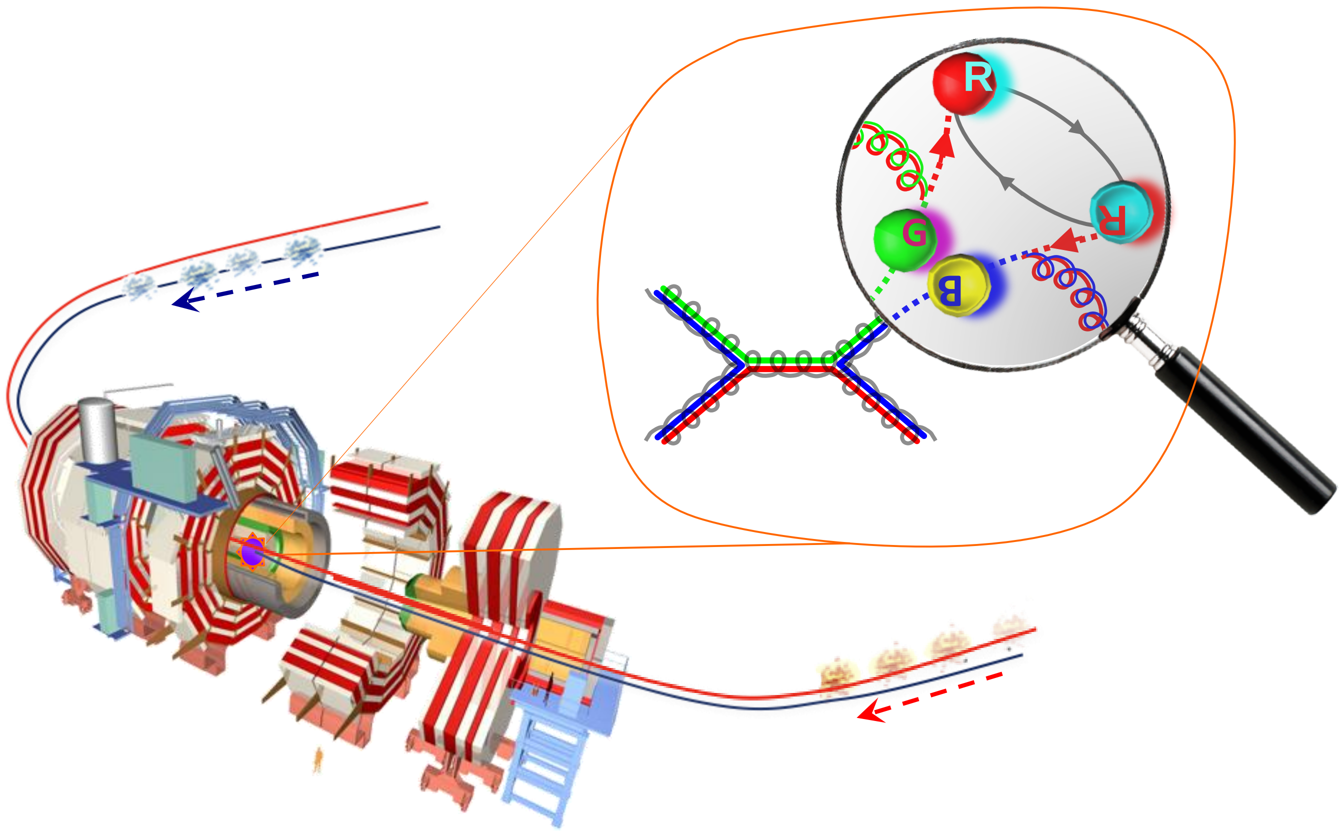
From identical S- and P-wave p_T/M spectra to maximally distinct polarizations: probing NRQCD with LHC data



Quarkonium Working Group workshop
Torino, May 2019

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Pietro Faccioli, Carlos Lourenço, and João Seixas

Unexpectedly simple data patterns

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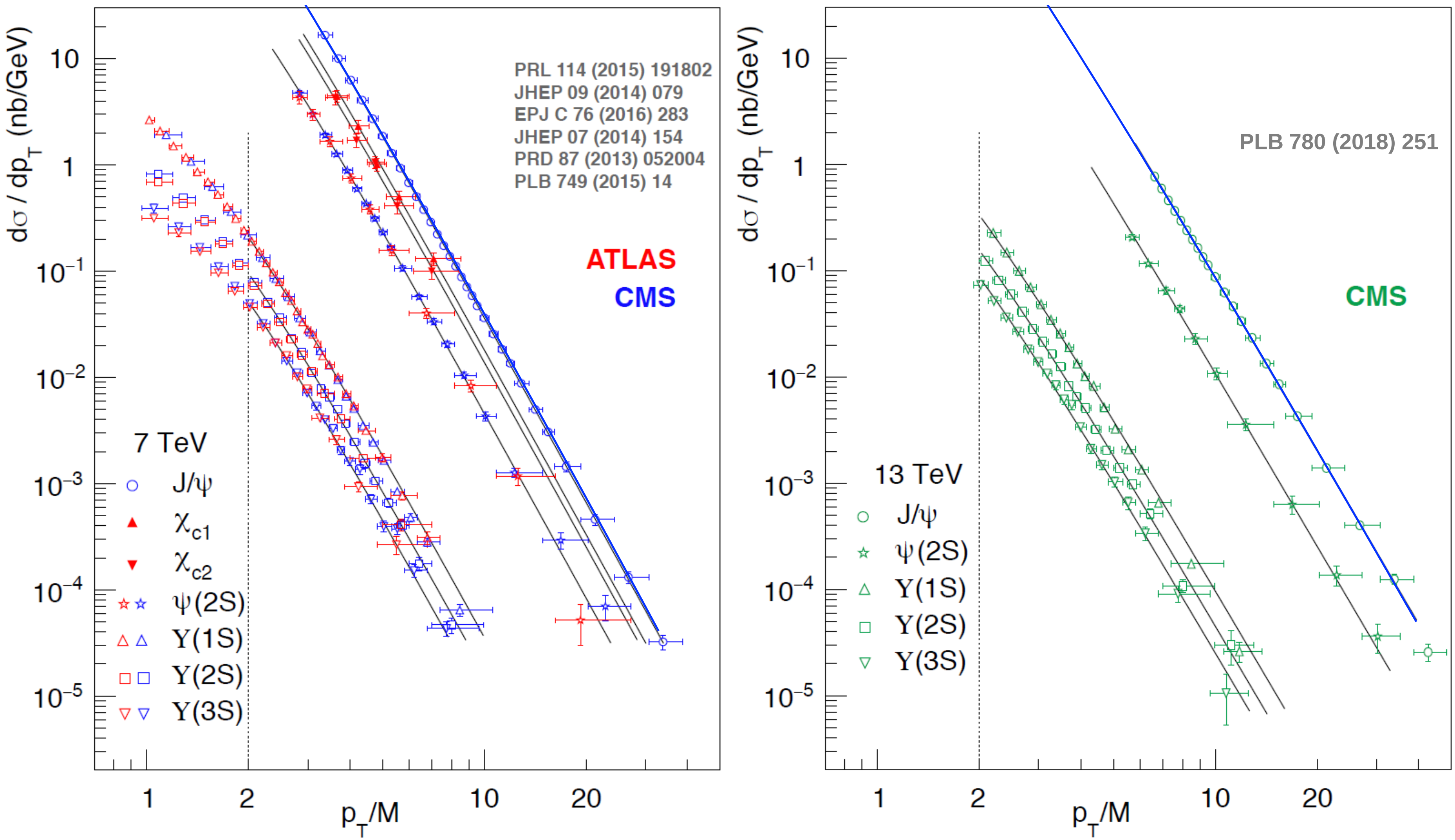
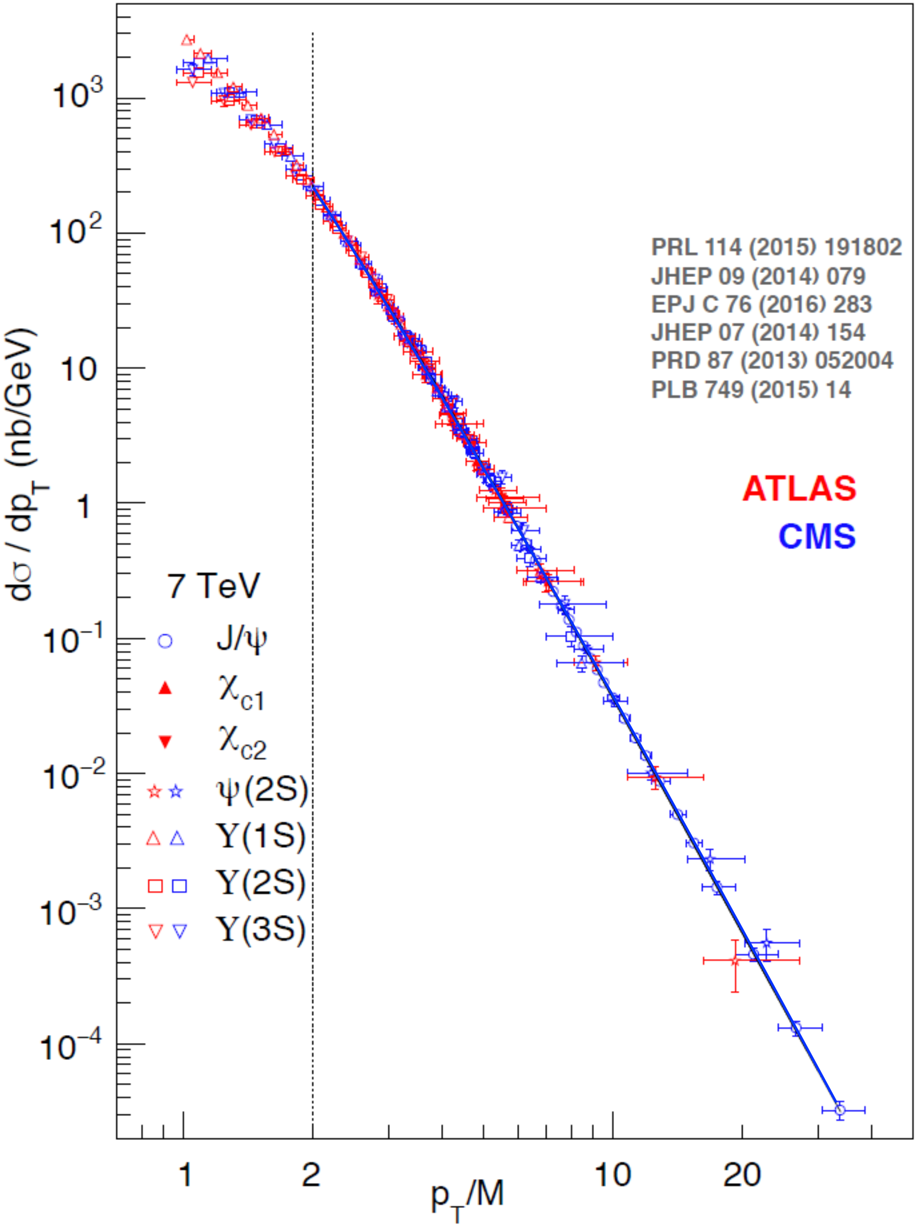
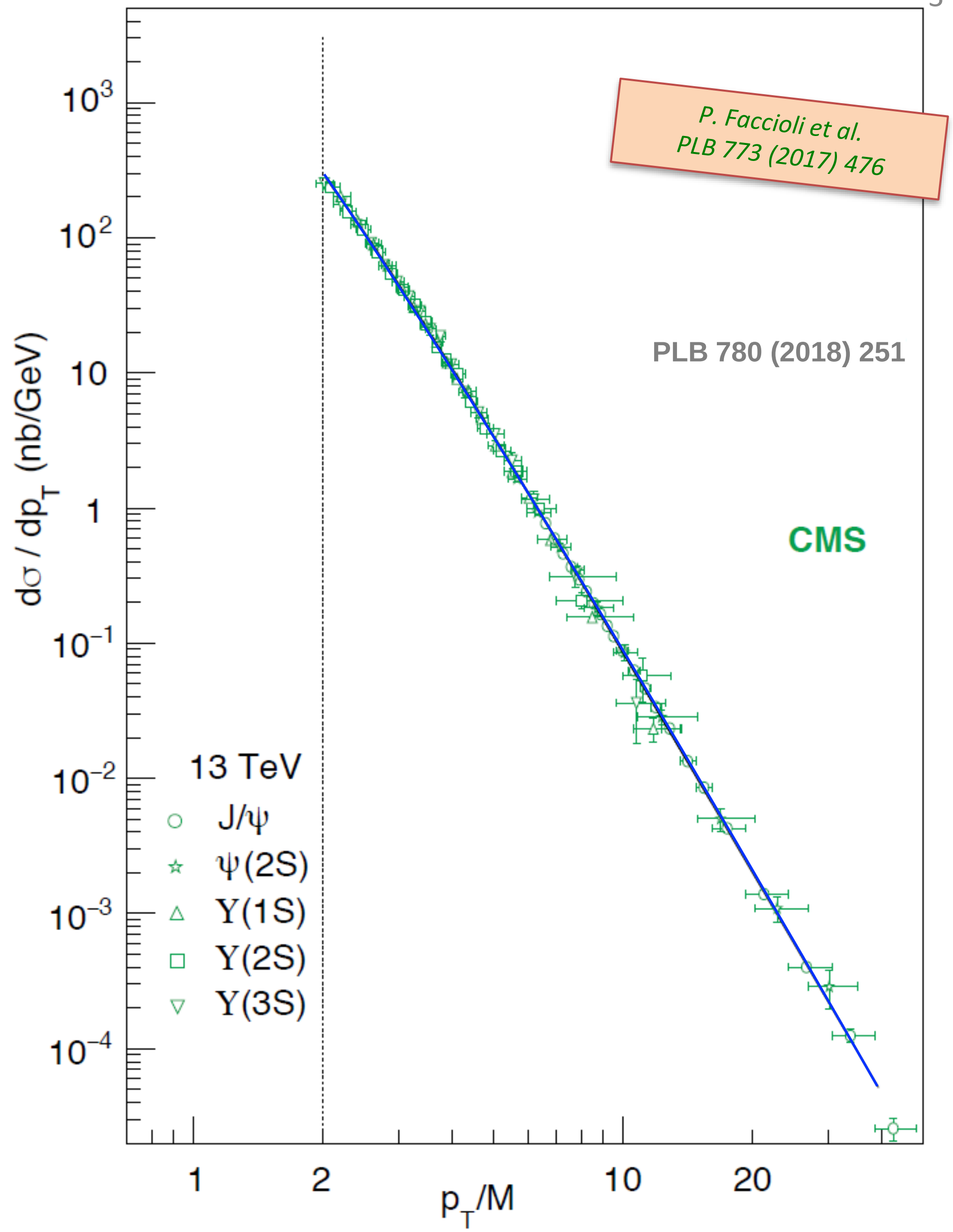
All quarkonia have identical p_T/M-differential cross section shapes,
for $p_T/M > 2$, at mid-rapidity, independently of mass and quantum numbers



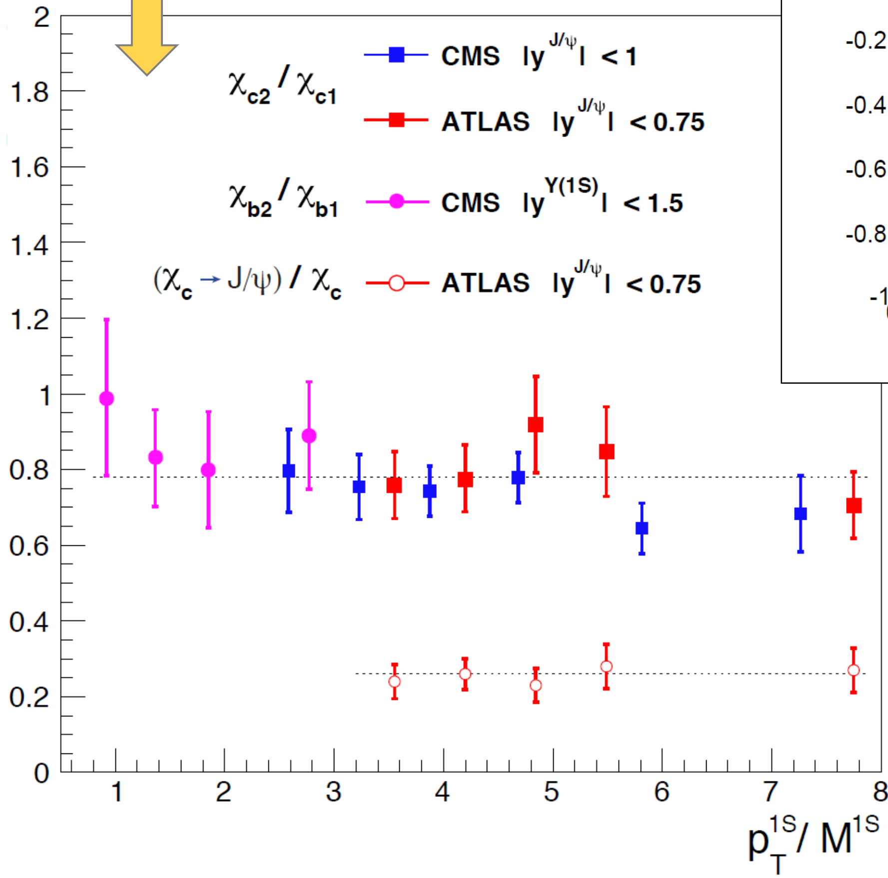


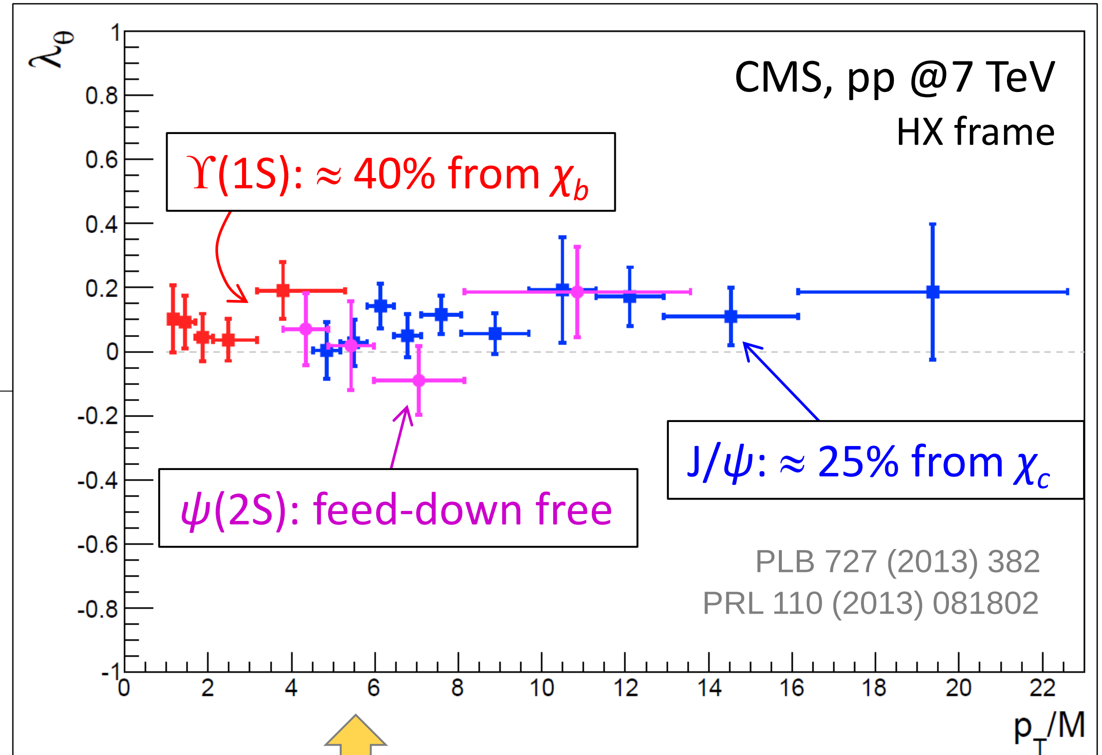


Scaling all data to match the J/ψ normalization

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 !





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

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 ψ(2S), J/ψ 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:

$$\psi(2S) \rightarrow \chi_{c1,2}\,\gamma$$
$$\psi(2S) \rightarrow J/\psi\ X$$
$$\chi_{c1,2} \rightarrow J/\psi\,\gamma$$

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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/ψ and ψ(2S) cross sections are parametrized as a **superposition** of unpolarized (λ_θ = 0) and transversely polarized (λ_θ = +1) processes: $\sigma_{\rm dir} \propto \left[\left(1 - f_p\right) g_u + f_p\, g_p\right]$

f_p: fractional contribution of the polarized process at an arbitrary reference point $(p_{\rm T}/M)^*$

g_u, g_p: shape functions that describe the $p_{\rm T}/M$ dependences of the unpolarized and polarized yields, respectively, normalized to unity at the chosen $(p_{\rm T}/M)^*$:

$$g(p_{\rm T}/M) = h(p_{\rm T}/M) \,/\, h[(p_{\rm T}/M)^*],$$

$$\text{with } h(p_{\rm T}/M) = (p_{\rm T}/M)\left(1 + \frac{1}{\beta-2}\frac{(p_{\rm T}/M)^2}{\gamma}\right)^{-\beta}$$

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f_p, g_u and g_p are **identical for the two S-wave states**. The unpolarized and polarized cross sections share the parameter γ, but have **distinct $\boldsymbol{\beta_u}$ and $\boldsymbol{\beta_p}$**. 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 χ_{c1} and χ_{c2}, without discriminating between polarized and unpolarized contributions, which cannot be individually constrained in the absence of χ_c polarization data

There are, hence, **four contributions** to direct quarkonium production:
the unpolarized and polarized ψ terms plus the χ_{c1} and χ_{c2} cross sections,
altogether characterized by one γ and four β parameters, β_u, β_p, $\beta(\chi_1)$ and $\beta(\chi_2)$

Correlated uncertainties

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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 λ_θ 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 λ_θ 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 (σ) from the measured values (B x σ)

Fit results

The fit has 100 constraints (data points) and 20 parameters:

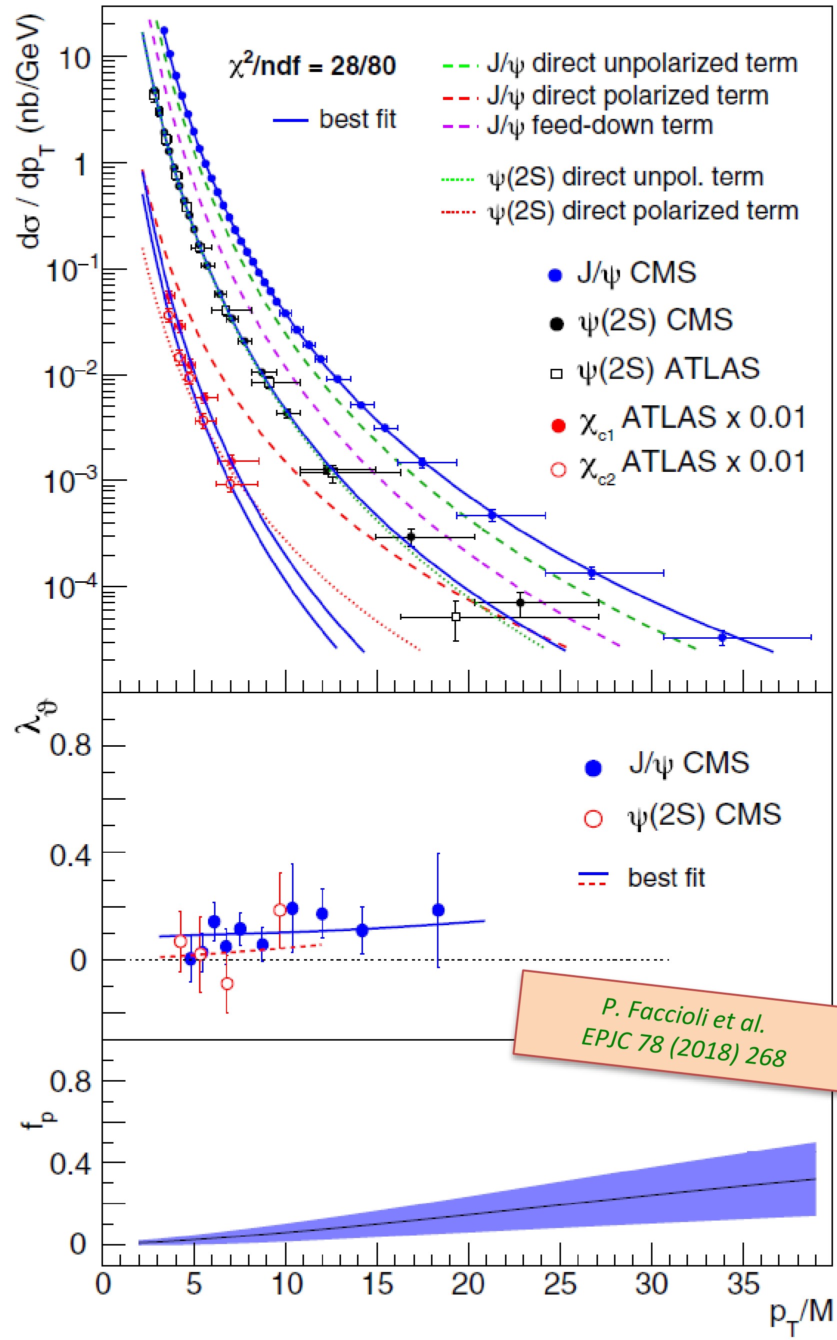
- 5 shape parameters,
- 4 normalizations,
- the fraction f_p
- and 10 nuisance parameters

The χ_{c1} and χ_{c2} p_T/M distributions are very similar to the unpolarized term dominating ψ 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 ψ data points contribute to the χ_c results

The polarized term has a weak contribution and the charmonium states are nearly unpolarized



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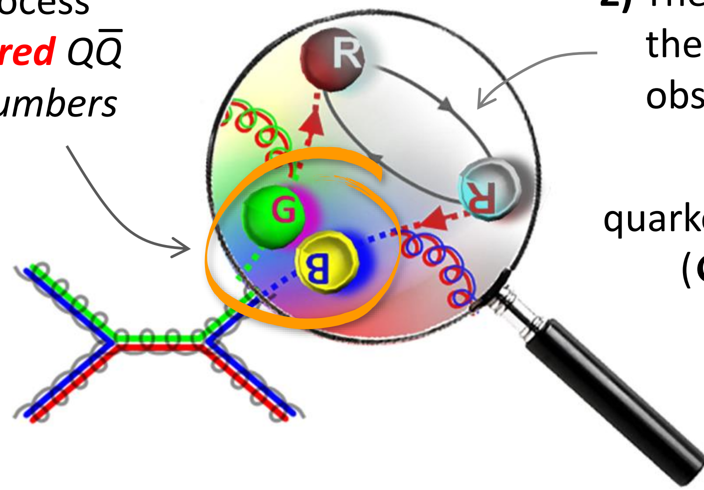
Quarkonium production in the NRQCD approach

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*

$^1S_0$ $^1S_0$ $^3S_1$ $^3P_0$ $^3P_2$ $^1D_2$ $^1P_1$ $^3S_1$ $^3P_1$ $^3P_2$ $^3D_3$ $^1P_1$ $^3D_2$ $^3D_1$ $^3P_1$



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

quarkonium ($\mathcal{Q}$)

- η_c , η_b [$^1S_0$]
- ψ, Υ [$^3S_1$] χ_{c0} , χ_{b0} [$^3P_0$]
- χ_{c1} , χ_{b1} [$^3P_1$] χ_{c2} , χ_{b2} [$^3P_2$]

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

1) *short-distance coefficients* (**SDCs**): p_T-dependent partonic cross sections

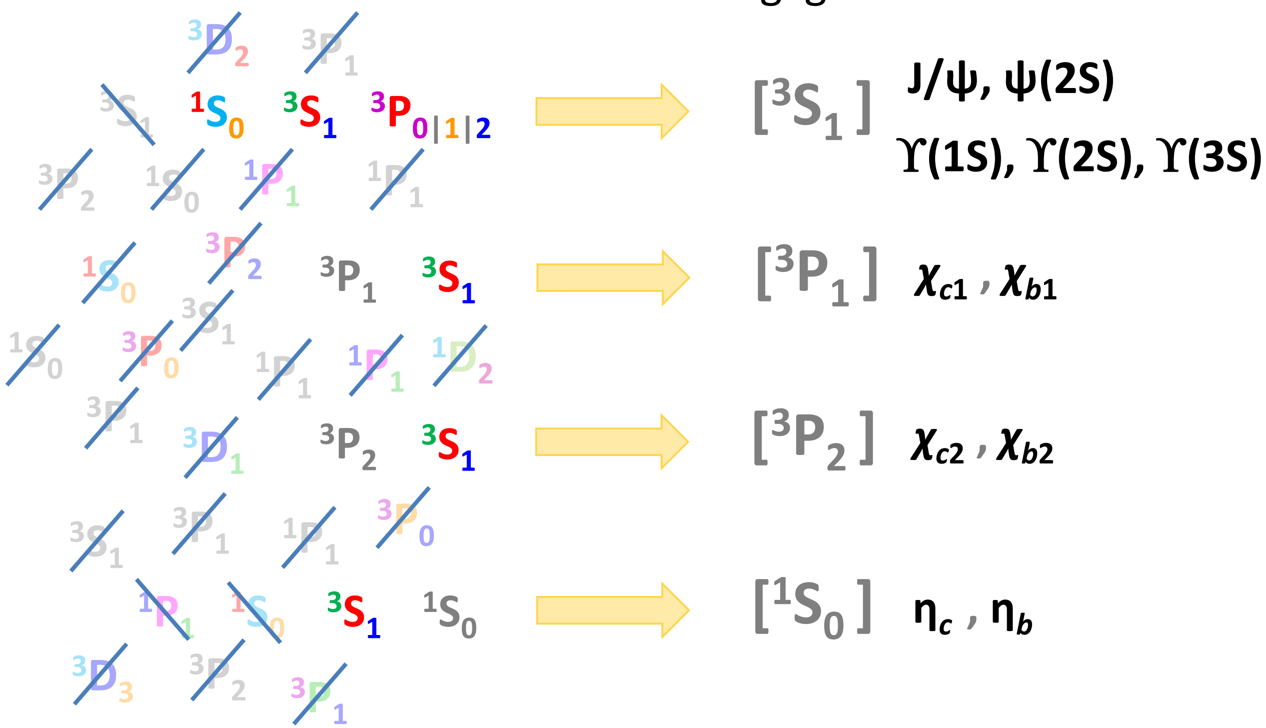
2) *long-distance matrix elements* (**LDMEs**): constant, **fitted from data**

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

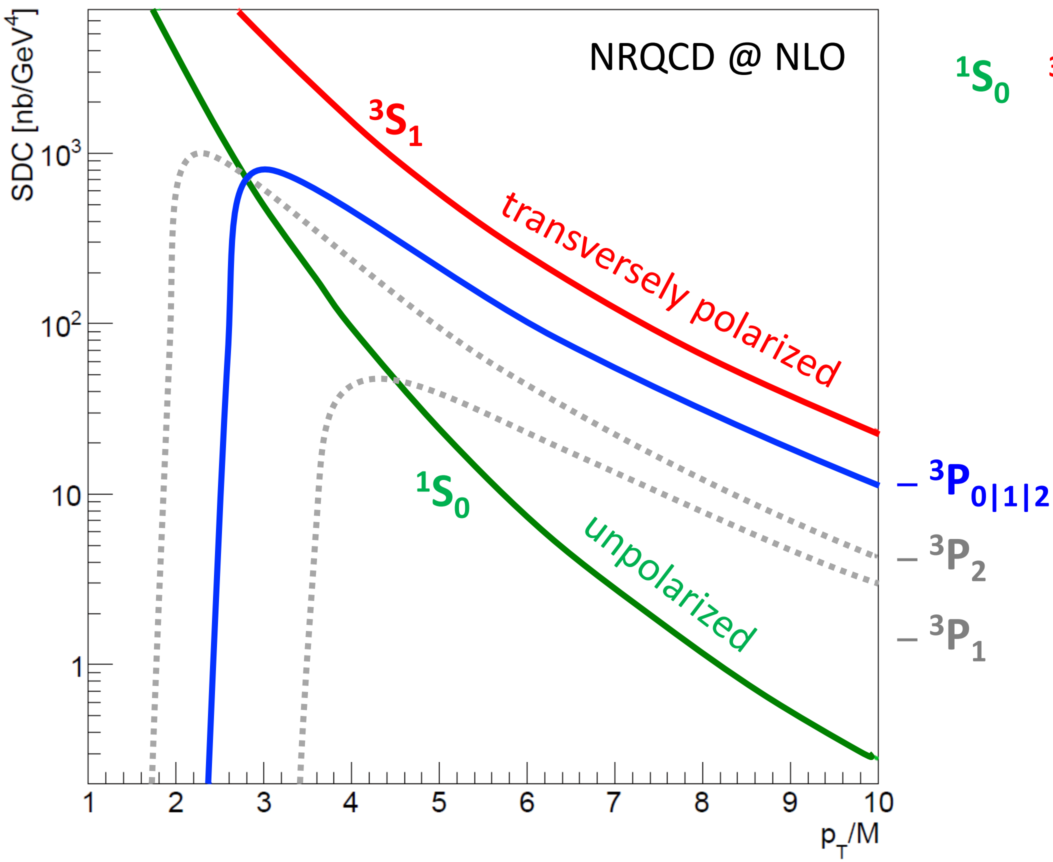
2) **Perturbative calculations** $\rightarrow$ some SDCs are negligible:



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

$$\frac{{}^3S_1 \rightarrow \chi_{c2}}{{}^3S_1 \rightarrow \chi_{c1}} = \frac{{}^3S_1 \rightarrow \chi_{b2}}{{}^3S_1 \rightarrow \chi_{b1}} = \frac{5}{3} \quad , \qquad \begin{matrix} {}^3S_1 \rightarrow \eta_c = {}^1S_0 \rightarrow J/\psi \\ {}^3S_1 \rightarrow \eta_b = {}^1S_0 \rightarrow \Upsilon \end{matrix} \quad , \text{ etc.}$$

Dominant short-distance cross section contributions



$^1S_0$ $^3S_1$ $^3P_{0|1|2}$ ⇨ **J/ψ, ψ(2S)**
ϒ(1S), ϒ(2S), ϒ(3S)

$^3P_1$ $^3S_1$ ⇨ χ_{c1} , χ_{b1}

$^3P_2$ $^3S_1$ ⇨ χ_{c2} , χ_{b2}

negative P-wave contributions,
(with large unphysical polarizations: see next slide), require proper cancellations to recover physical result

The variety of kinematic behaviours predicted in NRQCD seems **redundant** with respect to the measured universal p_T/M scaling and lack of polarization

Curves from H.-S. Shao et al., PRL 108, 242004; 112, 182003; Comput. Phys. Comm. 198, 238

The polarization dimension

Quarkonium polarization is characterized by λ_θ :

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

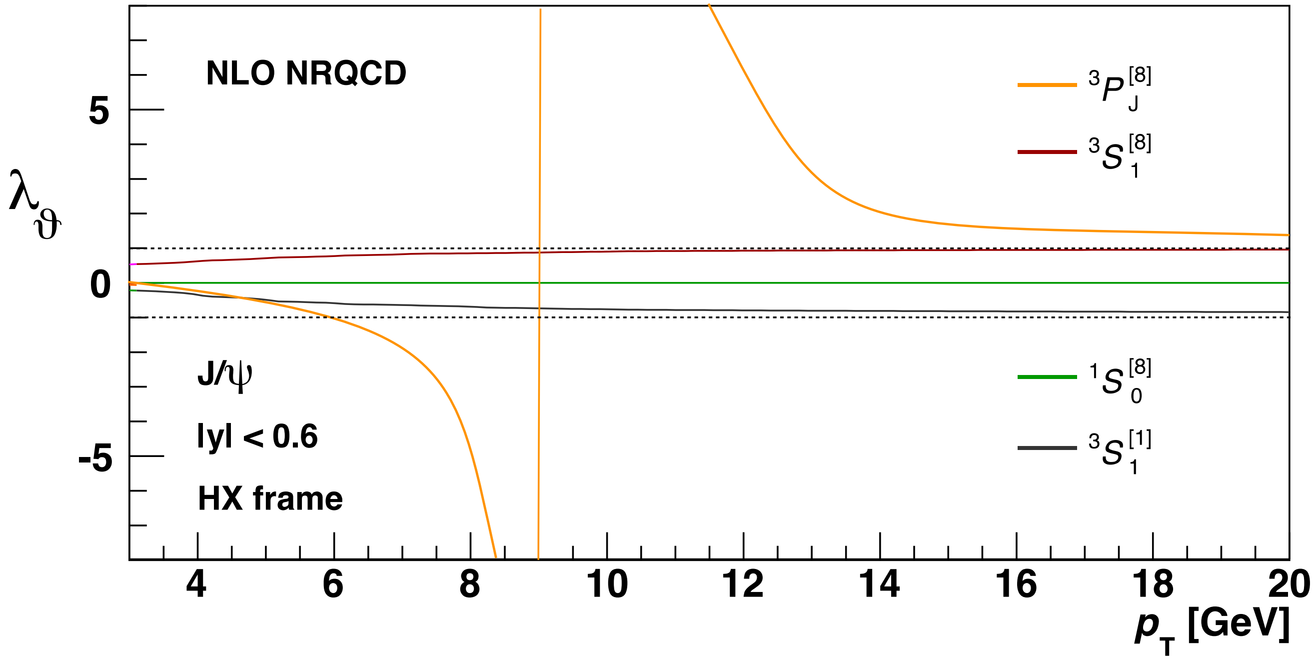
Each colour singlet and octet term has a specific polarization associated :

$^1S_0$ $\rightarrow$ $\lambda_\vartheta = 0$ at LO, NLO, etc; isotropic wave function

$^3S_1$ $\rightarrow$ $\lambda_\vartheta = +1$ at LO, NLO, etc, at high p_T, where the fragmenting gluon is "real"

^3P_J $\rightarrow$ $\lambda_\vartheta >> +1$ at NLO and high p_T ("hyper-transverse"); it is 0 at LO...

$^3S_1$ $\rightarrow$ $\lambda_\vartheta \sim -0.9$ at NLO and high p_T ; it is ≈ +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

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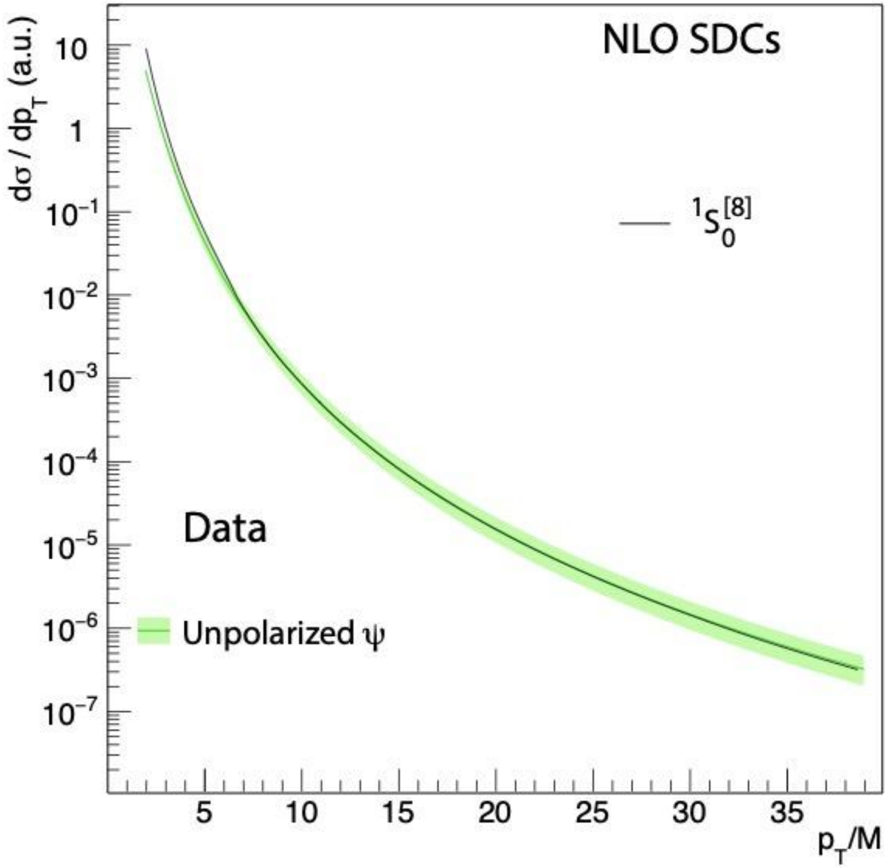
$^1S_0$ ⇨ **J/ψ, ψ(2S)**



The width of the data bands only reflects *shape* uncertainties

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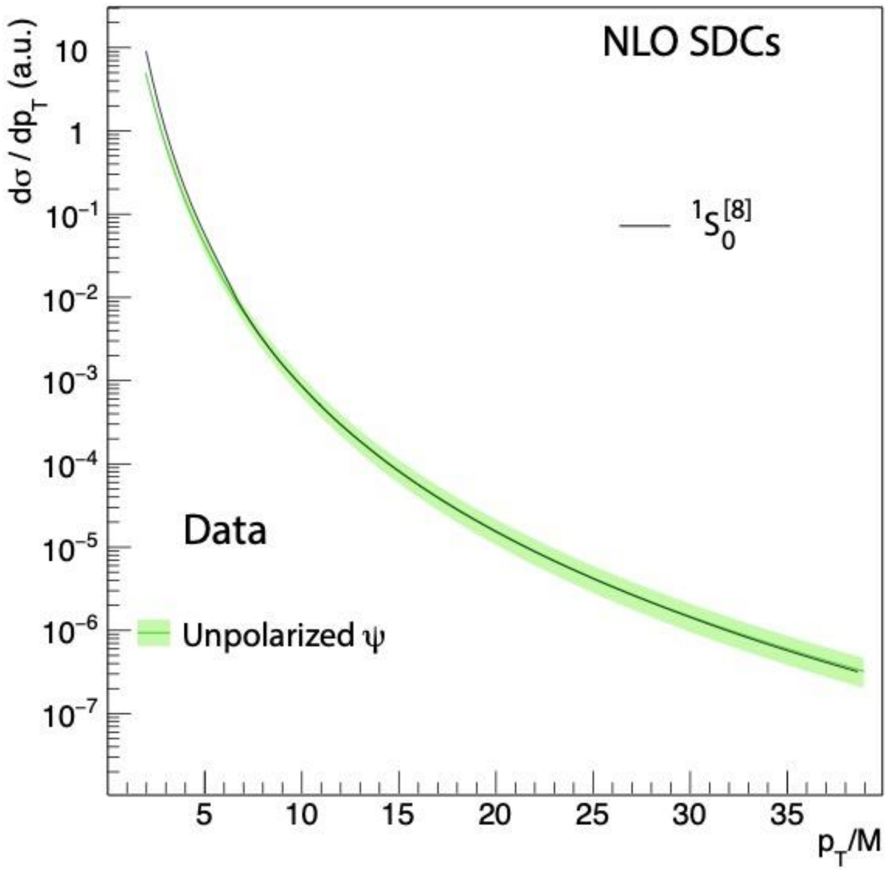
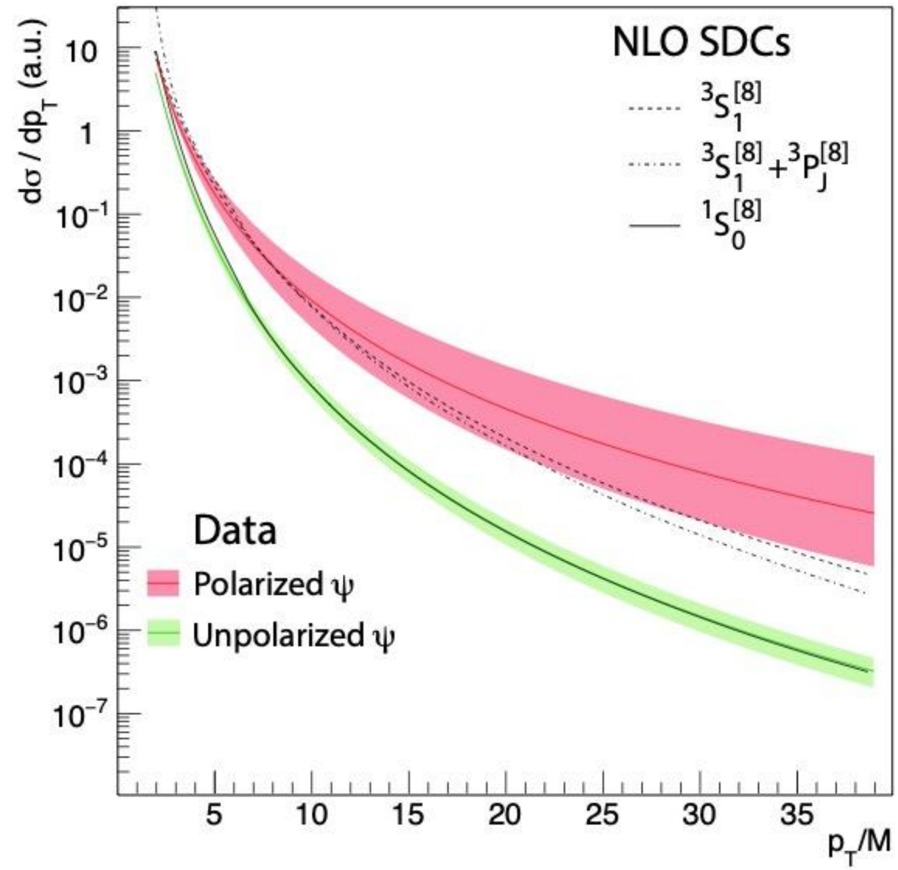
$^1S_0 \Rightarrow$ J/ψ, ψ(2S) $\qquad\qquad$ $^3S_1 \Rightarrow$ J/ψ, ψ(2S)





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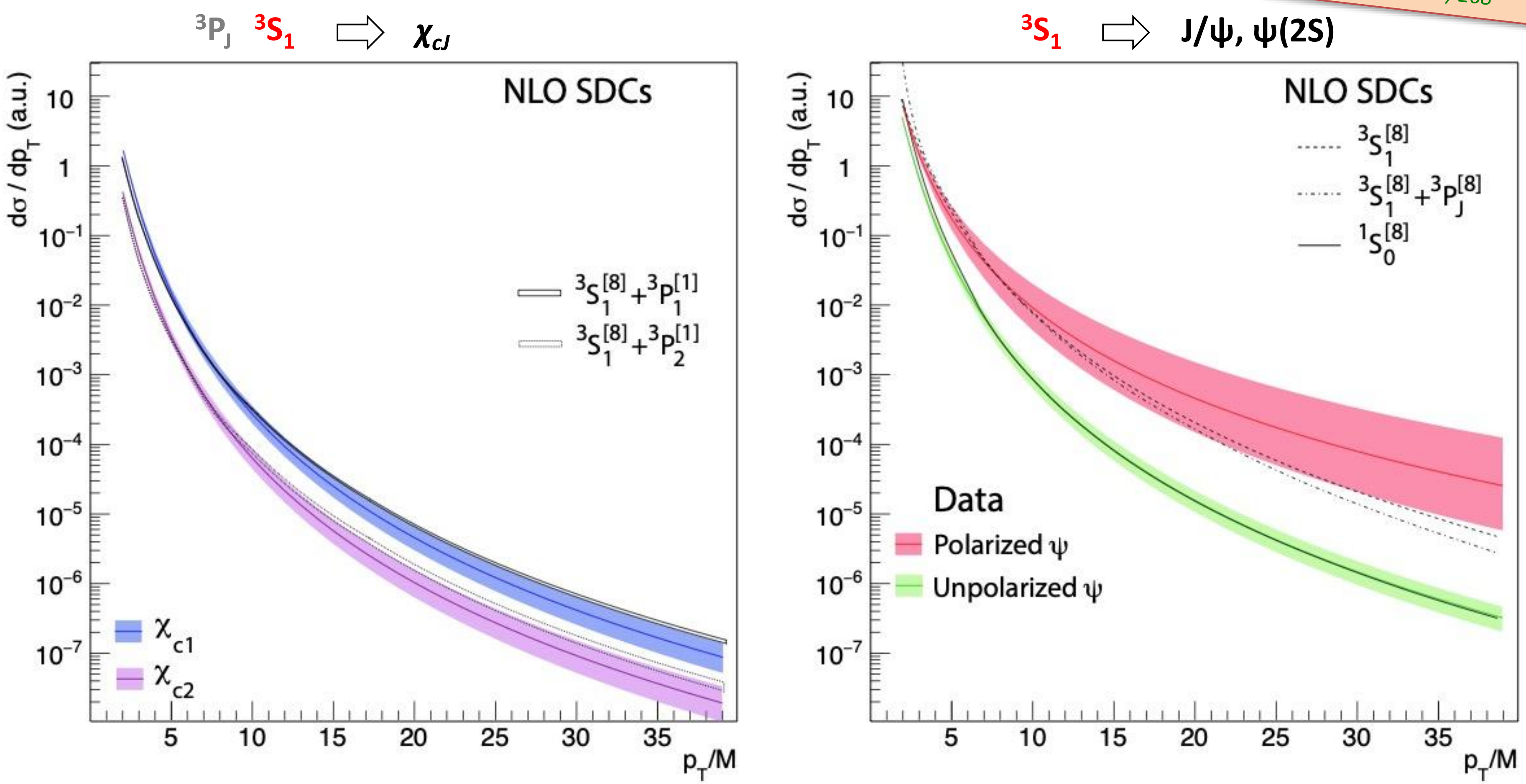
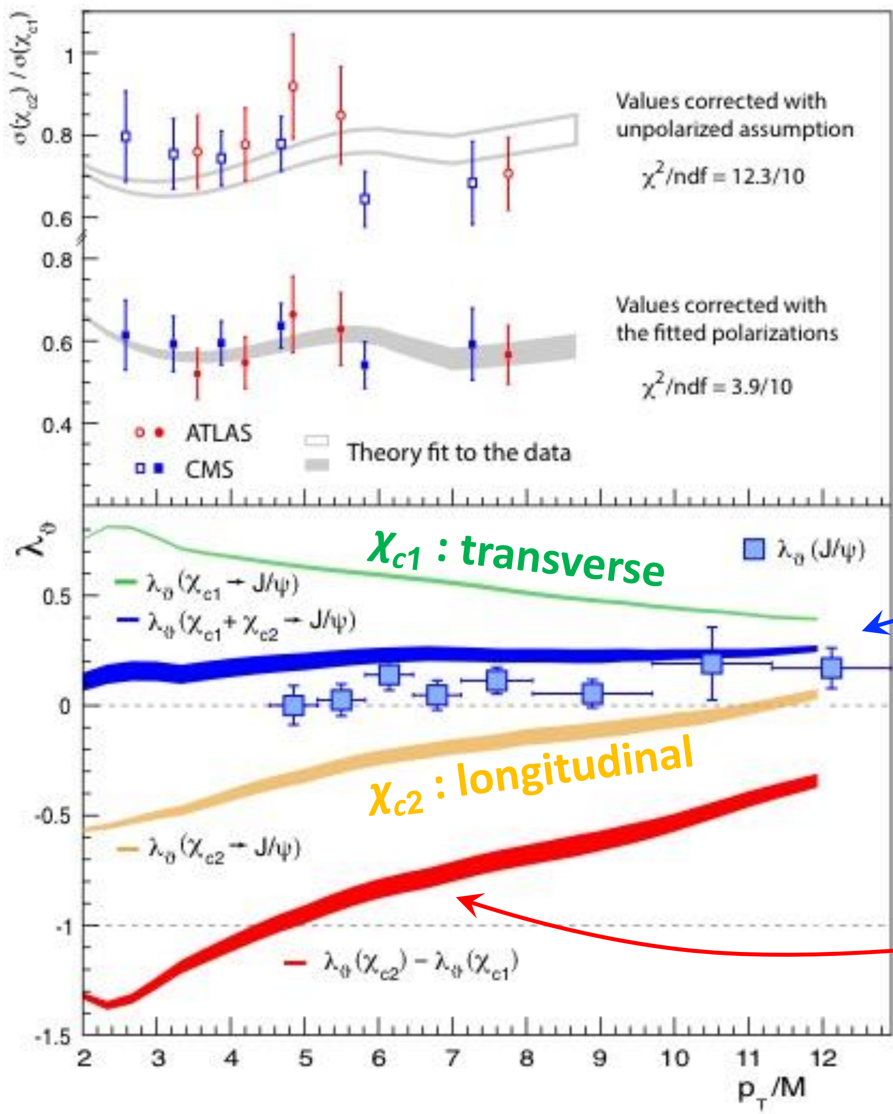


The width of the data bands only reflects *shape* uncertainties

Striking coincidence or trigger to improve NRQCD?

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



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

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

$\chi_{c1} + \chi_{c2} \to J/\psi$: weak polarization

≈ as observed in prompt J/ψ data!

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$|\Delta\lambda_\vartheta| \approx 1$

at the barycentre of current CMS χ_c data

Comparison to a previous prediction

In NRQCD, one single parameter determines *both* the χ_{c2} / χ_{c1} ratio and the two polarizations

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

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

<u>*CDF*</u>:

= central values using $\lambda_\vartheta = 0.13 \pm 0.15$ for χ_{c1} and χ_{c2}

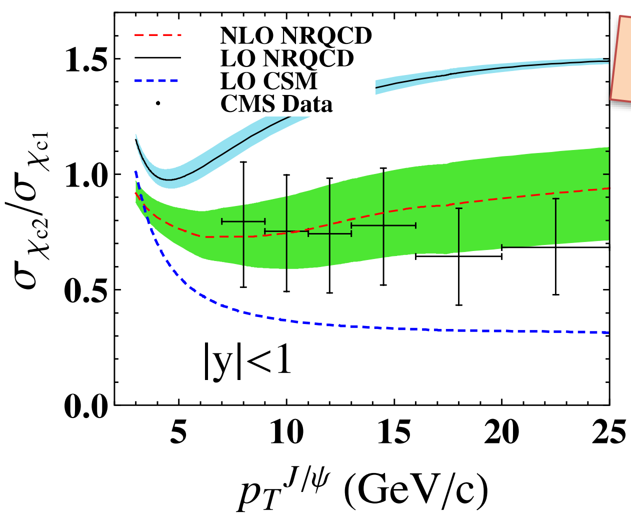
= no correlated variations considered

= uncertainty added in quadrature with all others

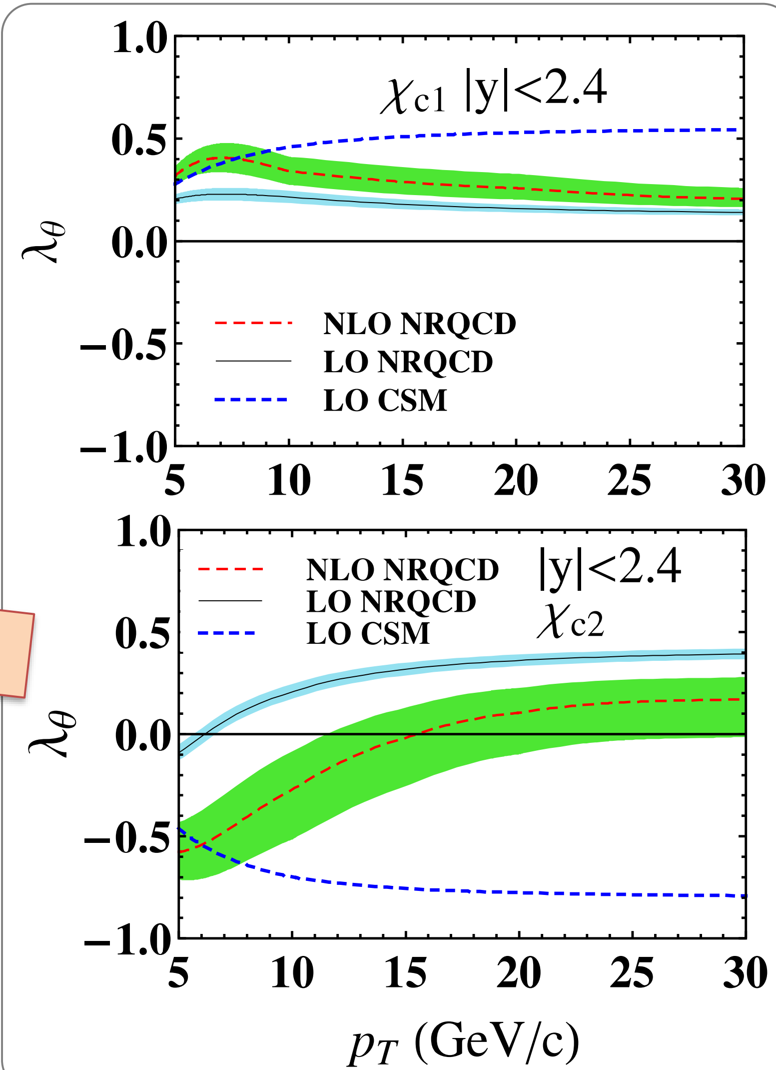
<u>*CMS*</u>:

= central values using $\lambda_\vartheta = 0$ for χ_{c1} and χ_{c2};

= polarization uncertainty from *maximum* range of correlated variations of $\lambda_\vartheta(\chi_{c1})$ and $\lambda_\vartheta(\chi_{c2})$



H.-S. Shao et al.
PRL 112 (2014) 182003



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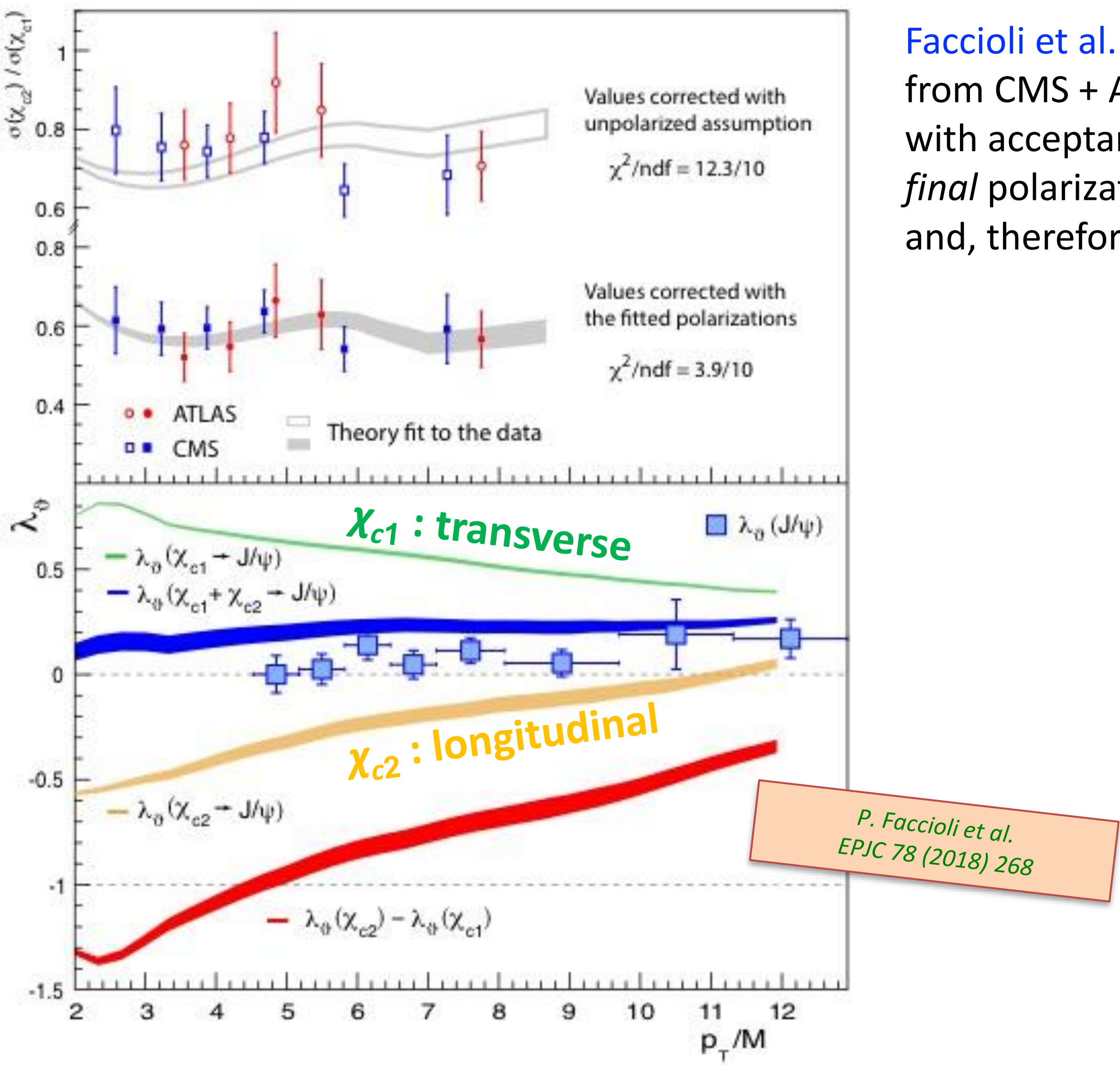
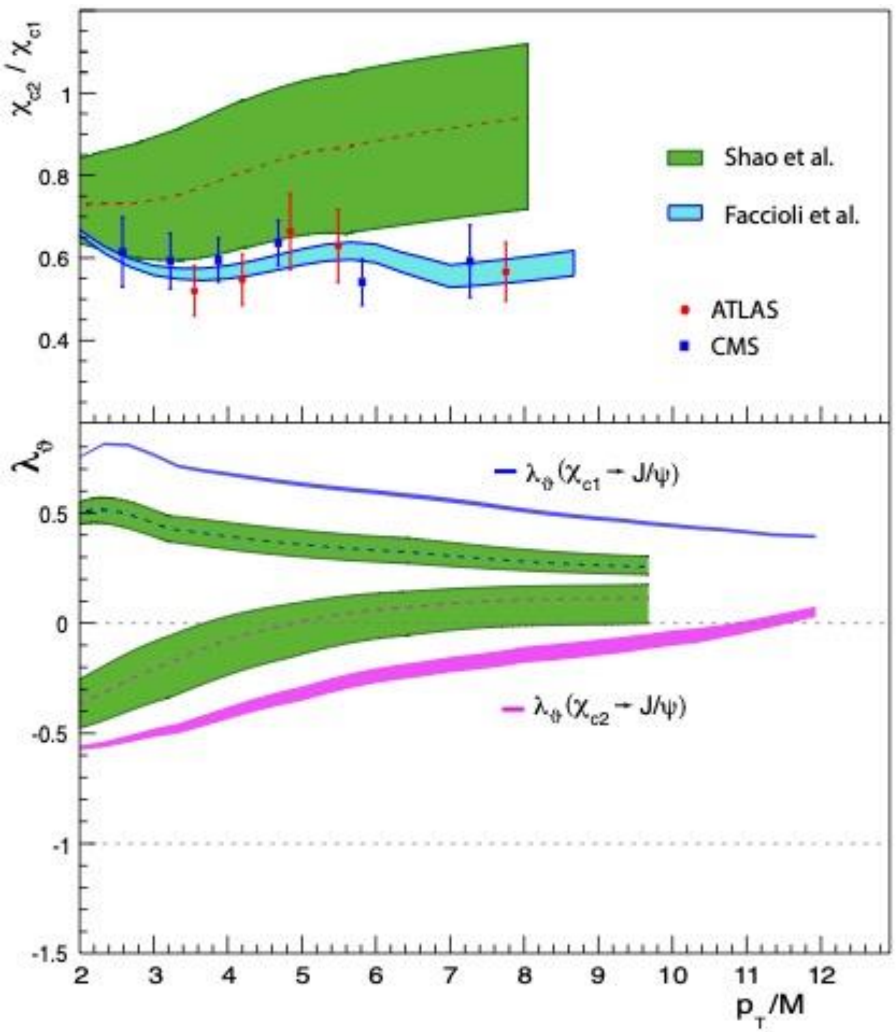


Faccioli et al. derive ***r* = 0.217 ± 0.003**
from CMS + ATLAS data (averaged)
with acceptance corrections corresponding to the *final* polarization prediction (*iterative* procedure)
and, therefore, no added "polarization uncertainty"

Comparison to a previous prediction

In NRQCD, one single parameter determines *both* the χ_{c2} / χ_{c1} ratio and the two polarizations

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



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 ± 0.06**

Faccioli et al.,
EPJC 78 (2018) 268
***r* = 0.217 ± 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 χ_{c1} and χ_{c2} polarizations must be **very different** from one another

Further reading

- P. Faccioli, C. Lourenço and J. Seixas,
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- P. Faccioli, C. Lourenço, M. Araújo, J. Seixas, I. Krätschmer and V. Knünz,
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  From identical S- and P-wave p_T spectra to maximally distinct polarizations: probing NRQCD with χ states,
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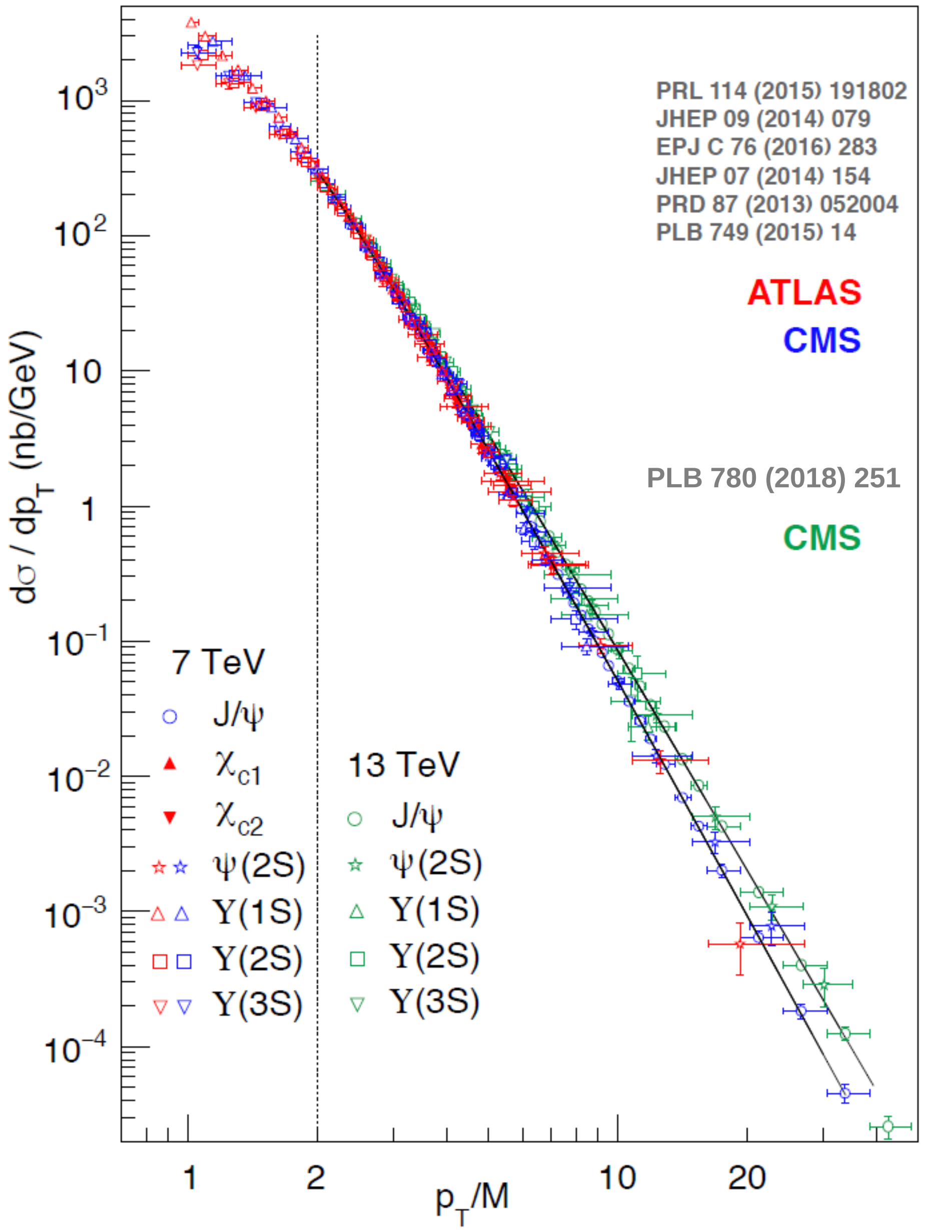
- P. Faccioli, C. Lourenço, M. Araújo and J. Seixas,
  Universal kinematic scaling as a probe of factorized long-distance effects in high-energy quarkonium production,
  Eur. Phys. J. C78 (2018) 118

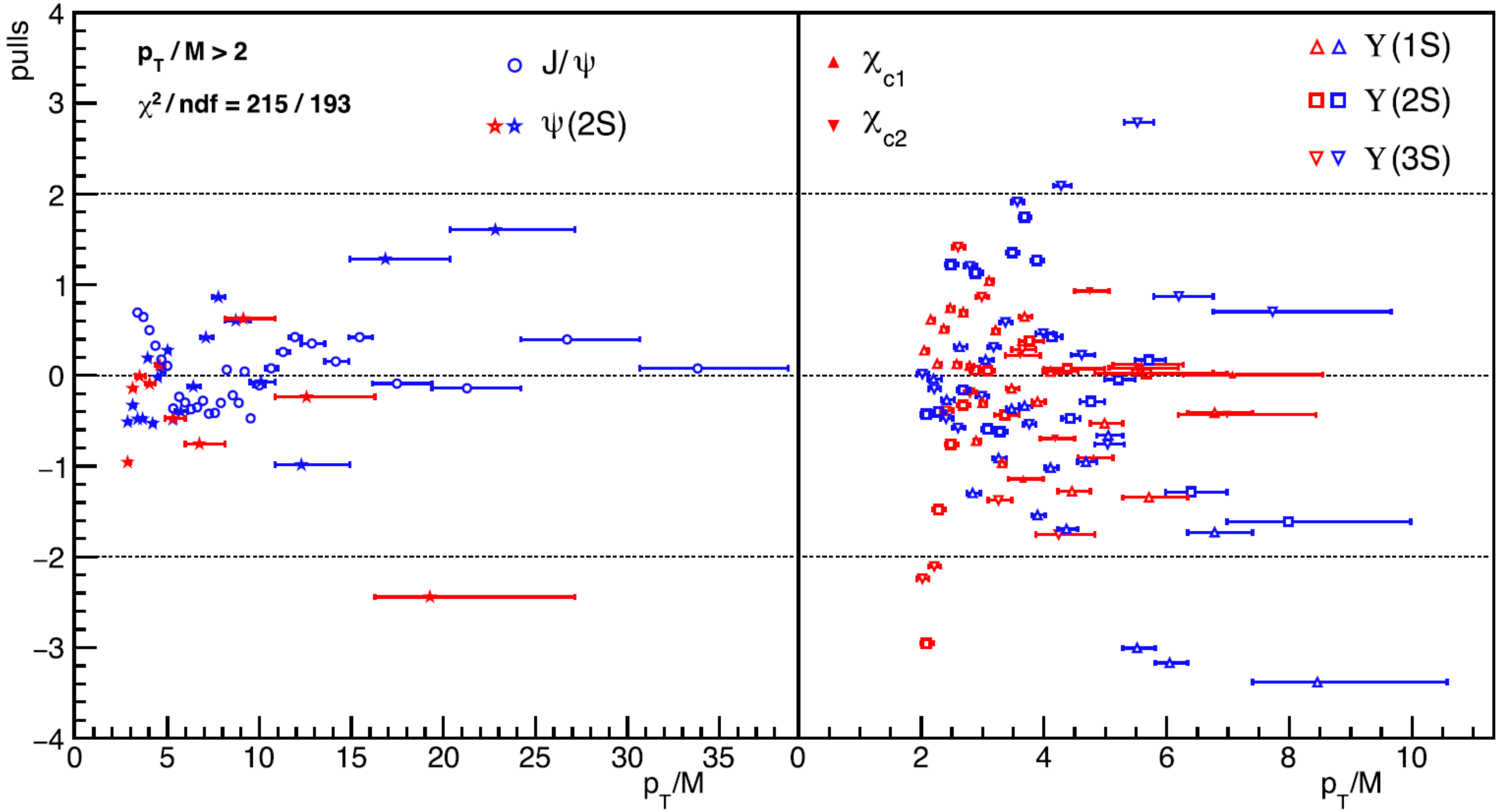
Backup

Higher energy, broader distribution



Backup

Distribution of pulls (7 TeV fit)



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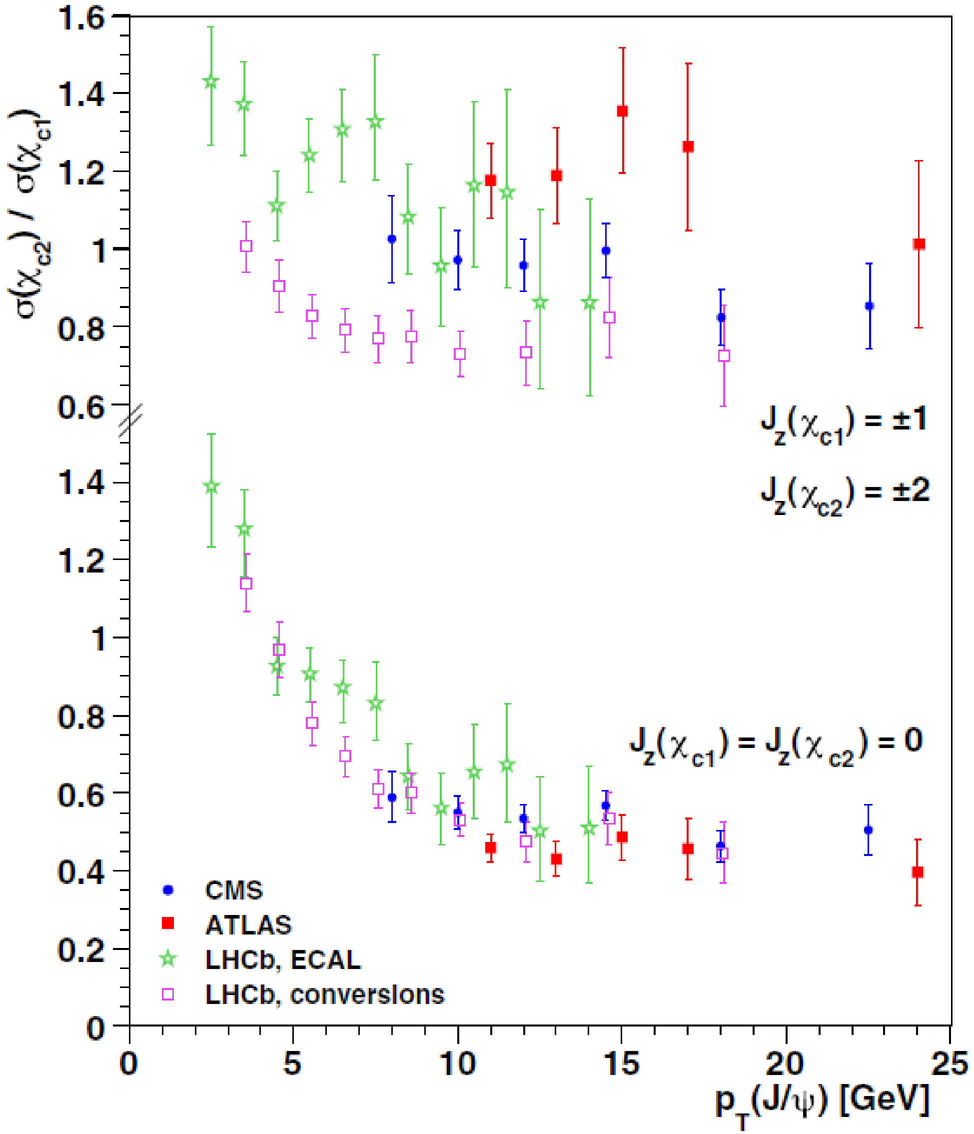

$\sigma(\chi_{c2}) / \sigma(\chi_{c1})$
$J_z(\chi_{c1}) = \pm 1$
$J_z(\chi_{c2}) = \pm 2$
$J_z(\chi_{c1}) = J_z(\chi_{c2}) = 0$
CMS
ATLAS
LHCb, ECAL
LHCb, conversions
$p_T(J/\psi)$ [GeV]