From identical S- and P-wave $p_T/M$ spectra to maximally distinct polarizations: probing NRQCD with LHC data

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Unexpectedly simple data patterns

All quarkonia have identical $p_T/M$-differential cross section shapes, for $p_T/M > 2$, at mid-rapidity, independently of mass and quantum numbers.
Scaling all data to match the J/ψ normalization
Same production dynamics for S- and P-wave states

Identical $p_T/M$ cross section shapes for S- and P-wave states \(\Rightarrow\) no sign of dependence of the production dynamics on the quantum numbers!

CMS, pp @7 TeV
HX frame

$\Upsilon(1S): \approx 40\%$ from $\chi_b$

$\Upsilon(2S):$ $J/\psi$ feed-down free

$\psi(2S):$ $J/\psi$ feed-down free

Small polar decay anisotropies, with no $p_T$ dependences, for all S-wave states, despite very different P-wave feed-down contributions

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To quantify: a model independent global charmonium fit

We probe the seemingly negligible differences between S- and P-wave production dynamics by doing a simultaneous global fit to mid-rapidity differential cross sections and polarizations of the charmonium states $\psi(2S)$, $J/\psi$ and $\chi_{c1,2}$

Includes a detailed account of the momentum and polarization transfer from the mother to the daughter particle in the relevant feed-down decays:

\[
\begin{align*}
\psi(2S) & \rightarrow \chi_{c1,2} \gamma \\
\psi(2S) & \rightarrow J/\psi \ X \\
\chi_{c1,2} & \rightarrow J/\psi \ \gamma
\end{align*}
\]

**Momentum propagation**: $p_T/m = P_T/M$

$M$ ($m$) and $P_T$ ($p_T$) are, respectively, the mass and laboratory transverse momentum of the mother (daughter) particle

**Polarization propagation**: calculated in the electric dipole approximation. Precisely accounts for the observable dilepton distribution with no need for higher-order terms

Perturbative calculations of the production kinematics are not used as ingredients anywhere in the analysis. The fit is *exclusively based on empirical parametrizations*
Parametrization

The $J/\psi$ and $\psi(2S)$ cross sections are parametrized as a superposition of unpolarized ($\lambda_\theta = 0$) and transversely polarized ($\lambda_\theta = +1$) processes: 

$$\sigma_{\text{dir}} \propto \left(1 - f_p\right) g_u + f_p g_p$$

- $f_p$: fractional contribution of the polarized process at an arbitrary reference point ($p_T/M$)*
- $g_u, g_p$: shape functions that describe the $p_T/M$ dependences of the unpolarized and polarized yields, respectively, normalized to unity at the chosen ($p_T/M$)*:

$$g(p_T/M) = h(p_T/M) / h[(p_T/M)^*],$$

with

$$h(p_T/M) = (p_T/M) \left(1 + \frac{1}{\beta-2} \frac{(p_T/M)^2}{\gamma}\right)^{-\beta}$$

- $f_p, g_u$ and $g_p$ are identical for the two S-wave states. The unpolarized and polarized cross sections share the parameter $\gamma$, but have distinct $\beta_u$ and $\beta_p$. By definition, the shapes and relative contributions of the $g_u$ and $g_p$ functions are constrained by the polarization data.

The same general shape parametrization is followed for $\chi_{c1}$ and $\chi_{c2}$, without discriminating between polarized and unpolarized contributions, which cannot be individually constrained in the absence of $\chi_c$ polarization data.

There are, hence, four contributions to direct quarkonium production: the unpolarized and polarized $\psi$ terms plus the $\chi_{c1}$ and $\chi_{c2}$ cross sections, altogether characterized by one $\gamma$ and four $\beta$ parameters, $\beta_u, \beta_p, \beta(\chi_1)$ and $\beta(\chi_2)$.
Correlated uncertainties

A crucial source of correlation between all the points being fitted is the dependence of the detection acceptances on the polarization.

For each set of parameter values considered while running the fit, the expected values of the polarizations and cross sections are calculated, for all states, as functions of $p_T$. The values obtained in this way for $\lambda_\theta$ can be immediately compared to the measured ones.

For the cross section, we first scale the measured cross sections by acceptance-correction factors calculated for the $\lambda_\theta$ value under consideration. These correction factors are computed using the tables published by the experiments for the cross sections of particles produced with fully transverse or fully longitudinal polarization, as a complement to the unpolarized assumption used for the default measured values.

Also considered in the fit are nuisance parameters from two sources:
1) The ATLAS and CMS integrated-luminosity uncertainties
2) The uncertainties of the branching ratios (B) used by the experiments to derive the cross sections ($\sigma$) from the measured values ($B \times \sigma$)
**Fit results**

The fit has 100 constraints (data points) and 20 parameters:
- 5 shape parameters,
- 4 normalizations,
- the fraction $f_p$
- and 10 nuisance parameters

The $\chi_{c1}$ and $\chi_{c2}$ $p_T/M$ distributions are very similar to the unpolarized term dominating $\psi$ production

$$\beta_u = 3.42 \pm 0.05$$

$$\beta(\chi_1) = 3.46 \pm 0.08$$

$$\beta(\chi_2) = 3.49 \pm 0.10$$

This very clear observation reflects the fact that the full chain of feed-down decays is taken into account, so that the high precision $\psi$ data points contribute to the $\chi_c$ results

The polarized term has a weak contribution and the charmonium states are nearly unpolarized
Quarkonium production in the NRQCD approach

In NRQCD several production mechanisms are foreseen for each quarkonium state.

What is produced in the hard scattering (and determines kinematics and polarization) is a *pre-resonance* $Q\bar{Q}$ state with specific quantum properties.

1) short-distance partonic process produces *neutral* or *coloured* $Q\bar{Q}$ of any $^{2S+1}L_J$ quantum numbers.

$$\sigma(A + B \rightarrow Q + X) = \sum_{S, L, C} S\{A + B \rightarrow (Q\bar{Q})_C^{^{2S+1}L_J} + X\} \cdot \mathcal{A}\{(Q\bar{Q})_C^{^{2S+1}L_J} \rightarrow Q\}$$

2) The quantum numbers change in the long-distance evolution to the observed (neutral) bound state.

$\eta_c, \eta_b \left[ ^1S_0 \right], \Psi, \Upsilon \left[ ^3S_1 \right], \chi_{c0}, \chi_{b0} \left[ ^3P_0 \right], \chi_{c1}, \chi_{b1} \left[ ^3P_1 \right], \chi_{c2}, \chi_{b2} \left[ ^3P_2 \right]$
NRQCD hierarchies

Approximations (heavy-quark limit) and calculations induce hierarchies and links between pre-resonance contributions

1) Small quark velocities $v$ in the bound state $\rightarrow$ “$v$-scaling” rules for LDMEs

2) Perturbative calculations $\rightarrow$ some SDCs are negligible:

3) Heavy-quark spin symmetry $\rightarrow$ relations between LDMEs of different states

\[
\begin{align*}
\frac{^3S_1 \to \chi_{c2}}{^3S_1 \to \chi_{c1}} &= \frac{^3S_1 \to \chi_{b2}}{^3S_1 \to \chi_{b1}} = \frac{5}{3}, \quad ^3S_1 \to \eta_c = ^1S_0 \to J/\psi, \\
& \quad ^3S_1 \to \eta_b = ^1S_0 \to \Upsilon, \text{ etc.}
\end{align*}
\]
The variety of kinematic behaviours predicted in NRQCD seems **redundant** with respect to the measured universal $p_T/M$ scaling and lack of polarization.
The polarization dimension

Quarkonium polarization is characterized by $\lambda_\theta$:

- measured as the polar anisotropy of the decay dilepton angular distribution
- calculated from the transverse and longitudinal cross sections: $(\sigma_T - \sigma_L) / (\sigma_T + \sigma_L)$

Each colour singlet and octet term has a specific polarization associated:

- $^1S_0 \rightarrow \lambda_\theta = 0$ at LO, NLO, etc; isotropic wave function
- $^3S_1 \rightarrow \lambda_\theta = +1$ at LO, NLO, etc, at high $p_T$, where the fragmenting gluon is “real”
- $^3P_J \rightarrow \lambda_\theta >> +1$ at NLO and high $p_T$ (“hyper-transverse”); it is 0 at LO...
- $^3S_1 \rightarrow \lambda_\theta \sim -0.9$ at NLO and high $p_T$; it is $\approx +1$ at LO (has a small impact)
Data fit vs. NRQCD: a surprising agreement

A comparison of the shape functions from the global fit (data bands) with their NRQCD counterparts, over 8 (!) orders of magnitude, shows a surprising result: within uncertainties, NRQCD can reproduce the similarity of the $p_T/M$ distributions

The data bands and the NLO SDCs were obtained in completely independent ways

$^1S_0 \quad \Rightarrow \quad J/\psi, \psi(2S)$

The width of the data bands only reflects *shape* uncertainties
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$^{1}\!S_0 \quad \Rightarrow \quad J/\psi, \psi(2S)$

$^{3}\!S_1 \quad \Rightarrow \quad J/\psi, \psi(2S)$

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P. Faccioli et al. EPJC 78 (2018) 268
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$^{3}p_{J} \overset{3S_{1}}{\longrightarrow} \chi_{cJ}$

$^{3}S_{1} \overset{J/\psi, \psi(2S)}{\longrightarrow}$

The width of the data bands only reflects shape uncertainties.
Striking coincidence or trigger to improve NRQCD?

The seeming success of NRQCD uncovers a strong prediction: the unmeasured $\chi_{c1}$ and $\chi_{c2}$ polarizations must be very different from one another.

Cross section ratio $\chi_{c2} / \chi_{c1}$: ATLAS and CMS data agree better with each other and with theory fit if their polarizations are different (acceptance correction depends on $\lambda_0$).

Potentially striking exception to the uniform picture of mid-rapidity quarkonium production!

$\chi_{c1} + \chi_{c2} \rightarrow J/\psi$: weak polarization $\approx$ as observed in prompt $J/\psi$ data!

$| \Delta \lambda_0 | \approx 1$

at the barycentre of current CMS $\chi_c$ data
Comparison to a previous prediction

In NRQCD, one single parameter determines both the $\chi_{c2}/\chi_{c1}$ ratio and the two polarizations

$$r \equiv m_c^2 \left( \mathcal{O}_{\chi_{c0}}(3 S_1^{[8]}) \right) \left( \mathcal{O}_{\chi_{c0}}(3 P_0^{[1]}) \right)$$

Shao et al. derive $r = 0.27 \pm 0.06$ from CDF or CMS data with the following polarization assumptions:

**CDF:**
- central values using $\lambda_\theta = 0.13 \pm 0.15$ for $\chi_{c1}$ and $\chi_{c2}$
- no correlated variations considered
- uncertainty added in quadrature with all others

**CMS:**
- central values using $\lambda_\theta = 0$ for $\chi_{c1}$ and $\chi_{c2}$
- polarization uncertainty from maximum range of correlated variations of $\lambda_\theta(\chi_{c1})$ and $\lambda_\theta(\chi_{c2})$
Comparison to a previous prediction

In NRQCD, one single parameter determines both the $\chi_{c2}/\chi_{c1}$ ratio and the two polarizations

$$r \equiv m_c^2 \left< \mathcal{O}_{\chi_{c0}} \left( ^3S_1^{[8]} \right) \right> \left< \mathcal{O}_{\chi_{c0}} \left( ^3P_0^{[1]} \right) \right>$$

Faccioli et al. derive $r = 0.217 \pm 0.003$ from CMS + ATLAS data (averaged) with acceptance corrections corresponding to the final polarization prediction (iterative procedure) and, therefore, no added “polarization uncertainty”
Comparison to a previous prediction

In NRQCD, one single parameter determines both the $\chi_{c2}/\chi_{c1}$ ratio and the two polarizations

$$ r \equiv m_{c}^{2} \left\langle O_{\chi_{c0}}(^{3}S_{1}^{[8]}) \right\rangle - \left\langle O_{\chi_{c0}}(^{3}P_{0}^{[1]}) \right\rangle $$

Same theory inputs but different analyses of the experimental data lead to very different determinations of $r$

Shao et al.,
PRL 112 (2014) 182003
$$ r = 0.27 \pm 0.06 $$

Faccioli et al.,
EPJC 78 (2018) 268
$$ r = 0.217 \pm 0.003 $$
Summary: LHC vs. NRQCD

1) The mid-rapidity data show a simple universal unpolarized pattern

2) In particular, it is found that the $p_T/M$ distributions of S- and P-wave states are almost identical

3) Despite its intrinsic complexity, NRQCD can reproduce this simple scenario

4) The surprisingly good success of NRQCD uncovers a strong prediction: the unmeasured $\chi_{c1}$ and $\chi_{c2}$ polarizations must be very different from one another
Further reading

• P. Faccioli, C. Lourenço and J. Seixas,
  "Rotation-invariant relations in vector meson decays into fermion pairs",

• P. Faccioli, C. Lourenço and J. Seixas,
  "New approach to quarkonium polarization studies",

• P. Faccioli, C. Lourenço, J. Seixas and H.K. Wöhri,
  "Towards the experimental clarification of quarkonium polarization",

• P. Faccioli,
  "Questions and prospects in quarkonium polarization measurements from proton-proton to nucleus-nucleus collisions",

• P. Faccioli, V. Knünz, C. Lourenço, J. Seixas and H.K. Wöhri,
  "Quarkonium production in the LHC era: a polarized perspective",

• P. Faccioli, C. Lourenço, M. Araújo, J. Seixas, I. Krätschmer and V. Knünz,
  "Quarkonium production at the LHC: a data-driven analysis of NRQCD’s predictions",

• P. Faccioli, C. Lourenço, M. Araújo, J. Seixas, I. Krätschmer and V. Knünz,
  "From identical S- and P-wave $p_T$ spectra to maximally distinct polarizations: probing NRQCD with $\chi$ states",

• P. Faccioli, C. Lourenço, M. Araújo and J. Seixas,
  "Universal kinematic scaling as a probe of factorized long-distance effects in high-energy quarkonium production",
Higher energy, broader distribution
Distribution of pulls (7 TeV fit)

- $p_T/M > 2$
- $\chi^2/\text{ndf} = 215/193$
- $J/\psi$
- $\psi(2S)$
- $\chi_{c1}$
- $\chi_{c2}$
- Y(1S)
- Y(2S)
- Y(3S)


$J_z(\chi_{c1}) = \pm 1$

$J_z(\chi_{c2}) = \pm 2$

$J_z(\chi_{c1}) = J_z(\chi_{c2}) = 0$

- CMS
- ATLAS
- LHCb, ECAL
- LHCb, conversions