The remaining parts for the long-standing $J/\psi$ polarization puzzle

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Heavy quarkonium

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

- 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

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

Parton Distribution Function

Hadronization (LDME)

Production of Heavy quark Pair
(Short Distance)

Bodwin, Braaten and Lepage, PRD 51, 1125 (1995)
LO NRQCD failed in the description of $J/\psi$ polarization.

- Prediction contradicts with CDF data

**Analysis**

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

\[
\alpha (or \, \lambda_0) = \frac{d\sigma_{11} - d\sigma_{00}}{d\sigma_{11} + d\sigma_{00}}
\]

Polarization at NLO

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

- Different fitting strategy $\rightarrow$ different LDMEs $\rightarrow$ 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);
$\eta_c$ and $J/\psi$ hadroproduction data reconciled

- $\eta_c$ 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/$\psi$ polarization puzzle remains

- Not very good with J/$\psi$ polarization in midrapidity region

Zhang, Sun, Sang and Li. PRL 114,092006 (2015)
The parameters describing $J/\psi$ polarization

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

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

- $\theta$ - polar angle between momentum of a positive lepton in the $J/\psi$ rest frame and the polarization axis $Z$
- $\phi$ – corresponding azimuthal angle

- Polarization axis $Z$
  - Helicity (HX) frame: along the $J/\psi$ 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 $J/\psi$ rest frame
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- Where

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

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

- **Experiment measurement:**
  - LHCb Collaboration, EPJC (2013) 73:2631

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

- Are the theoretical predictions on $\lambda_{\theta\phi}, \lambda_{\phi}$ 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 $J/\psi$

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

- **Feed-down contribution from $\chi_{cJ}$ and $\psi(2S)$**
  $$d\sigma_{\lambda\lambda'}^{J/\psi} |_{\chi_{cJ}} = B[\chi_{cJ} \rightarrow J/\psi] \sum_{J_z,J'_z} \delta_{J_z - \lambda, J'_z - \lambda'} C_{J_z,J'_z}^{\lambda,\lambda'} C^{*\lambda,\lambda'}_{J_z,J'_z} d\sigma_{J_z,J'_z}^{\chi_{cJ}}.$$  
  $$d\sigma_{\lambda\lambda'}^{J/\psi} |_{\psi(2S)} = B[\psi(2S) \rightarrow J/\psi] d\sigma_{\lambda\lambda'}^{\psi(2S)}.$$

- **87 parton level sub-processes**

- **Updated FDCHQHP package**

- **HPC Cluster of ITP-CAS (Thanks!)**
Interesting Features

• In helicity frame for inclusive $J/\psi$ production at the LHC, a symmetry (antisymmetry) relations can be deduced as

\[
\left. \frac{d\sigma}{dy} \right|_{y=a} = n_{\lambda\lambda'} \left. \frac{d\sigma}{dy} \right|_{y=-a} \\
\begin{array}{l}
\text{for } y > 0 \text{ and } y < 0 \\
\end{array}
\]

\[
n_{\lambda\lambda'} = \begin{cases} 
1 & \lambda = \pm \lambda' \\
-1 & \lambda = \pm 1, \lambda' = 0
\end{cases}
\]

\[
y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right)
\]

• 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.

✓ $\lambda_{\theta}$, $\lambda_{\phi}$ are symmetry for y>0 and y<0.
New fitting on the $J/\psi$ LDMEs

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

- LDMEs Strategy:
  - CS: potential model
    \[
    \langle O^{\psi}(^3 S_1^{[1]}) \rangle = \frac{3N_c}{2\pi}|R_\psi(0)|^2,
    \]
    \[
    \langle O^{\chi_cJ}(^3 P_J^{[1]}) \rangle = \frac{3}{4\pi}(2J + 1)|R'_{\chi_c}(0)|^2.
    \]
  - CO: $\chi_{cJ}$ and $\psi(2S)$ are from PRL110.042002(2013)

- Totally 86 data points of $J/\psi$, by minimizing $\chi^2$, we obtain

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

- $J/\psi$, $\psi(2S)$ 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 $\lambda_{\theta}, \lambda_{\theta \phi}, \lambda_{\phi}:$ CMS
Results for $\lambda_\theta$, $\lambda_{\theta\phi}$, $\lambda_\phi$: LHCb
We finished calculation on $\lambda_{\theta\phi}$, $\lambda_\phi$ for J/$\psi$ polarization in helicity frame based on NRQCD.

New fitting can describe both J/$\psi$ production and polarization.

LDMEs uncertainties are large for $\lambda_\theta$.

QCD NLO describe $\lambda_{\theta\phi}$, $\lambda_\phi$ quite well (medium and high $p_t$) by different LDMEs schemes.
Thank you!