A complete NLO calculation of the J/ψ production at Tevatron and LHC

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Contents

A complete NLO calculation of the J/ψ production Tevatron and LHC

Contents: Part 1

A complete NLO calculation of the J/ψ production Tevatron and LHC

1. Introduction
2. Calculation
3. Result and Discussion
4. Summary

Ψ' puzzle

- About twenty year ago, CDF collaboration found a surprising large production rate of Ψ' at high p_T.
- As shown on the right Fig, the yield is larger than the theoretic prediction by a factor of 30, even though the fragmentation contribution is included.

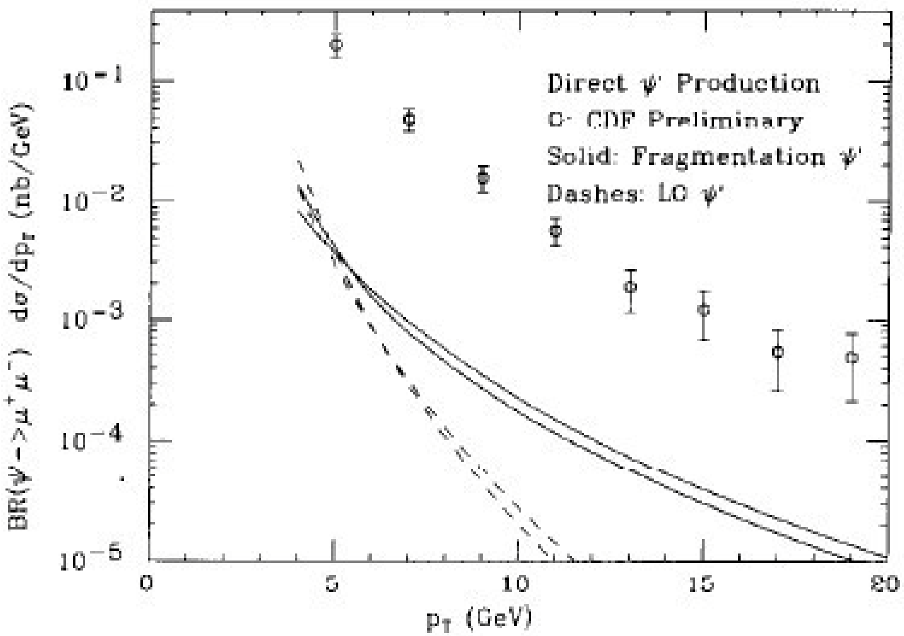


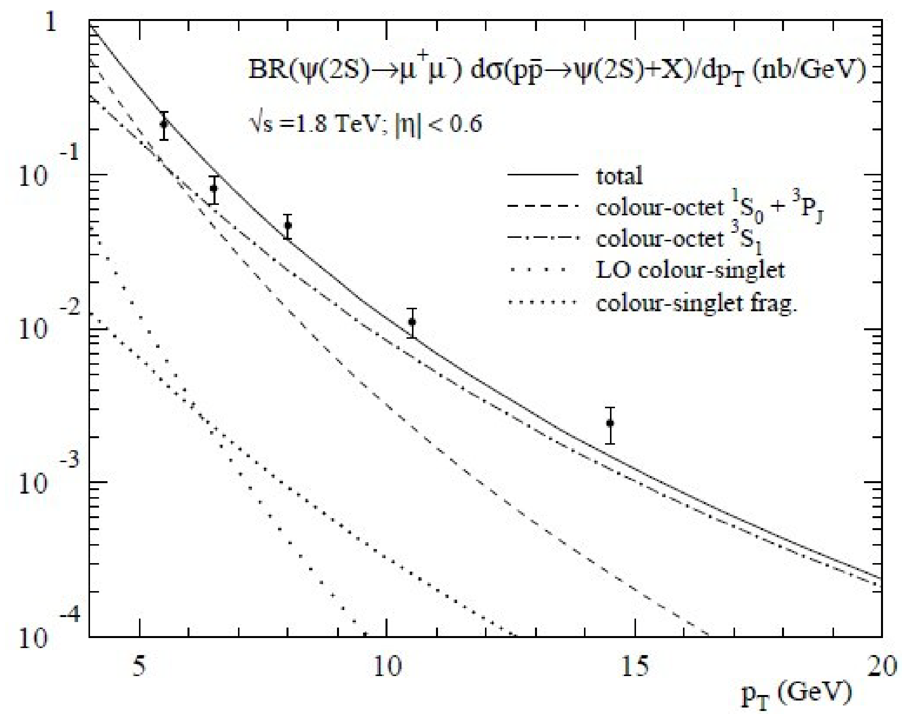
Fig. 4. Preliminary CDF data for prompt ψ' production (O) compared with theoretical predictions of the total fragmentation contribution (solid curves) and the total leading-order contribution (dashed curves).

E. Braaten et al. Physics Letter B333, 548 (1994)

Color-Octet mechanism

- To solve the Ψ' puzzle, a color-octet(CO) mechanism was proposed by Braaten and Fleming based on the NRQCD .
- The CO states decline much slower compared to the p_T^{-8} scaling of color-singlet(CS) state, and give an natural explanation of the observed experiment data.

States	p_T behavior at LO
$^3S_1^{[1]}$	p_T^{-8}
$^3S_1^{[8]}$	p_T^{-4}
$^1S_0^{[8]}$	p_T^{-6}
$^3P_J^{[8]}$	p_T^{-6}



M.Kramer, arXiv:hep-ph/0106120

J/ψ and ψ(2S) polarization puzzle

•Although it seems to successfully explain the differential cross sections, CO encounters difficulties when the polarization is also taken into consideration.
•Dominated by gluon fragmentation to $^3S_1^{[8]}$ at large p_T, LO NRQCD predicts a sizable transverse polarization, while the measurement gives almost unpolarized.

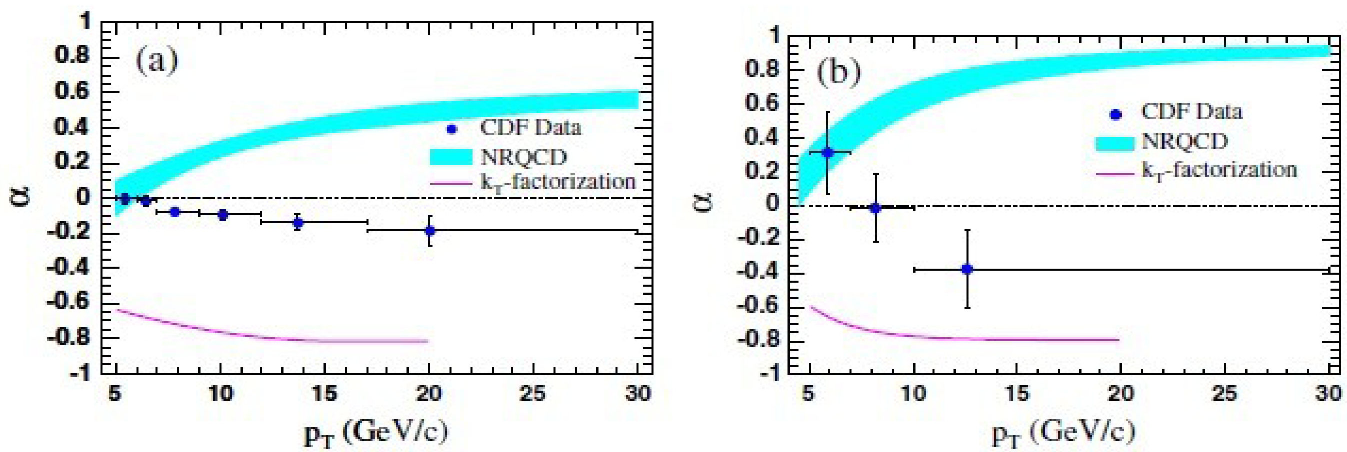


FIG. 4 (color online). Prompt polarizations as functions of p_T: (a) J/ψ and (b) $\psi(2S)$. The band (line) is the prediction from NRQCD [4] (the k_T-factorization model [9]).

A. Abulencia et al.[CDF Collaboration], Phys.Rev.Lett.99, 132001 (2007)

NLO calculation

- To solve the polarization puzzle, a lot of effort has been made.
- Breakthrough: NLO QCD correction to CS channel.
- Differential cross section is enhanced by 2 order relative to LO CS result at high p_T.

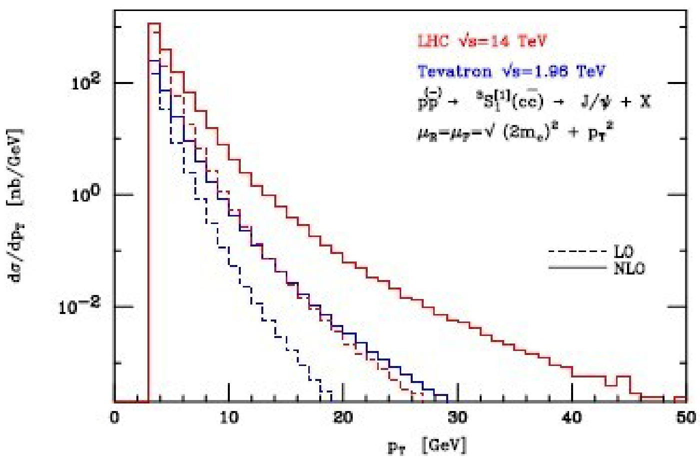
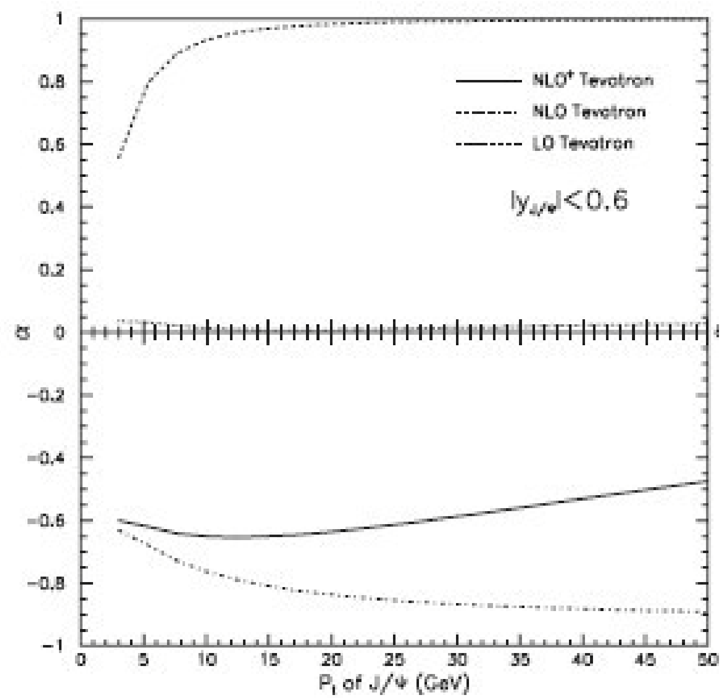


FIG. 5 (color online). Differential cross sections for direct J/ψ production via a ${}^3S_1^{[1]}$ intermediate state, at the Tevatron (lower histograms) and LHC (upper histograms), at LO (dashed line) and NLO (solid line). $p_T^{J/\psi} > 3$ GeV and $|y^{J/\psi}| < 3$. Details on the input parameters are given in the text.



Phys.Rev.Lett. 98, 252002

Phys.Rev.Lett. 100, 232001

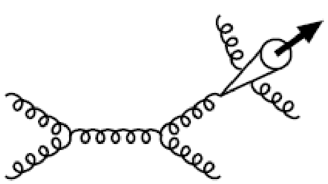
p_T enhancement is essential

- Although the NLO CS production can still not resolve the J/ψ and ψ(2S) production puzzle, it shows the importance of kinematic enhancement of p_T.

- So we can conclude nothing definitely until the p_T^{-4} behavior of all channels are opened.

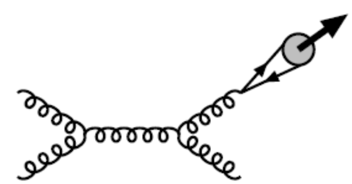
States	Order where p_T^{-4} present
${}^3S_1^{[1]}$	NNLO
${}^3S_1^{[8]}$	LO
${}^1S_0^{[8]}$	NLO
${}^3P_J^{[8]}$	NLO

(b) colour-singlet fragmentation: $g + g \to [c\bar{c}[{}^3S_1^{(1)}] + gg] + g$



$+ \ldots \qquad \sim \alpha_s^5 \frac{1}{p_t^4}$

(c) colour-octet fragmentation: $g + g \to c\bar{c}[{}^3S_1^{(8)}] + g$



$+ \ldots \qquad \sim \alpha_s^3 \frac{1}{p_t^4} v^4$

M.Kramer, arXiv:hep-ph/0106120

NNLO correction to CS

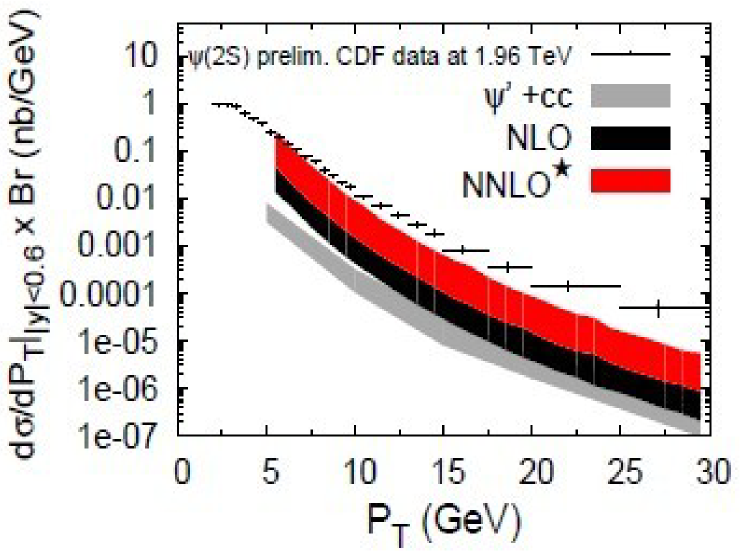
- For the NNLO correction to CS channel is out of current state of the art, we must estimate its contribution:

  - The only new behavior is the gluon fragmentation, which scaling as p_T^{-4}. Other contributions at this order is suppressed by α_s relative to NLO.

  - The fragmentation contribution has been calculated by E. Braaten et al. , and they are as small as 1/30 of the experiment data.

  - So we can ignore the NNLO CS contributions.

They maybe over estimate the NNLO CS contribution in a recent work:



Eur.Phys.J.C60:693-703,2009

Conclusion: a complete NLO correction to the Ψ family production is needed and enough!

Contents: Part 2

A complete NLO calculation of the J/ψ production Tevatron and LHC

1. Introduction
2. Calculation
3. Result and Discussion
4. Summary

Formalism

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

PDF

CTEQ6L1, CTEQ6M

Hadronization

Long distance (~1/(m_cv)) process: non-perturbative calculations and input from experiments needed.

Production of heavy quarks

Short distance (~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:

  KLN theorem *and* *collinear factorization of PDF*

- 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.

Divergence of NRQCD matrix element

It can be shown that,

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

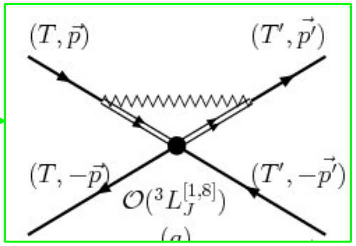
$$\left(T_f^a T_{f'}^a \mathcal{M}_{ff'}^{Born}\right)\left(M^{Born}\right)^\dagger = \left(T_f^a \mathcal{M}_f^{Born}\right)\left(T_{f'}^a \mathcal{M}_{f'}^{Born}\right)^\dagger, \ f' \neq Q, \overline{Q}$$

So only term that is not canceled between Real and Virtual is :

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

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

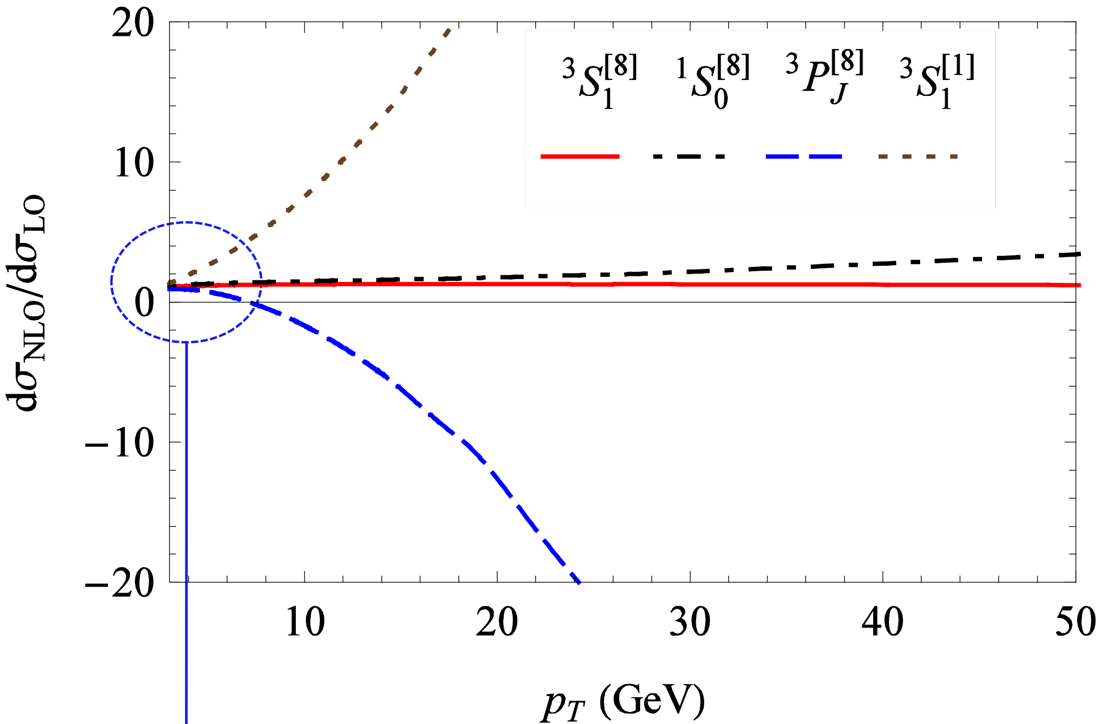
Finally, (1) is absorbed by NRQCD MEs →



Contents: Part 3

A complete NLO calculation of the J/ψ production Tevatron and LHC

K factor



K factor of each channel.

- Large but negative corrections for P wave.
- Subtraction scheme and NRQCD renormalization scale dependent.

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

Decomposition

For the large K factor of P-wave channel, $^3S_1^{[8]}$ channel is no longer the unique source at high p_T. We find the following decomposition holds: $\hat{d\sigma}[{}^3P_J^{[8]}] = r_0\ \hat{d\sigma}[{}^1S_0^{[8]}] + r_1\ \hat{d\sigma}[{}^3S_1^{[8]}]$

As a consequence, we will use two linear combined LDMEs:

$$M_{0,r_0}^{J/\psi} = \langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]})\rangle + \frac{r_0}{m_c^2}\langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]})\rangle$$
$$M_{1,r_1}^{J/\psi} = \langle \mathcal{O}^{J/\psi}({}^3S_1^{[8]})\rangle + \frac{r_1}{m_c^2}\langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]})\rangle,$$

r0=3.9
r1=-0.56

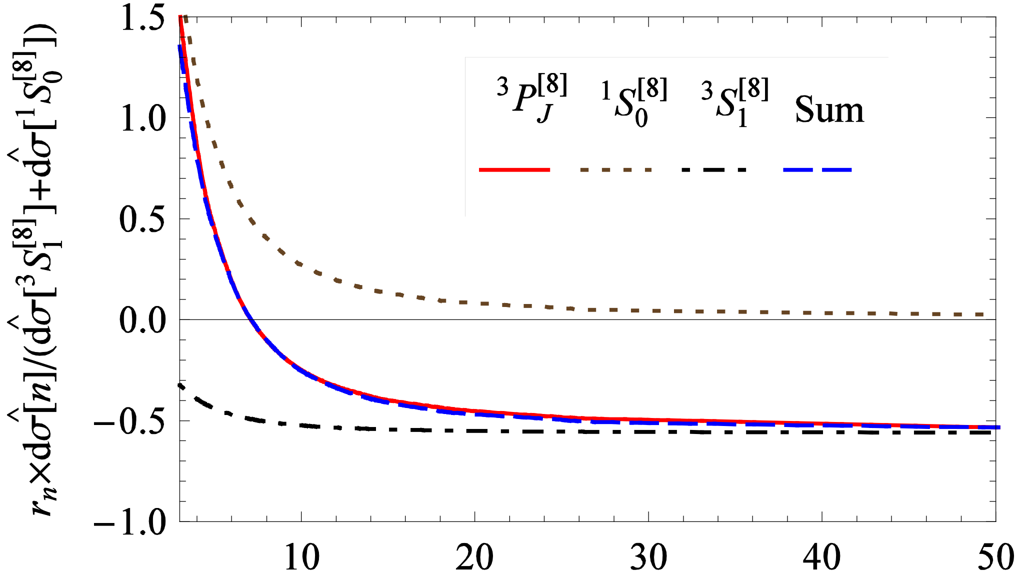


FIG. 2: Comparing of $\hat{d\sigma}[{}^3P_J^{[8]}]$ and $Sum = 3.9\hat{d\sigma}[{}^1S_0^{[8]}] - 0.56\hat{d\sigma}[{}^3S_1^{[8]}]$ in Tevatron, where a factor of $\hat{d\sigma}[{}^1S_0^{[8]}] + \hat{d\sigma}[{}^3S_1^{[8]}]$ is divided by each contribution.

Fit the experiment data (1)

- To extract LDMEs of J/ψ by fit the prompt production experimental data, we should consider the feed down contribution from heavier particle.
- Feed down contribution mainly from ψ(2S) and χ_{cJ} , all of which are calculated to NLO.
- The transverse momentum difference is considered and approximated as:

$$p_T = p_T^{\prime} \times \frac{m_{J/\psi}}{m_H}$$

Fit the experiment data (2)

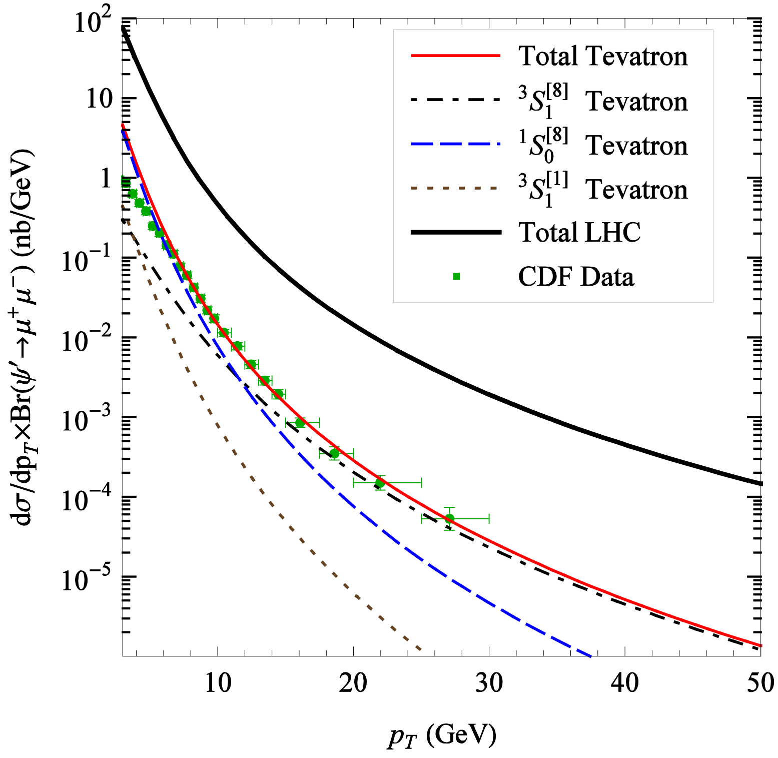
- In the fit procedure, we abandon data with p_T<7GeV, because we can not cover these data using unique LDMEs.
- To see this point, we perform a χ^2 analysis for J/ψ :

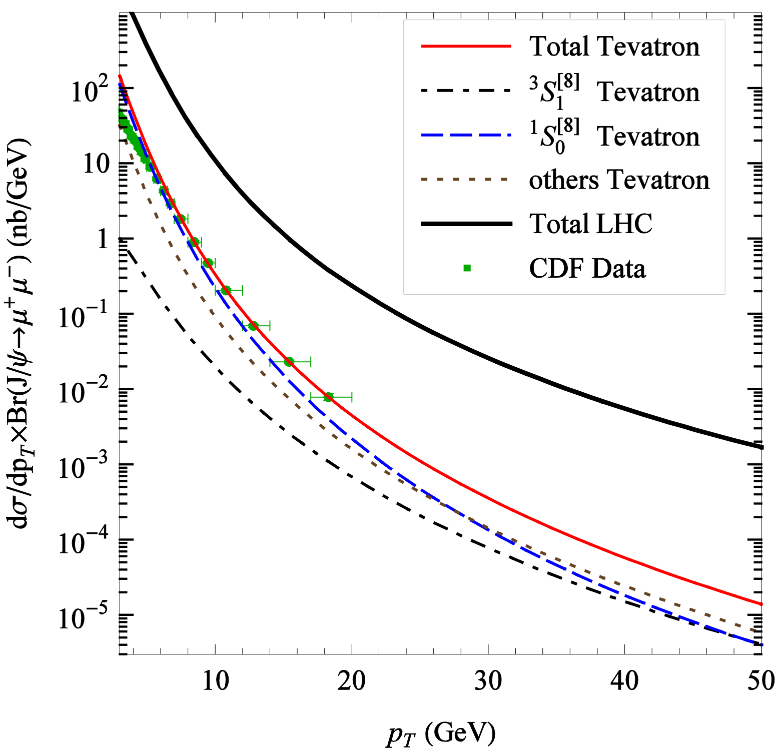
lower p_T cut (Gev)	χ^2/dof	$<O^3S_1^{[8]}>_{J/\psi}$	$<O^1S_0^{[8]}>_{J/\psi}$
3	236.269/16=14.7668	0.360089	1.78736
4	92.9272/12=7.74393	0.250964	3.49161
5	27.8681/8=3.48351	0.157748	5.1679
6	9.07871/6=1.51312	0.101501	6.28956
7	1.31256/4=0.328141	0.0492096	7.43362
8	0.817308/3=0.272436	0.037283	7.71245
9	0.434183/2=0.217091	0.0226552	8.07939
10	0.424269/1=0.424269	0.0192824	8.17001

The requirement of p_T cut can be understood as the factorization may be not reliable at small pT.

Fit the experiment data (3)

H	$\langle \mathcal{O}^H \rangle$ (GeV^3)	$M^H_{1,-0.56}$ (10^{-2} GeV^3)	$M^H_{0,3.9}$ (10^{-2} GeV^3)
J/ψ	1.16	0.049	7.4
ψ'	0.76	0.12	2.0





Solving J/ψ polarization puzzle

The two linear combined LDMEs for J/ψ have difference by two order!

$$M_{0,r_0}^{J/\psi} = \langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]})\rangle + \frac{r_0}{m_c^2}\langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]})\rangle$$
$$M_{1,r_1}^{J/\psi} = \langle \mathcal{O}^{J/\psi}({}^3S_1^{[8]})\rangle + \frac{r_1}{m_c^2}\langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]})\rangle,$$

We expect: $\langle \mathcal{O}^{J/\psi}({}^3S_1^{[8]})\rangle \approx \langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]})\rangle / m_c^2 \ll \langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]})\rangle.$

- As a result, the direct J/ψ production is dominated by ${}^1S_0^{[8]}$ up to a large p_T.

- Considered the feed down contributions are a little smaller than 50% at all pT region, we expect the prompt J/ψ production is mainly unpolarized as ${}^1S_0^{[8]}$ channel is unpolarized.

- Our polarization prediction match the measurement of experiment very well.

Discussion of ψ(2S)

- For ψ(2S) ,difference of the two linear combined LDMEs is not as dramatic as that of J/ ψ, so one gluon fragmentation to a $^3S_1^{[8]}$ or $^3P_J^{[8]}$ contribution may dominate the production at not too large p_T.

- So ψ(2S) production may be transversely polarized at large p_T, which can be test by LHC.

Contents: Part 4

A complete NLO calculation of the J/ψ production Tevatron and LHC

1. Introduction
2. Calculation
3. Result and Discussion
4. Summary

Summary

1. Based on NRQCD, we calculate the NLO correction to the J/ψ(ψ') production at Tevatron and LHC, which presents the $1/p_T^4$ behavior of all important channels.

2. The large K factor of P-wave CO channel at high p_T results two linear combined LDMEs.

3. The steep shape of experimental J/ψ prompt production data, smooth feed-down contribution, together with a reasonable fitting method, we find the ${}^1S_0^{[8]}$ channel dominates the direct J/ψ production.

4. As a result, J/ψ production should be mainly unpolarized at the pT region of measured at Tevatron, and may solve the J/ψ polarization puzzle.

Opportunities

1. The ψ’ can be transversely polarized, which needs further experiment to test.

2. NNLO CS channel contribution is neglected in this work. Whether it is ignorable needs further consideration.

3. The large CO LDMEs obtained in this work are in contradiction with the expectation in B factories.

4. Prediction the J/ψ(ψ’) hadron production including polarization information systematically at NLO is the most urgent task at the next step.