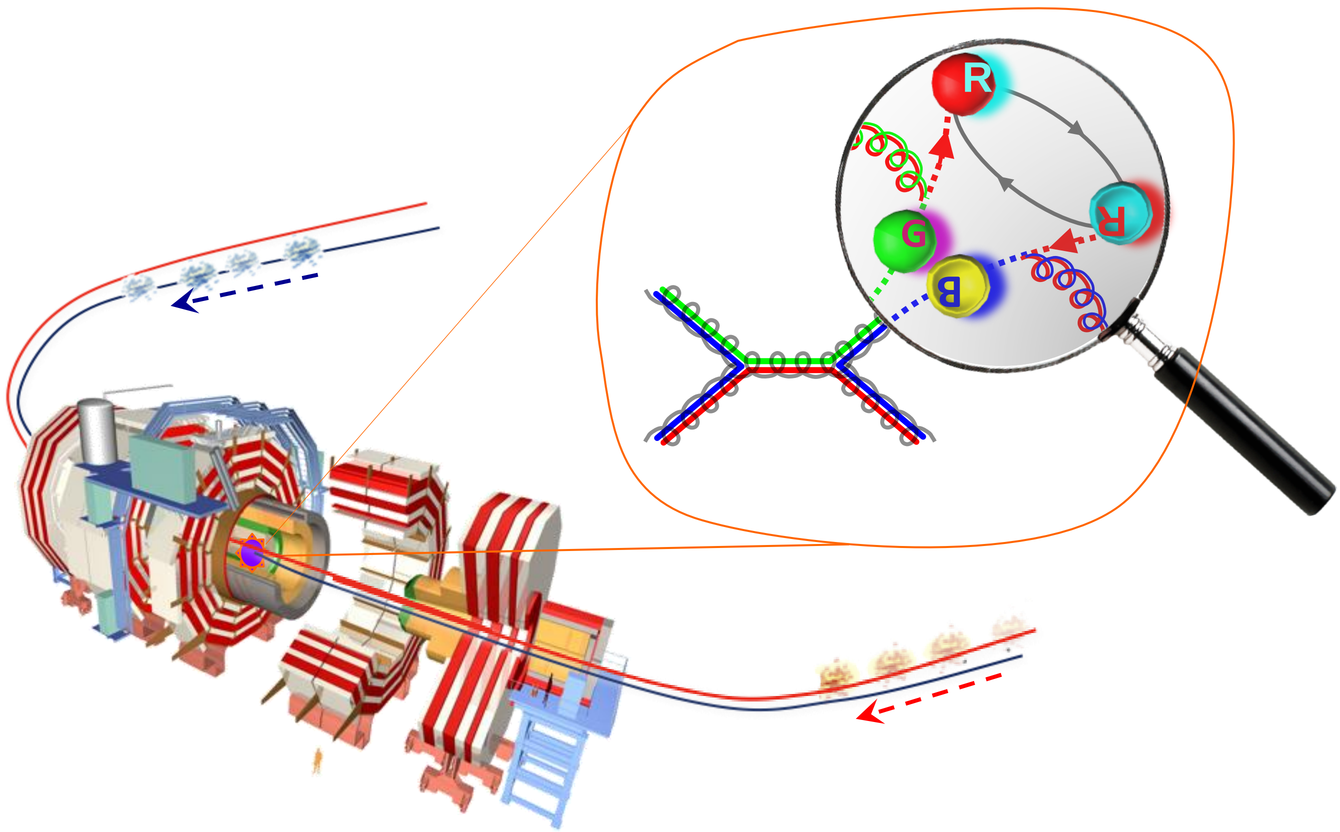
Advancing the understanding of quarkonium production through global-fit analyses of LHC data



LIP
FCT Fundação para a Ciência e a Tecnologia

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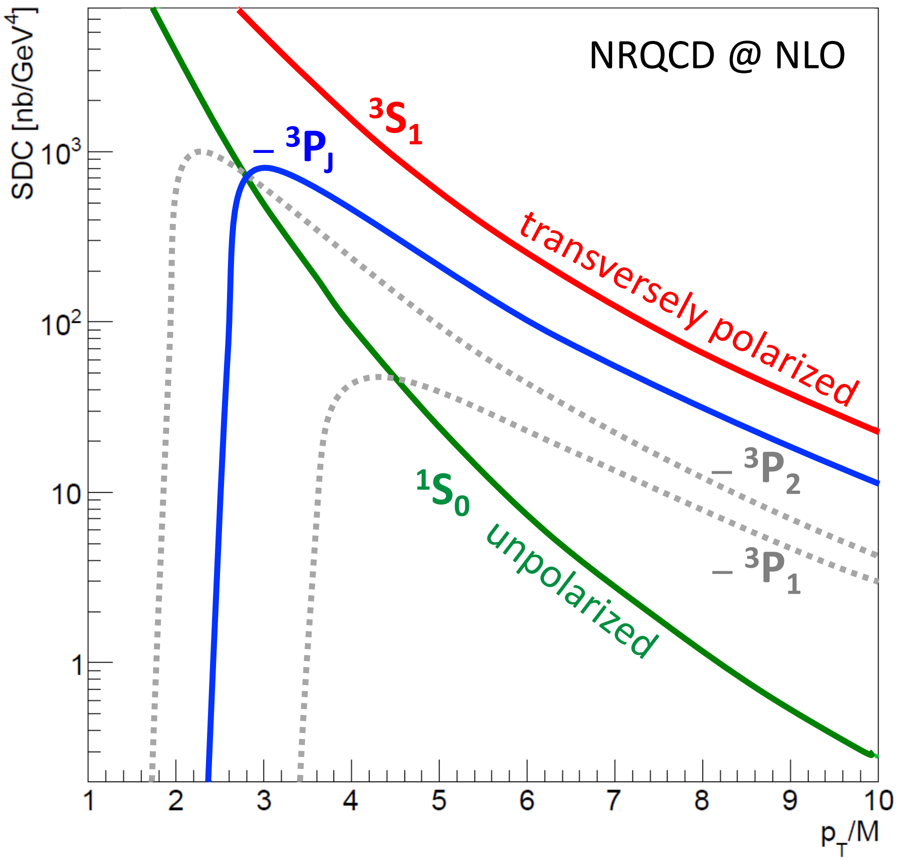
and Thomas Madlener

NRQCD: octet terms dominate quarkonium production

In NRQCD, S-wave quarkonia are mainly produced through a superposition of colour octet terms, with computed SDCs (functions of p_T) and unknown LDMEs (normalizations)



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

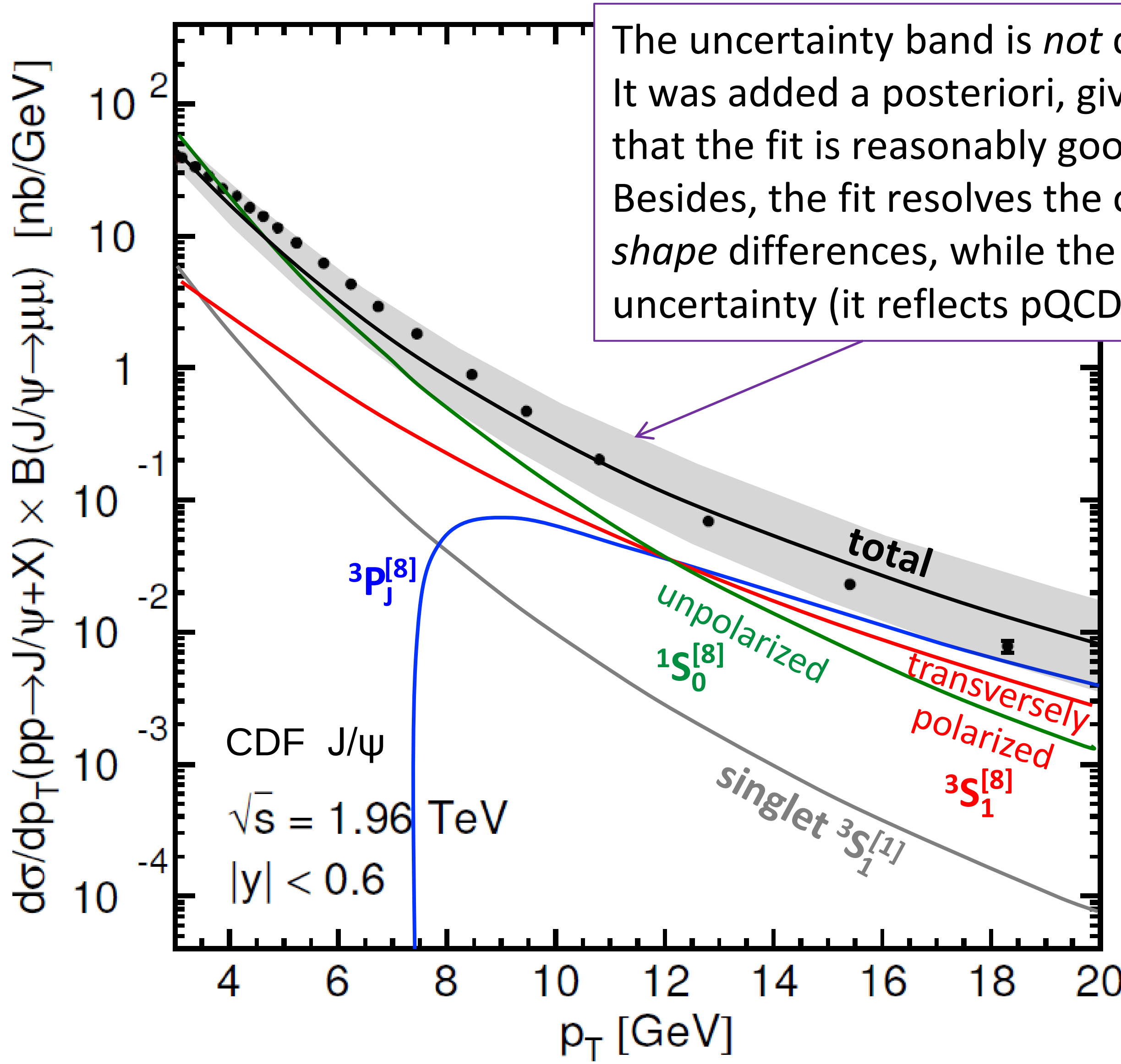
($^3P_{1(2)}$ $^3S_1$ ⇨ $\chi_{c1(2)}$, $\chi_{b1(2)}$)

Fits to measured p_T distributions provide the LDMEs, which are then used to predict the polarizations

If the fits of the S-wave quarkonium cross sections indicate $^3S_1$ and ^3P_J dominance, then one predicts transverse polarization ($\lambda_\vartheta \approx +1$) at high p_T

The famous “strong transverse polarization” prediction was not a “first principles” result of NRQCD but the outcome of fits of cross section measurements… *and those fits were biased*

Example of a biased fit



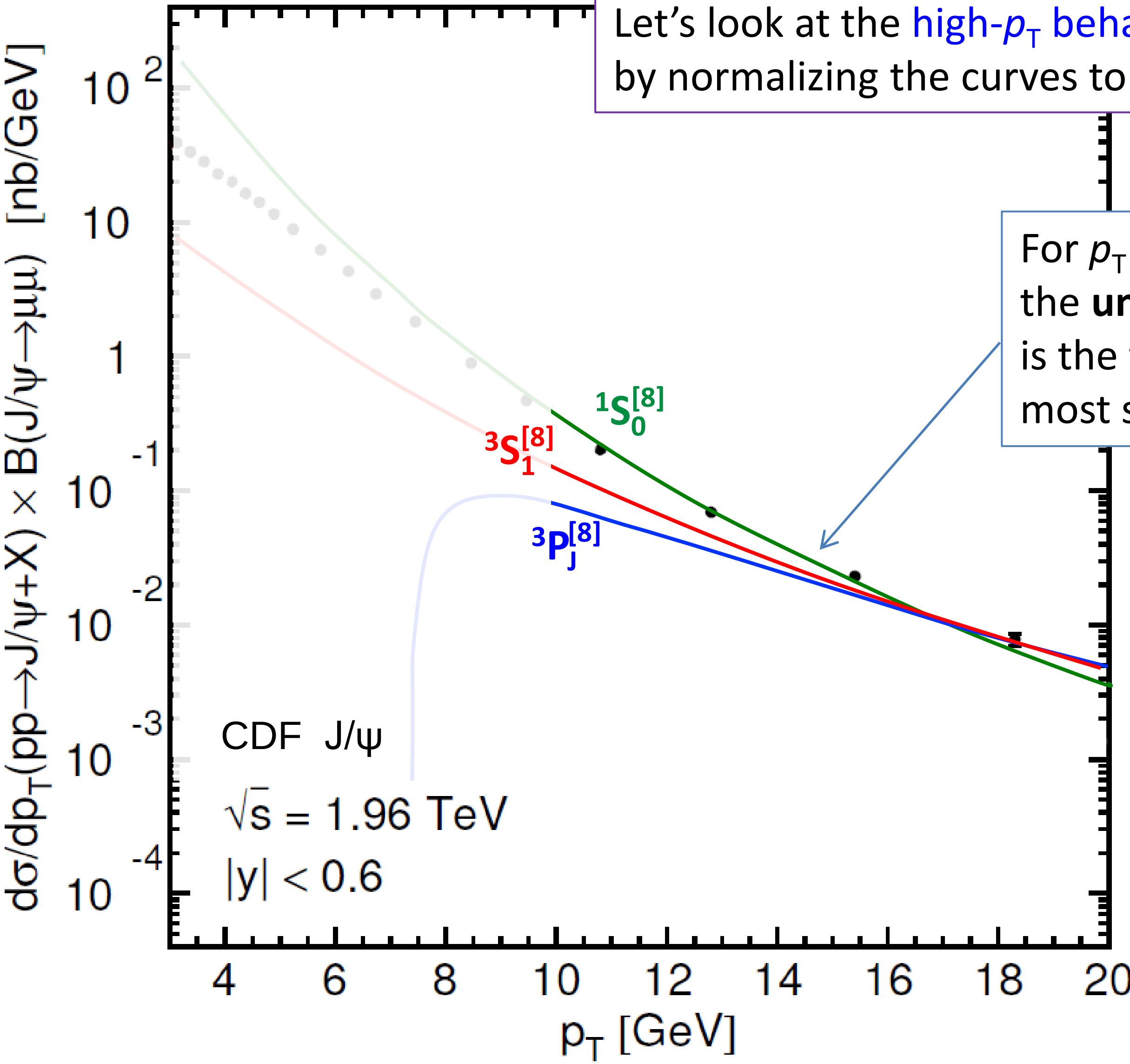
The uncertainty band is *not* coming from the fit !
It was added a posteriori, giving the misleading impression that the fit is reasonably good, when it is actually very bad.
Besides, the fit resolves the octet terms *only* by virtue of *shape* differences, while the band is mostly a normalization uncertainty (it reflects pQCD scale variations)

What does this fit imply for the polarization ?

At high p_T, the $^3S_1^{[8]}$ and $^3P_J^{[8]}$ terms **dominate**, so that the J/ψ mesons should be **transversely polarized**

What happens if we exclude the low p_T region?

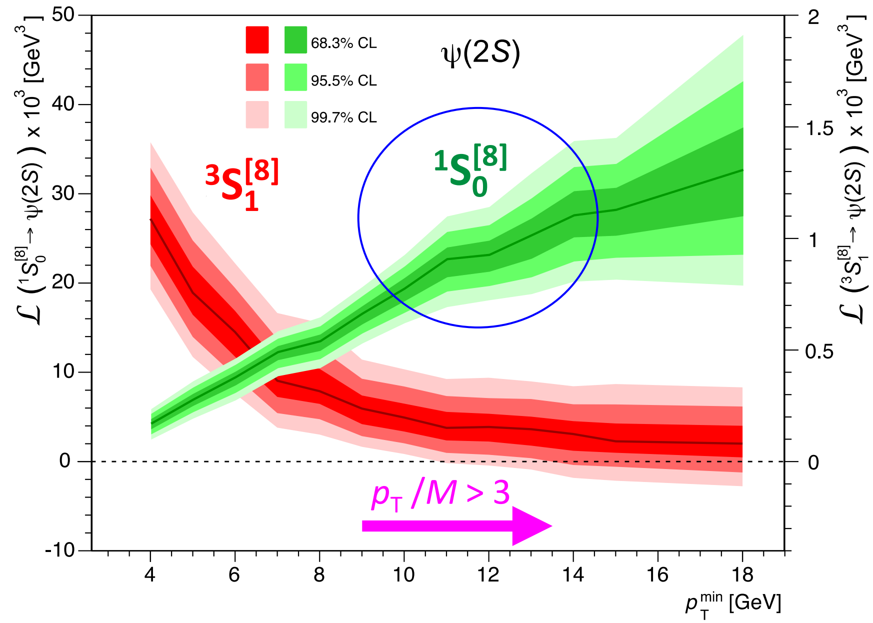
Let's look at the high-p_T behaviours, by normalizing the curves to the data for $p_T/M > 3$



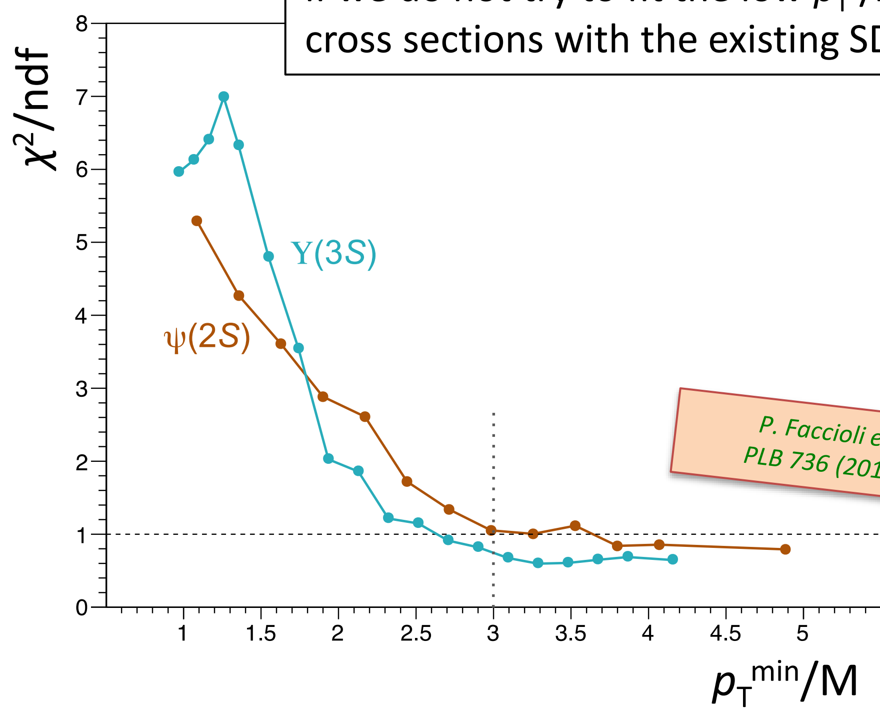
For $p_T > 9$ GeV, the **unpolarized** $^1S_0^{[8]}$ **octet** is the term that has the *shape* most similar to the data

There is no quarkonium polarization puzzle…

For $p_T/M > 3$,
the cross sections and polarizations *can* be simultaneously and consistently fitted;
the fit results are stable and show that
the measurements imply ${}^1S_0^{[8]}$ dominance



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



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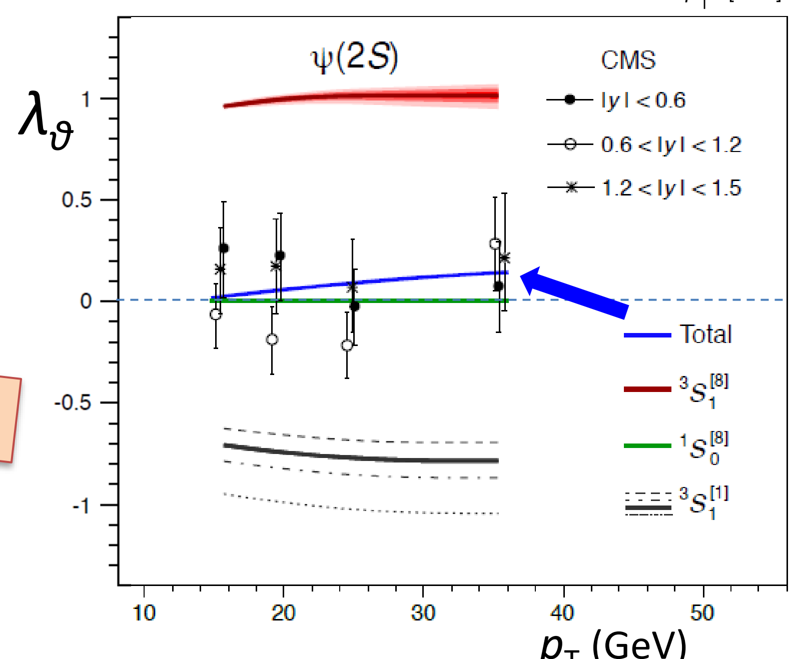
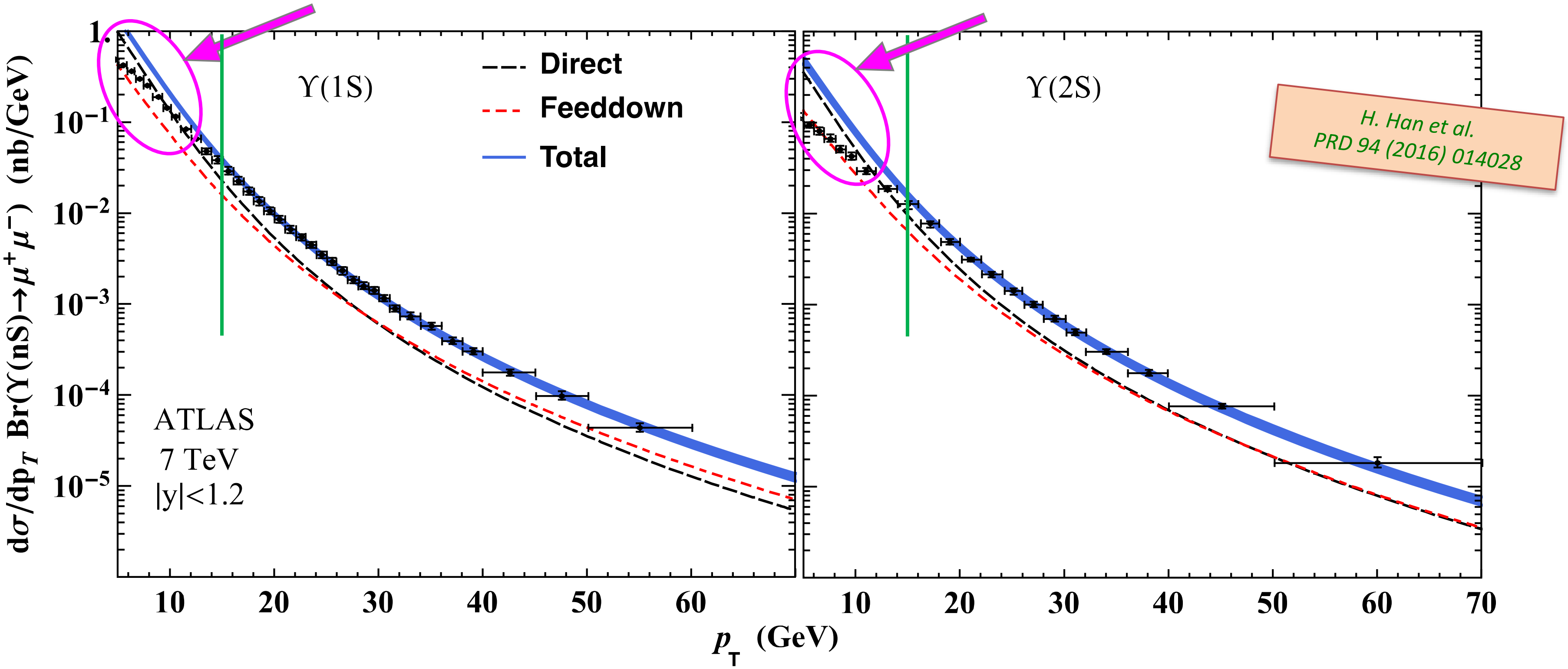


The low-p_T SDC problem

Current NLO SDCs are not valid in the low p_T region.
Fitting data with a wrong fit model necessarily leads to wrong fit results.



A model-independent global charmonium fit (1)

We made a simultaneous fit of the J/ψ, $\psi(2S)$ and $\chi_{c1,2}$ cross sections and polarizations measured by ATLAS and CMS

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

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

Momentum propagation: p_T/m *(daughter)* = P_T/M *(mother)*

Polarization propagation: calculated in the electric dipole approximation;
precisely accounts for the observable dilepton distribution, without higher-order terms

Theory calculations of the production kinematics are not used anywhere;
the fit is *exclusively based on empirical parametrizations*

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A model-independent global charmonium fit (2)

1) J/ψ and ψ(2S) directly produced cross sections: a superposition of two terms

$$\sigma_{\mathrm{dir}} \propto \left[\left(1 - f_p\right) g_u + f_p\, g_p\right] \quad \text{with} \quad g_{u,p} = (p_T/M)\left(1 + \frac{1}{\beta_{u,p}-2}\frac{(p_T/M)^2}{\gamma}\right)^{-\beta_{u,p}}$$

- The unpolarized (g_u; $\lambda_\theta = 0$) and transversely polarized (g_p; $\lambda_\theta = +1$) terms have a common γ.
- The g_u and g_p shapes and their relative contributions f_p are constrained by the polarization data.

2) χ_{c1} and χ_{c2} cross sections (and their J/ψ feed-down contributions):

- independent from the (direct) ψ terms;
- no separation of polarized and unpolarized contributions (study made before any χ_c polarization measurements)

The global fit has, hence, four terms and 6 free parameters:

- the unpolarized and polarized ψ terms, defined by $\beta_u(\psi)$, $\beta_p(\psi)$, f_p, γ
- plus the χ_{c1} and χ_{c2} cross sections, defined by $\beta(\chi_1)$, $\beta(\chi_2)$, γ

Cross sections and polarizations are correlated (1)

The detection acceptances depend on the polarization scenario assumed in their evaluation

For each set of parameter values considered while running the fit, the polarizations and cross sections are calculated, for all states, as functions of p_T

The resulting λ_θ values can be immediately compared to the measured ones

For the cross sections, we first scale the measured values by correction factors calculated for the λ_θ value under consideration

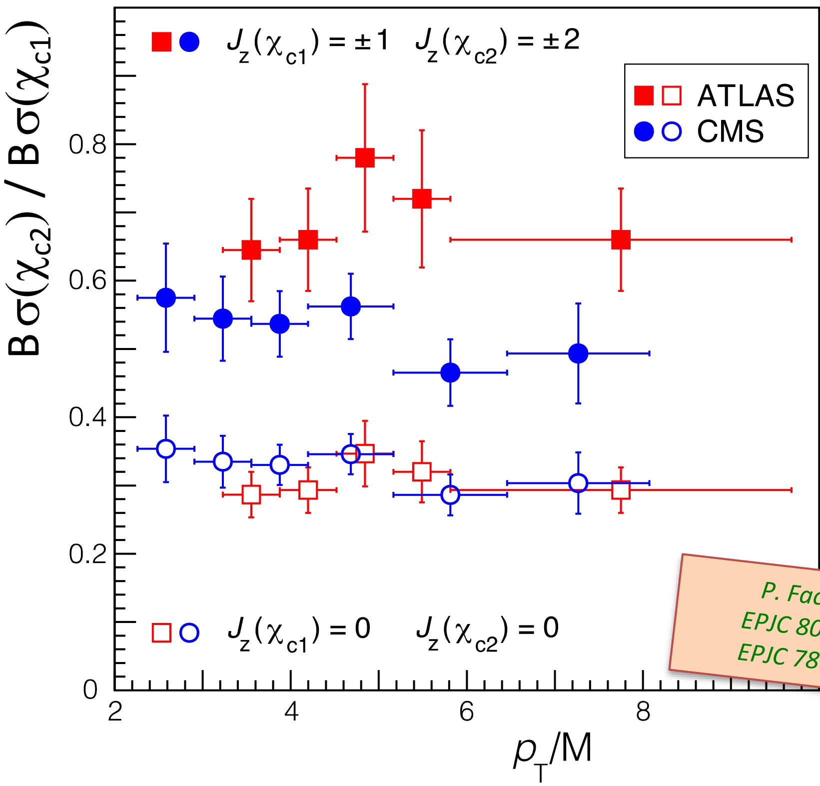
These acceptance corrections are computed using tables published by the experiments for the cross sections of particles produced with fully transverse or fully longitudinal polarization

Cross sections and polarizations are correlated (2)

The χ_{c2} over χ_{c1} cross section ratio provides a good example of the crucial importance of the polarization scenario assumed in the evaluation of the acceptance corrections

Very different patterns and consistencies among data sets are seen for two hypotheses: spin alignments $J_z(\chi_{c1}) = \pm 1$, $J_z(\chi_{c2}) = \pm 2$ and $J_z(\chi_{c1}) = J_z(\chi_{c2}) = 0$

The “default” unpolarized hypothesis leads to intermediate values



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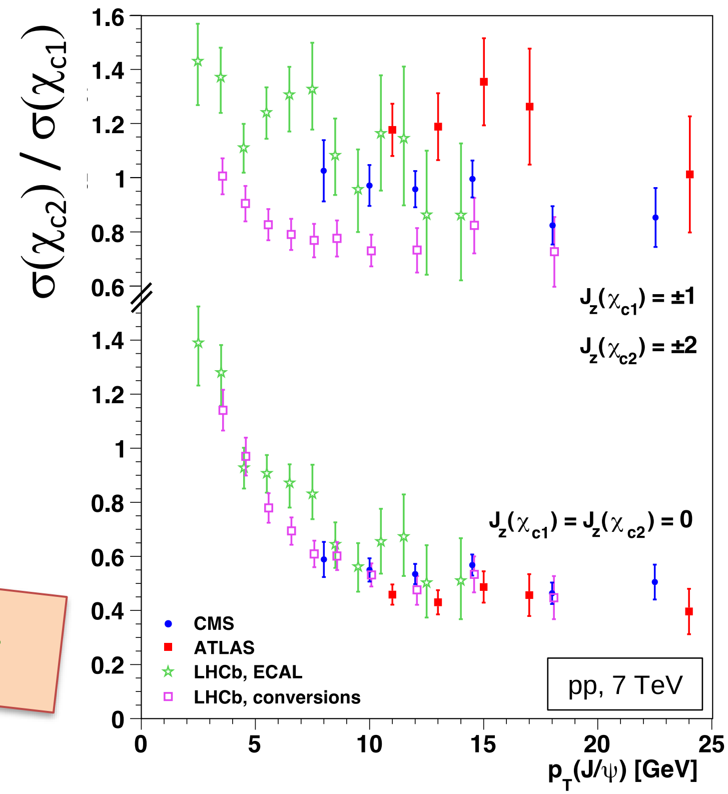


Fit results

The fit has 100 data points and 10 parameters:

- $\beta_u(\psi)$, $\beta_p(\psi)$, f_p, $\beta(\chi_1)$, $\beta(\chi_2)$, γ
- 4 normalizations

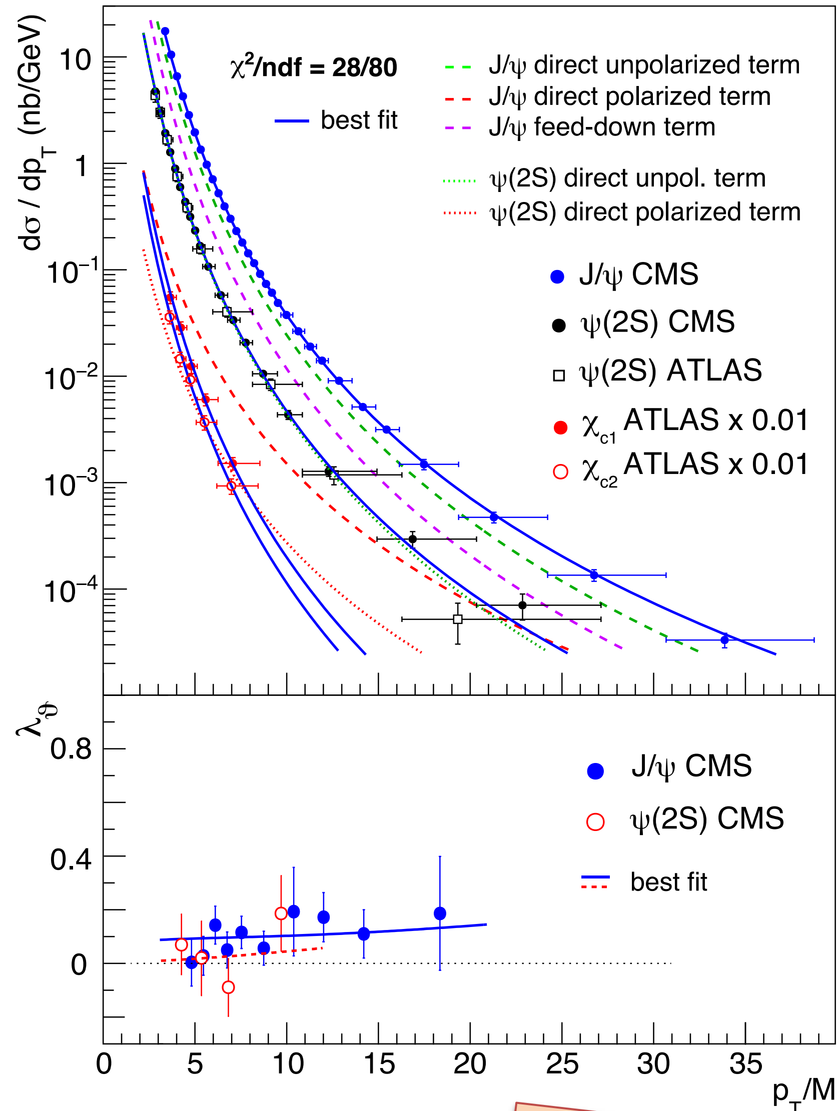
plus 10 nuisance parameters (*)

The χ_{c1} and χ_{c2} p_T/M distributions are very similar to the unpolarized term dominating ψ production

$$\beta_u(\psi) = 3.42 \pm 0.05$$
$$\beta(\chi_1) = 3.46 \pm 0.08$$
$$\beta(\chi_2) = 3.49 \pm 0.10$$

The high precision ψ data constrain the χ_c results

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



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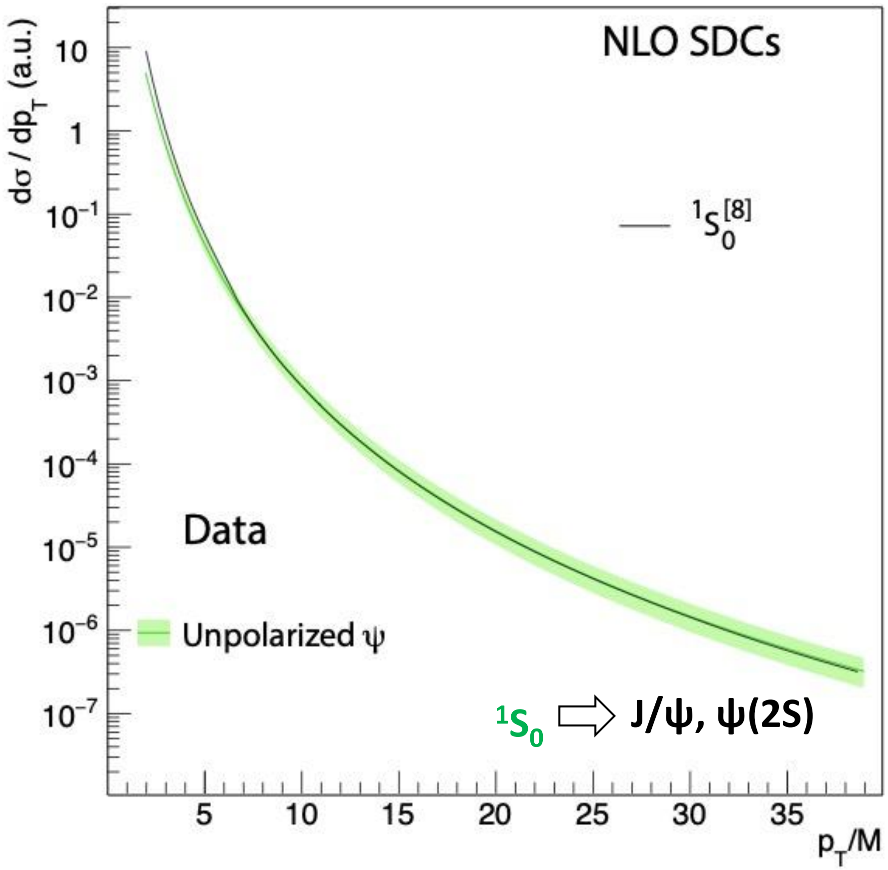
(*) The nuisance parameters are: ATLAS and CMS integrated-luminosity uncertainties; uncertainties on the branching ratios (B) used to derive the cross sections

Data fit vs. NRQCD (1)

The shape functions from the global fit agree **very well** with their NRQCD counterparts, over 8 orders of magnitude !

The data bands and the NLO SDCs were obtained in completely independent ways !

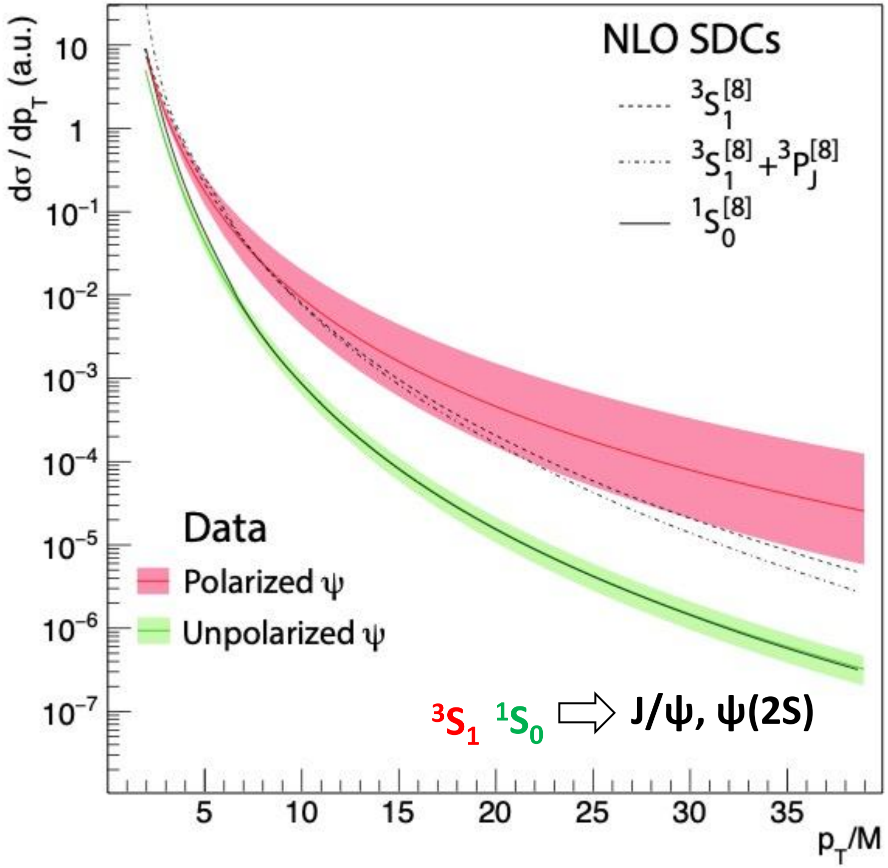


The width of the data bands only reflects *shape* uncertainties

Data fit vs. NRQCD (2)

The shape functions from the global fit agree **very well** with their NRQCD counterparts, over 8 orders of magnitude !

The data bands and the NLO SDCs were obtained in completely independent ways !

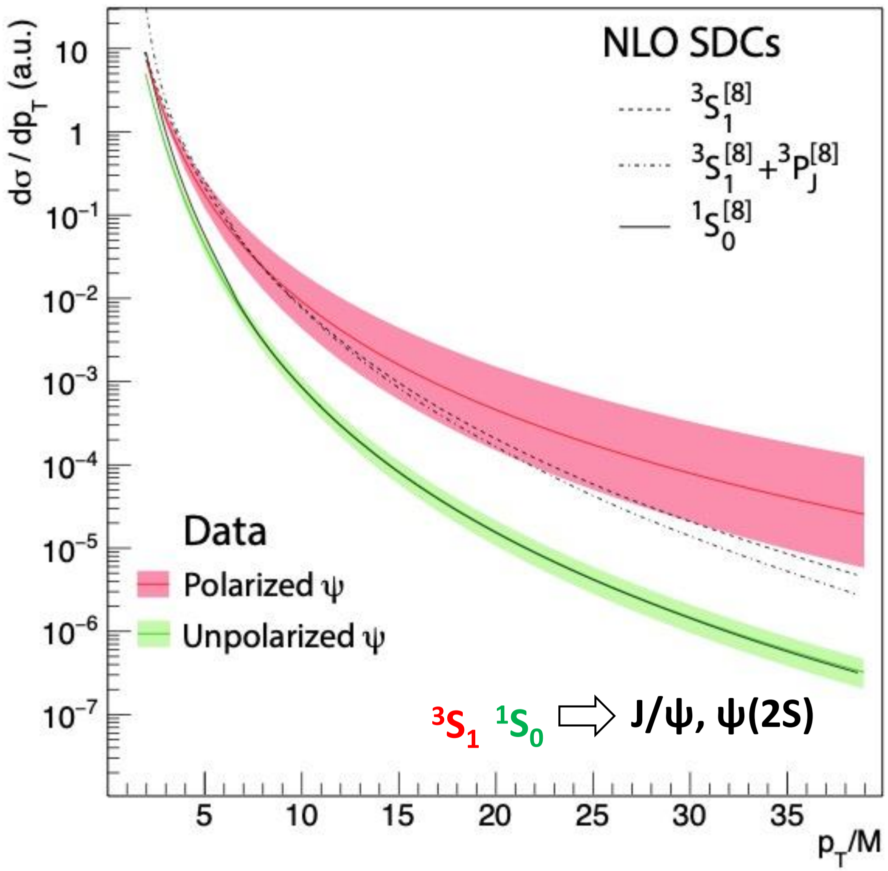


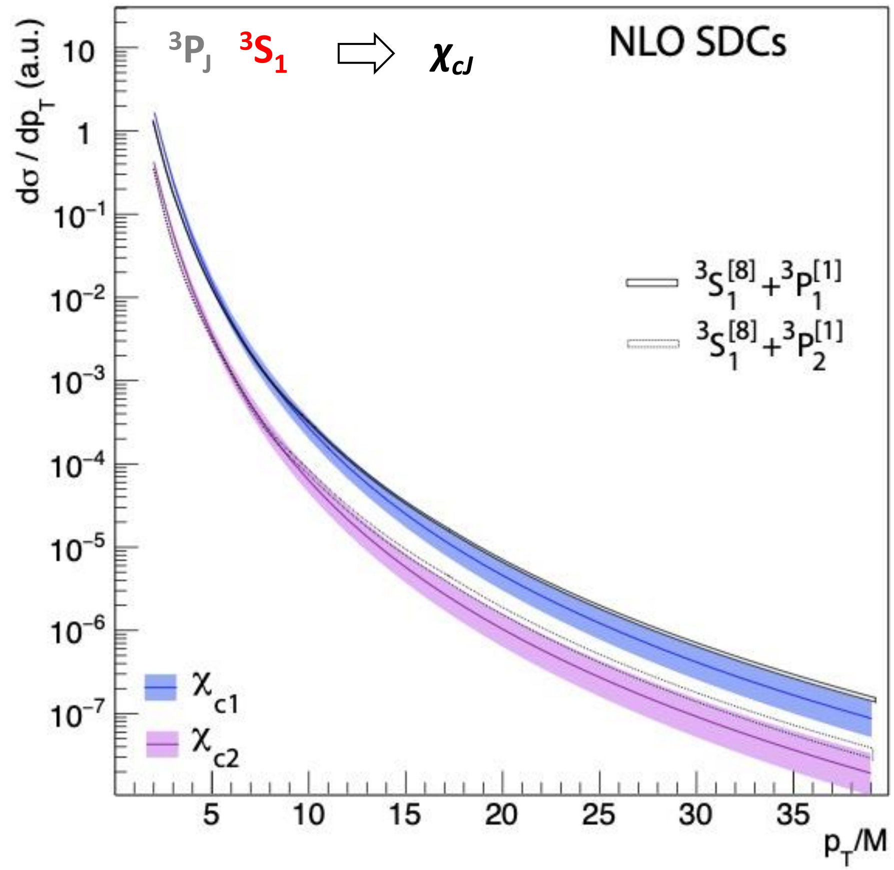
The width of the data bands only reflects *shape* uncertainties

Data fit vs. NRQCD (3)

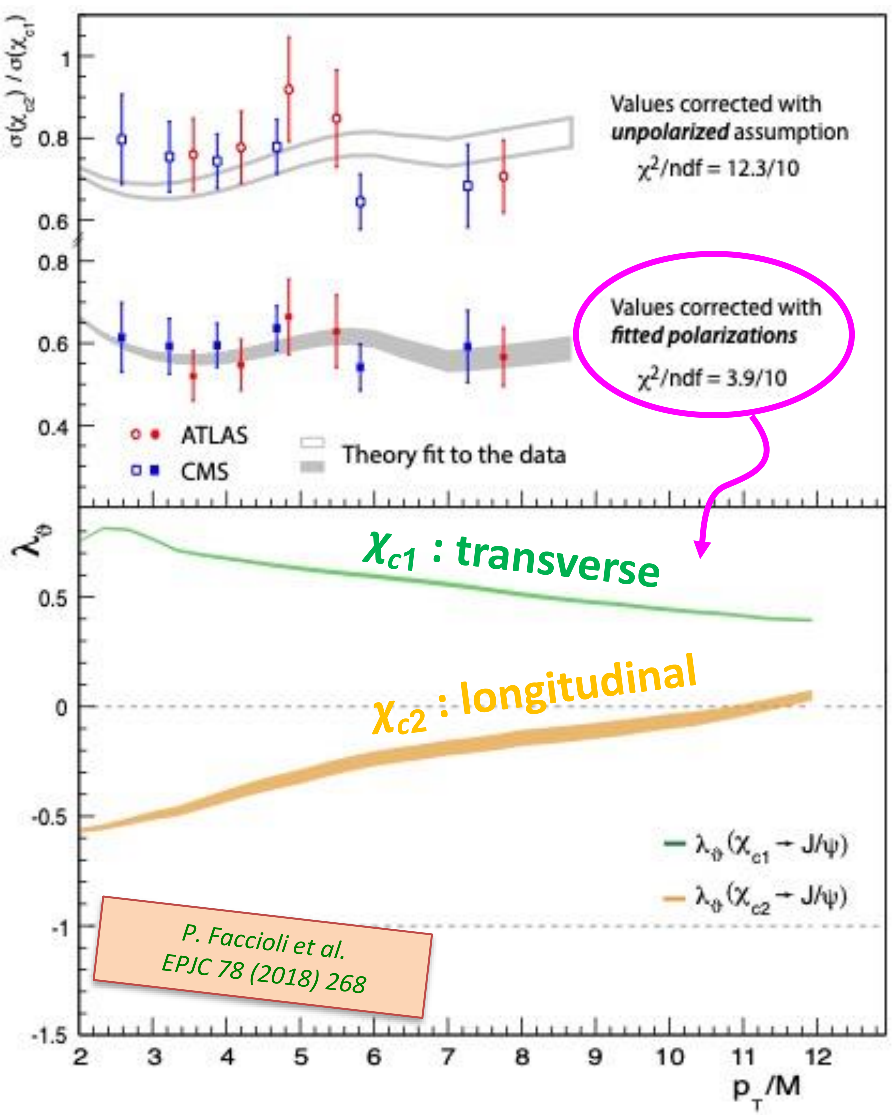
The shape functions from the global fit agree **very well** with their NRQCD counterparts, over 8 orders of magnitude !

The data bands and the NLO SDCs were obtained in completely independent ways !





A precise NRQCD prediction



In NRQCD, $\chi_{c1,2}$ 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) $\lambda_\vartheta(\chi_{c2})$

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

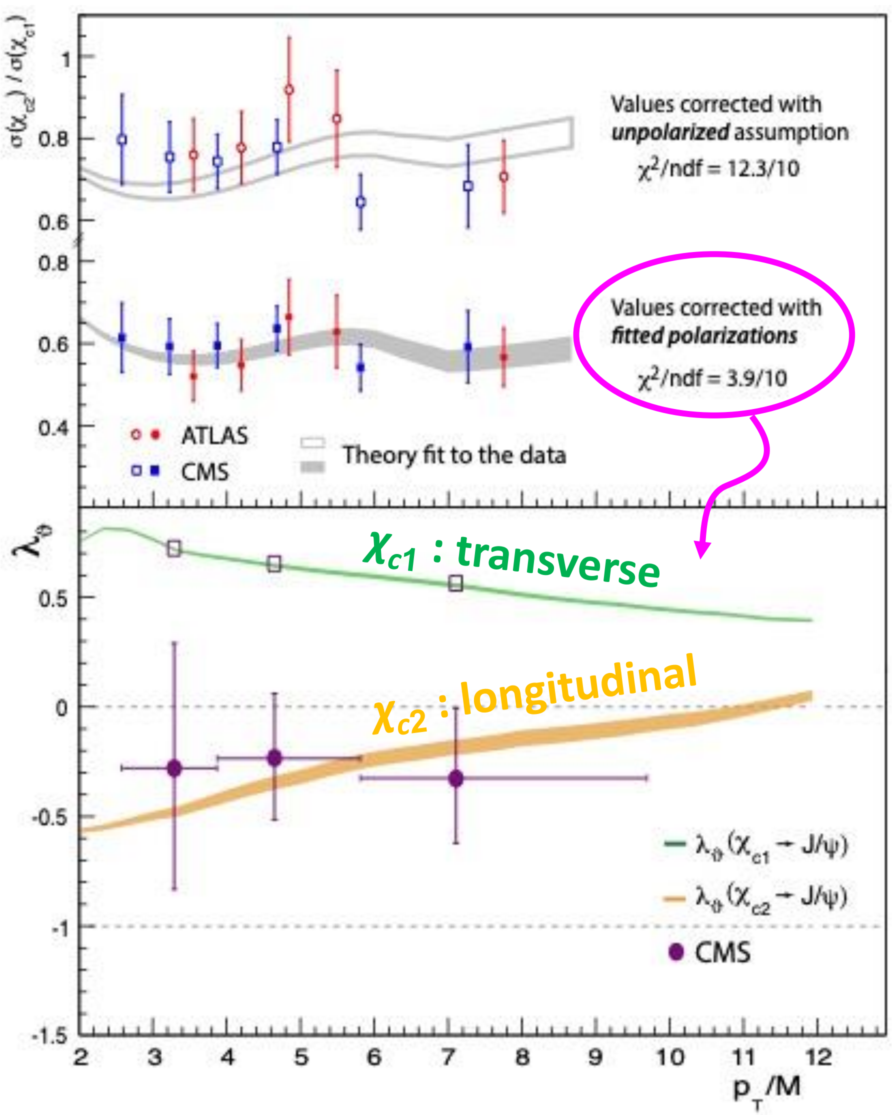
ATLAS and CMS χ_{c2} / χ_{c1} ratios imply

***r* = 0.217 ± 0.003**

(reminder: acceptance correction depends on λ_θ)

Conclusion: within NRQCD,
the χ_{c1} and χ_{c2} polarizations are predicted to be **very different** from one another;
a strongly constrained, precise and unambiguous prediction

A precise NRQCD prediction vs. CMS data



CMS measured the ratio between the cos ϑ distributions of the dimuons associated with the χ_{c2} and χ_{c1} radiative (J/ψ γ) decays (*)

This provides a constraint on the *difference* between the χ_{c2} and χ_{c1} polarizations

We fix $\lambda_\vartheta(\chi_{c1})$ to the prediction, and derive $\lambda_\vartheta(\chi_{c2})$

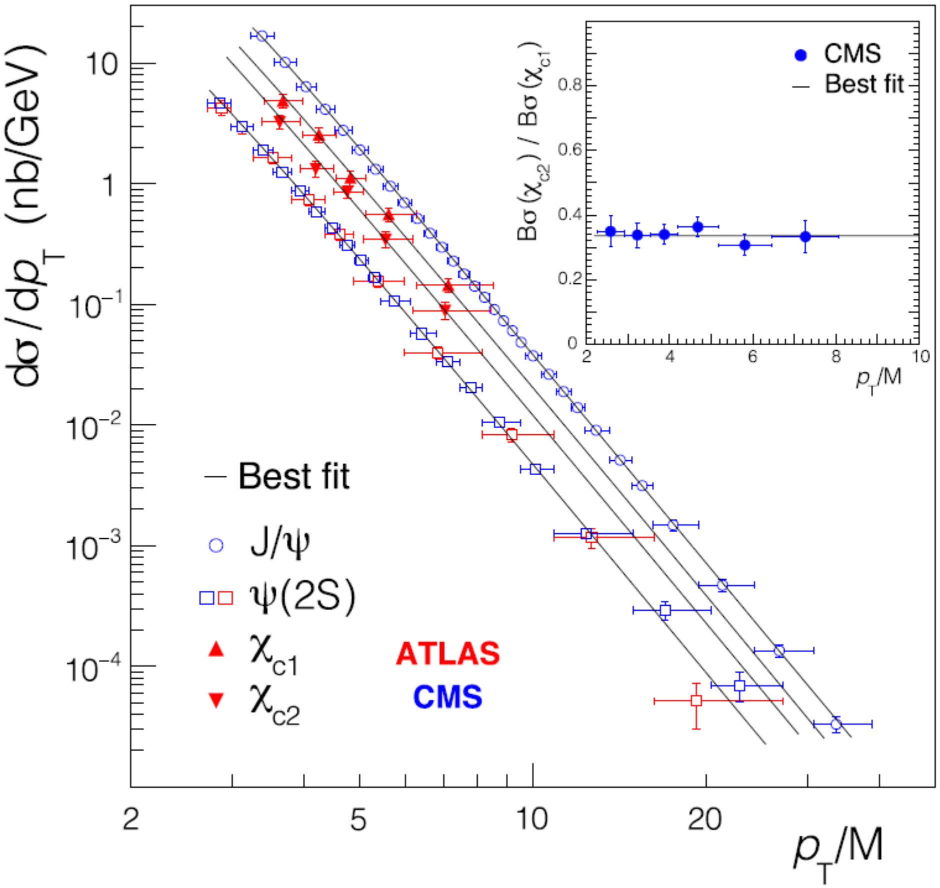
The data is in good agreement with the (quite extreme) predicted polarizations

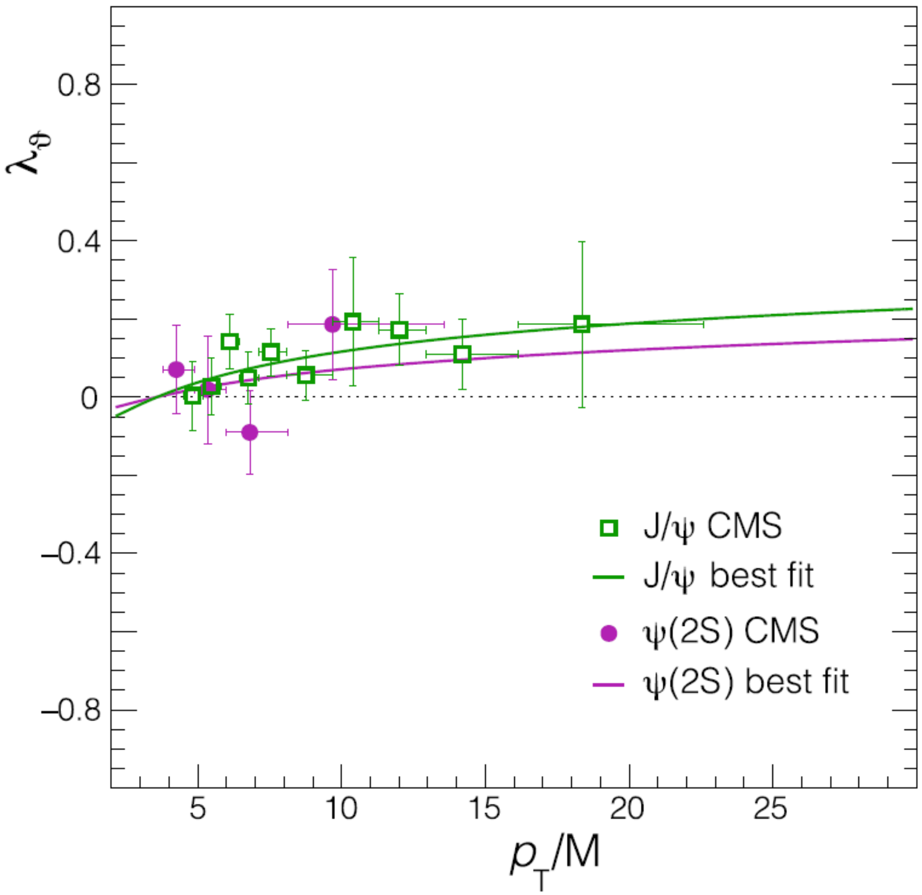
(*) See previous talk for all the details

A constraint on the sum of the χ_{c1} and χ_{c2} polarizations

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

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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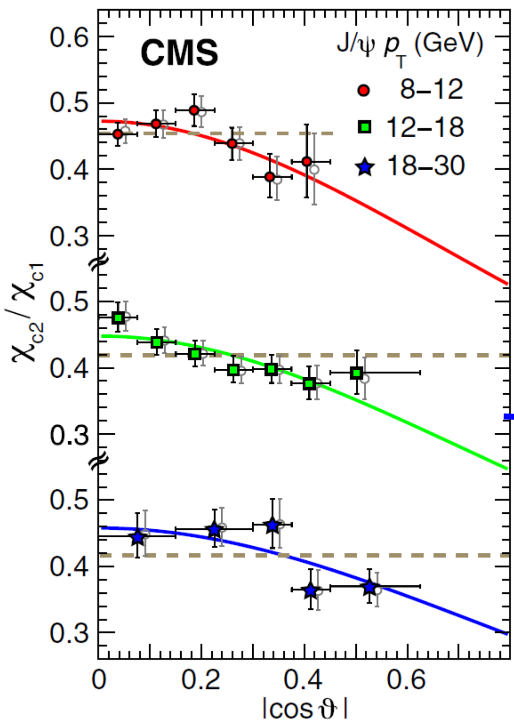
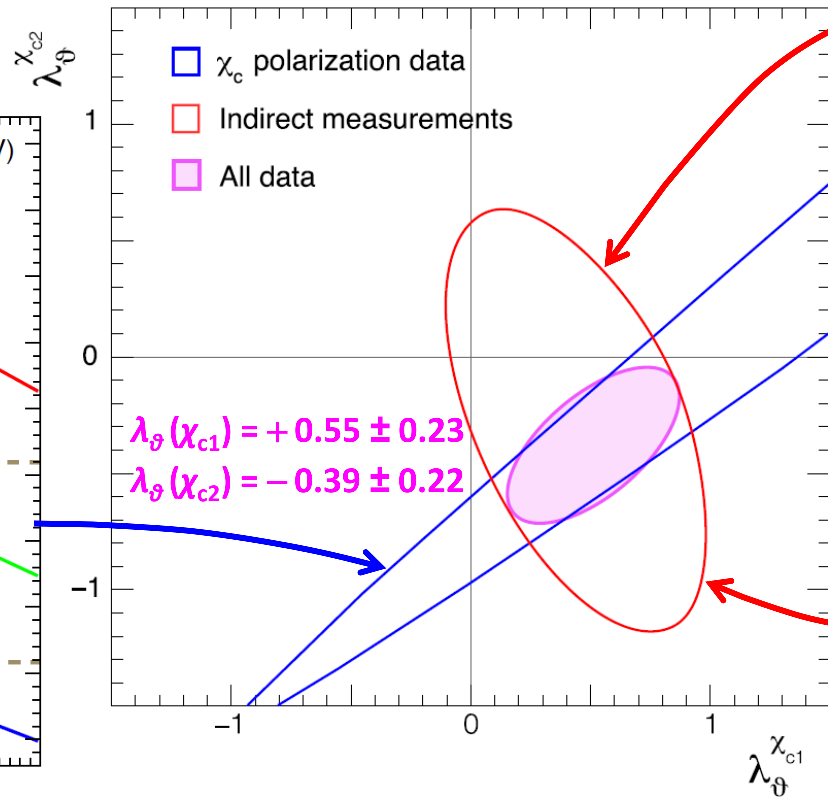
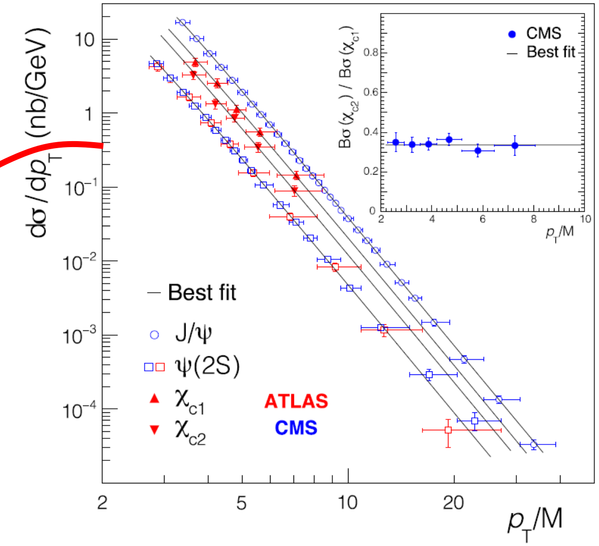
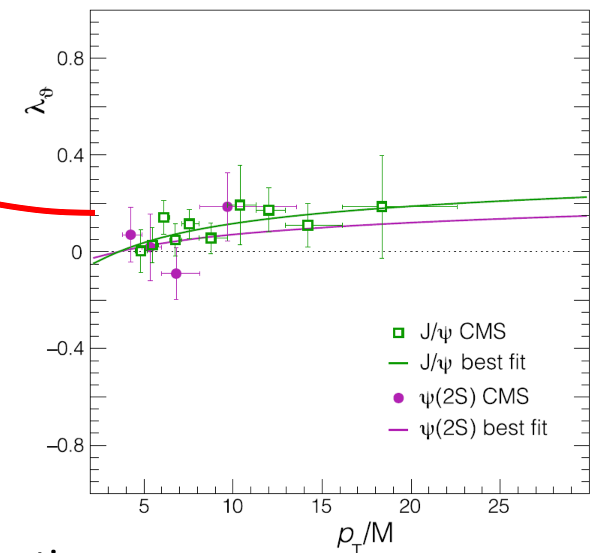
The combination of these “orthogonal” experimental constraints determines the two individual χ_{c1} and χ_{c2} polarizations;
this is a purely experimental result: no theory involved







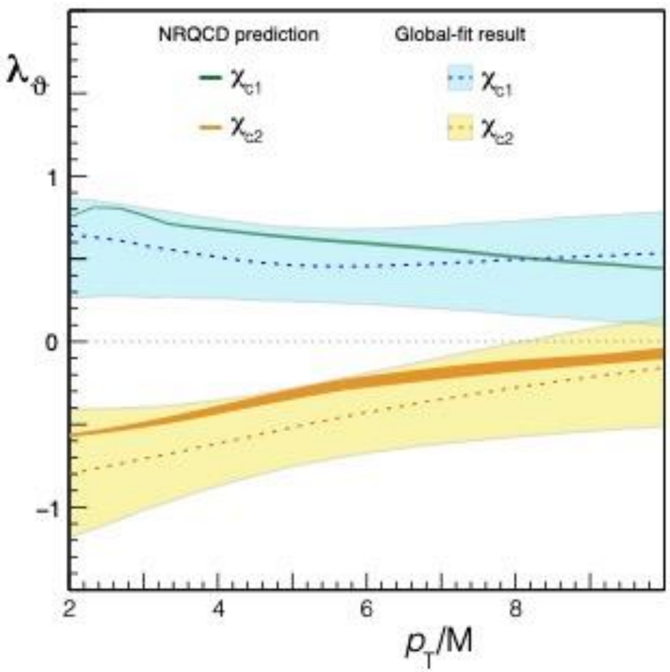


The J/ψ mesons from χ_{c1} and χ_{c2} decays are, respectively, transversely and longitudinally polarized

→ 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



Narrow bands: NRQCD prediction obtained from the ATLAS and CMS χ_{c2} / χ_{c1} ratios; $\boldsymbol{r = 0.217 \pm 0.003}$

Wide bands: result of the global fit of all charmonium cross sections and polarizations, with no theory inputs

The NRQCD prediction agrees perfectly with the data

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

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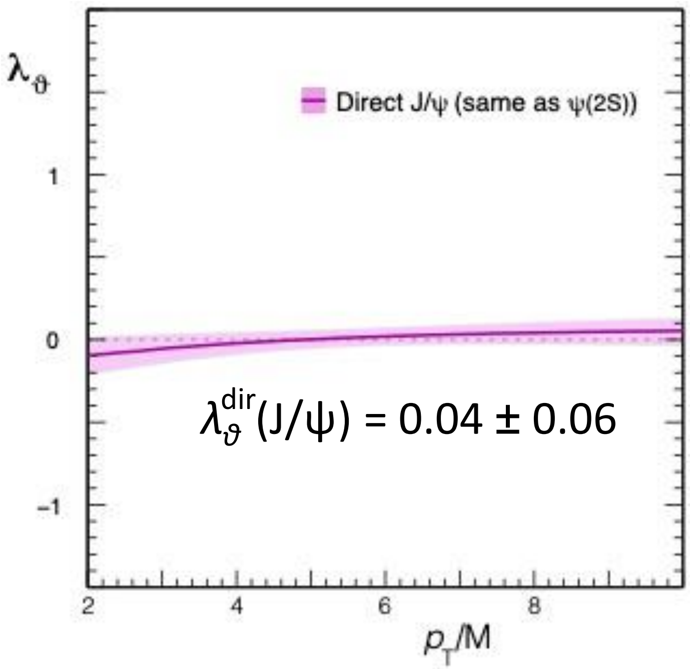
The (direct) J/ψ polarizations vs. p_T

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



$\lambda_\vartheta^{\mathrm{dir}}(\mathrm{J}/\psi) = 0.04 \pm 0.06$

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

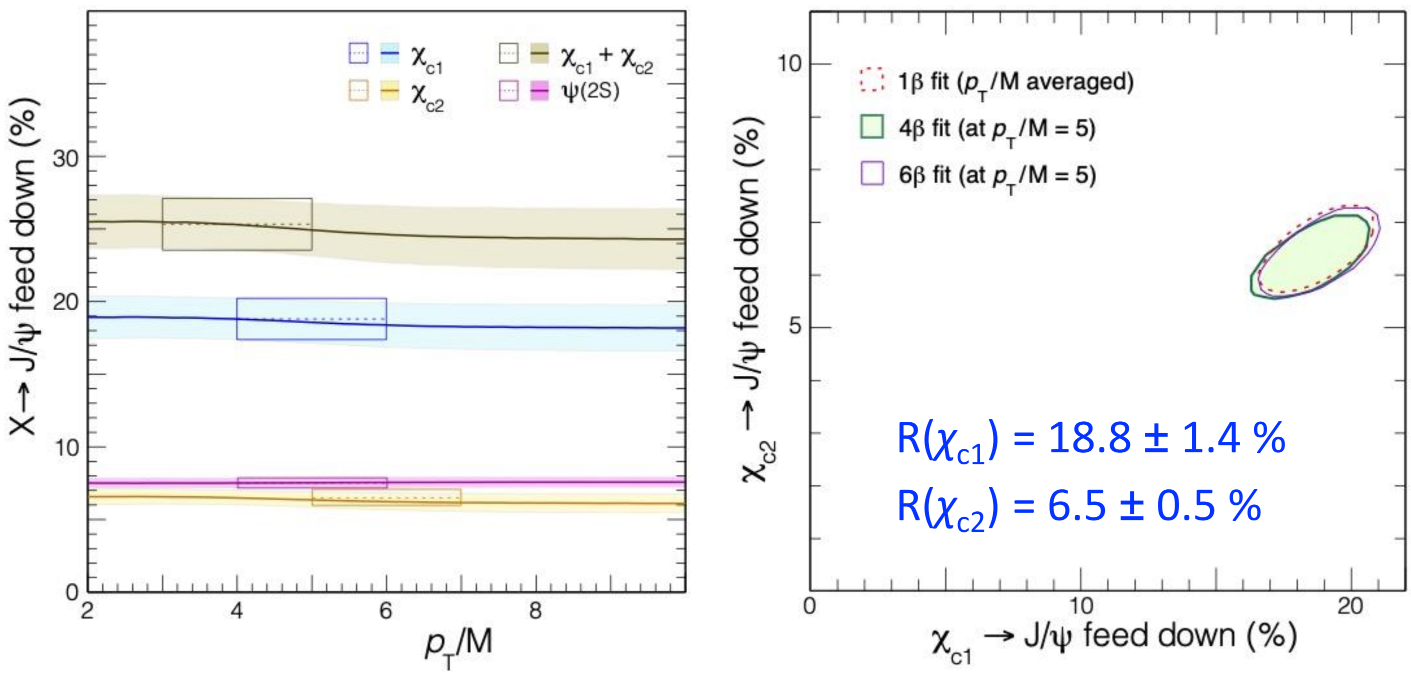
Zero and ***constant*** polarization: a big challenge to production models of vector quarkonia

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

Finally, the global-fit analysis also determines the fractions of J/ψ mesons produced from the feed-down decays of the χ_{c1} and χ_{c2} mesons



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

Summary

1) The methodology of global-fit analyses has a strong impact on the obtained results

The handling of correlations and uncertainties, both experimental and theoretical (including limitations in the validity domain of the perturbative calculations) is not trivial and can easily bias the results

The puzzling coexistence of several very different "NRQCD predictions" for the polarization was entirely due to the inconsistent treatments of data and theory

2) With a correct treatment of experimental and theoretical correlations and limitations, NRQCD describes remarkably well the J/ψ, ψ(2S), χ_{c1} and χ_{c2} yields and polarizations measured at mid rapidity

3) The new CMS measurement of χ_{c1} and χ_{c2} polarizations allows us to extract, for the first time, the polarization of the *directly* produced J/ψ mesons

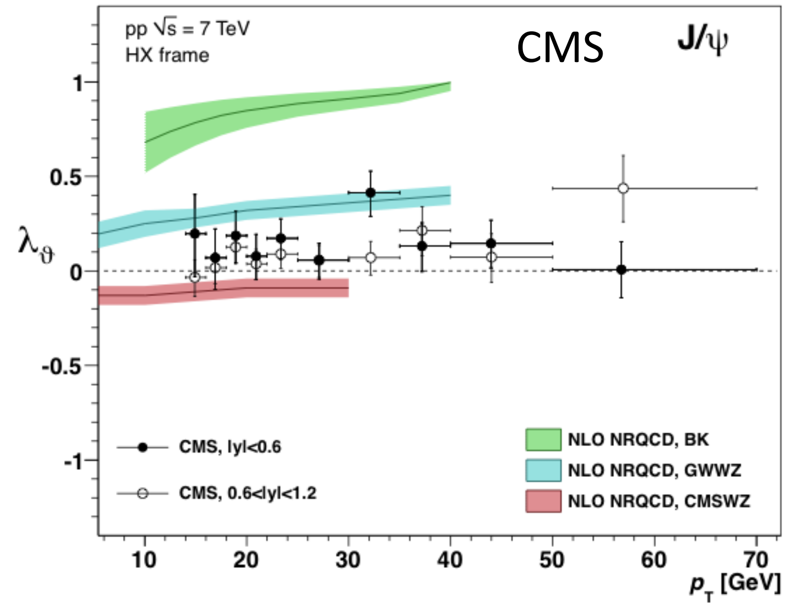
The result, $\lambda_{\vartheta}^{\mathrm{dir}}(J/\psi) = 0.04 \pm 0.06$, with no p_T dependence, is a *conceptual challenge* for NRQCD and any other production model

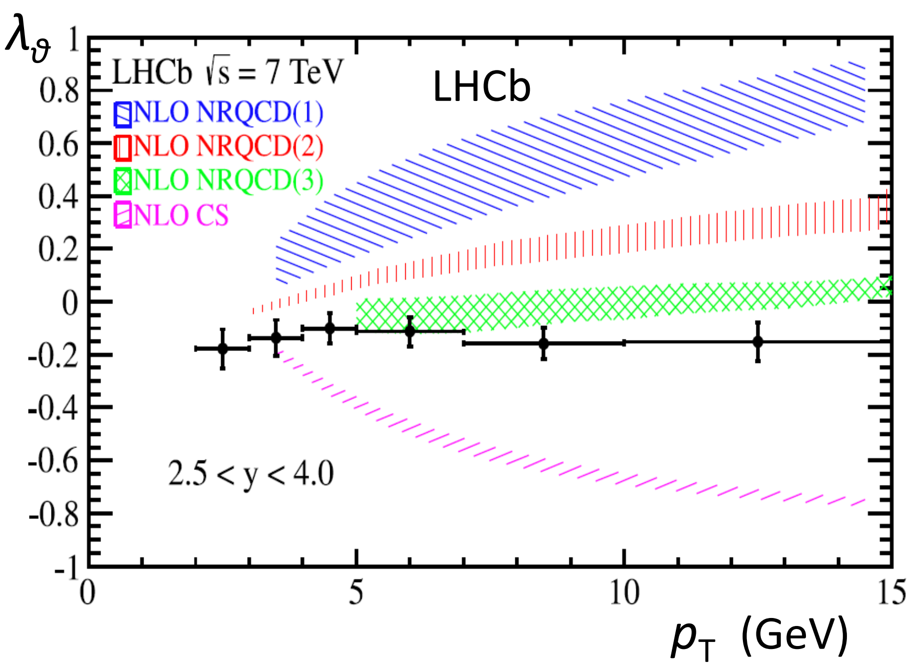
Backup

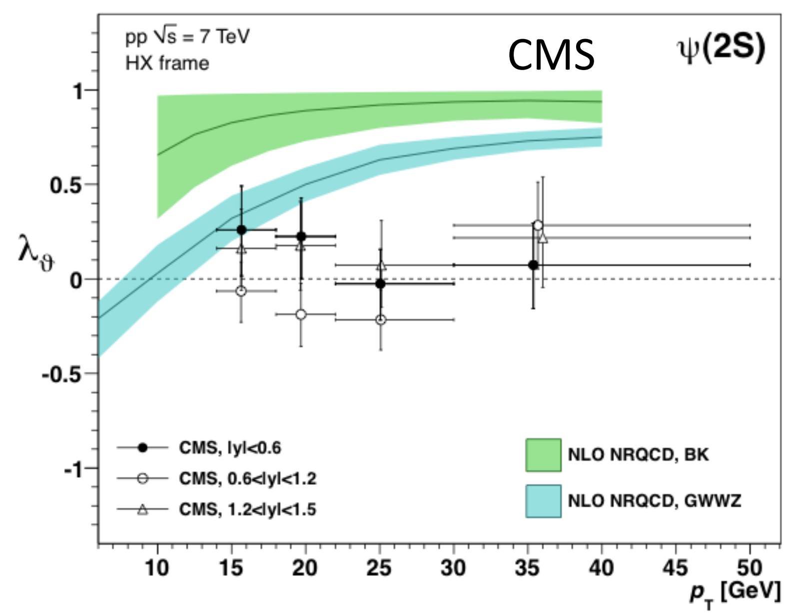
Inaccurate fit methodologies give unreliable results

The same theory inputs (NLO SDCs) result in very different quarkonium polarization "NRQCD predictions" simply because of inconsistent treatments of data and theory

With robust analysis techniques
and high quality data,
quarkonium production measurements
can become a high precision probe of QCD !



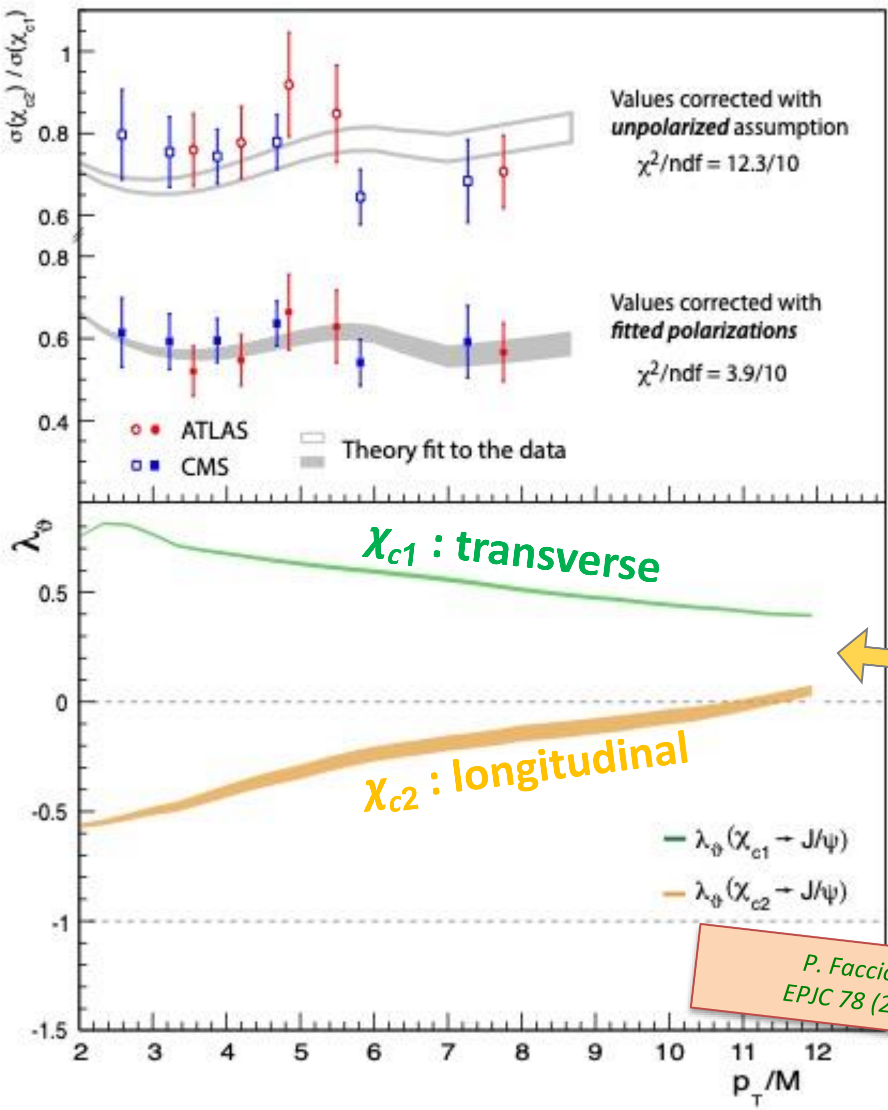




Comparison between two predictions (1)

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

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



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

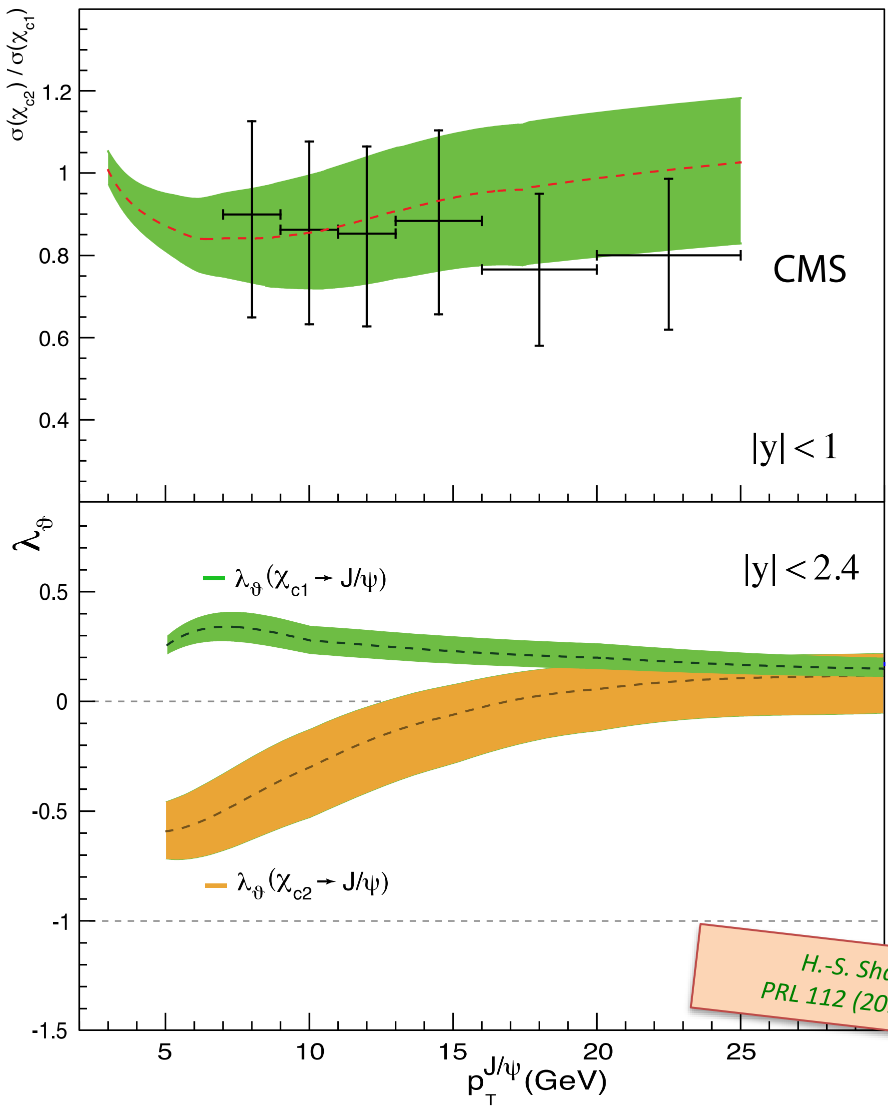
Faccioli et al. derive ***r* = 0.217 ± 0.003**
from CMS + ATLAS data (averaged)
with acceptance corrections corresponding to the *final* polarization prediction
(*iterative* procedure)
and, thus, no added “polarization uncertainty”

A very precise prediction

Comparison between two predictions (2)

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

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



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

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

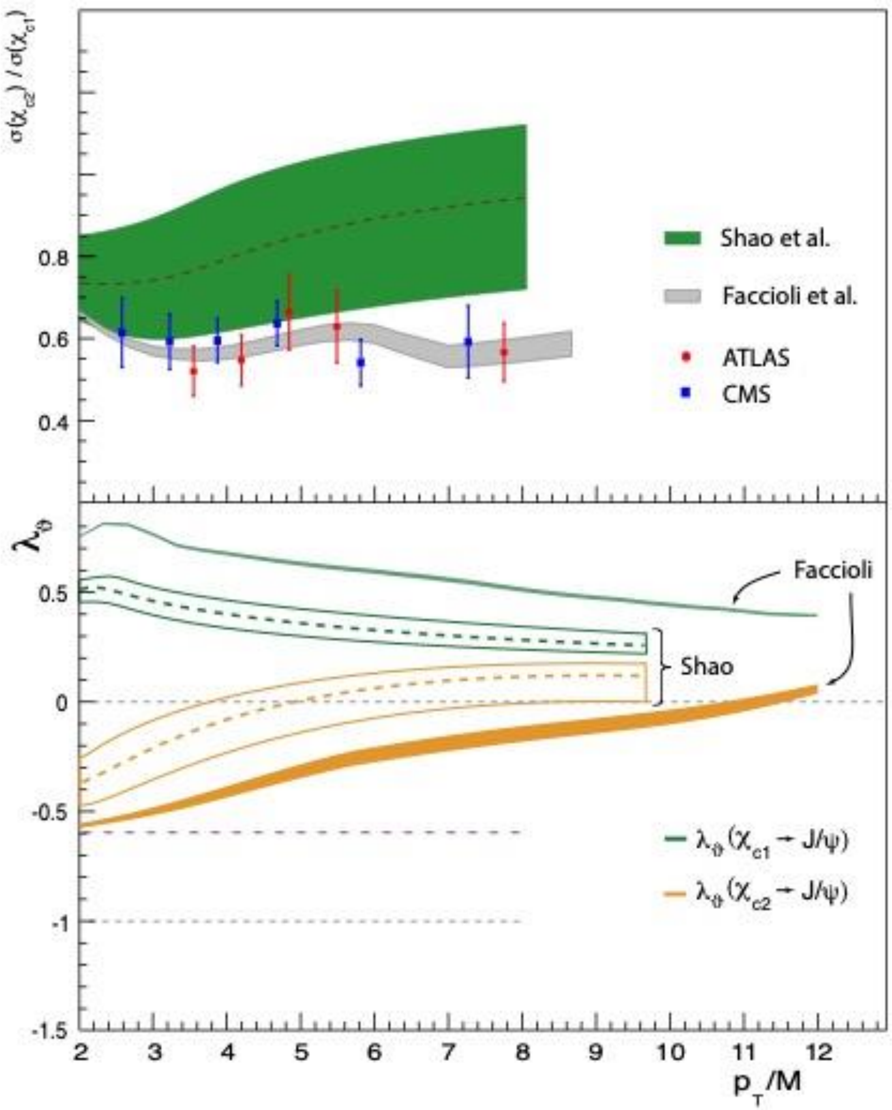
CDF:
= central values using $\lambda_\vartheta = 0.13 \pm 0.15$ for χ_{c1} and χ_{c2}
= no correlated variations considered
= uncertainty added in quadrature with all others

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

Comparison between two predictions (3)

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
$r = 0.27 \pm 0.06$

Faccioli et al., EPJC 78 (2018) 268
$r = 0.217 \pm 0.003$

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

There is no "*polarization uncertainty*"; instead, there is a *correlation* between the polarization and the cross sections