J/ψ polarization in pp collisions at √s = 7 TeV

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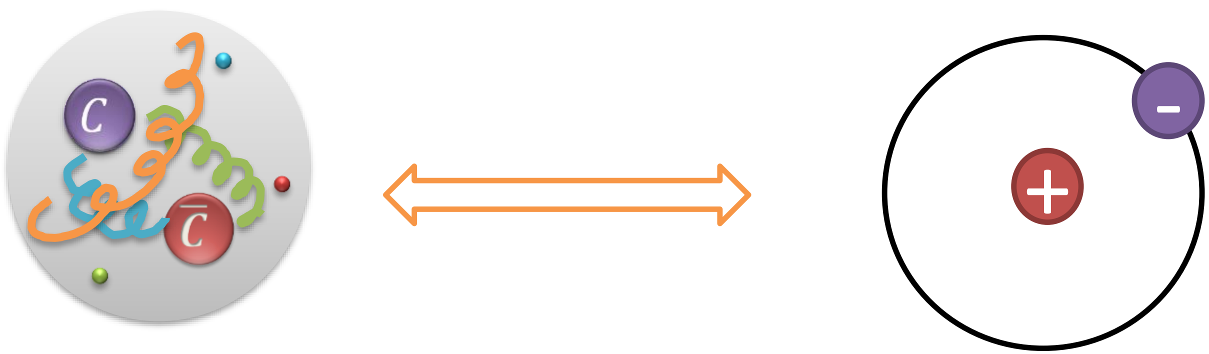
Outline

- Background
- J/ψ polarization puzzle
- New opportunity: $\lambda_{\theta\varphi}$, λ_{φ}
- Summary

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}, $\Upsilon(nS), \chi_{bJ}(nP)$....



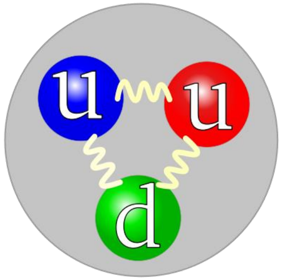
➢ Good features

✓ Heavy enough for perturbative calculation

✓ Clear signal— Lepton pair (e^+e^- and u^+u^-) decay

✓ Simplist system in QCD

QCD Effective Theory



- QCD involve partons (quarks and gluons)
  - Asymptotic freedom
  - Confinement
- Experiment measures hadrons
- The hadronization of partons ususally can not be calculated perturbatively.
- partons ← effective theory → hadrons

NRQCD Factorization

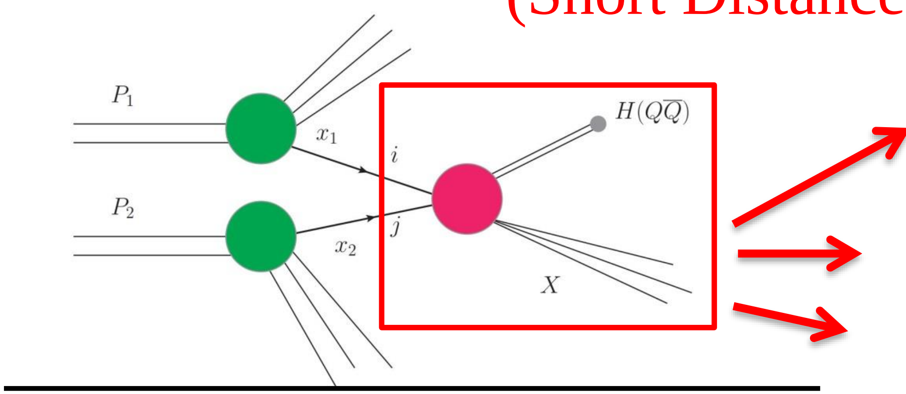
- An effective theory to describe quarkonium productions and decays

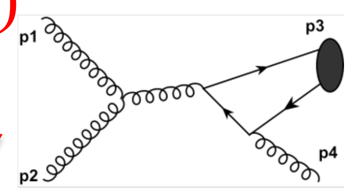
$$d\sigma[pp \to HX] = \sum_n \int dx_1 dx_2 G_i(x_1) G_j(x_2)\, d\hat{\sigma}[ij \to (Q\bar{Q})_n X] \langle O^H(n) \rangle$$

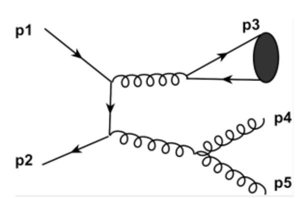
Parton Distribution Function

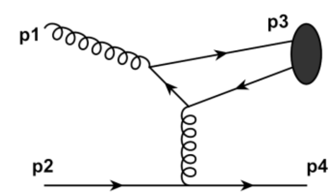
Hadronization(LDME)

Production of Heavy quark Pair
(Short Distance)





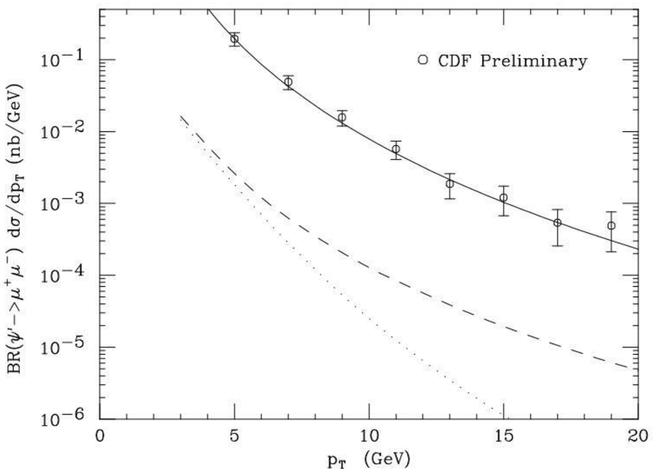




Bodwin, Braaten and Lepage, PRD 51, 1125 (1995)

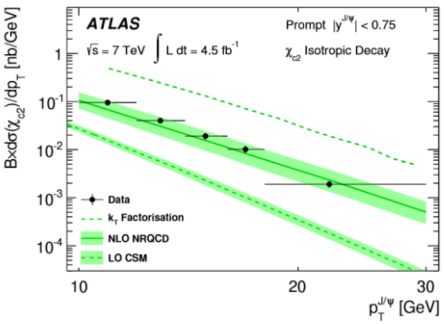
Achievement

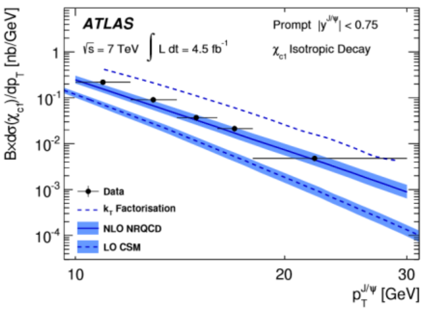
- Explain ψ’ surplus
  - The channels involved in production up to O(v^4)
  - $^3S_1^{[1]}$, $^1S_0^{[8]}$, $^3S_1^{[8]}$ and $^3P_J^{[8]}$ $\quad (C\bar{C})_n \Rightarrow {}^{2S+1}L_J^{[1,8]}$
  - NRQCD prediction for ψ’ hadroproduction



- prediction for χ_{cJ} production

  - **χ_{cJ} production:** $d\sigma_{\chi_{cJ}} \approx d\hat{\sigma}_{^3P_J^{[1]}} \left\langle O\left({}^3P_0^{[1]}\right)\right\rangle + (2J+1)d\hat{\sigma}_{^3S_1^{[8]}} \left\langle O({}^3S_1^{[8]})\right\rangle$

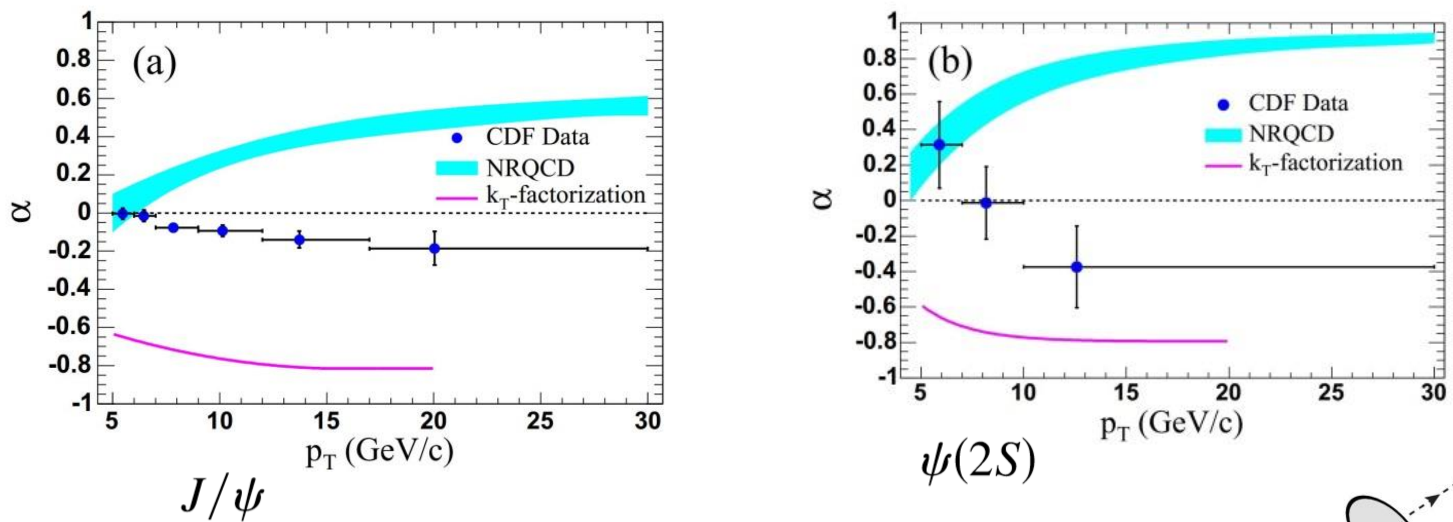




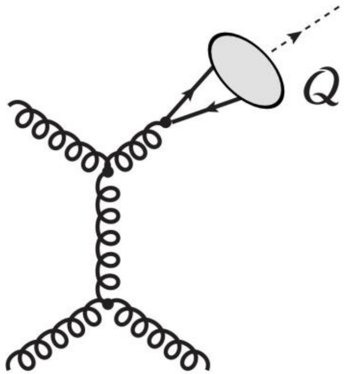
J/ψ polarization puzzle

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

- 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

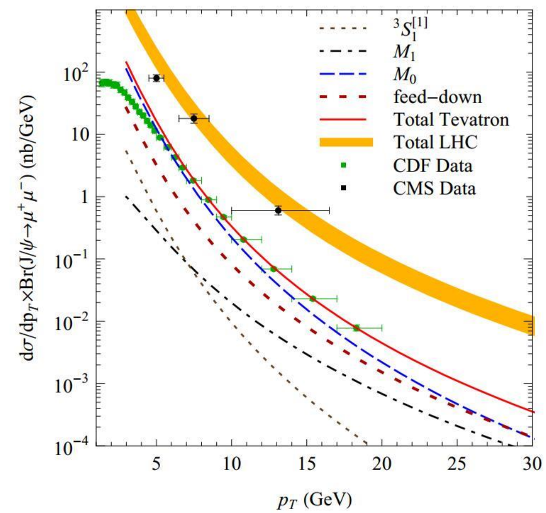


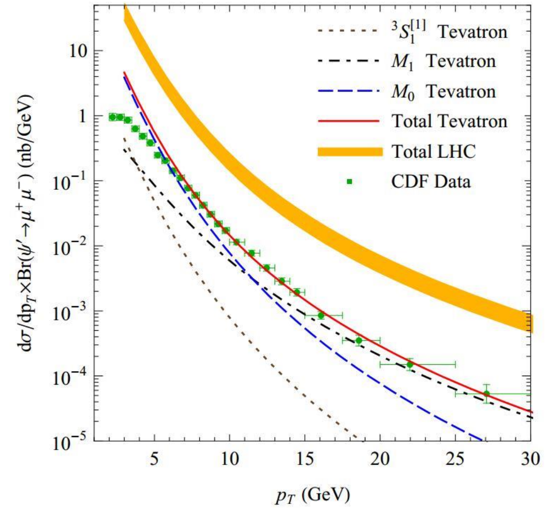
Braaten, Kniehl and Lee, PRD 62, 094005 (2000); CDF Collaboration, PRL 99, 132001(2007)

Color-Octet at NLO

NLO for CO

- $^3S_1^{[1]}$: $p_t^{-8} \rightarrow p_t^{-6}$, still very small
- $^1S_0^{[8]}$: $p_t^{-6} \rightarrow$ additional small pt^{-4} part emerges
- $^3S_1^{[8]}$: p_t^{-4} , almost unchanged
- $^3P_J^{[8]}$:positive$\rightarrow$minus, $p_t^{-6} \rightarrow p_t^{-4}$
- *df* ($^3P_J^{[8]}$)=r_0 *df* ($^1S_0^{[8]}$)+r_1 *df* ($^3S_1^{[8]}$) (medium and high p_t , roughly)

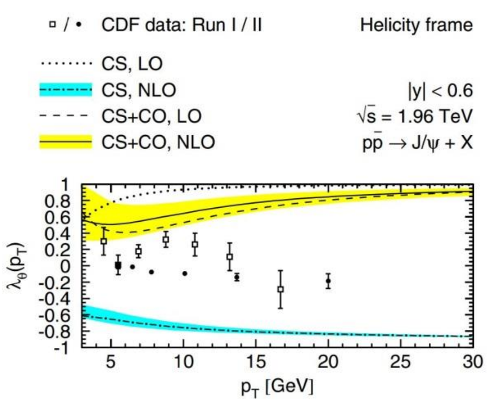


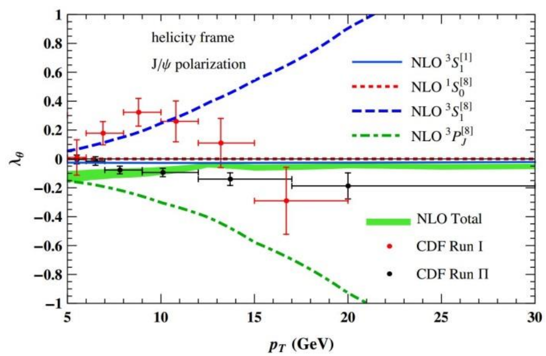


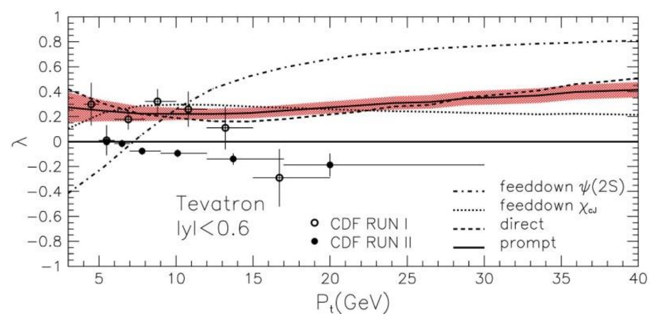
Ma, Wang and Chao, PRL 106, 042002 (2011);
Butenschon and Kniehl, PRL 106, 022003(2011)

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)

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

- ${}^1S_0^{[8]}$dominance picture suggested to solve the J/ψ polarization puzzle
- Reason:
  - Pt spectrum: NLO ${}^1S_0^{[8]}$ similar to prompt J/ψ
  - Polarization: ${}^1S_0^{[8]}$ unpolarized
- Other groups came to similar conclusions

(10^{-2} GeV)	Kniehl	Chao	Wang	Bodwin
$\langle O^{J/\psi}({}^1S_0^{[8]})\rangle$	3.04	8.9	9.7	9.9
$\langle O^{J/\psi}({}^3S_1^{[8]})\rangle$	0.168	0.3	-0.46	1.1
$\langle O^{J/\psi}({}^3P_J^{[8]})\rangle \; /m_c^2$	-0.403	0.56	-0.95	0.49

Butenschoen and Kniehl, PRD 84, 051501 (2011)
Chao, Ma, Shao, Wang and Zhang, PRL 108, 242004 (2012)
Gong, Wan, Wang and Zhang, PRL 110, 042002 (2013)
Bodwin, Chung, Kim and Lee, PRL 113, 022001 (2014)

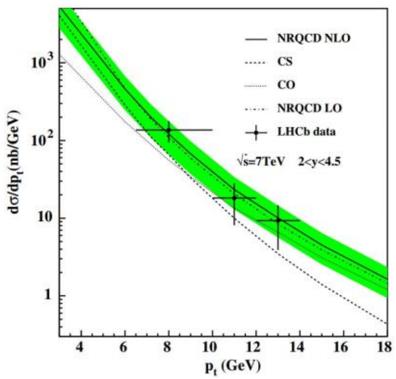
η_c and J/ψ hadroproduction data reconciled

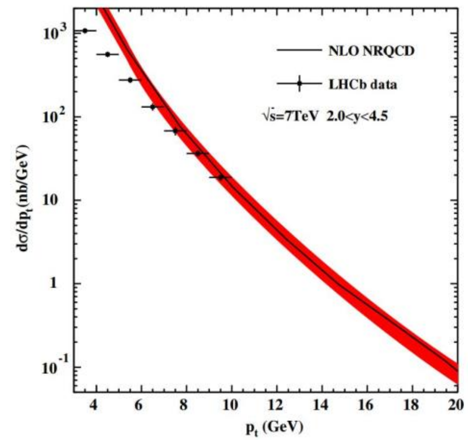
- η_c data help to determine LDMEs.
- Heavy quark spin symmetry (HQSS)
- Consistent with J/ψ hadroproduction data

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

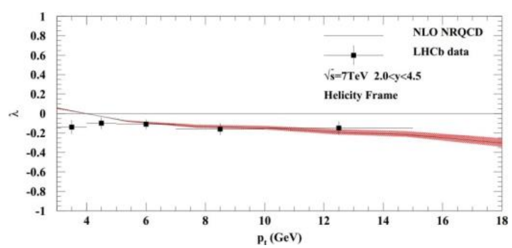
$$\langle O^{J/\psi}({}^1S_0^{[8]})\rangle \approx \langle O^{\eta_c}({}^3S_1^{[8]})\rangle$$

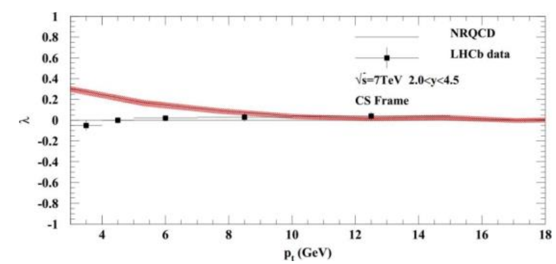
$$\langle O^{J/\psi}({}^3P_0^{[8]})\rangle \approx \frac{1}{3}\langle O^{\eta_c}({}^1P_1^{[8]})\rangle$$





- Good agreement at LHCb

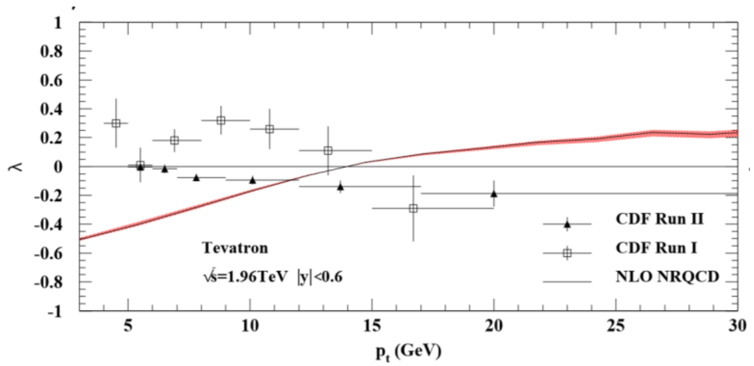


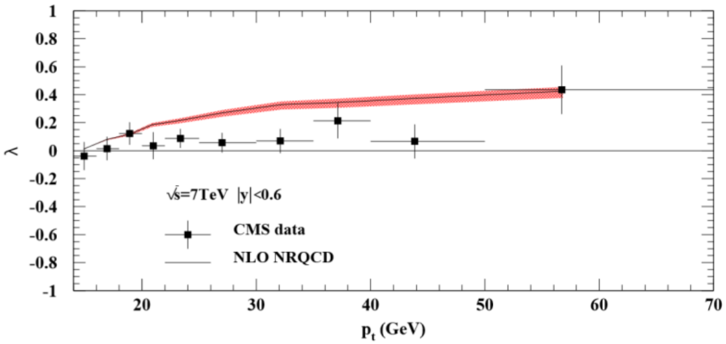


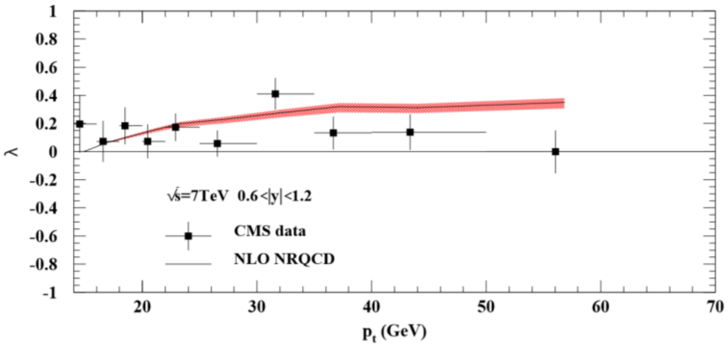
Zhang, Sun, Sang and Li. PRL 114,092006 (2015)
Han, Ma, Meng, Shao and Chao. PRL114,092005(2015)

J/ψ polarization puzzle remains

- Bad agreement with J/ψ polarization in midrapidity region





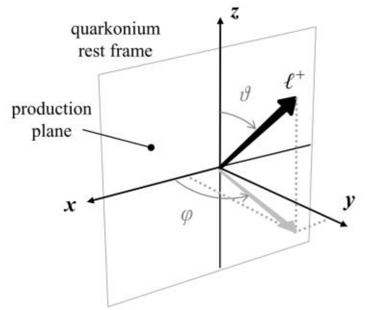


Zhang, Sun, Sang and Li. PRL 114,092006 (2015)

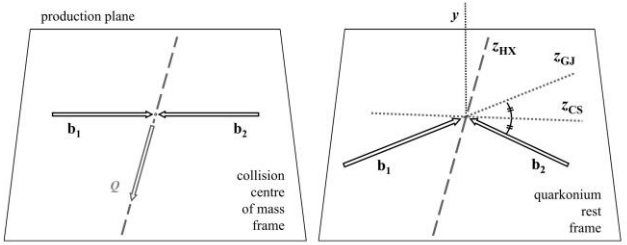
The parameters describing J/ψ polarization

- 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 ($\psi(2S)$) hadroproduction.
- All three parameters provide interesting and independent information
- The parameters are depending on the J/ψ polarization frames
- Most available experiments 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:** $$d\sigma^{J/\psi}_{\lambda\lambda'}|_{dir} = d\hat{\sigma}(^3S_1^1)\,\langle\mathcal{O}^{\psi}(^3S_1^{[1]})\rangle + d\hat{\sigma}(^1S_0^8)\,\langle\mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle + d\hat{\sigma}(^3S_1^8)\,\langle\mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle + \sum d\hat{\sigma}(^3\mathrm{P}_J^8)\,\langle\mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle$$

- **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

✓ FDCHQHP package

✓ HPC Cluster of ITP-CAS (Thanks!)

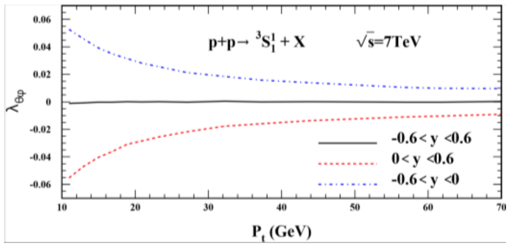
STATES	LO sub-process	number of Feynman diagrams	NLO sub-process	number of Feynman diagrams
$^3S_1^{(1)}$	$g+g\to(Q\bar{Q})_n+g$	6	$g+g\to(Q\bar{Q})_n+g$(one-loop)	128
			$g+g\to(Q\bar{Q})_n+g+g$	60
			$g+g\to(Q\bar{Q})_n+b+\bar{b}$	42
			$g+g\to(Q\bar{Q})_n+q+\bar{q}$	6
			$g+q(\bar{q})\to(Q\bar{Q})_n+g+q(\bar{q})$	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)

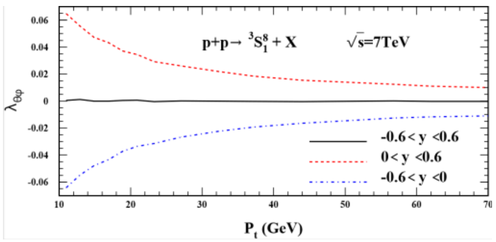
Interesting Featrues

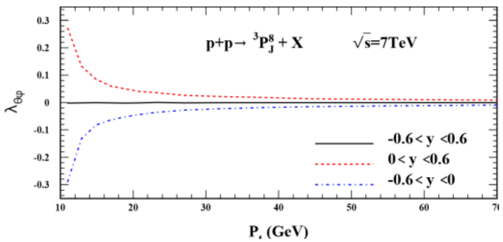
- In helicity frame for inclusive J/ψ production at the LHC, a symmetry (asymmetry) relations can be deduced as

$$\frac{d\sigma^{H}_{\lambda\lambda'}}{dy}\Big|_{y=a} = n_{\lambda\lambda'}\frac{d\sigma^{H}_{\lambda\lambda'}}{dy}\Big|_{y=-a} \qquad n_{\lambda\lambda'} = \begin{cases} 1 & \lambda=\pm\lambda' \\ -1 & \lambda=\pm1,\lambda'=0 \end{cases} \qquad y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

- Conclusion:
  - ✓ $\lambda_{\theta\phi}=0$ for experiment with symmetry rapidity range (a<|y|<b), e.g. CMS and ATLAS.
  - ✓ $\lambda_{\theta\phi}\neq0$ 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

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

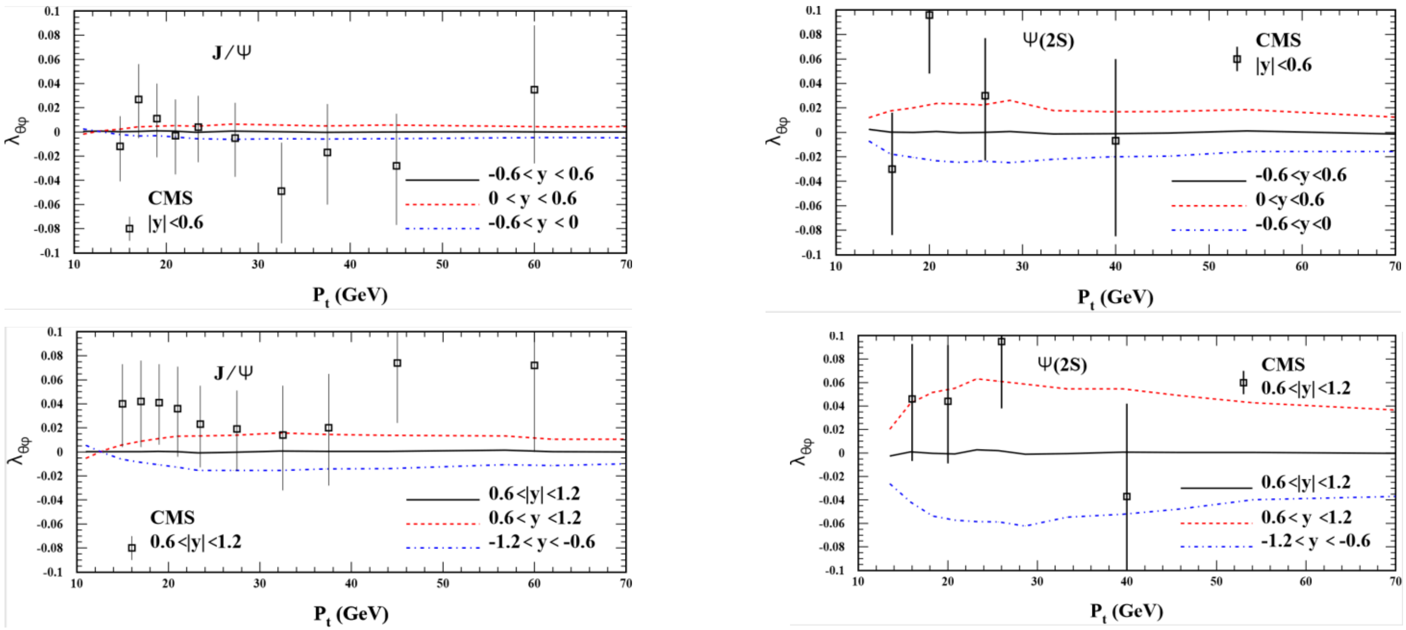
  - CO: χ_{cJ} and ψ(2S) are from PRL110.042002(2013)

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

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

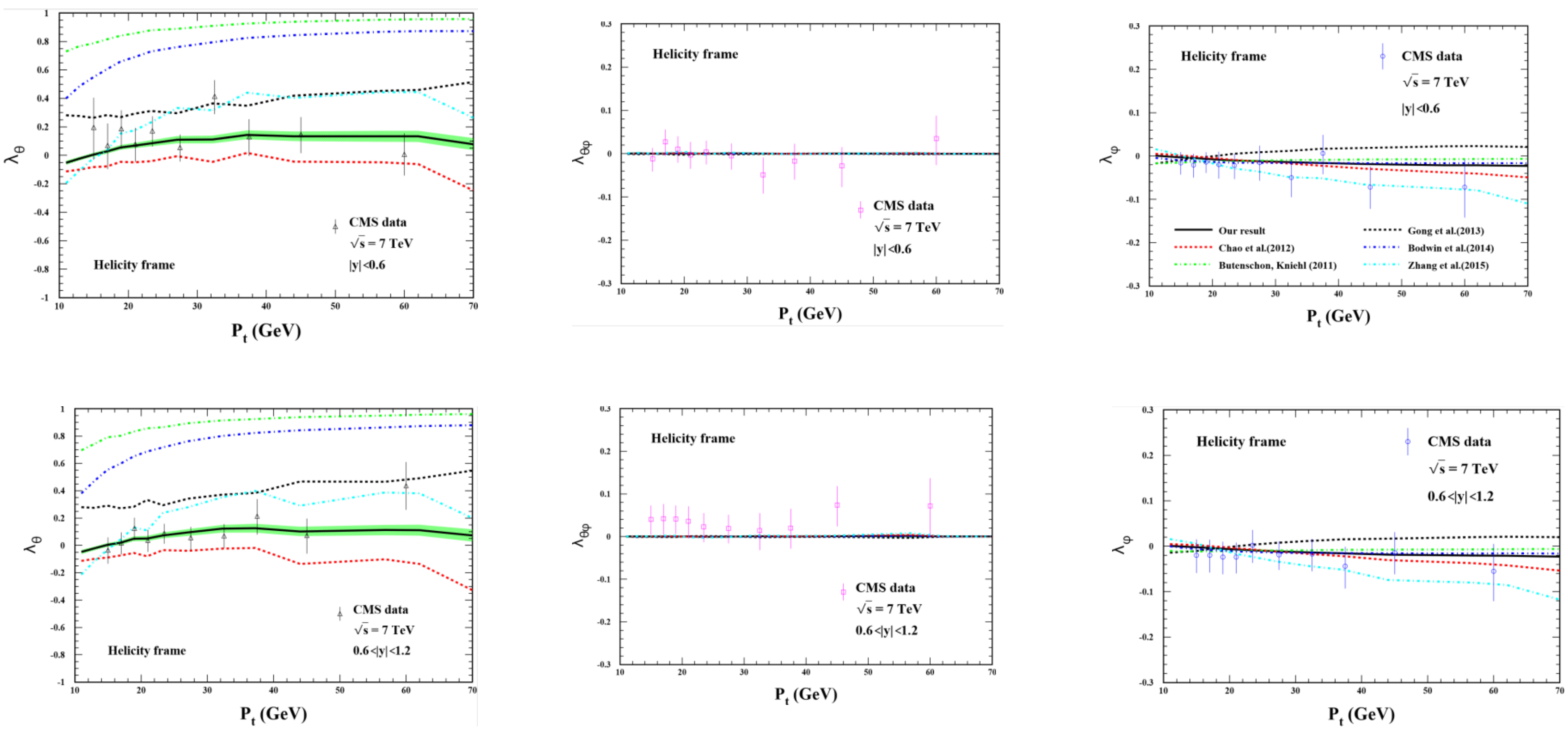
The asymmetry for $\lambda_{\theta\varphi}$

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



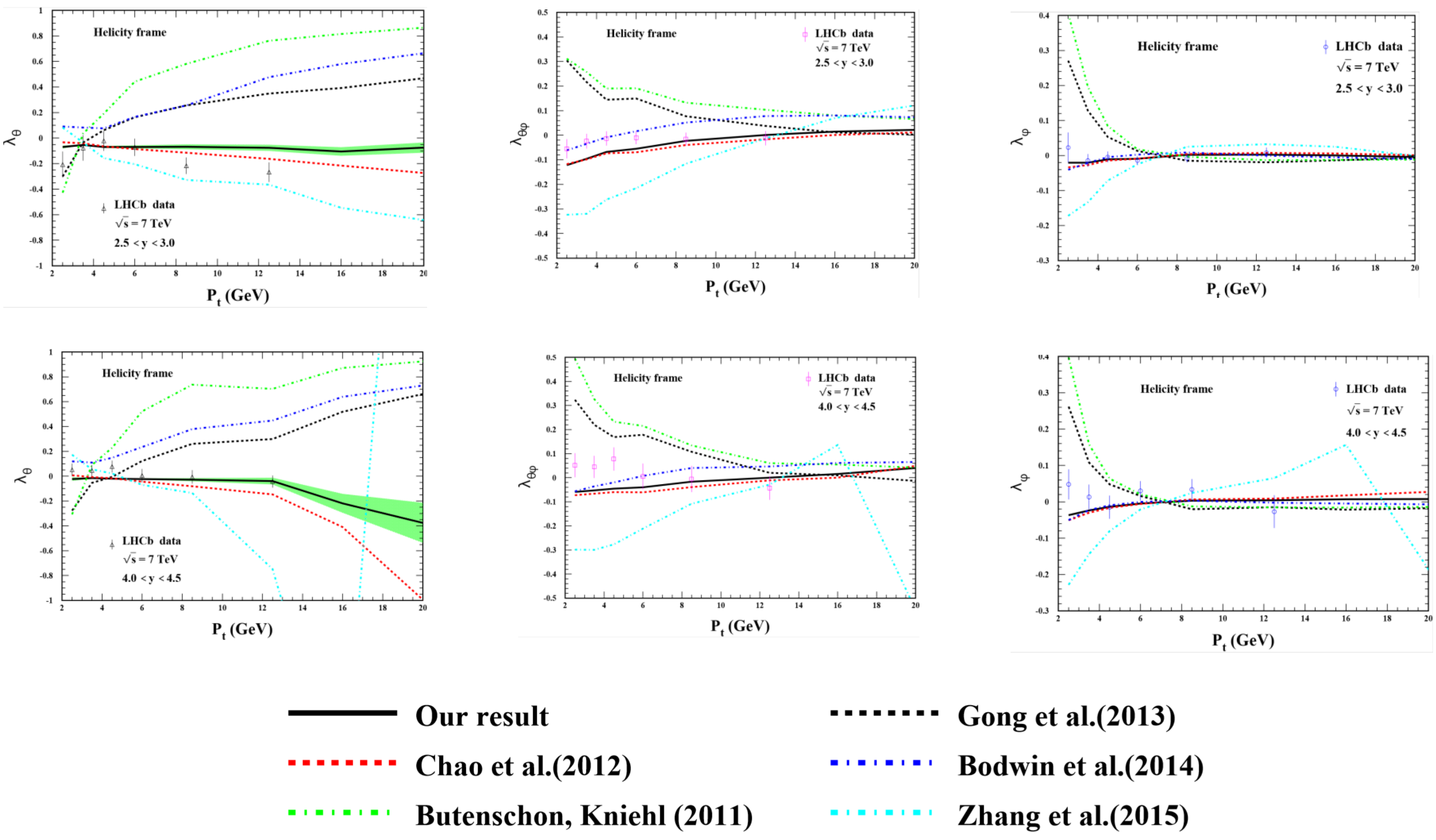
- $\lambda_{\theta\phi}$ is exactly zero in the calculation for CMS kinematical region

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



Our result
Chao et al.(2012)
Butenschon, Kniehl (2011)
Gong et al.(2013)
Bodwin et al.(2014)
Zhang et al.(2015)

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.