THE PUZZLE OF $\sigma(\chi_{c1})/\sigma(\chi_{c2})$ RATIO AND THE k_t-FACTORIZATION

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PLAN OF THE TALK

1. Introduction
2. Theoretical framework
3. Collinear approach versus CDF data
4. k_t-factorization versus CDF data
5. k_t-factorization versus HERA-b data
6. Conclusions

INTRODUCTION

The production of P-wave states is interesting:
– on its own
– as an additional source of J/ψ mesons

The ratios of the production rates are even better indicators of the production mechanism, as many theoretical uncertainties cancel out (no sensitivity to the choice of gluon densities, renormalization and factorization scales, quark masses, etc.)

Why do we say it is a puzzle?
Landau-Yang theorem implies strong suppression of χ_{c1} states. Experiment shows

$$\sigma(\chi_{c2})/\sigma(\chi_{c1}) = 0.75 \pm 0.03(\mathrm{stat}) \pm 0.03(\mathrm{syst})$$

A. Abulencia *et al.* (CDF), Phys. Rev. Lett. 98, 232001 (2007)

$$\sigma(\chi_{c1})/\sigma(\chi_{c2}) = 0.57 \pm 0.23(\mathrm{stat{+}syst})$$

I. Abt *et al.* (HERA-B), Phys. Rev. D 79, 012001 (2009)

Important points to be careful with

Experimental cuts

select some specific region where the visible ratio $\sigma(\chi_{c1})/\sigma(\chi_{c2})$ may be different from that averaged over the unrestricted phase space.

Polarization

affects the angular distributions of the decay products (J/ψ and γ) and, consequently, affects the efficiency of their detection.
Under the assumption of E1 dominance

$$\frac{d\Gamma(\chi_{c1}\to\psi\gamma)}{d\cos\theta} \propto \left[\left(1+\frac{1}{2}\rho\right)+\left(1-\frac{3}{2}\rho\right)\cos^2\theta\right],$$

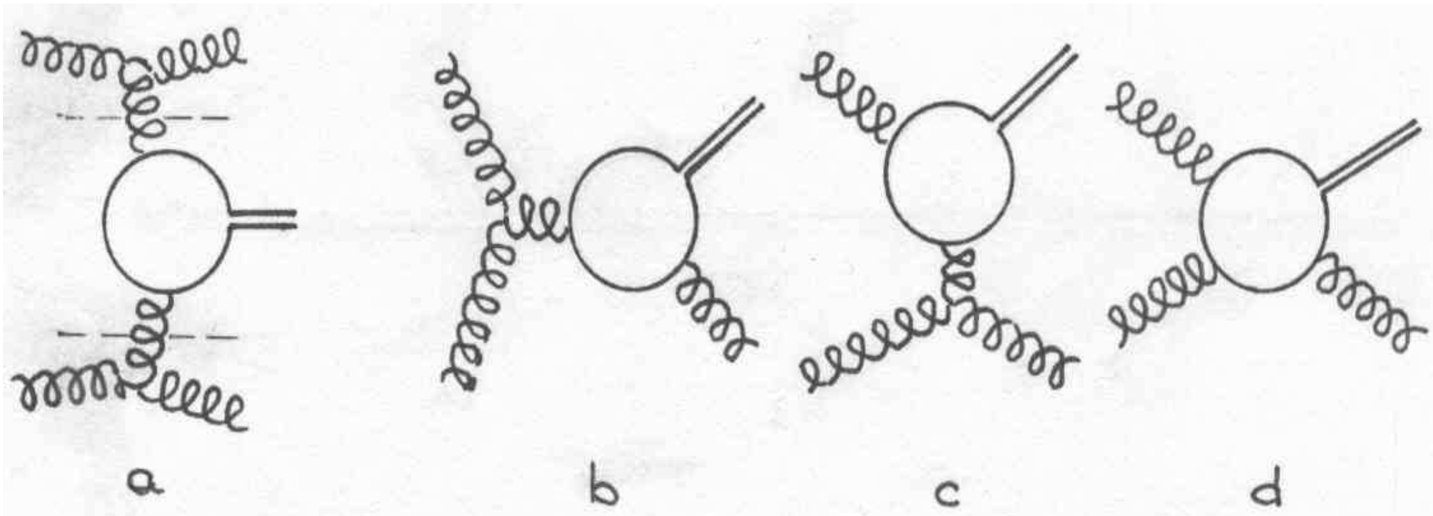
$$\frac{d\Gamma(\chi_{c2}\to\psi\gamma)}{d\cos\theta} \propto \left[\left(\frac{5}{6}-\frac{1}{12}\xi-\frac{1}{3}\tau\right)-\left(\frac{1}{2}-\frac{1}{4}\xi-\tau\right)\cos^2\theta\right]$$

The goal of this note

is to see to what extent can the experimental data be accommodated by the theory and what can be done in the theory to reach a better level of agreement.

THEORETICAL FRAMEWORK

Preface on k_t-factorization



(a) LO k_t-factorization approach;
the central part represents the hard partonic subprocess;
the upper and the lower parts represent the parton density evolution.
– **JB set:** J. Blümlein, DESY Report No.95-121, 1995; J. Phys. G 19, 1623 (1993)
– **A0 set:** H. Jung, http://www.desy.de/∼jung/cascade/updf.html

(b)-(d) LO collinear approach;
– **GRV98 set:** M. Glück, E. Reya, A. Vogt, Eur. Phys. J. C 5, 461 (1998)

COLOR-SINGLET GLUON-GLUON FUSION

Perturbative production of a heavy quark pair within QCD;

Gluon polarization vectors: $\epsilon_g^\mu = k_T^\mu/|k_T|$

E.A. Kuraev, L.N. Lipatov, V.S. Fadin, Sov. Phys. JETP 45, 199 (1977);
Ya. Balitsky, L.N. Lipatov, Sov. J. Nucl. Phys. 28, 822 (1978);
L.V. Gribov, E.M. Levin, M. G. Ryskin, Phys. Rep. 100, 1 (1983).

Spin projection operators to guarantee the proper quantum numbers:

for Spin-triplet states $\mathcal{P}(^3S_1) = \not\epsilon_V(\not p_Q + m_Q)/(2m_Q)$
for Spin-singlet states $\mathcal{P}(^1S_0) = \gamma_5(\not p_Q + m_Q)/(2m_Q)$

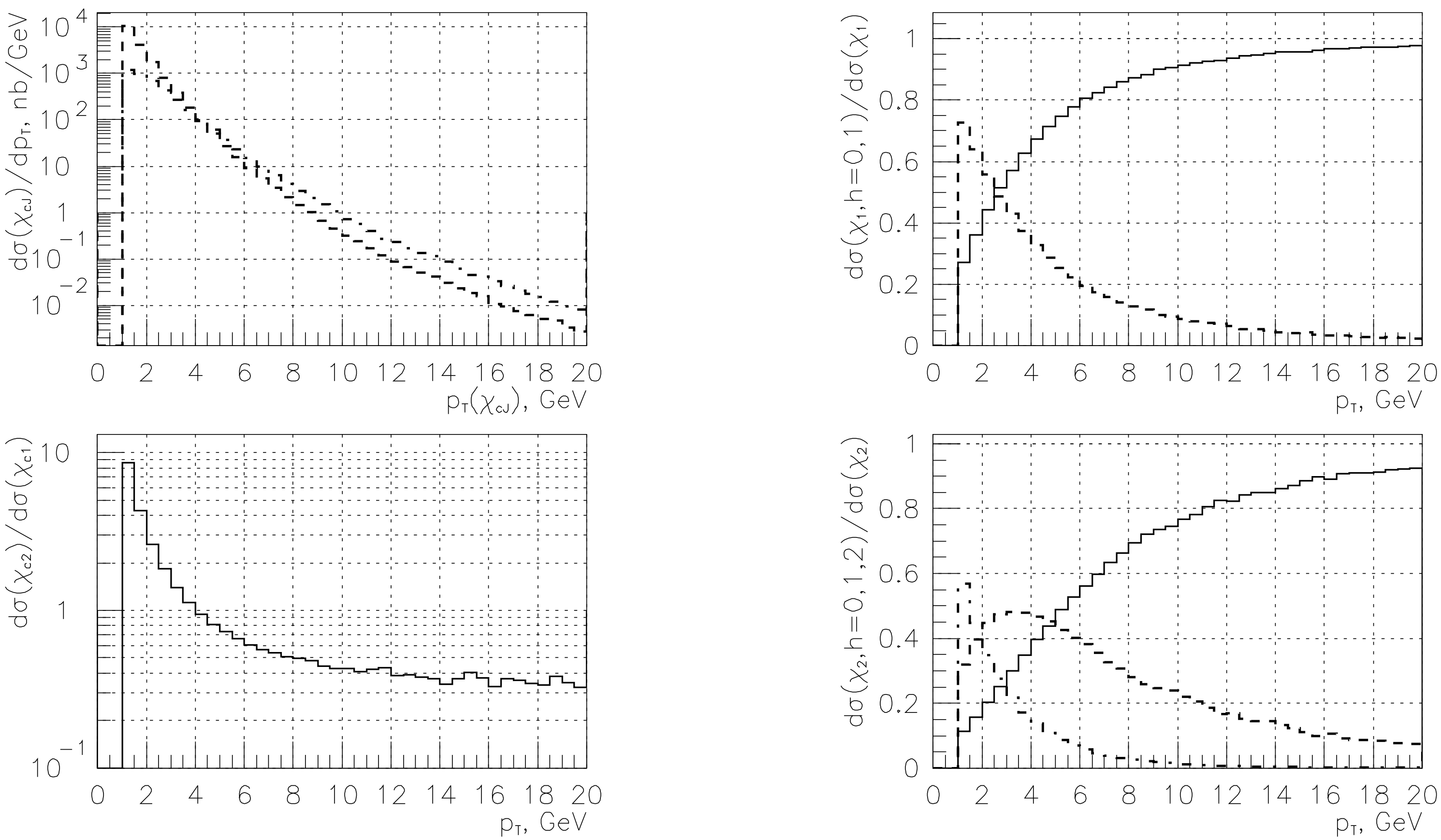
Probability to form a bound state is determined by the wave function:

for S-wave states $|R_S(0)|^2$ is known from leptonic decay widths;
for P-wave states $|R'_P(0)|^2$ is taken from potential models.

E. J. Eichten, C. Quigg, Phys. Rev. D 52, 1726 (1995)

If $L \neq 0$ and $S \neq 0$ we use the Clebsch-Gordan coefficients to reexpress the $|L, S\rangle$ states in terms of $|J, J_z\rangle$ states, namely, the χ_0, χ_1, χ_2 mesons.

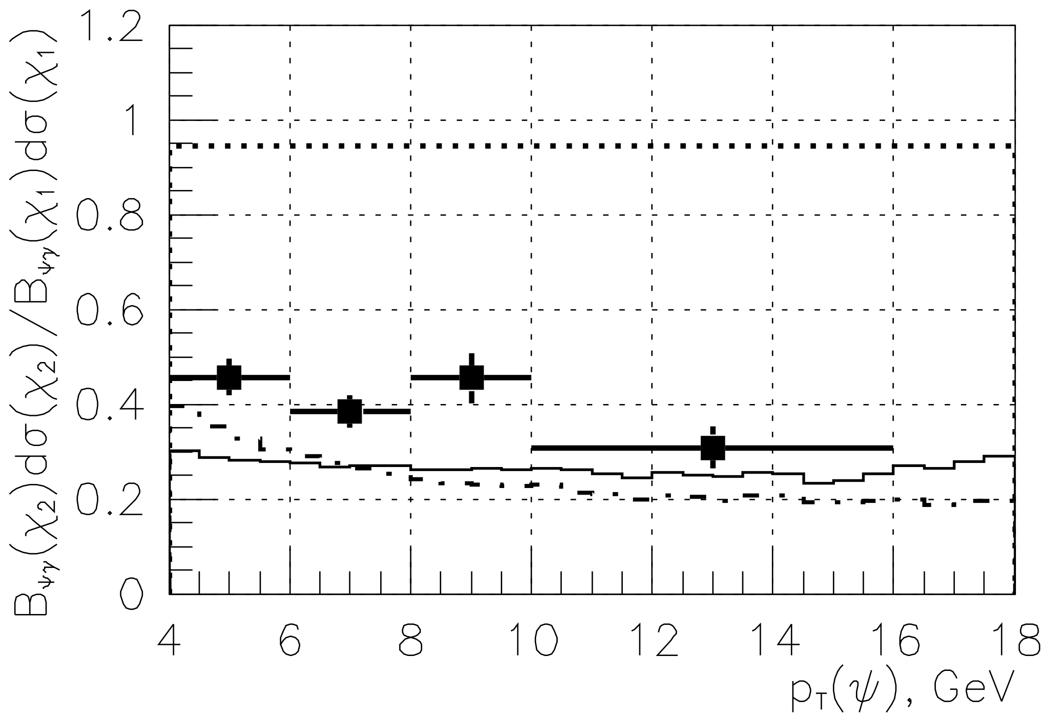
COLLINEAR APPROACH VERSUS CDF DATA



Upper panel, p_t spectra:
χ_{c1} dash-dotted; χ_{c2} dashed;
Lower panel, χ_{c2}/χ_{c1} ratio

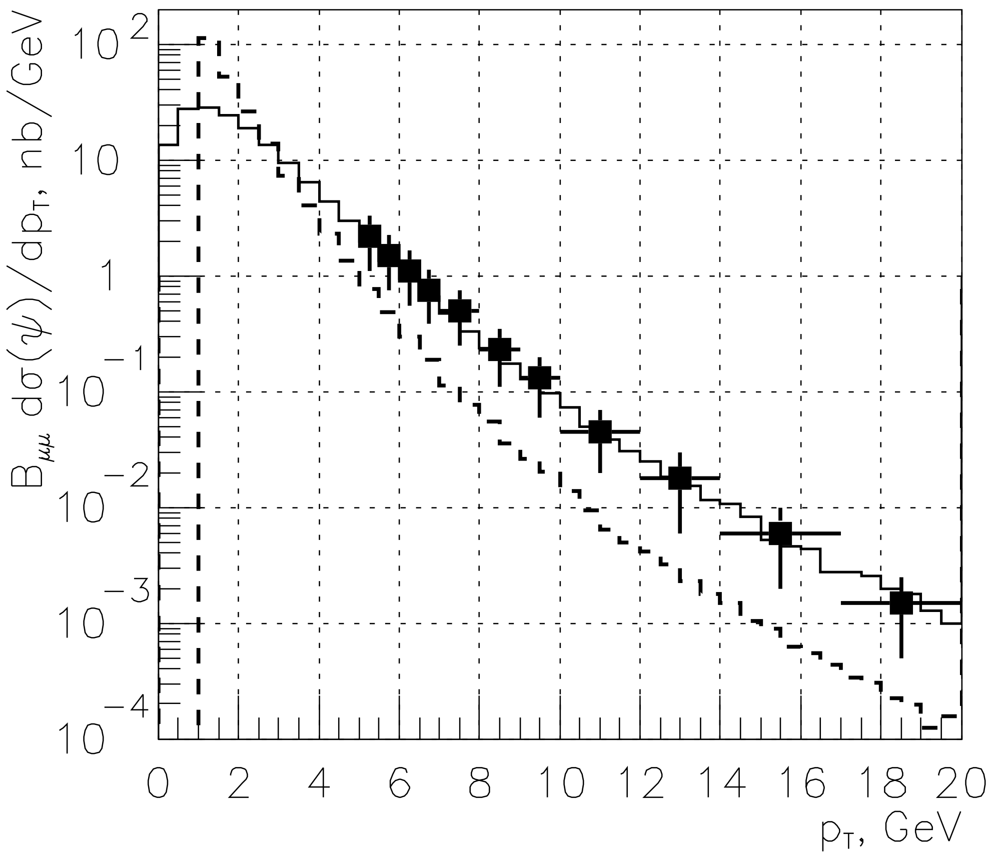
Spin alignement (HX frame):
h=0 solid; $|h|$=1 dashed;
$|h|$=2 dash-dotted

Predictions on the $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ ratio



Leading-Order Collinear Approach:
Solid line, under the hypothesis of electric dipole transitions;
Dash-dotted, for uniform (unpolarized) decay distributions.
Dotted line, prediction of the Color Evaporation Model.
■ **CDF data** **A. Abulencia** ***et al.*** **(CDF), Phys. Rev. Lett. 98, 232001 (2007)**

Predictions on the J/ψ spectra from χ_{cJ} decays



Solid histogram, k_t-factorization approach with JB gluons;
Dashed histogram, collinear parton model with GRV gluons;
■ **CDF data F. Abe *et al.* (CDF), Phys. Rev. Lett. 79, 578 (1997).**

Extending to NLO collinear calculations

Wrong LO p_t dependence necessitates including the NLO contributions. Requires quite a significant work; has recently been done in

Y.-Q. Ma, K. Wang, K.-T. Chao, arxiv:1002.3987

Main findings

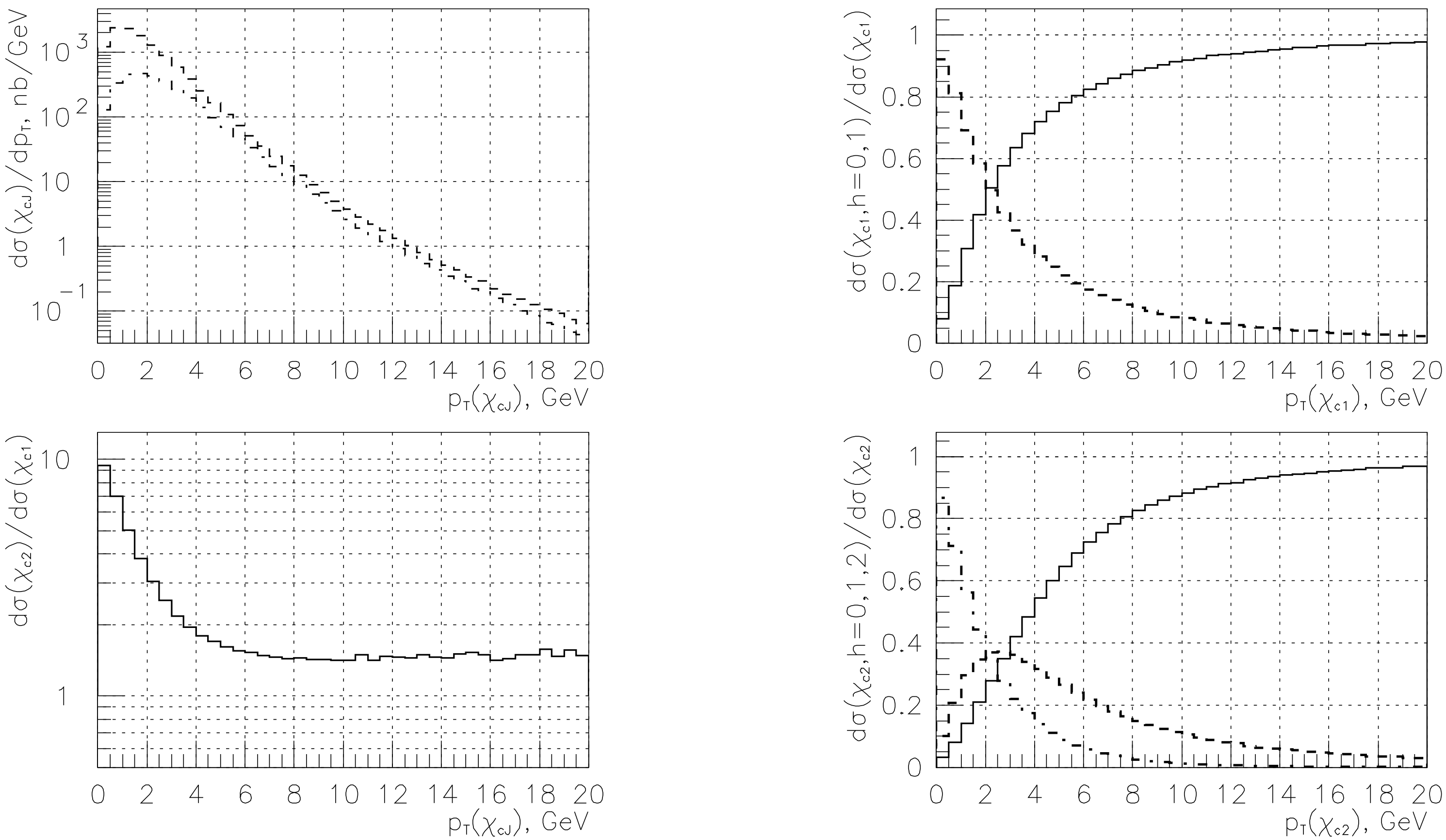
– Change in the p_T behavior of the color-singlet channels:
$d\sigma/dp_t \propto 1/p_T^4$ at the NLO in contrast with $d\sigma/dp_t \propto 1/p_T^6$ at LO.

– At relatively large p_T the NLO CS contributions become negative.

Need in color-octet contributions to preserve positivity of the cross sections. Thus, the solution of the problem is laid upon nonperturbative and essentially uncalculable color-octet mechanism.

The relative size of the color-singlet (CS) and color-octet (CO) contributions may change depending on the subtraction scheme, but the presence of both CS and CO parts is unavoidable, in order that the scheme dependence of the CS and CO contributions could cancel each other.

LO k_t-FACTORIZATION VERSUS CDF DATA



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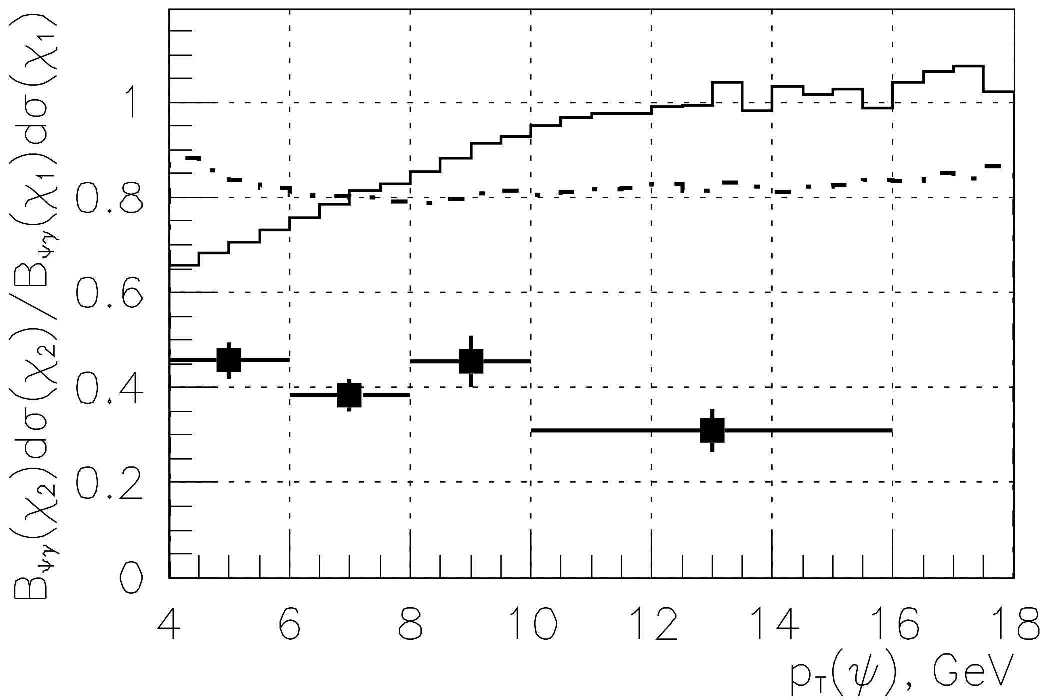

Leading-Order k_t-factorization approach:
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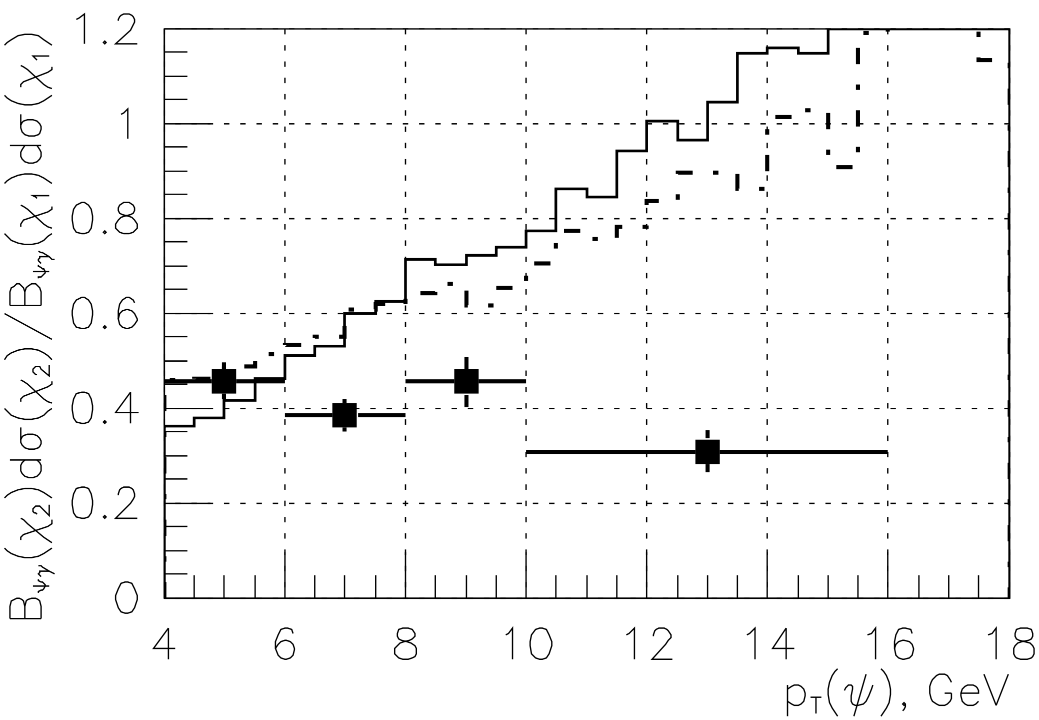
■ **CDF data** **A. Abulencia *et al.* (CDF), Phys. Rev. Lett. 98, 232001 (2007)**

Predictions on the $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ ratio



k_t-factorization approach, NLO contribution taken solely:
Solid line, under the hypothesis of electric dipole transitions;
Dash-dotted, for uniform (unpolarized) decay distributions.
■ **CDF data** **A. Abulencia *et al.* (CDF), Phys. Rev. Lett. 98, 232001 (2007)**

Way out: reconsidering the Wave Functions

Up to now, we were assuming $|\mathcal{R}'_{\chi 1}(0)|^2 = |\mathcal{R}'_{\chi 2}(0)|^2$ as taken from potential models with scalar quarks. That might be an oversimplification neglecting the spin-orbital interactions.

Motivations for reconsidering the Wave Functions:

– The mass of χ_{c1} state is lower than that of χ_{c2}; this means a tighter binding in the χ_{c1} system with accordingly narrower and higher wave function

– Decay branchings $Br(\psi_{(2S)}{\to}\chi_{c1}\gamma) : Br(\psi_{(2S)}{\to}\chi_{c2}\gamma) \simeq 1:1$, contrary to the spin algebra expectations 3:5 (by calculating the projections of the $\psi(2S)$ state onto $\chi_{cJ}{+}\gamma$ states using the Clebsch-Gordan coefficients and excluding helicity=0 photon states).

The wave functions need to be rescaled $|\mathcal{R}'_{\chi 1}(0)|^2 : |\mathcal{R}'_{\chi 2}(0)|^2 = 5:3$

Then, a much better agreement with the data is obtained

LO k_t-FACTORIZATION VERSUS HERA-b DATA

All calculations are on poorer theoretical grounds:

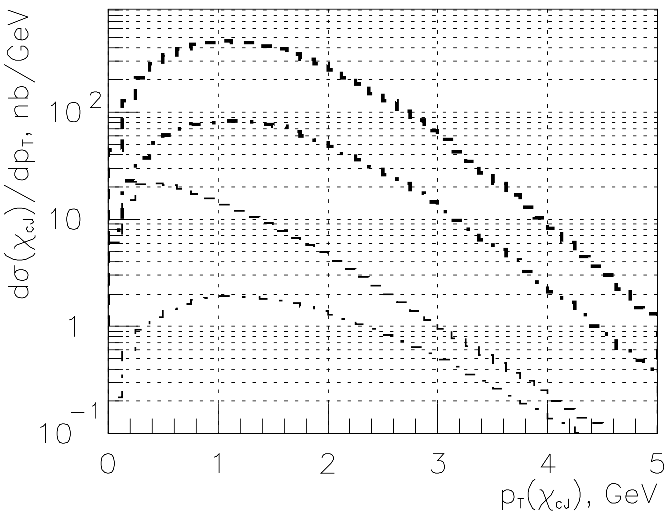
– collinear approach is unsuitable because of singularities:
$d\sigma(\chi_{c2})/dp_t \to 0$ when $p_t \to 0$, but lies inside the acceptance zone.

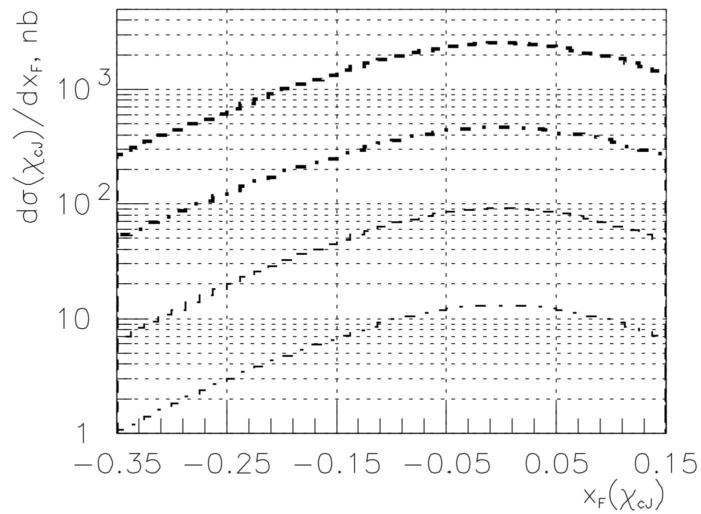
– k_t-factorization approach is beyond its favorite small-x range:
$\langle x \rangle \simeq m_\chi/\sqrt{s} \simeq 0.1$. Large theoretical uncertainties when using gluon densities fitted to small-x data.

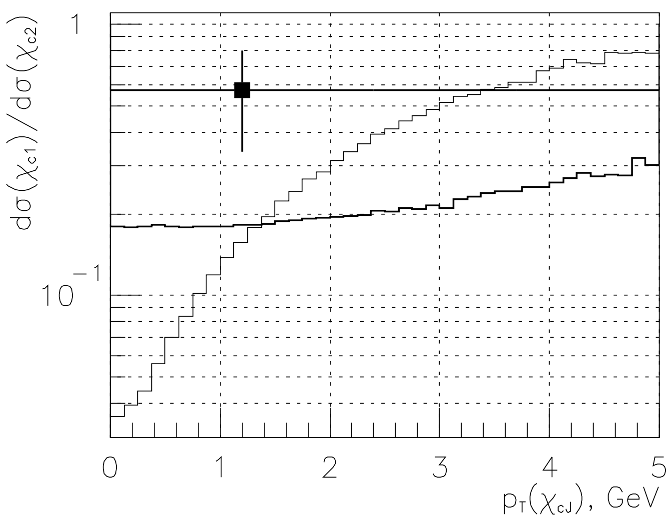
Predictions and the data

	A0 gluons	JB gluons	HERA-b data
$\sigma(\chi_{c1})$	160 nb	4.2 nb	133 ± 35 nb
$\sigma(\chi_{c2})$	850 nb	29 nb	231 ± 61 nb
$\sigma(\chi_{c1})/\sigma(\chi_{c2})$	0.19	0.15	0.53 ± 0.23

Comparisons with
I. Abt *et al.* (HERA-B), Phys. Rev. D 79, 012001 (2009)







χ_{c1} (dash-dotted);
χ_{c2} (dotted);
Thin lines, JB gluons;
thick lines, A0 gluons;
■ HERA-b data.

CONCLUISONS

In the Collinear approach

– Leading Order shows a wrong p_t dependence
– NLO shows negative Color Singlet contributions;
need in Color Octet contributions; the experiment can be described by postulating the (uncalculable) color-octet matrix elements

In the k_t-factorization approach

– $d\sigma(\chi_{cJ})/dp_t$ are allright
– $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ is off the data
– Polarization effects do not help
– NLO contributions do not help (and problems with double counting)
– Wave function correction does help (for both CDF and HERA-b)

$$|\mathcal{R}'_{\chi 1}(0)|^2 : |\mathcal{R}'_{\chi 2}(0)|^2 = 5 : 3$$

More indications for the need in correcting the wave functions

– Unequal χ_{c1} and χ_{c2} masses (= unequal binding energies)
– $\psi_{(2S)} \rightarrow \chi_{cJ} + \gamma$ decay branchings violating spin counting

THE END

THANK YOU