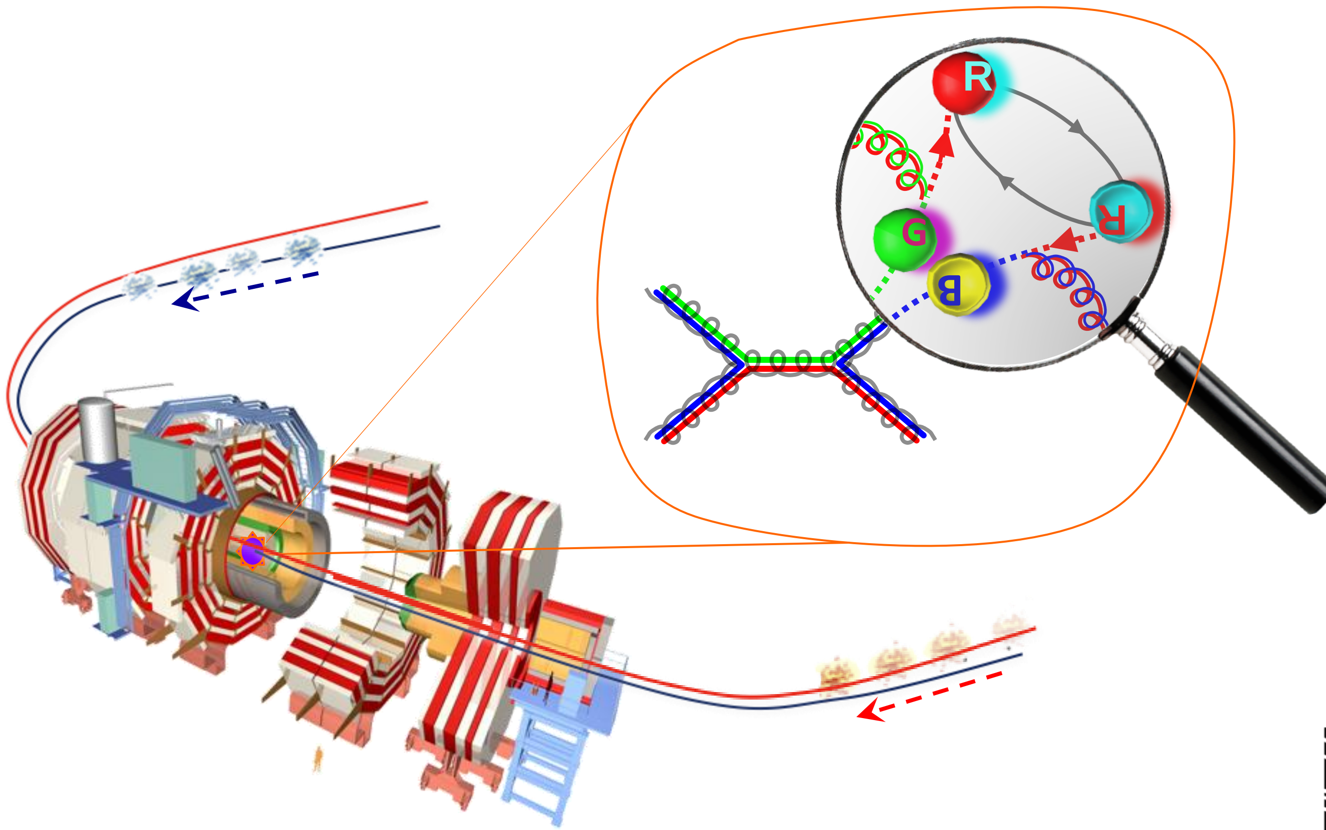
Towards the understanding of quarkonium production through global-fit analyses of LHC data



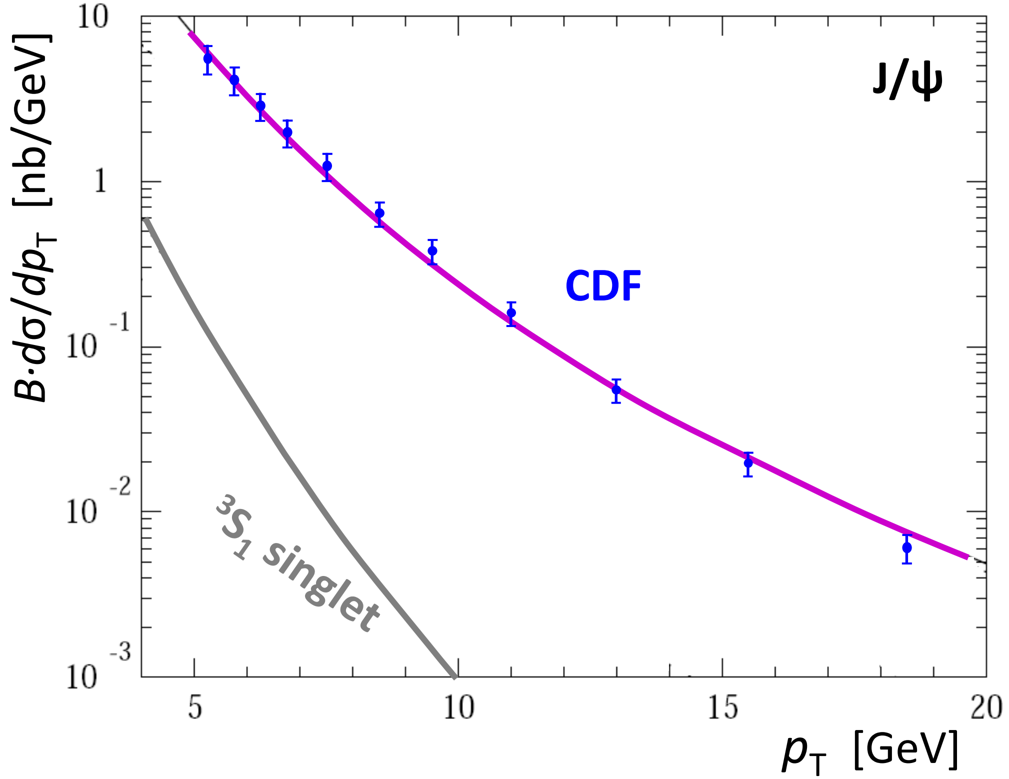
XXXII Int. Workshop on HEP
“Hot problems of Strong Interactions”
November 9-13, 2020

Mariana Araújo
with Pietro Faccioli and Carlos Lourenço

L I P

The “quarkonium polarization puzzle”

In the early 90’s, CDF measured J/ψ and ψ(2S) p_T -differential cross sections
50 times larger than expected in the color singlet model



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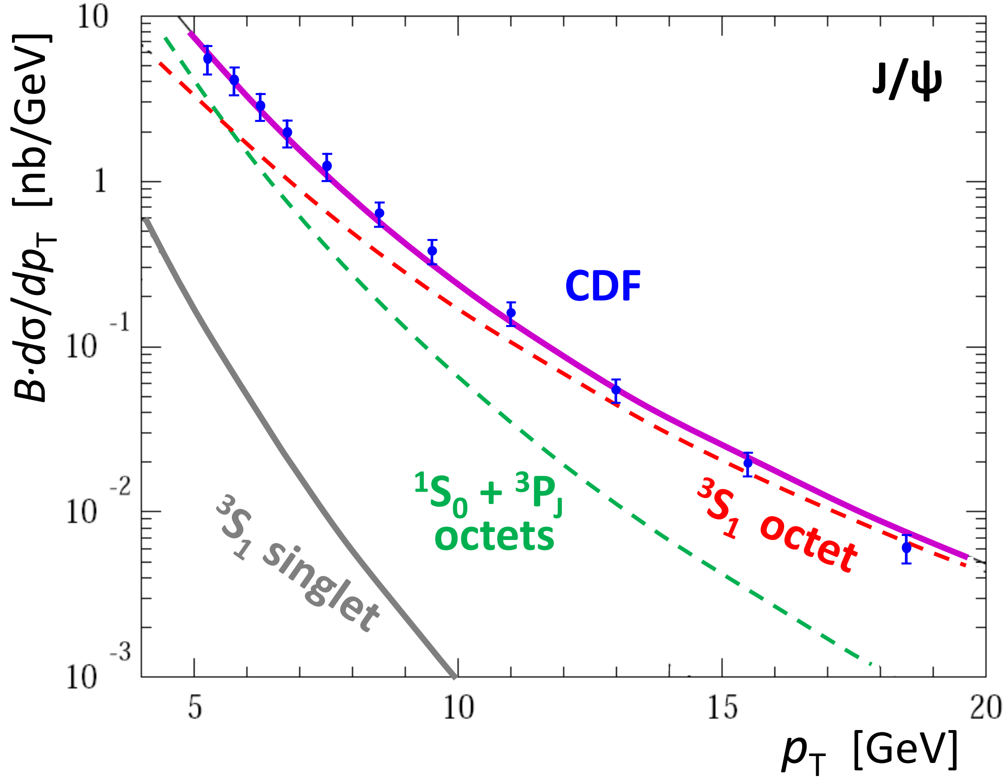

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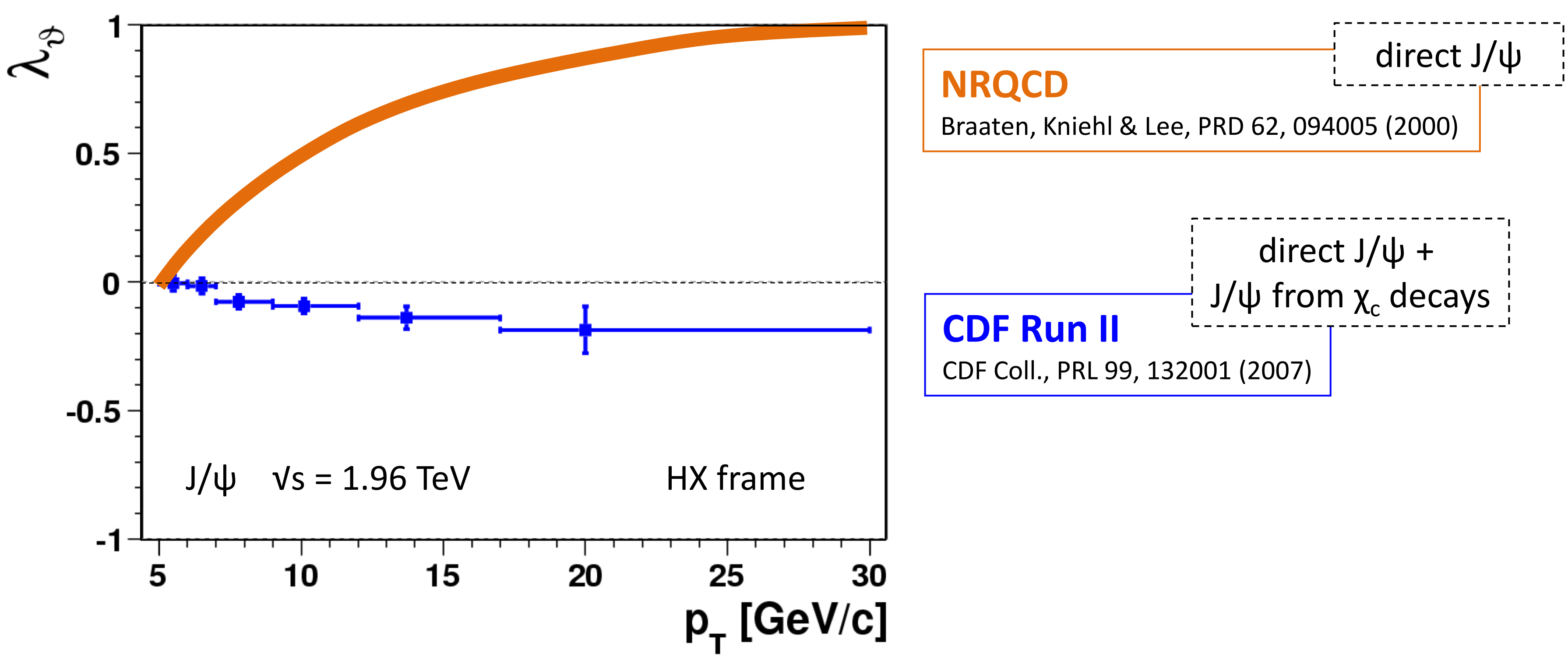

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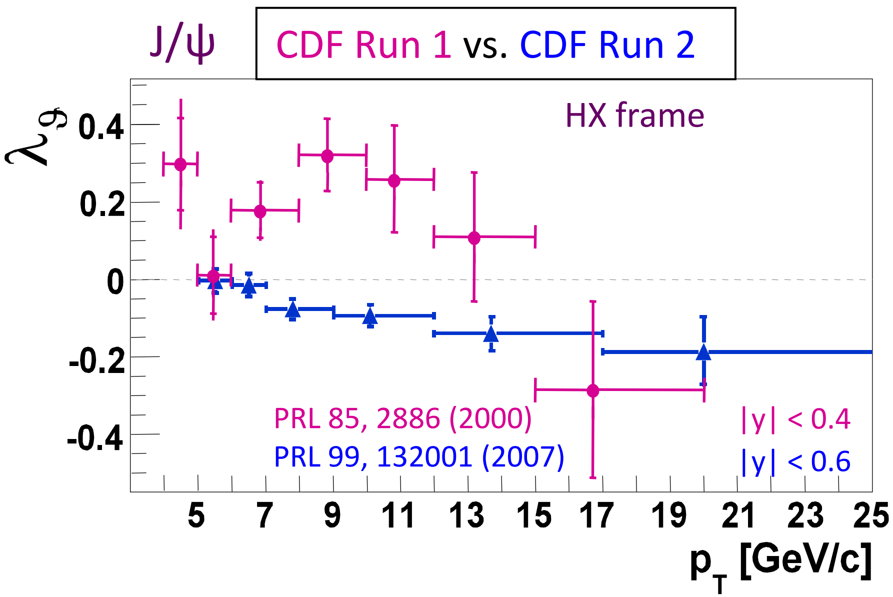
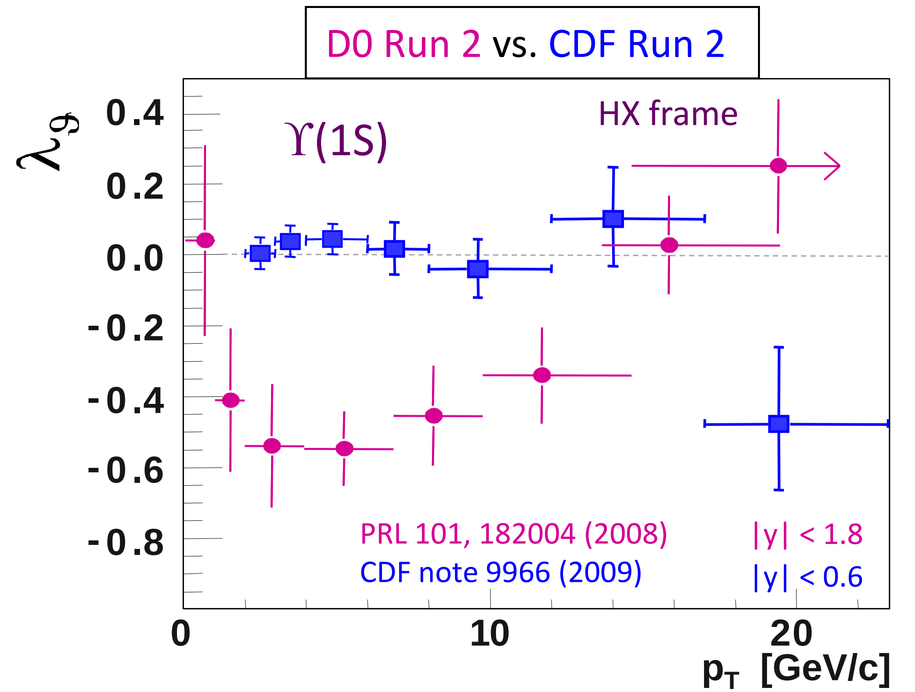
But the Tevatron results mutually excluded each other...

Improved data needed !!!





Improved measurements required better analysis methods and high-quality LHC data

PRL **102,** 151802 (2009) PHYSICAL REVIEW LETTERS week ending 17 APRIL 2009

J/ψ Polarization from Fixed-Target to Collider Energies

Pietro Faccioli,[1] Carlos Lourenço,[2] João Seixas,[1,3] and Hermine K. Wöhri[1]
[1]LIP, Lisbon, Portugal
[2]CERN, Geneva, Switzerland

PRL **105,** 061601 (2010) PHYSICAL REVIEW LETTERS

Rotation-Invariant Relations in Vector Meson Decays into Fermion Pairs

Pietro Faccioli,[1] Carlos Lourenço,[2] and João Seixas[1,3]
[1]LIP, 1000-149 Lisbon, Portugal
[2]CERN, 1211 Geneva, Switzerland

PHYSICAL REVIEW D **81,** 111502(R) (2010)

New approach to quarkonium polarization studies

Pietro Faccioli,[1] Carlos Lourenço,[2] and João Seixas[1,3]
[1]LIP, 1000-149 Lisbon, Portugal
[2]CERN, 1211 Geneva

PHYSICAL REVIEW D **82,** 096002 (2010)

Rotation-invariant observables in parity-violating decays of vector particles to fermion pairs

Pietro Faccioli,[1] Carlos Lourenço,[2] João Seixas,[1,3] and Hermine K. Wöhri[1]
[1]Laboratório de Instrumentação e Física Experimental de Partículas (LIP), 1000-149 Lisbon, Portugal
[2]European Organization for Nuclear Research (CERN), 1211 Geneva, Switzerland
[3]Physics Department, Instituto Superior Técnico (IST), 1049-001 Lisbon, Portugal
published 4 November 2010)

PHYSICAL REVIEW D **83,** 056008 (2011)

Model-independent constraints on the shape parameters of dilepton angular distributions

Pietro Faccioli,[1] Carlos Lourenço,[2] João Seixas,[1,3] and Hermine K. Wöhri[1,2]
[1]Laboratório de Instrumentação e Física Experimental de Partículas (LIP), 1000-149 Lisbon, Portugal
[2]European Organization for Nuclear Research (CERN), 1211 Geneva 23, Switzerland
[3]Physics Department, Instituto Superior Técnico (IST)
(Received 13 January 2011

Eur. Phys. J. C (2010) 69: 657–673
DOI 10.1140/epjc/s10052-010-1420-5

Special Article - Tools for Experiment and Theory

Towards the experimental clarification of quarkonium polarization

Pietro Faccioli[1], Carlos Lourenço[2,a], João Seixas[1,3], Hermine K. Wöhri[1]
[1]Laboratório de Instrumentação e Física Experimental de Partículas (LIP), Lisbon, Portugal
[2]CERN, Geneva, Switzerland
[3]Physics Department, Instituto Superior Técnico (IST), Lisbon, Portugal

Physics Letters B 727 (2013) 381–402

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

Measurement of the prompt J/ψ and $\psi(2S)$ polarizations in pp collisions at $\sqrt{s} = 7$ TeV

CMS Collaboration *

CERN, Switzerland

PRL **110,** 081802 (2013) PHYSICAL REVIEW LETTERS week ending 22 FEBRUARY 2013

Measurement of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ Polarizations in pp Collisions at $\sqrt{s} = 7$ TeV

S. Chatrchyan *et al.**
(CMS Collaboration)
published 20 February 2013)

PHYSICAL REVIEW LETTERS **124,** 162002 (2020)

Constraints on the χ_{c1} versus χ_{c2} Polarizations in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV

A. M. Sirunyan *et al.**
(CMS Collaboration)

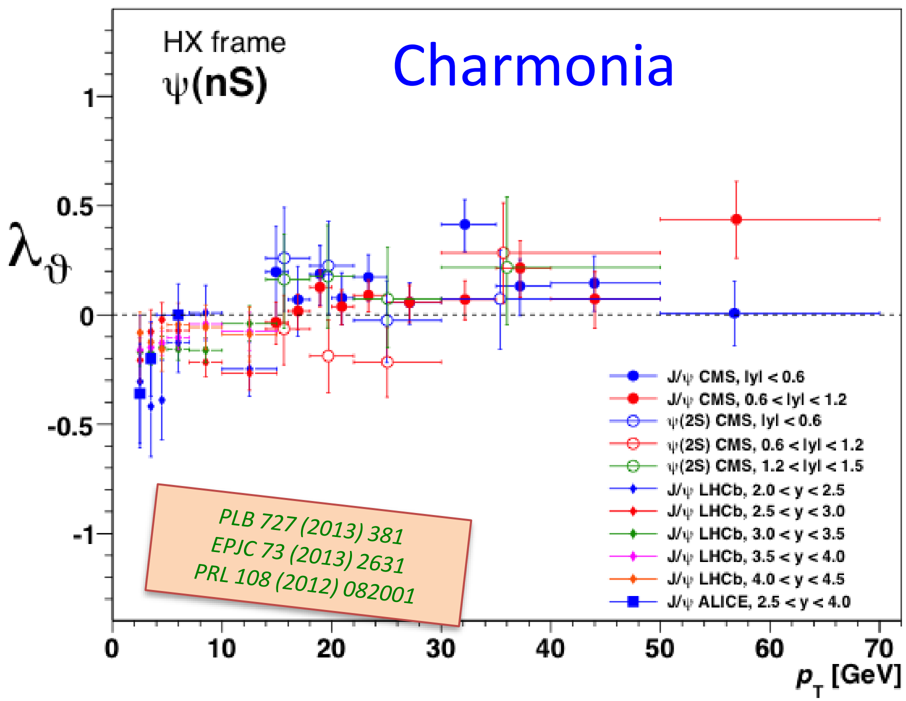
(Received 16 December 2019; revised manuscript received 25 January 2020; accepted 26 March 2020; published 24 April 2020)

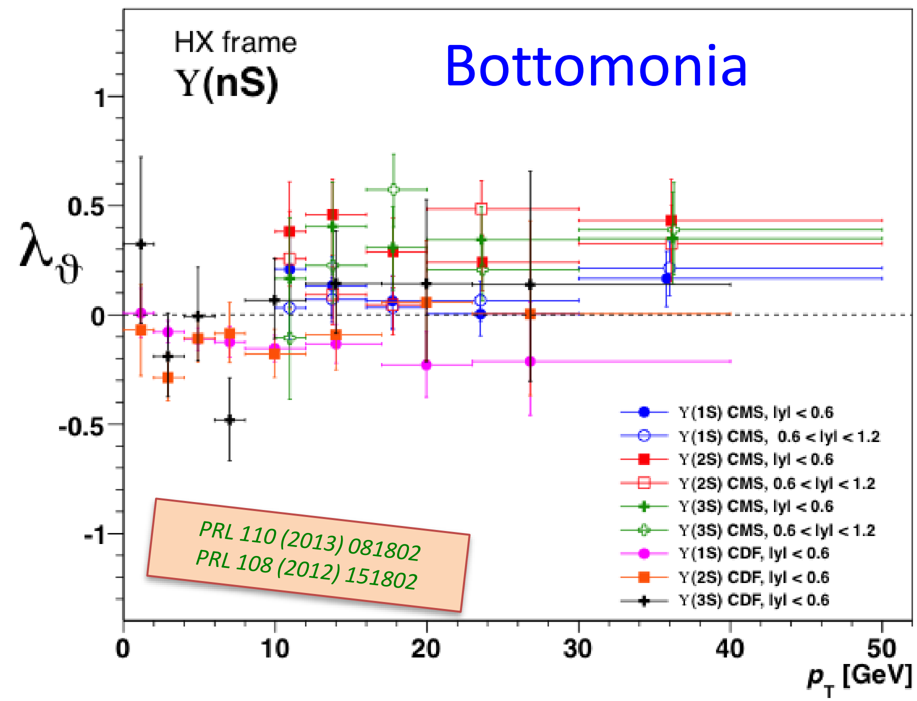
The polarizations of promptly produced χ_{c1} and χ_{c2} mesons are studied using data collected by the CMS experiment at the LHC, in proton-proton collisions at $\sqrt{s} = 8$ TeV. The χ_c states are reconstructed via their radiative decays $\chi_c \to J/\psi\gamma$, with the photons being measured through conversions to e^+e^-, which allows the two states to be well resolved. The polarizations are measured in the helicity frame, through the analysis of the χ_{c2} to χ_{c1} yield ratio as a function of the polar or azimuthal angle of the positive muon emitted in the $J/\psi \to \mu^+\mu^-$ decay, in three bins of J/ψ transverse momentum. While no differences are seen between the two states in terms of azimuthal decay angle distributions, they are observed to have significantly different polar anisotropies. The measurement favors a scenario where at least one of the two states is strongly polarized along the helicity quantization axis, in agreement with nonrelativistic quantum chromodynamics predictions. This is the first measurement of significantly polarized quarkonia produced at high transverse momentum.

DOI: 10.1103/PhysRevLett.124.162002

Polarization measurements at the LHC

Strong charmonium and bottomonium polarizations definitely excluded, up to the highest probed p_T values

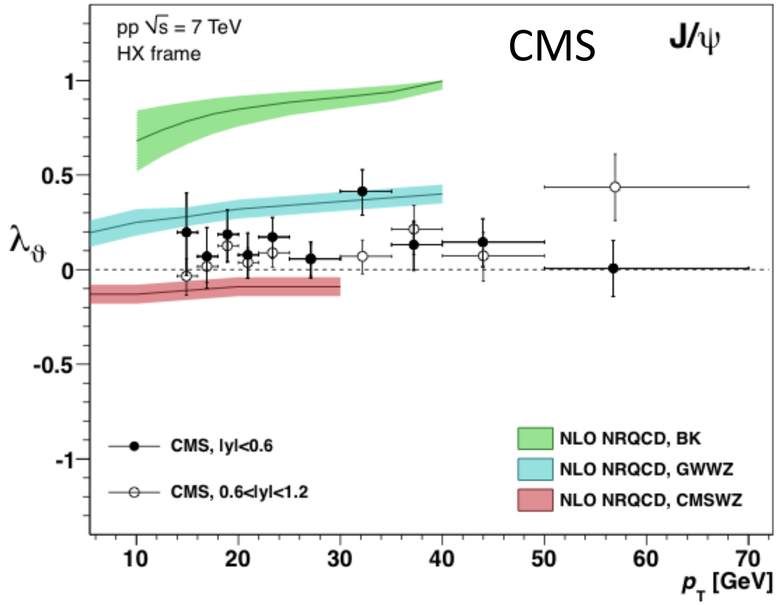


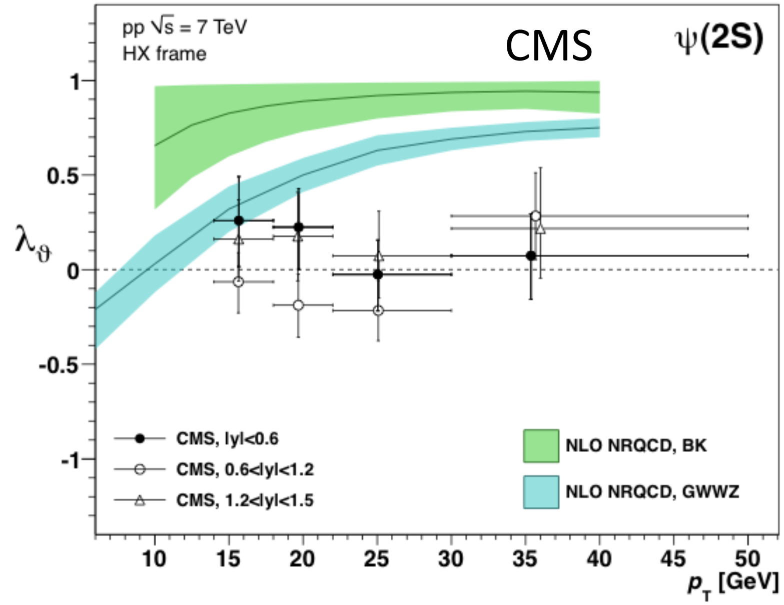


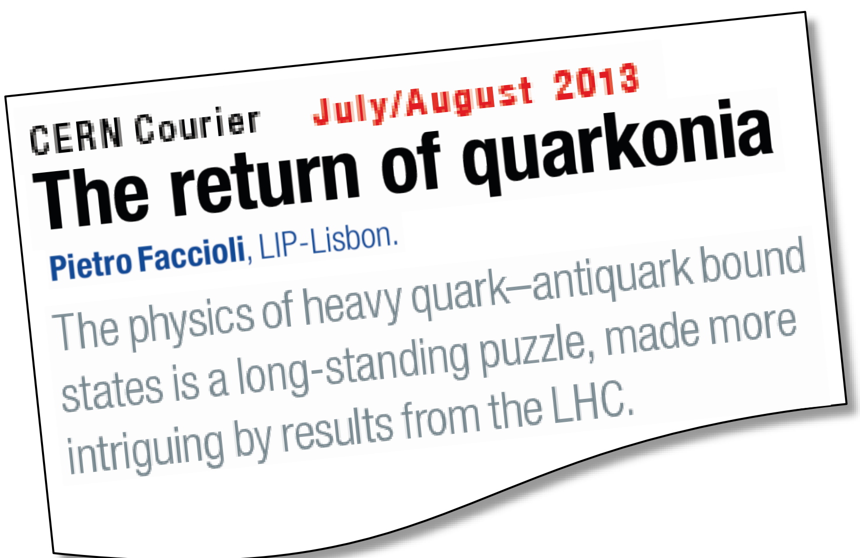
→ Also CDF used the improved methods to report a new measurement of Υ(nS) polarizations, consistent with the LHC results

→ the *polarization puzzle* became even more puzzling with the new (and more precise) experimental data

The even more puzzling polarization puzzle



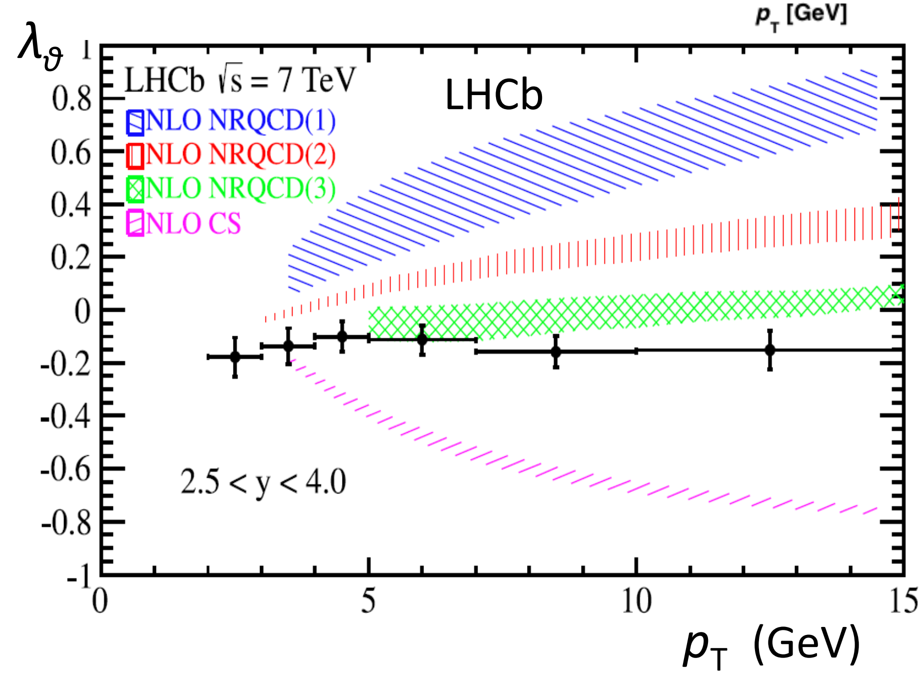



CERN Courier July/August 2013

The return of quarkonia

Pietro Faccioli, LIP-Lisbon.

The physics of heavy quark–antiquark bound states is a long-standing puzzle, made more intriguing by results from the LHC.



Towards the solution of the polarization puzzle

To solve the quarkonium polarization puzzle we must start by understanding that

1) the prediction of "strong transverse polarization" is not a "first principles" result of NRQCD but rather the outcome of fits of experimental measurements of quarkonium production cross sections

2) those fits were not correctly made and, hence, gave rise to biased results

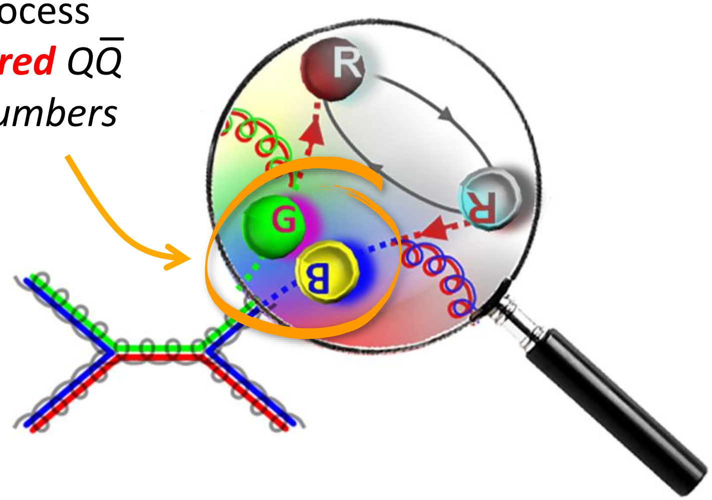
Quarkonium production in the NRQCD approach

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*

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



$$\mathcal{S}\{A + B \to (Q\bar{Q})_C[^{2S+1}L_J] + X\}$$

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

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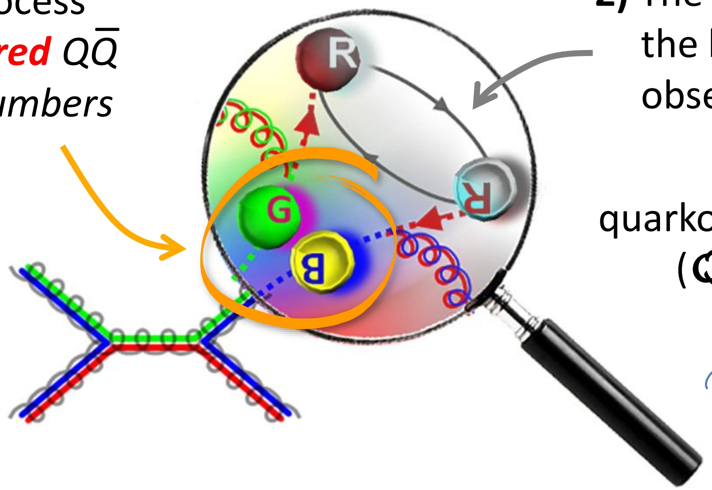

2) The *quantum numbers change* in the **long-distance** evolution to the observed (neutral) bound state

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} [$^3P_2$]

$$\underbrace{\mathcal{S}\{A + B \rightarrow (Q\bar{Q})_C[^{2S+1}L_J] + X\}}_{} \cdot \underbrace{\mathcal{L}\{(Q\bar{Q})_C[^{2S+1}L_J] \rightarrow \mathcal{Q}\}}_{}$$

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

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

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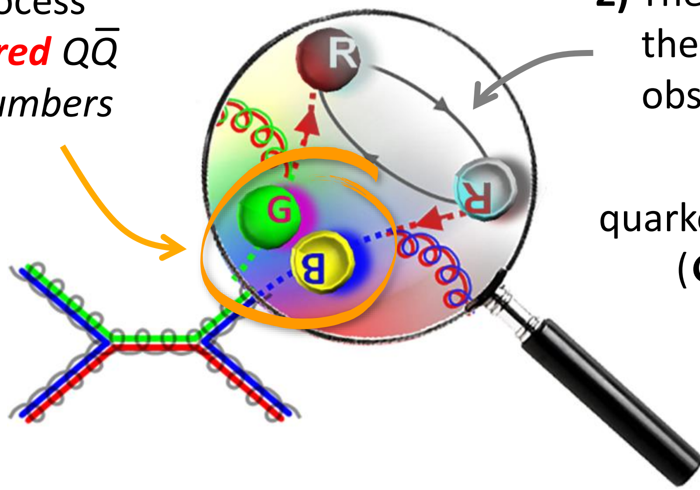

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χ_{c1} , χ_{b1} $[^3P_1]$ χ_{c2} , χ_{b2} $[^3P_2]$

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

$Q\bar{Q}$ **angular momentum** and **colour** configuration

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

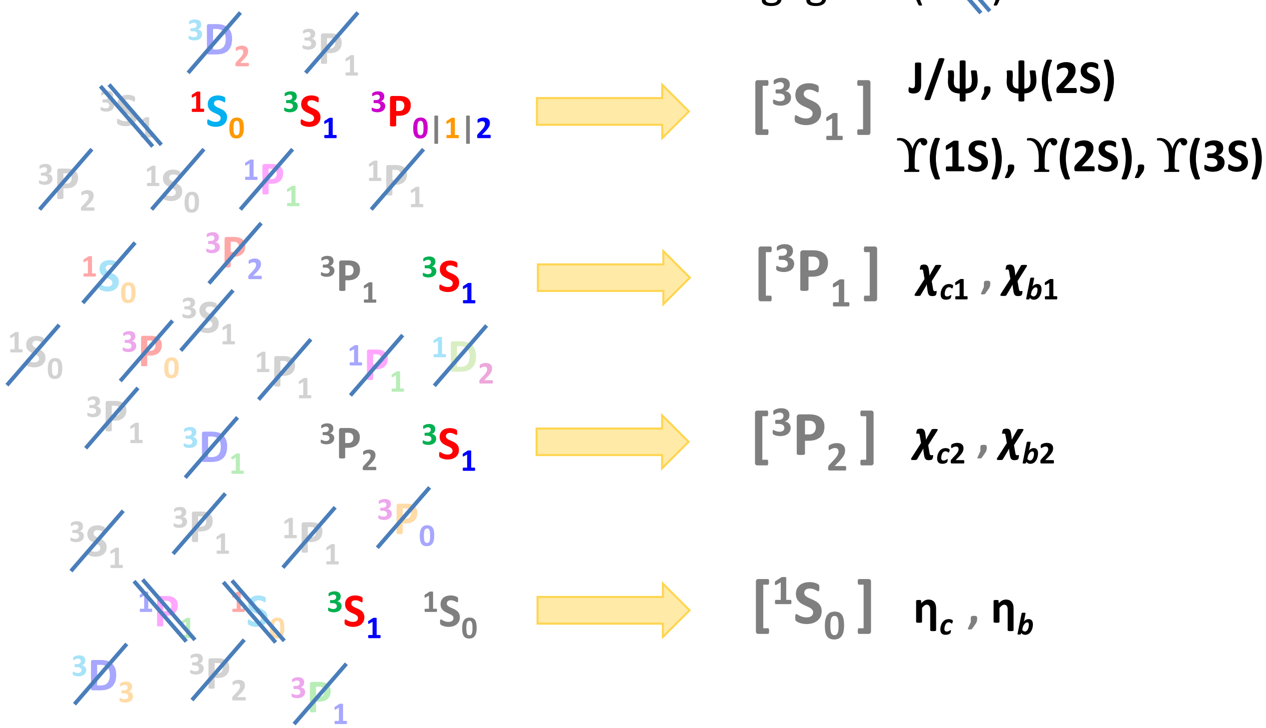
2) *long-distance matrix elements* (**LDMEs**): constant, **fitted from data**

NRQCD hierarchies

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

1) Small quark velocities v^2 in the bound state → "***v*-scaling**" rules for LDMEs (/)

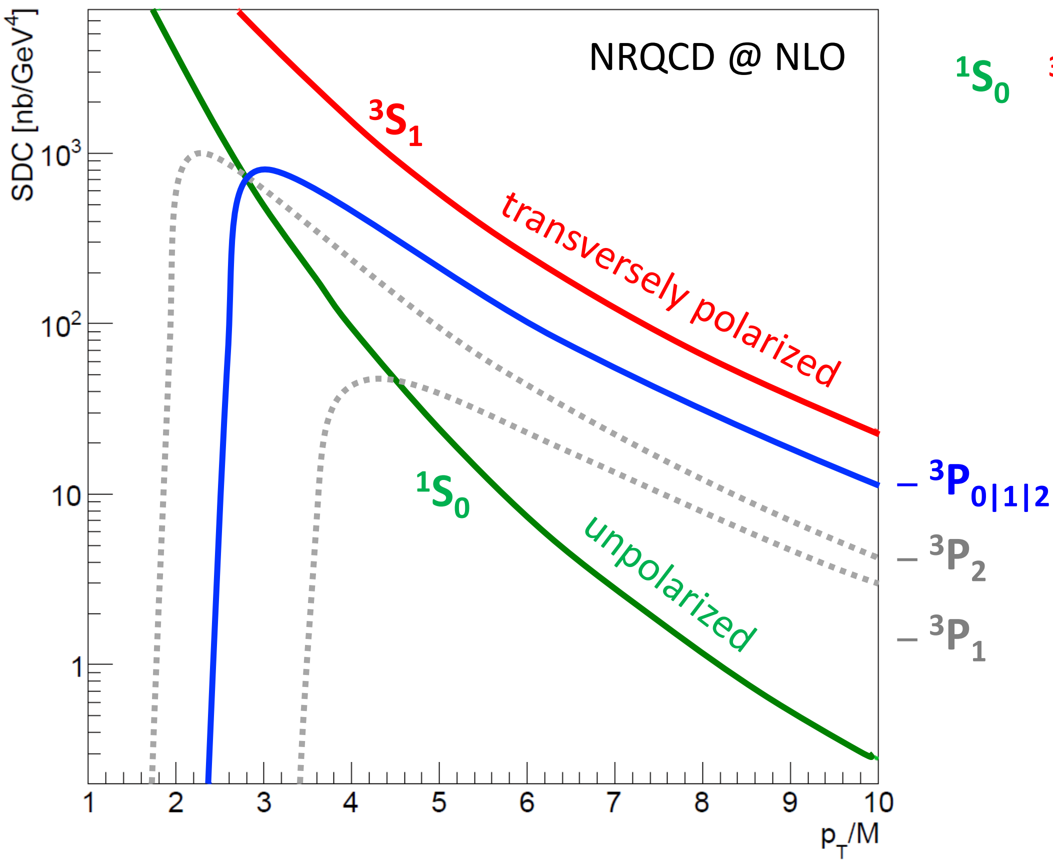
2) **Perturbative calculations** → some SDCs are negligible (\\ )



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

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

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, require proper cancellations to recover physical result

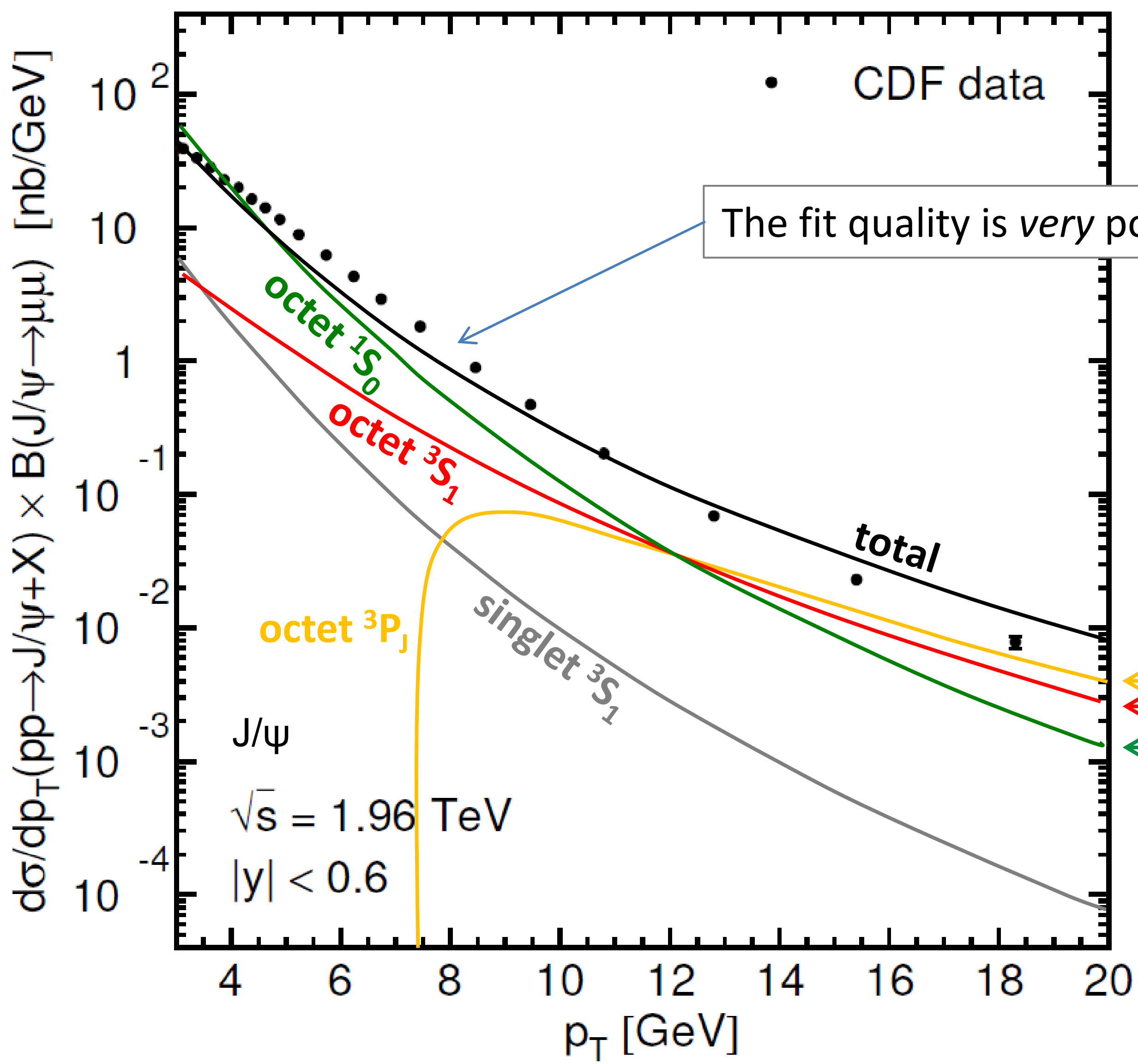
In NRQCD, one expects a mixture of different pre-resonance contributions, with rather **diversified** kinematics and characteristic polarizations
→ by fitting the measured p_T distributions, one determines the LDMEs of each term and consequently predict the polarizations

… a very delicate procedure !

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

A pedagogical look at past fits

An example of a fit that leads to the prediction of transverse polarization at high p_T



The free parameters of the fit are the normalizations (LDMEs) of the $^1S_0$, $^3S_1$ and ^3P_J colour-octet terms

The fit starts at p_T = 3 GeV
SDC functions at NLO by
M. Butenschön and B. Kniehl

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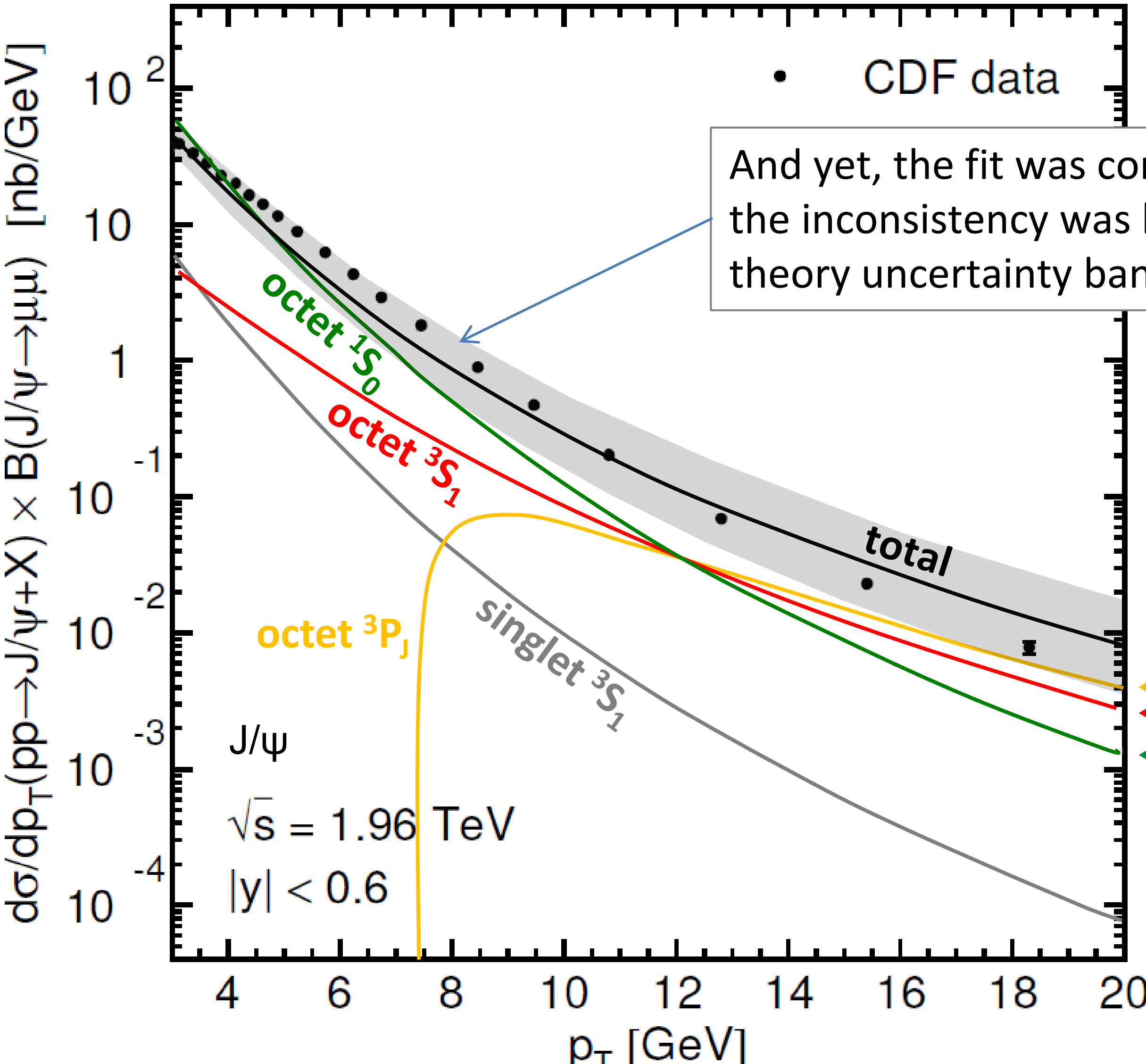

And yet, the fit was considered as very good : the inconsistency was hidden by the *a posteriori* theory uncertainty band (from scale variations)

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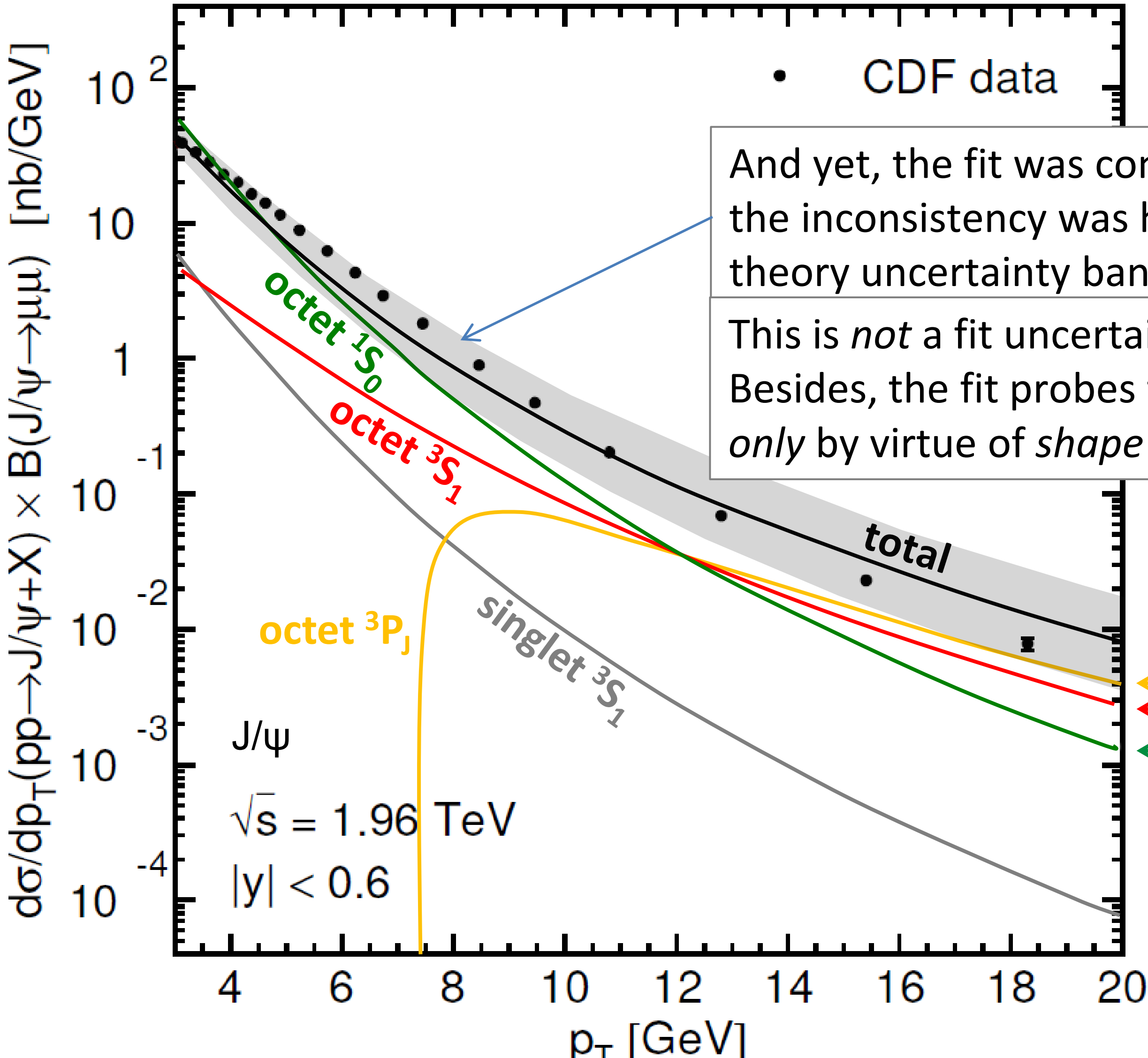

And yet, the fit was considered as very good : the inconsistency was hidden by the *a posteriori* theory uncertainty band (from scale variations)

This is *not* a fit uncertainty band ! Besides, the fit probes the subprocess composition *only* by virtue of *shape* differences

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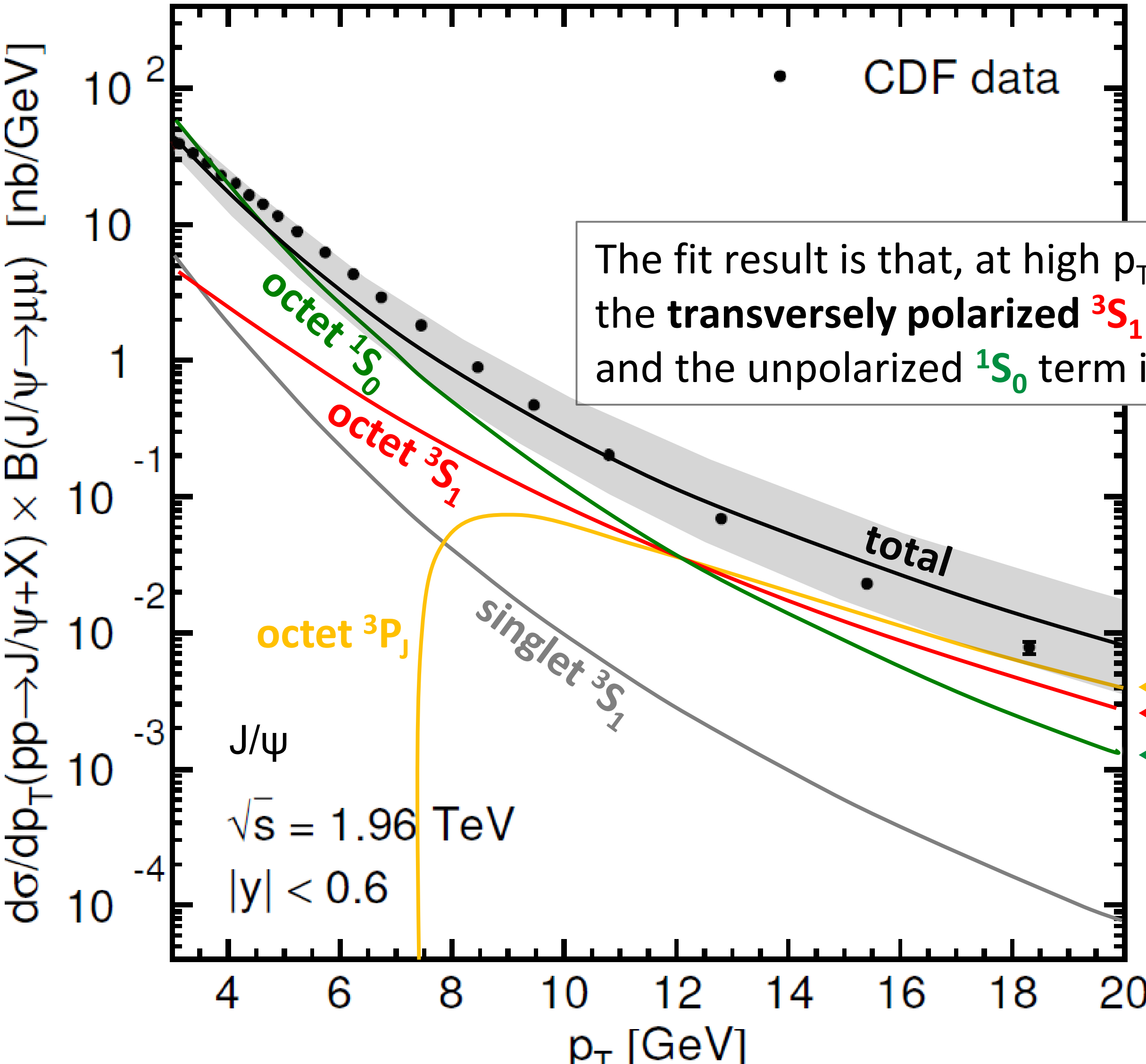


What does this imply for the polarization ?

The fit result is that, at high p_T, the **transversely polarized $^3S_1$ and ^3P_J octet** terms **dominate**, and the unpolarized $^1S_0$ term is only a "correction"

The free parameters of the fit are the normalizations (LDMEs) of the $^1S_0$, $^3S_1$ and ^3P_J colour-octet terms

The fit starts at p_T = 3 GeV
SDC functions at NLO by M. Butenschön and B. Kniehl

A detour through the polarization dimension

Quarkonium polarization is characterized by λ_θ :

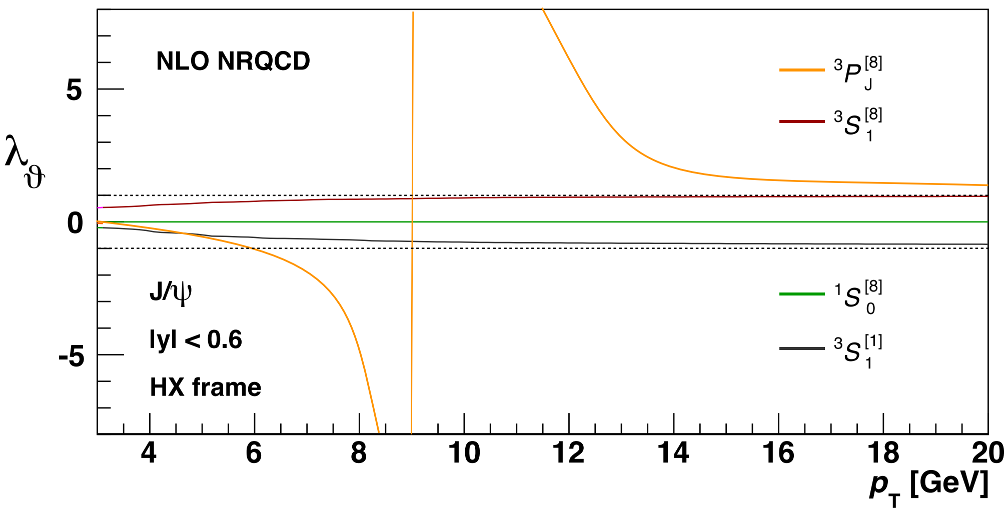
- *measured* as the polar anisotropy of the decay dilepton angular distribution
- *calculated* from the transverse and longitudinal cross sections: $(\sigma_T - \sigma_L) / (\sigma_T + \sigma_L)$

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"
$^3P_J \rightarrow \lambda_\vartheta >> +1$ for $p_T > 9$ GeV at NLO
$^3P_J \rightarrow \lambda_\vartheta < -1$ for $6 < p_T < 9$ GeV at NLO; and it is 0 at LO...
$^3S_1 \rightarrow \lambda_\vartheta \approx -0.9$ at NLO and high p_T ; it is ≈ +1 at LO (has a small impact)

Dominance of the $^3S_1$ and ^3P_J octets
$\rightarrow \lambda_\vartheta \approx +1$ for high-p_T S-wave quarkonia

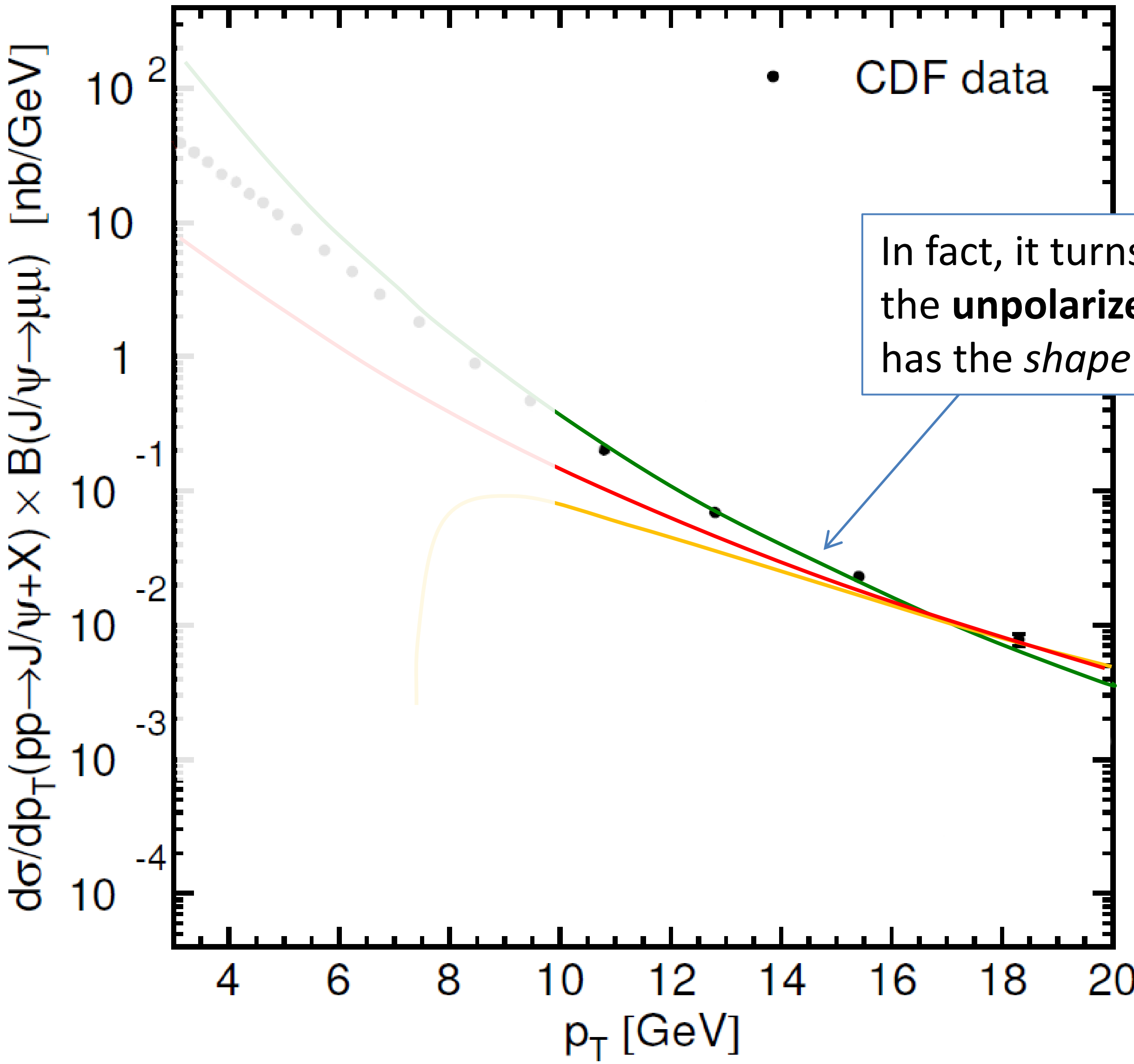
$\rightarrow$ NRQCD "predicts"
transverse polarization at high p_T



Note: the ^3P_J octet has *negative* cross sections... and λ_ϑ in the twilight zone

The solution of the quarkonium polarization puzzle

Let's look at the high-p_T behaviours, by normalizing the curves to the data for $p_T/M > 3$

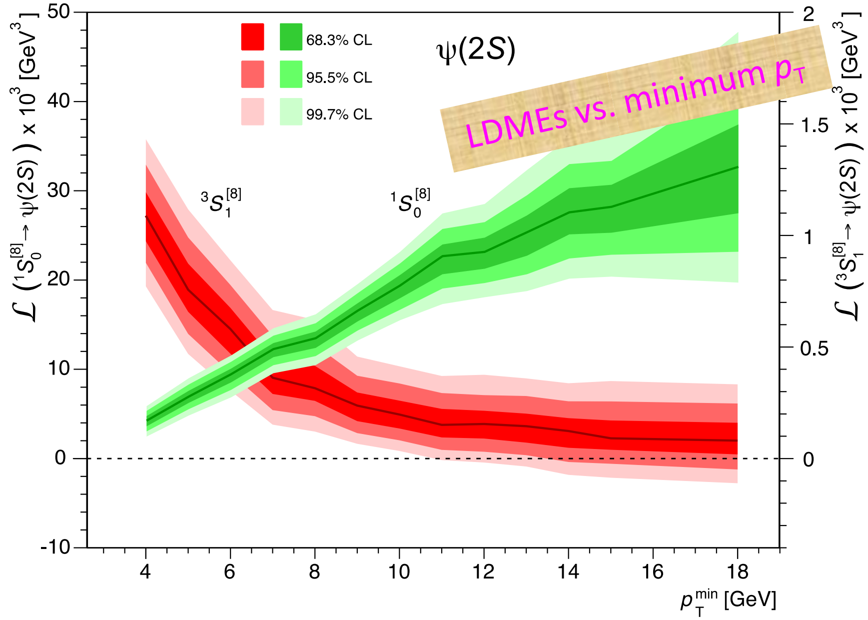


In fact, it turns out that, for p_T > 9 GeV, the **unpolarized $^1S_0$ octet** is the term that has the *shape* most similar to the data

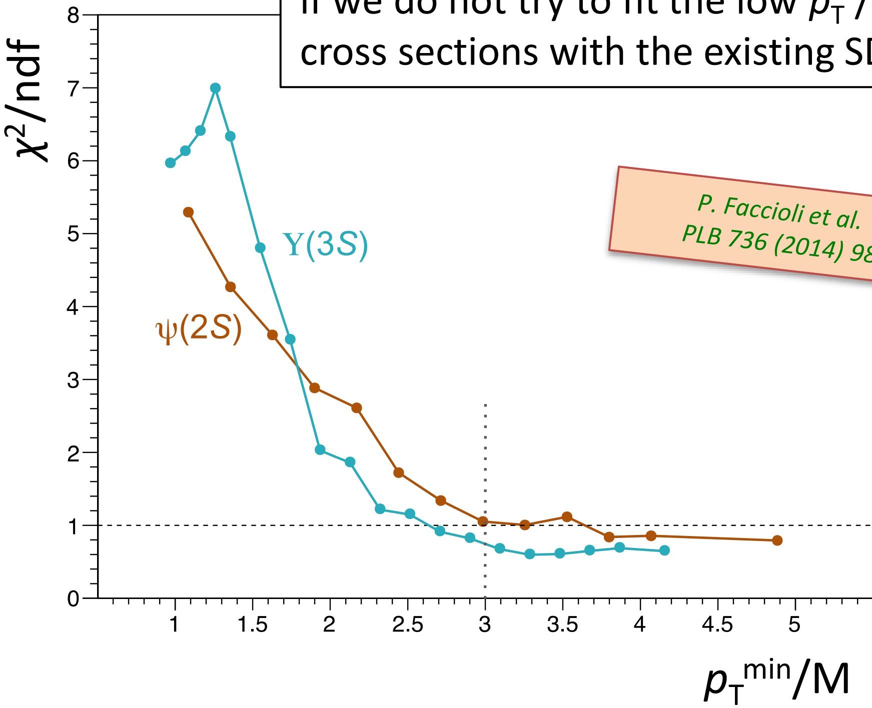
The solution of the quarkonium polarization puzzle

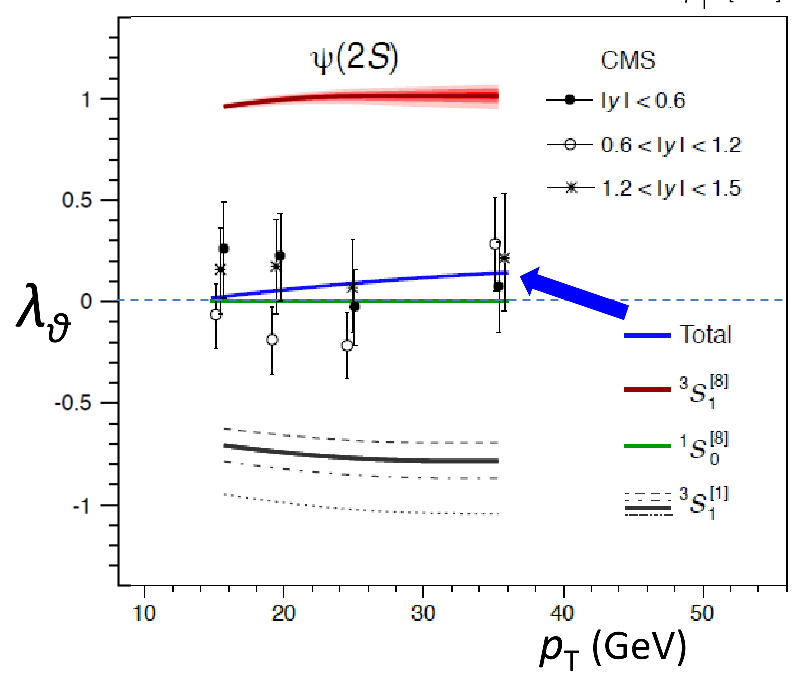
The cross sections and polarizations *can* be simultaneously and consistently described

For $p_T\,/M > 3$ the fit results are stable : the polarization *and* cross section data imply $^{1}\mathbf{S}_0^{[8]}$ octet dominance



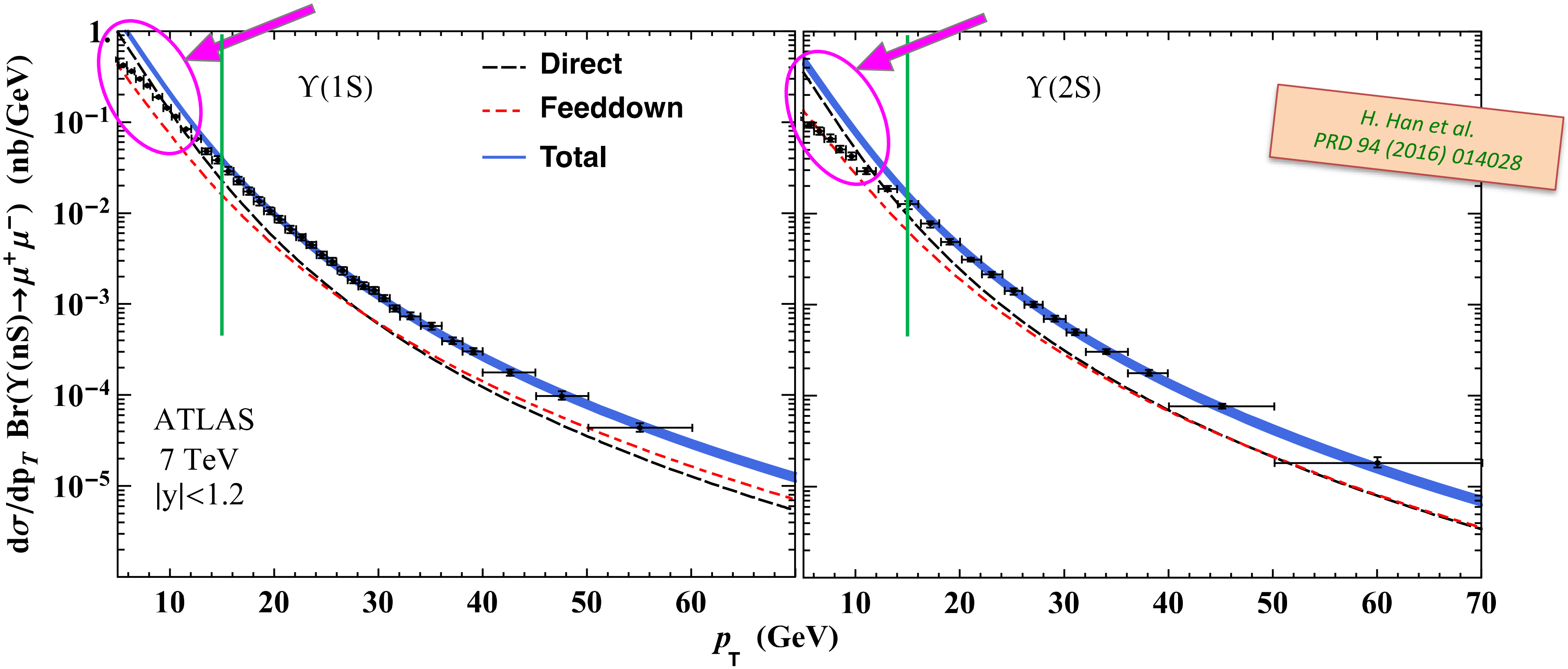
The fit quality improves dramatically if we do not try to fit the low $p_T\,/M$ cross sections with the existing SDCs





The low-p_T SDC problem

The SDCs used in most theory-driven analyses of the data are not valid in the low p_T region. Fitting data with a wrong fit model necessarily leads to wrong fit results, such as "the quarkonium polarization puzzle".



Conclusion:
the transverse polarization expectation is not a "first principles NRQCD prediction" but rather the result of fits biased by the inclusion of too-low p_T data

A model-independent global charmonium fit (1)

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

Accounting for the momentum and polarization transfer from the mother to the daughter particles in the relevant feed-down decays:

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

P. Faccioli et al.
EPJC 78 (2018) 268

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, without 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*

A model-independent global charmonium fit (2)

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

$$\sigma_{\mathrm{dir}} \propto \left[(1 - f_p)\, g_u + f_p\, g_p \right]$$

f_p: fractional contribution of the polarized process

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

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

f_p, g_u and g_p are **identical for the two S-wave states**

The unpolarized and polarized cross sections share 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} cross sections (and their feed-down contributions to the J/ψ) are parametrized independently from the (direct) ψ terms, without separating polarized and unpolarized contributions (this study was made before any χ_c polarization measurements)

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 observables

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

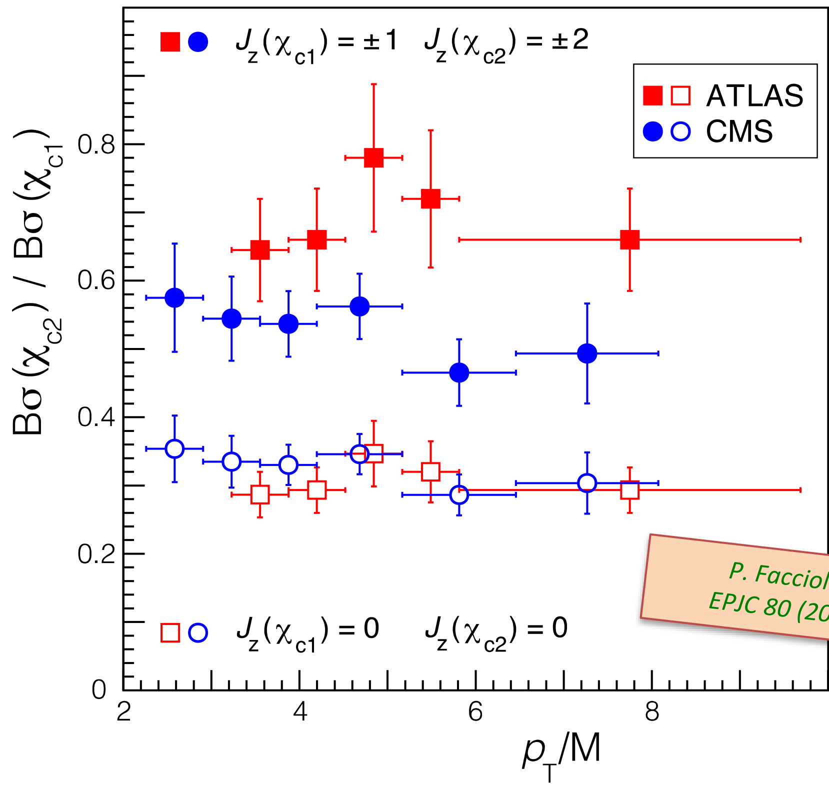
For each set of parameter values considered while running the fit, the expected values of the polarizations and cross sections are calculated, for all states, as functions of p_T ;
the values obtained in this way for λ_θ can be immediately compared to the measured ones.

For the cross section, we first scale the measured cross sections by acceptance-correction factors calculated for the λ_θ value under consideration;
these corrections are computed using the tables published by the experiments for the cross sections of particles produced with fully transverse or fully longitudinal polarization.

Assumed polarizations affect measured cross sections

The χ_{c2} to χ_{c1} cross section ratio measured by several experiments provides a good example of the crucial importance of the polarization scenario assumed in the evaluation of the acceptance corrections.

Very different patterns and levels of agreement among data sets are seen for acceptance corrections reflecting two polarization hypotheses: spin alignments $J_z(\chi_{c1}) = \pm1$, $J_z(\chi_{c2}) = \pm2$ and $J_z(\chi_{c1}) = J_z(\chi_{c2}) = 0$. The "default" unpolarized hypothesis leads to intermediate values.



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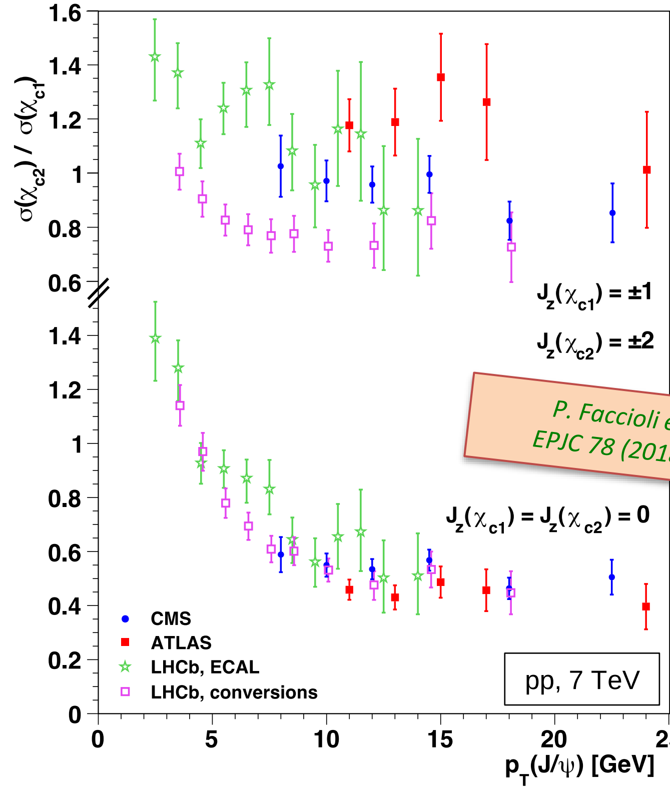

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Correlated uncertainties : nuisance parameters

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:

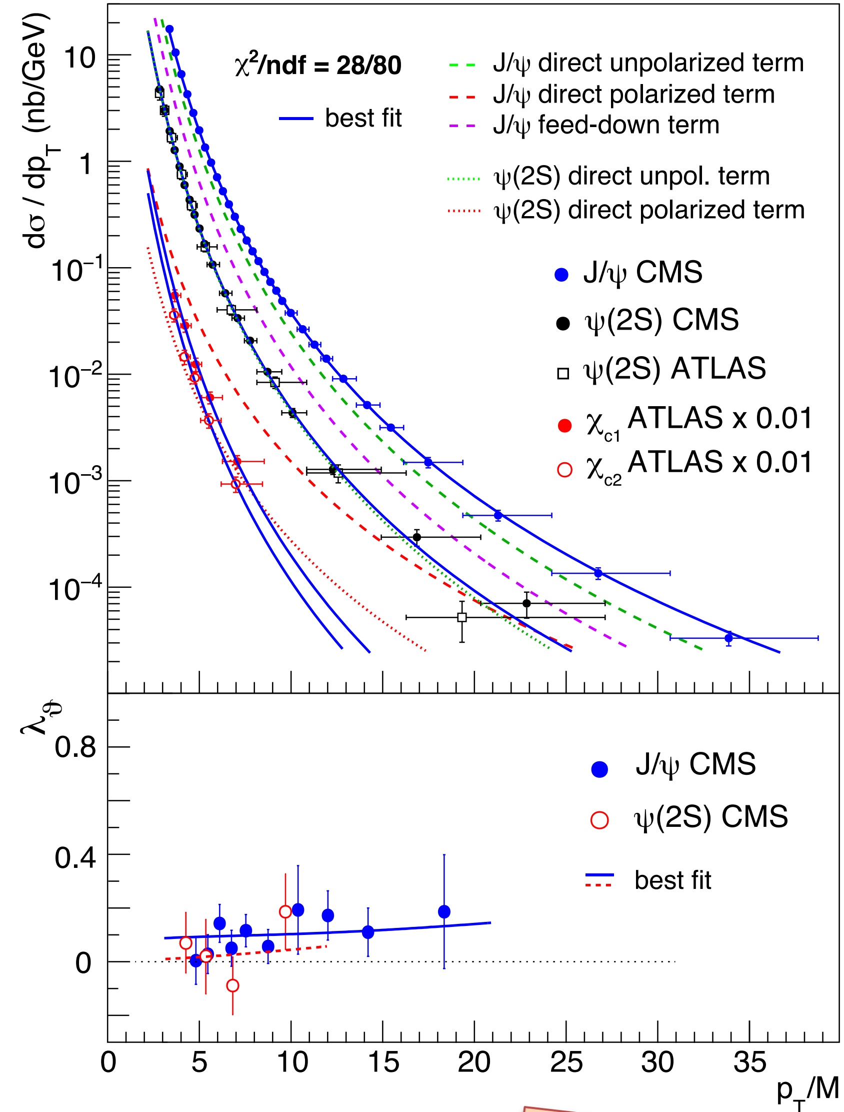
- 5 shape parameters,
- 4 normalizations,
- the fraction f_p
- and 10 nuisance parameters

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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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 reproduces well 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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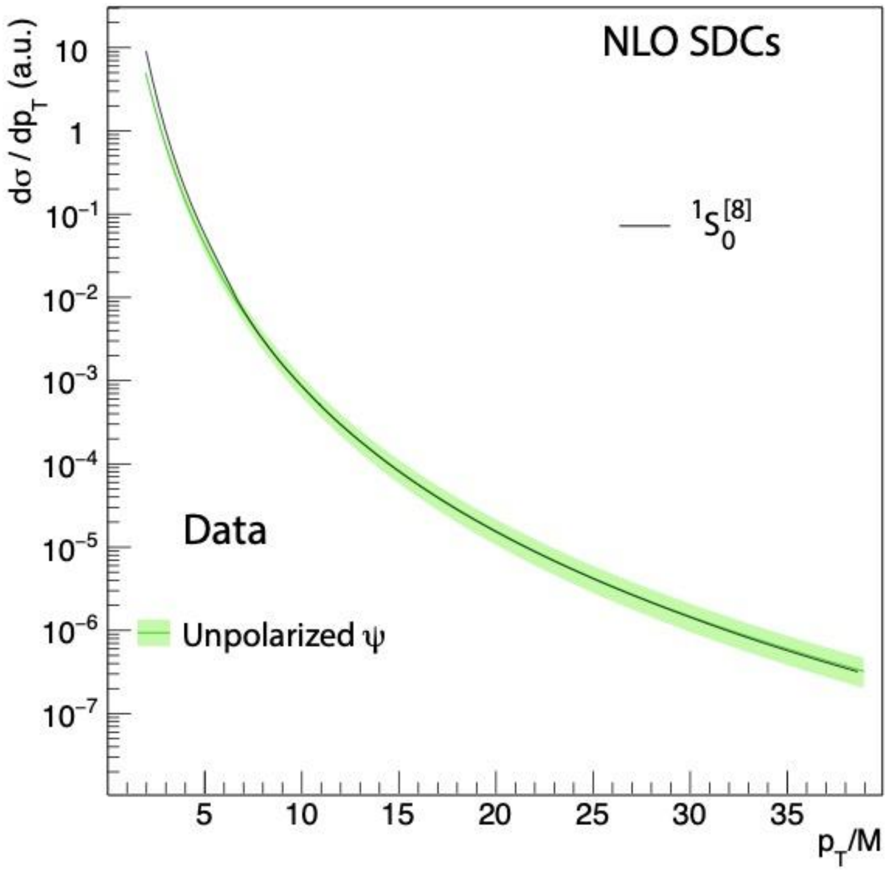
$^1S_0 \Rightarrow$ J/ψ, ψ(2S)



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

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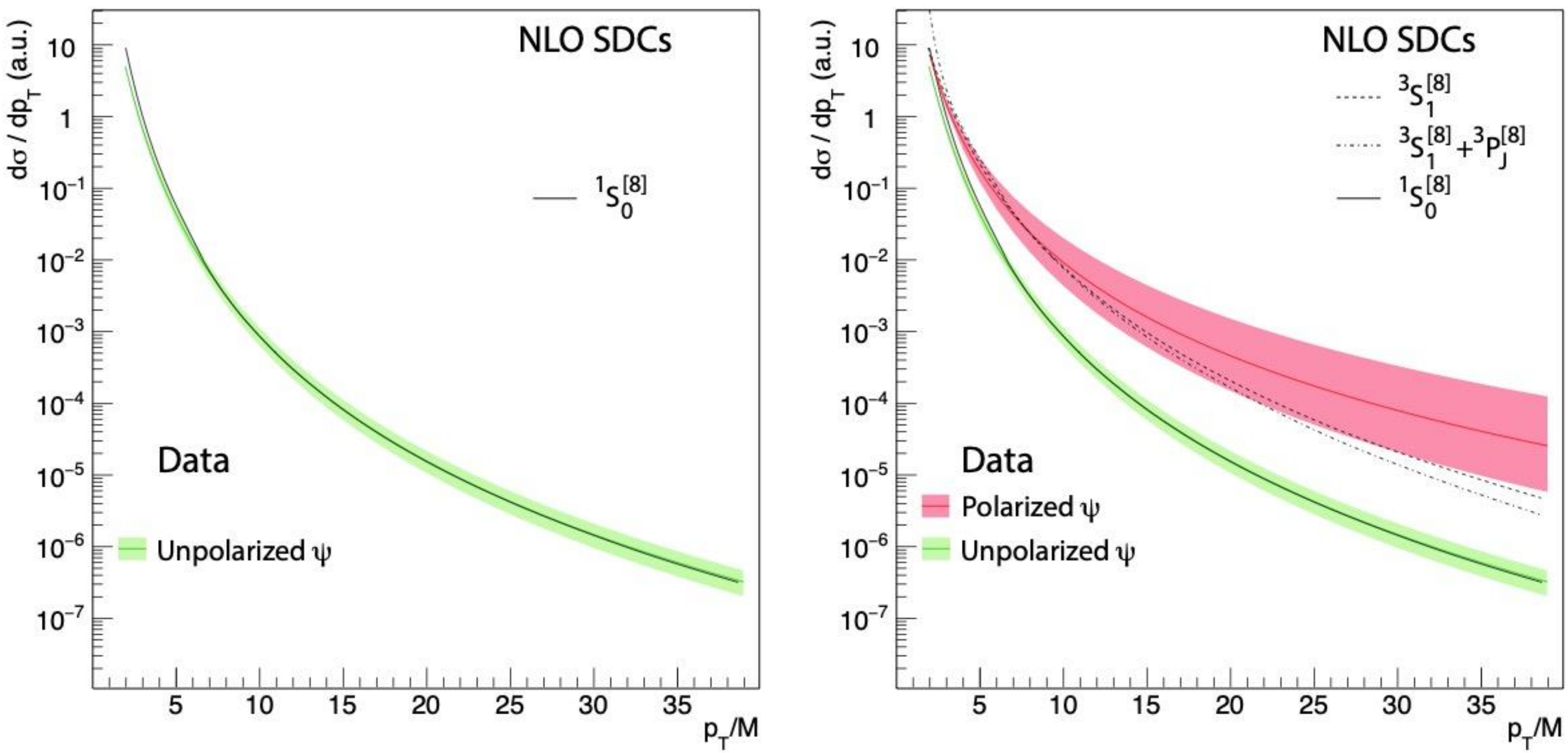
$^1S_0 \Rightarrow J/\psi, \psi(2S)$ $\quad$ $^3S_1 \Rightarrow J/\psi, \psi(2S)$



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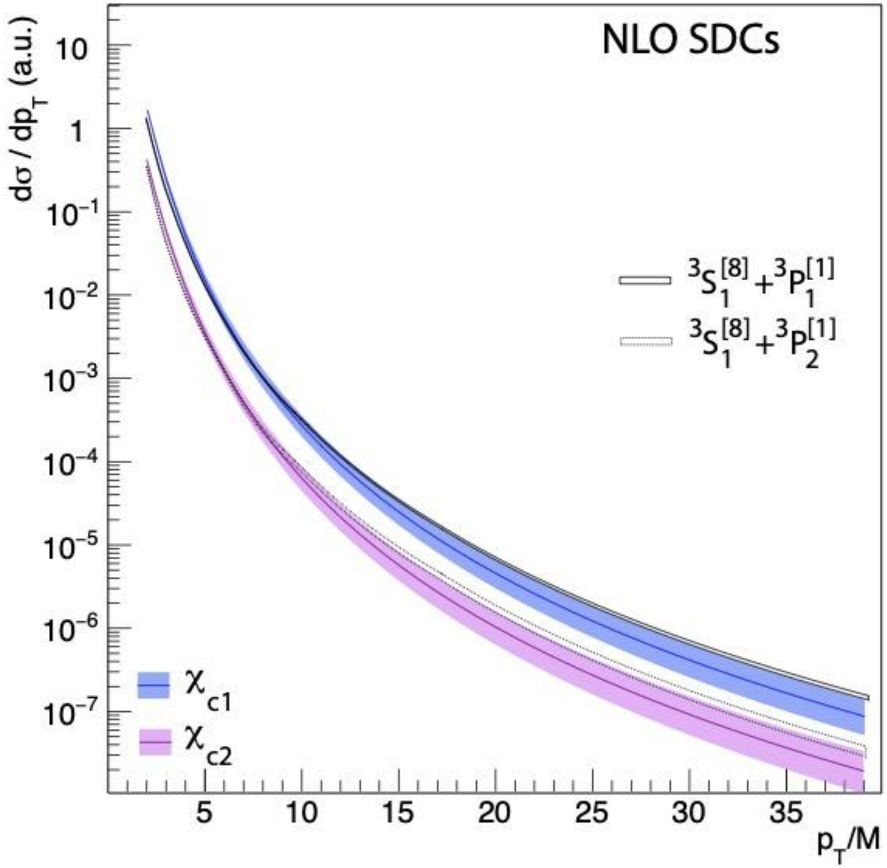
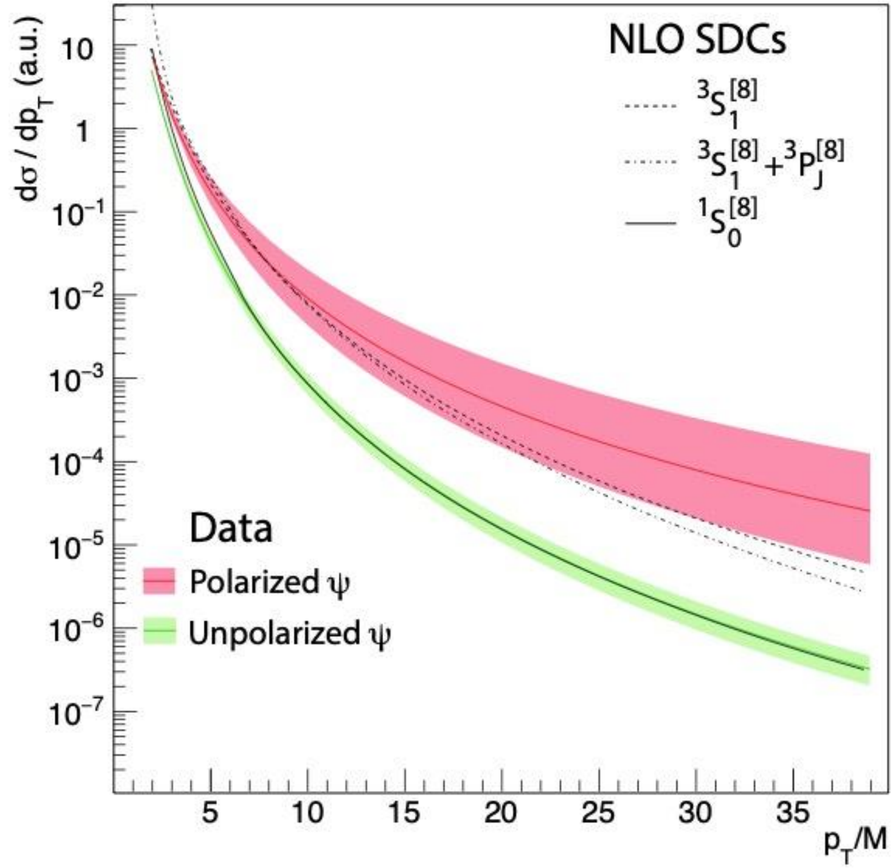
^3P_J $^3S_1$ ⇨ χ_{cJ}



$^3S_1$ ⇨ J/ψ, ψ(2S)



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

A strong NRQCD prediction

Within NRQCD, the unmeasured χ_{c1} and χ_{c2} polarizations are predicted to be **very different** from one another

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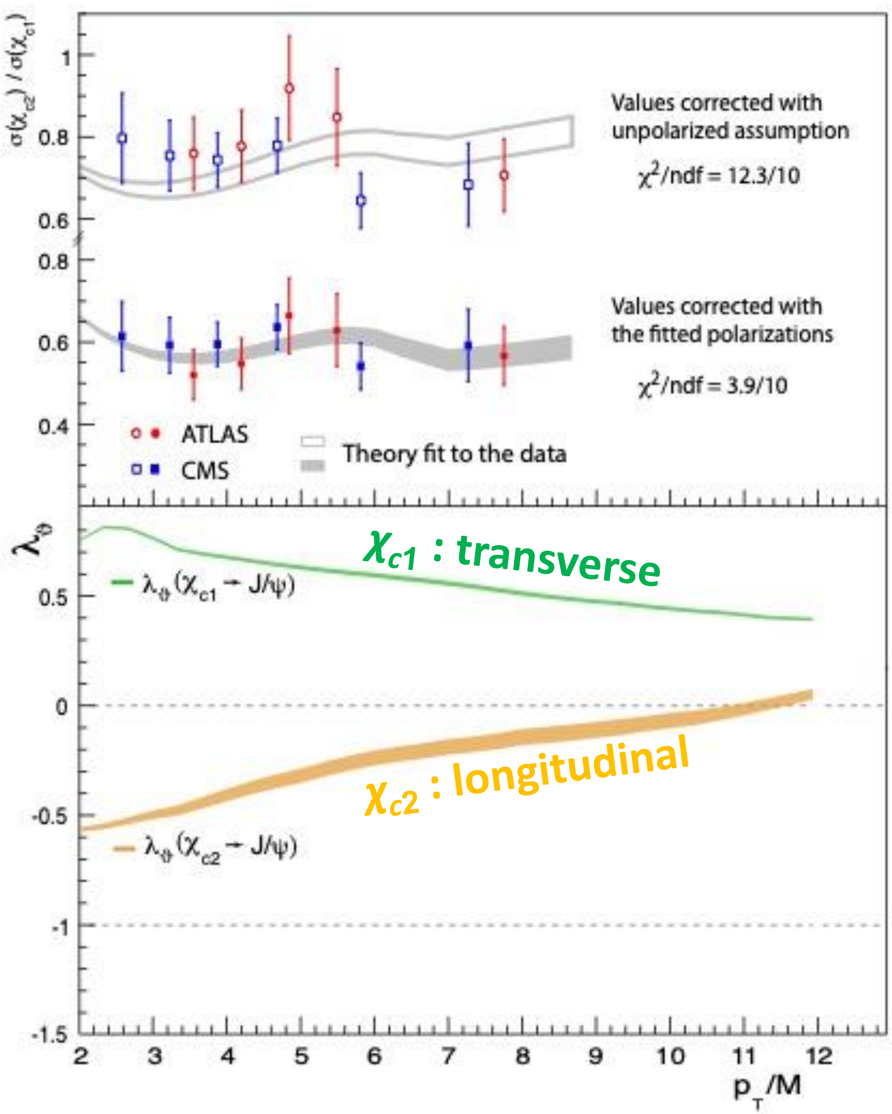


Within the NRQCD framework,
$\chi_{c1,2}$ production has two terms:
the $^3S_1$ octet and the $^3P_{1,2}$ singlet.
One single parameter r determines

1) the χ_{c2} / χ_{c1} yield ratio
2) $\lambda_\vartheta(\chi_{c1})$
3) $\lambda_\vartheta(\chi_{c2})$

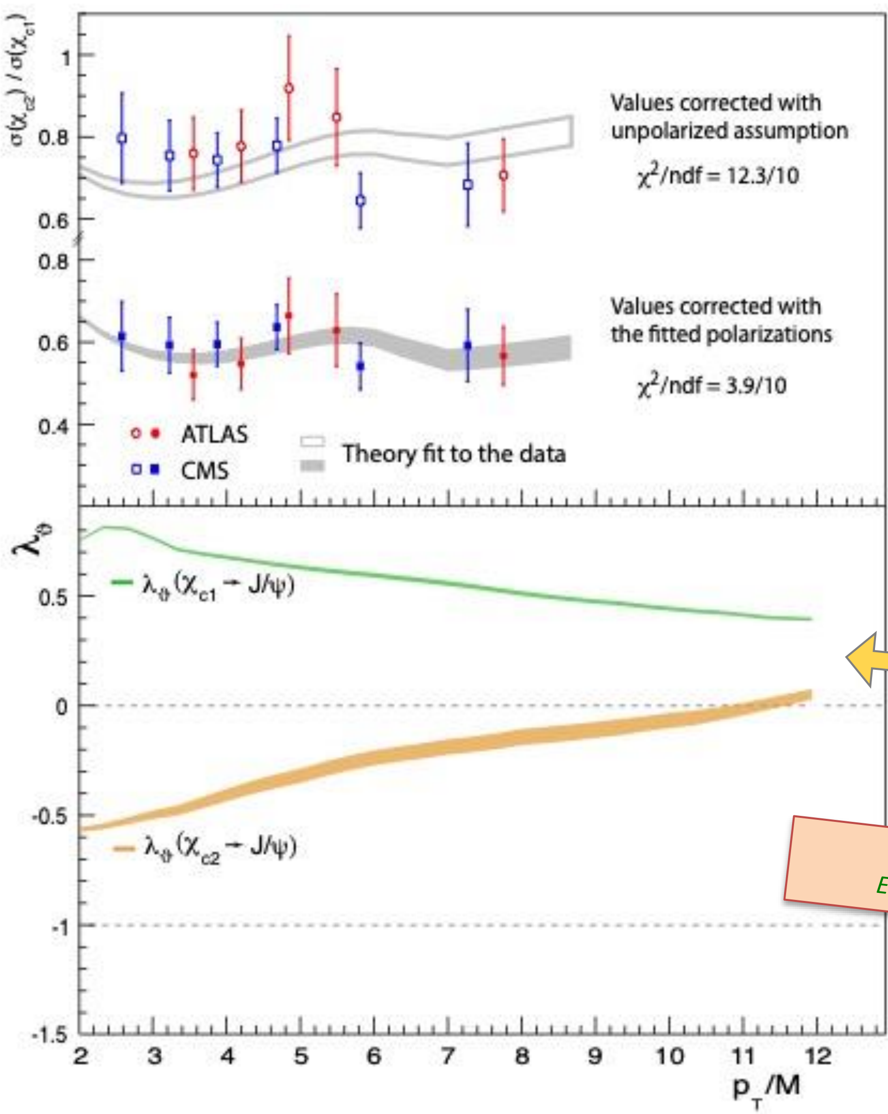
$$r \equiv m_c^2 \left\langle \mathcal{O}^{\chi_{c0}}(^3\mathbf{S}_1^{[8]}) \right\rangle \Big/ \left\langle \mathcal{O}^{\chi_{c0}}(^3\mathbf{P}_0^{[1]}) \right\rangle$$

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

Comparison between two predictions

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

$$r \equiv m_c^2 \left\langle \mathcal{O}^{\chi_{c0}}({}^3\mathbf{S}_1^{[8]}) \right\rangle \Big/ \left\langle \mathcal{O}^{\chi_{c0}}({}^3\mathbf{P}_0^{[1]}) \right\rangle$$



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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, thus, no added "polarization uncertainty"

A strongly constrained and unambiguous prediction,
not requiring any "fine-tuning"…

Comparison between two predictions

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

$$r \equiv m_c^2 \left\langle \mathcal{O}^{\chi_{c0}}({}^3\mathbf{S}_1^{[8]}) \right\rangle \Big/ \left\langle \mathcal{O}^{\chi_{c0}}({}^3\mathbf{P}_0^{[1]}) \right\rangle$$

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

<u>*CDF*</u>:

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

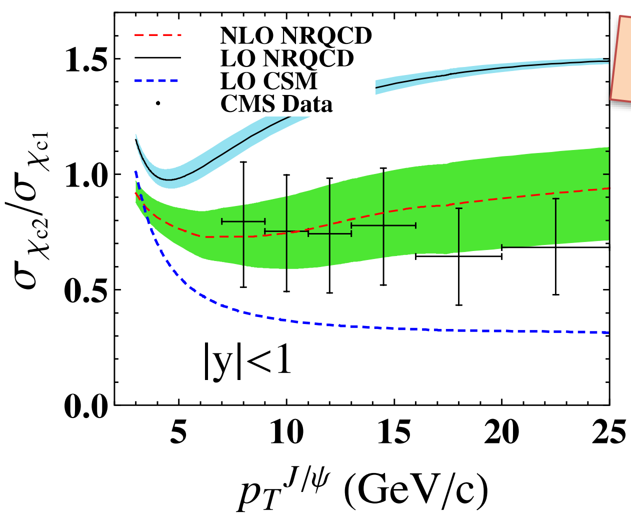
= no correlated variations considered

= uncertainty added in quadrature with all others

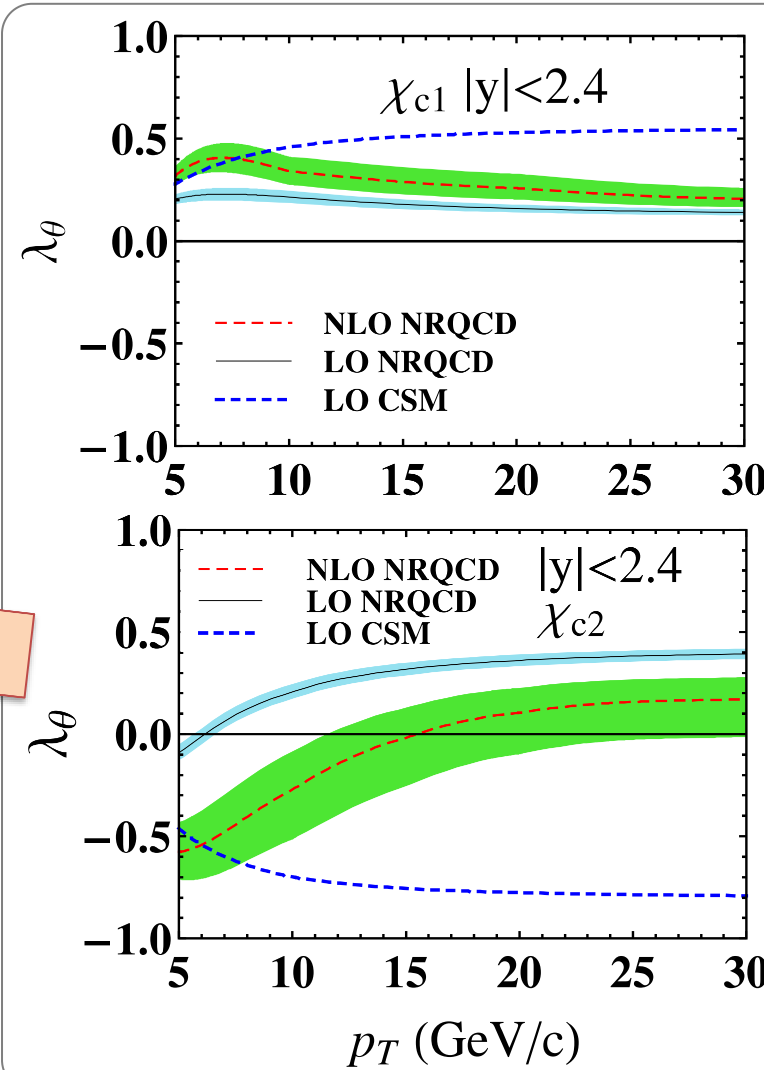
<u>*CMS*</u>:

= 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 $\lambda_\vartheta(\chi_{c2})$



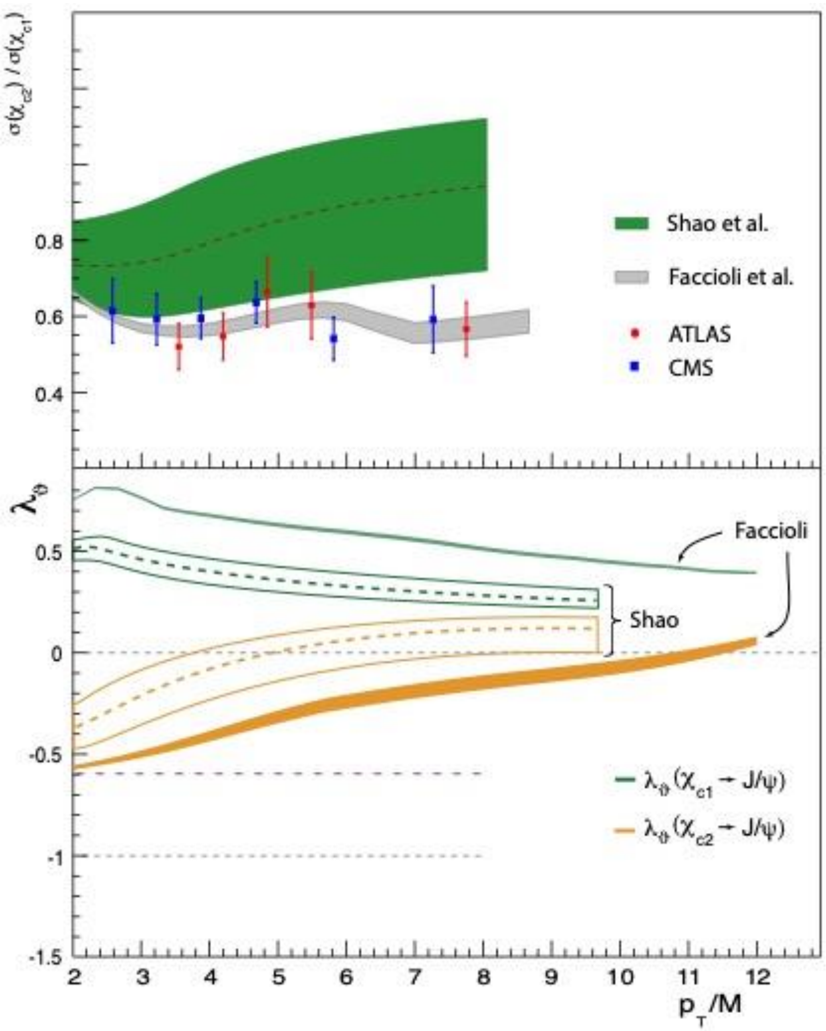
H.-S. Shao et al.
PRL 112 (2014) 182003



Comparison between two predictions

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

$$r \equiv m_c^2 \left\langle \mathcal{O}^{\chi_{c0}}({}^3\mathbf{S}_1^{[8]}) \right\rangle \Big/ \left\langle \mathcal{O}^{\chi_{c0}}({}^3\mathbf{P}_0^{[1]}) \right\rangle$$



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 ± 0.06**

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

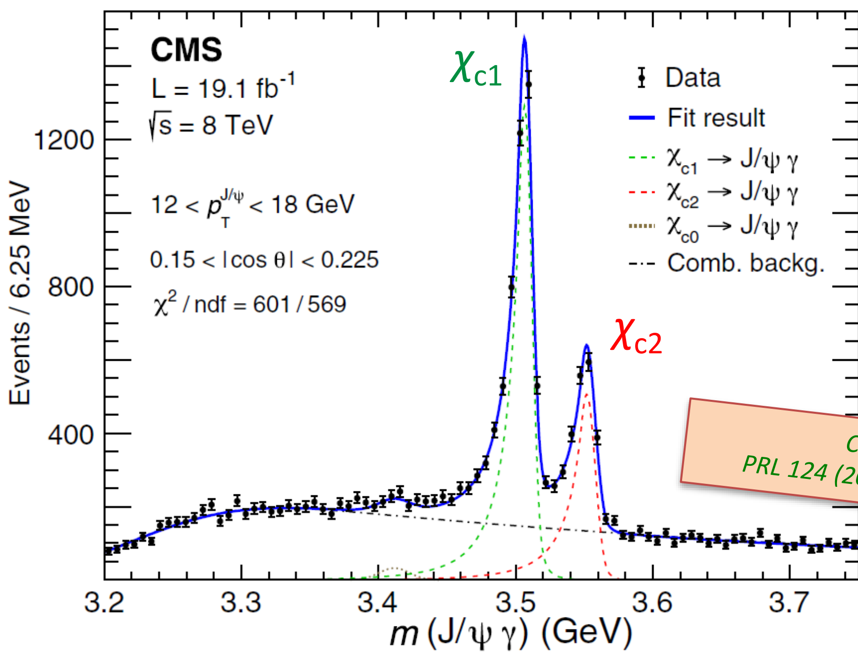
This shows how crucial it is to rigorously treat the correlations between the cross sections and the polarizations and to properly account for the uncertainties

The cross sections depend on the polarization but that is not an experimental uncertainty

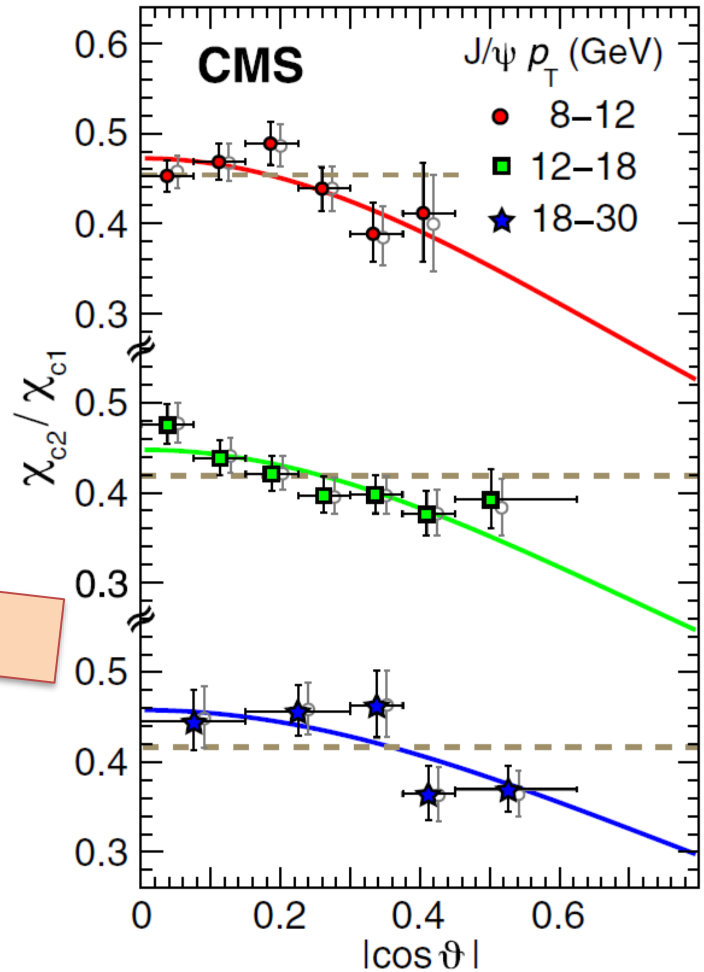
First measurement of χ_{c1} and χ_{c2} polarizations

The CMS experiment measured the ratio between the $\cos\vartheta$ distributions of the dimuons associated with the χ_{c2} and χ_{c1} radiative decays: $\chi_{c1,2} \to J/\psi\,\gamma$, with the γ detected via conversions to e^+e^- pairs.

This provides a constraint on *the difference* between the polarizations of the two states.

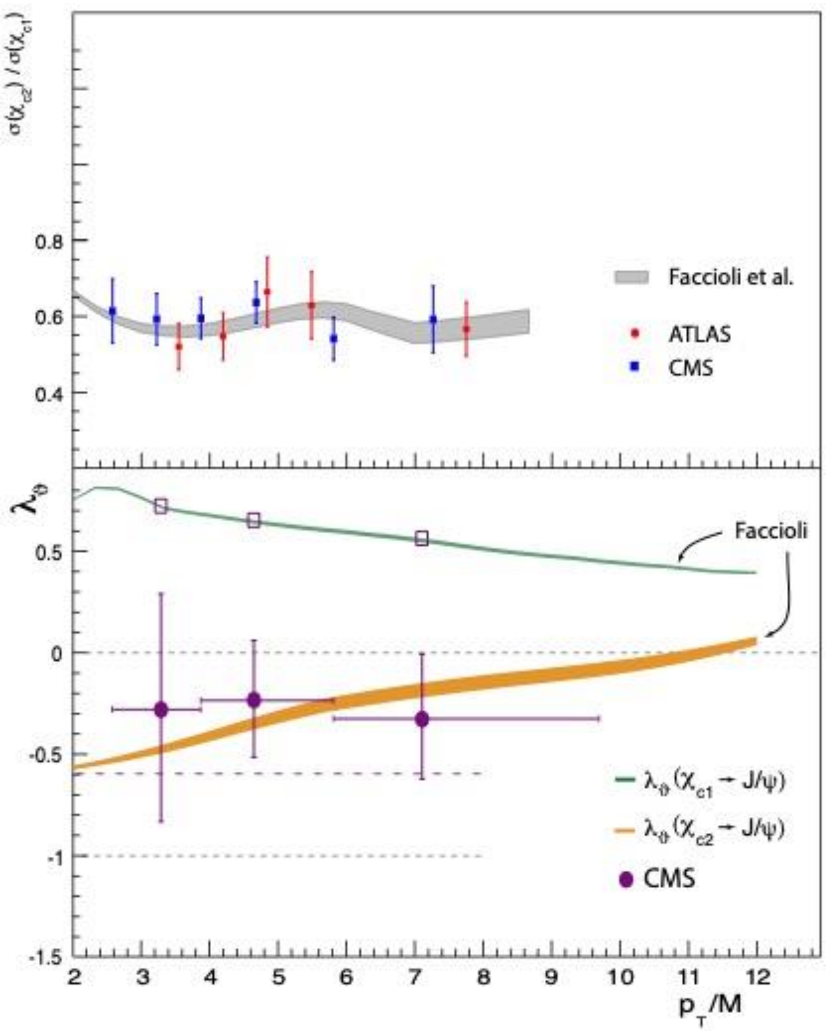


CMS
PRL 124 (2020) 162002



Comparison to CMS results

Since CMS only measured the *difference* between the χ_{c2} and χ_{c1} polarizations, the data-prediction comparison requires fixing $\lambda_\theta(\chi_{c1})$ and only looking at $\lambda_\theta(\chi_{c2})$.



The data is in good agreement with the (quite extreme) predicted polarizations.

However, the uncertainties are quite large…

Can we obtain a more precise derivation of the χ_{c1} and χ_{c2} polarizations ? Yes, we can.

Indirect experimental constraints

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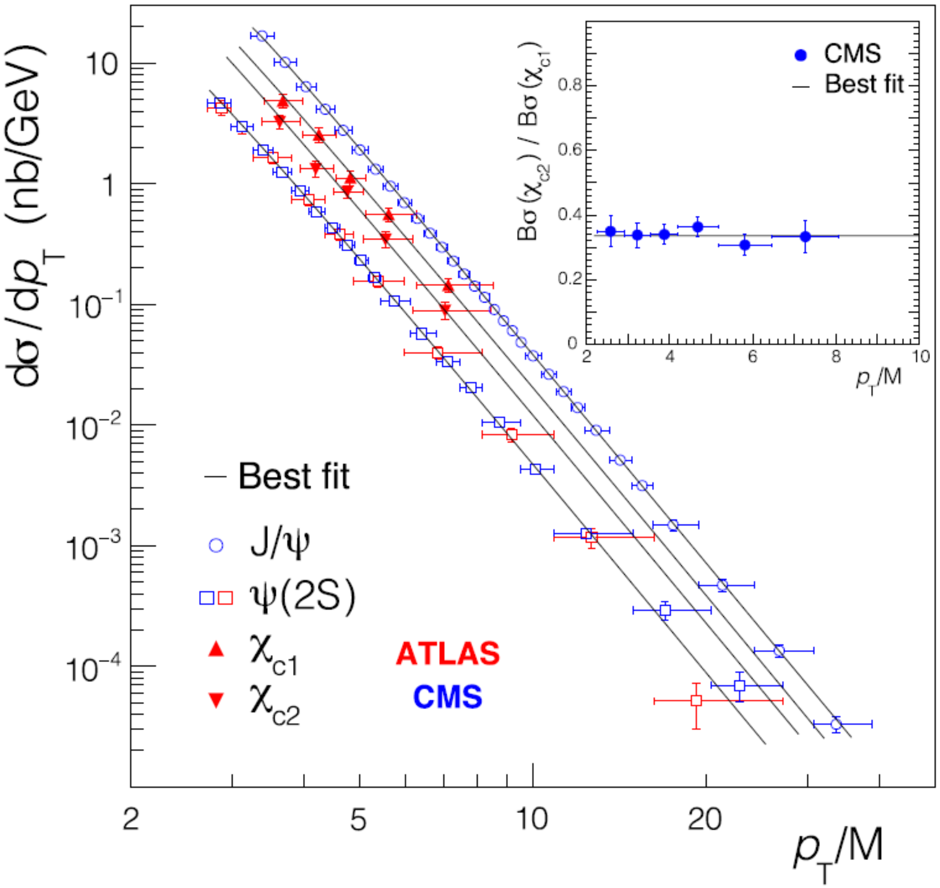
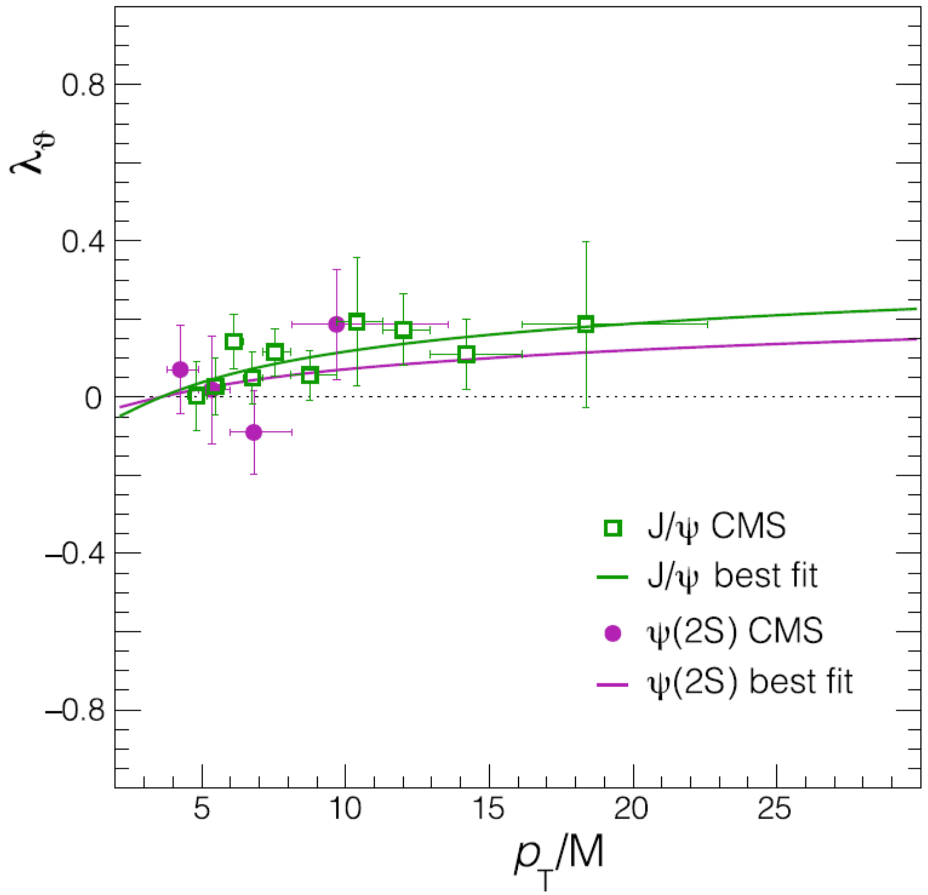
ATLAS and CMS measurements of the J/ψ, ψ(2S), χ_{c1} and χ_{c2} cross sections, together with J/ψ and ψ(2S) polarizations, constrain *the sum* of χ_{c1} and χ_{c2} polarizations.

Direct and indirect constraints were combined in a fit using the parametrization described previously, with no theory ingredients. Only assumption:

- the *directly produced* J/ψ and ψ(2S) states have identical polarizations, vs. p_T/M





The χ_{c1} and χ_{c2} states are strongly polarized !

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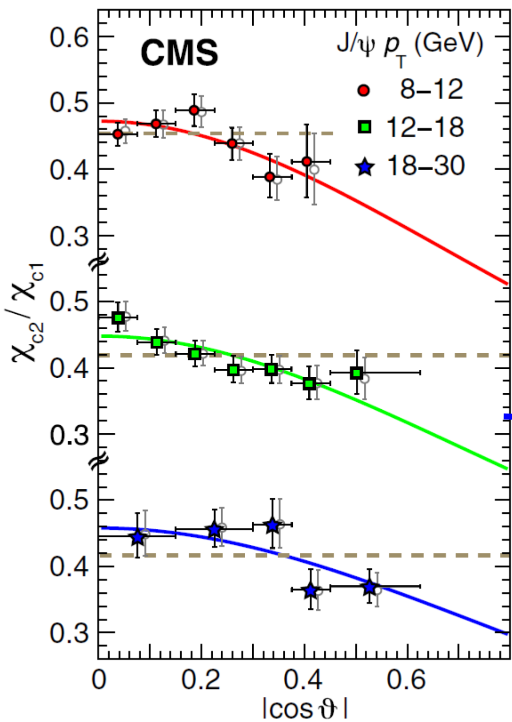
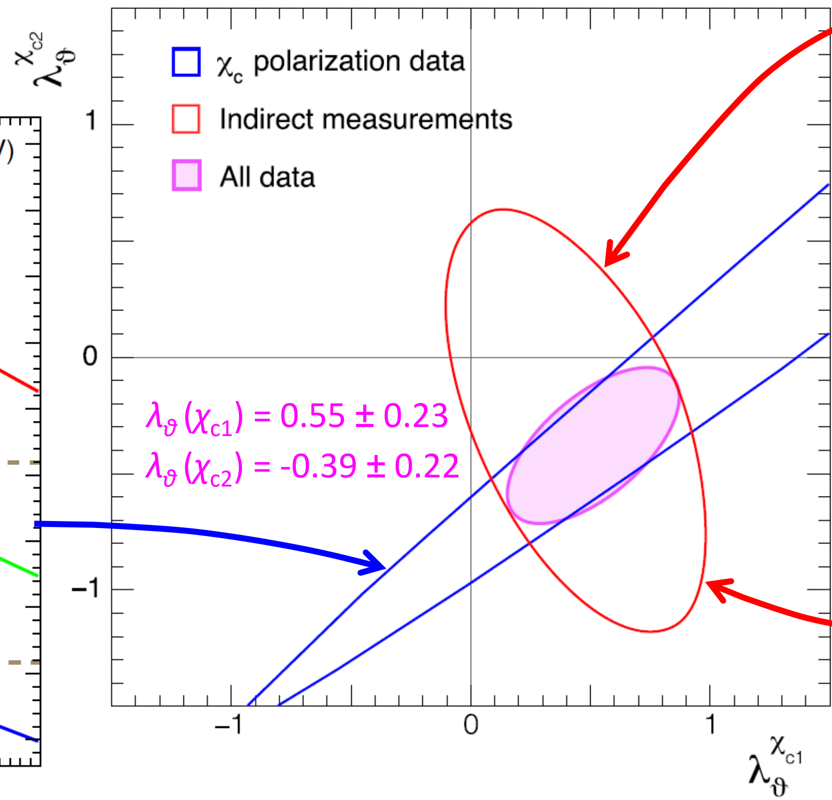
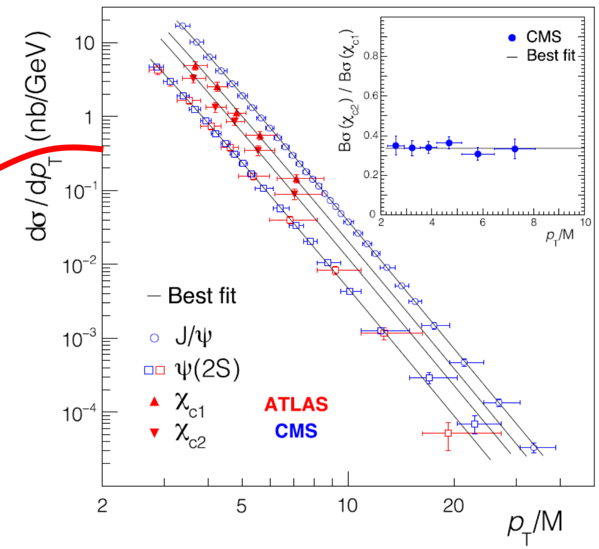
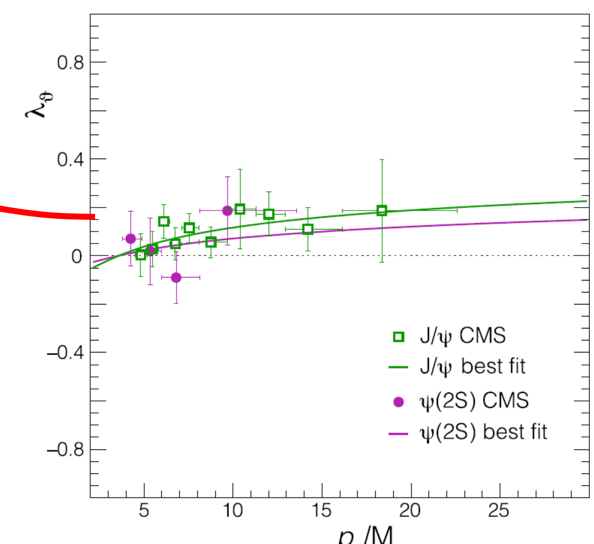
The combination of these two "orthogonal" experimental constraints determines the two individual χ_{c1} and χ_{c2} polarizations.
This is a purely experimental result: no theory involved.









The J/ψ mesons from χ_{c1} and χ_{c2} decays are, respectively, transversely and longitudinally polarized
→ they tend to cancel each other in their contribution to the J/ψ polarization

The χ_{c1} and χ_{c2} polarizations vs. p_T

The global fit of all charmonium data also provides results as a function of p_T, for the individual χ_{c1} and χ_{c2} polarizations

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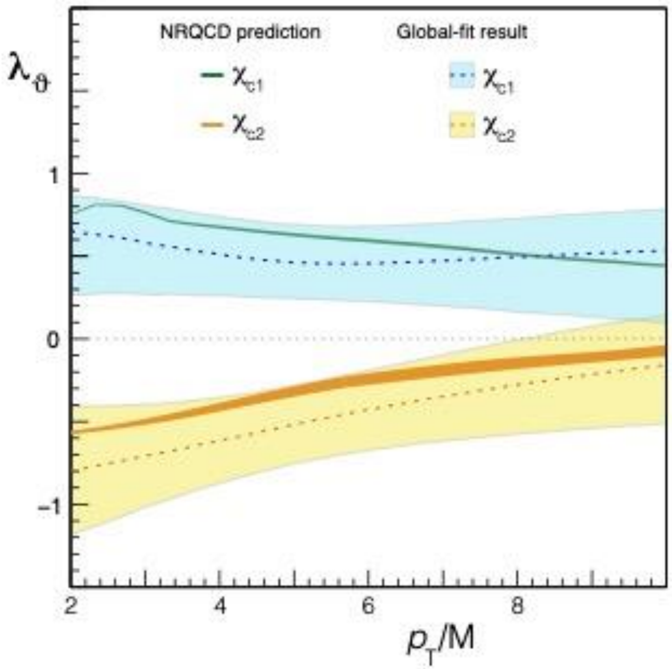


Narrow bands: NRQCD prediction obtained from the cross section ratios using the equation

$$r \equiv m_c^2 \left\langle \mathcal{O}^{\chi_{c0}}({}^3\mathbf{S}_1^{[8]}) \right\rangle \Big/ \left\langle \mathcal{O}^{\chi_{c0}}({}^3\mathbf{P}_0^{[1]}) \right\rangle$$

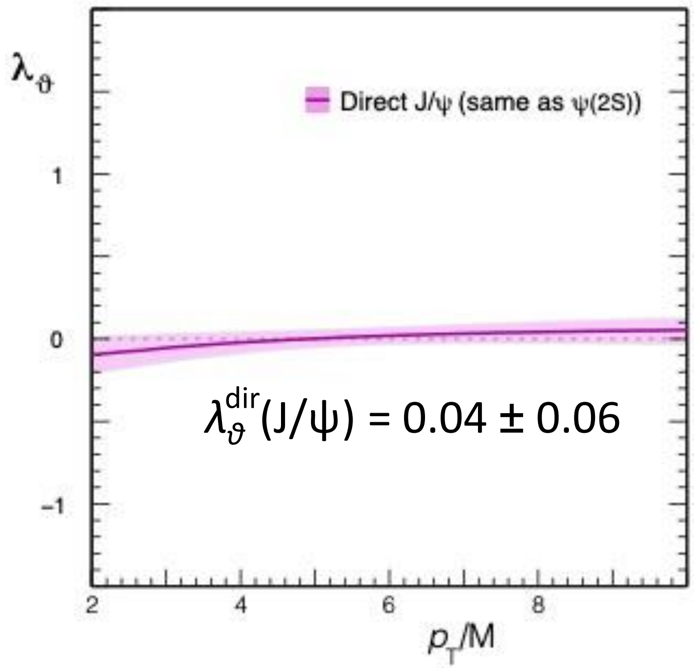
Wide bands: result of the global fit of all charmonium cross sections and polarizations, without any theory input

The NRQCD predictions agree perfectly with the two measurements

An out-of-the-box success of NRQCD !

The (direct) J/ψ polarizations vs. p_T

The global fit of all charmonium data also provides results as a function of p_T, for the *directly produced* J/ψ and ψ(2S) polarizations



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A very strong evidence of unpolarized J/ψ and ψ(2S) production !

This measurement of **zero** and ***constant*** polarization of vector quarkonia is a big challenge to production models

It is very unlikely that we are seeing a fine-tuned cancellation of a mixture of subprocesses

→ a clear sign of the **unique nature and production mechanism** of heavy quarkonia

The χ_{c1} and χ_{c2} feed-down fractions

Another interesting result of the global-fit analysis is the determination of the fractions of J/ψ mesons that are produced from the feed-down decays of the χ_{c1} and χ_{c2} mesons

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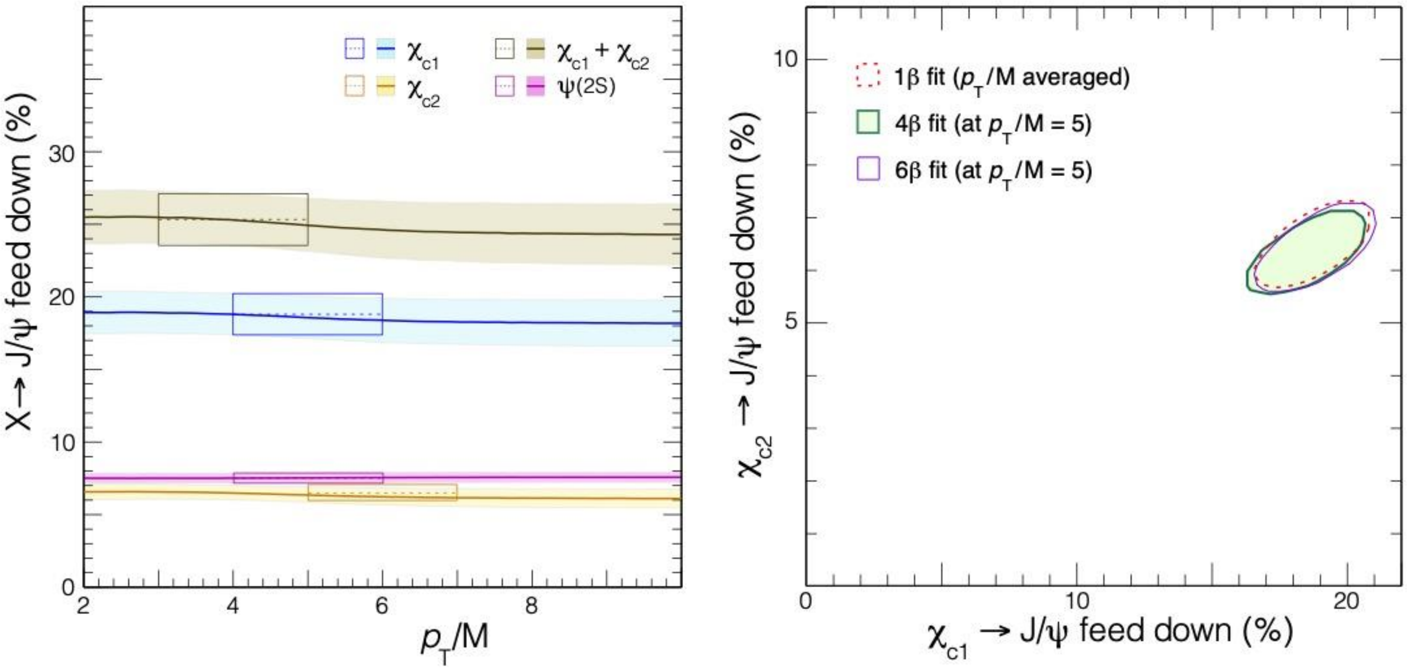

R(χ_{c1}) = 18.8 ± 1.4 %

R(χ_{c2}) = 6.5 ± 0.5 %

The fraction of the prompt J/ψ yield due to directly-produced mesons is 67.2 ± 1.9 %, a remarkably precise value

Summary

We have seen that the methodology of global-fit analyses has a profound impact on the obtained results. The handling of correlations and uncertainties is not a trivial task and doing it incorrectly can deeply bias the predictions of the fit.

- Handling theoretical uncertainties inside a global fit is a delicate task, as testified by the famous polarization puzzle, which was due to the neglected inability of NLO SDC calculations to reproduce the lowest- p_T data.
- We addressed this problem with a new method of theory-data comparison, where the data fit is made without any theory ingredient and the comparison is then made between an unbiased data-only term and the corresponding theory term. The results show a surprisingly good agreement between NLO NRQCD and the mid-rapidity data.

- Correlated uncertainties are usually neglected in global fit analyses of NRQCD, but they are crucial, as demonstrated by the example of the χ_c polarization.
- Improved predictions using a correct treatment of the acceptance-polarization correlation in χ_c yield measurements show a very good agreement with the new CMS measurement of the χ_c polarizations.

Take-home messages

- We must avoid repeating the kind of mistakes that created the polarization puzzle, such as neglecting that the computed SDCs have limitations
- Analysis techniques have evolved and much better measurements were made
- At the same time, it is crucial to properly account for correlated uncertainties, as clearly shown by the example of the χ_c polarization prediction
- The χ_c polarization is a brand new piece of information
- Combining brand new CMS data on χ_c polarizations with previous measurements it is now possible to determine the χ_{c1} and χ_{c2} polarizations
- The measured χ_{c1} and χ_{c2} polarizations agree very well with NRQCD predictions
- Also the *direct* J/ψ polarization can now be determined
- It is remarkable (and unexpected) to see how close to zero and independent of p_T it is
- This is a new "polarization puzzle", but this time at a much deeper conceptual level