Polarizations Of Chi_c1 And Chi_c2 At The LHC In Non-Relativistic QCD

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CERN, PH-TH

Based On Work In Collaboration With K.-T. Chao, Y.-Q. Ma, And K. Wang

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

2014.11.14

Polarizations Of Heavy Quarkonia At The LHC In Non-Relativistic QCD

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arXiv: 1410.8537

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POLARIZATION PUZZLE

Heavy quarkonium: progress, puzzles, and opportunities

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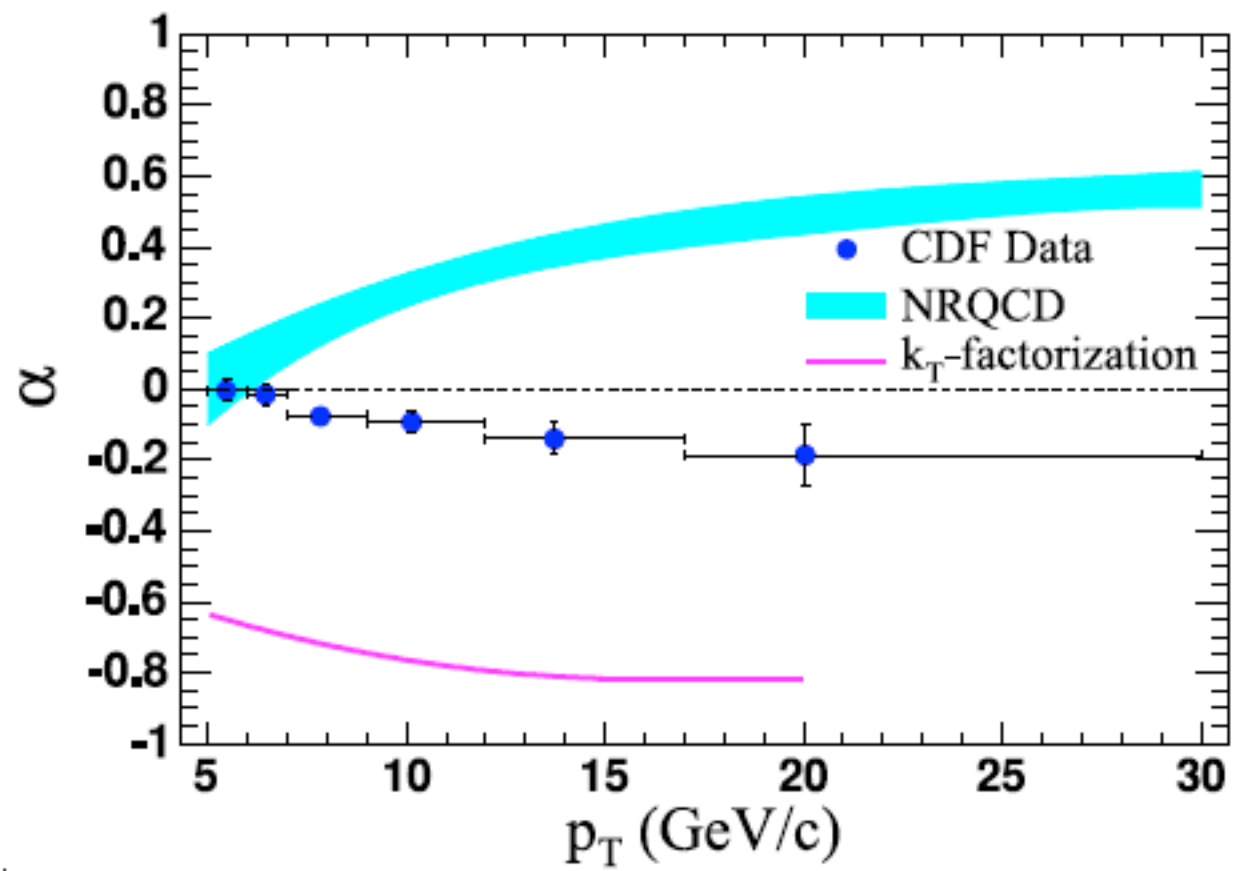

Thursday, November 13, 14

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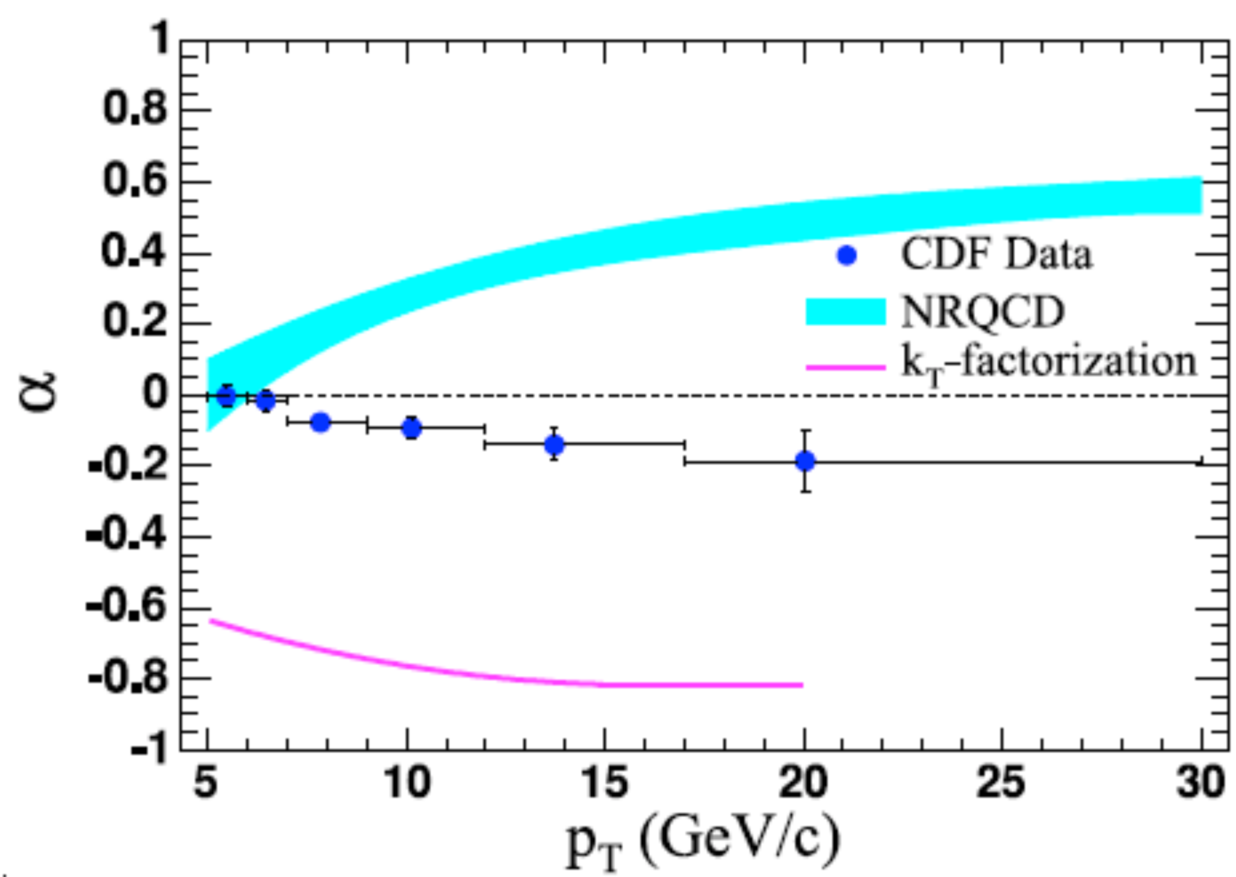

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POLARIZATION AT NLO NRQCD

PRL 108, 172002 (2012) PHYSICAL REVIEW LETTERS week ending 27 APRIL 2012

J/ψ Polarization at the Tevatron and the LHC: Nonrelativistic-QCD Factorization at the Crossroads

Mathias Butenschoen and Bernd A. Kniehl
II. Institut für Theoretische Physik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany
(Received 23 December 2011; published 24 April 2012)

PRL 108, 242004 (2012) PHYSICAL REVIEW LETTERS week ending 15 JUNE 2012

J/ψ Polarization at Hadron Colliders in Nonrelativistic QCD

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[2]*Center for High Energy Physics, Peking University, Beijing 100871, China*
[3]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA*
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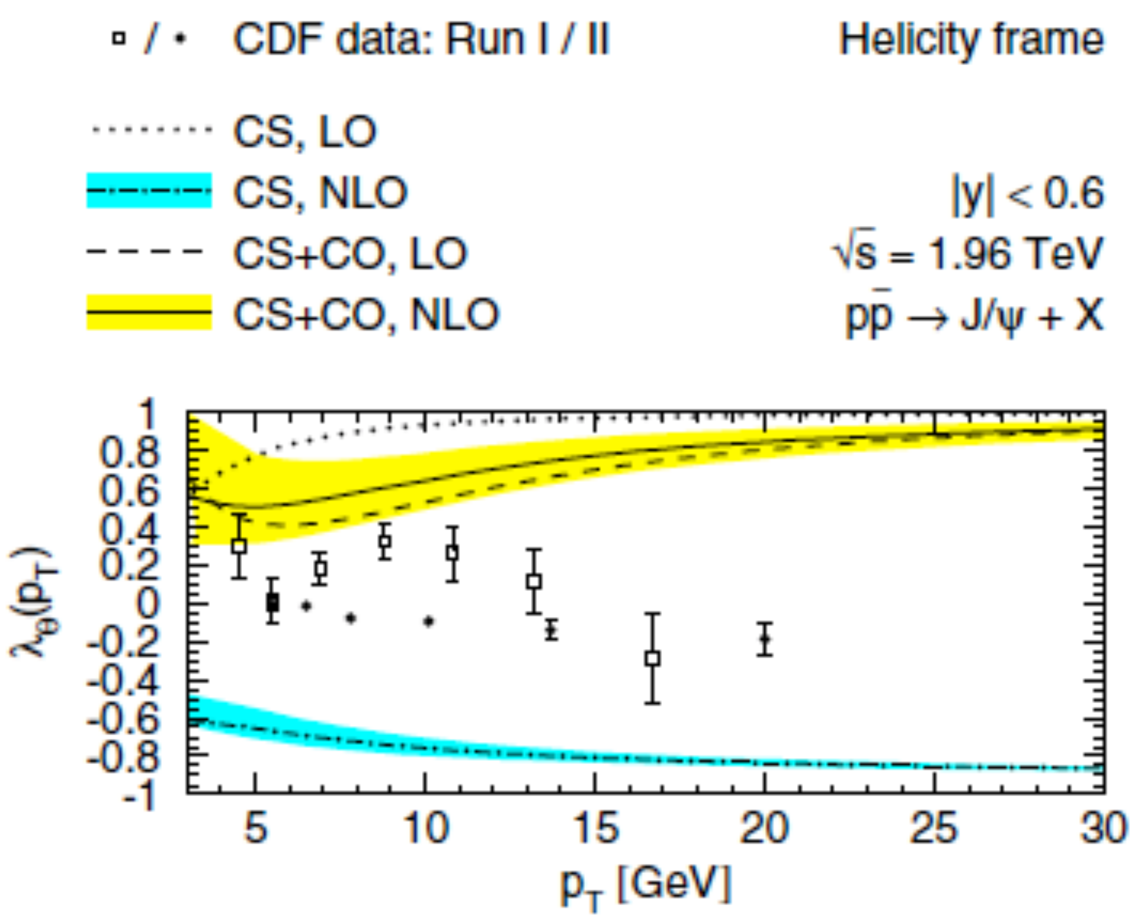

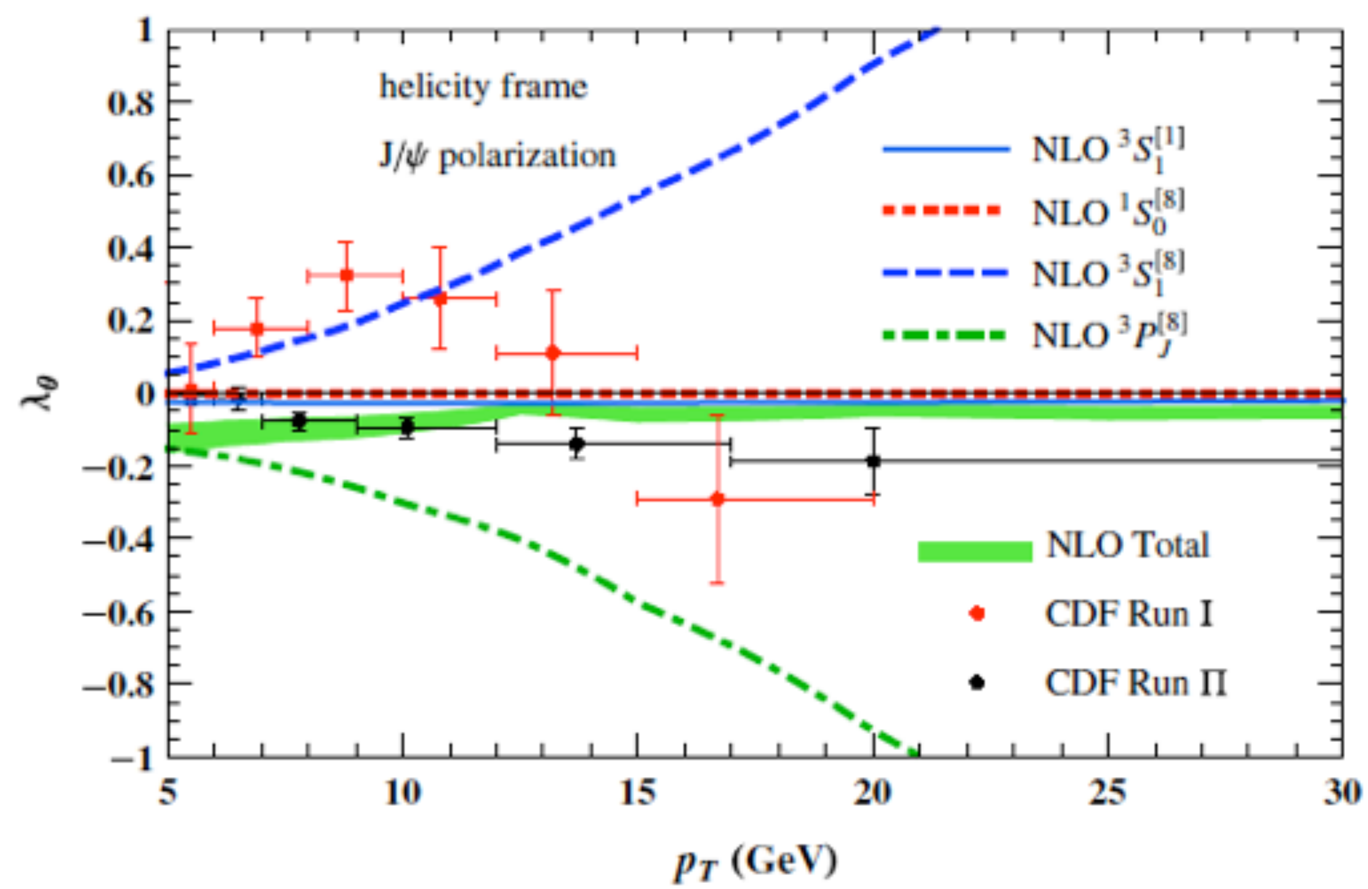

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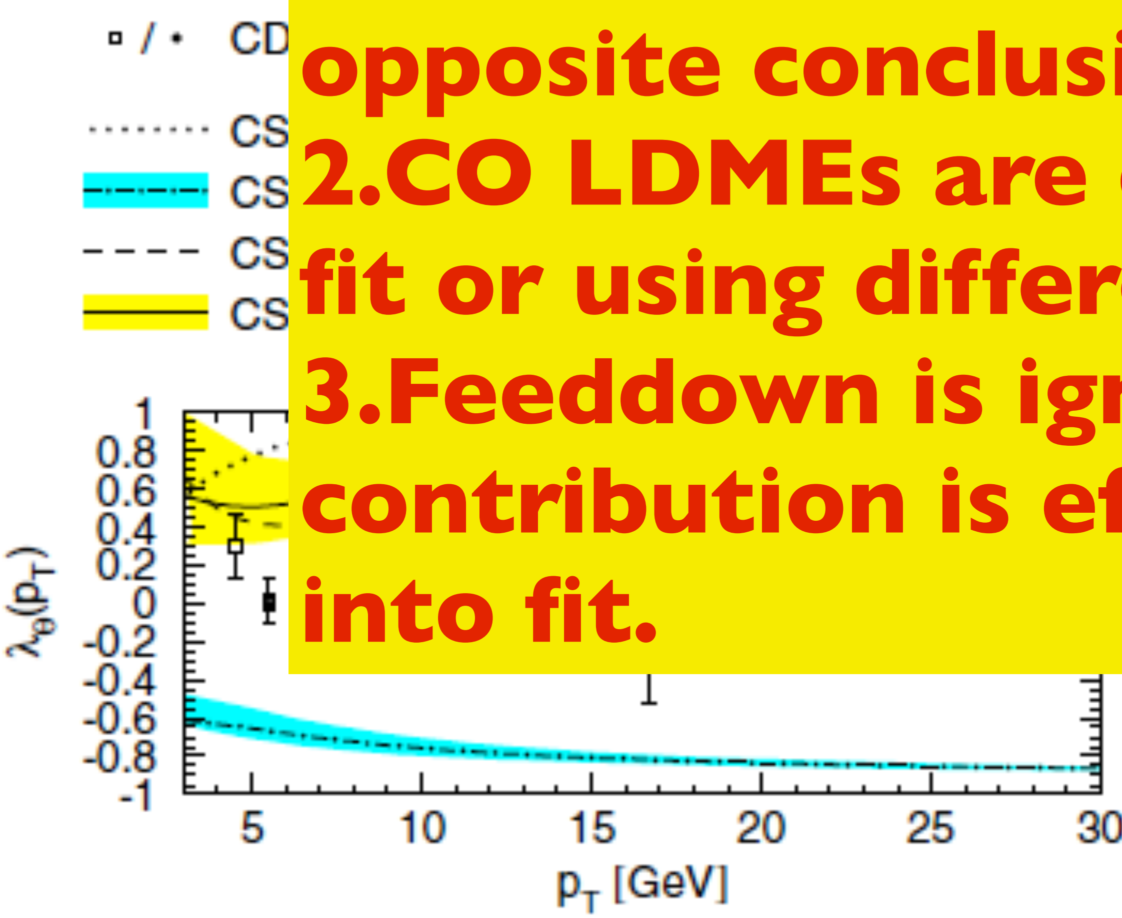
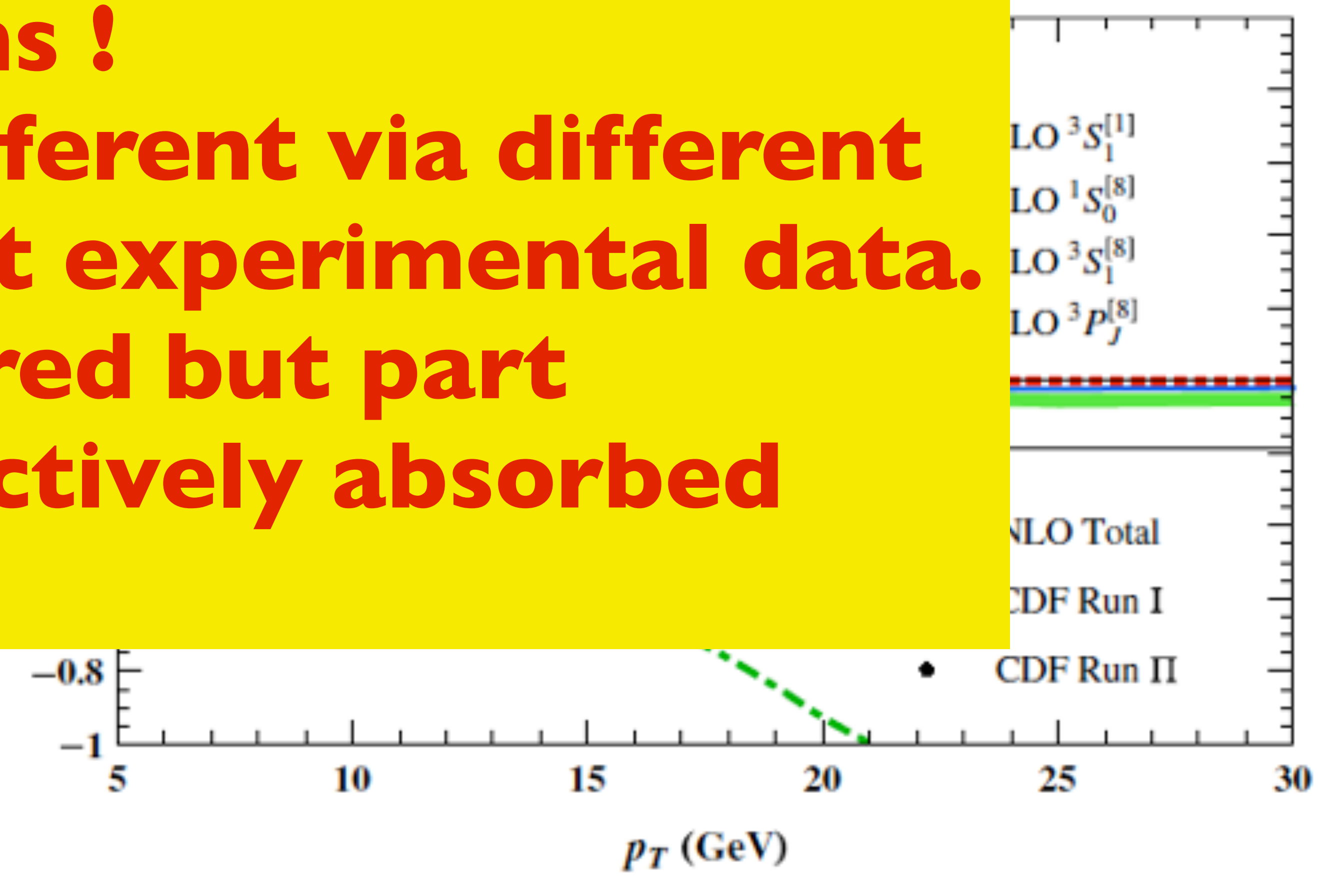
1. Same short-distance coefficient, BUT opposite conclusions !
2. CO LDMEs are different via different fit or using different experimental data.
3. Feeddown is ignored but part contribution is effectively absorbed into fit.





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POLARIZATION AT NLO

PRL **110,** 042002 (2013) PHYSICAL REVIEW LETTERS week ending 25 JANUARY 2013

Polarization for Prompt J/ψ and $\psi(2s)$ Production at the Tevatron and LHC

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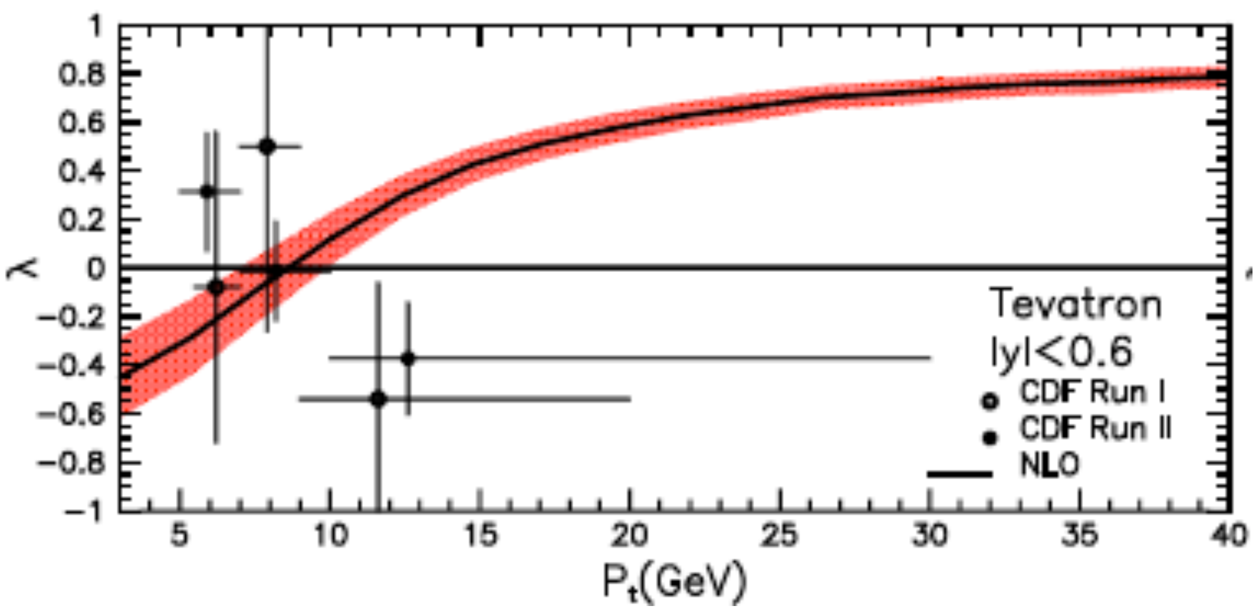

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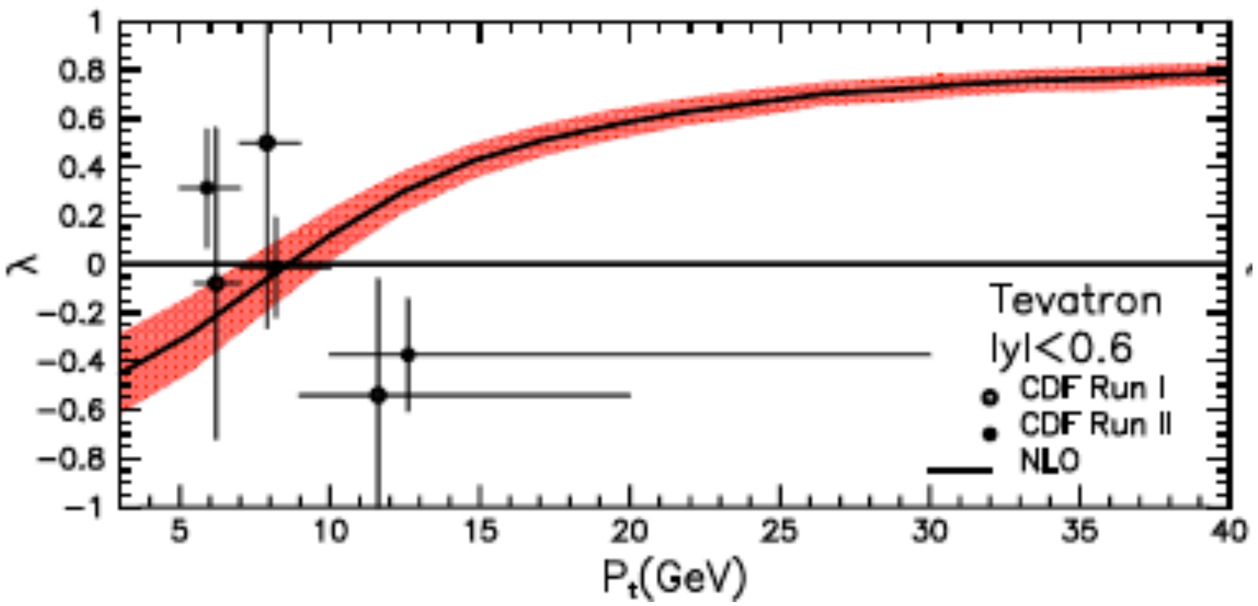

1.Include feeddown contribution.
2.Give out a third CO LDMEs and a third postdiction for polarizations.

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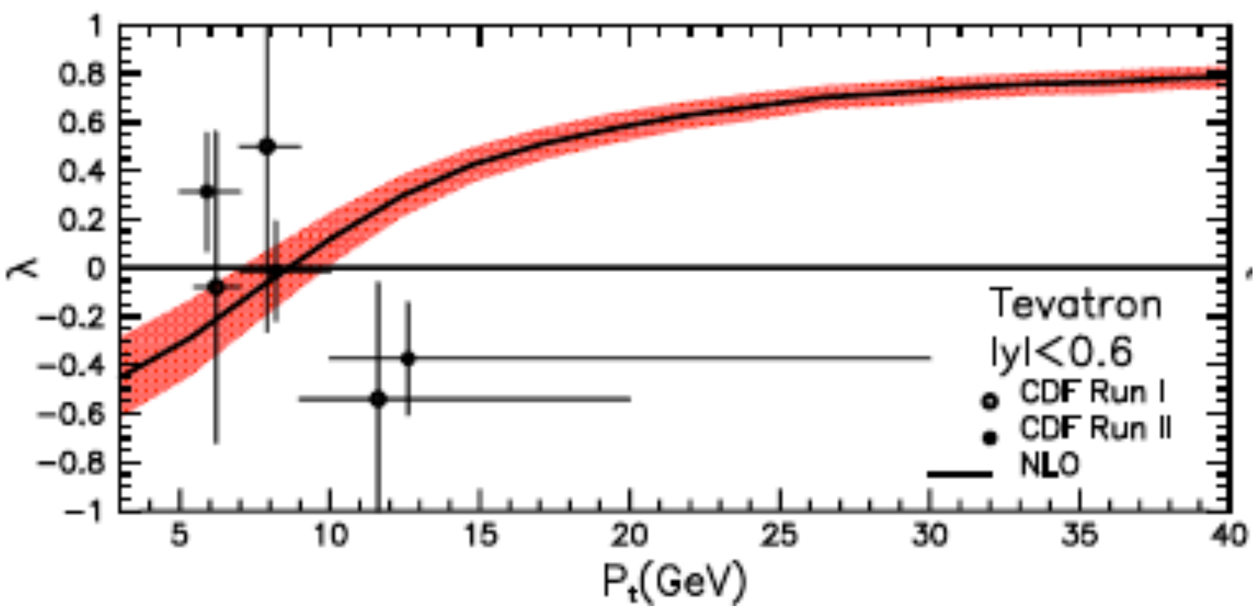

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Butenschoen & Kniehl

Global fit, but include a lot of small pT (small error) data

$\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$	$(4.97 \pm 0.44) \times 10^{-2}$ GeV^3
$\langle \mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle$	$(2.24 \pm 0.59) \times 10^{-3}$ GeV^3
$\langle \mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle$	$(-1.61 \pm 0.20) \times 10^{-2}$ GeV^5

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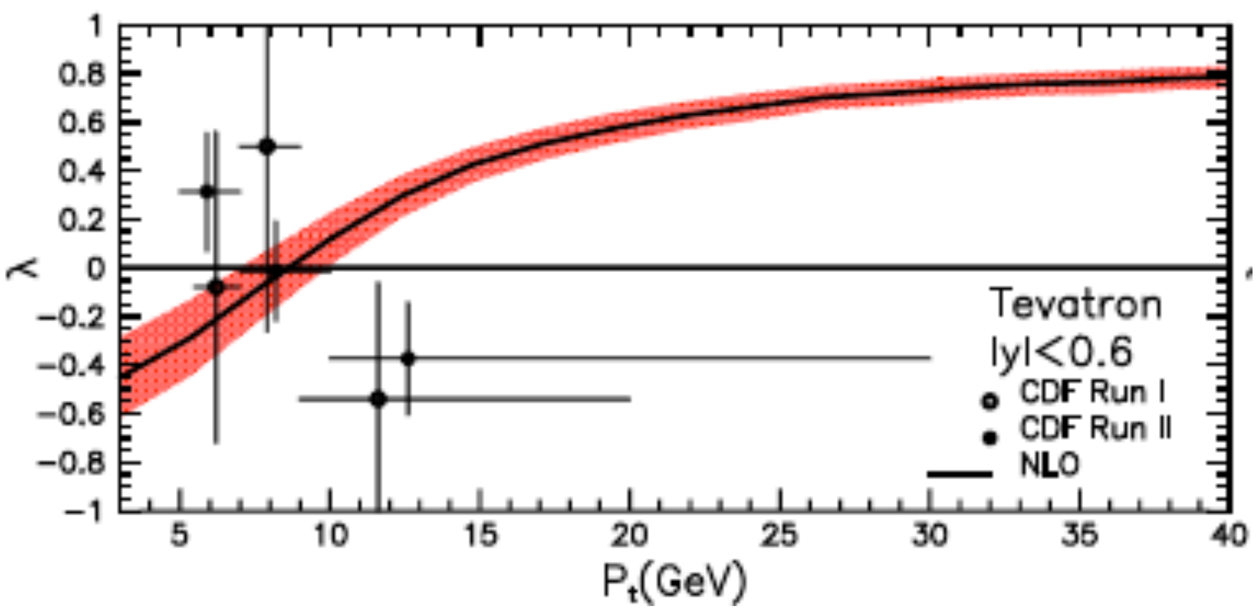

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Chao, Ma, HSS, Wang & Zhang

1.Restrict to hadroproduction data only, but at large pT.

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$\langle \mathcal{O}(^3S_1^{[1]})\rangle$	$\langle \mathcal{O}(^1S_0^{[8]})\rangle$	$\langle \mathcal{O}(^3S_1^{[8]})\rangle$	$\langle \mathcal{O}(^3P_0^{[8]})\rangle/m_c^2$
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1.16	8.9 ± 0.98	0.30 ± 0.12	0.56 ± 0.21
1.16	0	1.4	2.4
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PRL 110, 042002 (2013) PHYSICAL REVIEW LETTERS week ending 25 JANUARY 2013

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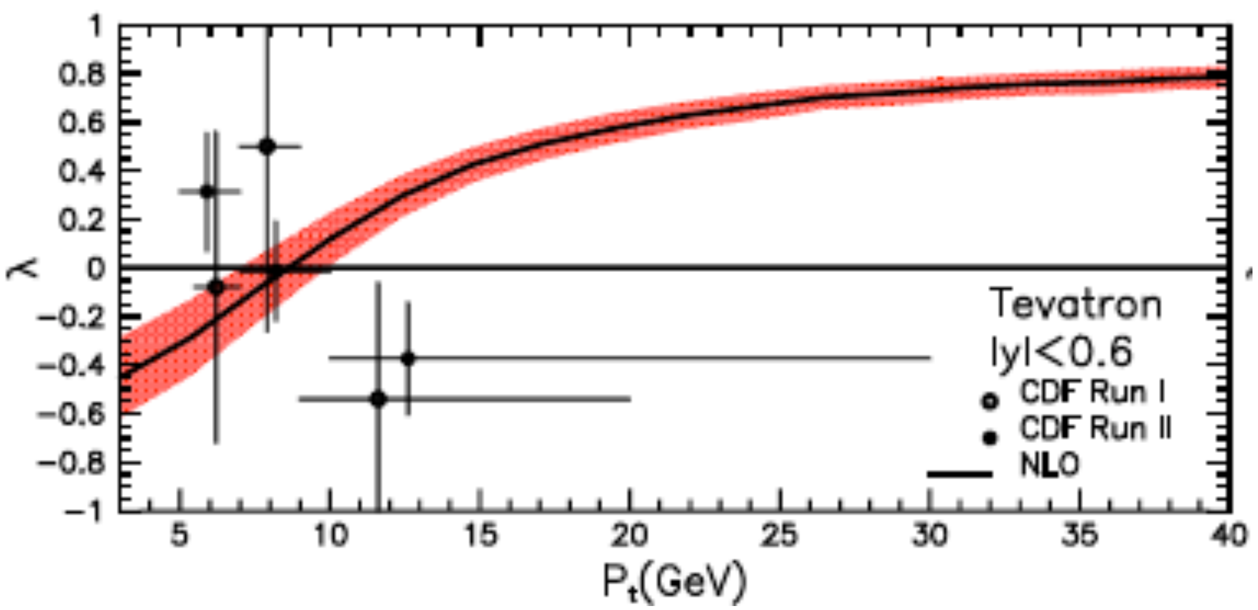

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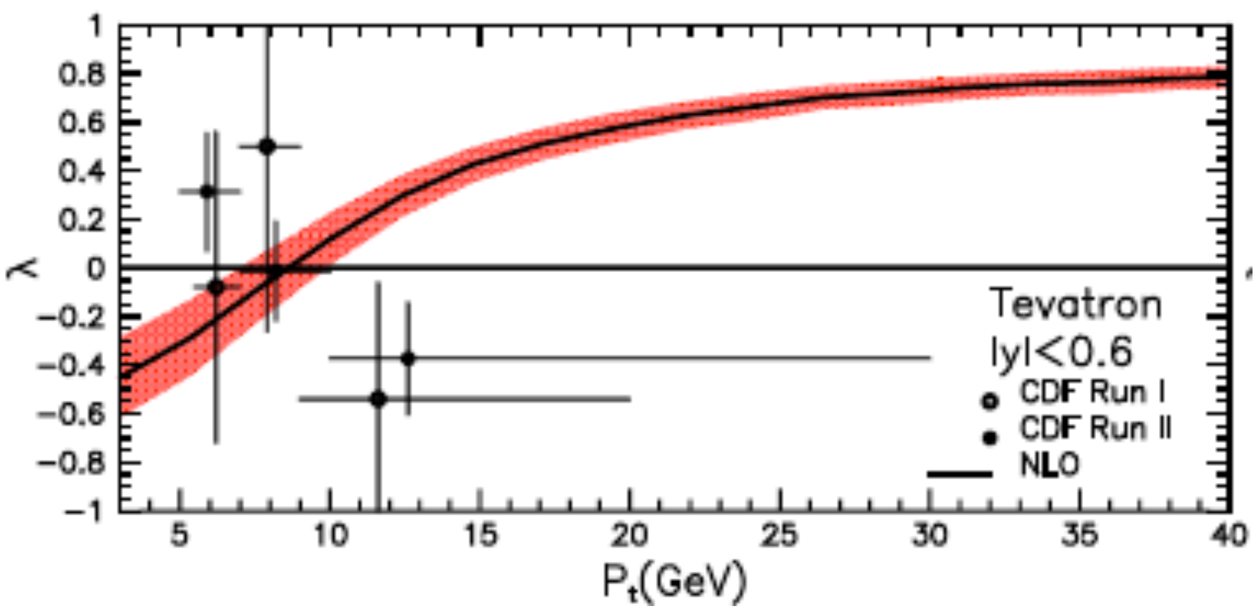

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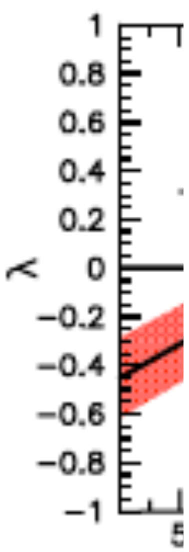

Butenschoen & Kniehl

Global fit, but include a lot of small pT

PHYSICAL REVIEW D **89,** 114018 (2014)

Next-to-leading-order study of the associated production of $J/\psi + \gamma$ at the LHC

Rong Li[1,3] and Jian-Xiong Wang[2,3]

[1]*Department of Applied Physics, Xi'an Jiaotong University, Xi'an 710049, China*
[2]*Institute of High Energy Physics, Chinese Academy of Sciences, P.O. Box 918(4), Beijing 100049, China*
[3]*Theoretical Physics Center for Science Facilities, CAS, Beijing, 100049, China*

(Received 28 January 2014; published 16 June 2014)

The associate $J/\psi + \gamma$ production at the LHC is studied completely at next-to-leading order within the framework of nonrelativistic QCD. By using three sets of color-octet long-distance matrix elements obtained in previous prompt J/ψ studies, we find that only one of them can result in a positive transverse momentum (p_t) distribution of J/ψ production rate at the large p_t region. Based on reasonable consideration to cut down background, our estimation is measurable up to $p_t = 50$ GeV with the present data sample collected at 8 TeV LHC. All the color-octet long-distance matrix elements in J/ψ production could be fixed sensitively by including this proposed measurement and our calculation, and then a confident conclusion on the J/ψ polarization puzzle could be achieved.

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eV^3
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$\rangle/m_c^2$
GeV^3
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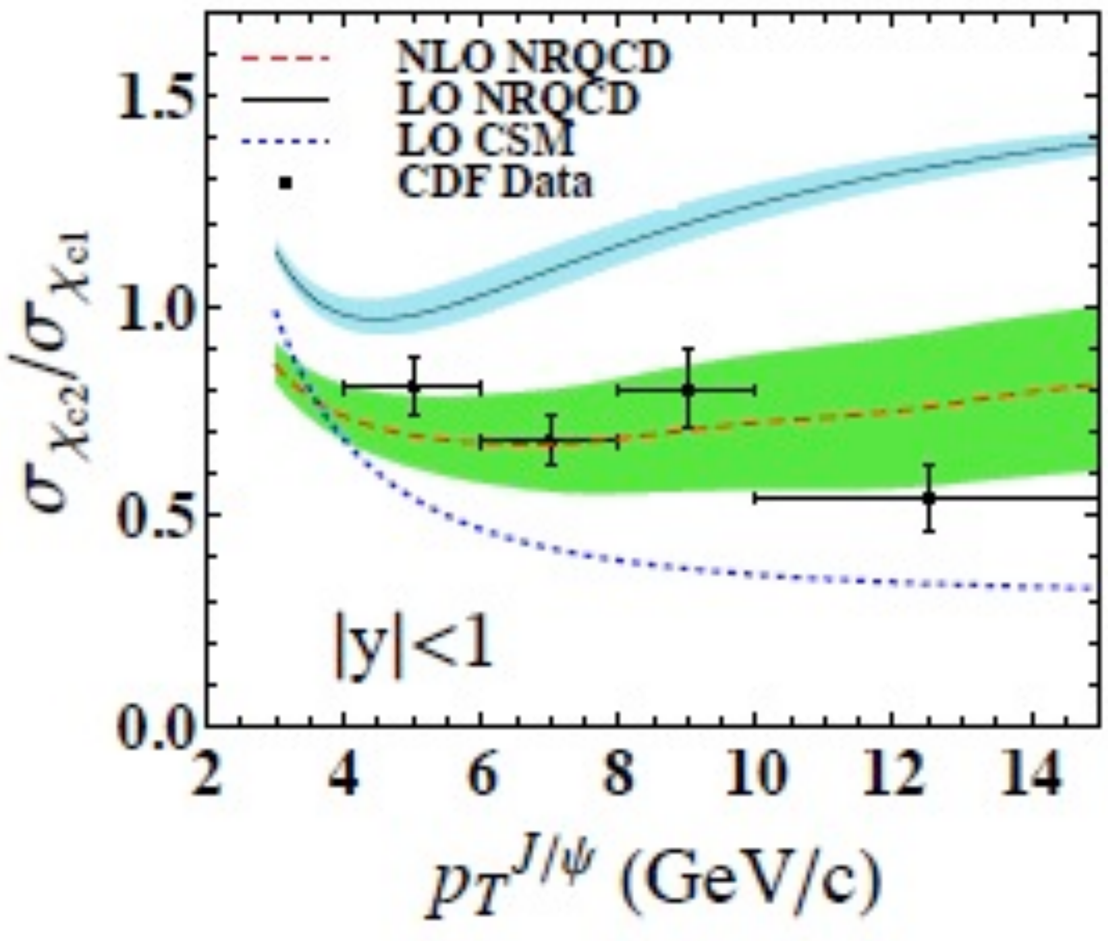
Thursday, November 13, 14

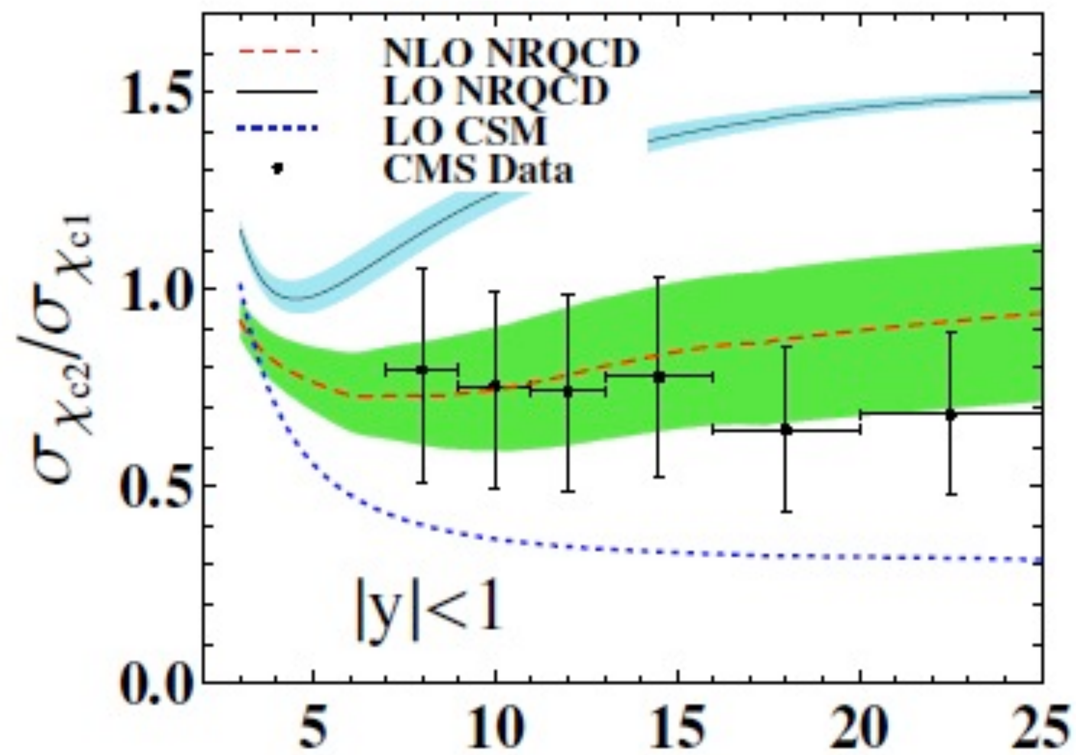
LESSONS

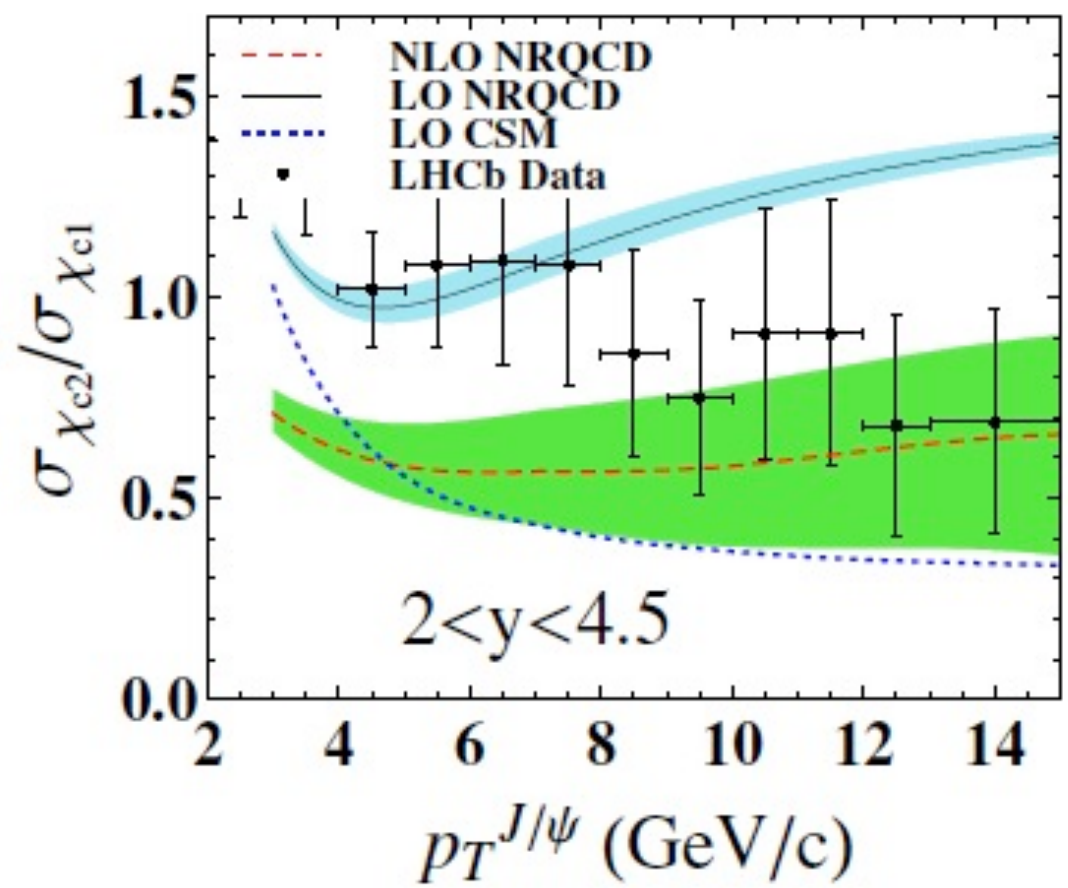
- If we restricted to large pT data only (which only hadroproduction data survive), only two linear combinations can be determined (corresponding to leading and subleading pT resp.). Other associate process of course might help to extract 3 LDMEs independently (for example, see Rong Li's talk).
- It is dangerous to take some of CO LDMEs to be negative, since it might result in negative cross section in some other processes and/or in some phase space region. (LHCb data also support the positive-definite assumption).
- Polarization is sensitive to the value of CO LDMEs, especially the CO triplet S-wave LDME which gives total transverse polarization and leading pT behaviour. S-wave is non-physical, P-wave can also cancel part of S-wave contribution.

CHI_C



- Fit Tevatron data only.
- Predict at the LHC.





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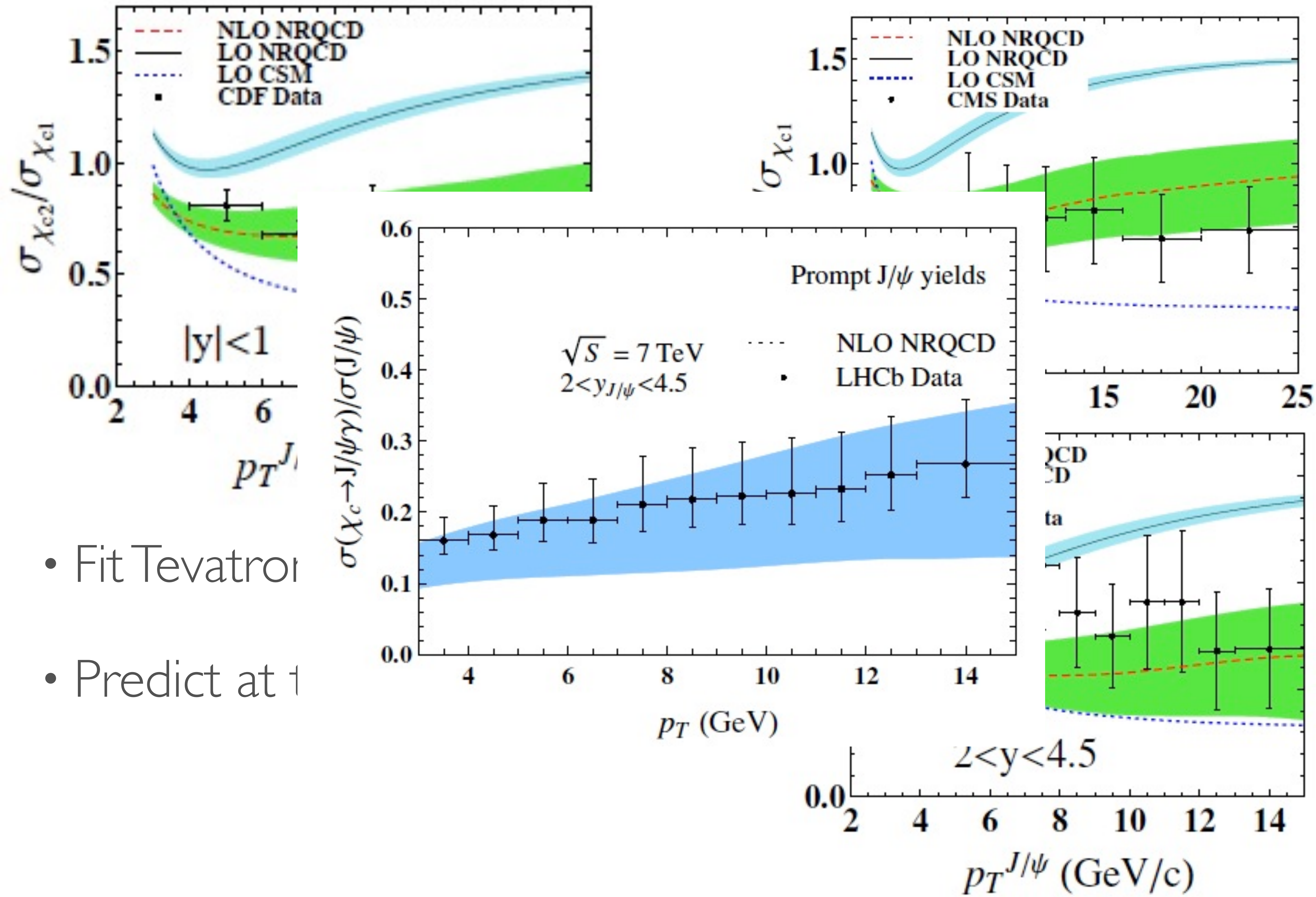

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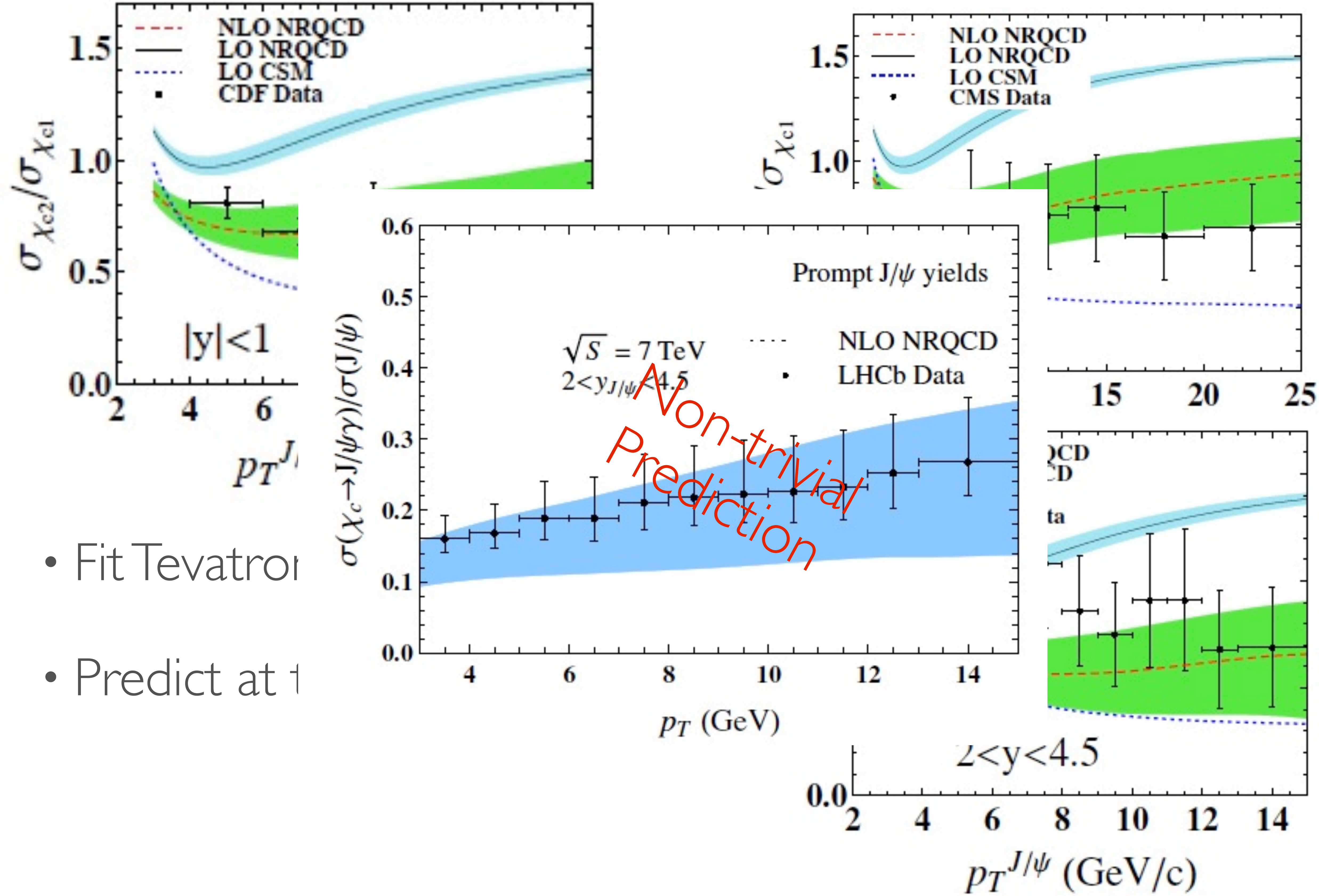

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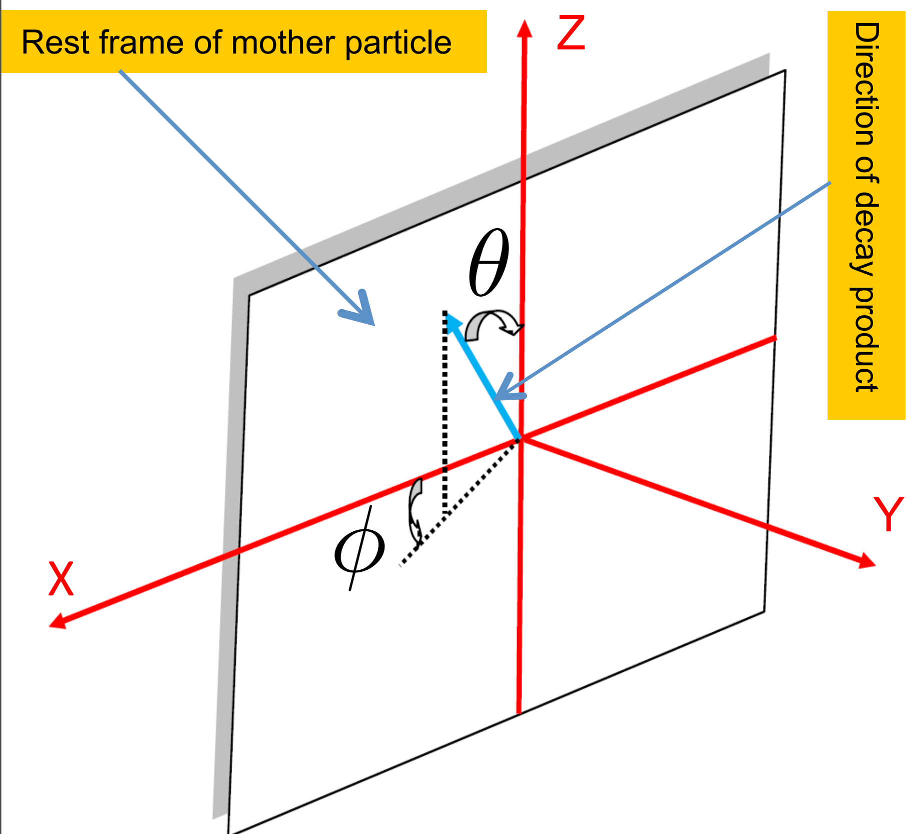
Thursday, November 13, 14

CHI_C POLARIZATION

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



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

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

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

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

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

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

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

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

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

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

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

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

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

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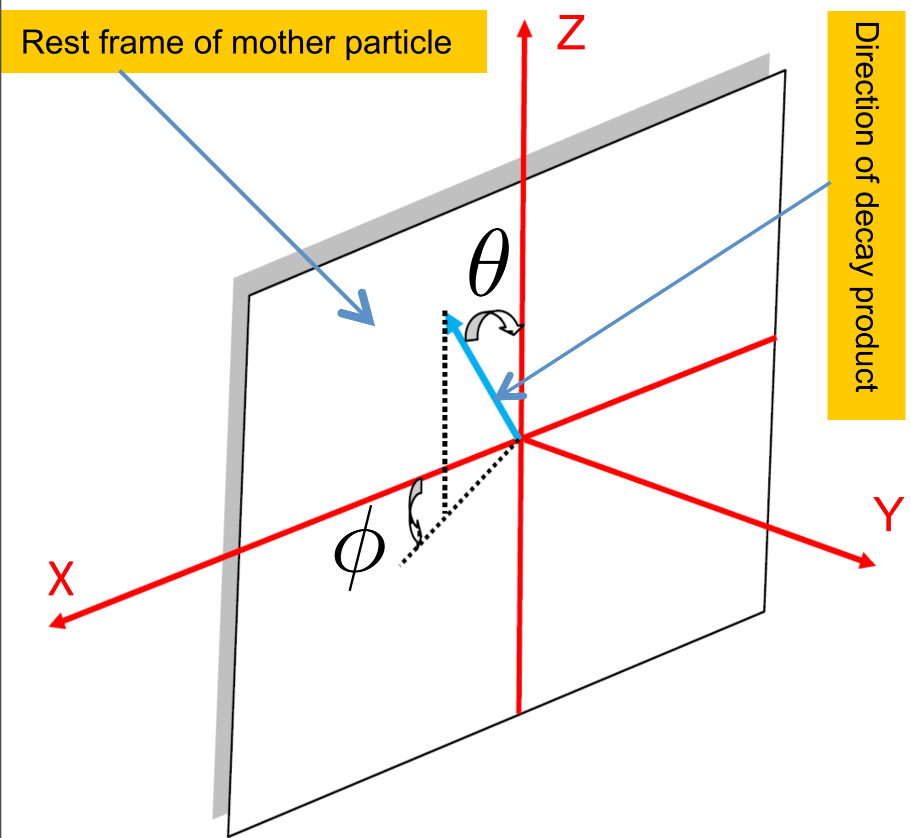

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$$N_{\chi_{c1}} \equiv \rho_{1,1}^{\chi_{c1}} + \rho_{0,0}^{\chi_{c1}} + \rho_{-1,-1}^{\chi_{c1}}$$

E1, M2, E3

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

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

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

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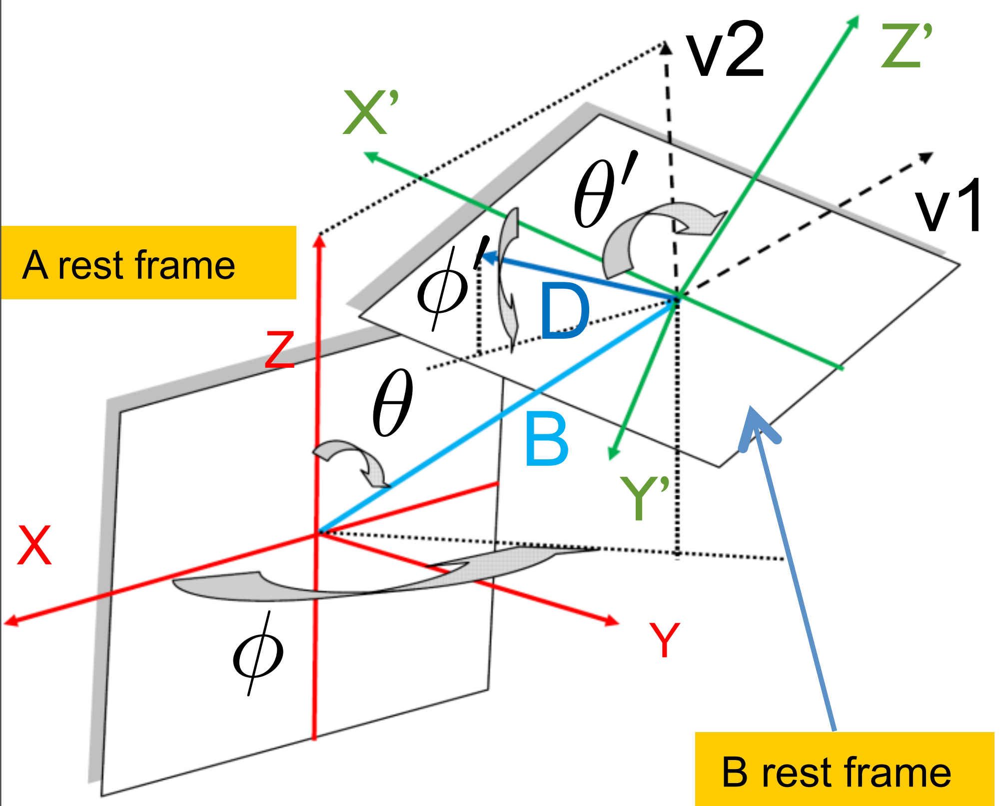

$$A \to B(\to D + E) + C$$

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

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

$$Z' = v2$$

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

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

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

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

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

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

CHI_C POLARIZATION

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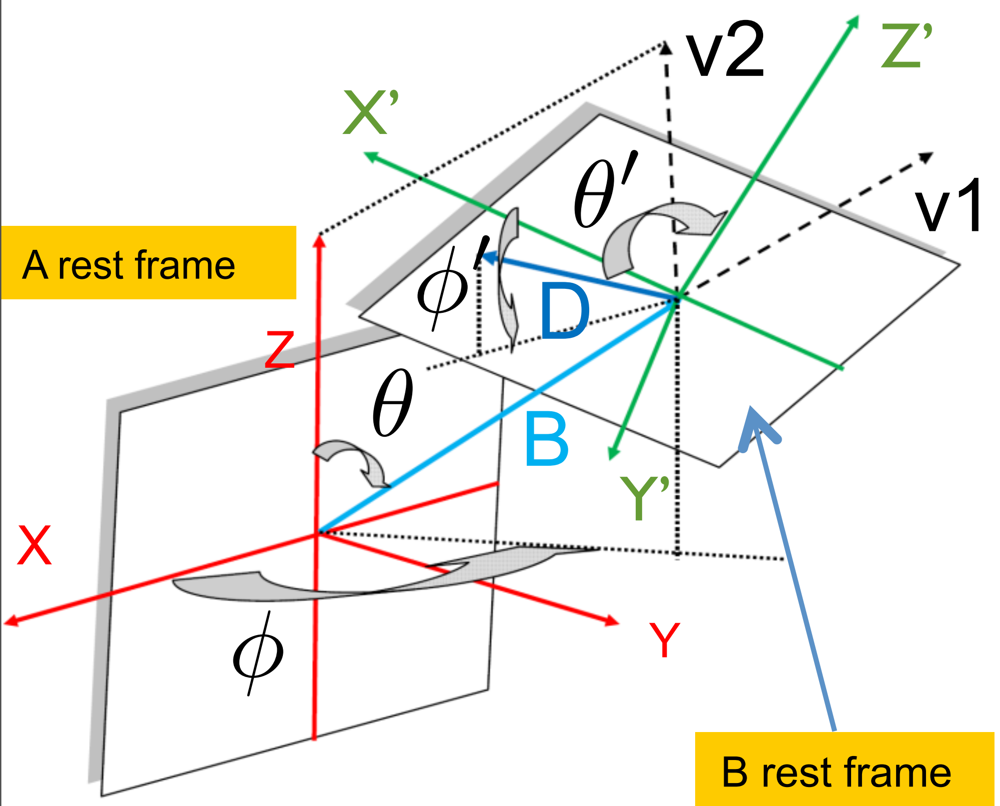

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M2, E3 square

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CHI_C POLARIZATION

- 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)
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Single quark radiation

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Single quark radiation

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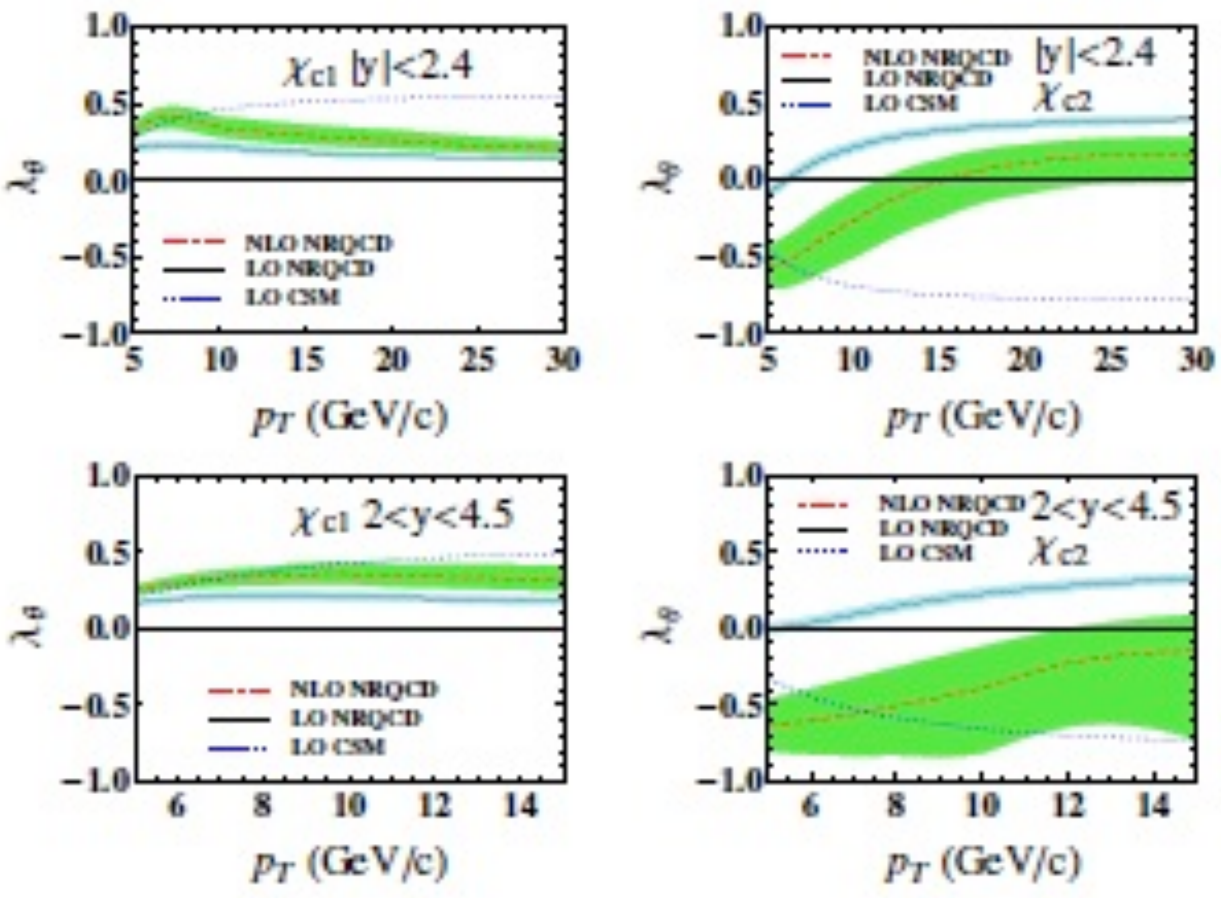
Any functions of $|b_n|^2$ and $N_n \equiv \sum_{k=-n}^{n} |a_n|^2$ are rotational invariant

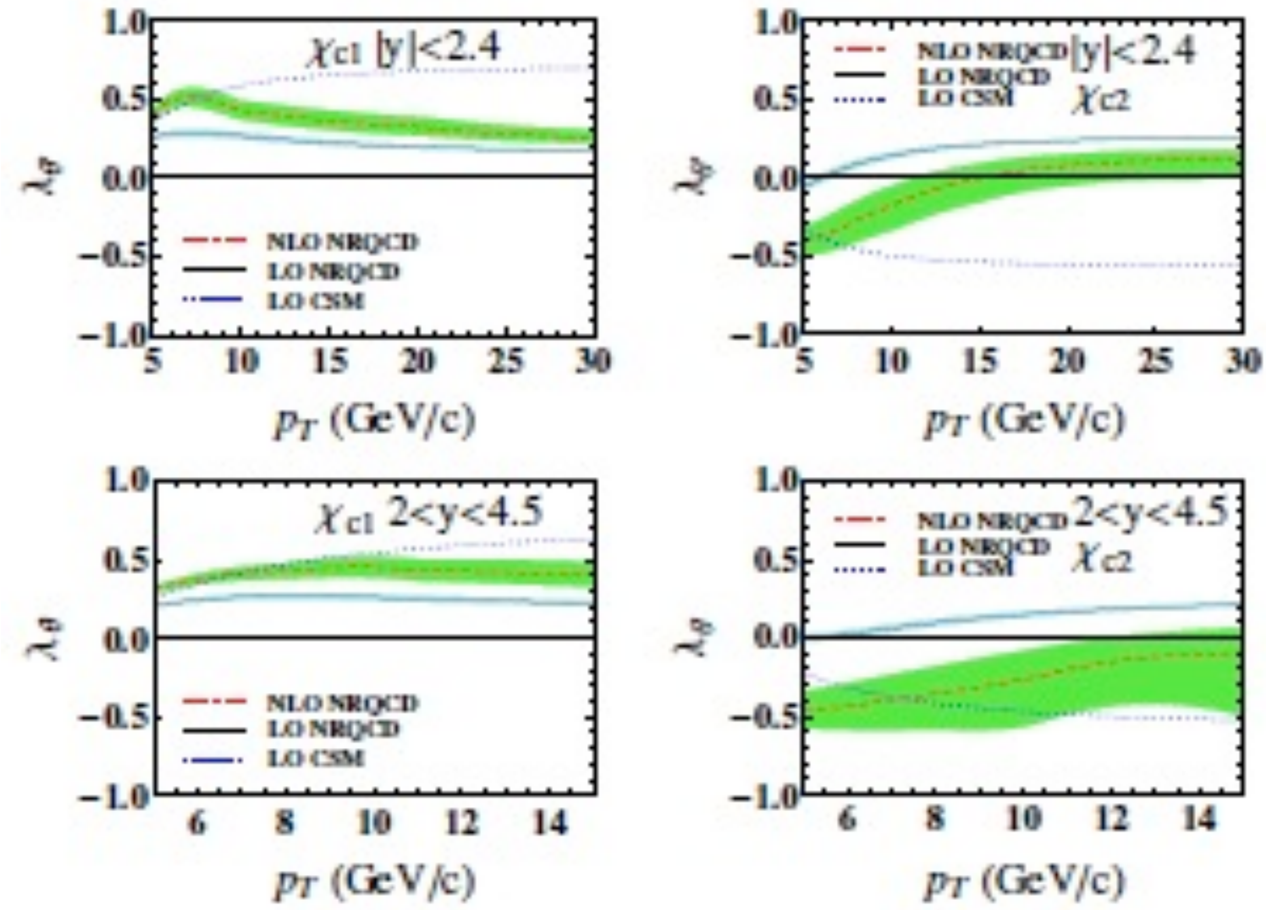
CHI_C POLARIZATION

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

HSS,Ma,Wang,Chao (2014)



photon angular distribution coefficient



di-lepton angular distribution coefficient

Thursday, November 13, 14

Υ(1S,2S,3S) YIELD AND POLARIZATION

PRL **112,** 032001 (2014) PHYSICAL REVIEW LETTERS week ending 24 JANUARY 2014

Complete Next-to-Leading-Order Study on the Yield and Polarization of Υ(1*S*, 2*S*, 3*S*) at the Tevatron and LHC

see Jian-Xiong Wang's talk

Bin Gong, Lu-Ping Wan, Jian-Xiong Wang, and Hong-Fei Zhang
Institute of High Energy Physics, Chinese Academy of Sciences, P.O. Box 918(4), Beijing 100049, China
(Received 6 May 2013; published 24 January 2014)

Based on the nonrelativistic QCD factorization scheme, we present the first complete next-to-leading-order study on the yield and polarization of Υ(1*S*, 2*S*, 3*S*) hadroproduction. By using the color-octet long-distance matrix elements obtained from fits of the experimental measurements on Υ yield and polarization at the Tevatron and LHC, our results can explain the measurements on the yield very well, and for the polarizations of Υ(1*S*, 2*S*, 3*S*), they are in (good, good, bad) agreement with recent CMS measurement, but still have some distance from the CDF measurement.

- All CO LDMEs (include chi_b) are fitted from Tevatron and LHC data.
- No feeddown from chi_b(3P) is included.
- pT cuts take as low as charmonia,i.e. 8 GeV.

Υ(1S,2S,3S) YIELD AND POLARIZATION

- Why feeddown to Υ(3S) is small since there is chi_b(3P) can decay into Υ(3S) ?
  - Potential model tells us $|R'_{3P}(0)| > |R'_{2P}(0)| > |R'_{1P}(0)|$.
  - LHCb new measurements tell us it will contribution Υ(3S) about 30-40%. LHCb Collaboration (2014)
- Is it suitable to apply the same pT cut in bottomnia and charmonia since their masses are so different ?
  - If non-factorization correction is at mv^2/pT (m/pT), yes (no). [also see Carlos Lourenco's talk and Geoffrey Bodwin's second talk.]

Υ(1S,2S,3S) YIELD AND POLARIZATION

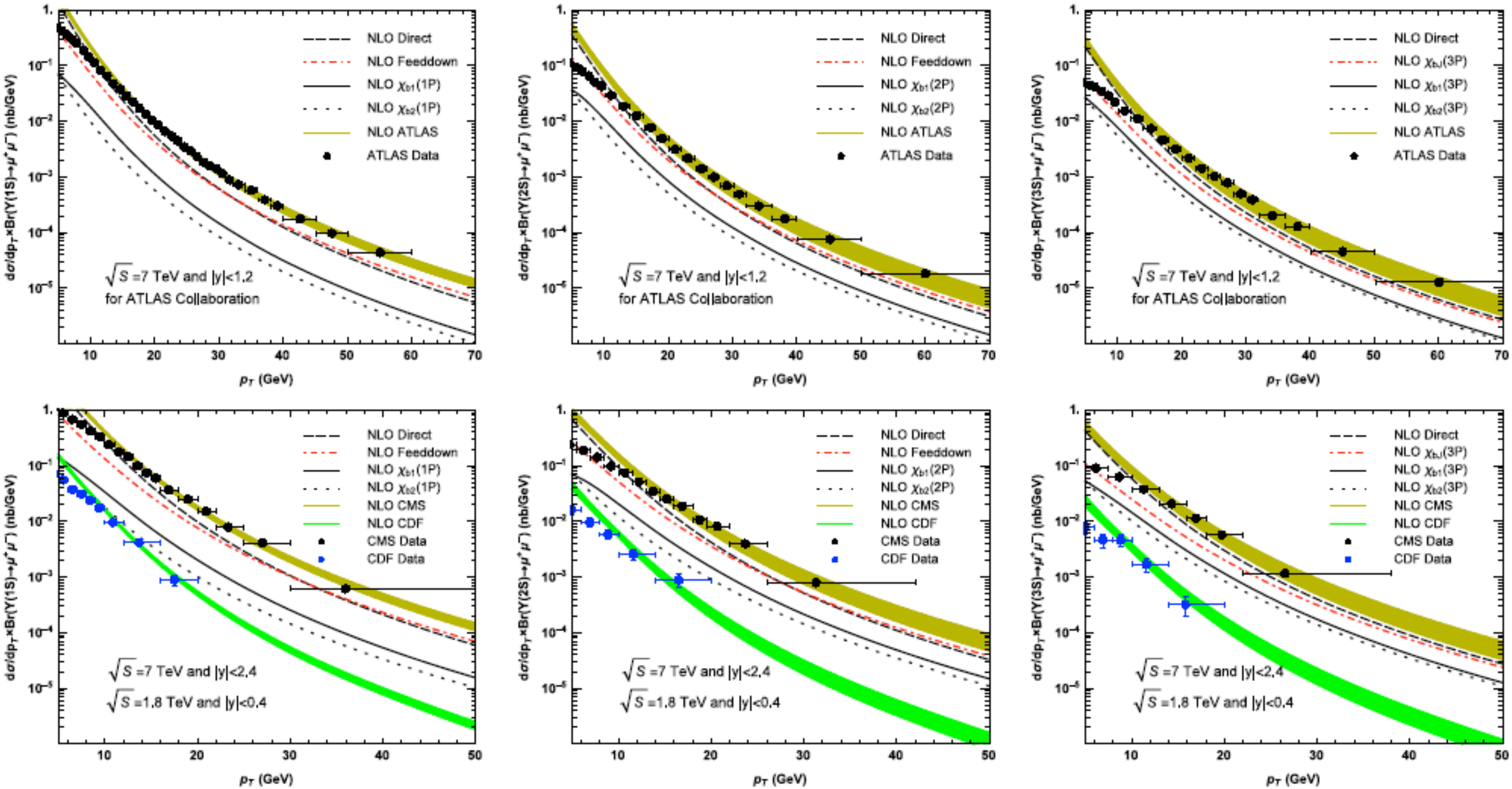
- By fitting the LHC yields and polarization data to determine the CO LDMEs of Υ(1S,2S,3S) but with larger pT cut (15 GeV in our case. Larger cut is still possible.).

- The CO LDMEs for chi_b(1P, 2P, 3P) are extracted from CMS chi_b2(1P)/chi_b1(2P) and the fraction of chi_b(1P,2P,3P) to Υ(nS) by LHCb.

- The braching ratios of chi_b(3P) to Υ(nS) are estimated via potential model only by assuming chi_b(3P) total decay width (mainly hadronic decay width) same as chi_b(1P). Good approximation has been verified to chi_b(2P).

Υ(1S,2S,3S) YIELD AND POLARIZATION

Han, Ma, Meng, HSS, Zhang ,Chao (2014)



Υ(1S,2S,3S) YIELD AND POLARIZATION

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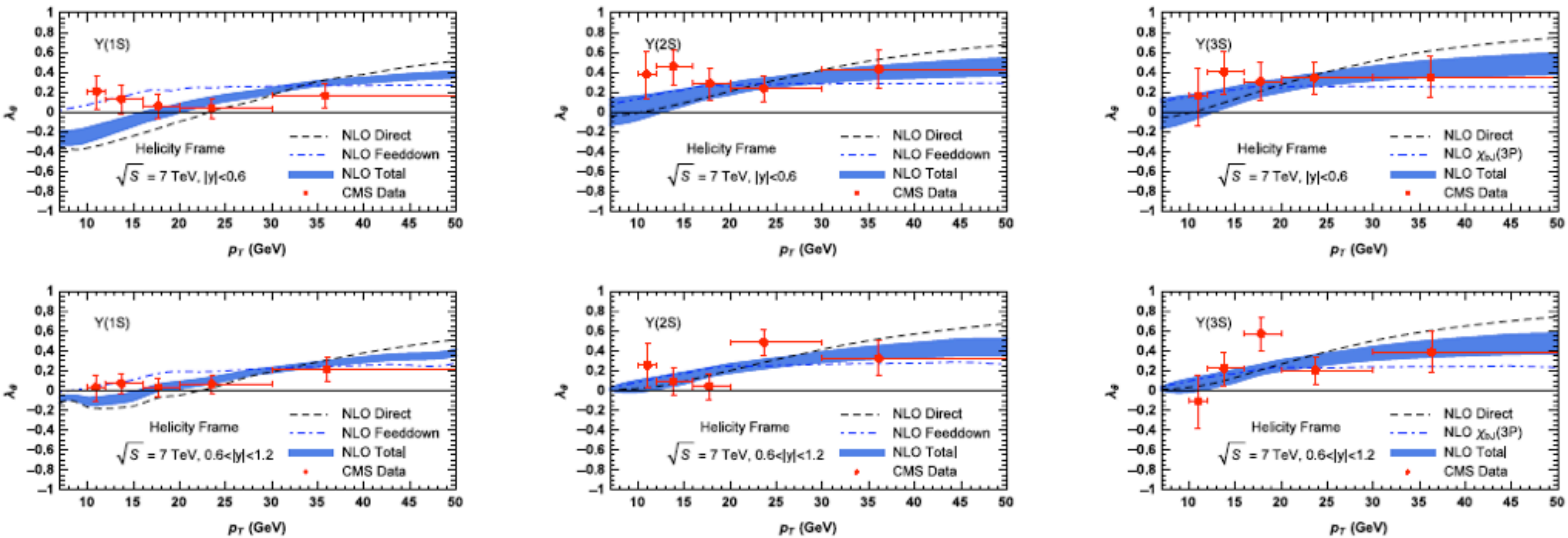
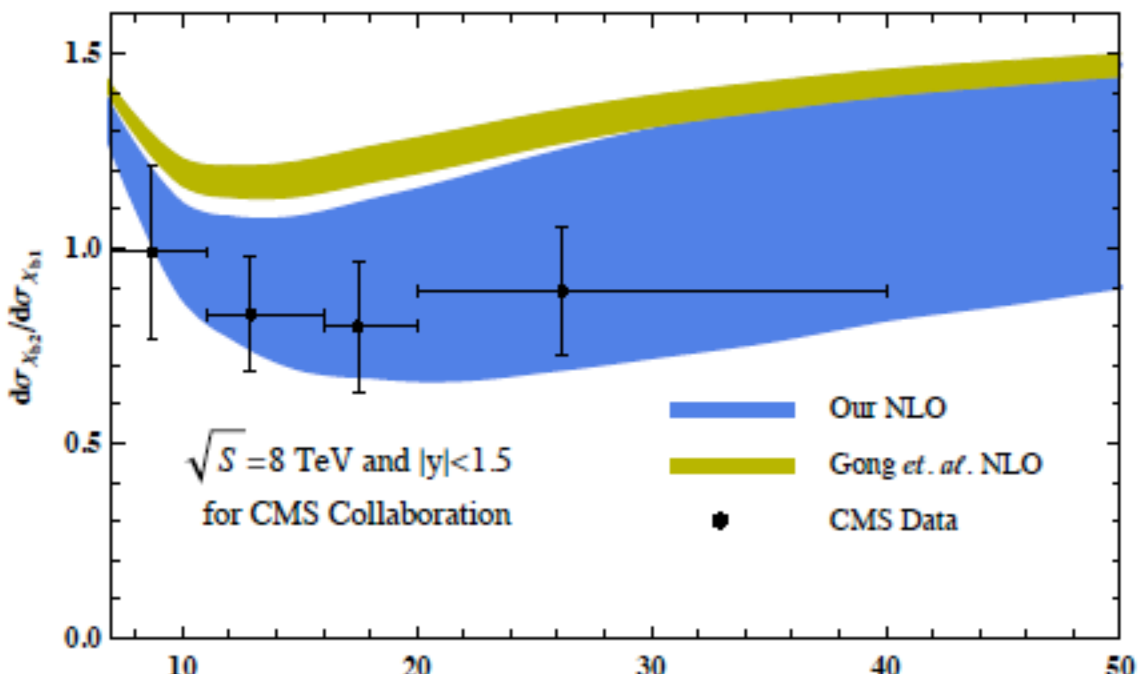


Y(1S,2S,3S) YIELD AND POLARIZATION



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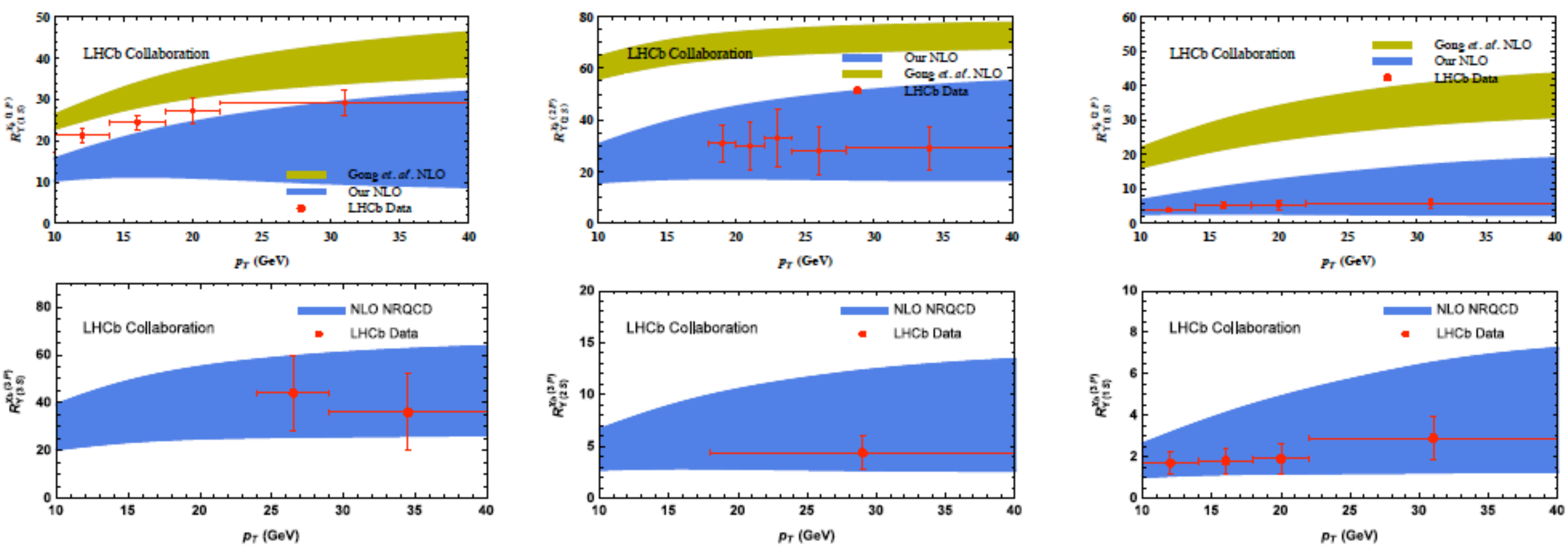

CONCLUSIONS

- COM (Fixed-order or Resummation[see Hee Sok Chung's talk]) CAN explain the current heavy quarkonium production data (both yields and polarization) in limited pT regime (it requires pT >> m).

- Charmonia and Bottomonia can be understood in a unified way.

- It is necessary to probe new mechanisms (e.g. CGC+NRQCD, see Raju Venugopalan's talk) to understand small and moderate pT regime heavy quarkonium production data.

- It would also be interesting to study heavy quarkonium associating processes (e.g. psi+photon, see Rong Li's talk) and/or new observables (e.g. fragmenting jet functions, see Thomas Mehen's talk). They might reveal the true heavy quarkonium production mechanism.