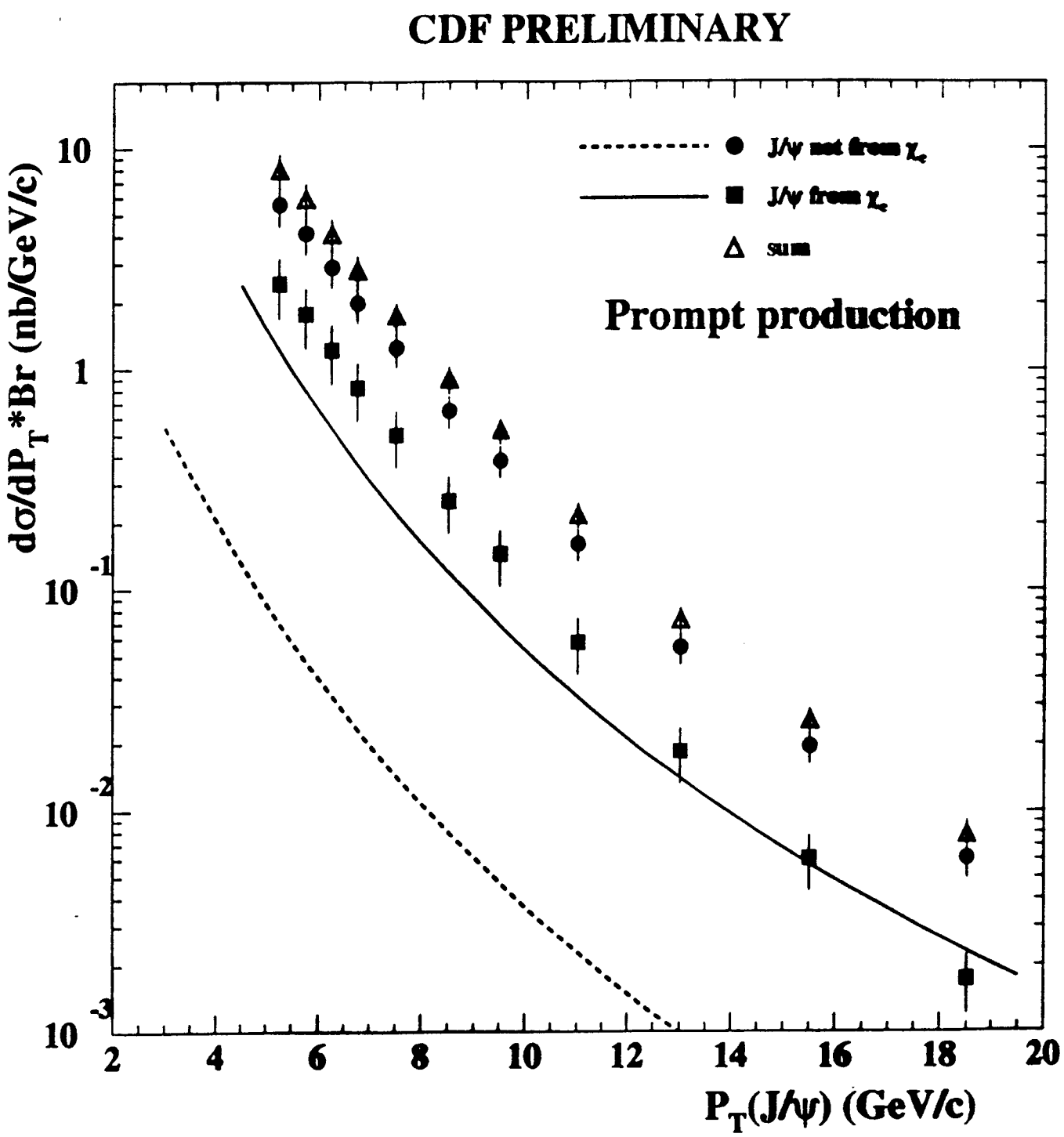
$$R = \frac{F_b^{\chi}}{F_b^{\psi}} = \frac{\frac{N_b^{\chi}}{N^{\chi}}}{\frac{N_b^{\psi}}{N^{\psi}}} = \frac{\left(\frac{N_b^{\chi}}{N_b^{\psi}}\right)^{MC}}{\frac{N^{\chi}}{N^{\psi}}}_{\text{measure}} \Rightarrow F(\text{pred})_b^{\chi} = R_{MC} F_b^{\psi}$$



$$F\,(N_{ob})_{\chi}^{J/\psi} = (31.2 \pm 1.8\,(stat) \pm 7.1\,(syst))\,\%$$

for $P_T^{J/\psi} > 4$ GeV/c

$|\eta^{J/\psi}| < 0.6$



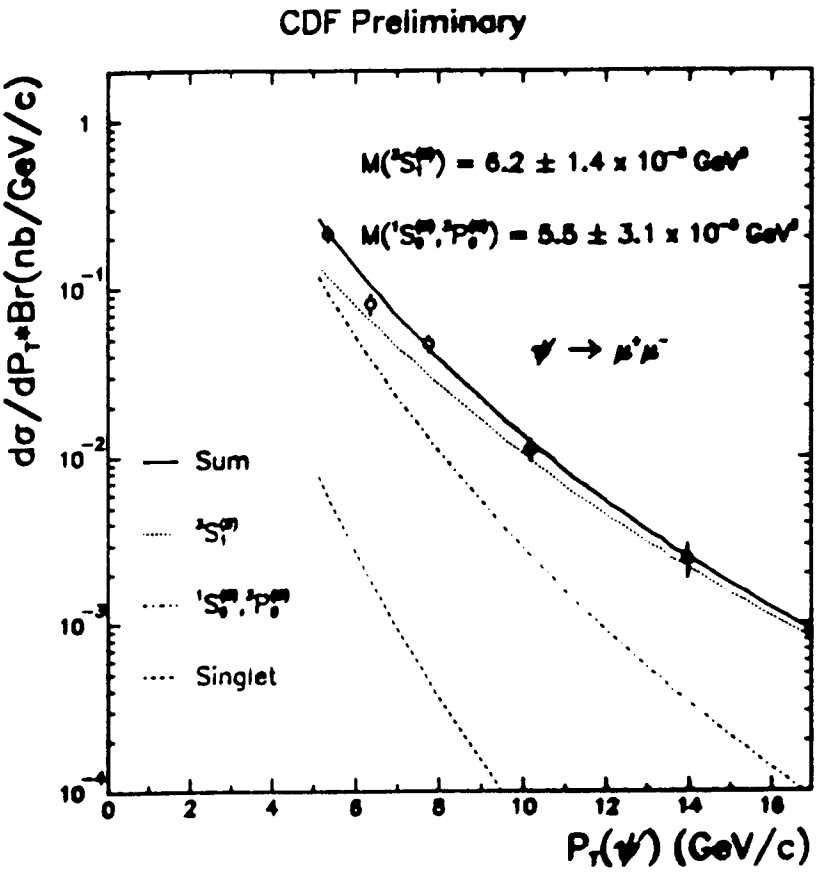
– – – Color Singlet

——— Color Singlet + $c\bar{c}[^3S_1^{(8)}]$

$J/\psi, \psi(2S) \rightarrow \mu^+\mu^-$

Fitting the color-octet shapes to the data

B contribution removed



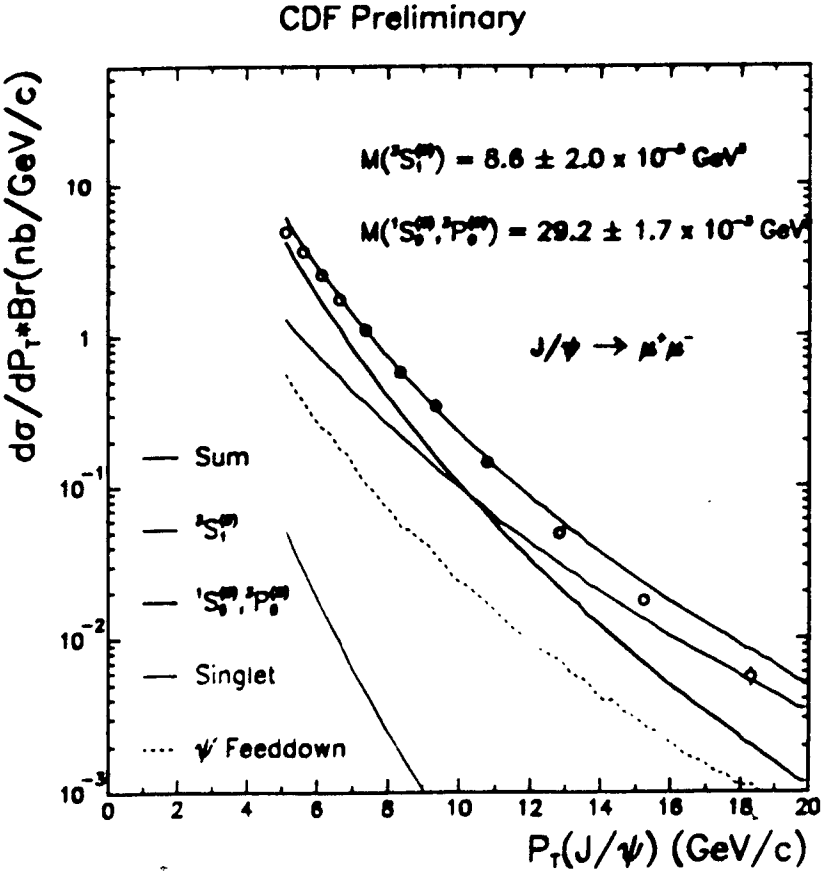
P.C + A.L

$(4.6 \pm 1.0) \times 10^{-3}$

$(5.9 \pm 1.9) \times 10^{-3}$

independent fits

B, χ contributions removed

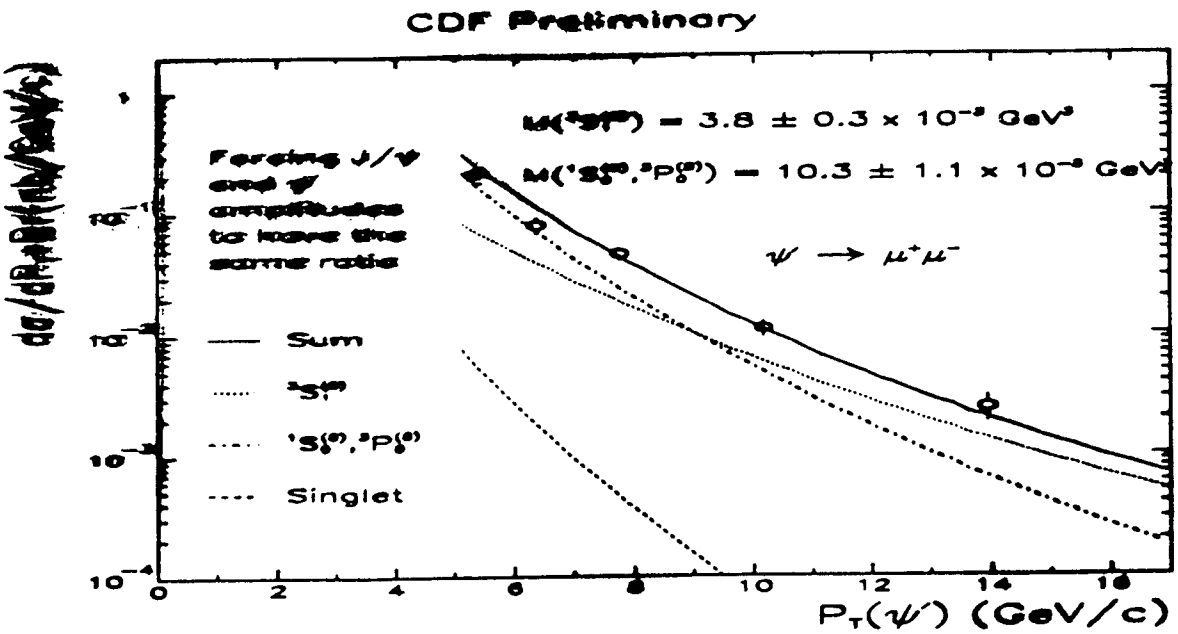


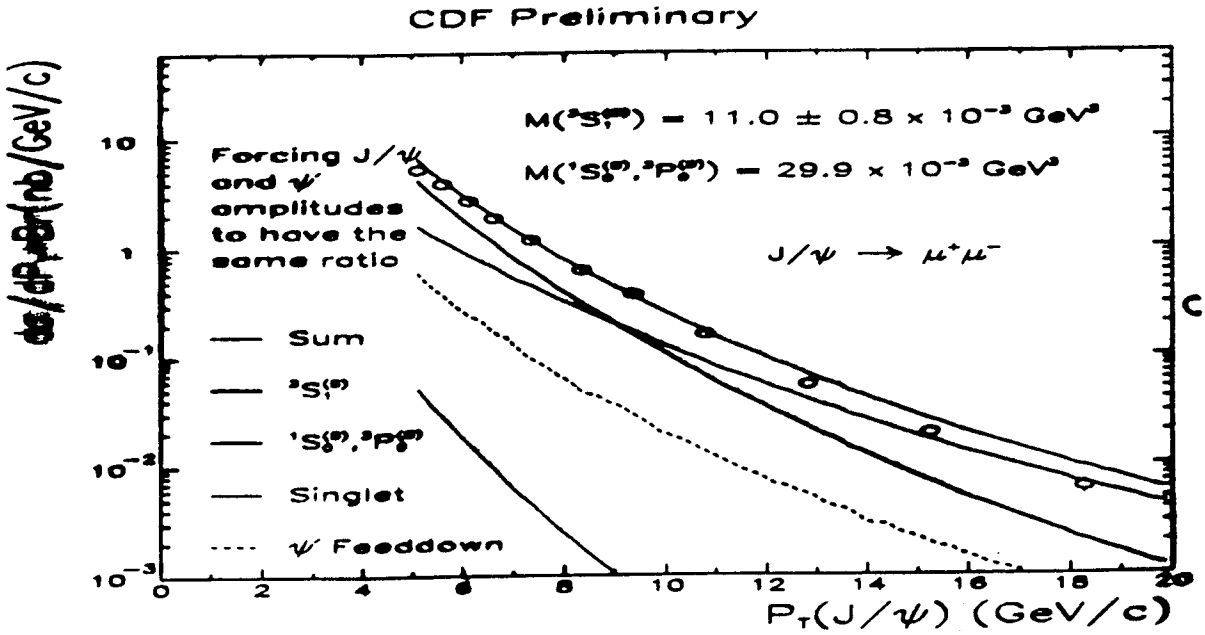
P.C + A.L

$(6.6 \pm 2.1) \times 10^{-3}$

$(22.0 \pm 5) \times 10^{-3}$

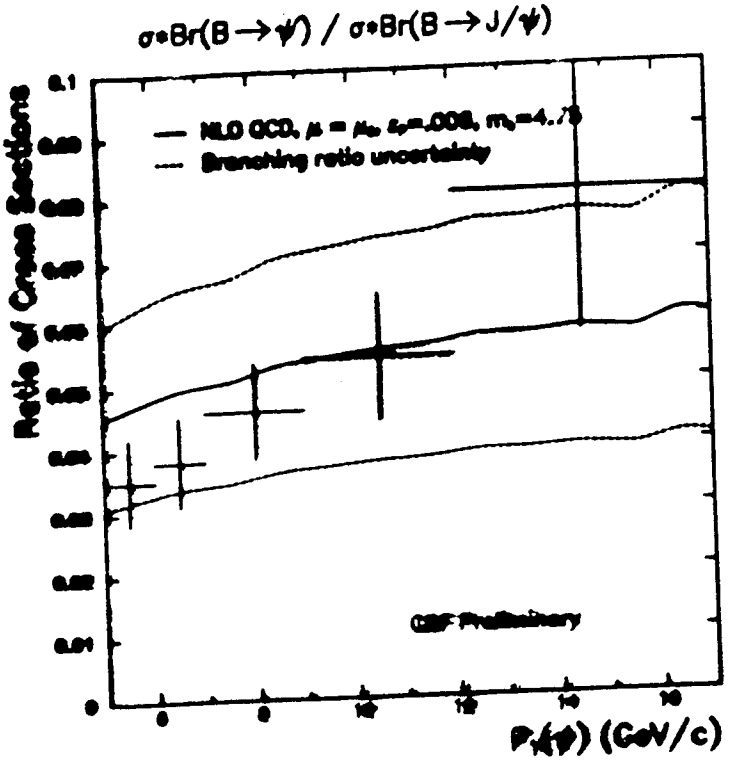
Combined fit to J/ψ and $\psi(2S)$

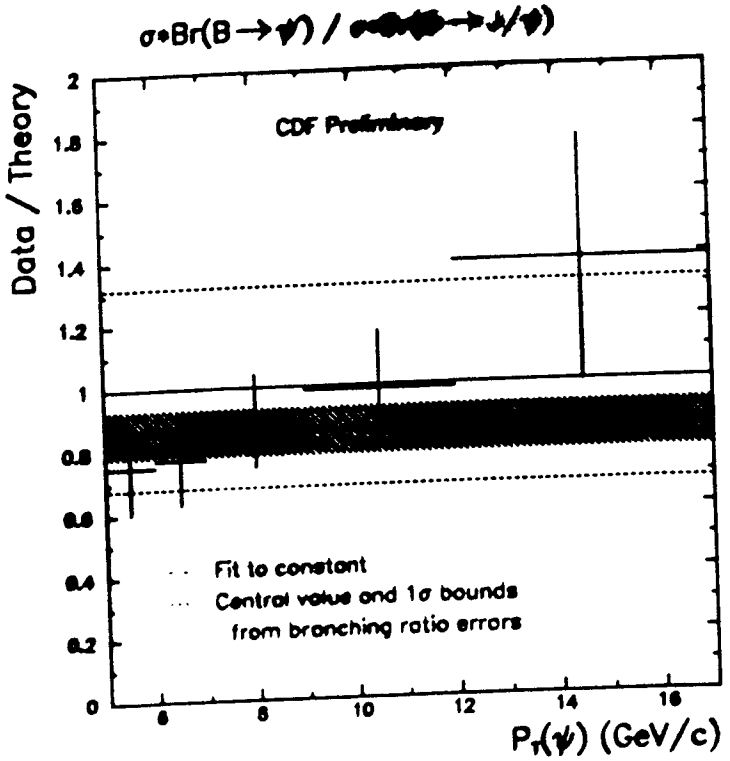




Ratio of Cross Sections from B Decays

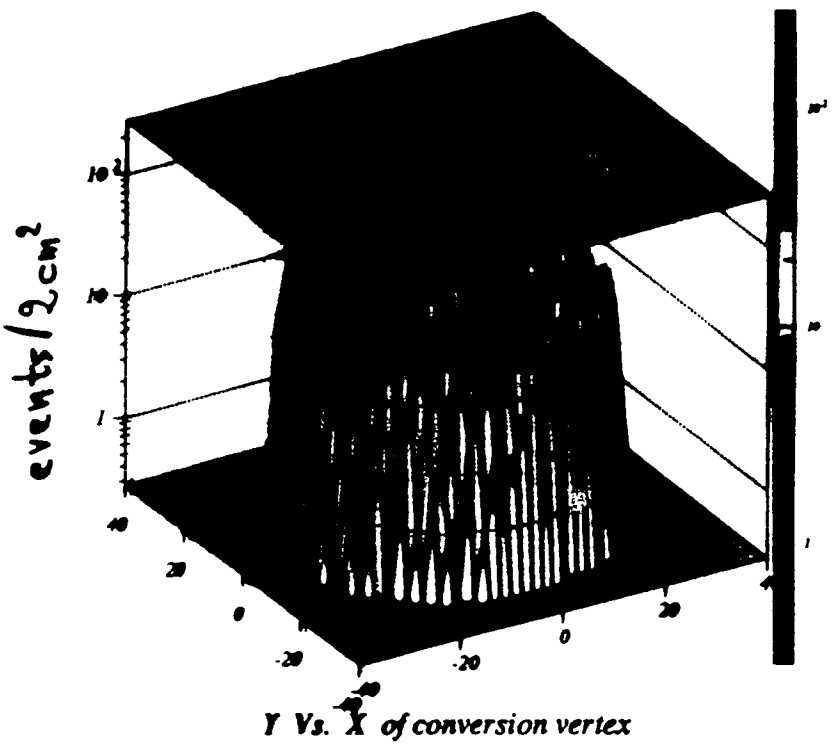
$J/\psi, \psi(2S) \rightarrow \mu^+\mu^-$





$$\frac{Br(B \rightarrow \psi' X) \cdot Br(\psi' \rightarrow \mu^+\mu^-)}{Br(B \rightarrow J/\psi X) \cdot Br(J/\psi \rightarrow \mu^+\mu^-)} = 0.033 \pm 0.003\ (\text{stat}) \pm 0.002\ (\text{sys})$$

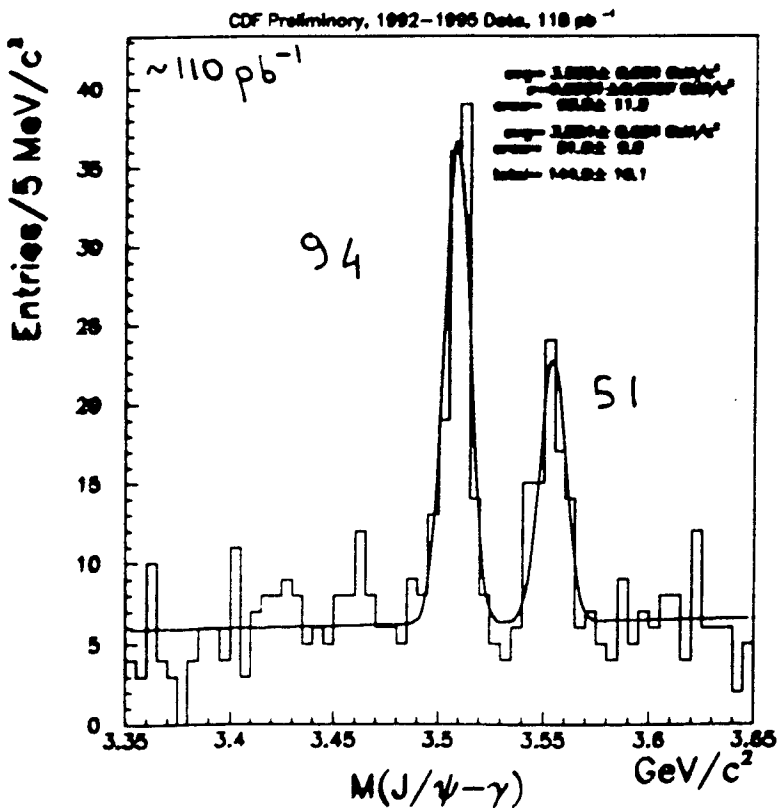
Identify χ_c's by using photon conversions (CDF)



e^+e^- picture of detector

$$\chi_c \longrightarrow J/\psi\,\gamma \longrightarrow J/\psi\, e^+ e^-$$

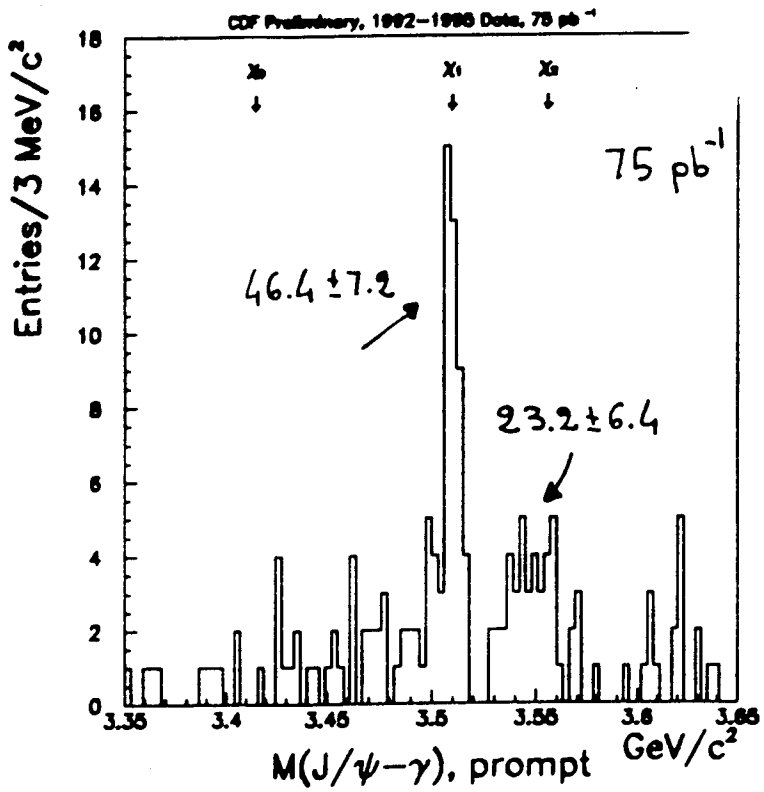
$P_T(e^+e^-) > 1$ GeV/c



Identify χ_c's by using photon conversions

$\chi_c \longrightarrow J/\psi\,\gamma \longrightarrow J/\psi\, e^+e^-$

For a prompt χ sample, $|\eta| < 100$



$P_T(e^+e^-) > 1$ GeV/c

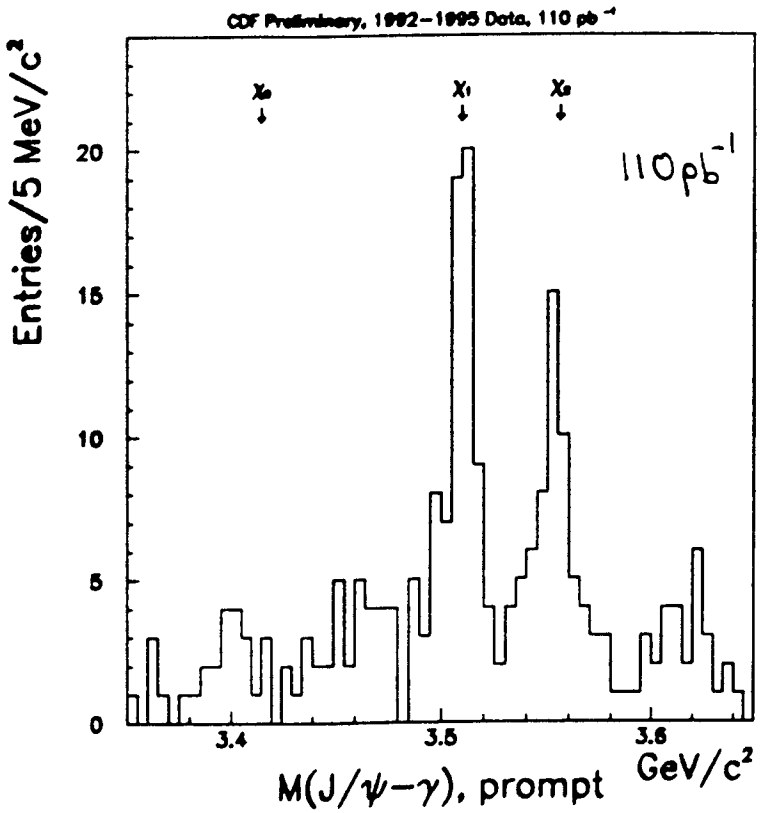
$|\eta| < 0.5$, $P_T^{\chi} > 6$ GeV/c

$$R_{CDF} = \frac{6\chi_{c2}}{6\chi_{c1} + 6\chi_{c2}} =$$

$0.47 \pm 0.08(\text{stat}) \pm 0.02(\text{sy}$

R (g-rag) spin counting $= 0.58$

R direct $= 0.36$



$P_T(e^+e^-) > 1$ GeV/c

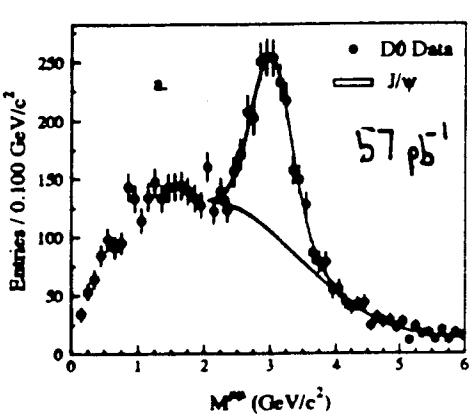
$|\eta^{\psi}| < 0.6$, $P_T^{\psi} > 4$ GeV/

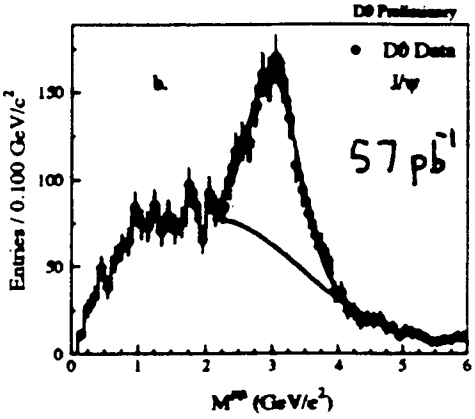
Invariant mass spectra for opposite sign muon pairs

DØ

$|\eta_{\mu\mu}| < 0.3$

1156 ± 75 events



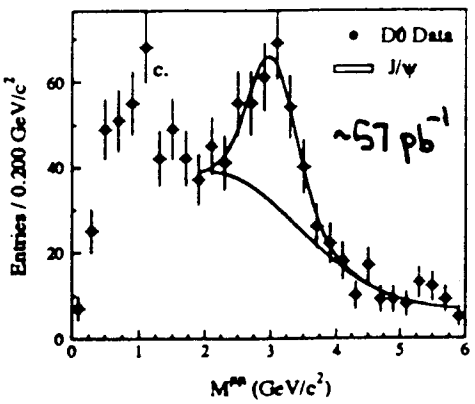


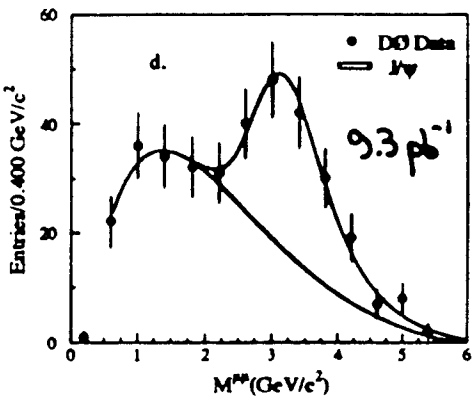
$0.3 < |\eta_{\mu\mu}| < 0.$

915 ± 99 events

$.9 < |\eta_{\mu\mu}| < 1.2$

152 ± 19 events



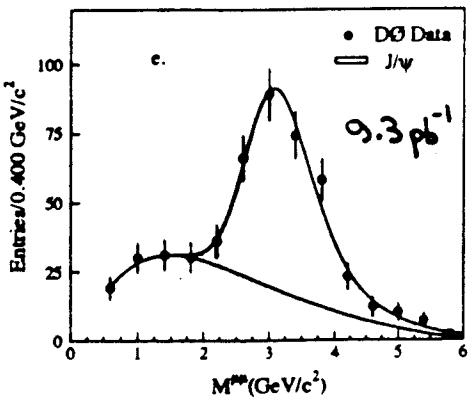


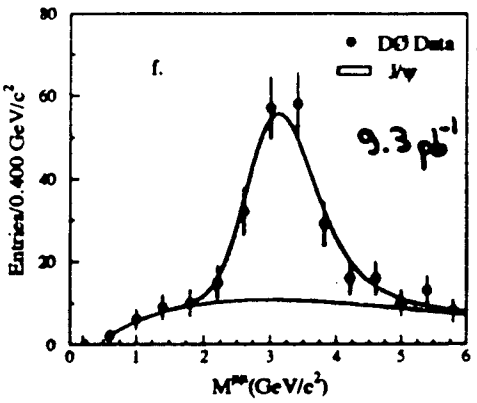
$2.5 < |\eta_{\mu\mu}| < 2.$

115 ± 12 events

$..8 < |\eta_{\mu\mu}| < 3.1$

255 ± 21 events





$3.1 < |\eta_{\mu\mu}| < 3.4$

159 ± 16 events

FIG. 1. The invariant mass spectra for opposite sign muon pairs. The hatched area corresponds to the fitted J/ψ signal. (a) $|\eta^{\mu\mu}| < 0.3$; (b) $0.3 < |\eta^{\mu\mu}| < 0.6$; (c) $0.9 < |\eta^{\mu\mu}| < 1.2$; (d) $2.5 < |\eta^{\mu\mu}| < 2.8$; (e) $2.8 < |\eta^{\mu\mu}| < 3.1$; (f) $3.1 < |\eta^{\mu\mu}| < 3.4$.

DØ

Forward J/ψ production as a function of $p_T^{J/\psi}$

$2.5 < |\eta^{J/\psi}| < 3.7$

$(p\bar{p} \to J/\psi + X) \cdot Br$

$0.40 \pm 0.04 \pm 0.04$ nb
(stat) (sys)

$p_T^{J/\psi} > 8.0$ GeV/c, $2.5 < |\eta^{J/\psi}| < 3.7$

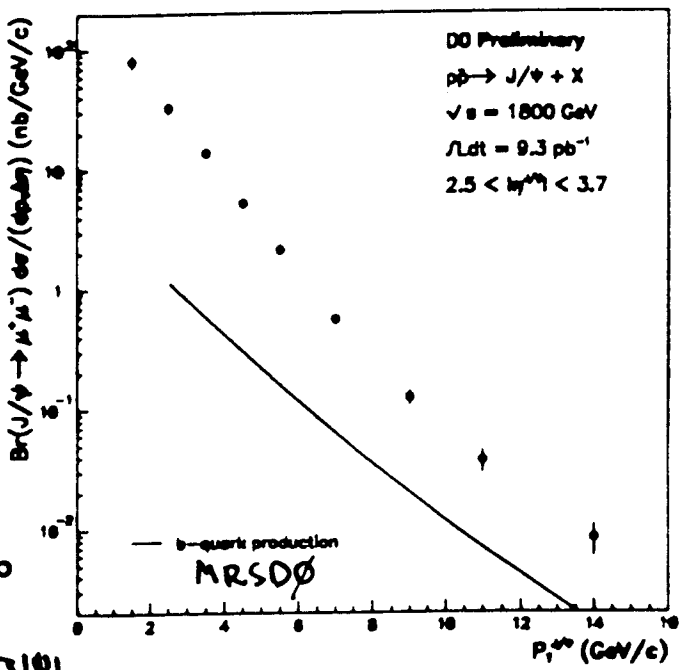


FIG. 1.

$p_T^{J/\psi} > 8$ GeV/c

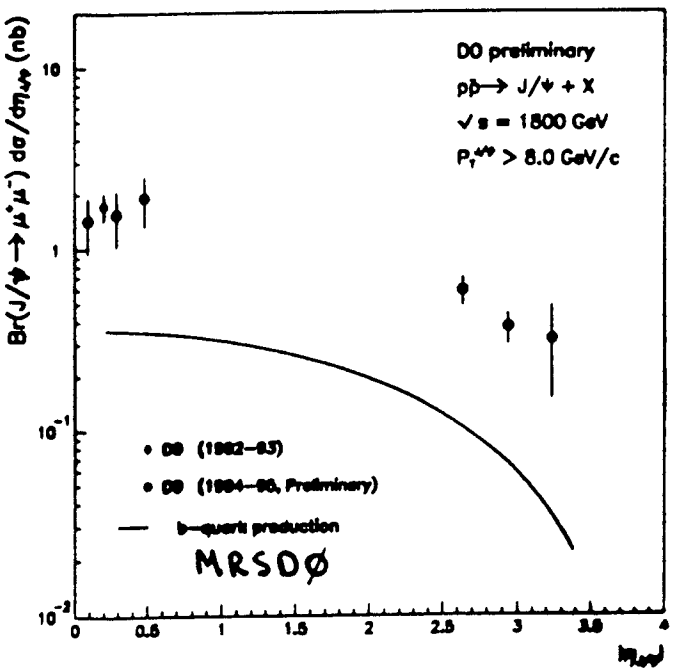


FIG. 2.

Υ Production at D0

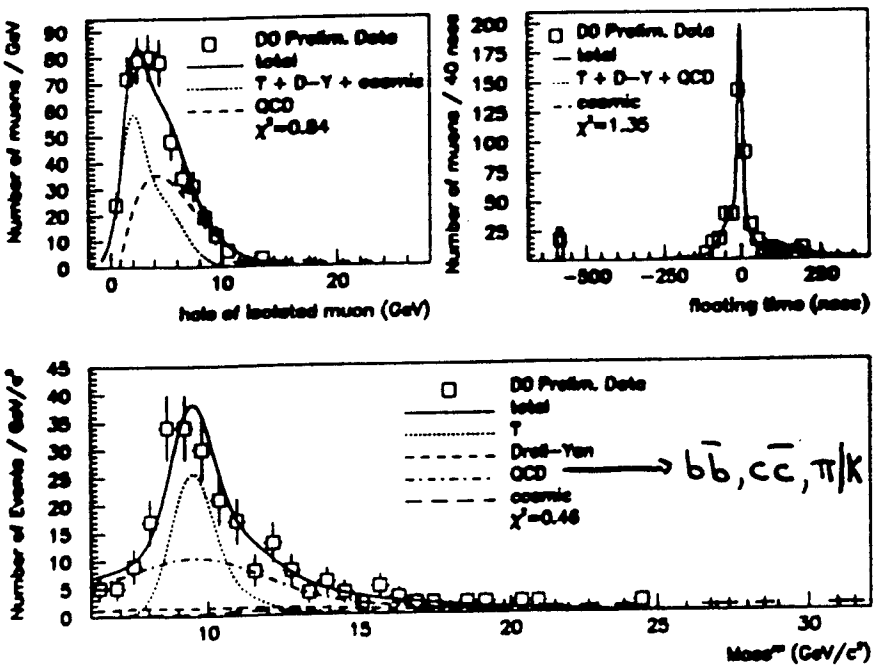
$\Upsilon \rightarrow \mu^+\mu^-$

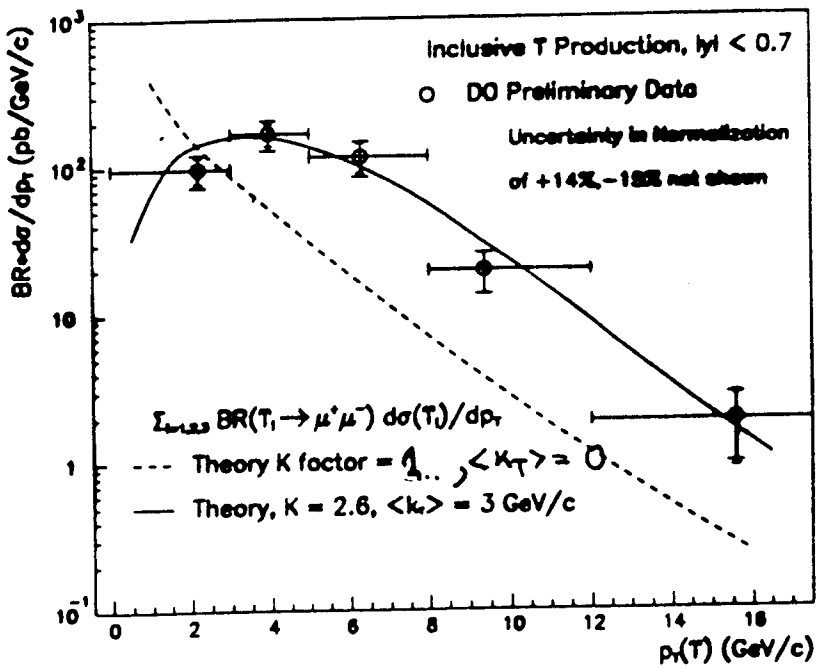
In 6.6 pb^{-1} and for $|y^{\Upsilon}| < 0.7$, D0 has:
(90 ± 11) $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$ events

Dimuon mass resolution = 1.3 GeV at 10 GeV/c,
therefore Υ states **are unresolved**

Signal and background contributions are resolved using a simultaneous maximum likelihood fit to the data variables $M_{\mu\mu}$, H , t_0

- H : ***halo of isolated muon*** $(E_{cal}^{\Delta R=0.6} - E_{cal}^{\Delta R=0.2})$
- t_0 : ***timing offset rel. to beam crossing***





$\sigma(\bar{p}p \rightarrow \Upsilon + X)$ x $Br = 768 \pm 81(\boldsymbol{stat}) \pm 142(\boldsymbol{syst})$ pb
$P_T^{\Upsilon} > 0.0$ GeV/c

- Υ cross section is higher than QCD prediction.
- Good agreement can be achieved for

$$< k_T > = 3 \text{ GeV and K factor of } 2.6$$

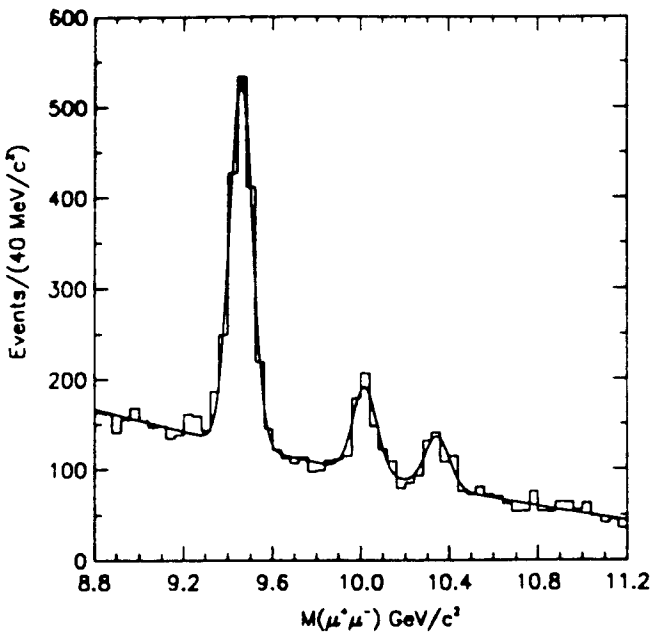
Υ Production at CDF

$\Upsilon \rightarrow \mu^+\mu^-$

$P_T^{\mu}(min) > 2.2$ GeV/c , $P_T^{\mu}(max) > 2.8$ GeV/c

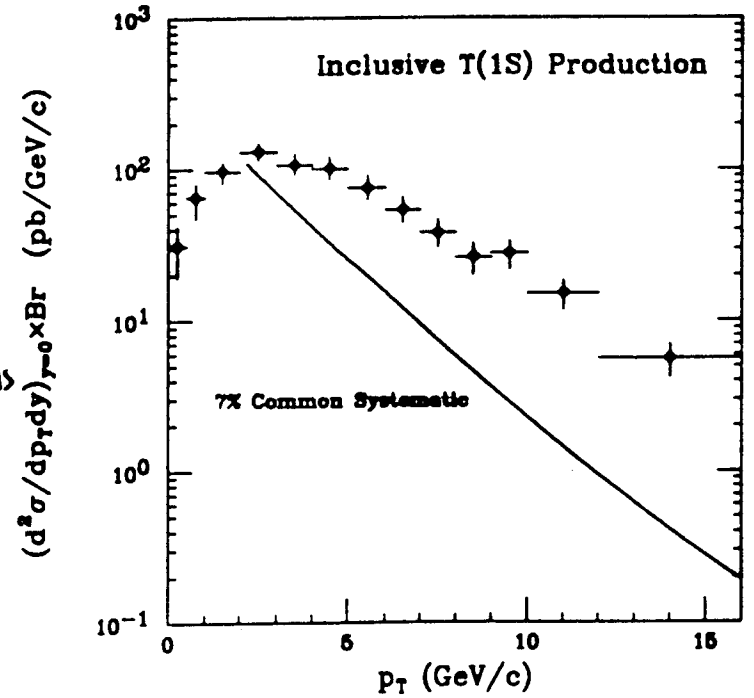
$|y| < 0.4$

in 16.6 pb^{-1} we have:
1274 Υ(1S) events
320 Υ(2S) events
196 Υ(3S) events



Theory
.....
color singlet
calculation

(includes contributions
from direct Υ(1S)
production and
χ_b(1P), χ_b(2P) decay)



$d\sigma/dy(\bar{p}p \rightarrow \Upsilon(1S)) \times Br = 753 \pm 29(stat) \pm 72(syst)$ pb
y=0, 0.0< $P_T^{\Upsilon(1S)}$ < 16.0 GeV/c

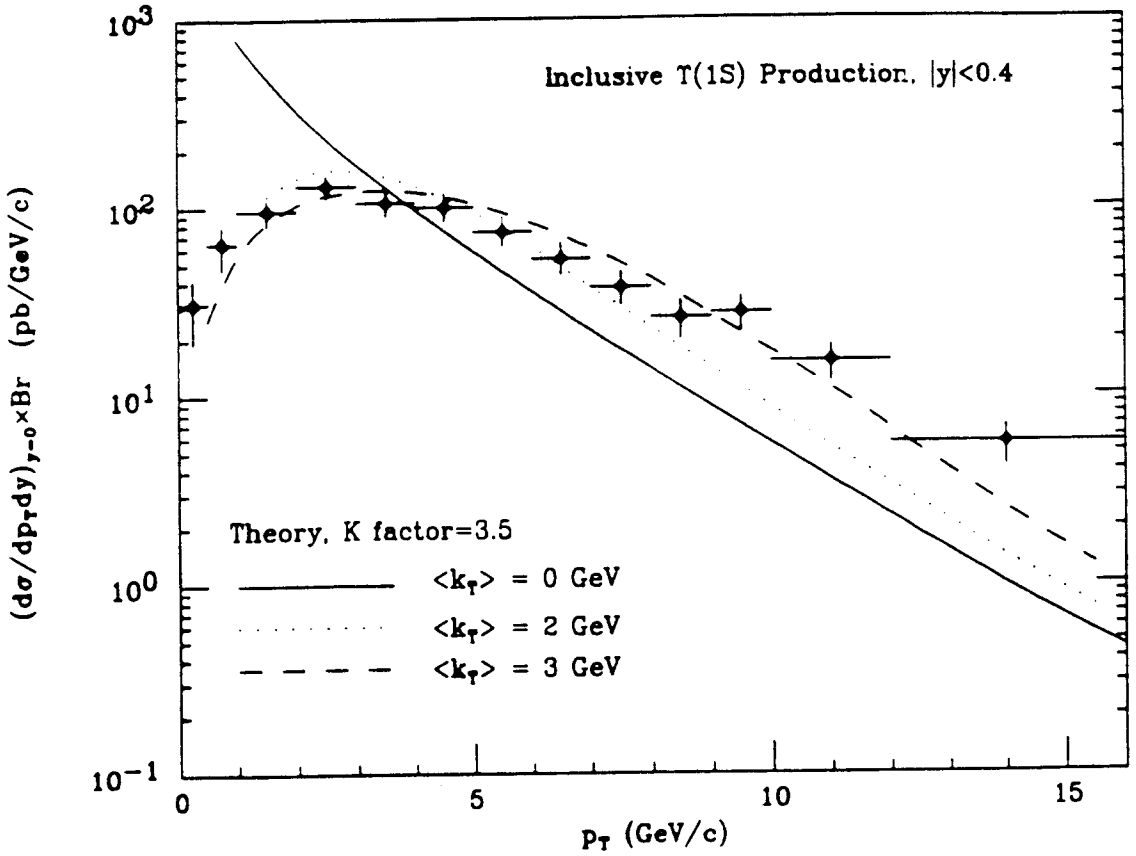
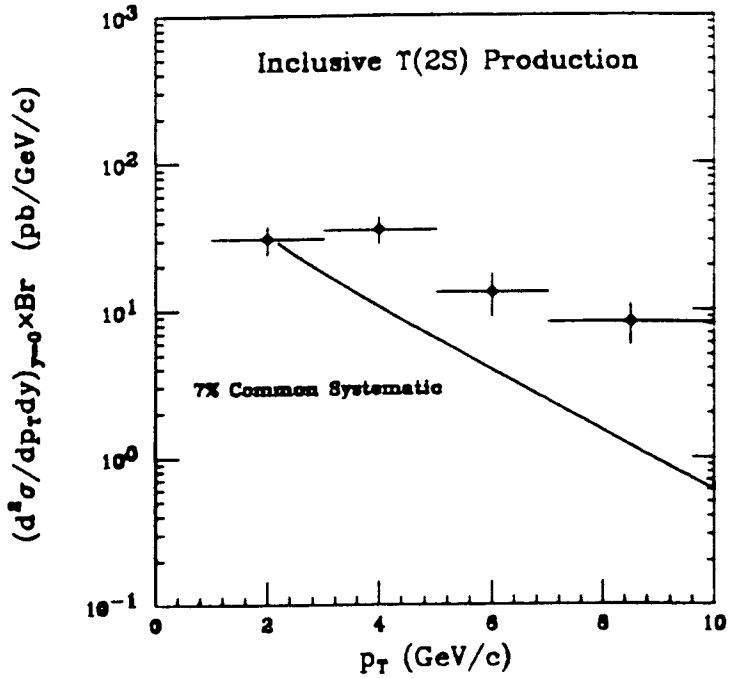


Figure 12: The product $\left(\frac{d\sigma}{dP_t dy}\right)_{y=0} \times Br$ vs. P_t for $\Upsilon(1S) \rightarrow \mu^+\mu^-$ for $|y| < 0.4$. The vertical error bars include the statistical error added in quadrature with the polarization, fitting procedure and acceptance model systematics. There is an additional common systematic of 6.6% not shown. The theoretical curves are the leading order QCD prediction and were generated using MRSA PDF with scale $\mu^2 = P_t^2 + m_\Upsilon^2$. The solid curve corresponds to $< k_T >$=0 GeV/c, the dotted curve corresponds to $< k_T >$=2 GeV/c and the dashed curve corresponds to $< k_T >$=3 GeV/c. The $K-$factor in all theory curves is 3.5.

Theory

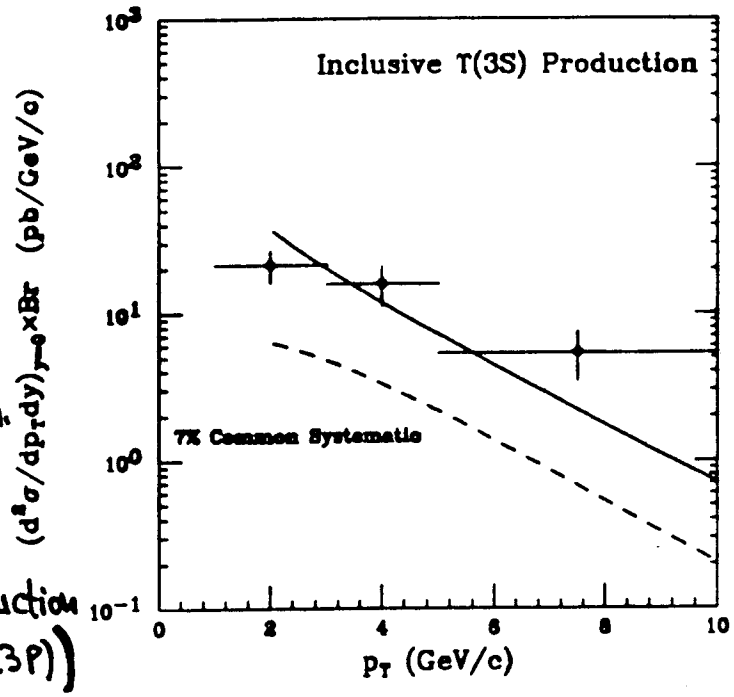
Color singlet calculation includes contributions from direct Υ(2S) production and $\chi_b(2P)$ decay)



$$d\sigma/dy(\bar{p}p \rightarrow \Upsilon(2S))xBr = 183 \pm 18(stat) \pm 24(syst) \text{ pb}$$
$$\text{y=0, } 1.0 < P_T^{\Upsilon(2S)} < 10.0 \text{ GeV/c}$$

Theory

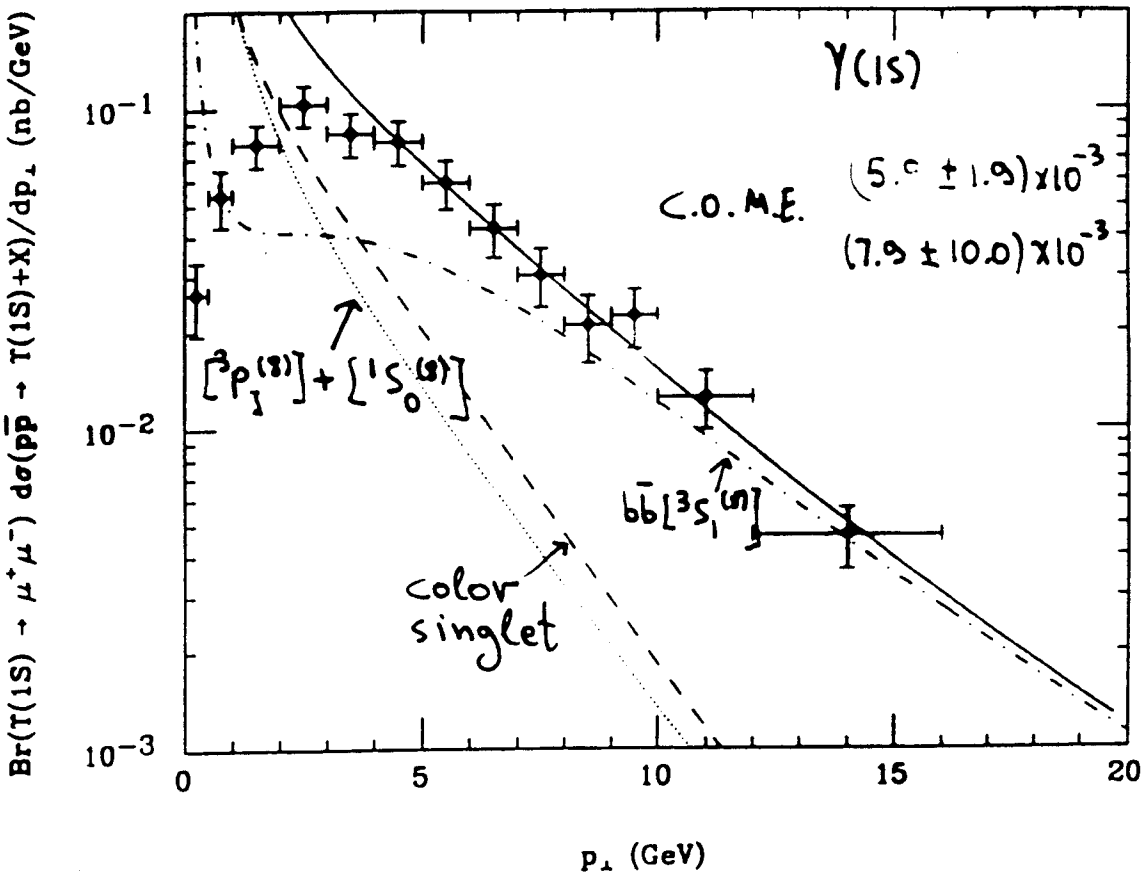
Color singlet calculation (The dashed line corresponds to the direct Υ(3S) production. The solid line to the sum of contributions from direct Υ(3S) production and the decay of $\chi_b(3P)$)

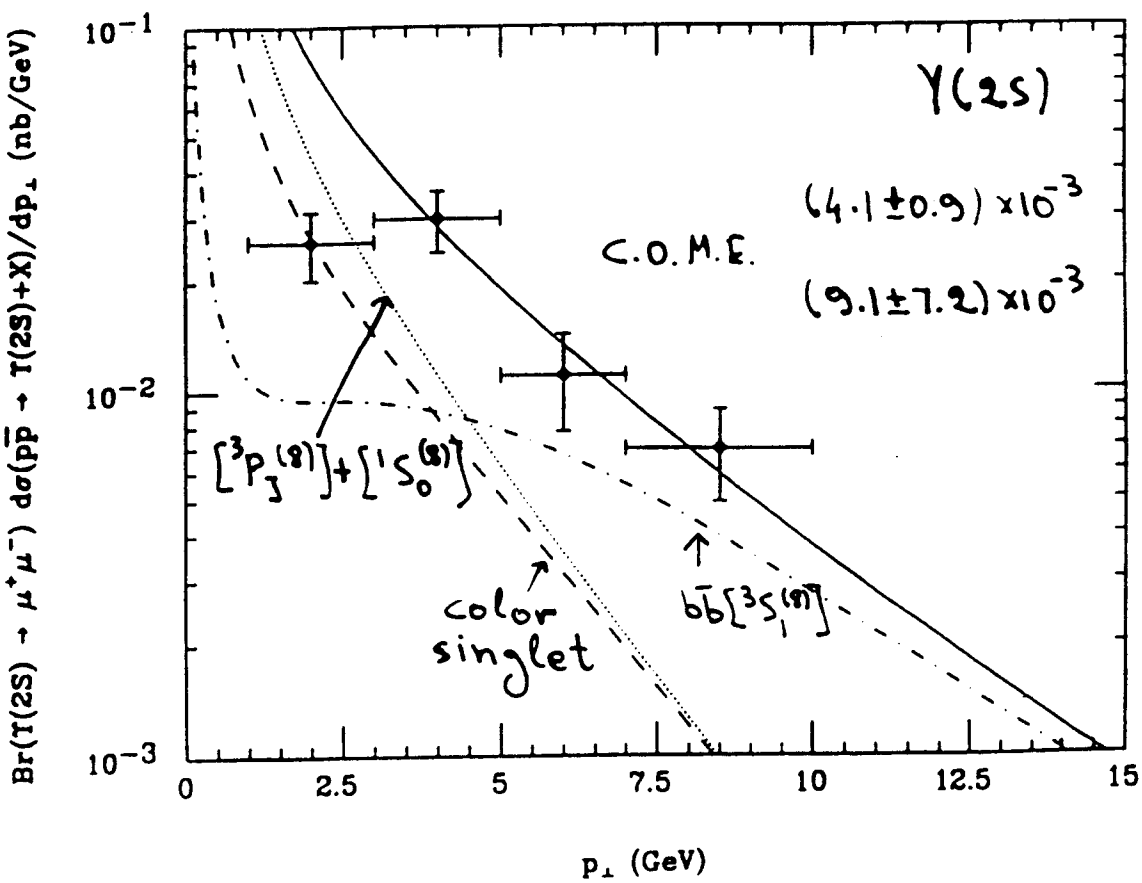


$$d\sigma/dy(\bar{p}p \rightarrow \Upsilon(3S))xBr = 101 \pm 15(stat) \pm 13(syst) \text{ pb}$$
$$1.0 < P_T^{\Upsilon(3S)} < 10.0 \text{ GeV/c}$$

CDF data — P. Cho, A. Leibovich theory

CALT-68-2026





CONCLUSION

- Color-octet production of heavy quarkonia does a relatively reasonable job in explaining the $p\bar{p}$ collider, $\sqrt{s} = 1.8$ TeV, quarkonia data (cross sections)
  (long distance matrix elements for the color-octet contribution determined using fits to the CDF data)

- More experimental tests of the theory model are needed (coming...)
  + other experiments

- The theoretical work needs to be improved and extended

PROSPECTS

- Improvements on the measurements of J/ψ, $\psi(2S)$ cross sections : * from B / prompt (from χ_c / direct)

  * as a function of rapidity

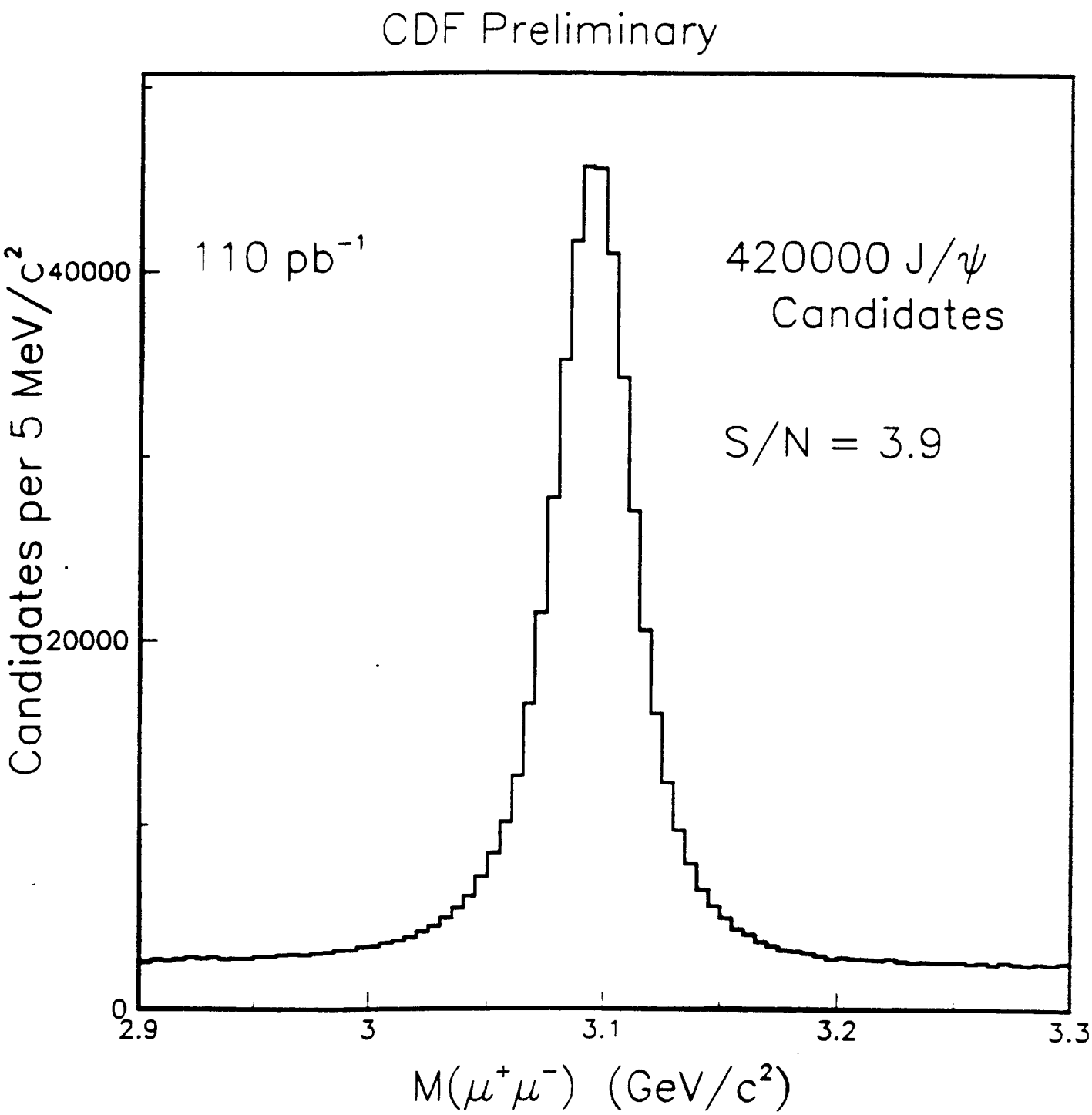
- Measurement of $\psi(2S)$, J/ψ polarization

- Search further for exotic states decaying to ψ

- Measure differential cross sections for χ_{c_1}, χ_{c_2} (from B, prompt) and their polarizations

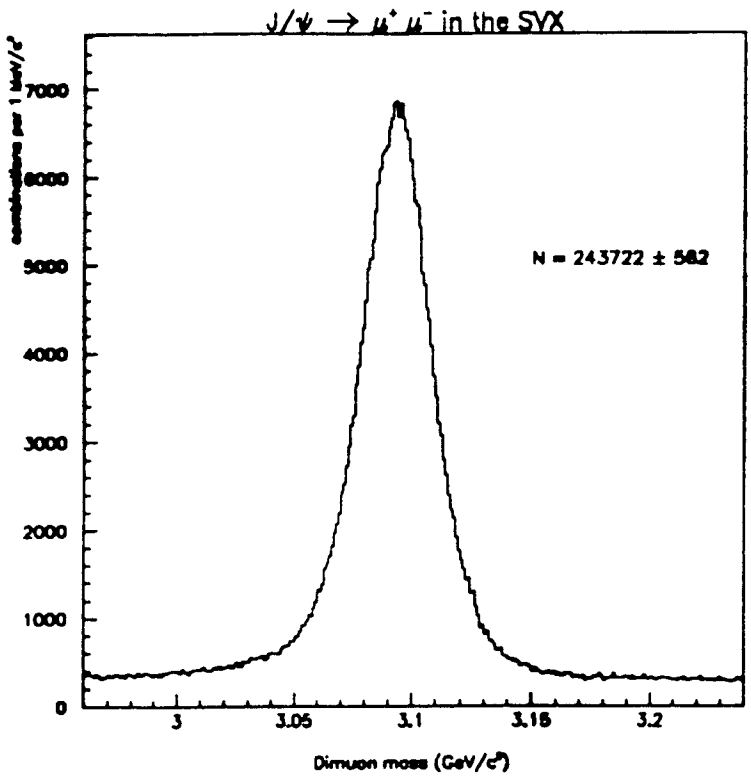
- Measure more accurately the $\Upsilon(2S)$, $\Upsilon(3S)$ spect especially at low p_T, and the polarization of th $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ states

- Search for and study χ_b states


CDF Preliminary
110 pb^{-1}
420000 J/ψ
Candidates
S/N = 3.9
Candidates per 5 MeV/c^2
40000
20000
0
2.9
3
3.1
3.2
3.3
M($\mu^+\mu^-$) (GeV/c^2)

$J/\psi \to \mu^+\mu^-$, $\psi(2S) \to J/\psi\pi^+\pi^-$ at CDF

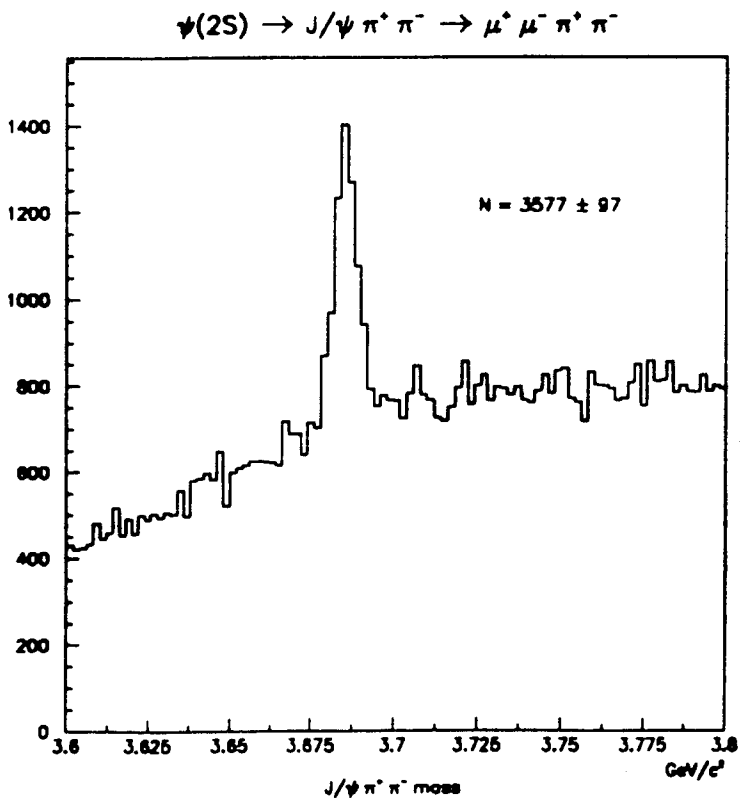
$$\int \mathcal{L}dt = 110\,\mathrm{pb}^{-1}$$

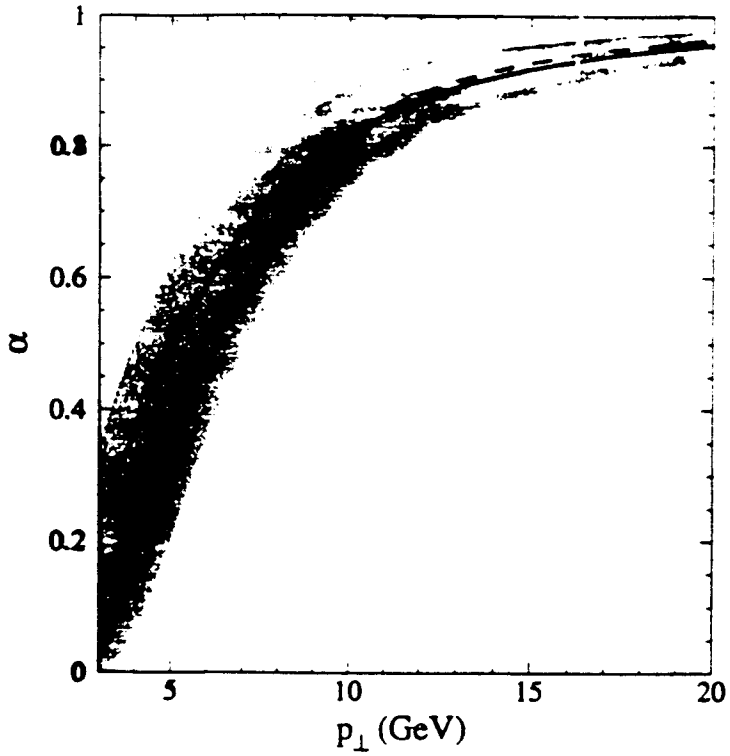


$p_T^\mu > 1.5$ GeV/c

$|\eta^\mu| < 1$

muons reconstr in SVX





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CALT-68-2082

FIG. 2. Coefficient α which governs the lepton angular distribution in $\psi' \to \ell^+\ell^-$ decay plotted as a function of $p_\perp$. The solid and dashed curves illustrate α for ψ' production at the Tevatron when $\langle \mathcal{O}_8^{\psi'}(^3P_0)\rangle$ and $\langle \mathcal{O}_8^{\psi'}(^1S_0)\rangle$ respectively vanish. The shaded region shows the effect of the uncertainty in the extraction of the matrix elements.

$$\frac{d\Gamma}{d\cos\vartheta} \propto 1 + \alpha\cos^2\vartheta$$

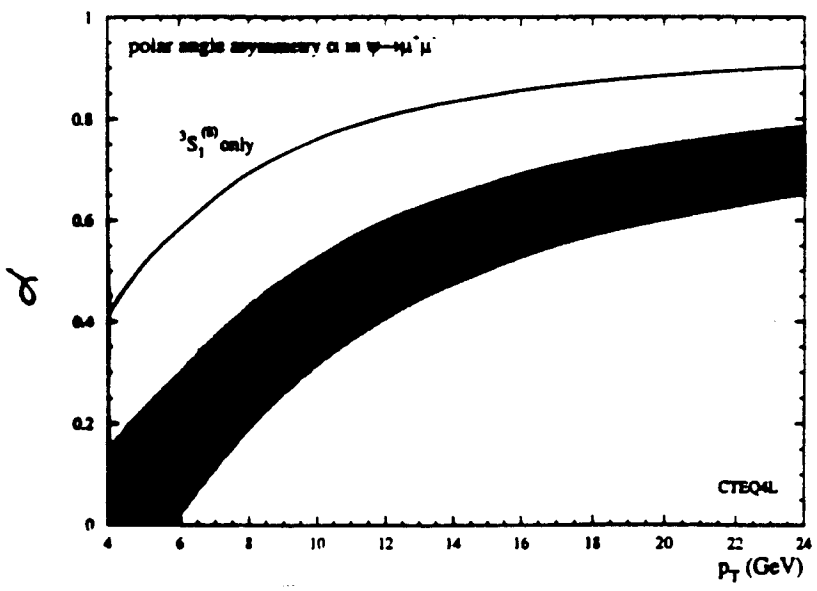

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Figure 3: α as a function of p_t. Parameter specifications as for Fig. 1. The band is obtained from Eq. (8) and the $\mathcal{O}(\alpha_s^4)$ fragmentation contributions from [6] as described in the text. The solid curve is obtained with $M^{\psi'}_{3.8}(^1S_0^{(8)}, ^3P_0^{(8)}) = 0$ and shows the importance of this parameter for polarization. The band does not include theoretical uncertainties in the short-