Probing Heavy Quarkonium Production Mechanism: χ_c Polarization

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Phys. Rev. Lett. 112, 182003 (2014)
Phys. Rev. D 90, 014002 (2014)
2014.09.11

OPENING WORDS

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- Do we understand QCD ?
  - Perturbative: yes !
  - Non-perturbative: no !
  - Heavy Quarkonium plays the role at the interplay between perturbative regime and non-perturbative regime.

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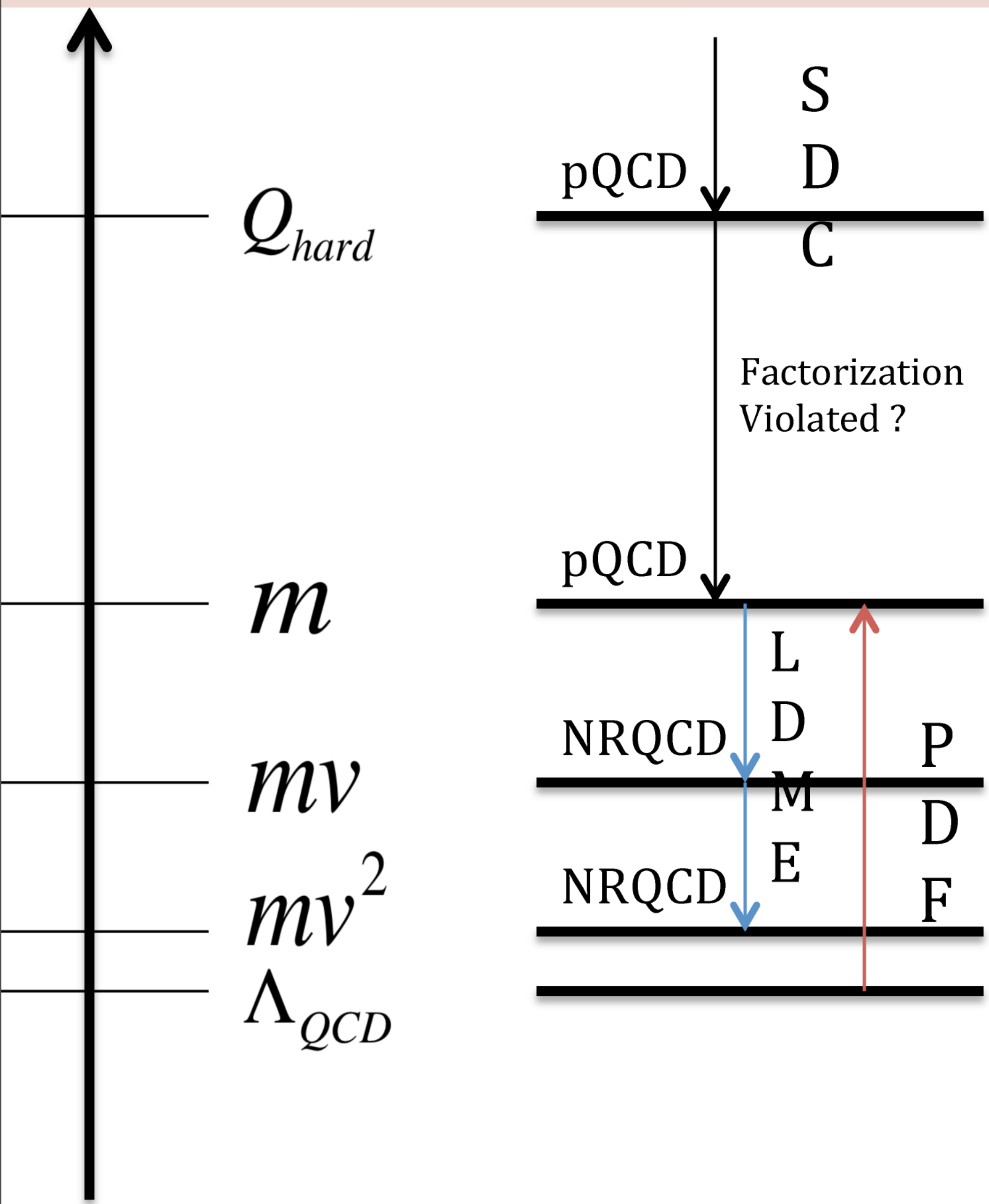
  - Heavy Quarkonium plays the role at the interplay between perturbative regime and non-perturbative regime.

BACKGROUND

- Heavy quarkonium
  - bound state with a heavy-flavor quark pair
  - color-singlet meson
  - the relative velocity of the quark pair is small
    - $v^2 \approx 0.3$ for charmonium
    - $v^2 \approx 0.1$ for bottomonium

BACKGROUND

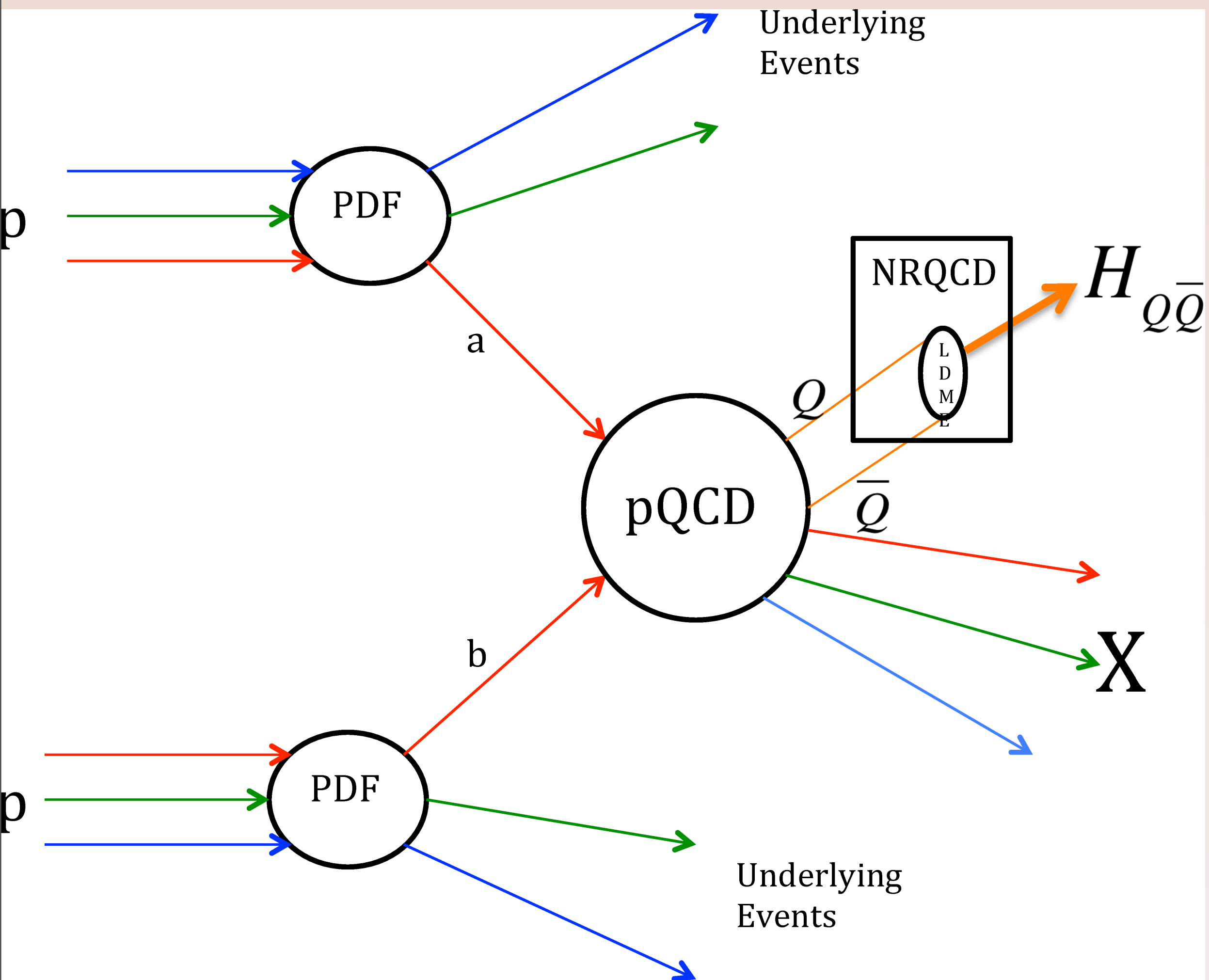


- Heavy quarkonium production is a multi-scale process:
  - Q_{hard} : scale at which a heavy-flavor quark pair is generated.
  - m : mass of heavy quarks.
  - mv : relative momentum of a heavy quark in the rest frame of heavy quarkonium.
  - mv^2:binding energy of heavy quarkonium.
  - Λ_{QCD} :intrinsic QCD scale

MODELS

- Color-Singlet Model (CSM) [Einhor, Ellis (1975) ...]
  - $Q\bar{Q}$ are produced in the CS state at scale Q_{hard}.
- Color-Evaporation Model (CEM) [Fritzsch (1977) ...]
  - Under quark-hadron duality, $Q\bar{Q}$ are produced with their invariant mass less than the threshold of open-flavor heavy meson pair.
- Fragmentation Function Approach (FF) [Braaten et al. (1996) ...]
  - Cross section can be factorized in terms of convolutions of parton production cross section with FFs in limit of $p_T \gg m$.
- Non-relativistic QCD (NRQCD) [Bodwin et al. (1995)]
  - An effective field theory based on factorization conjecture. $Q\bar{Q}$ can be produced in both of CS and CO states at scale Q_{hard}.

NRQCD FACTORIZATION



- NRQCD factorization

$$d\sigma(pp \to H_{Q\bar{Q}} + X)$$
$$= \sum_n d\sigma(pp \to Q\bar{Q}[n] + X) \times \langle \mathcal{O}^{H_{Q\bar{Q}}}(n) \rangle$$

- pQCD factorization

$$d\sigma(pp \to Q\bar{Q}[n] + X)$$
$$= \sum_{a,b} f_{a/p}(x_1) f_{b/p}(x_2) |\mathcal{A}(ab \to Q\bar{Q}[n] + X)|$$

- LDME $\langle \mathcal{O}^{H_{Q\bar{Q}}}(n) \rangle$ and PDF $f_{i/p}(x)$ are non-perturbative.

POWER COUNTING

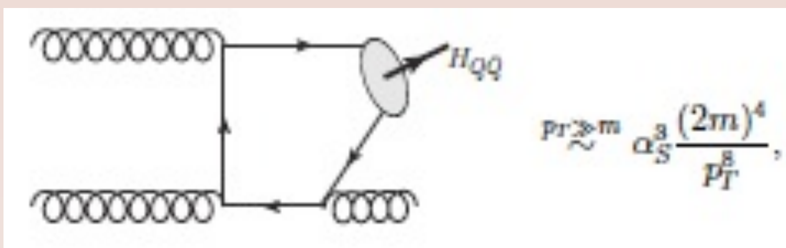
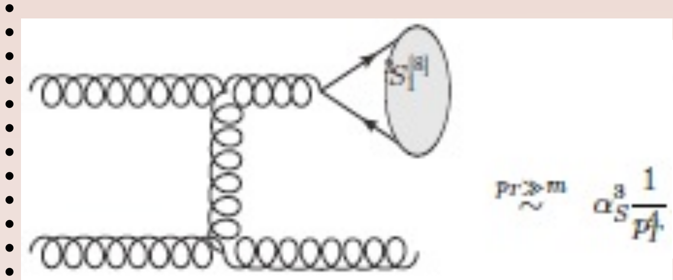
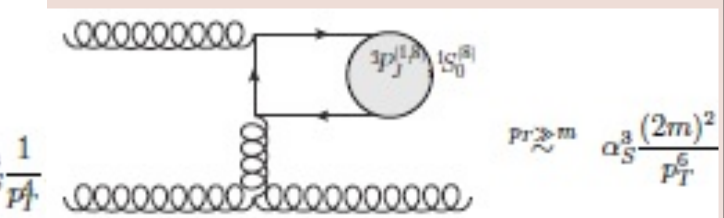
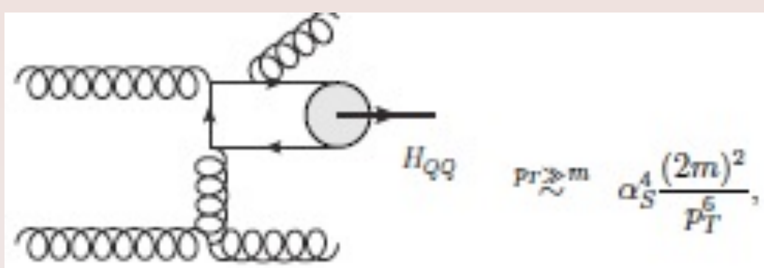
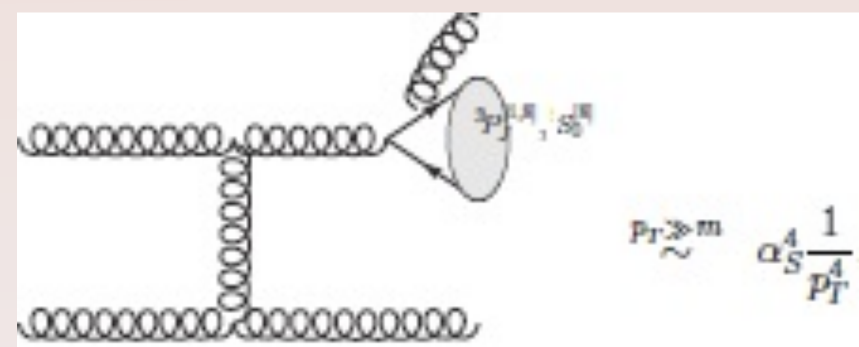
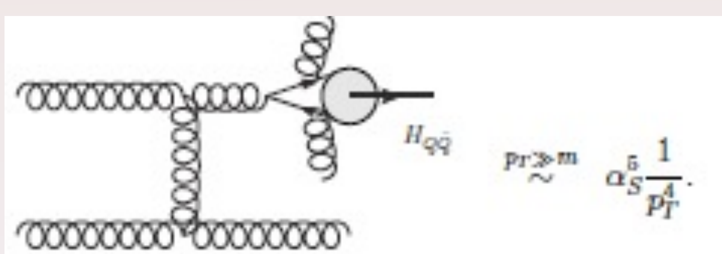
- Number of Fock states n= ${}^{(2S+1)}L_J^{[c]}$ is infinity but scaling in v. A practical perturbative calculation always truncates it at a specific order.
- Some examples in the following table

Power counting	η_c, η_b	$J/\psi, \psi(2S), \Upsilon$	h_c, h_b	χ_{cJ}, χ_{bJ}
v^3	${}^1S_0^{[1]}$	${}^3S_1^{[1]}$	—	—
v^5	—	—	${}^1P_1^{[1]}, {}^1S_0^{[8]}$	${}^3P_J^{[1]}, {}^3S_1^{[8]}$
v^7	${}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^1P_1^{[8]}$	${}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_J^{[8]}$	—	—

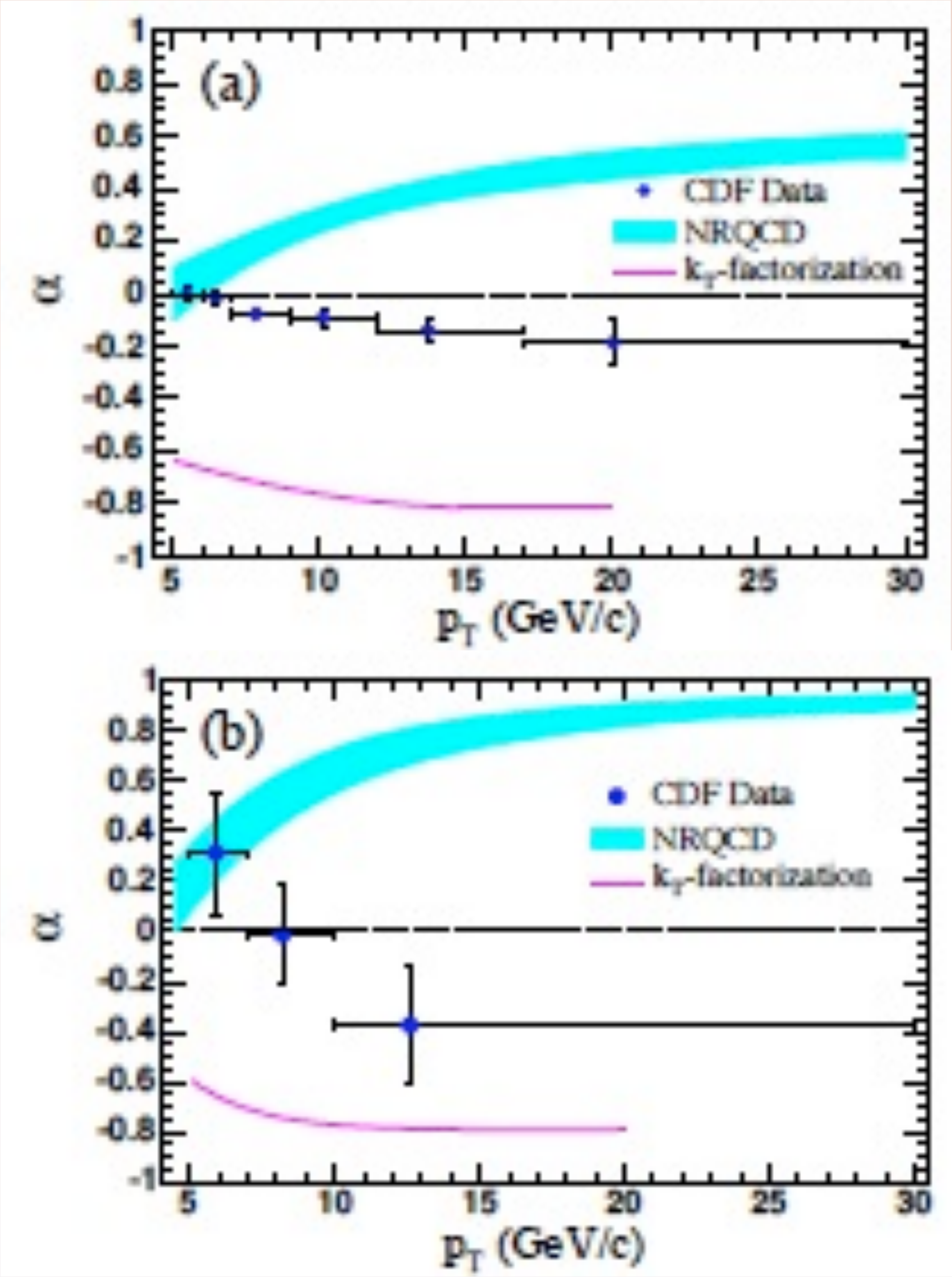
CHALLENGES IN NRQCD

- Lacking proof of NRQCD factorization conjecture.
- Very large higher-order corrections.
- NRQCD confronts experiments.

NEW TOPOLOGIES AT HO ONLY

	CSM	COM
LO		 
NLO		
NNLO		

CDF Collaboration (2007)



- NRQCD confronts various heavy quarkonium experimental data, include $pp, p\bar{p}, e^+e^-, \gamma p, \gamma\gamma, e^-p, pA, AA$,collisions.
- At low scale $Q_{hard} \sim m$ production (like integrated-p_T cross section in hadroproduction,B factories data [HSS (2014)]), CSM seems to be already fine to describe the data.
- At high scale$Q_{hard} \gg m$ quarkonium production (like high-p_T data at Tevatron and LHC), COM seems to be necessary especially for polarisation.

J/ψ CASE

- CSM cannot explain the yields and polarization (up to NNLO*).
  [Campbell, Maltoni, Tramontano (2007); Artoisenet, Lansberg, Maltoni (2007)]

- In NRQCD, there are three leading CO LDMEs should be tuned to data. However, the current hadroproduction experimental data are not sufficient to determine the three CO LDMEs (which means that most of these data are correlated). Other experimental data are most likely in the small momentum transfer region, where the factorization may be unreliable. [Chao, Ma, HSS, Wang, Zhang (2012); Bodwin, Chung, Km, Lee (2014);Faccioli, Knunz, Lourenco, Seixas, Wohri (2014)]

- It receives substantial smearing from feed-down contribution $(\chi_c, \psi(2S))$.

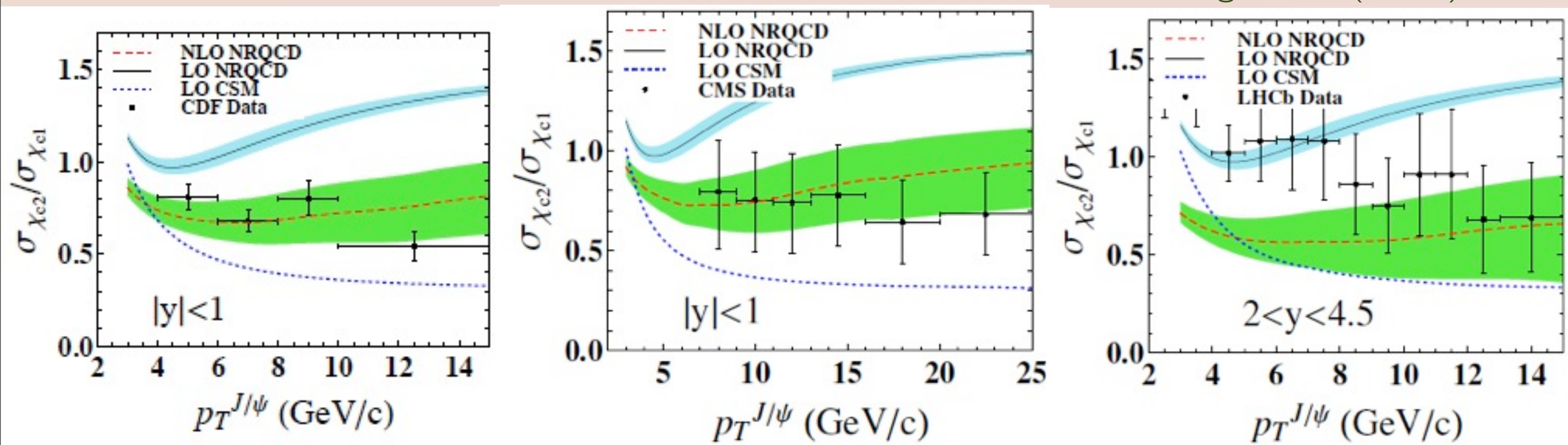
WHY χ_c ?

- CSM has the problem of canceling IR divergence. The only way to treat it perturbatively is by introducing a CO contribution to cancel the IR div, which is naturally guaranteed in NRQCD.
- In contrast to J/ψ, there is only ONE leading CO LDME should be determined from data in χ_c.
- No significant feed-down contribution in prompt χ_c production.
- Lesson from J/ψ case : the polarization may be sensitive to the value of the CO LDME, i.e. its CO production mechanism.

PROCEED TO NLO LEVEL

Yields of prompt χ_c in hadroproduction

HSS,Ma,Wang,Chao (2014)



- Fit the Tevatron data of $\sigma_{\chi_{c2}}/\sigma_{\chi_{c1}}$ to extract CO LDME.
- Good agreement achieved with LHC data.

PROCEED TO NLO LEVEL

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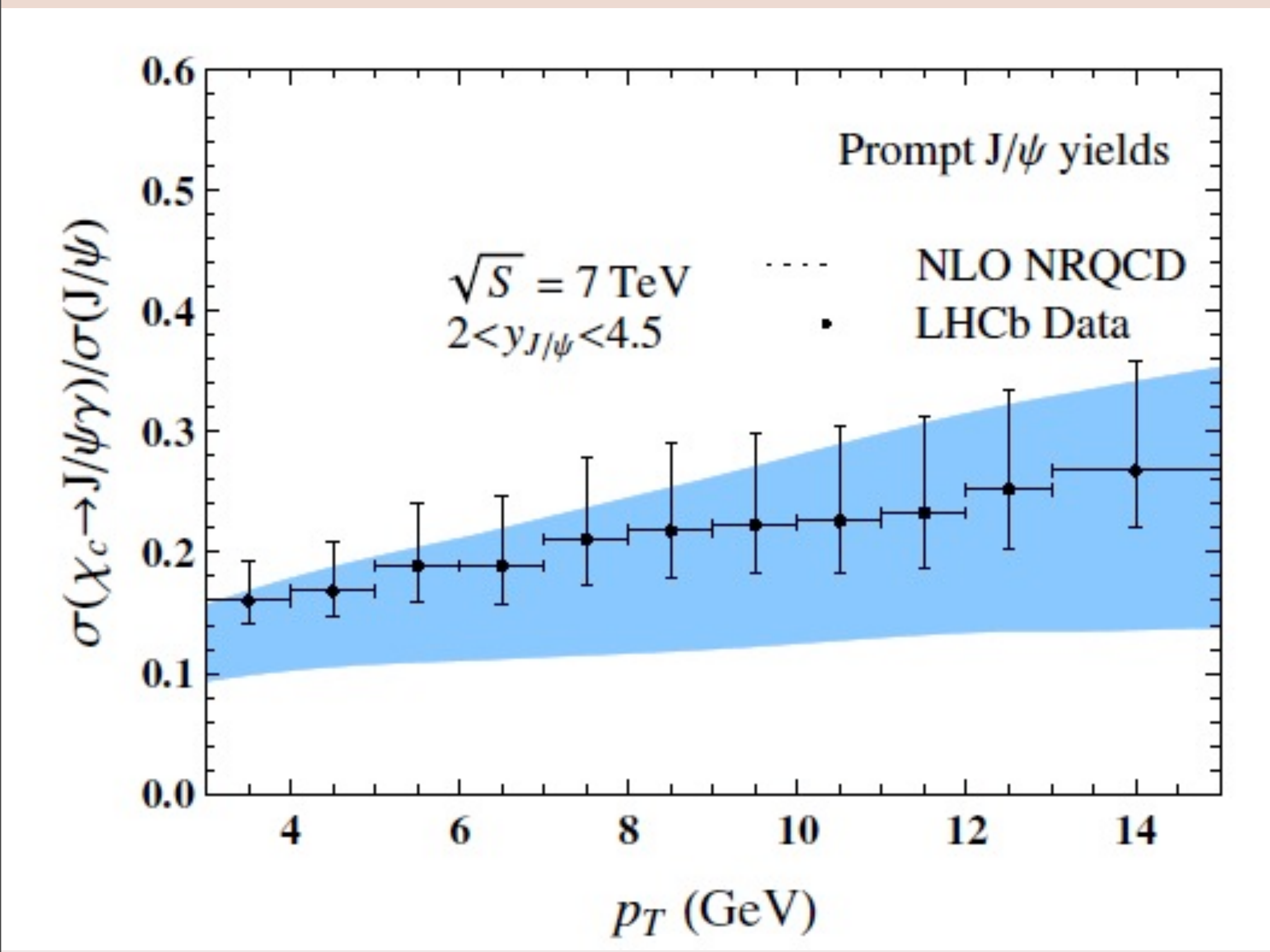

- Also predicts a very good feed-down ratio for prompt J/ψ production compared with LHCb data.

LHCb Collaboration (2012)

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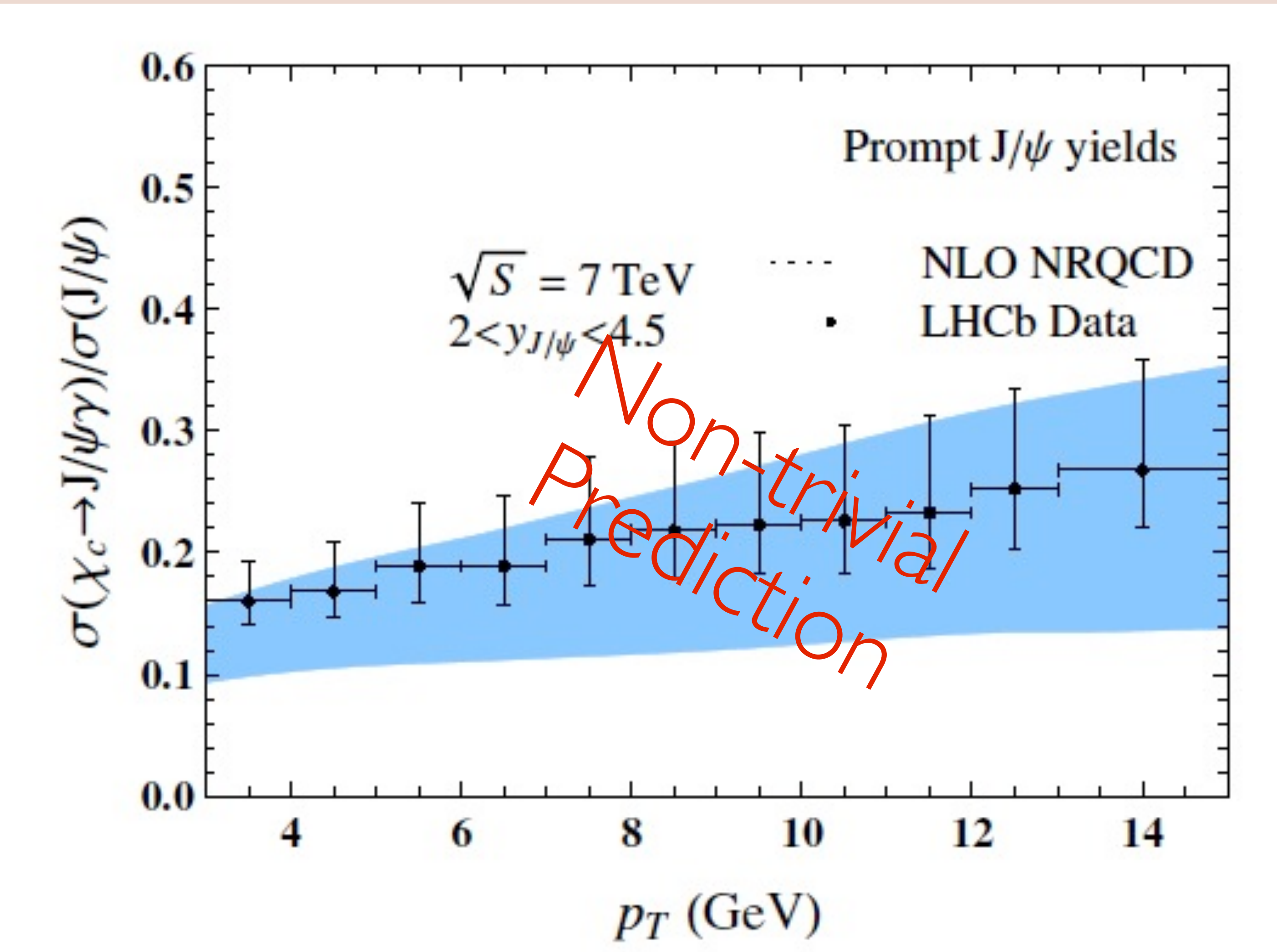

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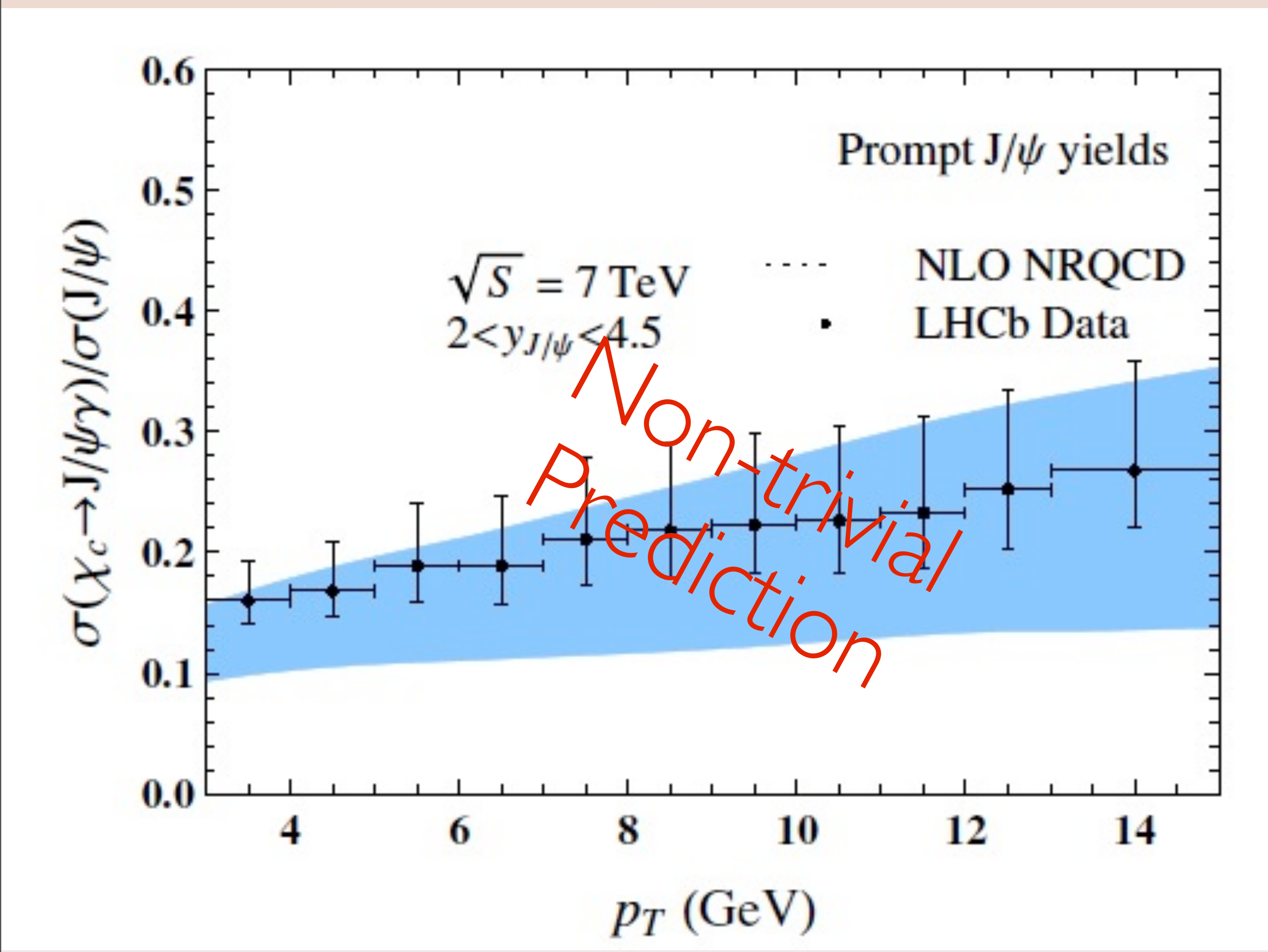

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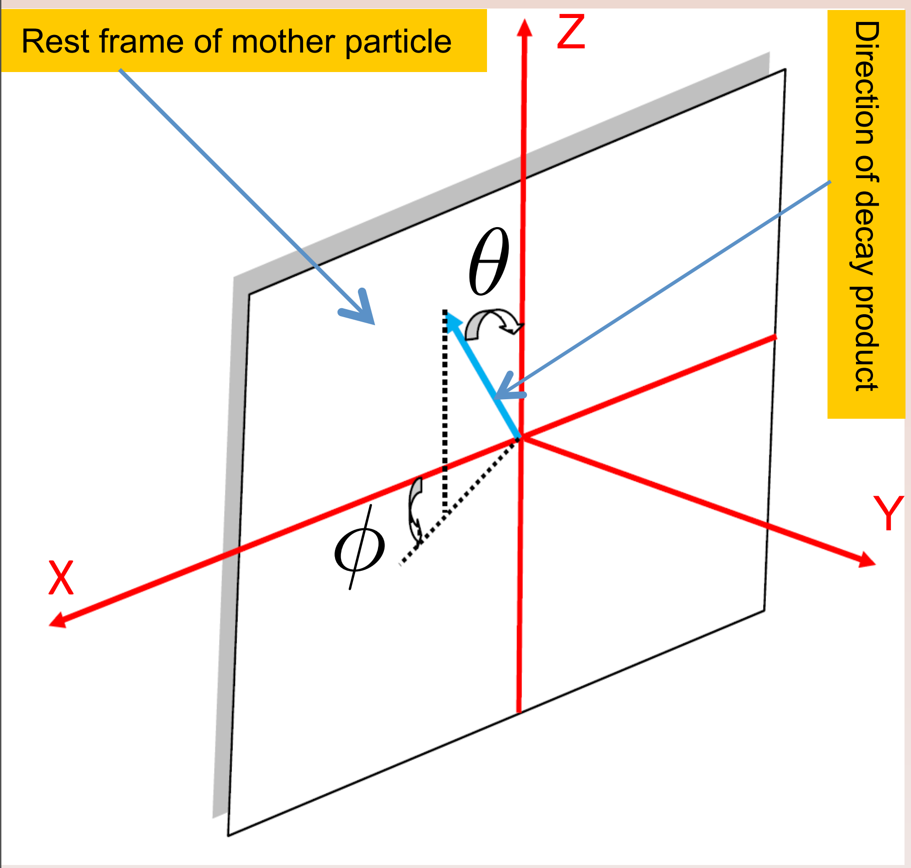
How about polarization ?

ANGULAR DISTRIBUTION I

Kniehl, Kramer, Palisoc(2003); Faccioli, Lourenco, Seixas, Wohri (2011); HSS, Chao (2012)



$$\chi_{cJ} \to J/\psi + \gamma$$

$$\frac{\mathrm{d}\mathcal{N}^{\chi_{cJ}}}{\mathrm{d}\cos\theta} \propto 1 + \sum_{k=1}^{J} \lambda_{k\theta} \cos^{2k}\theta$$

$$\chi_{c1} \to J/\psi + \gamma$$

$$\lambda_\theta = (1-3\delta)\frac{N_{\chi_{c1}} - 3\rho^{\chi_{c1}}_{0,0}}{(1+\delta)N_{\chi_{c1}} + (1-3\delta)\rho^{\chi_{c1}}_{0,0}}$$

$$N_{\chi_{c1}} \equiv \rho^{\chi_{c1}}_{1,1} + \rho^{\chi_{c1}}_{0,0} + \rho^{\chi_{c1}}_{-1,-1}$$

$$\delta = (1 + 2a_1^{J=1}a_2^{J=1})/2$$

$$\chi_{c2} \to J/\psi + \gamma$$

$$\lambda_\theta = 6[(1-3\delta_0-\delta_1)N_{\chi_{c2}} - (1-7\delta_0+\delta_1)(\rho^{\chi_{c2}}_{1,1} + \rho^{\chi_{c2}}_{-1,-1}) - (3-\delta_0-7\delta_1)\rho^{\chi_{c2}}_{0,0}]/R,$$

$$\lambda_{2\theta} = (1+5\delta_0-5\delta_1)[N_{\chi_{c2}} - 5(\rho^{\chi_{c2}}_{1,1} + \rho^{\chi_{c2}}_{-1,-1}) + 5\rho^{\chi_{c2}}_{0,0}]/R$$

$$N_{\chi_{c2}} \equiv \rho^{\chi_{c2}}_{2,2} + \rho^{\chi_{c2}}_{1,1} + \rho^{\chi_{c2}}_{0,0} + \rho^{\chi_{c2}}_{-1,-1} + \rho^{\chi_{c2}}_{-2,-2},$$

$$R \equiv (1+5\delta_0+3\delta_1)N_{\chi_{c2}} + 3(1-3\delta_0-\delta_1)(\rho^{\chi_{c2}}_{1,1} + \rho^{\chi_{c2}}_{-1,-1}) + (5-7\delta_0-9\delta_1)\rho^{\chi_{c2}}_{0,0}$$

$$\delta_0 = [1 + 2a_1^{J=2}(\sqrt{5}a_2^{J=2} + 2a_3^{J=2}) + 4a_2^{J=2}(a_2^{J=2} + \sqrt{5}a_3^{J=2}) + 3(a_3^{J=2})^2]/10,$$

$$\delta_1 = [9 + 6a_1^{J=2}(\sqrt{5}a_2^{J=2} - 4a_3^{J=2}) - 4a_2^{J=2}(a_2^{J=2} + 2\sqrt{5}a_3^{J=2}) + 7(a_3^{J=2})^2]/30$$

ANGULAR DISTRIBUTION I

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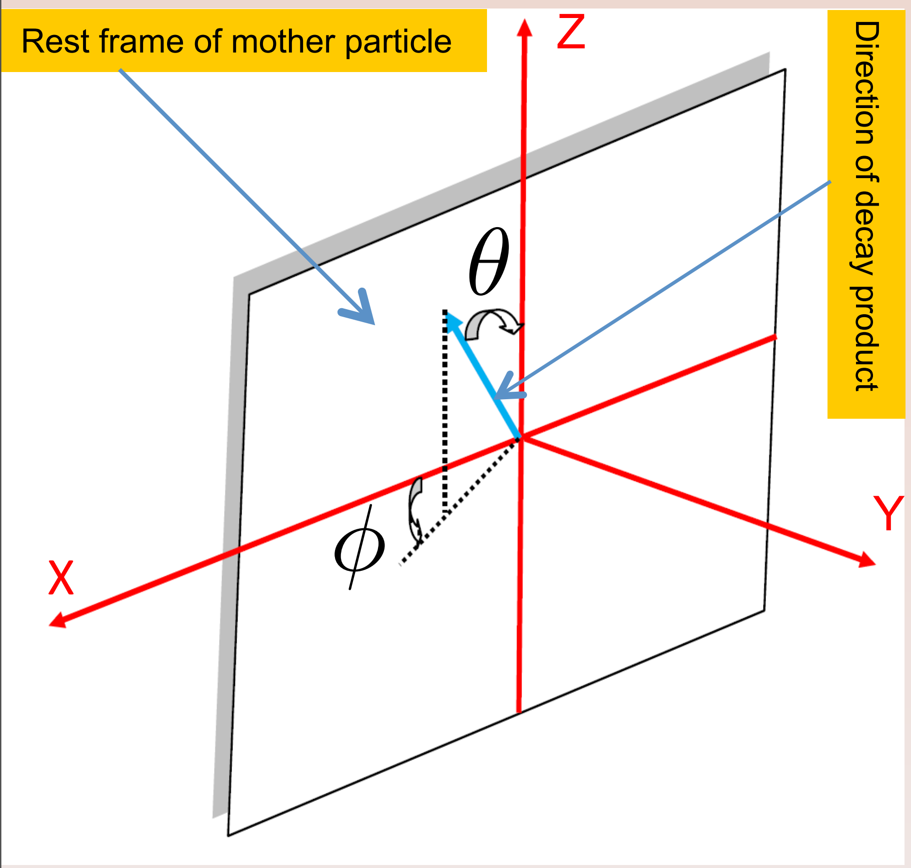

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$$N_{\chi_{c1}} \equiv \rho_{1,1}^{\chi_{c1}} + \rho_{0,0}^{\chi_{c1}} + \rho_{-1,-1}^{\chi_{c1}}$$

$$\delta = (1 + 2a_1^{J=1}a_2^{J=1})/2$$

E1, M2, E3

$$\chi_{c2} \to J/\psi + \gamma$$

$$\lambda_\theta = 6[(1-3\delta_0-\delta_1)N_{\chi_{c2}} - (1-7\delta_0+\delta_1)(\rho_{1,1}^{\chi_{c2}} + \rho_{-1,-1}^{\chi_{c2}}) - (3-\delta_0-7\delta_1)\rho_{0,0}^{\chi_{c2}}]/R,$$

$$\lambda_{2\theta} = (1+5\delta_0-5\delta_1)[N_{\chi_{c2}} - 5(\rho_{1,1}^{\chi_{c2}} + \rho_{-1,-1}^{\chi_{c2}}) + 5\rho_{0,0}^{\chi_{c2}}]/R$$

$$N_{\chi_{c2}} \equiv \rho_{2,2}^{\chi_{c2}} + \rho_{1,1}^{\chi_{c2}} + \rho_{0,0}^{\chi_{c2}} + \rho_{-1,-1}^{\chi_{c2}} + \rho_{-2,-2}^{\chi_{c2}},$$

$$R \equiv (1+5\delta_0+3\delta_1)N_{\chi_{c2}} + 3(1-3\delta_0-\delta_1)(\rho_{1,1}^{\chi_{c2}} + \rho_{-1,-1}^{\chi_{c2}}) + (5-7\delta_0-9\delta_1)\rho_{0,0}^{\chi_{c2}}$$

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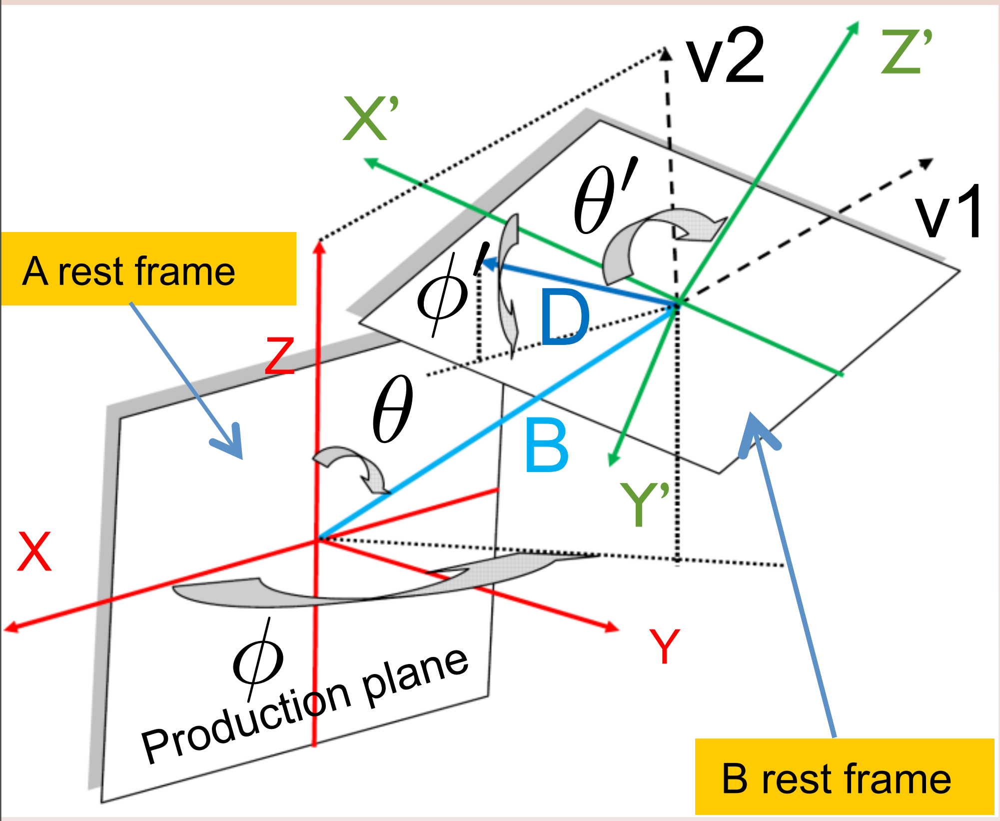
ANGULAR DISTRIBUTION II

Kniehl, Kramer, Palisoc(2003); Faccioli, Lourenco, Seixas, Wohri (2011); HSS, Chao (2012)



$$A \to B(\to D + E) + C$$

$$\chi_{cJ} \to J/\psi(\to \ell^+\ell^-) + \gamma$$

$$\frac{d\mathcal{N}^{\chi_{cJ}}}{d\cos\theta'} \propto 1 + \lambda_{\theta'}\cos^2\theta'$$

$$Z' = v2$$

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$$\lambda_{\theta'} = \frac{-N_{\chi_{c1}} + 3\rho^{\chi_{c1}}_{0,0}}{R_1},$$

$$N_{\chi_{c1}} \equiv \rho^{\chi_{c1}}_{1,1} + \rho^{\chi_{c1}}_{0,0} + \rho^{\chi_{c1}}_{-1,-1}$$

$$R_1 \equiv [(15 - 2(a_2^{J=1})^2)N_{\chi_{c1}}$$
$$-(5 - 6(a_2^{J=1})^2)\rho^{\chi_{c1}}_{0,0}]/(5 - 6(a_2^{J=1})^2)$$

$$\chi_{c2} \to J/\psi(\to \ell^+\ell^-) + \gamma$$

$$\lambda^{\chi_{c2}}_{\theta'} = \frac{6N_{\chi_{c2}} - 9(\rho^{\chi_{c2}}_{1,1} + \rho^{\chi_{c2}}_{-1,-1}) - 12\rho^{\chi_{c2}}_{0,0}}{R_2}$$

$$R_2 \equiv [2(21 + 14(a_2^{J=2})^2 + 5(a_3^{J=2})^2)N_{\chi_{c2}}$$
$$+3(7 - 14(a_2^{J=2})^2 - 5(a_3^{J=2})^2)(\rho^{\chi_{c2}}_{1,1} + \rho^{\chi_{c2}}_{-1,-1})$$
$$+4(7 - 14(a_2^{J=2})^2 - 5(a_3^{J=2})^2)\rho^{\chi_{c2}}_{0,0}]$$
$$\div[7 - 14(a_2^{J=2})^2 - 5(a_3^{J=2})^2]$$

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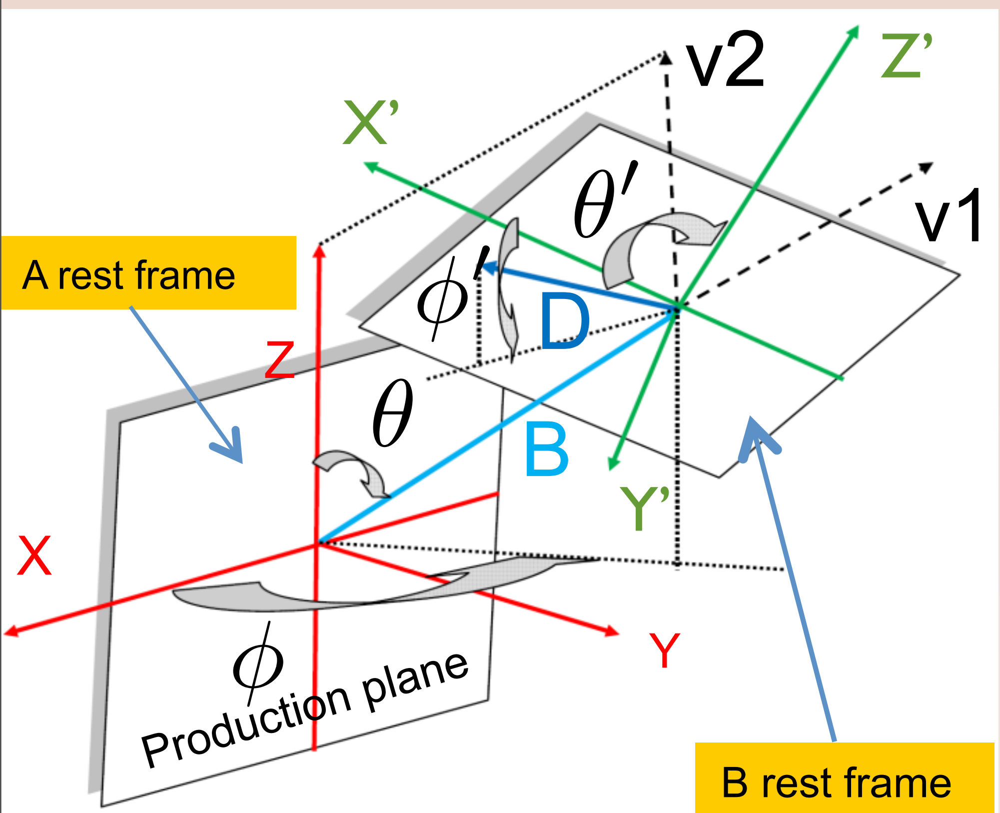

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M2, E3 square

$$R_1 \equiv [(15-2(a_2^{J=1})^2)N_{\chi_{c1}}$$
$$-(5-6(a_2^{J=1})^2)\rho^{\chi_{c1}}_{0,0}]/(5-6(a_2^{J=1})^2)$$

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$$R_2 \equiv [2(21+14(a_2^{J=2})^2+5(a_3^{J=2})^2)N_{\chi_{c2}}$$
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$$+4(7-14(a_2^{J=2})^2-5(a_3^{J=2})^2)\rho^{\chi_{c2}}_{0,0}]$$
$$\div[7-14(a_2^{J=2})^2-5(a_3^{J=2})^2]$$

ANGULAR DISTRIBUTIONS

- J/ψ or γ angular distribution is sensitive to the value of the higher order multipole amplitudes, which are still inconsistent from CLEO, Crystal Ball and E760 measurements. It might be helpful to measure these values from LHC data.

- $\lambda_{2\theta}$ is suppressed by the value of higher order multipole amplitudes. Re-weighting may help to extract it [HSS, Chao (2012)].

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)
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E835(Fit 1) [29]	$-9.3^{+3.9}_{-4.1} \pm 0.6$	0(fixed)
E835(Fit 2) [29]	$-7.6^{+5.4}_{-5.0} \pm 0.9$	$2.0^{+5.5}_{-4.4} \pm 0.9$

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Single quark radiation

ROTATION INVARIANT OBSERVABLES

HSS, Chao (2012)

- Angular distributions (as well as their coefficients) are frame dependent.
- A general relation between Wigner functions guarantees some rational functions of the angular coefficients are rotational invariant in its production plane.
- For an arbitrary integer-spin n particle, a_k (k=-n,...,n) are its polarized amplitudes. One is able to derive the following rotational invariant amplitudes

$$b_{2k} \equiv \sum_{m=-k}^{k} \langle k,m;k,m|2k,2m\rangle a_{2m}, \text{when} \quad n=2k,$$

$$b_{2k+1} \equiv \sum_{m=0}^{k} \langle 2k+1-m,0;m,0|2k+1,0\rangle (a_{2k+1-m}+a_{m-1-2k}), \text{when} \quad n=2k+1$$

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$$b_{2k+1} \equiv \sum_{m=0}^{k} \langle 2k+1-m, 0; m, 0 | 2k+1, 0 \rangle (a_{2k+1-m} + a_{m-1-2k}), \text{when} \quad n = 2k+1$$

Any functions of $|b_n|^2$ and $N_n \equiv \sum_{k=-n}^{n} |a_n|^2$ are rotational invariant

PROCEED TO NLO LEVEL

Polarization of prompt χ_c in hadroproduction

$\chi_c \to J/\psi(\to \ell^+\ell^-) + \gamma$

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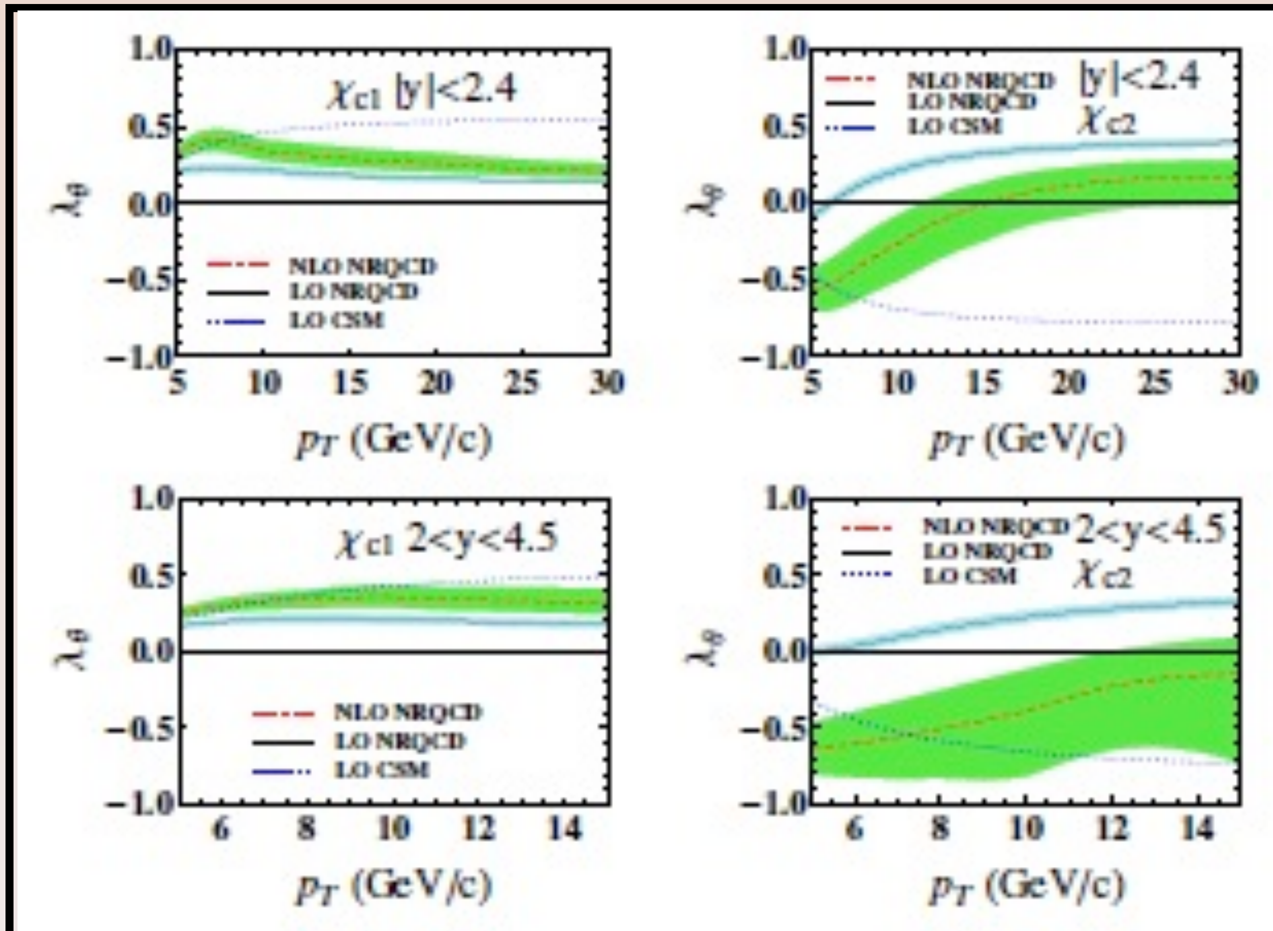
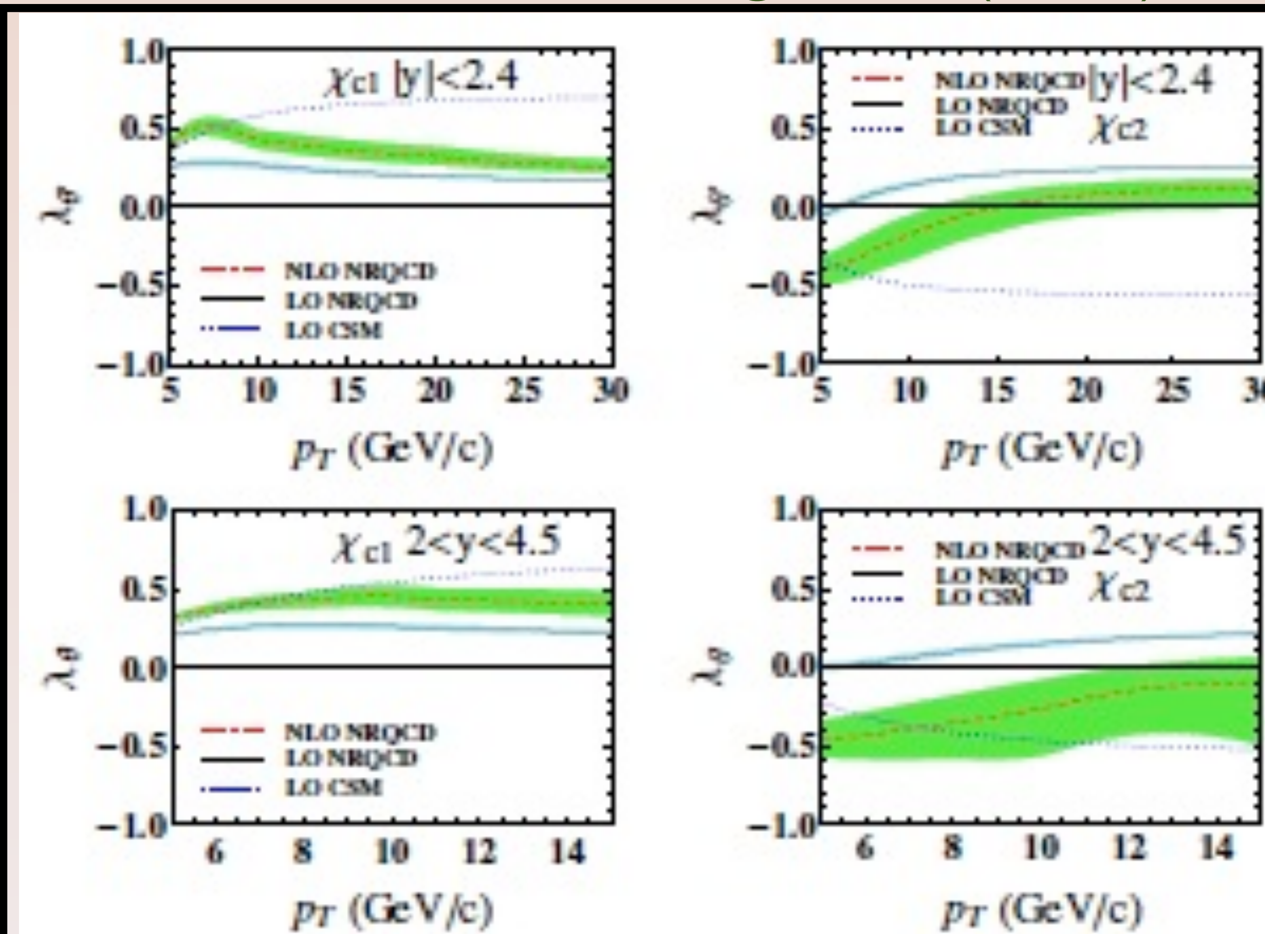


photon angular distribution coefficient



di-lepton angular distribution coefficient

CONCLUSION

- We can understand some features of the non-perturbative QCD through heavy quarkonium production.

- The simultaneously describing the yields and polarization of J/ψ and $\psi(2S)$ require tuning to the experimental data in NRQCD. On the contrast, χ_{cJ} has only ONE CO LDME to be determined from experimental data, i.e. has more predictive power.

- On the theoretical side, many features of the χ_{cJ} polarization have been explored. It may encode rich information about its production mechanism. The NRQCD predictions for the yields and polarization of prompt χ_{cJ} hadroproduction are already available up to NLO in QCD.

- We are looking forward to the future experimental measurements at the LHC on χ_{cJ} polarization to reveal the heavy quarkonium production mechanism.

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Thank you for your attention !