

# Recent Developments in Heavy Quark and Quarkonium Production

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## ● Quarkonium ( $J/\psi$ ) Production

NRQCD Factorization Formalism

old puzzles -  $J/\psi$  polarization at Tevatron

new puzzles -  $e^+e^- \rightarrow J/\psi + X$  at  $\Upsilon(4S)$

resummation of endpoint contributions to color-octet production

(S. Fleming, T.M., A. Leibovich)

large  $J/\psi + c + \bar{c}$ , exclusive  $J/\psi + \eta_c, \chi_0$  cross sections

## ● Open Charm/Bottom Production

perturbative  $c, b$  production at Tevatron

Leading Particle Effect - Heavy Quark Recombination

(Eric Braaten, Yu Jia, M. Kusunoki, T.M.)

# Review of NRQCD

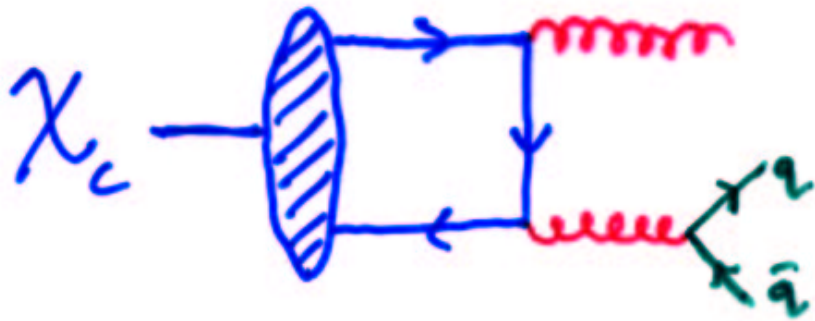
- EFT for Nonrelativistic Heavy  $Q\bar{Q}$  ( $J/\psi$ ,  $\Upsilon$ ,  $B_c$ )
- Factorization theorem for cross sections, decay rates:

(Braaten, Bodwin, Lepage)

$$d\sigma = \sum_n c_n(\alpha_s) \langle O_n \rangle, \quad \langle O_n \rangle \sim v^n$$

- double expansion  $\alpha_s$ ,  $v$
- color-singlet model ( $J/\psi$ ) lowest order in  $v$  expansion
- color-octet mechanisms  $v$  suppressed but often important

Theoretical: IR safe  $\chi_c$  decay rates



Phenomenological: high  $p_\perp$   $J/\psi$  and  $\psi'$



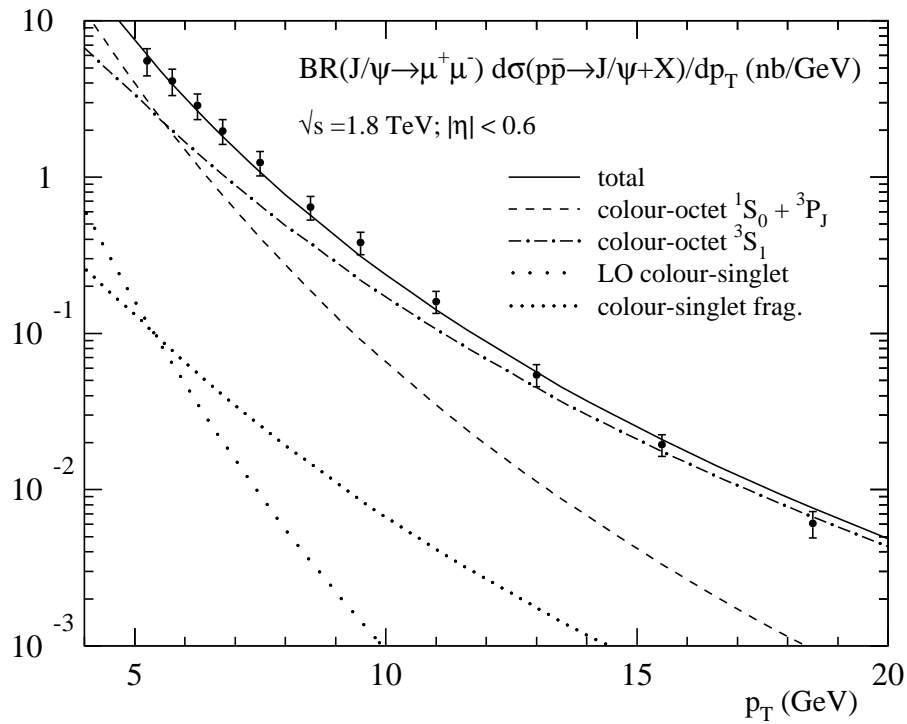
$$\frac{\alpha_s^3 V^3}{P_\perp^3}$$

$$\frac{\alpha_s^5 V^3}{P_\perp^4}$$

$$\frac{\alpha_s^3 V^7}{P_\perp^4}$$

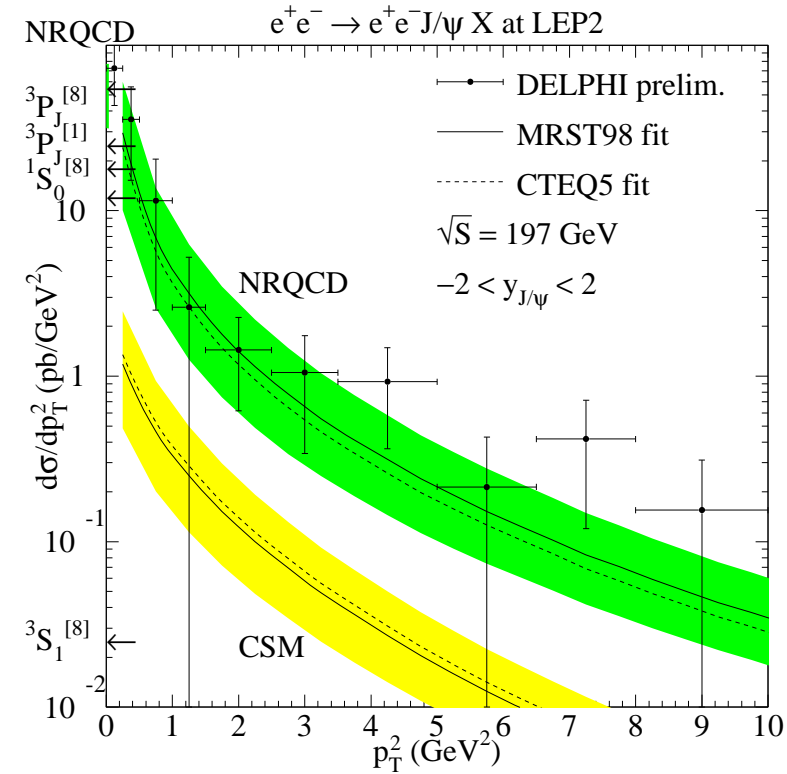
- Evidence for color-octet mechanisms

high  $p_T$   $J/\psi$  (Tevatron)



(Braaten, Fleming; Kramer)

$\gamma\gamma \rightarrow J/\psi + X$  (LEP)

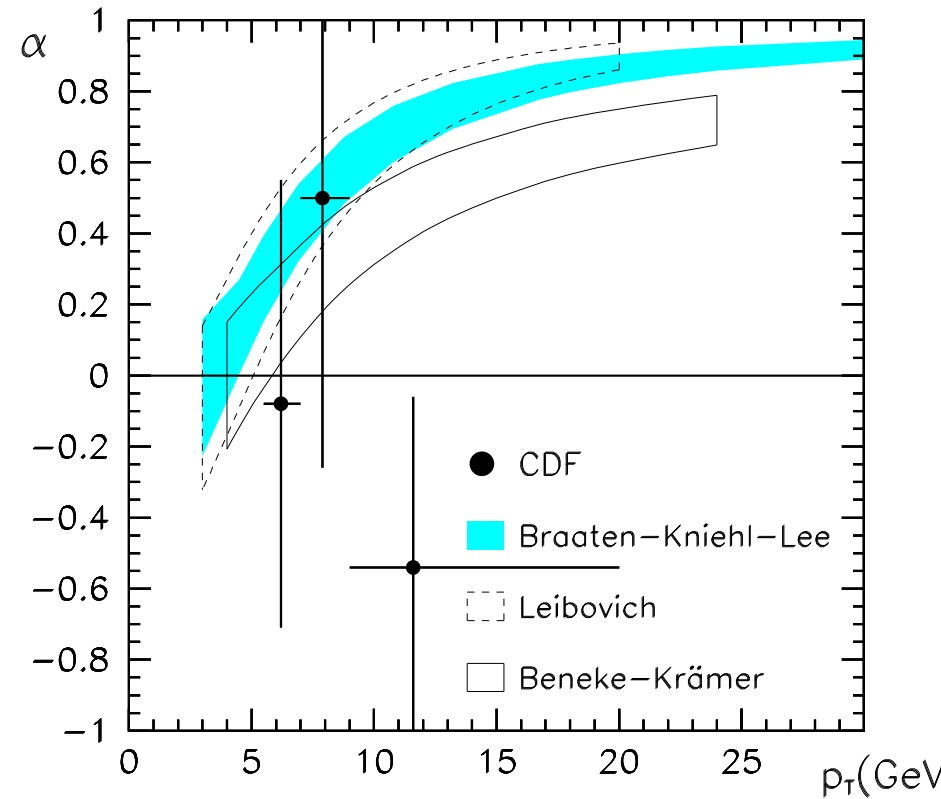
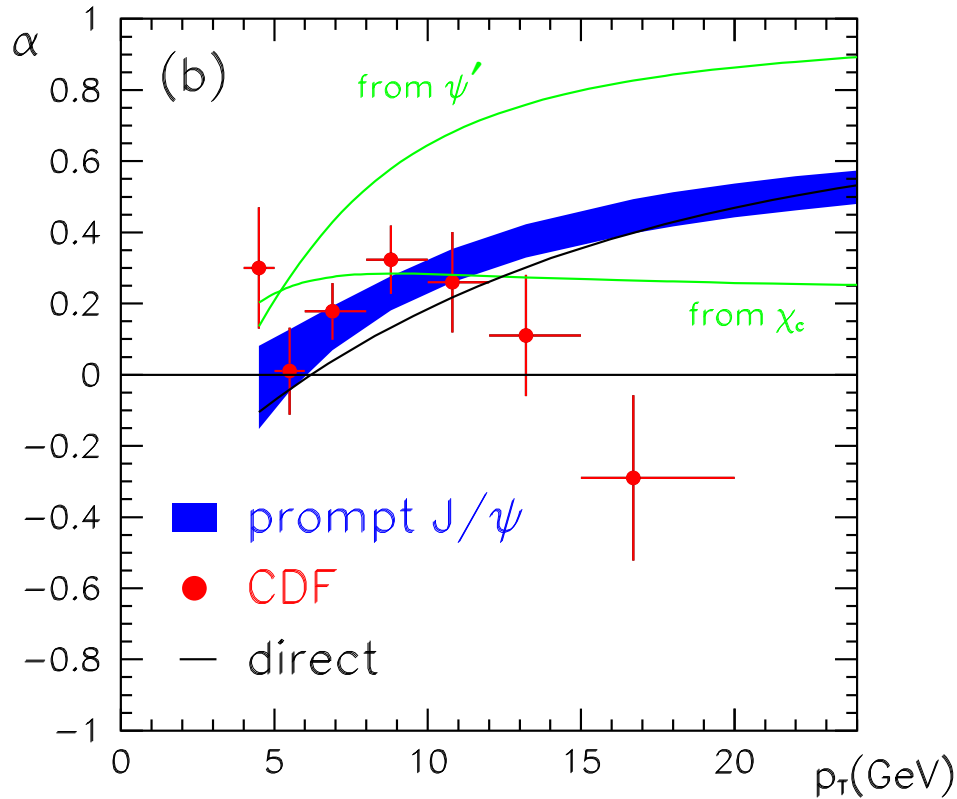


(Klasen *et. al.*)

# • Problem of $J/\psi$ , $\psi'$ Polarization

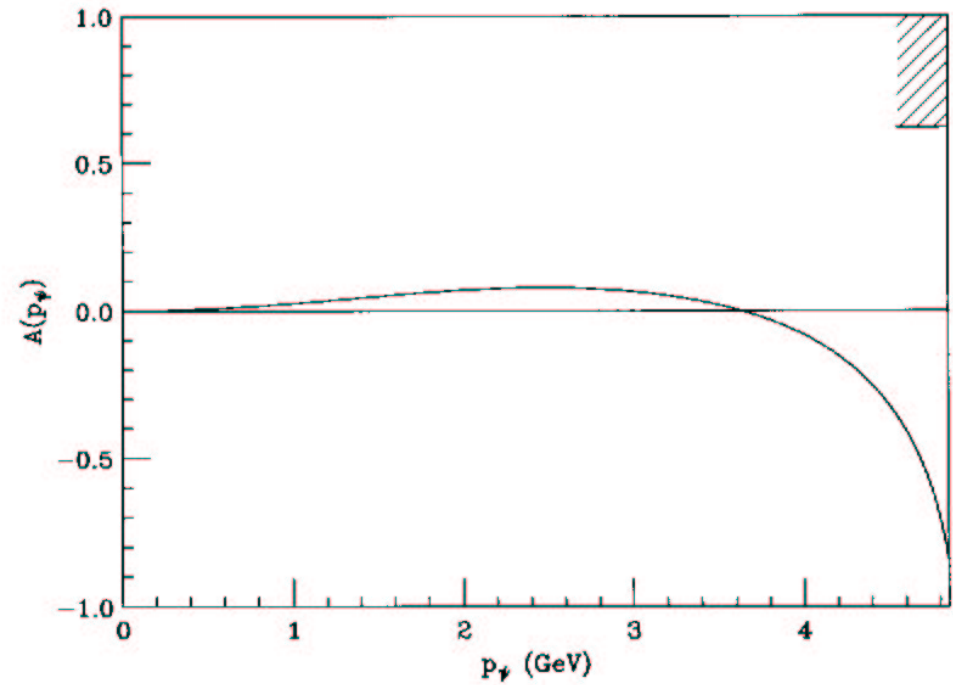
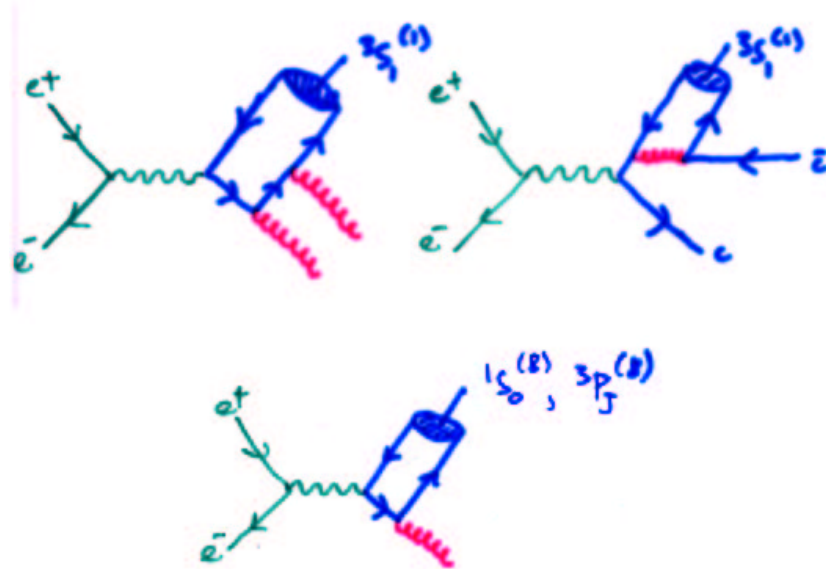
COM predicts  $J/\psi$ ,  $\psi'$  transversely polarized,  $p_{\perp} \gg 2m_c$

(Cho, Wise)



(Braaten, Kniehl, Lee)

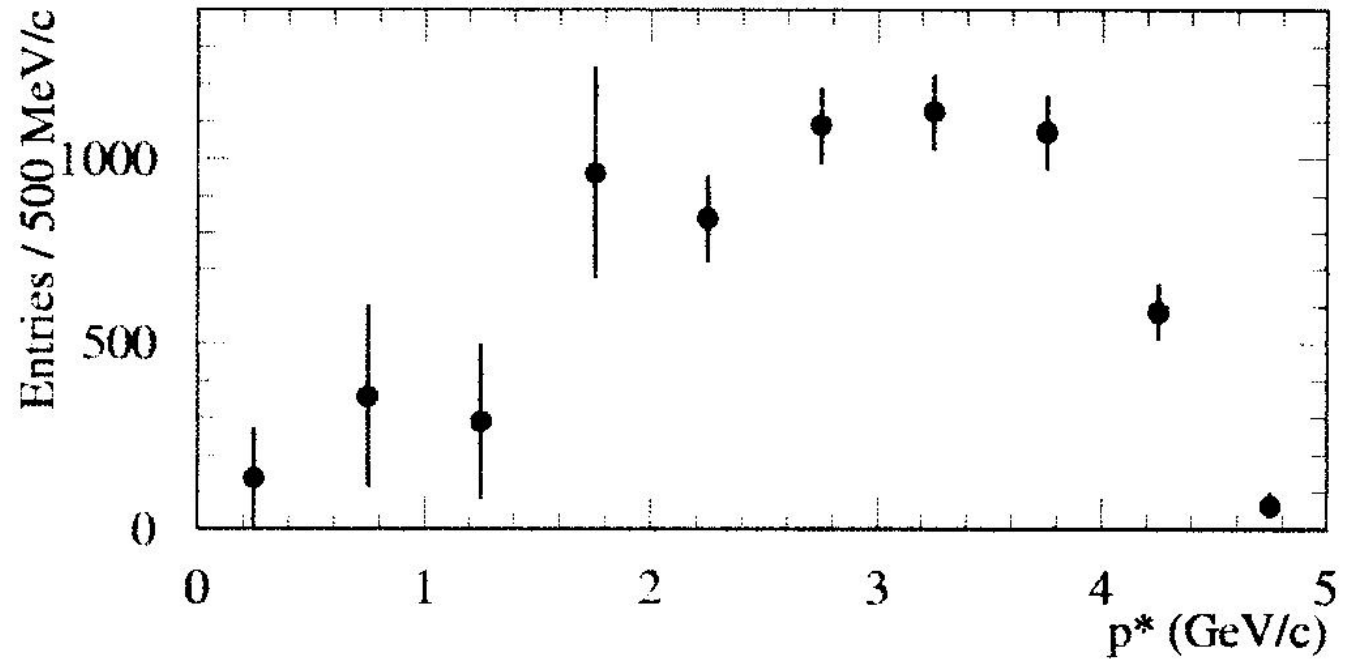
- **Color-Octet signal in  $e^+e^- \rightarrow J/\psi + X$**  (Braaten-Chen)
- large ( $\sim 1$  pb) CO contribution near endpoint (total CS 0.4-0.9 pb)



- angular distribution ( $\cos \theta$  - angle between  $J/\psi$  and beam)

$$\frac{d\sigma}{dp d \cos \theta} = S(p)(1 + A(p) \cos^2 \theta)$$

- BaBar ( $J/\psi$  cross section)



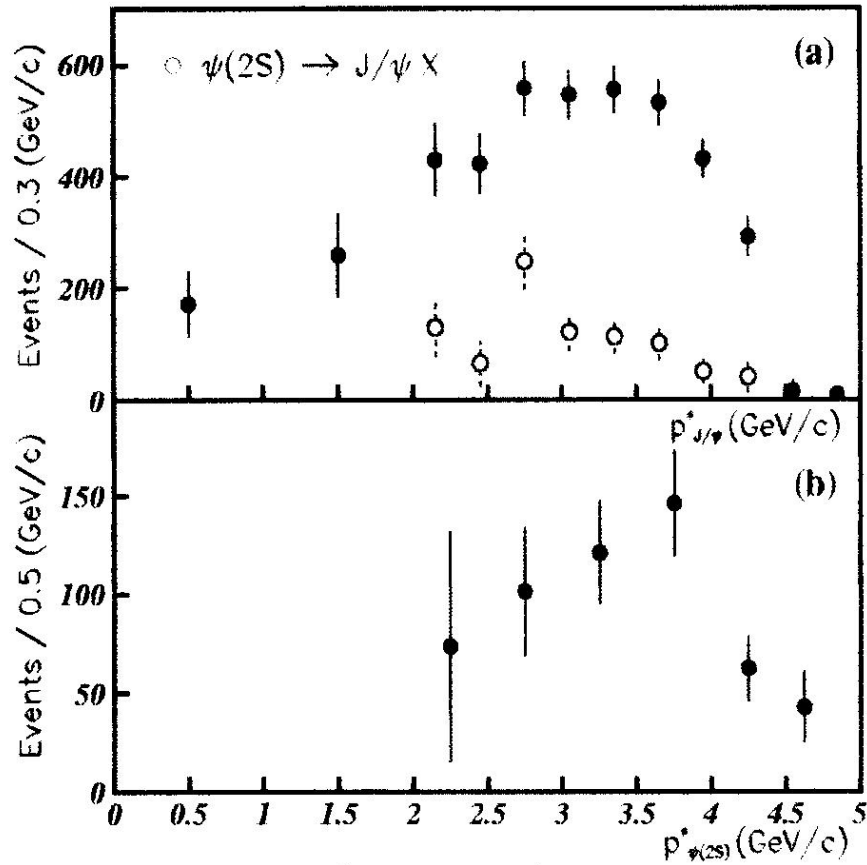
- $\sigma_{\text{tot}} = 2.52 \pm 0.21 \pm 0.21 \text{ pb}$

$$A(p) = \begin{cases} 0.05 \pm 0.22 & p < 3.5 \text{ GeV} \\ 1.5 \pm 0.6 & p > 3.5 \text{ GeV} \end{cases}$$

- Total cross section in excess of CSM,  $A \approx 1$  for large  $p$

- Where is color-octet contribution at endpoint?

- Belle



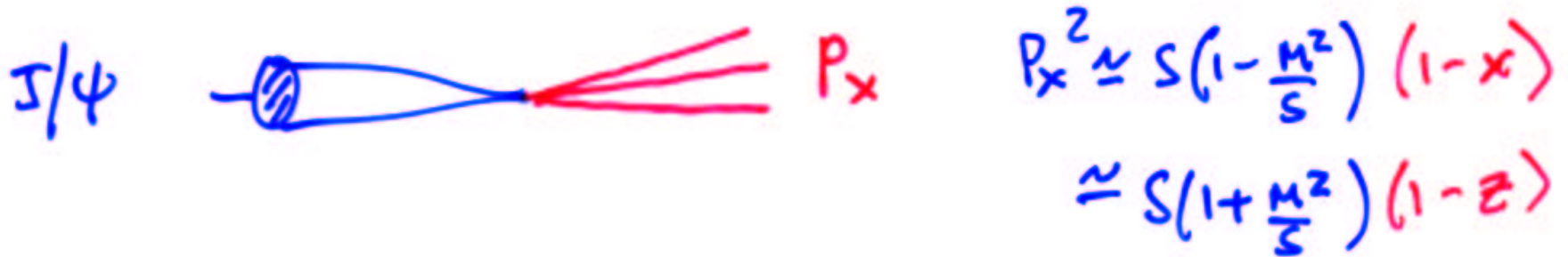
$$\sigma_{\text{tot}} = 1.47 \pm 0.10 \pm 0.13 \text{ pb}$$

$$A(p) = \begin{cases} 0.3^{+0.5}_{-0.4} & 2.0 < p < 2.6 \text{ GeV/c} \\ 1.1^{+0.4}_{-0.3} & 2.6 < p < 3.4 \text{ GeV/c} \\ 1.1^{+0.4}_{-0.3} & 3.4 < p < 4.9 \text{ GeV/c} \end{cases}$$

- Other puzzles  $\frac{\sigma(e^+e^- \rightarrow J/\psi c\bar{c})}{\sigma(e^+e^- \rightarrow J/\psi X)} = 0.59^{+0.15}_{-0.13} \pm 0.12$

- large exclusive  $J/\psi + (\eta_c, \chi_c)$  cross sections

- Near endpoint  $c\bar{c}$  recoiling against low mass energetic jet



- Large Perturbative, Nonperturbative Corrections

(Beneke, Rothstein, Wise)

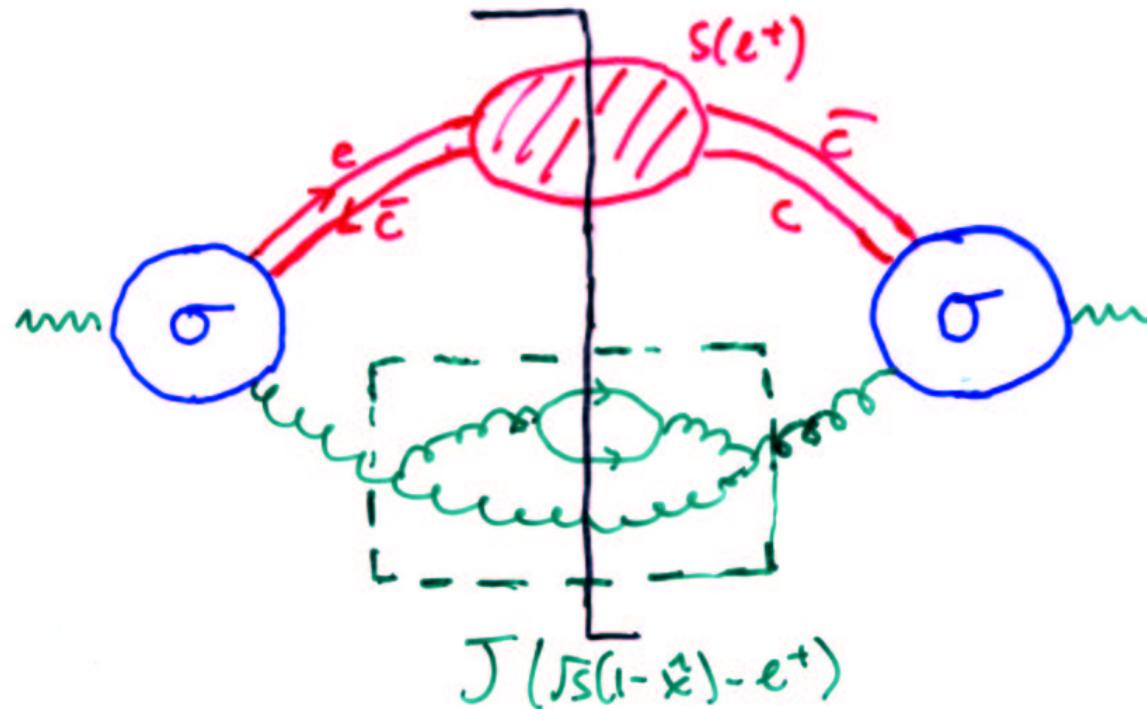
$$\alpha_s \frac{\ln(1-x)}{1-x} \quad \frac{v^2}{1-x}$$

- $1-x \sim v^2, \alpha_s \longrightarrow p \approx 3 \text{ GeV} \quad p_{\max} = 4.8 \text{ GeV}$

- as  $x \rightarrow 1$  need new factorization theorem:

(Fleming, Leibovich, T.M.)

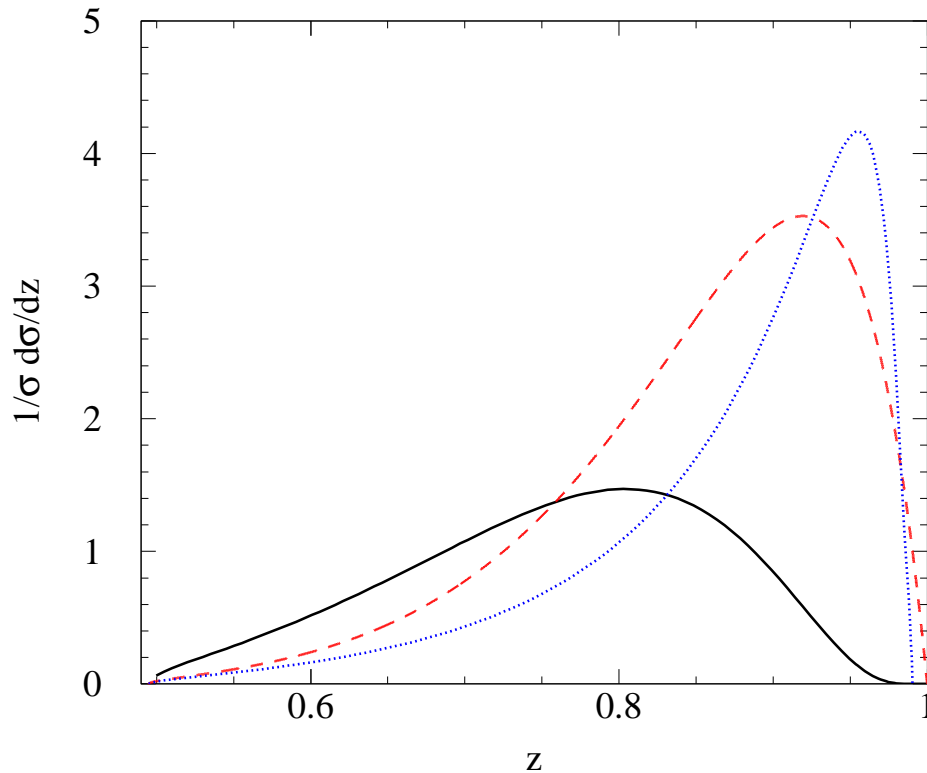
$$\frac{d\sigma}{dx} = \sigma(\mu) \int dl^+ S(l^+) J(\sqrt{s}(1 - \hat{x}) - l^+)$$



- resum large logs using RGE's for  $S(l^+)$ ,  $J(\sqrt{s}(1 - \hat{x}) - l^+)$
- nonperturbative corrections incorporated in **shape function  $S(l^+)$**

- **Not predictive** - depends on unknown **universal**  $S(\hat{\ell}_+)$

extract from  $e^+e^-$ , predict photo-, electroproduction

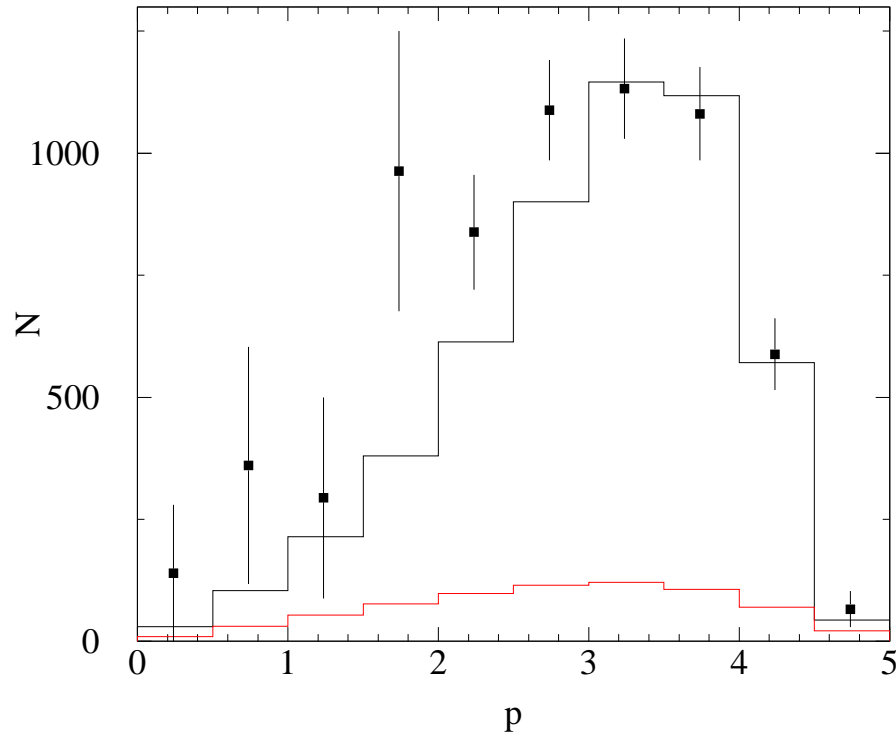


Dotted - resummation only  
 Dashed - shape function only  
 Solid - both

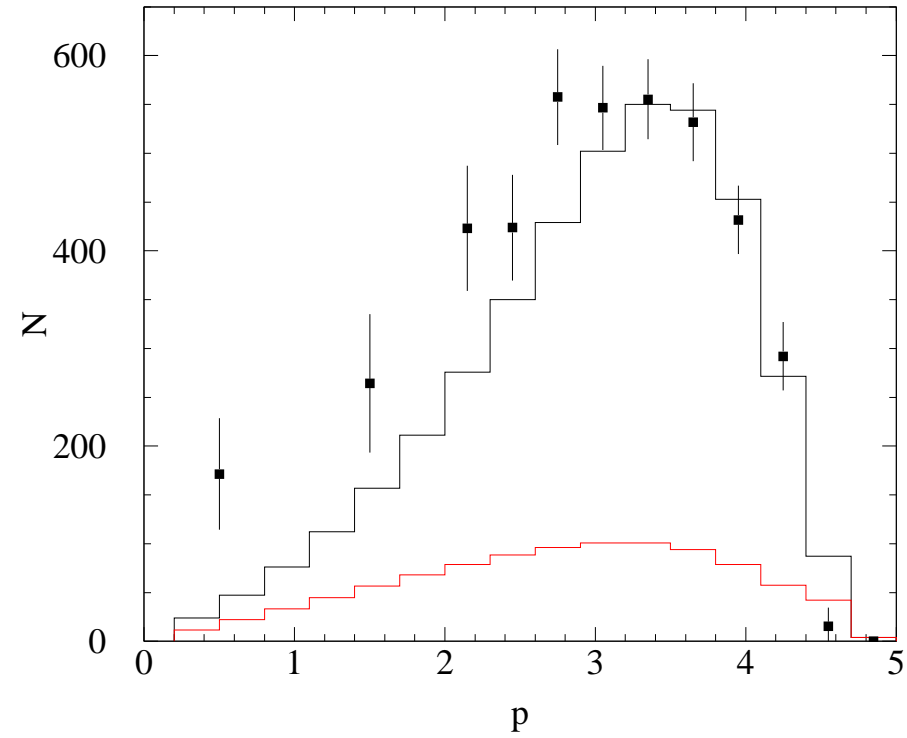
- NRQCD scaling rules:

$$S_N = \int d\hat{\ell}^+ (\hat{\ell}^+)^N S(\hat{\ell}^+) \sim (2m_c v^2)^N \sim \Lambda_{\text{QCD}}^N; N \geq 1$$

- Comparison with Data (Different Normalization)



BaBar



Belle

- Absence of color-octet near endpoint understood

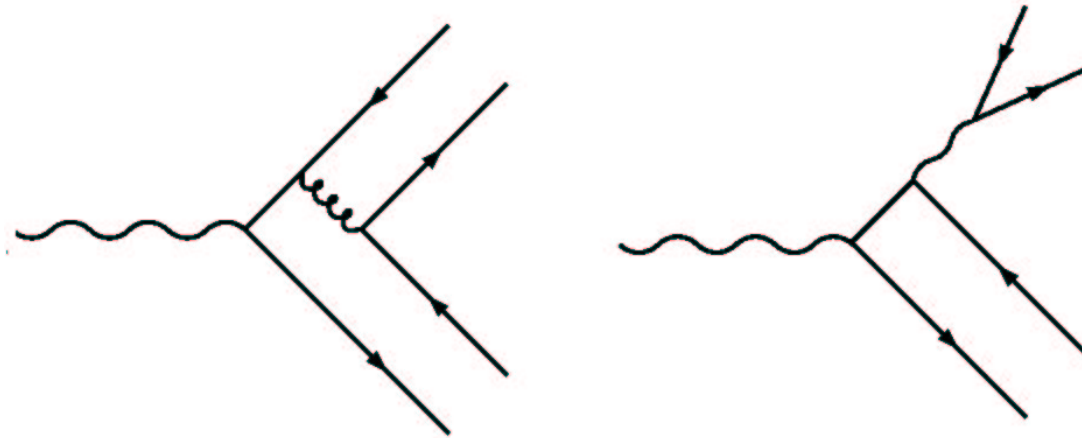
- $\frac{\sigma(e^+e^- \rightarrow J/\psi c\bar{c})}{\sigma(e^+e^- \rightarrow J/\psi X)}$  still unexplained!

- Exclusive Double Onium Production (Belle)

$$\sigma[J/\psi + \eta_c] \times Br[\eta_c \rightarrow \geq 4 \text{ charged}] = 33_{-6}^{+7} \pm 9 \text{ fb}$$

comparable cross sections for  $J/\psi + \eta_c(2S)$ ,  $J/\psi + \chi_{c0}$

- Theory (Braaten, Lee)



- w/o relativistic corrections  $2.3 \pm 1.06 \text{ fb}$

w/ relativistic corrections  $5.5_{-3.5}^{+10.6} \text{ fb}$

Errors:  $m_c$  only ( $1.4 \pm 0.2 \text{ GeV}$ ), pert. corr.  $\approx 50\%$

- Relativistic corrections large, hard to compute

# Open Charm/Bottom Production

- QCD Factorization Theorem (Collins, Soper, Sterman)

$$d\sigma[A B \rightarrow H_Q + X] = \sum_{ij} f_{i/A} \otimes f_{j/B} \otimes d\hat{\sigma}[ij \rightarrow Q\bar{Q}] \otimes D_{Q \rightarrow H_Q} + O(\Lambda_{\text{QCD}}/m_Q, \Lambda_{\text{QCD}}/p_{\perp})$$

- Leading Term

bottom/charm production at Tevatron, DIS,  $\gamma\gamma, \dots$

importance of resummation/ fragmentation functions

(Cacciari, Nason; Binnewies, Kniehl, Kramer)

- Power Corrections

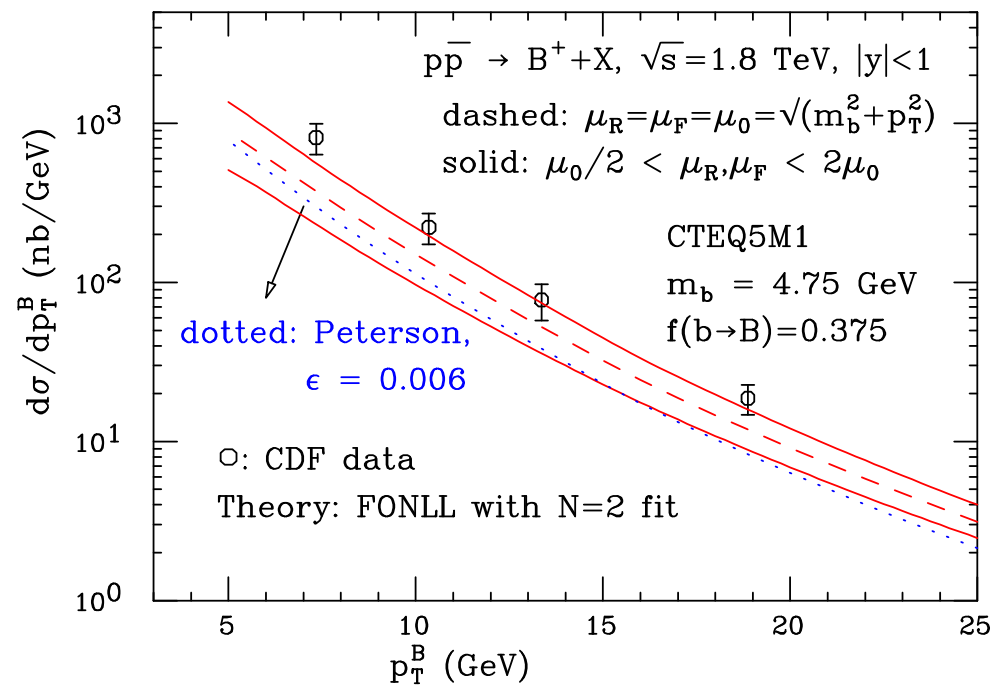
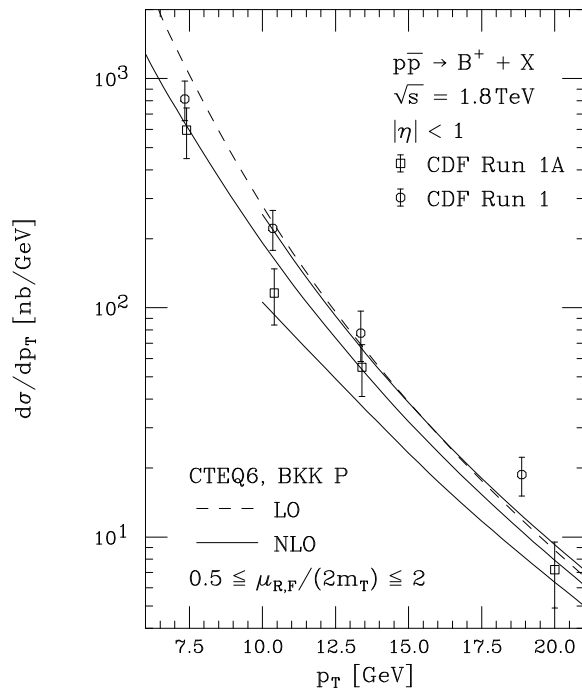
Charm Asymmetries and Heavy Quark Recombination

(Braaten, Jia, Mehen; Kusunoki)

- Bottom Production at Tevatron

- 2002 CDF Analysis - Compared w/NLO QCD + Petersen Frag.

Theory < data by  $2.9 \pm 0.2 \pm 0.4$  outside errors est. by varying  $\mu, \epsilon_b$



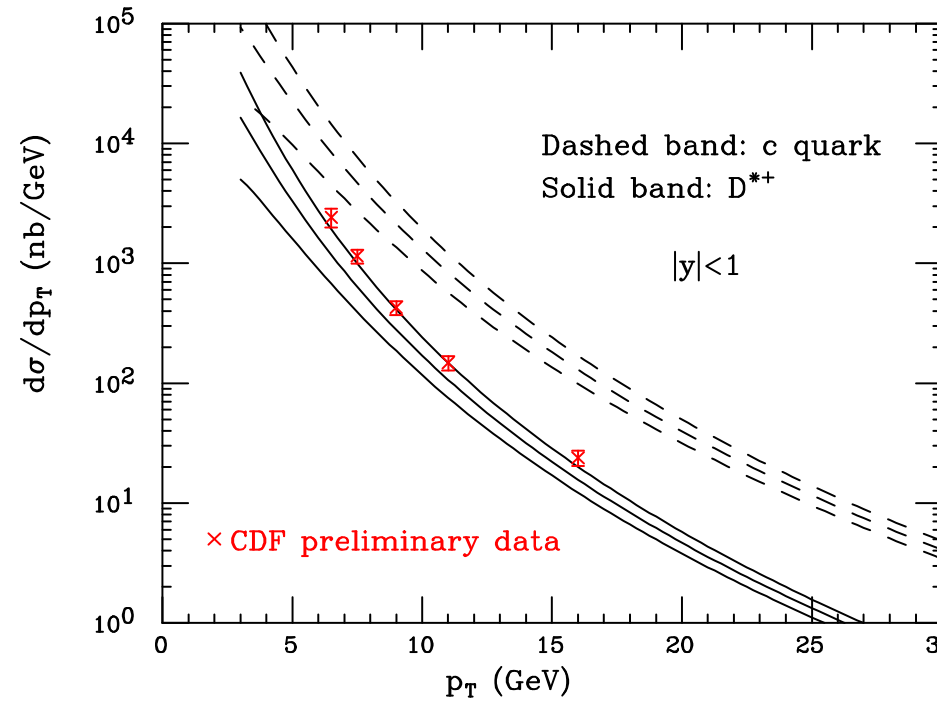
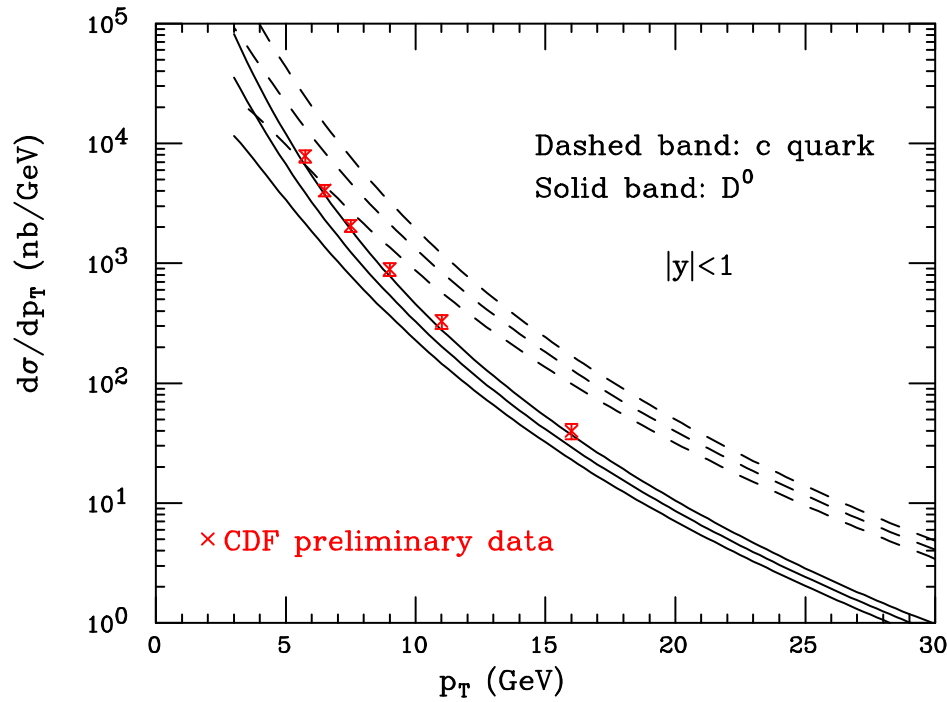
- (BKK) NLO massless scheme - sum  $\ln(p_{\perp}/m_b)$  using AP evolution

use  $D_{b \rightarrow B}$  fitted to OPAL data consistently

- (CN) FONLL - NLO w/ finite  $m_b$  + NLL resummation of logs

fit low moments of fragmentation function

- Charm Production at Tevatron **New CDF Measurement**

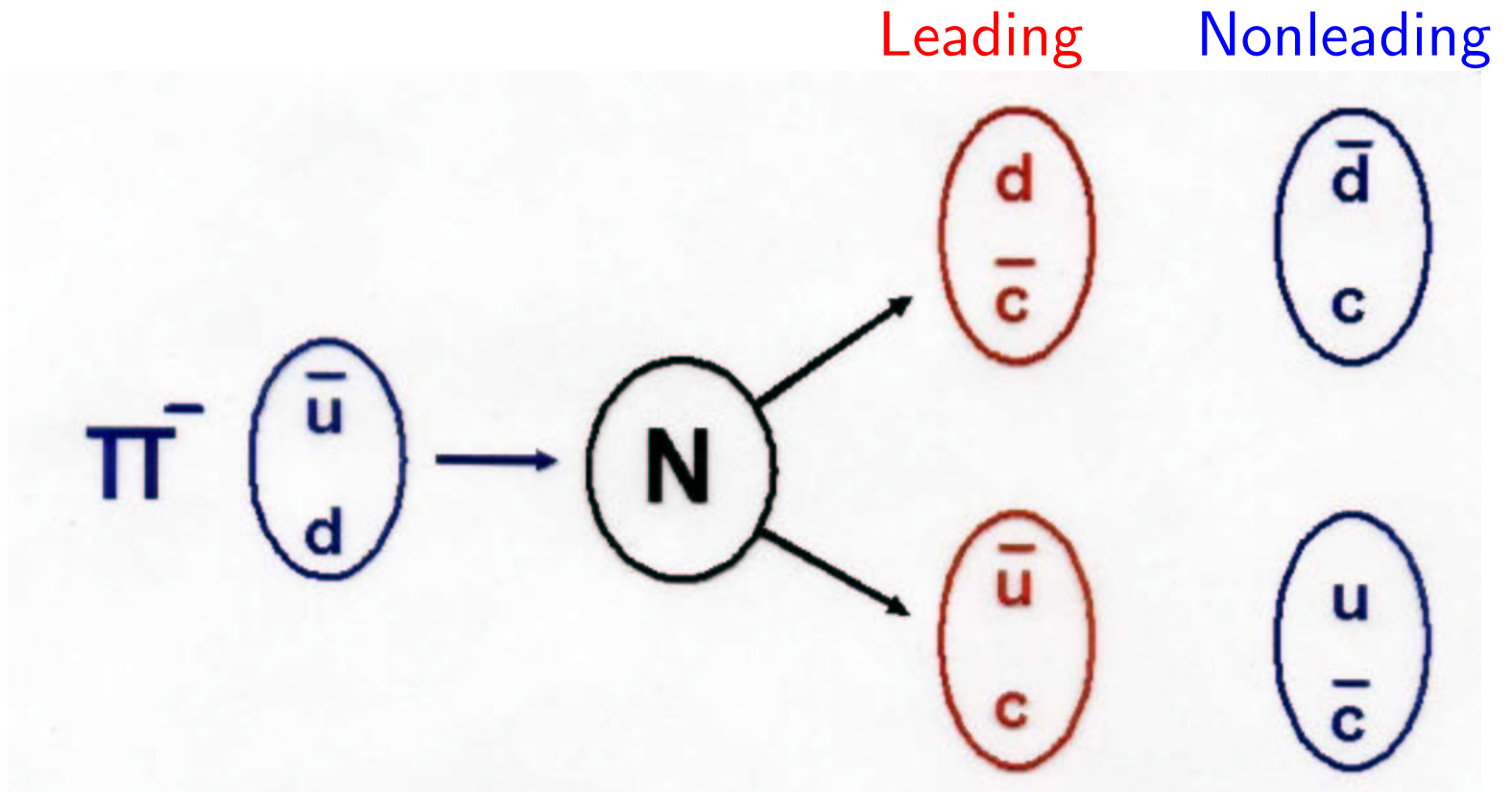


(Cacciari, Nason)

- $D$  meson results similar to  $B$  meson

# Charm Asymmetries

- Leading Particle Effect - Fixed Target Hadroproduction



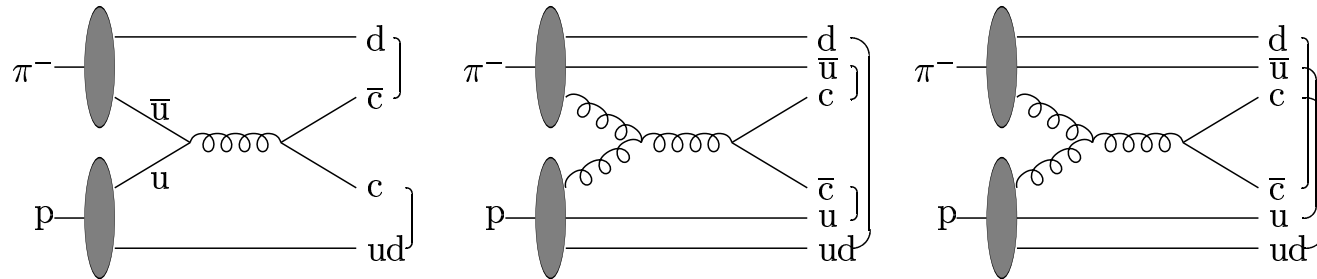
- Forward Direction of  $\pi^-$ :

$$\sigma[D^-, D^0] \gg \sigma[D^+, \bar{D}^0]$$

# Hadronization Models

- String Fragmentation model

(Norrbin, Sjöstrand)



PYTHIA tuned to fit data ( $m_c \approx 1.7 \text{ GeV}$ , intrinsic  $k_{\perp} \approx 1 \text{ GeV}$ )

- Intrinsic Charm Model

(Vogt, Brodsky)

hadronic Fock states with  $c\bar{c}$ :  $p \sim |uudc\bar{c}\rangle$ ,  $\pi^- \sim |\bar{u}dc\bar{c}\rangle$

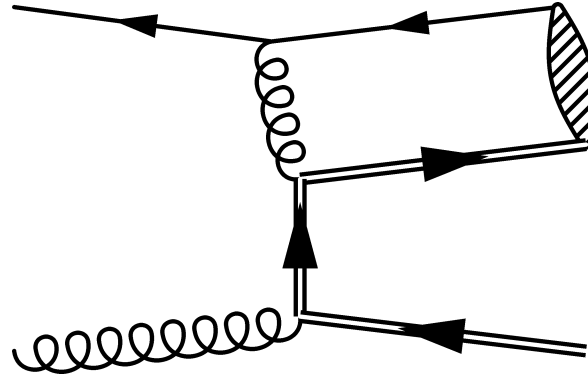
$\bar{c}$  recombines with projectile spectator after hard scattering

- Charm Asymmetries - Power Corrections?

# Heavy-Quark Recombination

(E. Braaten, Y. Jia, T. M.)

- Hard Process:  $\bar{q} + g \rightarrow \bar{c} + (c\bar{q})$ ,  $(c\bar{q})$  bind to form  $D$  meson

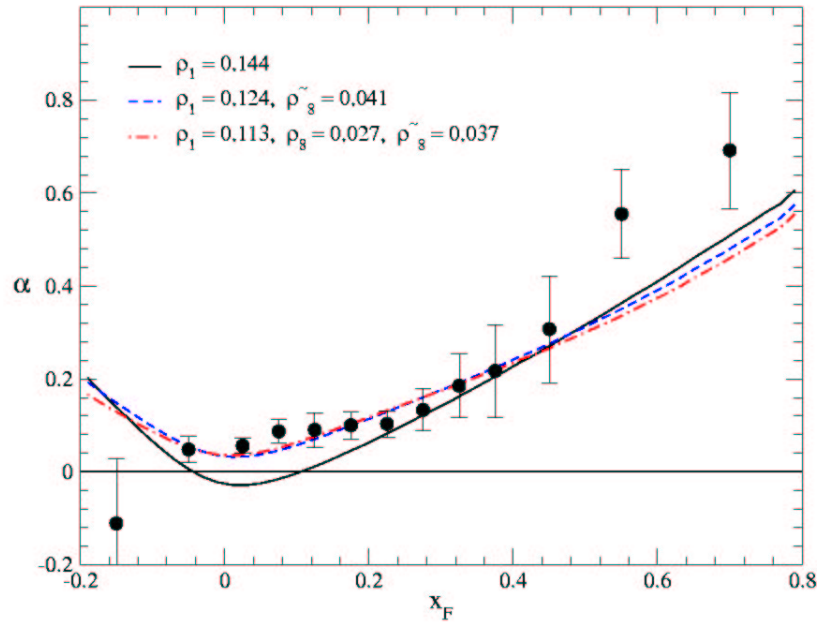


- Power suppressed correction to LO fragmentation:  $\alpha_s \frac{\Lambda_{\text{QCD}} m_c}{p_{\perp}^2 + m_c^2}$
- Cross section peaked when  $D$  in forward direction of  $\bar{q}$

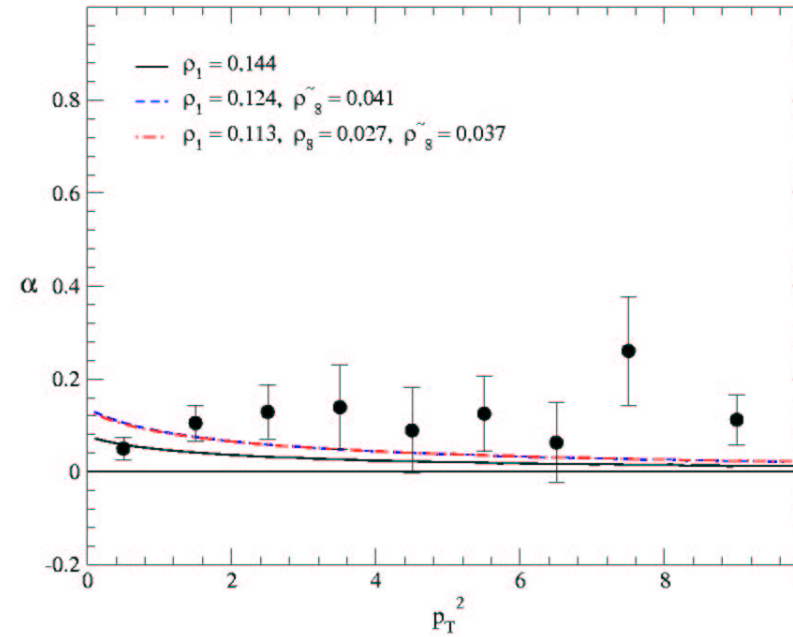
$$d\hat{\sigma}[D] = \sum_n d\hat{\sigma}[\bar{q}g \rightarrow c\bar{q}(n) + \bar{c}] \rho[c\bar{q}(n) \rightarrow D] \quad n = {}^1S_0^{(1,8)}, {}^3S_1^{(1,8)}$$

- 500 GeV  $\pi^-$  on  $N$  target

$$\alpha[D^+] = \frac{d\sigma[D^-] - d\sigma[D^+]}{d\sigma[D^-] + d\sigma[D^+]}$$

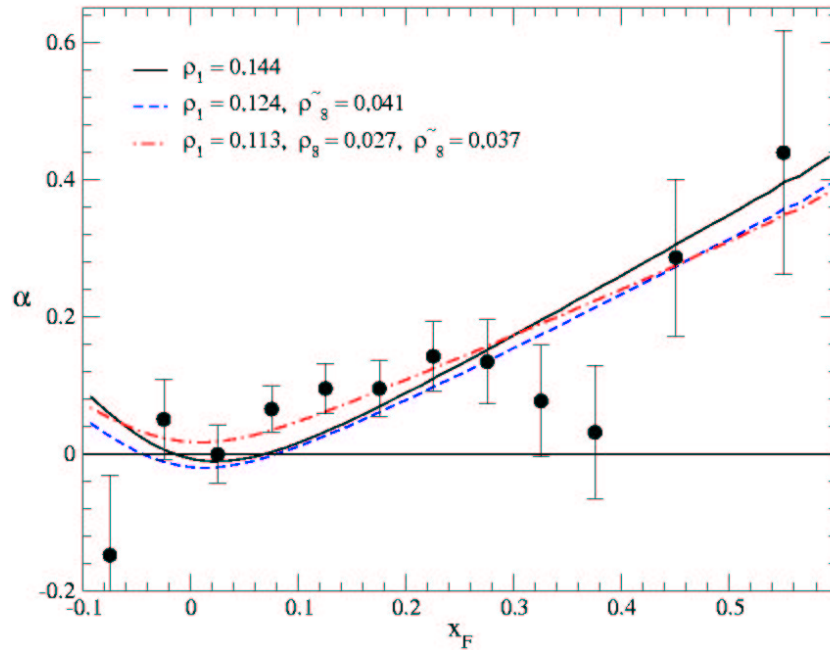


$\alpha[D^+] \text{ vs. } x_F$

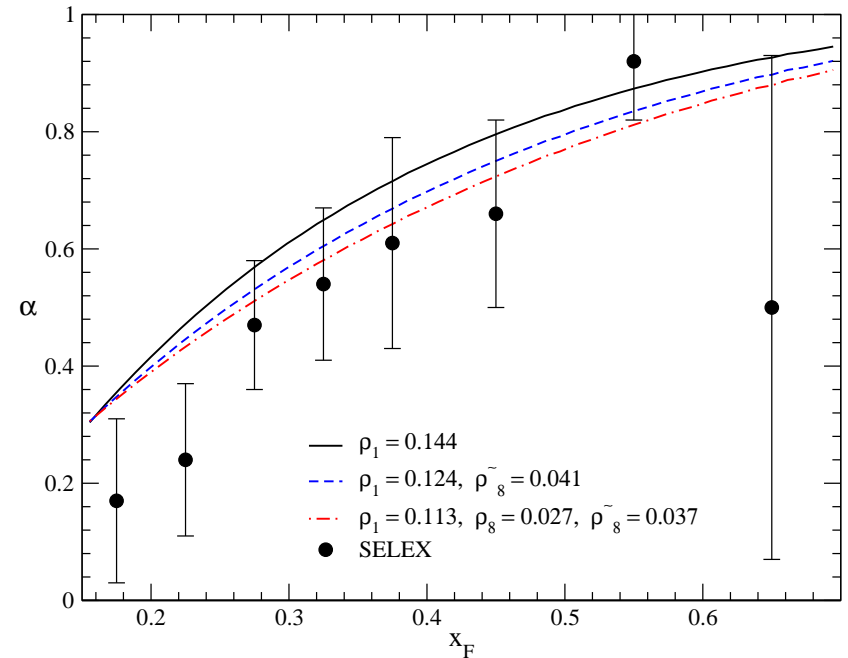


$\alpha[D^+] \text{ vs. } p_{\perp}$

- $\rho[{}^1S_0^{(1)}] = 0.11$  ,  $\rho[{}^1S_0^{(8)}] = 0.03$  ,  $\rho[{}^3S_1^{(8)}] = 0.04$  ,  $\rho[{}^3S_1^{(1)}] = 0.0$



$\alpha[D^{*+}]$  vs.  $x_F$



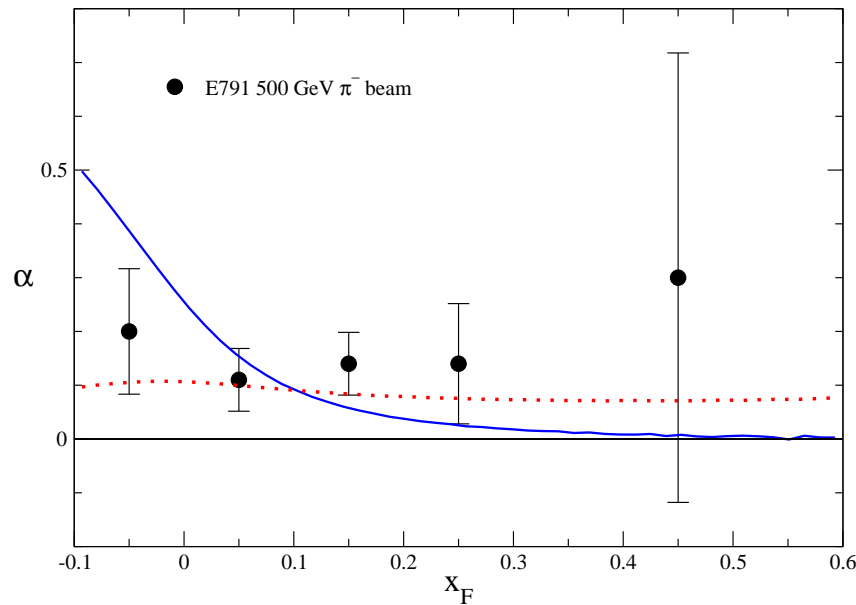
$\alpha[D_s]$  vs.  $x_F$  (600 GeV  $\Sigma^-$ )

- Global analysis: 340 GeV  $\Sigma^-$  (WA89) 500 GeV  $\pi^-$  (E791) 350 GeV  $\pi^-$  (Beatrice) 250 GeV  $\pi^\pm$  (E769) 340 GeV  $\pi^-$  (WA82) 600 GeV  $\Sigma^-$  (SELEX)
- Good fit to  $D$  asymmetries w/ 4 universal parameters

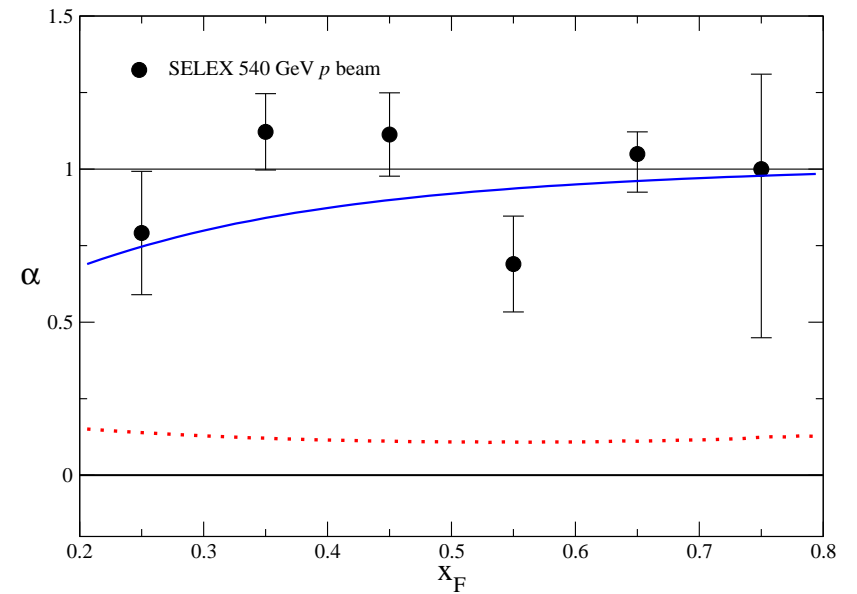
- Charm Baryon Asymmetries - Diquark Recombination

$$d\hat{\sigma}[\Lambda_c] = \sum_n d\hat{\sigma}[qg \rightarrow cq(n) + \bar{c}] \eta[cq(n) \rightarrow D]$$

- $\alpha[\Lambda_c^+]$  vs.  $x_F$



500 GeV  $\pi^-$



540 GeV  $p$

# Summary

- $e^+e^- \rightarrow J/\psi + X$

resummation of pert./nonpert. corrections for CO near endpoint

Large  $\frac{\sigma(e^+e^- \rightarrow J/\psi + c\bar{c})}{\sigma(e^+e^- \rightarrow J/\psi + X)}$ , exclusive  $J/\psi + \eta_c$  cross sections puzzling

- $b, c$  production at Tevatron

resummed calculations slightly below data, consistent within errors

- Charm Production Asymmetries and Heavy Quark Recombination

$D, D^*, D_s, \Lambda_c$  asymmetries w/ few universal parameters