NRQCD vs LHC quarkonium production: signs of a deeper J/ψ polarization puzzle?

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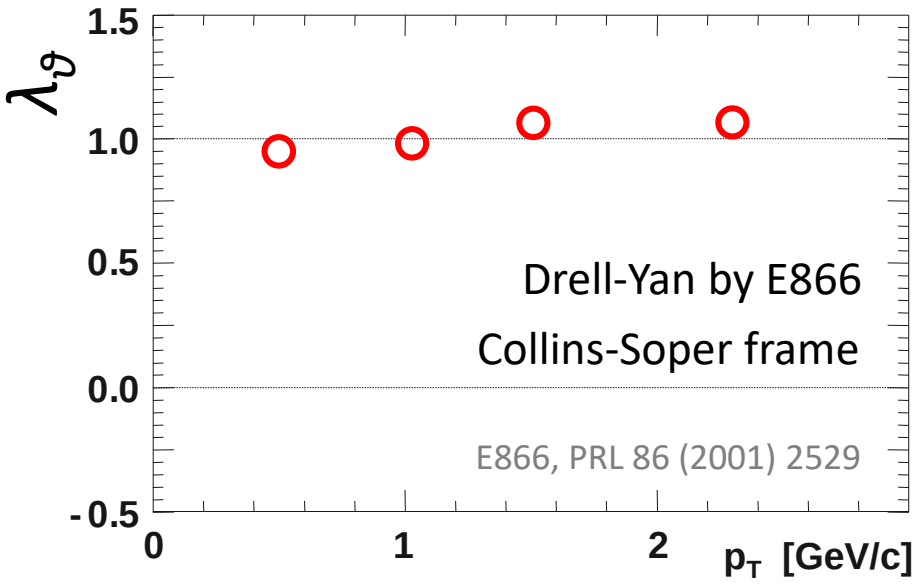
Quark Confinement and the Hadron Spectrum 2021, 6/8/2021

Vector particles are always polarized (1)

Sometimes the full polarization is immediately recognizable…



$$\frac{dN}{d\Omega} \propto 1 + \lambda_\vartheta \cos^2\vartheta$$

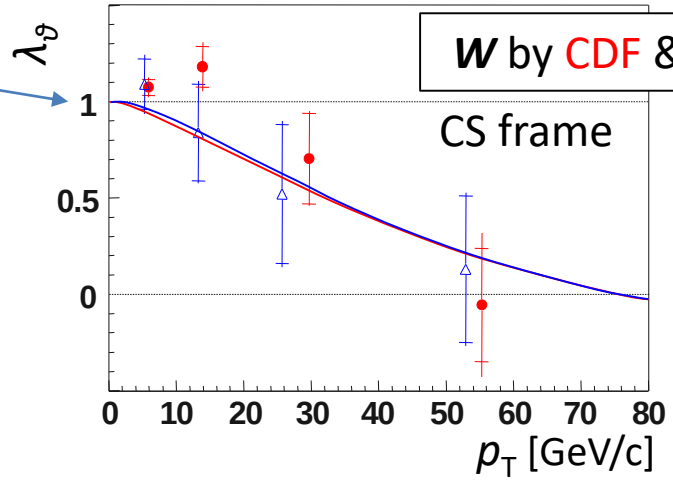
$$\lambda_\vartheta = +1 \rightarrow J_z = \pm 1$$

For dominant **2-to-1 processes**, of order $\mathcal{O}(\alpha_S^0)$,
maximum transverse polarization is seen in the Collins-Soper frame

Vector particles are always polarized (2)

But sometimes the superposition of different natural polarization axes (preventing an "optimal" frame choice) smears the magnitude of λ_ϑ *away from* $p_T = 0$.
As a recognizable consequence, the polarization becomes **strongly p_T dependent**.

$\lambda_\vartheta = +1 \leftrightarrow J_z = \pm 1$

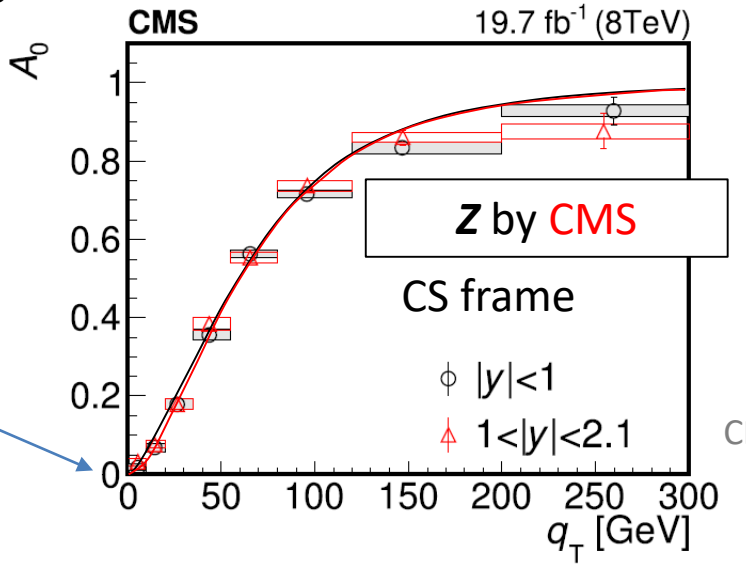


$$\frac{dN}{d\Omega} \propto 1 + \lambda_\vartheta \cos^2\vartheta$$

D0, PRD 63 (2001) 072001
CDF, PRD 70 (2004) 032004

Assuming $\mathbf{J_z = \pm 1}$ *along the HX and GJ axes,* as foreseen for 2-to-2 processes of $\mathcal{O}(\alpha_S^1)$, in suitable mixtures, we reproduce the trends seen in the CS frame:

the polarization *is* always **transverse**



$$\frac{dN}{d\Omega} \propto 1 + \frac{1-\frac{3}{2}A_0}{1+\frac{1}{2}A_0}\cos^2\vartheta$$

CMS, PLB 750, 154 (2015)

$A_0 = 0 \leftrightarrow J_z = \pm 1$

Is “unpolarized” even possible?

Vector states are intrinsically polarized for any given elementary process

Theorem P.F. et al., PRL 105, 061601

For any subprocess producing a **J = 1 state**

$| V; J, J_z \rangle = a_{-1} | 1, -1 \rangle + a_0 | 1, 0 \rangle + a_{+1} | 1, +1 \rangle$,

there exists a quantization axis

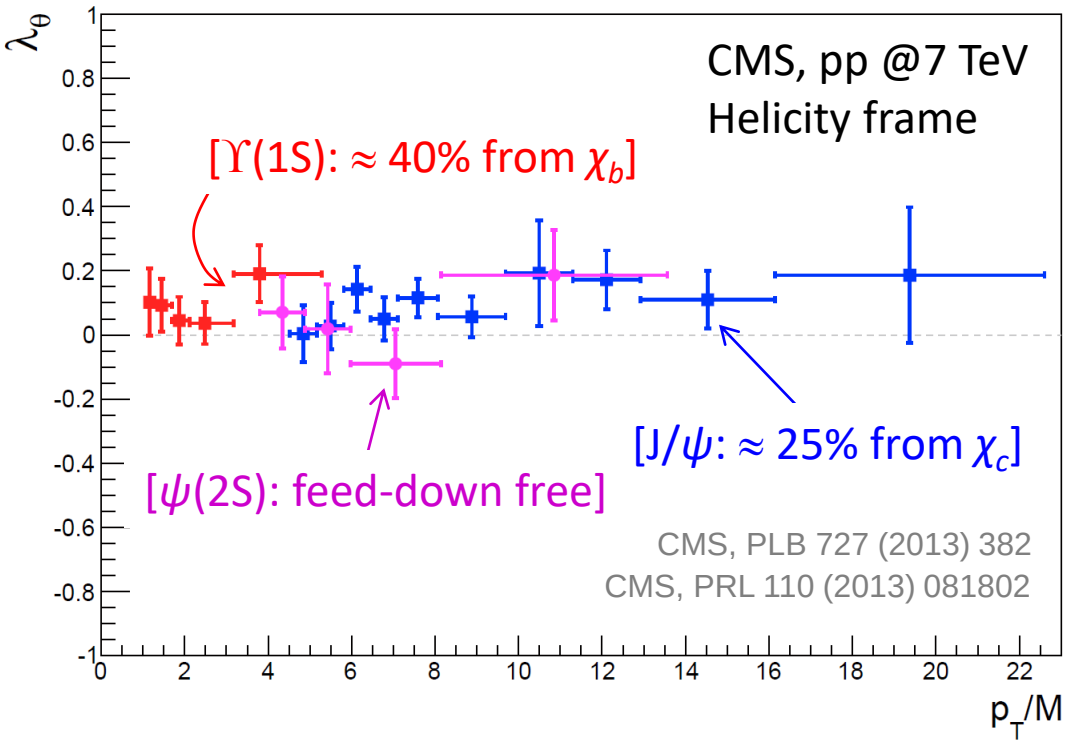
along which the $J_z = 0$ component a_0 **vanishes**

Intuitively consistent with classical expectation:
a vector of modulus 1 has always projection ±1 along some axis

…which implies that λ_ϑ **= +1 along that axis**

Vector quarkonia: a paradigmatic exception

Mid-rapidity LHC data show unpolarized production of vector quarkonia



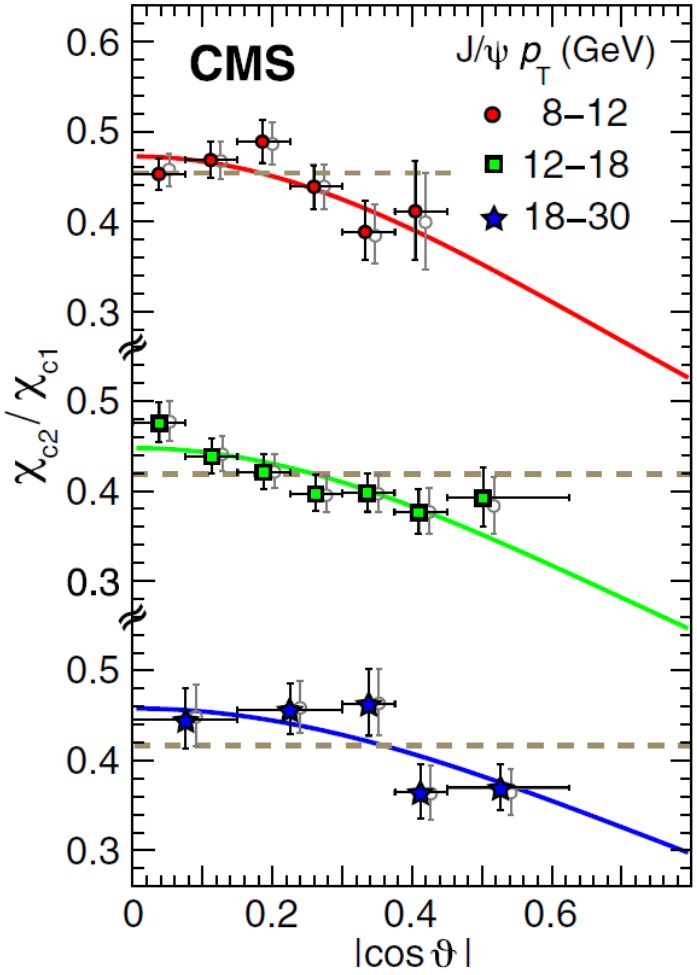
ψ(2S)
J/ψ
Υ(1S)

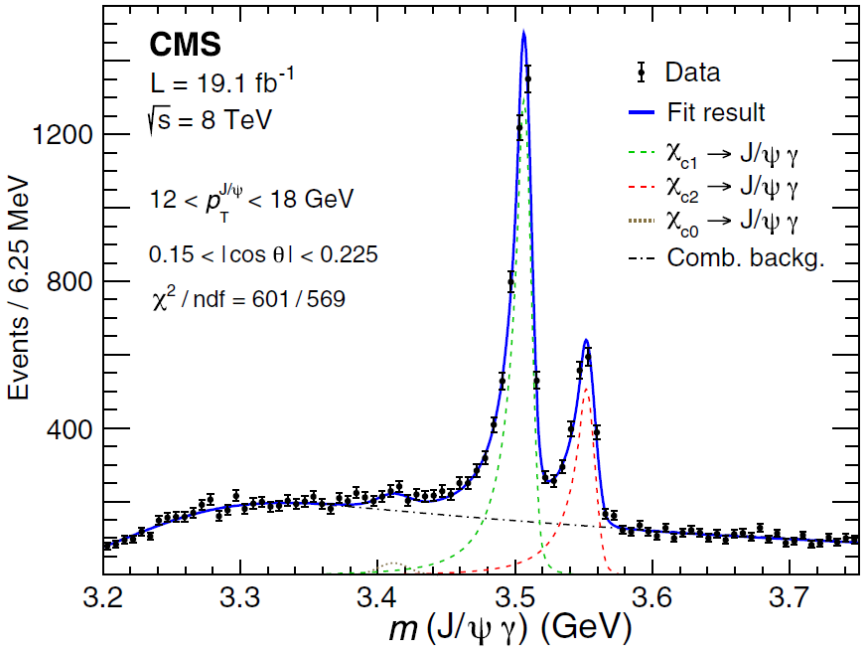
- None of the parameters λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$, $\tilde{\lambda}$ is significantly different from 0
- There is **no visible dependence on p_T** : seemingly not a transition domain
- No visible difference between states despite different χ feed-downs

What is the role of the χ feed-down decays ?

χ_{c2} vs. χ_{c1} polarizations: direct experimental constraints

CMS, PRL 124 (2020) 162002

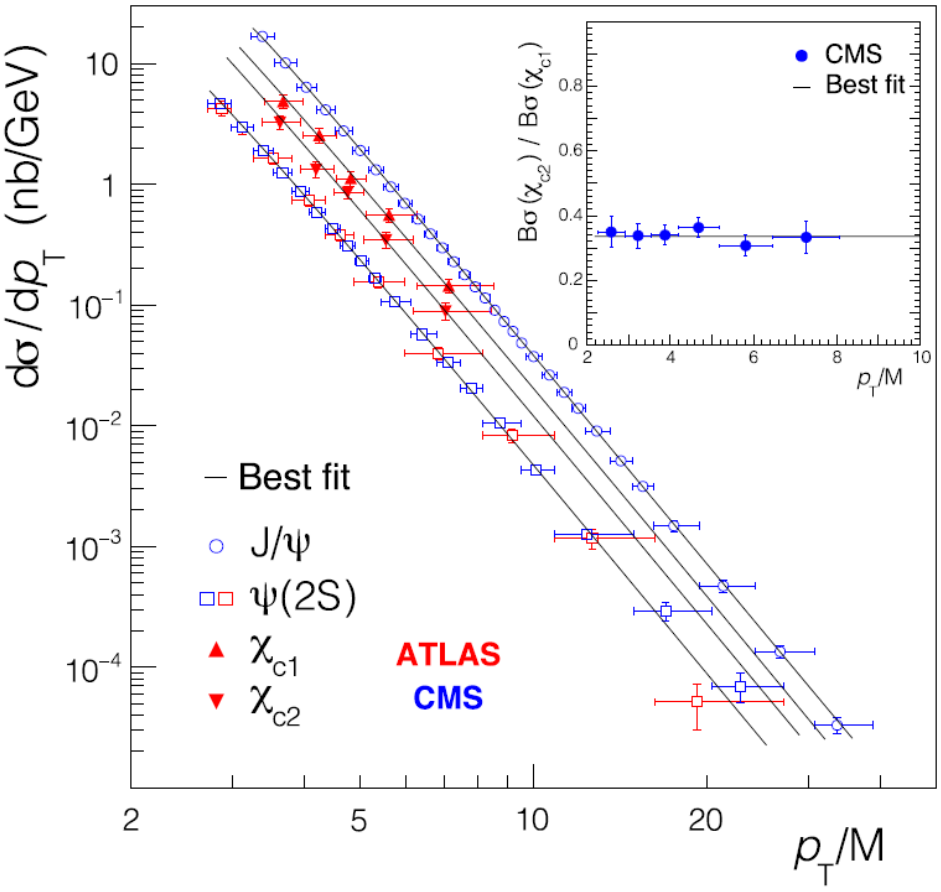


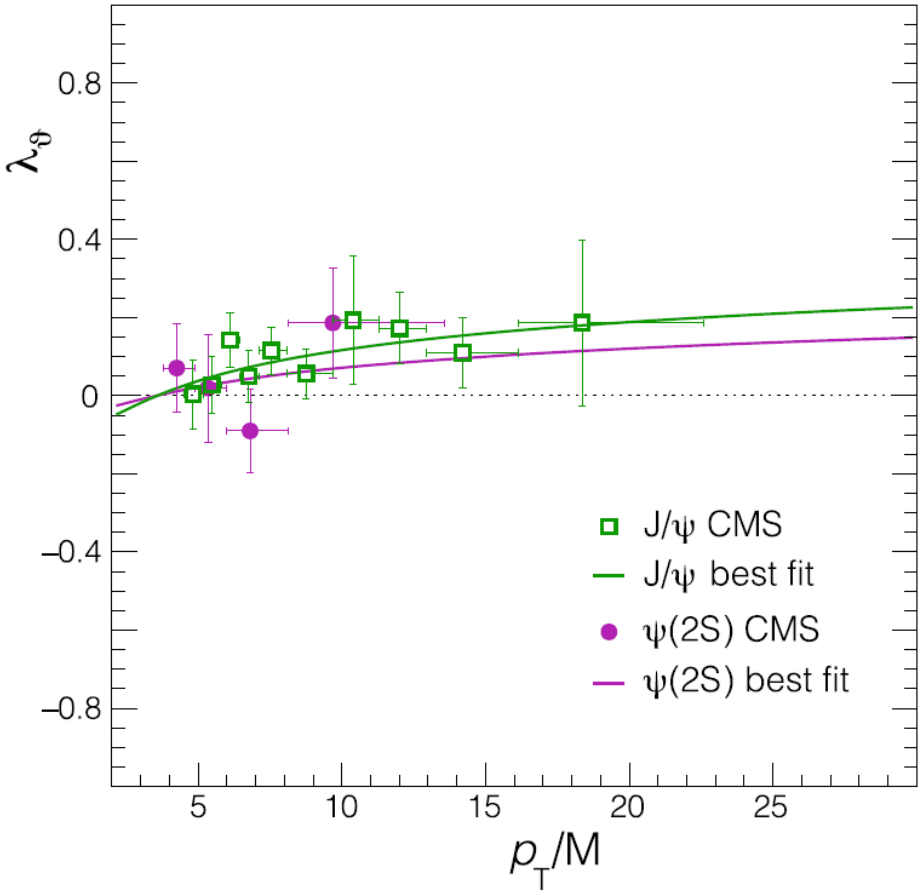


CMS measured the ratio between the (J/ψ from) χ_{c2} and χ_{c1} cosϑ distributions.

This provides a constraint on the *difference* between the two polarizations

χ_{c2} vs. χ_{c1} polarizations: indirect experimental constraints



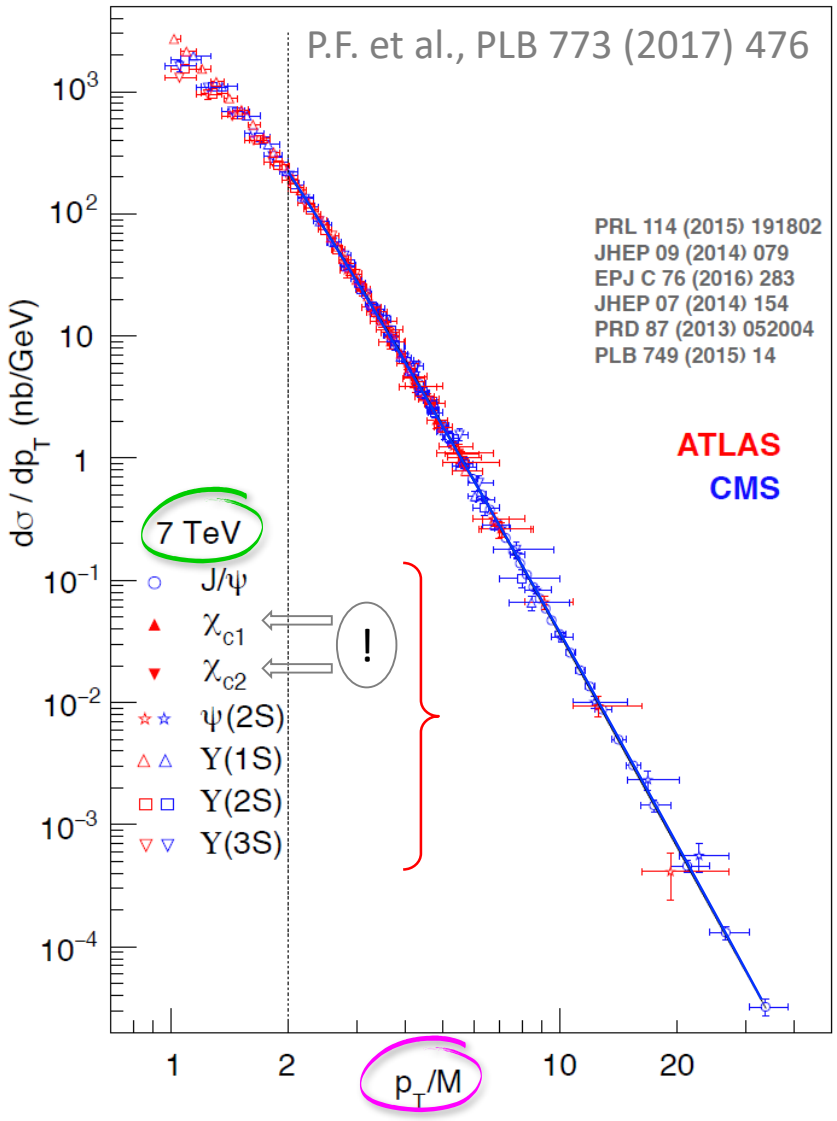


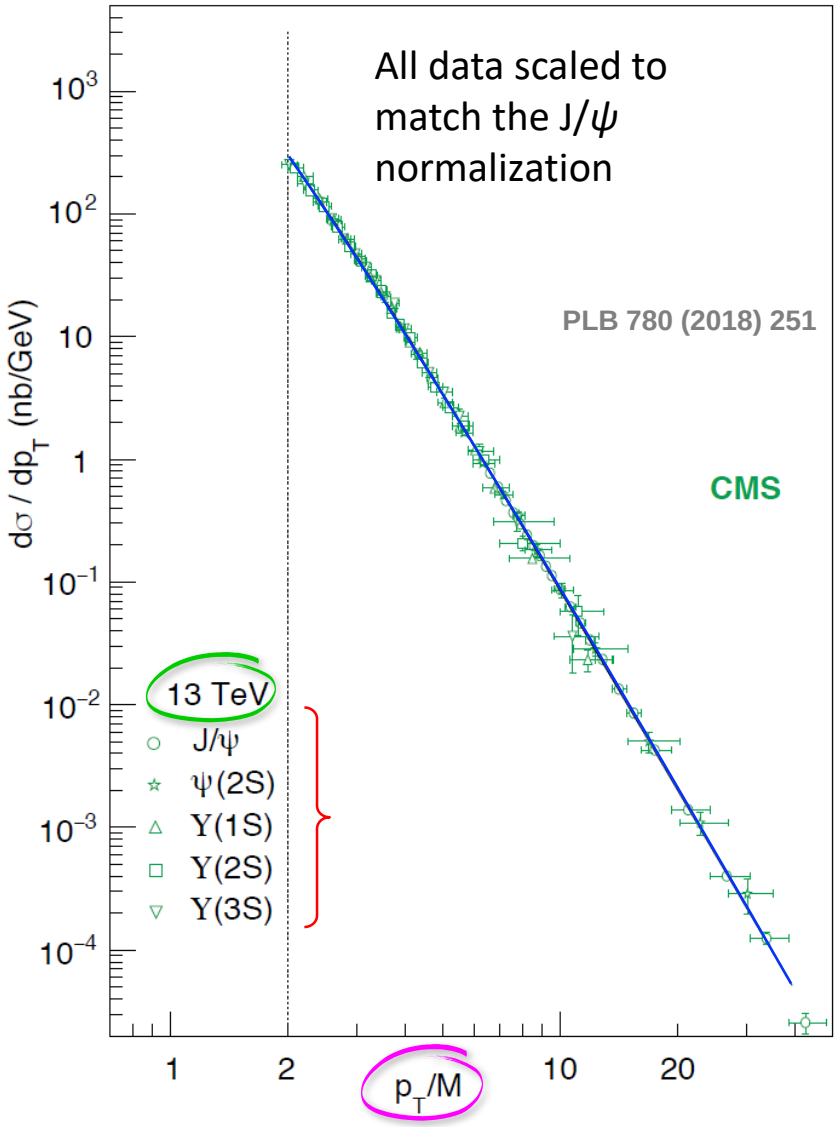
ATLAS and CMS measurements of J/ψ, ψ(2S), χ_{c1} and χ_{c2} cross sections, together with the J/ψ and ψ(2S) polarizations, constrain the *sum* of the χ_{c1} and χ_{c2} polarizations

Only assumption: *directly* produced J/ψ and ψ(2S) have the same polarization vs p_T /M

A "universal" p_T/M scaling

No hint of mass-dependence in mid-rapidity p_T distributions (nor for λ_ϑ)
from J/ψ to Υ(3S) after dimensional scaling, $p_T \rightarrow p_T/M$, at least for $p_T/M > 2$
$\rightarrow$ no reason to question similarity of direct J/ψ and ψ(2S) production dynamics

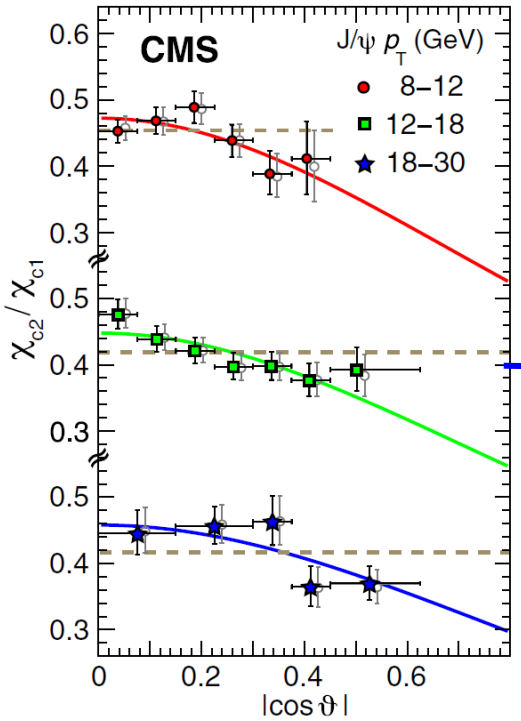


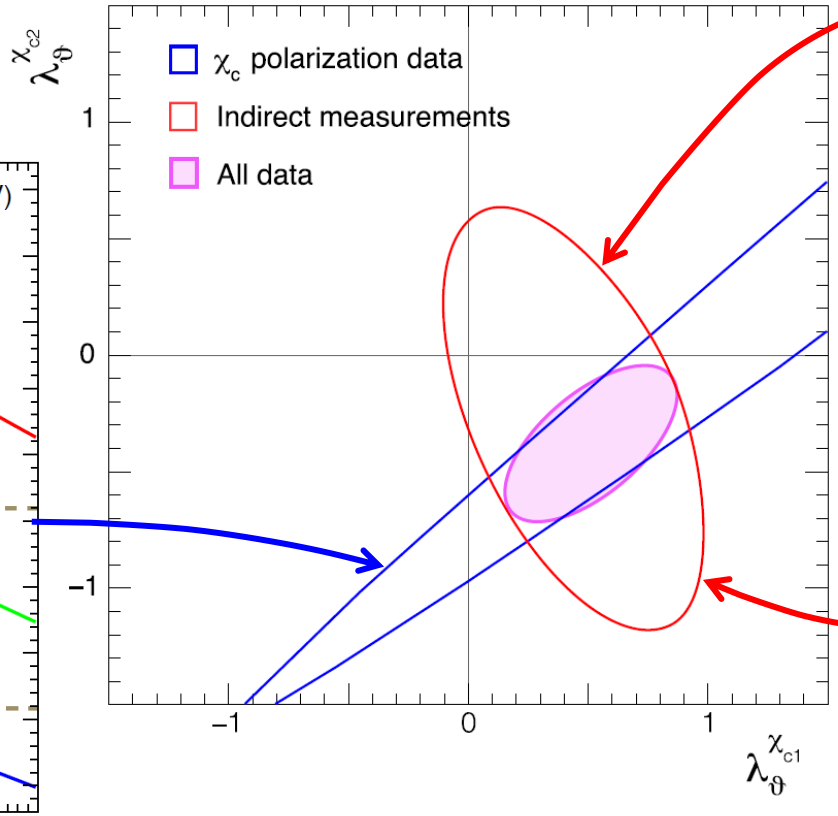


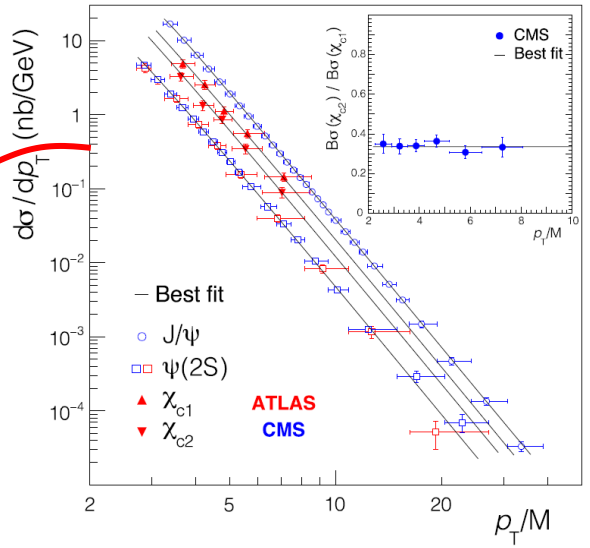
The χ_c states are strongly polarized !

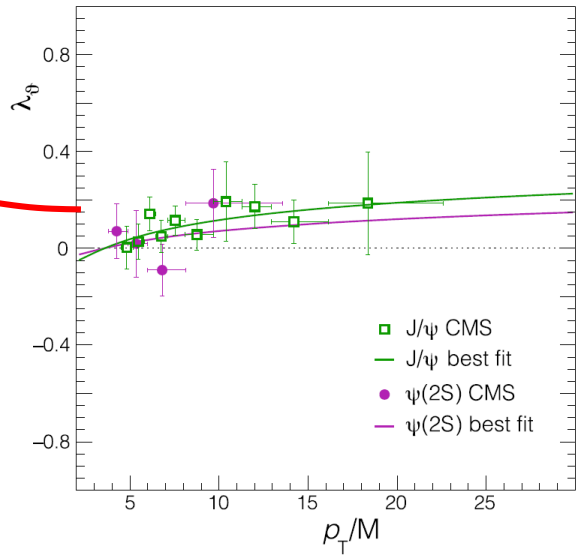
The combination of these two "orthogonal" experimental constraints determine the two individual χ_{c1} and χ_{c2} polarizations

P.F. et al., EPJC 80 (2020) 623







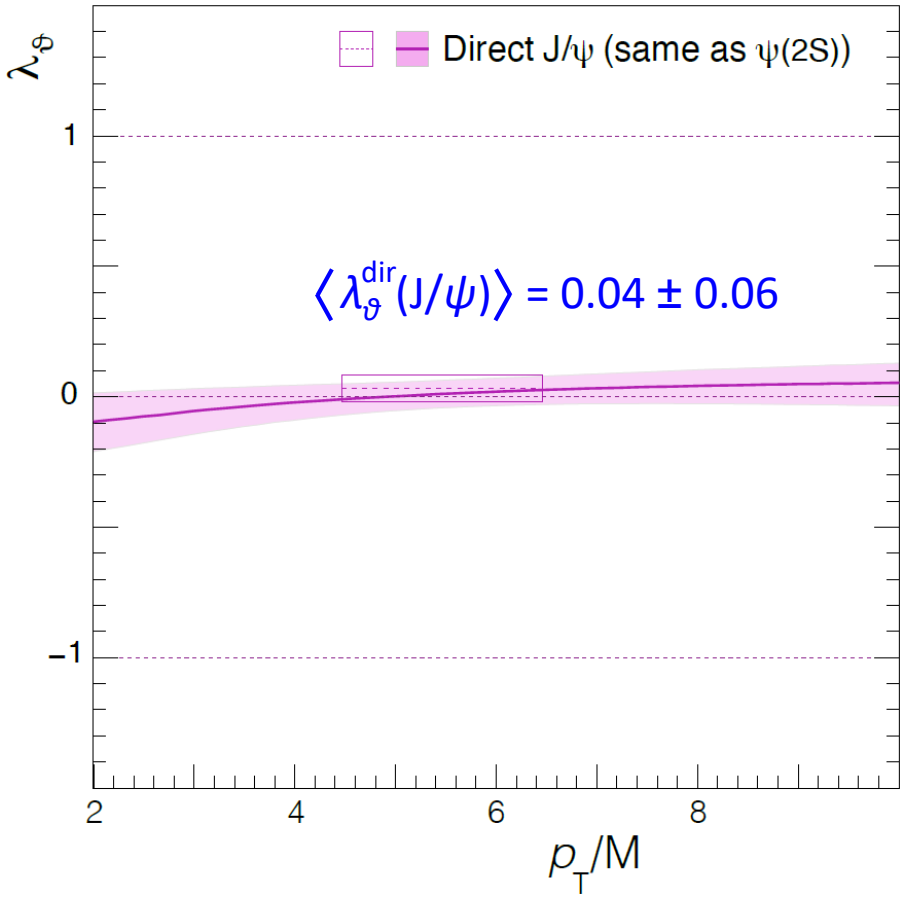


J/ψ from χ_{c1} and χ_{c2} are, respectively, transversely and longitudinally polarized

$\rightarrow$ they tend to cancel out in their contribution to J/ψ

…and the J/ψ polarization is even more "zero" !

The global data fit also allows us to extract a measurement of the polarization of the *directly produced* J/ψ



Strong evidence of unpolarized production

A challenge to production models: only a "fortunate" ***mixture of subprocesses*** or ***randomization effects*** can lead to zero polarization

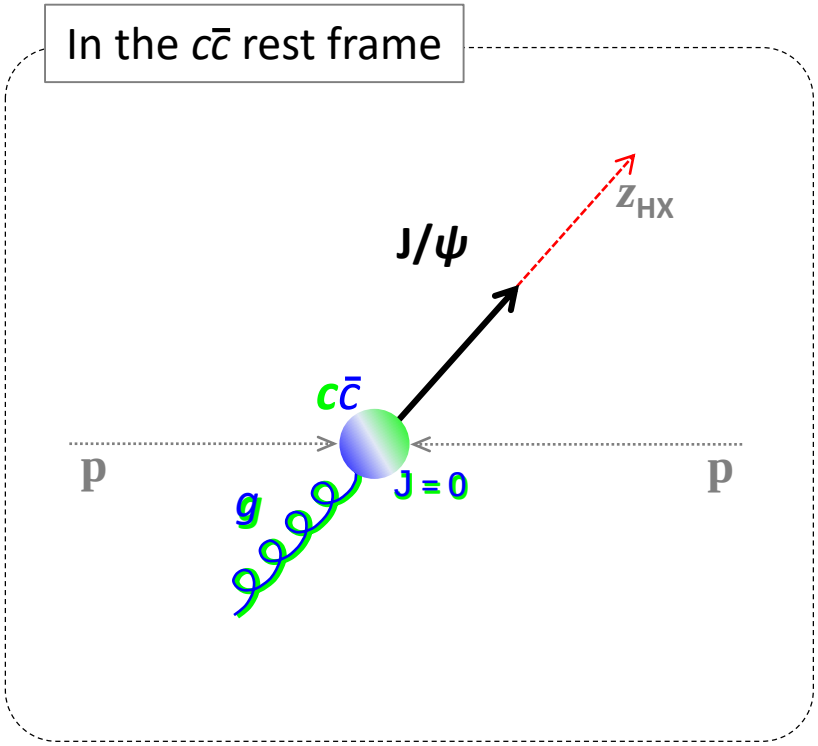
→ a clear sign of the **unique nature and production mechanism** of heavy quarkonia

Evidence of a “cascade” mechanism?

Without invoking any theory framework, the most ***natural*** way to explain a zero polarization observation is a two-step mechanism with an **unobserved intermediate *J* = 0 state**

E.g.: $pp \rightarrow c\bar{c}[J=0] \rightarrow J/\psi\, g\, g\, g$

In the transition from the *J* = 0 “pre-resonance” to the vector bound state,
the polarization is fully ***randomized*** because we lose connection to its natural reference



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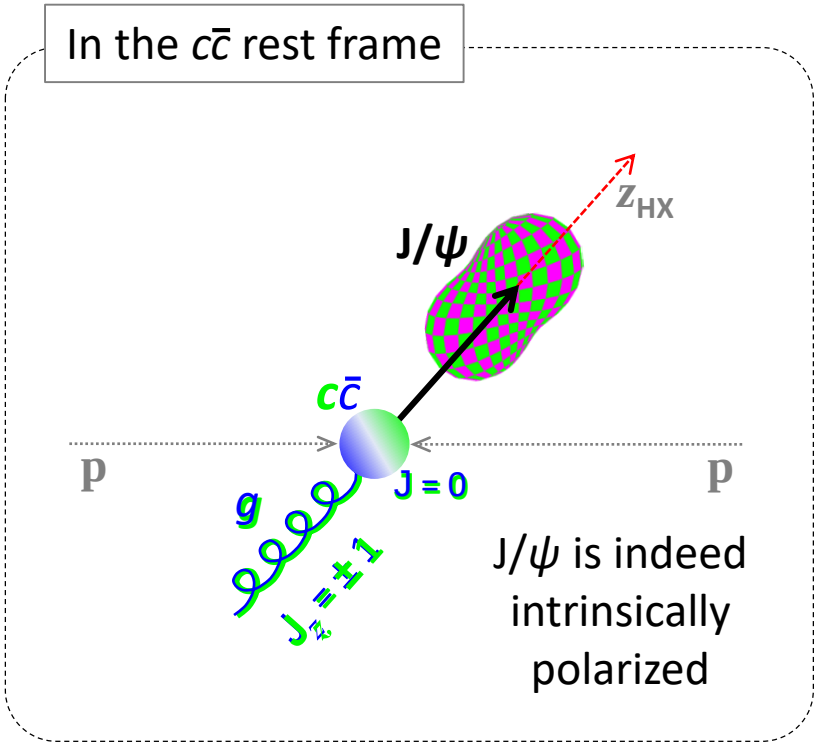

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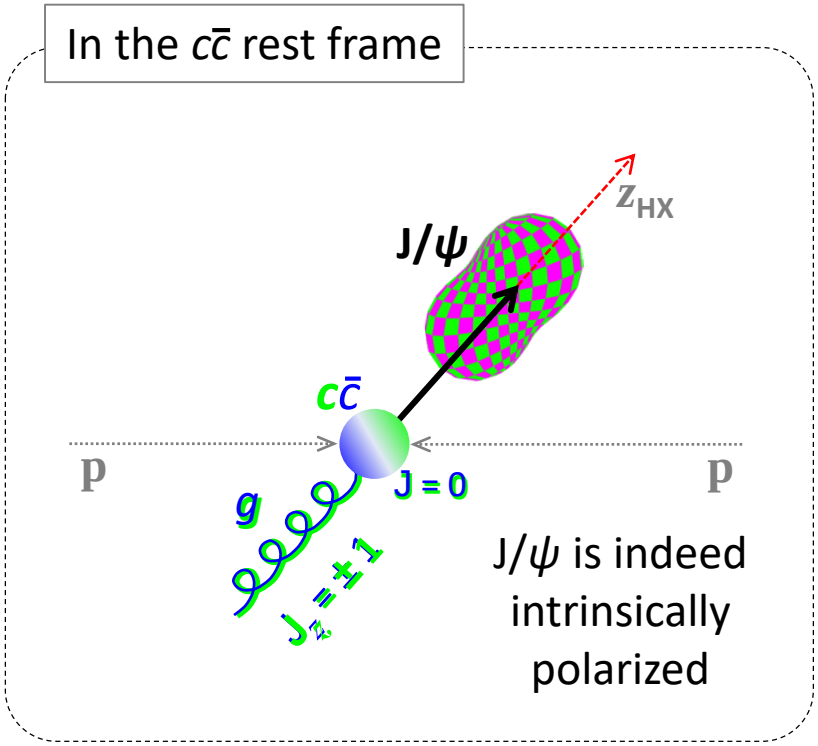

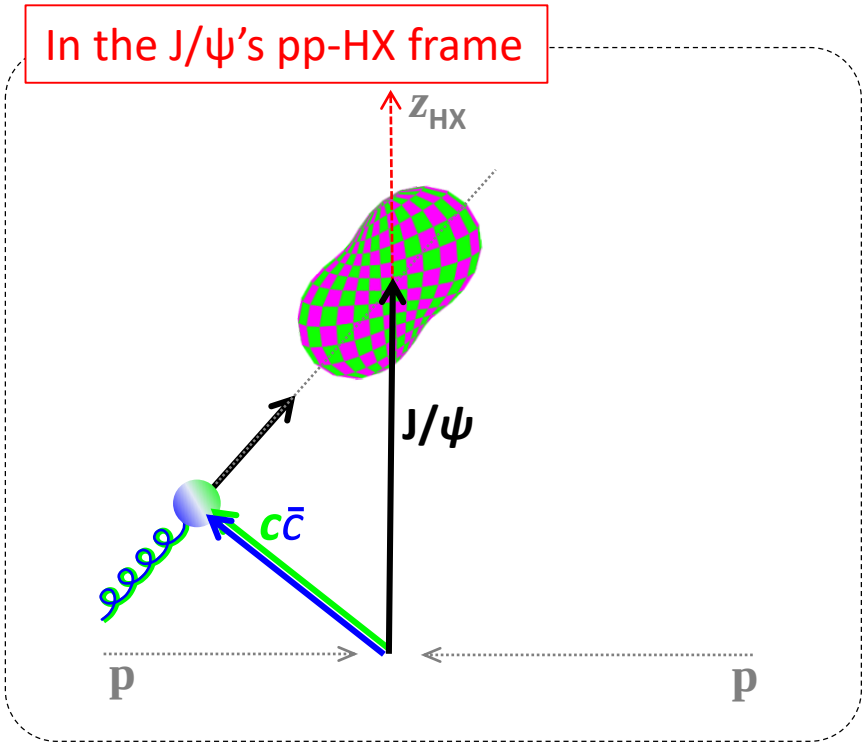

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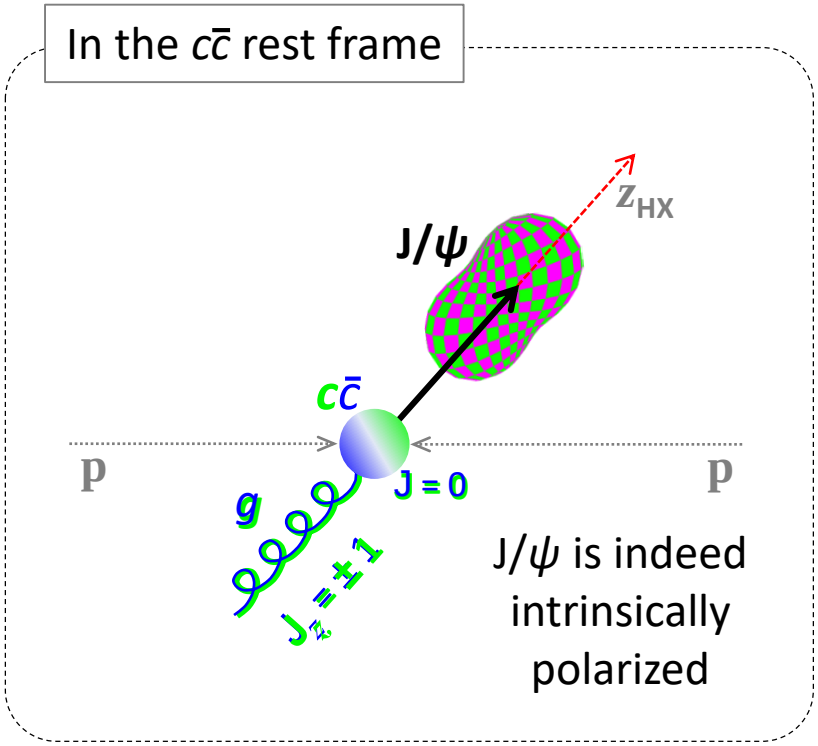

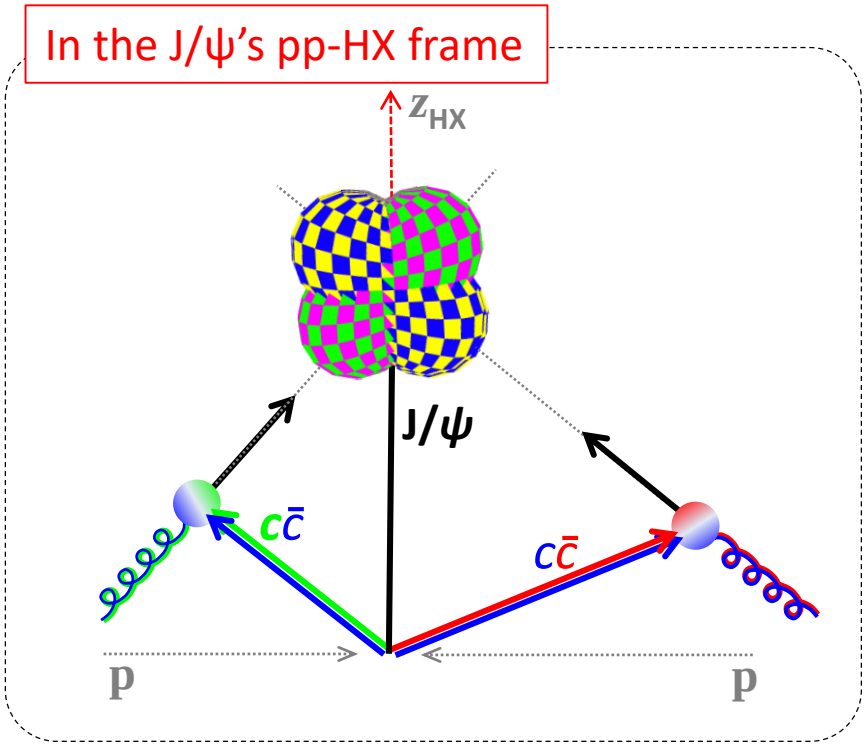

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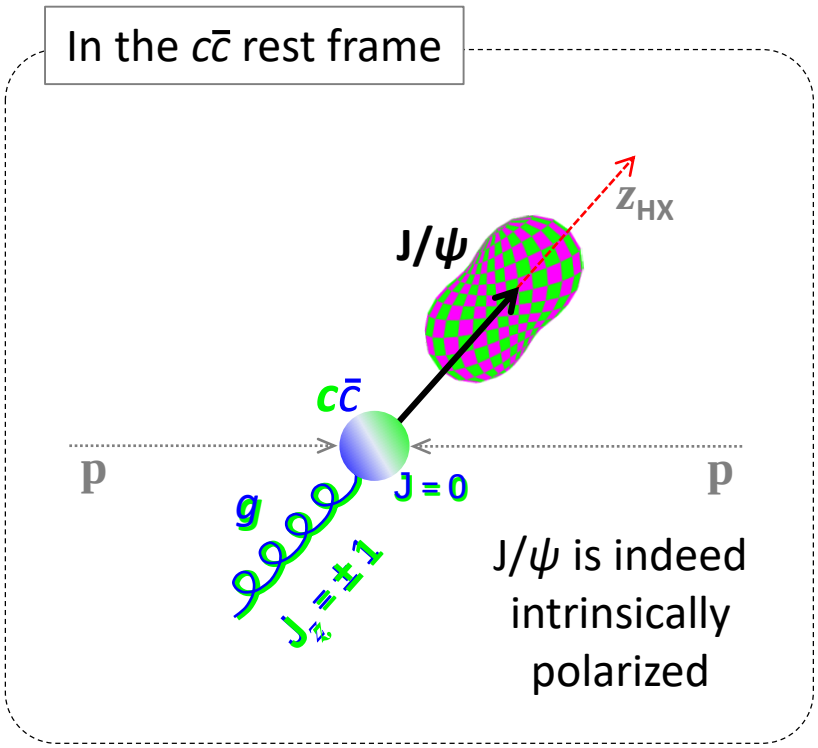
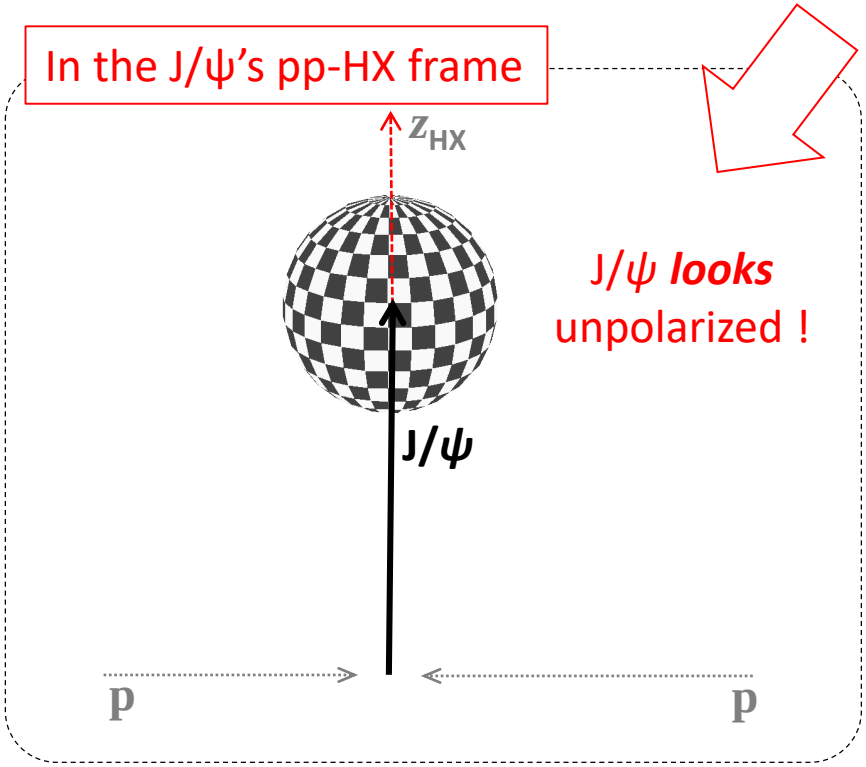
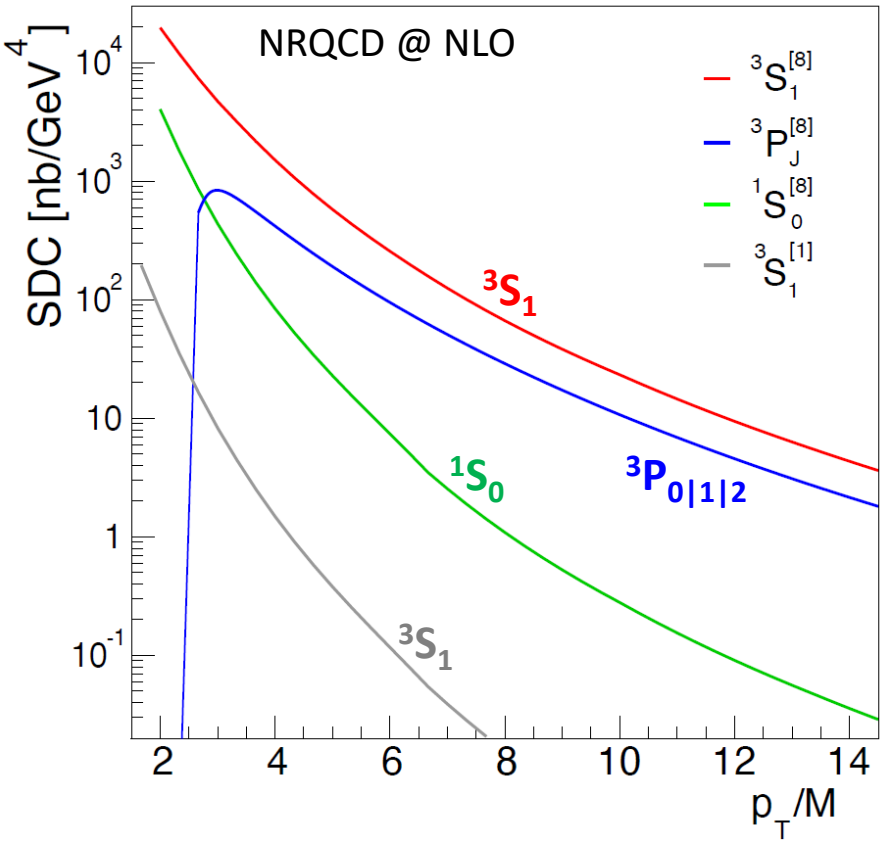




Direct J/ψ in NRQCD: the "bricks" of the p_T distribution

A hierarchy in the expansion over the "small" *Q*-*Q*bar relative velocity ("***v*-scaling**") foresees the dominance of a few of the $^{2S+1}L_J$ "cascade" channels:



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

$^1S_0$ octet

$^3S_1$ octet

$^3P_{0|1|2}$ octets

$^3S_1$ singlet

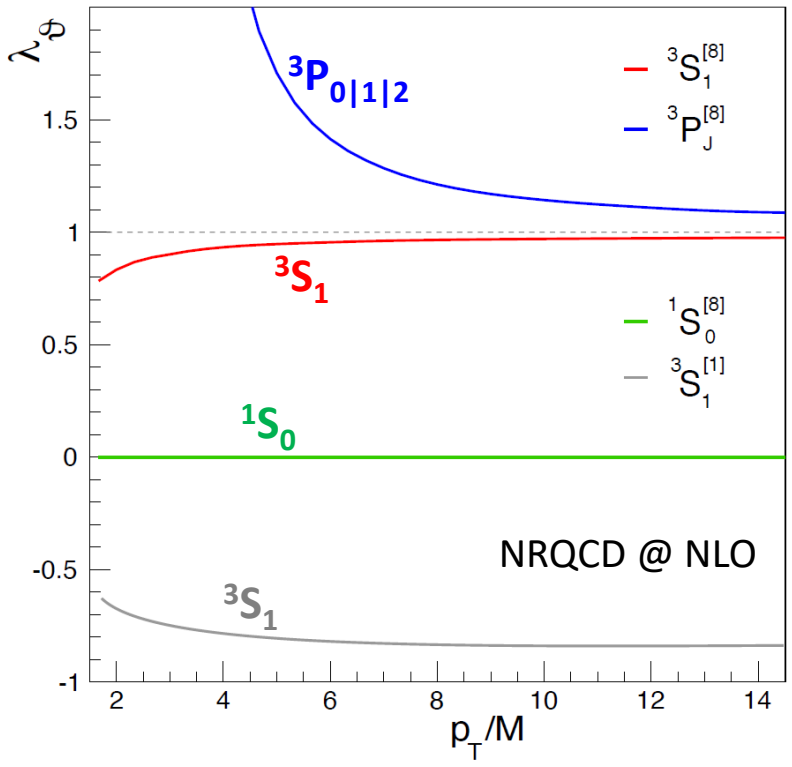
P-wave term actually negative*:*
proper cancellation needed
to recover the physical cross section

Mixture of different pre-resonance contributions,
with characteristic p_T spectra (and polarizations: see next slide)

→ by *fitting* the experimental p_T distributions it is possible to determine the coefficients of all terms (LDMEs) and consequently *predict* the polarizations

The polarization terms: pieces of a puzzle?

Of the four contributing terms, only the $^1S_0$ leads "naturally" to zero polarization



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

P-wave term actually unphysical (> +1)
proper cancellation needed
to recover the physical polarization

$^1S_0$ octet

$^3S_1$ octet

$^3P_{0|1|2}$ octets

$^3S_1$ singlet

To reproduce the data, the remaining terms must

- either be *individually suppressed*
  → violation of NRQCD's v^2 hierarchy !
- or sum to ~*zero* → redundant expansion basis !

Zero J/ψ polarization is a *conceptual* puzzle for NRQCD !

Is NRQCD too complex?

Vector quarkonium production at mid rapidity

LHC data

Surprisingly **uniform and simple** patterns:

- zero and flat polarization
- "universal" scaling of all cross sections with p_T/M

One basic mechanism would seem sufficient…

NRQCD

Combination of

three octet terms $^1S_0 \cong {}^3S_1 \cong {}^3P_J$

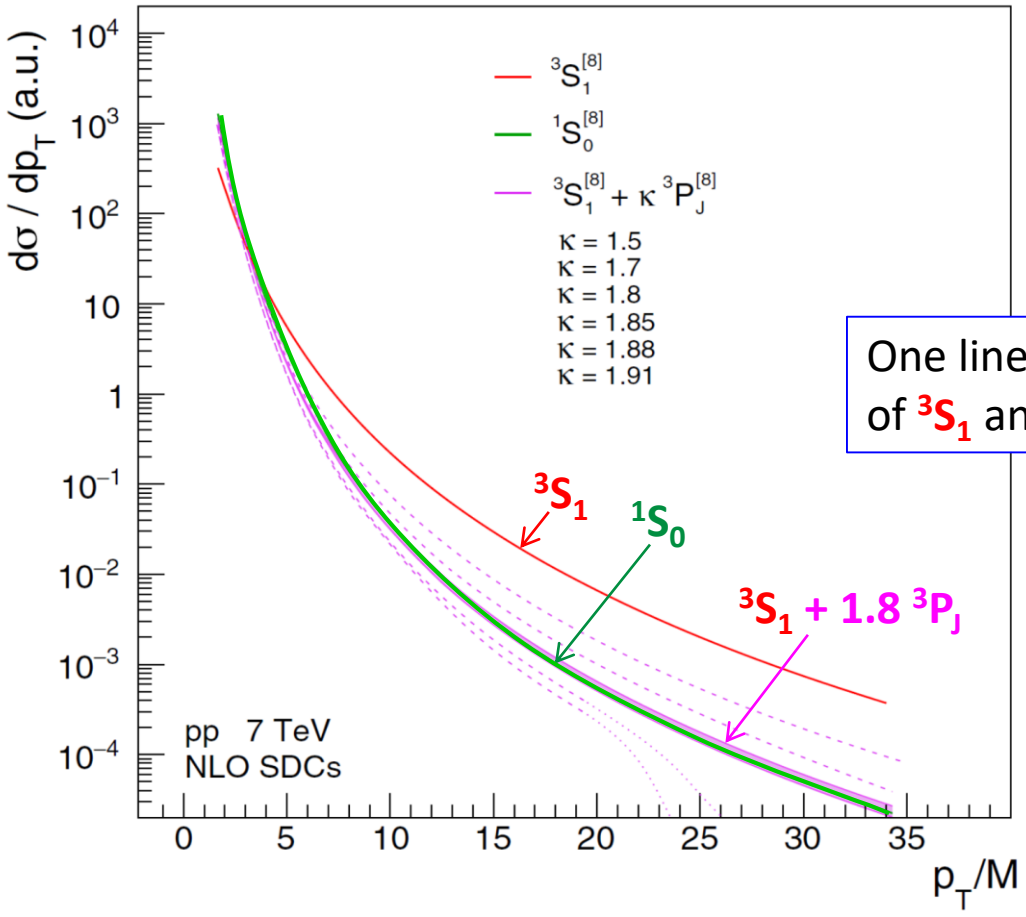
and one singlet term $^3S_1$,

all **differing** for p_T distributions and polarizations (SDCs),

with **state-dependent** coefficients (LDMEs)

A closer look (1)

1) Actually the 3 cross section shapes (SDCs) of NRQCD are linearly dependent !



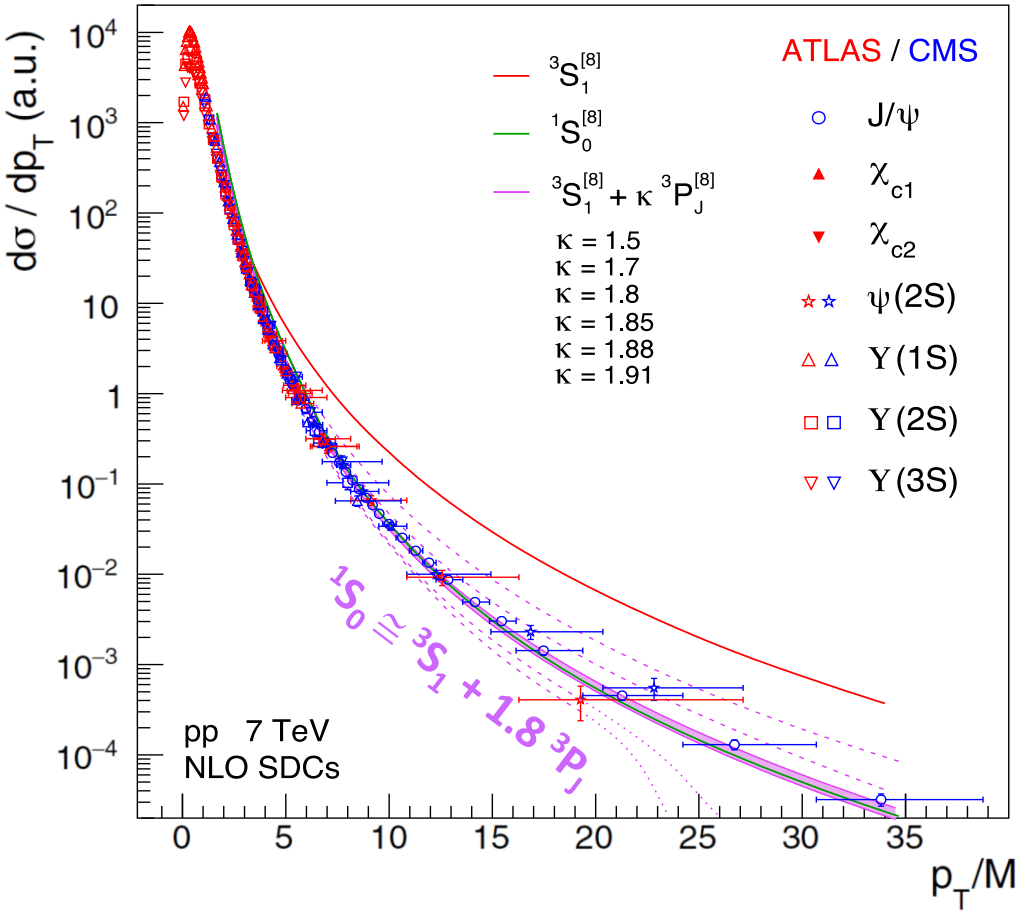
One linear combination of $^3S_1$ and ^3P_J gives $^1S_0$

P.F. and C.L., EPJC 79, 457 (2019)

A closer look (1)

1) Actually the 3 cross section shapes (SDCs) of NRQCD are linearly dependent !

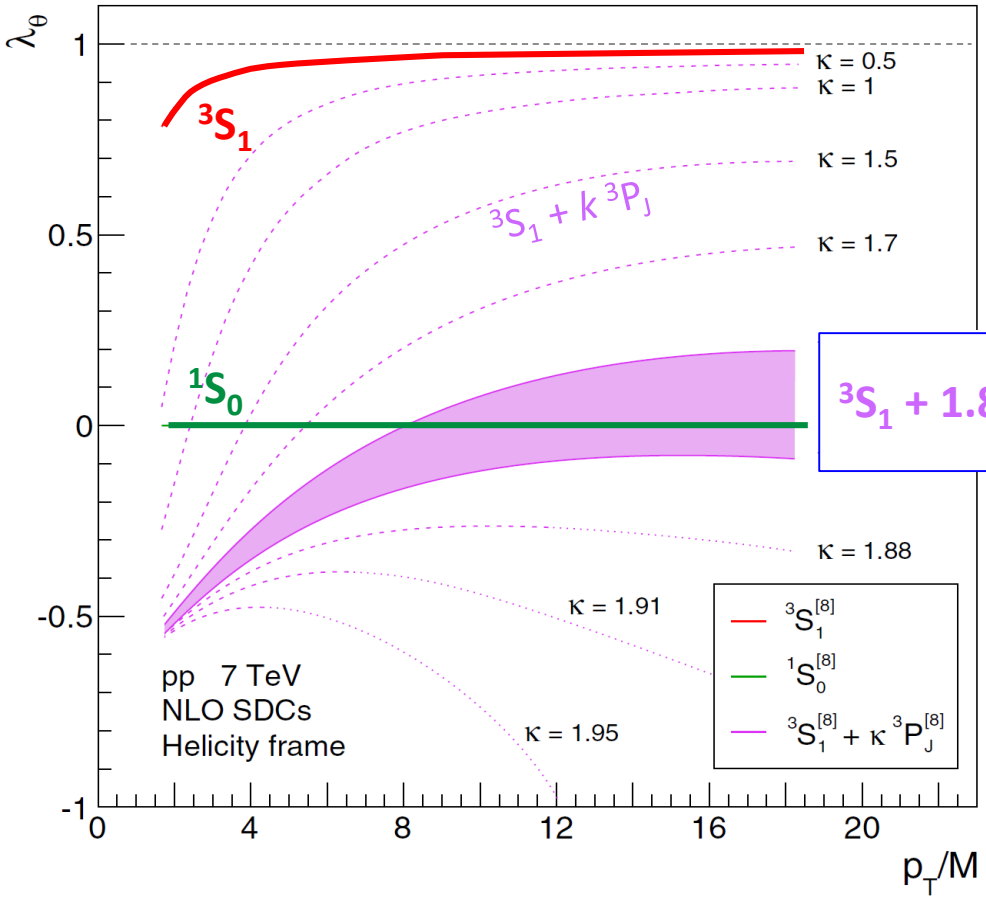
2) And the cross section data universally *agree* with the degenerate scenario where the three different shapes become “one” !



P.F. and C.L., EPJC 79, 457 (2019)

A closer look (2)

3) The *same* degenerate scenario minimizes, at the same time, the difference between the $^1S_0$ and $^3S_1 + k\ ^3P_J$ polarizations



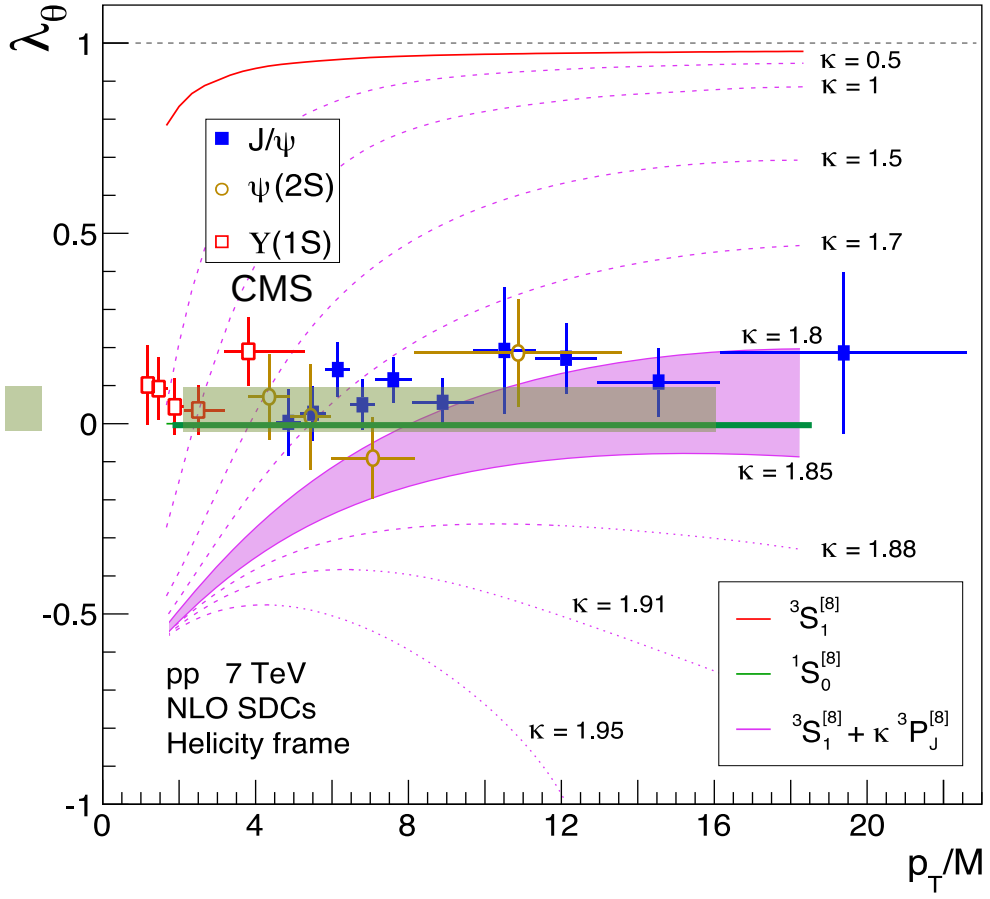
$^3S_1 + 1.8\ ^3P_J$ is closest to zero and flat

P.F. and C.L., EPJC 79, 457 (2019)

A closer look (2)

3) The *same* degenerate scenario minimizes, at the same time, the difference between the $^1S_0$ and $^3S_1 + k\ ^3P_J$ polarizations

4) … and agrees with the polarization data towards high p_T

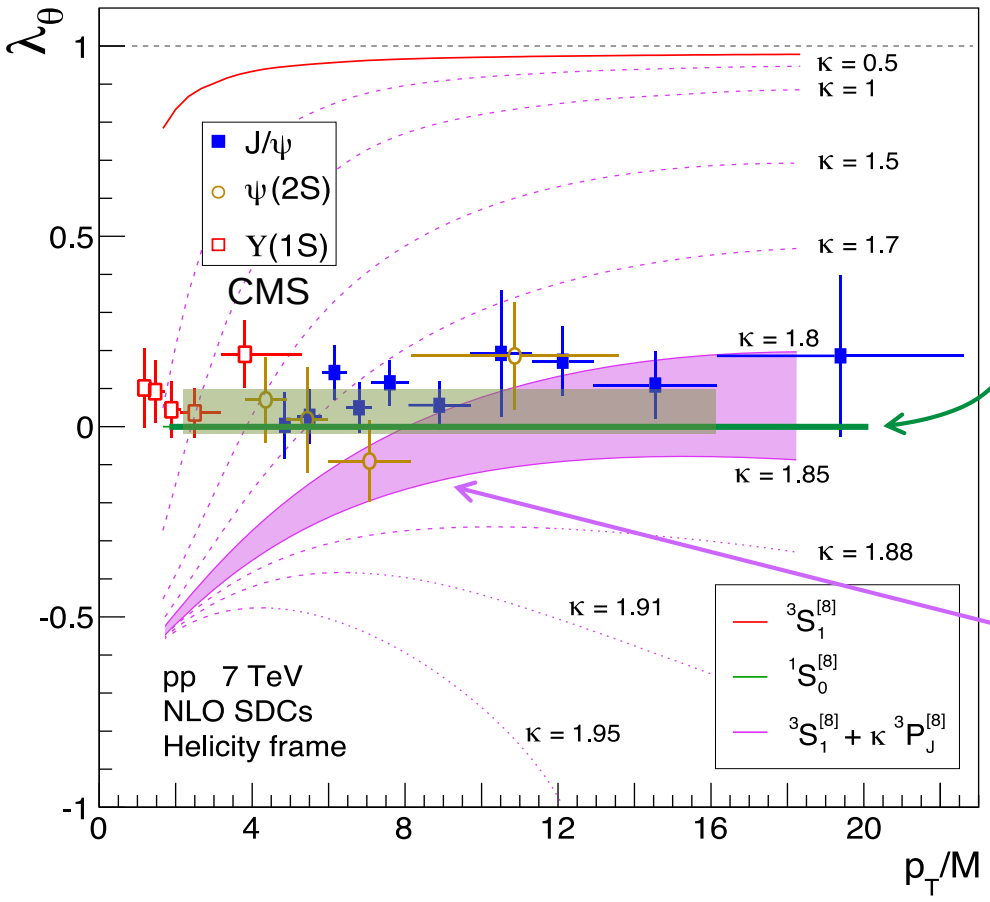


direct J/ψ

However, any $^3S_1 + 1.8\ ^3P_J$ contribution is strongly disfavoured by data

P.F. and C.L., EPJC 79, 457 (2019)

Summary: a new, conceptual, NRQCD puzzle ?



With current SDC calculations, NRQCD *does* reproduce well the polarization data, just like the p_T spectrum

But this requires **full $^1S_0$ dominance** ($^3S_1 + k\ ^3P_J$ term strongly suppressed)

→ **violation** of NRQCD v^2-scaling hierarchies

Will improved computations of the (perturbatively unstable) ^3P_J term lead to **flat $\lambda_\vartheta = 0$ also for $^3S_1 + k\ ^3P_J$**, so that this term can contribute?

→ FULL **degeneracy** of the NRQCD expansion

In either case, **zero** and ***constant*** polarization is the biggest challenge to NRQCD

More precise measurements are needed to reach a decisive conclusion

Backup

What about the χ_{c1} and χ_{c2}?

In NRQCD, $\chi_{c1,2}$ production has two terms: $^3S_1$ octet and $^3P_{1,2}$ singlet.

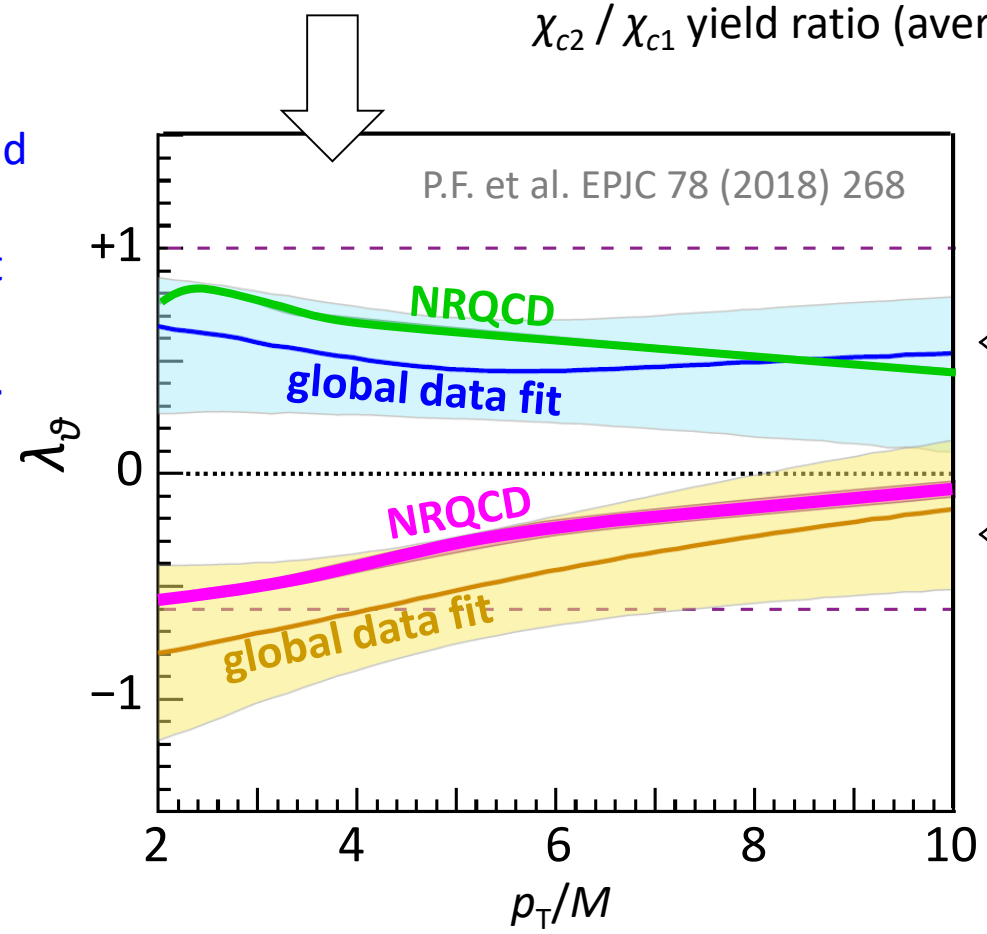
One parameter *r* determines

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

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

= 0.217 ± 0.003 from the CMS + ATLAS χ_{c2} / χ_{c1} yield ratio (averaged)

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



⇐ χ_{c1}

⇐ χ_{c2}

… and perfectly agreeing with data

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