Charmonium polarization in pp collisions

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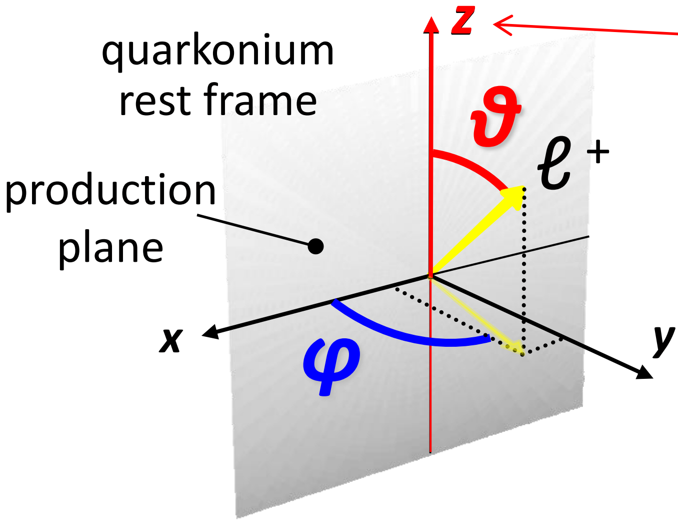
1. **The emblematic case of the J/ψ polarization at high-p_T**
2. **Low-p_T : puzzle or opportunity?**

In collaboration with Carlos Lourenço, CERN

Workshop
"Gluon content of proton and deuteron with the Spin Physics Detector at the NICA collider"
JINR, Dubna, October 1st, 2020

Vector particle polarization: frames and parameters



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

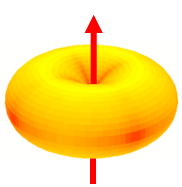
Gottfried-Jackson (GJ): dir. of one beam (or the target)

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

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

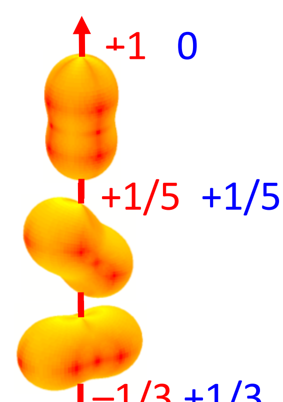
λ_ϑ λ_φ $\lambda_{\vartheta\varphi}$ frame-dependent

$J_z = \pm 1$ $\longrightarrow$ $\lambda_\varphi = \lambda_{\vartheta\varphi} = 0$, **$\lambda_\vartheta = +1$** : **"transverse"** (= photon-like) pol.



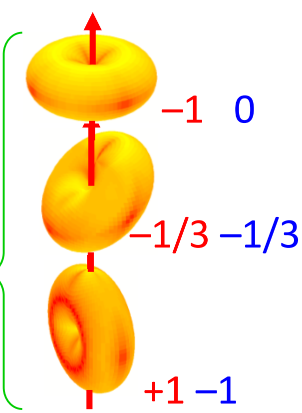
$J_z = 0$ $\longrightarrow$ $\lambda_\varphi = \lambda_{\vartheta\varphi} = 0$, **$\lambda_\vartheta = -1$** : **"longitudinal"** pol.

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



$\tilde{\lambda} = +1$

$\tilde{\lambda} = -1$

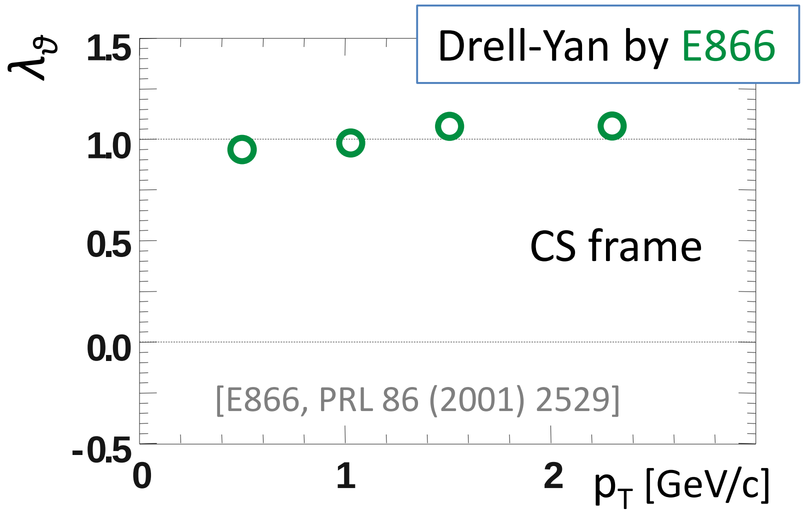


P.F. et al., PRL 105, 061601; PRD 82, 096002; PRD 83, 056008

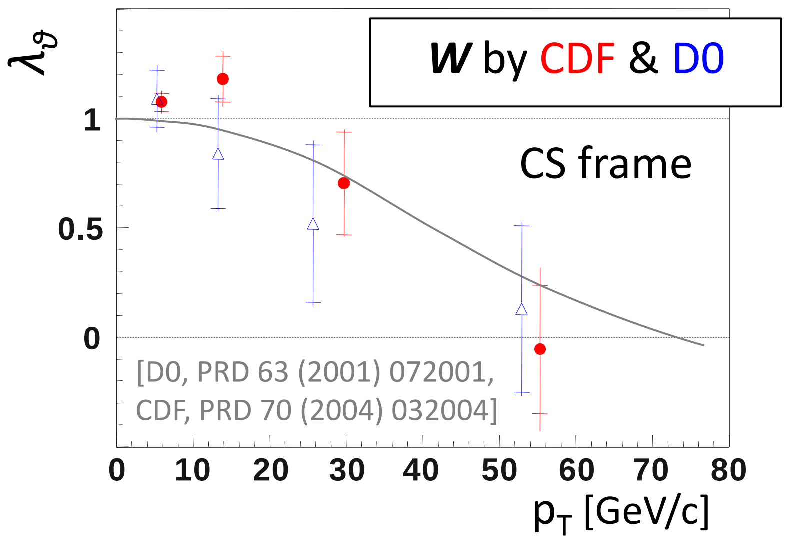
Vector particles are always polarized

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***



At very low p_T and for dominant **2-to-1 processes**, of order $\mathcal{O}(\alpha_S^0)$, a fully transverse polarization is seen in the **Collins-Soper** frame



At high p_T and for dominant **2-to-2 processes**, of order $\mathcal{O}(\alpha_S^1)$, a fully transverse polarization ***would be*** seen in the **helicity** frame.
The CS frame *smears* λ_ϑ *away from* $p_T = 0$.
As a recognizable consequence, the polarization becomes **strongly p_T dependent** (from **+1** to **−1/3**)

Is “unpolarized” even possible?

Vector states are intrinsically polarized for any given elementary process

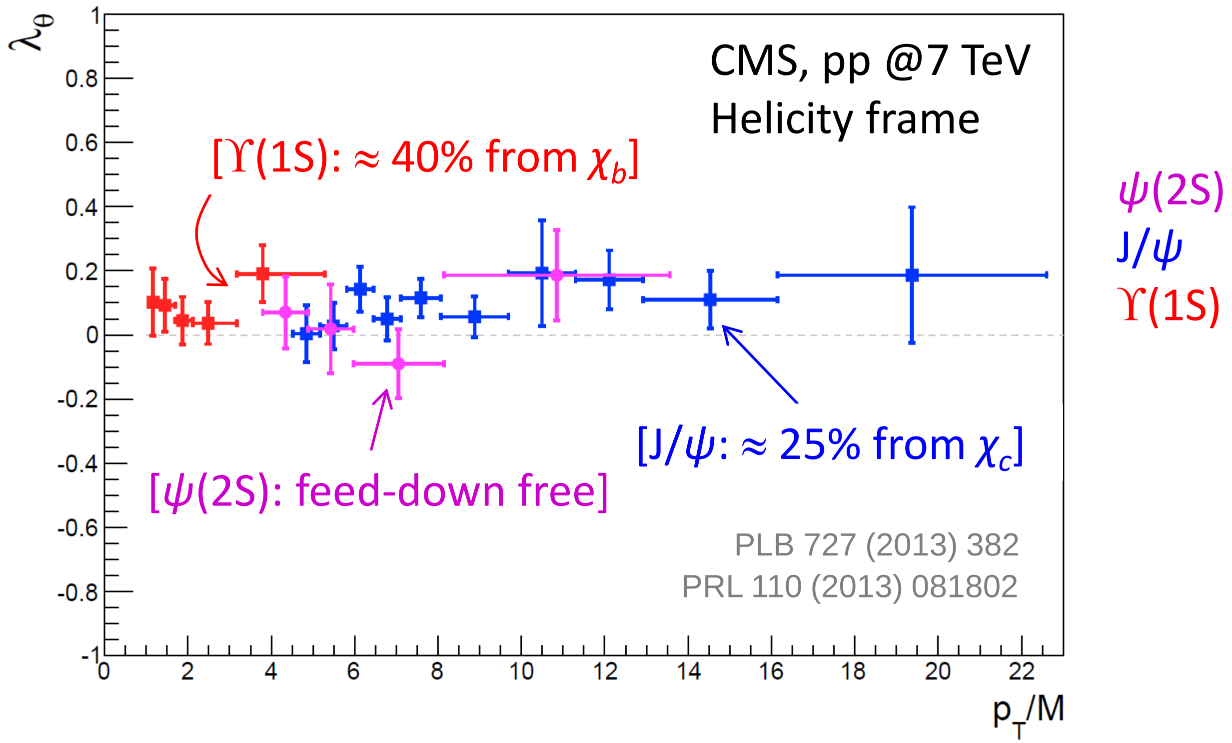
Theorem [P.F. et al., PRL 105, 061601]
For any subprocess producing a **J = 1 state**
$| V; J, J_z \rangle = a_{-1} | 1, -1 \rangle + a_0 | 1, 0 \rangle + a_{+1} | 1, +1 \rangle$,
there exists a quantization axis
along which the $J_z = 0$ component ***a_0* vanishes**

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

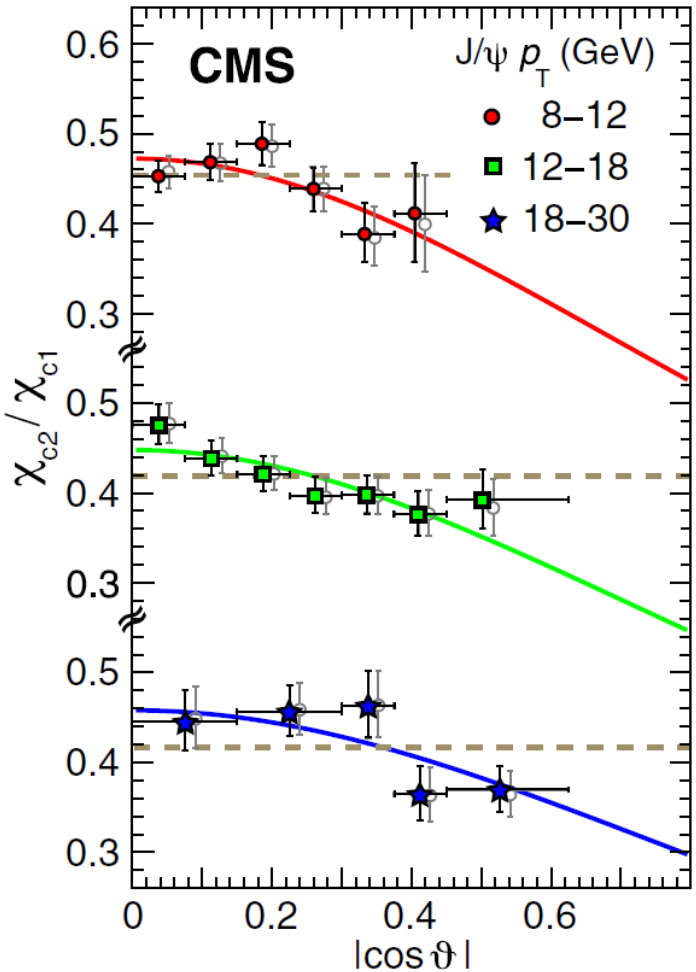
Mid-rapidity LHC data show unpolarized production of vector quarkonia

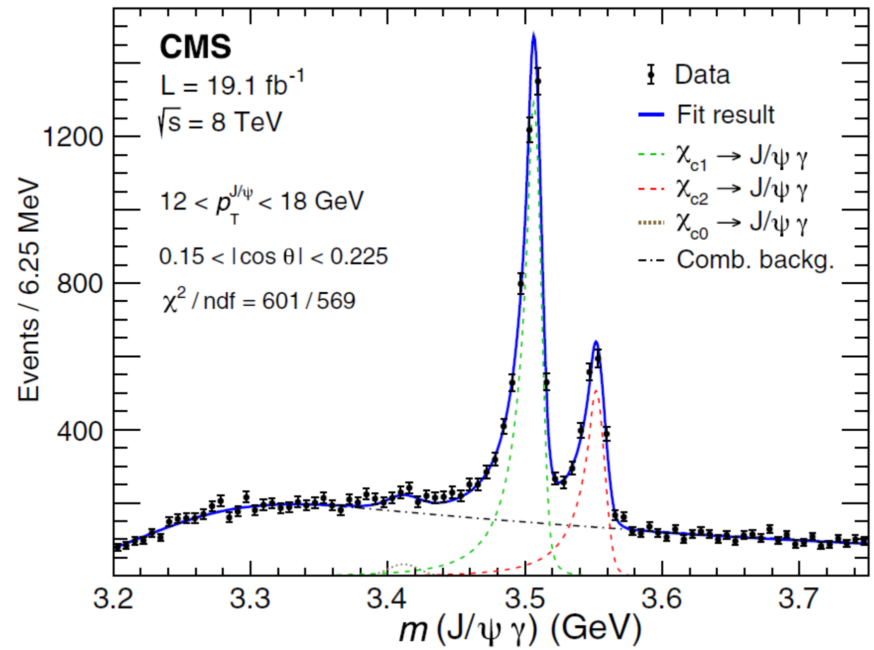


- None of the parameters λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$, $\tilde{\lambda}$ is significantly ≠ 0
- There is **no visible dependence on p_T**: seemingly not a transition domain
- No visible difference between states despite different χ feed-downs ⟶

The role of χ_c decays: finally from data

PRL 124 (2020) 162002]

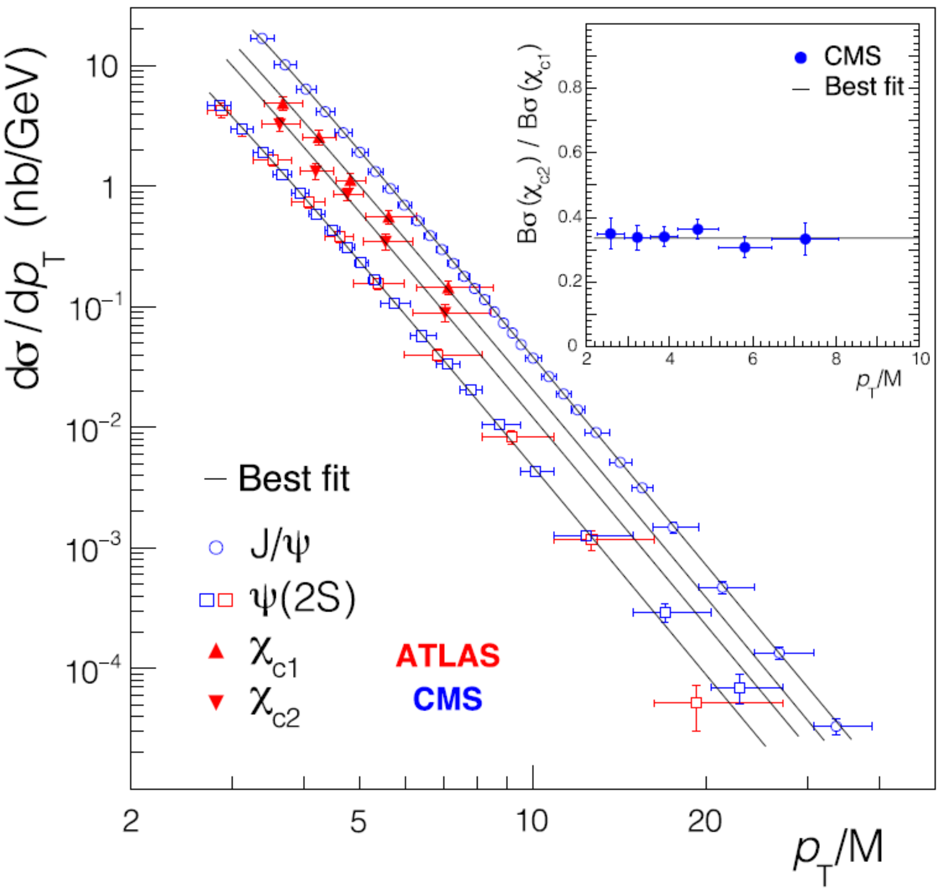


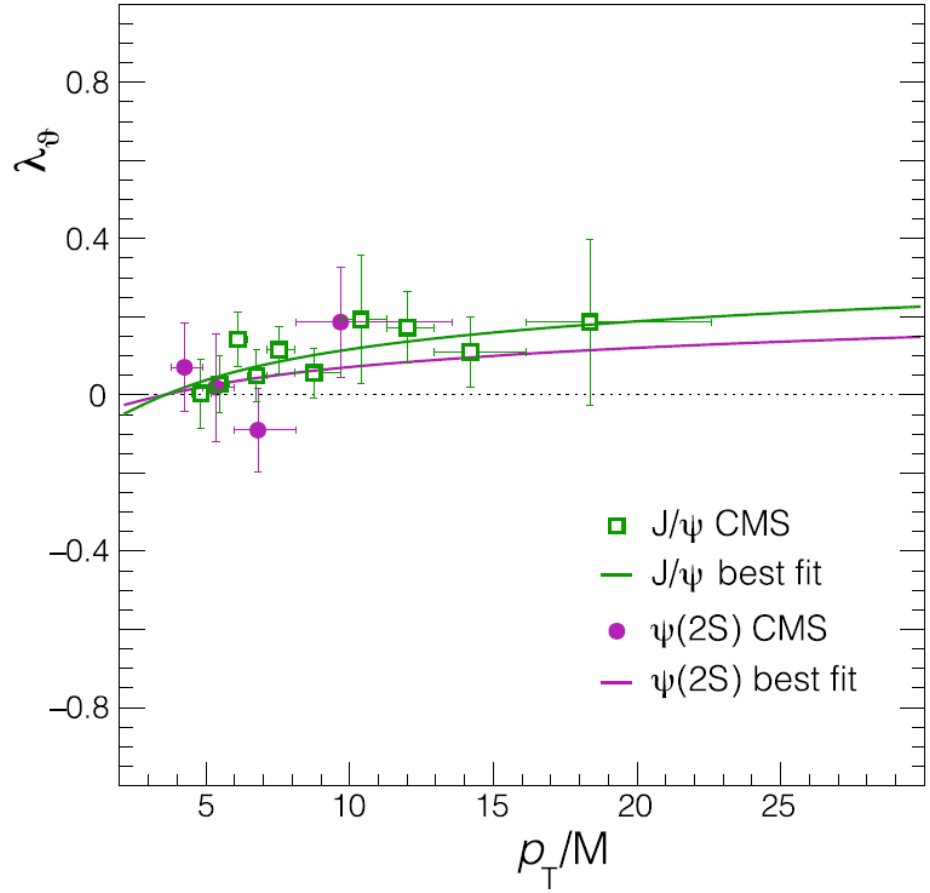


CMS measured the ratio between the (J/ψ from) χ_{c2} and χ_{c1} cosϑ distributions.

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

Indirect experimental constraints



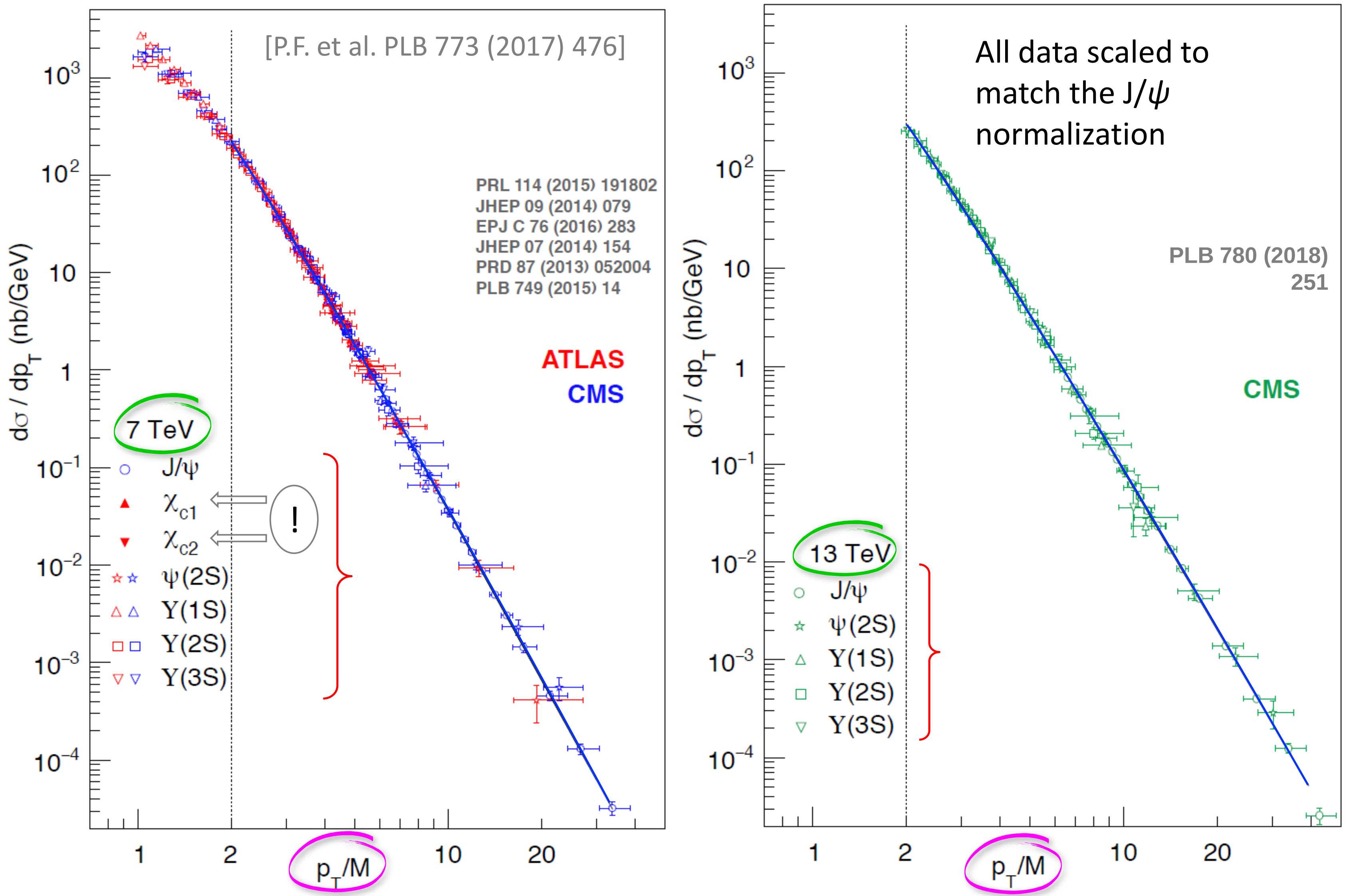


ATLAS and CMS measurements of J/ψ, $\psi(2S)$, χ_{c1} and χ_{c2} cross sections, together with the J/ψ and $\psi(2S)$ polarizations, constrain the *sum* of the χ_{c1} and χ_{c2} polarizations

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

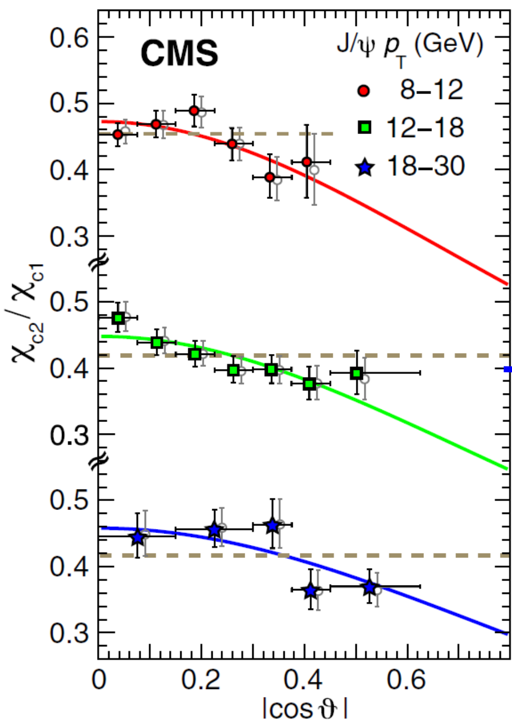
(*) A "universal" p_T/M scaling

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)

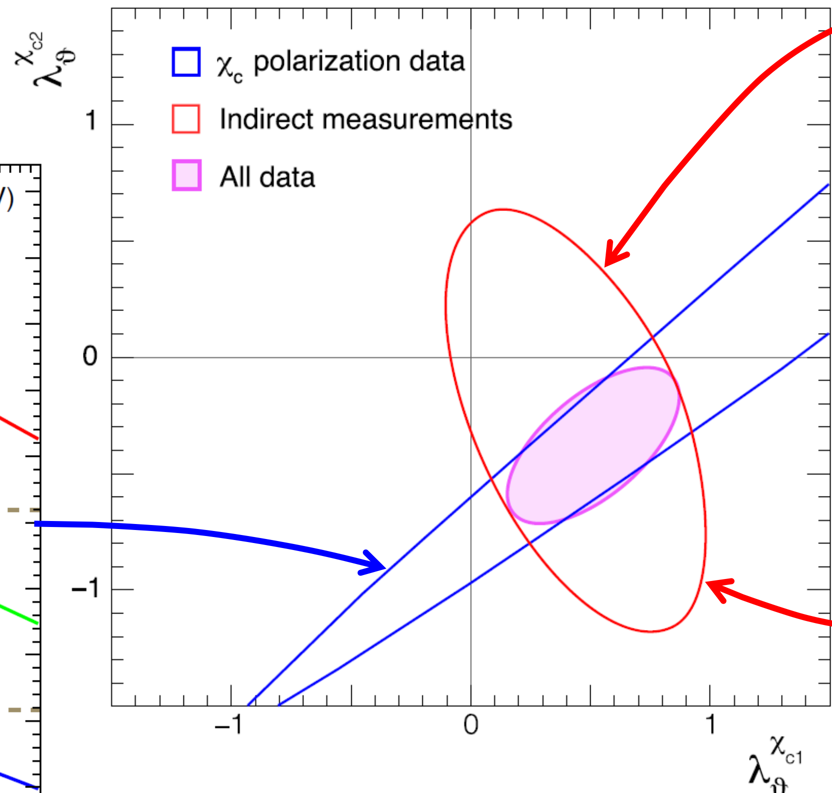


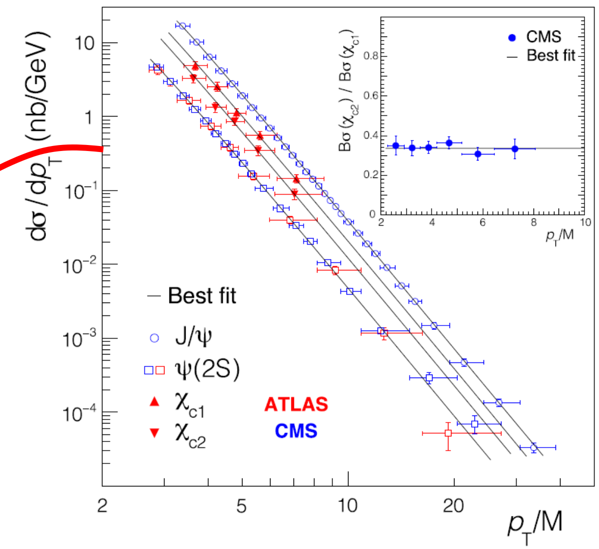
The χ_c states are strongly polarized!

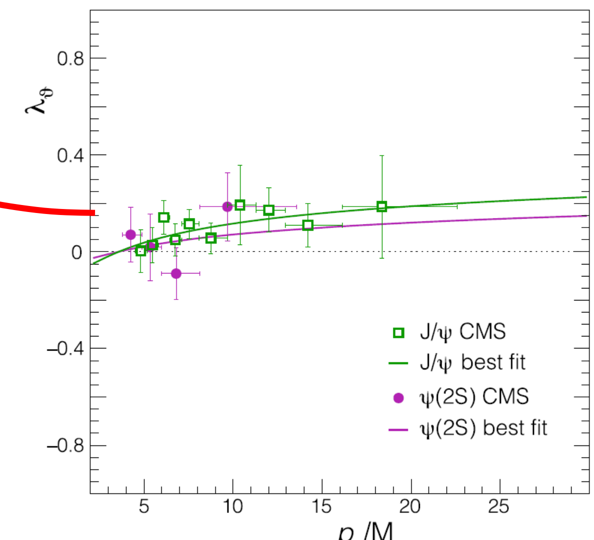
The combination of these two "orthogonal" experimental constraints determine the two individual χ_{c1} and χ_{c2} polarizations



[P.F. et al. EPJC 80 (2020) 623]



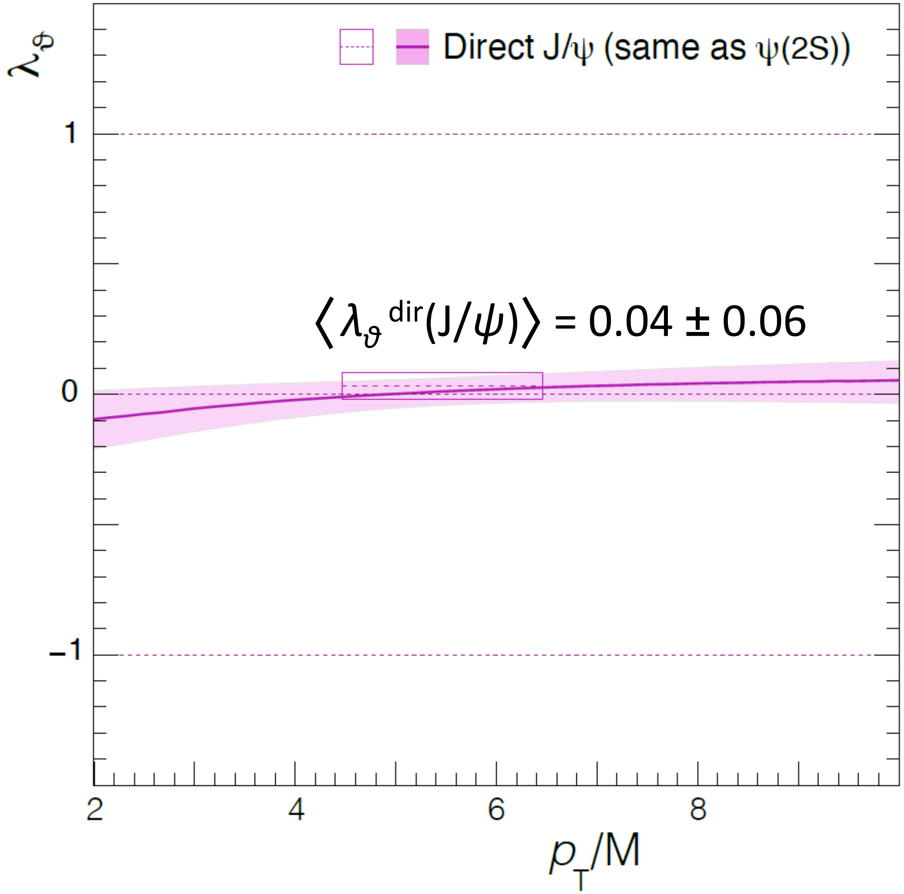




J/ψ from χ_{c1} and χ_{c2} are, respectively, transversely and longitudinally polarized
→ they tend to cancel out in their contribution to J/ψ

…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 stronger evidence of unpolarized production!

Zero and ***constant*** polarization is a big challenge to production models

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

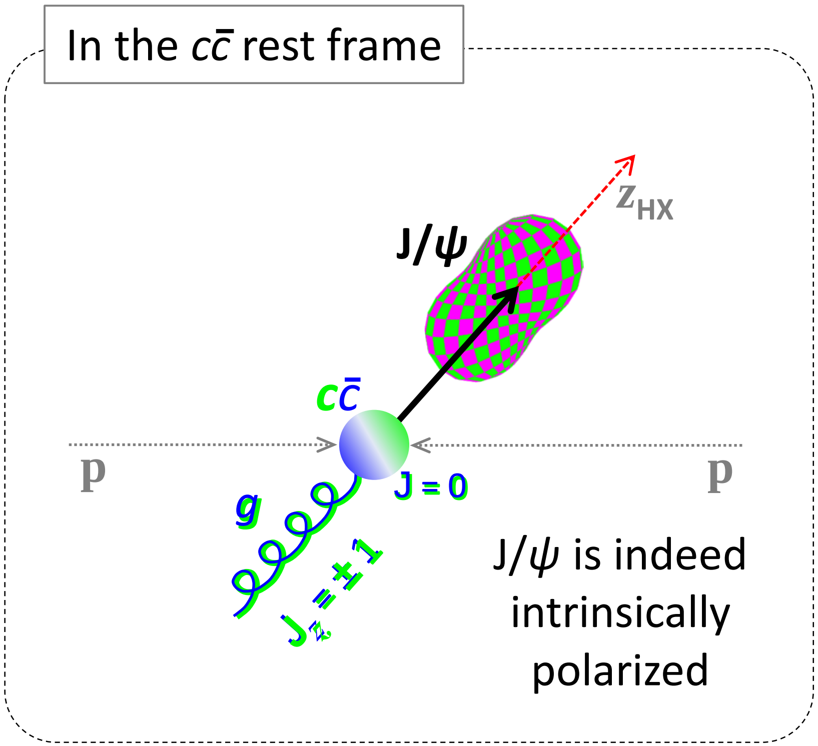
→ a clear sign of the **unique nature and production mechanism** of heavy quarkonia

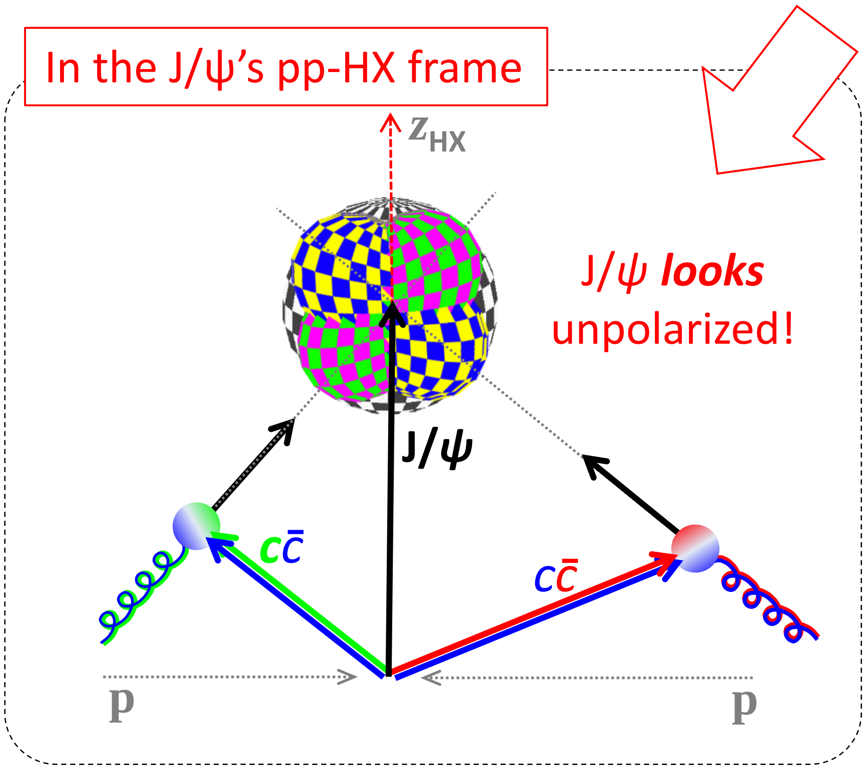
Are we seeing a cascade mechanism?

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/ψ 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





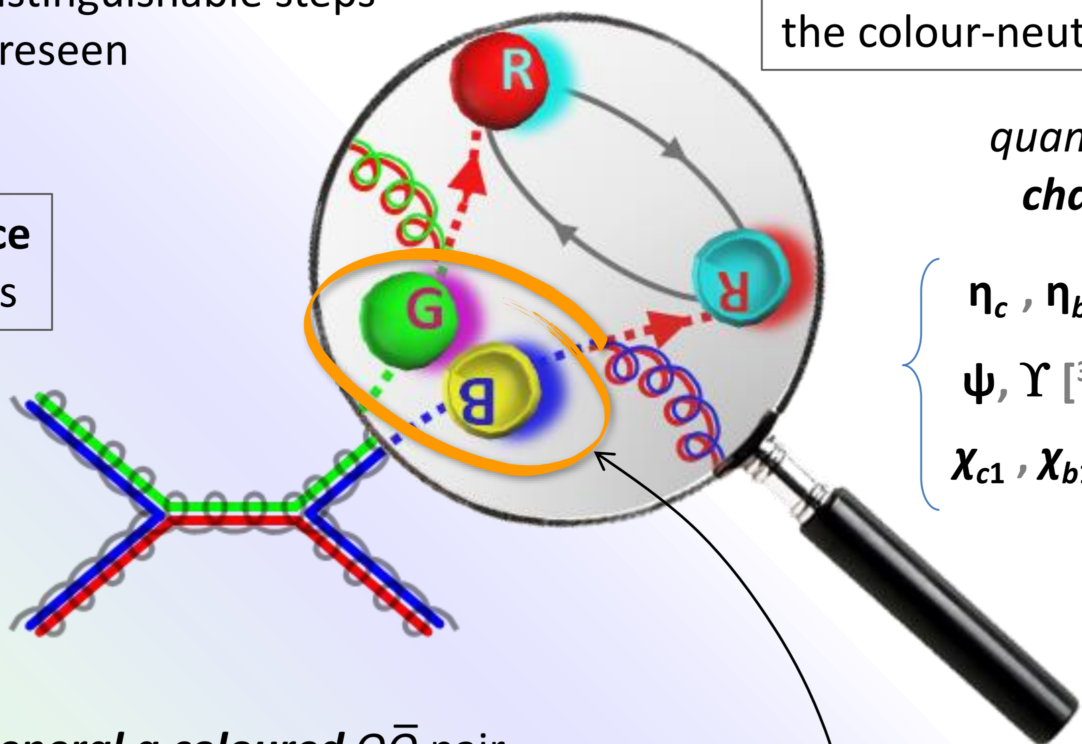
The “cascade” (*factorization*) approach of NRQCD

Non-Relativistic

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

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

1) **short-distance**
partonic process



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*

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

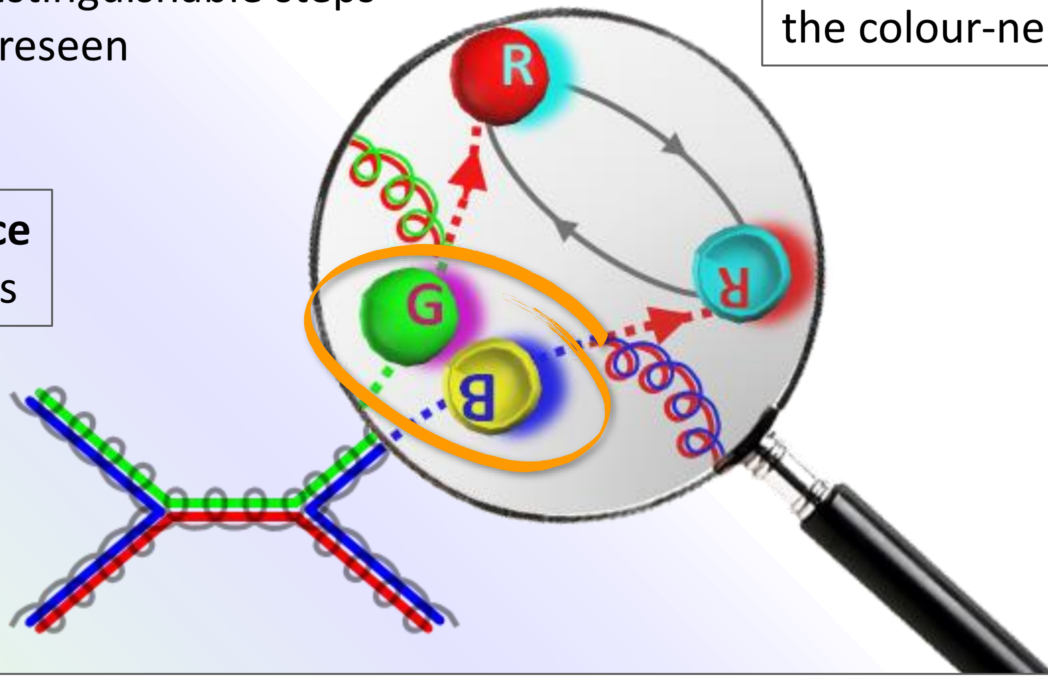
Even if the ***pre-resonance*** $Q\bar{Q}$ state
is not observed, it determines,
with its own quantum properties,
the observable kinematics and *polarization*

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**

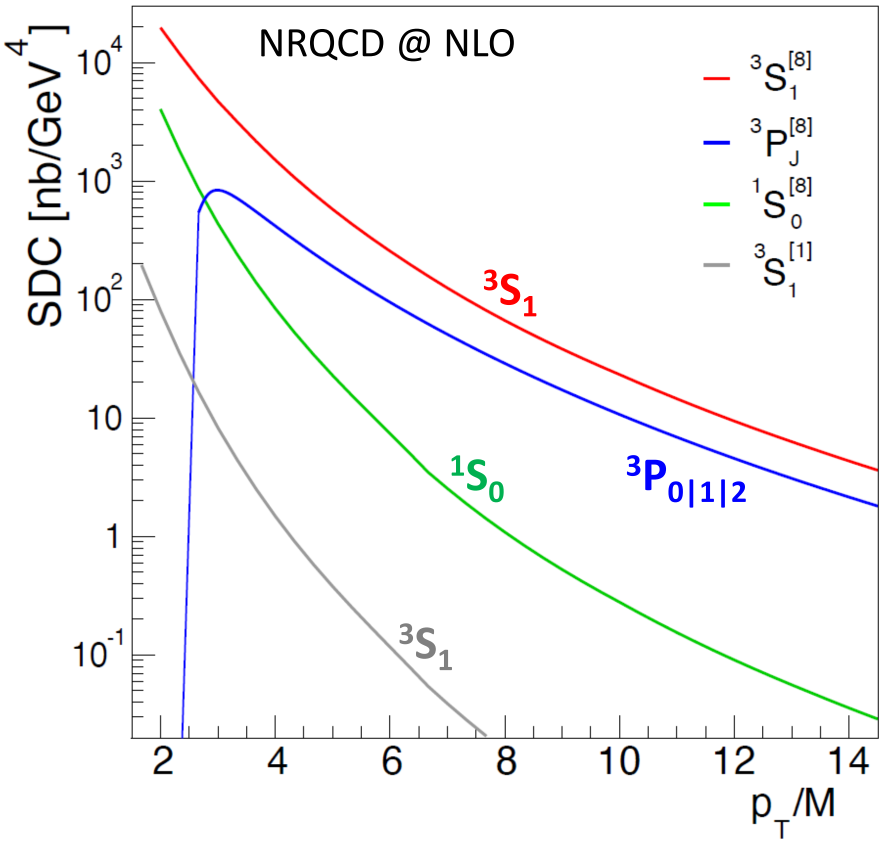
$$\sigma(A + B \to \mathcal{Q} + X) = \sum_{S,\,L,\,C} \mathcal{S}\{A + B \to (Q\bar{Q})_C[^{2S+1}L_J] + X\} \cdot \mathcal{L}\{(Q\bar{Q})_C[^{2S+1}L_J] \to \mathcal{Q}\}$$

$Q\bar{Q}$ **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

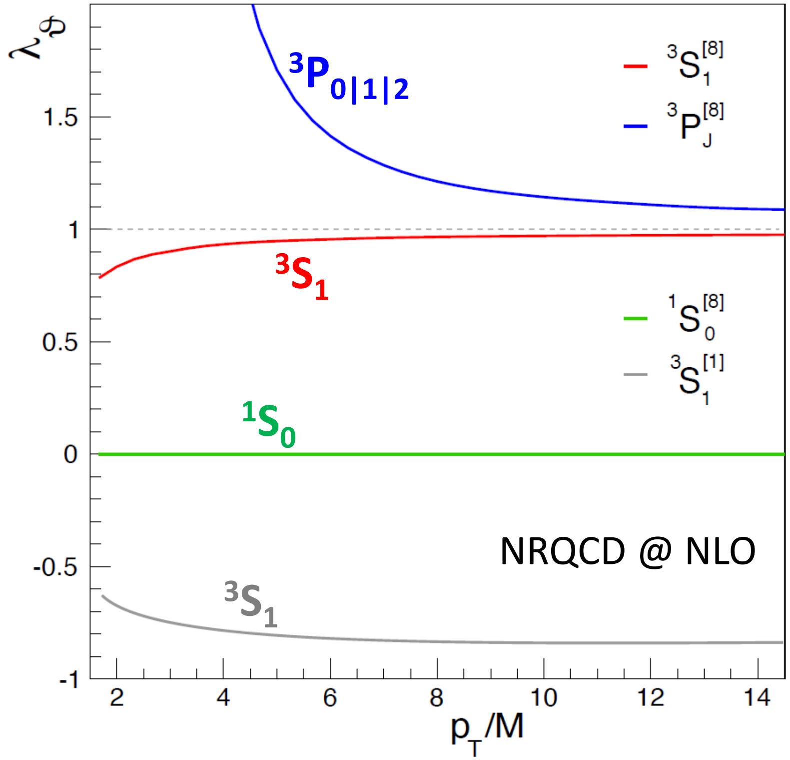
Mixture of different pre-resonance contributions, with characteristic p_T spectra (and polarizations: see next slide)

→ 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
  $\rightarrow$ violation of NRQCD's v^2 hierarchy!
- or sum to ~zero $\rightarrow$ redundant expansion basis!

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

What about χ_{c1} and χ_{c2}?

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

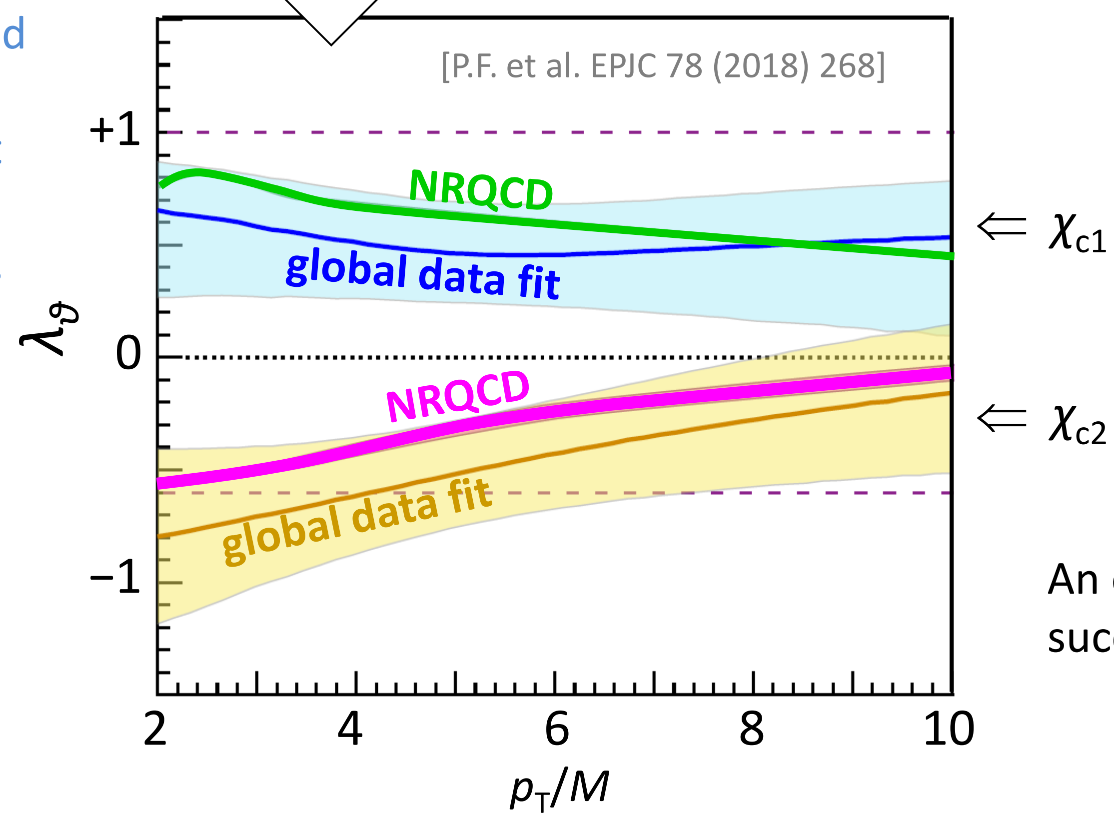
One parameter r determines

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

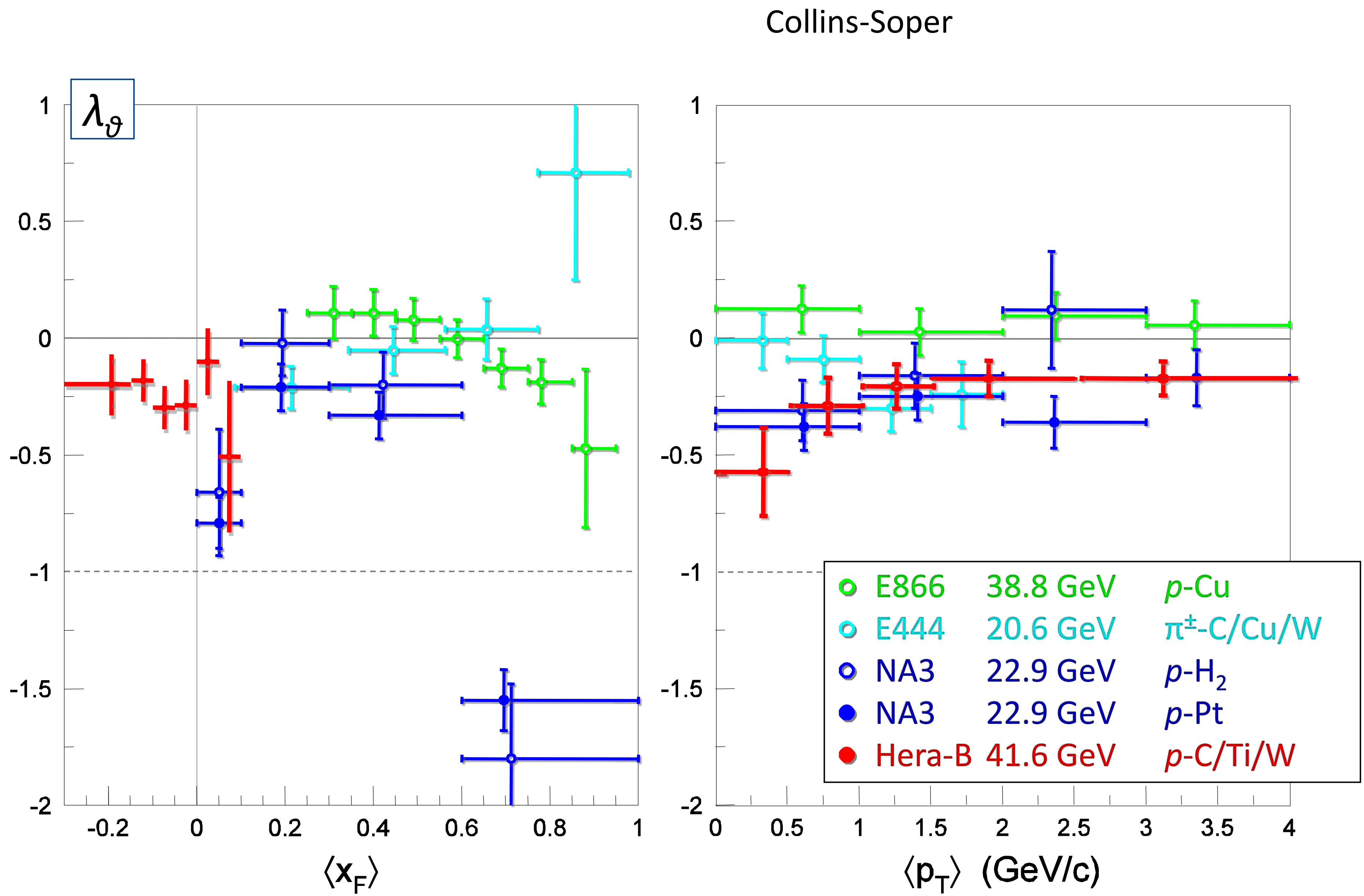
An out-of-the-box success of NRQCD!

Part 2
The puzzle of low-p_T (fixed target) data

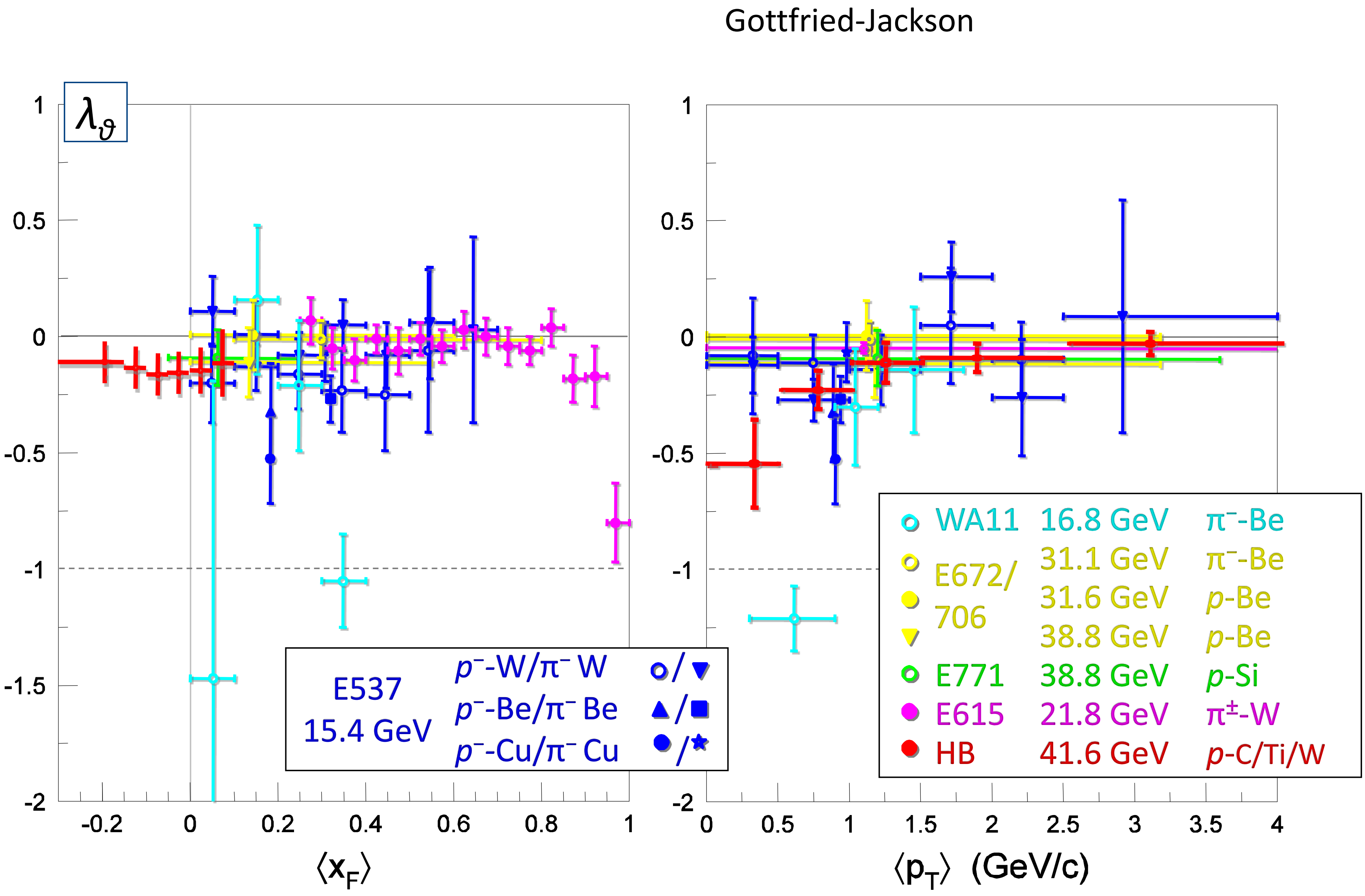
Past fixed-target experiments provided J/ψ and ϒ polarization measurements with different beams and targets, different energies, and in three different reference frames, as functions of p_T and x_F.

They form a very perplexing picture…

J/ψ polarization in the CS frame

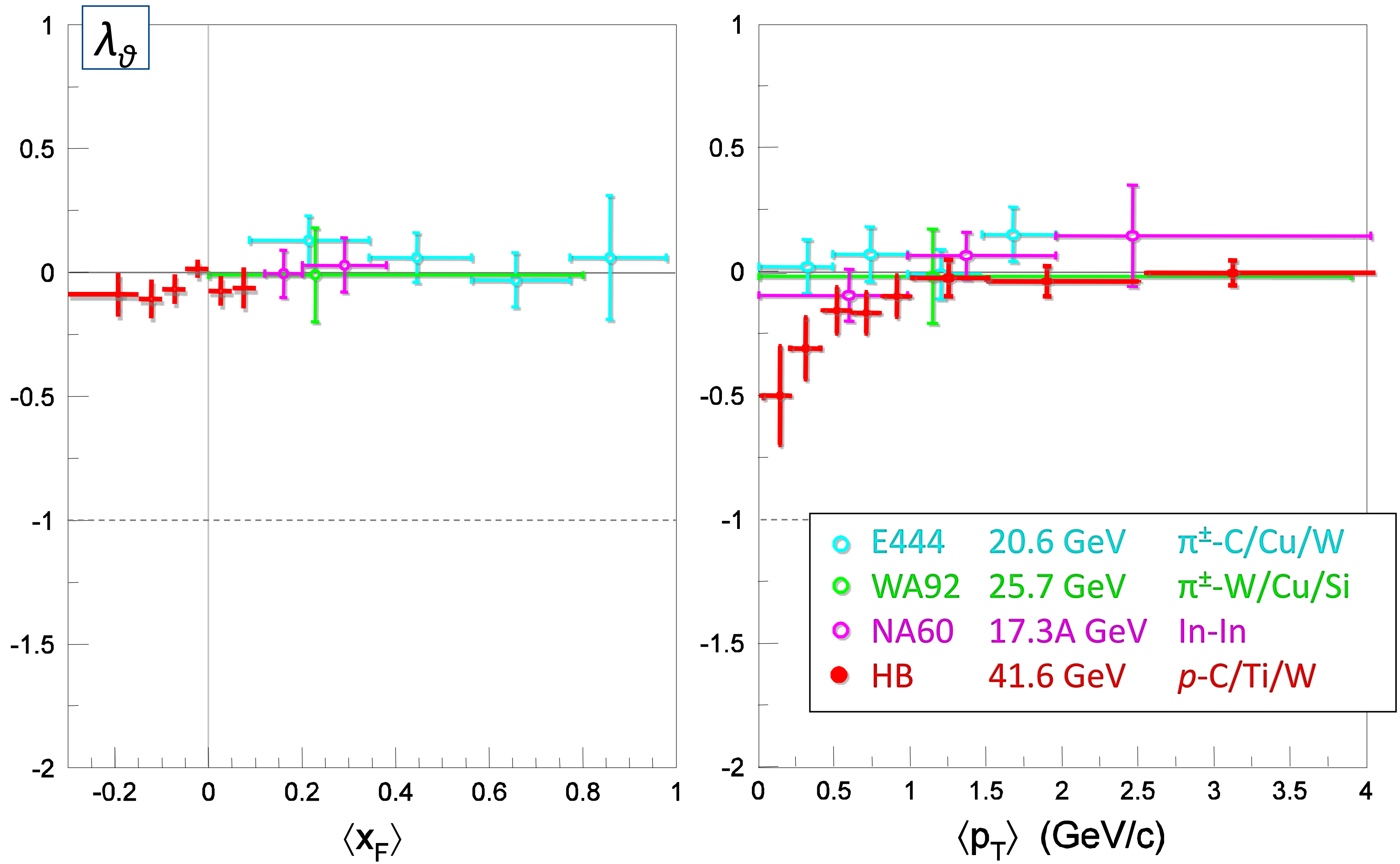


J/ψ polarization in the GJ frame

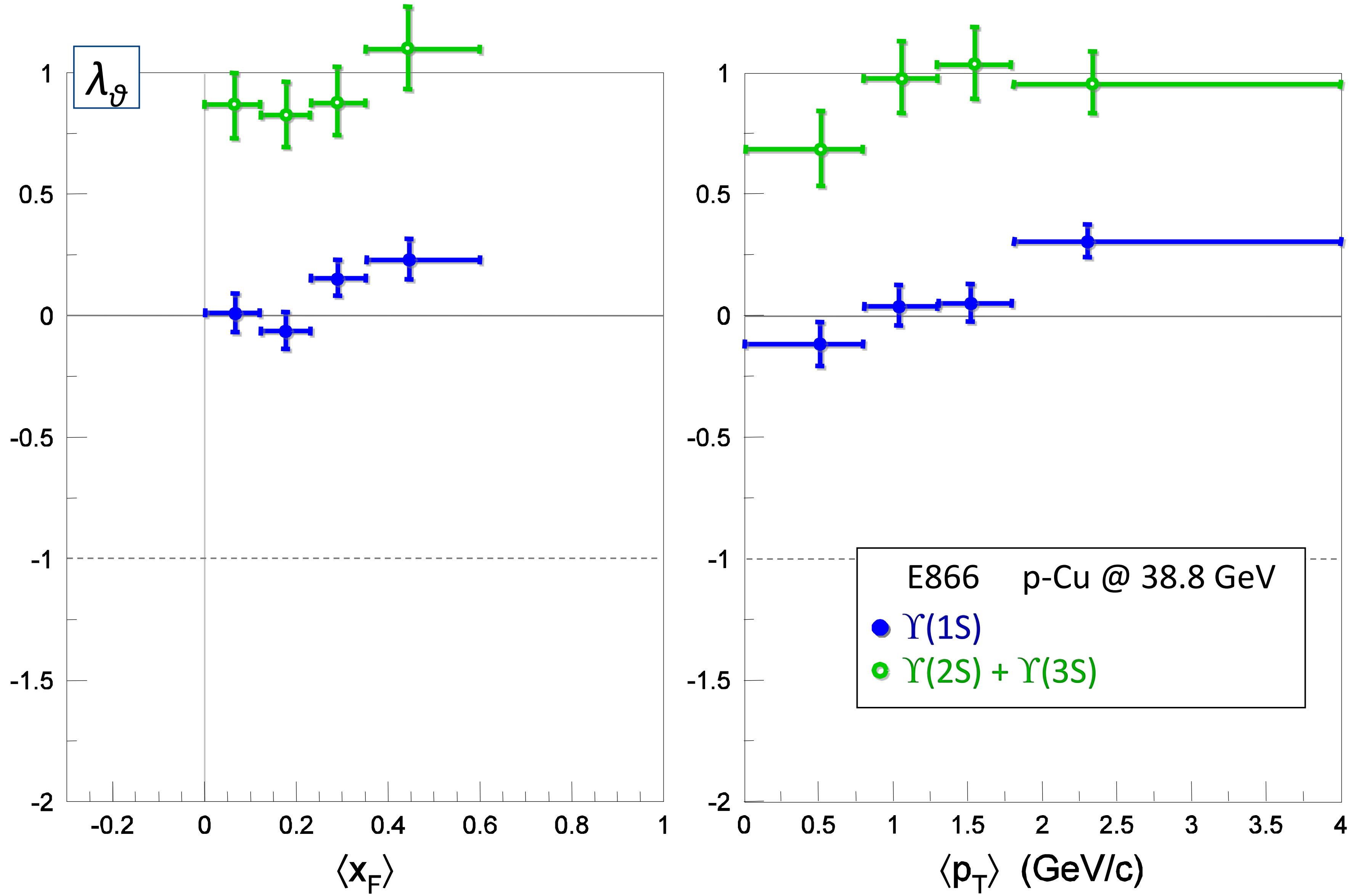


J/ψ polarization in the HX frame

centre-of-mass helicity



Υ Polarization in the CS frame



Picture to be observed “with a grain of salt”:

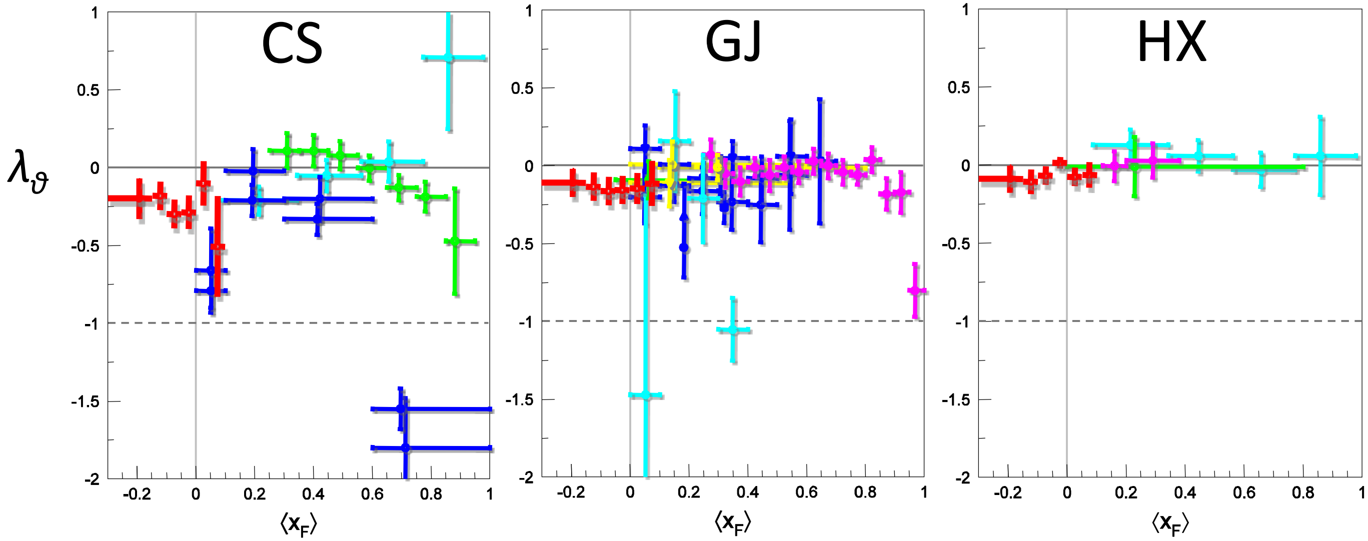
- most of these measurements were obtained from 1D analyses (with risks discussed in [P. Faccioli, Mod. Phys. Lett. A Vol. 27, 1230022 (2012)])
- for some of them systematic uncertainties were never evaluated
- some of them exhibit suspicious fluctuations, even reaching unphysical values
- we are mixing different energies and target nuclei (nuclear effects may exist)

Nevertheless, we can see some indications…

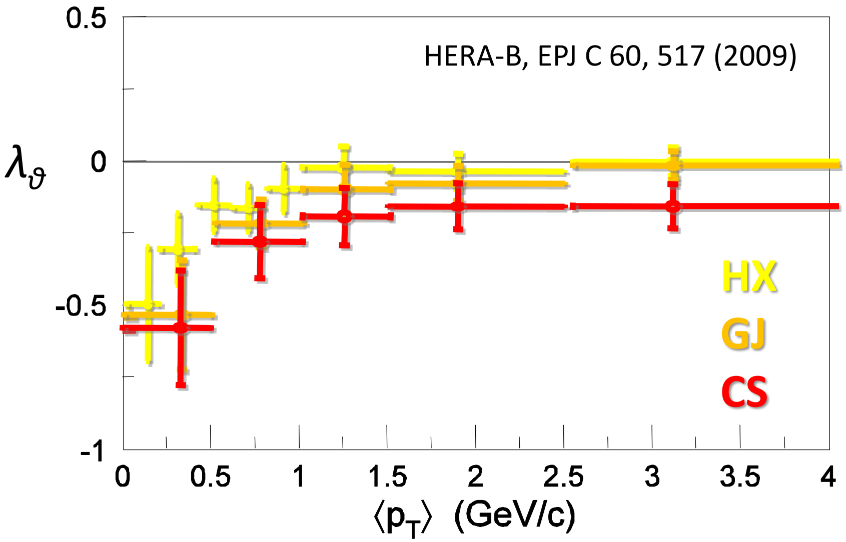
0) Obvious: new, better measurements are welcome

- Looking at polar and azimuthal components
- Using invariant polarization as check
- Possibly disentangling feed-down components: ψ(2S) and/or χ_c

1) CS/GJ > HX hierarchy: dominance of 2 $\to$ 1



λ_ϑ looks "flat" in the HX frame



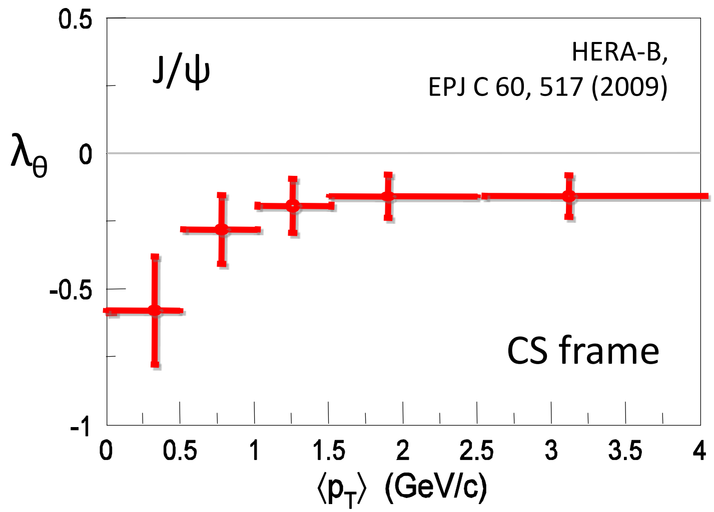
Hierarchy clearly seen by HERA-B in the three frames (uncertainties ~100% corr.)

$\to$ CS (direction of colliding partons) gives the "optimal" observation

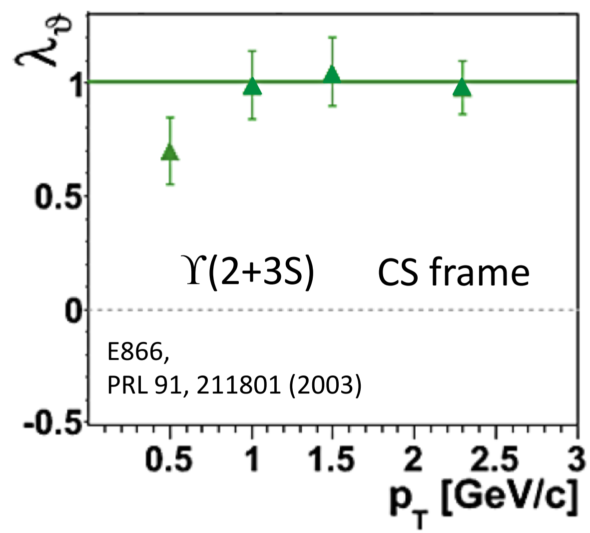
$\to$ probable dominance of **2$\to$1 *q-q*bar / *g-g* $\to$ *QQ*bar processes**, where the *QQ*bar is strongly polarized, directly inheriting the angular momentum state of the system of colliding partons: we see the **partons' natural polarizations**

2) Smearing with increasing p_T: importance of k_T effects

The J/ψ polarization *magnitude*,



but not the ϒ one,



seems to *decrease quickly with increasing* p_T.

In fact the J/ψ measurement reaches higher p_T/M values than the ϒ one.
Does this mean that in J/ψ production, but not in ϒ production,
we start seeing 2 → 2 processes "smearing" the polarization?

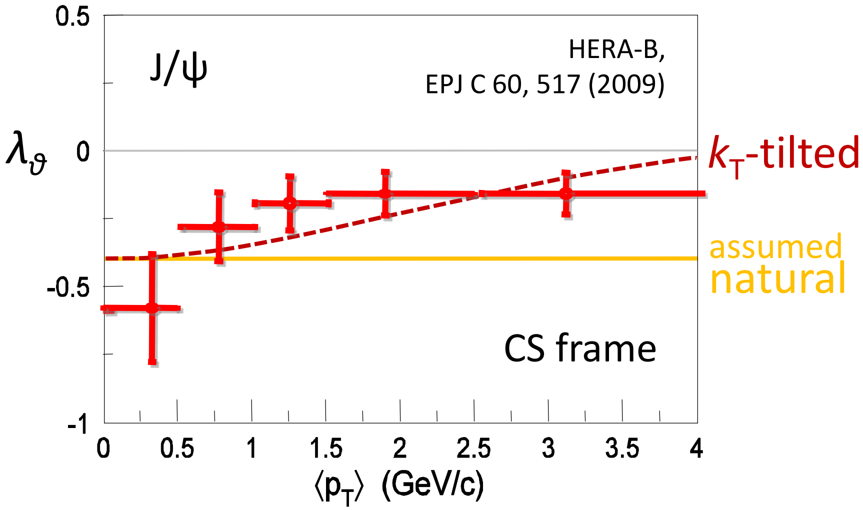
Or, what about the parton k_T?

2) Smearing with increasing p_T: importance of k_T effects

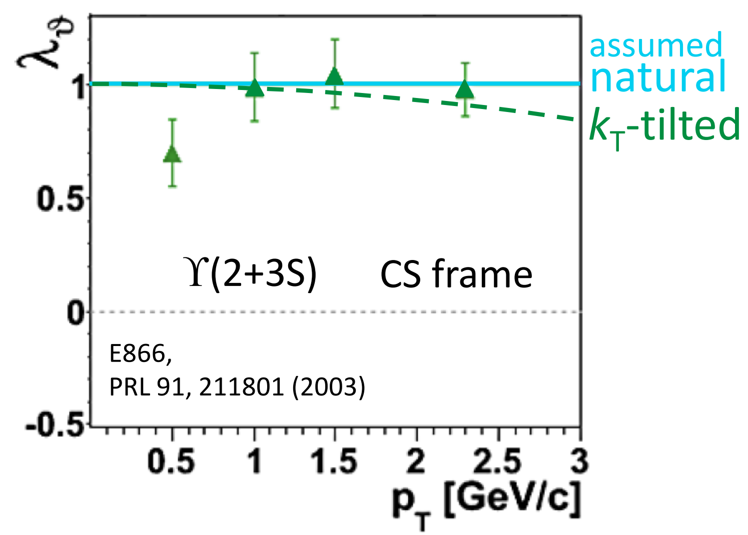
The intrinsic transverse momenta of the partons cause an *event-by-event tilt* between the “natural” polarization axis (relative direction of the colliding partons), and the polarization axis used in the experimental analysis (CS).

The tilt angle δ satisfies $\sin^2\delta \approx \frac{2k_T^2}{m_T^2} \approx \frac{p_T^2}{M^2 + p_T^2}$ [P. F. et al., EPJC 69, 657 (2010)]

This description approximately accounts for the p_T dependence observed for the $c\bar{c}$...

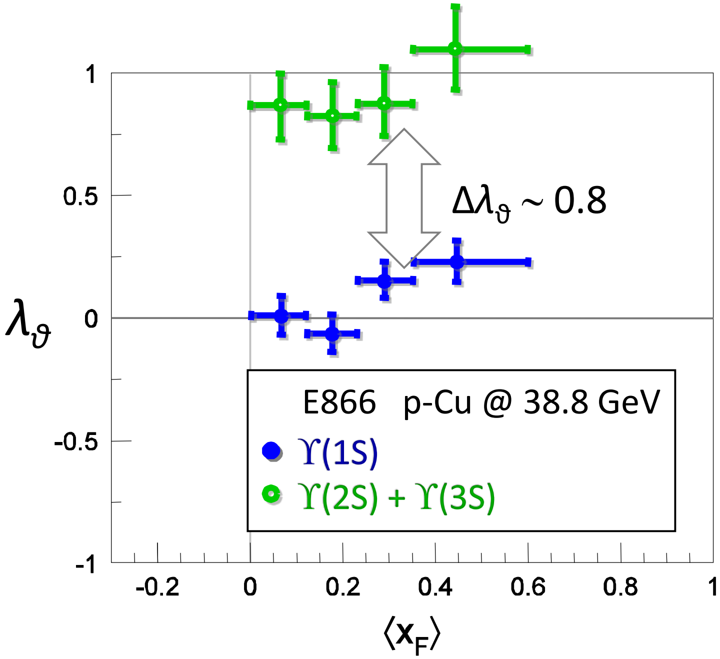


...and for the lack of a corresponding observation in the $b\bar{b}$ case



The $p_T \rightarrow 0$ limit gives the most interesting (unsmeared) polarization measurement!

3) E866's Υ puzzle: importance of the χ feed-down



1S, 2S and 3S states should have about the same polarization when **directly produced**
(or when coming from heavier Υ) $\rightarrow$ $\boldsymbol{\lambda_\vartheta \approx +1}$

To justify the large difference between 2-3S and 1S, we must assume that $\boldsymbol{\chi_1 + \chi_2}$ **feed-down**:
a) is **negligible for 2-3S states** and **large for 1S**
b) tends to be **longitudinal**

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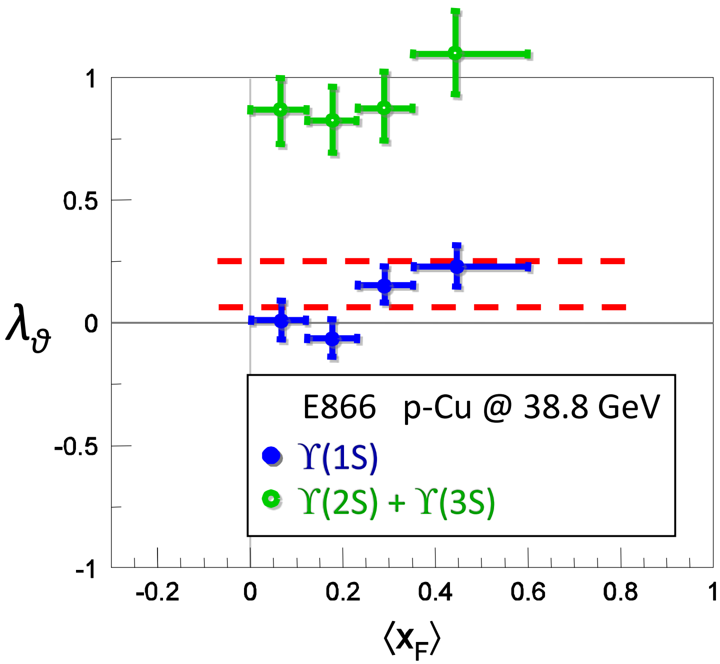

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b) tends to be **longitudinal**

If…

- **50–60%** of the Υ(1S) come from χ_b
- χ_b states are produced, e.g., with $J_z = \pm 1$ $\rightarrow \lambda_\vartheta(\chi_{b1}) = \lambda_\vartheta(\chi_{b2}) = -1/3$

(only an example: they have in general different polarizations, as seen for the χ_c at high p_T)

$\Rightarrow$ the observed Υ(1S) would have λ_ϑ in the range 1/13 – 1/4 = 0.08 – 0.25

χ production is **not a second-order correction** for J/ψ and Υ yields and polarizations!

4) Strong x_F (and mass) dependence: *q-q*bar vs gg ?

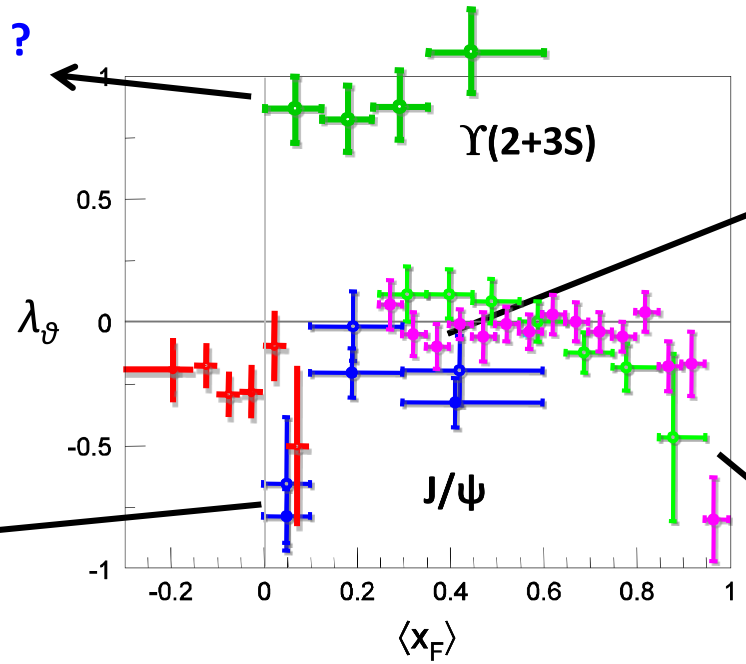
A trend may be recognized in the perplexing scenario of J/ψ and ϒ polarizations vs $x_F = x_1 - x_2$ when we correlate the observed **longitudinal** polarizations with the dominance of ***gg* → *QQ*bar processes** and **transverse** polarizations with the dominance of ***qq*bar → *QQ*bar processes**

***qq*bar$_{\Upsilon(nS)}$ >> *qq*bar$_{J/\psi}$?**

$$\frac{\langle x_1 \cdot x_2 \rangle_{\Upsilon(nS)}}{\langle x_1 \cdot x_2 \rangle_{J/\psi}} \sim 10$$

$x_1 \cong x_2 = \mathcal{O}(0.1)$

gg dominance?



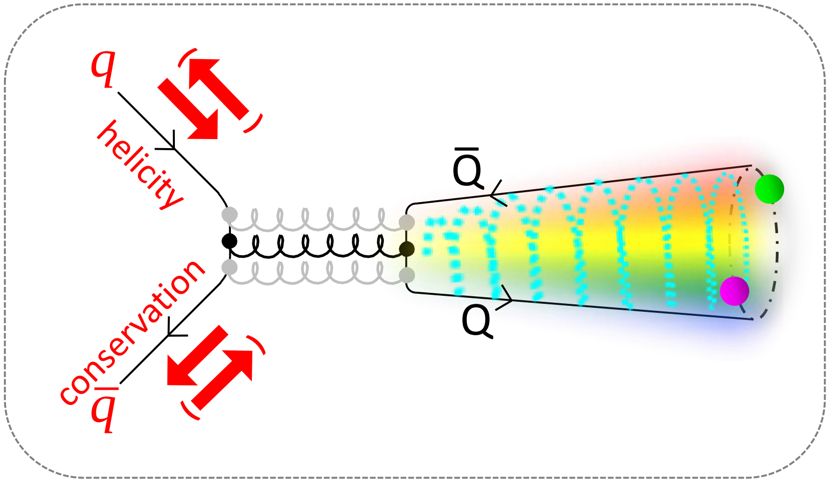
*qq*bar ~ *gg* ?

??

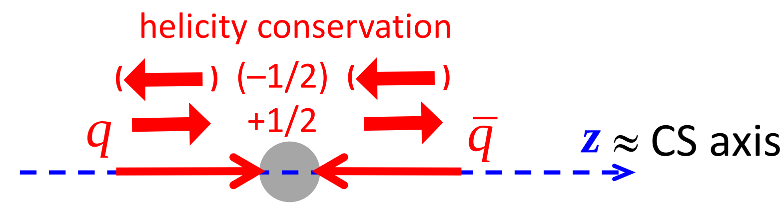
Comparing measurements with predictions for the *gg* and *qq*bar cases can probe the identity of the colliding partons

→ use polarization vs x_F as further constraint on gluon distribution!

(*gg* vs *qq*bar) ↔ (longitudinal vs transverse) ?

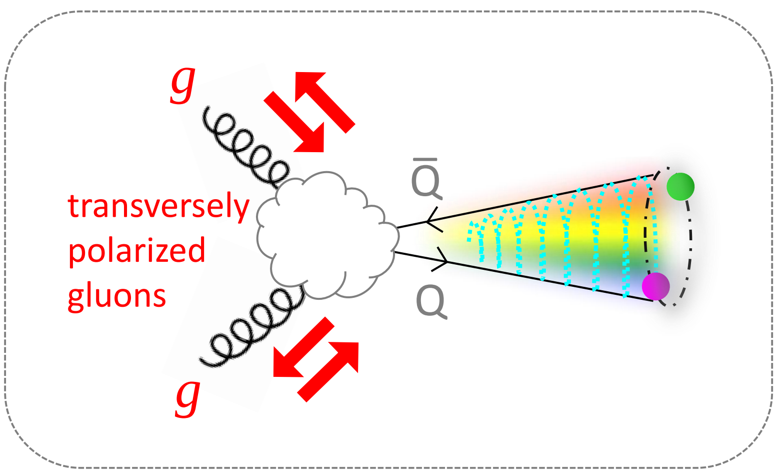


q-$\bar{q}$ rest frame = $Q\bar{Q}$ rest frame

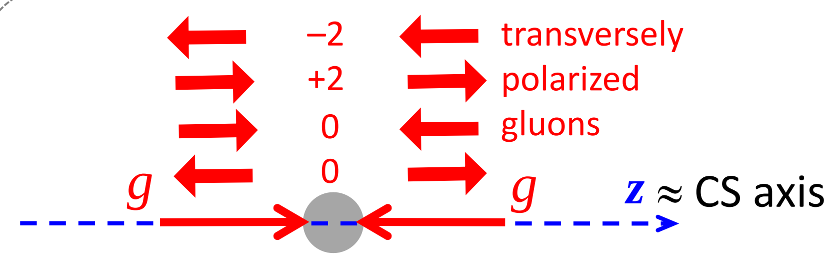


$\Rightarrow |Q\bar{Q}\rangle = |\, 1, \pm 1 \,\rangle$

⇒ e.g. "transverse" if *QQ*bar is a vector



g-g rest frame = $Q\bar{Q}$ rest frame



$|\, J, \pm 1 \,\rangle$ forbidden

⇒ e.g. "longitudinal" if *QQ*bar is a vector

(observed quarkonium polarization will depend on the J^P of the intermediate *QQ*bar)

Summary

High p_T

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 agreement with NRQCD 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.

Low p_T

The puzzling scenario of existing fixed-target data contains interesting indications:
- dominance of $2\rightarrow1$ processes
- importance of parton-k_T effects
- necessity to discriminate direct production and χ-state feed-down contributions
- maximal difference between polarizations in *q*-*q*bar and *gg* production: an opportunity to improve gluon PDF determination?