Heavy quarkonium polarization at Hadron Collider

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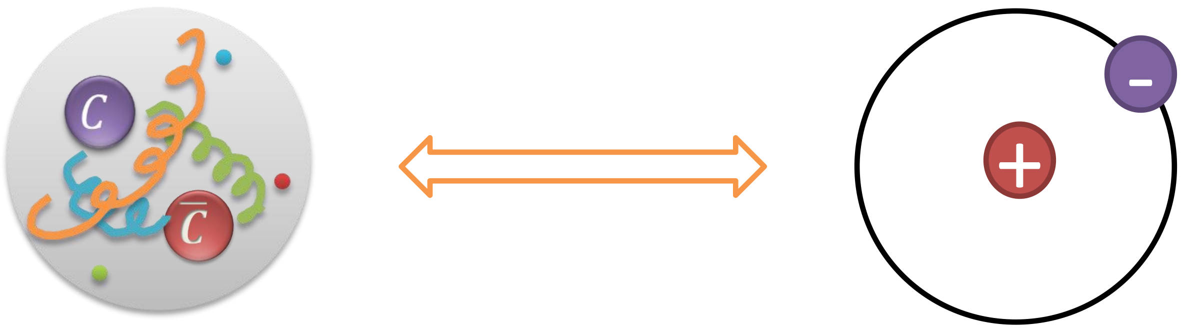
Outline

- Introduction
- J/ψ polarization puzzle
- Present status of J/ψ,$\psi(2S)$ and $\Upsilon(nS)$ polarization
- Summary

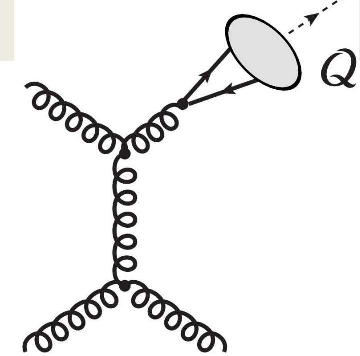
The 4th LHCb Workshop, July 31, 2024, YanTai

Heavy quarkonium

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

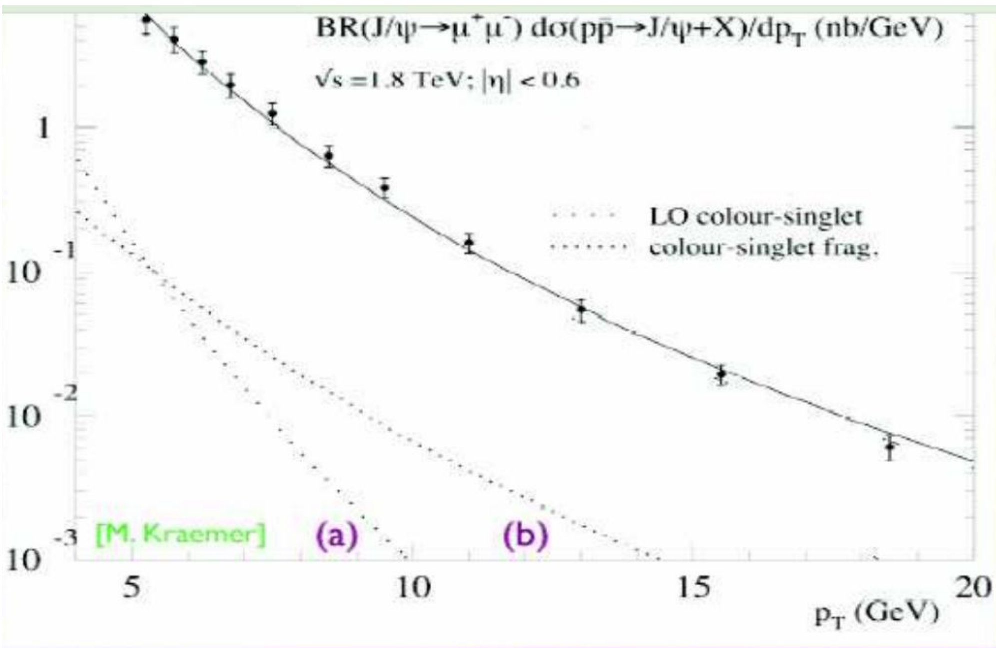


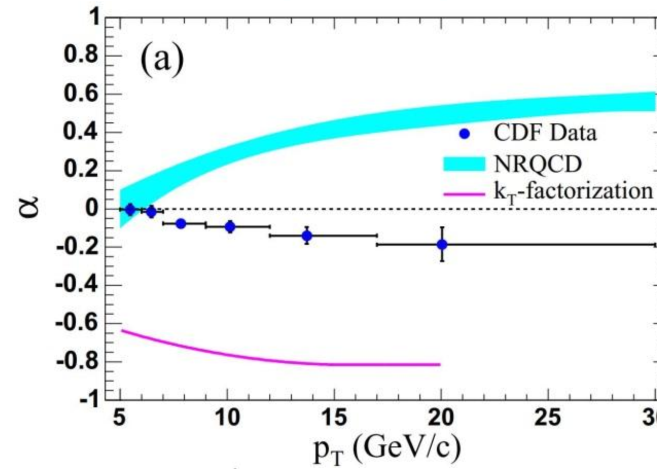
- Good features
  - ✓ Heavy enough for perturbative calculation
  - ✓ Clear signal to detect— Lepton pair (e^+e^- and u^+u^-) decay
  - ✓ Simplist system in QCD



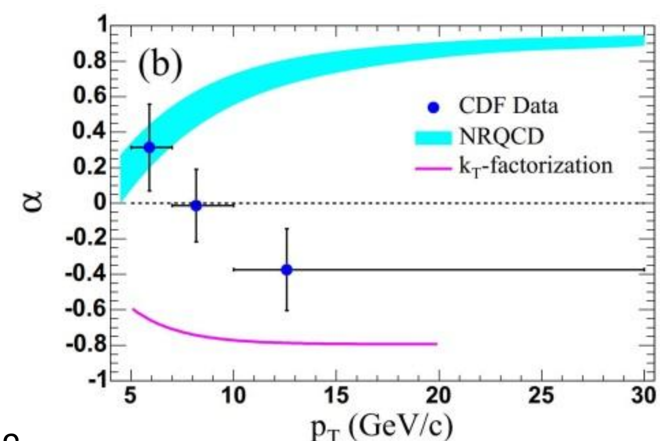
J/ψ polarization puzzle

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





J/ψ



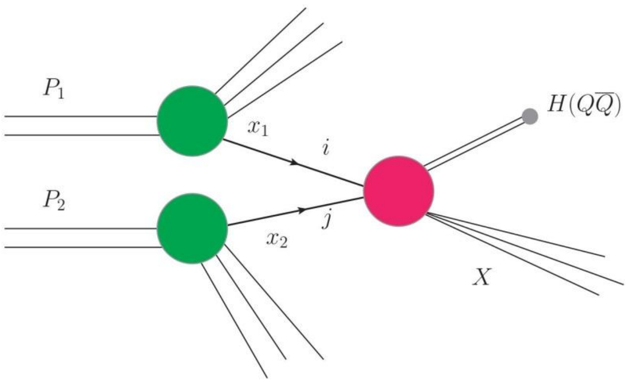
$\psi(2S)$

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

C.-H. Chang, Nucl.Phys.B172 (1980) , Bodwin, Braaten and Lepage, PRD 51, 1125 (19
Braaten, Kniehl and Lee, PRD 62, 094005 (2000); CDF Collaboration, PRL 99, 132001(2007)

NRQCD Factorization

- Color-singlet and Color-octet mechanism was proposed based on NRQCD since c and b-quark is heavy.



Parton Distribution Function

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

Production of Heavy quark Pair (Short Distance)

Hadronization(LDME)

$(Q\overline{Q})_n$ is ${}^3S_1^1, {}^3S_1^8, {}^1S_0^8, {}^3P_J^8$ for $J/\psi, \psi'$ and ${}^3P_J^1, {}^3S_1^8$ for χ_{CJ}

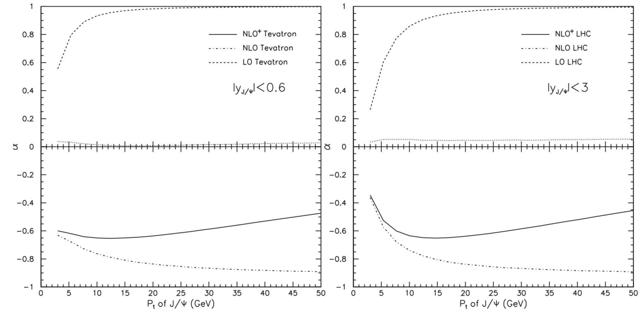
- A few non-perturbative parameters: universal NRQCD LDMEs
- Double expansion on QCD coupling α_s and velocity of heavy Quark v
- Successfully cancelled the infared divergences
- Good description for charmonium hadroproduction

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

QCD NLO

➢ Color-Singlet at QCD NLO

- Campbell, Maltoni and Tramontano, PRL 98,252002 (2007) J/ψ production
- Gong and Wang, PRL 100, 232001 (2008) J/ψ polarization



➢ NRQCD at QCD NLO

J/ψ production

- PLB 673:197(2009), B. Gong X. Q. Li and J. X. Wang; (without color octet P wave)
- PRL 106, 042002 (2011), Ma, Wang and Chao;
- PRL 106, 022003 (2011), Butenschon and Kniehl;

J/ψ polarization

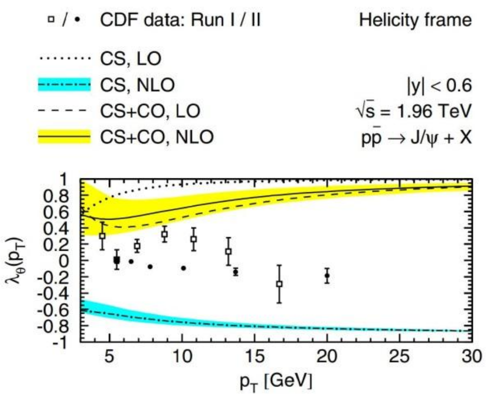
- PRL 108, 172002 (2012), Butenschon and Kniehl
- PRL 108, 242004 (2012), Chao, Ma, Shao, Wang and Zhang
- PRL 110, 042002 (2013), Gong, Wan, Wang and Zhang (prompt J/psi)

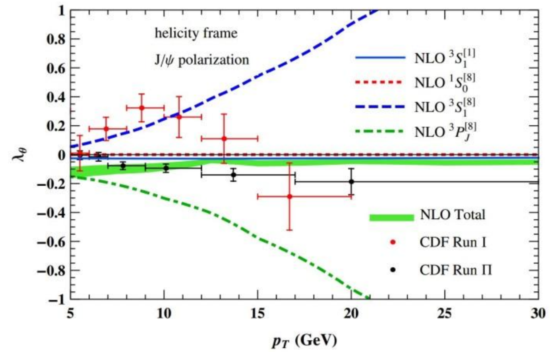
prompt: included the J/ψ feeddown from excited charmonium state than direct production

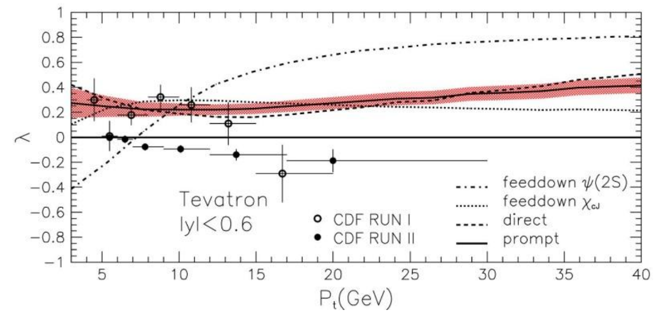
J/ψ polarization at QCD NLO

➢ QCD 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





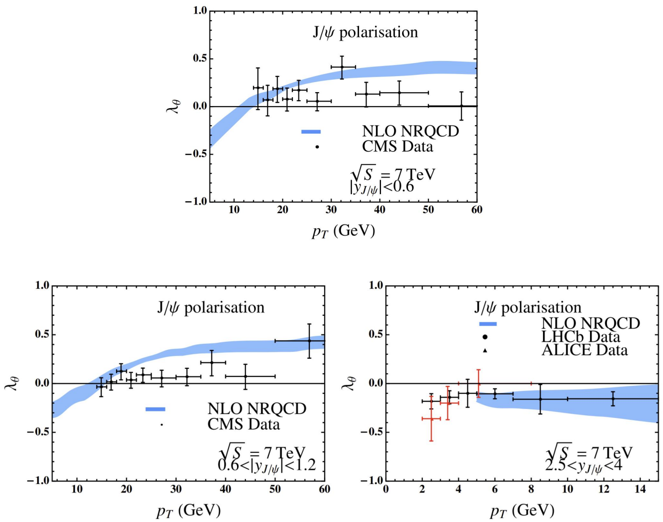


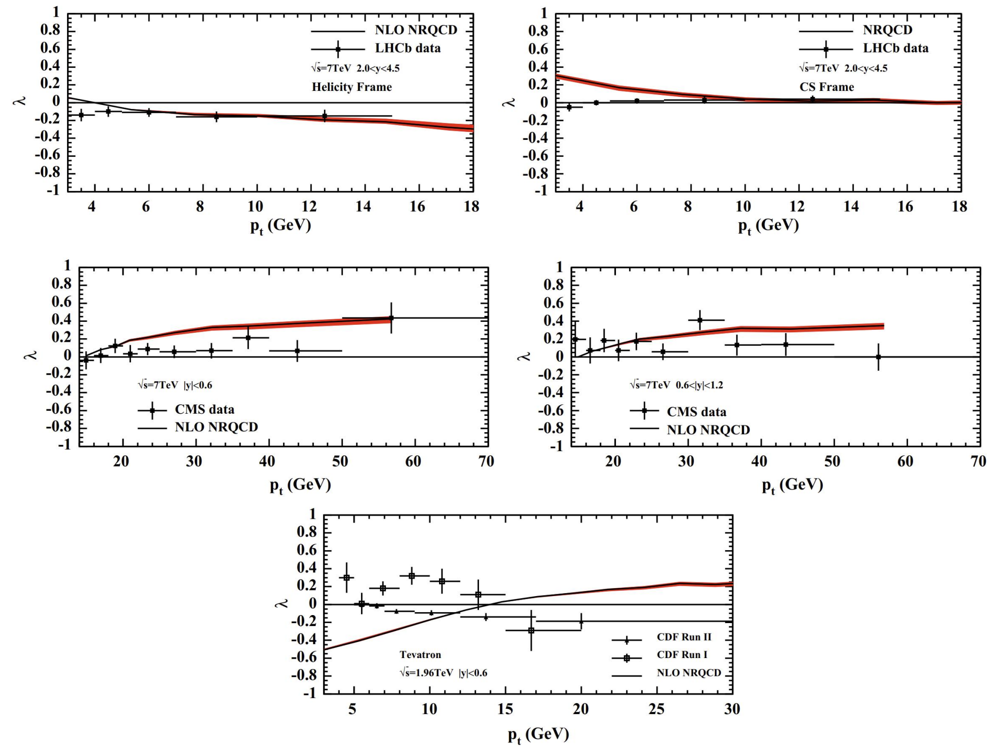
- Different fitting strategy→different LDMEs→different phenomenology

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

η_c hadroproduction at QCD NLO

- η_c data help to determine LDMEs
- Heavy quark spin symmetry (HQSS)
- Good agreement with J/ψ polarization at LHCb
- Bad agreement in midrapidity region





Phys.Rev.Lett. 114 (2015) 9, 092004, M.Butenschoen, Z.G.He and B A.Kniehl
Phys.Rev.Lett. 114 (2015) 9, 092005, H.Han, Y.Q.Ma, C.Meng, H.S.Shao, K.T.Chao
Phys.Rev.Lett. 114 (2015) 9, 092006, H.F.Zhang, Z.Sun, W.L.Sang, R.Li

$\Upsilon(nS)$ hadroproduction at QCD NLO

Υ may have better description of the experiments

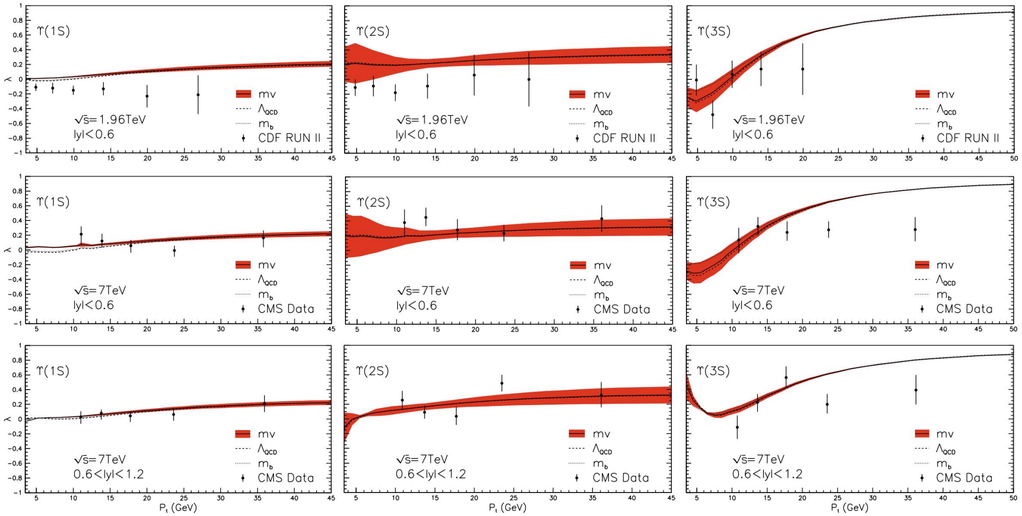
- Heavier mass than Charmonium
- Smaller relative velocity v and α_s

Υ production

- PRL 101, 152001 (2008), P.Artoisenet, J.Campell, J.P.Lansberge, F.Maltoni, F. Tramontano
- Phys. Rev. D83 (2011) 114021, B.Gong, J.X.Wang, H.F.ZHANG
- Phys. Rev. D85 (2012) 114003, K.Wang, Y.Q.MA, K.T.Chao

$\Upsilon(nS)$ polarization

- PRL 101, 152001 (2008), P.Artoisenet, J.Campell, J.P.Lansberge, F.Maltoni, F. Tramontano
- PRL 112, 032001 (2014), Gong, Wan, Wang and Zhang

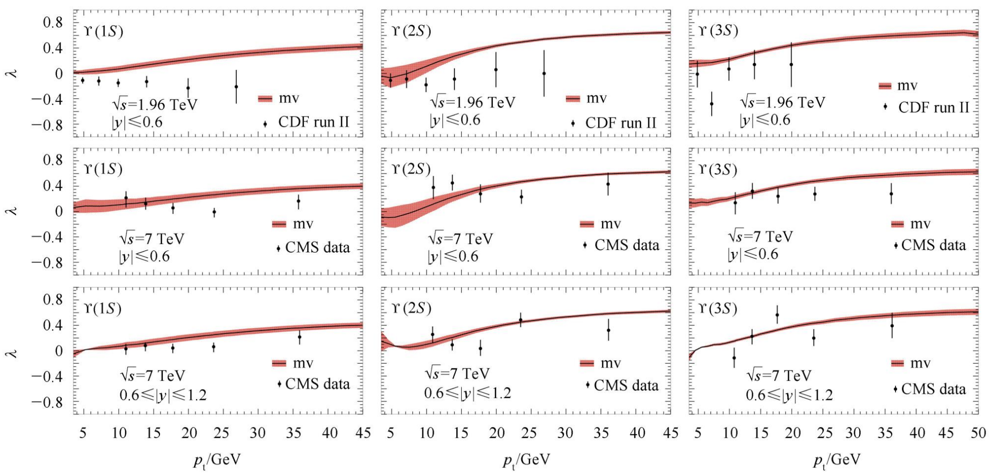


- The polarizations of $\Upsilon(1S, 2S, 3S)$ are in (good, good, bad) agreement with recent CMS data.
- Missing $\chi_c(3P)$ feed-down contributions for $\Upsilon(3S)$.
- Have some distance from CDF data.

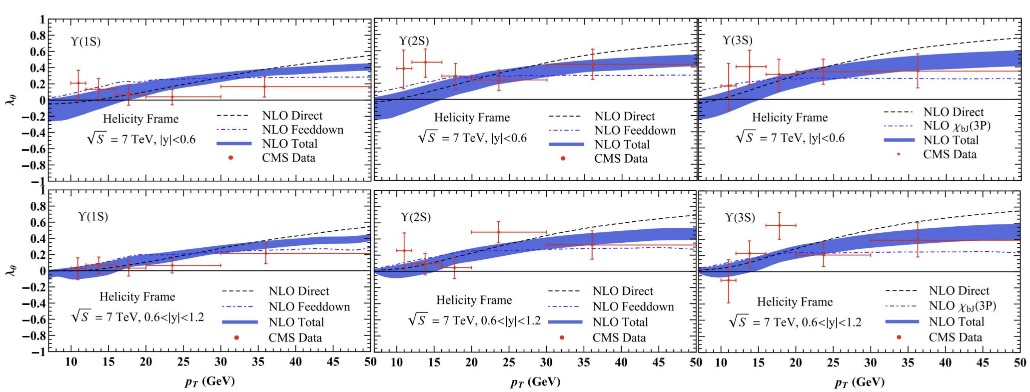
$\Upsilon(nS)$ hadroproduction at QCD NLO

$\Upsilon(nS)$ polarization

- $\chi_c(3P)$ measurement from LHCb. Eur.Phys.J.C,2014,74(10):3092
- $\Upsilon(3S)$ polarization puzzle can be understood by a large feed-down contribution from $\chi_b(3P)$



- Chin.Phys.C 39 (2015) 123102, Y.Feng, B.Gong, L.P.Wang, J.X.Wang



- Phys.Rev.D 94 (2016) 1, 014208, H.Hao, Y.Q.Ma, C.Meng, H.S.Shao, K.T.Chao

FDCHQHP: A Fortran Package generated by using FDC package

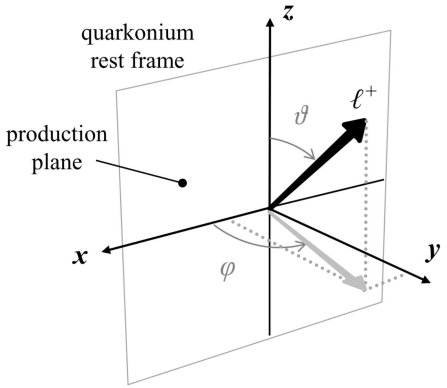
- This package includes
  - 6 channels
  - 76 sub-processes
  - Almost 2 millions lines Fortran codes in total.
- It can be run in paralleled mode with more than hundred thousands cpu with high efficiency.

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
			$g+g\to(Q\bar{Q})_n+g+g$	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)

- ✓ Lu-Ping Wan, Jian-Xiong Wang. Comput.Phys.Commun. 185 (2014) 2939-2949.
- ✓ Updated FDCHQHP package

The parameters describing J/ψ polarization

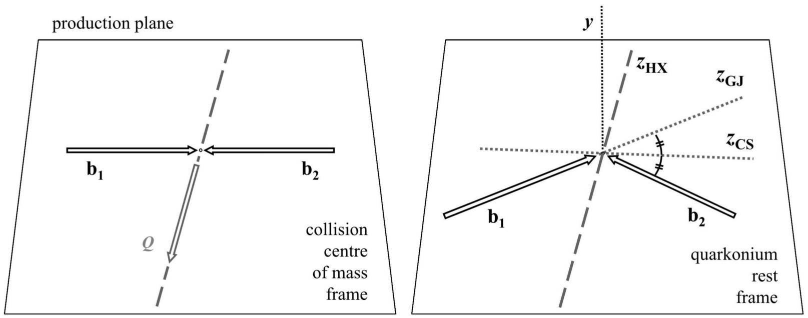
- J/ψ polarization can be analyzed via the angular distribution of the decayed positively charged leptons, which can be expressed as:



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

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

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



Complete study on polarization parameters $\lambda_\theta, \lambda_{\theta\varphi}, \lambda_\varphi$

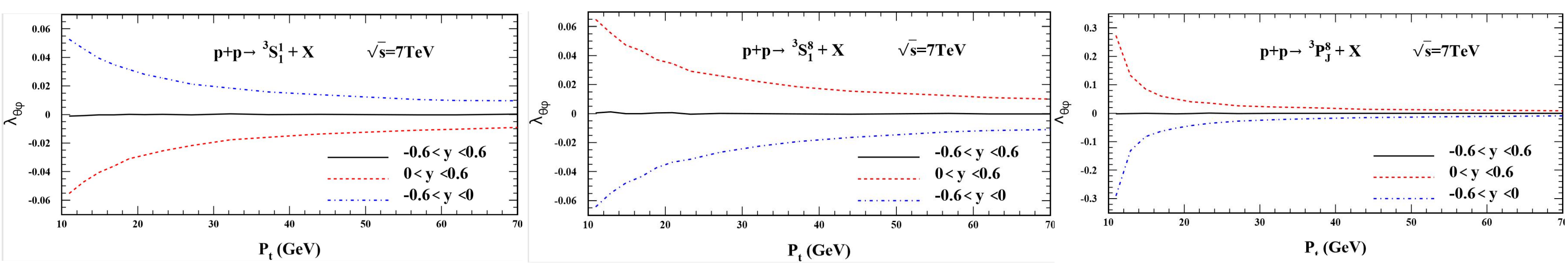
- J/ψ polarization measurement :
  - CMS Collaboration, Phys.Lett.B 727 (2013) 381
  - LHCb Collaboration, EPJC (2013) 73:2631
- $\Upsilon(nS)$ polarization measurement :
  - S. Chatrchyan et al. (CMS), Phys. Rev. Lett. 110, 081802(2013)
  - R. Aaij et al. (LHCb), JHEP 12, 110 (2017)

- Theoretical prediction at QCD NLO:
  - Most available works of J/ψ polarization are restricted to λ_θ. (before 2019)
  - λ_φ : PRL108.172002(2012) with three data points.
  - $\lambda_{\theta\varphi}$: No theoretical prediction.

- Complete study at QCD NLO:
  - Yu Feng, Bin Gong, Chao-Hsi Chang, Jian-Xiong Wang, PRD99.014044(2019) .
  - Yu Feng, Bin Gong, Chao-His Chang, Jian-Xiong Wang, Chin.Phys.C45, 013117 (2021)

J/ψ polarization $\lambda_\theta, \lambda_{\theta\varphi}, \lambda_\varphi$

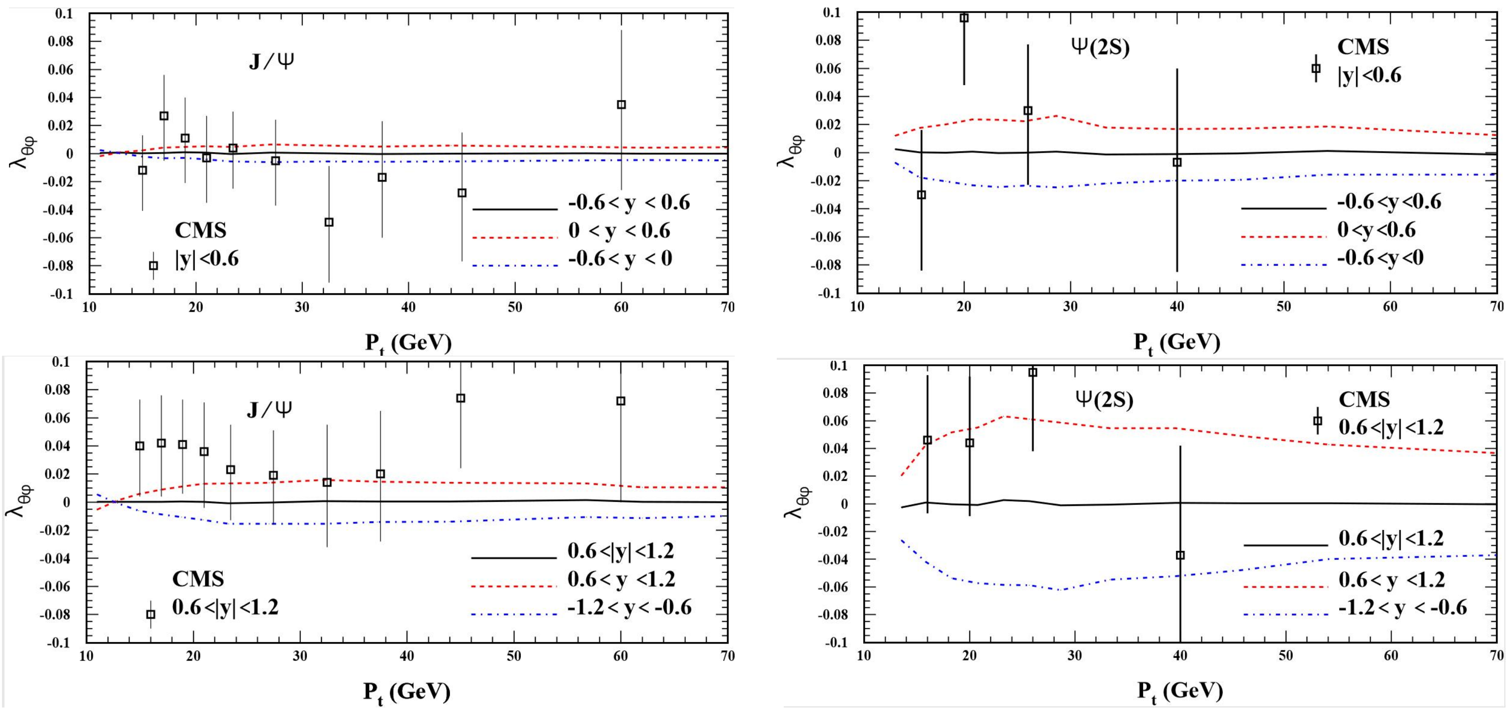
- New fitting on the J/ψ LDMEs
  - Yield and Polarization $(\lambda_\theta, \lambda_{\theta\varphi}, \lambda_\varphi)$
  - Totally 86 data points
  - Updated the CO J/ψ LDMEs
- Interesting Featrues
  - $\lambda_{\theta\varphi} = 0$ for experiment with symmetry rapidity range (a<|y|<b), e.g. CMS and ATLAS.
  - $\lambda_{\theta\varphi} \neq 0$ for half rapidity range (y>b), such as the case at LHCb.
  - $\lambda_\theta, \lambda_\varphi$ are symmetry for y>0 and y<0.



- Yu Feng, Bin Gong, Chao-Hsi Chang, Jian-Xiong Wang, PRD99.014044 (2019) .

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

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



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

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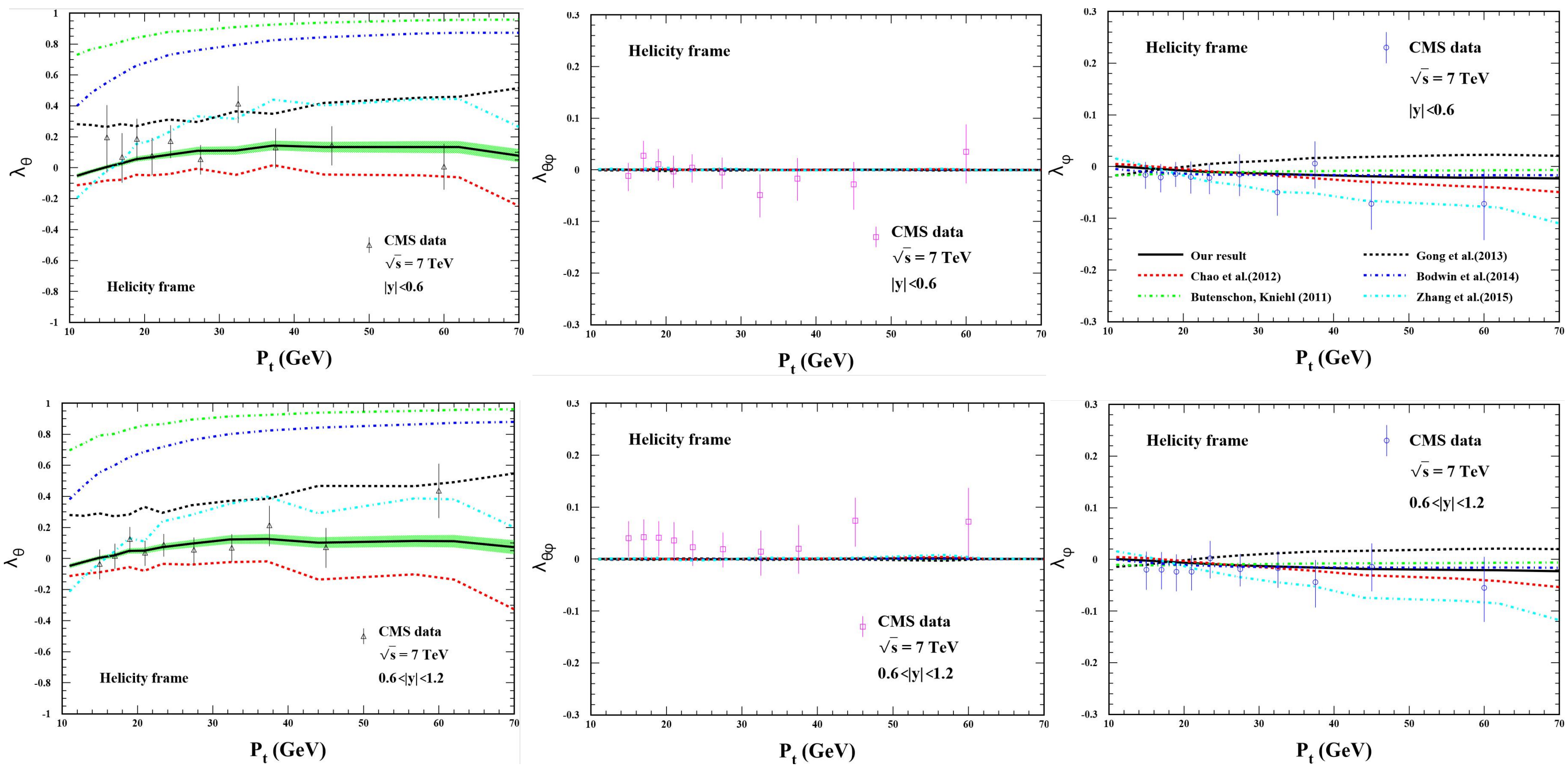
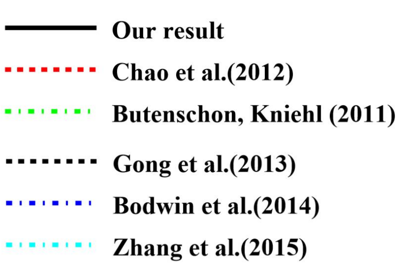
- Yu Feng, Bin Gong, Chao-Hsi Chang, Jian-Xiong Wang, PRD99.014044 (2019) .

J/ψ polarization $\lambda_\theta, \lambda_{\theta\varphi}, \lambda_\varphi$ at CMS

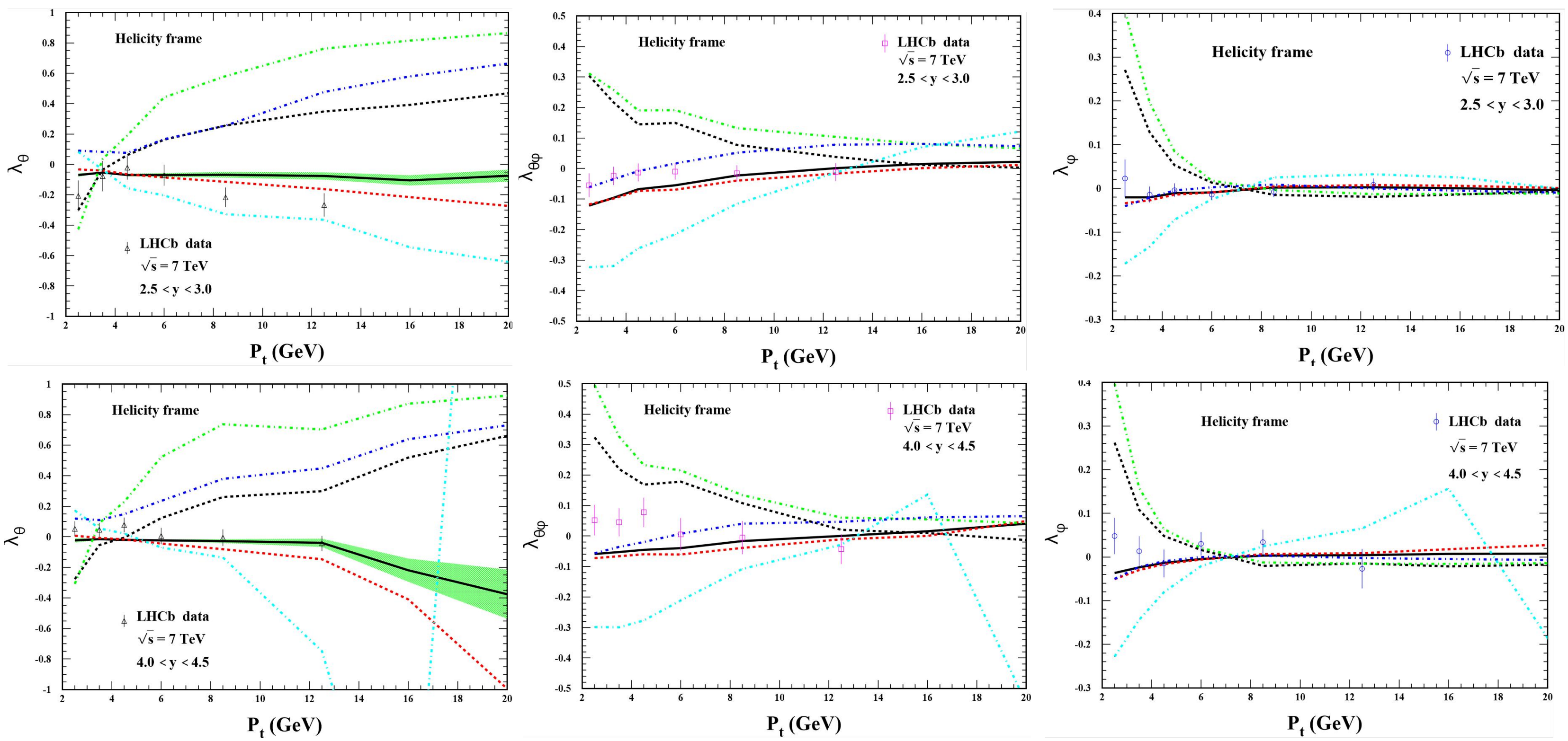


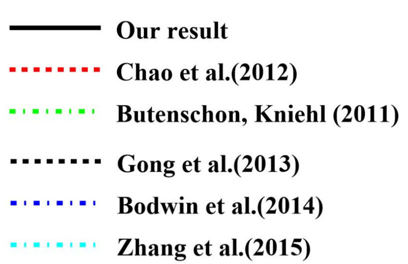


- All five fit schemes provide good descriptions of $\lambda_{\theta\varphi}, \lambda_\varphi$
- Large difference for λ_θ within different LDME schemes.
- Our new fits provides an excellent description of λ_θ

- Yu Feng, Bin Gong, Chao-Hsi Chang, Jian-Xiong Wang, PRD99.014044 (2019) .

J/ψ polarization $\lambda_\theta, \lambda_{\theta\varphi}, \lambda_\varphi$ at LHCb



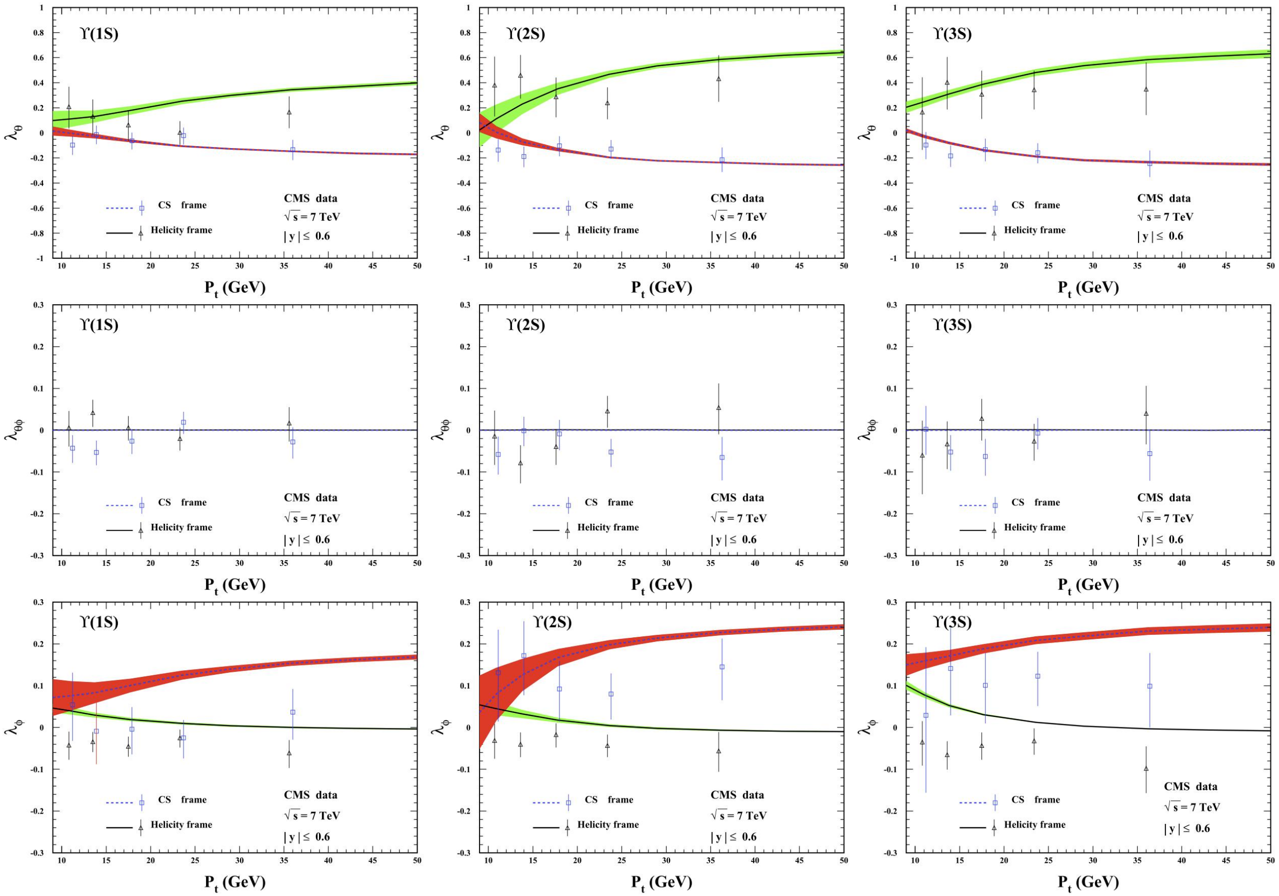


- Large uncertainties for different LDME schemes at low pt region.
- Our new fits describe the measurements at LHCb quite well

- Yu Feng, Bin Gong, Chao-Hsi Chang, Jian-Xiong Wang, PRD99.014044 (2019) .

$\Upsilon(nS)$ polarization $\lambda_\theta, \lambda_{\theta\varphi}, \lambda_\varphi$ at CMS

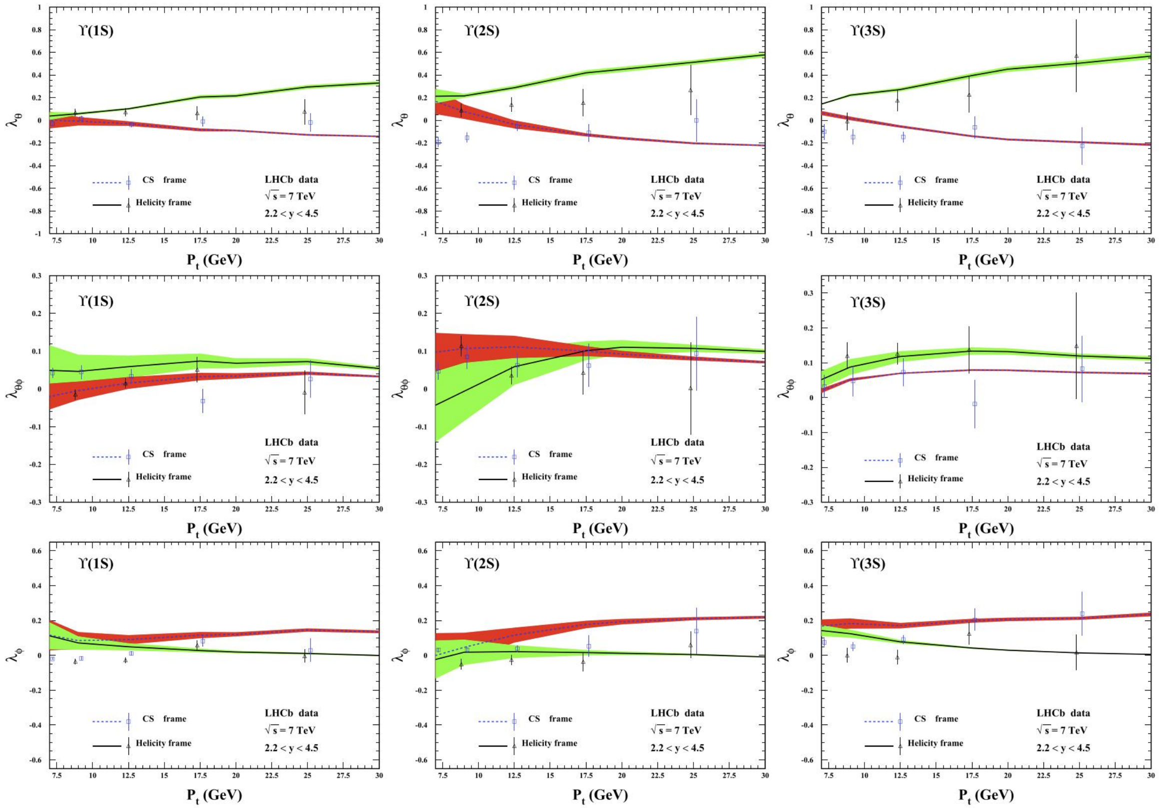
- Both in helicity frame and Collins-Soper frame.



Yu Feng, Bin Gong, Chao-His Chang, Jian-Xiong Wang. Chin.Phys.C45, 013117 (2021)

$\Upsilon(nS)$ polarization $\lambda_\theta, \lambda_{\theta\varphi}, \lambda_\varphi$ at LHCb

- Both in helicity frame and Collins-Soper frame.



- The theory results are in good agreement with the experimental data.
- But some problem remains at low pt region.

Yu Feng, Bin Gong, Chao-His Chang, Jian-Xiong Wang. Chin.Phys.C45, 013117 (2021)

Summary

- Measurements on pt distribution of yield and polarization by CMS,Atalas,LHCb and Alice.
- The prediction on the polarization of J/ψ and Υ hadroproduction is archived at QCD NLO
- Differenct fitting strategy→ different LDMEs
- With the LDMEs extracted from the production and polarization parameter λ_θ , there are good description of the $\lambda_{\theta\varphi}$, λ_φ for J/ψ and $\Upsilon(nS)$ in both helicity and CS frame.
- NRQCD LDMEs are universal? Theoretical calculation and experimental measurement in B-factory show no color-octet contribution.

Outlook

- The measurements are expected at HL-LHC
- New factorization scheme

PRL108,102002(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

Thank you!