The remaining parts for the long-standing J/ψ polarization puzzle

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Based on our work: Phys.Rev.D99,014044;

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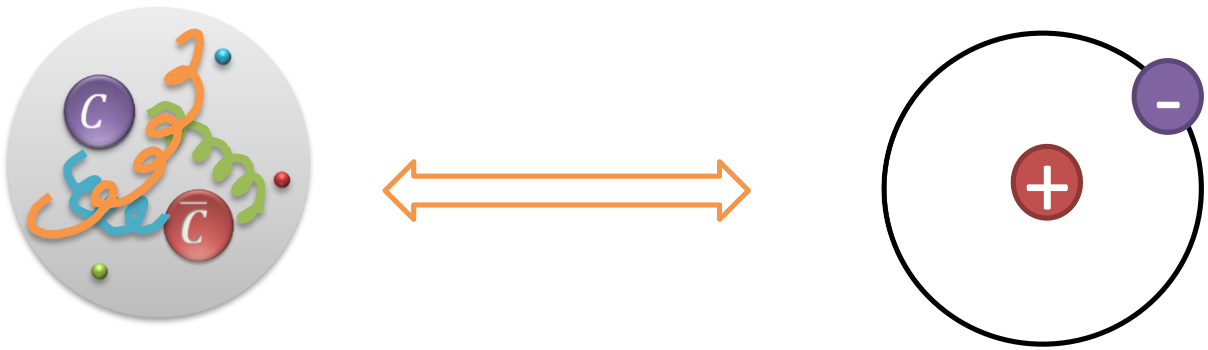
Quarkonium 2019 workshop

May 13, 2019, Torino,Italy

Heavy quarkonium

- Bound state of $Q\bar{Q}$ under strong interaction
  - First discovered: J/ψ in 1974
  - Family members: ψ(2S), η_c , χ_{cJ}, $\Upsilon(nS), \chi_{bJ}(nP)$....



- Good features
  - ✓ Heavy enough for perturbative calculation
  - ✓ Clear signal— Lepton pair (e^+e^- and u^+u^-) decay
  - ✓ Simplist system in QCD

NRQCD Factorization

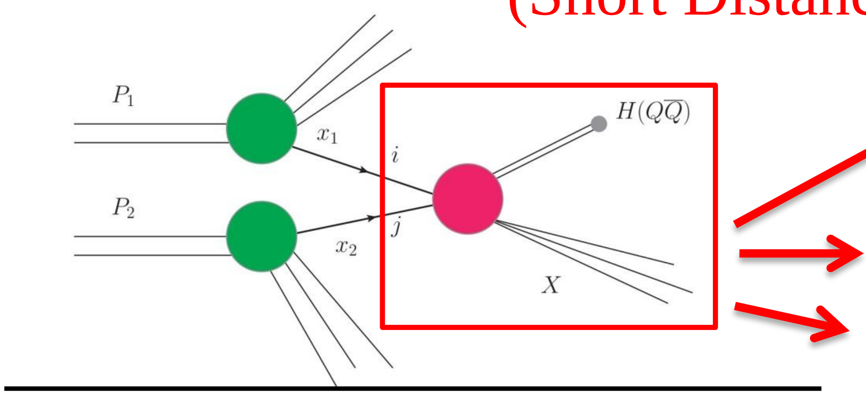
- An effective theory to describe quarkonium productions and decays

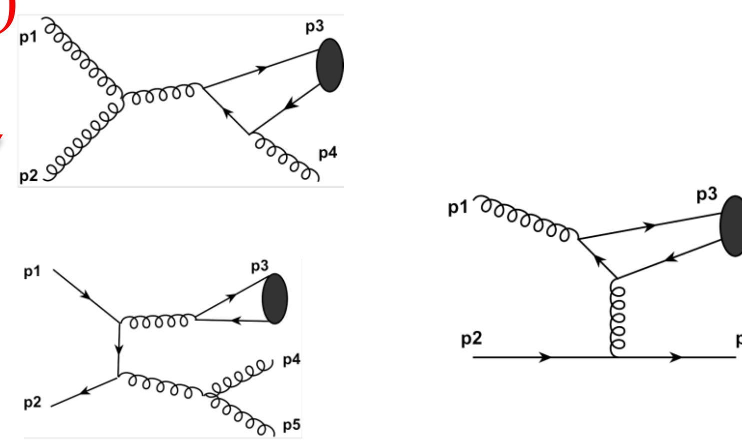
$$d\sigma[pp \to HX] = \sum_n \int dx_1 dx_2 G_i(x_1) G_j(x_2)\, d\hat{\sigma}[ij \to (Q\bar{Q})_n X] \langle \mathcal{O}^H(n) \rangle$$

Parton Distribution Function

Hadronization(LDME)

Production of Heavy quark Pair
(Short Distance)



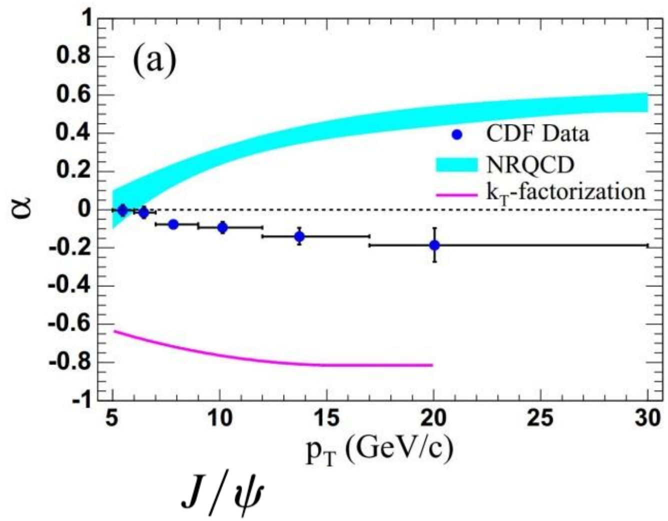


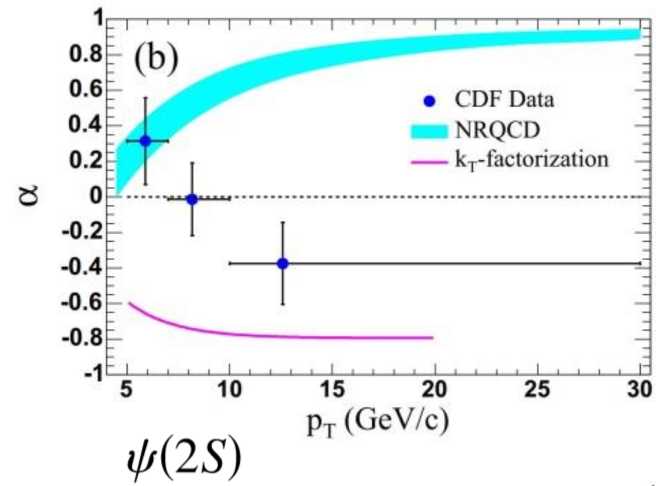
Bodwin, Braaten and Lepage, PRD 51, 1125 (1995)

J/ψ polarization puzzle

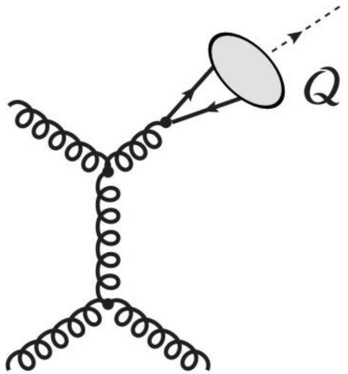
$$\alpha(or\ \lambda_\theta) = \frac{d\sigma_{11} - d\sigma_{00}}{d\sigma_{11} + d\sigma_{00}}$$

- LO NRQCD failed in the description of J/ψ polarization.
  - Prediction contradicts with CDF data





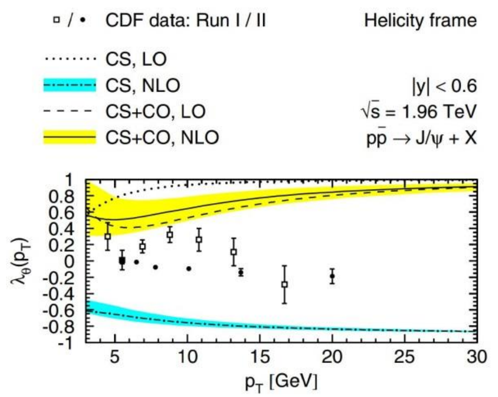
- Analysis
  - Dominant: gluon fragmentation → cc($^3S_1^{[8]}$)
  - Gluon is transversely polarized

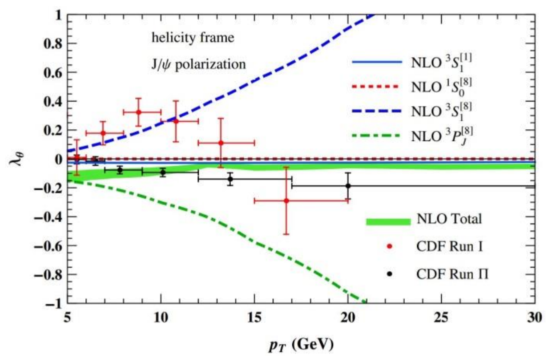


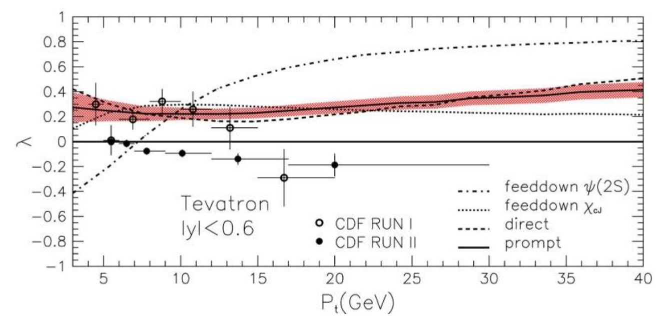
Braaten, Kniehl and Lee, PRD 62, 094005 (2000); CDF Collaboration, PRL 99, 132001(2007)

Polarization at NLO

- Left (missing feeddown): Global fit, bad agreement
- Middle(missing feeddown): ${}^1S_0^{[8]}$ dominance, agree with CDF RunII data
- Right(complete):agree with CDF RunI data, contradict CDF Run II data







- Differenct fitting strategy→ different LDMEs→ different phenomenology
- Three LDMEs to be determined, too many!

Butenschon and Kniehl, PRL 108, 172002(2012);
Chao, Ma, Shao, Wang and Zhang, PRL 108, 242004 (2012);
Gong, Wan, Wang and Zhang, PRL 110, 042002 (2013)

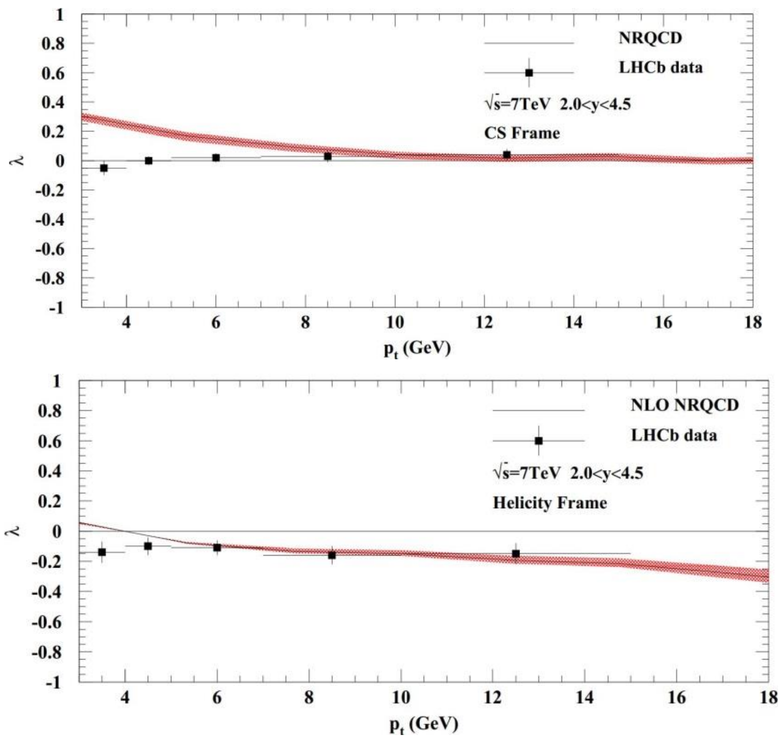
η_c and J/ψ hadroproduction data reconciled

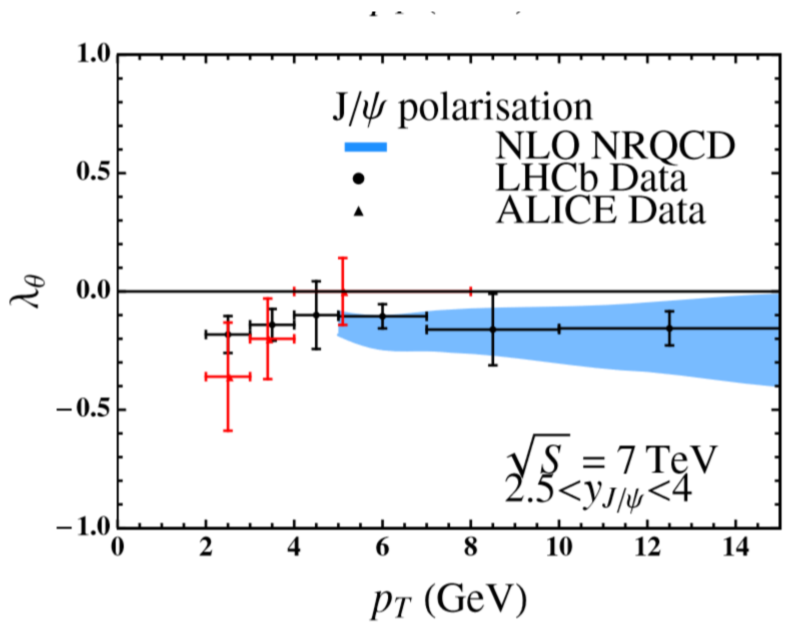
- η_c data help to determine LDMEs.
- Heavy quark spin symmetry (HQSS)
- Good agreement at LHCb

$$\langle O^{J/\psi}(^3S_1^{[n]})\rangle \approx 3\langle O^{\eta_c}(^1S_0^{[n]})\rangle$$

$$\langle O^{J/\psi}(^1S_0^{[8]})\rangle \approx \langle O^{\eta_c}(^3S_1^{[8]})\rangle$$

$$\langle O^{J/\psi}(^3P_0^{[8]})\rangle \approx \frac{1}{3}\langle O^{\eta_c}(^1P_1^{[8]})\rangle$$

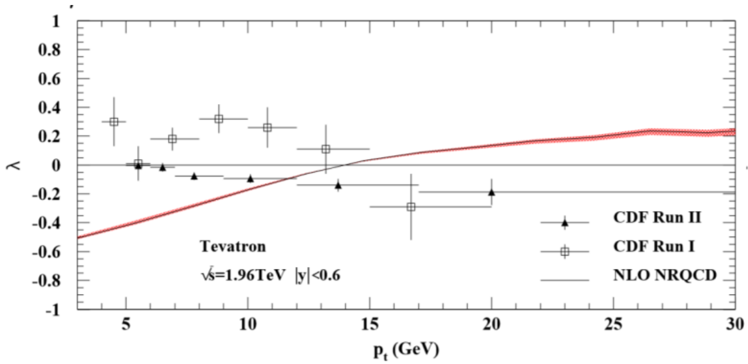


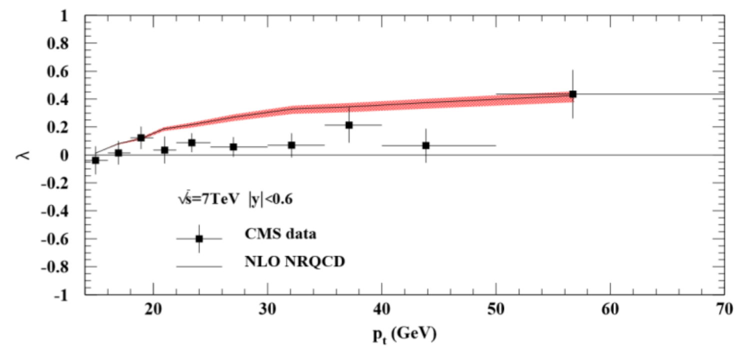


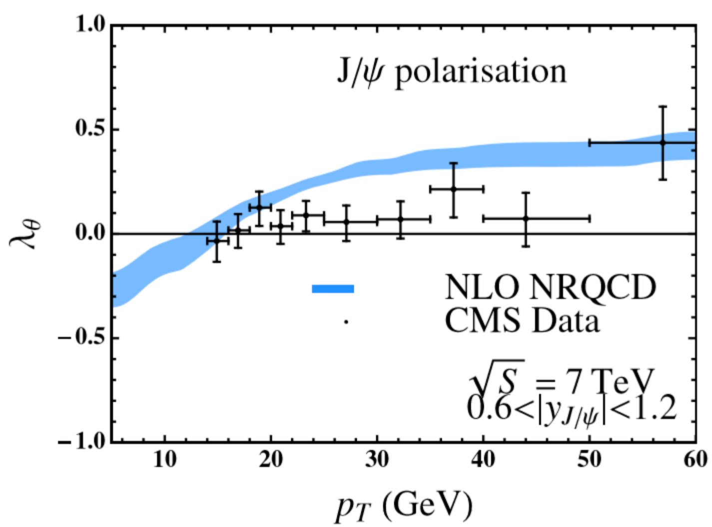
Zhang, Sun, Sang and Li. PRL 114,092006 (2015)
Han, Ma, Meng, Shao and Chao. PRL114,092005(2015)

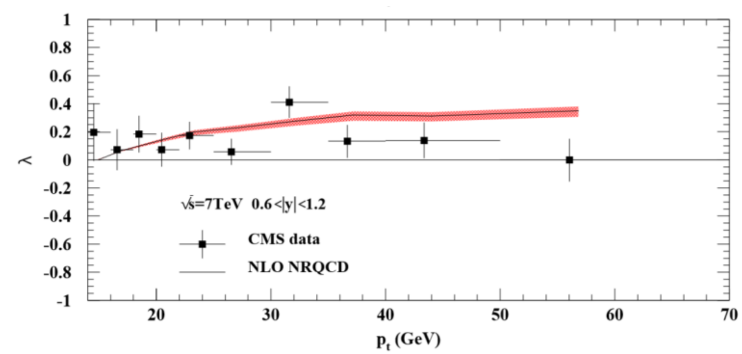
J/ψ polarization puzzle remains

- Not very good with J/ψ polarization in midrapidity region







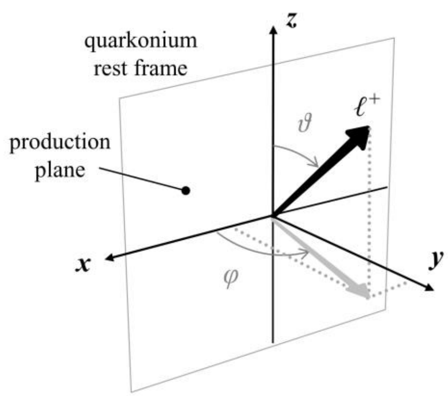


Zhang, Sun, Sang and Li. PRL 114,092006 (2015)

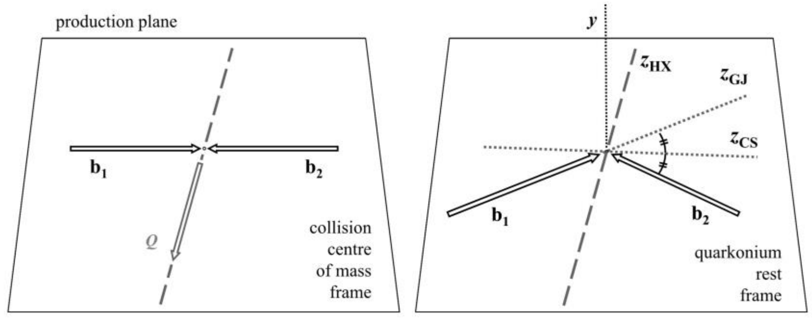
The parameters describing J/ψ polarization

- J/ψ polarization can be analyzed via the angular distribution of the decayed positively charged leptons, which can be expressed as:

$$\frac{d\sigma}{d\Omega dy} \propto 1 + \lambda_{\theta} cos^2\theta + \lambda_{\theta\phi} \sin 2\theta cos\phi + \lambda_{\phi} sin^2\theta cos2\phi$$



- θ - polar angle between momentum of a positive lepton in the J/ψ rest frame and the polaization axis Z
- ϕ – corresponding azimuthal angle



- Polarization axis Z
  - ✓ Helicity (HX) frame: along the J/ψ momentum in the center-of-mass of the colliding beams
  - ✓ Collins-Soper (CS) frame: bisector of the angle formed by one beam direction and the opposite direction of the other beam in the J/ψ rest frame

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$$\frac{d\sigma}{d\Omega dy} \propto 1 + \lambda_\theta cos^2\theta + \lambda_{\theta\phi} \sin 2\theta cos\phi + \lambda_\phi sin^2\theta cos2\phi$$

- Where

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

- ➢ $d\sigma_{\lambda\lambda'}(\lambda, \lambda' = 0, \pm 1)$ is the spin density matrix of J/ψ hadroproduction
- ➢ All three parameters provide interesting and independent information
- ➢ The parameters are depending on the J/ψ polarization frames
- ➢ Most available works of J/ψ polarization are restricted to λ_θ

New opportunity: polarization parameters $\lambda_{\theta\varphi}$, λ_{φ}

- Experiment measurement:
  - CMS Collaboration, Phys.Lett.B 727(2013)381
  - LHCb Collaboration, EPJC (2013) 73:2631

- Theoretical prediction at QCD NLO:
  - λ_{ϕ} : PRL108.172002(2012) with three data points.
  - $\lambda_{\theta\phi}$: No theoretical prediction.

- Are the theoretical predictions on $\lambda_{\theta\phi}$, λ_{ϕ} coincide with the experimental data?
- Could the uncertainty on the related LDMEs be reduced by fitting on these measurements together with previous data fit?

QCD NLO calculation for prompt J/ψ

- **Direct J/ψ:** $d\sigma^{J/\psi}_{\lambda\lambda'}|_{dir} = d\hat{\sigma}(^3S_1^1)\,\langle\mathcal{O}^{\psi}(^3S_1^{[1]})\rangle + d\hat{\sigma}(^1S_0^8)\,\langle\mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle + d\hat{\sigma}(^3S_1^8)\,\langle\mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle + \sum d\hat{\sigma}(^3P_J^8)\,\langle\mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle$

- **Feed-down contribution from χ_{cJ} and ψ(2S)**

$$d\sigma^{J/\psi}_{\lambda\lambda'}|_{\chi_{cJ}} = \mathcal{B}[\chi_{cJ}\to J/\psi]\sum_{J_z,J_z'}\delta_{J_z-\lambda,J_z'-\lambda'}\,C^{\lambda,J_z-\lambda}_{J,J_z}C^{*\lambda',J_z'-\lambda'}_{J,J_z'}\,d\sigma^{\chi_{cJ}}_{J_zJ_z'}. \qquad d\sigma^{J/\psi}_{\lambda\lambda'}|_{\psi(2S)} = \mathcal{B}[\psi(2S)\to J/\psi]\,d\sigma^{\psi(2S)}_{\lambda\lambda'}$$

✓ 87 parton level sub-processes

✓ Updated FDCHQHP package

✓ HPC Cluster of ITP-CAS (Thanks!)

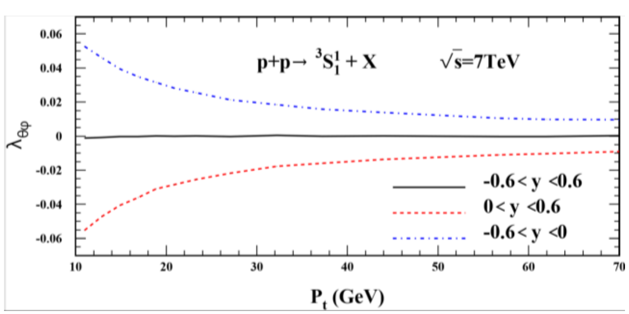
STATES	LO sub-process	number of Feynman diagrams	NLO sub-process	number of Feynman diagrams
$^3S_1^{(1)}$	$g+g\to(Q\bar{Q})_n+g$	6	$g+g\to(Q\bar{Q})_n+g$(one-loop)	128
			$g+g\to(Q\bar{Q})_n+g+g$	60
			$g+g\to(Q\bar{Q})_n+b+\bar{b}$	42
			$g+g\to(Q\bar{Q})_n+q+\bar{q}$	6
			$g+q(\bar{q})\to(Q\bar{Q})_n+g+q(\bar{q})$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

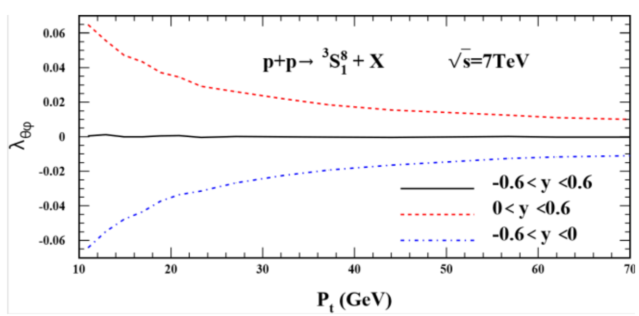
Interesting Featrues

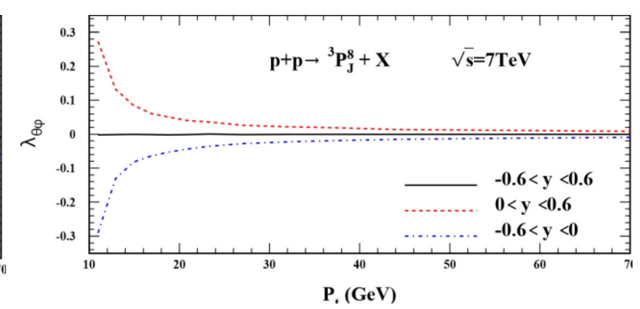
- In helicity frame for inclusive J/ψ production at the LHC, a symmetry (antisymmetry) relations can be deduced as

$$\frac{d\sigma^H_{\lambda\lambda'}}{dy}\Big|_{y=a} = n_{\lambda\lambda'}\frac{d\sigma^H_{\lambda\lambda'}}{dy}\Big|_{y=-a} \qquad n_{\lambda\lambda'} = \begin{cases} 1 & \lambda=\pm\lambda' \\ -1 & \lambda=\pm 1, \lambda'=0 \end{cases} \qquad y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

- Conclusion:
  - ✓ $\lambda_{\theta\phi}$=0 for experiment with symmetry rapidity range (a<|y|<b), e.g. CMS and ATLAS.
  - ✓ $\lambda_{\theta\phi}\neq 0$ for half rapidity range (y>b), such as the case at LHCb.
  - ✓ λ_{θ}, λ_{ϕ} are symmetry for y>0 and y<0.







New fitting on the J/ψ LDMEs

- The data used:
  - yield:
  - CDF : PRD71,032001(2005)
  - LHCb: EPJC71,1645(2011)
  - Polarization:
  - λ_θ, λ_φ CMS : Phys.Lett.B 727(2013)381
  - λ_θ, $\lambda_{\theta\varphi}$, λ_φ LHCb : EPJC (2013) 73:2631

- LDMEs Strategy:
  - CS: potential model

$$\langle \mathcal{O}^{\psi}({}^3S_1^{[1]})\rangle = \frac{3N_c}{2\pi}|R_\psi(0)|^2,$$
$$\langle \mathcal{O}^{\chi_{cJ}}({}^3P_J^{[1]})\rangle = \frac{3}{4\pi}(2J+1)|R'_{\chi_c}(0)|^2.$$

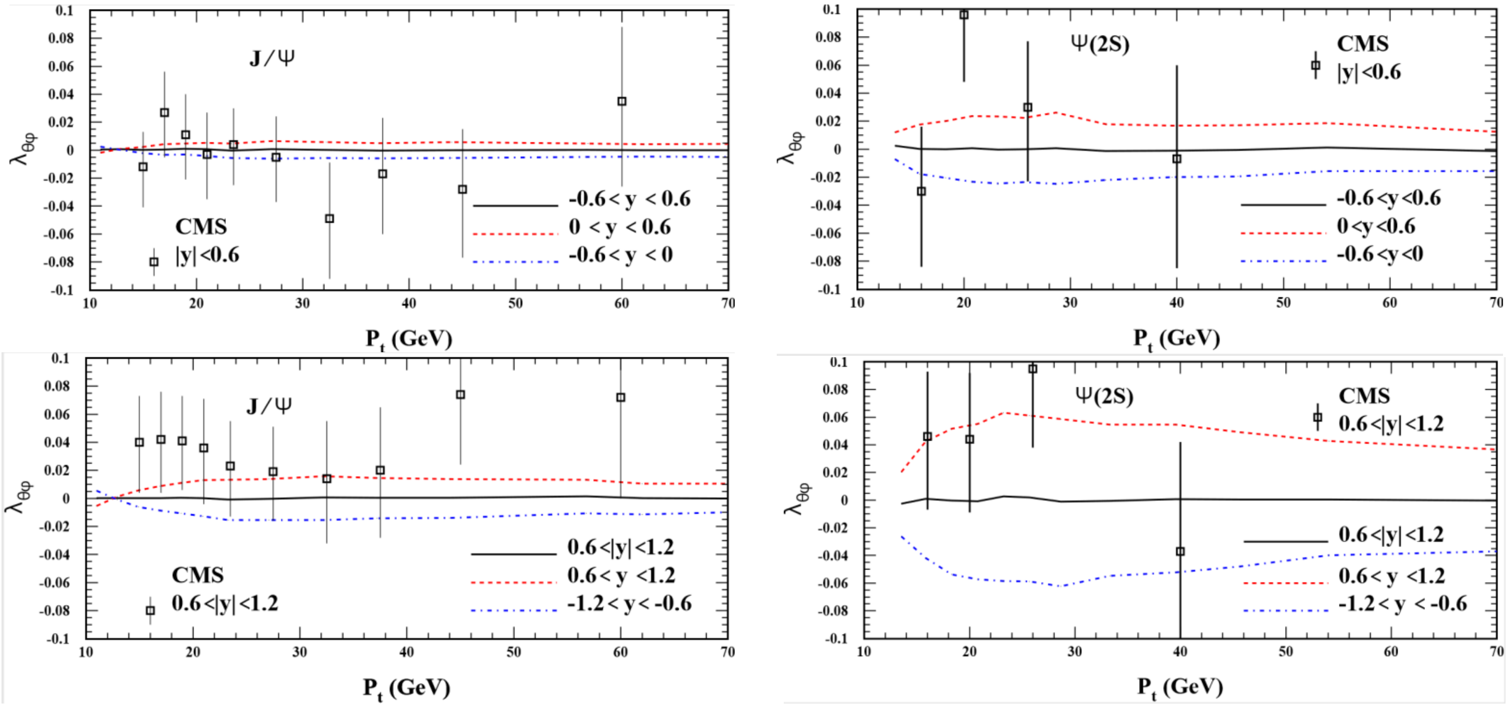
  - CO: χ_{cJ} and ψ(2S) are from PRL110.042002(2013)

- Totally 86 data points of J/ψ, by minimizing χ^2, we obtain

$$\langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]})\rangle = (5.66 \pm 0.47)\times 10^{-2} GeV^3,$$
$$\langle \mathcal{O}^{J/\psi}({}^3S_1^{[8]})\rangle = (1.17 \pm 0.58)\times 10^{-3} GeV^3,$$
$$\langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]})\rangle / m_Q^2 = (5.4 \pm 0.5)\times 10^{-4} GeV^3,$$

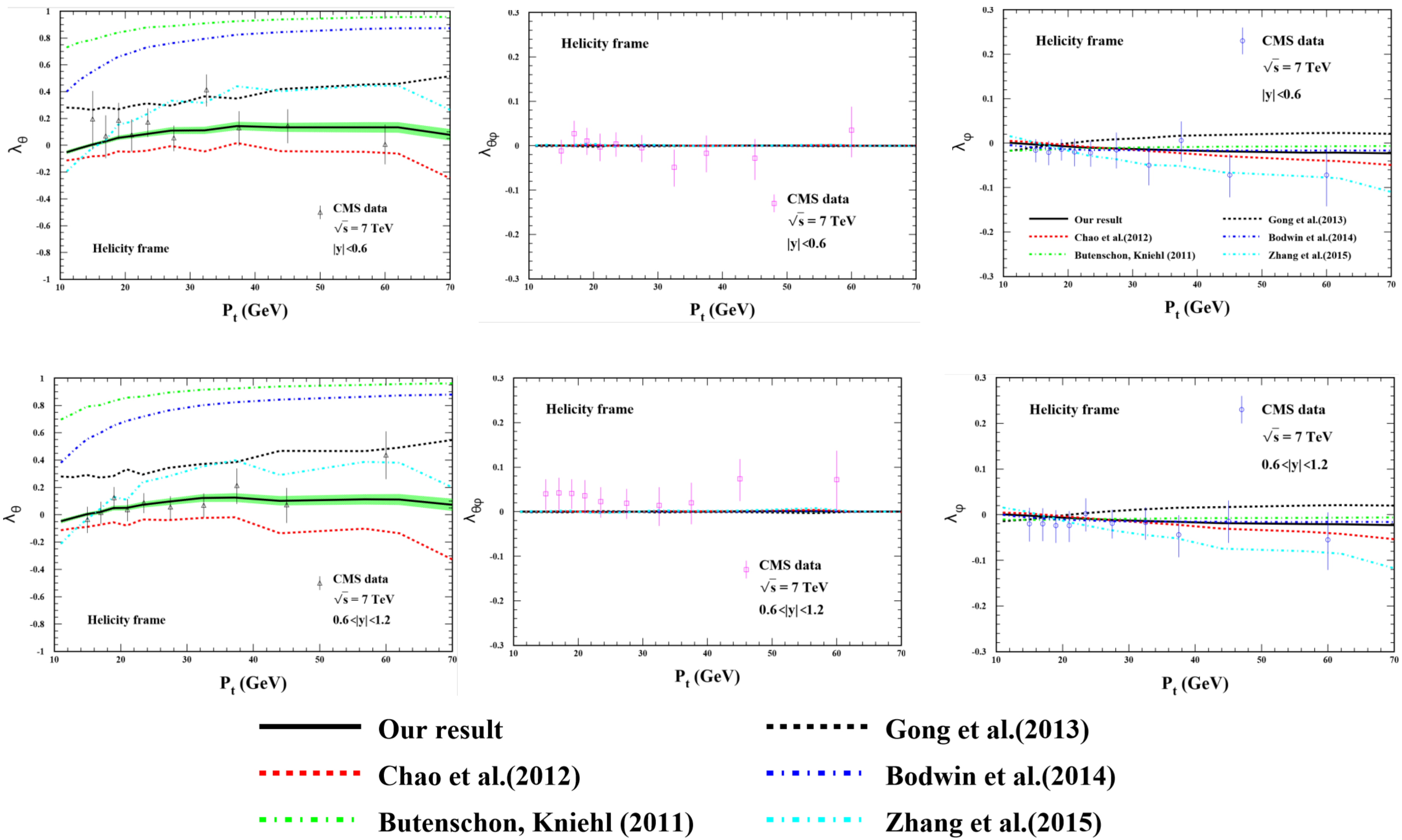
The antisymmetry for $\lambda_{\theta\varphi}$

- J/ψ、ψ(2S) Polarization in helicity frame

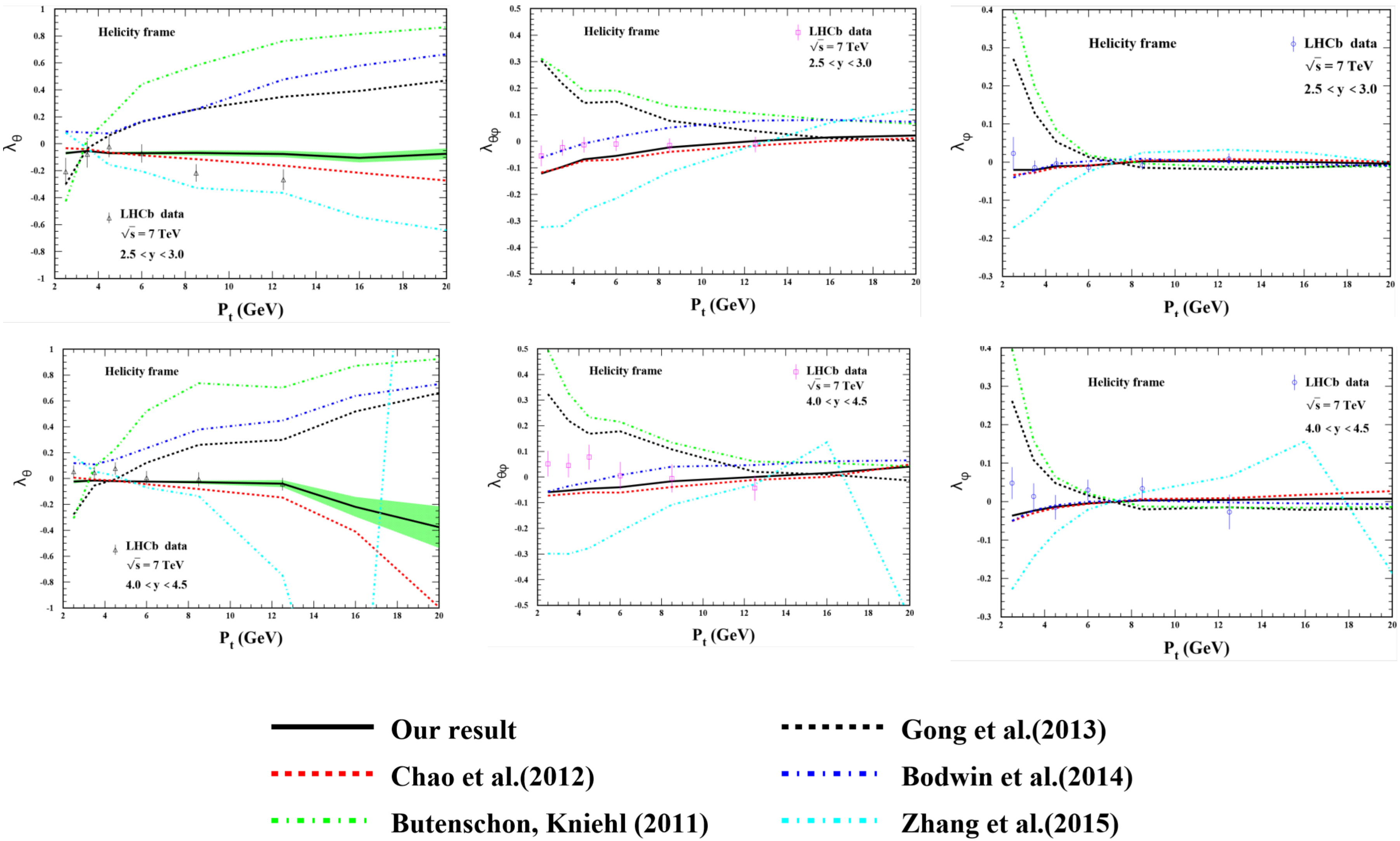


- ➢ $\lambda_{\theta\phi}$ is exactly zero in the calculation for CMS kinematical region
- ➢ Theoretical predictions describe the $\lambda_{\theta\phi}$ from CMS quite well

Results for λ_θ, $\lambda_{\theta\varphi}$, λ_φ: CMS



Results for λ_θ, $\lambda_{\theta\varphi}$, λ_φ: LHCb



Summary

- We finished calculation on $\lambda_{\theta\varphi}$, λ_{φ} for J/ψ polarization in helicity frame based on NRQCD.
- New fitting can describe both J/ψ production and polarization.
- LDMEs uncertainties are large for $\lambda_{\theta.}$
- QCD NLO decribe $\lambda_{\theta\varphi}$, λ_{φ} quite well (medium and high p_t) by different LDMEs schemes.

Thank you!