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

QwG workshop 2021

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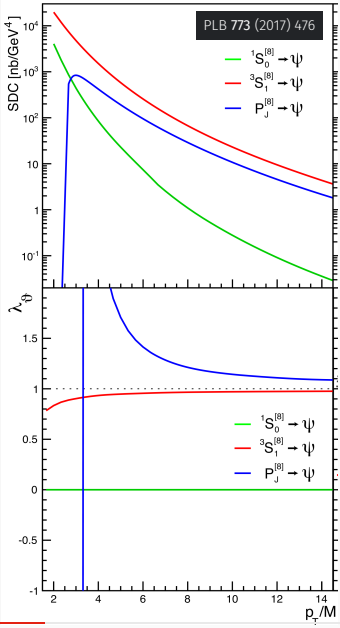
for the CMS collaboration

Mar 17, 2021

Quarkonium production - experimental observables



Cross sections

- Relatively easy to measure experimentally
- Cannot easily distinguish between different subprocesses that are considered in NRQCD

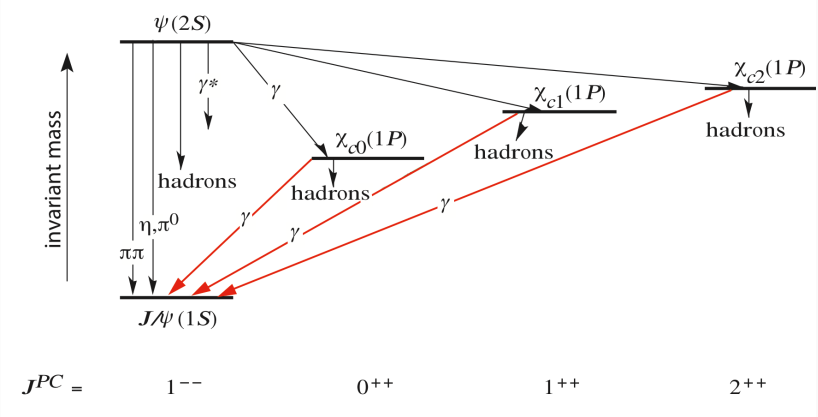
Polarization

- Polarization affects the decay angular distribution of the quarkonium states

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

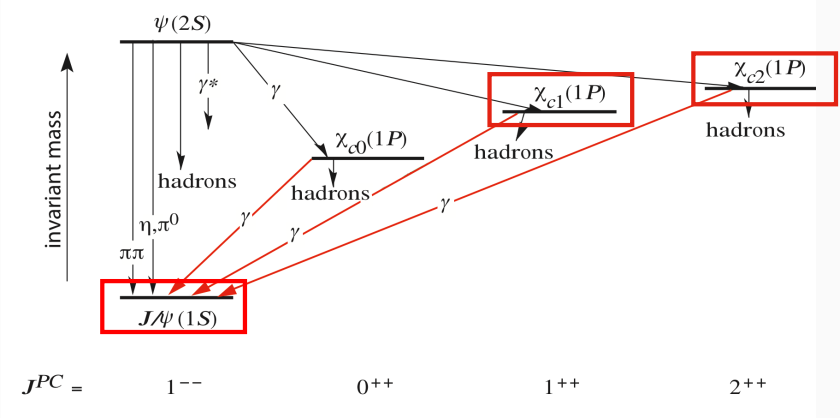
- Challenging experimental measurement due to angle dependent acceptance and efficiency effects

Charmonium spectrum



- All states, except the $\psi(2S)$ are affected by feed down contributions
  - Almost impossible to distinguish between direct production and feed down in pp collision environments
  - Between 20 and 30 % of promptly produced J/ψ are from feed down
- Non-prompt (NP) contributions from b-hadrons can be resolved experimentally

Charmonium spectrum



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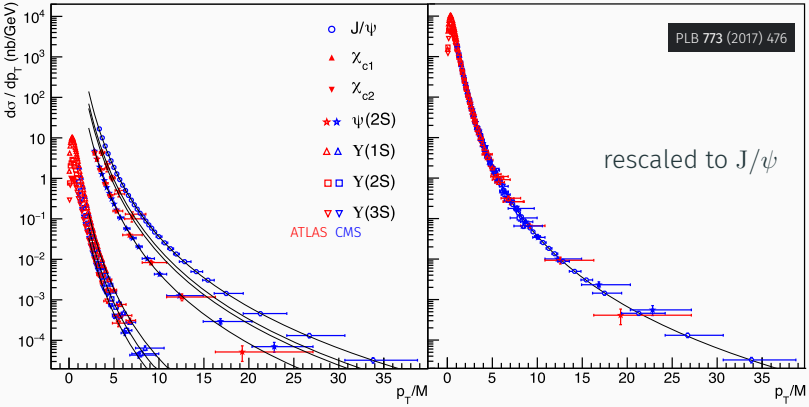
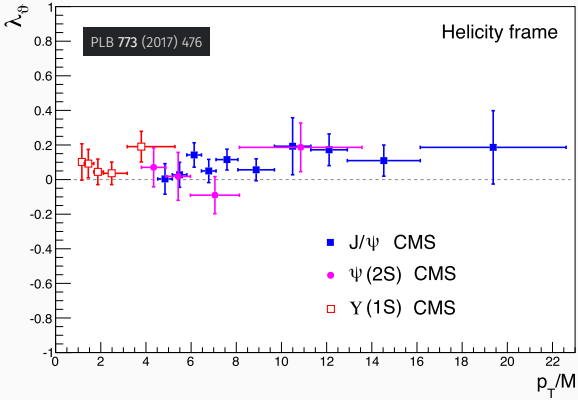
Experimental status - cross sections in pp collisions



*more details:
next talk by M. Araujo

- Cross section measurements for all S-wave states reported by ATLAS, CMS, LHCb, ALICE, CDF and D0
- Cross section measuremnts for χ_{c1} and χ_{c2} by ATLAS
- χ_{c2}/χ_{c1} cross section ratio measurements by CMS and ATLAS

Experimental status - polarizations in pp collisions



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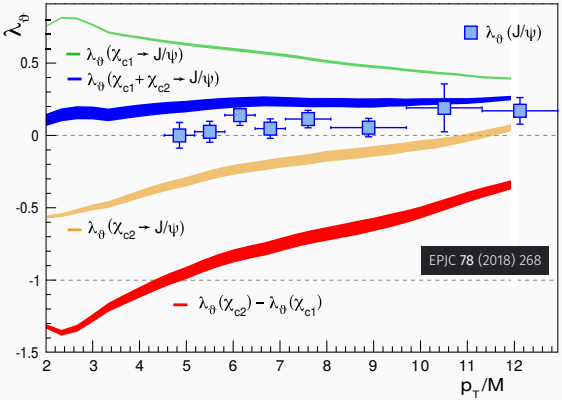
- Measured polarization of prompt *S*-wave states are compatible with unpolarized
- Very similar polarizations, despite vastly different feed-down contributions
- **No polarization measurements of *P*-wave quarkonia exist**

χ_{c1} and χ_{c2} polarization in NRQCD

- χ_{c1} and χ_{c2} production in NRQCD is governed by one phenomenological parameter that can obtained from fits to the measured χ_{c2}/χ_{c1} cross section ratios by ATLAS and CMS
- Use parameter to predict the χ_{c1} and χ_{c2} polarizations



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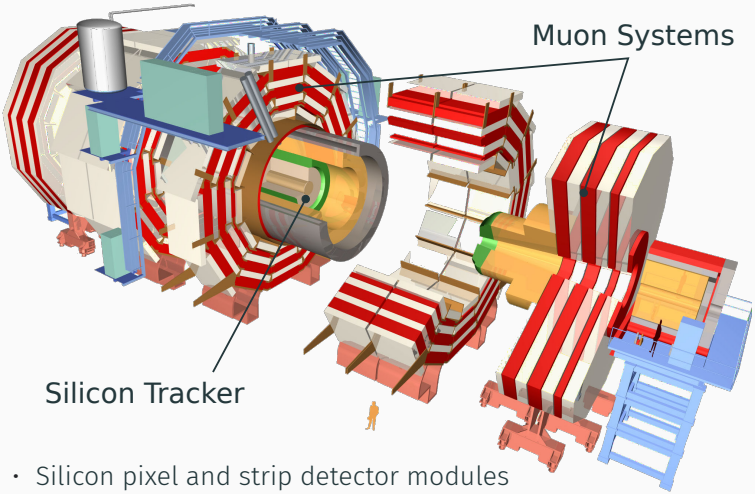
CMS Detector

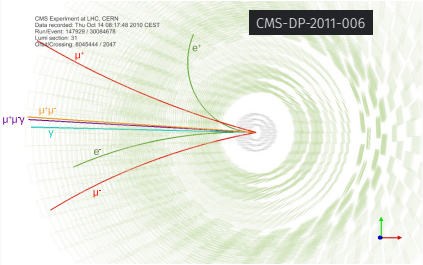


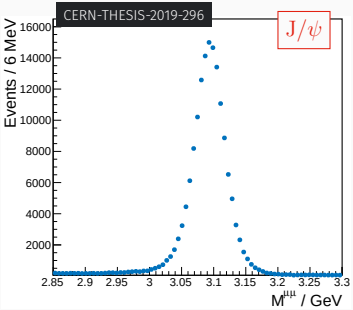
- Drift tubes, cathode strip chambers and resistive-plate chambers
- Used in first-level, hardware based trigger
- Segments are matched to charged tracks to identify muons
- High-level trigger has access to full event information

- Silicon pixel and strip detector modules
- Measurement of charged particles without particle identification
- Transverse impact parameter resolution $\sim 25 - 90\ \mu m$

χ_c reconstruction at CMS

- χ_c candidates are formed by combining a J/ψ with a photon candidate
- J/ψ are reconstructed through their dimuon decay
  - Trigger designed to select events with two oppositely charged muons
  - Muons have to be compatible with originating from the same vertex
- Photons are reconstructed via their conversion into an e^+e^- pair in the material of the tracker
- A kinematic vertex fit (KVF) is used to determine whether the photon and the J/ψ originate from a possible χ_c decay



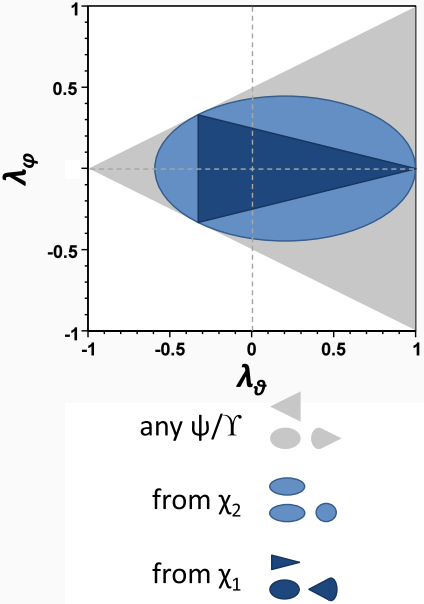


χ_c polarization

- 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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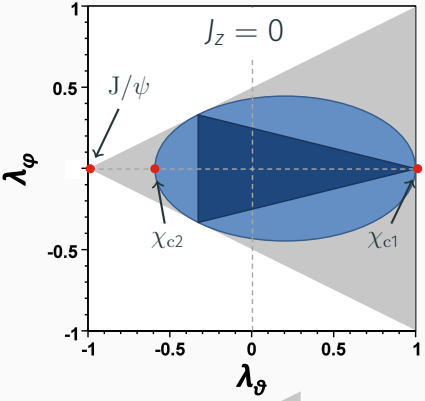
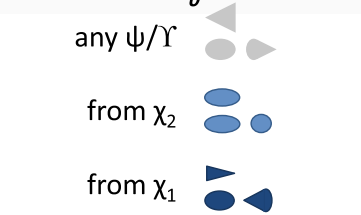
- The photon is used to resolve the χ_{c1} and χ_{c2} signals in the χ_c mass distribution
- Similar angular momentum configurations can lead to very different angular decay distributions





Analysis strategy

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

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

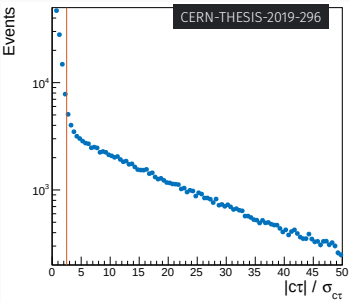
$$R(\varphi|\vec{\lambda}^{\chi_{c2}}, \vec{\lambda}^{\chi_{c1}}) = \frac{\int W(\cos\vartheta, \varphi|\vec{\lambda}_{\chi_{c2}})\,\mathrm{d}\cos\vartheta}{\int W(\cos\vartheta, \varphi|\vec{\lambda}_{\chi_{c1}})\,\mathrm{d}\cos\vartheta} \propto \frac{1+\kappa^{\chi_{c2}}\cos(2\varphi)}{1+\kappa^{\chi_{c1}}\cos(2\varphi)},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

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

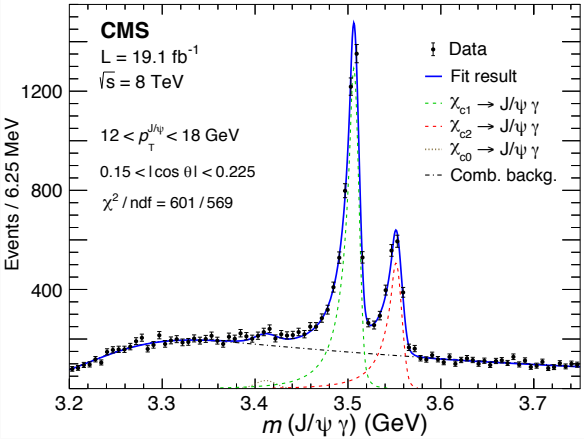
- Determining the ratio of χ_{c2}/χ_{c1} yields as a function of $\cos\vartheta$ or φ allows us to study the polarization of the χ_{c1} and χ_{c2}

Determination of prompt yield ratios

- Data collected in pp collisions at $\sqrt{s} = 8\,\text{TeV}$ in 2012 corresponding to $\mathcal{L} = 19.1\,\text{fb}^{-1}$
- The analysis is made integrating events in the $|y^{\mathrm{J}/\psi}| < 1.2$ rapidity window, in three $p_{\mathrm{T}}^{\mathrm{J}/\psi}$ ranges: 8–12, 12–18 and 18–30 GeV
- Non-prompt candidates are rejected using displacement from the primary vertex ($|c\tau|/\sigma_{c\tau}$)
- Measurement is done using the helicity (HX) frame
- The $\chi_{\mathrm{c}2}/\chi_{\mathrm{c}1}$ yield ratios are obtained from simultaneously fitting the mass distributions in bins of $|\cos\vartheta^{\mathrm{HX}}|$ or φ^{HX}



Mass fit model



- Model is a superposition of three peaks (χ_{c0}, χ_{c1} and χ_{c2}) and a smooth combinatorial background
- Simple functional relations on fit parameters are used to reduce the number of free parameters to minimize effects of statistical fluctuations
- The χ_{c2}/χ_{c1} yield 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

- Residual acceptance times efficiency effects are treated using three-dimensional correction maps obtained from simulated events

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

- Corrections are applied event-by-event
- Small kinematic differences between χ_{c1} and χ_{c2} taken into account by using independent correction maps
- Probability of event being χ_{c1} or χ_{c2} calculated from results of mass fits

Checks for systematic effects

Considered sources of possible systematic effects

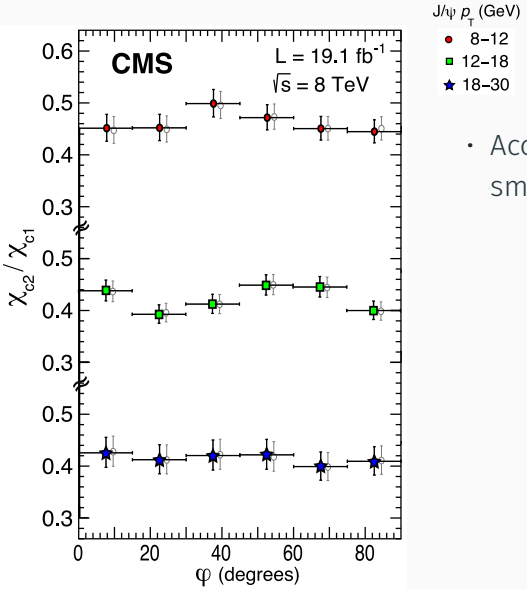
1. Signal peak fit model
2. Background continuum fit model
3. Acceptance and efficiency corrections
4. Rejection of non-prompt events
5. Kinematic vertex fit probability cut

Important remarks

- Only interested in systematic effects on the shape of the χ_{c2}/χ_{c1} yield ratio as a function of $|\cos\vartheta^{\mathrm{HX}}|$ or φ^{HX}
- Variations only leading to changes in normalization have no influence on the extracted polarization parameters

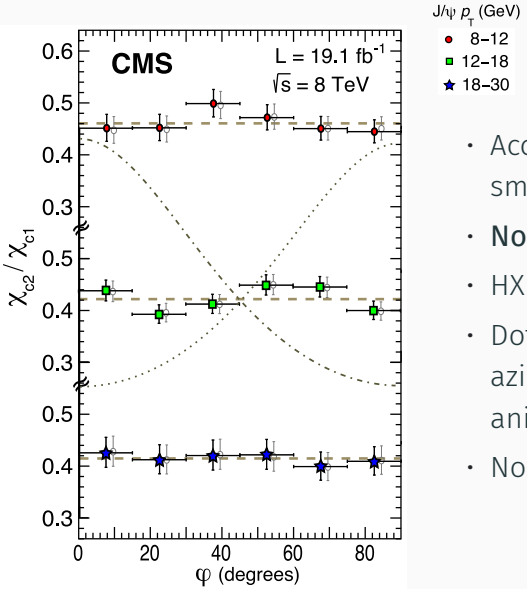
All systematic effects are found to be very small

χ_{c2} over χ_{c1} ratios vs φ^{HX}



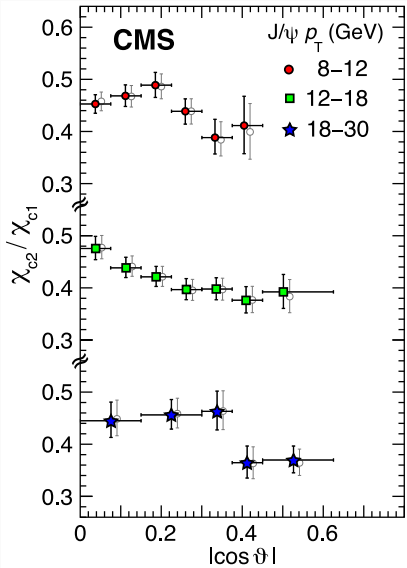
- Acceptance times efficiency corrections only have a small effect on the measured ratios

χ_{c2} over χ_{c1} ratios vs φ^{HX}



- Acceptance times efficiency corrections only have a small effect on the measured ratios
- **No azimuthal polarization differences**
- HX frame is close to the natural polarization frame
- Dotted and dash-dotted lines: Observable azimuthal differences for extreme polar anisotropies in CS frame
- No sign of unaccounted systematic effects

χ_{c2} over χ_{c1} ratios vs $|\cos\vartheta^{HX}|$



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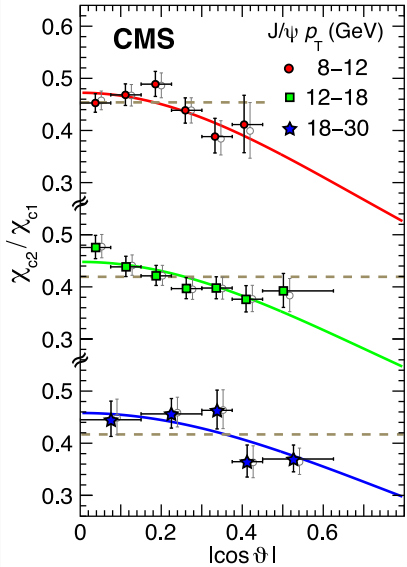
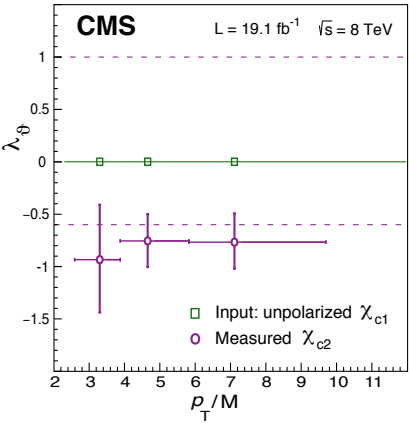
χ_{c2} over χ_{c1} ratios vs $|\cos\vartheta^{\mathrm{HX}}|$



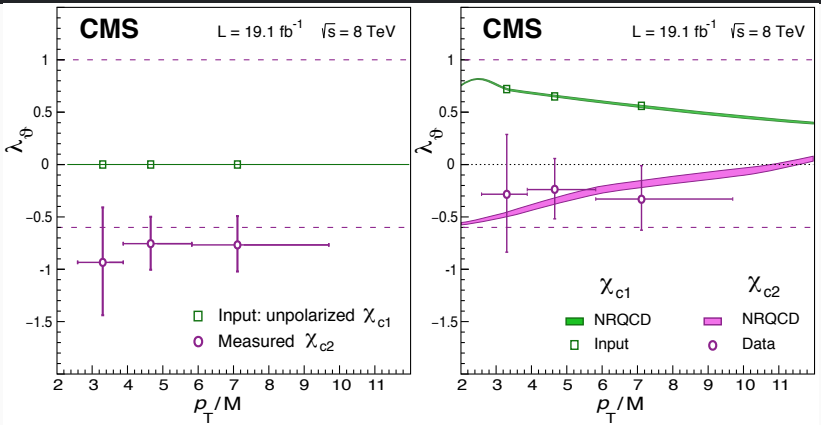
- Acceptance times efficiency corrections only have small effect on the measured ratios
- **Ratios as a function of $|\cos\vartheta^{\mathrm{HX}}|$ disfavor unpolarized scenario**
- Solid lines: Expected shapes for the predicted polarizations
  - $\propto \frac{1+\lambda_\vartheta^{\chi_{c2}}\cos^2\vartheta}{1+\lambda_\vartheta^{\chi_{c1}}\cos^2\vartheta}$ (slide 9)
  - $\lambda_\vartheta^{\chi_{c1}}$ and $\lambda_\vartheta^{\chi_{c2}}$ as function of $p_{\mathrm{T}}^{\mathrm{J}/\psi}$ from slide 5
- **Measured ratios are available on HEPData:** hepdata.net/record/ins1771351

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



- Measurement of $|\cos\vartheta^{HX}|$ ratios is effectively a polarization difference measurement
  - For fixed values of $\lambda_\vartheta^{\chi_{c1}}$ it is possible to determine $\lambda_\vartheta^{\chi_{c2}}$
- Fixing $\lambda_\vartheta^{\chi_{c1}} = 0$ (unpolarized hypothesis) $\rightarrow \lambda_\vartheta^{\chi_{c2}}$ incompatible with 0

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



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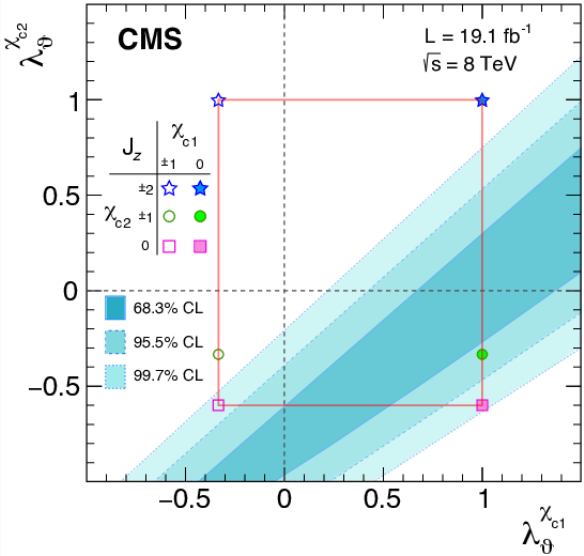
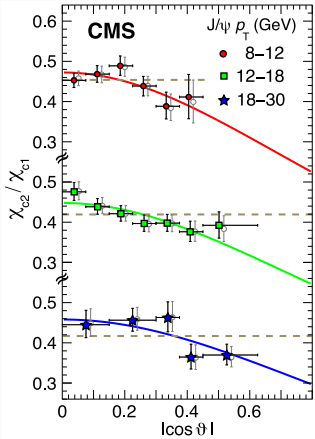
- Fixing $\lambda_\vartheta^{\chi_{c1}}$ to NRQCD predicted values $\rightarrow \lambda_\vartheta^{\chi_{c2}}$ compatible with prediction

$\lambda_\vartheta^{\chi_{c2}}$ vs $\lambda_\vartheta^{\chi_{c1}}$ - two dimensional contours

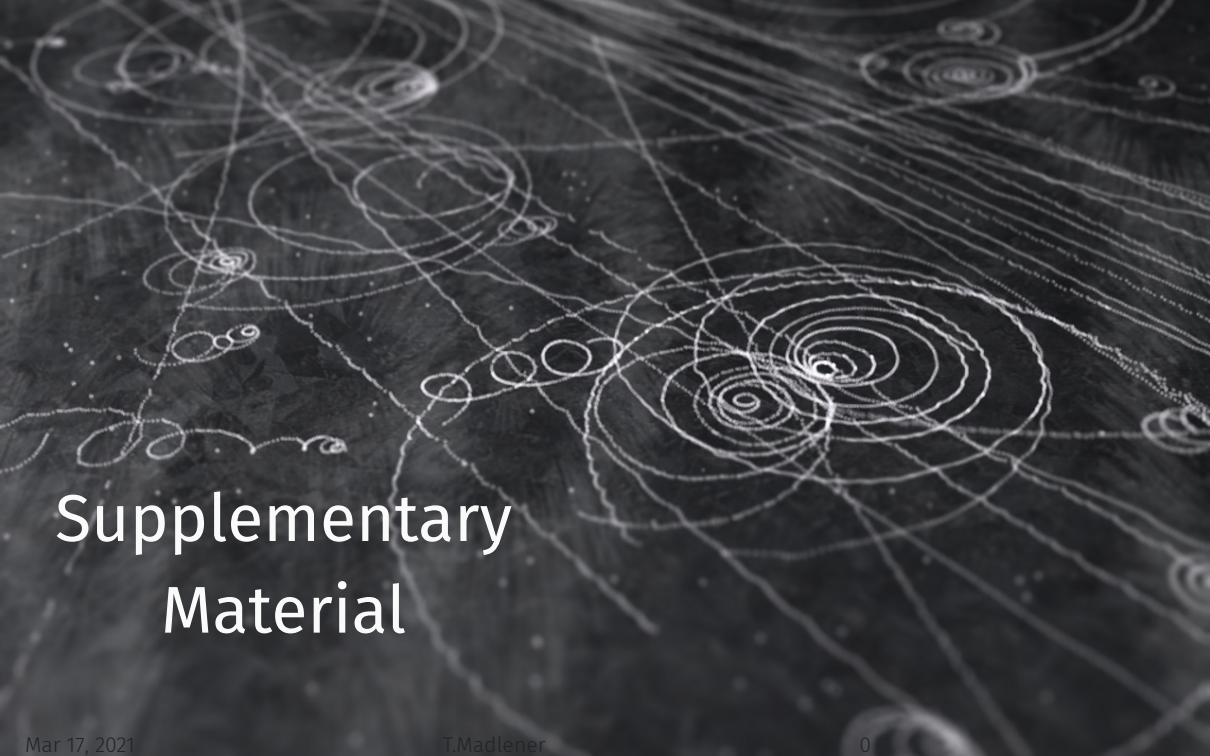


- Simultaneously fitting the yield ratios as a function of $|\cos\vartheta^{\mathrm{HX}}|$ in all three $p_{\mathrm{T}}^{\mathrm{J}/\psi}$ ranges imposing $p_{\mathrm{T}}^{\mathrm{J}/\psi}$ independent values of $\lambda_\vartheta^{\chi_{c1}}$ and $\lambda_\vartheta^{\chi_{c2}}$
- Unpolarized scenario and more than half of the physically allowed region (red rectangle) excluded at 99.7 % CL
- **First measurement of significantly polarized quarkonium states**

Summary & Conclusions



- Quarkonium production is a stepping stone to understand hadron formation
- The J/ψ, $\psi(2S)$ and $\Upsilon(nS)$ states are relatively well measured
- This is the **first measurement of *P*-wave quarkonium states polarization** in the form of χ_{c2}/χ_{c1} ratios as a function of $|\cos\vartheta^{\mathrm{HX}}|$ and φ^{HX}
- Unpolarized production is strongly disfavored, contrary to the *S*-wave measurements
- The results are in good agreement with NRQCD predictions
- More details in: PRL **124**, 162002 (2020) , `arXiv:1912.07706`, and CERN-THESIS-2019-296



Supplementary Material

$\lambda_\vartheta^{\chi_{c2}}$ as a function of $\lambda_\vartheta^{\chi_{c1}}$

- $\lambda_\vartheta^{\chi_{c2}}$ values obtained from the yield ratios for different fixed values of $\lambda_\vartheta^{\chi_{c1}}$ in the three $p_{\mathrm{T}}^{\mathrm{J}/\psi}$ ranges
- Parametrized results:
  - 8–12 GeV: $\lambda_\vartheta^{\chi_{c2}} = (-0.94 + 0.90\lambda_\vartheta^{\chi_{c1}}) \pm (0.51 + 0.05\lambda_\vartheta^{\chi_{c1}})$
  - 12–18 GeV: $\lambda_\vartheta^{\chi_{c2}} = (-0.76 + 0.80\lambda_\vartheta^{\chi_{c1}}) \pm (0.26 + 0.05\lambda_\vartheta^{\chi_{c1}})$
  - 18–30 GeV: $\lambda_\vartheta^{\chi_{c2}} = (-0.78 + 0.77\lambda_\vartheta^{\chi_{c1}}) \pm (0.26 + 0.06\lambda_\vartheta^{\chi_{c1}})$

Table of systematic uncertainties

$p_{\mathrm{T}}^{\mathrm{J}/\psi}$ / GeV	8–12	12–18	18–30
$\Delta\lambda_{\vartheta}$			
signal peak fit model	0.075	0.034	0.029
background continuum fit model	0.040	0.024	0.053
acceptance times efficiency corrections	0.029	0.019	0.047
prompt selection cut	–	–	–
KVF probability cut	–	–	–
statistical uncertainty	0.406	0.275	0.293
$\Delta\lambda_{\varphi}$			
signal peak fit model	0.003	0.002	0.002
background continuum fit model	0.002	0.003	0.002
acceptance times efficiency corrections	0.003	0.002	0.001
prompt selection	–	–	–
KVF probability cut	–	–	–
statistical uncertainty	0.031	0.028	0.047

Event selection

Muons

- Soft muon ID J Inst **7**, P10002 (2012)
- High purity track quality J Inst **9**, P10009 (2014)
- $p_{\mathrm{T}}^{\mu} > 3.5$ GeV and $|\eta^{\mu}| < 1.6$

Dimuons (trigger)

- $p_{\mathrm{T}}^{\mu\mu} > 7.9$ GeV, $|y^{\mu\mu}| < 1.25$
- $2.8 < M^{\mu\mu} < 3.35$ GeV
- Opposite sign, DCA < 0.5 cm
- Vertex fit χ^2 prob > 0.5 %

Dimuons (offline)

- $8 < p_{\mathrm{T}}^{\mathrm{J}/\psi} < 30$ GeV, $|y^{\mathrm{J}/\psi}| < 1.2$
- Dimuon vertex fit χ^2 prob > 1 %
- $|c\tau/\sigma_{c\tau}| < 2.5$

Photon (conversion)

- Oppositely charged tracks with vertex $r > 1.5$ cm from beam axis
- Kinematic (zero) mass vertex fit χ^2 prob > 0.05 %
- $p_{\mathrm{T}}^{\gamma} > 0.4$ GeV, $|\eta^{\gamma}| < 1.5$

χ_{c} candidates

- $dz(\mathrm{J}/\psi, \gamma) < 0.5$ mm
- $3.2 < M^{\chi_{\mathrm{c}}} < 3.75$ GeV
- Kinematic vertex fit χ^2 prob > 1 %

Mass fit model details

$$\mathcal{M}(M^{\chi}) = N^{\chi_{c1}}\mathcal{M}_{\chi_{c1}}(M^{\chi}) + N^{\chi_{c2}}\mathcal{M}_{\chi_{c2}}(M^{\chi}) + N^{\chi_{c0}}\mathcal{M}_{\chi_{c0}}(M^{\chi}) + N^{\mathrm{bg}}\mathcal{M}_{\mathrm{bg}}(M^{\chi}) \quad (3)$$

- $\mathcal{M}_{\chi_{c1,2}}(M^{\chi}) = \mathrm{DSCB}_{\chi_{c1,2}}(M^{\chi}|\mu^{\chi_{c1,2}}, \sigma^{\chi_{c1,2}}, \alpha_L^{\chi_{c1,2}}, n_L^{\chi_{c1,2}}, \alpha_R^{\chi_{c1,2}}, n_R^{\chi_{c1,2}})$ - Double sided crystal ball function
- $\mathcal{M}_{\chi_{c0}}(M^{\chi}) = V_{\chi_{c0}}(M^{\chi}|\mu^{\chi_{c0}}, \sigma^{\chi_{c0}}, \Gamma^{\chi_{c0}})$ - Voigtian distribution
- $\mathcal{M}_{bg}(M^{\chi}) = \left[1 + \mathrm{erf}(\frac{M^{\chi} - \mu^{\mathrm{bg}}}{\sigma^{\mathrm{bg}}})\right] \cdot \exp(M^{\chi} \cdot \lambda^{\mathrm{bg}})$ - Error function times exponential distribution