Quarkonium Polarization at LHCb

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Outline

- Introduction
- LHCb experiment and data taking
- Prompt $J/\psi$ polarization measurement
- Prompt $\psi(2S)$ polarization measurement
- Summary and prospects

More LHCb quarkonium productions summarized in talk by E. Tournefier
Introduction

- Heavy quarkonium: bound state of $Q\bar{Q}$ with $M_Q \gg \Lambda_{QCD}$, $\nu^2 \ll 1$
  - Factorization: hard production of $Q\bar{Q}$ at distance $\sim M_Q$, hadronization of $Q\bar{Q} \rightarrow H$
  - Probe both perturbative and non-perturbative aspects of QCD

- Color Singlet Mechanism (CSM)
  - $Q\bar{Q}$ colorless, coincides $H$ in quantum numbers
  - Logarithm infrared divergences in $P$-wave production
  - Poor description of production data at high-$p_T$, better agreement at NLO and NNLO*

![Graph](image)

**EPJ C61 (2008) 693**
Non-relativistic QCD (NRQCD)

- All intermediate $Q\bar{Q}$ states contribute to quarkonium production
- Described by non-perturbative long distance matrix elements (LDME)
- LDMEs determined by fitting experimental production data, could describe data very well
- Tested by independent data and/or independent measurements

- Polarization at high-$p_T$
  - Gluon fragmentation dominates $\rightarrow$ transverse polarization of $1^{--}$
  - CSM predicts longitudinal polarization
LHCb experiment

Aiming for precision measurements in heavy flavor

Good vertex separation:
Decay time resolution 45 fs for $B_s \rightarrow J/\psi \phi$
Discriminating prompt quarkonium production and those from $b$ decays

RunI: 3 fb$^{-1}$

High muon ID performance:
$\sim 97\%$, with 1-3 % $\pi \rightarrow \mu$ mis-id probability

QWG 2014
Prompt $J/\psi$ polarization

EPJ C73 (2013) 2631
\( J/\psi \) reconstructed in \( J/\psi \rightarrow \mu^+ \mu^- \) decays

Polarization encoded in muon angular distribution:

\[
\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos \theta + \lambda_{\theta \phi} \sin 2\theta \cos \phi + \lambda_\phi \sin^2 \theta \cos 2\phi
\]

- Full angular analysis to determine all three parameters simultaneously

- Full transverse/longitudinal polarization: \((\lambda_\theta, \lambda_{\theta \phi}, \lambda_\phi) = (+1, 0, 0)/(-1, 0, 0)\)

Angular distribution reported in two frames

- Helicity frame (HX): \( z \parallel \vec{P}_{J/\psi} \) in lab frame
- Collins-Soper frame (CS):
  \( z \sim \) direction of colliding partons in \( J/\psi \) rest frame

- One frame invariant parameter

\[
\lambda_{\text{inv}} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}
\]
Selection

- Dataset: $\sim 0.37$ fb$^{-1}$ $pp$ collision at $\sqrt{s} = 7$ TeV
- Forward acceptance: $2<p_T<15$ GeV, $2.0<y<4.5$
- Dedicated muon triggers, loose muonID, good vertex
  - Very efficient, resulting high signal/background ratio
- $J/\psi$ from $b$ suppressed by pseudo-proper time cut
  \[ \tau_z = \frac{d_z M_{J/\psi}}{p_z} \]
  Fraction of $J/\psi$ from $b$ reduces from 15% to 3%

Crystal ball + Straight line fit
Strategy

- Weighted unbinned maximum likelihood fit

\[
\ln \mathcal{L} = \alpha \sum_{i=1}^{N_{\text{tot}}} w_i \times \ln \left[ \frac{P(\cos \theta_i, \phi_i | \lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi) \epsilon(\cos \theta_i, \phi_i)}{\text{Norm}(\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi)} \right]
\]

- \(P(\cos \theta, \phi | \lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi) \equiv 1 + \lambda_\theta \cos \theta + \lambda_{\theta\phi} \sin 2\theta \cos \phi + \lambda_\phi \sin^2 \theta \cos 2\phi\) angular distribution

- \((\cos \theta_i, \phi_i)\): experimental observables for each event

- \(\epsilon(\cos \theta_i, \phi_i)\): efficiency, not uniform in general, determined with simulation

- \(\text{Norm}(\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi)\): normalization of numerator

- \(w_i\): sWeights to subtract background, \(\alpha \equiv \sum_{i=1}^{N_{\text{tot}}} w_i / \sum_{i=1}^{N_{\text{tot}}} w_i^2\): to correctly estimate stat. uncertainty

\[\text{arXiv:0905.0724}\]
Efficiency in simulation validated using $B^+ \rightarrow J/\psi K^+$ decay

- $J/\psi$ completely longitudinally polarized in $B^+$ rest frame ($\lambda_\theta = -1$)
- Discrepancy of angular distribution due to imperfectness of simulation of muon efficiencies

Corrections determined as function of $(p, \eta)$ of muon

- Remove inconsistencies in $B^+ \rightarrow J/\psi K^+$ events
- Applied to inclusive $J/\psi$ simulation
Results

- Both direct production and feed down included → prompt $J/\psi$
- $(\lambda_\theta, \lambda_{\phi}, \lambda_{\phi})$ measured in $(p_T, y)$ bins of $J/\psi$ in HX&CS independently
- No large polarization observed, no strong $p_T$ dependence
- Weighted average: $\lambda_\theta = -0.145 \pm 0.027$ in HX, small longitudinal polarization
  - Weights according to signal yields in each $(p_T, y)$ bin
- $\lambda_{\text{inv}}$: good agreement in HX and CS
Comparison with ALICE

- ALICE: $2 < p_T < 8 \text{ GeV}$, $2.5 < y < 4.0$, \( J/\psi \) from \( b \) decay included (inclusive)
  - Effect due to secondary contamination is small as studied by LHCb
  - Two measurements compatible

\( \lambda_\theta \) also consistent
Comparison with theory

**Calculations at NLO**

- CSM: no feed down, PRL 108 (2012) 172002
- NRQCD: no feed down, PRL 108 (2012) 172002
- NRQCD: w/ feed down, PRL 110 (2013) 042002
- NRQCD: w/ feed down, PRL 108 (2012) 242004

Different LDMEs

LDMEs matter and not trivial

Feed down could also change polarization prediction

arXiv:1410.8537
Prompt $\psi(2S)$ polarization

EPJ C74 (2014) 2872
Compared to $J/\psi$ analysis

- Feed down negligible, no ambiguity in interpreting results
  \[
  \frac{\sigma(\psi(2S)) \times B(\psi(2S) \to \mu^+\mu^-)}{\sigma(J/\psi) \times B(J/\psi \to \mu^+\mu^-)} \sim 2\% , \ 1 \text{ fb}^{-1} pp \text{ data at } \sqrt{s} = 7 \text{ TeV}
  \]
- Higher combinatorial background → tighten muonID
- Selections and strategy similar
- Measurements performed in $3.5 < p_T < 15 \text{ GeV}, 2.0 < y < 4.5$

![Crystal ball + Straight line fit](image)
Results

- $\lambda_\theta$ compatible with no polarization in HX frame
- $\lambda_{\text{inv}}$ shows small negative polarization, consistent in HX&CS frame
- $\lambda_\theta$ in HX frame and $\lambda_{\text{inv}}$ no significant kinematic dependence
- No strong transverse/longitudinal polarization, supporting CMS results

$\lambda_\theta$ in HX frame
$\lambda_\theta$ in CS frame
$\lambda_{\text{inv}}$
Comparison with theory

* CSM: no feed down, PRL 108 (2012) 172002
* NRQCD: no feed down, PRL 108 (2012) 172002
* NRQCD: w/ feed down, PRL 110 (2013) 042002
* NRQCD: w/ feed down, PRL 108 (2012) 242004
* Consistent with NRQCD at low $p_T$
* Don’t support large transverse polarization at high-$p_T$ predicted by NRQCD
Heavy quarkonium production ideal to study perturbative and non-perturbative part of QCD

Prompt $J/\psi$ and $\psi(2S)$ polarization measured as a function of $(p_T, y)$ at LHCb

in range $2(3.5) < p_T < 15 \text{ GeV}$, $2.0 < y < 4.5$

Results of ALICE, CMS and LHCb consistent

No large transverse/longitudinal polarization observed, no evidence of kinematic dependence

In general, do not favor NRQCD or CSM calculations at NLO

Prospects:

G polarization coming soon

New opportunities with LHC RunII at $\sqrt{s} = 13 \text{ TeV}$

Stay tuned
Spare slides
Polarization frames
$J/\psi$ polarization parameter $\lambda_\phi, \lambda_{\theta \phi}$
$\psi(2S)$ 2D efficiency & $\lambda_{\text{inv}}$ variation

Error bars are statistical uncertainty

LHCb $\sqrt{s} = 7$ TeV

$\psi(2S) p_T$ [GeV/c]
ψ(2S) polarization parameter $\lambda_\phi$, $\lambda_\theta\phi$