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

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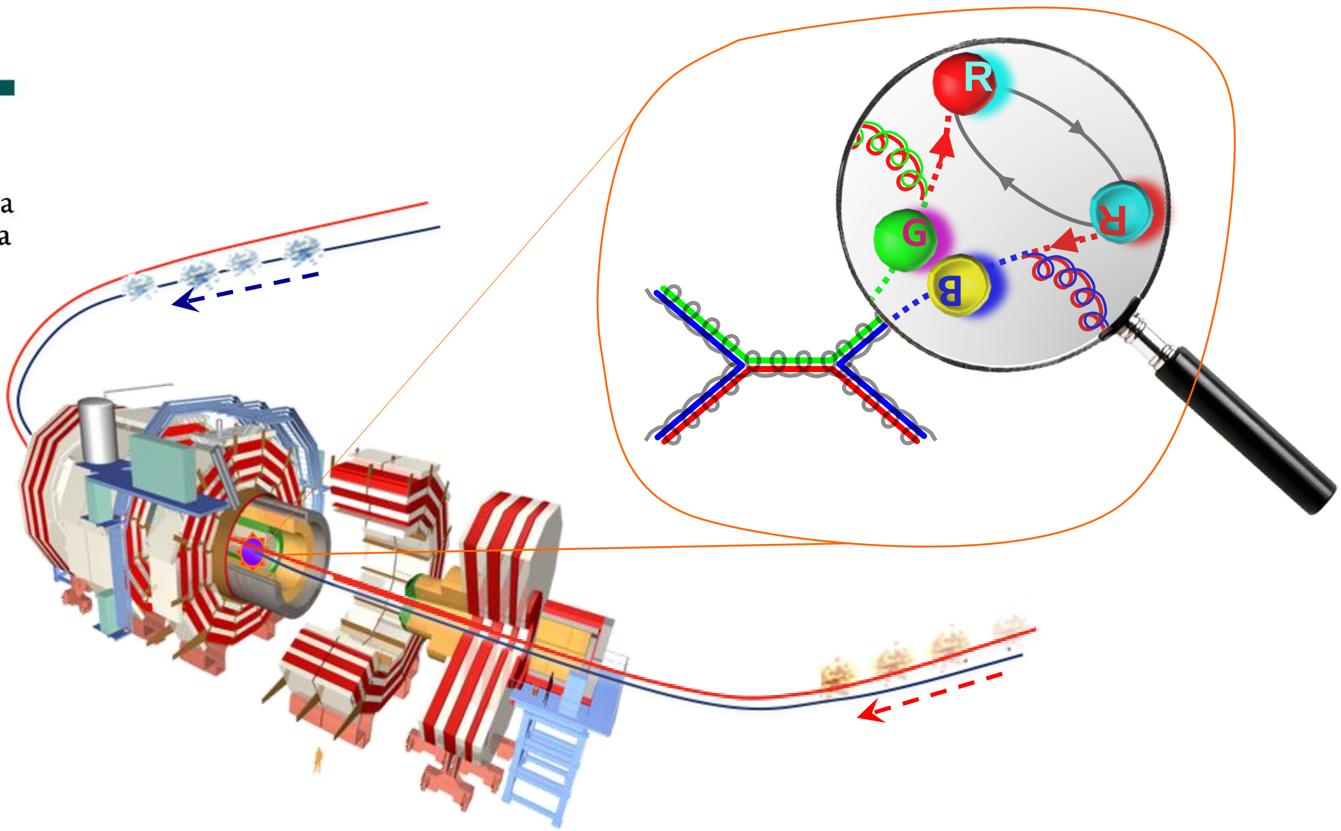

5th IDPASC/LIP PhD Students Workshop
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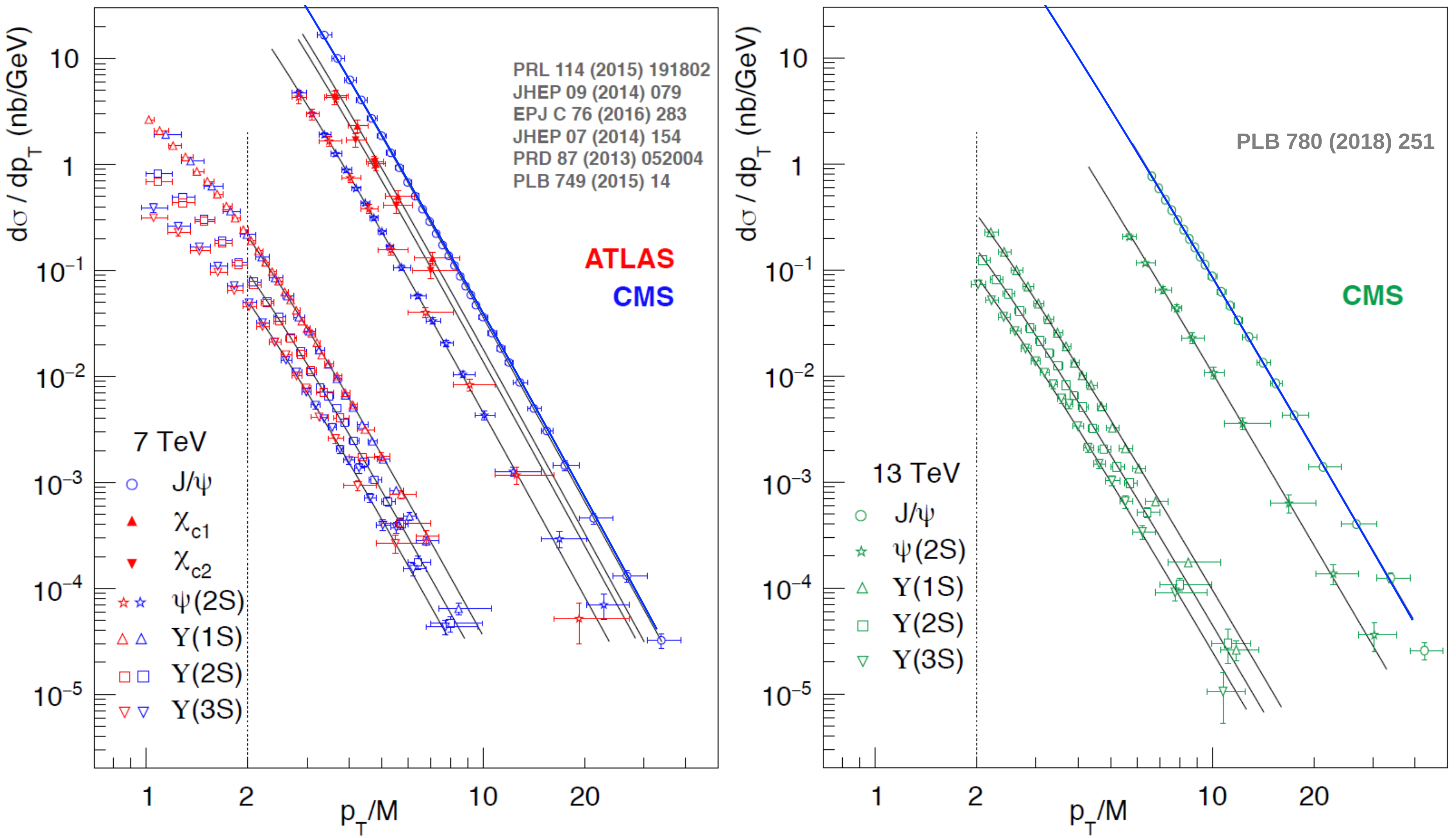
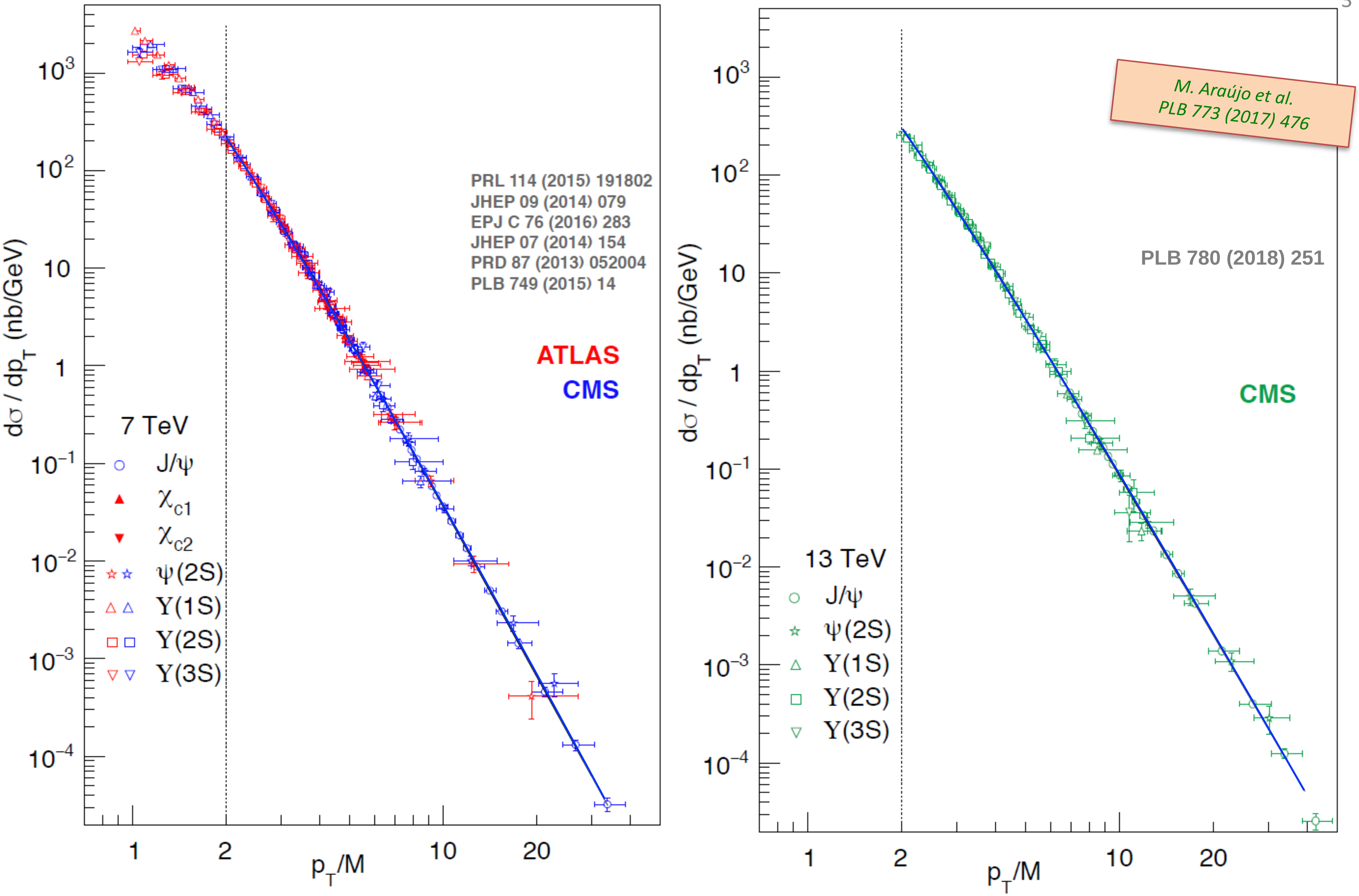
Mariana Araújo, in collaboration with
Pietro Faccioli, Carlos Lourenço, and João Seixas

Unexpectedly simple data patterns

M. Araújo et al.
PLB 773 (2017) 476

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

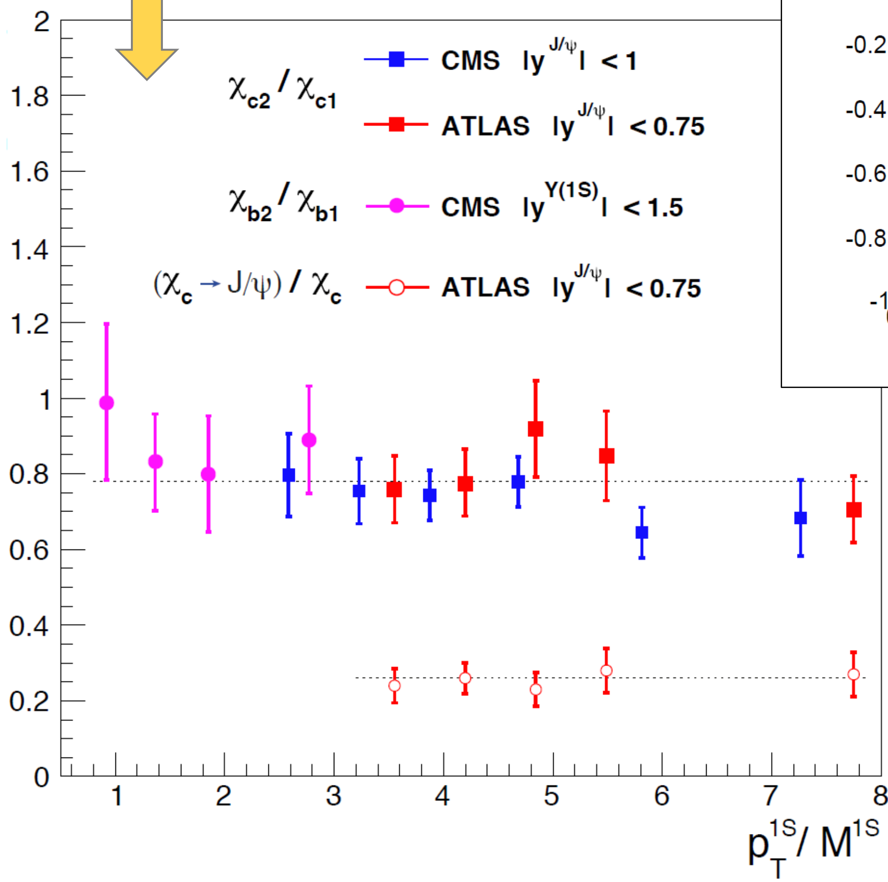


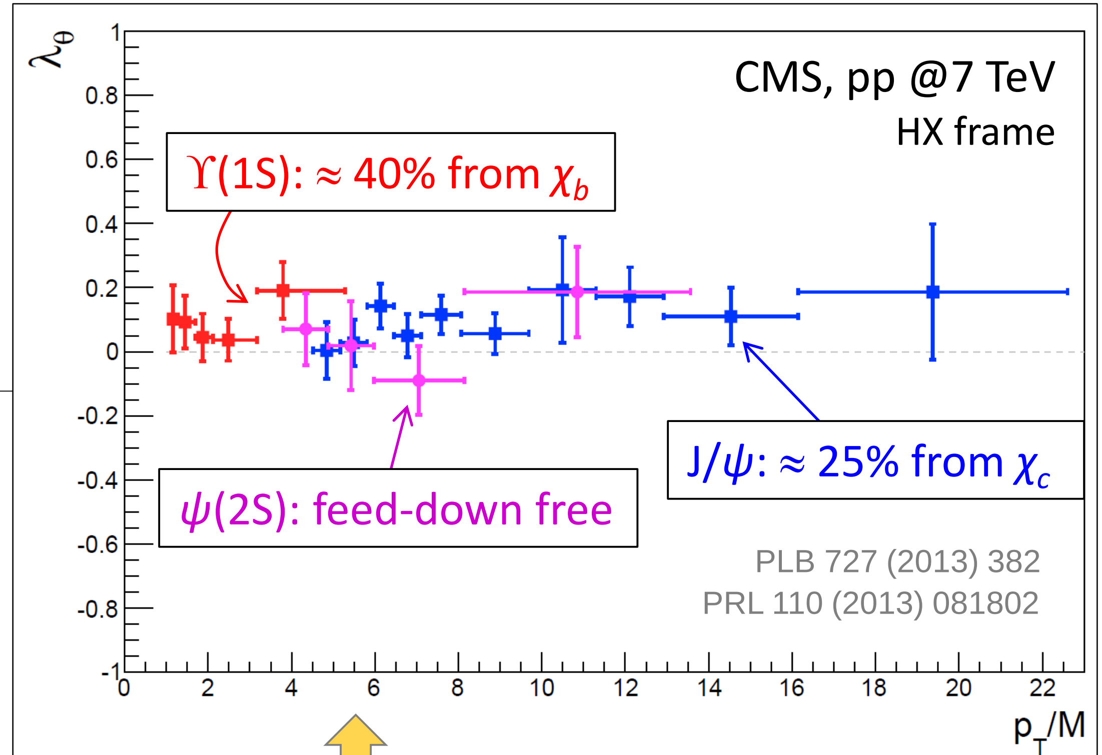


Scaling all data to match the J/ψ normalization

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

A model-independent global charmonium fit

M. Araújo et al.
EPJC 78 (2018) 268

We did a simultaneous global fit to mid-rapidity differential cross sections and polarizations of the charmonium states ψ(2S), J/ψ and $\chi_{c1,2}$

Accounting for the momentum and polarization transfer in the feed-down decays

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

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

f_p: fractional contribution of the polarized process

g_u, g_p: shape functions that describe the p_T/M dependence :

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

The unpolarized and polarized cross sections share γ but have **distinct $\boldsymbol{\beta_u}$ and $\boldsymbol{\beta_p}$**

The g_u and g_p shapes and relative contributions are **constrained by the polarization data**

The χ_{c1} and χ_{c2} follow the same parametrization but without separating u and p terms, given the absence of χ_c polarization data

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:

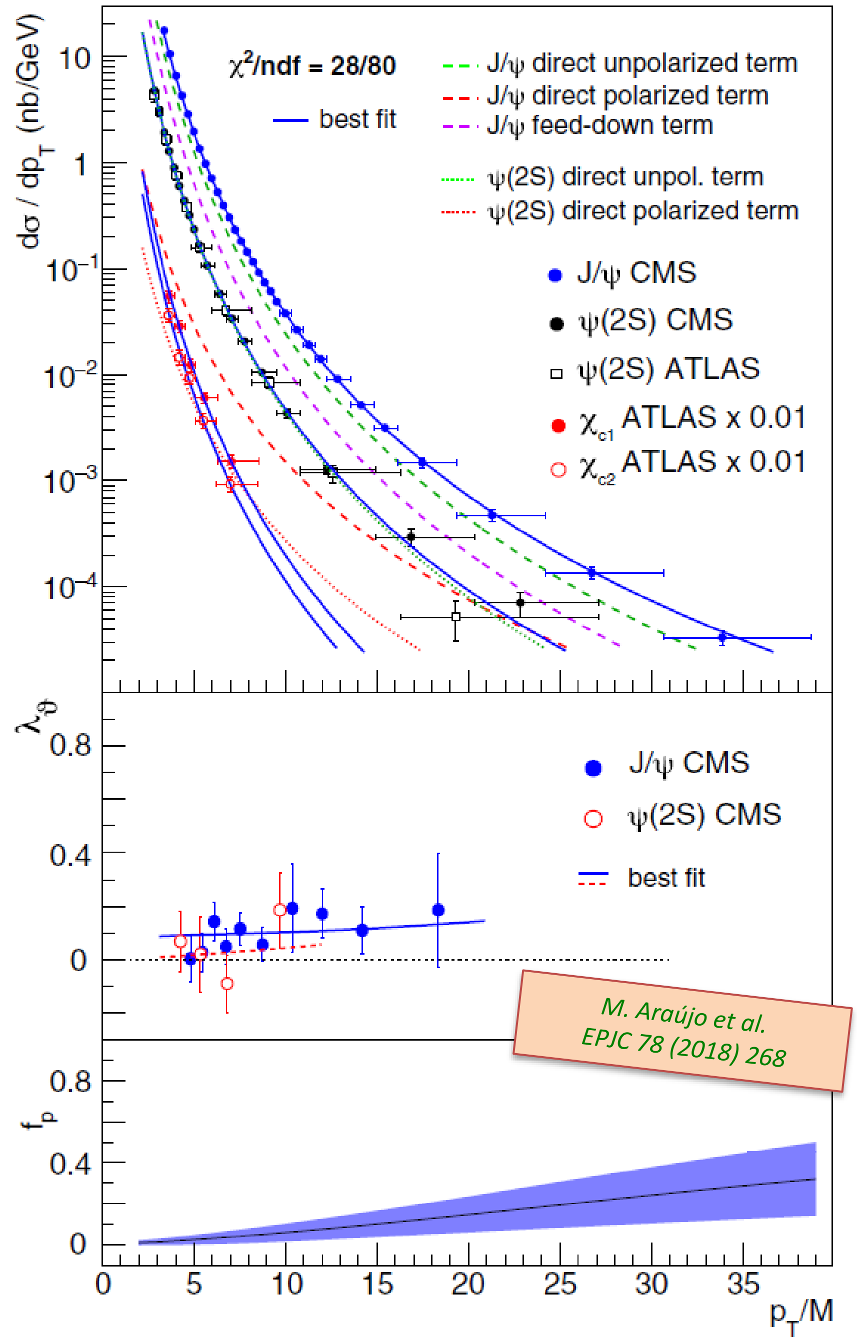
- 5 shape parameters,
- 4 normalizations,
- the fraction f_p
- and 10 nuisance parameters

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



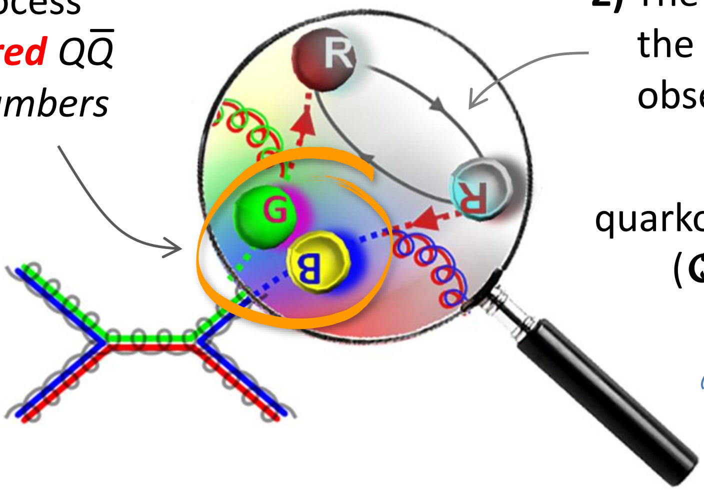
Quarkonium production in the NRQCD approach

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

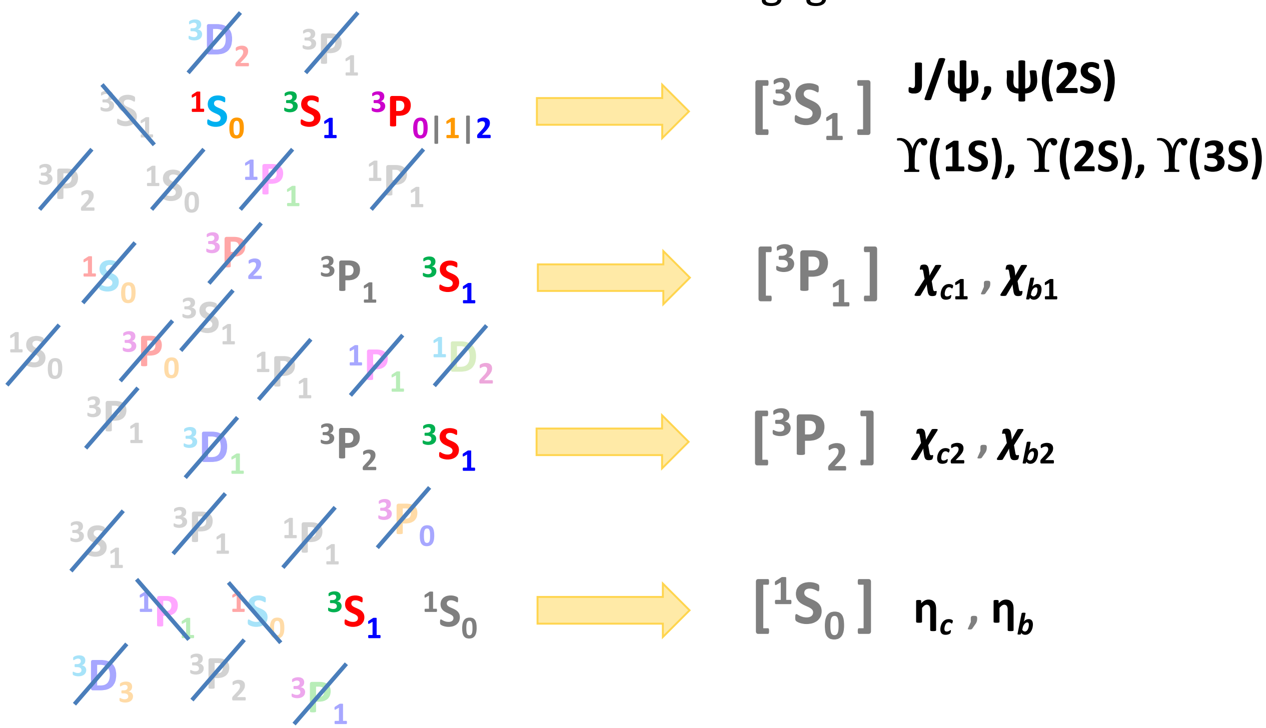
2) *long-distance matrix elements* (**LDMEs**): constant, **fitted from data**

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 → "***v*-scaling**" rules for LDMEs

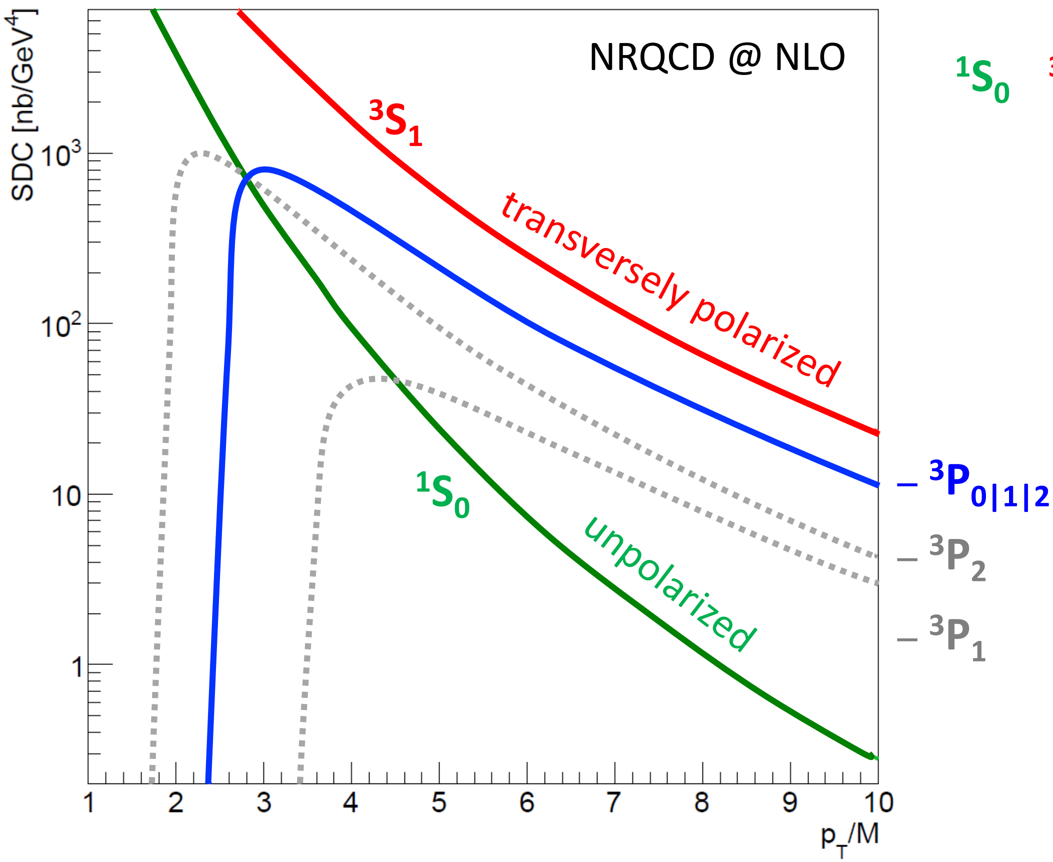
2) **Perturbative calculations** → some SDCs are negligible:



3) **Heavy-quark spin symmetry** → relations between LDMEs of different states

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

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

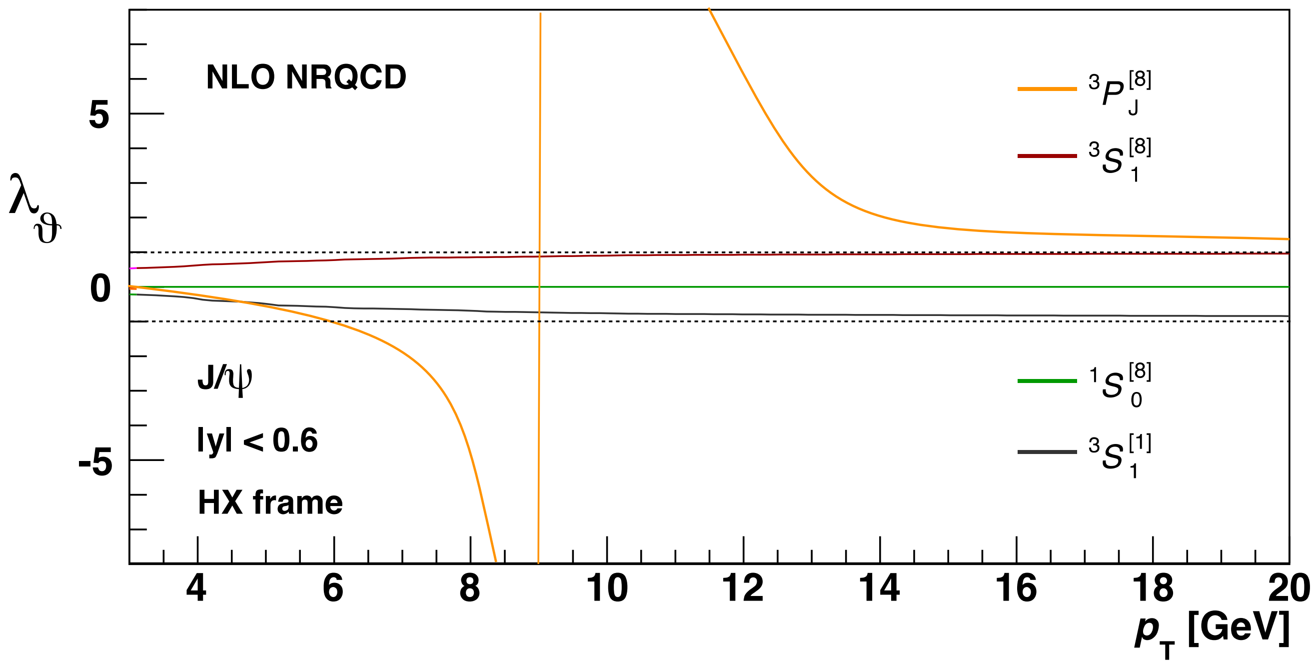
The polarization dimension

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 :

$^1S_0$ → $\lambda_\vartheta = 0$ at LO, NLO, etc; isotropic wave function
$^3S_1$ → $\lambda_\vartheta = +1$ at LO, NLO, etc, at high p_T, where the fragmenting gluon is "real"
^3P_J → $\lambda_\vartheta >> +1$ at NLO and high p_T ("hyper-transverse"); it is 0 at LO...
$^3S_1$ → $\lambda_\vartheta \sim -0.9$ at NLO and high p_T ; it is ≈ +1 at LO (has a small impact)



Data fit vs. NRQCD: a surprising agreement

The shape functions from the global fit to the data (bands) and their NRQCD theory counterparts (lines), obtained in completely independent ways,
agree with each other <u>over 8 (!) orders of magnitude</u>:
within uncertainties, NRQCD can reproduce the similarity of the p_T /M distributions

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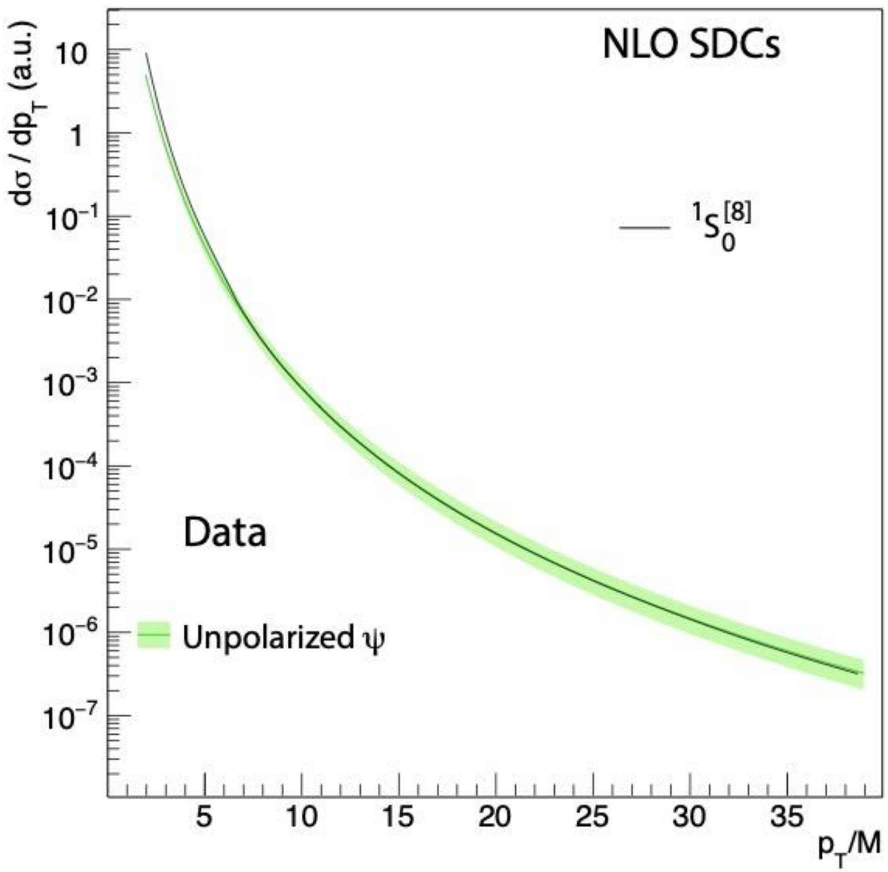
$^1S_0$ ⇨ J/ψ, ψ(2S)



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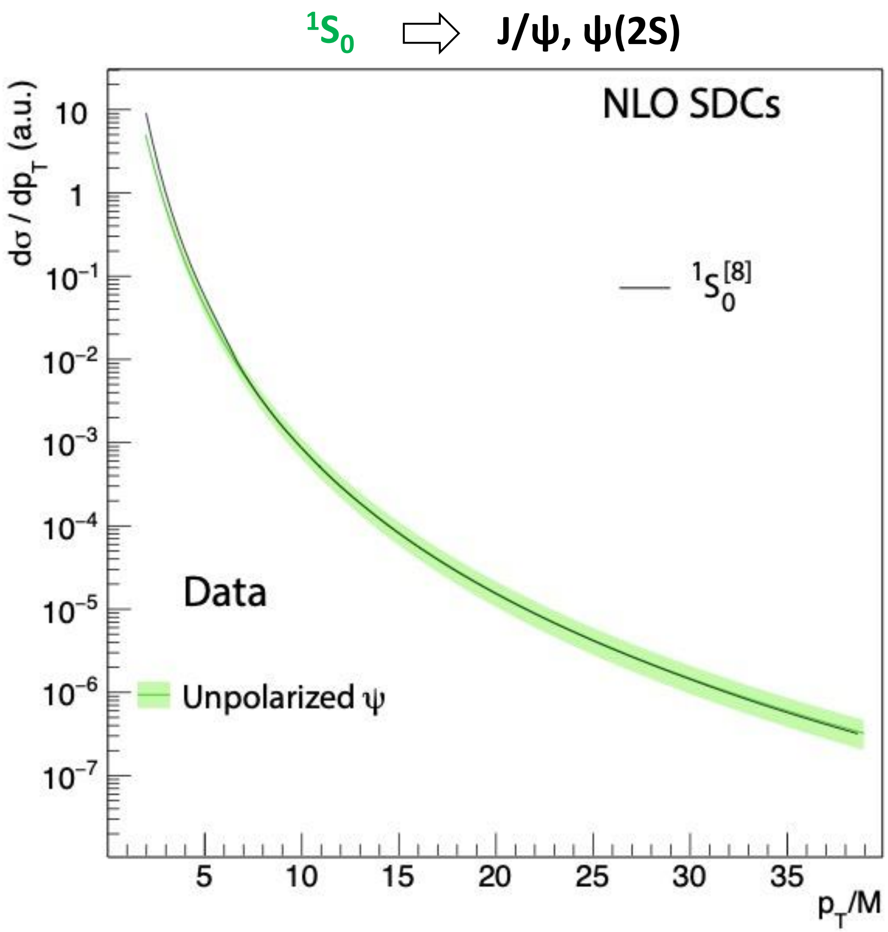

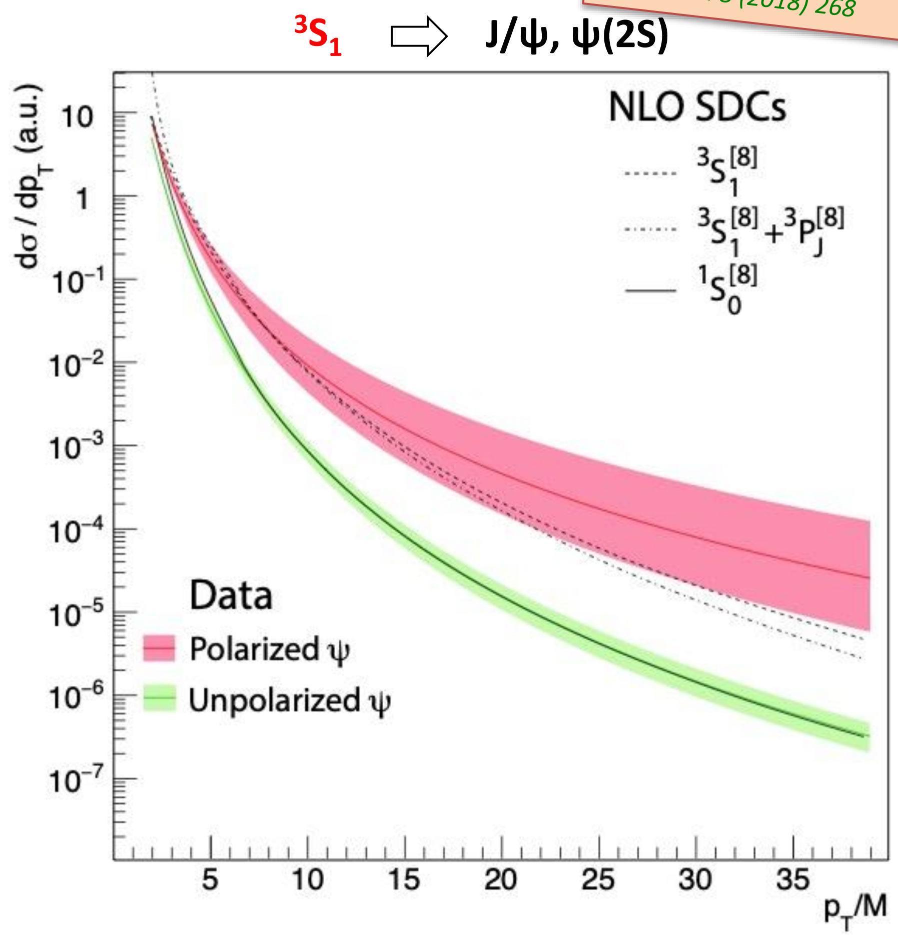

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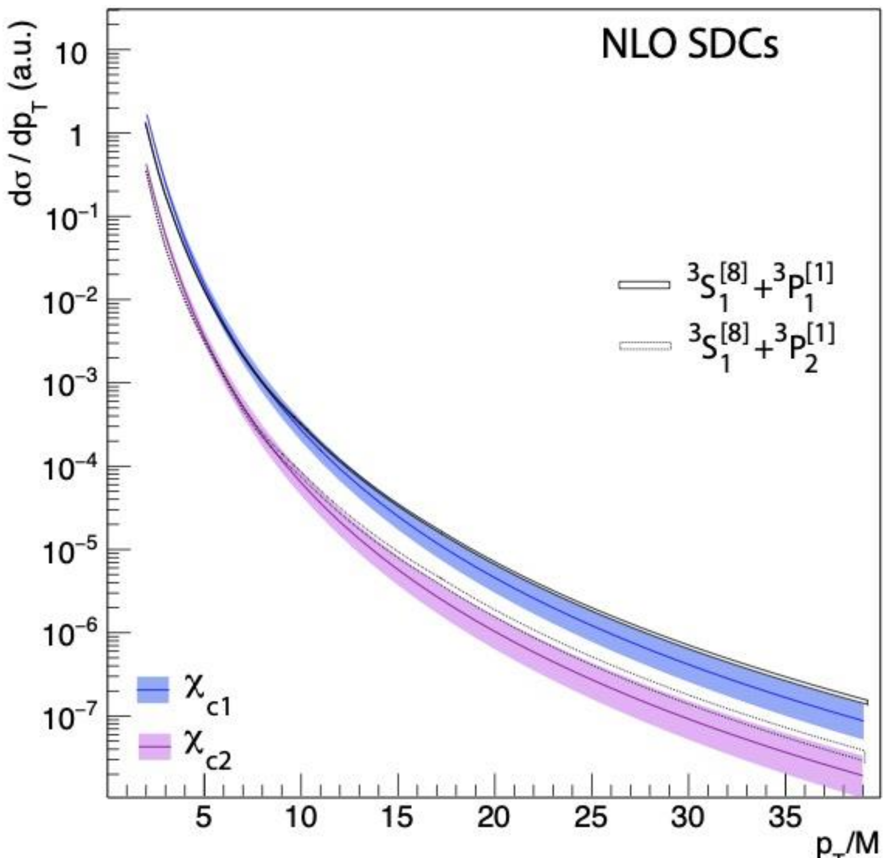
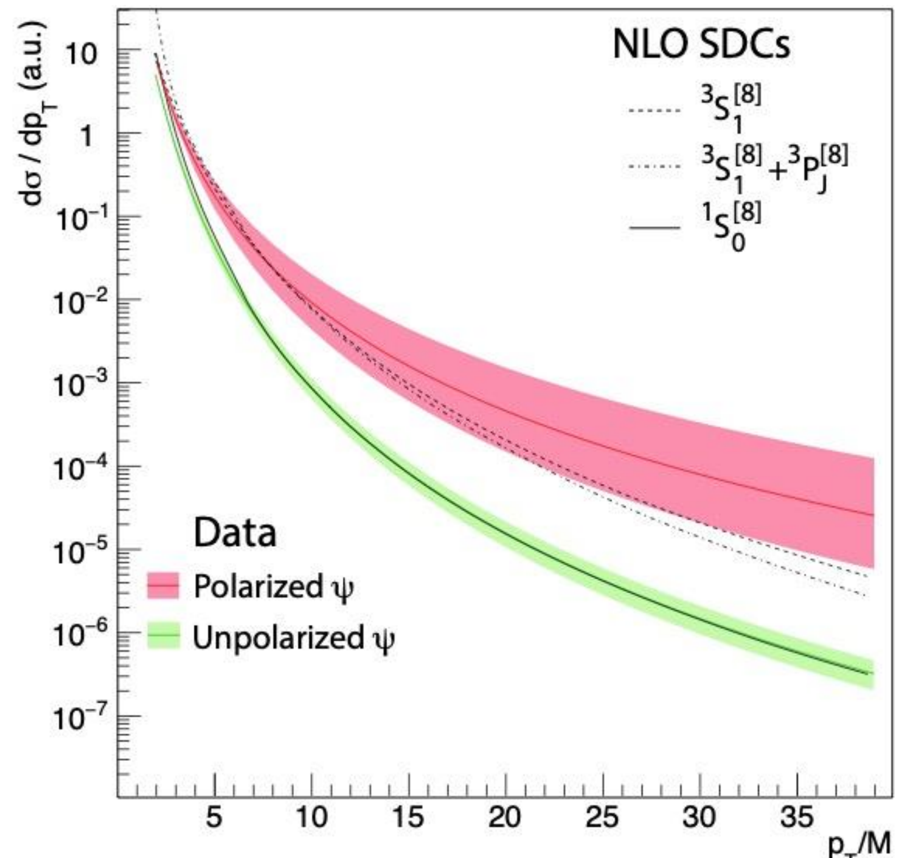
^3P_J $^3S_1$ ⇨ χ_{cJ}

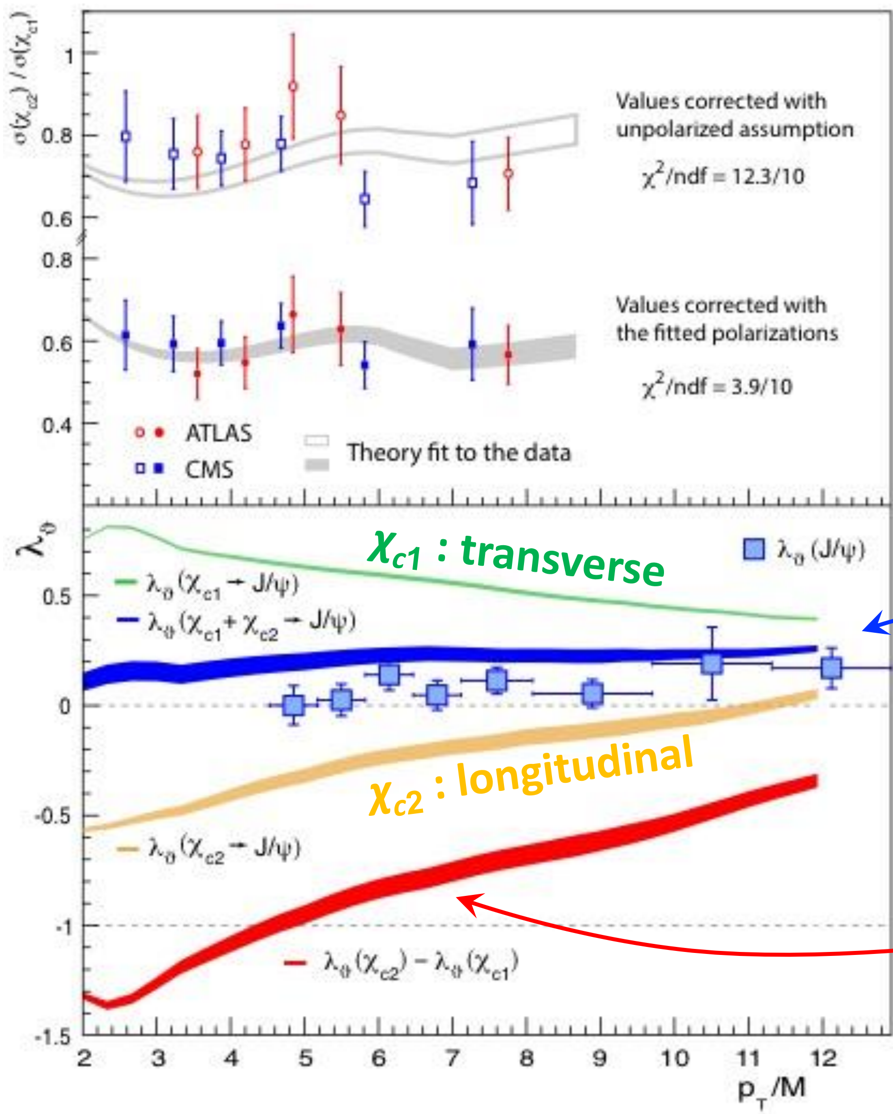


$^3S_1$ ⇨ J/ψ, ψ(2S)



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

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

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

CDF:

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

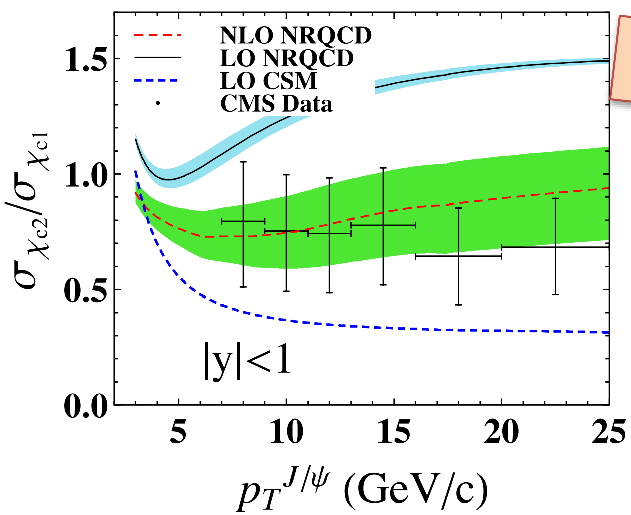
= no correlated variations considered

= uncertainty added in quadrature with all others

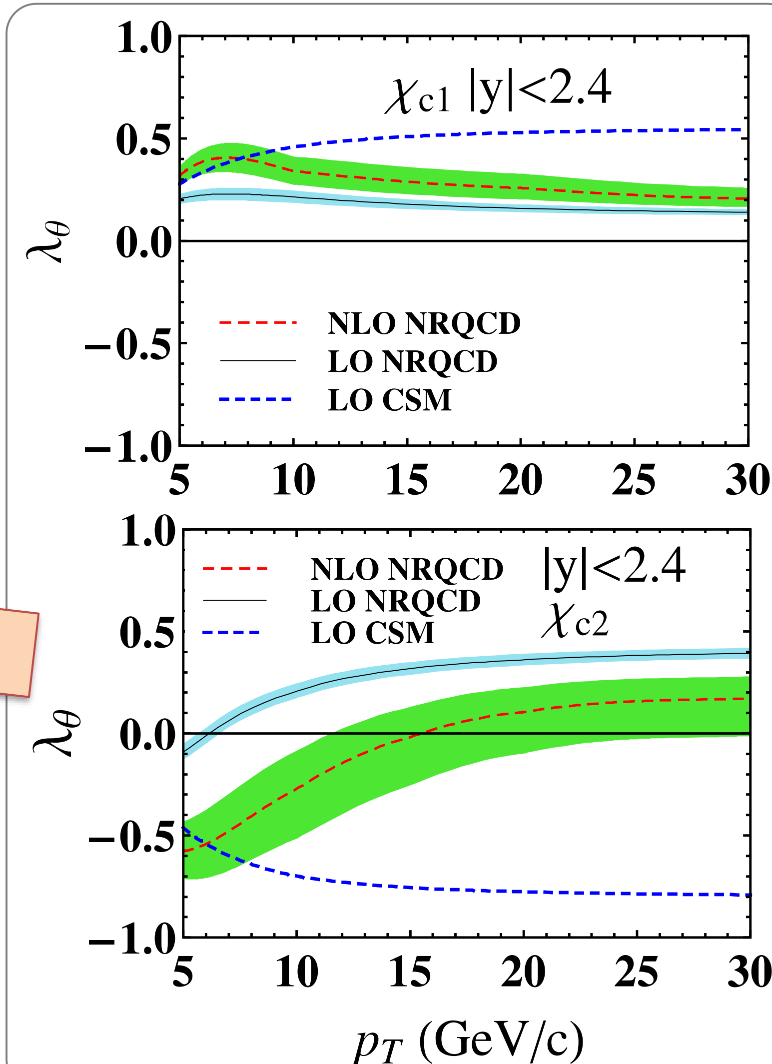
CMS:

= 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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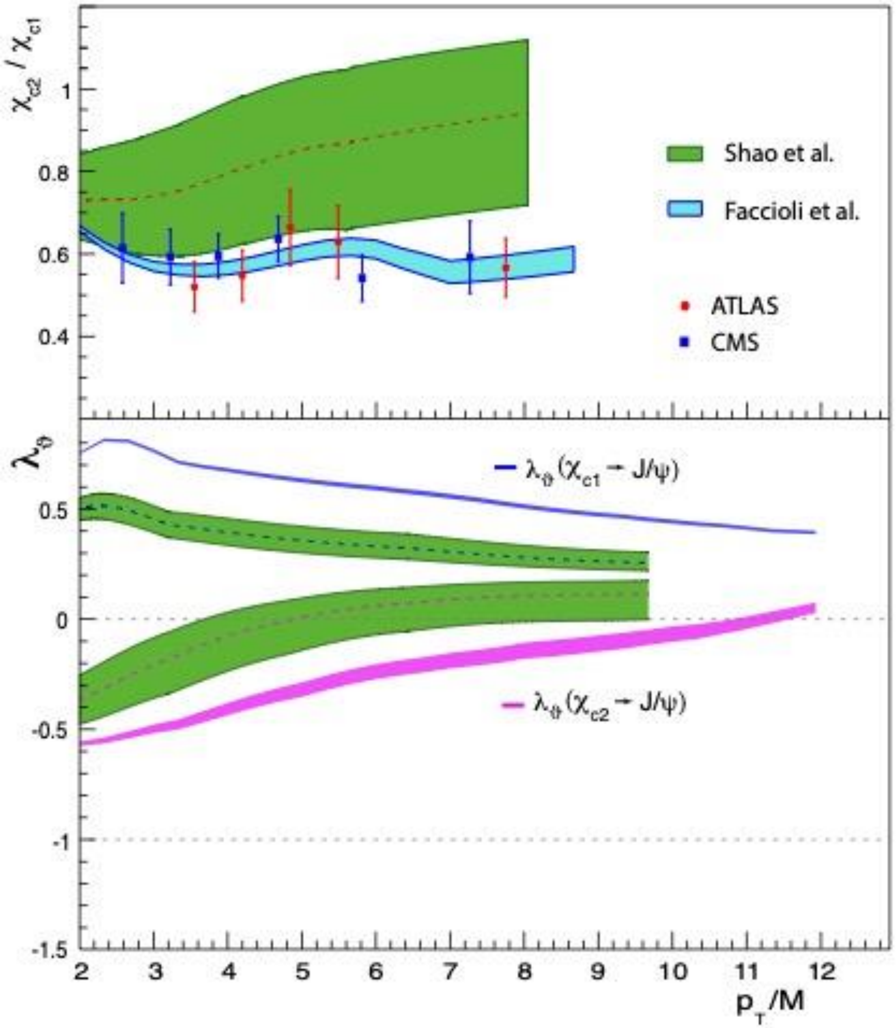

Same theory inputs but
different analyses *of the experimental data*
lead to very different determinations of *r*

Shao et al.,
PRL 112 (2014) 182003
***r* = 0.27 ± 0.06**

Faccioli et al.,
EPJC 78 (2018) 268
***r* = 0.217 ± 0.003**

Faccioli et al. use CMS + ATLAS data (averaged) with acceptance corrections corresponding to the *final* polarization prediction (*iterative* procedure) and, therefore, no added “polarization uncertainty”

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
   within the p_T region covered by the Run 1 CMS data

Work plan

- Determination of $\Delta\lambda_\vartheta(\chi_{c1,2})$: most urgent open question. Analysis is nearing its conclusion

- More analogous polarization measurements, with higher precision and extending over broader p_T ranges, using run 1 and 2 data

- Further phenomenological studies including y and $\sqrt{s}$ dependences: extend analysis with rapidity-dependent data from LHCb and investigate the role of gluon distribution functions on the observed scaling

Further reading

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