



Leptonic Angular Coefficients in J/ψ Production within the Parton Reggeization Approach

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Outline

- ▶ Factorisation framework: High Energy Factorisation — Parton Reggeization Approach
- ▶ Hadronisation model: NRQCD
- ▶ Polarised J/ψ production & leptonic angular coefficients within NRQCD
- ▶ Results of calculations:
 - Unpolarised J/ψ spectra
 - Leptonic angular coefficients, ALICE & LHCb data

Introduction

- ▶ J/ψ production as a probe for:
 - initial parton dynamics via certain factorisation framework
 - nonperturbative quantities of hadronisation model
- ▶ Hadronisation approaches: NRQCD and ICEM
- ▶ «Quarkonium polarisation puzzle» — no consistent description of polarised J/ψ production
- ▶ Polarised J/ψ production — more precise test and source for nonperturbative details of hadronisation [Faccioli, Knünz, Lourenço, Seixas, Wöhri (2014)]
- ▶ Parton Reggeization Approach (PRA) — High Energy Factorisation (HEF) based on modified multi-Regge kinematics [Nefedov, Saleev, Shipilova (2013); Karpishkov, Nefedov, Saleev (2017); Nefedov, Saleev (2020)]

Parton Reggeization Approach

► Parton Reggeization Approach — HEF framework

[Collins, Ellis (1991); Catani, Hautmann (1994); Gribov, Levin, Ryskin (1983)]

- with the base of modified multi-Regge (mMRK) kinematics $\Lambda_{\text{QCD}} \ll \mu \ll \sqrt{s}$ for QCD amplitudes and Reggeized initial partons

► Master formula for High Energy Factorisation for $p + p \rightarrow \mathcal{C} + X$:

$$d\sigma = \sum_{i,j=R,Q,\bar{Q}} \int \frac{dx_1}{x_1} \frac{d\vec{q}_{1T}}{\pi} \int \frac{dx_2}{x_2} \frac{d\vec{q}_{2T}}{\pi} \Phi^i(x_1, \vec{q}_{1T}^2, \mu^2) \Phi^j(x_2, \vec{q}_{2T}^2, \mu^2) d\hat{\sigma}(x_1, x_2, \vec{q}_{1T}^2, \vec{q}_{2T}^2, \mu^2) \quad (1)$$

- with process-independent unintegrated PDFs $\Phi(x, q_T^2, \mu^2)$ normalised to collinear PDFs:

$$\int_0^{\mu^2} dq_T^2 \Phi(x, q_T^2, \mu^2) = x f(x, \mu^2)$$

- with hard partonic cross section $d\hat{\sigma}(x_1, x_2, \vec{q}_{1T}^2, \vec{q}_{2T}^2, \mu^2)$
- with off-shell initial partons, $q_{1,2}^2 = -t_{1,2} = -\vec{q}_{1,2T}^2$:

$$q_{1,2}^\mu = x_{1,2} p_{1,2}^\mu + q_{1,2T}^\mu, \quad p_{1,2}^\mu = \frac{\sqrt{s}}{2} (1, 0, 0, \pm 1), \quad q_{1,2T}^\mu = (0, \vec{q}_{1,2T}, 0)$$

► Accounted partonic subprocesses: $R + R \rightarrow \mathcal{C}$ and $R + R \rightarrow \mathcal{C} + g$

Parton Reggeization Approach, unPDFs evolution

- Unintegrated PDFs in modified Kimber-Martin-Ryskin-Watt (mKMRW) model can be written as [Kimber, Martin, Ryskin (2001); Watt, Martin, Ryskin (2003); Nefedov, Saleev (2020)]

$$\Phi^i(x, t, \mu^2) = \frac{T^i(x, t, \mu^2)}{t} \frac{\alpha_s(t)}{2\pi} \sum_j \int_x^1 dz \frac{x}{z} P_{ji}(z) f^j\left(\frac{x}{z}, t\right) \theta(\Delta_{\text{KMR}}(t, \mu^2) - z)$$

- with the following Sudakov form factor [Nefedov, Saleev (2020)]:

$$T^i(x, t, \mu^2) = \exp \left\{ - \int_t^{\mu^2} \frac{dt'}{t'} \frac{\alpha_s(t')}{2\pi} (\tau_i(t', \mu^2) + \Delta\tau_i(t', \mu^2, x)) \right\}$$

- boundary conditions for Sudakov form factor $T^i(x, t = 0, \mu^2) = 0$ and $T^i(x, t = \mu^2, \mu^2) = 1$
- KMR cutoff function [Kimber, Martin, Ryskin (2001)]:

$$\Delta_{\text{KMR}}(t, \mu^2) = \frac{\sqrt{\mu^2}}{\sqrt{t} + \sqrt{\mu^2}}$$

Hadronisation model: NRQCD

- ▶ J/ψ wave function as a series w.r.t. relative constituent quarks velocity v (approximate scaling, $v^2 \approx 0.2$):
[Bodwin, Braaten, Lepage (1995)]

$$|J/\psi\rangle = \mathcal{O}(v^0) |c\bar{c}[^3S_1^{(1)}]\rangle + \mathcal{O}(v^1) |c\bar{c}[^3P_J^{(8)}]g\rangle + \mathcal{O}(v^2) |c\bar{c}[^3S_1^{(1,8)}]gg\rangle + \mathcal{O}(v^2) |c\bar{c}[^1S_0^{(8)}]g\rangle + \dots$$

- ▶ Hard cross section factorisation:

$$d\hat{\sigma}(ab \rightarrow \mathcal{C}X) = \sum_n d\hat{\sigma}(ab \rightarrow c\bar{c}[n]X) \langle \mathcal{O}^{\mathcal{C}}[n] \rangle$$

- ▶ Long-distance matrix elements (LDME) $\langle \mathcal{O}^{\mathcal{C}}[n] \rangle$: phenomenological potential models, **experimental data fitting**
- ▶ Amplitude of J/ψ production projected onto necessary spin state: $\mathcal{M} = \mathcal{M}_\alpha \varepsilon^\alpha(S_z)$
- ▶ Cross section for direct J/ψ production within PRA:

$$\text{for } R + R \rightarrow \mathcal{C} \quad \frac{d\sigma}{dydp_T} = \frac{p_T}{M_T^4} \int dt_1 t_1 d\varphi_1 \Phi(x_1, t_1, \mu^2) \Phi(x_2, t_2, \mu^2) |\overline{\mathcal{M}}|^2 \quad (2)$$

$$\text{for } R + R \rightarrow \mathcal{C} + g \quad \frac{d\sigma}{dydp_T} = \frac{p_T}{(2\pi)^3} \int \frac{dx_2 dt_1 dt_2 d\varphi_1 d\varphi_2}{(2x_1 x_2 s)^2 (x_2 - M_T e^{-y}/\sqrt{s})} \Phi(x_1, t_1, \mu^2) \Phi(x_2, t_2, \mu^2) |\overline{\mathcal{M}}|^2 \quad (3)$$

Leptonic angular coefficients, NRQCD

- ▶ Angular distribution of leptonic J/ψ -decay:

$$\frac{1}{\sigma} \frac{d\sigma}{d\Omega} = \frac{3}{4\pi} \frac{1}{3 + \lambda} \left[1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \varphi + \frac{\nu}{2} \sin^2 \theta \cos 2\varphi \right] \quad (4)$$

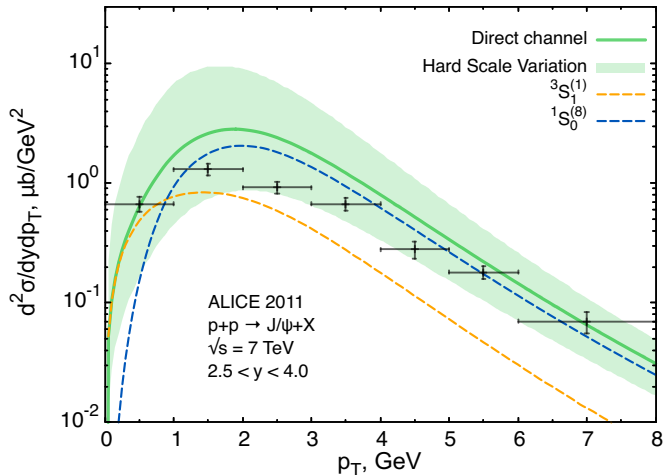
- obtained as a contraction $d\sigma \sim W_{\mu\nu} L^{\mu\nu} \rightarrow$ only symmetric part of $W_{\mu\nu}$ manifests
 - in a rest frame of J/ψ : Collins-Soper (CS), Gottfried-Jackson (GJ), Helicity (HX) frames
- ▶ Leptonic angular coefficients related to spin states of J/ψ :

$$\lambda = \frac{d\sigma - 3d\sigma_{00}}{d\sigma + d\sigma_{00}}, \quad \mu = \frac{\sqrt{2} \operatorname{Re} d\sigma_{10}}{d\sigma + d\sigma_{00}}, \quad \nu = \frac{2d\sigma_{1-1}}{d\sigma + d\sigma_{00}} \quad (5)$$

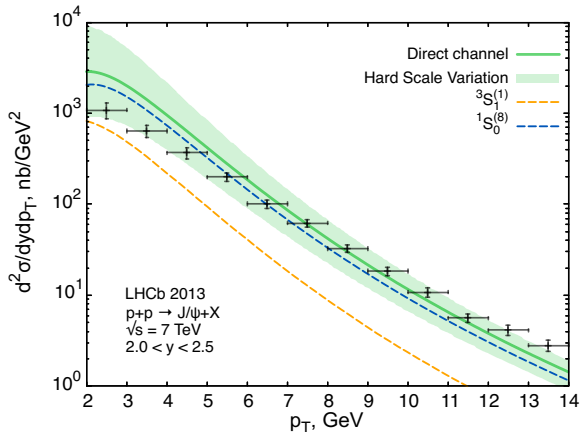
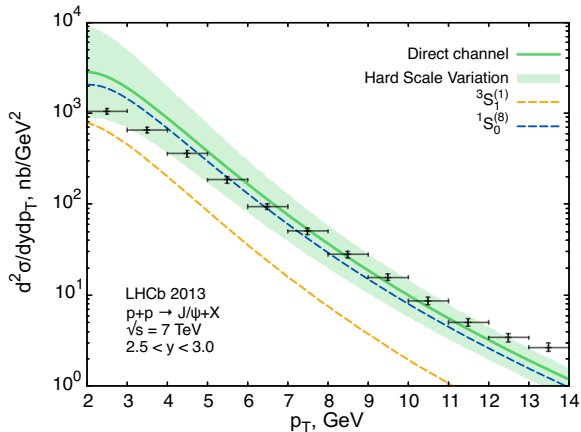
- ▶ Calculation of cross sections and interferences as projections onto necessary spin states for $R + R \rightarrow J/\psi$ and $R + R \rightarrow J/\psi + g$:

$$d\sigma_{ij} \sim \overline{\mathcal{M}_\alpha} \mathcal{M}_\beta^* \varepsilon^\alpha(S_z = i) \varepsilon^{*\beta}(S_z = j) \quad (6)$$

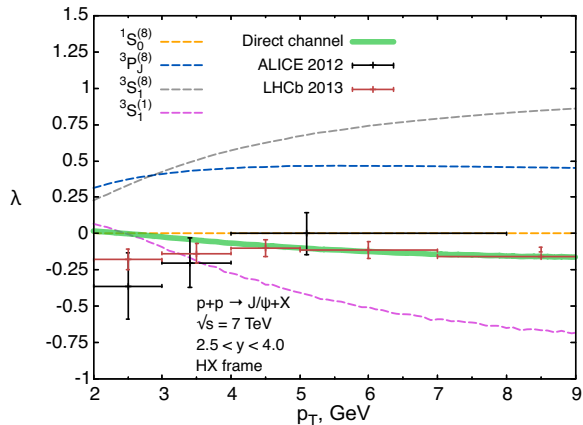
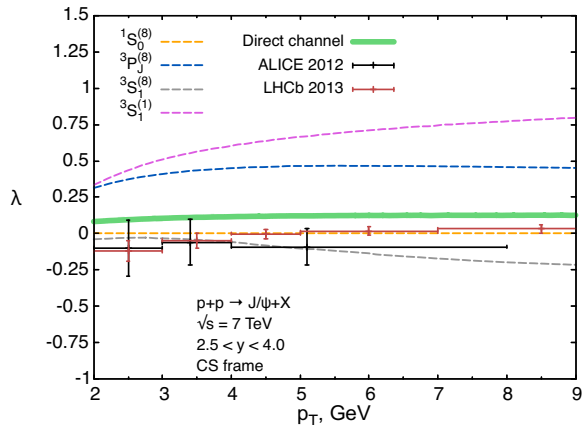
Unpolarised J/ψ production at $\sqrt{s} = 7$ TeV, ALICE data



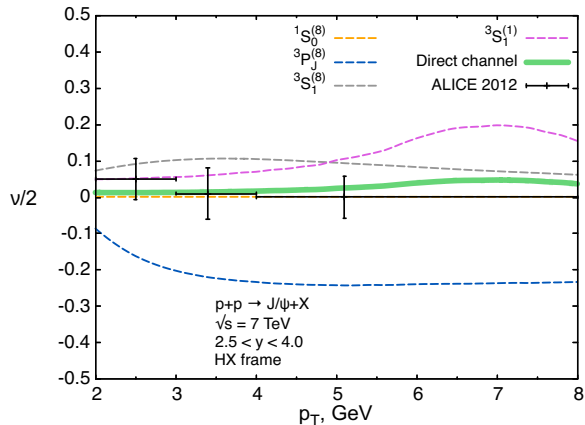
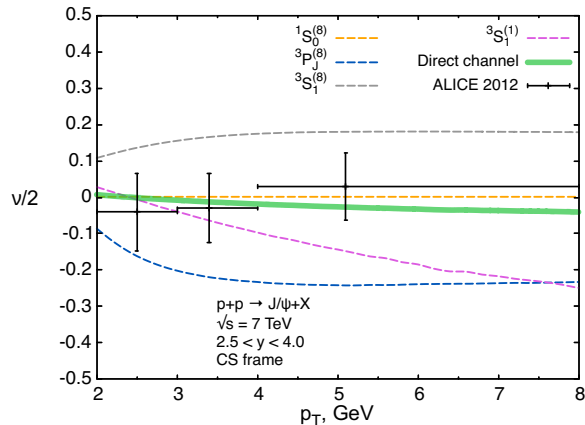
Unpolarised J/ψ production at $\sqrt{s} = 7$ TeV, LHCb data



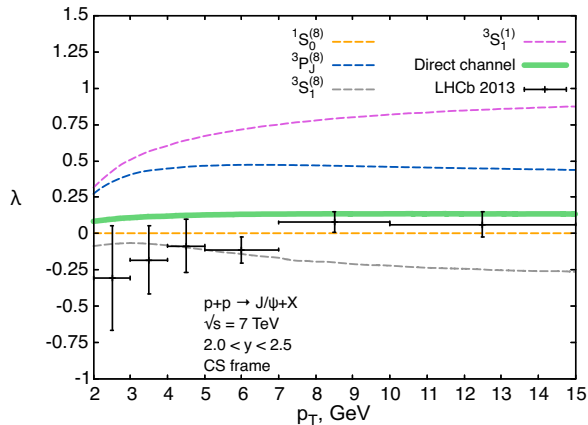
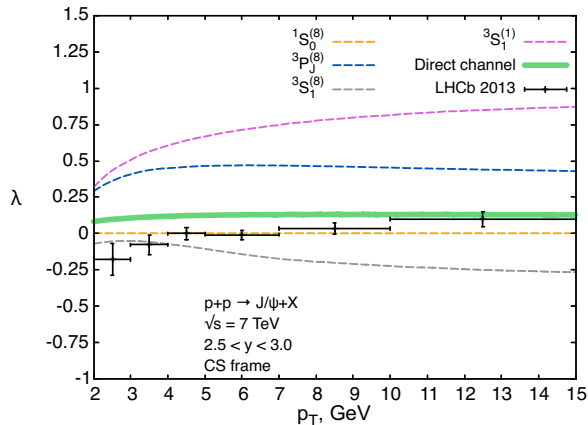
Leptonic angular coefficients at $\sqrt{s} = 7$ TeV, ALICE & LHCb data



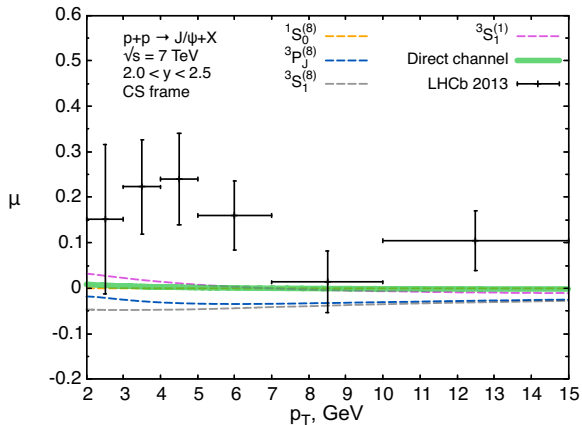
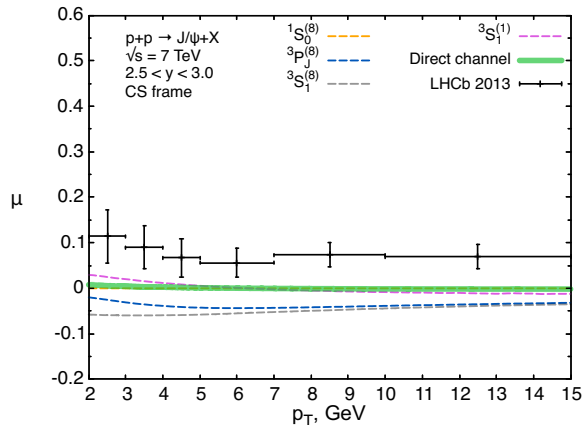
Leptonic angular coefficients at $\sqrt{s} = 7$ TeV, ALICE data



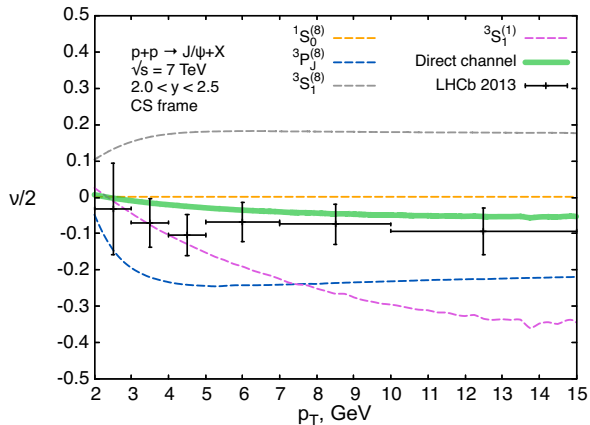
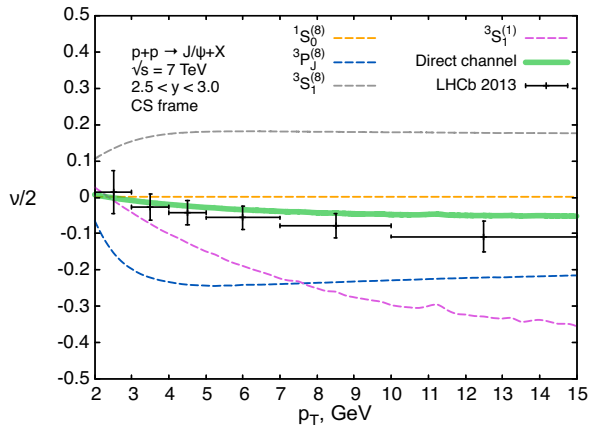
Leptonic angular coefficients at $\sqrt{s} = 7$ TeV, LHCb data



Leptonic angular coefficients, LHCb data



Leptonic angular coefficients, LHCb data



Summary

- ▶ Parton Reggeization Approach firstly probed for calculation of J/ψ leptonic angular coefficients μ and ν
- ▶ We found acceptable agreement with the experimental data for λ and ν coefficients within LO PRA at high p_T
- ▶ We found persistent underestimation for μ coefficient within LO PRA
- ▶ Different intermediate Fock states produce various patterns in p_T -dependence of λ , μ , ν coefficients
 - more accurate analysis of LDMEs is provided
 - J/ψ polarisation — not only a test of LDMEs but a data for LDMEs extraction
- ▶ Feed-down of χ_{cJ} and ψ' states (which are estimated commonly as $\sim 40\%$) may influence on leptonic coefficients λ , μ , ν non-negligibly

THANK YOU FOR ATTENTION!

Backup page. LDME fit [Alimov, Saleev (2026)]

LDME	Value	LDME	Value
$\langle \mathcal{O}^{J/\psi} [{}^3S_1^{(1)}] \rangle, \text{ GeV}^3$	1.3	$\langle \mathcal{O}^{\psi'} [{}^3S_1^{(1)}] \rangle, \text{ GeV}^3$	$6.5 \cdot 10^{-1}$
$\langle \mathcal{O}^{J/\psi} [{}^1S_0^{(8)}] \rangle, \text{ GeV}^3$	$4.54^{+0.07}_{-0.07} \cdot 10^{-2}$	$\langle \mathcal{O}^{\psi'} [{}^1S_0^{(8)}] \rangle, \text{ GeV}^3$	$0.0^{+5.7}_{-5.8} \cdot 10^{-4}$
$\langle \mathcal{O}^{J/\psi} [{}^3P_0^{(8)}] \rangle, \text{ GeV}^5$	$0.0^{+2.7}_{-3.2} \cdot 10^{-4}$	$\langle \mathcal{O}^{\psi'} [{}^3P_0^{(8)}] \rangle, \text{ GeV}^5$	$1.01^{+0.03}_{-0.03} \cdot 10^{-2}$
$\langle \mathcal{O}^{J/\psi} [{}^3S_1^{(8)}] \rangle, \text{ GeV}^3$	$0.0^{+0.9}_{-2.2} \cdot 10^{-5}$	$\langle \mathcal{O}^{\psi'} [{}^3S_1^{(8)}] \rangle, \text{ GeV}^3$	$9.34^{+0.2}_{-0.2} \cdot 10^{-4}$
$\langle \mathcal{O}^{\chi_{c0}} [{}^3P_0^{(1)}] \rangle, \text{ GeV}^5$	$8.9 \cdot 10^{-2}$	$\langle \mathcal{O}^{\chi_{c0}} [{}^3S_1^{(8)}] \rangle, \text{ GeV}^3$	$1.59^{+0.02}_{-0.02} \cdot 10^{-2}$