J/Ψ and Xc Polarization at Hadron Colliders

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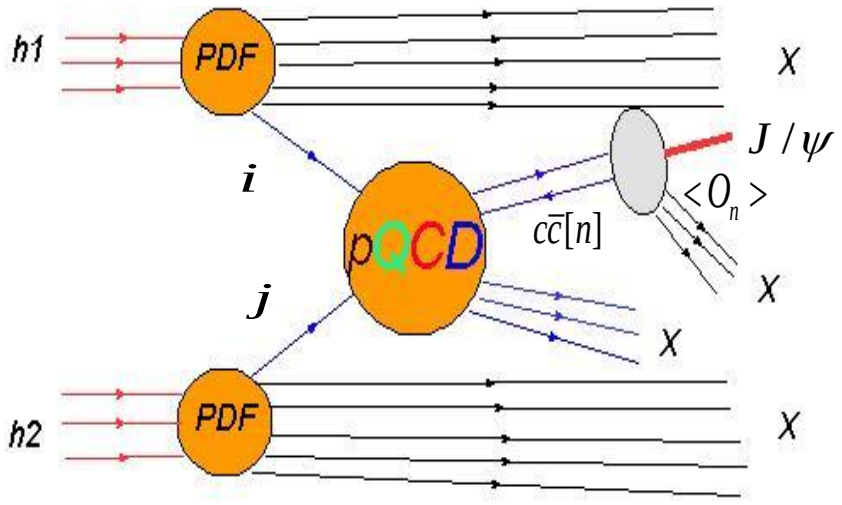
factorization



- QCD factorization:

$$\sigma_{hadron} = f_{i/h1} \otimes f_{j/h2} \otimes \sigma^{ij}_{parton}$$

- NRQCD factorization *G. Bodwin et al. (1995)*:

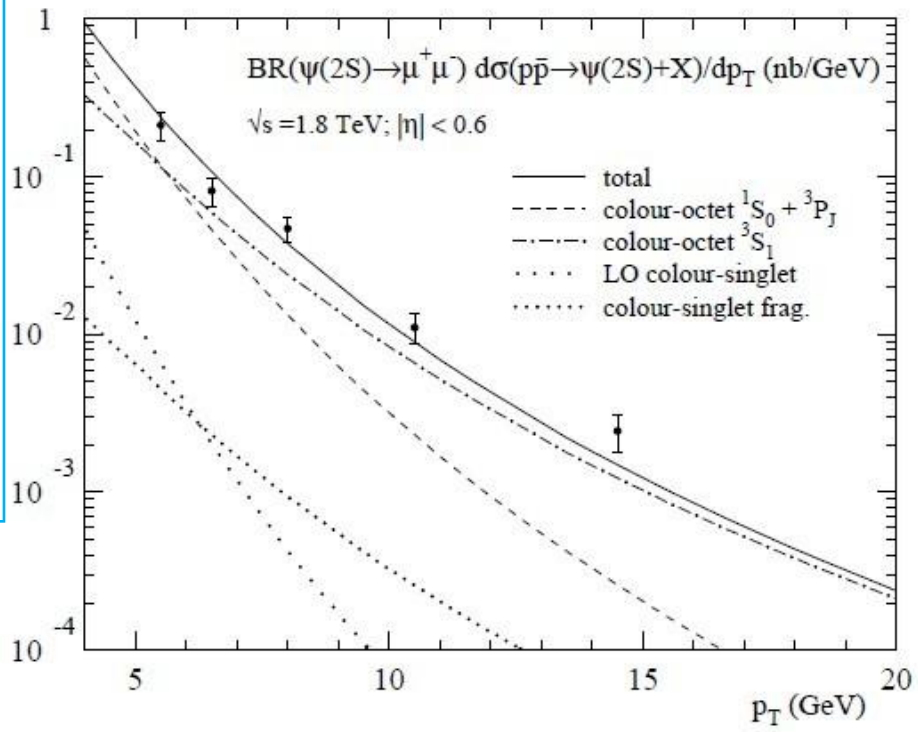
$$\sigma^{ij}_{parton} = \sigma(ij \to c\bar{c}[n] + X) < O_n >$$

- The short distance parton level cross section is perturbative and process-dependent.
- The parton distribution functions and long distance matrix elements $< O_n >$ are non-perturbative but universal.
- The long distance matrix elements are matrix elements of four-fermion operators in NRQCD: $\langle O_n \rangle = \langle 0 | \chi^\dagger \kappa_n \psi (\sum_X | H + X \rangle \langle H + X |) \psi^\dagger \kappa_n' \chi | 0 \rangle$
- The long distance matrix elements are scaled by v: $v_c^2 \approx 0.23, v_b^2 \approx 0.08$

NRQCD @ LO

- To solve the Ψ' surplus puzzle, the color-octet (CO) mechanism was proposed by Braaten and Fleming based on NRQCD factorization.
- The CO yield scales as p_T^{-4} decreases much slower than p_T^{-8} of color-singlet (CS) state.
- A natural explanation of observed Ψ' (and J/Ψ)surplus at theTevatron.

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}



Kramer, arXiv:hep-ph/0106120

NRQCD @ LO:
J/ψ(ψ(2S)) polarization puzzle

- Although it seems to successfully explain the 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.
- In gluon fragmentation, the spin-flip interaction is suppressed (*Cho, Wise (1994)*).

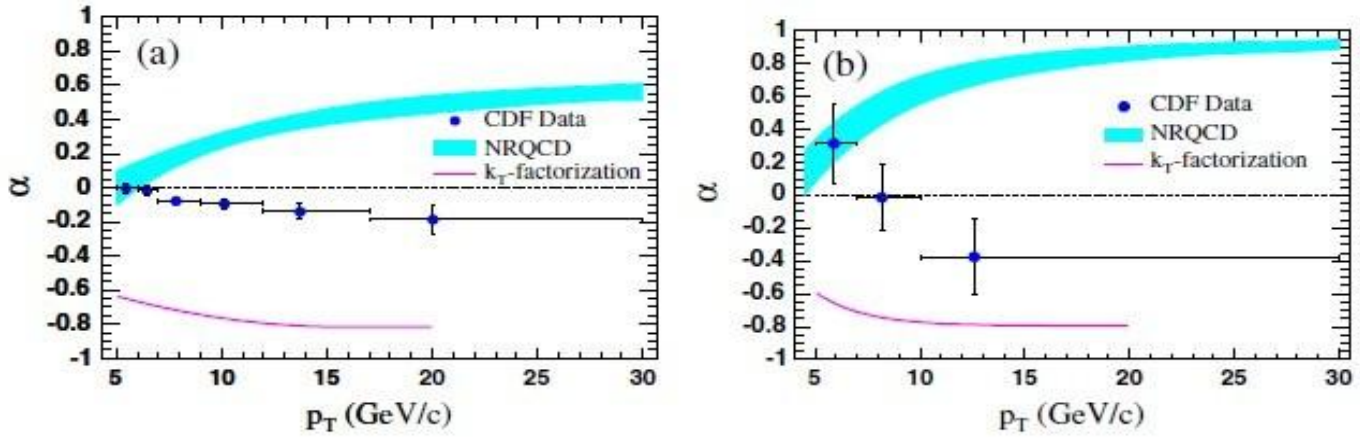


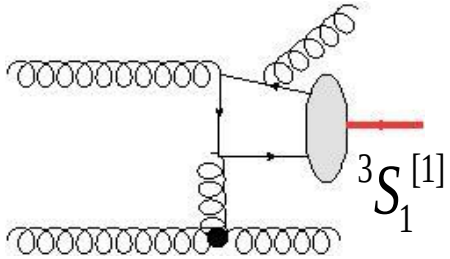
FIG. 4 (color online). Prompt polarizations as functions of p_T: (a) J/ψ and (b) $\psi(2S)$. The band (line) is the prediction from NRQCD [4] (the k_T-factorization model [9]).

A. Abulencia et al. (2007)

NRQCD @ NLO

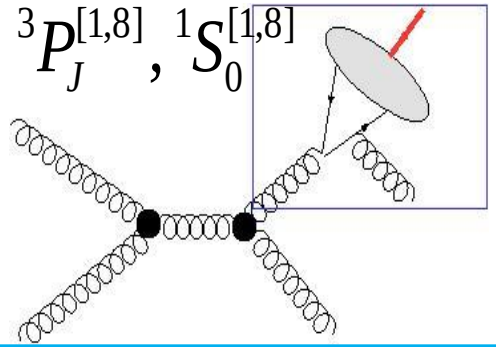
Kinematical enhancements at large PT

NLO color-singlet



$\propto \alpha_S^4 m_H^2 p_T^{-6}$

NLO color-octet



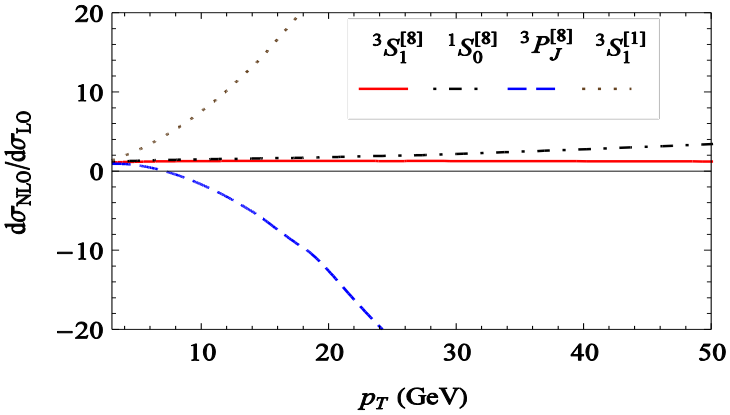
$\propto \alpha_S^4 p_T^{-4}$

Fock states	p_T scaling at NLO
$^3S_1^{[1]}$	p_T^{-6}
$^3S_1^{[8]}$	p_T^{-4}
$^1S_0^{[1,8]}$	p_T^{-4}
$^3P_J^{[1,8]}$	p_T^{-4}

- The NLO color-singlet differential cross section is enhanced by 2 order relative to LO $^3S_1^{[1]}$ result at large pT. [*J.M.Campbell et al. (2007)*]
- Corrections to $^3P_J^{[1,8]}$ should be more important at large pT.
- The soft gluon radiations are canceled in the channel $^1S_0^{[1,8]}$, thus, the corrections to these channels are not very significant.

NRQCD @ NLO: Fock states

- Two groups calculated it independently: Ma, Wang, Chao (2011) and Butensckön, Kniehl (2011).
- The results of the two groups for the short-distance coefficients agree.



➢ Decomposition of P-wave channel:

Ma, Wang, Chao, (2011)

- At NLO and lager p_T., roughly $d\sigma[^3S_1^{[8]}]\sim pT^{-4}$ and $d\sigma[^1S_0^{[8]}]\sim pT^{-6}$, and we find the following decomposition holds within error of a few percent:

$$\hat{d\sigma}[^3P_J^{[8]}] = r_0\ \hat{d\sigma}[^1S_0^{[8]}] + r_1\ \hat{d\sigma}[^3S_1^{[8]}]$$

- As a result, we use two linearly combined LDMEs:

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

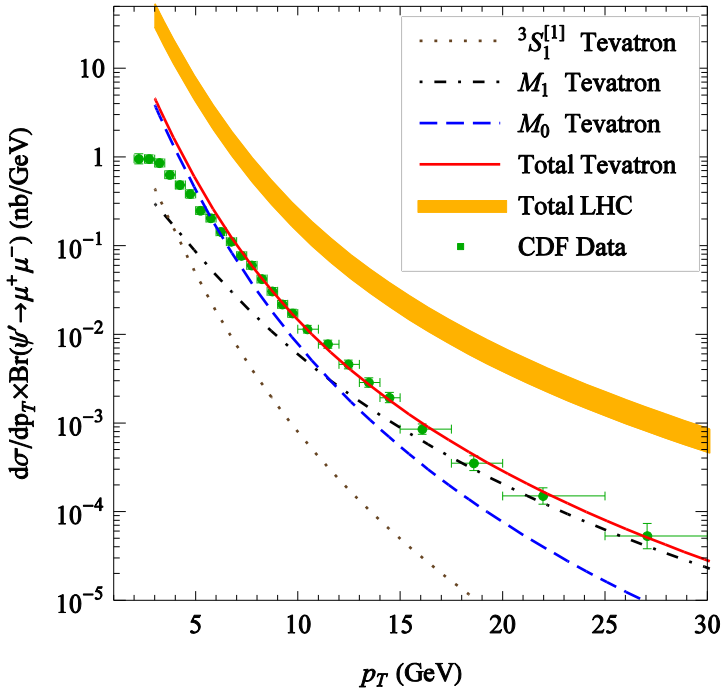
➢ For CDF: r_0=3.9, r_1=-0.56

NRQCD @ NLO: Fit LDMEs

Fit LDMEs using Tevatron Data

Ma, Wang, Chao (2011)

p_T^{cut} GeV	H	$\langle \mathcal{O}^H \rangle$ GeV^3	M^H_{1,r_1} 10^{-2} GeV^3	M^H_{0,r_0} 10^{-2} GeV^3	$\chi^2/d.o.f.$
7	J/ψ	1.16	0.05 ± 0.02	7.4 ± 1.9	0.33
	ψ'	0.76	0.12 ± 0.03	2.0 ± 0.6	0.56
5	J/ψ	1.16	0.16 ± 0.05	5.2 ± 1.3	3.5
	ψ'	0.76	0.17 ± 0.04	1.1 ± 0.3	2.2

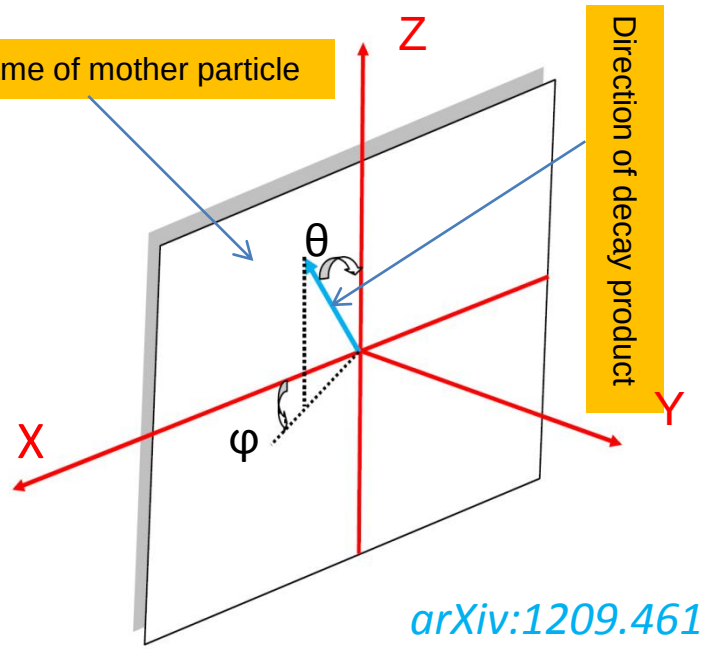


- Agree with data only for p_T>7GeV, but the agreement is very good
- The smallness of M_1 for J/ψ due to the steep experimental curve, which is roughly shows the p_T^{-6}-p_T^{-5} behavior in the moderate p_T region.

Could the smallness of M_1 for J/ψ account for the nearly non-polarized CDFII data?

J/ψ and Xc Polarization

Polarization observables I



arXiv:1209.4610

1. J/Ψ (J=1) → l+ l-:

$$I_J = \frac{N - 3\frac{ds_{00}}{dp_T}}{N + \frac{ds_{00}}{dp_T}}, N = \frac{ds_{11}}{dp_T} + \frac{ds_{00}}{dp_T} + \frac{ds_{-1-1}}{dp_T}$$

2.χc1 (J=1) → J/Ψ γ:

E1, M2, E3

$$I_J = (1-3\alpha)\frac{N - 3\frac{ds_{00}}{dp_T}}{(1+\alpha)N + (1-3\alpha)\frac{ds_{00}}{dp_T}},$$

$$N = \frac{ds_{11}}{dp_T} + \frac{ds_{00}}{dp_T} + \frac{ds_{-1-1}}{dp_T}, \alpha = \frac{1 + 2a_1^{J=1}a_2^{J=1}}{2}$$

3. χc2 (J=2) → J/Ψ γ:

$$I_J = 6\frac{(1-3\alpha_0-\alpha_1)N - (1-7\alpha_0+\alpha_1)(\frac{ds_{11}}{dp_T} + \frac{ds_{-1-1}}{dp_T}) - (3-\alpha_0-7\alpha_1)\frac{ds_{00}}{dp_T}}{(1+5\alpha_0+3\alpha_1)N + 3(1-3\alpha_0-\alpha_1)(\frac{ds_{11}}{dp_T} + \frac{ds_{-1-1}}{dp_T}) + (5-7\alpha_0-9\alpha_1)\frac{ds_{00}}{dp_T}},$$

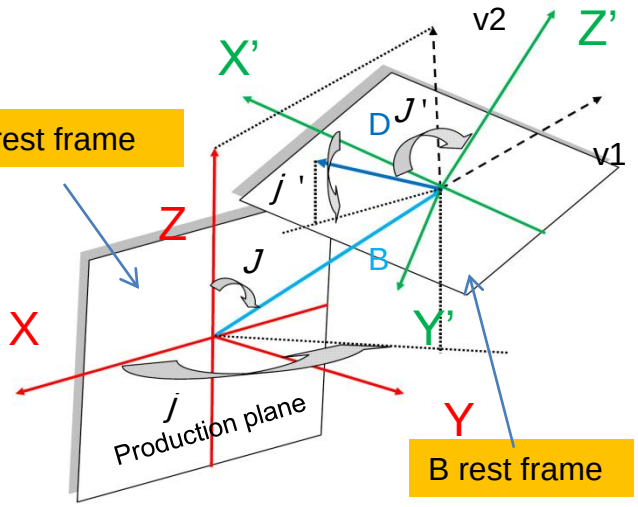
$$N = \sum_{s=-2}^{2}\frac{ds_{ss}}{dp_T}, \alpha_0 = \frac{1 + 2a_1^{J=2}(\sqrt{5}a_2^{J=2} + 2a_3^{J=2}) + 4a_2^{J=2}(a_2^{J=2} + \sqrt{5}a_3^{J=2}) + 3(a_3^{J=2})^2}{10},$$

$$\alpha_1 = \frac{9 + 6a_1^{J=2}(\sqrt{5}a_2^{J=2} - 4a_3^{J=2}) - 4a_2^{J=2}(a_2^{J=2} + 2\sqrt{5}a_3^{J=2}) + 7(a_3^{J=2})^2}{30}$$

2-body decay of spin-J particle

$$\frac{dN}{d\cos J} \mu 1 + \sum_{k=1}^{J} I_{kJ}\cos^{2k} J$$

Polarization observables II



A → B+C
└→ D+E

arXiv:1209.4610

1.χc1 → J/ψ γ → l+ l- γ (Z'=v2):

$$I_{J'} = (5 - 6(a_2^{J=1})^2)\frac{-N + 3\frac{ds_{00}}{dp_T}}{(15 - 2(a_2^{J=1})^2 N - (5 - 6(a_2^{J=1})^2)\frac{ds_{00}}{dp_T})},$$

$$N = \frac{ds_{11}}{dp_T} + \frac{ds_{00}}{dp_T} + \frac{ds_{-1-1}}{dp_T}$$

M2, E3

2. χc2 → J/ψ γ → l+ l- γ (Z'=v2):

$$I_{J'} = (7 - 14(a_2^{J=2})^2 - 5(a_3^{J=2})^2)$$

$$\frac{6N - 9(\frac{ds_{11}}{dp_T} + \frac{ds_{-1-1}}{dp_T}) - 12\frac{ds_{00}}{dp_T}}{2(21 + 14(a_2^{J=2})^2 + 5(a_3^{J=2})^2)N + (7 - 14(a_2^{J=2})^2 - 5(a_3^{J=2})^2)(3\frac{ds_{11}}{dp_T} + 3\frac{ds_{-1-1}}{dp_T} + 4\frac{ds_{00}}{dp_T})},$$

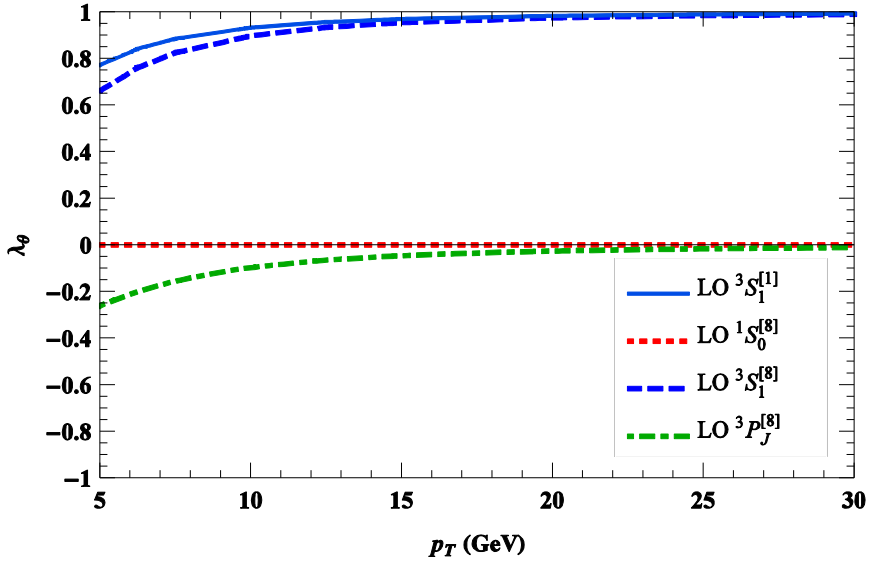
$$N = \sum_{s=-2}^{2} \frac{ds_{ss}}{dp_T}$$

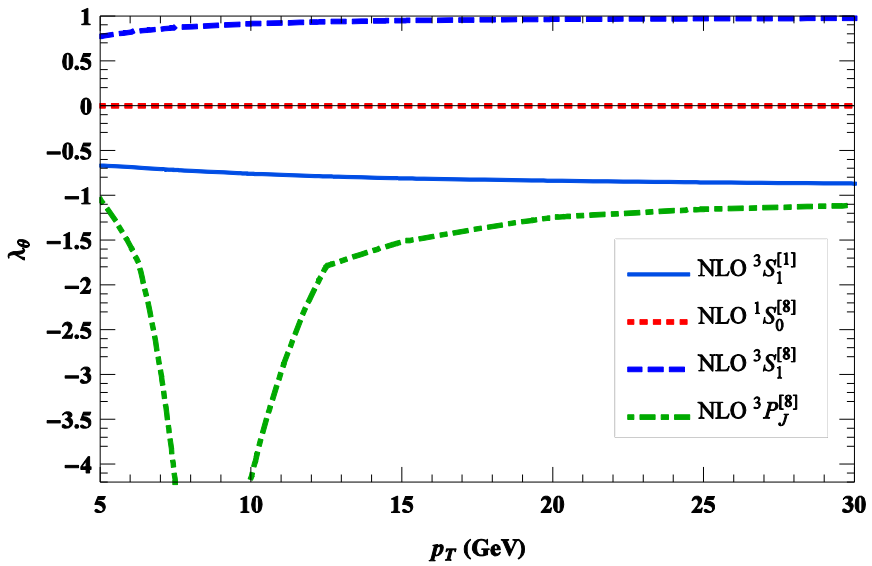
χcJ → J/ψ γ → l+ l- γ :

$$\frac{dN}{d\cos J'} \mu 1 + I_{J'} \cos^2 J'$$

Complete NLO correction for Ψ – polarization

Chao,Ma,Shao,Wang,Zhang (2012)



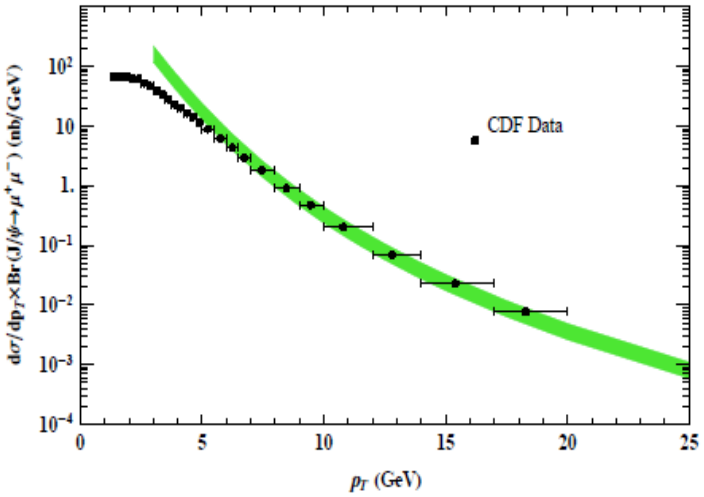


- Negative transverse component of $^3P_J^{[8]}$ channel may cancel that of $^3S_1^{[8]}$ channel, leading to mainly unporalarized J/Ψ.
- Strong correlation between the cross section and the polarization is observed:

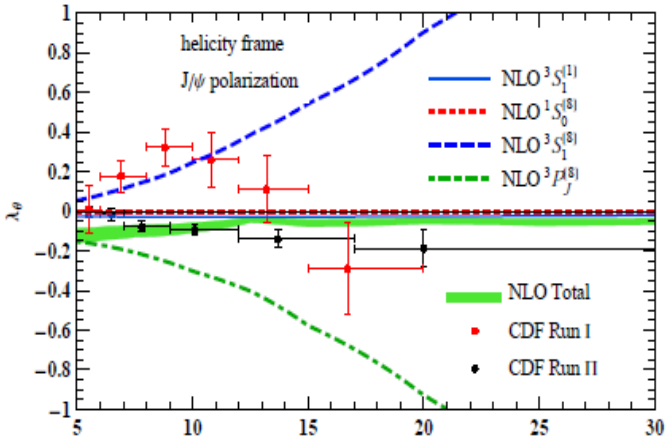
$d\sigma_{tot} \sim M_1/pT^4+\ldots$, with r1=-0.56

$d\sigma_{11} \sim M_1'/pT^4+\ldots$, with r1'=-0.52

Fit CO LDMEs: “fit” V.S. “scan+fit"



KTC, et al. (2012)



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

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

[Y.Q.Ma & K.Wang & K.T.Chao (2011)]

Hadroproduction unpolarized data can only fit two LDMEs combination unambigutly (pT>7GeV).

$\langle \mathcal{O}(^3S_1^{[1]}) \rangle$	M_{0,r_0}	M_{1,r_1}
GeV^3	$10^{-2}\mathrm{GeV}^3$	$10^{-2}\mathrm{GeV}^3$
1.16	7.4 ± 1.9	0.05 ± 0.02

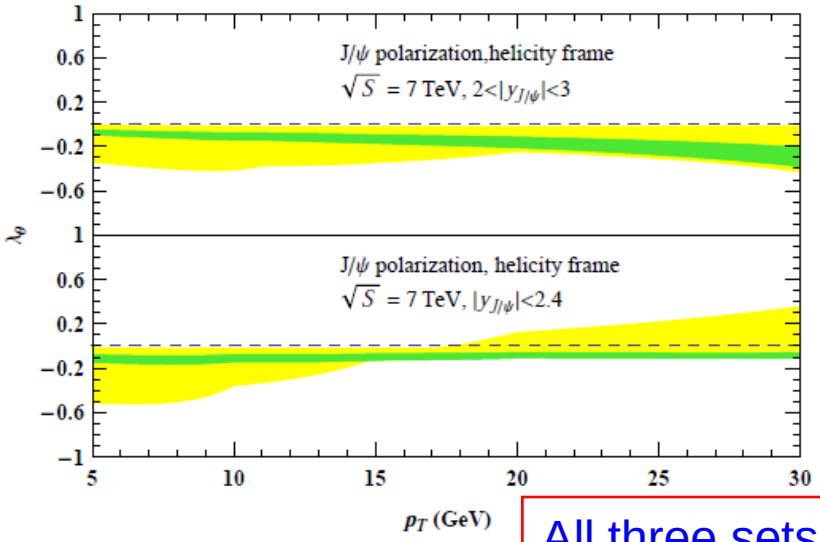
Compatible !

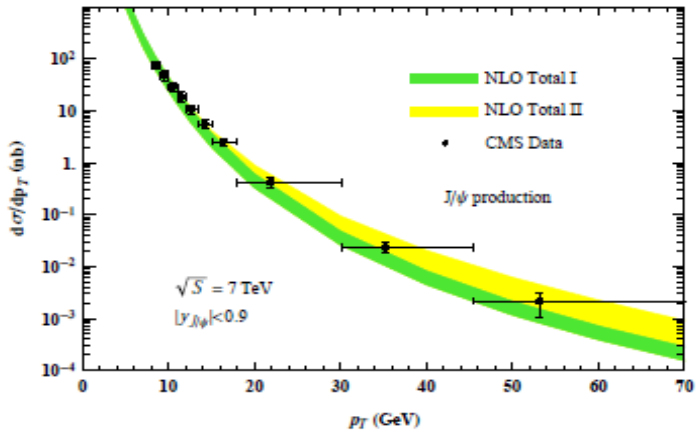
$\Downarrow$ χ^2 fit to $\frac{d\sigma}{dp_T}$ and λ_θ

$\langle \mathcal{O}(^3S_1^{[1]}) \rangle$	$\langle \mathcal{O}(^1S_0^{[8]}) \rangle$	$\langle \mathcal{O}(^3S_1^{[8]}) \rangle$	$\langle \mathcal{O}(^3P_0^{[8]}) \rangle / m_c^2$
GeV^3	$10^{-2}\mathrm{GeV}^3$	$10^{-2}\mathrm{GeV}^3$	$10^{-2}\mathrm{GeV}^3$
1.16	8.9 ± 0.98	0.30 ± 0.12	0.56 ± 0.21
1.16	0	1.4	2.4
1.16	11	0	0

First line: fit three LDMEs using yield and polarization data;
Second and third line: “scan” all possible value of $\langle O(^1S_0^{[8]}) \rangle$ and then fit the other two LDMEs. Using condition: LDMEs >0.

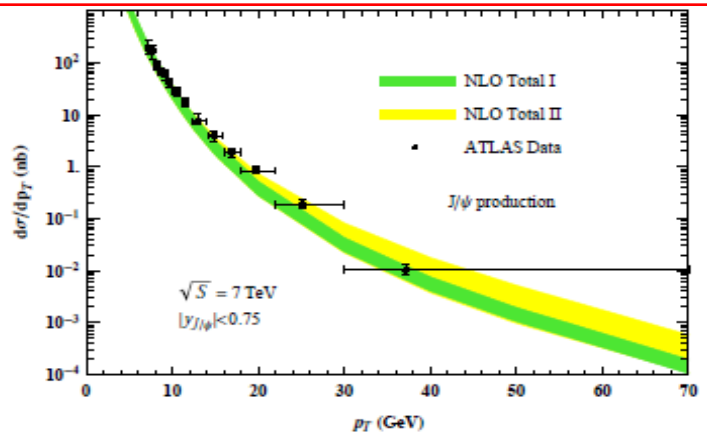
J/ψ polarization @LHC





All three sets of LDMEs can give good predictions for yield!

Chao,Ma,Shao,Wang,Zhang (2012)



- Reasonable good for the pT distribution of cross section up to 70 GeV at the LHC.
- To predict unpolarized results at hadron colliders, a linear combination of CO LDMEs similar to M_1 (i.e., M_1') should be near zero.
- Only direct J/ψ contributions.

Comments on our "scan + fit" method

A necessary condition to guarantee the cross section be positive at high p_T is M1>0, comparing with:

$\langle O(^1S_0^{[8]})\rangle$	$\langle O(^3S_1^{[8]})\rangle$	$\langle O(^3P_0^{[8]})\rangle$	$M_{0,3.9}$	$M_{1,-0.56}$
8.9±0.98	0.3±0.12	0.56±0.21	11.1±1.3	-0.016±0.168
0	1.4	2.4	9.36	0.056
11	0	0	11	0

Note: First line: fit three LDMEs using yield and polarization data; Second (third) line: choose a minimum (maximum) value of $\langle O(^1S_0^{[8]})\rangle$ and then fit the other two LDMEs.

Observation:

1. The central value of the first line gives negative cross section (p_T>300 GeV for LHC and p_T>100 GeV for Tevatron), but positive cross section can be obtained in all p_T region within the error bar.
2. Although $\langle O(^1S_0^{[8]})\rangle$, $\langle O(^3S_1^{[8]})\rangle$ and $\langle O(^3P_0^{[8]})\rangle$ in the second and third lines are not within the error bar of the first line, the corresponding $M_{0,3.9}$ and $M_{1,-0.56}$ are within the error bar.
3. $\langle O(^1S_0^{[8]})\rangle$, $\langle O(^3S_1^{[8]})\rangle$ and $\langle O(^3P_0^{[8]})\rangle$ in the first line may be unphysical!

Comments on our “scan + fit” method

Conclusion:

1. Because only $M_{0,r0}$ and $M_{1,r1}$ can be well constrained by the data, using the **fit three parameters method** alone **cannot** gives all allowable parameter space for $\langle O(^1S_0^{[8]})\rangle$, $\langle O(^3S_1^{[8]})\rangle$ and $\langle O(^3P_0^{[8]})\rangle$, although it can determine the allowable parameter space for $M_{0,r0}$ and $M_{1,r1}$
2. A **scan + fit method** is more suitable to find out all allowable parameter space.

To avoid the fit be trapped in unphysical parameter space,

using “scan+fit” method instead of “fit” method!

Comments:

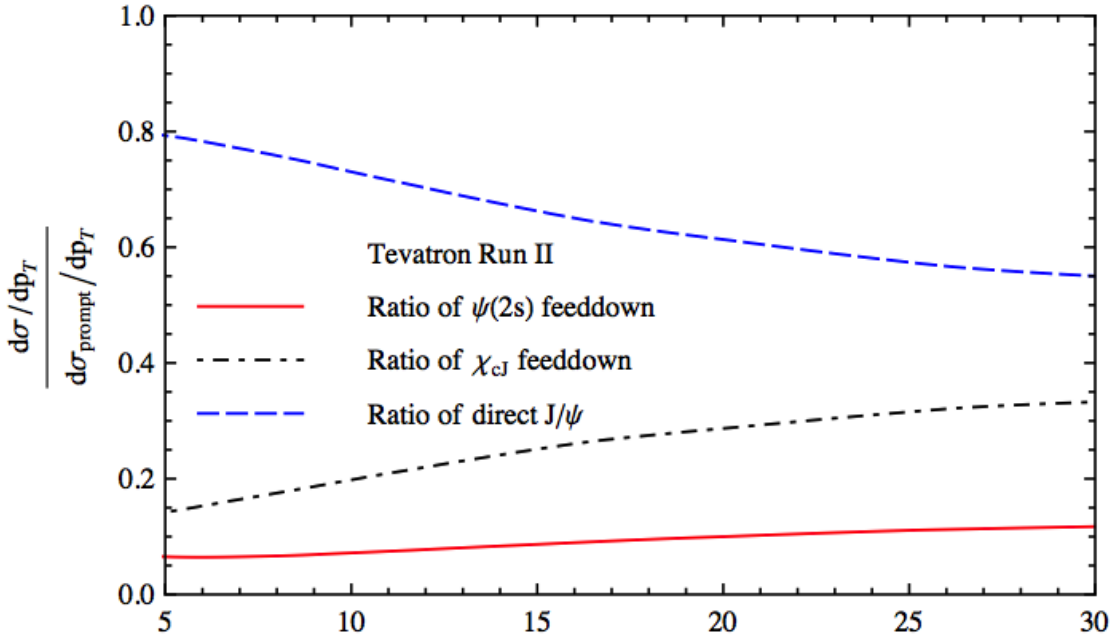
- In our “scan+fit” method, we introduce the condition that all LDMEs >0, which we cannot prove.
- However, at least our result means that even under this constraint, all data of J/ψ hadroproduciton at large pT can be described by NLO NRQCD.

Feeddown contributions

- Feeddown contribution mainly from ψ(2S) and χ_{cJ} , all of which are calculated to NLO and their CO LDMEs are determined by fit Tevatron data.
- The transverse momentum difference is considered and approximated as:

$$p_T^{J/\psi} \approx p_T^H \times \frac{m_{J/\psi}}{m_H}$$

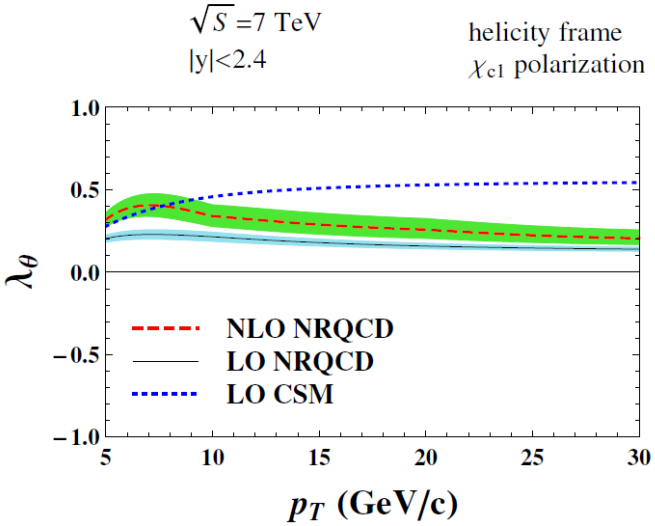
with an very small error $O(\frac{(m_{J/\psi}-m_H)^2}{m_H^2})$. (*We thank J.P. Lansberg and P. Faccioli for helping to test this approximation by simulation.*)

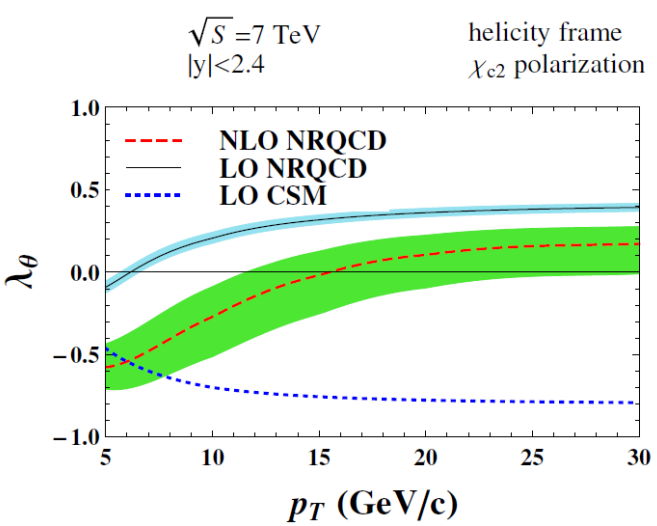


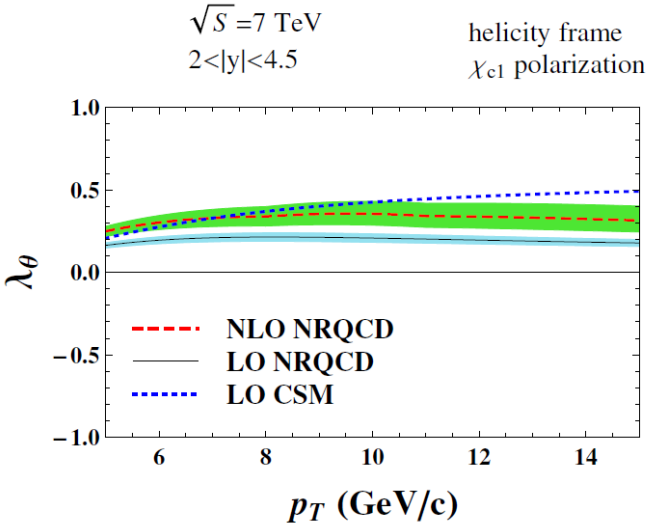
At large p_T:
J/ψ ~ 0.6
χ_{cJ} ~ 0.3
Ψ(2S) ~ 0.1

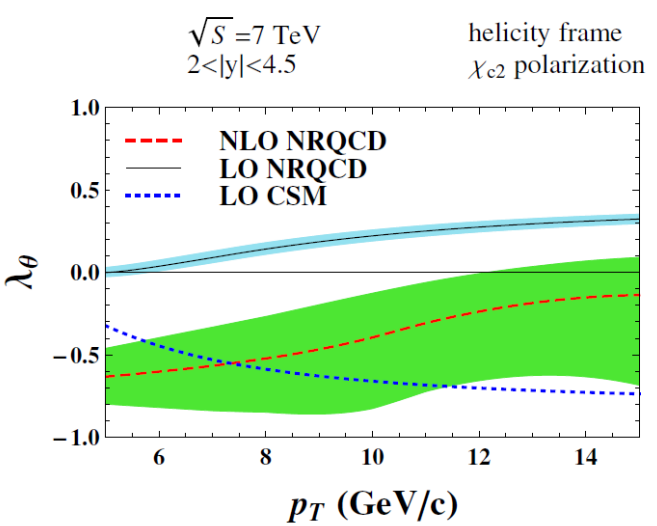
XcJ → J/ψ γ → l+ l- γ

Shao & Ma & Han & Chao, in progress



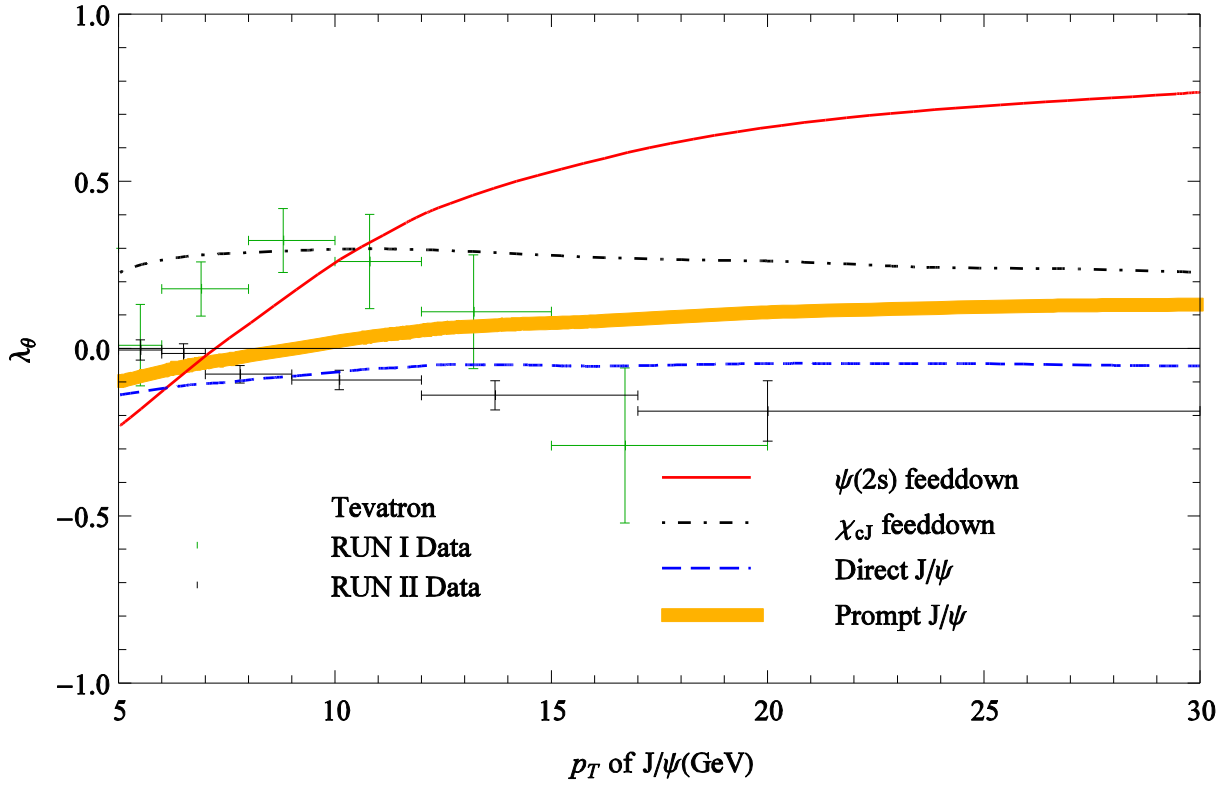






Prompt J/ψ polarization: preliminary estimations

Shao & Ma & Han & Chao, in progress

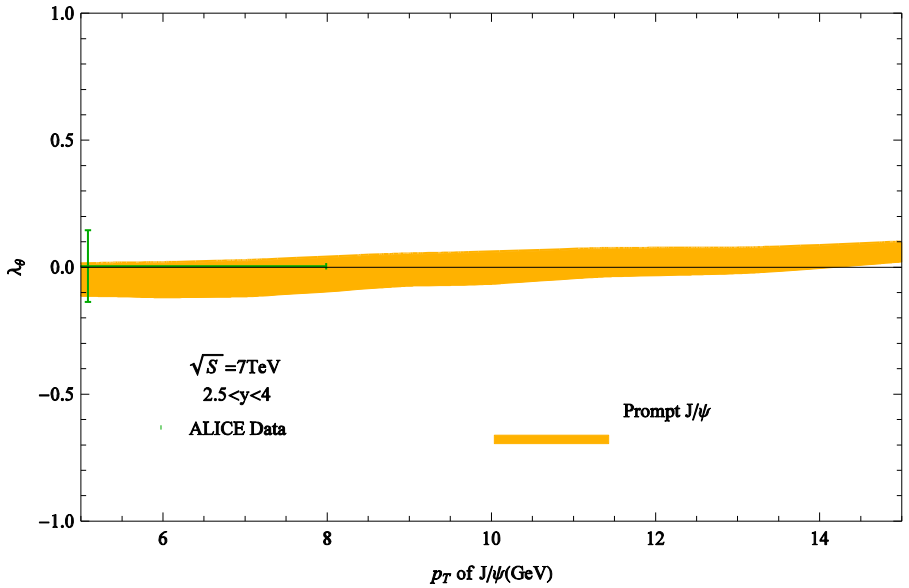


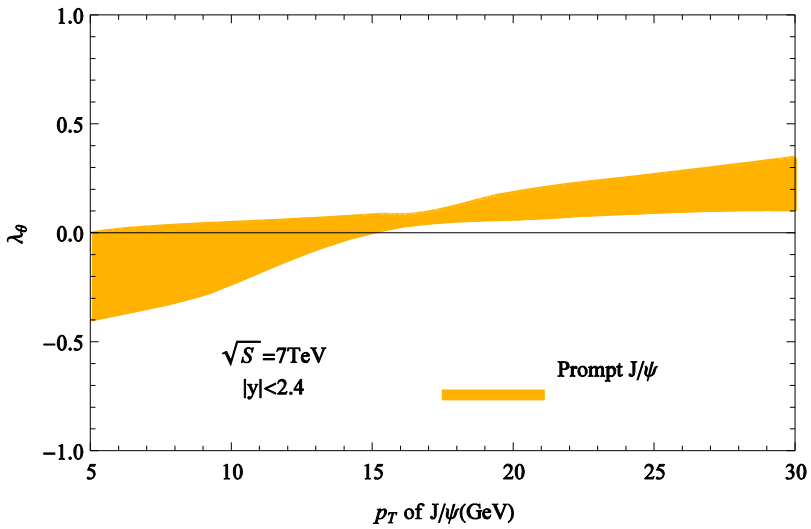
- Summing the feeddown contributions and the direct ones.
- Only slight change of polarization by the feeddown contributions (at large p_T: -0.05 → 0.1).

Prompt J/ψ polarization@LHC:

preliminary estimations

Shao & Ma & Han & Chao, in progress





Similar to the results of direct contributions only

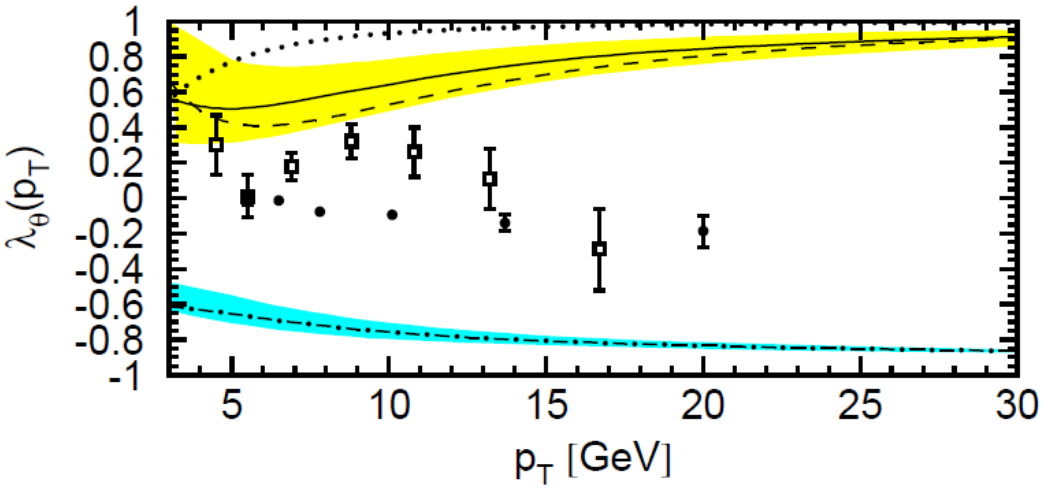
Comparing with other groups

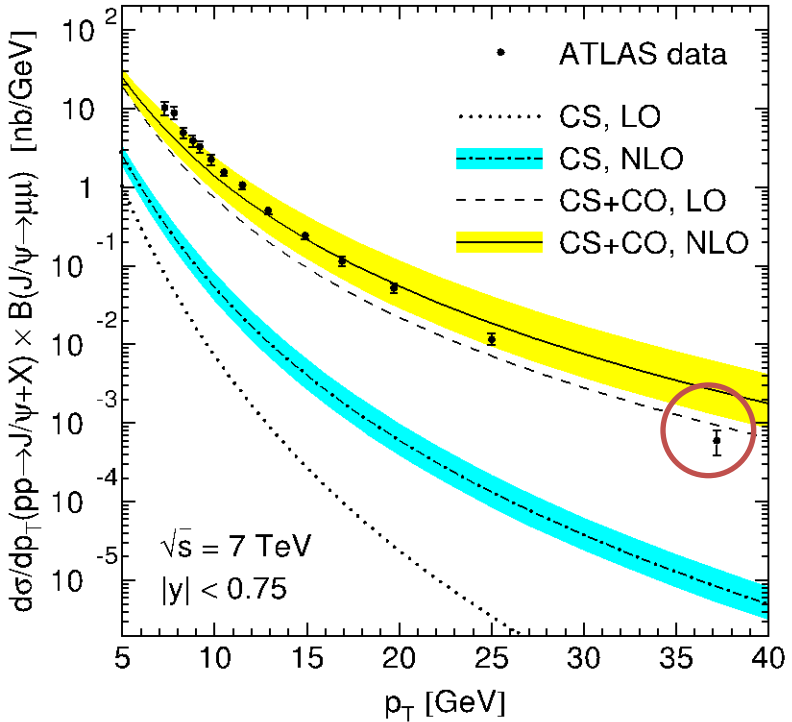
Butenschon and Kniehl, PRL 108 107002 (2012):

- Using global fit LDMEs, which gives negative $\langle O(^3P_0^{[8]})\rangle$.
- Transverse polarizations do not cancel between $^3S_1^{[8]}$ and $^3P_0^{[8]}$ channels , giving transverse polarization.

$$\langle O^{J/\Psi}(^1S_0^{[8]})\rangle = (4.97 \pm 0.44)\times 10^{-2}\,GeV^3, \langle O^{J/\Psi}(^3S_1^{[8]})\rangle = (2.24 \pm 0.59)\times 10^{-3}\,GeV^3,$$

$$\langle O^{J/\Psi}(^3P_0^{[8]})\rangle = (-1.61 \pm 0.20)\times 10^{-2}\,GeV^5$$





Comparing with other groups

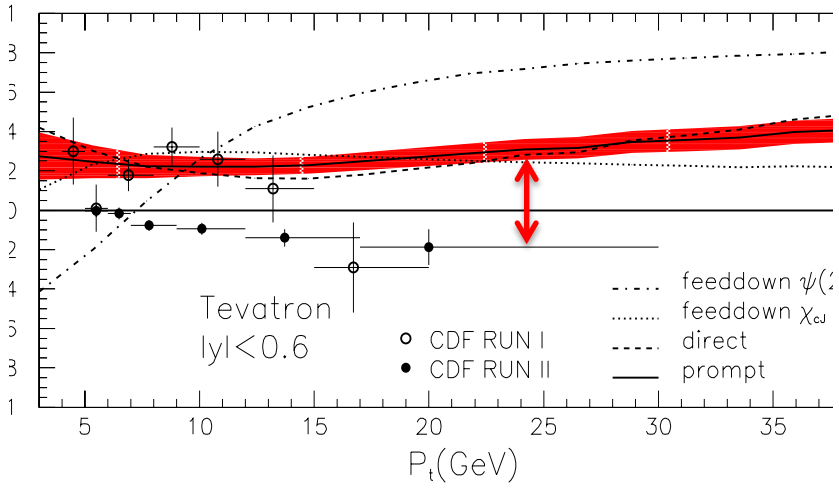
Gong, Wan, Wang and Zhang, PRL 110 042002 (2013):

- Similar to our central value fit, but feeddown contributions are subtracted.
- Feeddown contributions cannot change the polarization too much, as discussed.
- This "fit method" may not be suitable for finding out all possible parameter space.

$$\left(\langle \mathcal{O}(^1S_0^{[8]})\rangle, \langle \mathcal{O}(^3S_1^{[8]})\rangle, \frac{\langle \mathcal{O}(^3P_0^{[8]})\rangle}{m_c^2}\right) \equiv \frac{\mathcal{O}}{100}\ \mathrm{GeV}^3$$

$$\mathcal{O} = (9.7 \pm 0.9, -0.46 \pm 0.13, -0.95 \pm 0.25),$$

$$\Lambda = (-9.6 \pm 1.0, 1.7 \pm 0.1, -0.37 \pm 0.01),$$



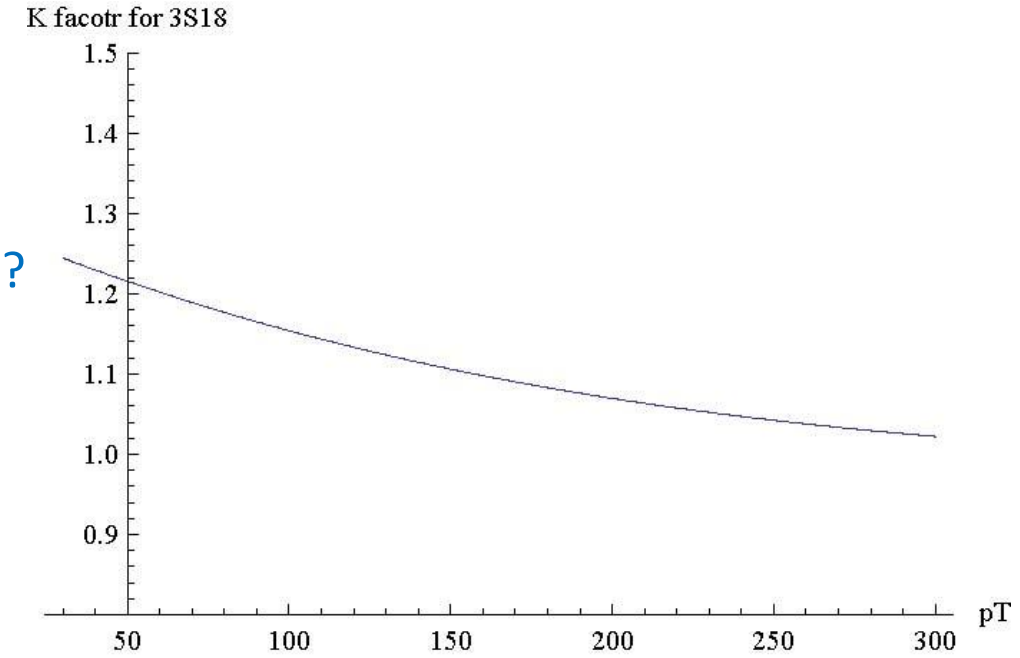
Summary

- Kinematic enhancement of NRQCD amplitudes in hadroproduction pT spectrum motivated us to do complete NLO level analysis.
- It seems that all hadroproduction data of J/Ψ, including both polarization and yield, can be consistent described by NRQCD at NLO level.
- But S-wave and P-wave cancellation is needed (fine tunning?).
- There is still no consistent solution between NRQCD factorization, hadroproduction (polarization and yield) data, photoproduction data, two-photo production data, BELLE e+e- data at NLO level.
- χcJ polarization at NLO level is also presented.

Back up slides

Comments on the resummations of $\alpha_s \text{Log}\, P_T^2/m_c^2$

Could the resummation of $\alpha_s \text{Log}\, P_T^2/m_c^2$ change the fit of M_1, and thus change our explaination of the yield and polarization of J/ψ production?



Quantitatively, Yes!
Qualitatively, No!

P_T~300GeV, Log P_T^2/m_c^2 ~10

- At NLO and lager p_T, the short distance coefficient of M_1 is dominated by one gluon fragmentation and gives $d\sigma[^3S_1^{[8]}] \sim p_T^{-4}$
- The k-factor of $^3S_1^{[8]}$ channel is small (0.98-1.3) for $5\text{GeV} < p_T < 300\text{GeV}$, which means the coefficients of $\alpha_s \text{Log}\, P_T^2/m_c^2(\sim 1)$ is not important. Thus, there should not be significant effects of large p_T resummation for this channel.
- The $^3P_J^{[8]}$ channel at large p_T is also dominated by one gluon fragmenation, so its behavior may be similar to $^3S_1^{[8]}$: resummation is not very important.

M.Butenschon and B.Kniehl's fit

M.Butenschon, B.Kniehl, (2011)

- 1.Use unpolarized data in pp (not include ATLAS and CMS large pT data), γp,γγ and e+e- collisions.
- 2. pT>1 GeV for γp,γγ data and pT>3 GeV for pp. There is only one data for e+e-.

$$\langle O^{J/\Psi}(^1S_0^{[8]})\rangle = (4.97 \pm 0.44) \times 10^{-2} GeV^3, \langle O^{J/\Psi}(^3S_1^{[8]})\rangle = (2.24 \pm 0.59) \times 10^{-3} GeV^3,$$

$$\langle O^{J/\Psi}(^3P_0^{[8]})\rangle = (-1.61 \pm 0.20) \times 10^{-2} GeV^5$$

- 3. After feeddown was included (pp:36%, γp:15%, γγ: 9%, e+e-: 26%),

$$\langle O^{J/\Psi}(^1S_0^{[8]})\rangle = (3.04 \pm 0.35) \times 10^{-2} GeV^3, \langle O^{J/\Psi}(^3S_1^{[8]})\rangle = (1.68 \pm 0.46) \times 10^{-3} GeV^3,$$

$$\langle O^{J/\Psi}(^3P_0^{[8]})\rangle = (-9.08 \pm 1.61) \times 10^{-3} GeV^5$$

fit by GWWZ group

B.Gong, L.-P.Wan,J.-X.Wang, H.-F.Zhang (2012)

- 1.Use unpolarized data and fit central region data by CDF Run II and forward region data by LHCb simultaneously (r0 and r1 in M0 and M1 are slightly different in these two regions!!!).
- 2.pT> 7 GeV.
- 3.Include feeddown from χc and Ψ(2S).

$$\langle O^{J/\Psi}(^1S_0^{[8]})\rangle = 0.097 \pm 0.009 GeV^3, \langle O^{J/\Psi}(^3S_1^{[8]})\rangle = (-0.46 \pm 0.13)\times 10^{-2} GeV^3,$$

$$\langle O^{J/\Psi}(^3P_0^{[8]})\rangle = -0.0214 \pm 0.0056 GeV^5, \langle O^{\Psi'}(^1S_0^{[8]})\rangle = (-0.012 \pm 0.869)\times 10^{-2} GeV^3,$$

$$\langle O^{\Psi'}(^3S_1^{[8]})\rangle = (0.34 \pm 0.12)\times 10^{-2} GeV^3, \langle O^{\Psi'}(^3P_0^{[8]})\rangle = (0.945 \pm 0.54)\times 10^{-2} GeV^5,$$

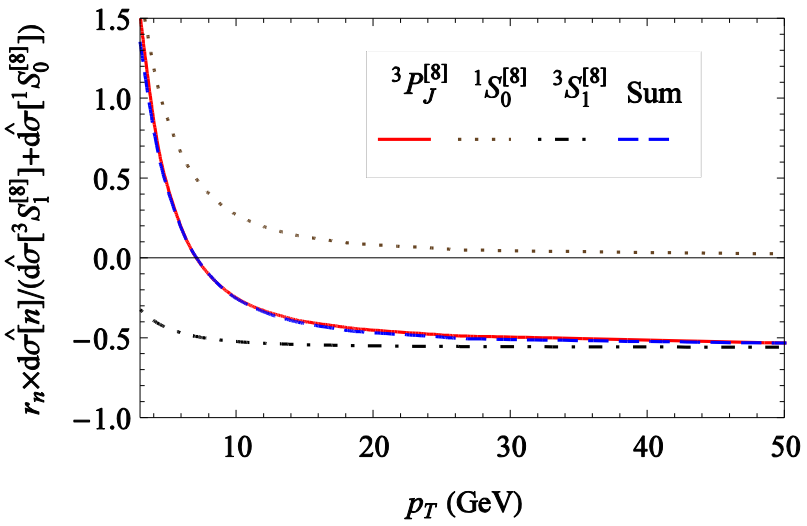
$$\langle O^{c\bar{c}0}(^3S_1^{[8]})\rangle = (0.22 \pm 0.012)\times 10^{-2} GeV^3$$

Cancellation is not sufficient to give an unpolarized prediction.

Decomposition of P-wave channel

- Because of 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 within error of a few percent:

$$d\hat{\sigma}[^3P_J^{[8]}] = r_0\, d\hat{\sigma}[^1S_0^{[8]}] + r_1\, d\hat{\sigma}[^3S_1^{[8]}]$$



NLO short-distance coefficients of $d\hat{\sigma}[^3P_J^{[8]}]$, $r_0\, d\hat{\sigma}[^1S_0^{[8]}]$, $r_1\, d\hat{\sigma}[^3S_1^{[8]}]$ and Sum=$r_0\, d\hat{\sigma}[^1S_0^{[8]}]$+$r_1\, d\hat{\sigma}[^3S_1^{[8]}]$ in Tevatron.

- As a result, we will use two lineal combined LDMEs:

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

$\sqrt{S}$(TeV)	region of y	r_0	r_1
1.96	(0 ,0.6)	3.9	-0.56
7	(0 ,0.75)	4.0	-0.55
7	(0.75,1.50)	3.9	-0.56
7	(1.50,2.25)	3.9	-0.59
7	(0 ,2.4)	4.1	-0.56
7	(0 ,1.2)	4.1	-0.55
7	(1.2,1.6)	3.9	-0.57
7	(1.6,2.4)	3.9	-0.59
7	(2.5, 4)	3.9	-0.66
7	(2 ,2.5)	4.0	-0.61
7	(2.5, 3)	4.0	-0.65
7	(3 ,3.5)	4.0	-0.68
7	(3.5, 4)	4.0	-0.74
7	(4 ,4.5)	4.2	-0.81
14	(0 , 3)	3.9	-0.57
0.2	(0 , 0.35)	3.8	-0.60
0.2	(1.2 , 2.4)	4.0	-0.66

Uncertainty: decomposition (1)

$$d\hat{\sigma}[^3P_J^{[8]}] = r_0\, d\hat{\sigma}[^1S_0^{[8]}] + r_1\, d\hat{\sigma}[^3S_1^{[8]}]$$

- Two errors induced by decomposing the P-wave channel:
  1) The decomposition has an error of a few percent;
  2) The resulted r_0 and r_1 vary for different experimental condition.
- The above uncertainties can be determined by using three unconstrained LDMEs to fit data (*we thank G. Bodwin for pointing out this*). Choosing p_T^{cut}=7GeV and by minimizing χ^2 we get:

$$O_1 \equiv \langle \mathcal{O}^{J/\psi}(^1S_0^{[8]}) \rangle = \quad 15.7 \times 10^{-2} GeV^3 (\pm 129\%)$$
$$O_2 \equiv \langle \mathcal{O}^{J/\psi}(^3S_1^{[8]}) \rangle = -1.18 \times 10^{-2} GeV^3 (\pm 249\%)$$
$$O_3 \equiv \frac{\langle \mathcal{O}^{J/\psi}(^3P_0^{[8]}) \rangle}{m_c^2} = -2.28 \times 10^{-2} GeV^3 (\pm 239\%)$$

- These LDMEs are obviously unphysically determined. Physical variables are eigenvectors of correlation matrix, which corresponds to linear combinations of these LDMEs:

$$\begin{pmatrix} \Lambda_1 \\ \Lambda_2 \\ \Lambda_3 \end{pmatrix} = \begin{pmatrix} 0.96 & -0.14 & -0.26 \\ 0.29 & 0.31 & 0.91 \\ 0.047 & 0.94 & -0.33 \end{pmatrix} \begin{pmatrix} O_1 \\ O_2 \\ O_3 \end{pmatrix} = \begin{pmatrix} 15.8 \pm 134\% \\ 2.11 \pm 5.13\% \\ 0.39 \pm 2.45\% \end{pmatrix} \times 10^{-2} GeV^3$$

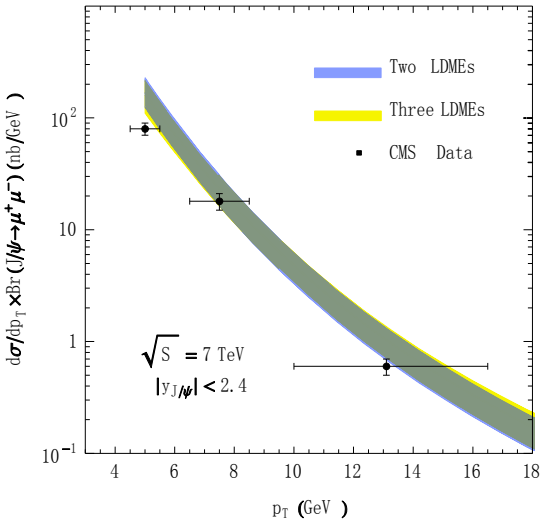
Comparison:

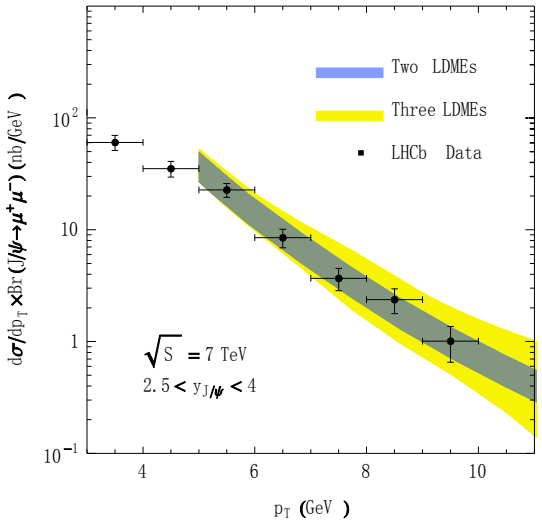
$$\vec{\mathbf{v}}_{\mathrm{M}_0} = (0.25 \quad 0 \quad 0.97)$$
$$\vec{\mathbf{v}}_{\mathrm{M}_1} = (0 \quad 0.87 \quad -0.48)$$

$M_{0,r_0}^{J/\psi}$ and $M_{1,r_1}^{J/\psi}$ are approximately equivalent to the two well constrained LDMEs:

$$\Lambda_2 \leftrightarrow \mathrm{M}_0$$
$$\Lambda_3 \leftrightarrow \mathrm{M}_1$$

Uncertainty: decomposition (2)





- Predictions between using two LDMEs method and three LDMEs implies:
  1) In central region, two methods give almost the same error bar;
  2) In forward region, three LDMEs method has larger error bar, which means two LDMEs method may underestimates its theoretical uncertainty. (It is interesting to note that the data still seems to locate within the error bar of two LDMEs method predictions.)
- Reason: r_i have small differences between CMS and CDF, but larger difference between LHCb and CDF.
- **It is possible to determine all three LDMEs when data in forward region are sufficient enough!**

Uncertainty: p_T^{cut}

- In the fit procedure, we abandon data with p_T<7GeV, **which is essential in our work**. There are various reasons for this p_T cut:

✓ Theoretically:

(1) Small p_T region is dominated by non-perturbative effect because of initial state gluon showers (*Berger, Qiu, Wang, PRD 2005*).

(2) NRQCD factorization is still not proven. But for large p_T region, it was found the factorization holds up to $O(m^4/p_T^4)$ correction (*Kang, Qiu, Sterman, PRL 2011*). So data in large p_T are more confident to describe.

✓ Experimentally: In the plot, the curvature of data curve is positive at large p_T but negative at small p_T, with a turning point at $p_T \approx 6\ GeV$. Thus data below 7GeV cannot be described by perturbative factorization theory.

✓ Fit: We perform a χ^2 analysis for J/ψ, and find χ^2/d.o.f. decreases rapidly as the cut increases from 3GeV to 7GeV, and then it almost unchanges when the cut becomes larger:

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

Comparing with BK's work

- Butenschön and Kniehl (BK) do a similar work for J/ ψ production differences from ours include:
  1) BK use both Tevatron data (p_T^{cut}=3GeV) and HERA data (p_T^{cut}=1GeV) ;
  2) BK neglect the feeddown contribution;
  3) BK determine all three CO LDMEs.
- To take advantage of their results, we also neglect feeddown contribution and using three LDMEs to fit (because these choices do not change final results qualitatively, as discussed above), but we still use only Tevatron data with p_T^{cut}=7GeV.

BK's results (errors may be smaller than 10%):

$$M_{0,r_0}^{J/\psi} = 2.47 \times 10^{-2} GeV^3$$
$$M_{1,r_1}^{J/\psi} = 0.594 \times 10^{-2} GeV^3$$

Our results:

$$M_{0,r_0}^{J/\psi} = 8.54 \times 10^{-2} GeV^3 (\pm 12\%)$$
$$M_{1,r_1}^{J/\psi} = 0.167 \times 10^{-2} GeV^3 (\pm 63\%)$$

- $M_{0,r_0}^{J/\psi}$ is well constrained in both two groups, but two results are different significantly. Only difference: using different data!!!

★ Observation: **perturbative NRQCD factorization cannot give a consistent description of both** Tevatron data ($7GeV > p_T > 3GeV$) + HERA data ($p_T > 1GeV$) and Tevatron data ($p_T > 7GeV$).

χc Polarization

normalized multipole amplitudes

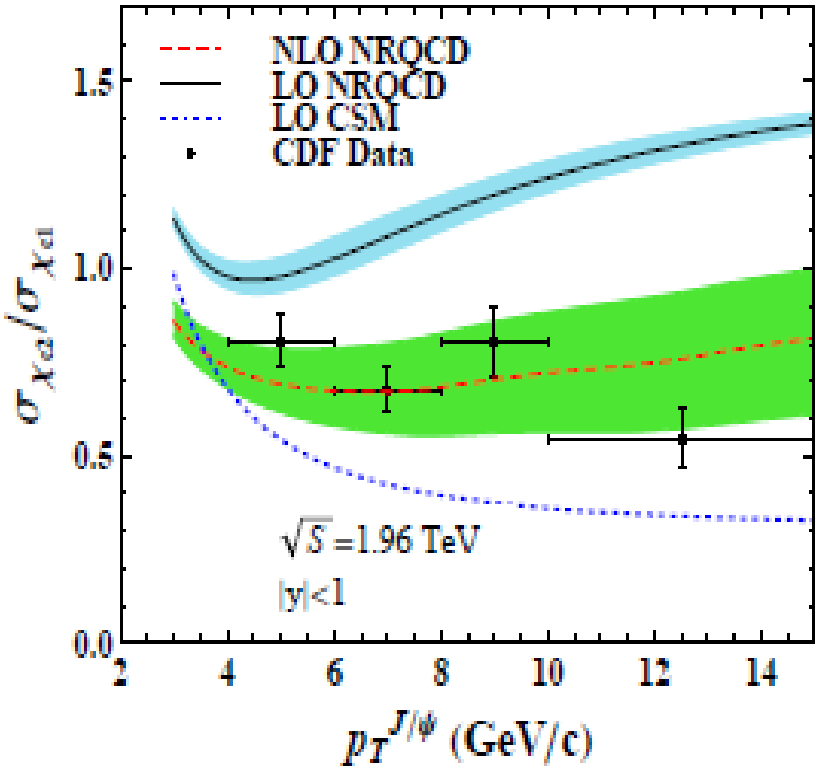
Experiment	$a_2^{J=1}(10^{-2})$
CLEO[26]	$-6.26 \pm 0.63 \pm 0.24$
Crystal Ball [27]	$-0.2^{+0.8}_{-2.0}$
E835 [29]	$0.2 \pm 3.2 \pm 0.4$

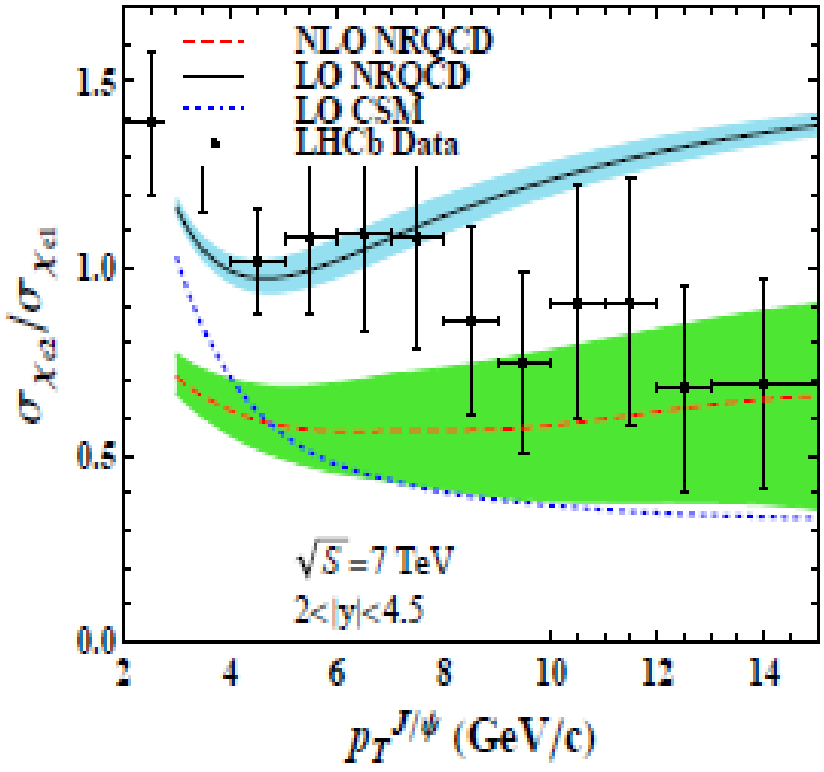
Experiment	$a_2^{J=2}(10^{-2})$	$a_3^{J=2}(10^{-2})$
CLEO(Fit 1)[26]	$-9.3 \pm 1.6 \pm 0.3$	0(fixed)
CLEO(Fit 2)[26]	$-7.9 \pm 1.9 \pm 0.3$	$1.7 \pm 1.4 \pm 0.3$
Crystal Ball [27]	$-33.3^{+11.6}_{-29.2}$	0(fixed)
E760(Fit 1) [28]	-14 ± 6	0(fixed)
E760(Fit 2) [28]	-14^{+8}_{-7}	0^{+6}_{-5}
E835(Fit 1) [29]	$-9.3^{+3.9}_{-4.1} \pm 0.6$	0(fixed)
E835(Fit 2) [29]	$-7.6^{+5.4}_{-5.0} \pm 0.9$	$2.0^{+5.5}_{-4.4} \pm 0.9$

Our choice !

Single quark radiation

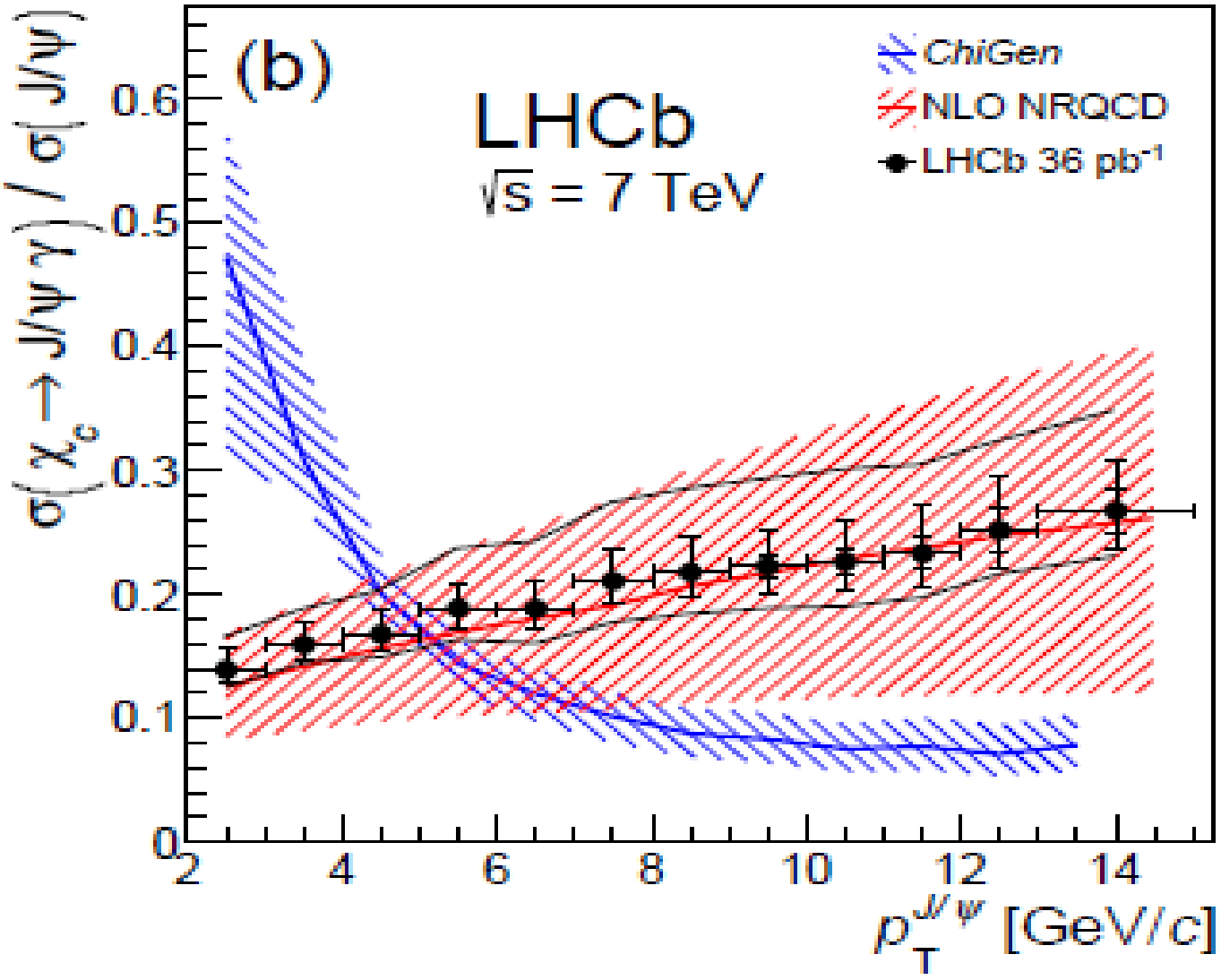
Ratio and LDMEs





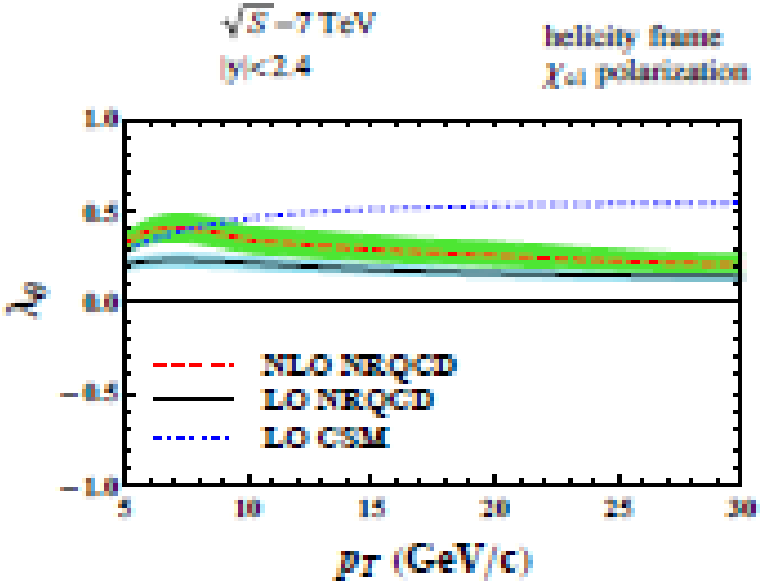
$$\langle O^{ccJ}(^3S_1^{[8]})\rangle = (2J+1)\times(2.2^{+0.48}_{-0.32})\times 10^{-3}\,GeV^3$$

$$\langle O^{ccJ}(^3P_J^{[1]})\rangle = (2J+1)\frac{3N_c\,|R'(0)|^2}{2\rho}, |R'(0)|^2 = 0.075\,GeV^5$$



arXiv:1204.1462

XcJ > J/ψ γ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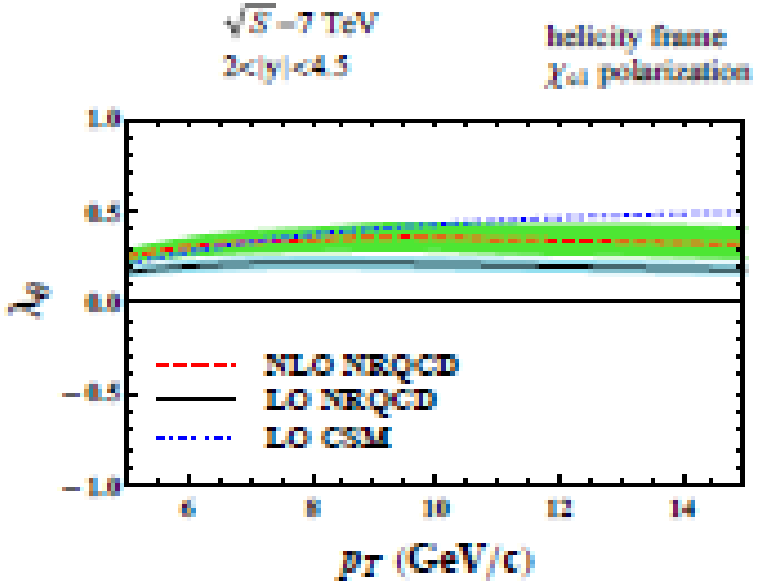
helicity frame
χ_{c1} polarization
NLO NRQCD
LO NRQCD
LO CSM
λ_θ
p_T (GeV/c)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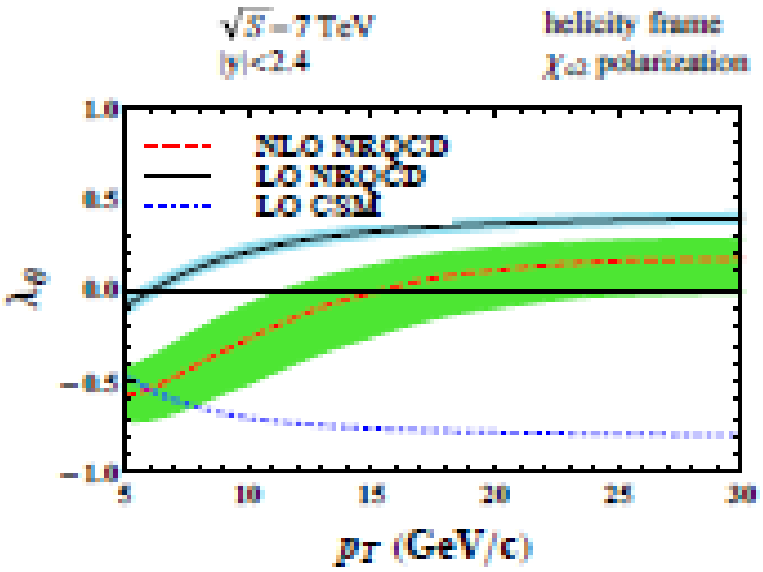
NLO NRQCD
LO NRQCD
LO CSM
λ_θ
p_T (GeV/c)


$\sqrt{S}$ = 7 TeV
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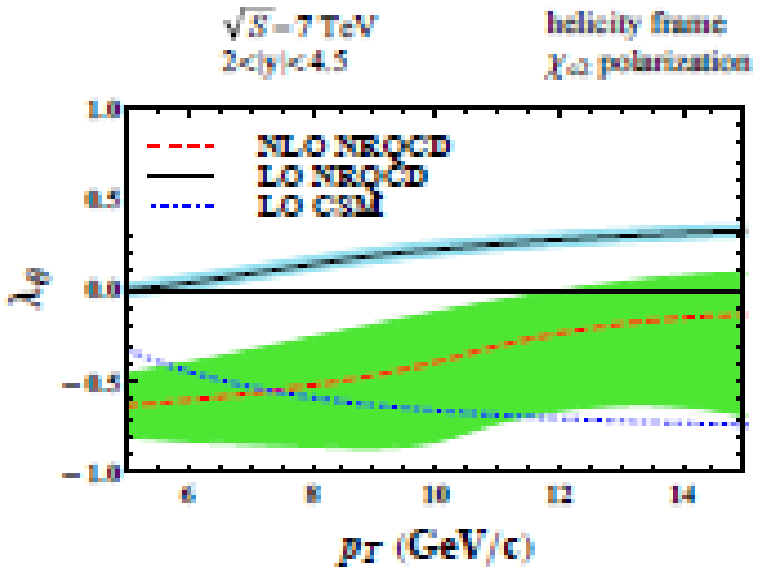
helicity frame
χ_{c2} polarization
NLO NRQCD
LO NRQCD
LO CSM
λ_θ
p_T (GeV/c)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helicity frame
χ_{c2} polarization
NLO NRQCD
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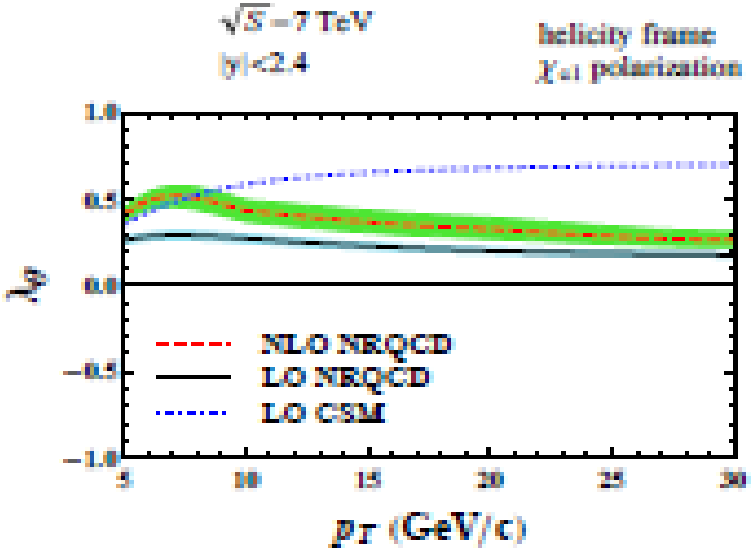
λ_θ
p_T (GeV/c)

XcJ > J/ψ γ > l+ l- γ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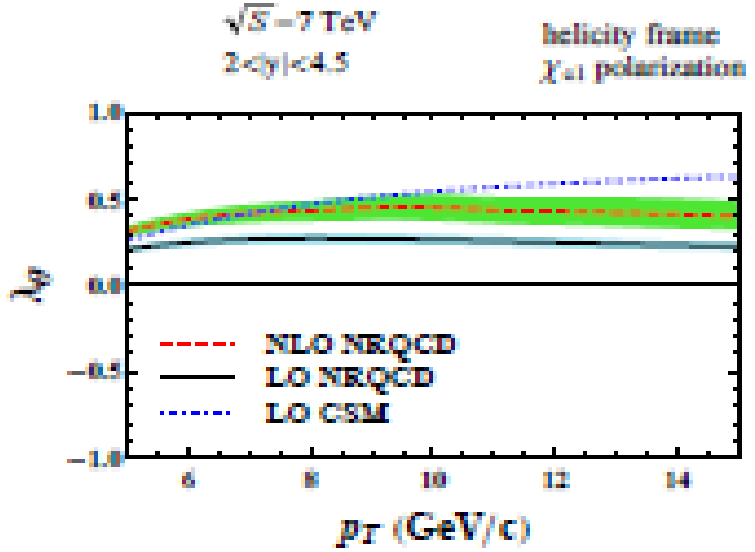
χ_{c1} polarization
NLO NRQCD
LO NRQCD
LO CSM
λ_θ
p_T (GeV/c)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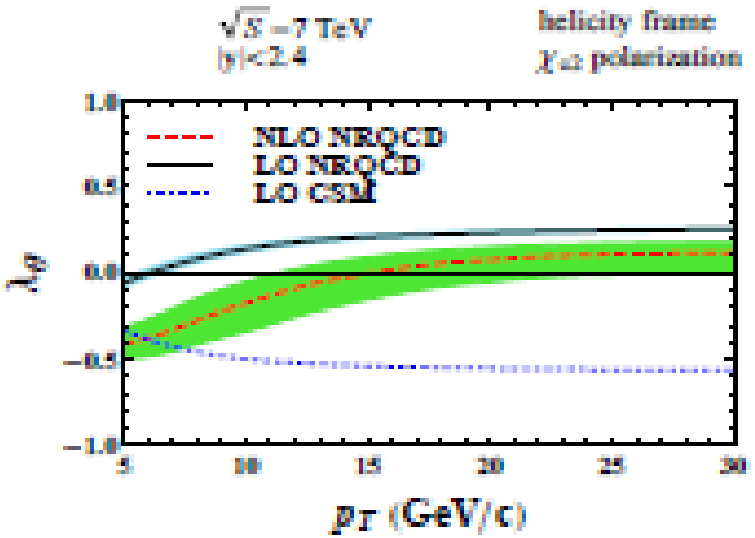
p_T (GeV/c)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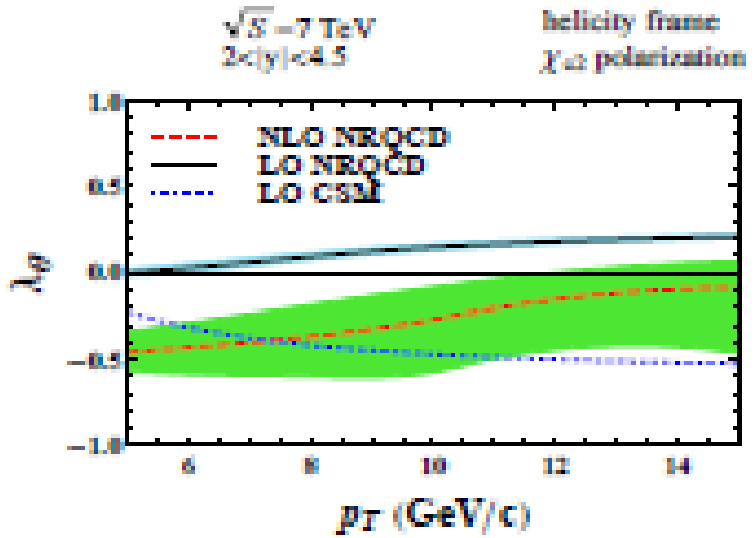
helicity frame
χ_{c2} polarization
NLO NRQCD
LO NRQCD
LO CSM
λ_θ
p_T (GeV/c)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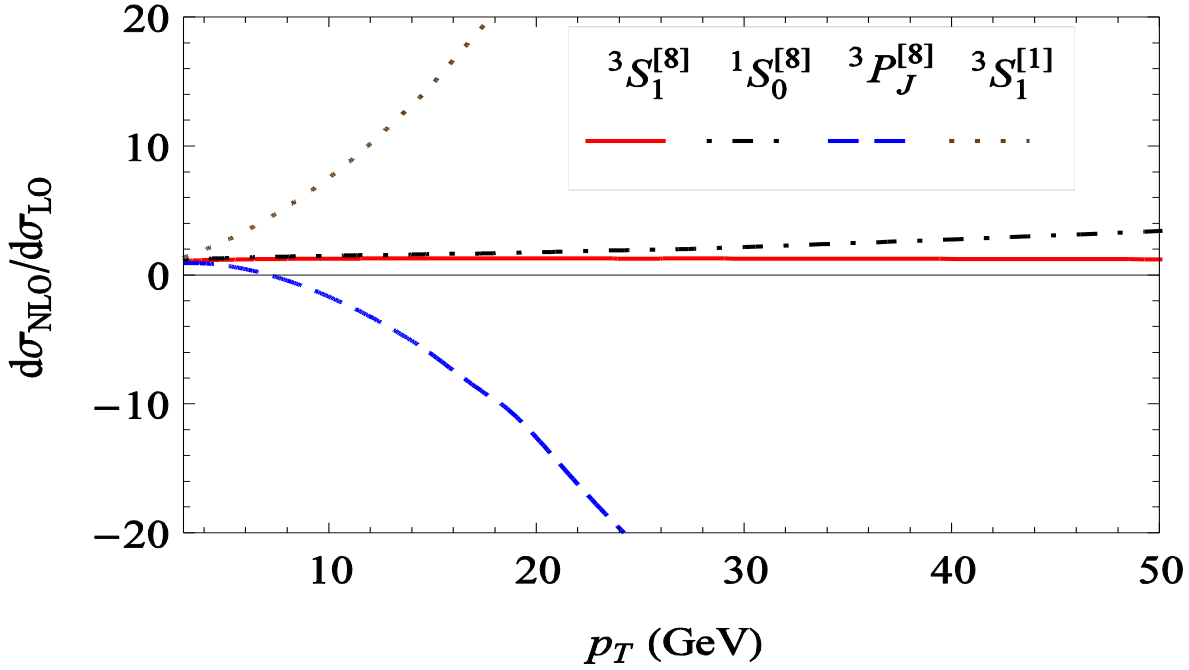
2<|y|<4.5
helicity frame
χ_{c2} polarization
NLO NRQCD
LO NRQCD
LO CSM
λ_θ
p_T (GeV/c)

K factor of short distance coefficient



Ma, Wang, Chao, (2011)