Status of Quarkonium Production on Proton-Proton collider

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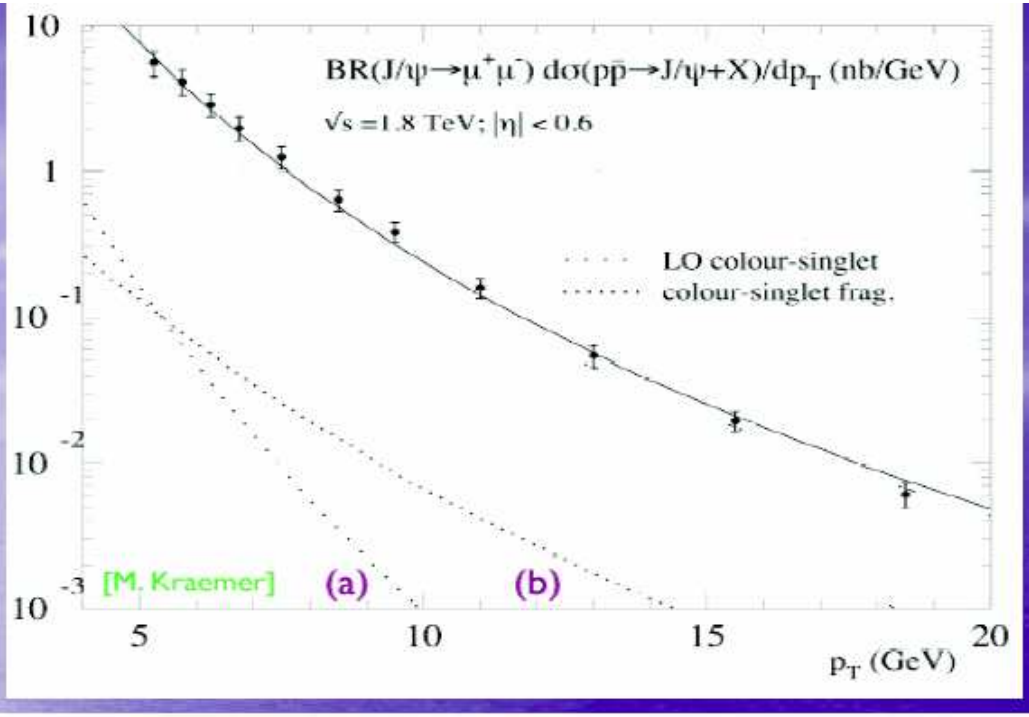
Introduction

- Perturbative and non-perturbative QCD, hadronization, factorization
- Color-singlet and Color-octet mechanism was proposed based on NRQCD since b and c-quark is heavy.
- Why so serious to on the test: Clear signal to detect J/ψ and Υ, very limited number of nonperturbative parameters, double perturbative expansions on α_s and v (the vilocity of heavy quark in quarkonium) are better since b and c-quark is heavy.
- heavy quarkonium production is a good place to testify these theoretical framework.
- J/ψ photoproduction at HERA
- J/ψ production at the B factories
- J/ψ and Υ production and polarization at the Tevatron and LHC
- LO theoretical predication were given before more than 15 years
- NLO theoretical predications were given within last 8 years.
- It seems that the QCD NLO calculations can adequately describe the experimental data.



PRL **99,** 132001 (2007) PHYSICAL REVIEW LETTERS week ending 28 SEPTEMBER 2007

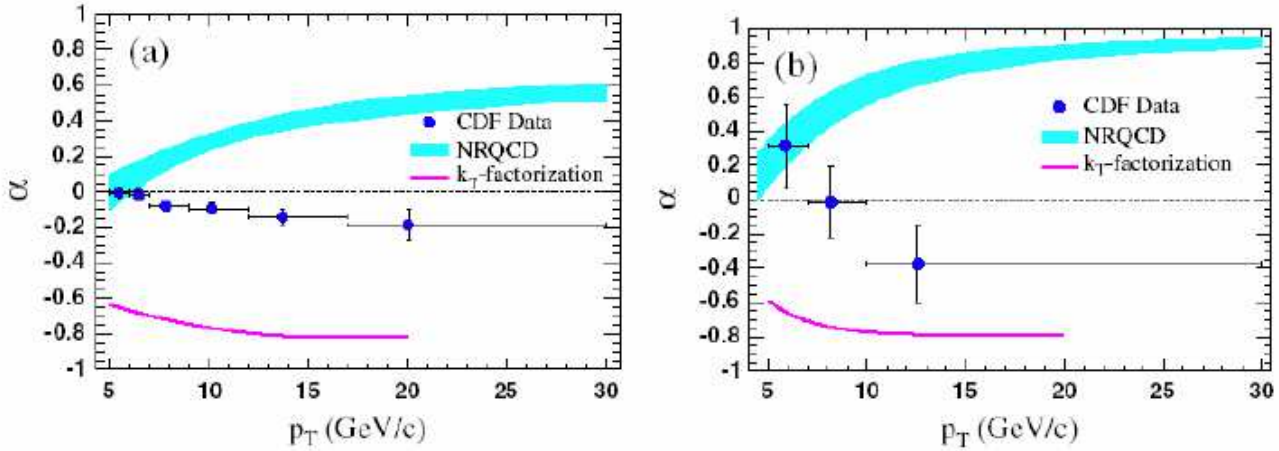
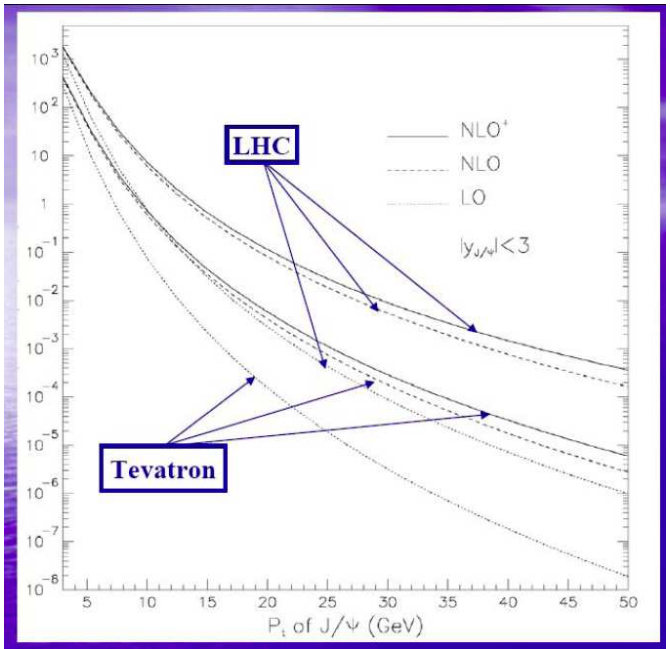


FIG. 4 (color online). Prompt polarizations as functions of p_T: (a) J/ψ and (b) $\psi(2S)$. The band (line) is the prediction from NRQCD [4] (the k_T-factorization model [9]).

Situation on J/ψ hadroproduction and polarization

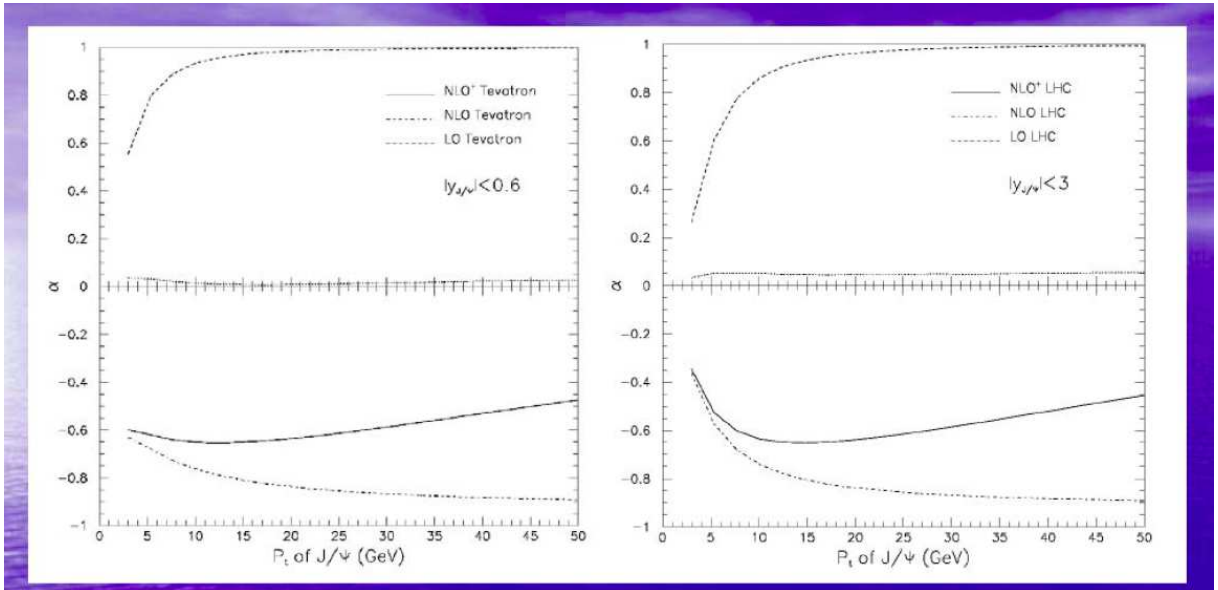
- color-singlet at QCD NLO:
  PRL98,252002 (2007), J. Campbell, F. Maltoni F. Tramontano
  PRL100,232001 (2008), B. Gong and J. X. Wang
- NRQCD at QCD NLO:
  PLB 673:197,2009, B. Gong X. Q. Li and J. X. Wang
  PRL 106, 042002,2011, Y.-Q. Ma, K. Wang, K.-T. Chao
  PRL 106, 022003,2011, M. Butenschoen, B. A. Kniehl
  PRL 108, 248004,2012,K.-T.Chao,Y.-Q.Ma,H.-S.Shao,K.Wang,Y.-J.Zhang
  PRL 108, 172002,2012, M. Butenschoen, B. A. Kniehl
  PRL 110, 042002,2013, B. Gong, L.-P. Wan, J. X. Wang and H. F. Zhang
  PRL 112, 182003,2014, H. S. Shao, Y. Q. Ma, K. Wang and K. T. Chao
  PRL 112, 032001,2014, B. Gong, L.-P. Wan, J. X. Wang and H. F. Zhang
- New fit by using NRQCD at QCD NLO:
  PRL 113, 022001,2014, G. T. Bodwin, H. S. Chung, U. R. Kim and J. Lee
  PRL 114, 092005,2015, H. Han, Y. Q. Ma, C. Meng, H. S. Shao and K. T. Chao
  PRL 114, 092006,2015, H. F. Zhang, Z. Sun, W. L. Sang and R. Li
  arXiv:1410.8537 [hep-ph]. H. Han, Y. Q. Ma, C. Meng, H. S. Shao, Y. J. Zhang and K. T. Chao
  Chinese Phys. C 39 123102,2015, Y. Feng, B. Gong, L. P. Wan, J. X. Wang
- Relativistic Correction in NRQCD
  PRD 86, 094017,2012, G. Z. Xu, Y. J. Li, K. Y. Liu and Y. J. Zhang
- New factorization scheme
  PRL 108, 102002 (2012), Z. B. Kang, J. W. Qiu and G. Sterman
  PRL 113, 142002 (2014), Y. Q. Ma, J. W. Qiu, G. Sterman and H. Zhang
- New method
  PRL 113, 192301,2014, Y. Q. Ma and R. Venugopalan
- Associated production of quarkonium $+\ \gamma$, (w,z)
  .....
- Many new measurements on p_t distribution of yield and polarization by CMS, Atalas, LHCb and Alice.

QCD Correction to color-singlet J/ψ production



Transverse momentum distribution of J/ψ production

NLO+ : contribution from $J/\psi + c\bar{c}$ is included



Transverse momentum distribution of J/ψ polarization parameter α

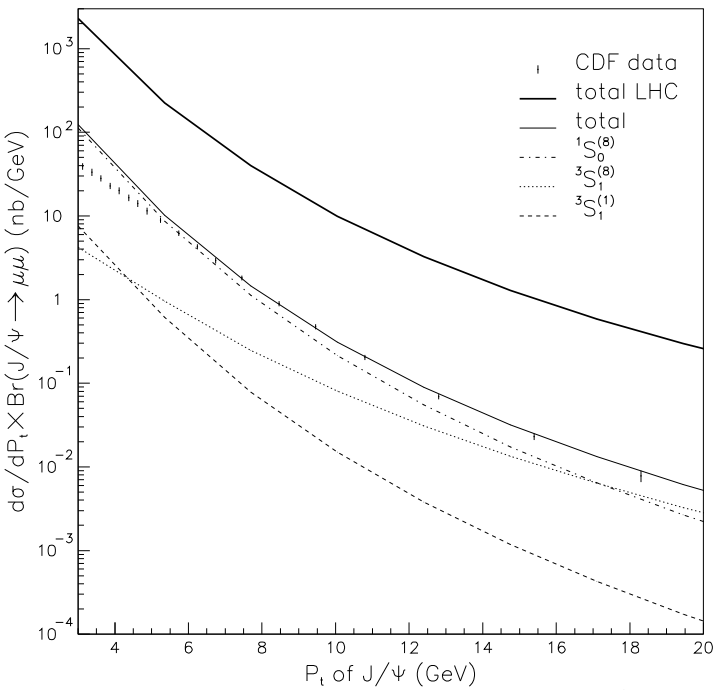
J/ψ polarization status drastically changes from transverse polarization dominant at LO into longitudinal polarization dominant at NLO

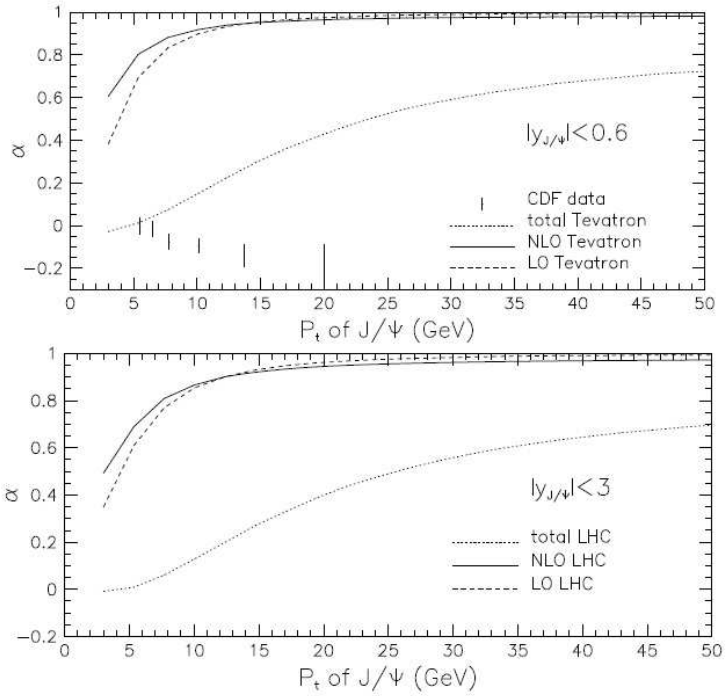
P_t distribution of J/ψ production at QCD NLO was calculated in PRL98,252002 (2007), J. Campbell, F. Maltoni F. Tramontano

Some technique problems must be solved to calculate J/ψ polarization

P_t distribution of J/ψ polarization at QCD NLO was calculated in PRL100,232001 (2008), B. Gong and J. X. Wang

QCD Correction to $J/\psi(^3S_1^1,\ ^1S_0^8,\ ^3S_1^8)$ production and polarization without $^3P_J^8$ contribution





To fit the Tevatron P_t distribution give more $\langle \mathcal{O}_8^{\psi}(^1S_0)\rangle = 0.075\ \mathrm{GeV}^3$ and less $\langle \mathcal{O}_8^{\psi}(^3S_1)\rangle = 0.0021\ \mathrm{GeV}^3$ than they are at LO fitting The experimental data with $p_t < 6$ GeV have to abandon

PLB673:197,2009, Erratum-ibid.693:612,2010 , B. Gong X. Q. Li and J. X. Wang

QCD Correction to prompt $J/\psi(^3S_1^1,\ ^1S_0^8,\ ^3S_1^8,\ ^3P_J^8)$ production

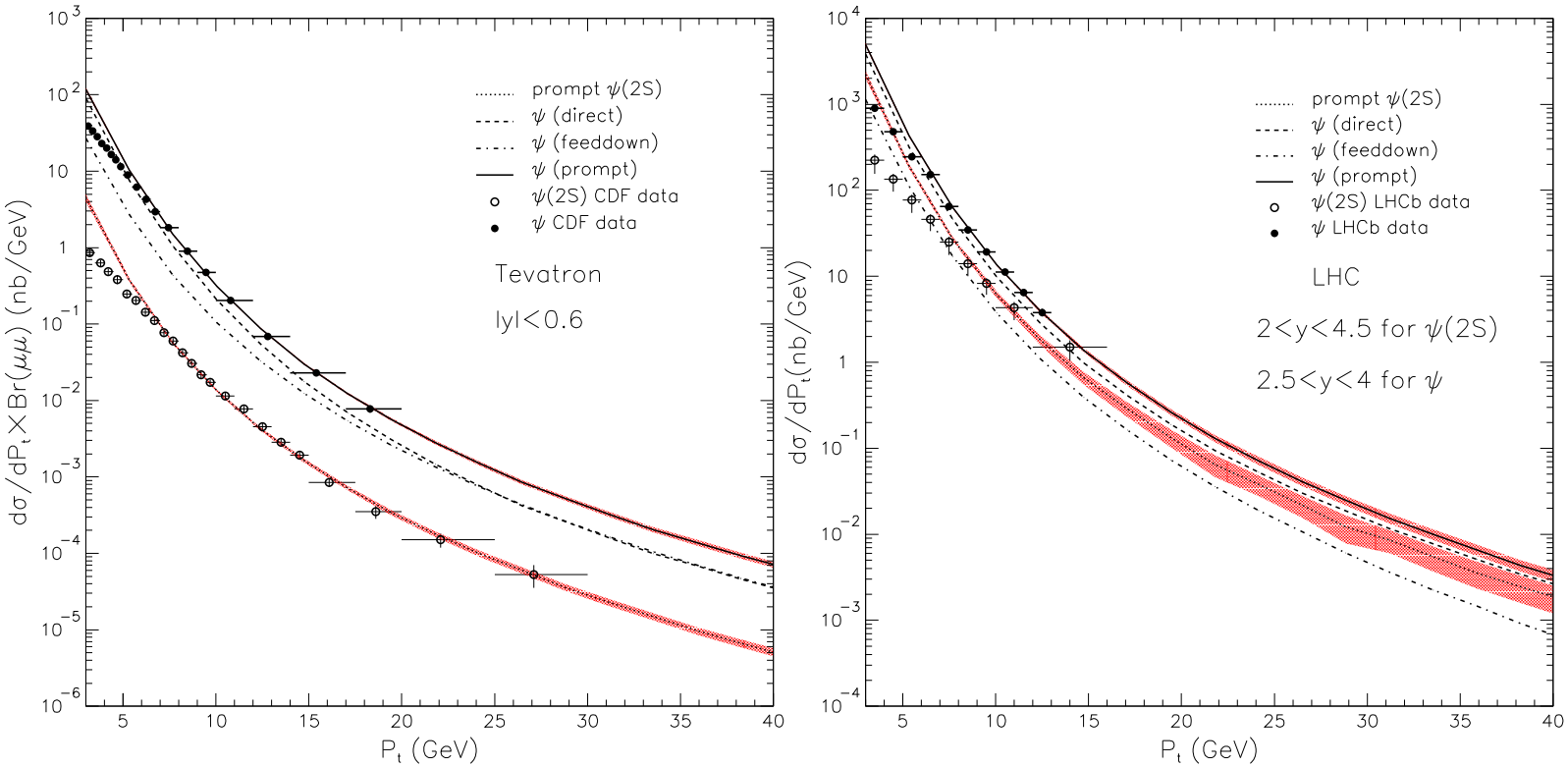


Figure: p_t distribution of prompt J/ψ and ψ' hadroproduction. The CDF and LHCb data are taken in the fitting.

PRL110, 042002, 2013, ArXiv:1205.6682, Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang

QCD Correction to $\psi'(^3S_1^1,\ ^1S_0^8,\ ^3S_1^8,\ ^3P_J^8)$ polarization

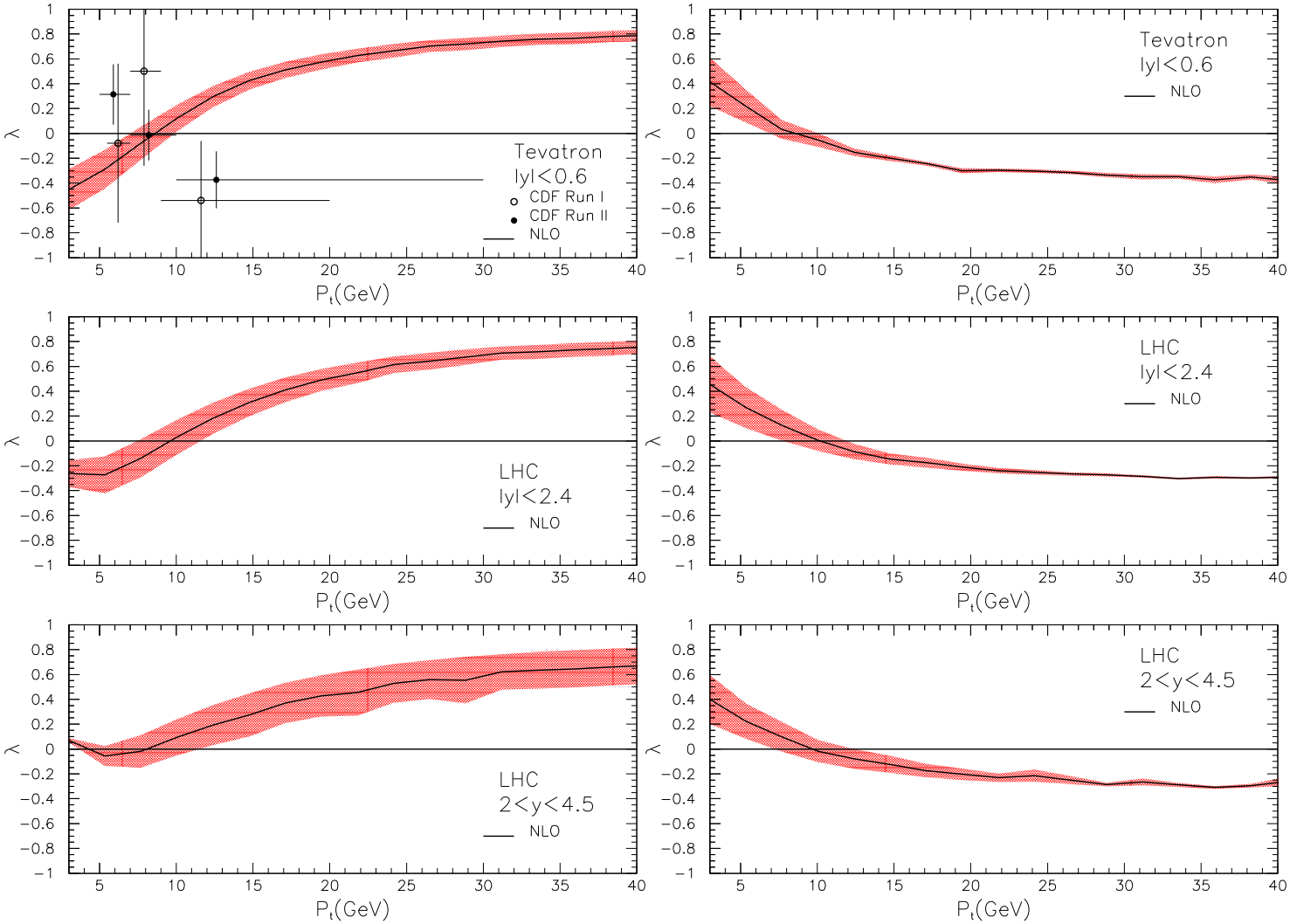


Figure: Polarization parameter λ of J/ψ' in helicity(left) and CS(right) frames.

PRL110, 042002, 2013, ArXiv:1205.6682, Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang

QCD Correction to $\chi_{cJ}(^3P_J^1,\ ^3S_1^8) \to J/\psi$ polarization

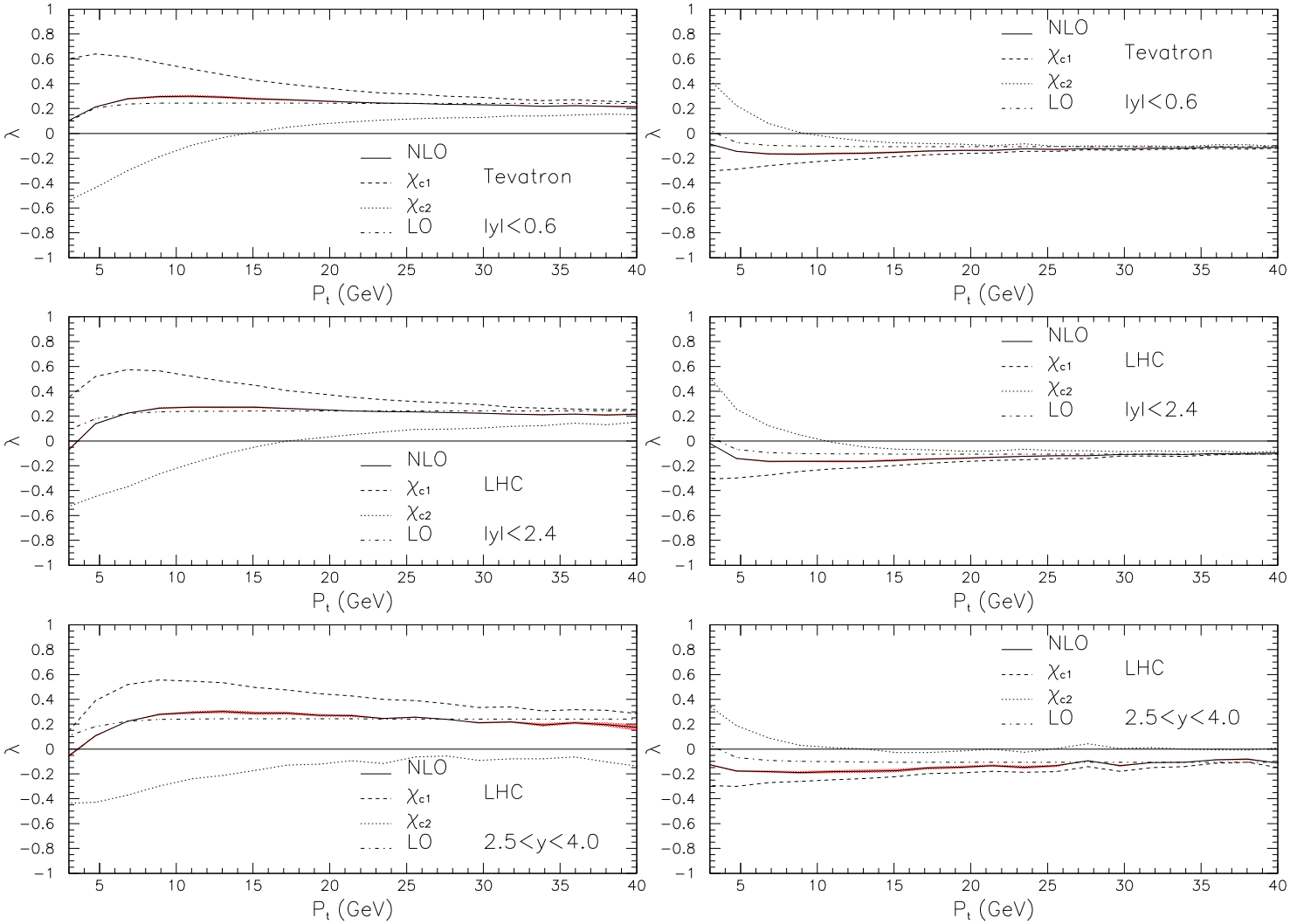


Figure: Polarization parameter λ of J/ψ in helicity(left) and CS(right) frames.

PRL1100420022013), ArXiv:1205.6682, Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang

QCD Correction to prompt $J/\psi(^3S_1^1,\ ^1S_0^8,\ ^3S_1^8,\ ^3P_J^8)$ polarization

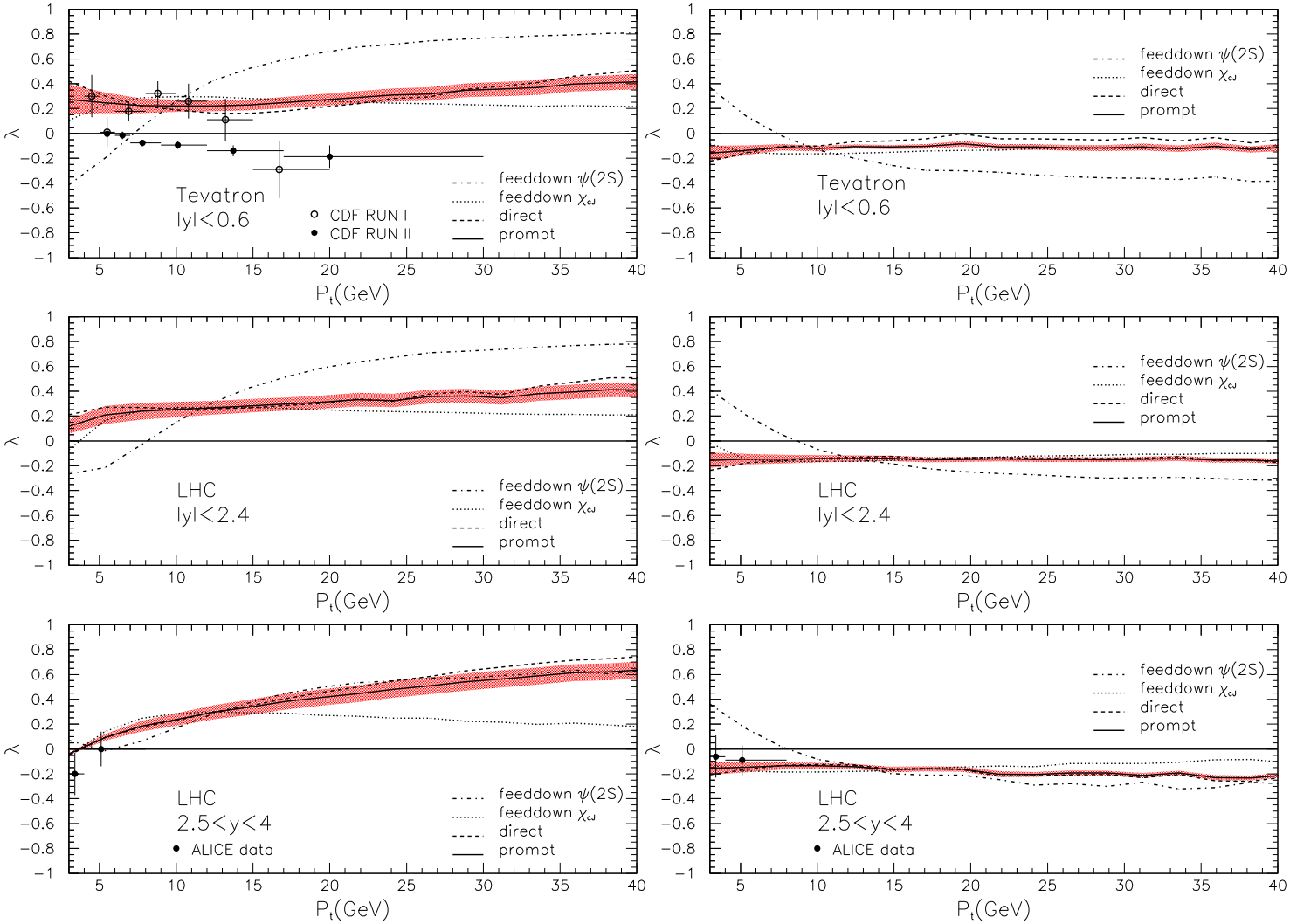


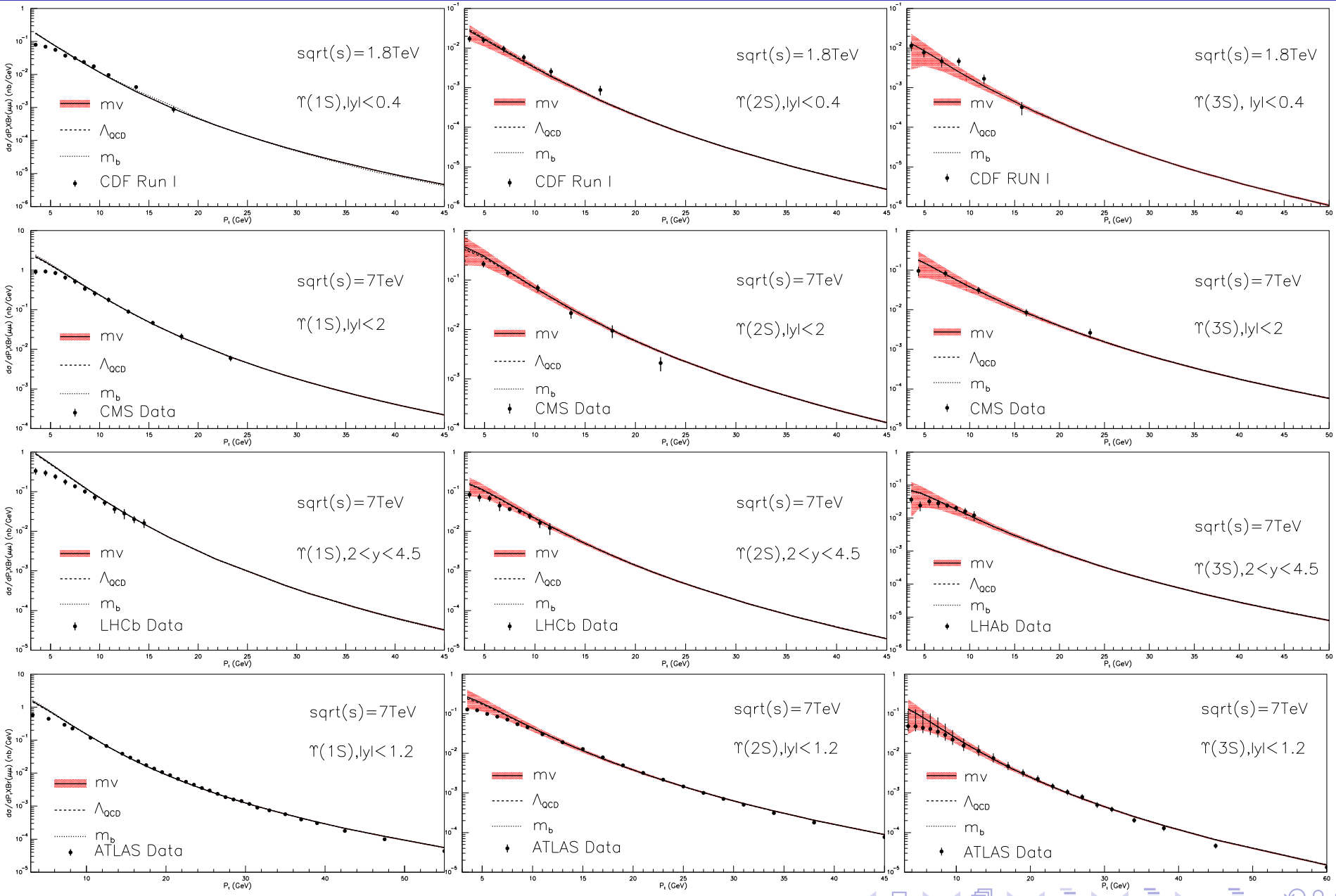
Figure: Polarization parameter λ of prompt J/ψ hadroproduction in helicity(left) and CS(right) frames.

PRL110, 042002, 2013, ArXiv:1205.6682, Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang

QCD Correction to $\Upsilon(1S, 2S, 3S)$ and $\chi_b(1P, 2P)$ production and polarization

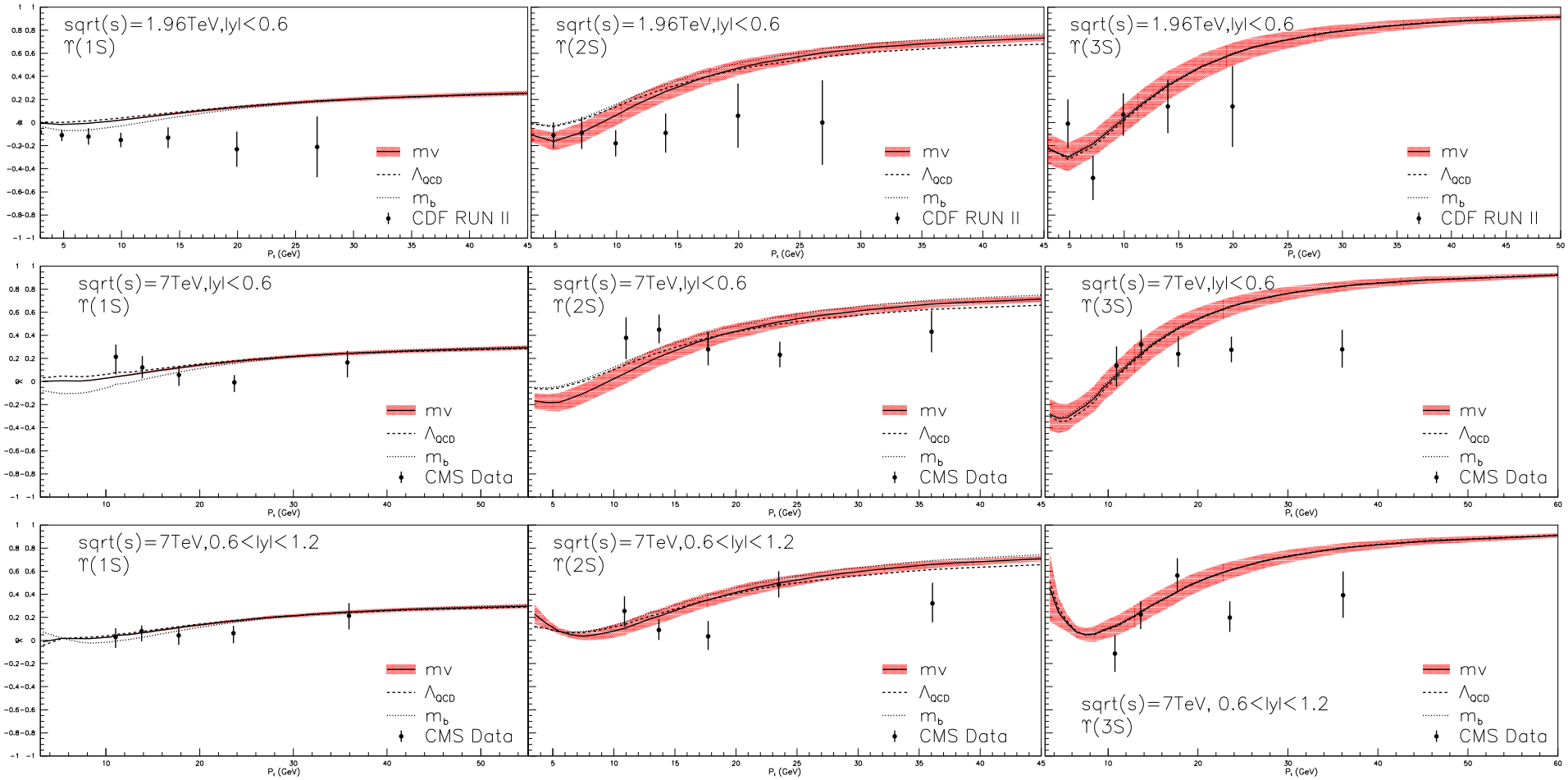
- recent measurement by the CMS collaboration at the LHC
- $m_b \sim 3m_c$ measns the perturbative QCD expansion in bottomium case is better than charmonium case.
- For heavy quark Q velocity v_Q at quarkonium rest frame, $v_b^2 \sim 0.1$ and $v_c^2 \sim 0.3$, it measns that nonrelativistic expansion in bottomium case is better than charmonium case.
- logarithm term $ln(m_Q/p_t)$ plays important role later, i.e. $p_t = 30$ GeV for $J/\psi \sim p_t = 3x30$ GeV for Υ.
- Can we expect better desciption of experimental measurement on $\Upsilon(1S, 2S, 3S)$ by NLO NRQCD calculation?
- $\chi_b(1P, 2P)$ must be included.
- Much more numerical calculation and more long-distance matrix parameters needed to be fixed from fit.
- The NRQCD scale dependence is studied by choice different $\mu_\Lambda = m_b, m_b v_b, \Lambda_{QCD}$.

QCD Correction to $\Upsilon(1S, 2S, 3S)$ and $\chi_b(1P, 2P)$ production



PRL112, 032001, 2014, by Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang

QCD Correction to $\Upsilon(1S, 2S, 3S)$ and $\chi_b(1P, 2P)$ polarization

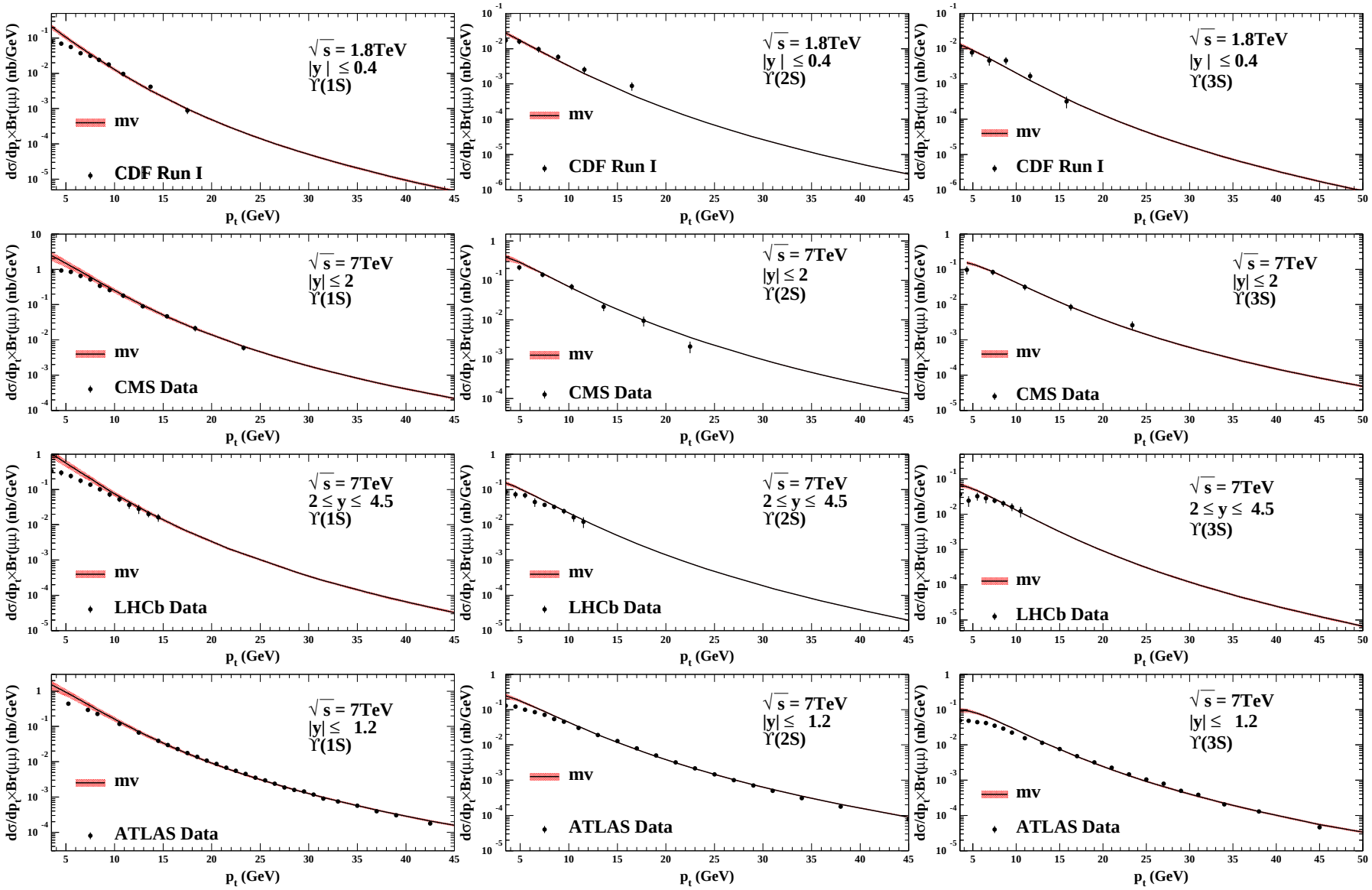


PRL112, 032001, 2014, arXiv:1305.0748, by Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang

Figure: Polarization parameter λ of prompt $\Upsilon(1S, 2S, 3S)$ hadroproduction in helicity frame

- The ratio of differential cross sections of $\chi_{b2}(1P)$ to $\chi_{b1}(1P)$ V. Khachatryan *et al.* (CMS Collaboration), arXiv:1409.5761 [hep-ex].
- The fractions of $\Upsilon(mS)$ $(m = 1, 2, 3)$ production from $\chi_b(nP)$ $(n = 1, 2, 3)$ feeddown contributions Aaij *et al.* (LHCb Collaboration), arXiv:1407.7734 [hep-ex].
- Updated fit has been presented by Hao Han, Yan-Qing Ma, Ce Meng, Hua-Sheng Shao, Yu-Jie Zhang, Kuang-Ta Chao in arXiv:1410.8537

Updated Fit on p_t distribution for $\Upsilon(1S, 2S, 3S)$ production



Updated fit for *Upsilon* (2015 Chinese Phys. C 39 123102) by Yu Feng, Bin Gong, Lu-Ping Wan, Jian-Xiong Wang

Figure: Polarization parameter λ of prompt $\Upsilon(2S)$ hadroproduction in helicity frame

Updated Fit on p_t distribution for $\Upsilon(1S, 2S, 3S)$ polarization

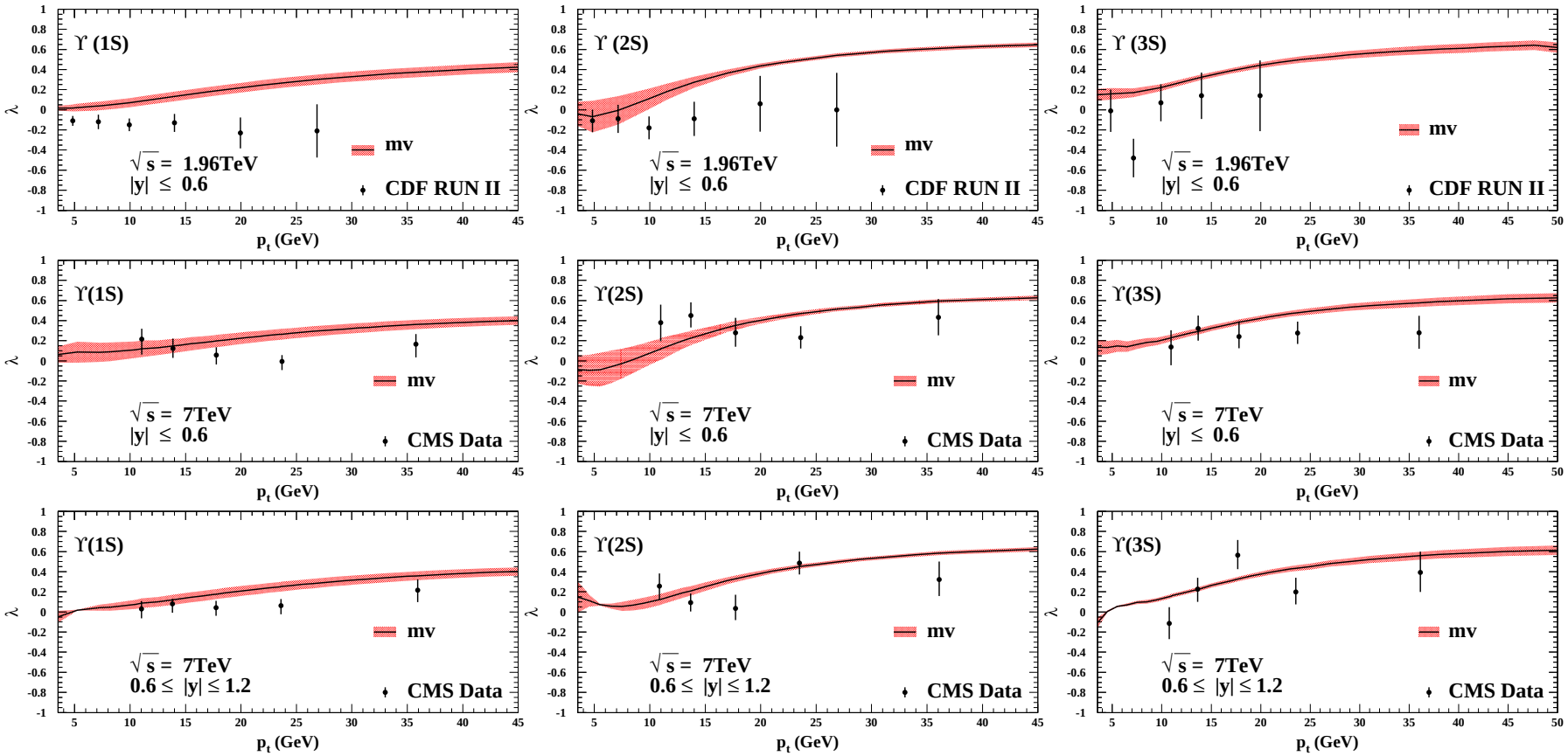


Figure: Polarization parameter λ for Υ hadroproduction at the Tevatron and LHC. From left to right: $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$. Rows from top to bottom correspond to different experimental conditions of CDF run II, CMS($|y| < 0.6$), and CMS($0.6 < |y| < 1.2$). The experimental data are taken from Refs.[**?**, **?**].

Updated fit for *Upsilon* (2015 Chinese Phys. C 39 123102) by Yu Feng, Bin Gong, Lu-Ping Wan, Jian-Xiong Wang

Figure: Polarization parameter λ of prompt $\Upsilon(2S)$ hadroproduction in helicity frame

Fractions $\mathcal{R}^{\chi_b(mP)}_{\Upsilon(nS)}$ and Ratio of the cross sections of $\chi_{b2}(1P)$ to $\chi_{b1}(1P)$

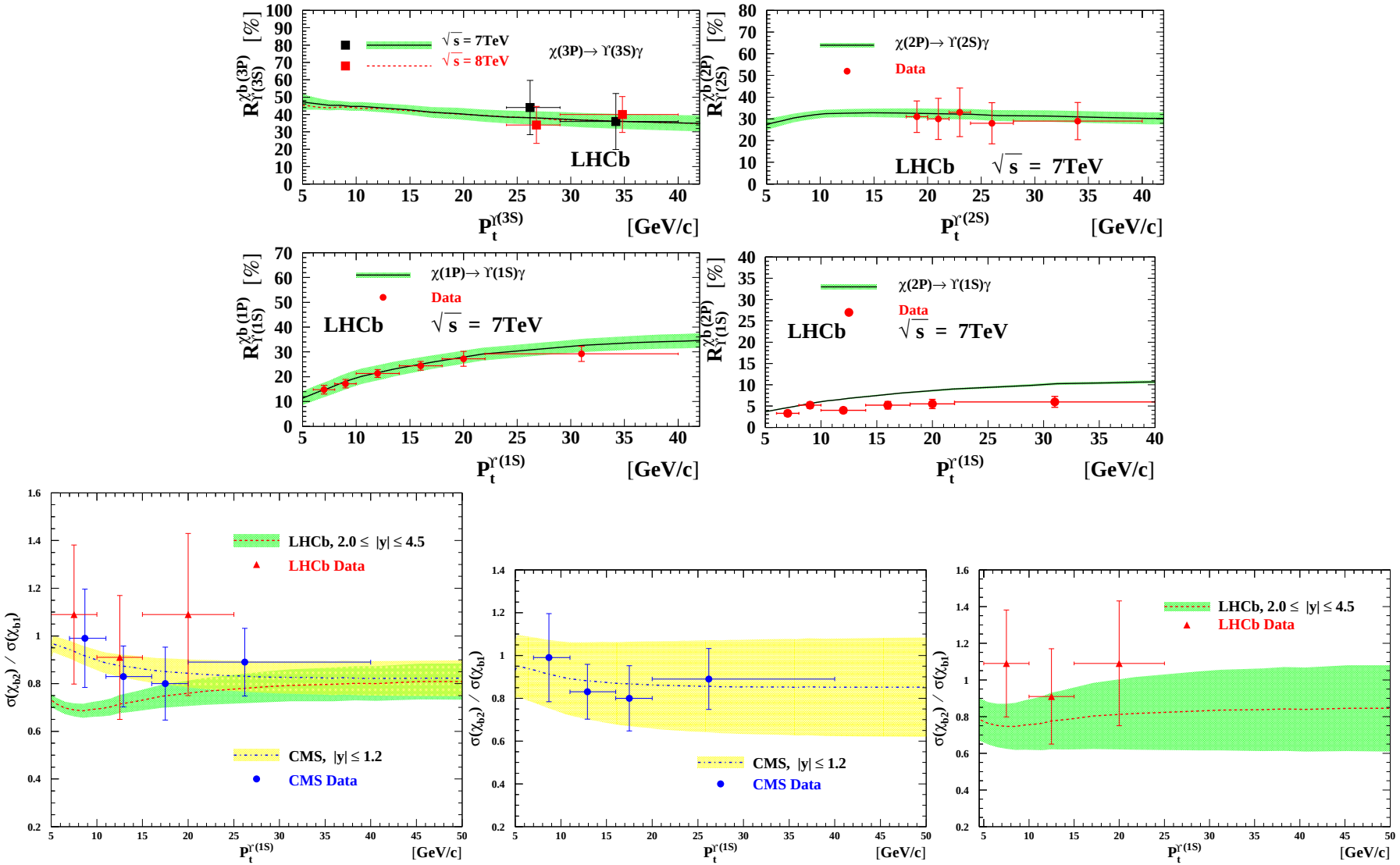


Figure: The experimental data are collected from Ref. [?].; The ratio of the cross sections of $\chi_{b2}(1P)$ to $\chi_{b1}(1P)$ production , as a function of p_t. The yellow band is the results for CMS experimental condition while the green band is for LHCb

$\mathcal{R}^{\chi_b(mP)}_{\Upsilon(nS)}$ as functions of p_t^{Υ}

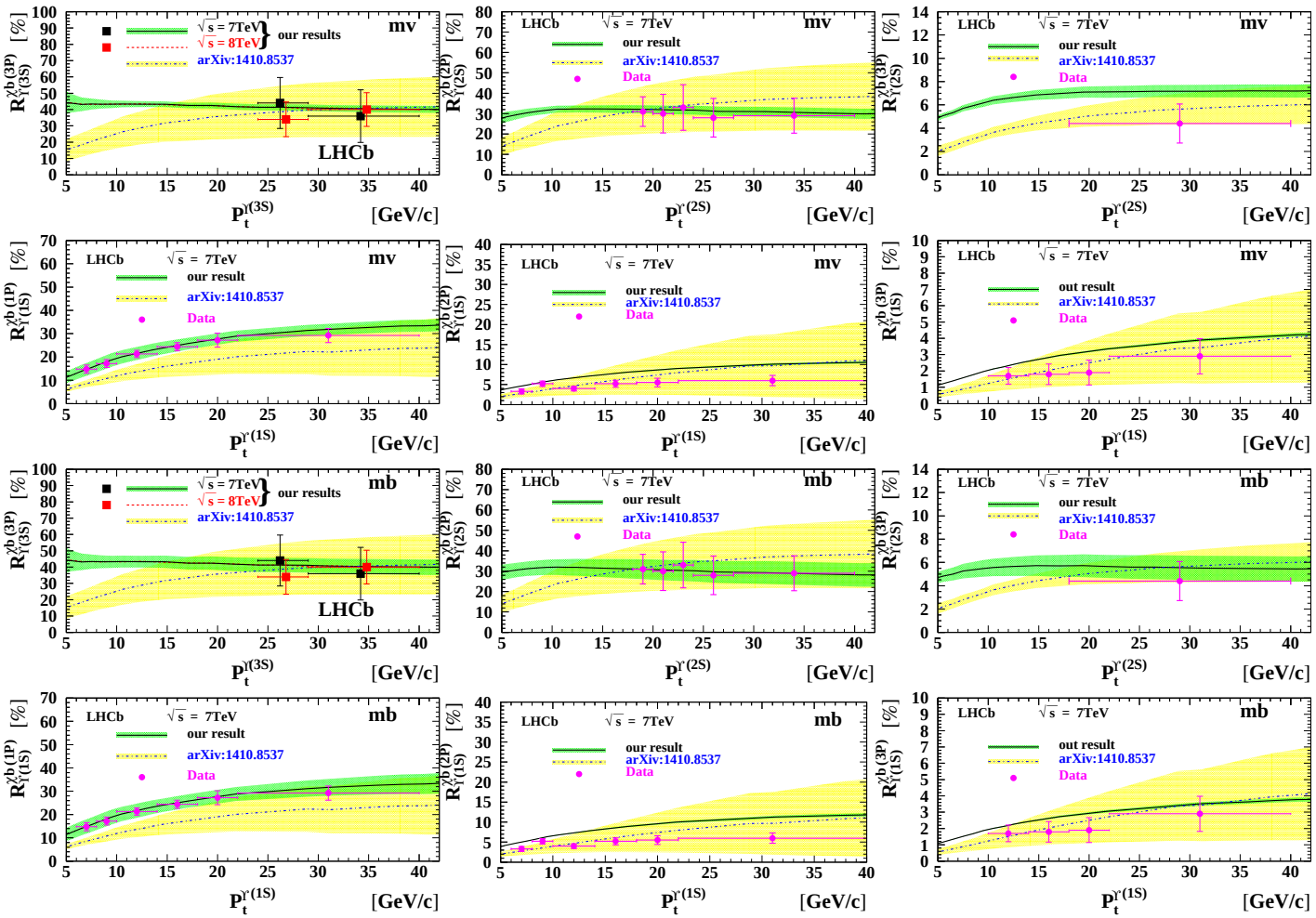


Figure: Different scheme to fit the experimental data. From left to right: $\mathcal{R}^{\chi_b(3P)}_{\Upsilon(3S)}$, $\mathcal{R}^{\chi_b(2P)}_{\Upsilon(2S)}$, $\mathcal{R}^{\chi_b(3P)}_{\Upsilon(2S)}$ in the first and third row and $\mathcal{R}^{\chi_b(1P)}_{\Upsilon(1S)}$, $\mathcal{R}^{\chi_b(2P)}_{\Upsilon(1S)}$, $\mathcal{R}^{\chi_b(3P)}_{\Upsilon(1S)}$ in the second and forth row. The experimental data are collected from Ref. [?].

${}^1S_0^{[8]}$ Dominance

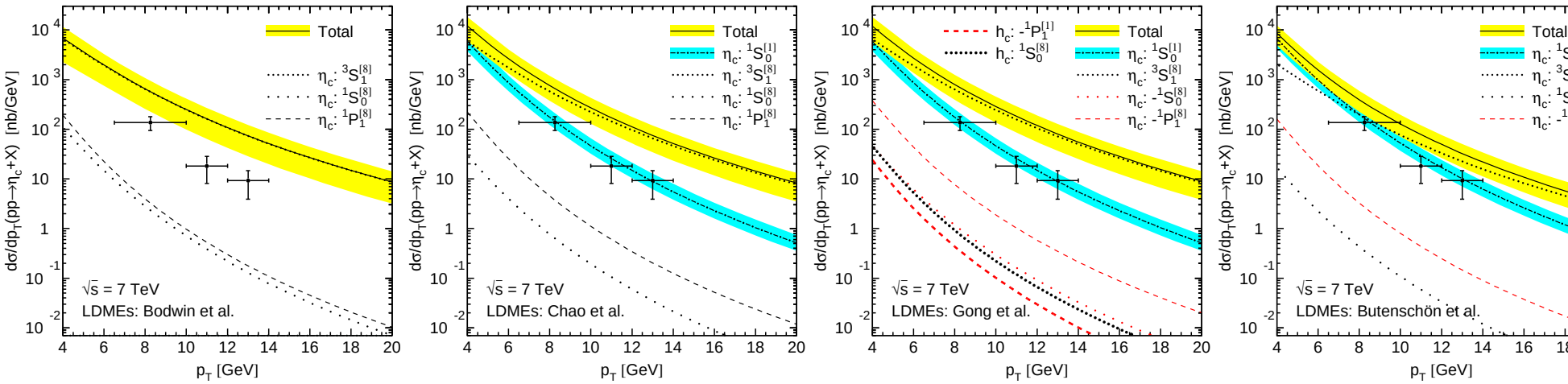
- K. T. Chao's group suggested ${}^1S_0^{[8]}$ dominance picture to solve the J/ψ polarization puzzle
- Reason:
  - p_t spectrum: NLO ${}^1S_0^{[8]}$ similar to direct J/ψ
  - Polarization: ${}^1S_0^{[8]}$ unpolarized
- Other groups came to the similar conclusions

$(\times 10^{-2}\ \mathrm{GeV}^3)$	Kniehl[1]	Chao[2]	Wang[3]	Bodwin[4]
$\langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]})\rangle$	3.04	8.9	9.7	9.9
$\langle \mathcal{O}^{J/\psi}({}^3S_1^{[8]})\rangle$	0.17	0.3	-0.46	1.1
$\langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]})\rangle/m_c^2$	-0.91	0.56	-0.95	1.1

[1] Butenschoen and Kniehl, PRL 107, 232001 (2011)
[2] Chao, Ma, Shao, Wang and Zhang, PRL 108, 242004 (2012)
[3] Gong, Wan, Wang and HFZ, PRL 110, 042002 (2013)
[4] Bodwin, Chung, Kim and Lee, PRL 113, 022001 (2014)

$^1S_0^{[8]}$ Dominance Picture Faces Challenge

- Challenges
  - LHCb Collaboration[5] released η_c hadroproduction measurement
  - Violate velocity scaling rule
  - Kniehl's group[6] cannot be described by the LDMEs which concide with the $^1S_0^{[8]}$ dominance picture (here they employed the heavy quark spin symmetry to obtain the LDMEs for η_c production)

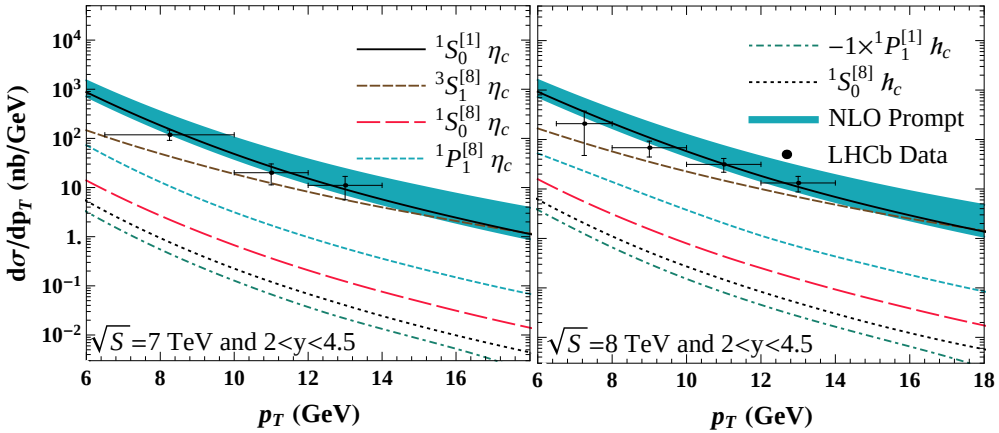


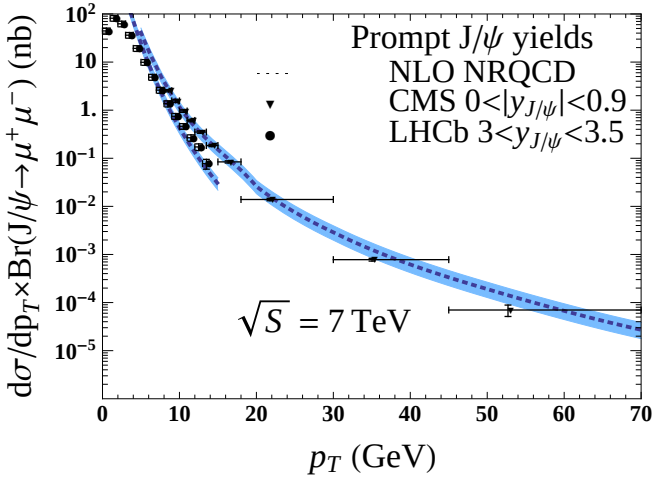
[5] LHCb Collaboration, EPJC 75, 311

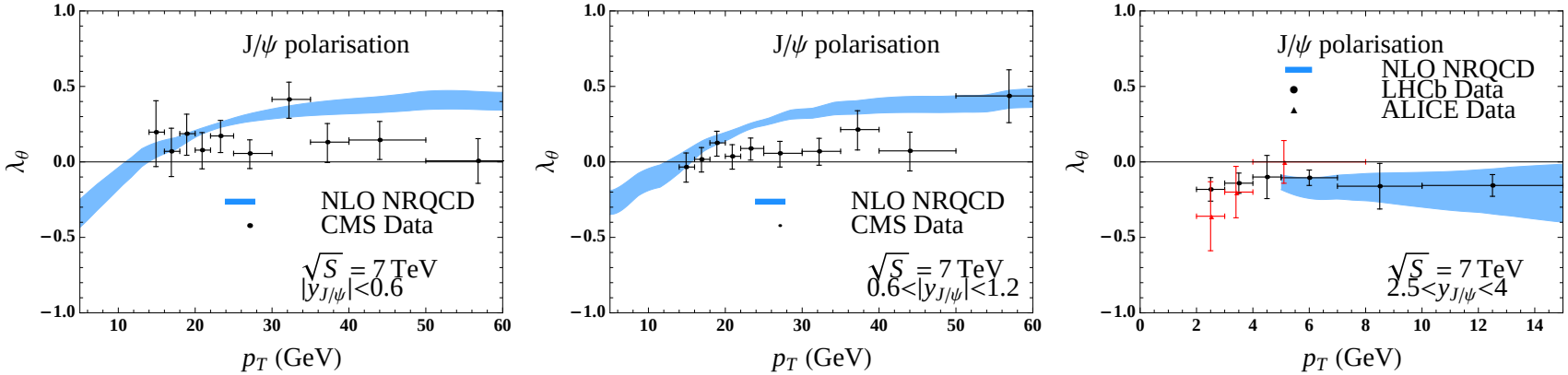
[6] Butenschoen, He and Kniehl, PRL 114, 092004 (2015); LHCb, EPJC 75, 311 (2015)

η_c and J/ψ hadroproduction data reconciled

- Chao's group[7] insist that only two degrees of freedom can be fixed using J/ψ yield data, namely M_0 and M_1
- η_c data can help to constrain the LDMEs for J/ψ production
- J/ψ and η_c data can both be described well at QCD NLO within the NRQCD framework



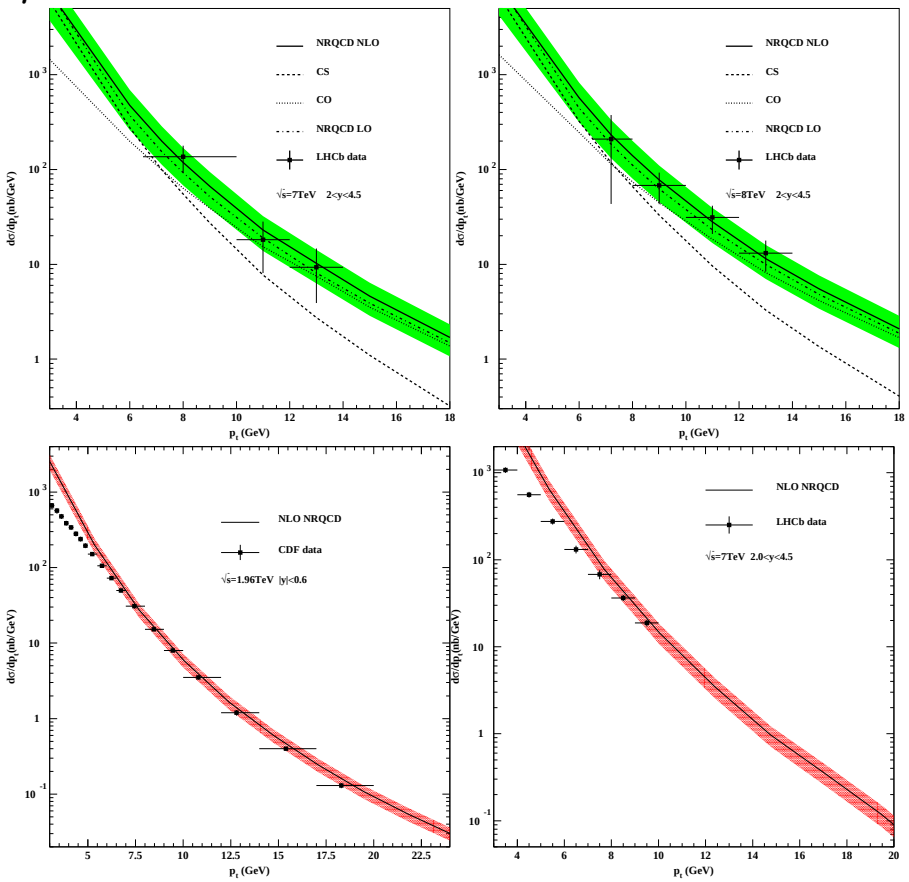




[7] Han, Ma, Meng, Shao and Chao, PRL 114, 092005

η_c and J/ψ hadroproduction data reconciled

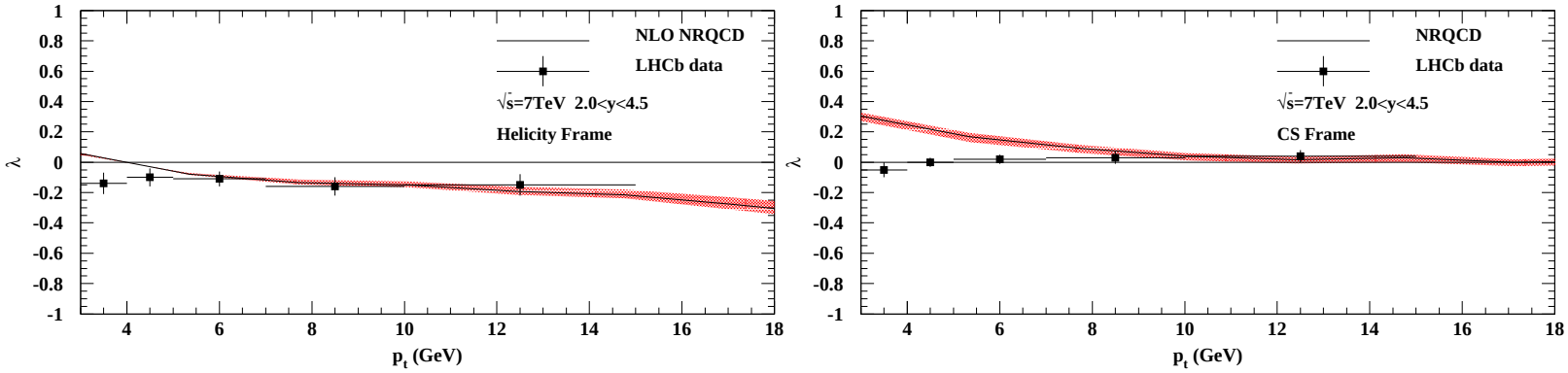
- Zhang'et. at[8] further pointed out that η_c data provided an excellent opportunity for the determination not only $\langle O^{J/\psi}(^1S_0^{[8]})\rangle$ but also the CS LDME, which is essential in the study of charmonium exclusive productions
- η_c data do not contradict NRQCD



[8] H. F. Zhang, Sun, Sang and Li, PRL 114, 092006 (2015)

Surprising Results for J/ψ Polarization

- J/ψ polarization at LHCb
- Good agreement



Surprising Results for J/ψ Polarization

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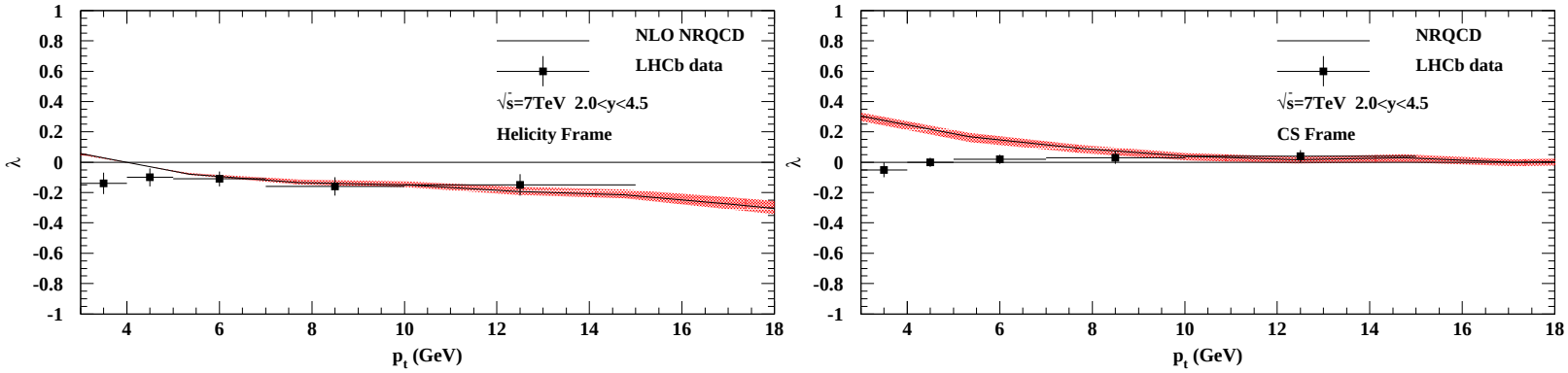

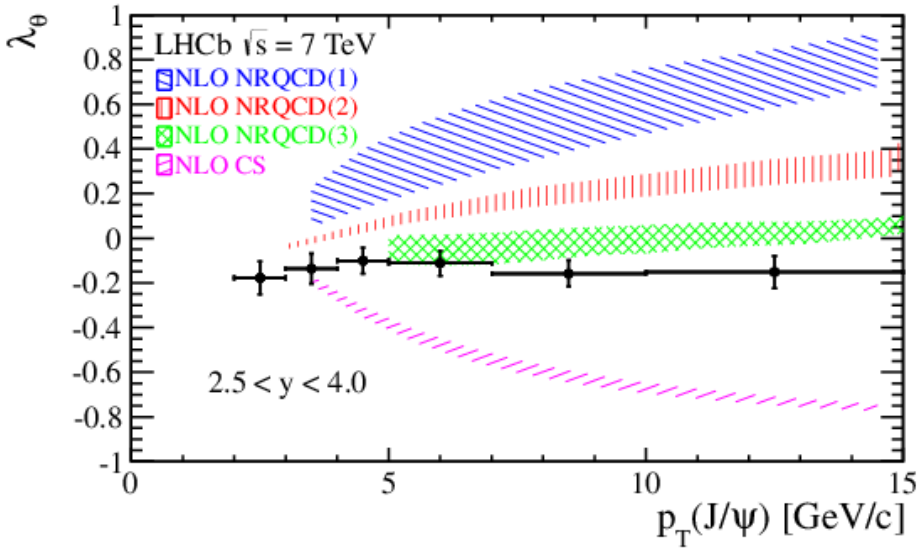

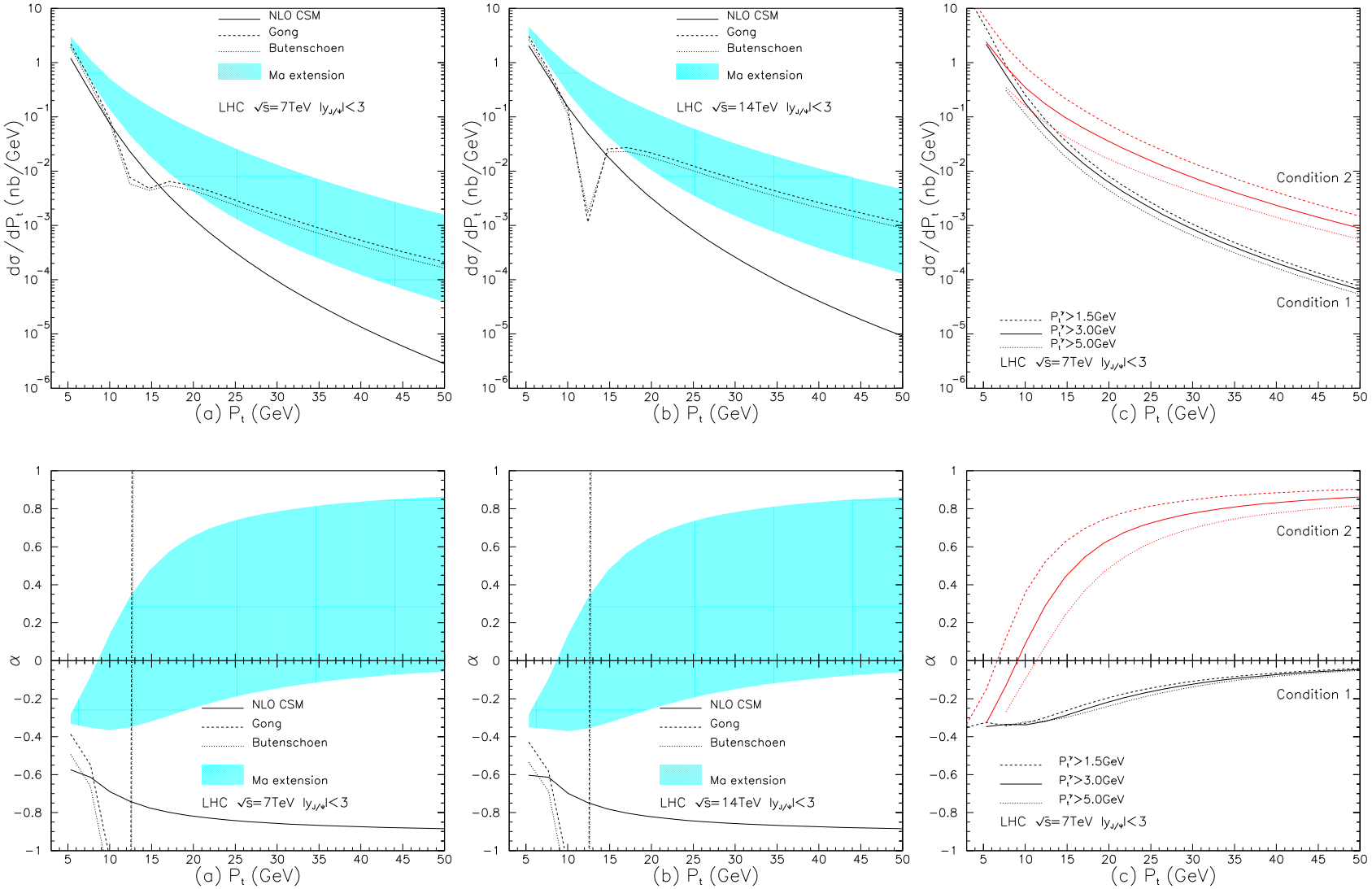

Figure: (a) and (b) are the p_t distribution for J/ψ production rate and polarization with $p_t^\gamma > 3$GeV cuts of the photon. The shaded band represent the uncertainty coming from the variation of scales(μ_f and μ_r), charm quark mass and the extension LDMEs listed in table II. (c) shows the p_t distribution different p_t^γ cuts and LDMEs.

Conclusion on: QCD Correction to $J/\psi(^3S_1^1, ^1S_0^8, ^3S_1^8, ^3P_J^8) + \gamma$ hadroproduction by Li Rong, Jian-Xiong Wang

- The three sets of LDMEs extracted at the NLO are used to obtain the numerical results and there is only one set of LDMEs can give a positive p_t distribution while the other two give negative p_t distribution at the large p_T region.
- This results indicates that the extraction of the NRQCD LDMEs from χ^2 fit between the theoretical calculation and experimental measurement is quite sensitive and trick due to the cancellation between the three color-octet channels.
- The color-octet contribution enhances the differential cross section about 2 order in the large p_t region.
- The color-octet contribution changes J/ψ polarization from longitudinal to transverse.

Brief Introduction to FDC package

Feynman Diagram Calculation(FDC).
This first version of FDC was presented at AIHENP93 workshp,1993.

FDC Homepage::
http://www.ihep.ac.cn/lunwen/wjx/public_html/index.html

FDC-LOOP
FDC-PWA
FDC-EMT

FDC-SM-and-Many-Extensions
FDC-NRQCD
FDC-MSSM

→ **Written in REDUCE, RLISP,C++. To generate Fortran**

→ **Event Generator**

Based on NRQCD factorization scheme, the cross section of h hadroproduction is

$$\sigma[pp \to hx] = \sum \int dx_1\, dx_2\, G_p^i G_p^j \hat{\sigma}[ij \to (Q\bar{Q})_n x] \langle \mathcal{O}_n^h \rangle, \tag{1}$$

where p is either a proton or antiproton, the indices i, j run over all the partonic species and n represents the $Q\bar{Q}$ intermediate states ($^3S_1 1$, $^3S_1 8$, $^1S_0 8$, $^3P_J 8$) for s-wave heavy quarkonium state, or ($^3P_J 1$, $^3S_1 8$) for p-wave heavy quarkonium state. The short-distance contribution $\hat{\sigma}$ can be perturbatively calculated and the long-distance matrix elements (LDMEs) $\langle \mathcal{O}_n^h \rangle$ represent the nonperturbative QCD effects.
For FDCHQHP, In order to calculate the short-distance coefficient, two spin projection operators

$$\begin{aligned} \Pi_0(P,p) &= \frac{1}{2\sqrt{2}E(E+m)} \left(\frac{1}{2} \not{P} + m + \not{p}\right) \frac{\not{P} + 2E}{4E} \gamma_5 \left(\frac{1}{2} \not{P} - m - \not{p}\right), \\ \Pi_1(P,p,\epsilon) &= \frac{-1}{2\sqrt{2}E(E+m)} \left(\frac{1}{2} \not{P} + m + \not{p}\right) \frac{\not{P} + 2E}{4E} \not{\epsilon} \left(\frac{1}{2} \not{P} - m - \not{p}\right), \end{aligned} \tag{2}$$

are implemented in for spin singlet and triplet intermediate states, where m is the mass of heavy quark, P is the momentum of quarkonium, $p = (p_Q - p_{\bar{Q}})/2$ is the "relative momentum" between heavy quark pair, and $E \equiv \sqrt{m^2 - p^2}$ can be regarded as half of the "mass" of quarkonium.
the heavy quarkonium polarization parameters λ_θ, $\lambda_{\theta\phi}$, λ_ϕ is defined as

$$\lambda_\theta = \frac{\mathrm{d}\sigma_{11} - \mathrm{d}\sigma_{00}}{\mathrm{d}\sigma_{11} + \mathrm{d}\sigma_{00}}, \lambda_{\theta\phi} = \frac{\sqrt{2}\mathrm{Re}\mathrm{d}\sigma_{10}}{\mathrm{d}\sigma_{11} + \mathrm{d}\sigma_{00}}, \lambda_\phi = \frac{2\mathrm{d}\sigma_{1,-1}}{\mathrm{d}\sigma_{11} + \mathrm{d}\sigma_{00}},$$

where $d\sigma_{S_z S_z'}$ is the spin density matrix of heavy quarkonium hadroproduction.

FDCHQHP: A Fortran Package generated by using FDC package

This package includes

- 6 channels
- 76 sub-processes
- almost 2 millions lines Fortran codes in total.

It can be run in paralleled mode with more than hundren thousands cpu with high efficiency.

STATES	LO sub-process	number of Feynman diagrams	NLO sub-process	number of Feynman diagrams
${}^3S_1^{(1)}$	$g+g \to (Q\bar{Q})_n + g$	6	$g+g \to (Q\bar{Q})_n + g$(one-loop)	128
			$g+g \to (QQ)_n + g + g$	60
			$g+g \to (QQ)_n + Q + Q$	42
			$g+g \to (QQ)_n + q + \bar{q}$	6
			$g+q(\bar{q}) \to (QQ)_n + g + q(\bar{q})$	6
${}^1S_0^{(8)}$(also ${}^3P_J^8$) or ${}^3S_1^{(8)}$ or ${}^3P_J^1$	$g+g \to (Q\bar{Q})_n + g$	(12,16,12)	$g+g \to (Q\bar{Q})_n + g$(one-loop)	(369,644,390)
	$g+q(\bar{q}) \to (QQ)_n + q(\bar{q})$	(2,5,2)	$g+q(\bar{q}) \to (QQ)_n + q(\bar{q})$(one-loop)	(61,156,65)
	$q+\bar{q} \to (Q\bar{Q})_n + g$	(2,5,2)	$q+\bar{q} \to (Q\bar{Q})_n + g$(one-loop)	(61,156,65)
			$g+g \to (QQ)_n + g + g$	(98,123,98)
			$g+g \to (Q\bar{Q})_n + q + \bar{q}$	(20,36,20)
			$g+q(\bar{q}) \to (QQ)_n + g + q(\bar{q})$	(20,36,20)
			$q+\bar{q} \to (Q\bar{Q})_n + g + g$	(20,36,20)
			$q+\bar{q} \to (QQ)_n + q + \bar{q}$	(4,14,4)
			$q+\bar{q} \to (Q\bar{Q})_n + q' + q'$	(2,7,2)
			$q+q \to (QQ)_n + q + q$	(4,14,4)
			$q+q' \to (QQ)_n + q + q'$	(2,7,2)

Table: The sub-processes for heavy quarkonium $c\bar{c}$ and $b\bar{b}$ prompt production at LO and NLO.

HELAC-Onia: an upgraded matrix-element and event generator for heavy quarkonium physics Hua-Sheng Shao (CERN),Comput.Phys.Commun. 198 (2016) 238-259

Summary

- It seems that NLO QCD for heavy Quarkonium production work well.
- For B-factories: NRQCD at NLO of α_s and v can well described J/ψ production data. strong constraint to **the values of color-octect matrix element of** $c\bar{c}(^1S_0^8, 3P_J^8)$ **to almost zero**. The dominant part $c\bar{c}(^3S_1^8)$ for hadronproduction is still there.
- The prediction on the polarization of prompt J/ψ hadroproduction is archived at QCD NLO, It seems that the polarization puzzle is solved (The fits to expermimental data is trick).
- The study on $J/\psi + \gamma$ production at the LHC show that there are still problem in the previous fits to explain J/ψ production. The experimental measurements on it are needed to clarify the situation.
- For Υ, The QCD NLO results can explain the measurements on the transverse momentum distribution of producation rate very well, and for the polarizations of $\Upsilon(1S, 2S, 3S)$, they are in good agreement with recent CMS measurement, but still have some distance from the CDF measurement.

Summary

- The polarization puzzle is solved. ....
  universality of NRQCD long-distance matrix elements
  Fix-order result is not good at small and large p_t region
  unphysics solution in large p_t, small p_t, for transverse or longitude polarization
  NRQCD factorization scale dependent problem.
  relativstic corrections
  freedom in fit,
- measurement on the $J/\psi + \gamma$ hadroproductioin can fix the freedom.
- new measurement with the p_t extend to very high p_t range, the theortical prediction for them are sensitive for LDMEs.
- no theortical predictions on other two polarization parameters, these should be archieved.
- the problem for large p_t predication based on fix-order perturbative calculation, resumation on large logrithm term $ln(p_t/m_q)$

Thank you!