POLARIZATION OF PROMPT J/ψ

AT THE TEVATRON

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Charmonium production at CDF

NRQCD Factorization

Symmetries & Polarization

Prompt J/ψ & polarization

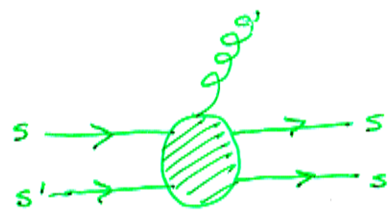
Summary

Heavy Quark Spin Symmetry

No $\boldsymbol{\sigma}$ in $\mathcal{L}_{\text{heavy}}$

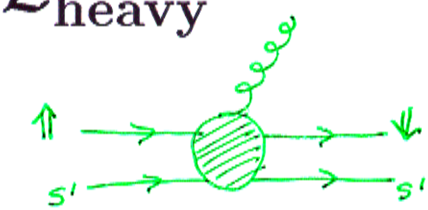
$\longrightarrow$ No Spin flip

E1 transition



$$gA \cdot D \longrightarrow \Delta L = 1 \text{ in } \mathcal{L}_{\text{heavy}}$$

M1 transition



$$gB \cdot \sigma \longrightarrow \Delta S = 1 \text{ in } \mathcal{L}_{\text{BL}}$$

$\longrightarrow$ Spin flip

$\longrightarrow v_Q$ Scaling

VSR for E1 & M1

$^3S_1^{(1)} \to J/\psi$: Direct

$^3P_J^{(8)} \to J/\psi$: $(E1)^1$

: $v_Q^2 \times (^3S_1^{(1)} \to J/\psi)$

(additional v_Q^2 from D)

$^1S_0^{(8)} \to J/\psi$: $(M1)^1$

: $v_Q^3 \times (^3S_1^{(1)} \to J/\psi)$

$^3S_1^{(8)} \to J/\psi$: $(E1)^2$

: $v_Q^4 \times (^3S_1^{(1)} \to J/\psi)$

Factorization Formula

$$d\sigma^{H_\lambda(P)} = \sum_n d\sigma^{c\bar{c}_n(P)} \, \langle O_n^{H_\lambda(P)} \rangle,$$

important NRQCD ME's

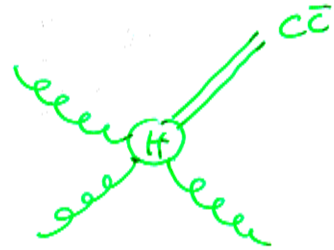
For J/ψ and ψ'

$$\langle O_1^{\psi(nS)}(^3S_1)\rangle \quad \langle O_8^{\psi(nS)}(^3S_1)\rangle$$
$$\langle O_8^{\psi(nS)}(^1S_0)\rangle \quad \langle O_8^{\psi(nS)}(^3P_0)\rangle$$

For χ_c

$$\langle O_1^{\chi_{c0}}(^3P_0)\rangle \quad \langle O_8^{\chi_{c0}}(^3S_1)\rangle$$

Fusion Process



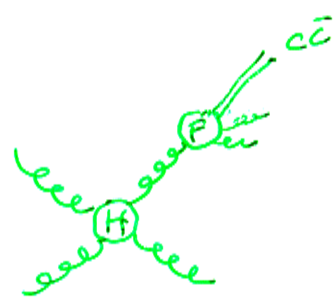
$$p_T \not\gg m_c$$

$$i + j \rightarrow c\bar{c}_n + k$$

$$\frac{d\hat{\sigma}}{dp_T^2} \sim \frac{1}{p_T^8} \text{ or } \frac{1}{p_T^6} \text{ or } \frac{1}{p_T^4}$$

$$d\sigma_{\mathrm{fu}}^{H_\lambda(P)} = f_{i/p} \otimes f_{j/\bar{p}} \otimes d\hat{\sigma}_{ij}^{c\bar{c}_n(P)} \times \langle O_n^{H_\lambda(P)} \rangle,$$

Fragmentation Process



$$p_T \gg m_c$$

$$i + j \rightarrow k + l, \qquad k \rightarrow c\bar{c}_n + X$$

$$\frac{d\hat{\sigma}}{dp_T^2} \sim \frac{1}{p_T^4}$$

$$d\sigma_{\mathrm{fr}}^{H_\lambda(P)} = f_{i/p} \otimes f_{j/\bar{p}} \otimes d\hat{\sigma}_{ij}^{k(P/z)} \otimes D_k^{c\bar{c}_n} \langle O_n^{H_\lambda(P)} \rangle,$$

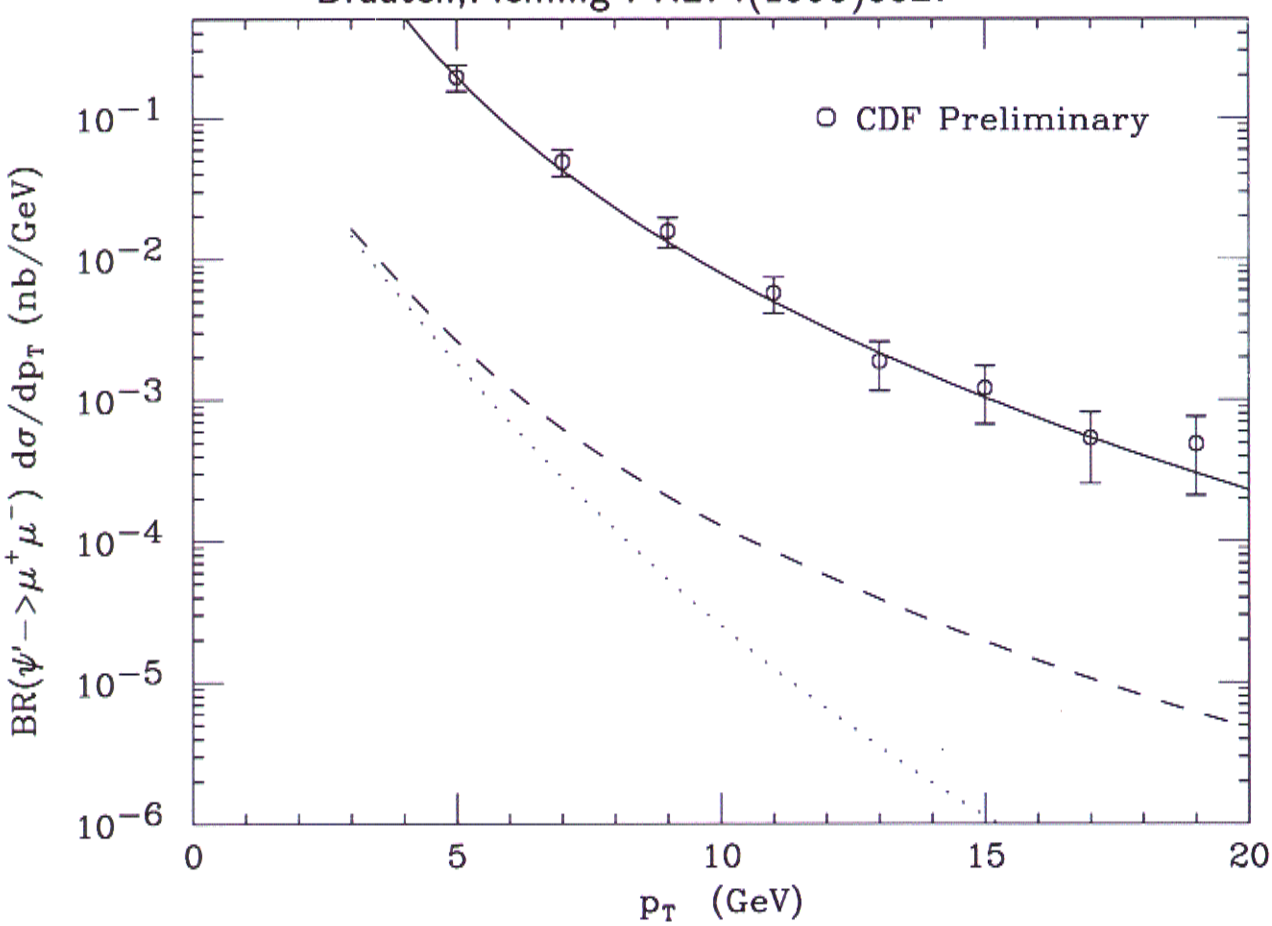
Fragmentation dominance in high p_T

- CS-Fusion : α_s^3/p_T^8
- CS-FR : α_s^5/p_T^4 :Braaten,Yuan PRL71(1993)1673

  $g^* \to 2g + c\bar{c}(^3S_1^{(1)}) \to \psi'$
- CO-FR : $\alpha_s^3 v_c^4/p_T^4$:Braaten,Fleming PRL74(1995)3327

  $g^* \to c\bar{c}(^3S_1^{(8)}) \to \psi'$

Braaten,Fleming PRL74(1995)3327



Color Singlet Matrix Elements

Phenomenological Determination

by use of Vacuum Saturation Approximation

$$M_{J/\psi}\Gamma[J/\psi \to e^+e^-] =$$

$$\frac{4\pi\alpha^2 e_c^2}{9}\left(1 - \frac{16}{3}\frac{\alpha_s}{\pi}\right)\frac{\langle O_1^{J/\psi}(^3S_1)\rangle}{m_c}.$$

$$M_{\chi_{c2}}\Gamma[\chi_{c2} \to \gamma\gamma] =$$

$$\frac{16\pi\alpha^2 e_c^4}{5}\left(1 - \frac{16}{3}\frac{\alpha_s}{\pi}\right)\frac{\langle O_1^{\chi_{c0}}(^3P_0)\rangle}{m_c^3}.$$

OPAL, PLB 439, 197 (1998)

FR Correction Factor

$$d\sigma^{H_\lambda} = d\sigma_{\text{fu}}^{H_\lambda} \times \frac{d\sigma_{\text{fr}}^{H_\lambda}[\mu_{\text{fr}} = \mu]}{d\sigma_{\text{fr}}^{H_\lambda}[\mu_{\text{fr}} = 2m_c]}$$

Octet ME Determination ($\psi(ns)$)

determine $\langle O_8(^3S_1)\rangle$ and M_r
by fitting the p_T distributions to CDF DATA

$$M_r = \langle O_8(^1S_0)\rangle + r\langle O_8(^3P_0)\rangle/m_c^2,$$

$$3.0(p_T = 5.5\text{GeV}) < M_r < 3.55(18)$$

$$x = \frac{\langle O_8(^1S_0)\rangle}{M_r}, \quad 0 < x < 1$$

Octet ME Determination (χ_c)

determine $\langle O_8(^3S_1)\rangle$
by fitting the p_T distributions to CDF DATA

Theoretical INPUTS

Partons

$$i, j = g, q, \bar{q}, \quad q = u, d, s$$

Fragmentation Function

LO $g^* \to c\bar{c}_8(^3S_1)$

Evolution $\mu_{\mathrm{fr}} > 4m_c^2/z$

Neglect massive evolution effect(Boundary)
Kniehl, Zwirner, hep-ph/9909517.

$1.45 < m_c < 1.55$ GeV

MRST98LO, CTEQ5L

One Loop α_s with Λ_{QCD}

Scale μ_T, $\mu_T/2$, $2\mu_T$

$$k^\mu \neq P^\mu / z$$

$$P^2 = 4m_c^2 \neq 0$$

$$z \equiv \frac{P \cdot n}{k \cdot n}$$

$n \sim (1, 0, 0, -1)$: Frame Dependent

We choose Partonic CM for $\mathbf{k} \parallel \mathbf{P}$

→ LO FR : NOT 100% TRANS POL

$$k^\mu = \left[(\Delta + K \cdot P) P^\mu - P^2 K^\mu \right] / (2z\Delta)$$

$$K = P + \bar{P}$$

$$\Delta = [(K \cdot P)^2 - K^2 P^2]^{1/2}$$

J/ψ Matrix Elements

ME	MRST98LO	CTEQ5L	unit
$\langle O_1(^3S_1)\rangle$	1.34 ± 0.10	1.38 ± 0.10	
$\langle O_8(^3S_1)\rangle$	4.42 ± 0.73	3.95 ± 0.66	10^{-3}
M_r	8.75 ± 0.87	6.59 ± 0.69	10^{-2}
r	3.44	3.55	

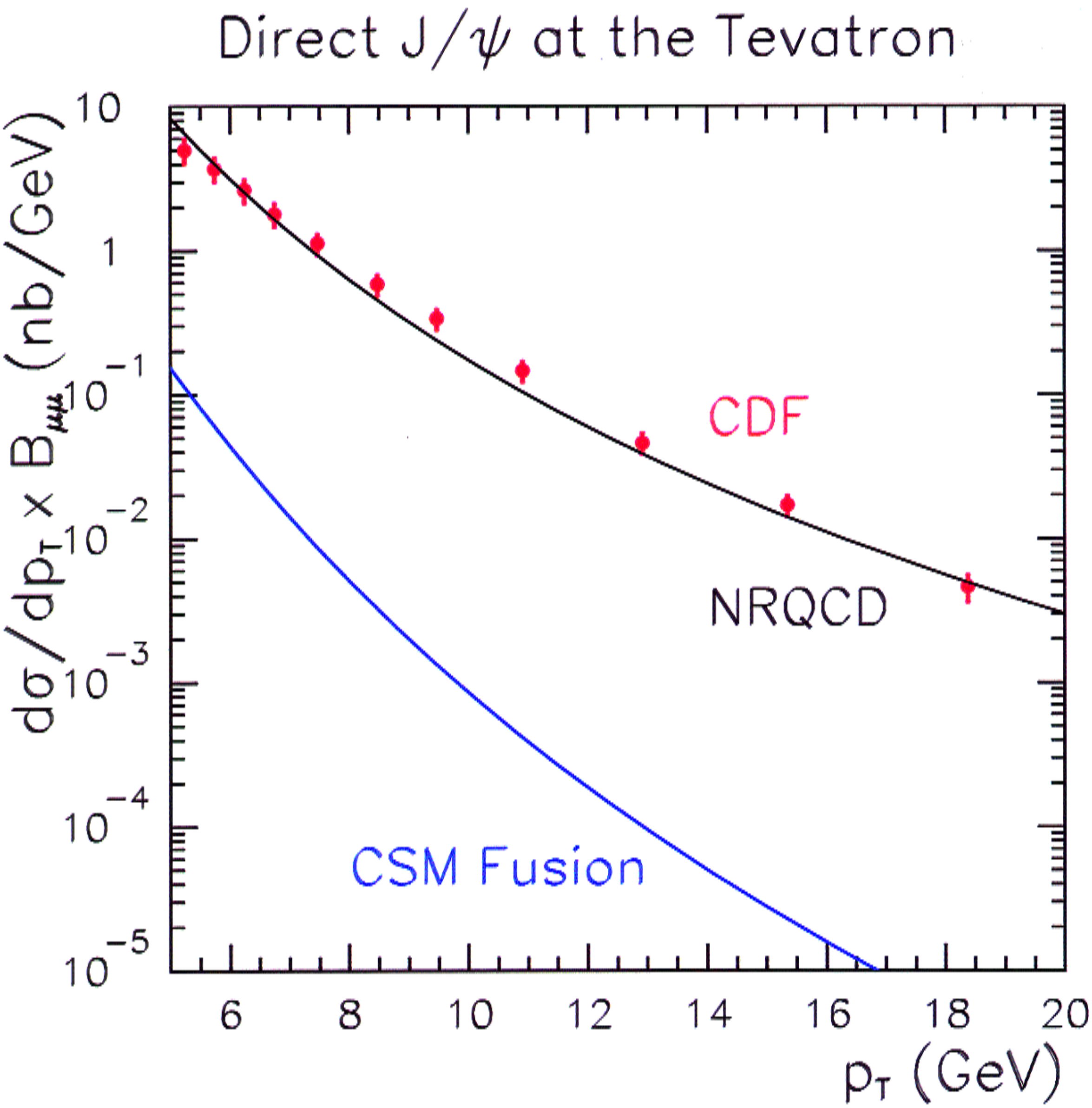
ψ' Matrix Elements

$\langle O_1(^3S_1)\rangle$	6.50 ± 0.64	6.70 ± 0.66	10^{-1}
$\langle O_8(^3S_1)\rangle$	4.20 ± 1.00	3.66 ± 0.88	10^{-3}
M_r	1.30 ± 0.45	0.78 ± 0.36	10^{-2}
r	3.46	3.46	

χ_{c0} Matrix Elements

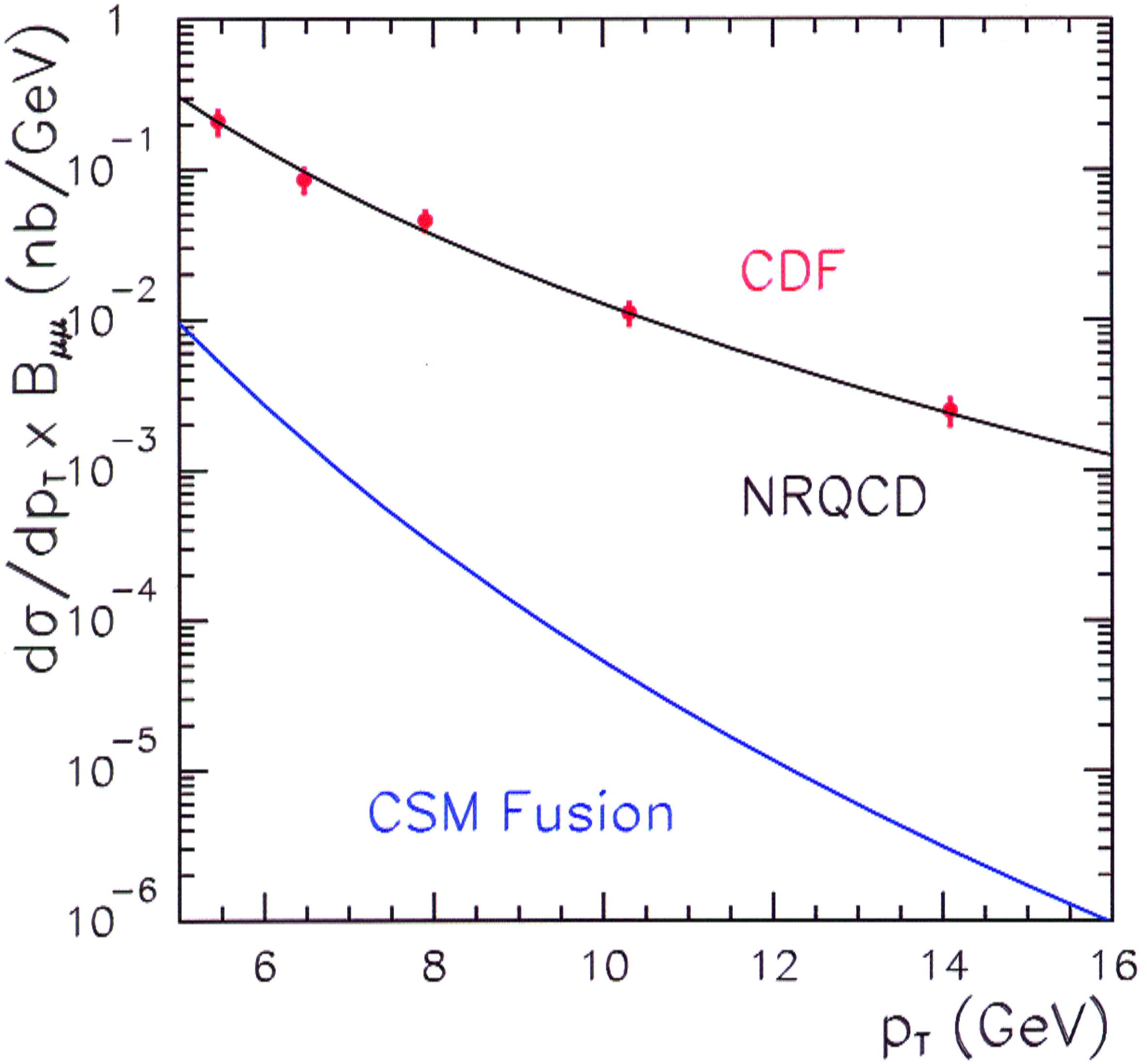
$\langle O_1(^3P_0)\rangle$	3.63 ± 1.27	3.74 ± 1.31	10^{-1}
$\langle O_8(^3S_1)\rangle$	3.55 ± 2.05	-0.75 ± 1.77	10^{-4}

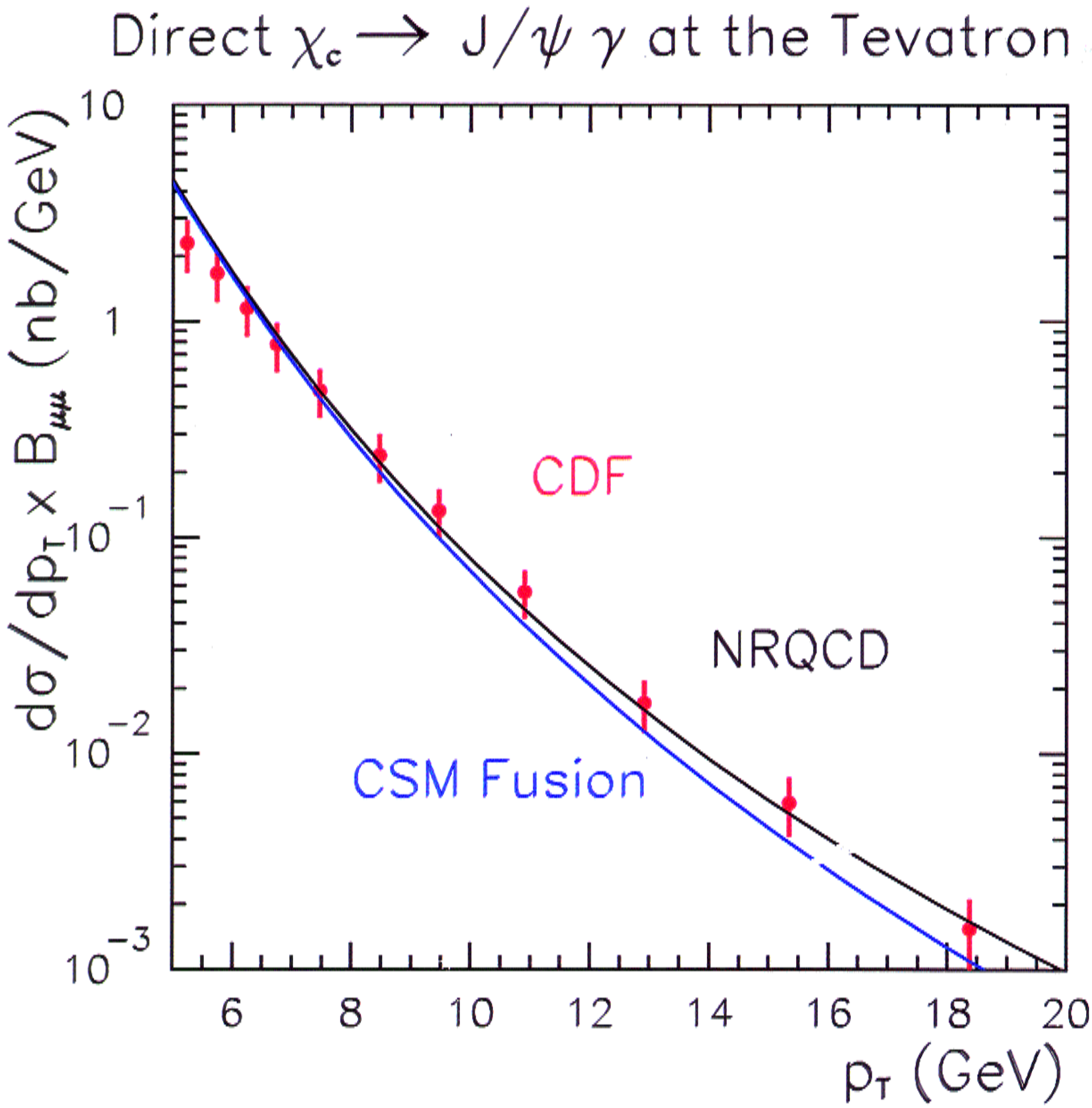
$^3S_1$, M_r:GeV^3 $\quad$ $^3P_0$:GeV^5



Direct J/ψ at the Tevatron
dσ/dp_T × B_μμ (nb/GeV)
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
6
8
10
12
14
16
18
20
p_T (GeV)
CDF
NRQCD
CSM Fusion

Direct $\psi(2S)$ at the Tevatron





Direct $\chi_c \rightarrow J/\psi\ \gamma$ at the Tevatron
$d\sigma/dp_T \times B_{\mu\mu}$ (nb/GeV)
10
1
10^{-1}
10^{-2}
10^{-3}
6
8
10
12
14
16
18
20
p_T (GeV)
CDF
NRQCD
CSM Fusion

Polarization vector in a special frame

Where will you measure?

hadronic CM = collider CM

dirty formula : GOOD for measurement

partonic CM

helicity amplitude method : simple formula

Express basis vector in fully covariant form

hadronic CM = collider CM

$$p^\mu \sim (0, \hat{z})$$

$$(P + \bar{P})^\mu \sim (1, 0)$$

$$Z^\mu \sim p^2 (P + \bar{P}) - p \cdot (P + \bar{P}) p^\mu$$

if we sum $\pm \longrightarrow$ azimuthal symmetry

$\alpha = \dfrac{\text{TOT} - 3\text{LON}}{\text{TOT} + \text{LON}}$ and J/ψ Polarization

We see J/ψ by measuring $\mu^+\mu^-$ pair

$$d\Gamma/d\cos\theta \sim 1 + \alpha\cos^2\theta$$

$$\theta = \angle(\mathrm{p}_{J/\psi}, \mu^+)$$

We get LON/TOT by fitting α to

$d\Gamma/d\cos\theta$ measurement

POL	100% TRAN	UNPOL	100% LON
α	+1	0	-1

χ_{c2} polarization vector

$$\epsilon^{\mu\nu}(\lambda)_{J=2} = \sum_{\lambda_L, \lambda_S} \epsilon^{\mu}(\lambda_L)\epsilon^{\mu}(\lambda_S) \times \langle L = 1, \lambda_L; S = 1, \lambda_S | J = 2, \lambda \rangle$$

$\chi_{cJ} \to J/\psi\gamma$ polarization

EM-E1 transition : dipole approximation

$$P(\chi_0 \to \psi_L) = \frac{1}{3}$$

$$P(\chi_1(\pm) \to \psi_L) = \frac{2}{3}$$

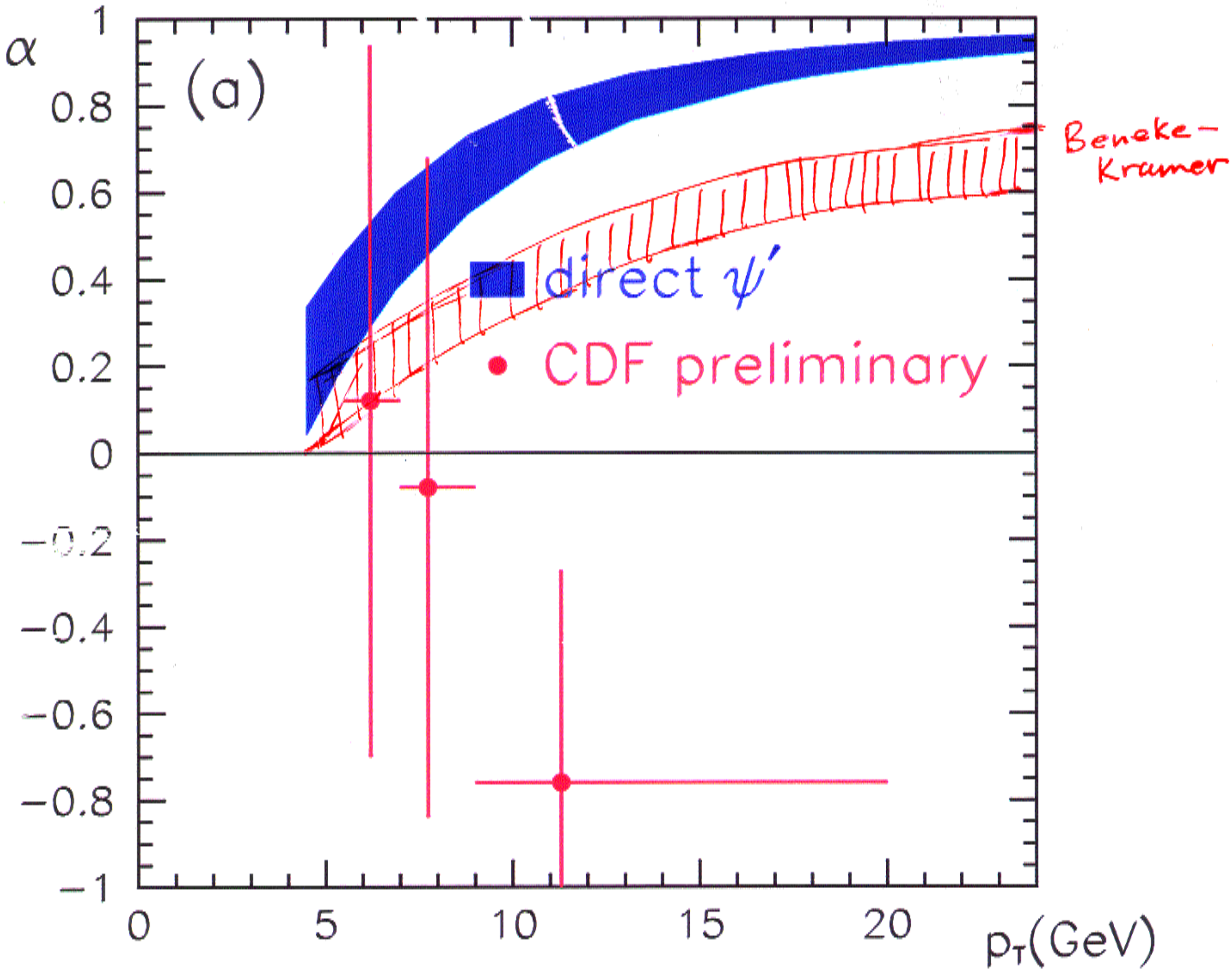
$$P(\chi_2(0) \to \psi_L) = \frac{1}{2}$$

$$P(\text{others} \to \psi_L) = 0$$

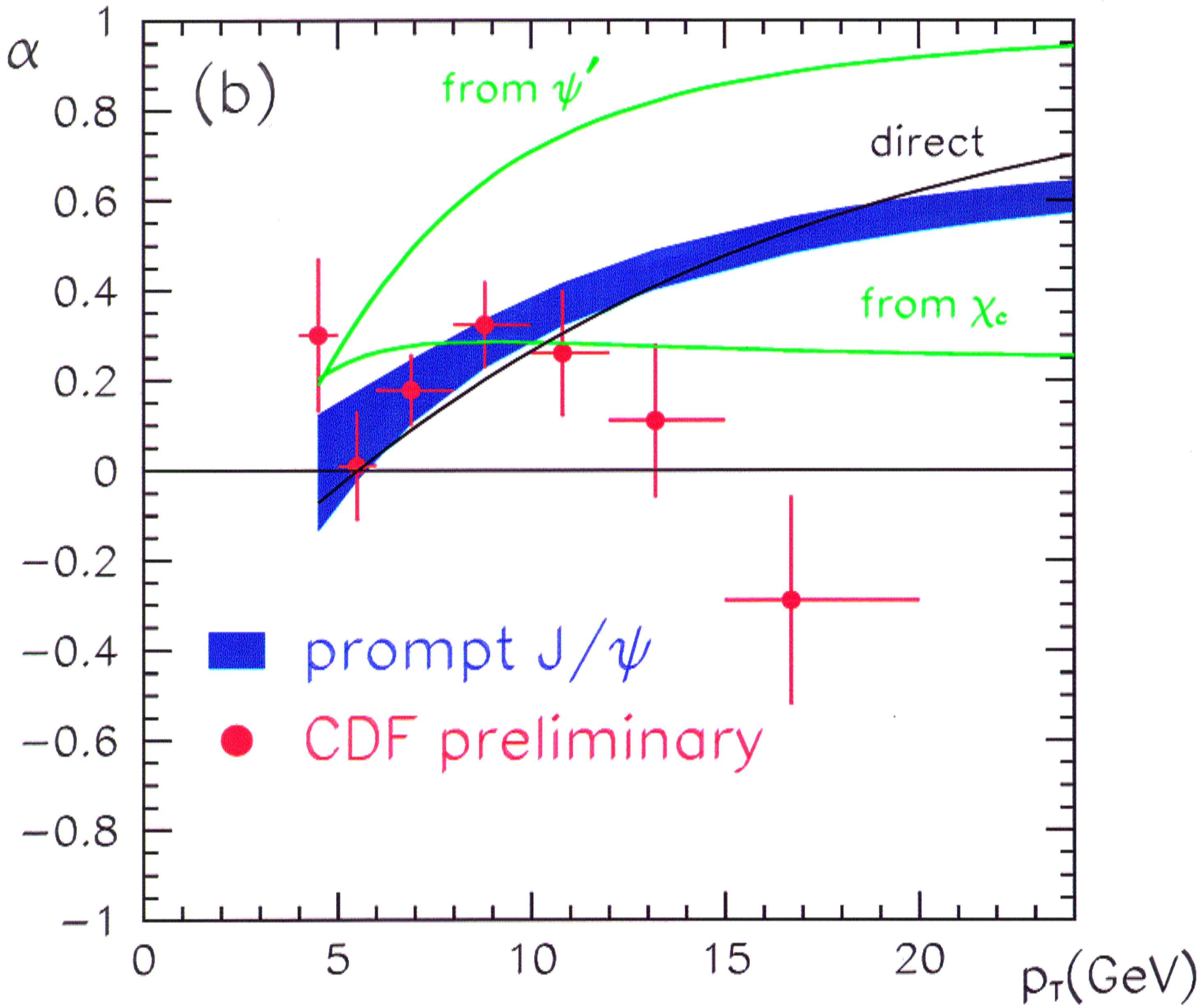
$\psi' \to J/\psi\pi\pi$ polarization

S—wave dominance

No difference


α
(a)
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
0
5
10
15
20
p_T(GeV)
direct ψ'
CDF preliminary
Beneke-Kramer

Prompt ~~Direct~~ ψ at the Tevatron



Summary

ψ' polarization disagrees with CDF data

ERROR-BARs are TOO large

First calculation of prompt J/ψ polarization

χ adds TRANS $p_T < 15$GeV

ψ' and χ POL cancel in the high p_T region

AGREES	LOW & INTERMEDIATE p_T
DISAGREES	HIGHEST p_T bin by 3σ

Discussion

Let's wait for the RUN II data!

Higher order corrections?

Fragmentation dominance at High p_T

$\longrightarrow$ explains CDF UNPOL DATA

$\longrightarrow$ POL DATA : SERIOUS CHALLENGE

If wrong, Why?

predictions of LO perturbative QCD

for spin-dependence : wrong?

m_c might be too small to use NRQCD?

If J/ψ is not for NRQCD,
How about Υ ?