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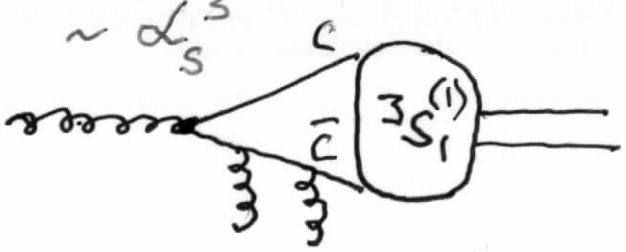
La Thuile 11.03.03

Mysteries in charmonium production

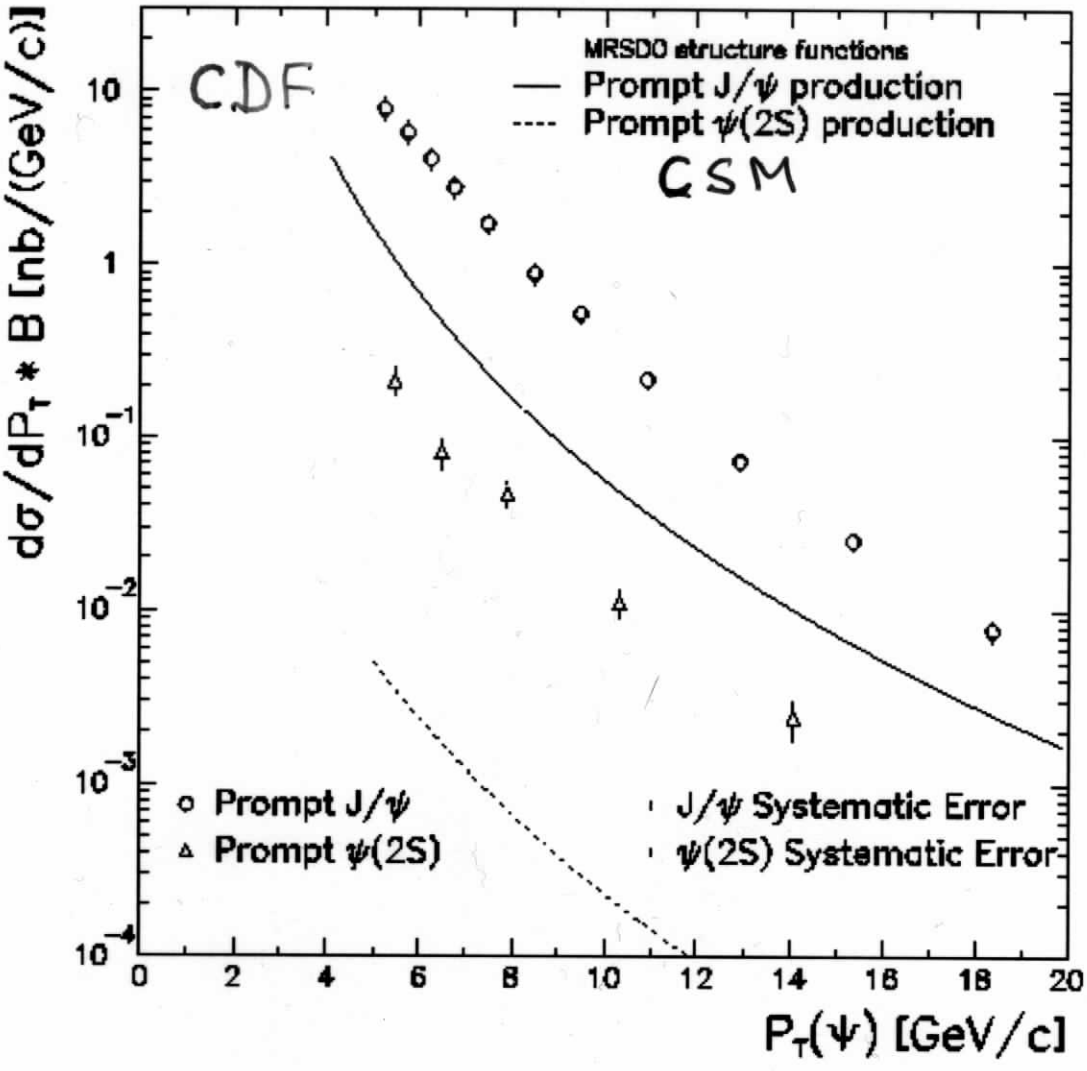
Outline

1. Hadronic interactions
2. B mesons
3. ep interactions
4. $\gamma\gamma$ interactions
5. e^+e^- annihilation
6. x_F distribution in pA

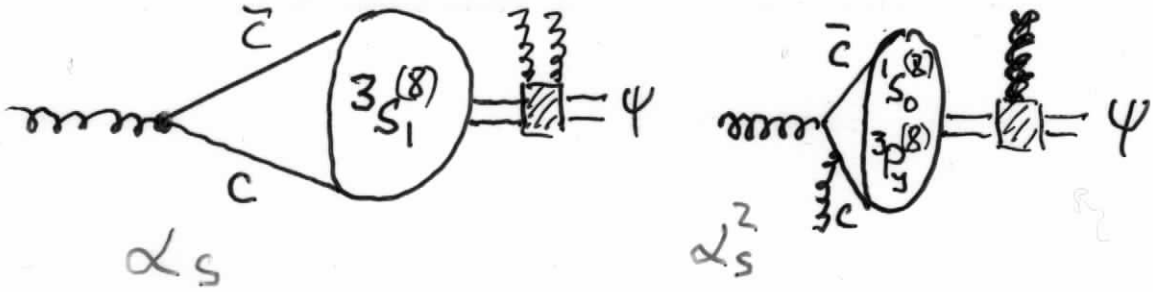
Conclusions

CSM: 

CSM underestimates seriously J/ψ and especially ψ' production rate at Tevatron

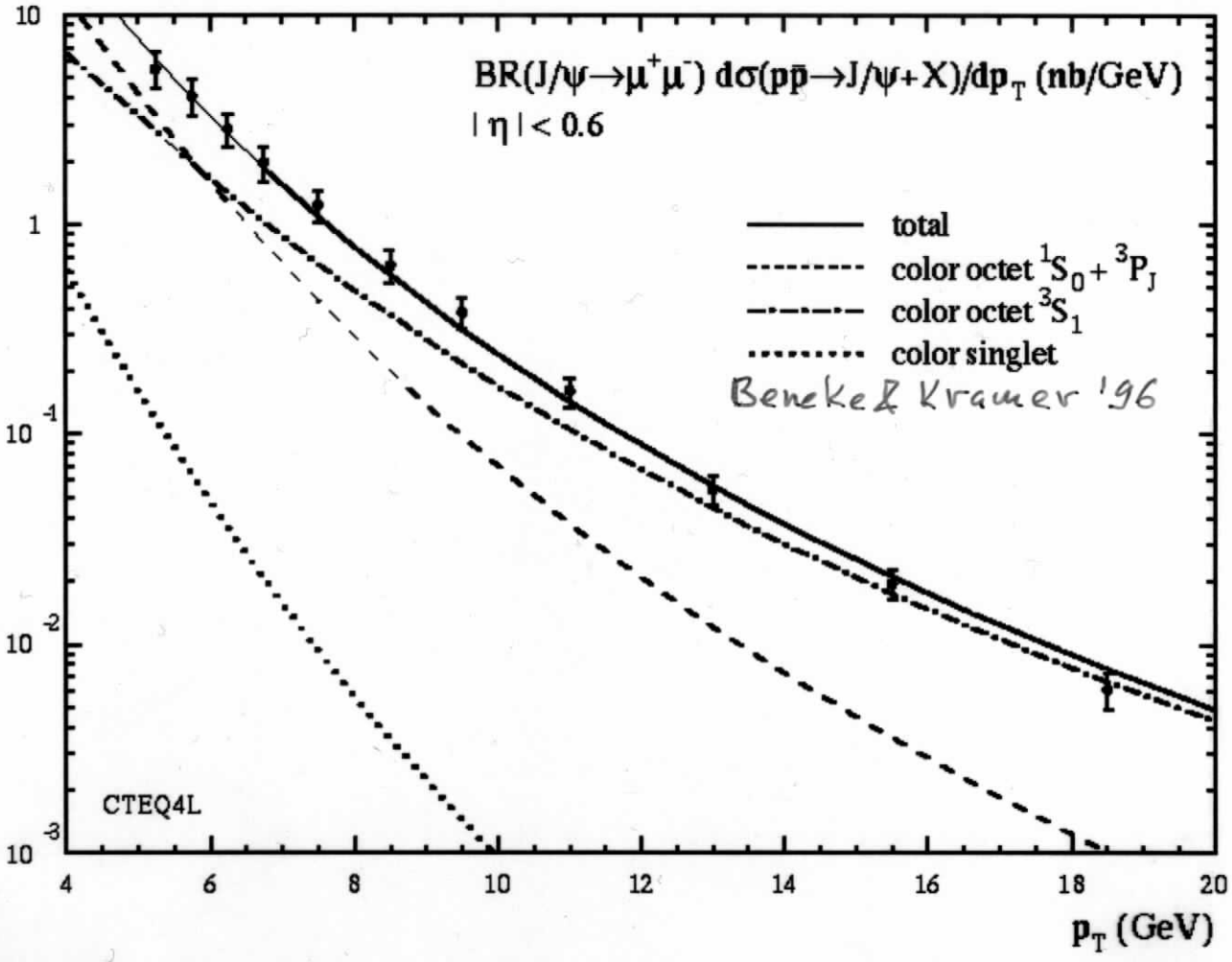


Parton fragmentation is the main mechanism at high p_T

COM: 

COM can explain J/ψ and ψ' production rate (Braaten & Fleming '95)

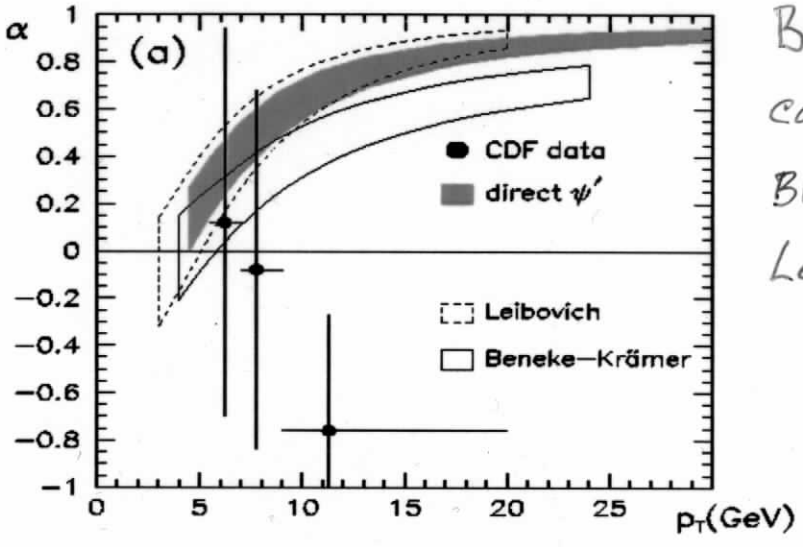
Nonperturbative matrix elements obtained from fit to experimental data



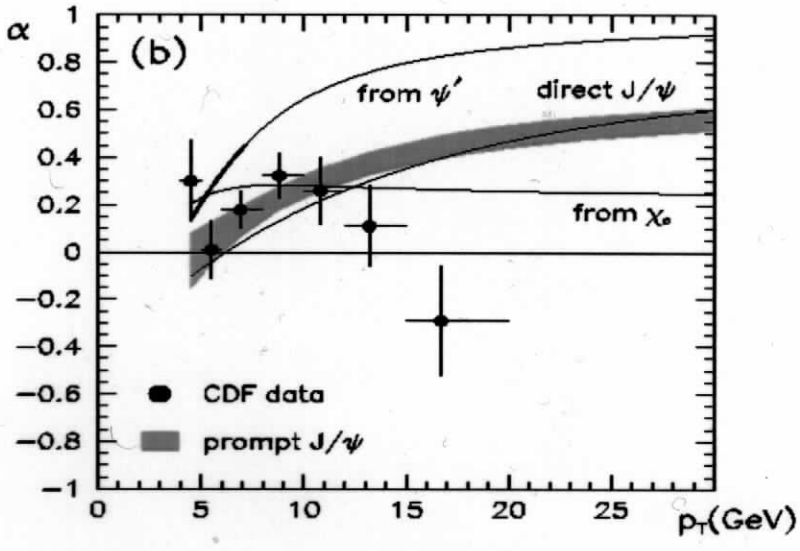
- NRQCD contains CSM and COM (Bodwin Braaten Lepage '95)
- It is easy to fit data with free parameters How about predictions?

  → J/ψ^{dir} and ψ' should be transversely polarized (Cho & Wise '95)

- No sign of Ψ' & J/ψ transverse polarization in CDF data
- But disagreement is not very significant statistically



Blue area shows calculations by Braaten, Kniehl, Lee '00



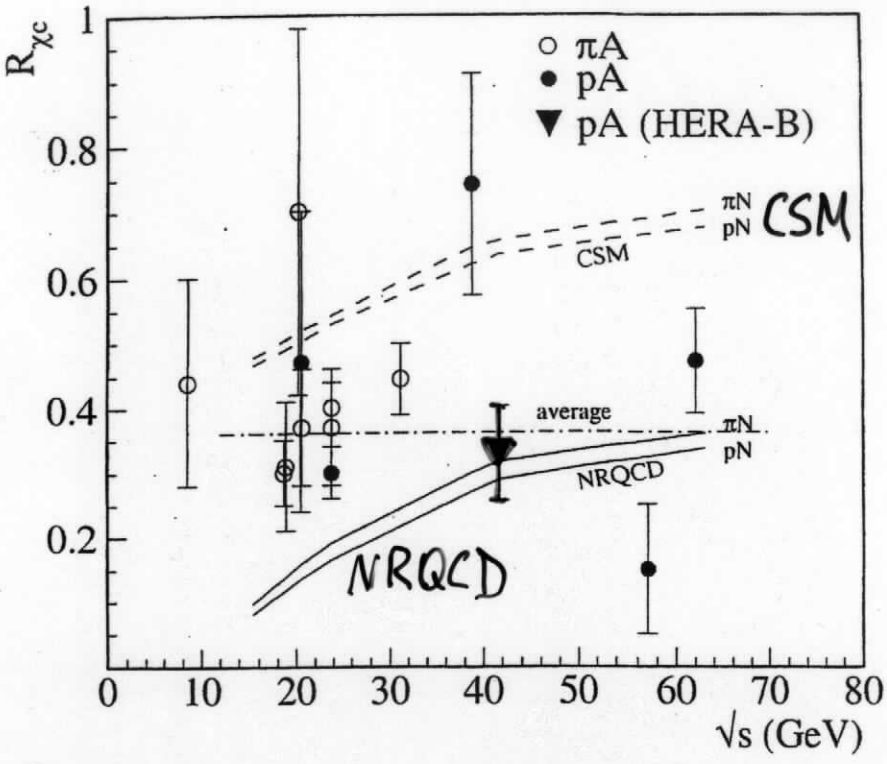
➥ Check NRQCD predictions in different processes

χ_c production in hadronic interactions

$$R_{\chi_c} = \left(\sigma_{\chi_1} Br(\chi_1 \to \gamma J/\psi) + \sigma_{\chi_2} Br(\chi_2 \to \gamma J/\psi)\right) / \sigma_{J/\psi}$$

$R_{\chi_c}(\sqrt{s})$ is sensitive to production mechanism

In CSM J/ψ is suppressed in comparison with χ_c

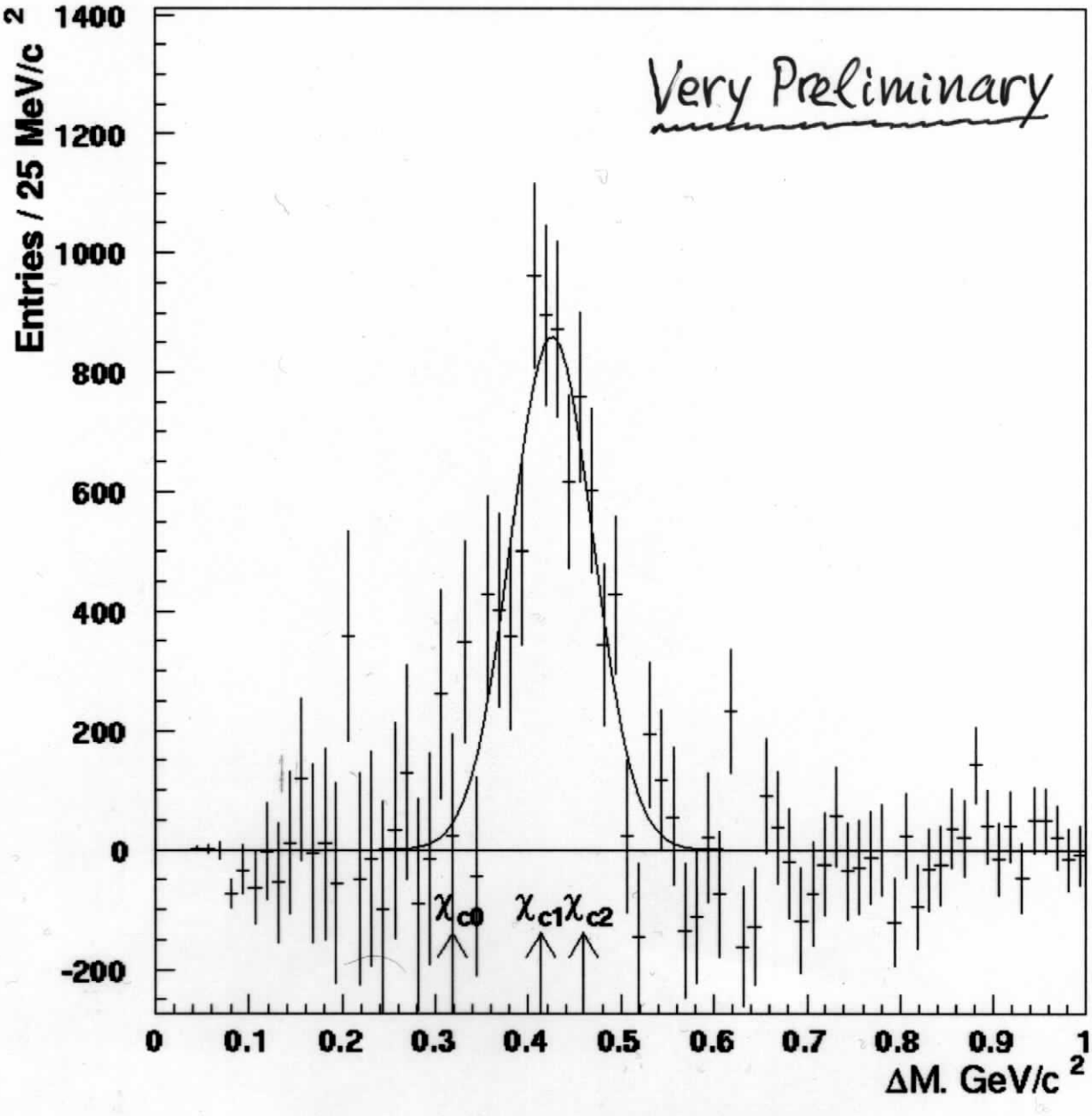


Data at high energies prefer NRQCD
(especially recent HERA-B measurement)

Colour evaporation model (CEM) (Fritzsch '7)
predicts $R_{\chi_c}(\sqrt{s}) = \text{const}$
It is consistent with data

χ_c signal at HERA-B

after background subtraction



Precise measurements of χ_c production are expected soon from 30x larger new HERA-B sample (including P_T, x_F and angular distributions)
We even hope to resolve statistically χ_{c_1} and χ_{c_2}

$B \to J/\psi X$

- First measurements by ARGUS & CLEO:

$$Br(B \to J/\psi X) \approx 1\%$$

smaller than CEM predictions of ~3% (Fritzsch '78)
(CEM includes colour octet contribution)

- COM with parameters fixed by Tevatron data overestimates $Br^{dir}(B \to J/\psi X)$:

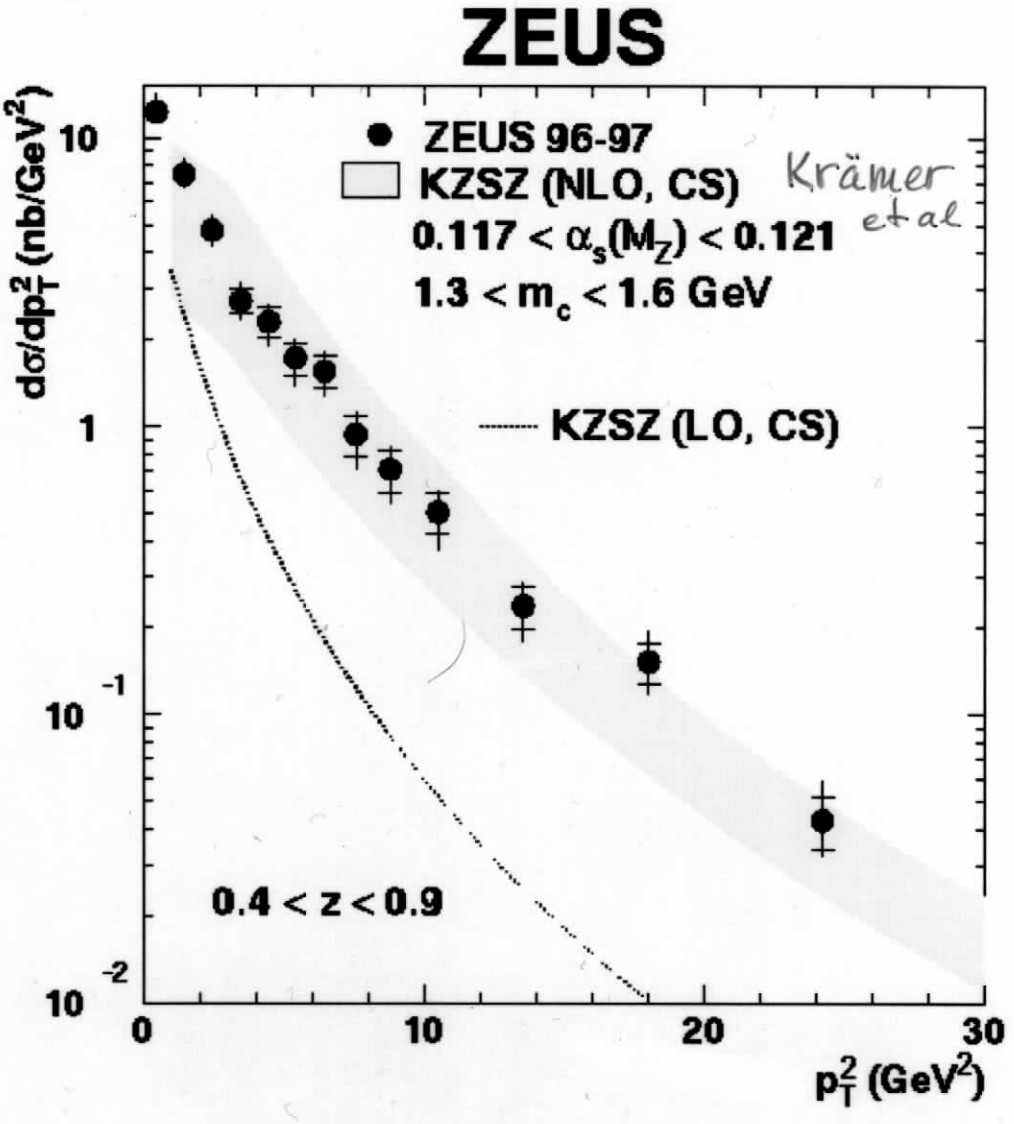
$$Br^{dir}(B \to J/\psi X)_{COM} > 5\% \quad \text{(P. Ko '96)}$$

$$Br^{dir}(B \to J/\psi X) = (0.8 \pm 0.08)\% \quad \text{PDG}$$

- However CSM alone is not sufficient

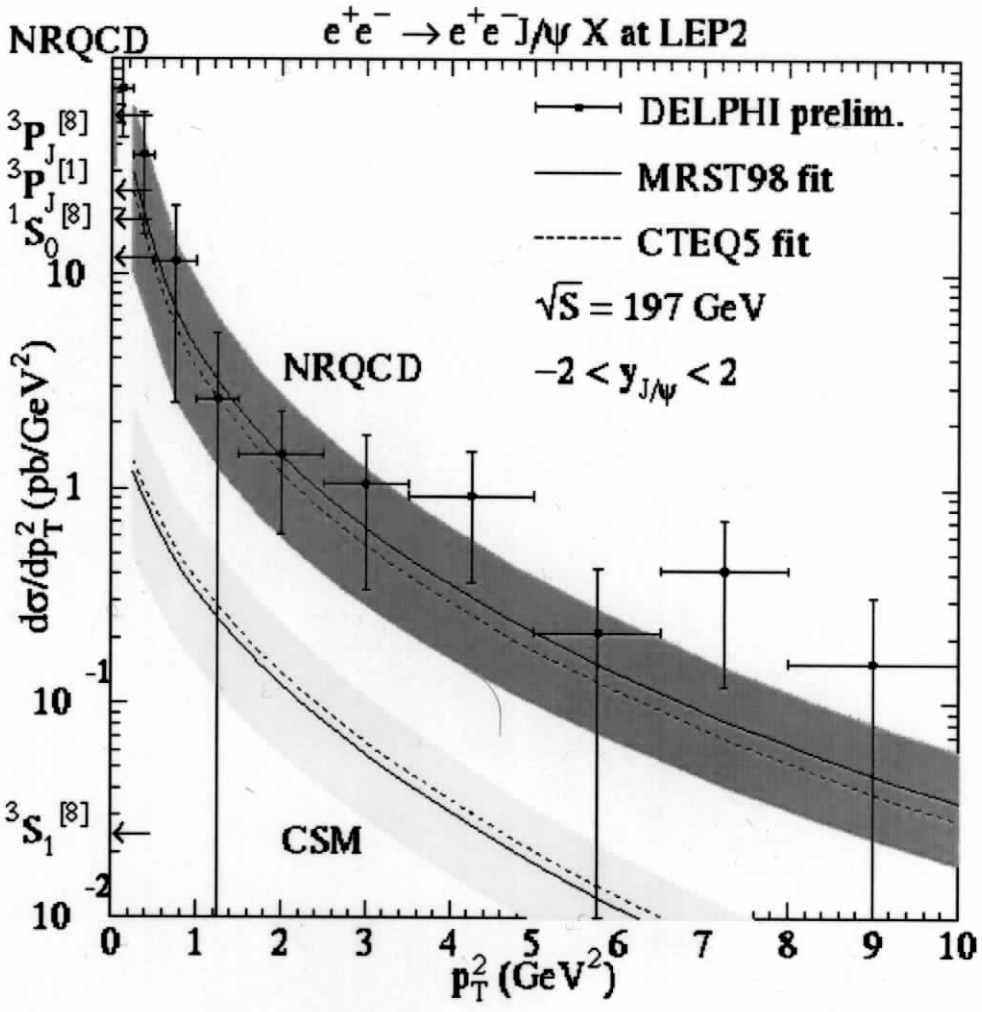
$$Br^{dir}(B \to J/\psi X)_{CSM} = 0.23\% \quad \text{(P. Ko '96)}$$

- Inelastic J/ψ and ψ' photoproduction at HERA is well described by NLO CSM



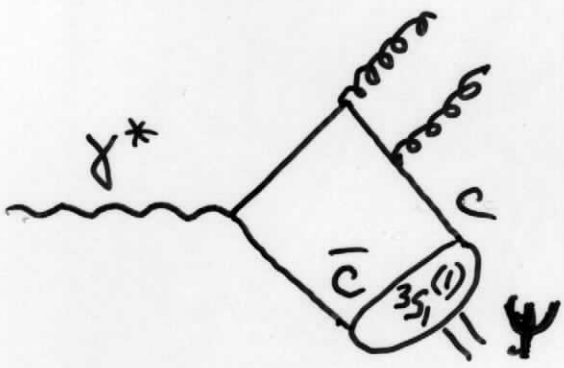
$\gamma\gamma \to J/\psi X$ data favors NRQCD predictions

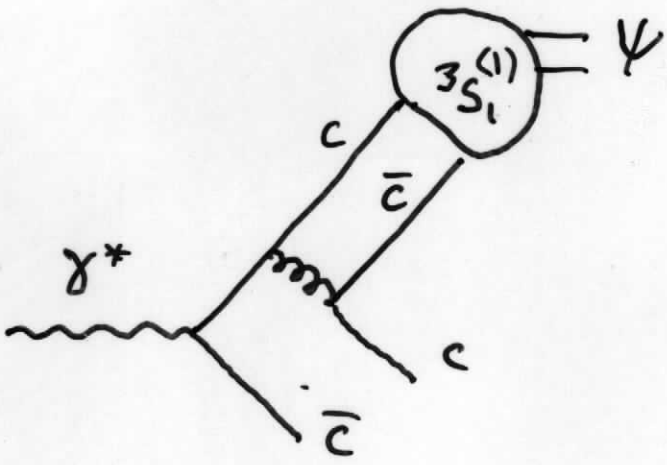
(Klasen, Kniehl, Michaila, Steinhauser '01)



Ψ production in e^+e^- annihilation

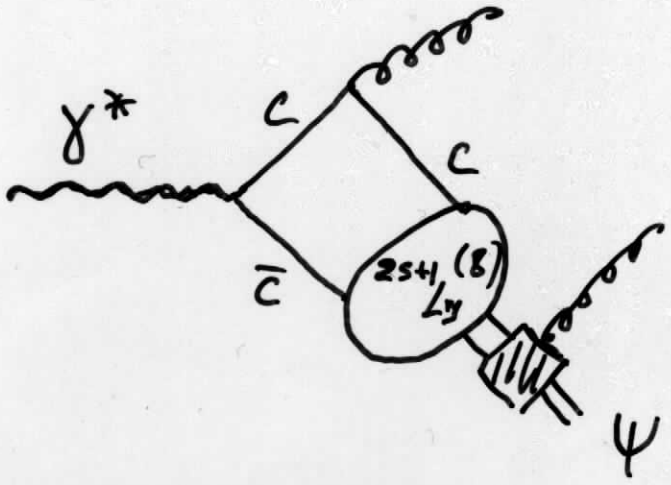
Colour singlet





Ψgg $\qquad$ $\Psi c\bar{c}$

Colour octet



Predictions NRQCD

- $\sigma(J/\psi gg) > 10 \times \sigma(J/\psi c\bar{c})$
- $\sigma(e^+e^- \to J/\psi X) \sim 0.8 - 1.7$ pb
- COM contribution near $p_{max} \Rightarrow$ "dramatic" change of angular distribution

(Braaten & Chen '95)

Belle'01

pb

$\sigma_{J/\psi}$ $1.47 \pm 0.10 \pm 0.13$

$\sigma_{J/\psi}$ $1.05 \pm 0.04 \pm 0.09$

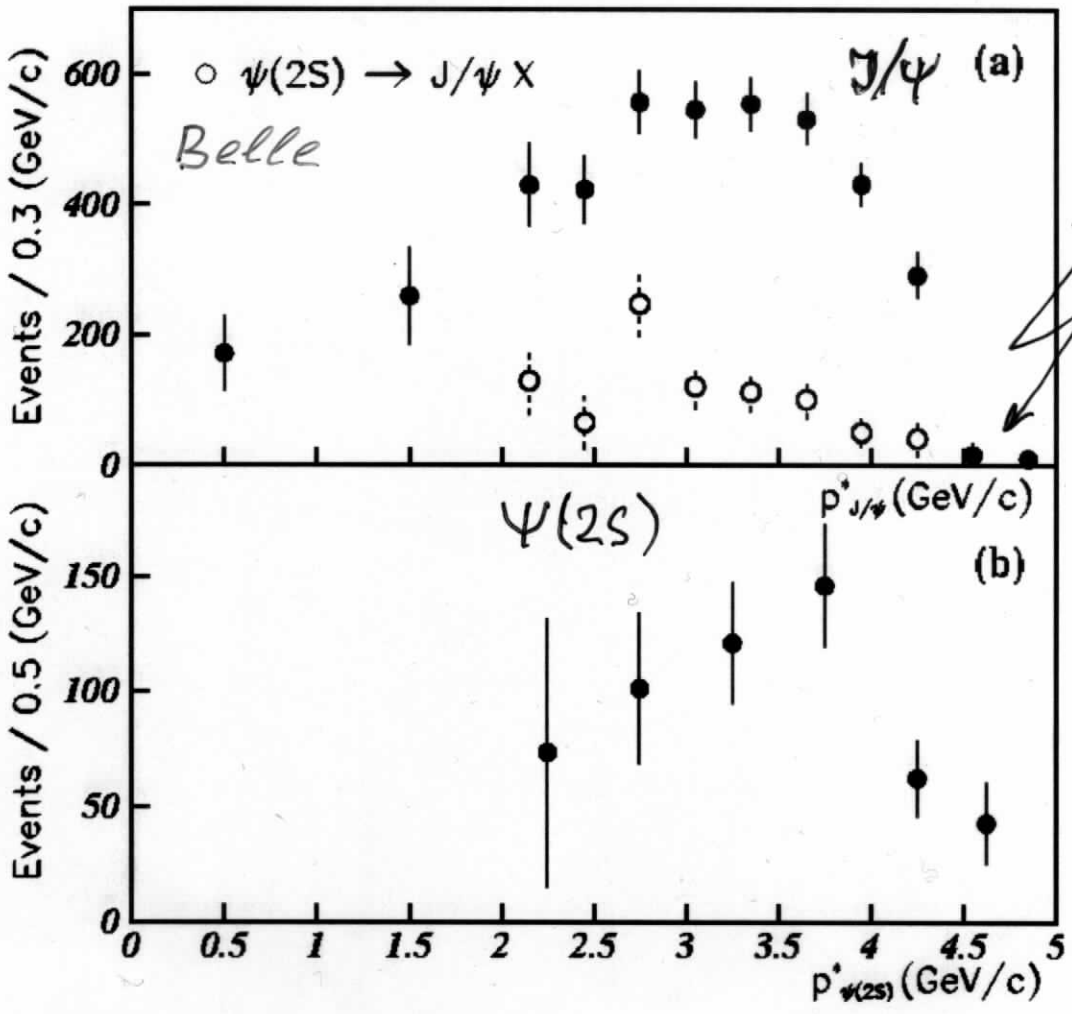
$\sigma^{dir}_{J/\psi}$ $0.72 \pm 0.08 \pm {}^{0.13}_{0.12}$

$\sigma_{\psi(2S)}$ $0.67 \pm 0.09 \pm {}^{0.09}_{0.01}$

$\sigma_{\chi_{c1}}$ < 0.35

$\sigma_{\chi_{c2}}$ < 0.66

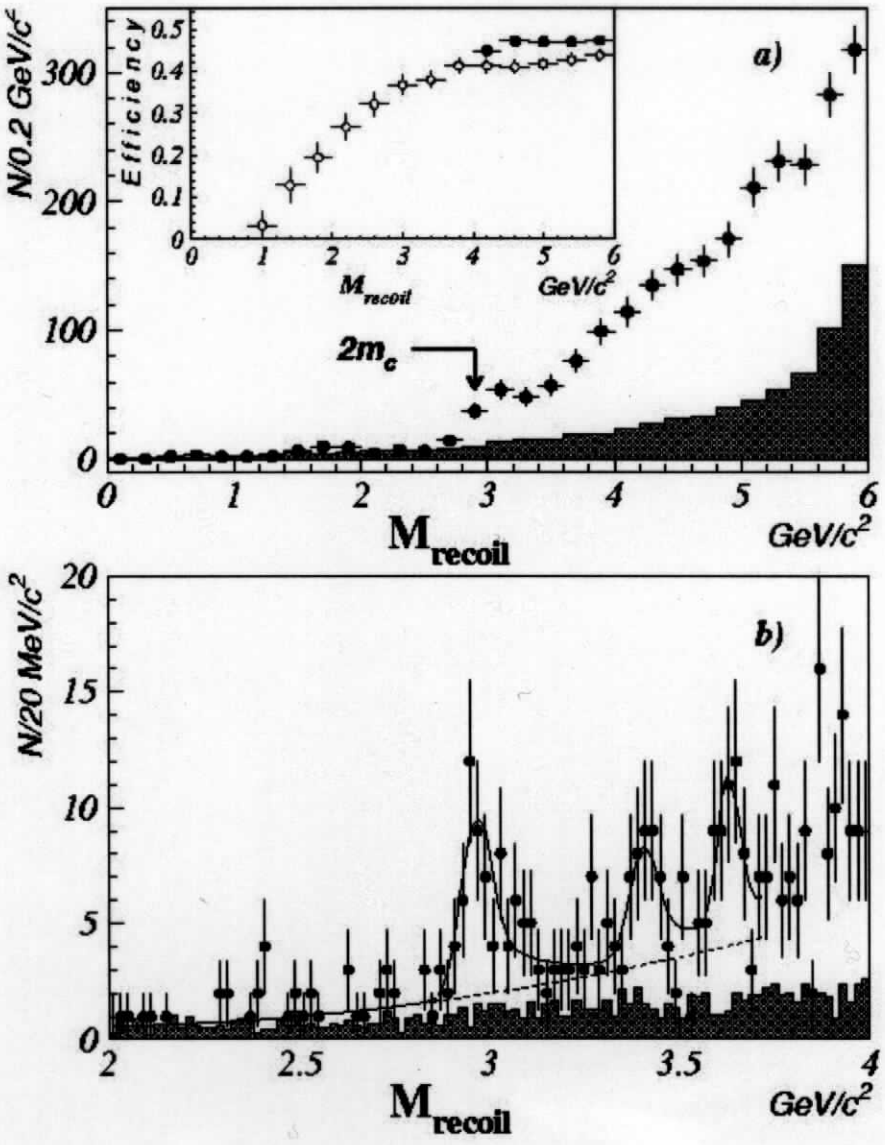
$p^* >$ [redacted] 2.0 GeV



No sign of COM

Observation of large $e^+e^- \to J/\psi c\bar{c}$ (Belle '02)

	M (GeV)	Significance
$N_{\eta_c} = 67^{+13}_{-12}$	2.962 ± 0.013	$6.7\,\sigma$
$N_{\chi_{c0}} = 39^{+14}_{-13}$	3.403 ± 0.014	$3.3\,\sigma$
$N_{\eta_c(2S)} = 42^{+15}_{-13}$	3.622 ± 0.012	$3.4\,\sigma$



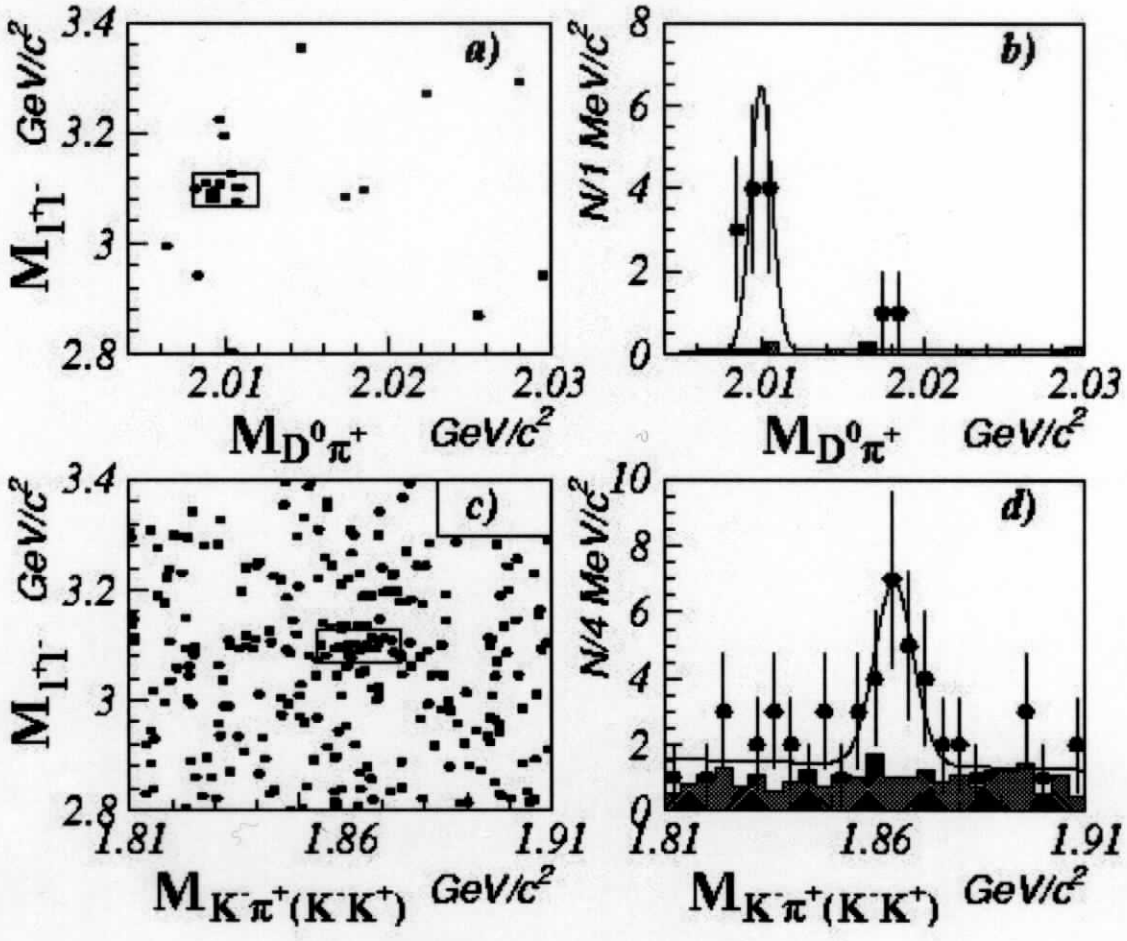
$\sigma(e^+e^- \to J/\psi\,\eta_c) \times Br(\eta_c \to \geq 4 \text{ charged tr.}) = 0.033^{+0.007}_{-0.006} \pm 0.009$ pb

NRQCD can not explain this result

$\sigma(e^+e^- \to J/\psi\,\eta_c) \sim 0.002$ pb (Braaten & Lee '02)

Observation of large $e^+e^- \to J/\psi D^{(*)} X$ (Belle '02)

- $\sigma(e^+e^- \to J/\psi D^0 X) = 0.87 \pm 0.32 \pm 0.20$ pb
- $\sigma(e^+e^- \to J/\psi D^{*+} X) = 0.53 \pm 0.19 \pm 0.14$ pb
- $\dfrac{\sigma(e^+e^- \to J/\psi c\bar{c})}{\sigma(e^+e^- \to J/\psi X)} = 0.59 \pm 0.15 \pm 0.12$
- $\sigma(e^+e^- \to J/\psi c\bar{c}) = 0.87 \pm 0.21 \pm 0.17$ pb



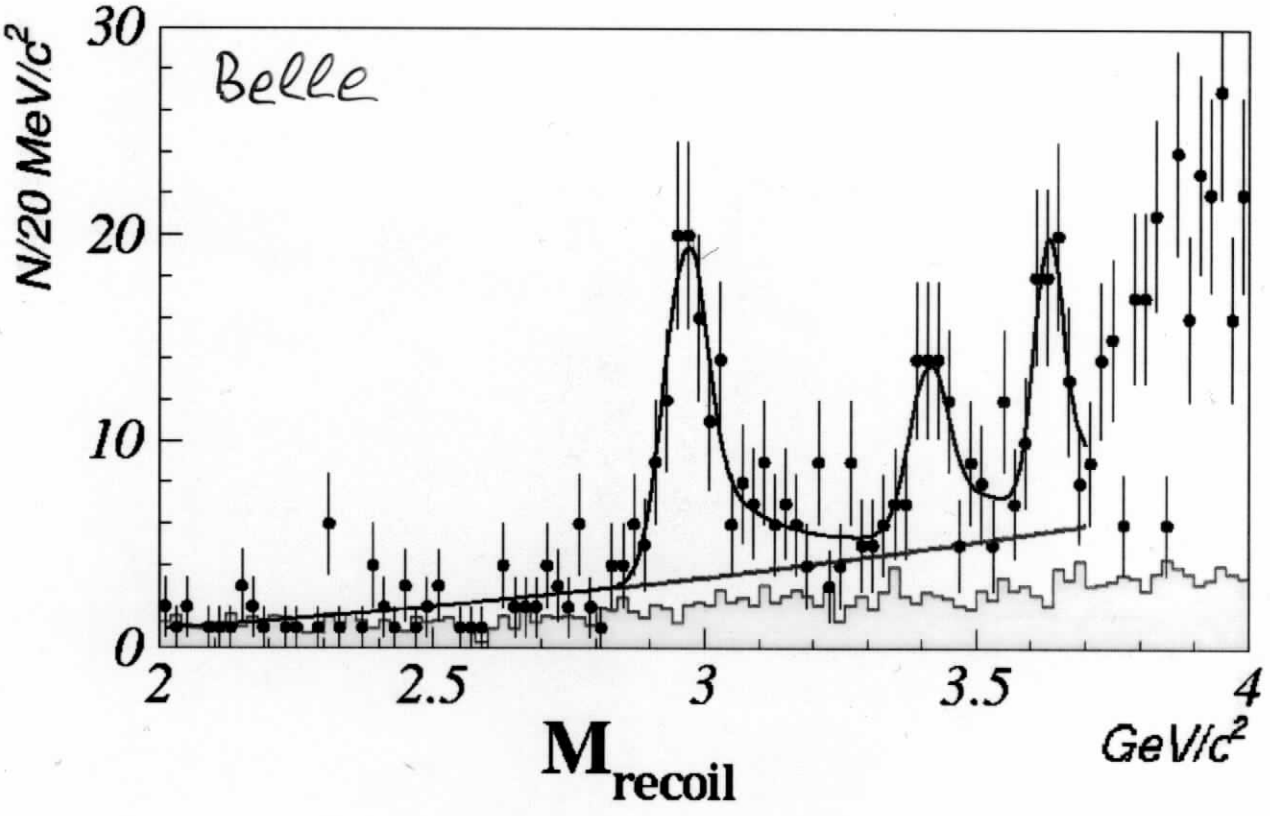
- NRQCD can not explain these results even after stretching parameters

$\sigma(e^+e^- \to J/\psi c\bar{c}) = 0.148$ pb (K-Y. Liu, Z-G. He, K-T. Chao) '03

J/ψ Recoil Mass

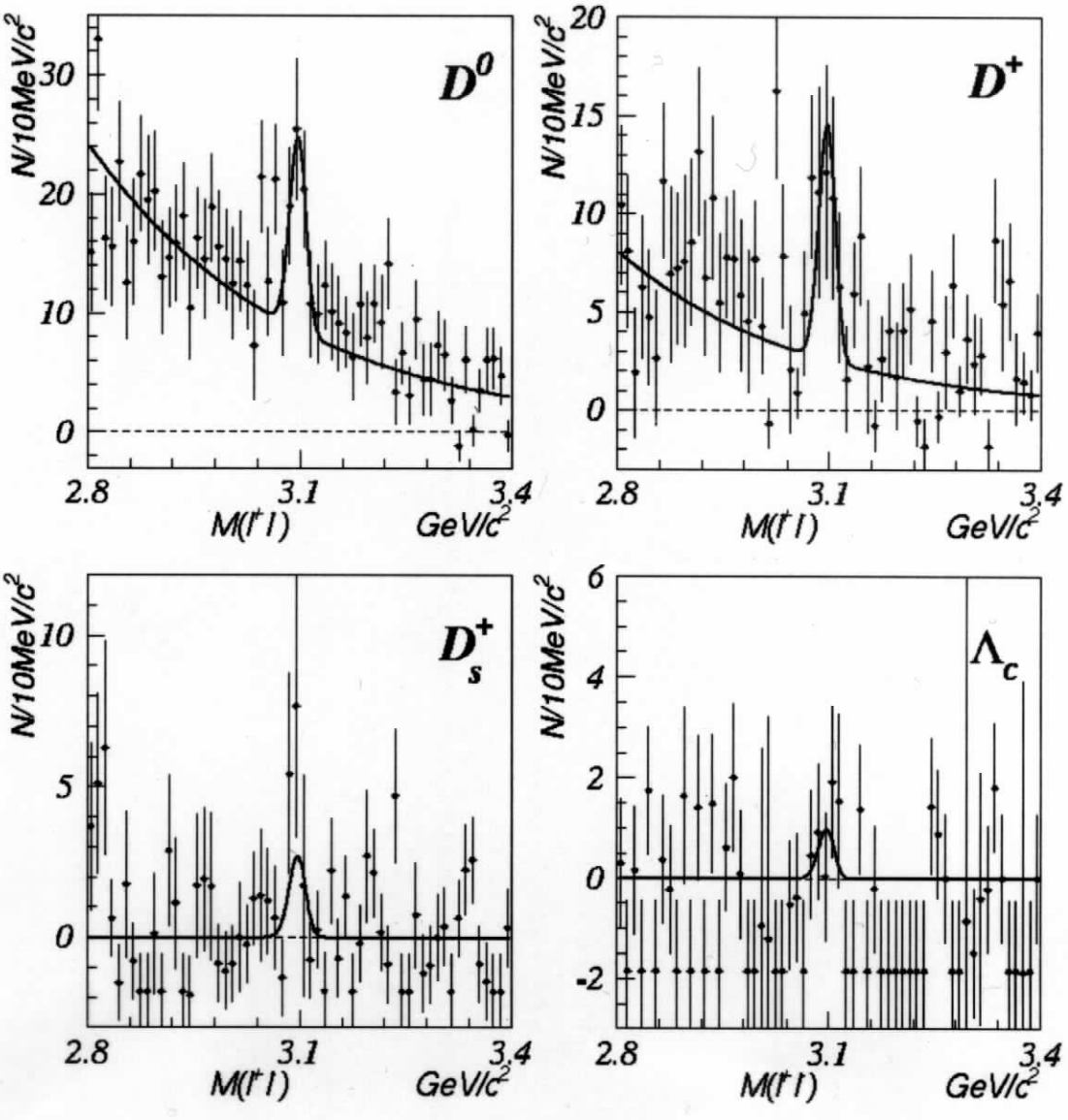
($L \approx 90\ fb^{-1}$)

Preliminary



Open Charm Production with J/ψ

$(L \approx 90\ fb^{-1})$

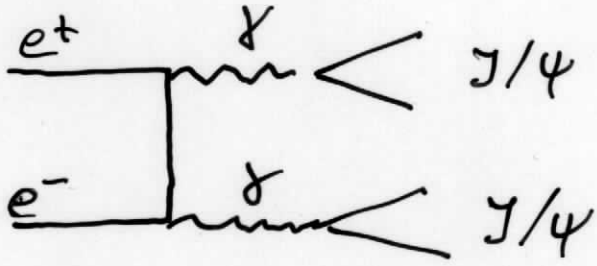


$$\frac{\sigma(e^+e^- \to J/\psi\, c\bar{c})}{\sigma(e^+e^- \to J/\psi\, X)} = 0.68 \pm 0.12 \quad \text{(preliminary)}$$

↪ Dominant process!

How to solve the puzzle?

- Bodwin, Lee, Braaten '02
  Large contribution from



  ↳ Part of Belle signal in $J/\psi\eta_c$ is from $J/\psi\,J/\psi$

  $$\sigma(e^+e^- \to J/\psi\, J/\psi) \approx 4\,\sigma(e^+e^- \to J/\psi\,\eta_c)$$

- Belle – no sign of this process in M_{rec} (no shifted peaks)
- Luchinsky '03 Bodwin et al overestimated $\sigma(e^+e^- \to J/\psi\, J/\psi)$ by a factor of 4
- Kaidalov '03 Quark-Gluon-Strings model can explain Belle result

  $$\sigma(e^+e^- \to J/\psi\, c\bar{c}) = 1.2 \text{ pb}$$

- QGS model predicts $\dfrac{\sigma(hA \to J/\psi c\bar{c} X)}{\sigma(hA \to J/\psi X)} \approx 10\%$ at 900 GeV.
- HERA-B is checking this prediction

A-dependence of J/ψ production

$$\sigma_{pA} = \sigma_{pp} A^{\alpha(x)}$$

$\alpha(x) < 1$ means suppression

- $\alpha(x)$ sensitive to J/ψ production mechanism

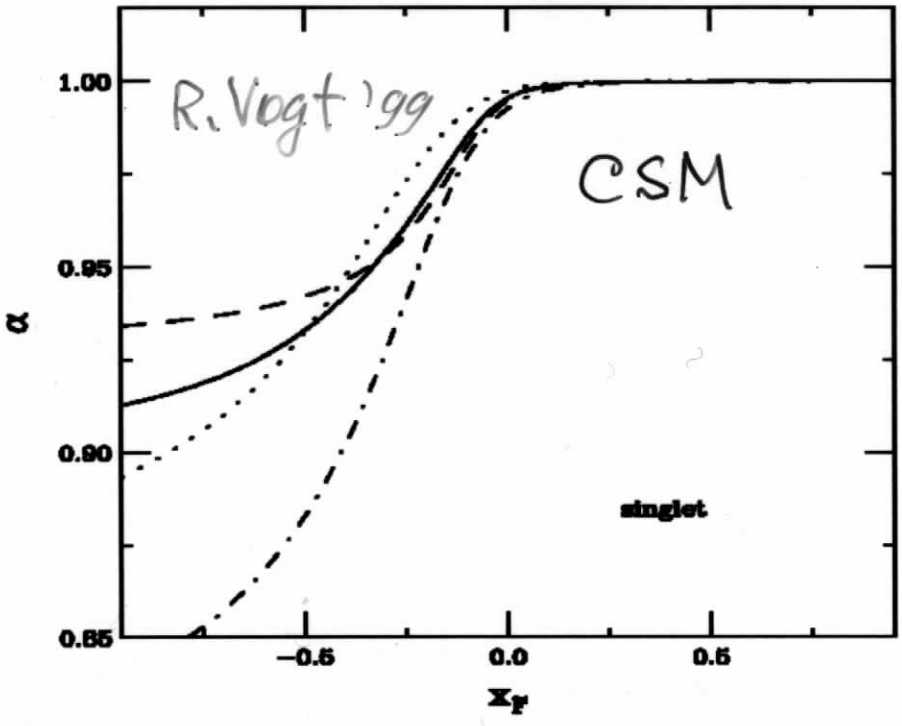
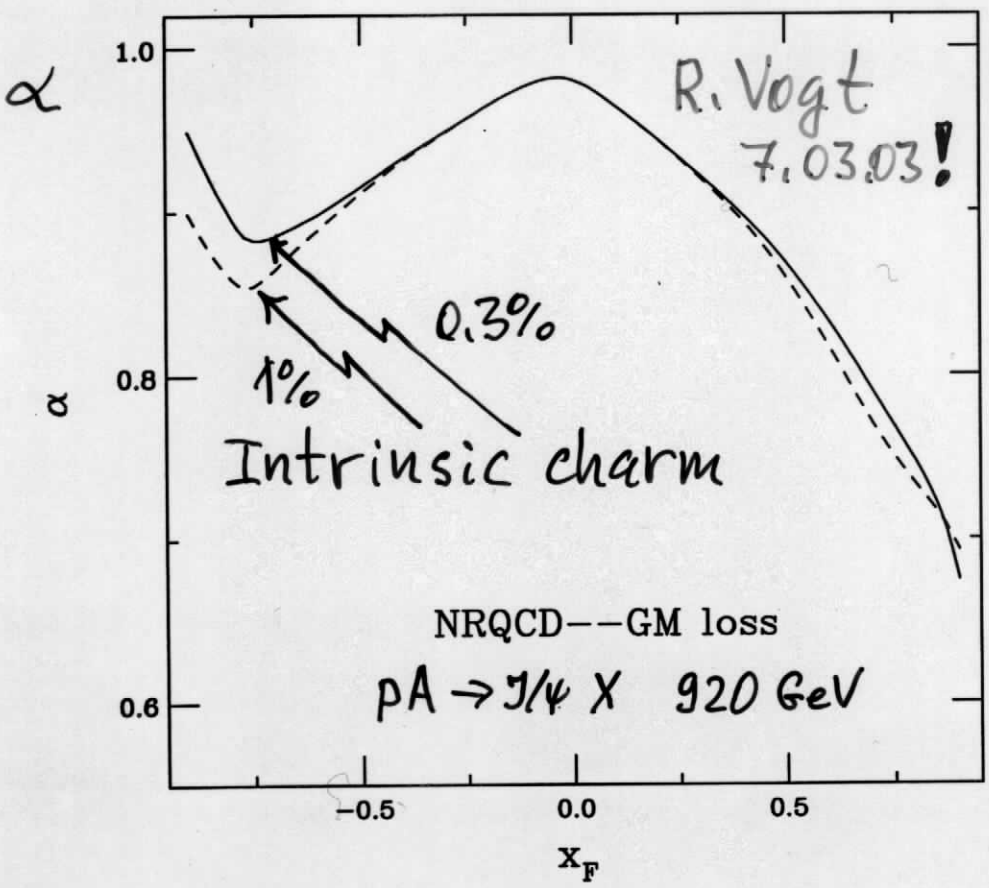
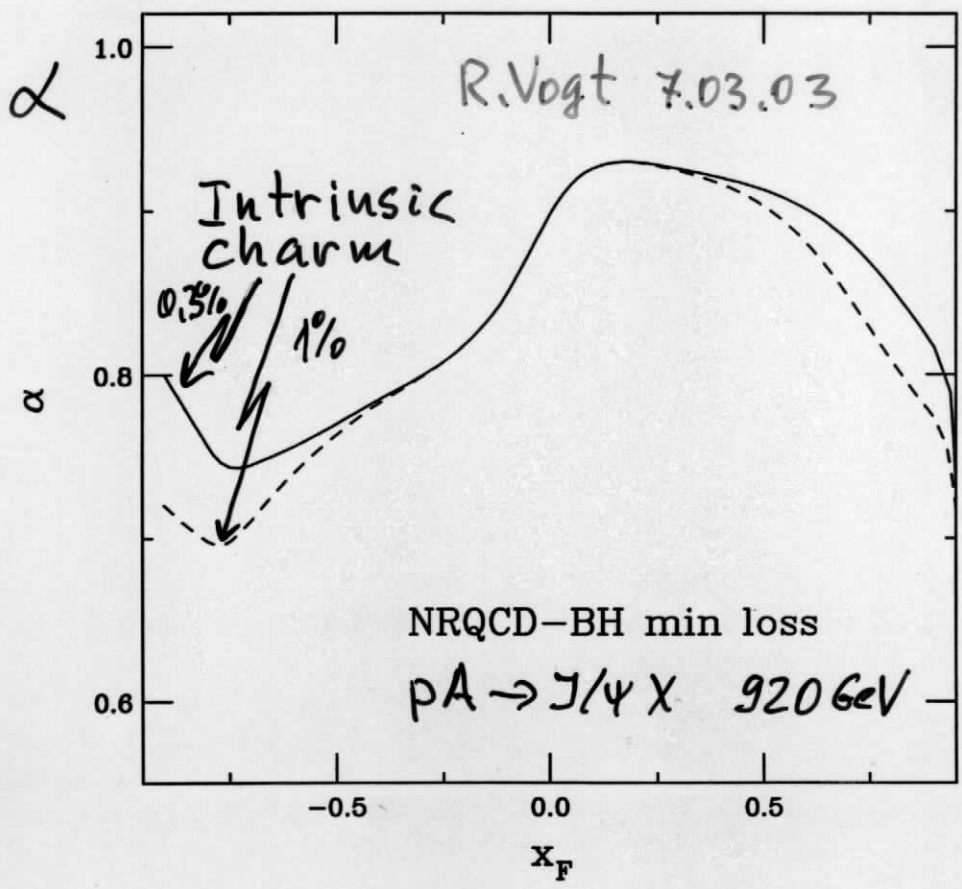


Figure 4: The A dependence of singlet absorption is shown for 920 GeV interactions with $\sigma^s_{\psi N} = 5$ mb. The total J/ψ (solid), direct J/ψ (dashed), ψ' (dot-dashed) and χ_c (dotted) dependencies are shown.

- $\alpha(x) \approx$ const in COM

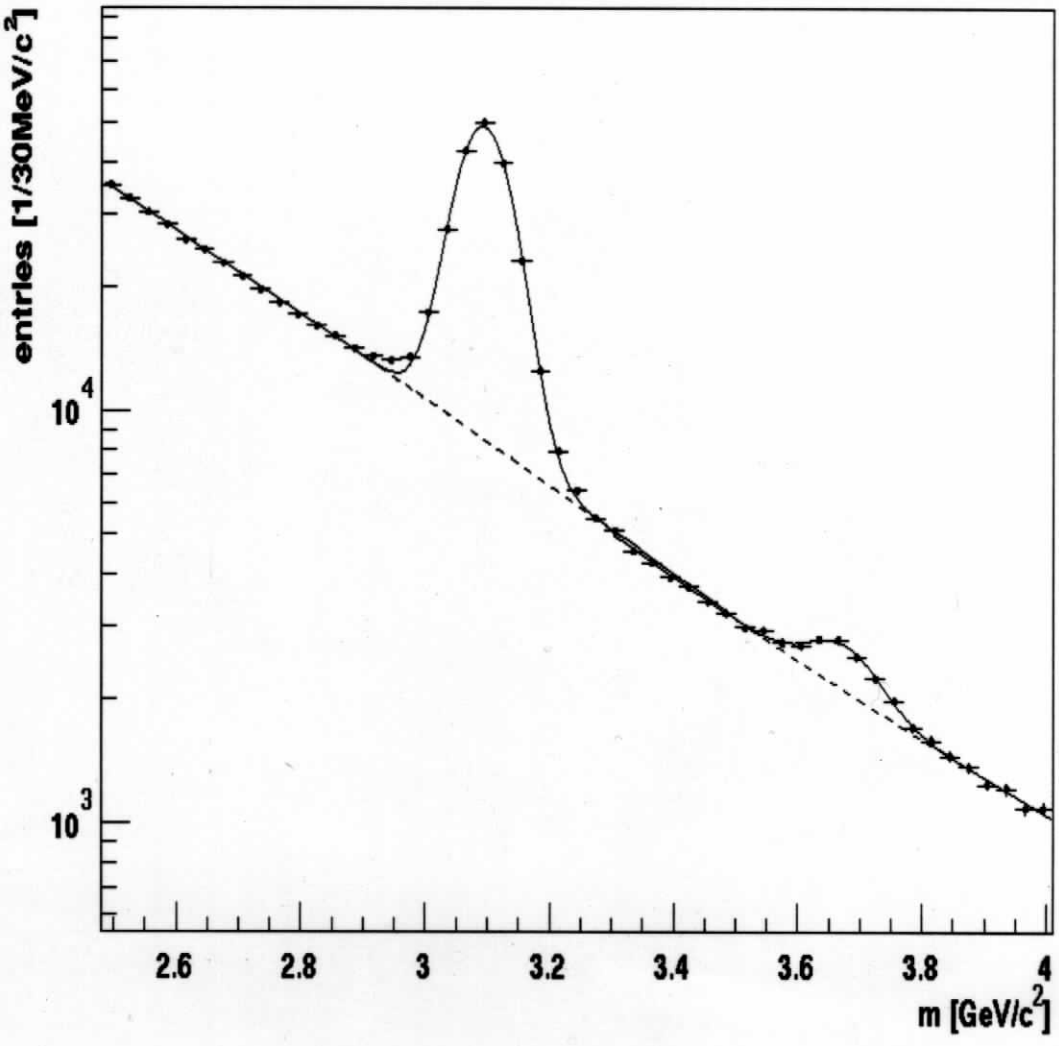
- $\alpha(x)$ is sensitive to many nuclear effects
  - shadowing
  - parton energy loss
  - $c\bar{c}$ system energy loss
  - intrinsic charm
- shape details depend on models but general trend is the same

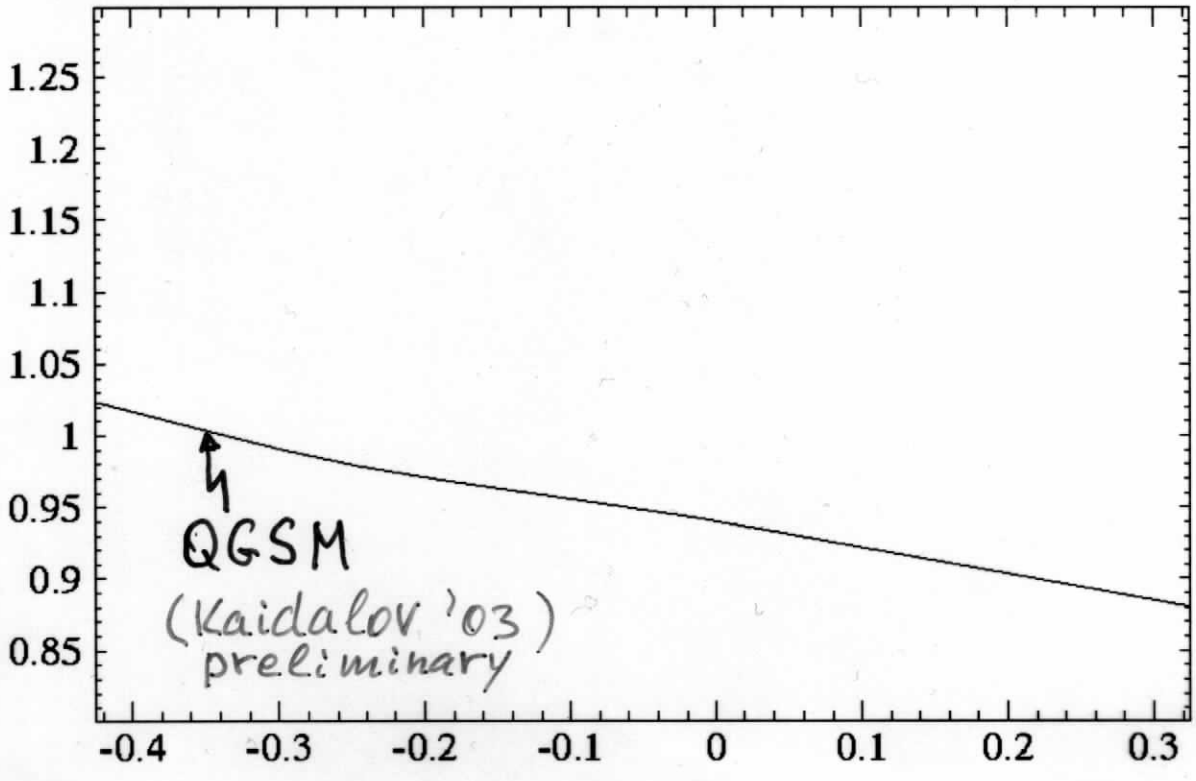



α
1.0
0.8
0.6
α
R.Vogt 7.03.03
Intrinsic charm
0.3%
1%
NRQCD–BH min loss
pA → J/ψ X 920 GeV
−0.5
0.0
0.5
x_F

J/ψ production at HERA-B

HERA-B collected ~300k J/ψ, ~6k ψ', ~10^4 χ_c



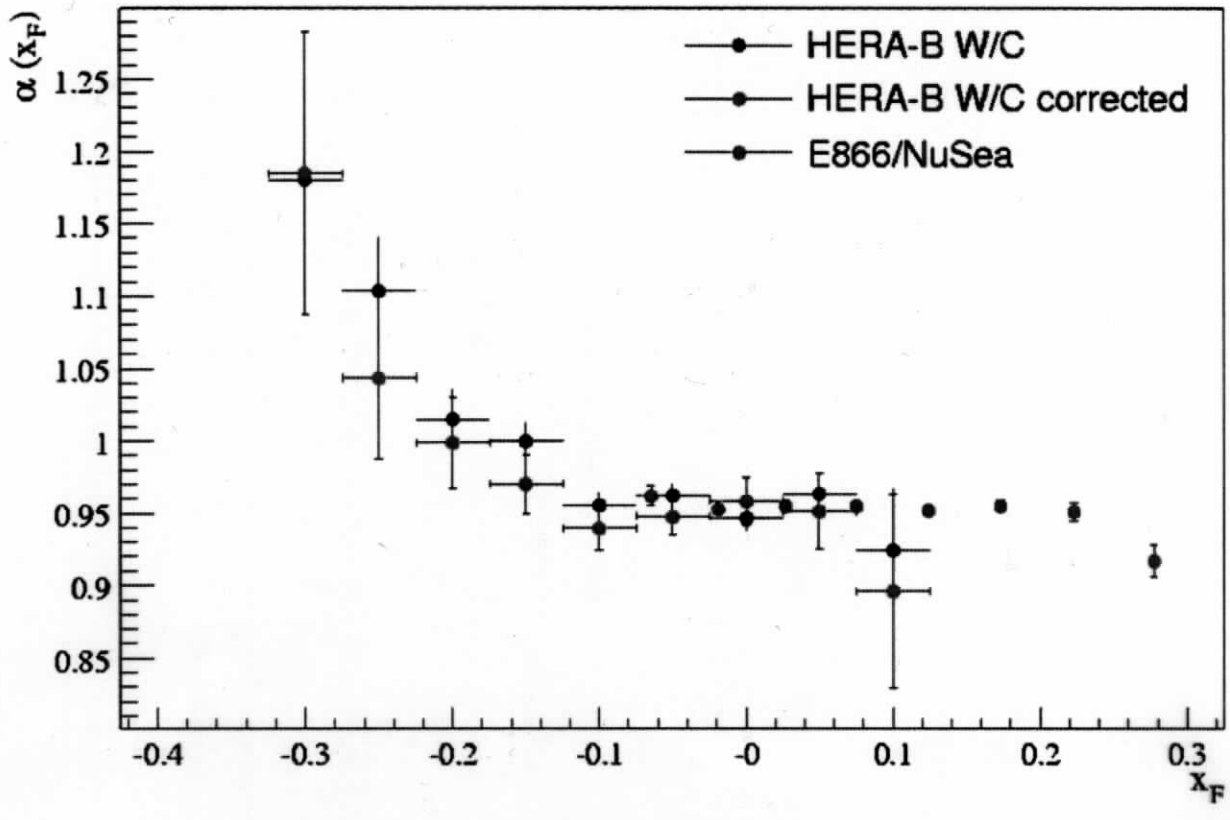

1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
QGSM
(Kaidalov '03)
preliminary

A-dependence of J/ψ production

$$\sigma_{pA} = \sigma_{pp} A^{\alpha}$$

Very preliminary !

MC not ready – normalized to E866 at $x_F \sim 0$



Strong contradiction with NRQCD

Qualitative agreement with Kaidalov's model

Conclusions

- Charmonium production is even more mysterious now than 8 years ago
  Therefore it is a very exciting field

- More theoretical and experimental efforts are needed in order to resolve the puzzle

- New data are expected soon from B factories, HERA-B, Tevatron, ...