Constraints on the χ_{c1} and χ_{c2} polarizations

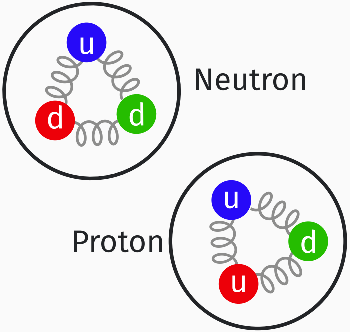
6th IDPASC/LIP PhD Students Workshop
25-27 June 2020

Analysis team:
Carlos Lourenço (CERN)
Thomas Madlener and Ilse Krätschmer (HEPHY)
Mariana Araújo, Pietro Faccioli and João Seixas (LIP)

arXiv:1912.07706
PRL 124 (2020) 162002.

Strong interactions

- The strong force binds quarks into nucleons and nucleons into atomic nuclei, determining the innermost structure of matter
- The interactions between quarks and gluons are described by quantum chromodynamics (QCD)
- Hadron formation involves non-perturbative processes and is not yet fully understood



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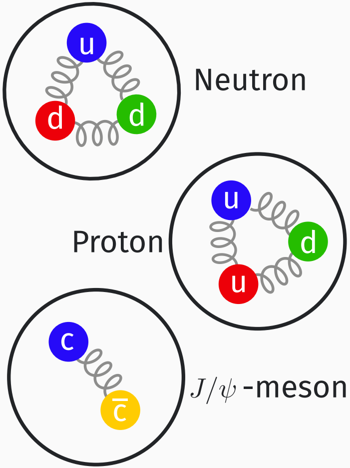
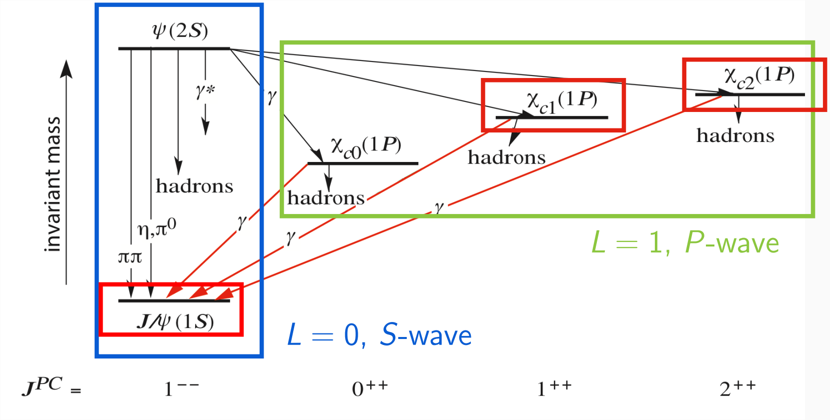
- Quarkonia:
  $\rightarrow$ bound states of heavy quark-antiquark pairs
  $\rightarrow$ ideal probes to study hadron formation



Charmonium spectrum

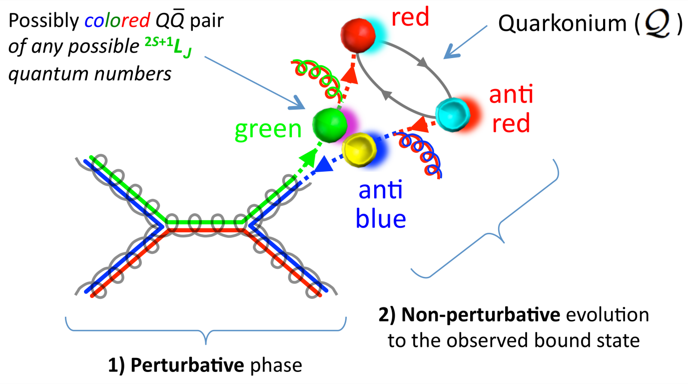


- All states, except the $\psi(2S)$, are affected by feed-down decays
  - All measurements refer to "prompt" (direct+feed-down) production
  - Around 30% of the promptly produced J/ψ mesons are from feed-down decays
  - Non-prompt (NP) contributions from b-hadron decays can be removed experimentally

NRQCD - Non-Relativistic Quantum Chromodynamics

NRQCD is an effective field theory factorizing quarkonium production in two steps:

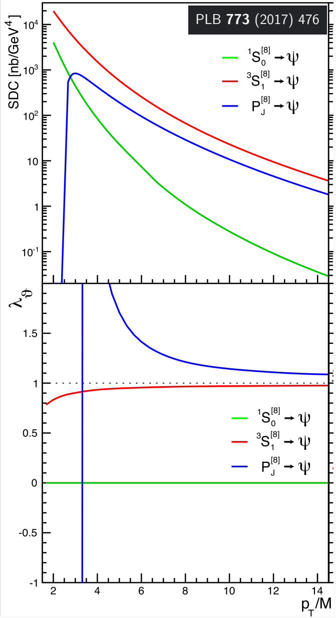
1. Creation of the initial quark-antiquark pair (perturbative QCD)
2. Hadronization of the pair into bound Quarkonium state $\mathcal{Q}$ (non-perturbative QCD)



$$\sigma(\mathcal{Q}) = \sum_{\{n\}} \mathcal{S}[Q\bar{Q}(\{n\})] \cdot \mathcal{O}^{\mathcal{Q}}(\{n\})$$

- $\mathcal{S}$ Partonic processes via expansion in α_S (SDCs: theory)
- $\mathcal{O}$ (Assumed) universal constants giving the probability to evolve from an initial state to a bound state (LDMEs: experiment)

Experimental observables



Cross sections

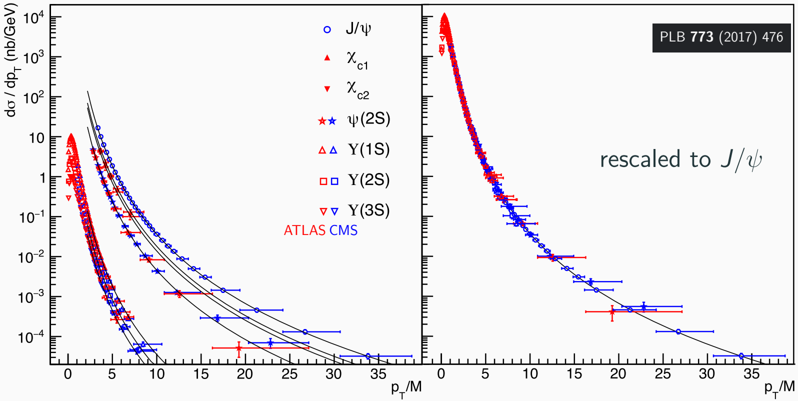
- Cannot easily distinguish between different subprocesses

Polarization

- Quarkonium states can be observed in different eigenstates of the angular momentum component J_z. Observing states in a preferred eigenstate is referred to as polarization
- The polarization is reflected in the decay angular distribution of the quarkonium states

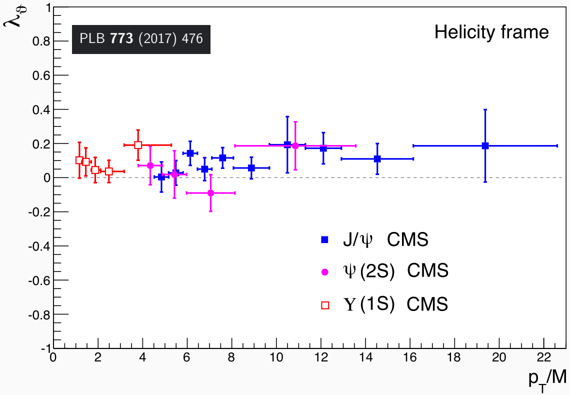
$$W(\cos\vartheta, \varphi|\vec{\lambda}) \propto \frac{1}{3+\lambda_\vartheta}\Big(1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi\Big)$$

Experimental status - cross sections in pp collisions



- Cross section measurements for seven states reported, at mid-rapidity, by ATLAS and CMS
- Universal pattern of the shapes as a function of p_T/M
- In stark contrast with the intrinsic diversity of the NRQCD SDCs

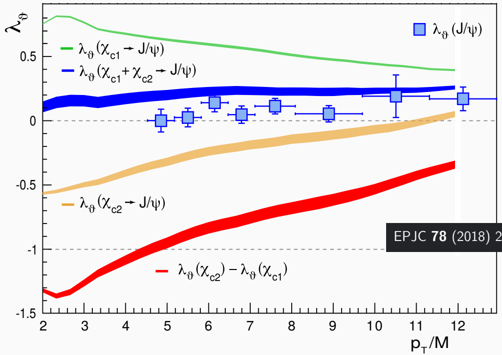
Experimental status - polarizations in pp collisions



- Measurements of prompt S-wave states exclude strong polarizations
- Very similar trends, despite vastly different feed-down contributions
- **Polarization measurements of P-wave quarkonia are missing**

Predicted polarizations of the χ_{c1} and χ_{c2} states

- In NRQCD, the χ_{c1} and χ_{c2} polarizations and cross sections are functions of one single parameter, K_χ, the ratio between the ${}^3P_0^{[1]}$ singlet LDME and the ${}^3S_1^{[8]}$ octet LDME, which is the same for all three χ_{cJ} states
- By fitting the χ_{c2} over χ_{c1} cross section ratios, measured by ATLAS and CMS, one determines the parameter K_χ, which is then used to predict the two polarizations
- Since there is only one parameter to fit, the result is strongly constrained



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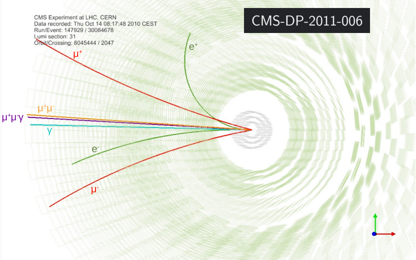
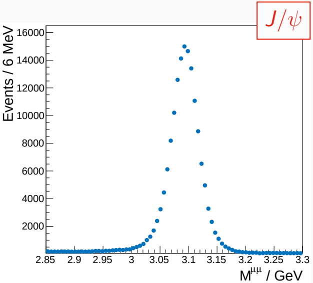
- **Large and opposite polarizations** are predicted for the χ_{c1} and χ_{c2}
- Measuring the χ_{c1} and χ_{c2} polarizations is a crucial test for NRQCD

χ_c reconstruction in CMS

- The χ_c candidates are formed by combining a J/ψ with a photon
- The J/ψ is reconstructed through its dimuon decay
- The trigger selects events with two oppositely charged muons, compatible with originating from the same vertex
- The photon is reconstructed via conversion into an e^+e^- pair in the material of the tracker
- A kinematic vertex fit is used to evaluate if the photon and the J/ψ originate from a common vertex



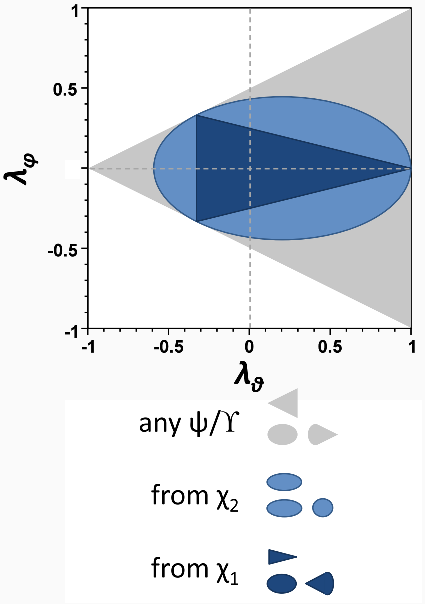


χ_c polarization

- Measuring the χ_{cJ} polarization is equivalent to measuring the polarization of the J/ψ in the radiative $\chi_{cJ} \to J/\psi\,\gamma$ decay

PRD **83**, 096001 (2011)

- The photon is used to resolve the χ_{c1} and χ_{c2} signals in the χ_c mass distribution



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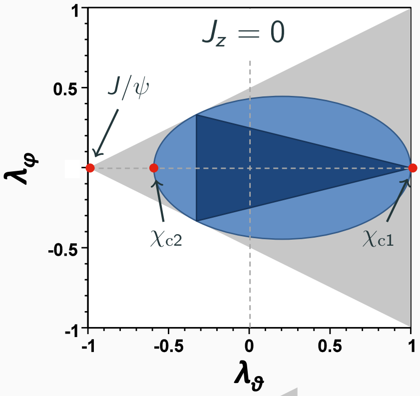
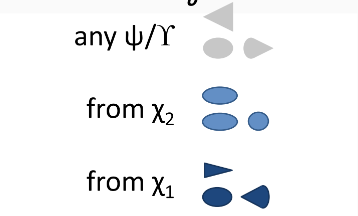
- Similar angular momentum configurations can lead to very different angular decay distributions





Analysis strategy

- The $W(\cos\vartheta,\varphi|\vec{\lambda})$ distribution is sculpted by the event selection criteria and by the reconstruction efficiencies
- Shaping effects cancel in a relative measurement

$$R(\cos\vartheta|\lambda_\vartheta^{\chi_{c2}},\lambda_\vartheta^{\chi_{c1}}) = \frac{\int W(\cos\vartheta,\varphi|\vec{\lambda}_{\chi_{c2}})\,\mathrm{d}\varphi}{\int W(\cos\vartheta,\varphi|\vec{\lambda}_{\chi_{c1}})\,\mathrm{d}\varphi} \propto \frac{1+\lambda_\vartheta^{\chi_{c2}}\cos^2\vartheta}{1+\lambda_\vartheta^{\chi_{c1}}\cos^2\vartheta} \tag{1}$$

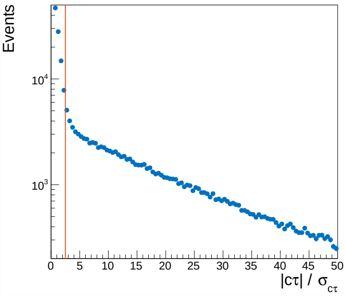
$$R(\varphi|\vec{\lambda}^{\chi_{c2}},\vec{\lambda}^{\chi_{c1}}) = \frac{\int W(\cos\vartheta,\varphi|\vec{\lambda}_{\chi_{c2}})\,\mathrm{d}\cos\vartheta}{\int W(\cos\vartheta,\varphi|\vec{\lambda}_{\chi_{c1}})\,\mathrm{d}\cos\vartheta} \propto \frac{1+\kappa^{\chi_{c2}}\cos(2\varphi)}{1+\kappa^{\chi_{c1}}\cos(2\varphi)}, \tag{2}$$

with $\kappa = \frac{3-|\cos\vartheta|^2_{\max}}{3+\lambda_\vartheta|\cos\vartheta|^2_{\max}}\lambda_\varphi$

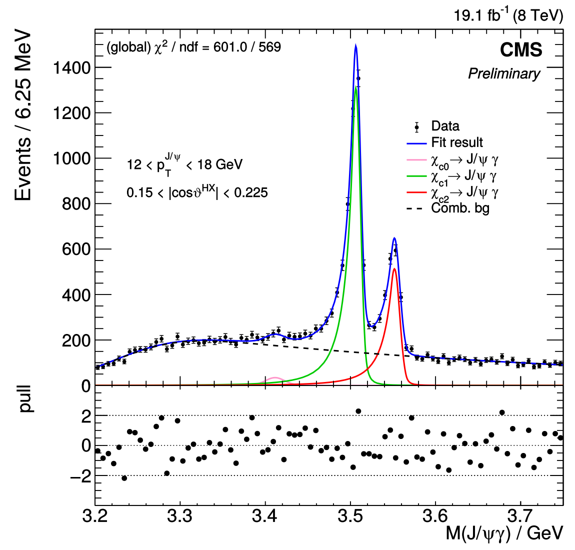
- The χ_{c1} and χ_{c2} polarization parameters, λ_ϑ and λ_φ, can be deduced from the $\cos\vartheta$ or φ dependences of the χ_{c2}/χ_{c1} ratio

Data samples, event selection, etc

- The measurement uses data collected in pp collisions at $\sqrt{s} = 8\,\text{TeV}$, corresponding to $\mathcal{L} = 19.1\,\text{fb}^{-1}$
- The dimuons must be within $|y^{J/\psi}| < 1.2$
- Three $p_T^{J/\psi}$ ranges are used: 8–12, 12–18 and 18–30 GeV
- Prompt dimuons are selected using their displacement from the primary vertex: $|c\tau|/\sigma_{c\tau} < 2.5$
- The measurement is done in the helicity frame (HX)
- The χ_{c2}/χ_{c1} ratios are obtained by simultaneously fitting the mass distributions in bins of $|\cos\vartheta|$ or φ



Mass fit model



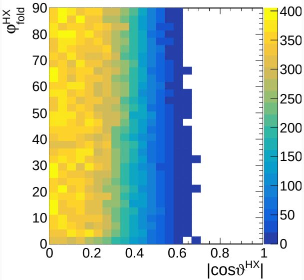
- The fit model is a superposition of three peaks (χ_{c0}, χ_{c1} and χ_{c2}) and a smooth combinatorial background
- A few simple relations on some fit parameters are used to reduce the number of free parameters and minimize the effects of statistical fluctuations
- The χ_{c2}/χ_{c1} ratio is a free parameter in all bins
- The model describes the data well in all $p_T^{J/\psi}$ ranges

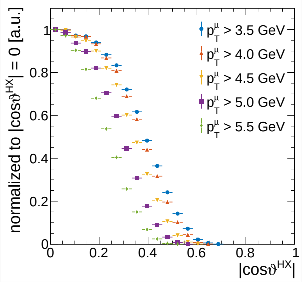
Acceptance times efficiency corrections

- Acceptance times efficiency effects are corrected using high-granularity three-dimensional maps obtained from fast-simulation

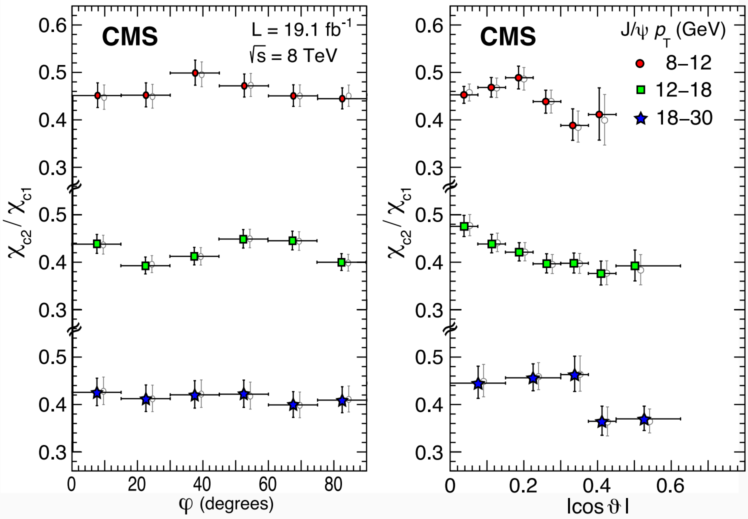
$$\mathcal{A}(\cos\vartheta, \varphi, p_T^{J/\psi}) = \frac{(\cos\vartheta, \varphi, p_T^{J/\psi}) \text{ at reconstruction level}}{(\cos\vartheta, \varphi, p_T^{J/\psi}) \text{ at generation level}}$$

- Corrections are applied event-by-event
- Small kinematic differences between χ_{c1} and χ_{c2} are taken into account by using independent correction maps
- The probability of an event being a χ_{c1} or a χ_{c2} is calculated from the mass of the candidate, using the post-fit signal shapes





Yield ratios



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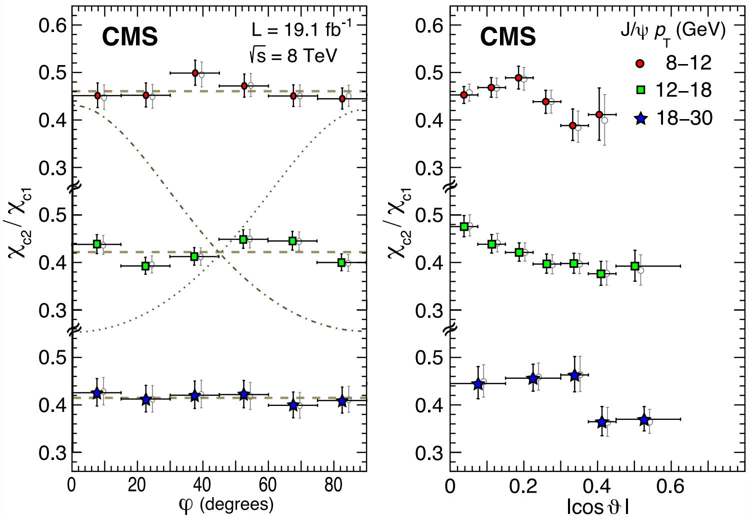

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- No azimuthal polarization differences

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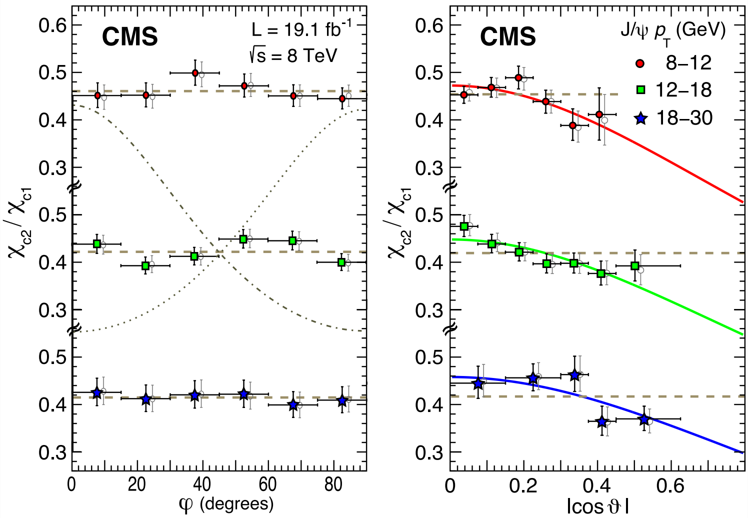


- The acceptance times efficiency corrections have a negligible effect on the trends; and the overall normalizations are irrelevant for the polarization measurement
- No azimuthal polarization differences
- Ratios as a function of $|\cos\vartheta|$ disfavor unpolarized scenario and agree with NRQCD prediction

Systematic uncertainties

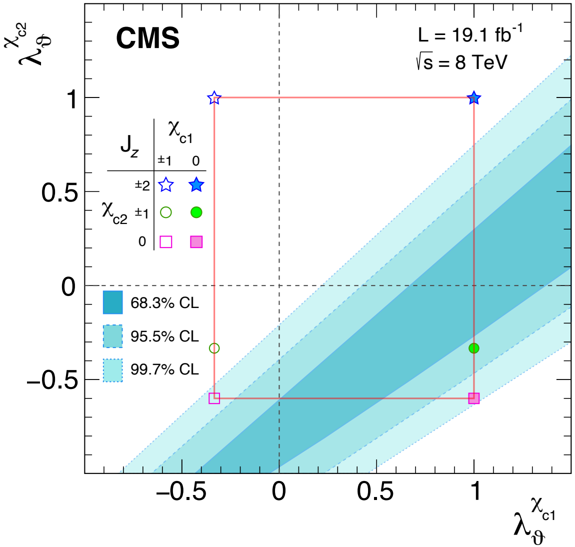
Sources of systematic effects

1. Mass fit model: Signal peaks
2. Mass fit model: Background continuum
3. Acceptance and efficiency corrections
4. Rejection of non-prompt mesons
5. Kinematic vertex fit probability cut

- We are only interested in effects that might lead to changes in the *shape* of the χ_{c2}/χ_{c1} yield ratio as a function of $|\cos\vartheta|$ or φ
- Changes in the normalization do not affect the polarization parameters

The systematic effects cancel to a very large extent in the *relative variation* of the χ_{c2}/χ_{c1} *ratio* $\rightarrow$ the systematic uncertainties are negligible (less than 20% of the statistical uncertainties, in the worst case)

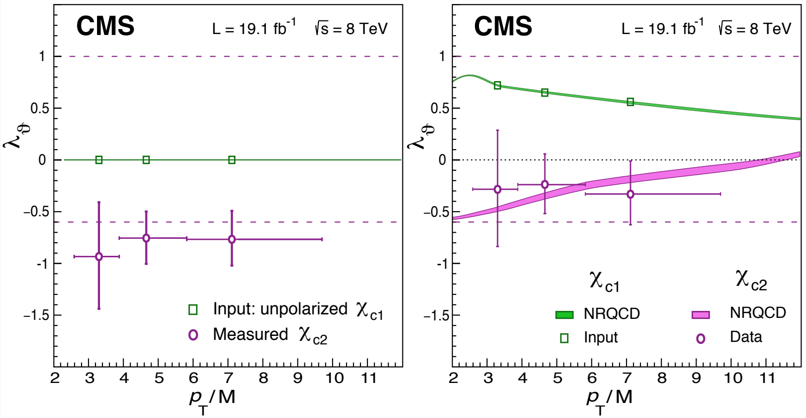
Two-dimensional contours



- Simultaneously fitting the three yield ratios as a function of $|\cos\vartheta|$, imposing $p_T^{J/\psi}$ independent values of $\lambda_\vartheta^{\chi_{c1}}$ and $\lambda_\vartheta^{\chi_{c2}}$
- The unpolarized scenario and more than half of the physically allowed region (red rectangle) are excluded at more than 99.7% CL

This is the first observation of significantly polarized quarkonium states

$\lambda_\vartheta^{\chi_{c2}}$ as a function of p_T/M



- We can fix $\lambda_\vartheta^{\chi_{c1}}$ to specific scenarios, so as to measure the corresponding $\lambda_\vartheta^{\chi_{c2}}$
  - The unpolarized option is strongly disfavoured
  - The NRQCD prediction is in good agreement with the data

Summary

- The study of heavy-quarkonium production in pp collisions offers the best path to understand hadron formation in (non-perturbative) QCD
- The production mechanisms are studied in NRQCD, a rigorous theory derived from QCD, with no empirical ingredients, that exploits the conjectured factorization of short- and long-distance effects in the limit of small relative velocity of the quark and antiquark forming the bound state
- The complexity and variety of kinematic behaviours (SDCs) predicted in NRQCD seems redundant with respect to the measured universal p_T/M scaling (all states) and lack of polarization (S-wave states)
- Before this measurement, we did not know if the (prompt) χ_{c1} and χ_{c2} P-wave quarkonia were also produced essentially unpolarized (as the S-wave states) or with strong and opposite polarizations (as predicted by NRQCD, through a very reliable computation)
- The conclusion is that NRQCD survived this crucial test with excellent marks

Outlook: improved measurement of J/ψ polarization

The unpolarized and p_T-independent scenario established by existing LHC data is

- *Physically peculiar:* it requires the cancellation of two (or more) oppositely polarized processes or the production from an intermediate $J = 0$ state;
  in fact, while not excluded in NRQCD, it is certainly not its *natural* prediction
- *Unique among all vector particles:* Drell–Yan dileptons and vector bosons are always produced with strong polarizations, changing significantly with p_T and rapidity

By combining the statistics of the Run 1 and Run 2 data samples, together with an analysis methodology that minimizes systematic uncertainties, we can probe these results with a higher precision, especially at high p_T, and see whether any deviations become evident.