Quarkonium polarization in $pp$ collisions: a long-standing puzzle

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Probing the strong interaction at AFTER
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Quarkonium production involves different energy scales: the $q\bar{q}$ formation is a hard process, while the binding of the constituents and the evolution of the bound state occur at softer scales.

Theoretical models assume factorization:

$$\sigma[H] = \sum_n \sigma_n(\Lambda) \langle 0 | O_n^H | 0 \rangle$$

Cross section for the production of the quarkonium $H$

Short distance coefficients: perturbative cross sections (+PDF) for the production of a $qq$ pair in a given quantum state $n$

Long distance matrix elements: embed the non-perturbative part. THEY ARE ASSUMED TO BE UNIVERSAL

Different implementations of the factorization formula:

- **Color Singlet Model (CSM):** the color of the $q\bar{q}$ pair neutralizes in the hard process
- **Nonrelativistic QCD (NRQCD):** the color can be neutralized also in the long distance part $\rightarrow$ the perturbative cross section can create singlet and octet $q\bar{q}$ systems. The color octet matrix elements are estimated through a fit to the $p_t$-differential $J/\psi$ cross sections
The $J/\psi$ production mechanism in hadronic collisions is still an open issue.

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N. Brambilla et al., arXiv:hep-ph/0412158v2
Trying to describe CDF results

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LO CS + LO CO + gluon fragment. (LO NRQCD): perfect agreement

N. Brambilla et al., arXiv:hep-ph/0412158v2
How to experimentally study polarization
How to study quarkonium polarization

In a two-body decay quarkonium polarization is measured through the extraction of the anisotropies in the angular distribution of its daughter particles.

Taking as a reference the $\mu^+$ (conventionally), the angular distribution can be expressed as:

$$W(\cos \theta, \phi) \propto \frac{1}{3 + \lambda_\theta} \cdot (1 + \lambda_\theta \cos^2 \theta + \lambda_\phi \sin^2 \theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos \phi)$$

$\theta$ and $\phi$ are the polar and azimuth angles of the $\mu^+$ momentum in a given reference frame.

$$|\Psi\rangle = a_+ |+1\rangle + a_0 |0\rangle + a_- |-1\rangle \rightarrow \lambda$$ parameters can be expressed in terms of $a_i$

$\lambda_\theta$ is the fundamental parameter, directly affected by polarization:

$\lambda_\theta = +1 \rightarrow$ transverse polarization

$\lambda_\theta = 0 \rightarrow$ no polarization

$\lambda_\theta = -1 \rightarrow$ longitudinal polarization

P. Faccioli et al., EPJ C69 (2010) 657673
Polarization is extracted in the quarkonium rest frame.

Several possible definitions of the z-axis (always contained in the production plane):

- **helicity**: quarkonium momentum direction in the collision’s reference frame;
- **Collins-Soper**: bisector of the angle between one beam and the opposite of the other beam in the quarkonium rest frame;
- **Gottfried-Jackson**: direction of one beam in the quarkonium rest frame (mostly used in fixed target experiments)

For this analysis the helicity and Collins-Soper definitions were used.

P. Faccioli *et al.*, EPJ C69 (2010) 657673
Kinematical constraints and invariant quantities

From the definition of the $\lambda$ parameters and considering rotations among the reference frames it is possible to define a class of invariant quantities:

For each combination of integer numbers $(c_1, c_2, c_3)$, it must be the same for all the reference frames.

$$\mathcal{F}_{c_1,c_2,c_3} = \frac{(3 + \lambda_\theta) + c_1(1 - \lambda_\phi)}{c_2(3 + \lambda_\theta) + c_3(1 - \lambda_\phi)}$$

Moreover, it is possible to define a 3D region in the $[\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}]$ space that corresponds to the variability domain of the parameters.

The projections of this 3D figure on the 2D plots $[\lambda_\theta, \lambda_\phi]$, $[\lambda_\theta, \lambda_{\theta\phi}]$ and $[\lambda_\phi, \lambda_{\theta\phi}]$ are:

If the analysis is performed in more than one frame this quantity can be used as a check.
Results
The CDF experiment measured the $\lambda_\theta (= \alpha)$ parameter for prompt $J/\psi$ hadroproduction.

Only the $\cos \theta$ part of the full angular distribution analyzed (no estimation of $\lambda_\phi$ and $\lambda_{\theta \phi}$).

Results from Run I and Run II of the Tevatron:

no consistency between the two
not in agreement with LO and NLO NRQCD
The disagreement of NRQCD with data triggered strong efforts from the CSM side

More detailed calculations at higher order (NLO, NNLO*) showed a better agreement with polarization data, despite the huge uncertainty bands
$\Upsilon$ polarization from CDF and D0

$\Upsilon(1S)$ polarization measurement from the two experiments (Run II) in disagreement

Still puzzling
Also PHENIX and STAR measured J/ψ polarization in pp collisions at √s = 200 GeV

Agreement between the two experiments, but too low p_T to perform a real comparison with theory
No significant polarization observed in all the $p_t$ range

Hint for longitudinal polarization at low $p_t$ in the helicity frame which vanishes at higher $p_t$

In the Collins-Soper reference frame $\lambda_\theta$ always compatible with (but sistematically lower than) zero

$\lambda_\phi$ always compatible with zero in both the reference frames.

Also $\lambda_{\theta\phi}$ checked to be compatible with zero
ALICE results compared with LO and NLO NRQCD and CSM predictions
(M. Butenschön B.A. Kniehl, PRL 106 (2011) 022003), obtained making use of the non perturbative coefficients extracted from a global fit to the differential cross sections measured in hadron-hadron, lepton-hadron and lepton-lepton collisions

None of the two curves can perfectly describe the data
NRQCD slightly favored, in particular in the Collins-Soper frame
Also another theory group made a comparison with ALICE’s results (B. Gong at al., arXiv:1205.6682).

The theoretical curves (NLO NRQCD) were in this case obtained for prompt $J/\psi$ production and only the $\lambda_0$ parameter was considered.

In order to make the comparison data-theory more conclusive need to reach higher $p_t$. 

B. Gong at al., PRL 110, 042002 (2013)
J/ψ polarization with LHCb

Multi-differential measurement performed up to 15 GeV/c in the range $2 < y < 4.5$

In the helicity reference frame slightly longitudinal polarization observed.

In the Collins-Soper reference $\lambda_0$ goes to zero at high $p_T$.
All the other parameters consistent with zero.
The comparison between ALICE and LHCb shows a very good agreement in the common $y$ region for both the reference frames.
The comparison data/theory is still puzzling.

A better agreement is achieved when polarization measurements are used for the global fit (green band)

M. Butenschön B.A. Kniehl, PRL 108(2011) 172002
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B. Gong at al., PRL 110(2013) 042002
K.-T. Chao et al., PRL 108(2012) 242004

Charmonium polarization from CMS (I)

CMS measured $J/\psi$ and $\psi(2S)$ polarization in a large $p_T$ domain (up to 70 GeV/c) and in three different rapidity ranges ($|y| < 0.6$, $0.6 < y < 1.2$ and $1.2 < y < 1.5$).

Multi-dimensional analyses performed in different reference frames: $\lambda_\phi$ and $\lambda_{\theta \phi}$ found to be everywhere compatible with zero.

Charmonium polarization from CMS (II)

Parameters compatible with zero, both for \(J/\psi\) and \(\psi(2S)\)

No significant dependence on the charmonium rapidity

The comparison with NLO NRQCD is again not satisfactory

[26] B. Gong et al., PRL 110(2013) 042002

Multi-dimensional analysis performed on the three $\Upsilon$ resonances up to large $p_T$ and in two rapidity bins ($|y| < 0.6$ and $0.6 < y < 1.2$).

Hint for non-zero $\lambda_\theta$ for $\Upsilon$(2S) and $\Upsilon$(3S)
Summing-up theoretical procedure:

- Take all the cross-section data for a given quarkonium production (hadro, photo, etc.) and fit them leaving the LDMEs free

- Use the estimated LDMEs to predict the degree of polarization (FAIL)

BUT

In this way the fit to the cross-section data is describing the trend JUST QUALITATIVELY and tends to be constrained by low-pt data points!

Possible different approach:

Let’s assume NRQCD is valid, but we need to understand what is the validity domain!

We concentrate on a single set of data and we try to fit the cross section from a certain $p_T$ onwards: we try to define a minimum $p_T$ value from which NRQCD correctly predicts polarization
Change of perspective: example on $\psi(2S)$

C. Lourenço et al., Hard Probes 2013

Considering CMS data on $\psi(2S)$, one sees that the fit to the $p_T$-differential cross-section gives the best $\chi^2$ for $p_T > 13 \text{ GeV/c}$

While $p_T$ increases, the different LDMEs evolve and the relative importance of them changes!

For $p_T > 13 \text{ GeV/c}$ the dominant contribution is from $^1S_0$
Change of perspective: what happens to polarization

C. Lourenço et al., Hard Probes 2013

$^1S_0$ is the LDME which carries the zero-polarization contribution!!

Fitting $\psi(2S)$ data for $p_T$ higher than 13 GeV/c, one can correctly provide predictions on the degree of polarization.

Is this the correct way to proceed?
Need large data samples from the same experiment for different quarkonia in the $p_T$ range 5-50 GeV/c
The degree of polarization of hadro-produced quarkonia is a key-observable. Tevatron experiments measured it, but the disagreement between CDF and D0 on $\Upsilon$ and the internal disagreement between CDF Run I and Run II on $J/\psi$ made the comparison with theory less meaningful.

$J/\psi$ polarization has also been studied at RHIC at very low $p_T$.

LHC experiments have been delivering high-precision results for $J/\psi, \psi(2S), \Upsilon(1S), \Upsilon(2S)$ and $\Upsilon(3S)$. The agreement among the experiment is very good.

The comparison of LHC results with theoretical predictions is still giving no satisfying answers and a new approach seems to emerge in order to understand the origin of the discrepancy.

The need of a theoretical effort is clear, but still need very precise data for different quarkonia in the intermediate and large $p_T$ regions.

**AFTER?**

Thank you.