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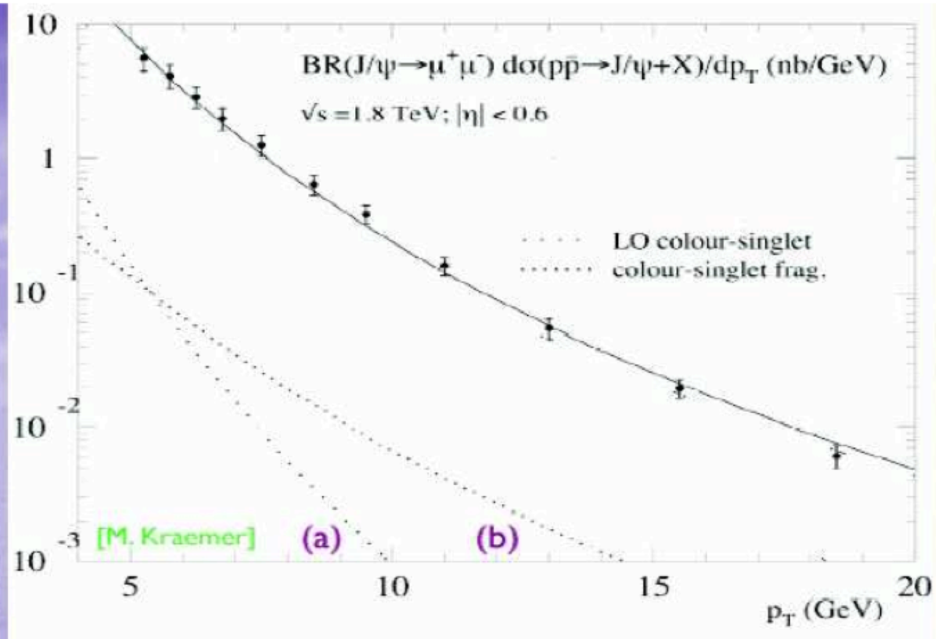
Uncertainty in the theoretical prediction for the polarization of heavy quarkonium produced at the LHC

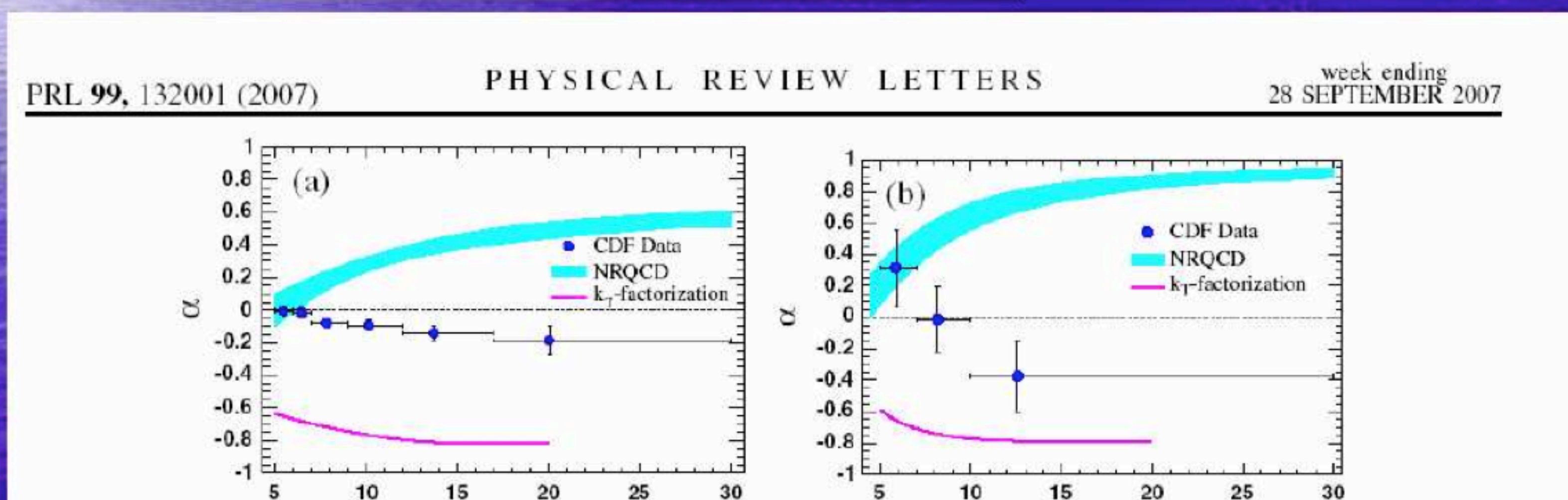
Jian-Xiong Wang

Institute of High Energy Physics, Chinese Academy of Science, Beijing

Based on our recently wrok with: B. Gong, R. Li, L. P. Wan

Introduction





- Perturbative and non-perturbative QCD, hadronization, factorization
- Color-singlet and Color-octet mechanism was proposed based on NRQCD since c-quark is heavy.
- Clear signal to detect J/ψ.
- heavy quarkonium production is a good place to testify these theoretical framework.
- But there are still many difficulties.
  - J/ψ photoproduction at HERA
  - J/ψ production at the B factories
  - J/ψ polarization at the Tevatron
- NLO corrections are important.
  - Double charmonium production at the B factories

- The predicacation for J/Ψ Polarization at LO was done by Color---singlet and Octect: E. Braaten, B. A. Kniehl and J. Lee, 2000, others ……

- The predication for J/Ψ Polarization at NLO was done by
Color---singlet: B. Gong, J. X. Wang, 2007
Color---octet (${}^3S_1^8, {}^1S_0^8$) : B. Gong, X. Q. Li and J. X. Wang, 2008

- How about (${}^3P_J^8$) color---octet contribution to J/Ψ polarization?
****Very difficult and not available yet.(Butenschoen, Bernd A. Kniehl, arXiv: 1109.1476, for photoproduction)

To go through the problem to obtain the predication for LHC measurement:

- Complete calculation

- One possible way: New Factorization scheme for Heavy Quarkonium Production, Z. B. Kang G. Sterman, J. W. Qiu, arXiv: 1109.1520

- Another way: Try to give a estimate under some reasonable approximation with uncertainty.

polarization of quarkonium

$$\frac{d\sigma}{d\Omega dy} \propto 1 + \lambda(y)\cos^2\theta + \mu(y)\sin 2\theta\cos\phi + \frac{\nu(y)}{2}\sin^2\theta\cos 2\phi,$$

where y stands for a suitable variable (such as transverse momentum p_t) and the θ and ϕ are the polar an

azimuthal angles of the outgoing l^+ respectively. The polarization parameters, λ, μ and ν, are related to tl

density matrix of quarkonium production as

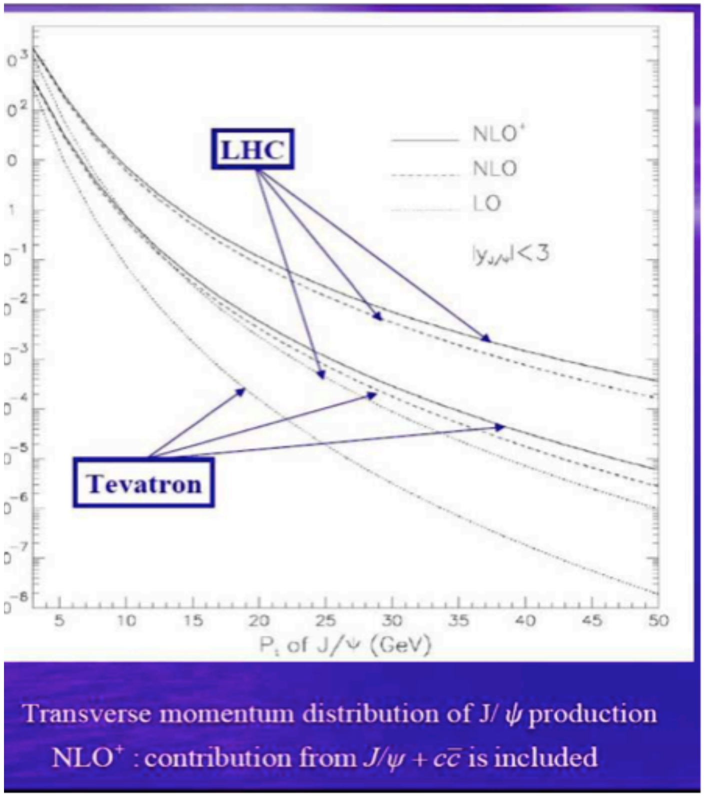
$$\lambda(y) = \frac{\frac{d\sigma_{11}}{dy} - \frac{d\sigma_{00}}{dy}}{\frac{d\sigma_{11}}{dy} + \frac{d\sigma_{00}}{dy}}, \quad \mu(y) = \frac{\sqrt{2}Re\frac{d\sigma_{10}}{dy}}{\frac{d\sigma_{11}}{dy} + \frac{d\sigma_{00}}{dy}}, \quad \nu(y) = \frac{2\frac{d\sigma_{1-1}}{dy}}{\frac{d\sigma_{11}}{dy} + \frac{d\sigma_{00}}{dy}}$$

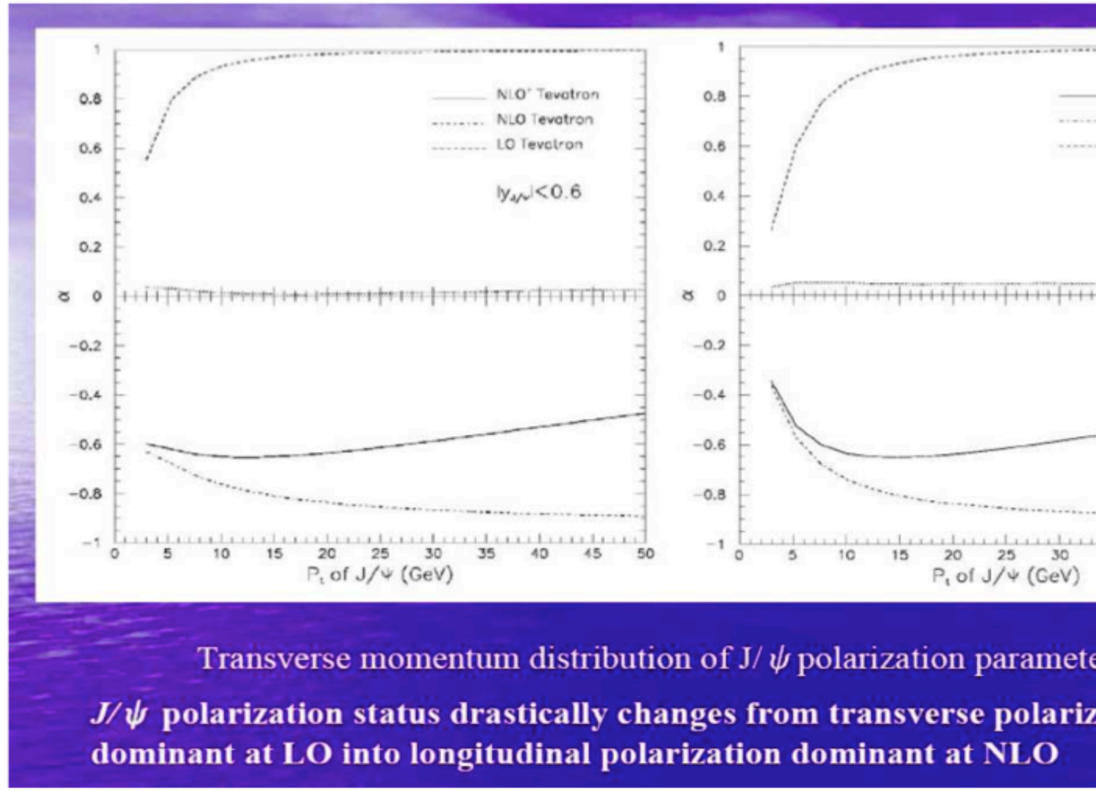
Here $d\sigma_{\lambda\lambda'}/dy$ are the 'differential density matrix elements' and defined as

$$\frac{d\sigma_{\lambda\lambda'}}{dy} = \frac{1}{F}\int\prod_{i=1}^{n}\frac{d^3p_i}{2E_i}\delta^4(p_a + p_b - \sum_{i=1}^{n}p_i)\delta(y - y(p_{J/\psi}))M(\lambda)M^*(\lambda'),$$

where $M(\lambda)$ is the matrix element of polarized J/ψ production, λ and λ' stand for the polarization,

Correction to color-singlet J/ψ production



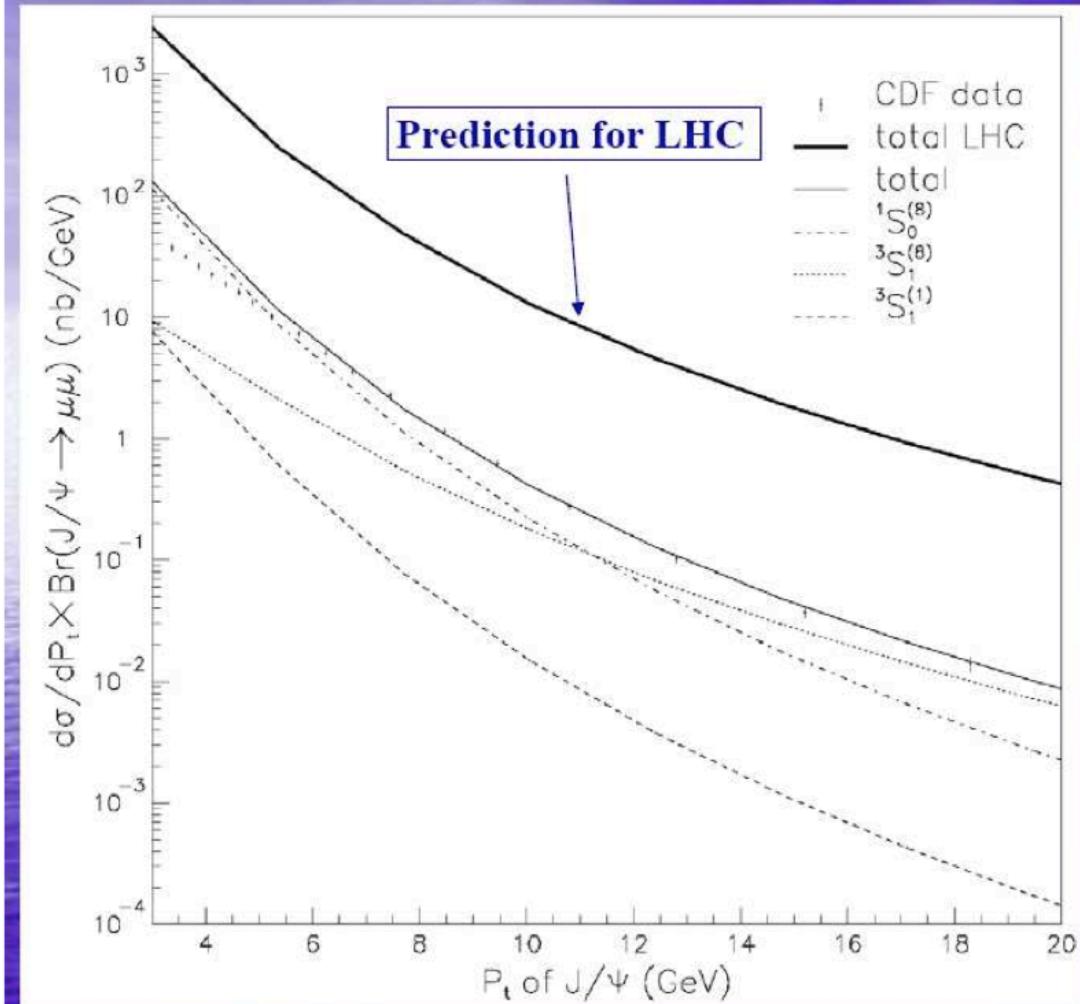


P_t distribution of J/ψ production at QCD NLO was calculated in
PRL98,252002 (2007), J. Campbell, F. Maltoni F. Tramontano

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 color-octet J/ψ production–p_t



$$\mu_r = \mu_f = \sqrt{(2m_c)^2 + p_t^2}$$

$$\left| y_{J/\psi} \right|_{\text{Tevatron}} < 0.6$$

$$\left| y_{J/\psi} \right|_{\text{LHC}} < 3$$

Our fitted matrix elements:

$$\langle \mathcal{O}_8^{\psi}(^3S_1) \rangle = 0.0045 \ \text{GeV}^3$$

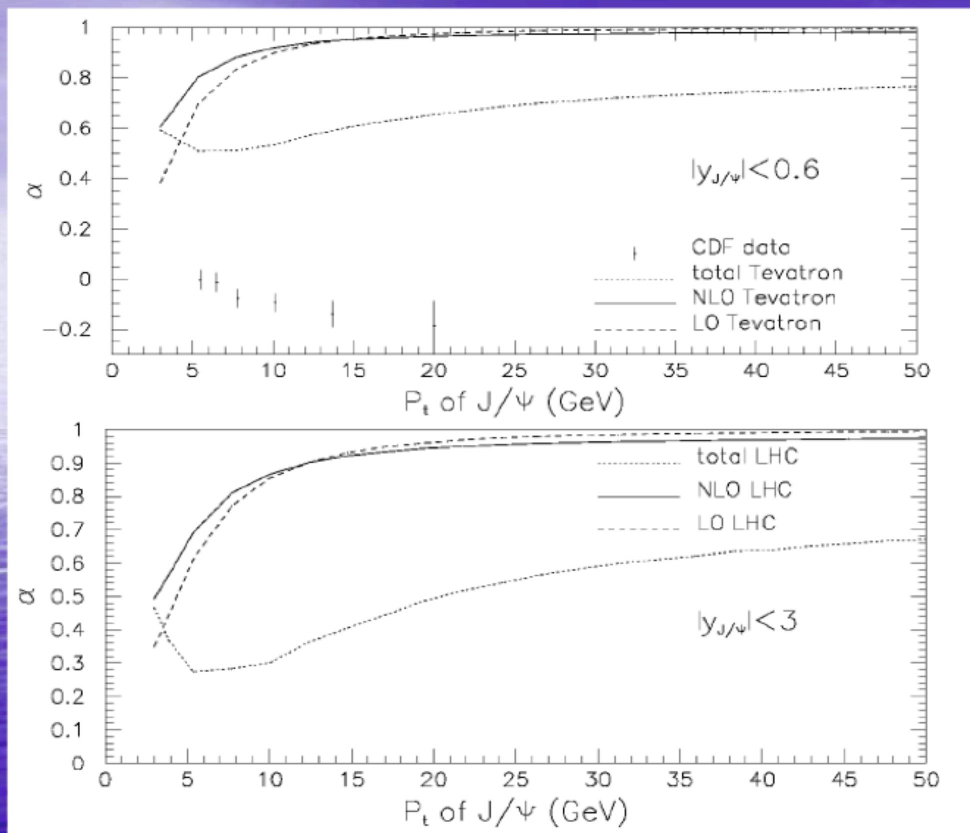
$$\langle \mathcal{O}_8^{\psi}(^1S_0) \rangle = 0.0760 \ \text{GeV}^3$$

Notes in fitting

- Experimental data with p_t<6 GeV has been abandoned
- Feed down from ψ' has been included by multiplying a factor of $B(\psi' \to J/\psi + X) \times \langle \mathcal{O}_n^{\psi'} \rangle / \langle \mathcal{O}_n^{\psi} \rangle$
- Contribution via P-wave has not been included

QCD Correction to color-octet J/ψ production–polarization

Transverse momentum distribution of polarization parameter α for prompt J/ψ



Upper: Tevatron
Lower: LHC

- Dash and solid lines are LO and NLO results for J/psi polarization via color octet state $^3S_1$. It has changed little when NLO QCD corrections are included.
- $^1S_0$ gives contribution to $\alpha=0$.
- Obvious gap is shown between our prediction and experimental data at Tevatron.

Phys.Lett.B673:197-200,2009, Erratum-ibid.693:612-613,2010.
arXiv:0805.4751 [hep-ph], B. Gong, X. Q. Li and J. X. Wang

Complete QCD correction to Color-Octet J/Ψ

Y. Q. Ma, K. Wang and K. T. Chao, Phys. Rev. Lett. **106**, 042002 (2011)

M. Butenschoen and B. A. Kniehl, Phys. Rev. Lett. **106**, 022003 (2011)

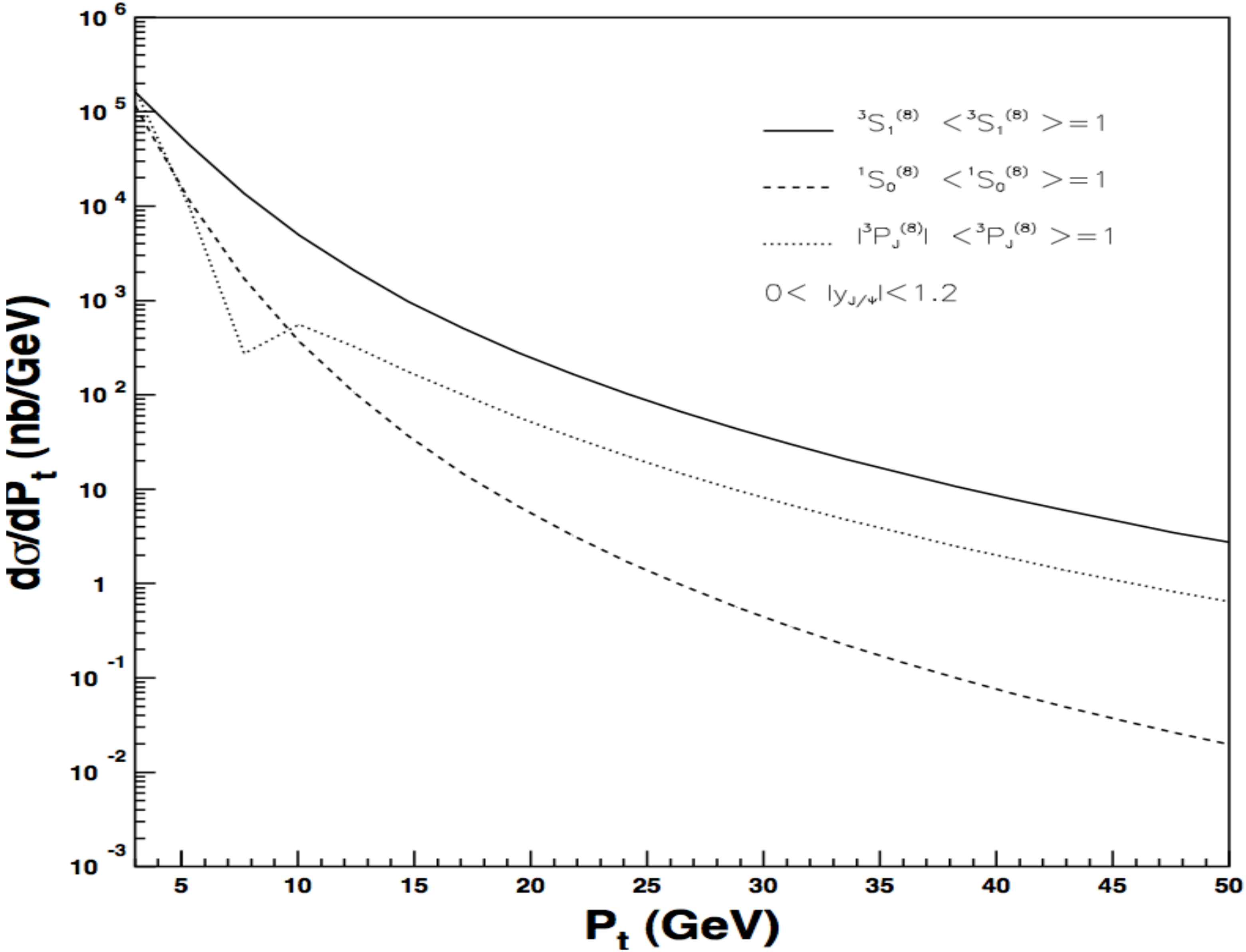
There are negtive non-perturbative matrix elements for color-octet states in p_t distribution fitting in both work. In first paper, the authors show that the short-distance coefficient of ${}^3P_J^8$ can be decomposed as

$$\frac{d\hat{\sigma}[{}^3P_J^8]}{dp_t} = \frac{r_0}{m_c^2}\frac{d\hat{\sigma}[{}^1S_0^8]}{dp_t} + \frac{r_1}{m_c^2}\frac{d\hat{\sigma}[{}^3S_1^8]}{dp_t}. \tag{8}$$

They obtain that $r_0 = 4.1$ and $r_1 = -0.56$ for the LHC. And then the contribution from color-octet P-wave states can be properly included by using the linearly combined long-distance matrix elements defined as

$$\begin{aligned} M_{0,r_0}^{J/\psi} &=< \mathcal{O}^{J/\psi}({}^1S_0^8 > + \frac{r_0}{m_c^2} < \mathcal{O}^{J/\psi}({}^3P_0^8) >, \\ M_{1,r_1}^{J/\psi} &=< \mathcal{O}^{J/\psi}({}^3S_1^8 > + \frac{r_1}{m_c^2} < \mathcal{O}^{J/\psi}({}^3P_0^8) > \end{aligned} \tag{9}$$

From the above decomposition, the matrix elements $M_{1,r_1}^{J/\psi} = 0.0021$ and $M_{0,r_0}^{J/\psi} = 0.0075$ were extracted in our previous work Gong:2008ft. Keeping the $< \mathcal{O}^{J/\psi}({}^3S_1^8 >$ and $< \mathcal{O}^{J/\psi}({}^1S_0^8 >$ being positive and sovled the



$^3S_1^{(8)}$ $\langle{}^3S_1^{(8)}\rangle=1$
$^1S_0^{(8)}$ $\langle{}^1S_0^{(8)}\rangle=1$
$|{}^3P_J^{(8)}|$ $\langle{}^3P_J^{(8)}\rangle=1$
$0<|y_{J/\psi}|<1.2$
$d\sigma/dP_t$ (nb/GeV)
P_t (GeV)

Problem of Negative color-octet matrix elements

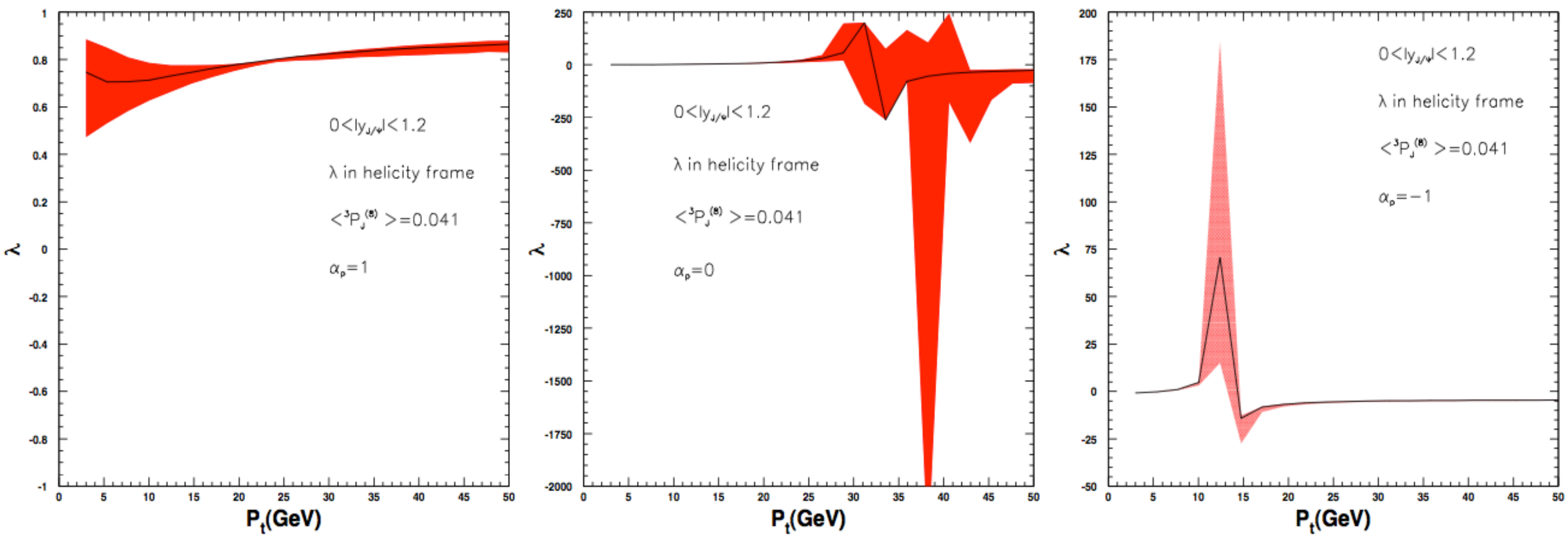


Figure: The band of the polarization parameter λ of J/ψ production including ${}^3P_J^{(8)}$ contributions. The polarization of ${}^3P_J^{(8)}$ is α=1, α=0, and α=-1 respectively.

$$<^3\ P_J^{(8)}>=0.041GeV^3,\ \ <^3\ S_1^{(8)}>=0.0123GeV^3,\ \ <^1\ S_0^{(8)}>=0. \qquad (10)$$

Problem of Negative color-octet matrix elements

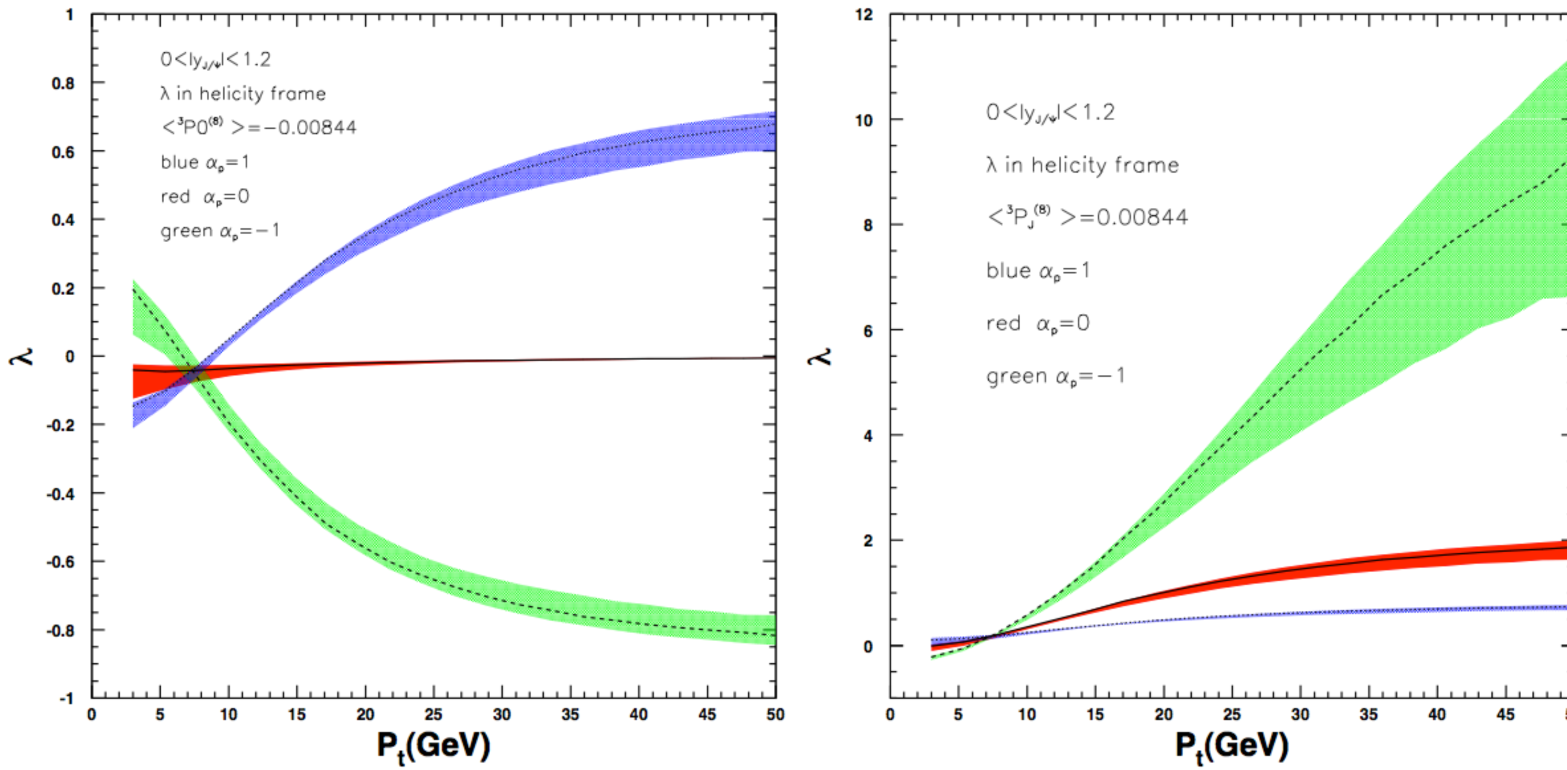


Figure: The band of the polarization parameter λ of J/ψ production including ${}^3P_J^{(8)}$ contributions. The polarization of ${}^3P_J^{(8)}$ is α=1, α=0, and α=-1 in each figure.

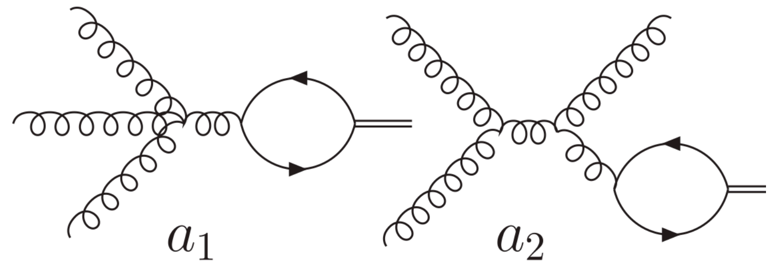
We give two different ${}^3P_J^{(8)}$ matrix elements with

$$right - figure : <^3\ P_J^{(8)}>= -0.00844GeV^3,\ <^3\ S_1^{(8)}>= 0,\ <^1\ S_0^{(8)}>= 0.0904GeV^3. \quad (11)$$

$$left - figure :\ <^3\ P_J^{(8)}>= 0.00844GeV^3,\ <^3\ S_1^{(8)}>= 0.0042,\ <^1\ S_0^{(8)}>= 0.0596GeV^3. \quad (12)$$

Our way to treat color octet ($^3P_J^8$)contribution to J/Ψ polarization

Dominant contribution Feynman Diagrams for $^3S_1^8$



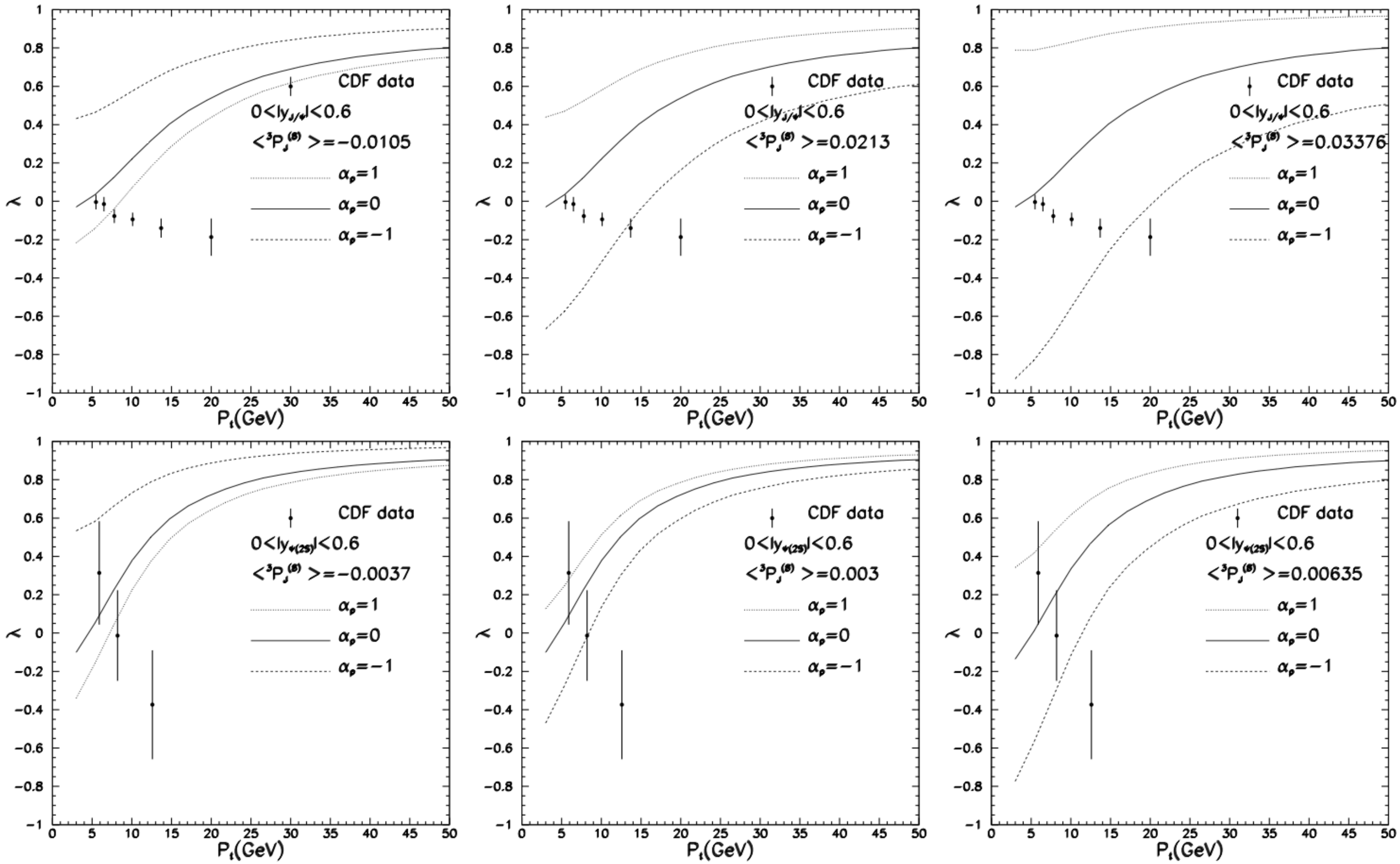
For all the Feynman Diagram, do $^3S_1^8 \Rightarrow {}^3P_J^8 + g(soft)$

Will generate the 1/P_t^4 term in P-wave color-octet contribution

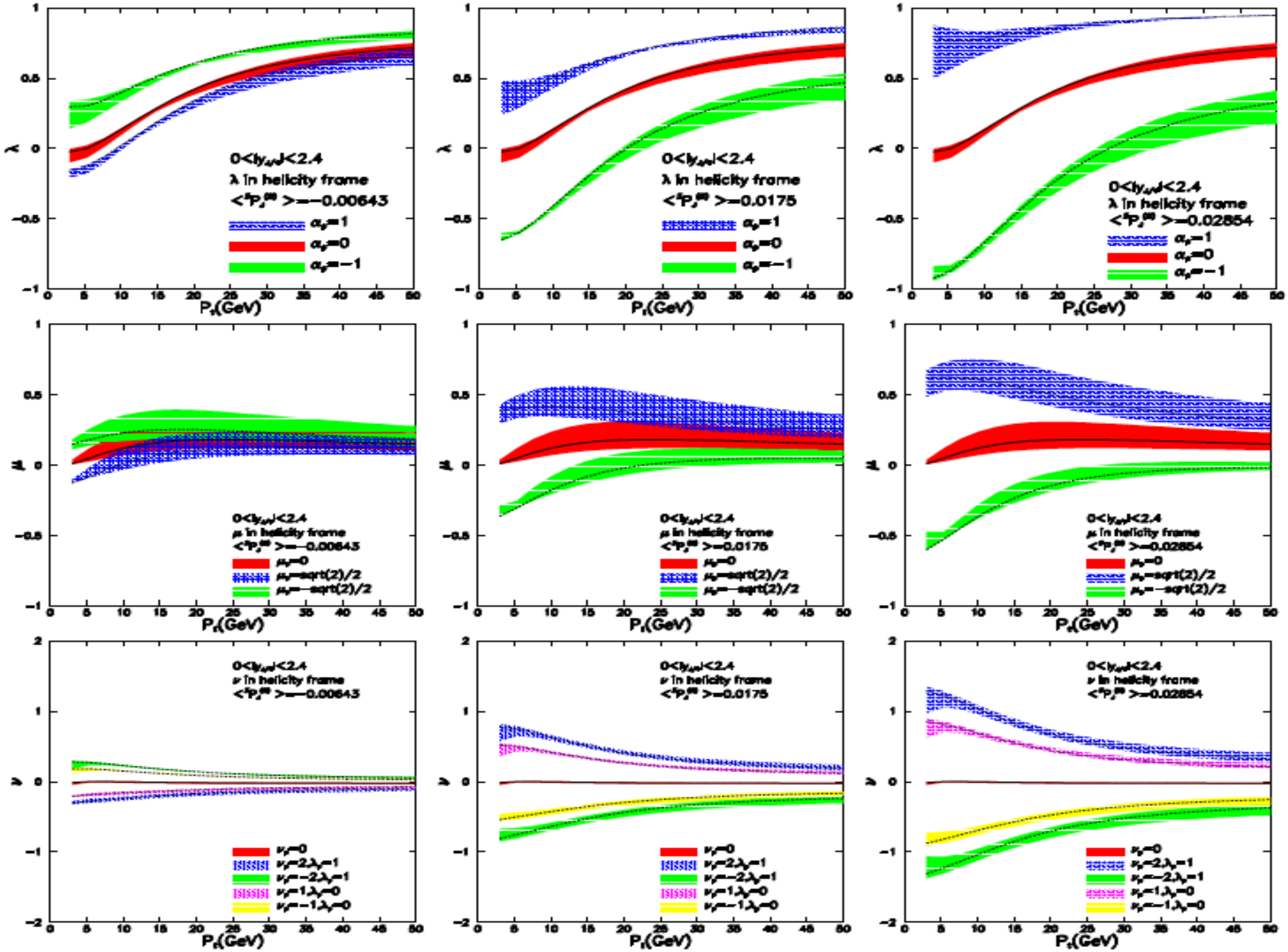
Therefore, we made two approximations:

1. The polarization of the $^3S_1^8$ like part of $^3P_J^8$ will be treated exactly the same as $^3S_1^8$
2. The polarization of the $^1S_0^8$ like part of $^3P_J^8$ will be treated exactly the same as $^1S_0^8$

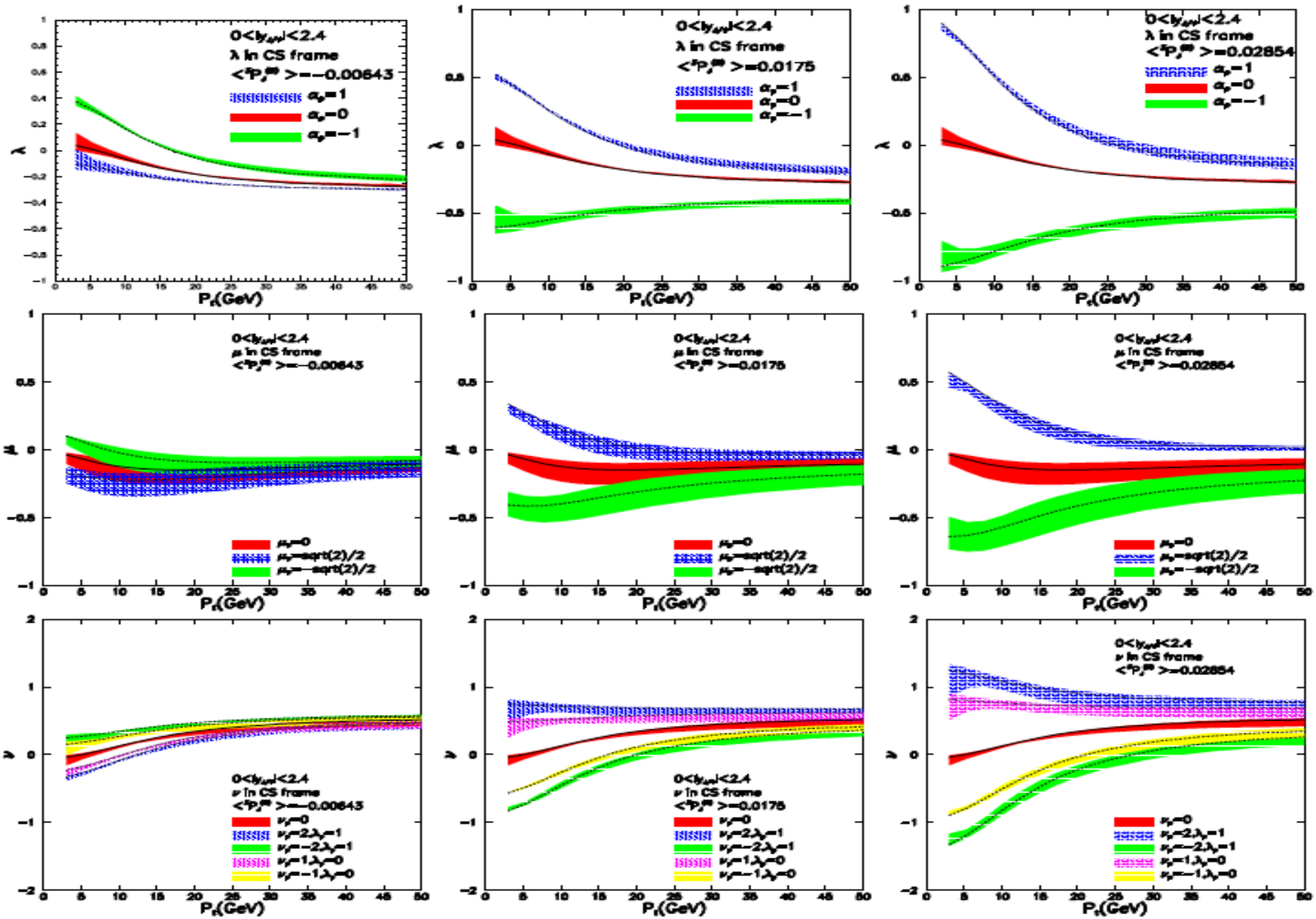
J/Ψ,Ψ(2s) Polarization at Tevatron at NLO level



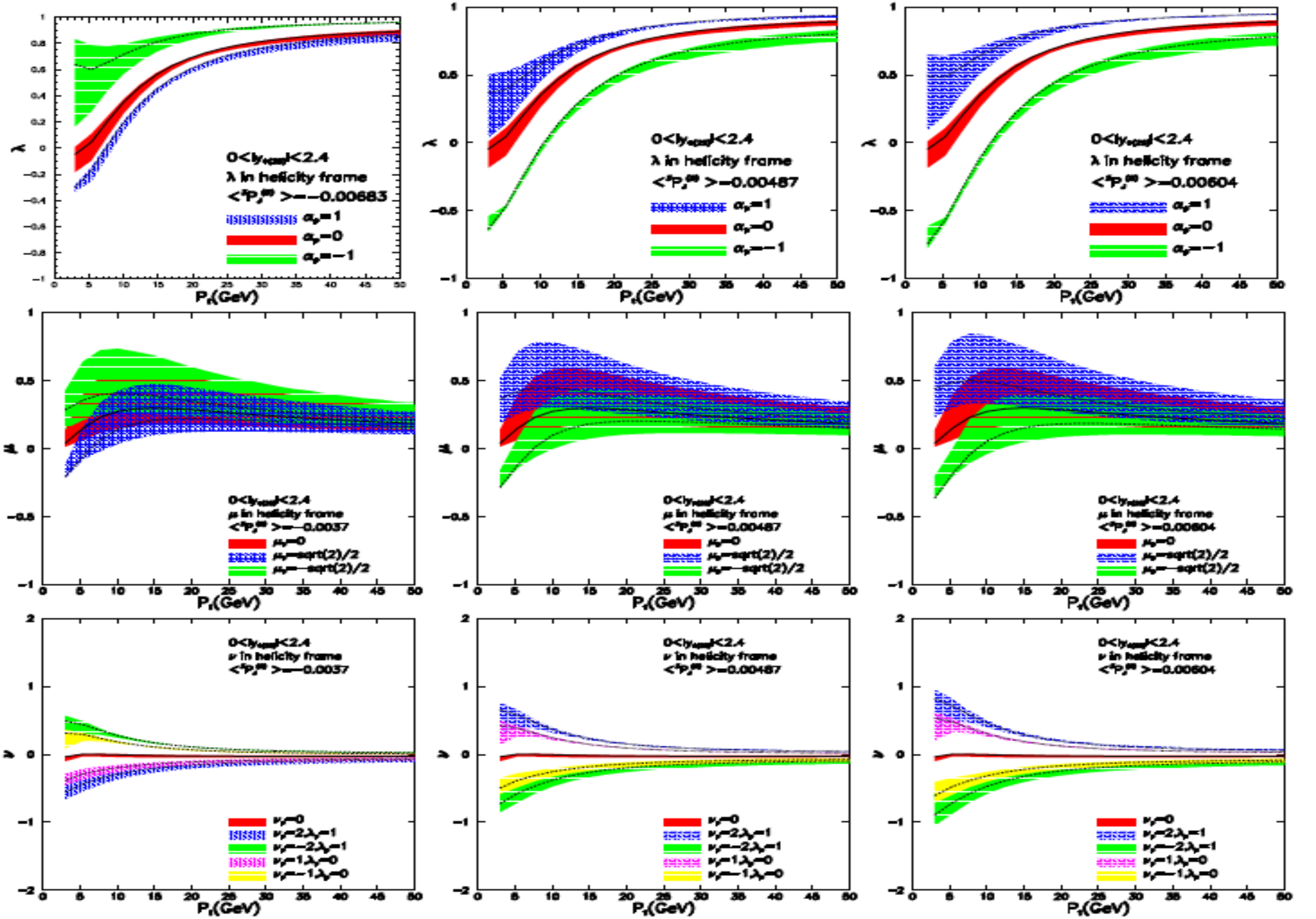
The predication for J/Ψ polarization at LHC (Helicity frame)



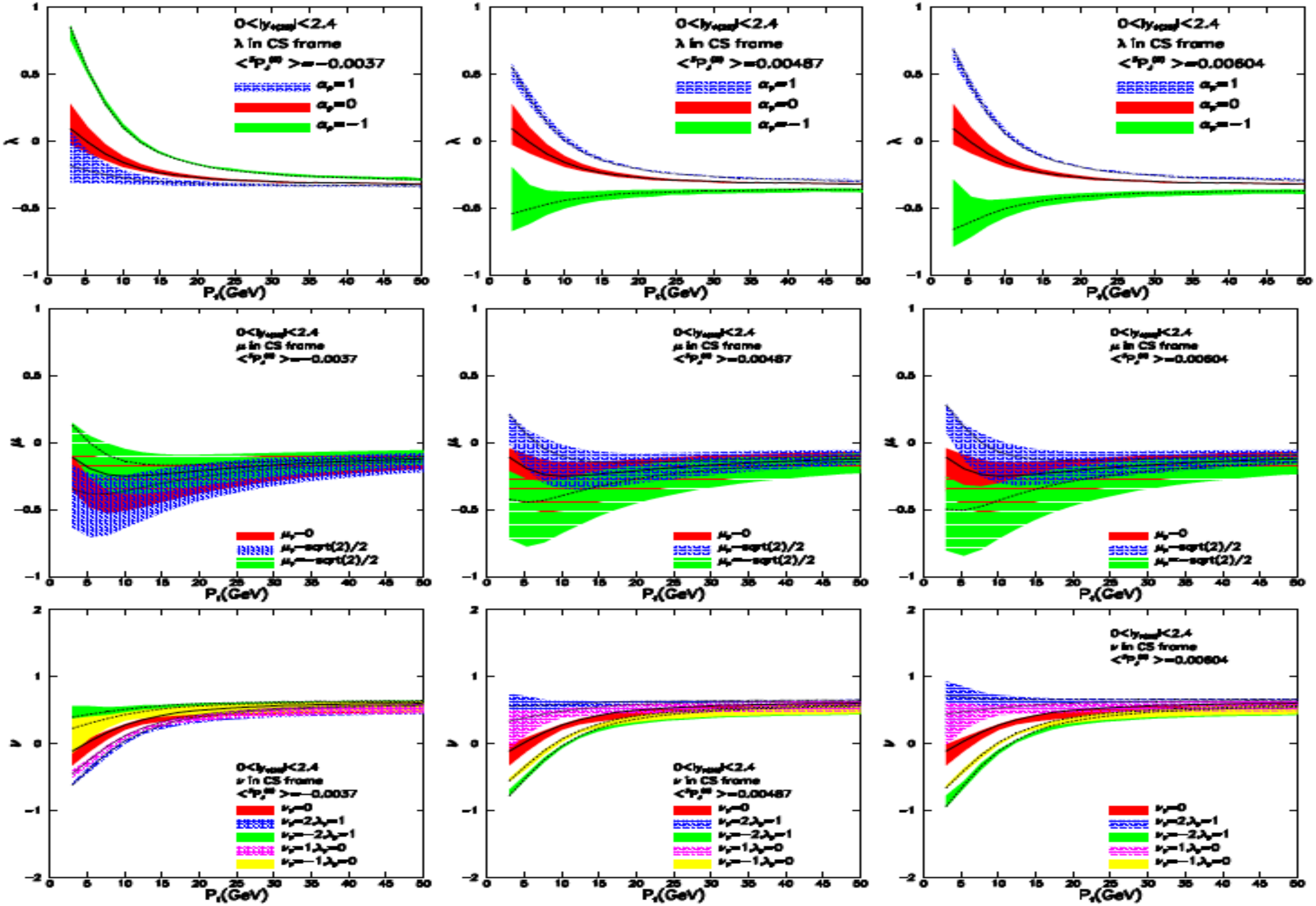
The predication for J/Ψ polarization at LHC (CS frame)



The predication for Ψ(2s) at LHC (Helicity frame)



The predication for Ψ(2s) at LHC (CS frame)



Summary and Discussion

- The negtive non-perturbative matrix elements for color-octet states in pt distribution fitting will bring trouble in polarization calculation.
- Based on some resonable assumptions, a: (${}^3P_J^8$+ g(E < Ec)) part should be treated as exactly as ${}^3S_1^8$ in polarization calculation, b: the remained part be approximationly treated as the LO result, the heavy quarkonium polarization can be presented at QCD NLO.
- The complet theoretical prediction at QCD NLO on heavy quarkonium polarization is a challenge task, (Mathias Butenschoen, Bernd A. Kniehl, arXiv:1109.1476)
- The uncertainty of the polarizatioin prediction on Ψ(2s),ϒ(2s),ϒ(3s) production is easier to control than it in J/Ψ ,cases.

Thank you!