QCD@LHC, August 26th, 2016

A data-driven interpretation of heavy quarkonium measurements at the LHC

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in collaboration with
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- A "universal production" scenario?
- How easily can NRQCD account for it?
- A simple interpretation
- Test: global fit of charmonium data

LIP
SFRH / BPD / 98595 / 2013
CERN/FIS-NUC/0029/2015
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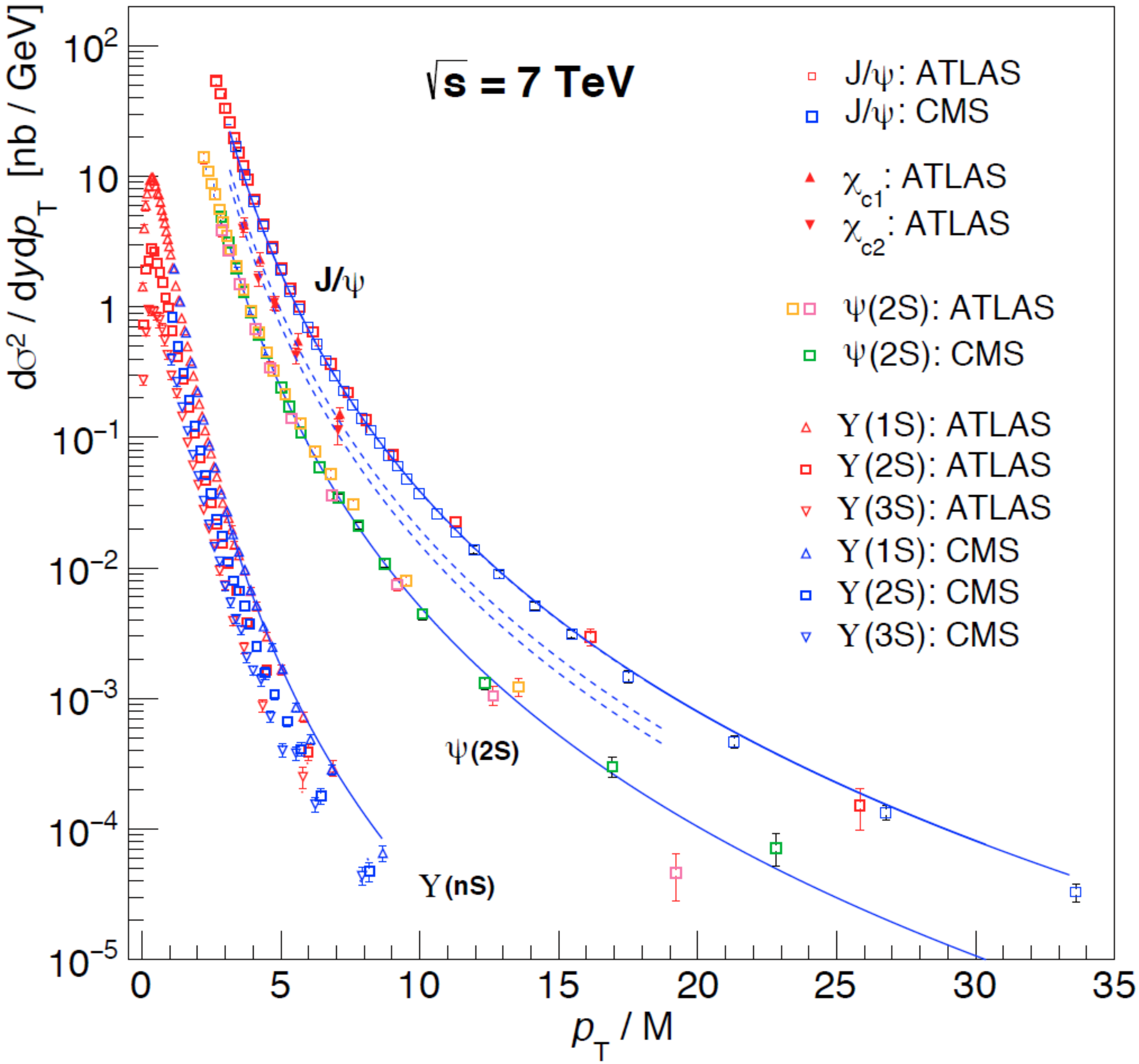
What data say

p_T/M scaling



Mid-rapidity cross sections vs p_T/M

PRL 114 (2015) 191802
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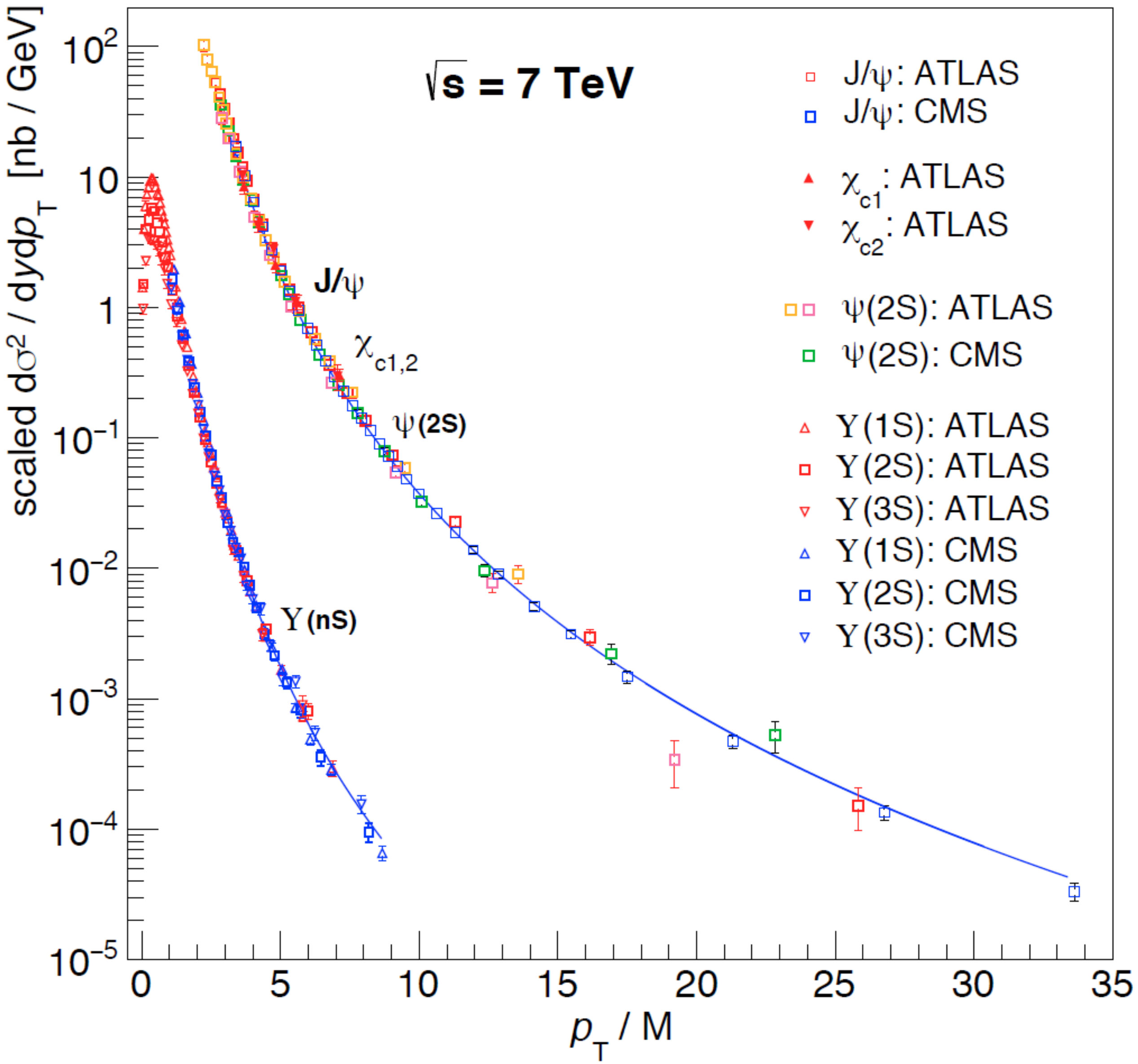
p_T/M scaling



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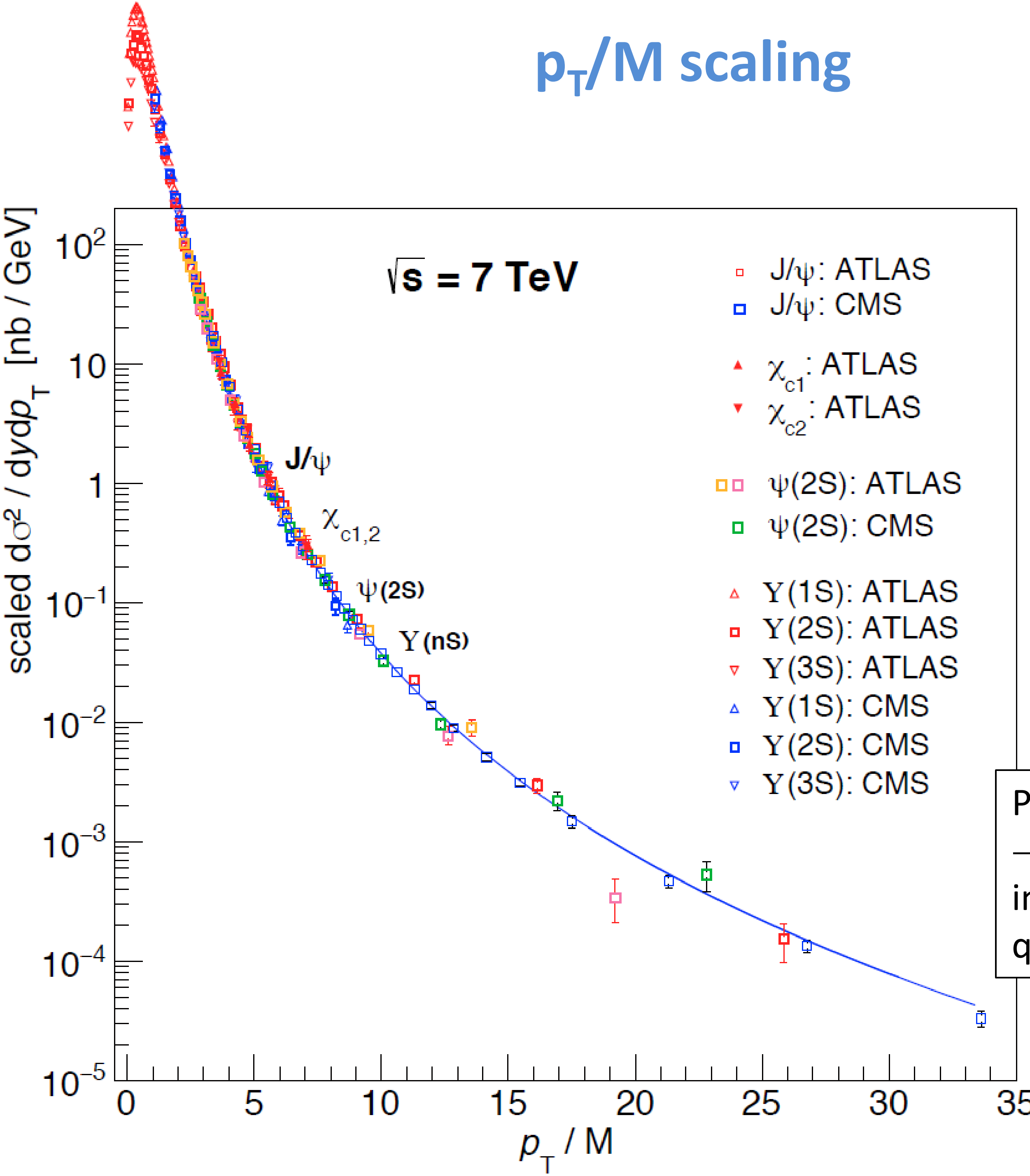

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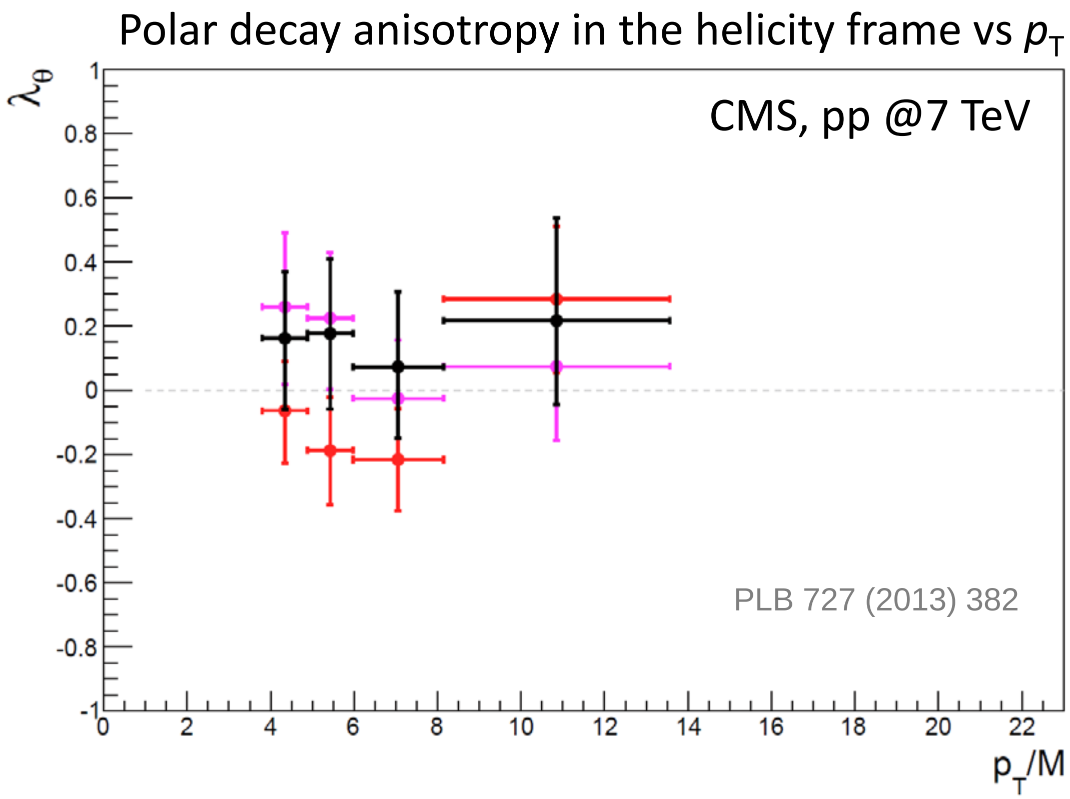
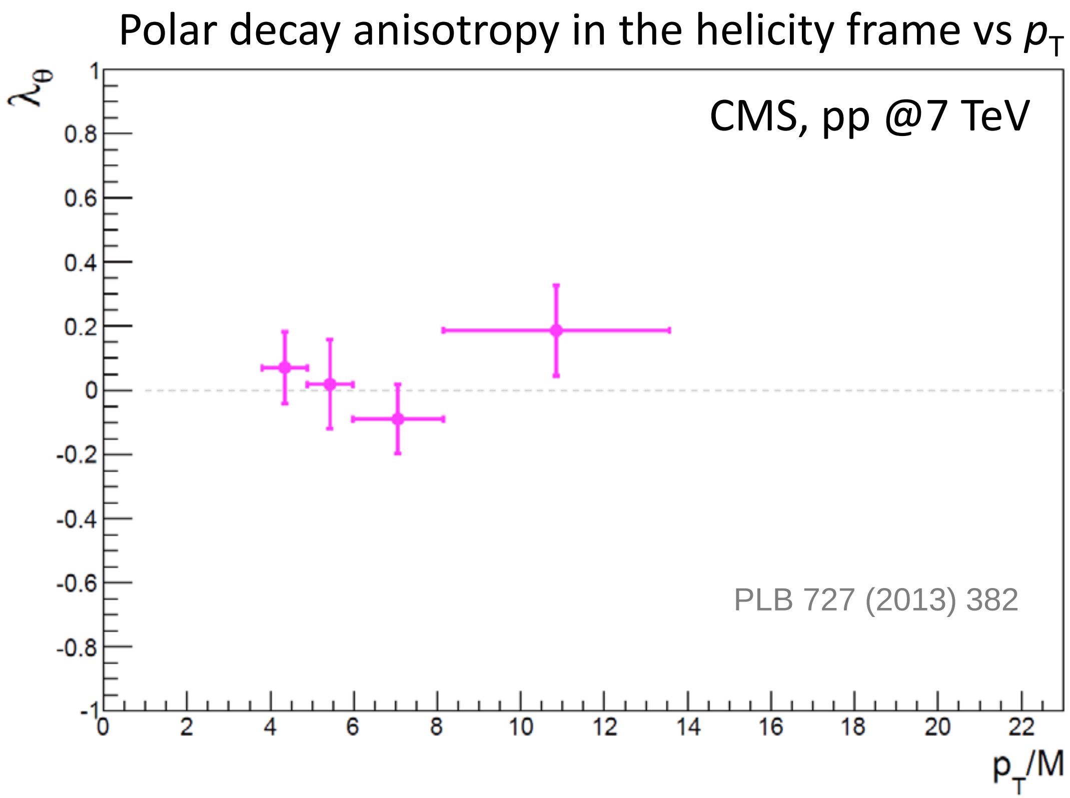
Purely *kinematic* scaling → production *dynamics* independent of quantum numbers!

Polarization



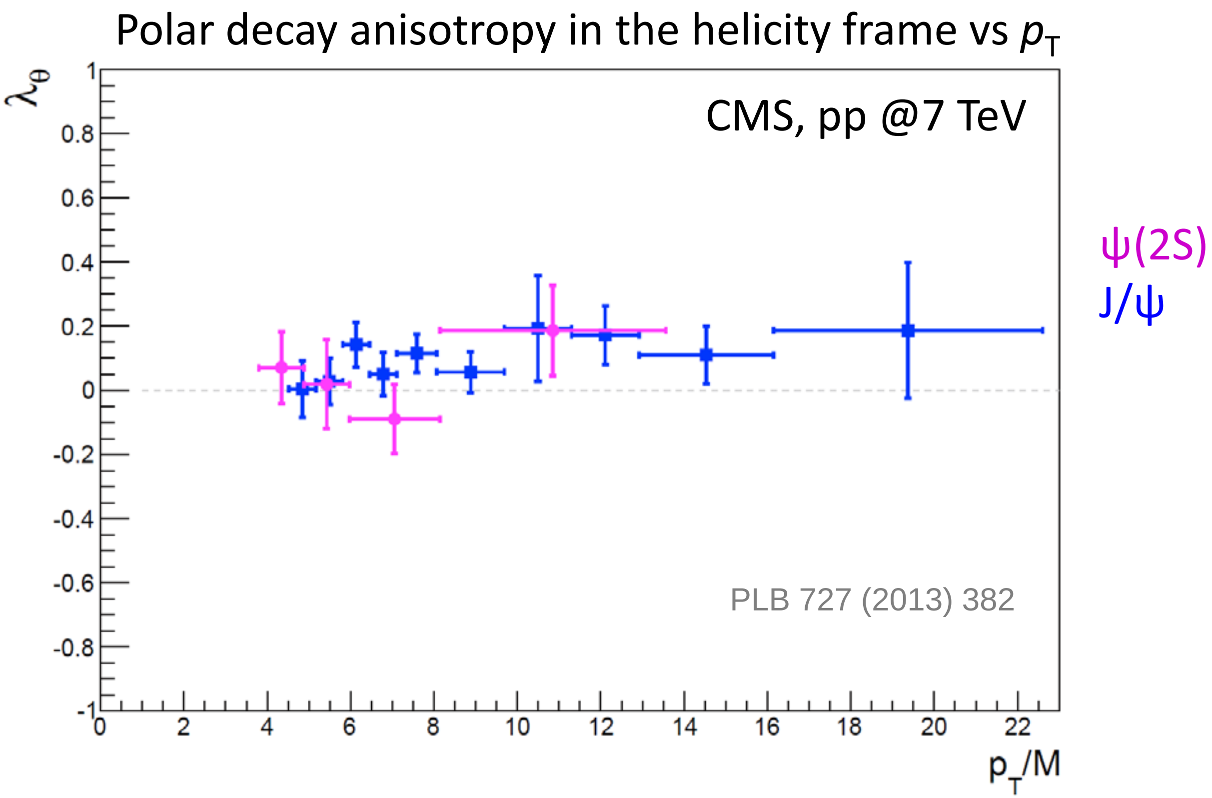
ψ(2S), 3 rapidity bins

Polarization



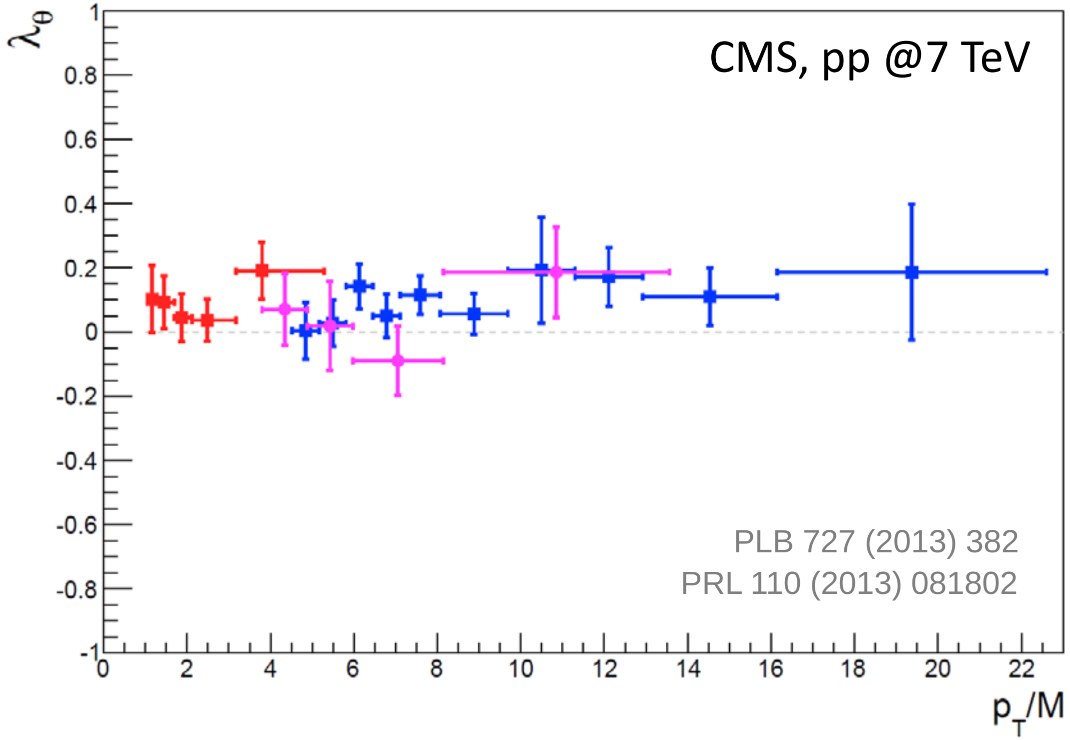
ψ(2S), averaged

Polarization



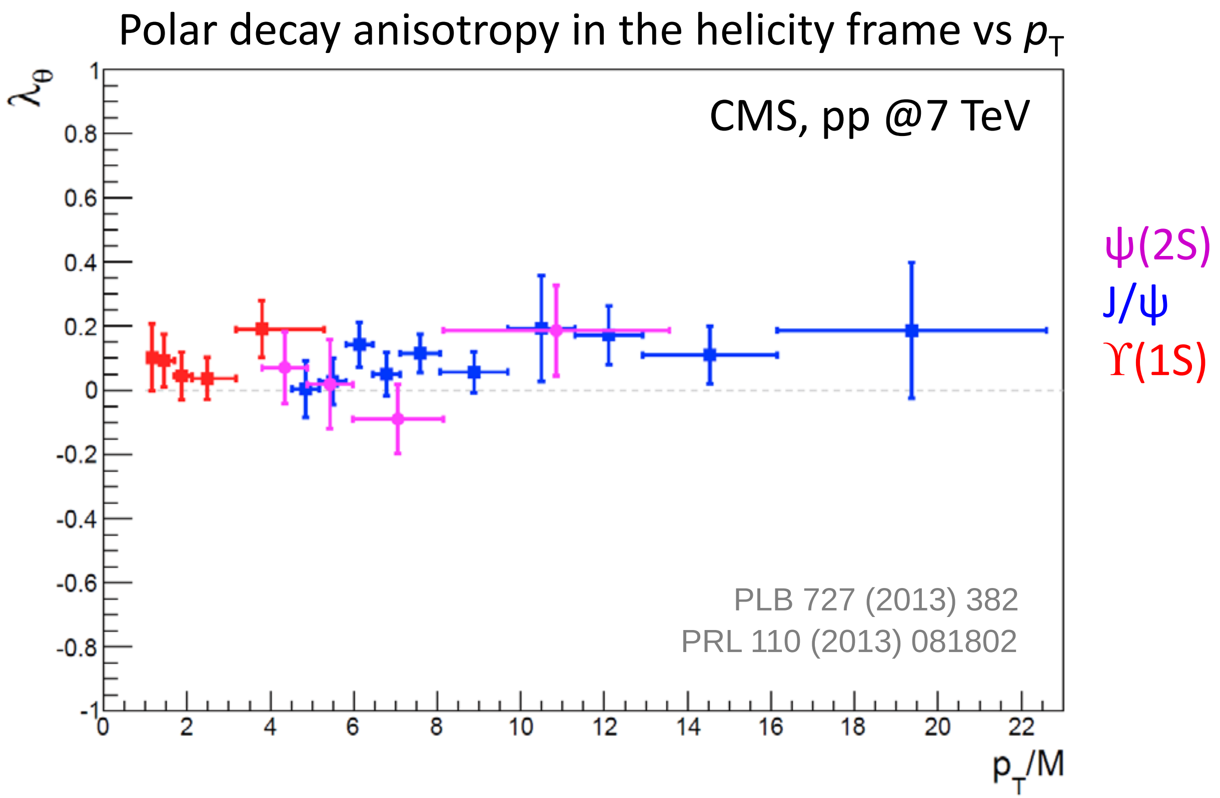
Polarization

Polar decay anisotropy in the helicity frame vs p_T



ψ(2S)
J/ψ
ϒ(1S)

Polarization



- S-wave quarkonia: small decay anisotropies with no significant p_T dependencies

Polarization

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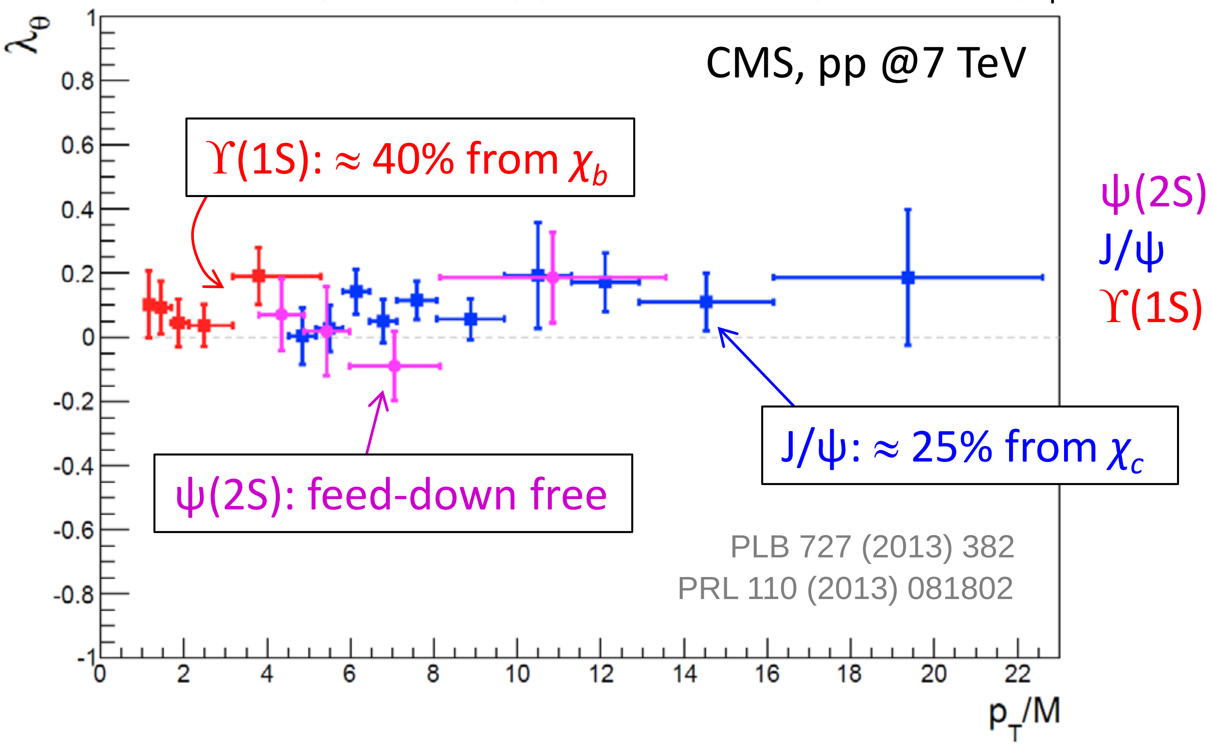


- S-wave quarkonia: small decay anisotropies with no significant p_T dependencies
- No apparent differences between states, despite very different feed-down contributions from P-wave states
  $\rightarrow$ expect similar, weak polarizations also for $\chi_{c(1,2)}$ and $\chi_{b(1,2)}$

Surprising simplicity

- There is today no experimental evidence of **differences in production and decay kinematics** between quarkonium states of **different masses and angular momentum properties**

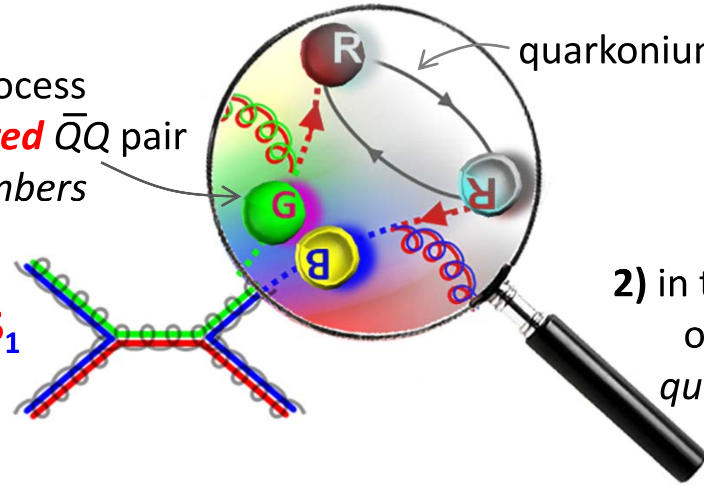
- Such scenario**,** with all quarkonia produced in the same way, is not expected a priori: because of conservation rules, partonic production cross sections are in principle different for states of different quantum numbers

Theory has the floor

- How does NRQCD relate to the simple, “universal” scenario?
- In the “factorization” hypothesis, cornerstone of NRQCD, a variety of production mechanisms is in principle foreseen for each quarkonium state

1) short-distance partonic process produces *neutral* or ***coloured*** $\bar{Q}Q$ pair *of any* $^{2S+1}L_J$ *quantum numbers*

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



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} [$^3P_2$]

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

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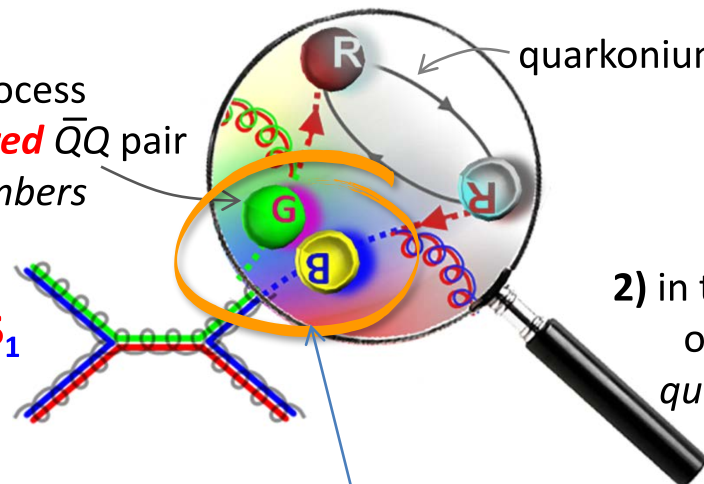

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2) in the **long-distance** evolution to the observed (netural) bound state *quantum numbers change* to final

What is produced in the hard scattering
(and determines kinematics and polarization)
is a *pre-resonance* $Q\bar{Q}$ state
with its own quantum properties

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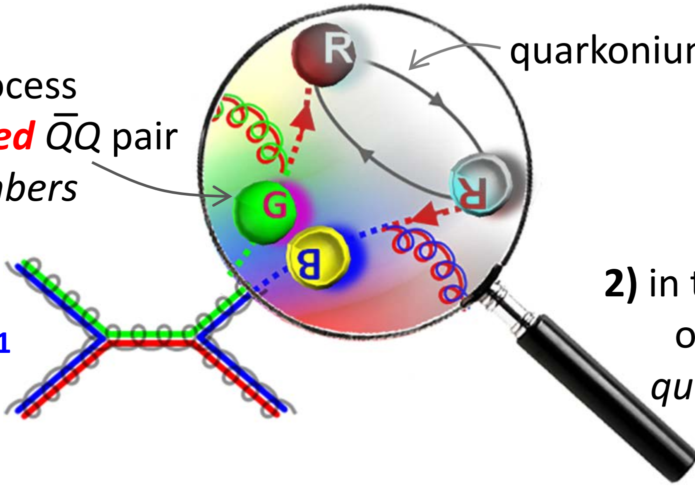

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χ_{c1}, χ_{b1} [$^3P_1$] χ_{c2}, χ_{b2} [$^3P_2$]

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

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

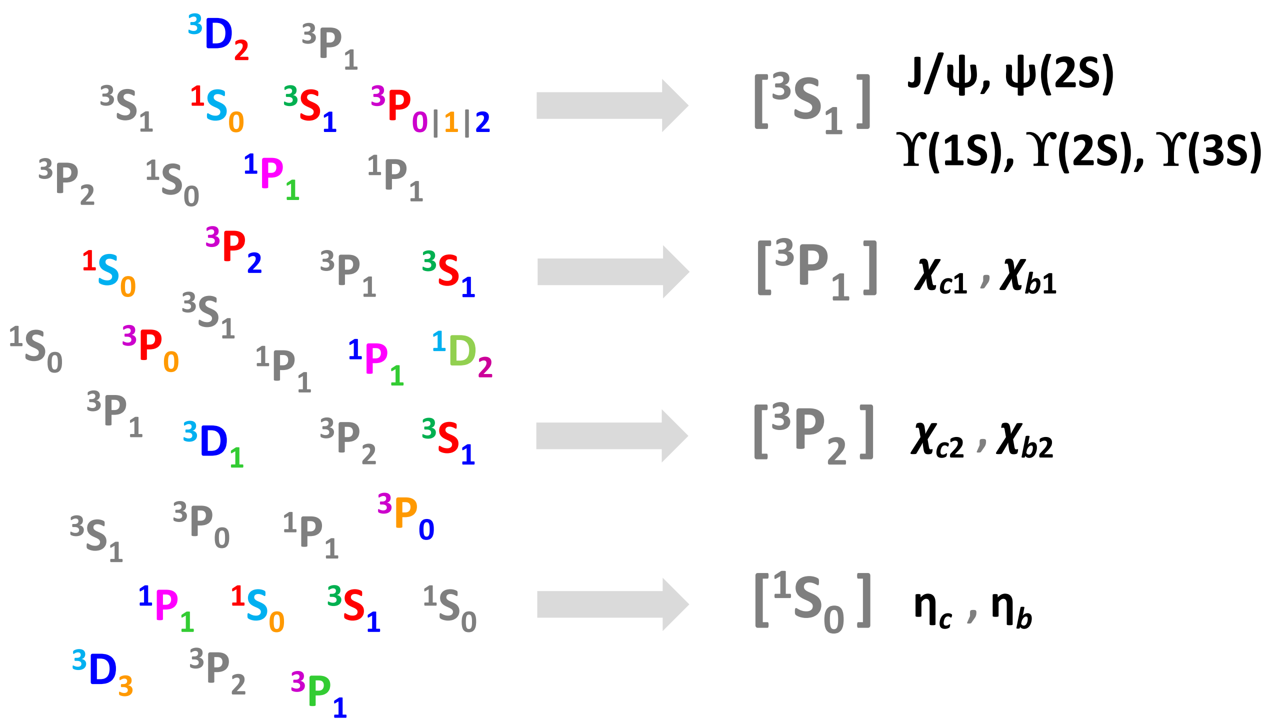
2) *long-distance matrix elements* (**LDMEs**): constant, fitted from data

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

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

How “simple” is NRQCD?

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



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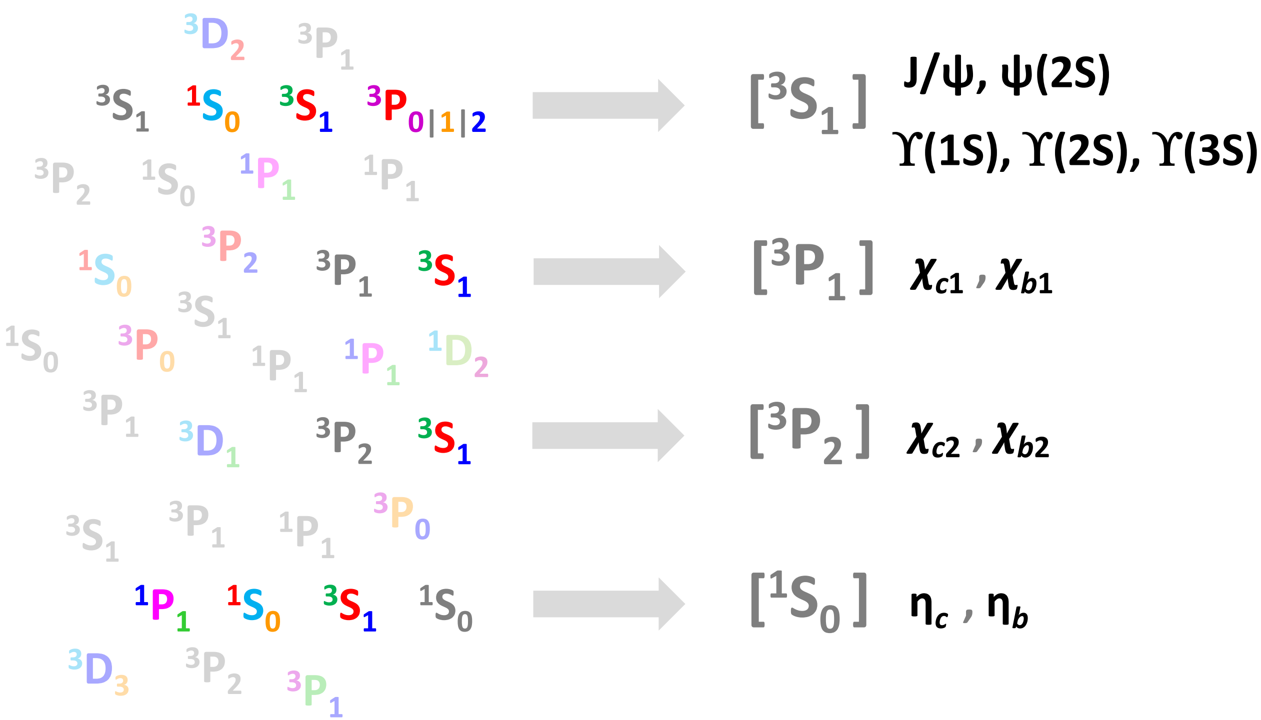
1) Small quark velocities *v* in the bound state → "***v*-scaling**" rules for LDMEs



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

$^3P_1$ $^3S_1$ $\Rightarrow$ $[^3P_1]$ χ_{c1} , χ_{b1}

$^3P_2$ $^3S_1$ $\Rightarrow$ $[^3P_2]$ χ_{c2} , χ_{b2}

$^1P_1$ $^1S_0$ $^3S_1$ $^1S_0$ $\Rightarrow$ $[^1S_0]$ η_c , η_b

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1) Small quark velocities *v* in the bound state → “***v*-scaling**” rules for LDMEs

2) **Perturbative calculations** → some SDCs are negligible:

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$^3P_1$ $^3S_1$ → $[^3P_1]$ χ_{c1} , χ_{b1}

$^3P_2$ $^3S_1$ → $[^3P_2]$ χ_{c2} , χ_{b2}

$^1P_1$ $^1S_0$ $^3S_1$ $^1S_0$ → $[^1S_0]$ η_c , η_b

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$^{3}P_1$ $^{3}S_1$ → $[^{3}P_1]$ χ_{c1} , χ_{b1}

$^{3}P_2$ $^{3}S_1$ → $[^{3}P_2]$ χ_{c2} , χ_{b2}

$^{3}S_1$ $^{1}S_0$ → $[^{1}S_0]$ η_c , η_b

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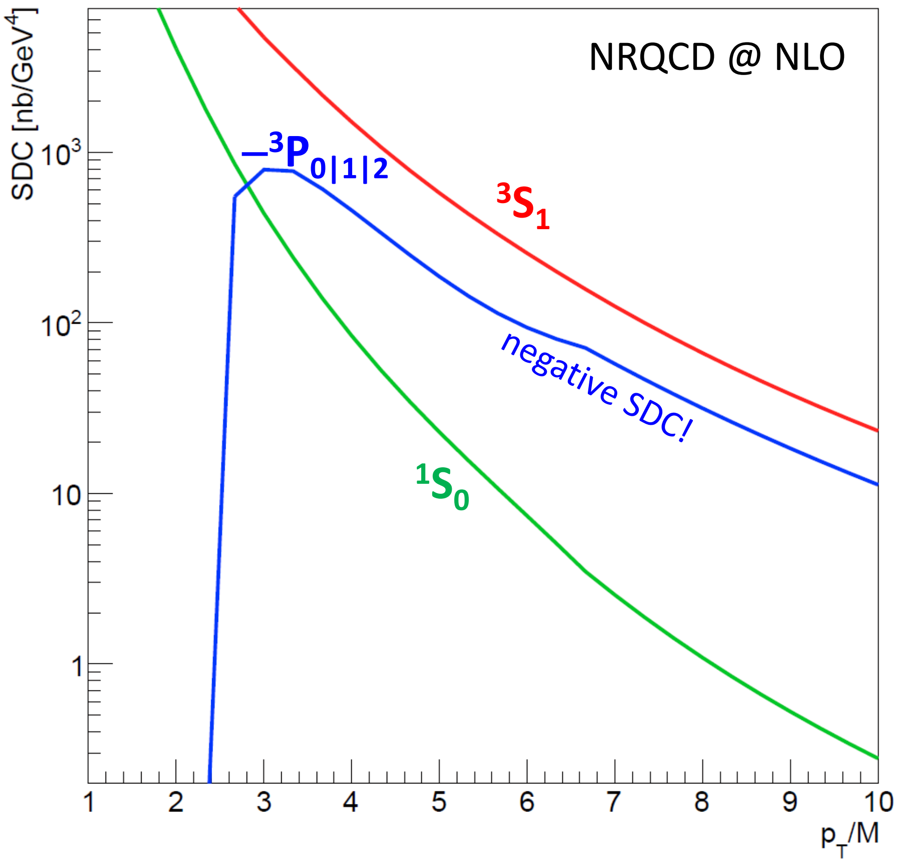
$^3P_2 \quad ^3S_1 \Rightarrow [^3P_2]$ χ_{c2}, χ_{b2}

$^3S_1 \quad ^1S_0 \Rightarrow [^1S_0]$ η_c, η_b

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

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

NRQCD vs universal p_T/M scaling

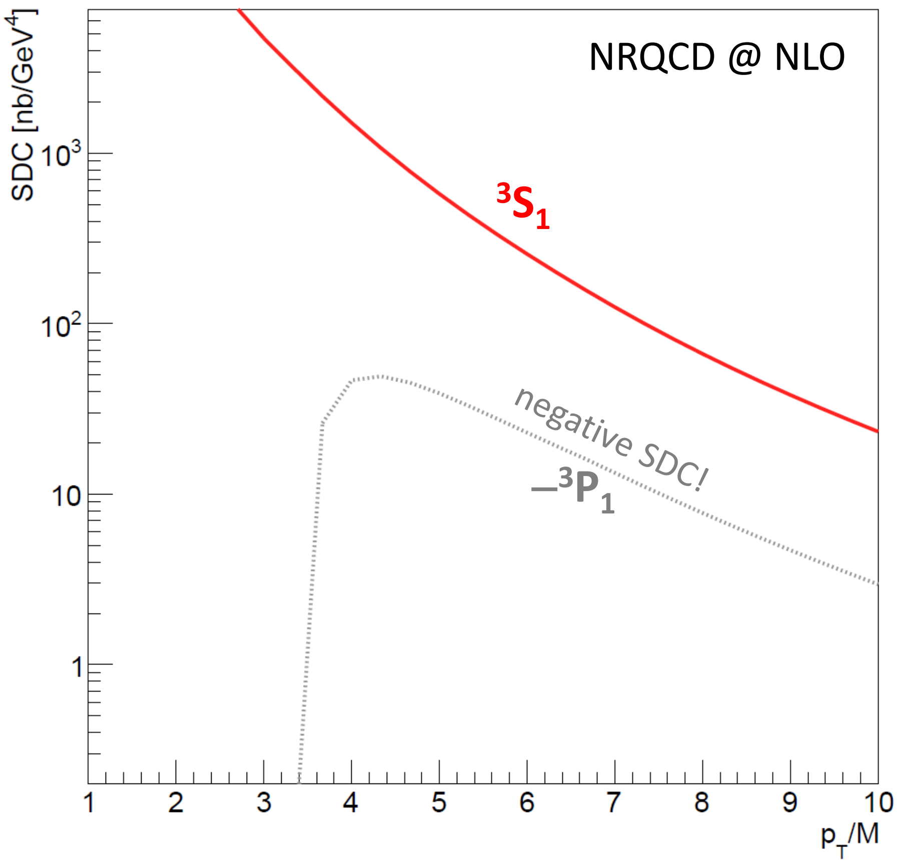


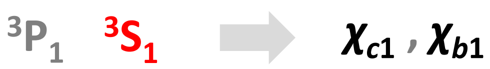
$^1S_0$ $^3S_1$ $^3P_{0|1|2}$ → **J/ψ, ψ(2S)**
ϒ(1S), ϒ(2S), ϒ(3S)

- Negative P-wave contributions require proper **cancellation** for every p_T/M to recover physical result

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

NRQCD vs universal p_T/M scaling





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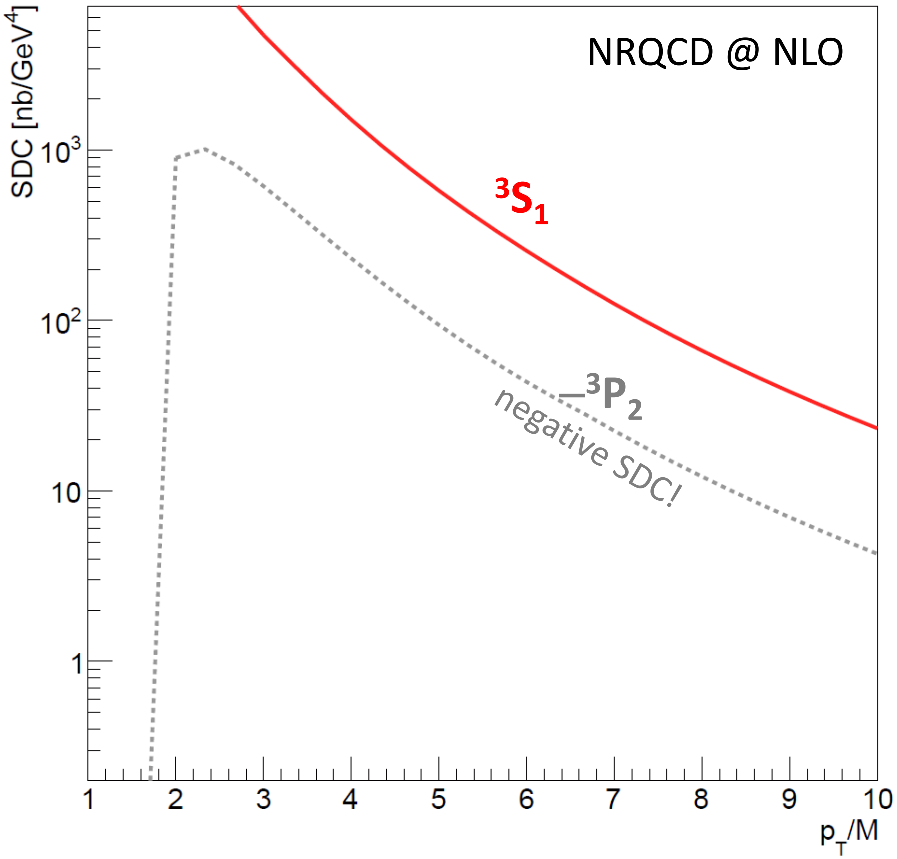
NRQCD vs universal p_T/M scaling



$^3P_2$ $^3S_1$ → χ_{c2} , χ_{b2}

- Negative P-wave contributions require proper **cancellation** for every p_T/M to recover physical result

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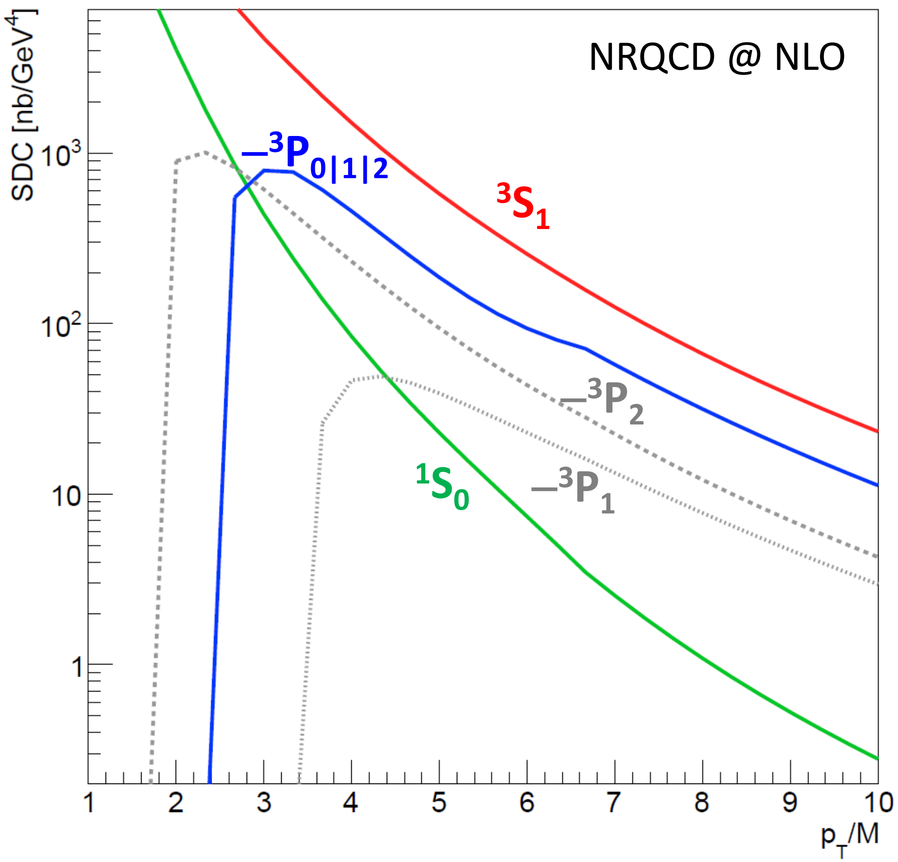


$^1S_0$ $^3S_1$ $^3P_{0|1|2}$ → J/ψ, ψ(2S), Υ(1S), Υ(2S), Υ(3S)

$^3P_1$ $^3S_1$ → χ_{c1} , χ_{b1}

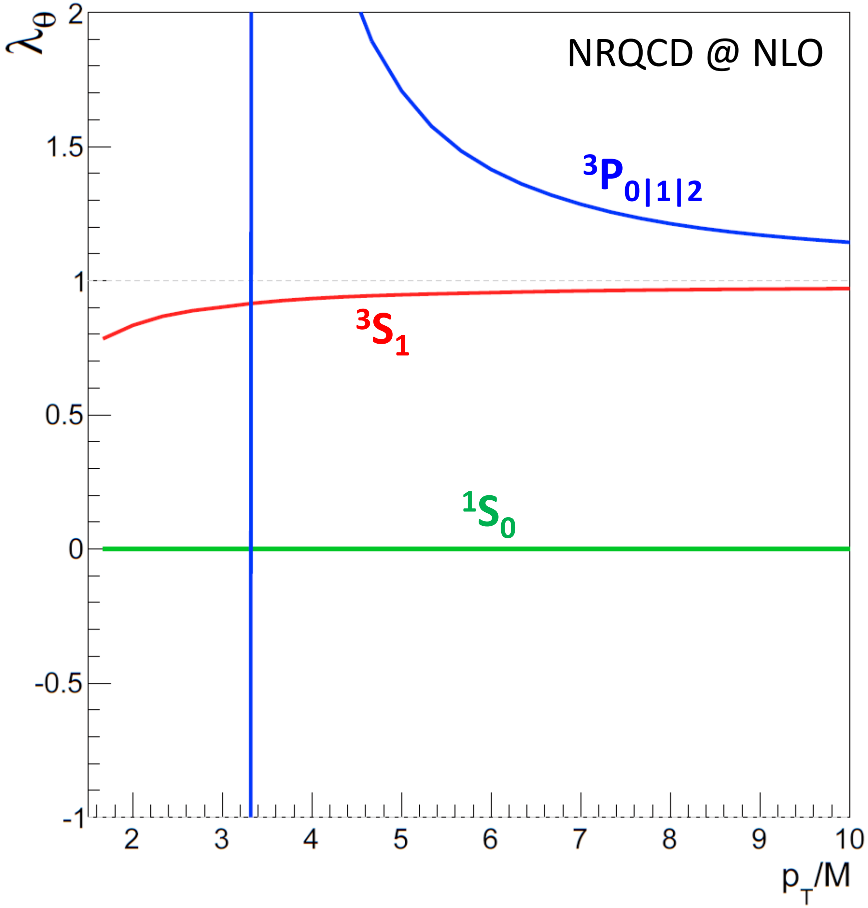
$^3P_2$ $^3S_1$ → χ_{c2} , χ_{b2}

- Negative P-wave contributions require proper **cancellation** for every p_T/M to recover physical result
- Different final states come from different pre-resonance mixtures, with rather **diversified** kinematic behaviours

→ Conspiring SDC×LDME combinations needed to approximately reproduce observed p_T/M scaling

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

NRQCD vs unpolarized scenario



$^1S_0 \approx {}^3S_1 \approx {}^3P_{0|1|2}$ ⇒ **J/ψ, ψ(2S)**

ϒ(1S), ϒ(2S), ϒ(3S)

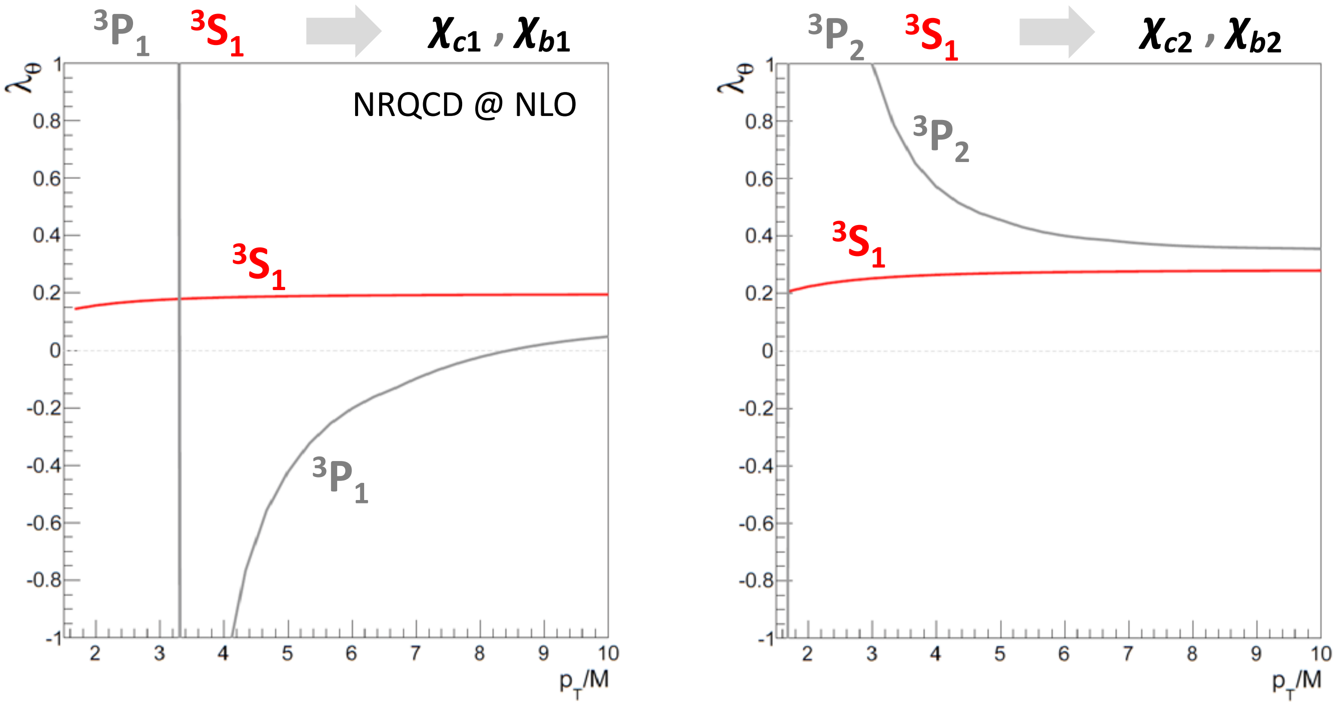
comparable magnitudes according to ***v*-scaling** rules

- Unphysical P-wave polarization (*"hyper-transverse"* for $p_T/M > 3$)
- must have SDC×LDME < 0 to become longitudinal and be **cancelled** by the transverse $^3S_1$ contribution

→ Chirurgical cancellation needed to approximately reproduce measured polarizations

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

The χ case



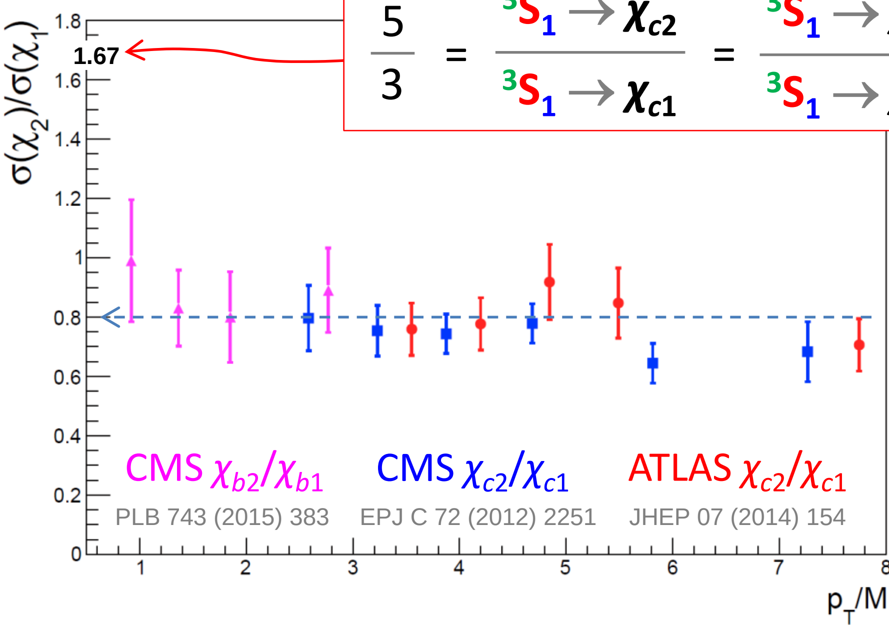
Colour-singlet contributions:

- **strongly polarize** χ production (λ_ϑ even diverges at $p_T/M \approx 3$)
- **strongly differentiate** J=2 from J=1

Might they be found to be negligible, as in ψ and ϒ production?

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

Singlet dominance?



$$\frac{5}{3} = \frac{{}^3S_1 \to \chi_{c2}}{{}^3S_1 \to \chi_{c1}} = \frac{{}^3S_1 \to \chi_{b2}}{{}^3S_1 \to \chi_{b1}}$$

(heavy-quark spin-symmetry)

The measured $\boldsymbol{\chi_{c2}/\chi_{c1}}$ and $\boldsymbol{\chi_{b2}/\chi_{b1}}$ ratios are *half* of the *pure*-octet expectation, indicating that the **singlet** components should be very important

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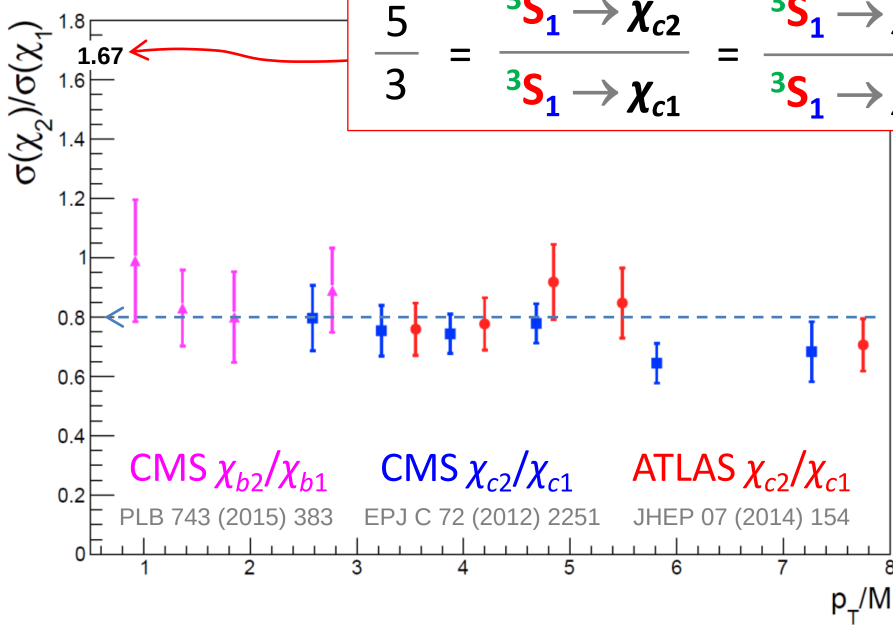
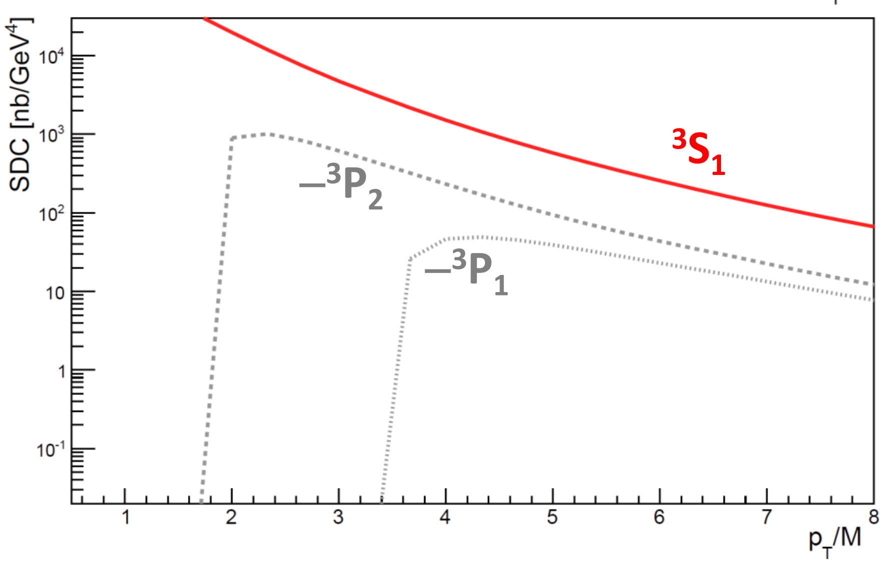
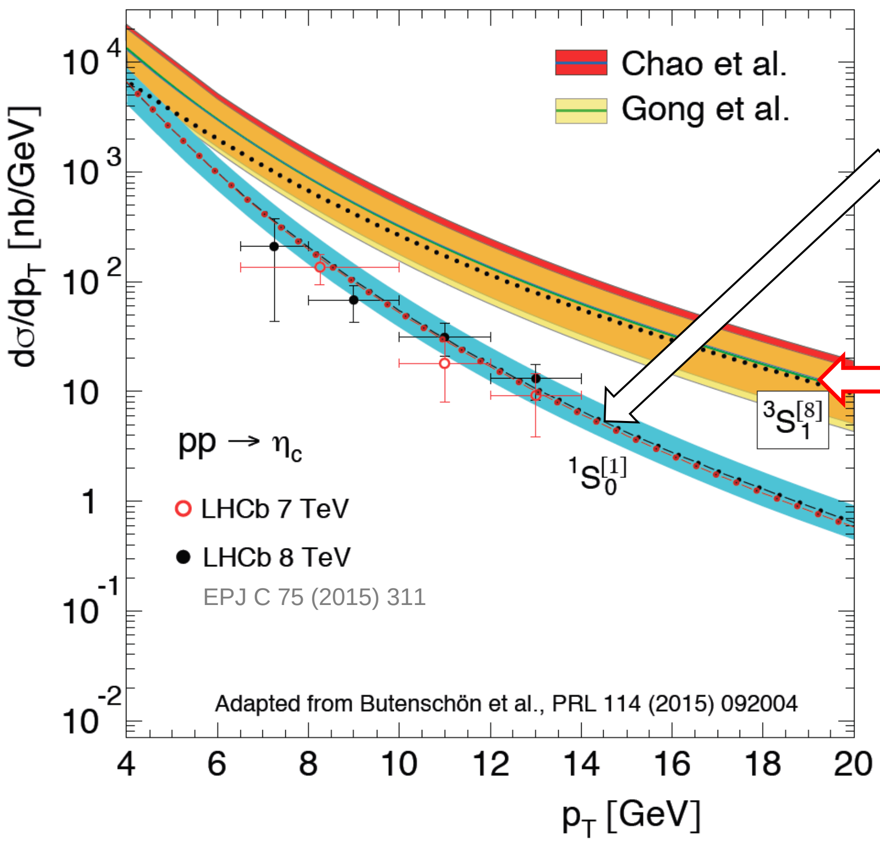


The measured χ_{c2}/χ_{c1} and χ_{b2}/χ_{b1} ratios are *half* of the *pure*-octet expectation, indicating that the **singlet** components should be very important



On the other hand, large singlet terms would also lead to a large difference in p_T-dependence between J=1 and J=2, contradicting the remarkably flat p_T/M dependence of the measured ratio

The η_c "puzzle"



η_c measurements are explained by **pure $^1S_0$ singlet production**

but heavy-quark spin-symmetry relations

$$^3S_1 \rightarrow \eta_c \;=\; {}^1S_0 \rightarrow J/\psi$$

impose **sizeable octet contributions,** severely overshooting data

NRQCD vs simplicity

- The variety of pre-resonances implied by *v*-scaling hierarchies seems **redundant** with respect to the observed "universal" p_T/M scaling and lack of polarization
- Constraints imposed by heavy-quark symmetry relations further complicate the theory scenario, forcing the necessity of **conspiracies** to reproduce the simple data patterns

Occam's razor

We want to explore a much simpler picture, directly implied by data

NRQCD heavy-quark-limit hierarchies and constraints

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

$^3P_1 \quad ^3S_1 \Rightarrow \chi_{c1}, \chi_{b1}$

$^3P_2 \quad ^3S_1 \Rightarrow \chi_{c2}, \chi_{b2}$

$^3S_1 \quad ^1S_0 \Rightarrow \eta_c, \eta_b$

$$\frac{^3S_1 \to \chi_{c2}}{^3S_1 \to \chi_{c1}} = \frac{^3S_1 \to \chi_{b2}}{^3S_1 \to \chi_{b1}} = \frac{5}{3}$$

$$^3S_1 \to \eta_c = {}^1S_0 \to J/\psi$$

$$^3S_1 \to \eta_b = {}^1S_0 \to \Upsilon$$

Pure angular-momentum excitation hierarchy

$$^1S_0 > {}^3S_1 > \ldots$$

The fractional contribution of $^3S_1$ may depend on the final state.
The unpolarized scenario indicates that it is very small for J/ψ and ψ(2S) states

Occam's razor

Why to abdicate heavy-quark-limit hierarchies?

For example, because they neglect mass-difference effects (M = 2 m_Q for all states) and spin-orbit interactions

Pure angular-momentum excitation hierarchy

$$^1S_0 > {}^3S_1 > \ldots$$

E.g.:

$$\frac{^3S_1 \rightarrow \chi_{c2}}{^3S_1 \rightarrow \chi_{c1}} = \frac{^1S_0 \rightarrow \chi_{b2}}{^1S_0 \rightarrow \chi_{b1}} = \frac{5}{3}$$

Real-world counterparts strongly violate this rule:

$$\frac{\psi(2S) \rightarrow \chi_{c2}\gamma}{\psi(2S) \rightarrow \chi_{c1}\gamma} = 0.95 \pm 0.05 \qquad \frac{\Upsilon(2S) \rightarrow \chi_{b2}\gamma}{\Upsilon(2S) \rightarrow \chi_{b1}\gamma} = 1.04 \pm 0.08$$

coming closer to the measured χ yield ratios ≈ 0.8

Occam's razor

Instead, we introduce the constraint

$$\frac{{}^3S_1 \to \chi_{c,b2}}{{}^3S_1 \to \chi_{c,b1}} = \frac{{}^1S_0 \to \chi_{c,b2}}{{}^1S_0 \to \chi_{c,b1}} = R_\chi$$

(model parameter)

and, analogously, for the ψ and Υ states

$$\frac{{}^3S_1 \to \psi/\Upsilon(2S)}{{}^3S_1 \to \psi/\Upsilon(1S)} = \frac{{}^1S_0 \to \psi/\Upsilon(2S)}{{}^1S_0 \to \psi/\Upsilon(1S)} = R_\psi$$

Pure angular-momentum excitation hierarchy

$${}^1S_0 > {}^3S_1 > \ldots$$

Occam's razor

- naturally explains **universal p_T/M scaling** and **the lack of polarization**

Pure angular-momentum excitation hierarchy

$^1S_0 > {}^3S_1 > \ldots$

- avoids necessity of cancellations involving the unphysical P-wave contributions

- predicts **flat p_T/M dependence** of the χ_{c2}/χ_{c1} ratio (as well as of the ψ(2S)/ψ(1S) ratio)

- eases the η_c "puzzle"

Test: global charmonium fit

We want to test the hypothesis using charmonium data from the LHC:

- **J/ψ**, **ψ(2S)**, χ_{c1}, χ_{c2} **cross sections** measured by CMS and ATLAS
- **J/ψ** and **ψ(2S) polarizations** measured by CMS

We take into account:

- all relevant **feed-downs**

$$\psi(2S) \to \chi_{c1,2} \qquad \psi(2S) \to J/\psi \qquad \chi_{c1,2} \to J/\psi$$

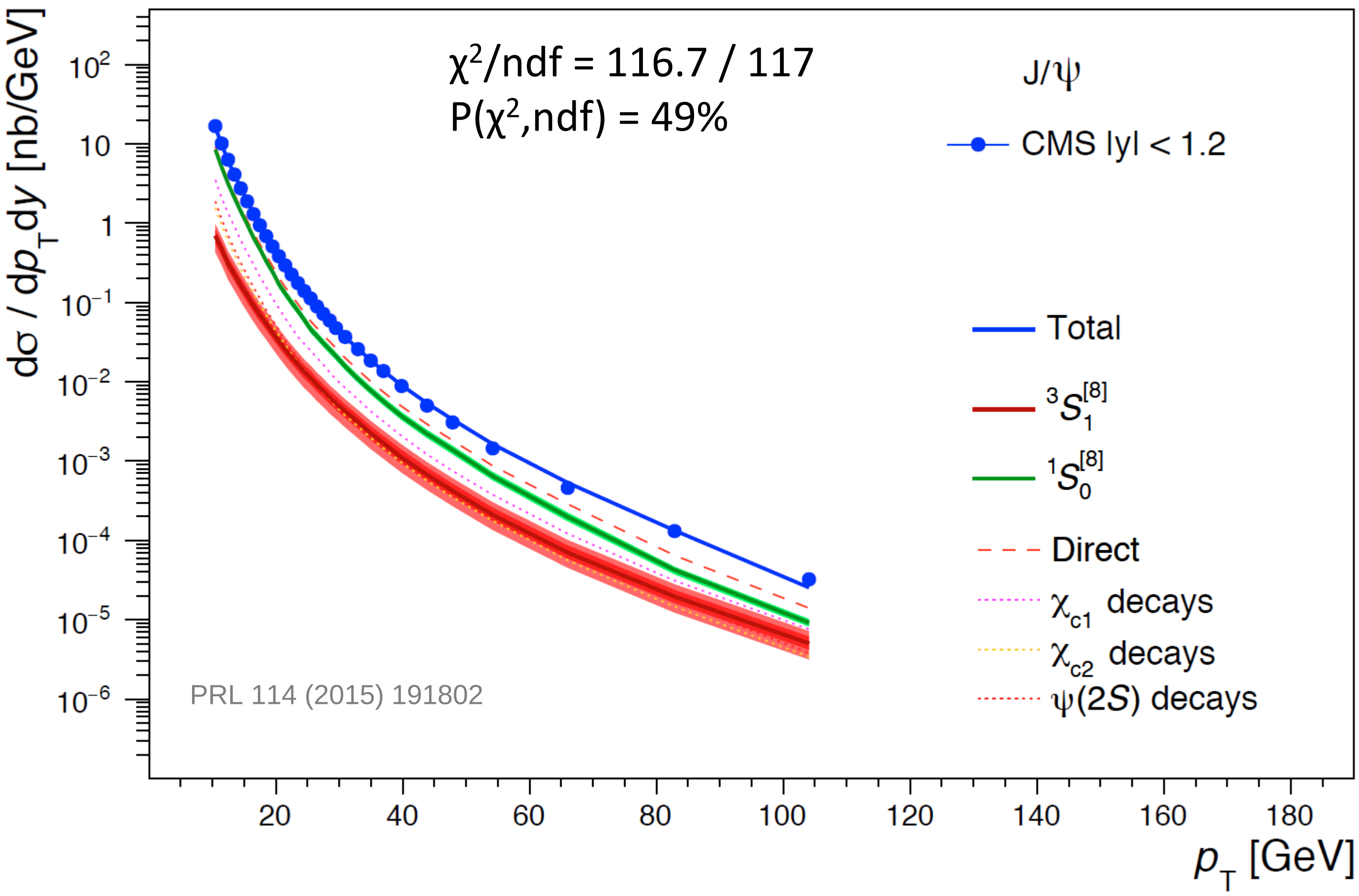
  with the correct **kinematic** transformations and **polarization-transfer** relations

- **luminosity** and **branching-ratio** uncertainties and correlations
- dependence of cross sections on polarization, via **acceptance**

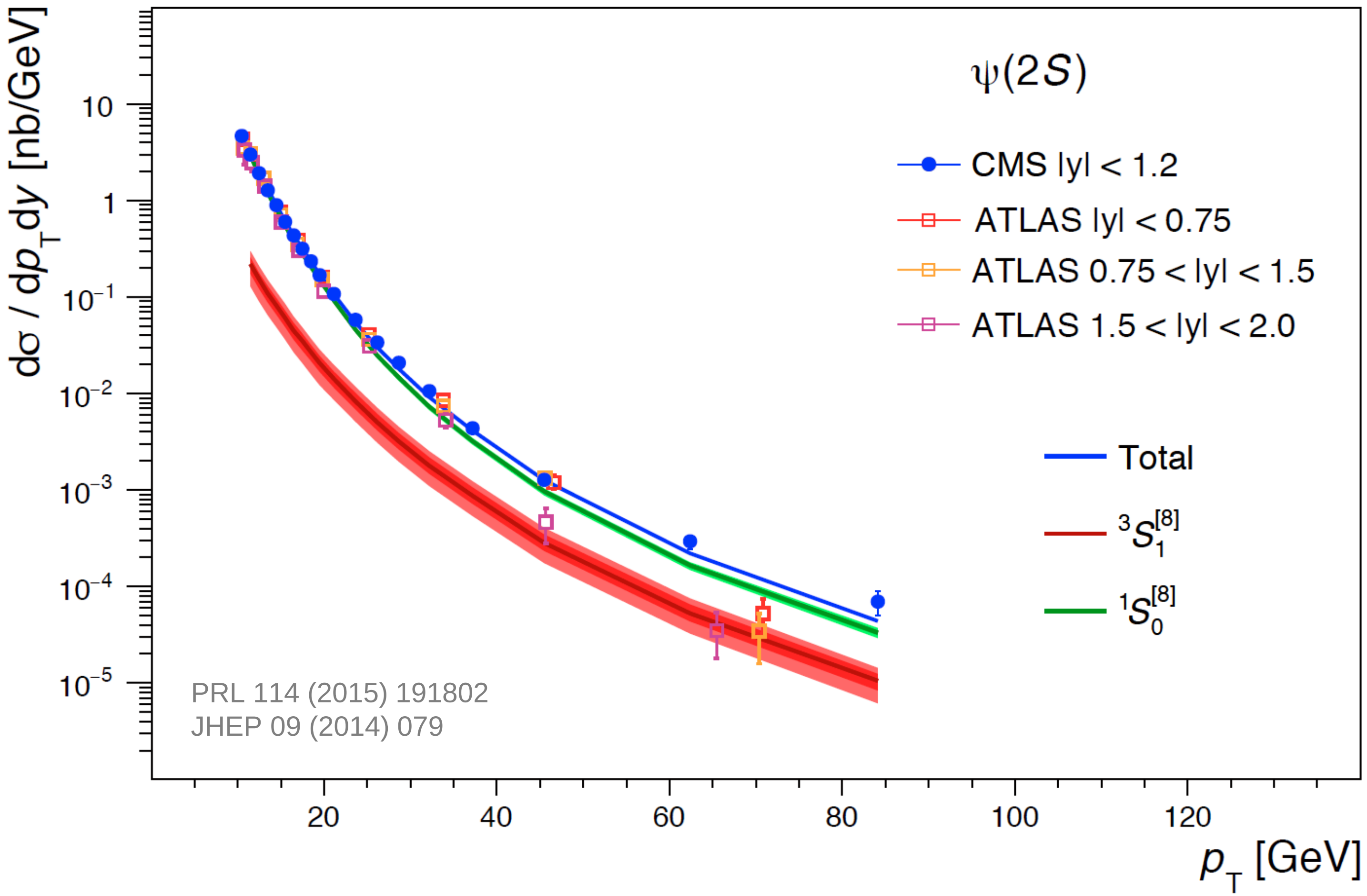
Theory ingredients:

- $^1S_0$ and $^3S_1$ octet-SDC calculations by H.-S. Shao et al.
  (PRL 108, 242004; PRL 112, 182003; Comput. Phys. Commun. 198, 238)
- Leading-power fragmentation corrections by G.T. Bodwin et al. (PRL 113, 022001)
- Theory uncertainty modelled as NLO-LO difference (= 100%-confidence-level semi-interval of a flat distribution)

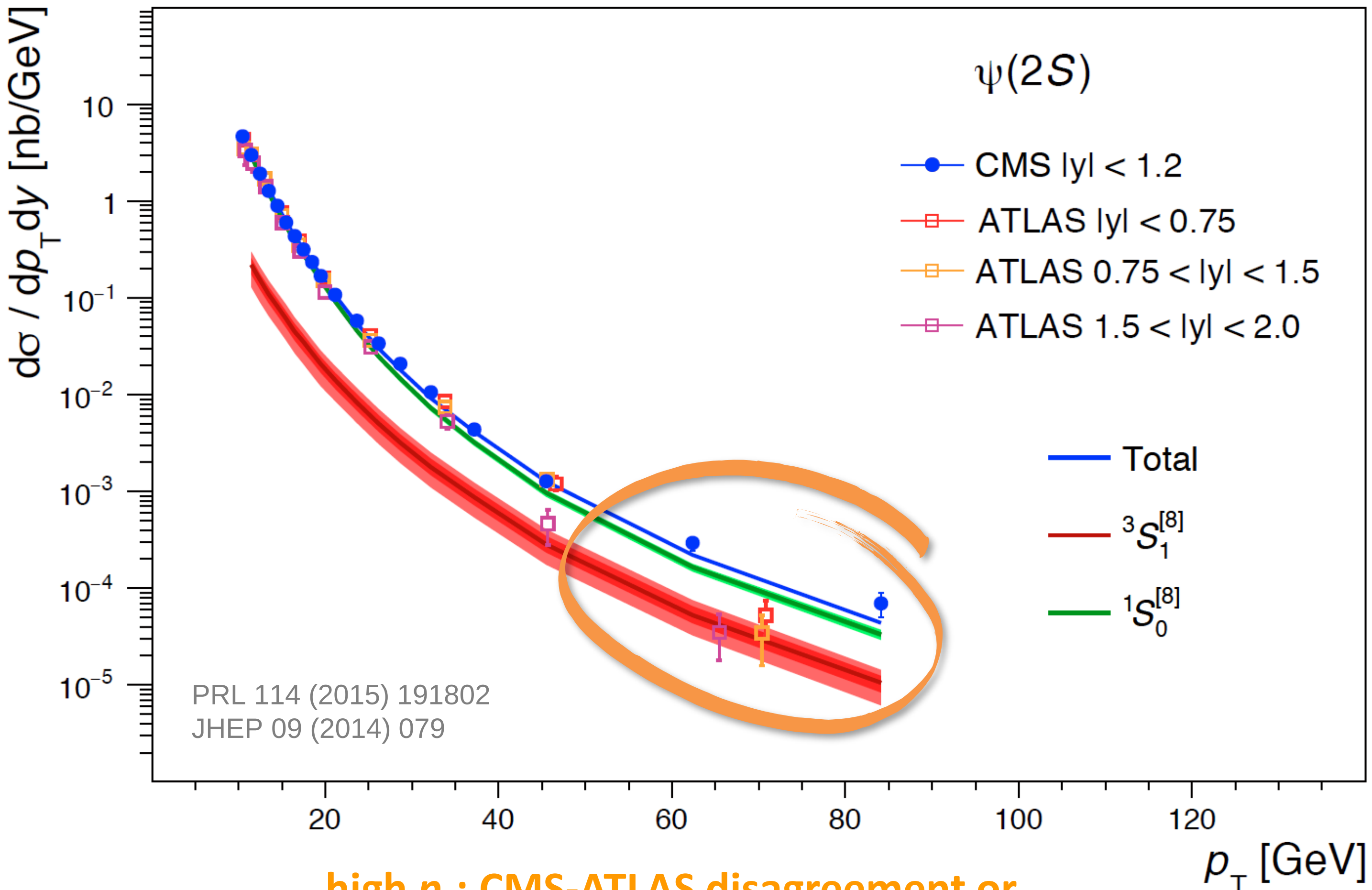
Test: global charmonium fit



Test: global charmonium fit

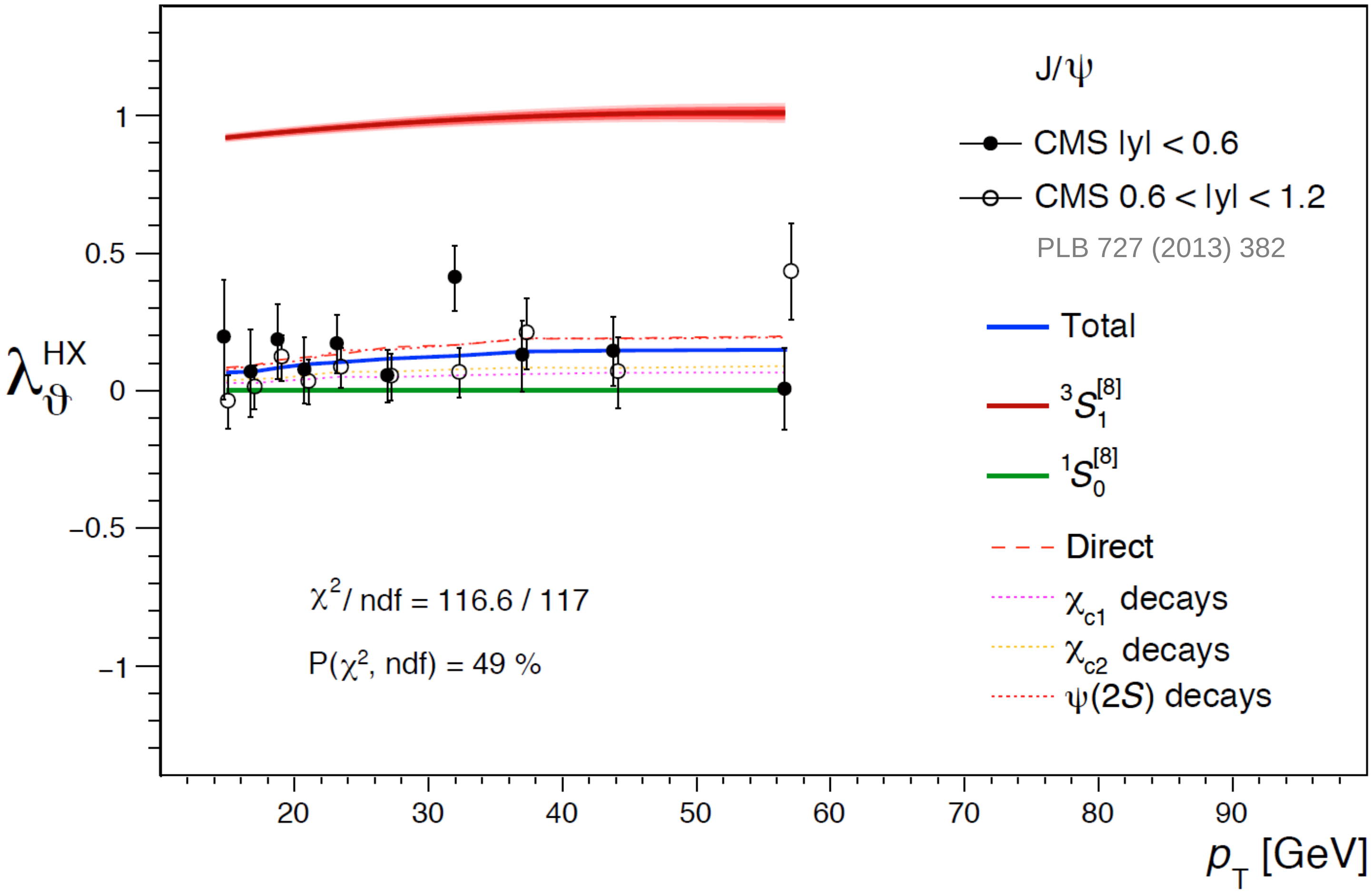


Test: global charmonium fit



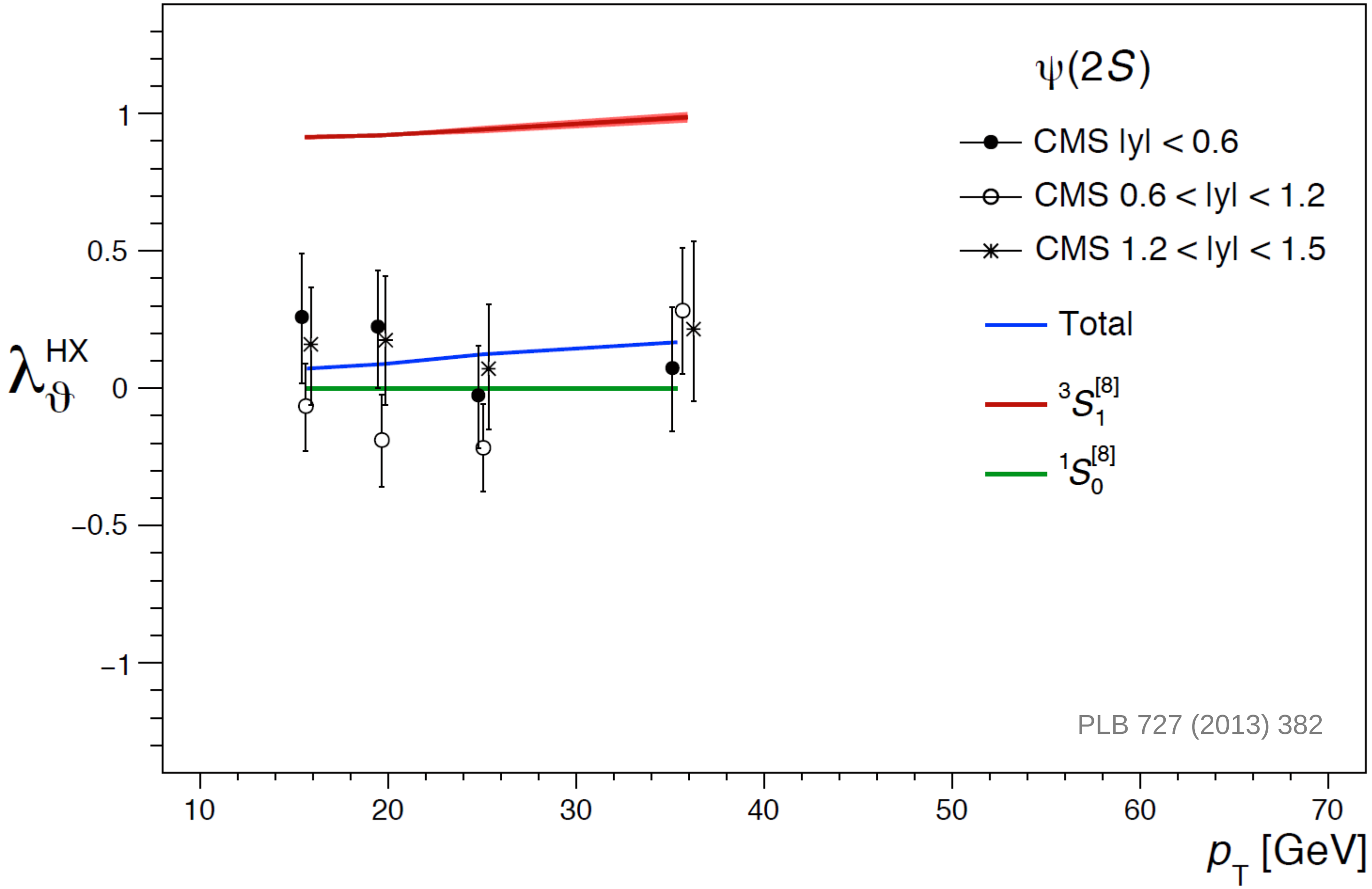
high p_T: CMS-ATLAS disagreement or significant rapidity dependence?

Test: global charmonium fit



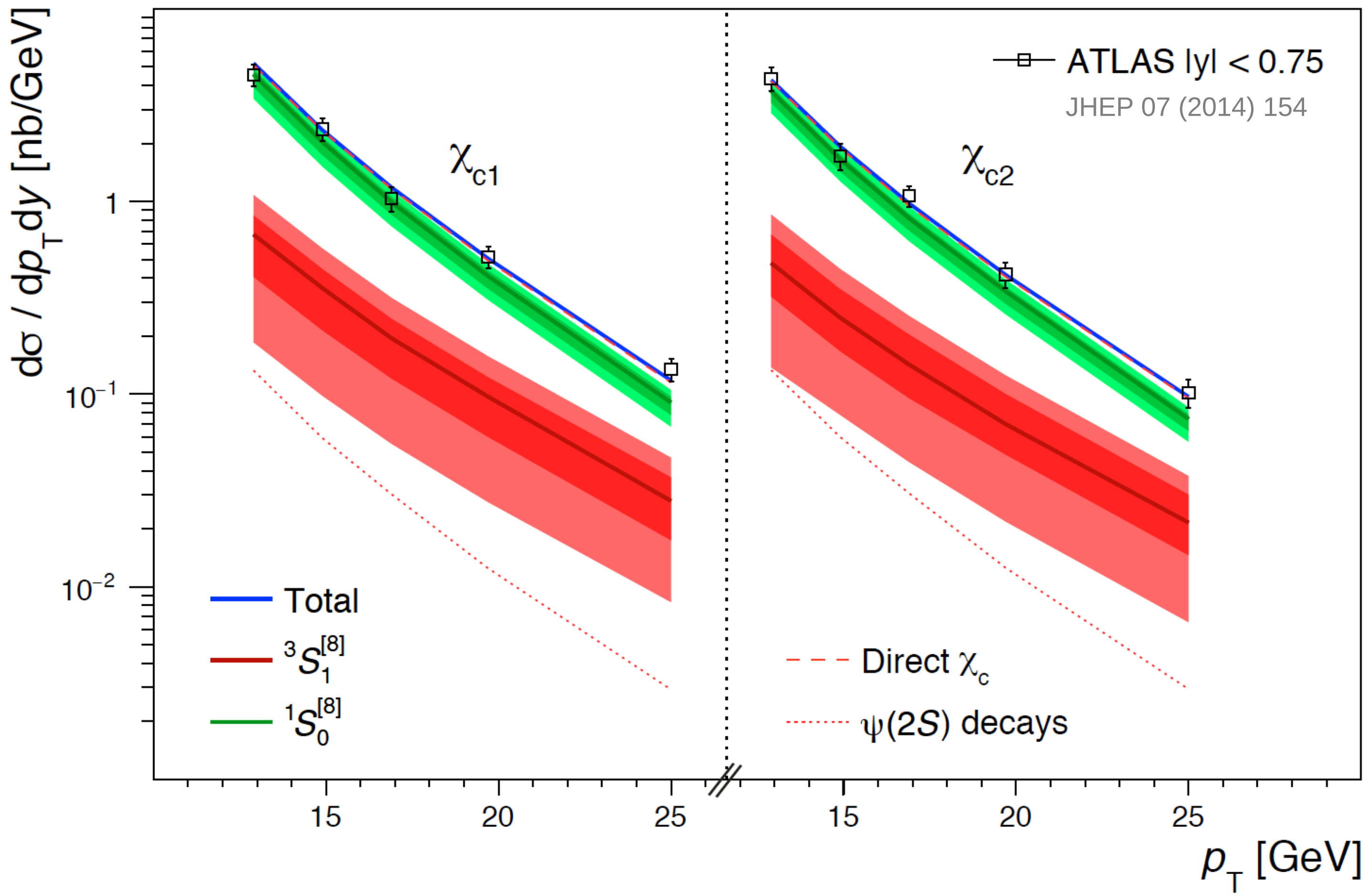
Note: result sensitive to assumed theoretical uncertainties in $^1S_0$ and $^3S_1$ SDCs. Removing the uncertainty leads to stronger increase of polarization at high pT

Test: global charmonium fit



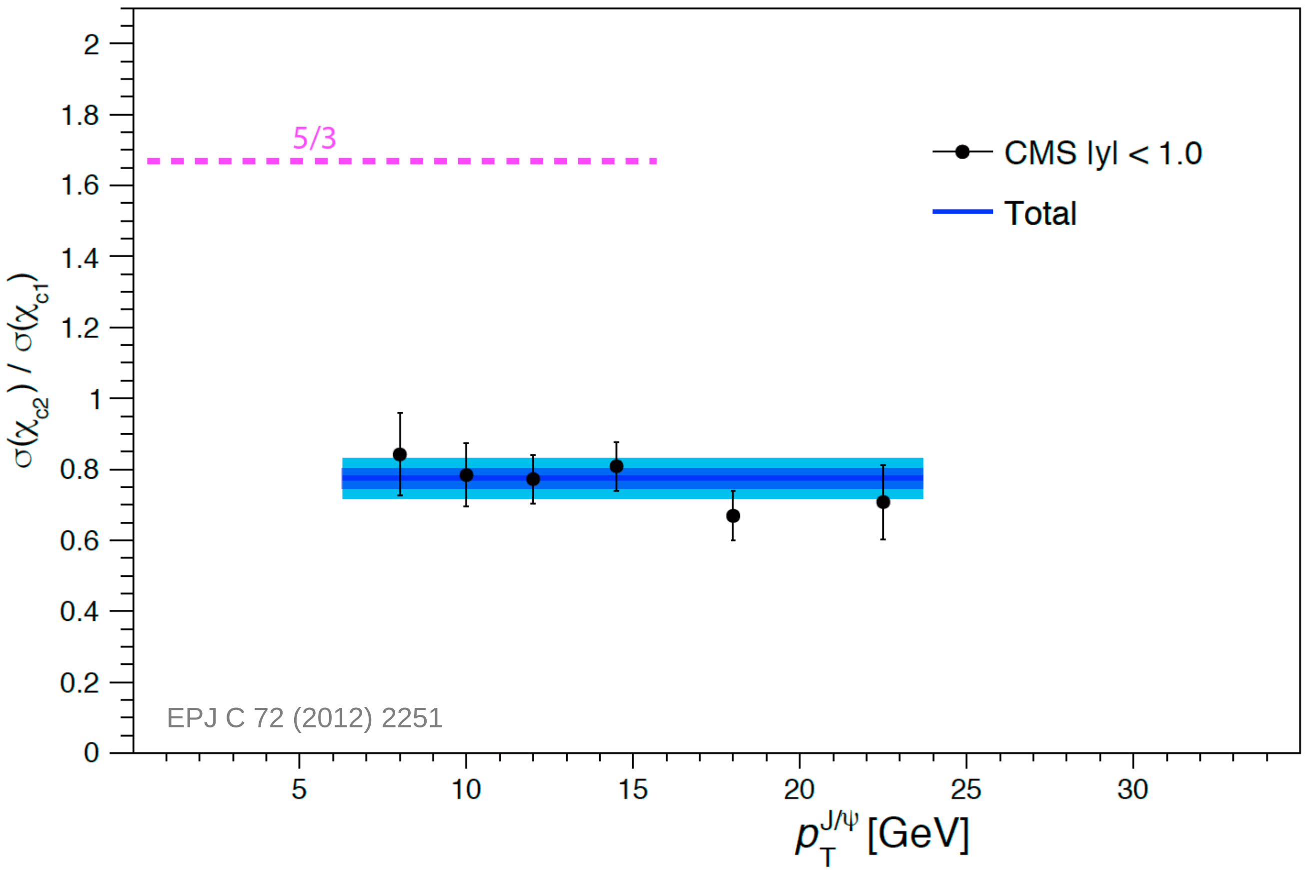
Note: result sensitive to assumed theoretical uncertainties in $^1S_0$ and $^3S_1$ SDCs. Removing the uncertainty leads to stronger increase of polarization at high pT

Test: global charmonium fit



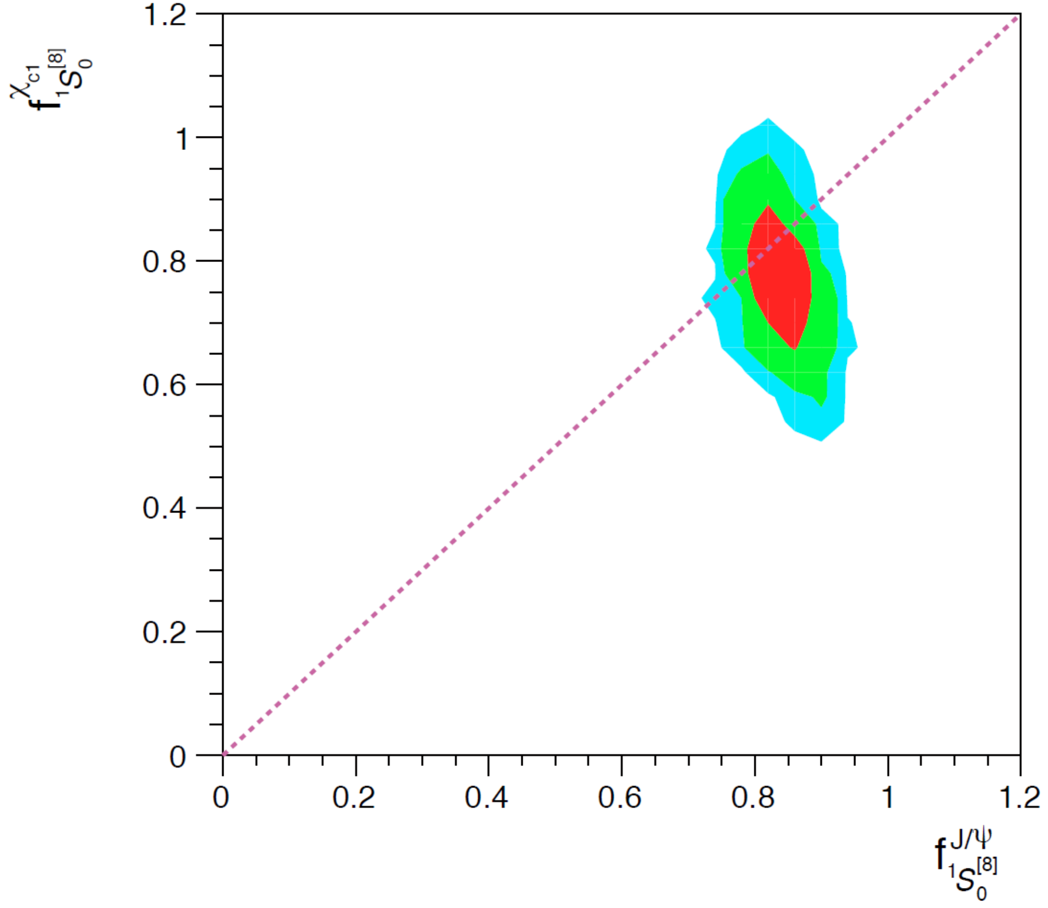
Large uncertainty in the ${}^3S_1$ term. More χ_c data needed!

Test: global charmonium fit



Test: global charmonium fit

$^1S_0$ cross-section fractions for ψ and χ_c at $p_T/M = 6$

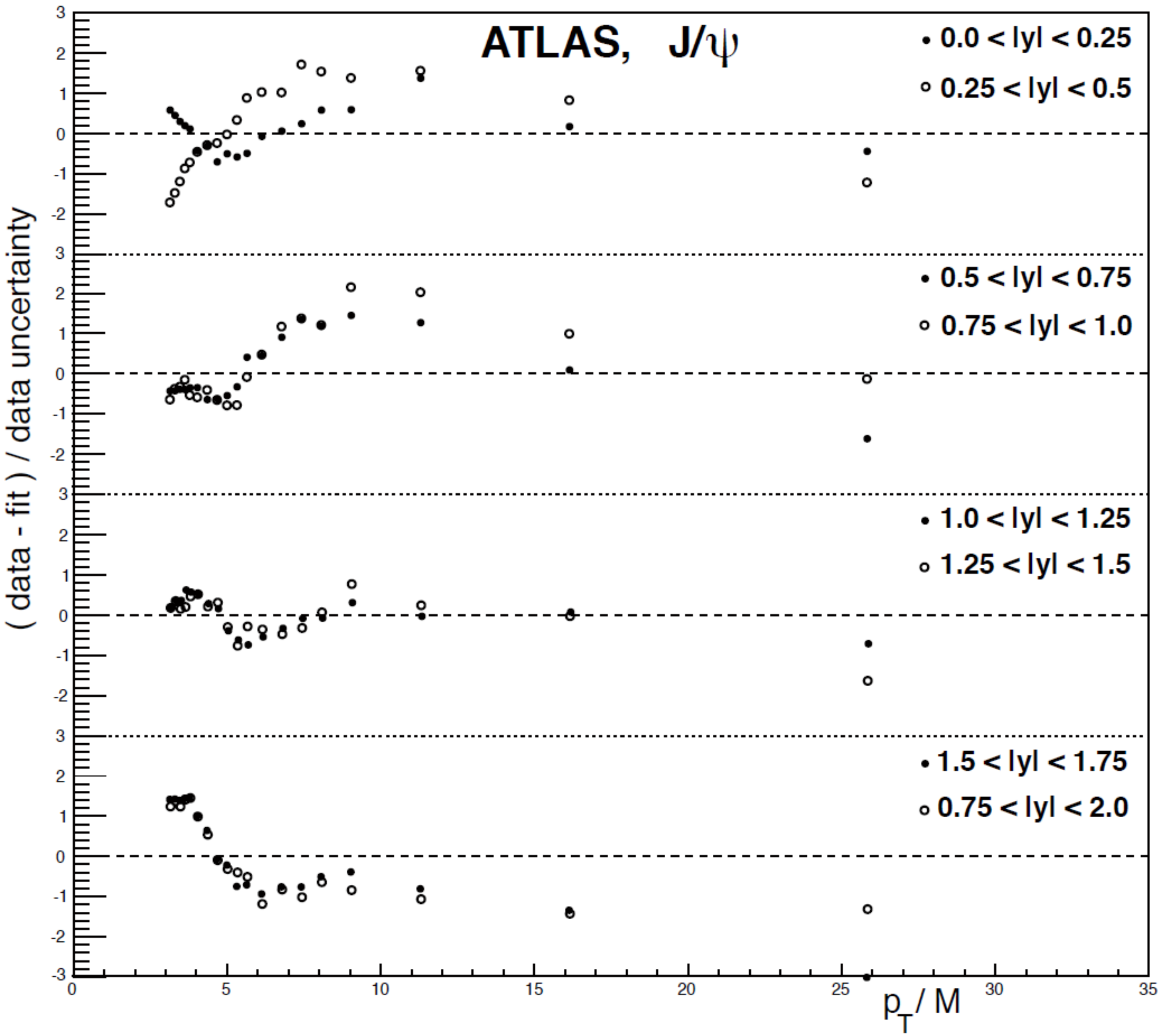


- $^1S_0$ is the larger contribution for both χ_c and ψ, dominating the total cross sections

Summary

- LHC data depict a scenario of maximum simplicity: universal p_T/M scaling and lack of polarization
- NRQCD, with its heavy-quark-limit hierarchies and constraints, can accommodate this scenario only through precise cancellations of extreme kinematic behaviours and polarizations
- We tested a simple hypothesis, assuming only one, strong hierarchy based on angular momentum: production happens only via S-wave pre-resonances
- A global fit of recent charmonium production data, taking into account feed-down relations, shows perfect compatibility with this interpretation
- $^1S_0$ dominates quarkonium cross sections at low p_T/M

Backup: ATLAS $J/\psi \rightarrow \mu\mu$ cross sections



8 rapidity bins
pulls with respect to common fitting function

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