χ_{cJ} production at hadron colliders with QCD radiative corrections

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Department of physics, Peking University

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Contents: Part 1

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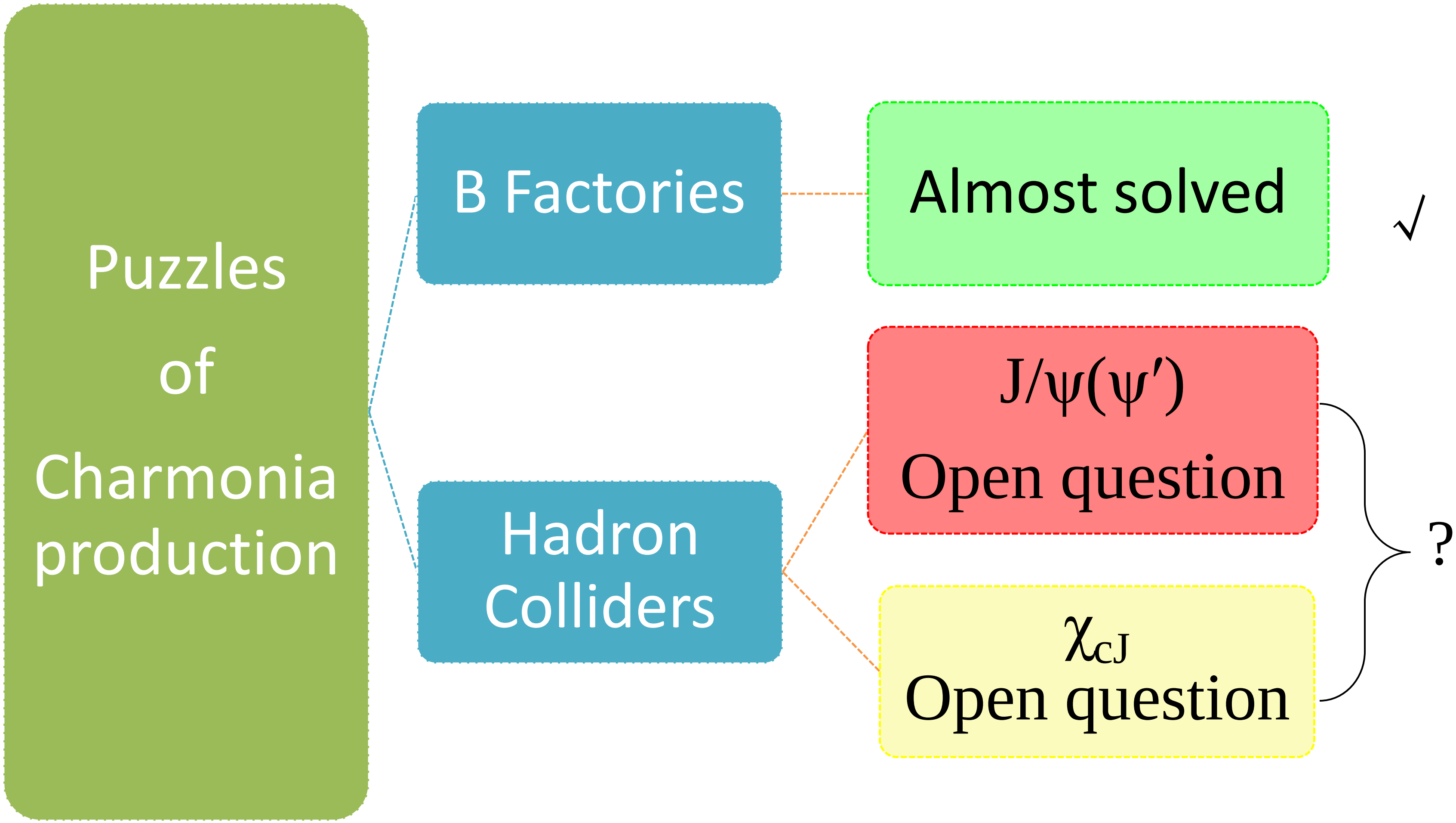
Puzzles in Charmonia

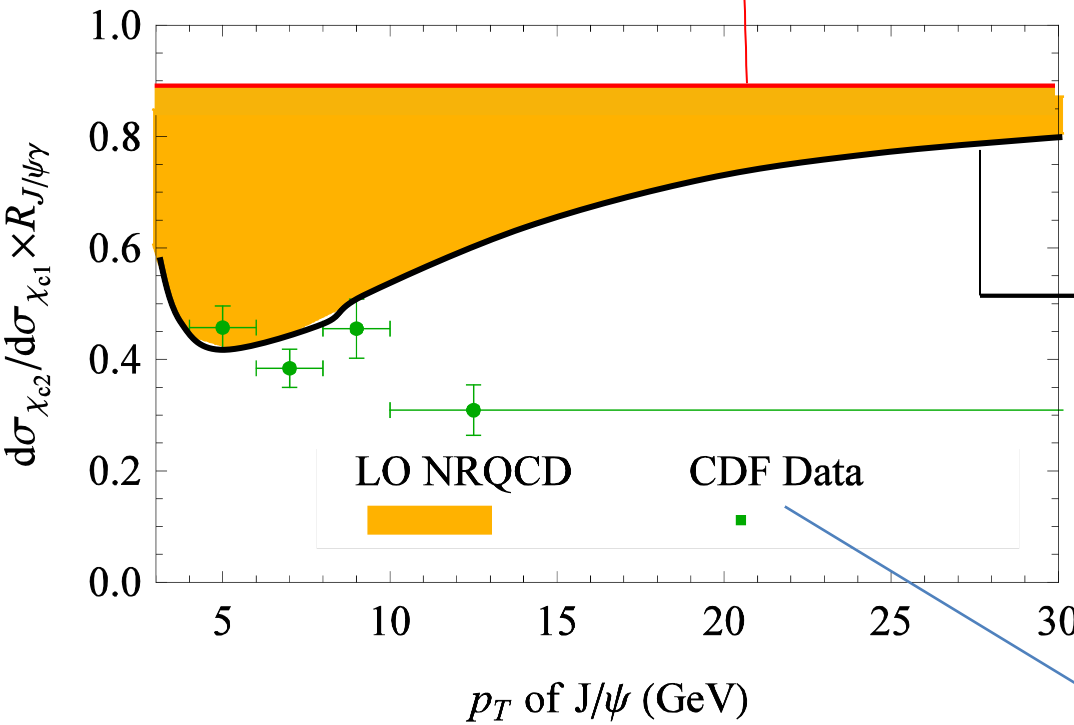


Advantage of χ_{cJ} relative to ψ

	J/ψ | ψ′	$\boldsymbol{\chi_{cJ}}$
Number of Color-Octet (CO) Matrix-Elements	3 $({}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_0^{[8]})$	1 $({}^3S_1^{[8]})$
Number of States	1	3
Leading contributions for Color-Singlet (CS) channel at high p_T	α_s^5 (NNLO)	α_s^4 (NLO)
Feed-down dependence	ψ′、 χ_{cJ} | --	--

Conclusion: χ_{cJ} production should be relatively easier to be understood – although P-wave.

χ_{cJ} production at Tevatron



r=10 and CEM

r=0.1

$$r = \frac{\langle \mathcal{O}^{\chi_{c0}}(^3S_1^{[8]})\rangle}{\langle \mathcal{O}^{\chi_{c0}}(^3P_0^{[1]})\rangle / m_c^2}\Big|_{\overline{MS},\mu_\Lambda = m_c}$$

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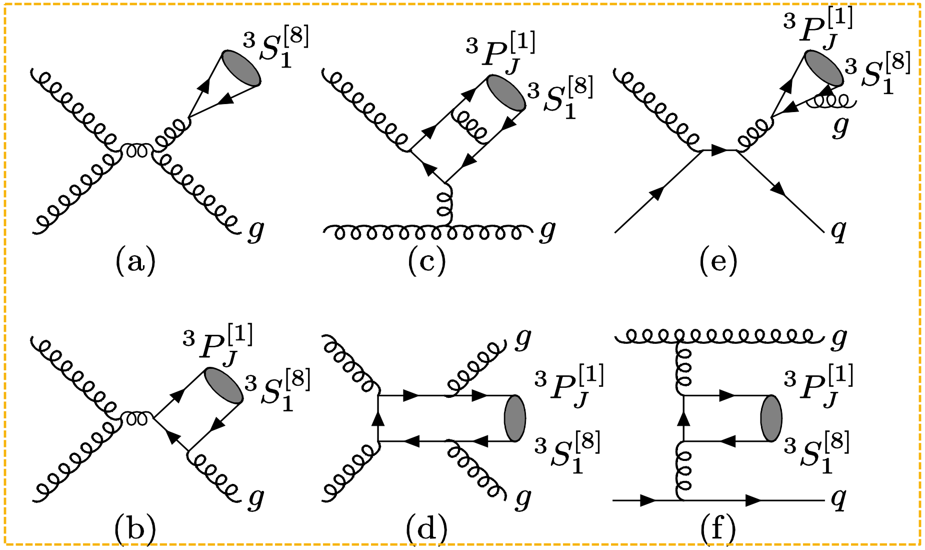
•LO NRQCD prediction, dominated by CO channel at high p_T, is far away from the experiment data even though 0.1<r<10 (r ≈ 1 based on NRQCD).

$$\frac{d\sigma_{\chi_{c2}}}{d\sigma_{\chi_{c1}}} \xrightarrow{p_T \gg m_c} \frac{5}{3}$$

•CEM is even worse: $d\sigma_{\chi_{c2}} / d\sigma_{\chi_{c1}} \equiv 5/3$

Why NLO?

- At LO in α_S, CO channel scales as $1/p_T^4$ (a), while CS channel is dominated by$1/p_T^6$(b).
- Up to NLO in α_S, CS channel has $1/p_T^4$ (e) behavior.



- Although suppressed by α_S, CS channel may comparable with CO channel at NLO.
- *NLO contribution is crucial in this problem.*

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Formalism

$$d\sigma_{\chi_{cJ}} = \sum_{i,j,n} \int \underbrace{dx_1 dx_2 \boxed{G_{i/A} G_{j/B}}}_{\Lambda_{QCD}} \times \underbrace{\boxed{\hat{\sigma}[ij \to c\bar{c}[n] + X]}}_{m_c} \times \underbrace{\boxed{\langle \mathcal{O}_n^{\chi_{cJ}} \rangle}}_{m_c v}$$

PDF

CTEQ6L1, CTEQ6M

Hadronization

Long distance ($\sim 1/(m_c v)$) process: non-perturbative calculations and input from experiments needed.

Production of heavy quarks

Short distance ($\sim 1/m_c$) process: perturbative calculation.

Main task in this work.

Code and packages

Mathematica control code

Self-written Mathematica code

Analyze process with bound state and generate parton-level sub processes

FeynArts

Generate parton-level Feynman amplitudes and Feynman Diagrams

Self-written Mathematica code

Perform tensor integral reduction and analytically simplify

Self-written C++ code

Perform phase space integration and convolution with PDF

LoopTools or QCDOneLoop

Calculate scalar functions

IR singularities

- Collinear singularities and soft singularities of S-wave channel:

  collinear factorization of PDF and KLN theorem

- Soft Singularities of P-wave channel:

  NRQCD MEs + Real + Virtual

$$\mathcal{M}^{\mathrm{R}}|_{s} = g\mu_r^{\epsilon}\varepsilon_{\mu}J_f^{a,\mu}\mathcal{M}_f^{Born}$$

$$\mathcal{M}^{V}|_{s} = \frac{1}{2}g^2\mu_r^{2\epsilon}I_{ff'}\mathcal{M}_{ff'}^{Born}$$

Where $J_f^{a,\mu} = \frac{p_f^{\mu}}{p_f \cdot k}T_f^a$ and $I_{ff'} = J_f^{a,\mu}J_{f',\mu}^{a}$

While $\mathcal{M}_f^{Born}$ and $\mathcal{M}_{ff'}^{Born}$ are color connected born level amplitudes.

Why NRQCD?

It can be shown that,

$$\left(T_f^a T_{f'}^a \mathcal{M}_{ff'}^{Born}\right)^\dagger \left(M^{Born}\right) = \left(T_f^a \mathcal{M}_f^{Born}\right)^\dagger \left(T_{f'}^a \mathcal{M}_{f'}^{Born}\right),$$

$$\left(T_f^a T_{f'}^a \mathcal{M}_{ff'}^{Born}\right)\left(M^{Born}\right)^\dagger = \left(T_f^a \mathcal{M}_f^{Born}\right)\left(T_{f'}^a \mathcal{M}_{f'}^{Born}\right)^\dagger, \; f' \neq Q,\overline{Q}$$

So only terms that are not canceled between Real and Virtual are :

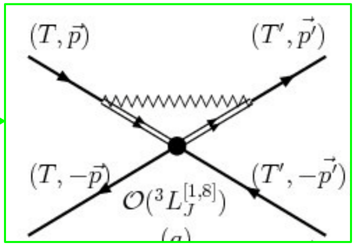
$$-g^2\mu_r^{2\epsilon}\varepsilon^\alpha\varepsilon^\beta \frac{\partial J_F^{a,\mu}}{\partial q^\alpha}\frac{\partial J_{F',\mu}^{a}}{\partial q^\beta}\left|\mathcal{M}^{Born}\right|_{FF'}^2, (1)$$

$$\frac{1}{2}g^2\mu_r^{2\epsilon}\varepsilon^\alpha\varepsilon^\beta \frac{\partial\left(I_{FF'}\mathcal{M}_{FF'}^{Born}\right)^\dagger}{\partial q^\alpha}\frac{\partial\left(\mathcal{M}^{Born}\right)}{\partial q^\alpha} + c.c., (2)$$

Where $F, F' = Q,\overline{Q}$ and q is the relative momentum of heavy quarks.

(2) = 0 because of color-singlet nature: $\delta_{C_Q C_{\overline{Q}}} \sum_{F=Q,\overline{Q}} J_F^{a,\mu}|_{q=0} = 0$

Finally, (1) is absorbed by NRQCD MEs



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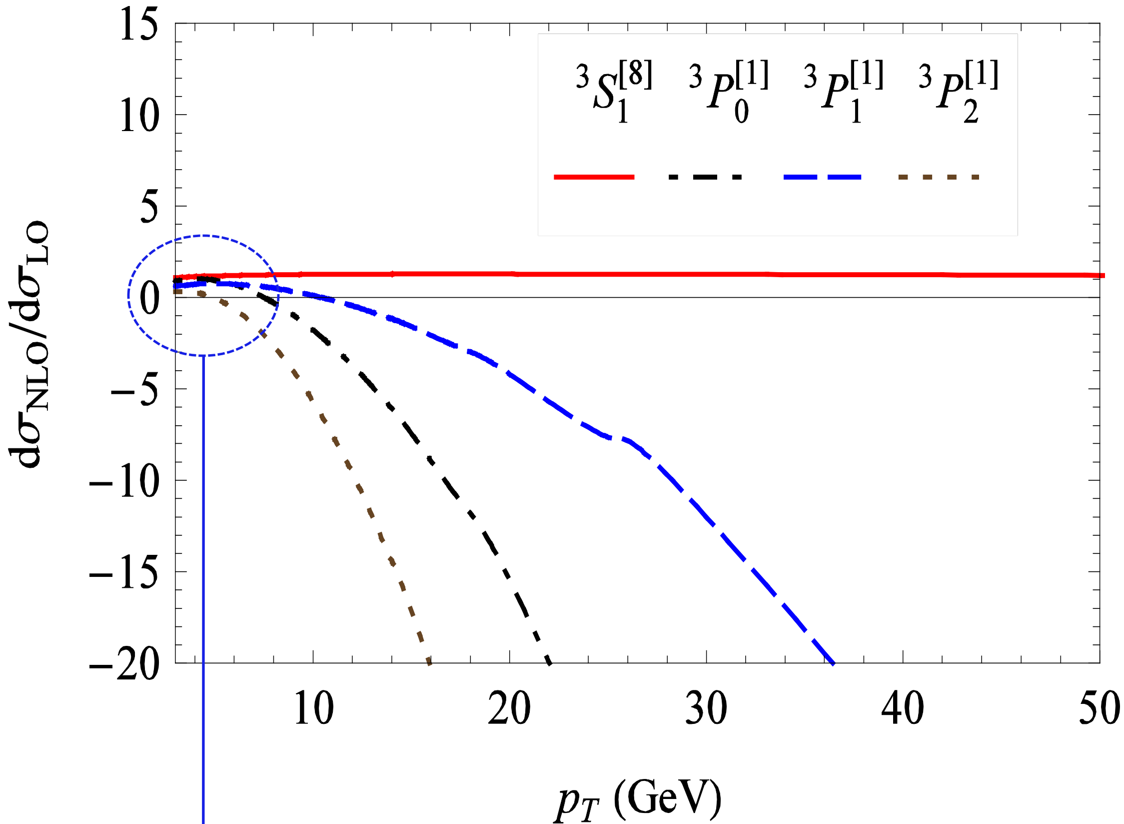
K factor



K factor of each channel.

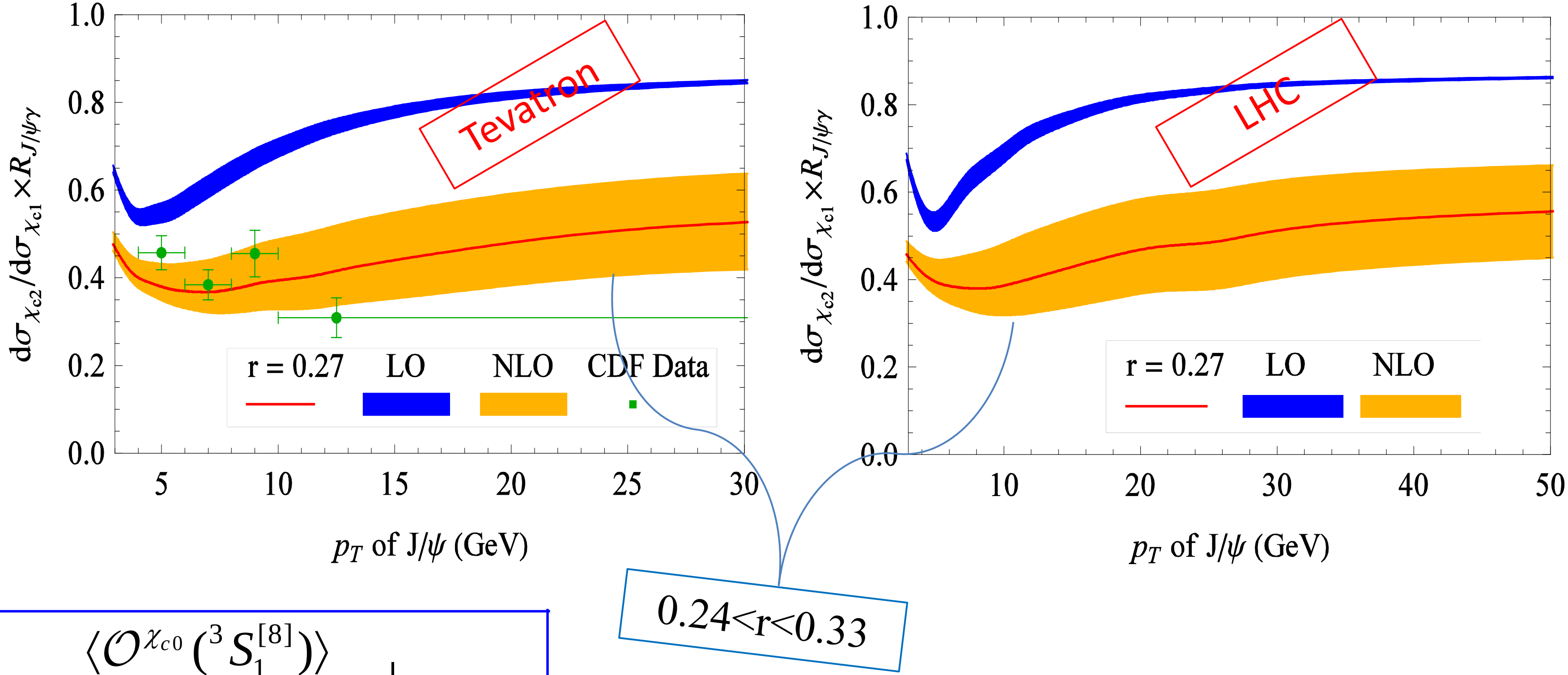
- Large but negative corrections are found.
- CS channel of χ_{c2} declines much faster than χ_{c1}.

Different behavior from CO channel.

Large corrections are originated from $p_T/(2m_c)$

Subtraction scheme and NRQCD renormalization scale dependent.

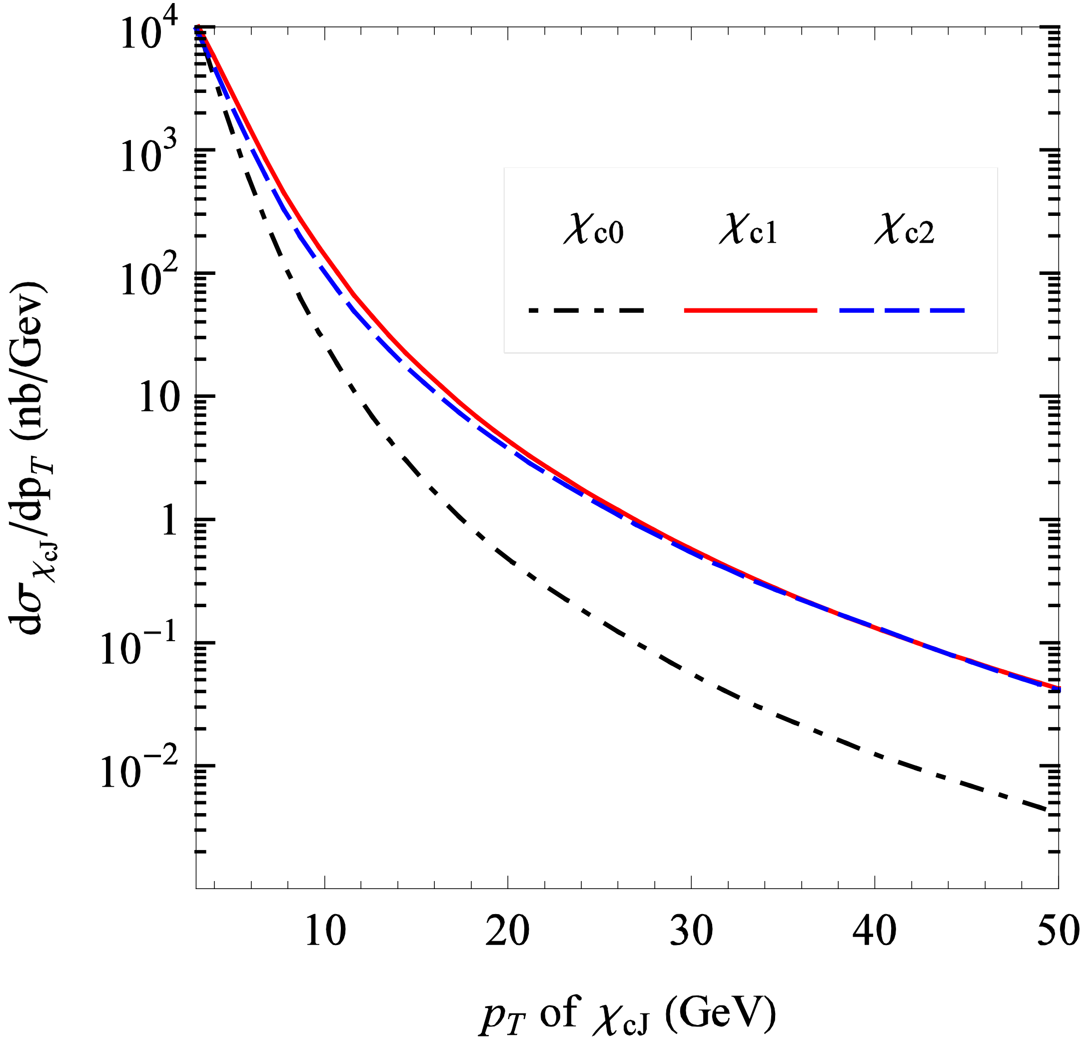
Ratio of χ_{c2} to χ_{c1}



$$r = \frac{\langle \mathcal{O}^{\chi_{c0}}({}^3S_1^{[8]}) \rangle}{\langle \mathcal{O}^{\chi_{c0}}({}^3P_0^{[1]}) \rangle / m_c^2} \Big|_{\overline{MS}, \mu_\Lambda = m_c}$$

NLO NRQCD fit the experiment data well.

Cross section for r=0.27



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Summary

1. Based on NRQCD, we calculate the NLO correction to the χ_{cJ} production at Tevatron and LHC, which presents the $1/p_T^4$ behavior of CS channel.

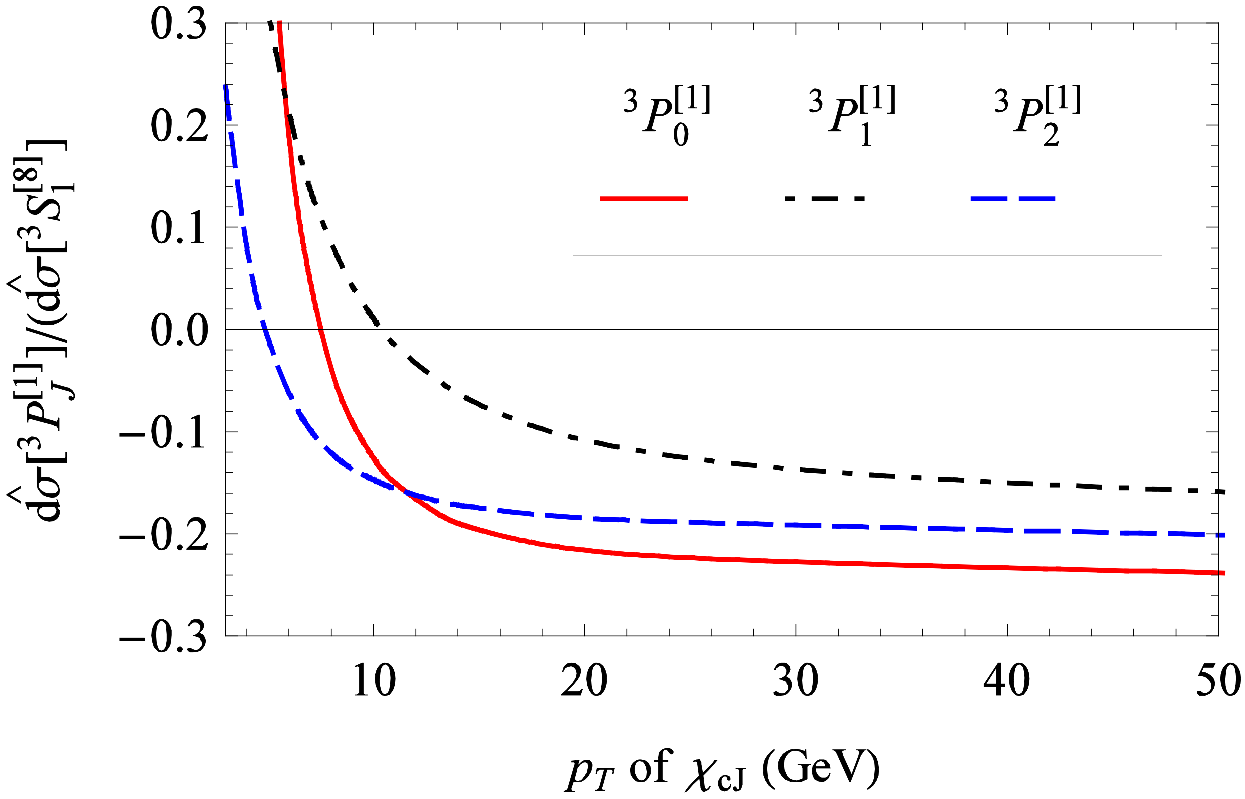
2. Our result indicates that NRQCD is consistent with the experiment data of χ_{cJ} production while CEM is not.

3. To further test NRQCD and determine the CO matrix-elements, data at high p_T in LHC is expected.

4. Our study also shine some lights on J/ψ hadron production.

Thanks!

Back up



0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
10
20
30
40
50
$^3P_0^{[1]}$
$^3P_1^{[1]}$
$^3P_2^{[1]}$
$d\hat{\sigma}[^3P_J^{[1]}]/(d\hat{\sigma}[^3S_1^{[8]}])$
p_T of χ_{cJ} (GeV)