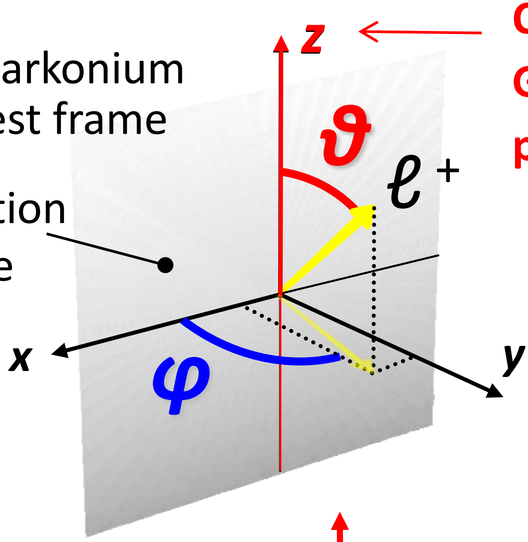
J/ψ production and polarization in pp collisions

Pietro Faccioli, LIP, Lisbon

In collaboration with Carlos Lourenço, CERN

IWHSS 2020, Trieste, November 16th-20th, 2020

Vector particle polarization: frames and parameters



Collins-Soper axis (CS): ≈ direction of colliding partons

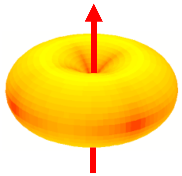
Gottfried-Jackson (GJ): dir. of one beam (or the target)

pp-helicity axis (HX): dir. of particle momentum w.r.t. to the pp c.o.m.

$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi$$

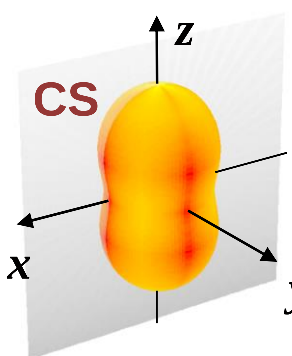
$J_z = \pm 1$ → $\lambda_\vartheta = +1$: **"transverse"** (= photon-like) pol.

$\lambda_\varphi = \lambda_{\vartheta\varphi} = 0$



$J_z = 0$ → $\lambda_\vartheta = -1$: **"longitudinal"** pol.

$\lambda_\varphi = \lambda_{\vartheta\varphi} = 0$

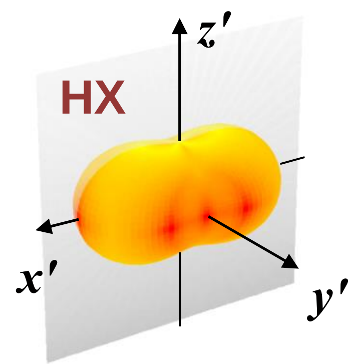


CS ⊥ HX for mid rap. / high p_T

$\lambda_\vartheta = +1$
$\lambda_\varphi = 0$

90º

$\lambda_\vartheta = -1/3$
$\lambda_\varphi = +1/3$

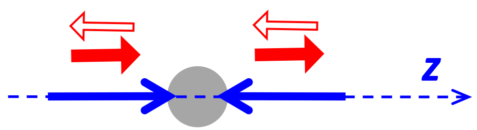


Vector particle polarization: the "transverse" expectation

The production of Z, W, γ and γ^* (Drell-Yan) is generally well explained by the short-distance coupling of quarks and gluons.

In particular, for **helicity conservation** the polarization is always **transverse** along some natural axis ***z***

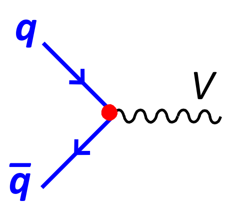
$V = \gamma^*, Z, W$



Helicity conservation at the *q-q-V* (q-$\bar{q}$*-*V*) vertex:

$\boldsymbol{J_z = \pm 1}$ along the q-$\bar{q}$ (q-q^*) scattering direction ***z***

$O(\alpha_S^0)$



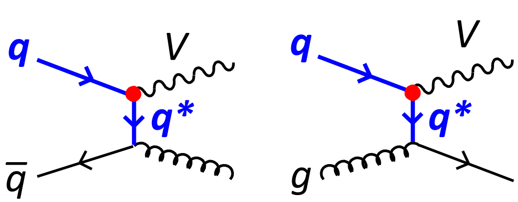
z = relative dir. of incoming *q* and *q*bar

(**λ_ϑ = +1 in the Collins-Soper frame**)

important only up to $p_T = \mathcal{O}$(parton k_T)

$O(\alpha_S^1)$

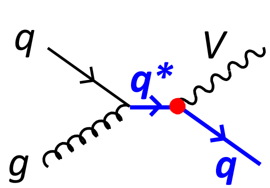
QCD corrections



z = dir. of *one* incoming quark

(**λ_ϑ = +1**

in the Gottfried-Jackson frame)



z = dir. of outgoing *q*

(**λ_ϑ = +1 in the parton-cms-helicity**

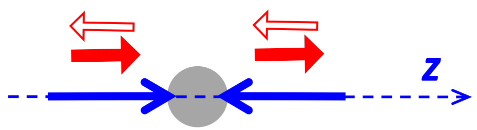
$\approx$ **lab-cms-helicity frame**)

Vector particle polarization: the “transverse” expectation

The production of Z, W, γ and γ^* (Drell-Yan) is generally well explained by the short-distance coupling of quarks and gluons.

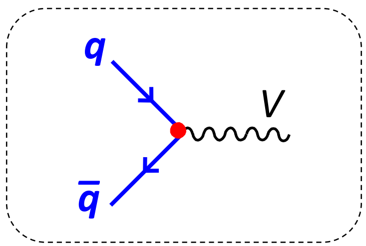
In particular, for **helicity conservation** the polarization is always **transverse** along some natural axis ***z***

$V = \gamma^*, Z, W$



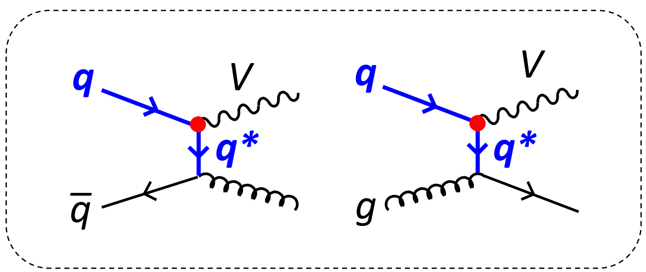
Helicity conservation at the *q-q-V* (q-$\bar{q}^*$-V) vertex:
$J_z = \pm 1$ along the q-$\bar{q}$ (q-q^*) scattering direction ***z***

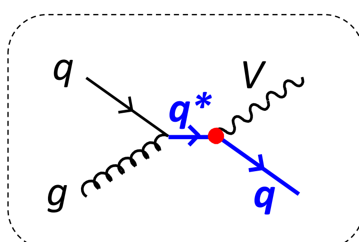
$O(\alpha_S^0)$



$O(\alpha_S^1)$

QCD corrections





P.F. et al., PRL 105, 061601 (2010)

frame-invariant polarization

$$\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi} = +1$$

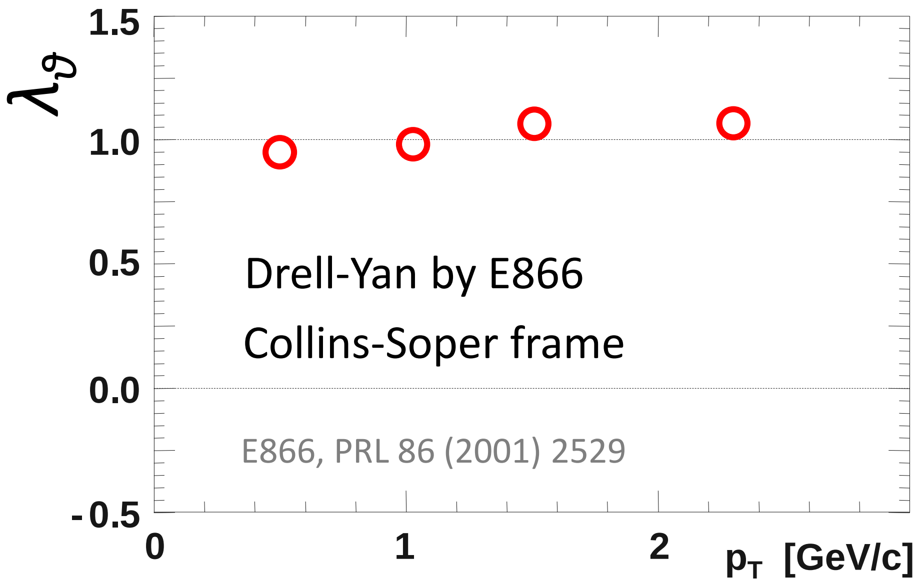
wrt *any* axis

$\rightarrow$ Lam-Tung relation

PRD 18, 2447 (1978)

Vector particle polarization: experimental confirmation

Sometimes the fully transverse polarization is immediately recognizable…



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

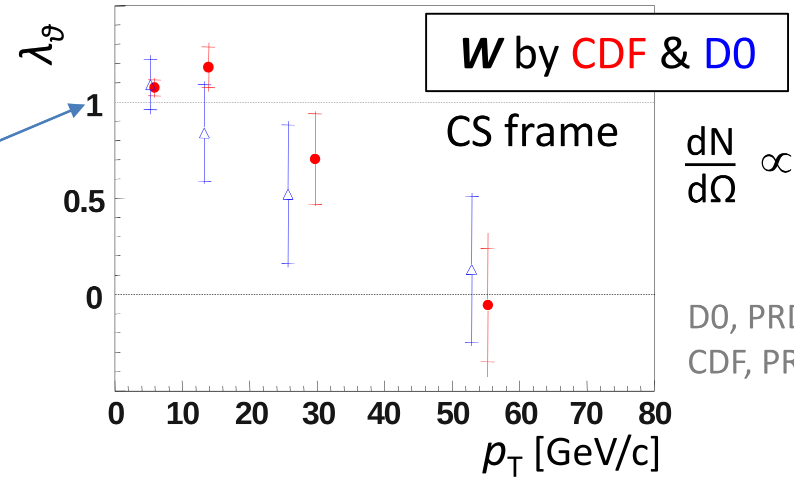
$$\lambda_\vartheta = +1 \rightarrow J_z = \pm 1$$

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

(Less immediate) experimental confirmation

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**.

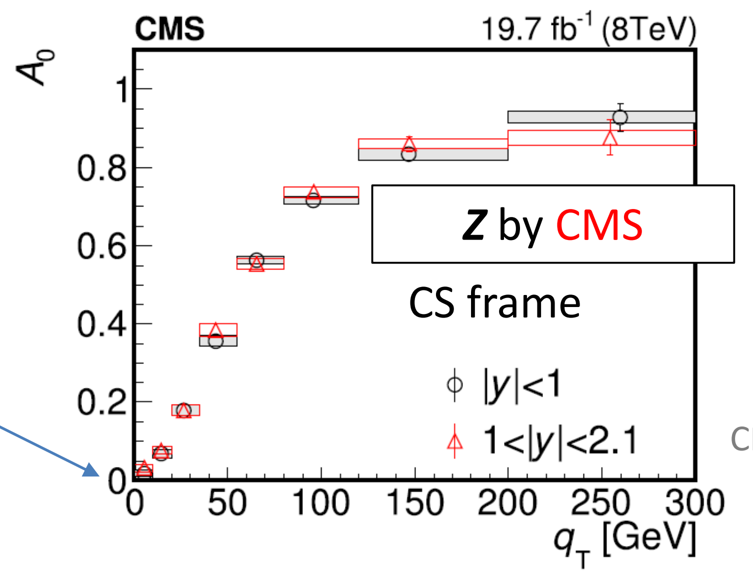
$\lambda_\vartheta = +1 \leftrightarrow J_z = \pm 1$



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

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

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



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

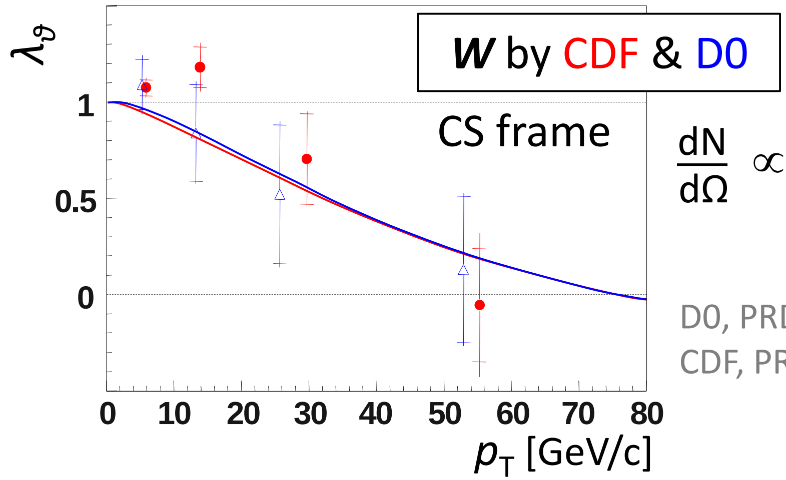
CMS, PLB 750, 154 (2015)

(Less immediate) experimental confirmation

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**.

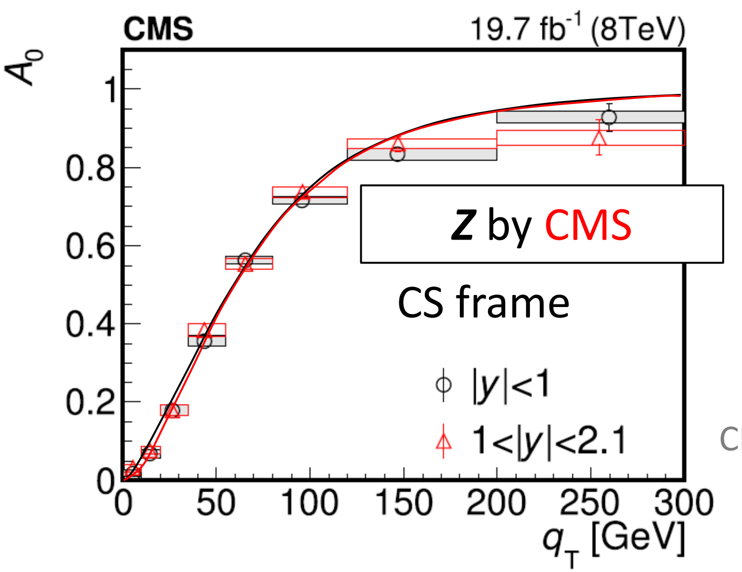
Assuming $\mathbf{J_z = \pm 1}$ *along the HX and GJ axes,* as foreseen for 2-to-2 processes of $\mathcal{O}(\alpha_S^1)$, in suitable mixtures, we reproduce the trends seen in the CS frame:

the polarization *is* always **transverse**



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

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



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

CMS, PLB 750, 154 (2015)

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

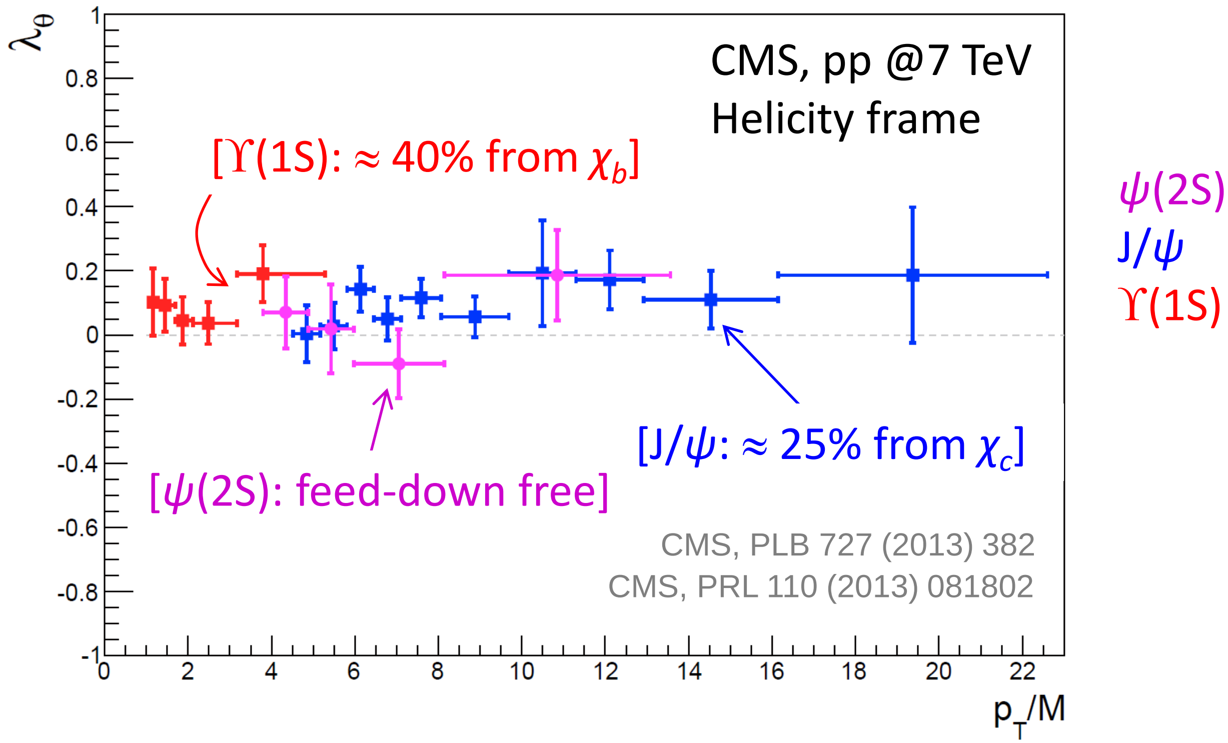
along which the $J_z = 0$ component ***a_0* vanishes**

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

…which implies that **$\lambda_\vartheta = +1$ along that axis**

Vector quarkonia: a paradigmatic exception

Mid-rapidity LHC data show unpolarized production of vector quarkonia

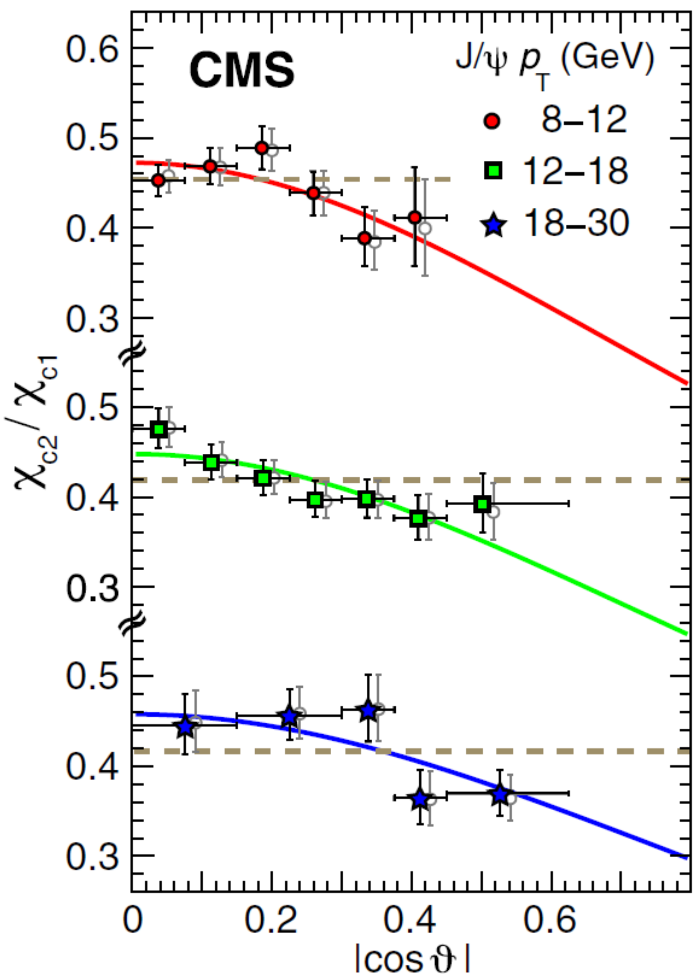


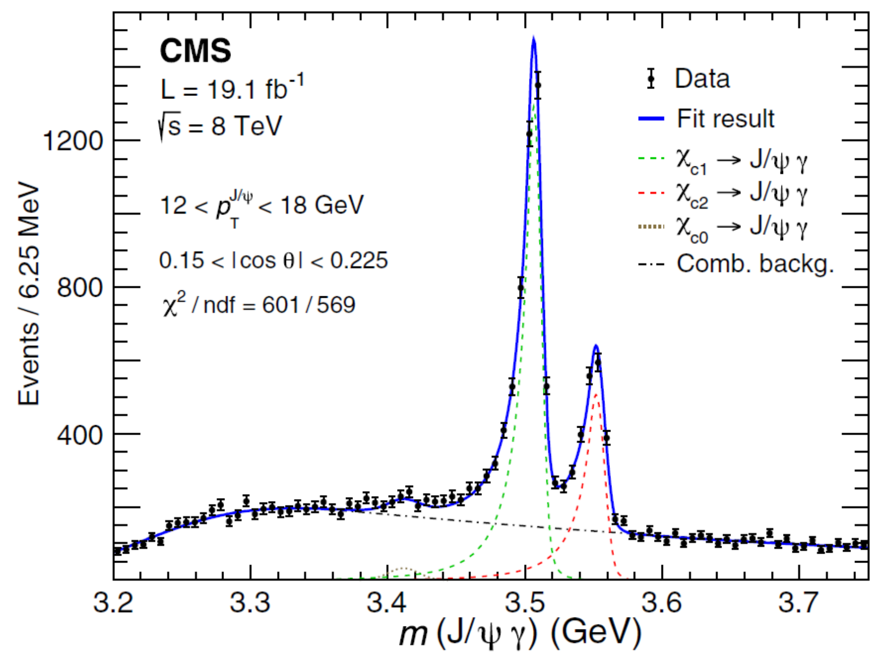
- None of the parameters λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$, $\tilde{\lambda}$ is significantly ≠ 0
- There is **no visible dependence on p_T**: seemingly not a transition domain

- No visible difference between states despite different χ feed-downs ⟶

The role of χ_c decays: finally from data

CMS, PRL 124 (2020) 162002

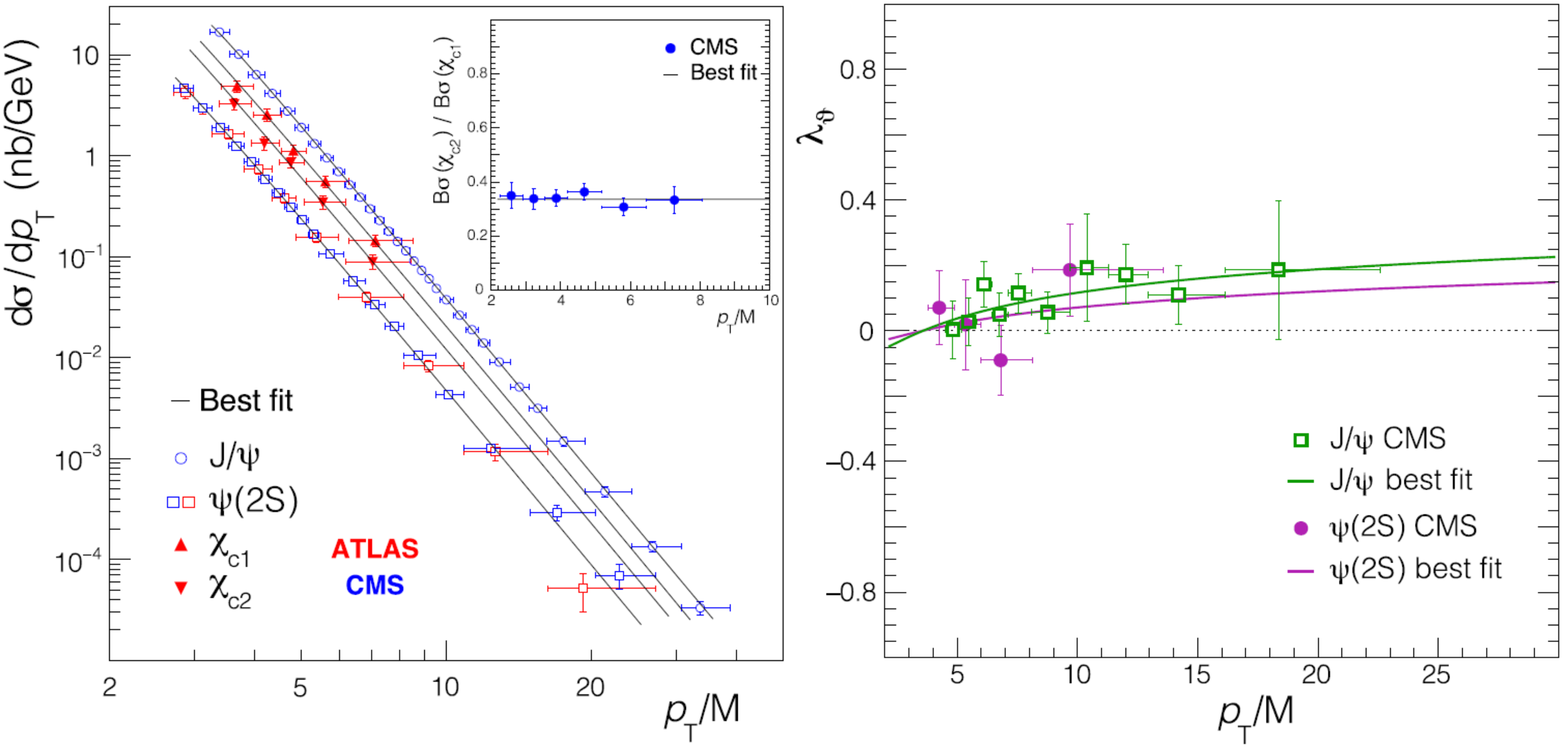




CMS measured the ratio between the (J/ψ from) χ_{c2} and χ_{c1} $\cos\vartheta$ distributions.

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

Indirect experimental constraints

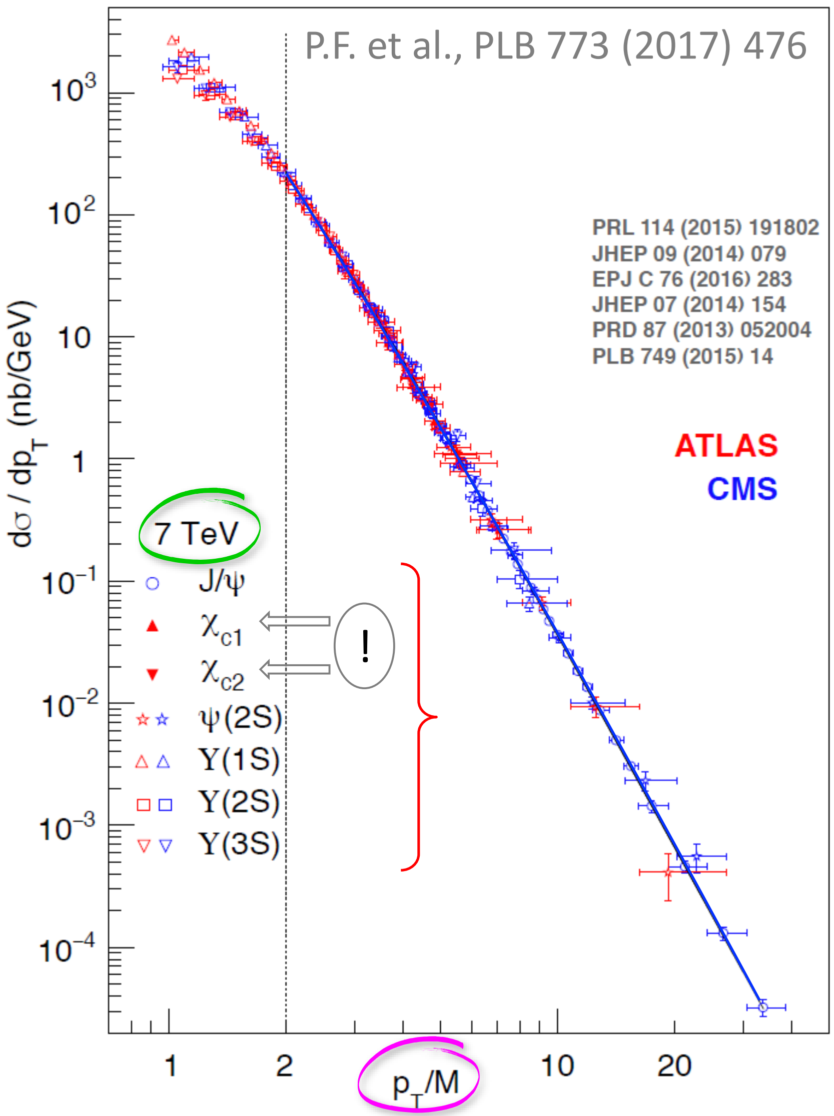


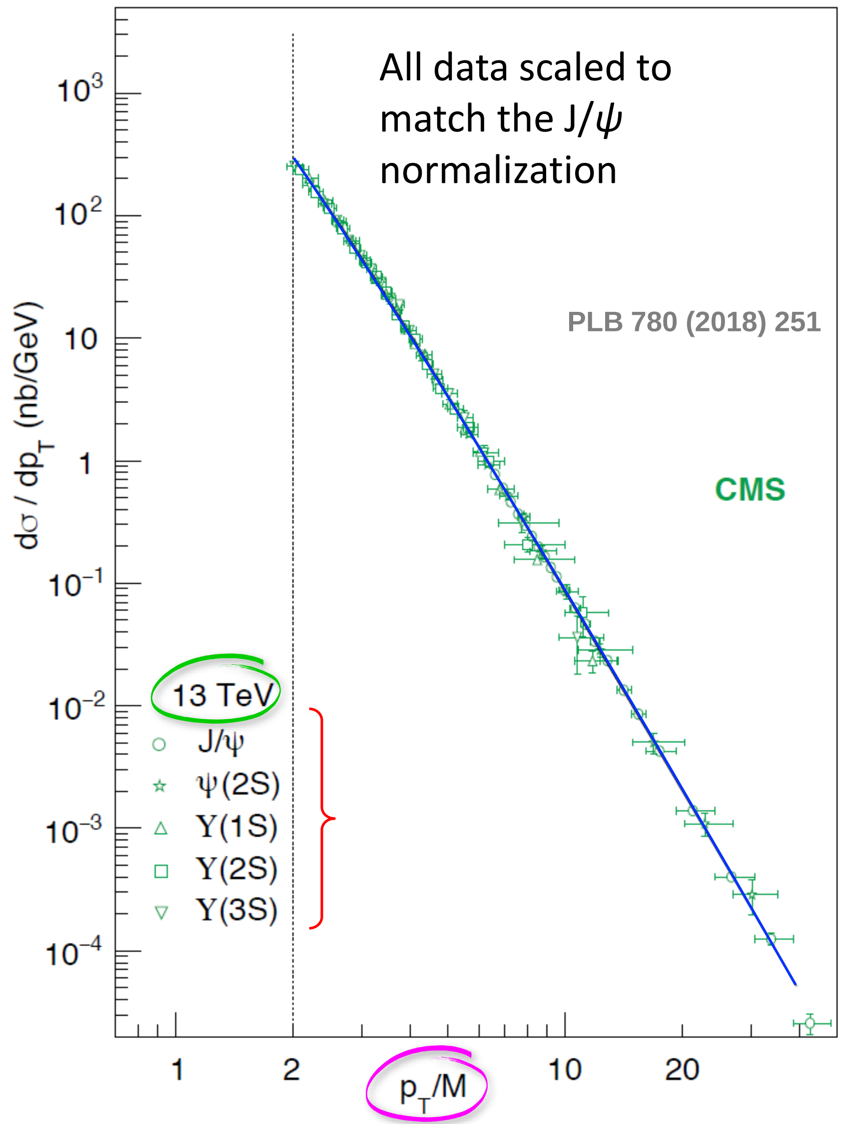
ATLAS and CMS measurements of J/ψ, $\psi(2S)$, χ_{c1} and χ_{c2} cross sections, together with the J/ψ and $\psi(2S)$ polarizations, constrain the *sum* of the χ_{c1} and χ_{c2} polarizations

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

(*) A "universal" p_T/M scaling

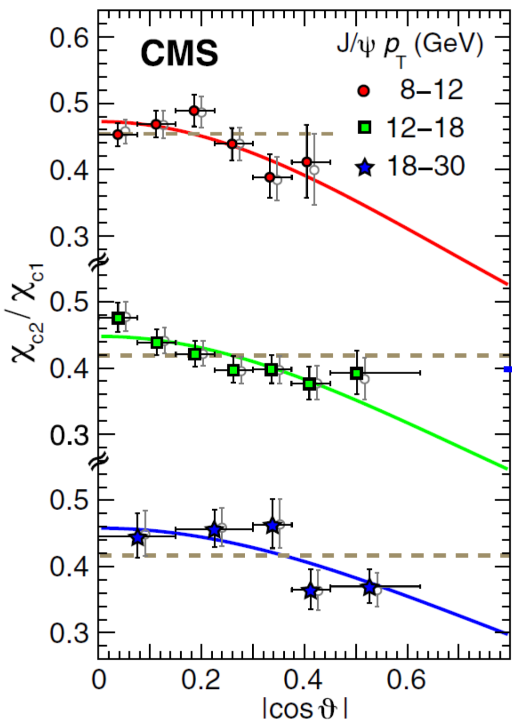
No hint of mass-dependence in mid-rapidity p_T distributions (nor for λ_ϑ)
from J/ψ to Υ(3S) after dimensional scaling, $p_T \rightarrow p_T/M$, at least for $p_T/M > 2$
$\rightarrow$ no reason to question similarity of production dynamics between direct J/ψ and ψ(2S)



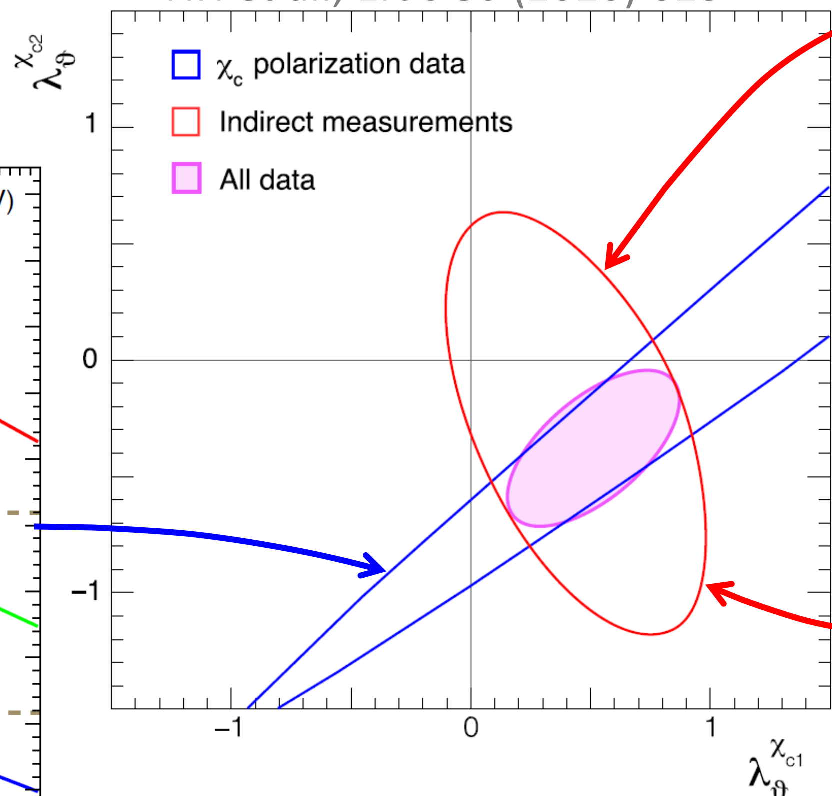


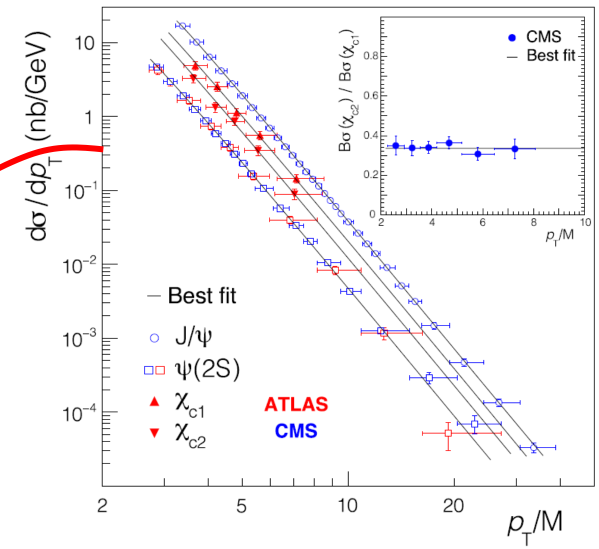
The χ_c states are strongly polarized!

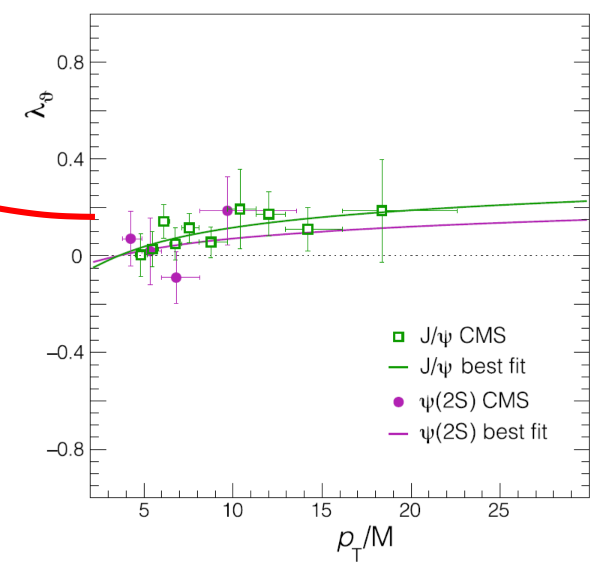
The combination of these two "orthogonal" experimental constraints determine the two individual χ_{c1} and χ_{c2} polarizations



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





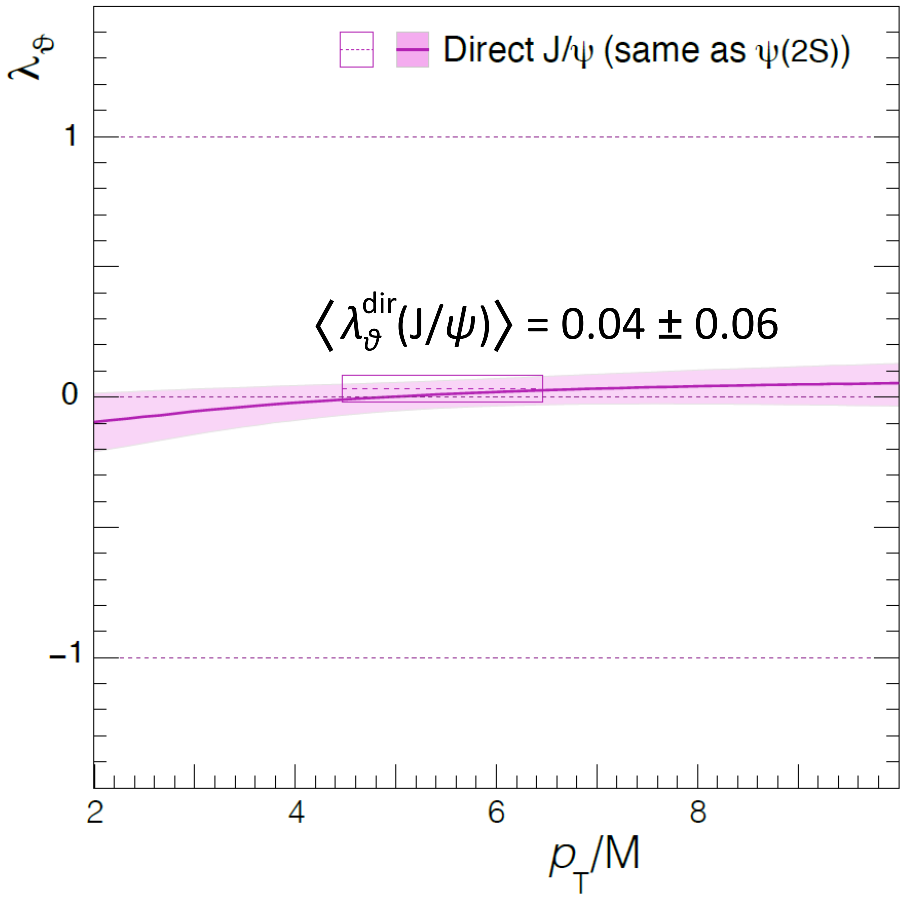


J/ψ from χ_{c1} and χ_{c2} are, respectively, transversely and longitudinally polarized

→ 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



A strong evidence of unpolarized production, challenging production models

Only a "fortunate" ***mixture of subprocesses*** or ***randomization effects*** can lead to zero polarization

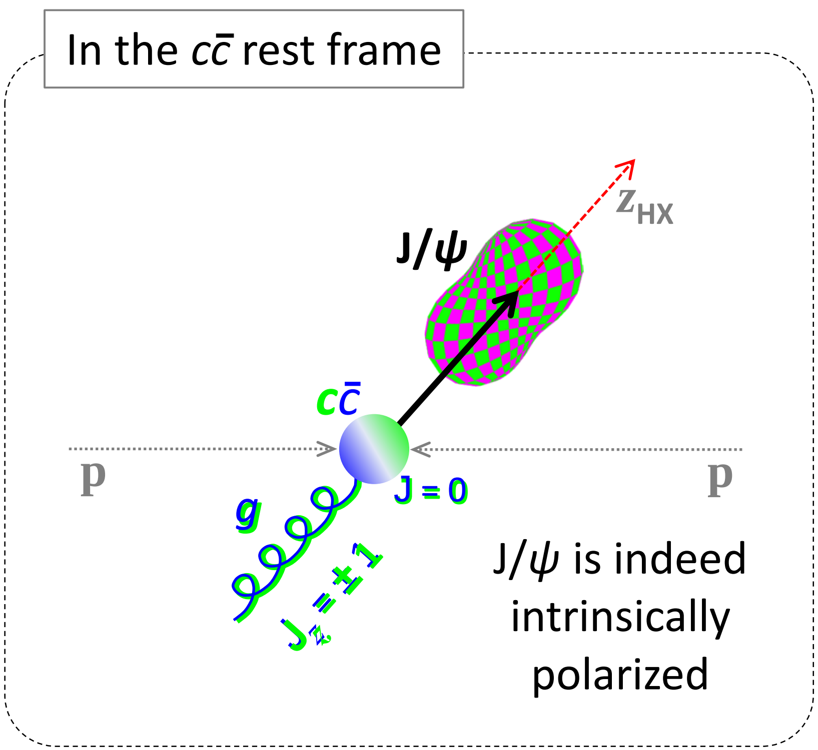
→ a clear sign of the **unique nature and production mechanism** of heavy quarkonia

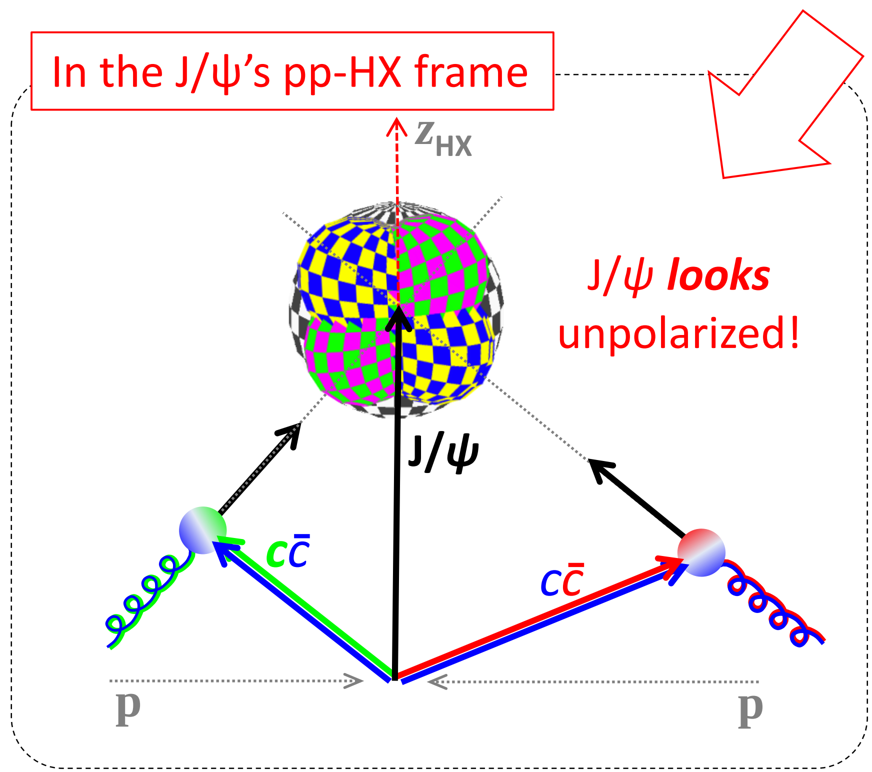
Are we seeing a cascade mechanism?

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





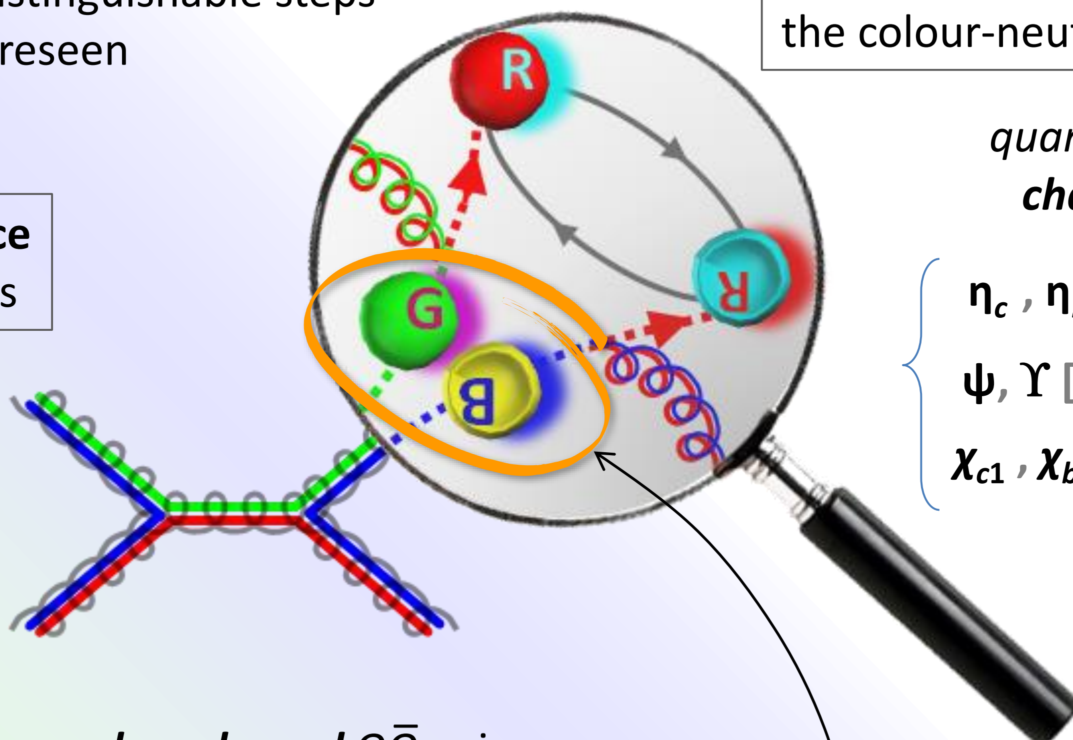
The "cascade" (*factorization*) approach of NRQCD

Non-Relativistic

For **heavy** quarkonia
two distinguishable steps
are foreseen

1) **short-distance**
partonic process

2) **long-distance** evolution to
the colour-neutral bound state



quantum numbers
change to final

- 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} [$^3P_2$]

produces ***in general a coloured*** $Q\bar{Q}$ pair
of any $^{2S+1}L_J$ *quantum numbers*

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

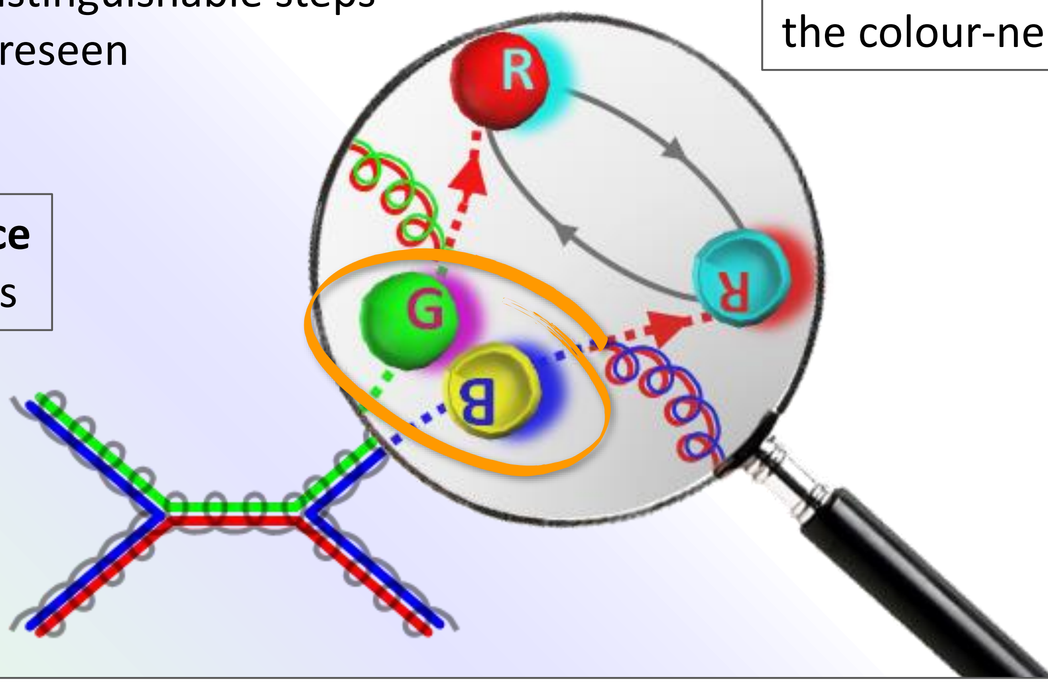
Even if the ***pre-resonance*** $Q\bar{Q}$ state
is not observed, it determines,
with its own quantum properties,
the observable kinematics and *polarization*

The "cascade" (*factorization*) approach of NRQCD

For **heavy** quarkonia two distinguishable steps are foreseen

2) **long-distance** evolution to the colour-neutral bound state

1) **short-distance** partonic process



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

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

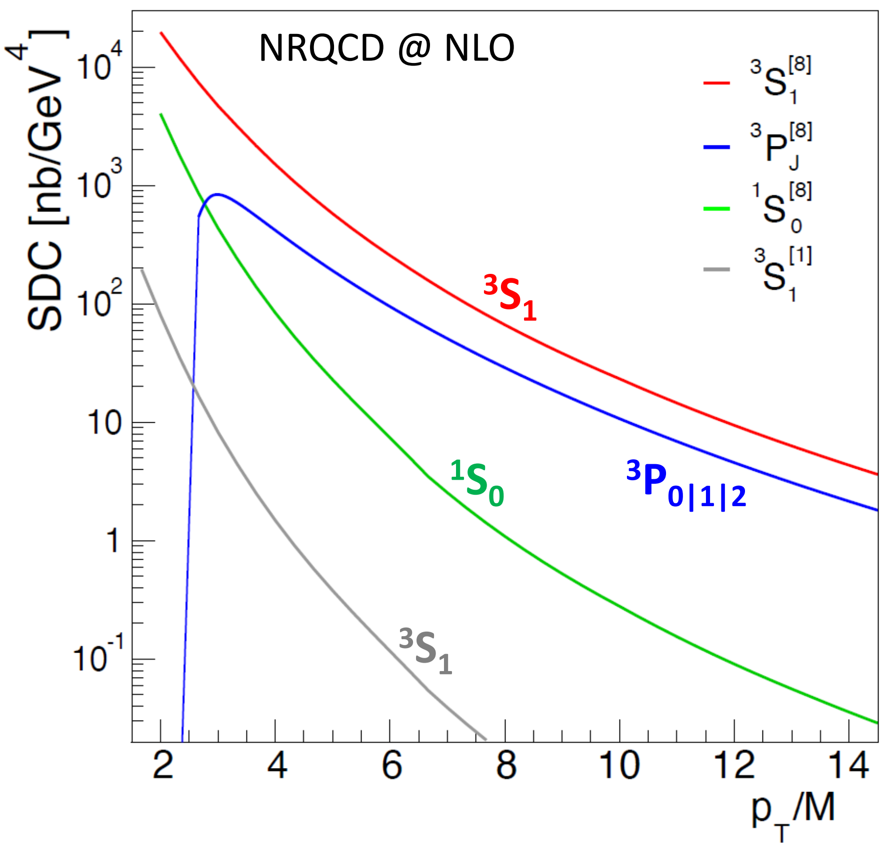
$$\sigma(A + B \to \mathcal{Q} + X) = \sum_{S,\,L,\,C} \mathcal{S}\{A + B \to (Q\bar{Q})_C[^{2S+1}L_J] + X\} \cdot \mathcal{L}\{(Q\bar{Q})_C[^{2S+1}L_J] \to \mathcal{Q}\}$$

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

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

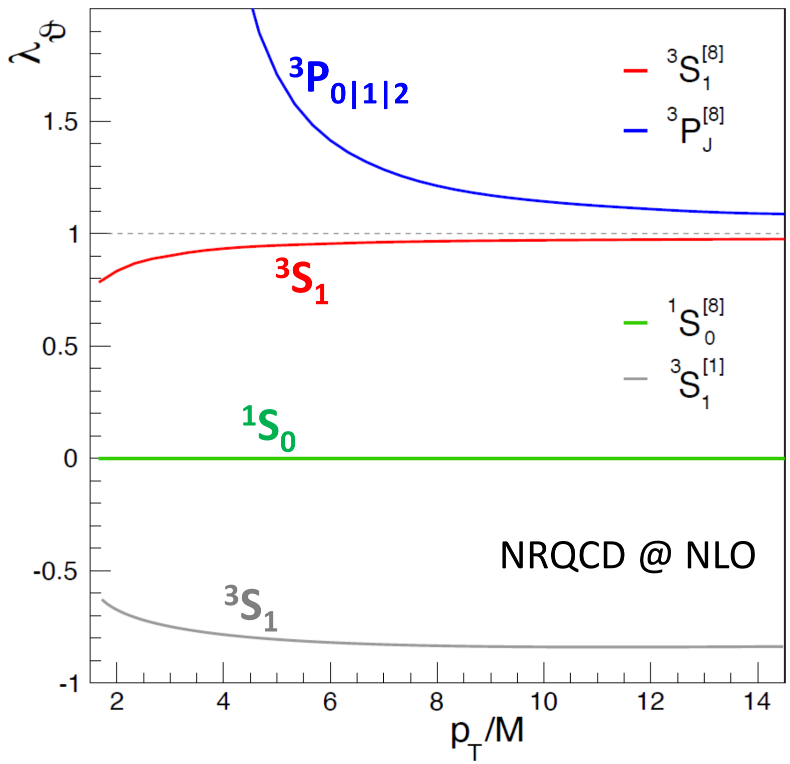
Mixture of different pre-resonance contributions,
with characteristic p_T spectra (and polarizations: see next slide)

$\rightarrow$ 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!

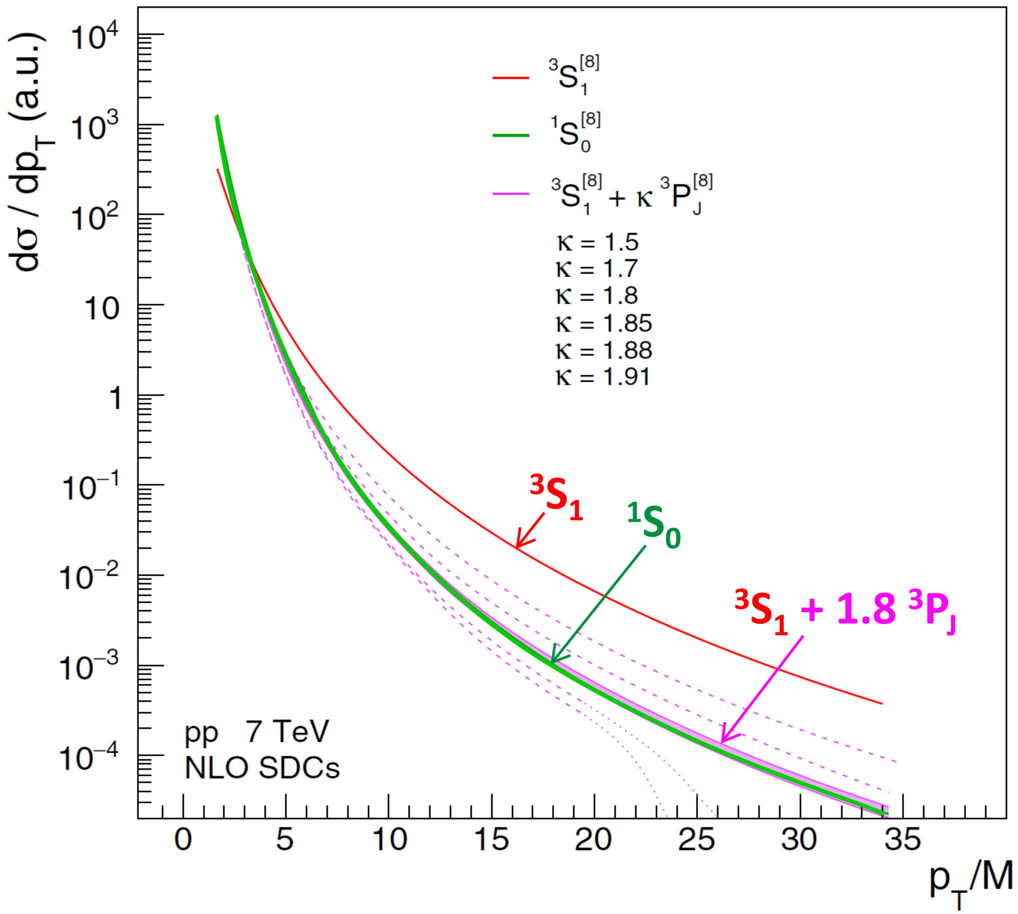
Is NRQCD too complex?

Vector quarkonium production at mid rapidity

LHC data	NRQCD
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…	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) Actually the 3 cross section shapes (SDCs) of NRQCD are linearly dependent!



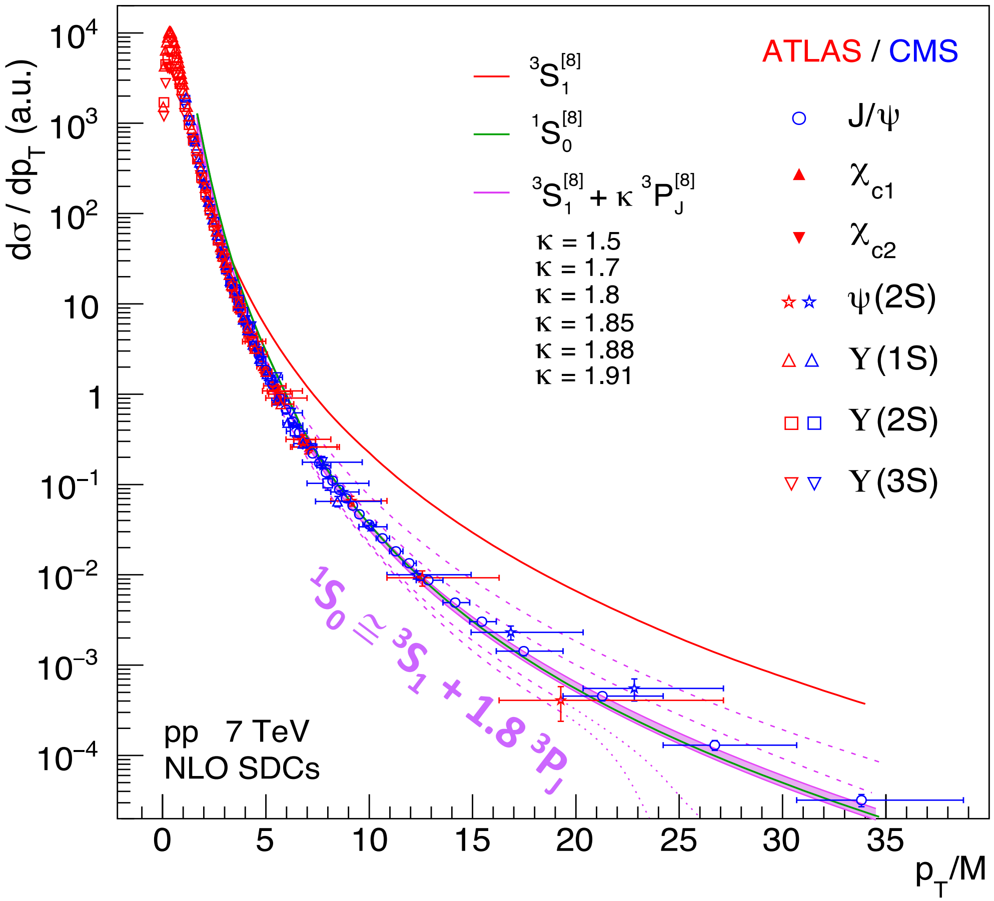
One linear combination of $^3S_1$ and ^3P_J gives $^1S_0$

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

A closer look

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

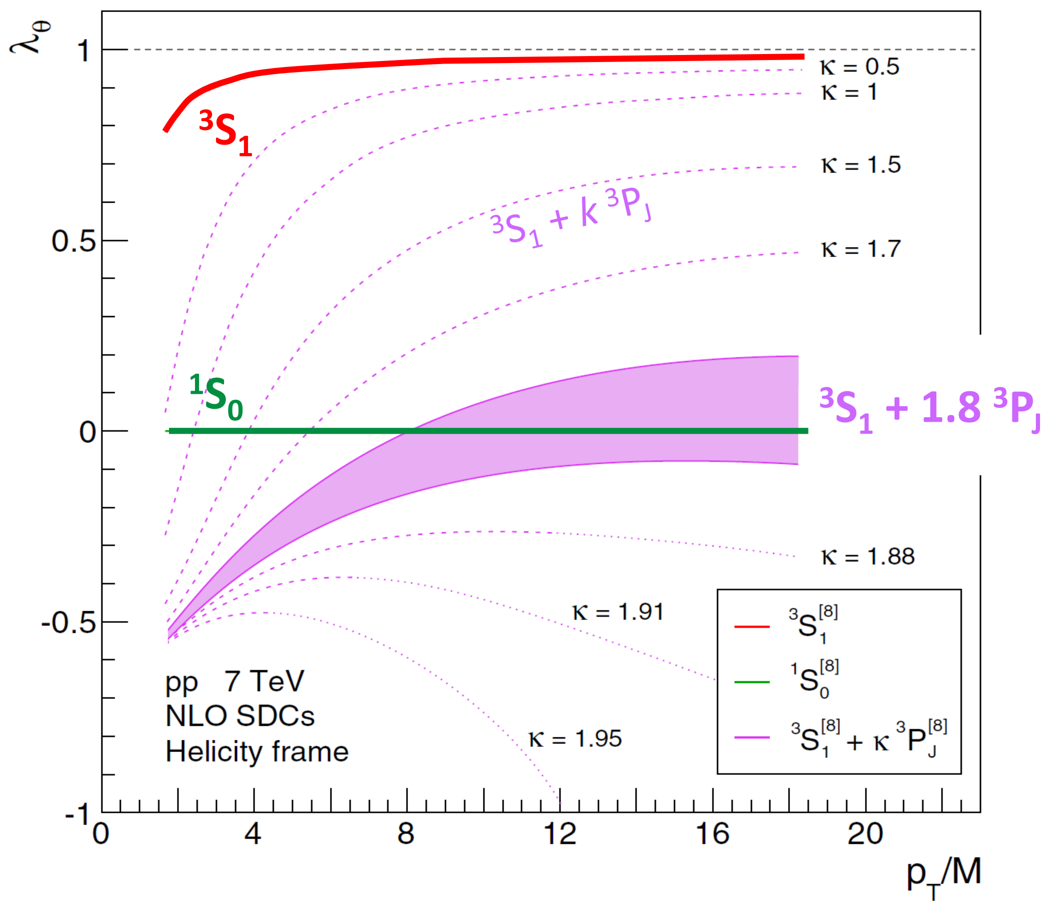
2) And the cross section data universally *agree* with the degenerate scenario where the three different shapes become “one”!



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

A closer look

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



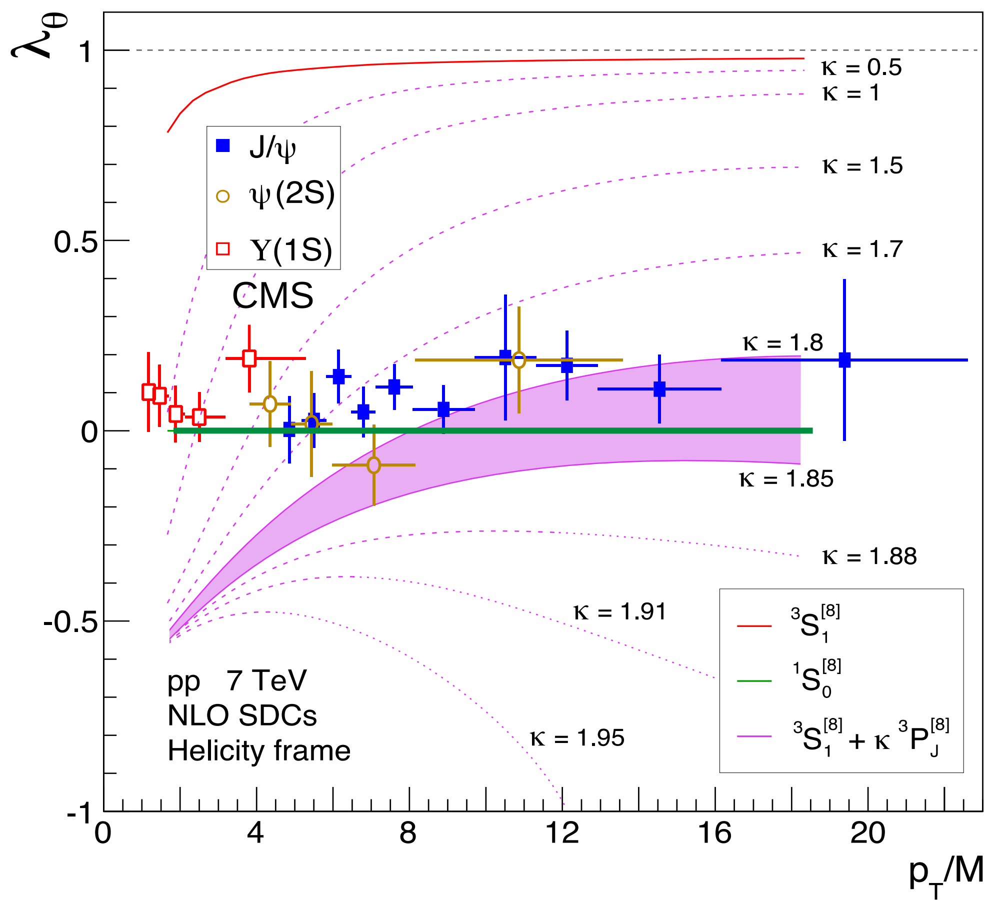
$^3S_1 + 1.8\,^3P_J$ is closest to zero and flat

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

A closer look

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

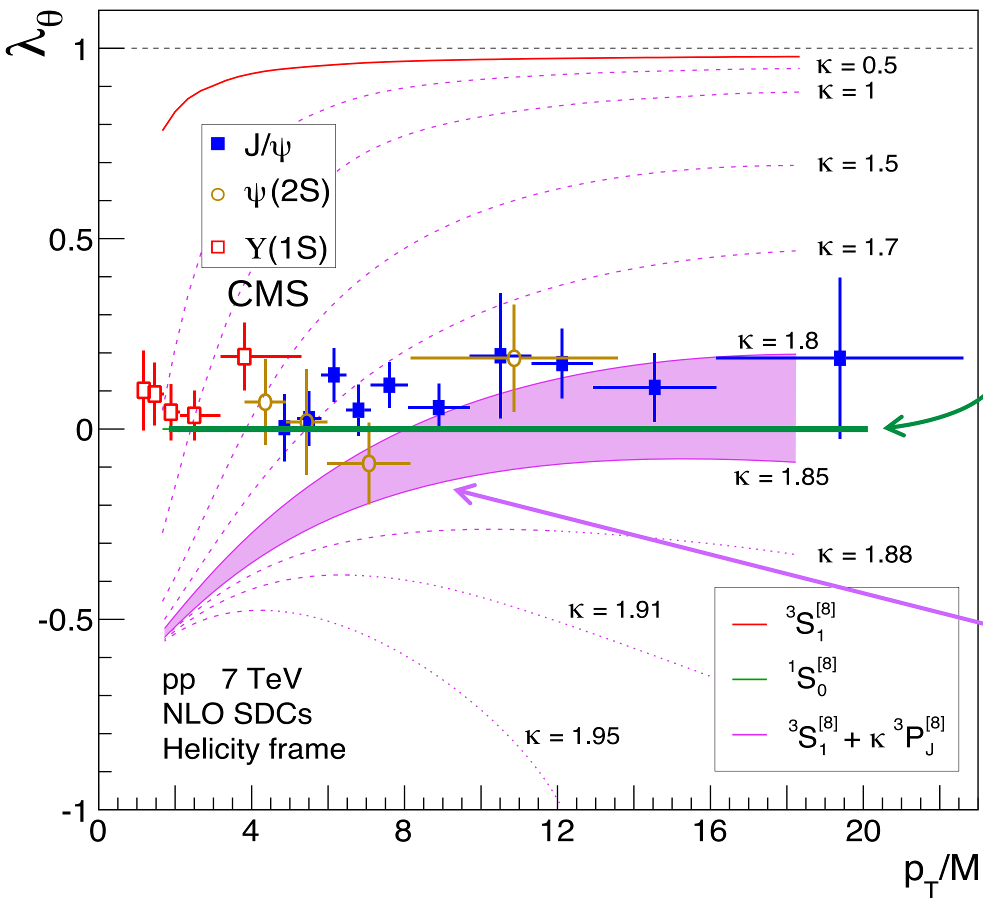
4) … and agrees with the polarization data towards high p_T



However, any **$^3S_1 + 1.8\ ^3P_J$** contribution is disfavoured by low-p_T data

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

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.

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

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.

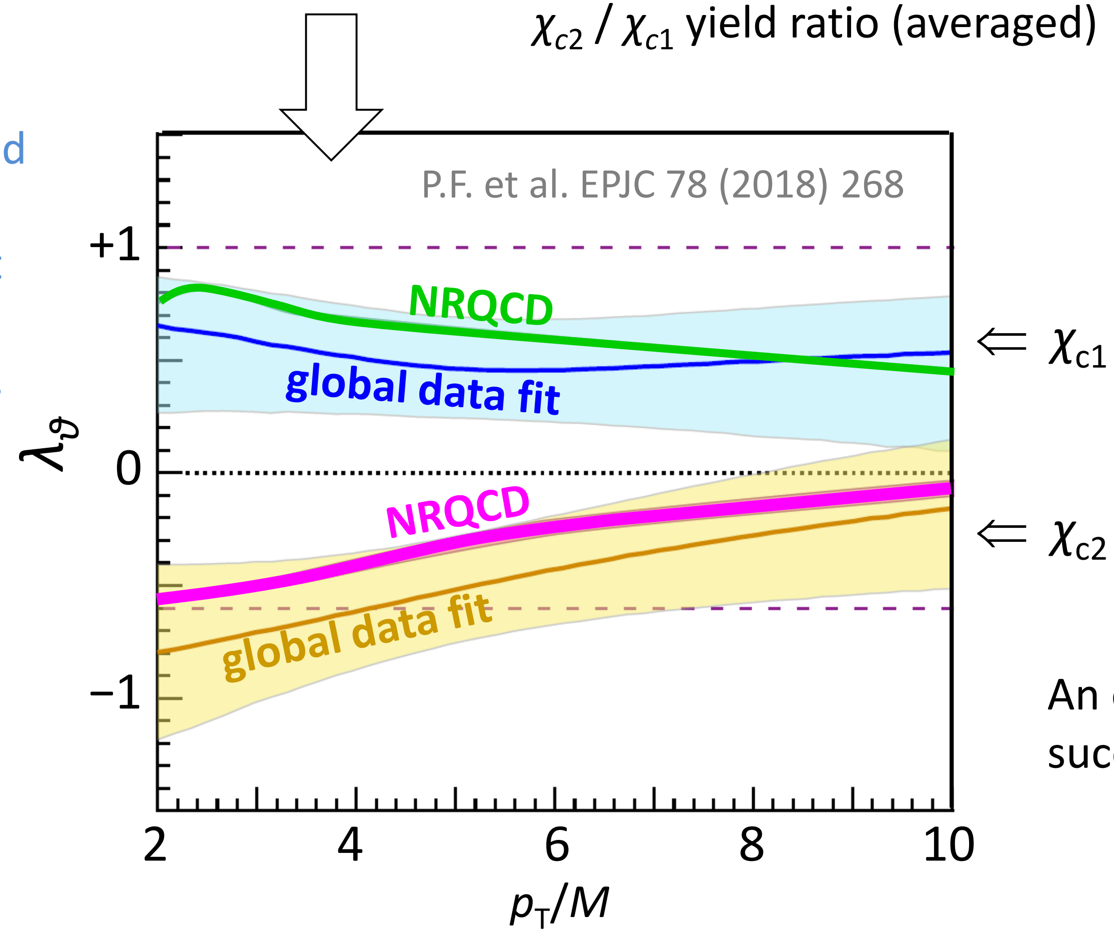
One parameter r determines

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

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

= 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"…



… and perfectly agreeing with data

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

Summary

Zero polarization for the J/ψ, given that it is a vector (=intrinsically polarized) particle, is an emblematic manifestation of its peculiar production mechanism

The observation is no longer in formal disagreement with NRQCD,
but it requires a specific parameter tuning, possibly pointing to the existence of a simpler (more natural) hierarchy of processes

More precise measurements are needed to assess whether the polarization always remains zero and flat vs p_T