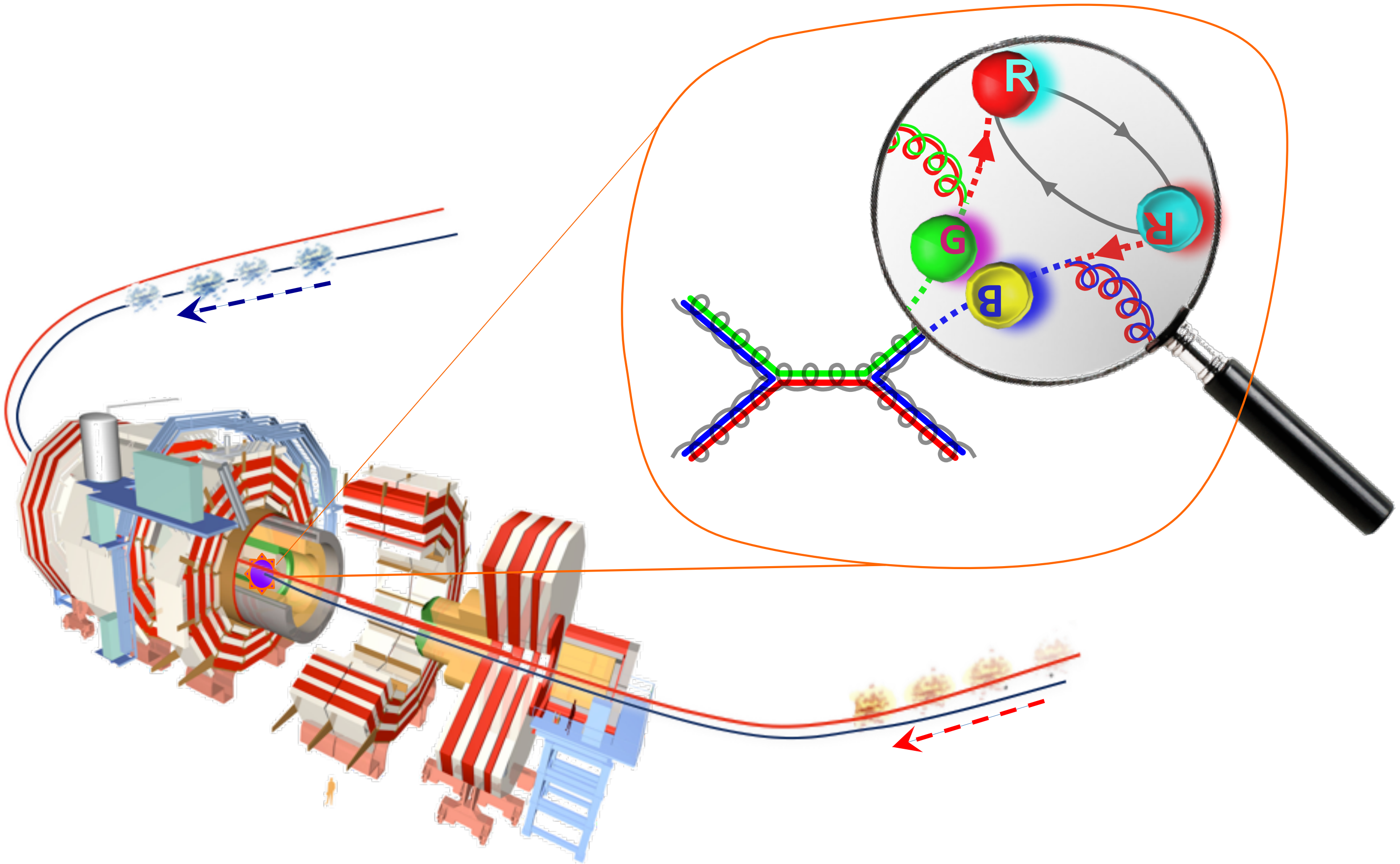
Analysis of LHC quarkonium production data from pp to Pb-Pb collisions

- Quarkonium production: from puzzles to understanding
- NRQCD vs. LHC data: remarkably simple and universal patterns
- Production in pp and suppression in Pb-Pb: a binding energy matter

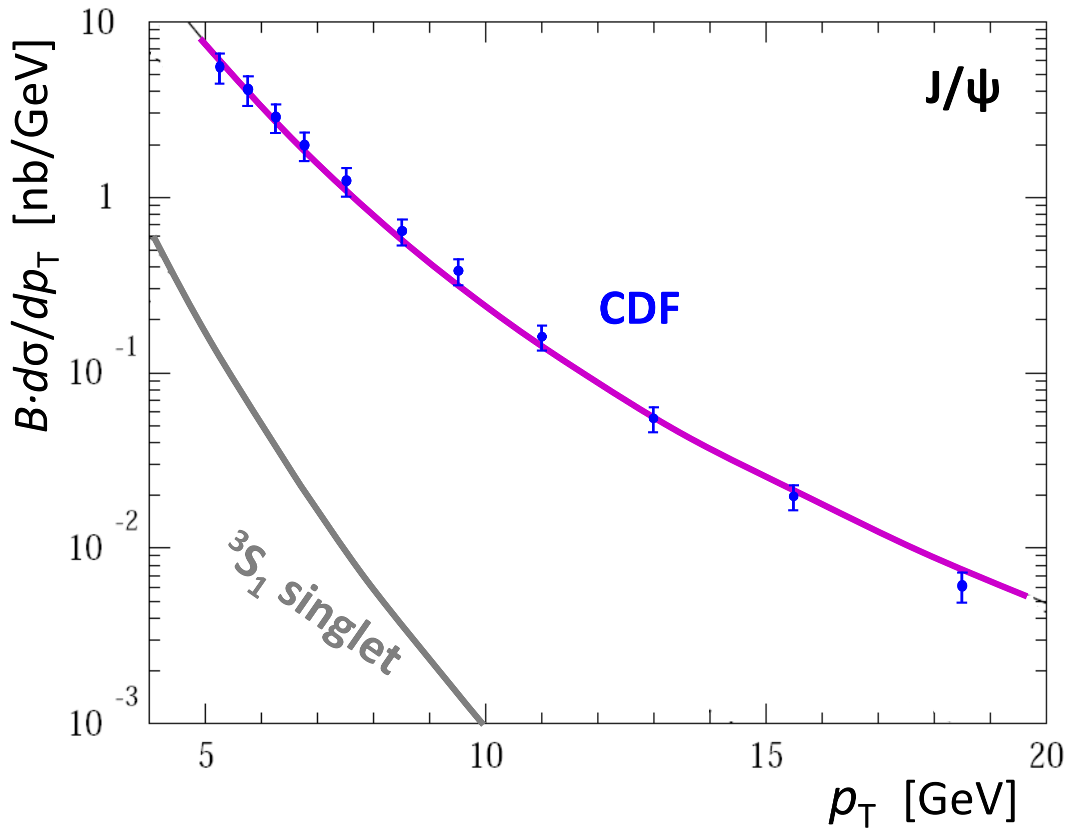


Quark Confinement and the Hadron Spectrum
Maynooth, Ireland, 2018

Carlos Lourenço, in collaboration with
Pietro Faccioli, Mariana Araujo, and João Seixas

The “quarkonium polarization puzzle”

In the early 90’s, CDF measured J/ψ and ψ(2S) p_T -differential cross sections
50 times larger than expected in the color singlet model



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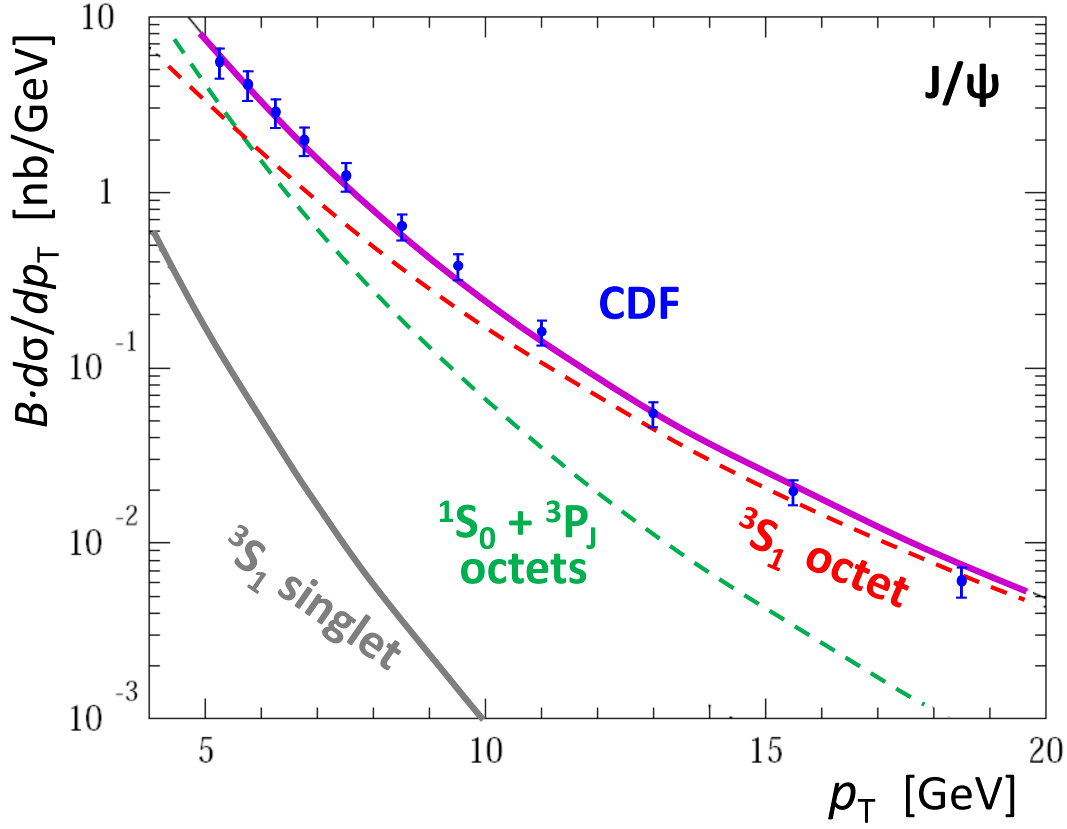

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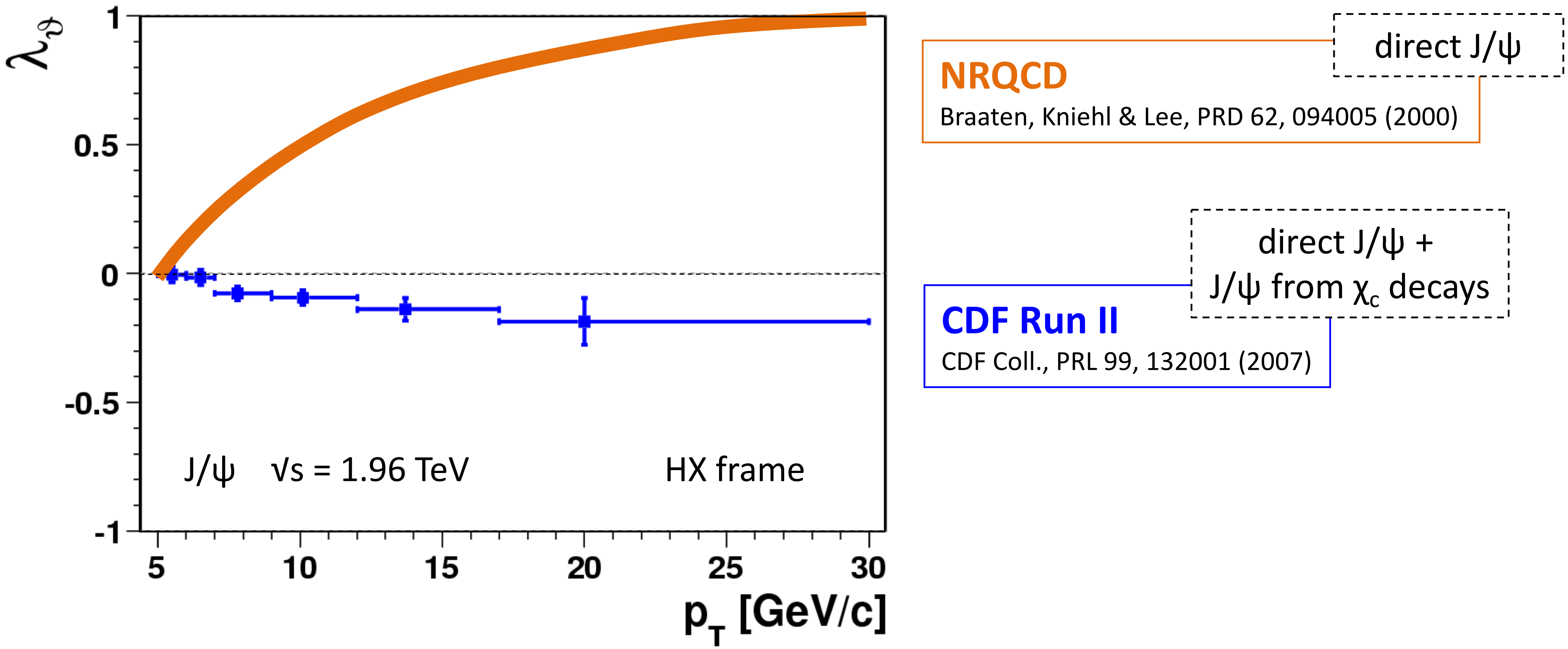

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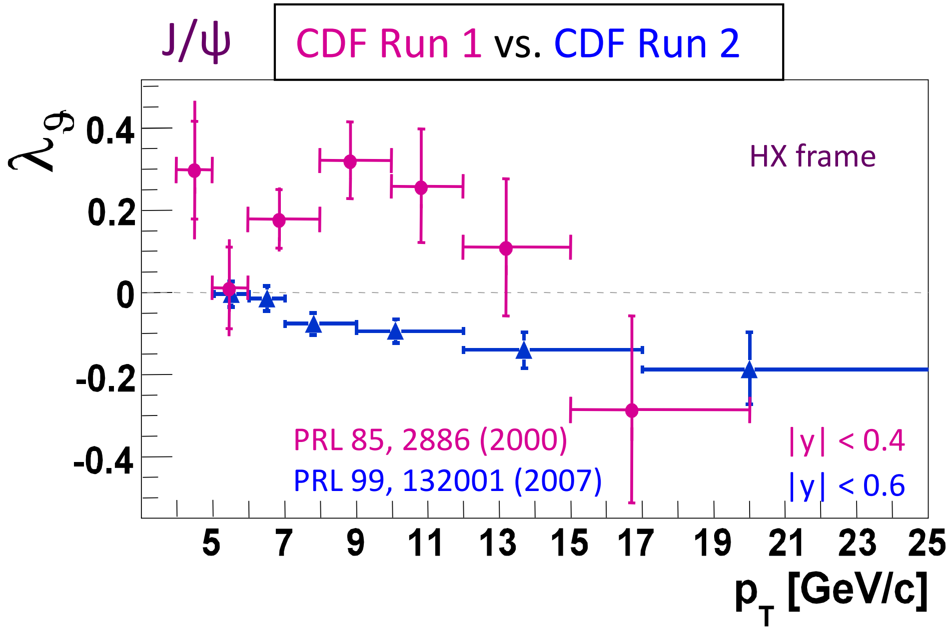
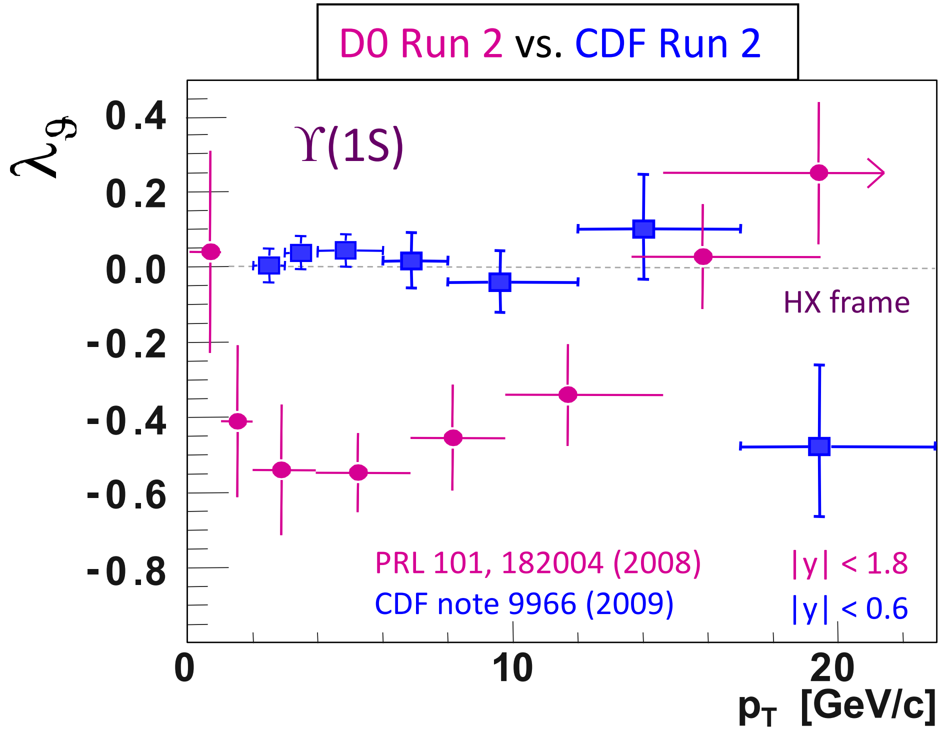
But the Tevatron results mutually excluded each other...

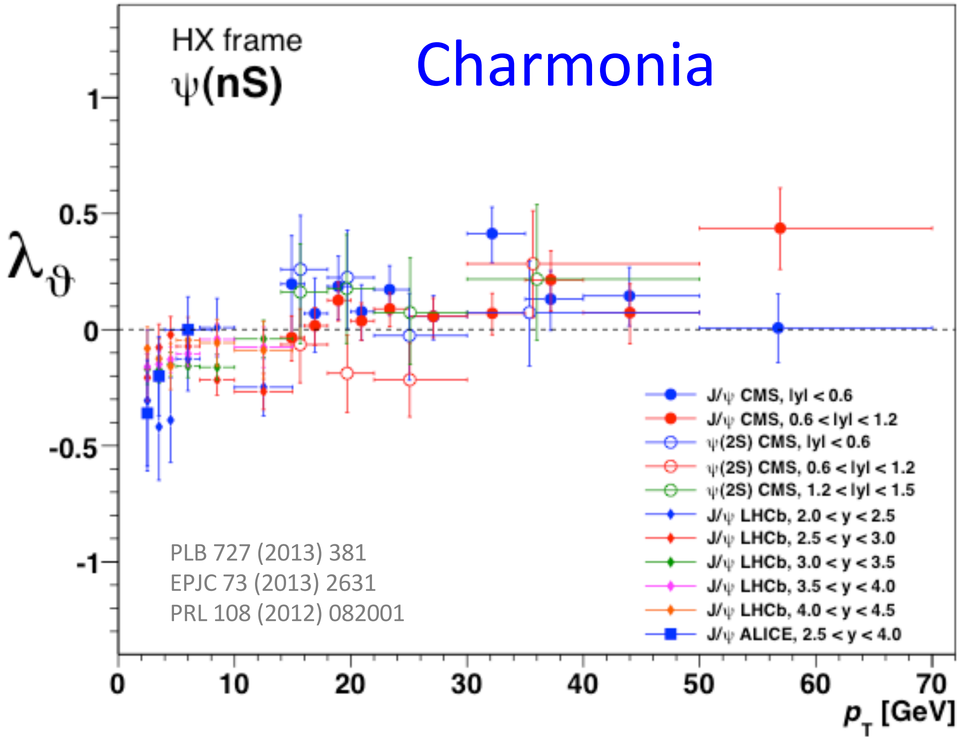
Improved data needed !

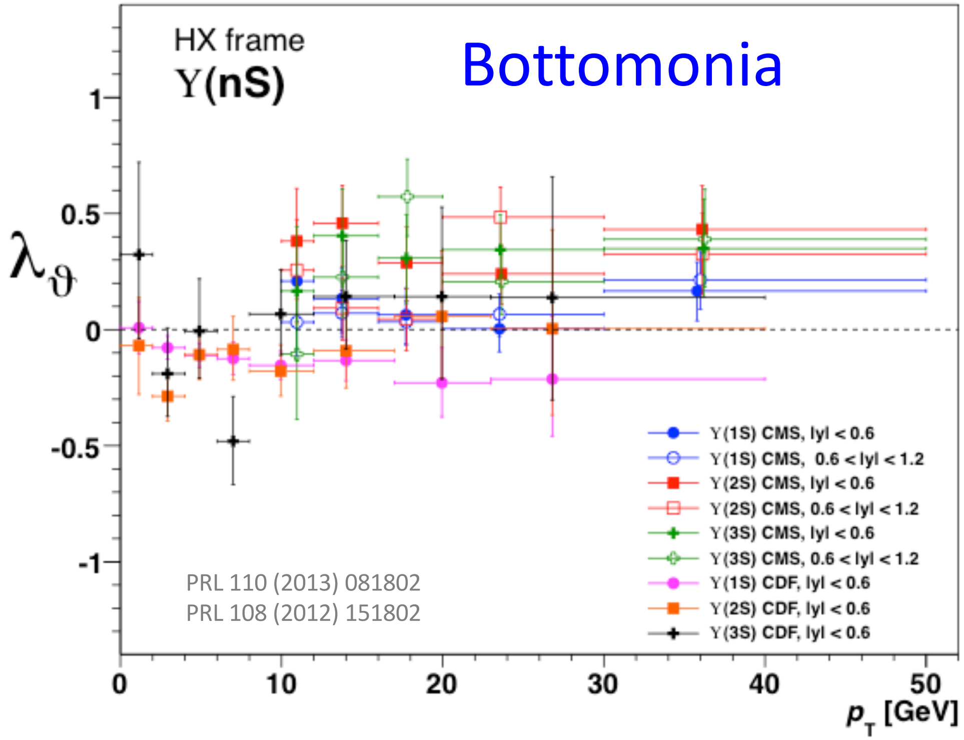




Polarization measurements at the LHC

Vastly improved measurement techniques* lead to robust polarization experiments





No strong transverse polarizations seen, up to the highest probed p_T values

→ the *polarization puzzle* was not caused by problems in the Tevatron data

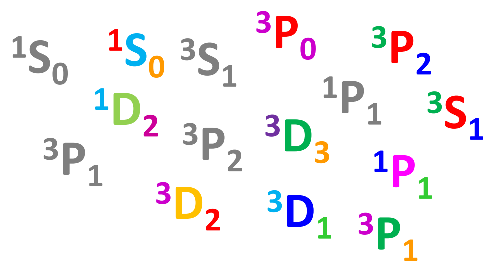
* P. Faccioli et al., EPJC 69 (2010) 657; PRL 105 (2010) 061601; PRD 81 (2010) 111502

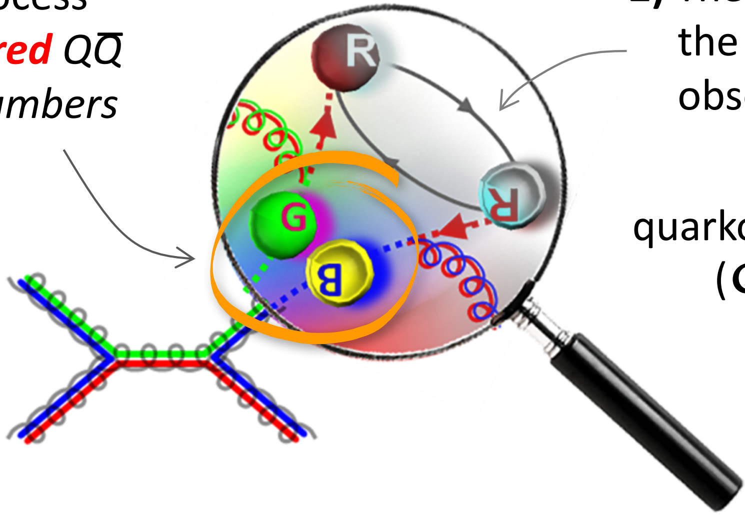
Quarkonium production in the NRQCD approach

In NRQCD several production mechanisms are foreseen for each quarkonium state

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

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





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

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} $[^3P_2]$

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

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

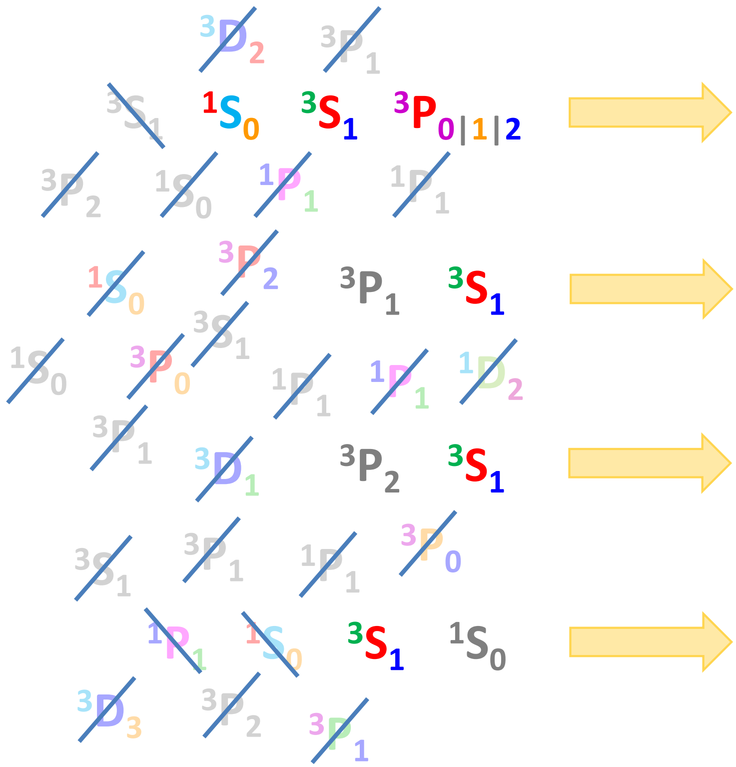
2) *long-distance matrix elements* (**LDMEs**): constant, **fitted from data**

NRQCD hierarchies

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

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

2) **Perturbative calculations** $\rightarrow$ some SDCs are negligible:



$[^3S_1]$ J/ψ, ψ(2S), Υ(1S), Υ(2S), Υ(3S)

$[^3P_1]$ χ_{c1} , χ_{b1}

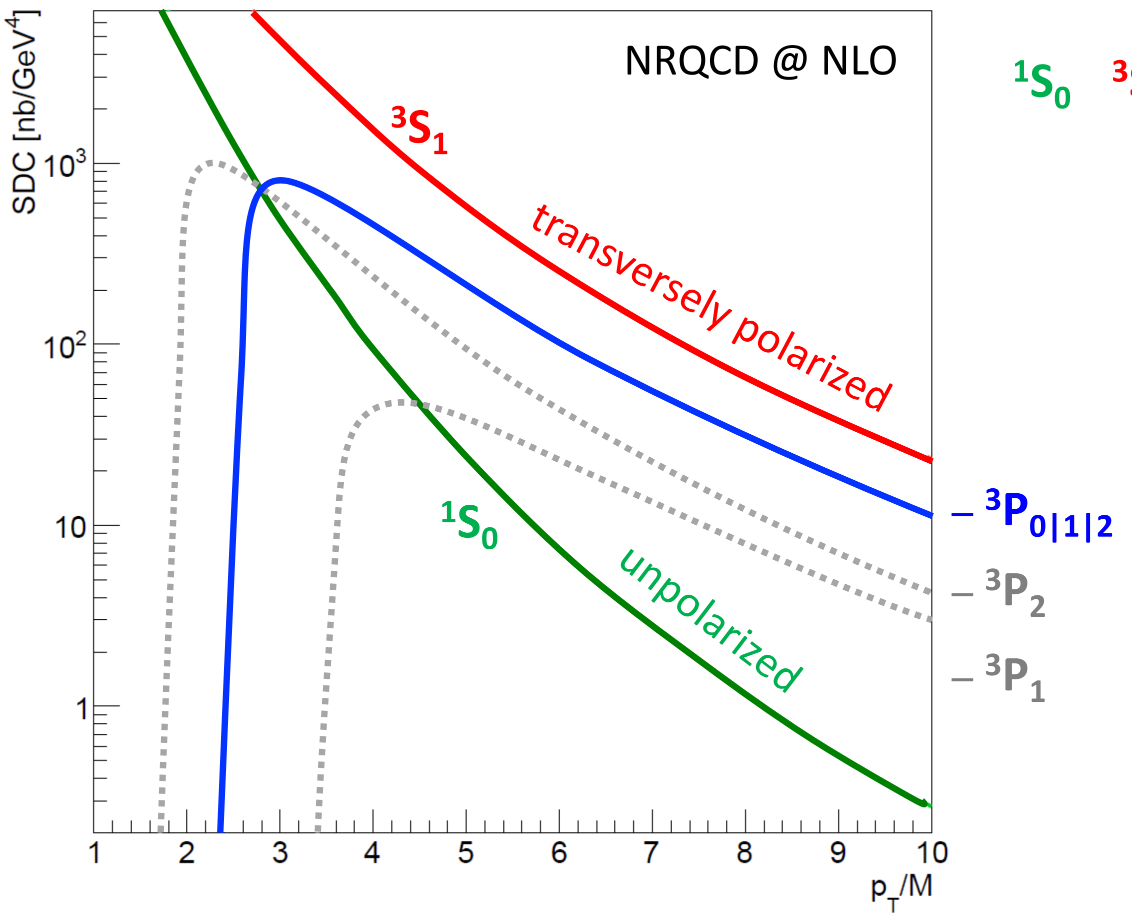
$[^3P_2]$ χ_{c2} , χ_{b2}

$[^1S_0]$ η_c , η_b

3) **Heavy-quark spin symmetry** $\rightarrow$ relations between LDMEs of different states

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

Dominant short-distance cross section contributions



$^1S_0$ $^3S_1$ $^3P_{0|1|2}$ ⇨ **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,
with large unphysical polarizations,
require proper cancellations
to recover physical result

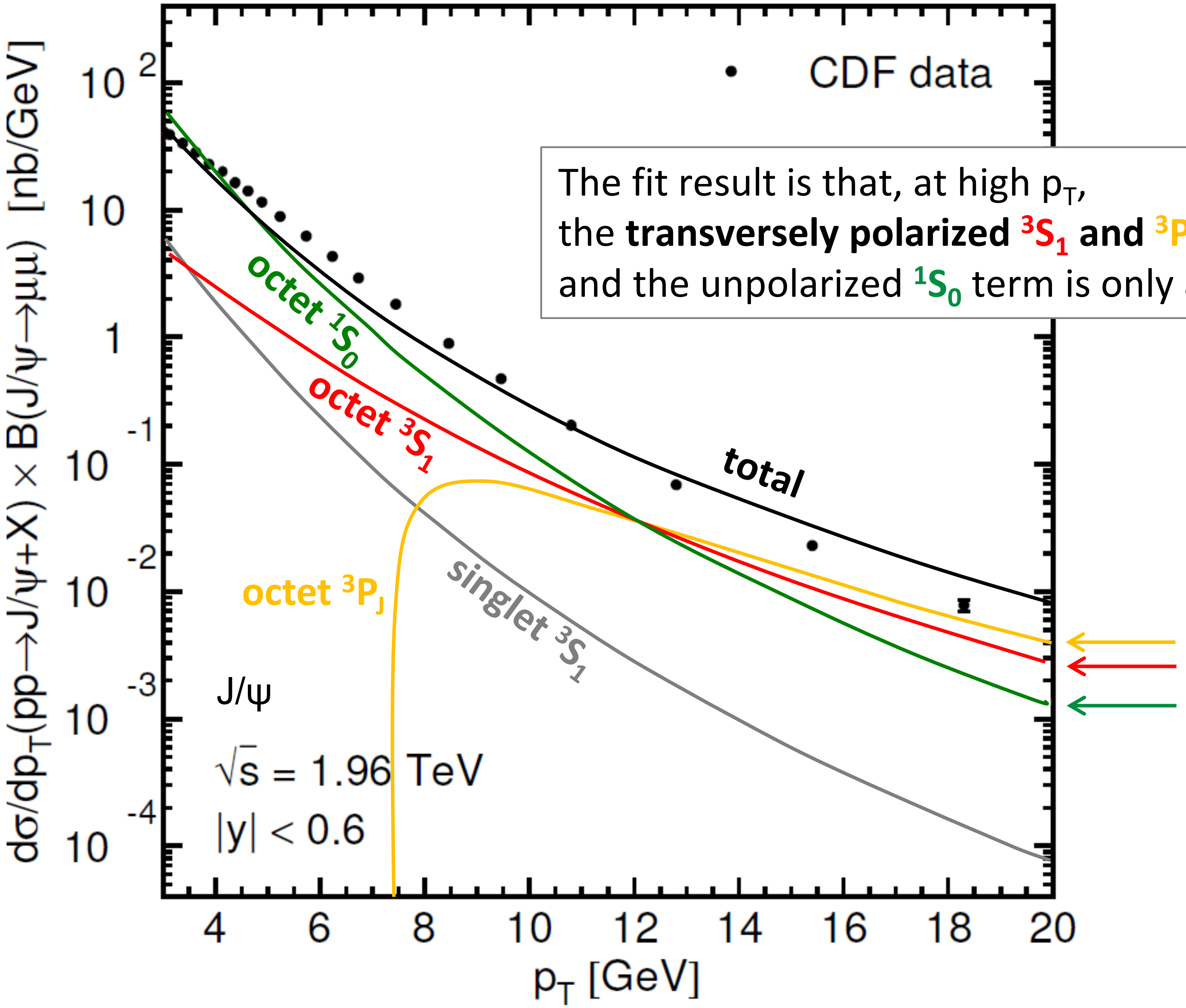
Mixture of different pre-resonance contributions,
with rather **diversified** kinematics and characteristic polarizations
→ by fitting the measured p_T distributions, one determines the LDMEs of each term
and consequently predict the polarizations

… a very delicate procedure !

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

A pedagogical look at past fits

The fit freely adjusts the normalizations (LDMEs) of the $^1S_0$, $^3S_1$ and ^3P_J colour-octet terms



The fit result is that, at high p_T, the **transversely polarized** $^3S_1$ **and** ^3P_J **octet** terms **dominate**, and the unpolarized $^1S_0$ term is only a "correction"

What does this imply for the polarization ?

Notes:
The fit starts at p_T = 3 GeV
SDC functions at NLO by
M. Butenschön and B. Kniehl

The polarization dimension

Quarkonium polarization is characterized by λ_θ :

- *measured* as the polar anisotropy of the decay dilepton angular distribution
- *calculated* from the transverse and longitudinal cross sections: $(\sigma_T - \sigma_L) / (\sigma_T + \sigma_L)$

Each color singlet and octet term has a specific polarization associated :

$^1S_0 \rightarrow \lambda_\vartheta = 0$ at LO, NLO, etc; isotropic wave function

$^3S_1 \rightarrow \lambda_\vartheta = +1$ at LO, NLO, etc, at high p_T, where the fragmenting gluon is "real"

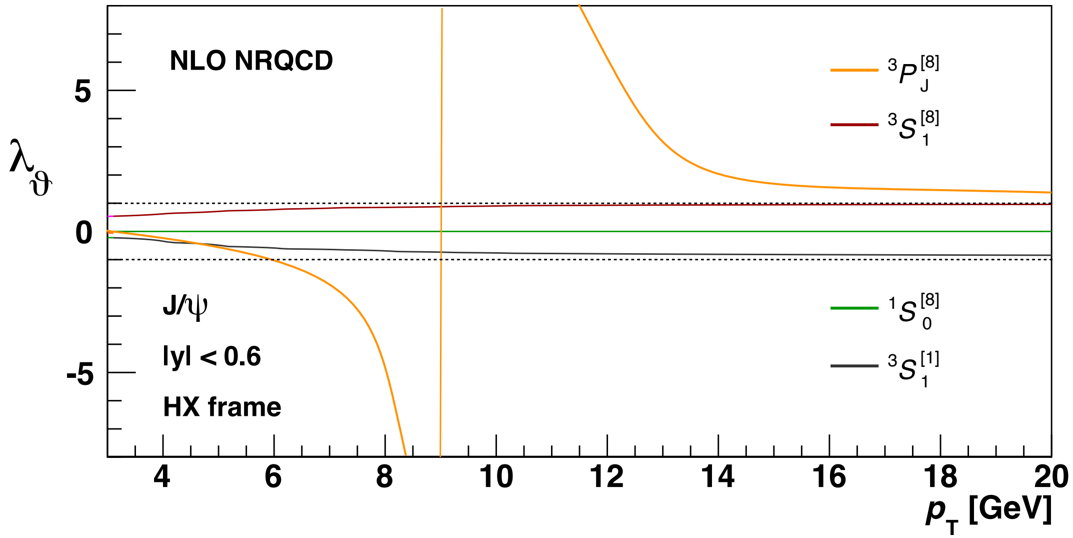
$^3P_J \rightarrow \lambda_\vartheta >> +1$ at NLO and high p_T ("hyper-transverse"); it is 0 at LO...

$^3S_1 \rightarrow \lambda_\vartheta \sim -0.9$ at NLO and high p_T ; it is ≈ +1 at LO (has a small impact)

Dominance of the $^3S_1$ and ^3P_J octets

→ $\lambda_\vartheta \approx +1$ for high-p_T S-wave quarkonia

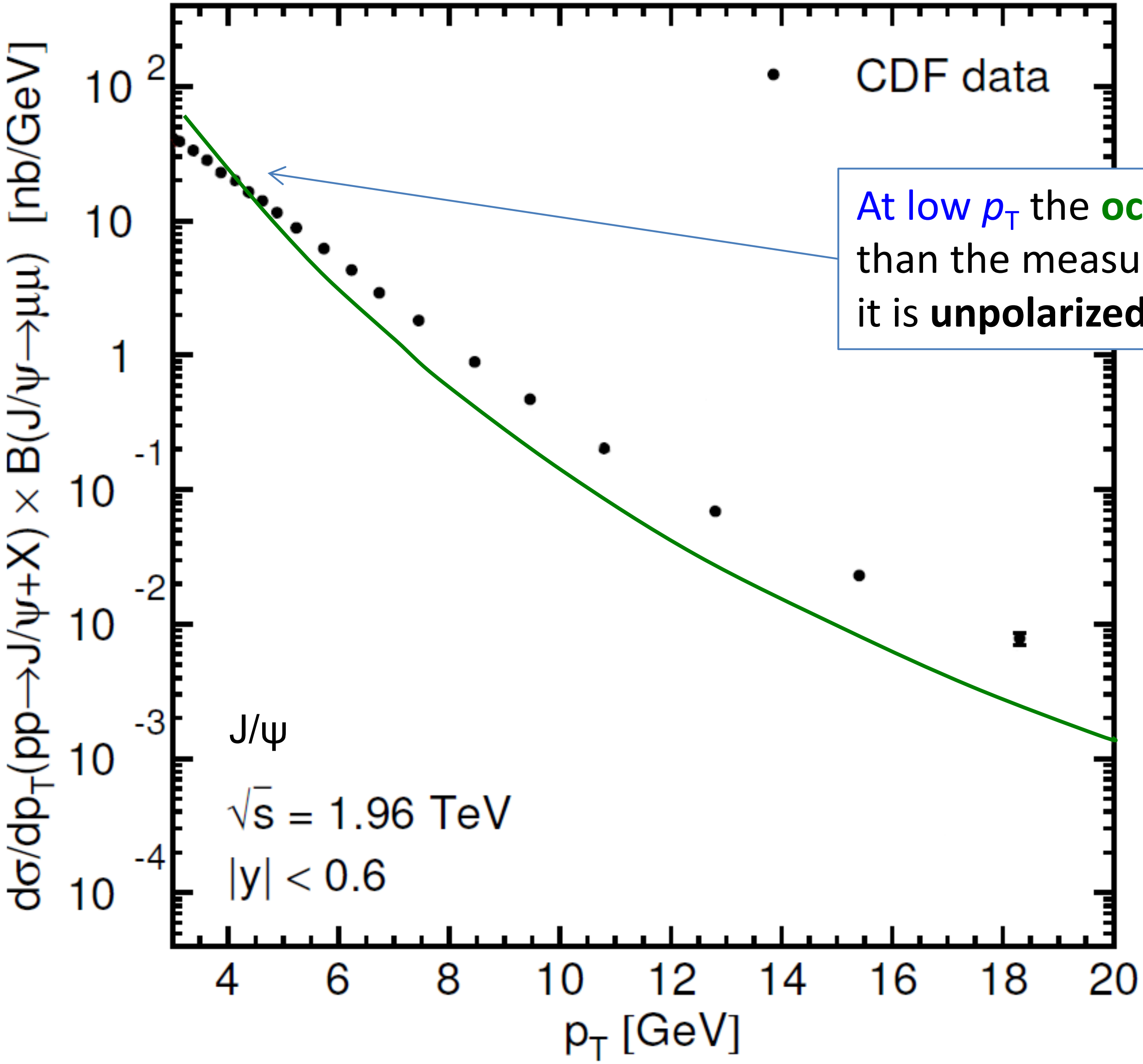
→ NRQCD "predicts"
transverse polarization at high p_T



Note: the ^3P_J octet has *negative* cross sections... and $\lambda_\vartheta >> +1$

A pedagogical look at past fits

Let's consider how the individual contributions compare to the data

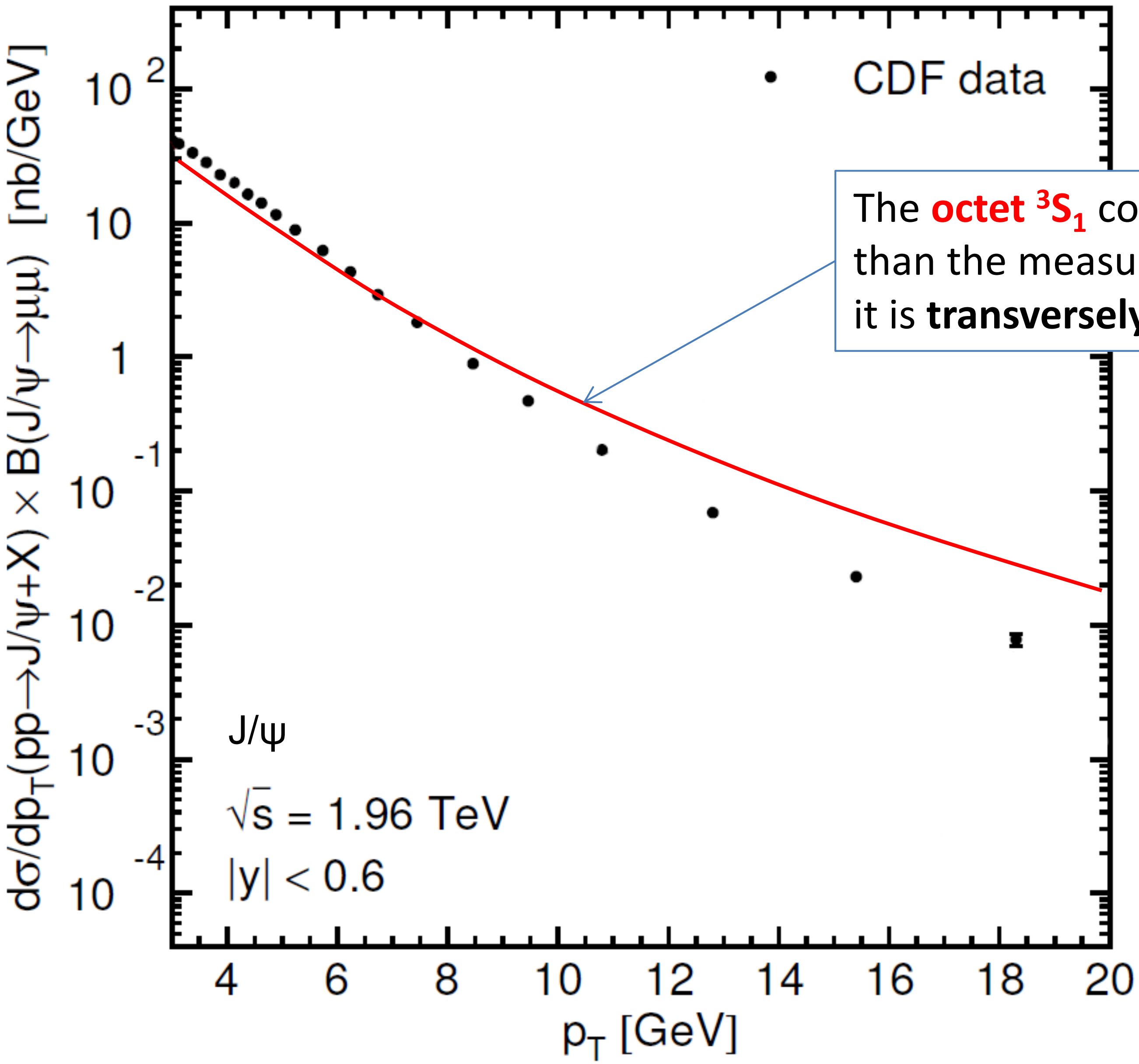


At low p_T the **octet $^1S_0$** contribution is steeper than the measured cross section; it is **unpolarized**

Reminder:
Color-octet contributions have fixed shape but adjustable normalizations (the LDMEs)

A pedagogical look at past fits

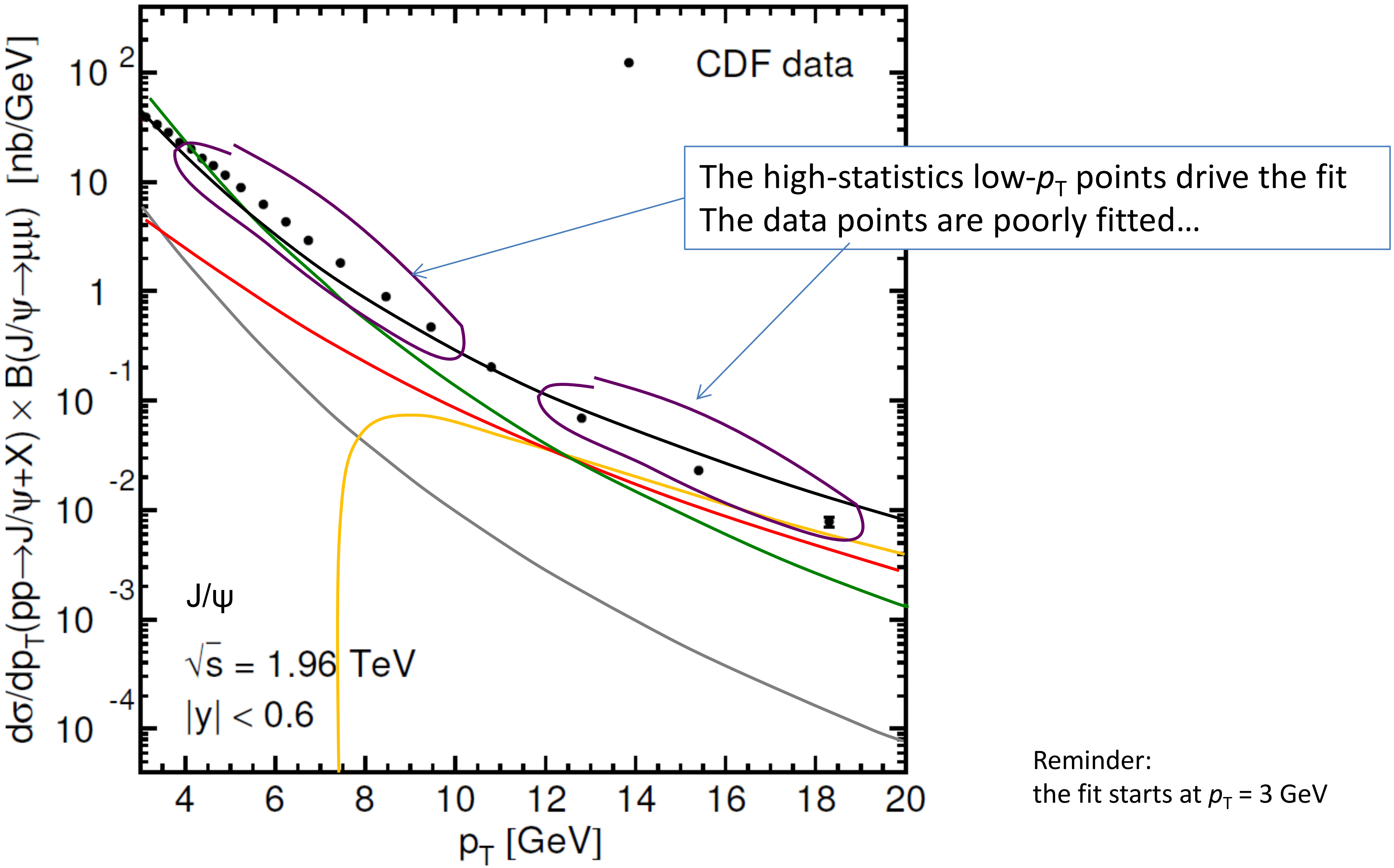
Let's consider how the individual contributions compare to the data



The **octet $^3S_1$** contribution is flatter than the measured cross section; it is **transversely polarized**

A pedagogical look at past fits

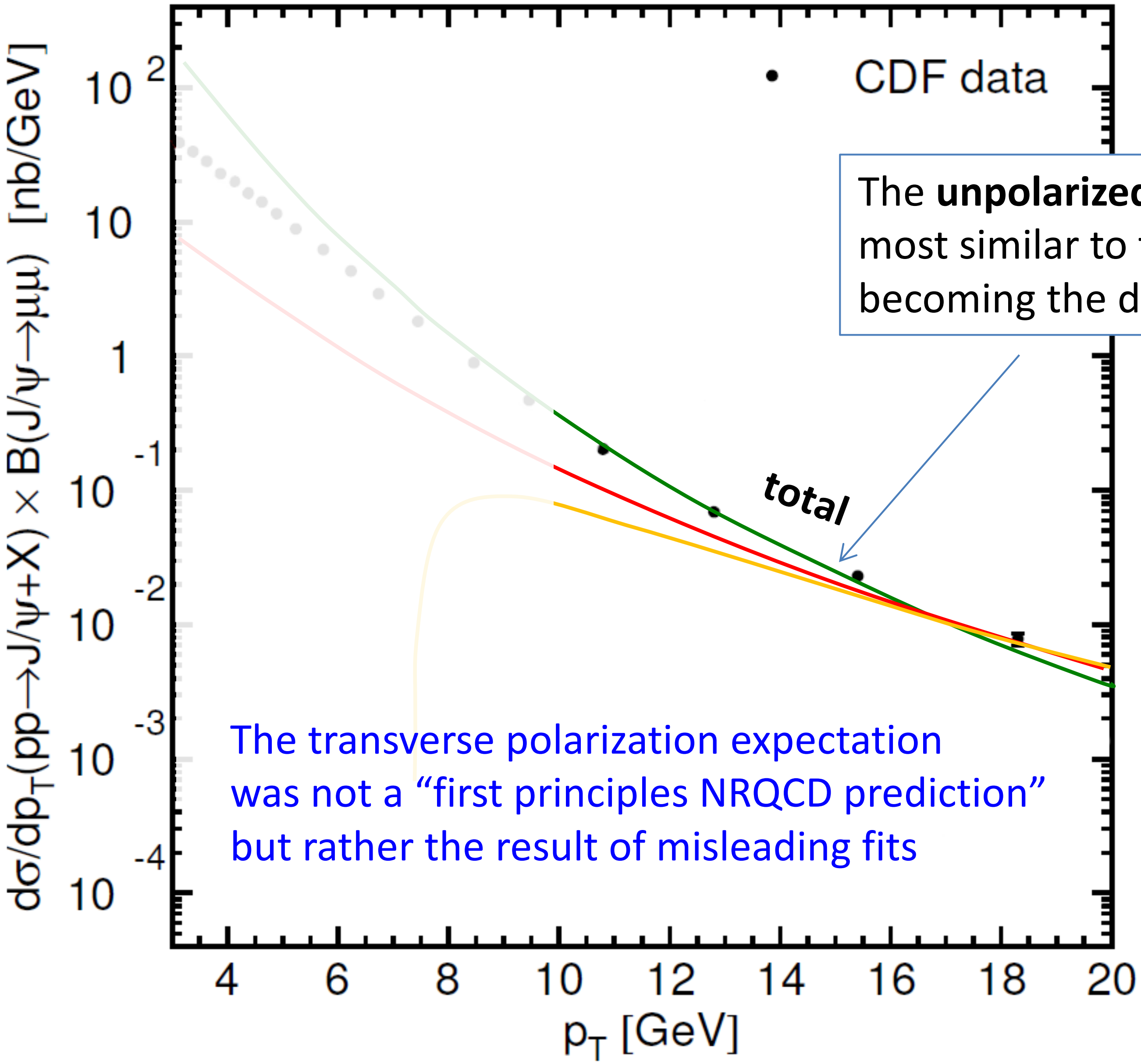
All together now...



Reminder:
the fit starts at p_T = 3 GeV

A closer look at past fits

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



The **unpolarized** $^{1}S_0$ **octet** has the *shape* most similar to the data, becoming the dominating term

The low p_T shapes of the SDCs are unreliable
(as often happens with fixed-order pQCD calculations)

Data-driven global fit of LHC quarkonium measurements

P. Faccioli et al.
PLB 736 (2014) 98

Cross sections and polarizations are *simultaneously* used in the fit

In each step, the probed LDMEs are used to compute the *theoretical* $\lambda_\vartheta(p_T)$ and $d\sigma/dp_T$, and the *measured* $d\sigma/dp_T$ spectra, recalculating the acceptance for the polarization under test

All other analyses fit the *unpolarized* $d\sigma/dp_T$ spectra
ignoring that the detection acceptance depends on the assumed polarization

Point-to-point and global (luminosity) experimental uncertainties are properly considered

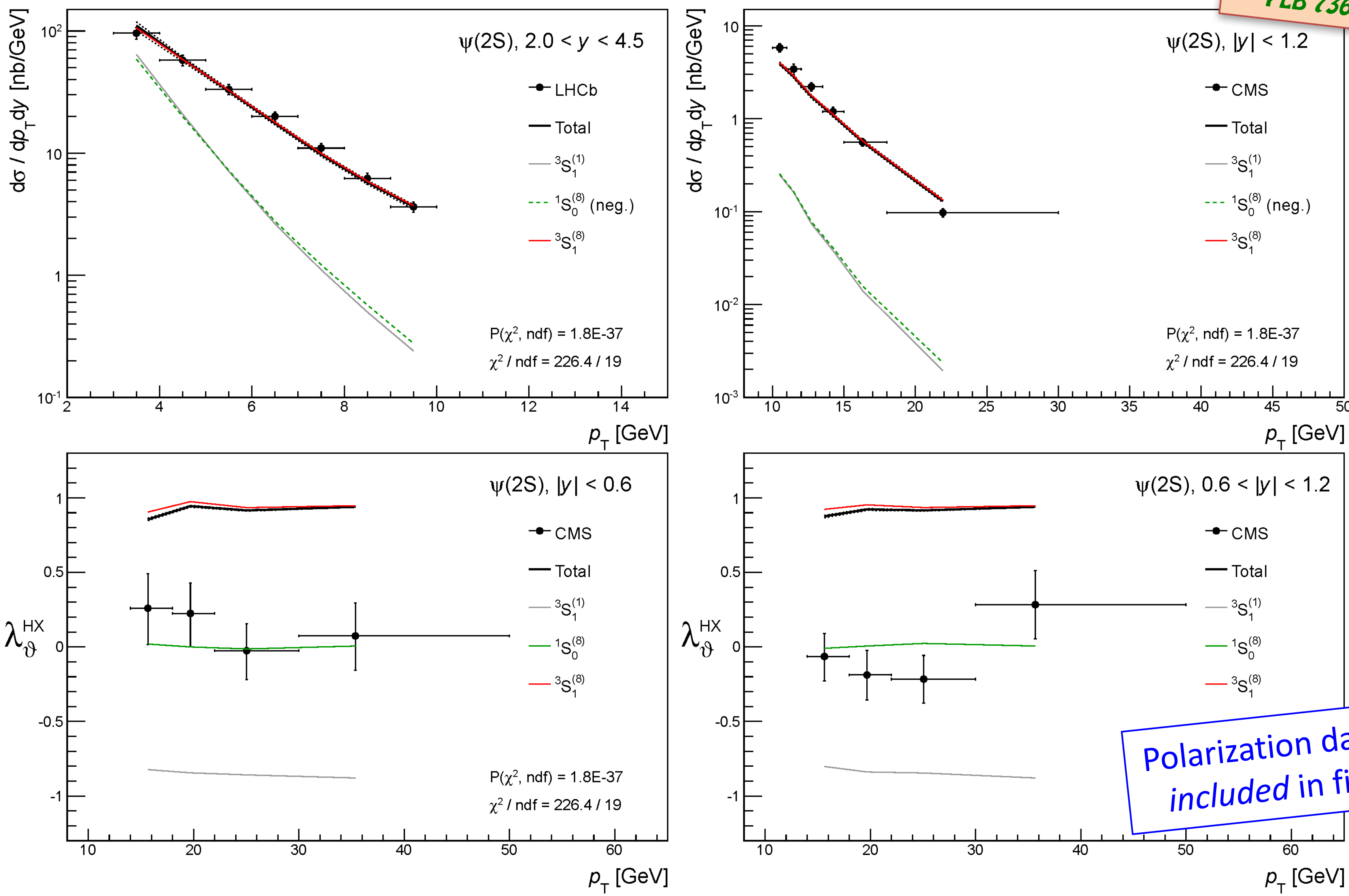
The analysis is restricted to the $\psi(2S)$ and $\Upsilon(3S)$ data, to minimise the feed-down

To get more stable results, the initial fits are made without the $^3P_J^{[8]}$ octet
When we include it, the fit quality does not improve and the results are not affected

Takes into account the low-p_T limitations of the calculated SDCs

Illustration of a ψ(2S) fit, starting from p_T = 3 GeV

P. Faccioli et al.
PLB 736 (2014) 98

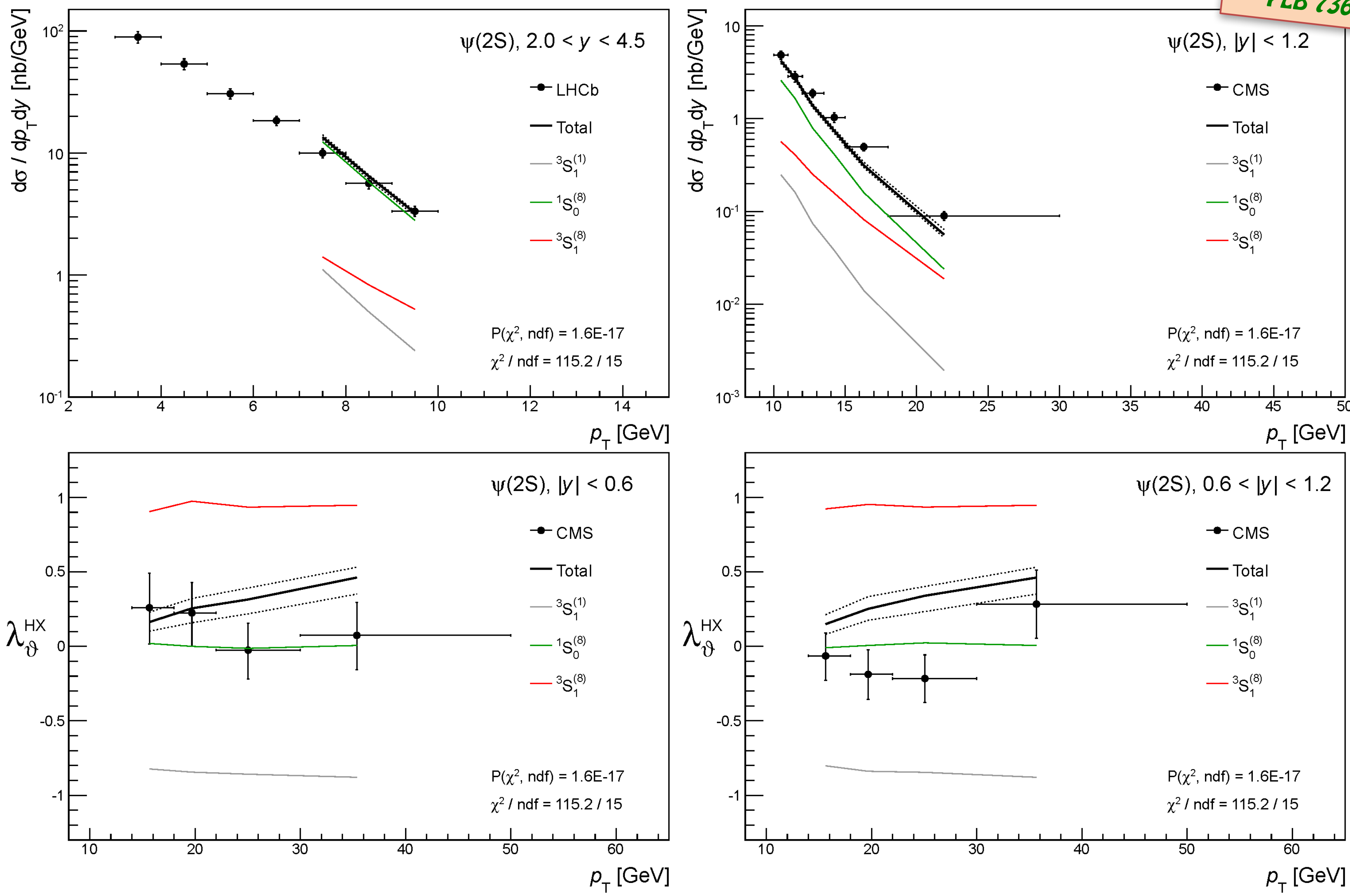


- $^3S_1^{[8]}$ dominates
- $^1S_0^{[8]}$ small (and negative)

P(χ²) 1.8E-37

Illustration of a ψ(2S) fit, starting from p_T = 7 GeV

P. Faccioli et al.
PLB 736 (2014) 98

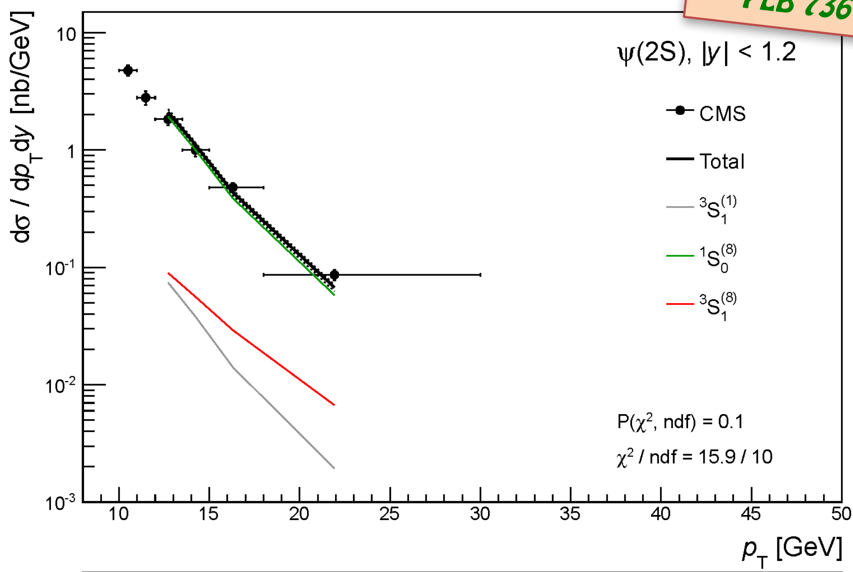


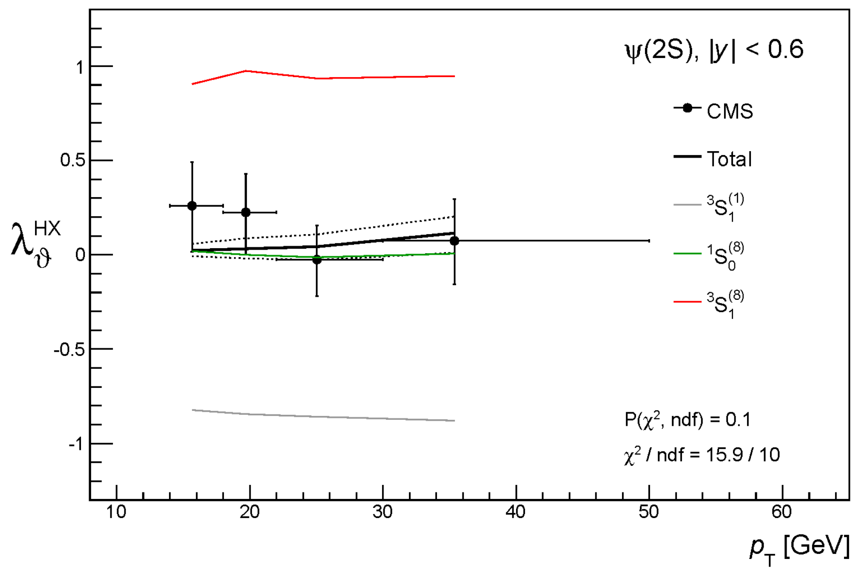
- $^1S_0^{[8]}$ is more important than $^3S_1^{[8]}$
- polarization gets closer to the data

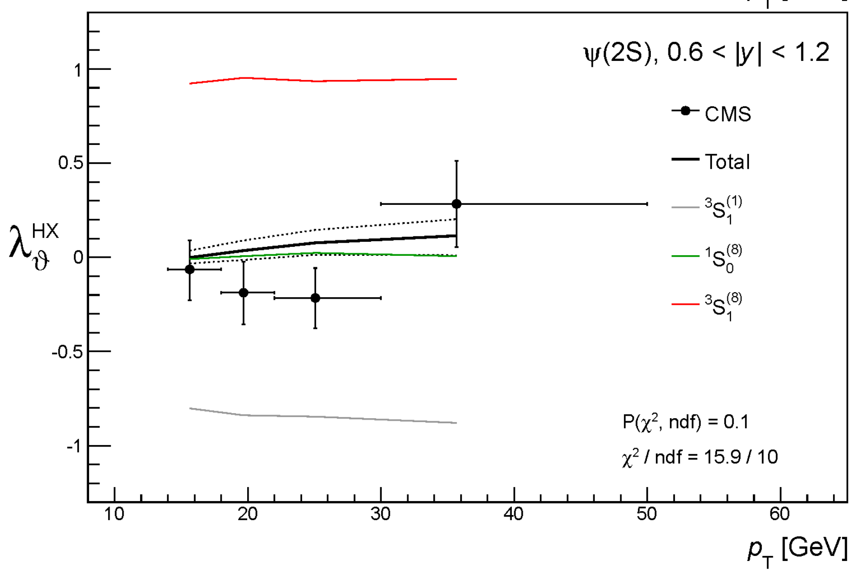
P(χ²) 1.6E-17

Illustration of a ψ(2S) fit, starting from p_T = 12 GeV

P. Faccioli et al.
PLB 736 (2014) 98







- $^1S_0^{[8]}$ dominates
- polarization agrees with the data

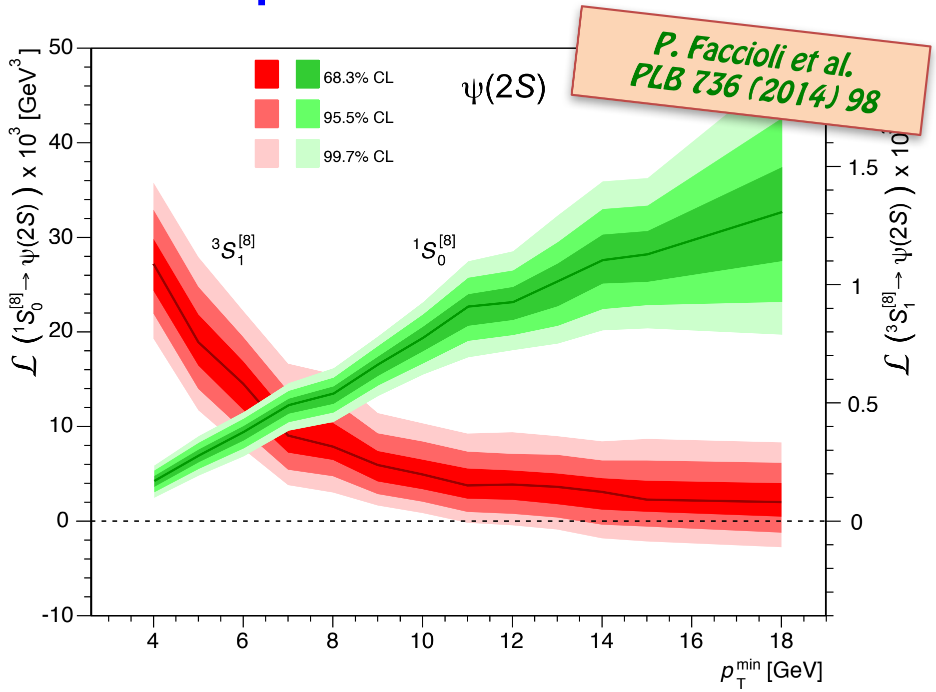
$P(\chi^2)$ 10%

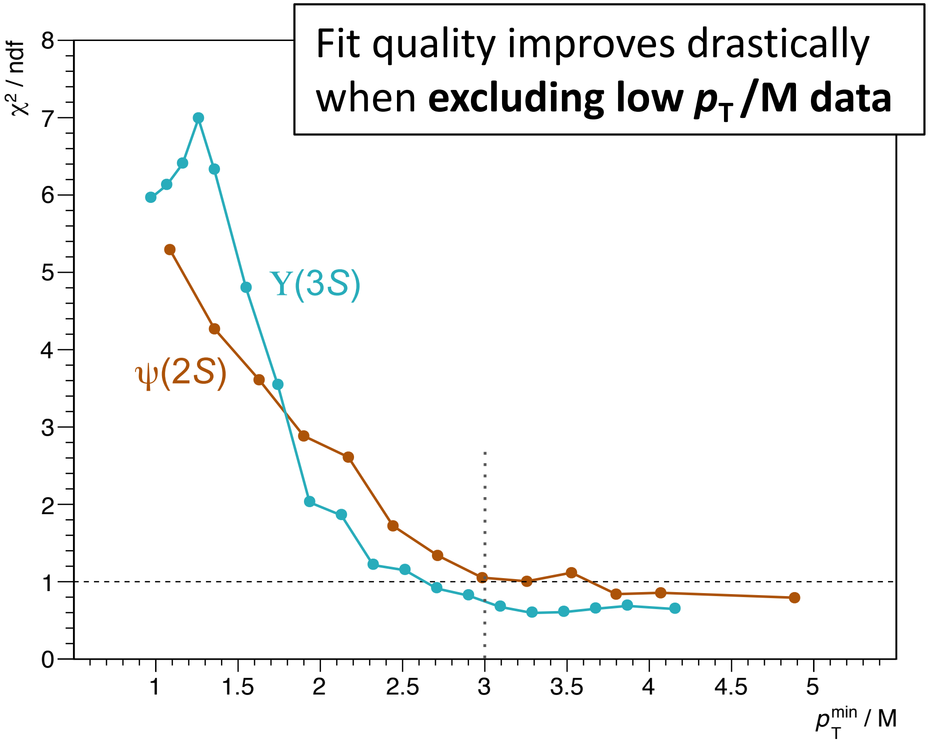
All data are equal but some are more equal than others

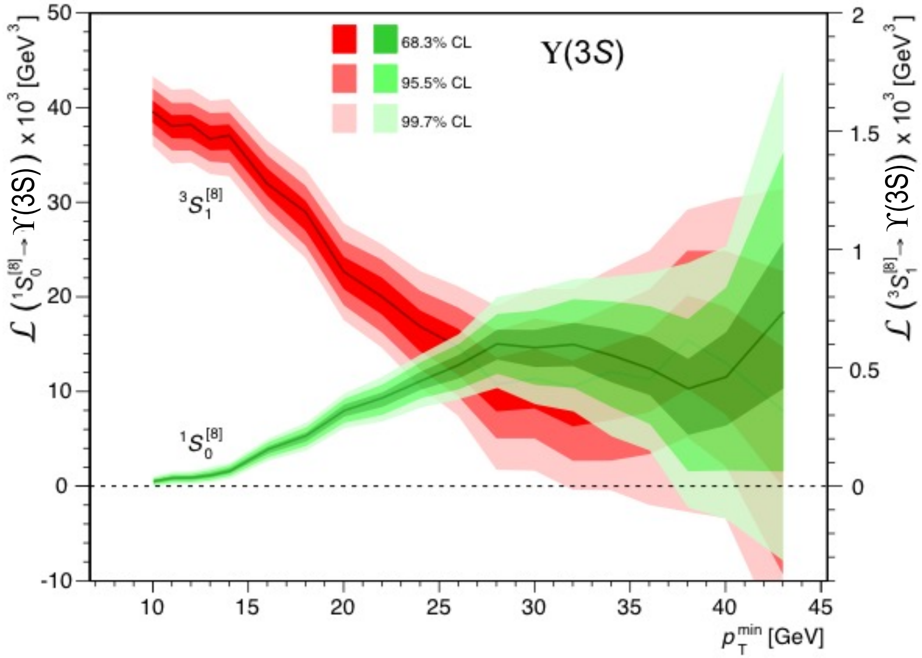
The fit quality improves dramatically
if we do not include low p_T / M cross sections

For $p_T / M > 3$ the fit results are stable

The polarization data and
the $p_T / M > 3$ cross section data
imply $^1S_0^{[8]}$ octet dominance

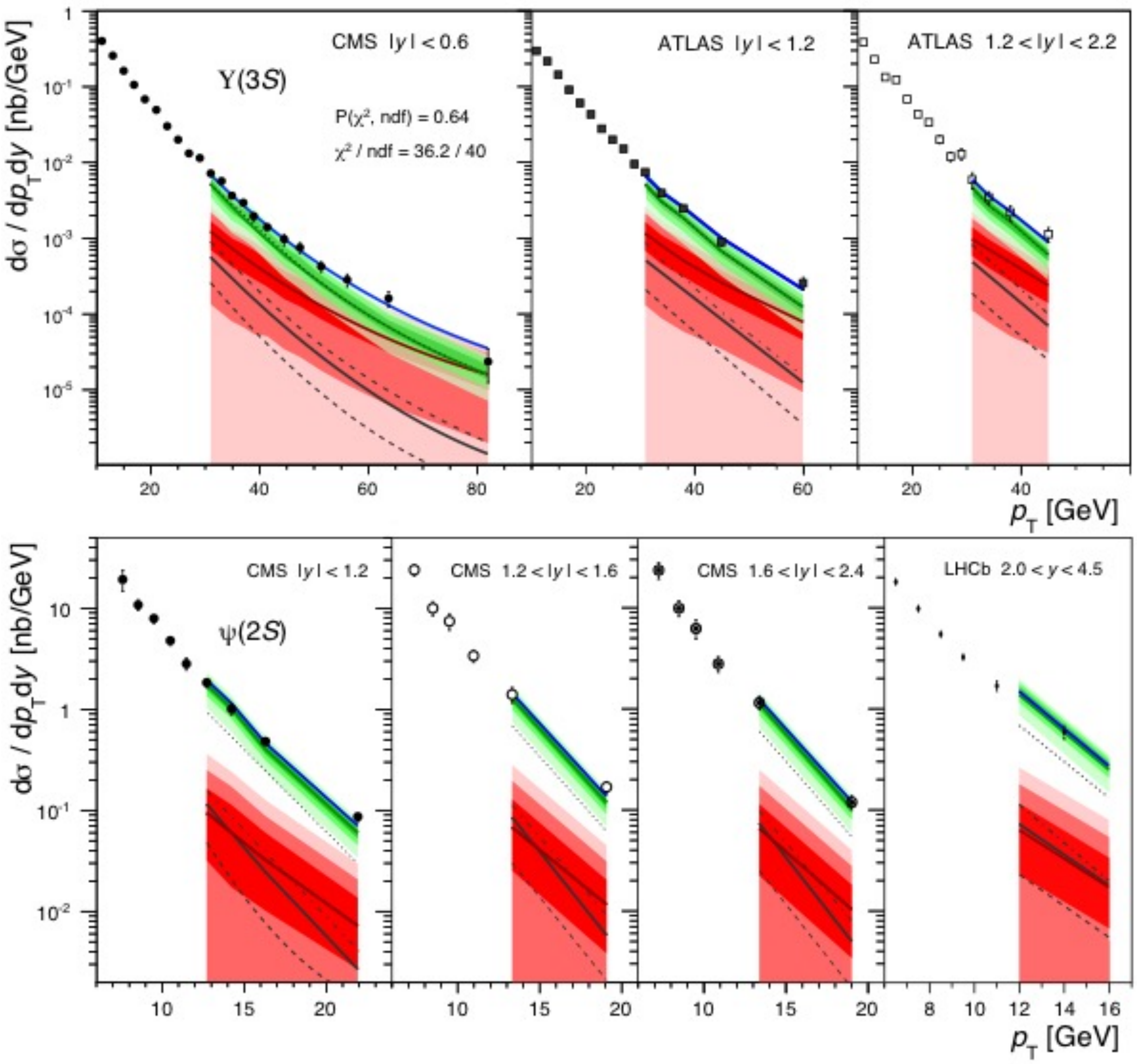






The solution of the quarkonium polarization puzzle

The ψ(2S) and ϒ(3S) cross sections and polarizations *can* be simultaneously and consistently described as a superposition of singlet and octet SDCs for $p_T/M > 3$



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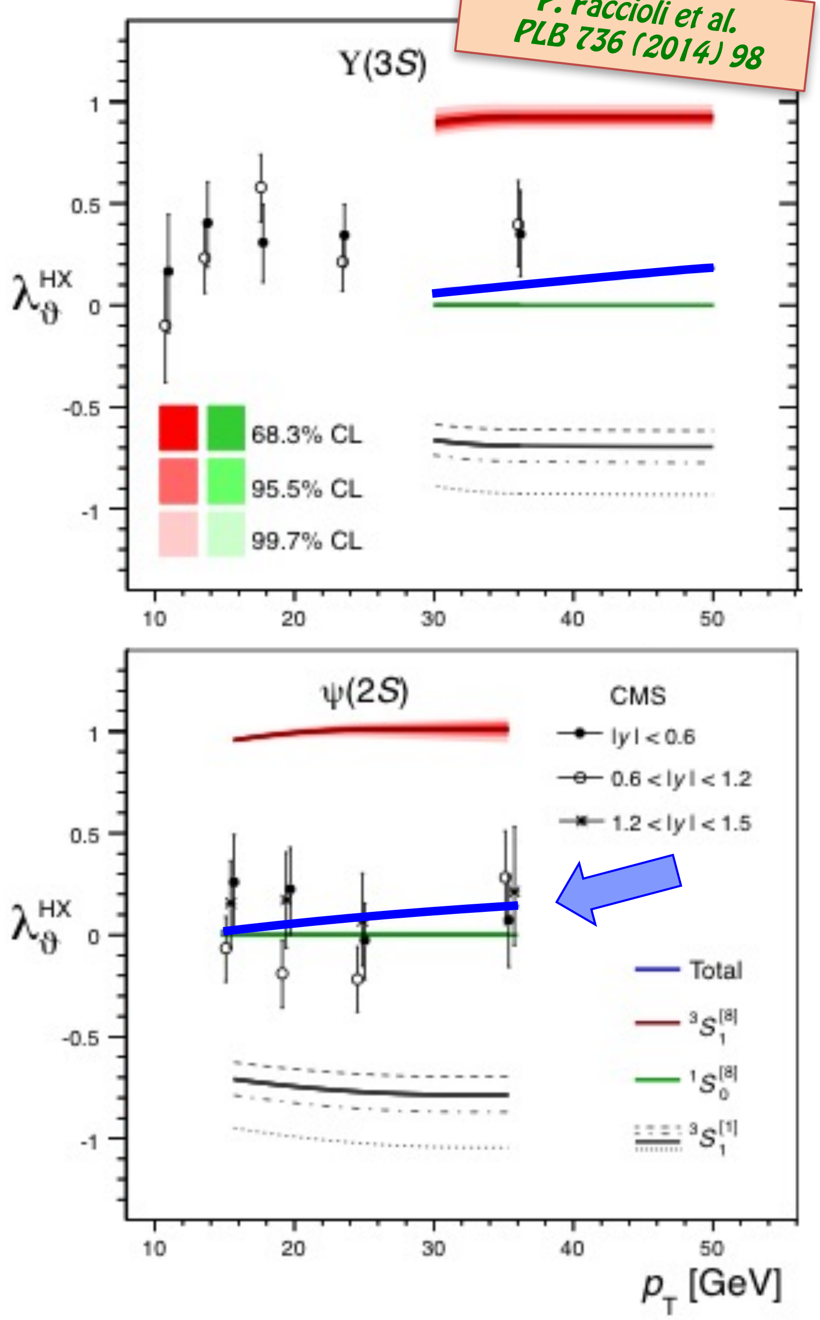
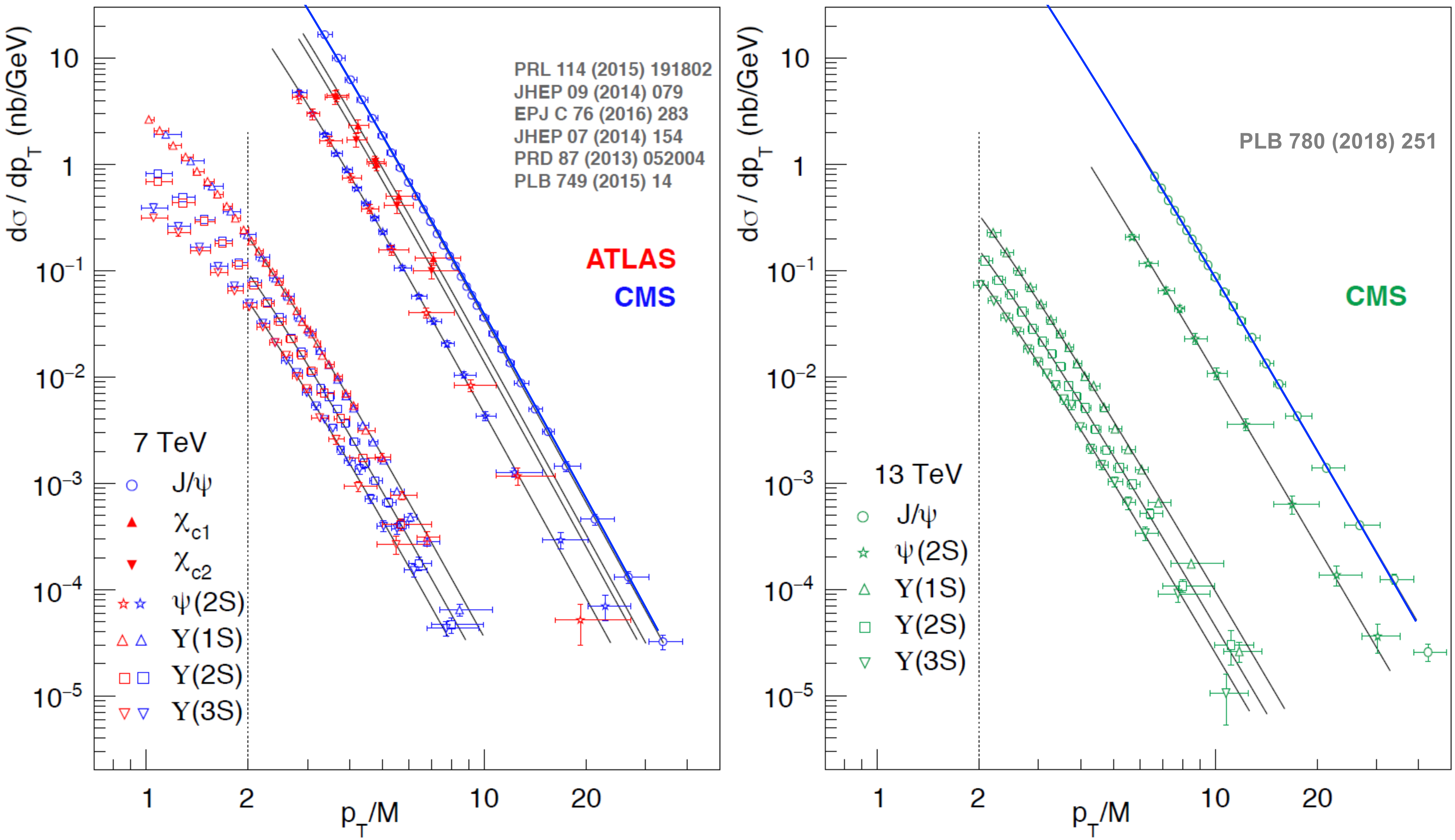
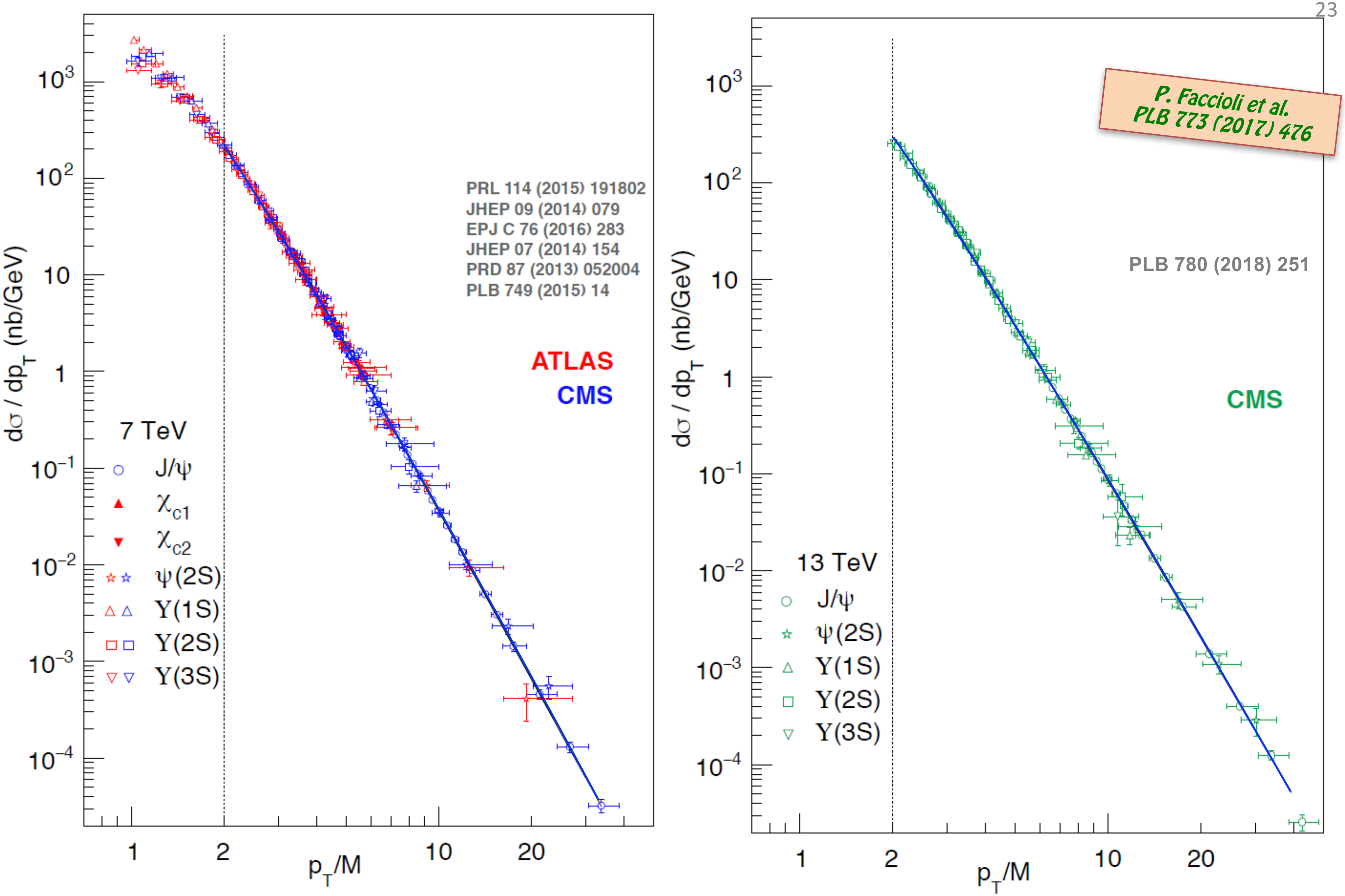


Unexpectedly simple data patterns

P. Faccioli et al.
PLB 773 (2017) 476

All quarkonia have identical p_T/M-differential cross section shapes, for $p_T/M > 2$, at mid-rapidity, independently of mass and quantum numbers

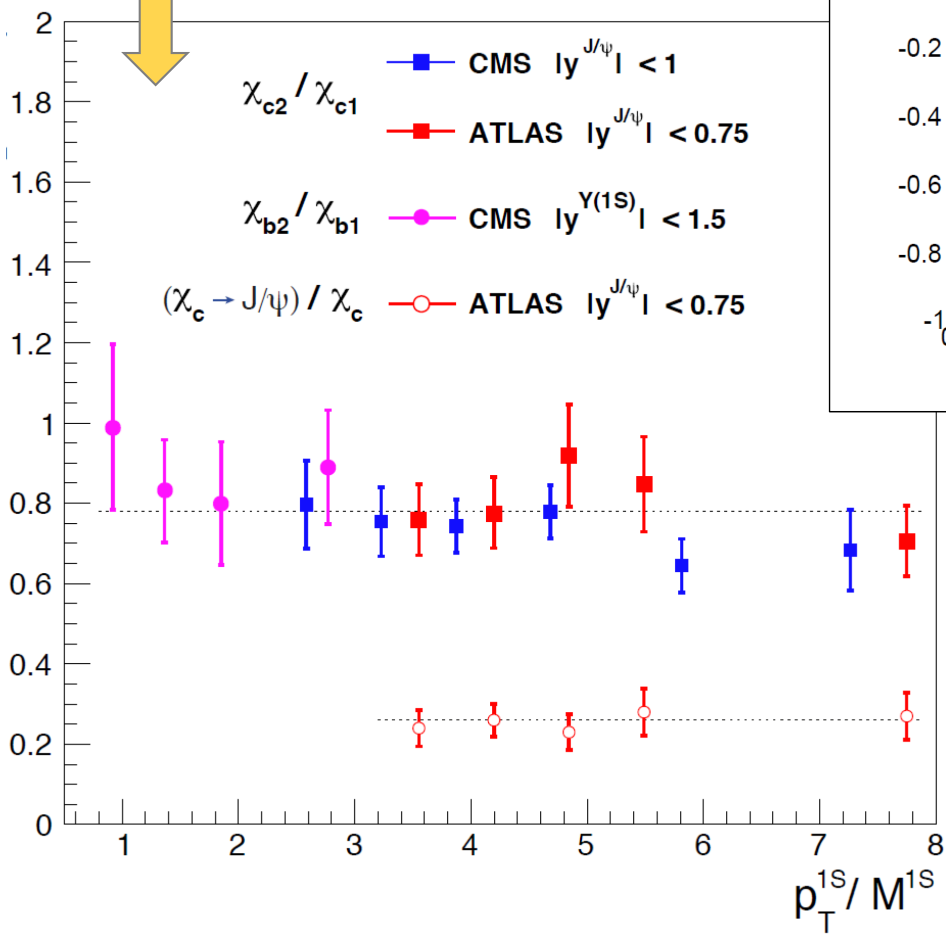


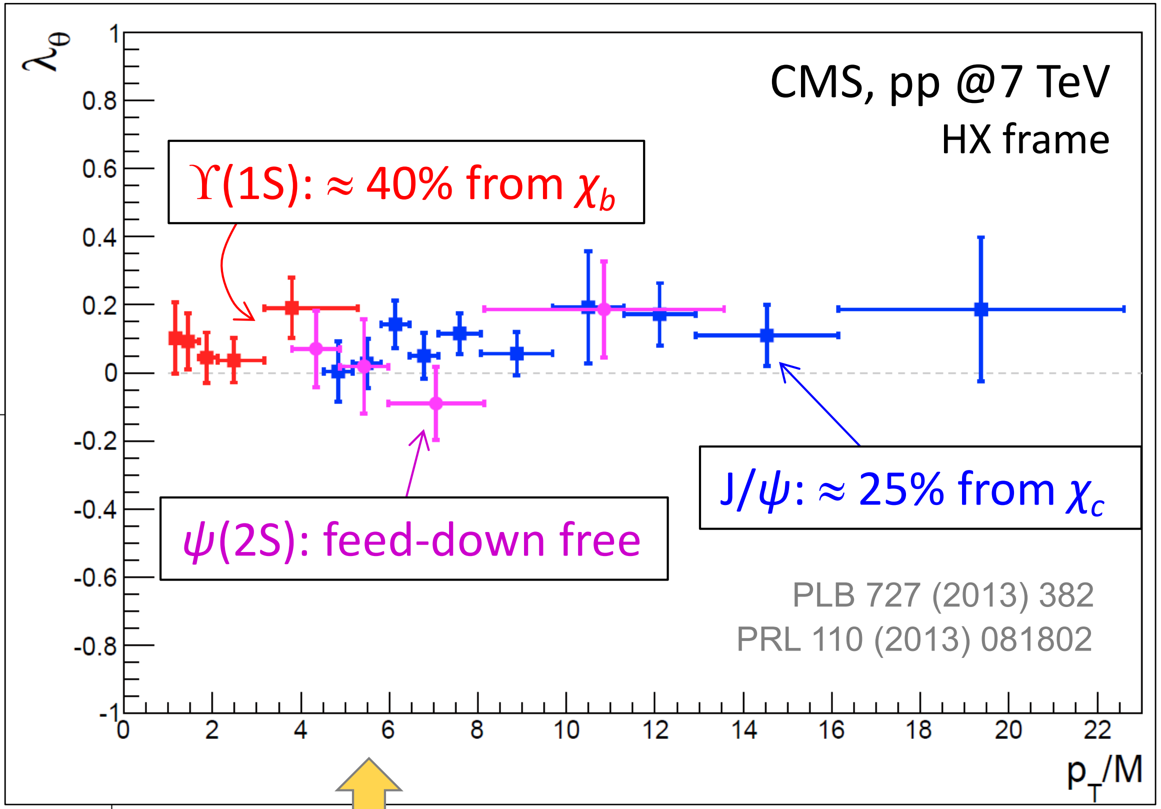


Scaling all data to match the J/ψ normalization

Same production dynamics for S- and P-wave states

Identical p_T/M cross section shapes for S- and P-wave states
⇒ no sign of dependence of the production *dynamics* on the quantum numbers !





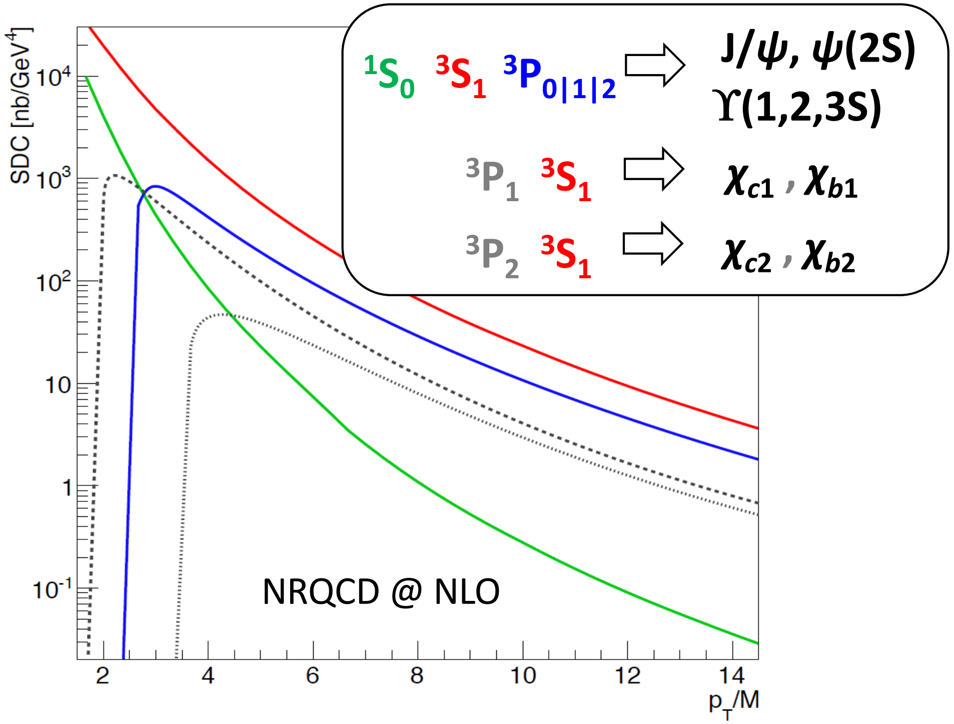
Small polar decay anisotropies, with no p_T dependences, for all S-wave states, despite very different P-wave feed-down contributions

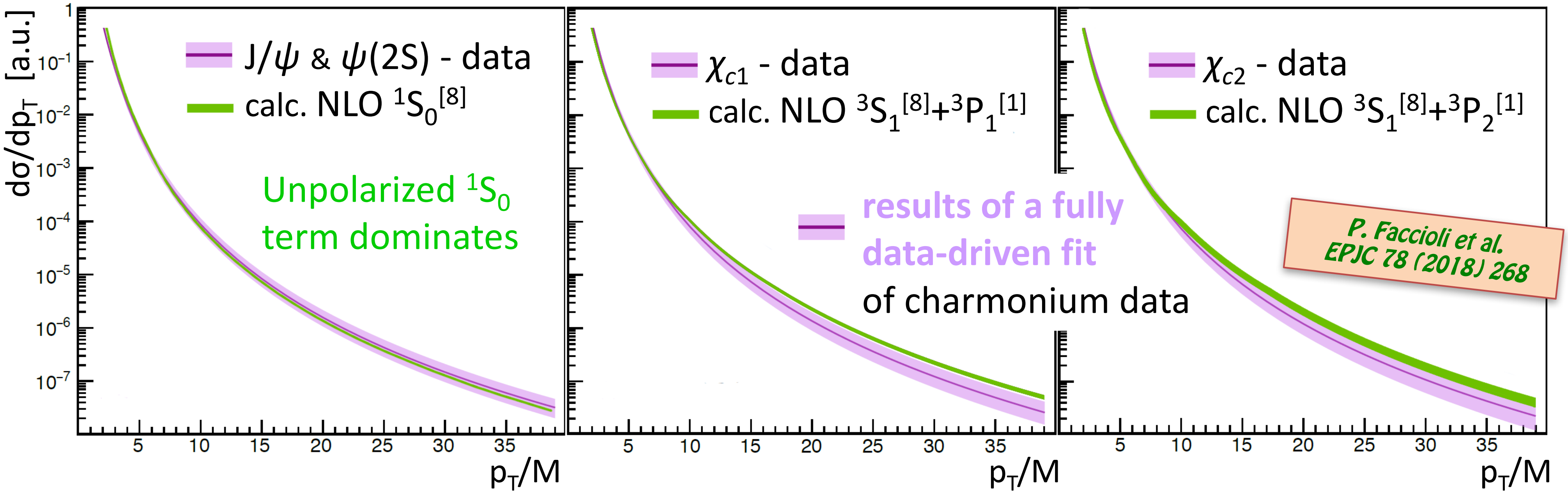
A "surprising" agreement with NRQCD

The variety of kinematic behaviours predicted in NRQCD
seems **redundant** with respect to the measured universal p_T/M scaling and lack of polarization

$\Rightarrow$ *Fine-tuned cancellations* are needed to reproduce the data

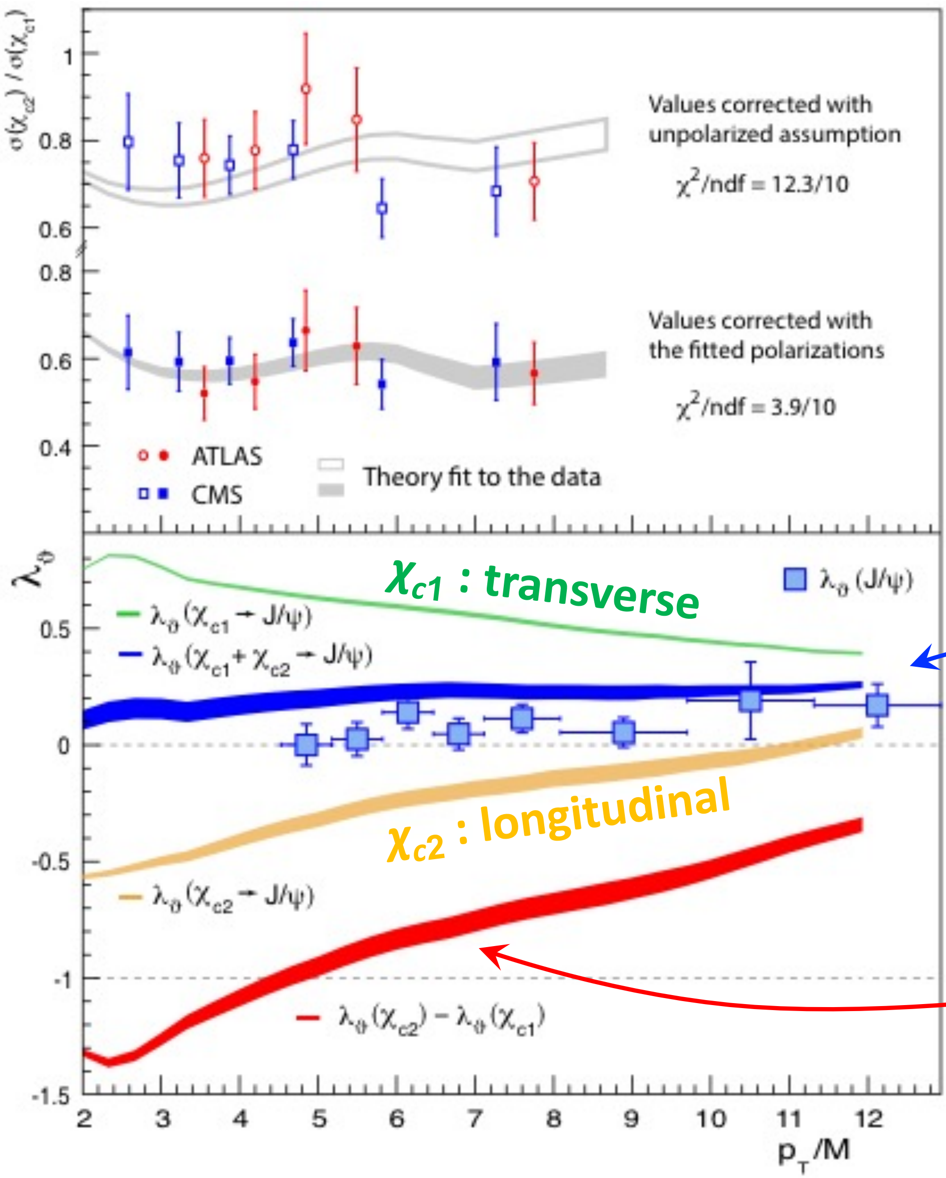
and they actually happen !





Striking coincidence or trigger to improve NRQCD?

The seeming success of NRQCD uncovers a strong prediction:
the unmeasured χ_{c1} and χ_{c2} polarizations must be **very different** from one another



Cross section ratio χ_{c2} / χ_{c1} : ATLAS and CMS data agree better with each other and with theory fit if their polarizations are different (acceptance correction depends on λ_θ)

Potentially striking exception to the uniform picture of mid-rapidity quarkonium production !

$\chi_{c1} + \chi_{c2} \rightarrow$ **J/ψ** : weak polarization
≈ as observed in prompt J/ψ data!

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

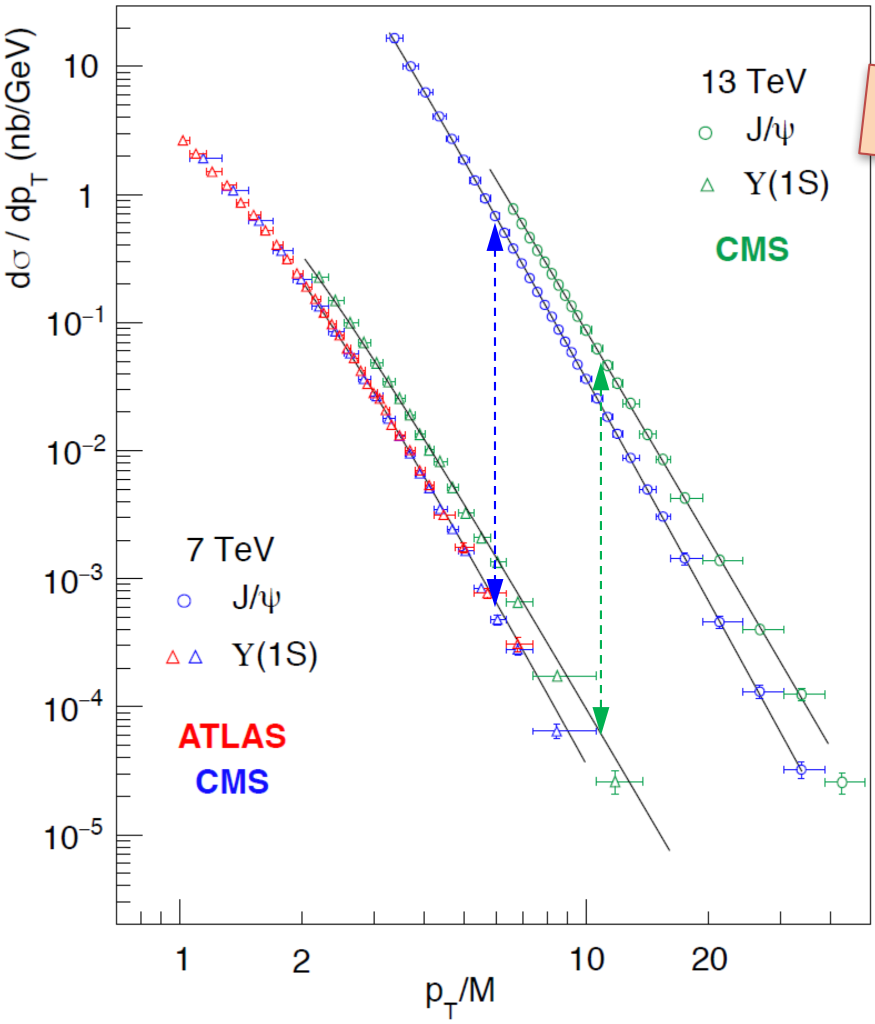
$|\ \Delta\lambda_\vartheta\ | \approx 1$

at the barycentre of current CMS χ_c data

Long-distance scaling: another universal pattern?

The quarkonium cross section scales from J/ψ to ϒ(1S) as

$$\frac{d\sigma/dp_T\,(\Upsilon(1S))}{d\sigma/dp_T\,(J/\psi)} = \left(\frac{m_b}{m_c}\right)^{-\alpha} \qquad \alpha = \begin{cases} 6.6 \pm 0.1 & 7\text{ TeV} \\ 6.5 \pm 0.1 & 13\text{ TeV} \end{cases}$$



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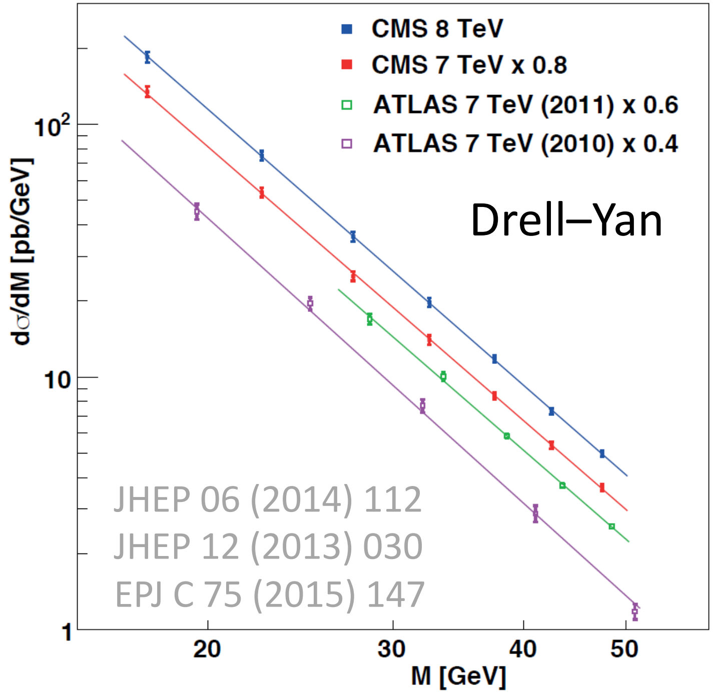
EPJC 78 (2018) 118



The Drell–Yan cross section scales with mass as

$$\frac{d\sigma/dM\,(M_2)}{d\sigma/dM\,(M_1)} = \left(\frac{M_2}{M_1}\right)^{-(3+\beta)} \qquad \beta = 0.63 \pm 0.03$$

$(\sqrt{s}/M)^{\beta}$ is a parton-luminosity factor common to all processes

The quarkonium cross section scales as $m_Q^{-(6.0 \pm 0.1)}$

Implications of the observed scaling patterns

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EPJC 78 (2018) 118

Inclusive quarkonium production cross section from pure dimensional analysis:

$$\frac{d\sigma}{dp_T} = \sum_i m_Q^{-3} \times \frac{\mathcal{L}_i}{m_Q^3} \times \mathcal{F}_i \times \left(\frac{\sqrt{s}}{M}\right)^{\beta}$$

$\mathcal{L}_i$ and $\mathcal{F}_i$ are *generic* functions of the variables m_Q, M, p_T/M, y, $\sqrt{s}/M$

No a priori assumption about factorization into $Q\bar{Q}$ creation × bound-state formation

ATLAS and CMS data at $|y| \lesssim 2$ and $p_T/M \gtrsim 2$ tell us that:

the p_T/M dependence is the same, irrespectively of m_Q and M ↓ p_T/M and $\{m_Q, M\}$ do not mix: we can write $\mathcal{L} \times \mathcal{F}$ as $\mathcal{L}(m_Q, M, \sqrt{s}/M) \times \mathcal{F}(p_T/M, y, \sqrt{s}/M)$ ↓ experimental evidence that short- and long-distance effects "factorize"	from charmonium to bottomonium the partonic-level (PDF-undressed) cross section scales like m_Q^{-6}, with no observed dependence on $\sqrt{s}$ ↓ further specification of the "LDME": $\mathcal{L} = \mathcal{L}(M/m_Q)$ independent of m_Q and $\sqrt{s}$

Mass scaling of S-wave cross sections

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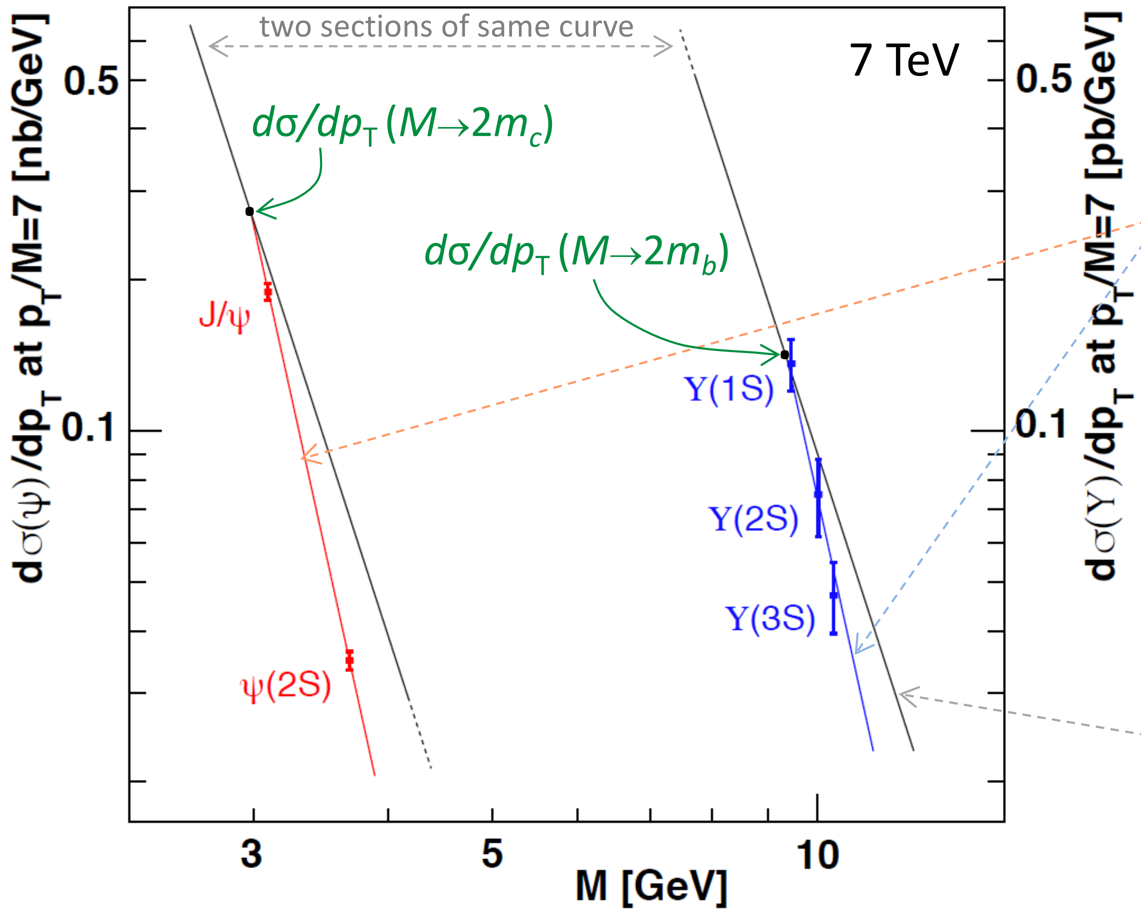
Refined determination of the mass scaling, **using all S states** and adopting the short × long-distance "factorized" point of view :



"within each quarkonium family"

(M/m_Q)-dependent "LDME" :

$$\frac{d\sigma/dp_T\,(M = M_{\psi|\Upsilon})}{d\sigma/dp_T\,(M\to 2m_{c|b})} = \left(\frac{M_{\psi|\Upsilon}}{2m_{c|b}}\right)^{-(9.7\,\pm\,0.3)}$$

one common slope parameter fits well both ψ and Υ states

"from charmonium to bottomonium"

(dependence on m_Q) :

$$\frac{d\sigma/dp_T\,(M\to 2m_b)}{d\sigma/dp_T\,(M\to 2m_c)} = \left(\frac{m_b}{m_c}\right)^{-(6.63\,\pm\,0.08)}$$

Using:
$2m_Q = M_{\eta_c(1S)}\,|\,M_{\eta_b(1S)}$

initial assumption (iteratively improved): f_{DIR} = (50|60|70 ± 10)% for Υ(1|2|3S) inspired by data including LHCb's forward-rapidity χ_b [EPJ C 74, 3092]

Long-distance scaling: a universal pattern?

P. Faccioli et al. EPJC 78 (2018) 118

The $Q\bar{Q} \rightarrow$ bound-state “transition probabilities” (“LDMEs”) show a clear correlation with **binding energy**

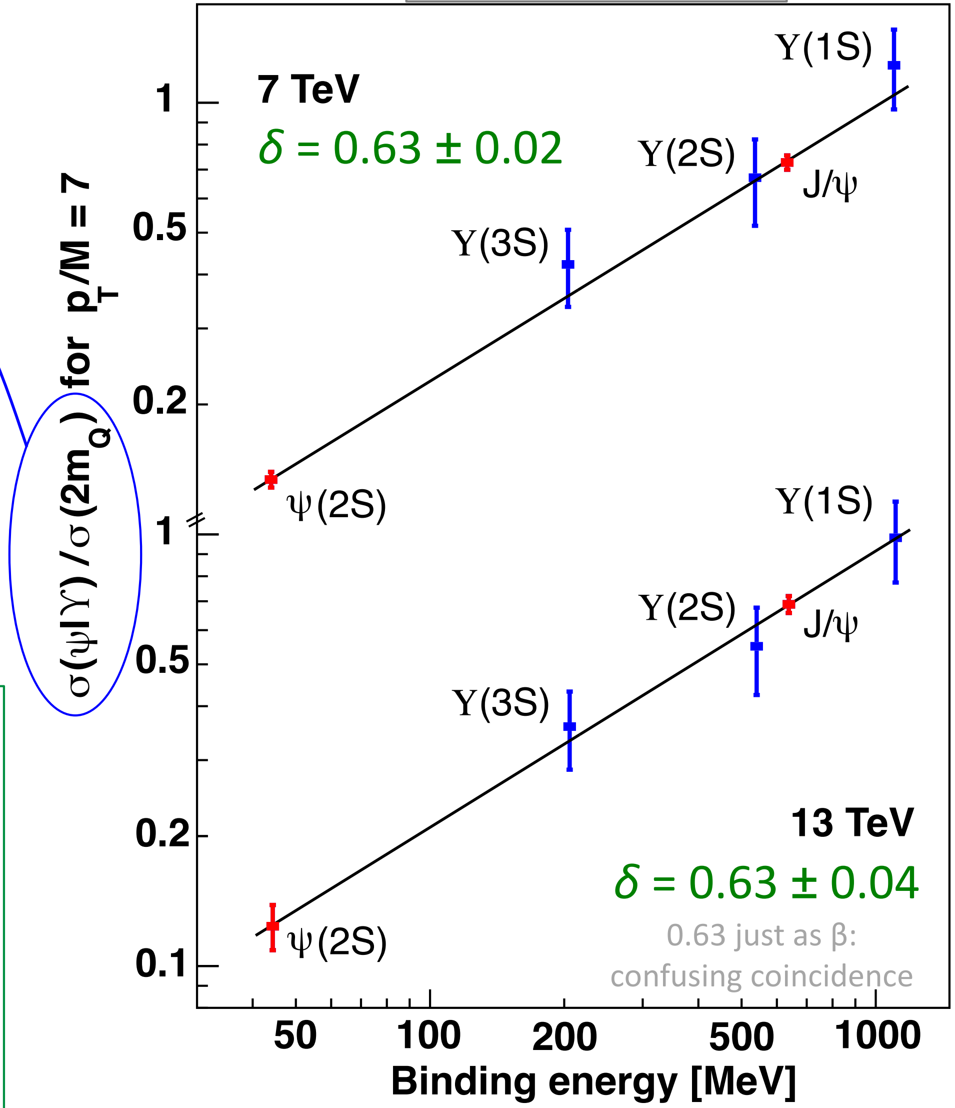
1) common to charmonium and bottomonium
2) identical at 7 and 13 TeV

$$\frac{\sigma_{\psi/\Upsilon}}{\sigma_{Q\bar{Q}}} \propto E_b^{\delta}$$

measured

$$\frac{d\sigma/dp_T\,[\text{quarkonium}]}{d\sigma/dp_T\,[2m_Q]}$$

evaluated by extrapolating $d\sigma/dp_T\,(M)$ to $2m_Q = M_{\eta_c(1S)}$ or $M_{\eta_b(1S)}$



Further experimental evidence that the dependence on bound-state mass is a “*factorizable*” long-distance effect (independent of lab momentum dependence)

→ an experimental validation of the “factorization” ansatz of NRQCD

The “missing pieces” of quarkonium feed-down

P. Faccioli et al.
EPJC 78 (2018) 118

Assuming that the “universal” E_b dependence hypothesis can be extended to the P-wave states

$$\frac{\sigma_{\chi}}{\sigma_{Q\bar{Q}}} \propto E_b^{0.63 \pm 0.02}$$

χ_c data come to constrain the χ_b(1-2-3P) cross sections and, using BFs from PDG, the feed-down structure of quarkonium production can be fully predicted

Feed-down fractions in pp (%):

Jpsi	tot	31.9 +- 1.6
	from chic0	0.762 +- 0.059
	from chic1	15.61 +- 0.99
	from chic2	7.83 +- 0.53
	from psi2S	7.67 +- 0.88
	from Y1S	(5.57 +- 0.69) E-5
	from Y2S	(2.2 +- 2.2) E-5
chic0	tot	2.09 +- 0.26
	from psi2S	2.09 +- 0.26
	from Y1S	(3.4 +- 3.4) E-5
	from Y2S	(1.5 +- 1.5) E-5
chic1	tot	2.61 +- 0.33
	from psi2S	2.61 +- 0.33
	from Y1S	(4.26 +- 0.89) E-5
	from Y2S	(2.10 +- 0.55) E-5
chic2	tot	2.81 +- 0.35
	from psi2S	2.81 +- 0.35
	from Y1S	(7.1 +- 2.) E-5
	from Y2S	(2.48 +- 0.92) E-5
psi2S	tot	(1.36 +- 0.43) E-4
	from Y1S	(1.01 +- 0.22) E-4
	from Y2S	(0.35 +- 0.35) E-4

Y1S	tot	59.0 +- 4.9
	from chib0_1P	1.22 +- 0.29
	from chib1_1P	21.7 +- 3.6
	from chib2_1P	11.5 +- 2.1
	from Y2S	11.3 +- 1.6
	from chib0_2P	0.167 +- 0.082
	from chib1_2P	5.1 +- 1.1
	from chib2_2P	3.40 +- 0.74
	from Y3S	1.51 +- 0.28
	from chib0_3P	0.018 +- 0.016
	from chib1_3P	1.59 +- 0.52
	from chib2_3P	1.35 +- 0.52
chib0_1P	tot	2.67 +- 0.62
	from Y2S	2.58 +- 0.61
	from Y3S	0.099 +- 0.028
chib1_1P	tot	4.8 +- 1.0
	from Y2S	4.7 +- 1.0
	from Y3S	0.033 +- 0.020
chib2_1P	tot	5.3 +- 1.1
	from Y2S	5.0 +- 1.1
	from Y3S	0.372 +- 0.099

Y2S	tot	45.0 +- 5.7
	from chib0_2P	1.42 +- 0.43
	from chib1_2P	19.0 +- 3.8
	from chib2_2P	9.2 +- 2.1
	from Y3S	5.7 +- 1.2
	from chib0_3P	0.15 +- 0.12
	from chib1_3P	5.9 +- 1.7
	from chib2_3P	3.7 +- 1.3
chib0_2P	tot	3.09 +- 0.79
	from Y3S	3.09 +- 0.79
chib1_2P	tot	6.5 +- 1.6
	from Y3S	6.5 +- 1.6
chib2_2P	tot	6.8 +- 1.7
	from Y3S	6.8 +- 1.7
Y3S	tot	25.9 +- 5.5
	from chib0_3P	1.02 +- 0.61
	from chib1_3P	17.0 +- 4.5
	from chib2_3P	7.8 +- 2.4

Summary: 1) NRQCD vs. LHC

Long-lasting experimental and theoretical polarization puzzles have been solved:
NRQCD describes very well the cross section *and* polarization measurements.
However, the presently existing SDCs are not good in the $p_T/M < 3$ domain.

The mid-rapidity charmonium and bottomonium pp data are well described by a simple parametrization reflecting a **universal (*state-independent*) scaling** with two variables:

1. **shapes of the p_T distributions** → p_T/M short distance
2. **cross-section scaling with mass** → E_b long distance

This parametrization mirrors well the general idea of **factorization**

Quarkonium suppression in Pb-Pb collisions

P. Faccioli et al.
Submitted to EPJC

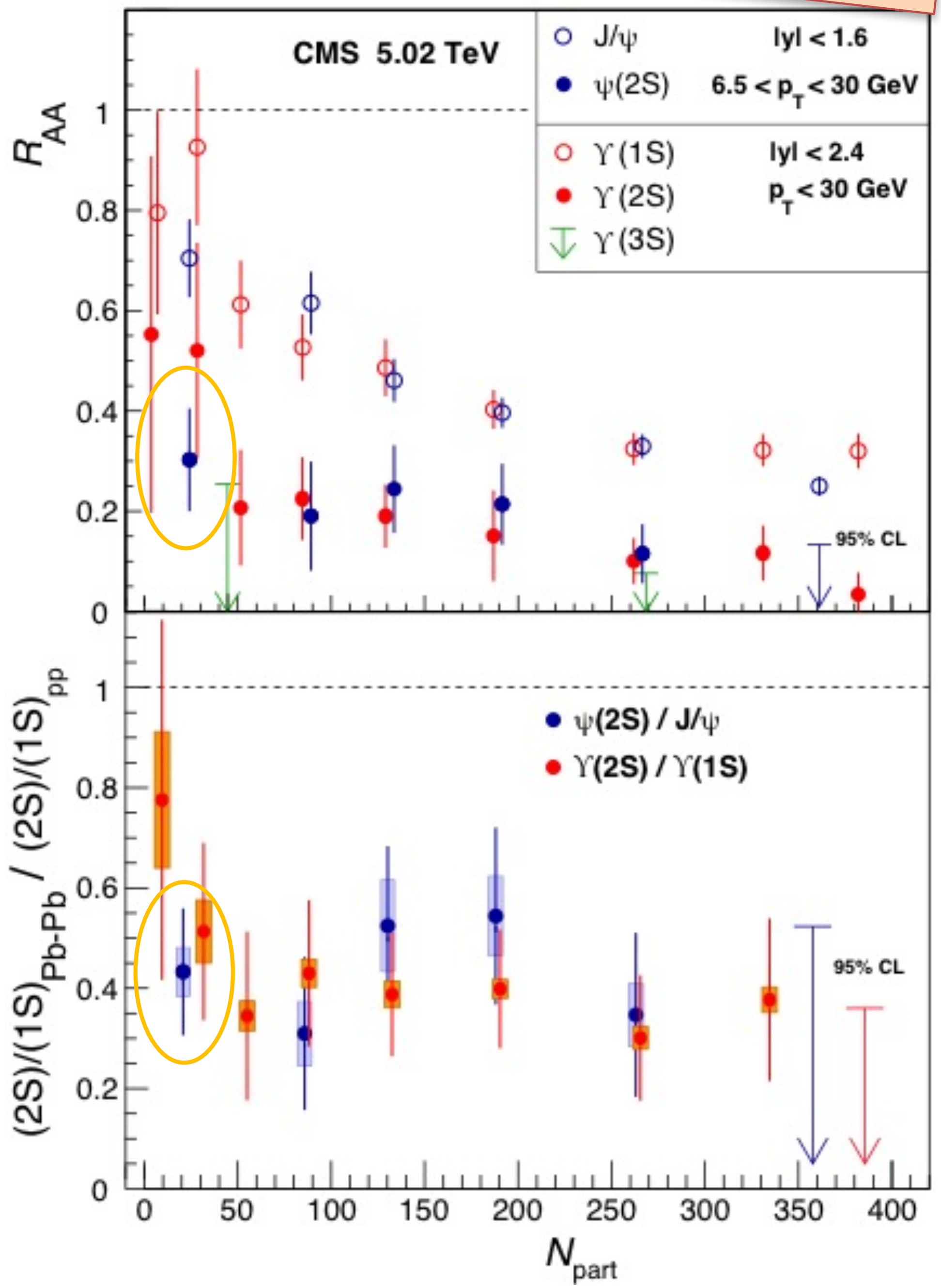
Can we describe the Pb-Pb data assuming a minimal modification of the universal $E_{binding}$-scaling found for pp data ?

Can we find evidence of the conjectured quarkonium sequential suppression ?

The $\psi(2S)$ is strongly suppressed already in the most peripheral events probed by experiments

The $\psi(2S)$ has a very small binding energy

threshold effect in binding energy ?



Quarkonium suppression as a penalty in binding energy

Basic hypothesis: the "universal bound-state transition function" is modified by the hot nuclear medium effects through a penalty in the binding energy

$$f_{\mathrm{pp}}^{\psi/\Upsilon}(E_{\mathrm{b}}) \equiv \left(\frac{\sigma^{\mathrm{dir}}(\psi/\Upsilon)}{\sigma(2m_Q)}\right)_{\mathrm{pp}} = \left(\frac{E_{\mathrm{b}}}{E_0}\right)^{\delta}$$

$$f_{\mathrm{PbPb}}^{\psi/\Upsilon}(E_{\mathrm{b}},\epsilon) \equiv \left(\frac{\sigma^{\mathrm{dir}}(\psi/\Upsilon)}{\sigma(2m_Q)}\right)_{\mathrm{PbPb}} = \left(\frac{E_{\mathrm{b}}-\epsilon}{E_0}\right)^{\delta}$$

where **ε** is assumed to follow a Gaussian distribution, of average <ε> and width σ_{ε}.

With increasing **ε** it becomes less and less probable to *form* the bound state and for E_b – **ε** < 0 the quarkonium state is no longer produced.

The nuclear suppression ratio for *direct* production of the quarkonium state ψ_k is

$$R_{AA}^{\mathrm{dir}}(E_{\mathrm{b}},\langle\epsilon\rangle,\sigma_\epsilon) = F_{\mathrm{PbPb}}^{\psi/\Upsilon}(E_{\mathrm{b}},\langle\epsilon\rangle,\sigma_\epsilon)\ /\ f_{\mathrm{pp}}^{\psi/\Upsilon}(E_{\mathrm{b}})$$

where <ε> and σ_{ε} are *the same for all states.*

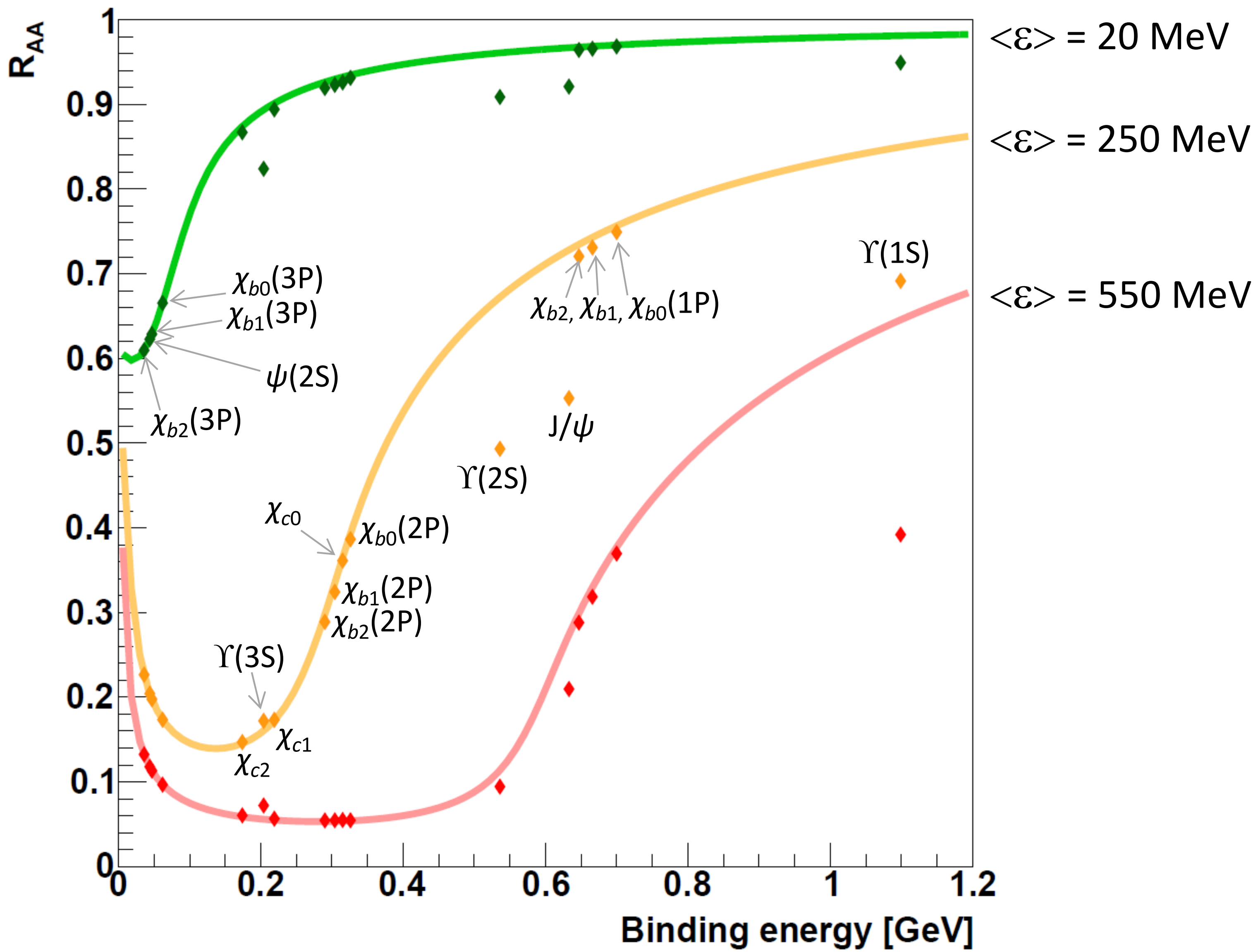
The suppression ratio for *inclusive* quarkonium production depends on the feed-down:

$$R_{AA}^{\mathrm{inc}}(\psi_k,\langle\epsilon\rangle,\sigma_\epsilon) = \frac{\sum_j R_{AA}^{\mathrm{dir}}[E_{\mathrm{b}}(\psi_j),\langle\epsilon\rangle,\sigma_\epsilon]\ \sigma_{\mathrm{pp}}^{\mathrm{dir}}(\psi_j)\ \mathcal{B}(\psi_j\to\psi_k)}{\sum_j \sigma_{\mathrm{pp}}^{\mathrm{dir}}(\psi_j)\ \mathcal{B}(\psi_j\to\psi_k)}$$

Graphical illustrations

Curves: suppression of *direct production*

Points: suppression of *inclusive production*, with feed-down effects specific to each state



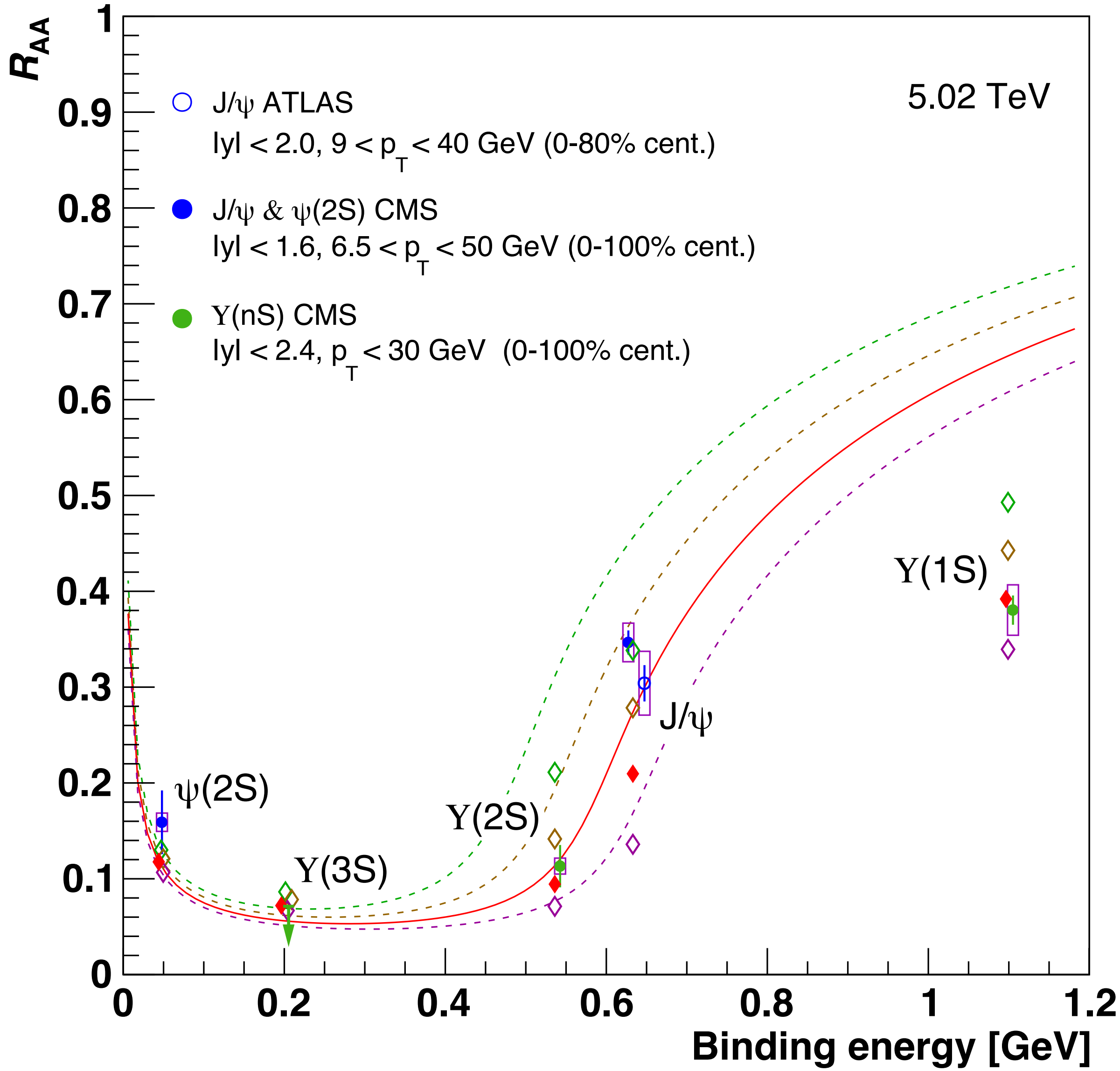
σ_ε = 30 MeV

δ = 0.63 ± 0.04

Qualitative comparison with data integrated over centrality

Curves: suppression of *direct production*

Points: suppression of *inclusive production*, with feed-down effects specific to each state



<ε> [MeV]

450
500
550
600

ATLAS-CONF-2016-109

CMS HIN-16-025
EPJC 78 (2018) 509

CMS HIN-16-023
arXiv:1805.09215

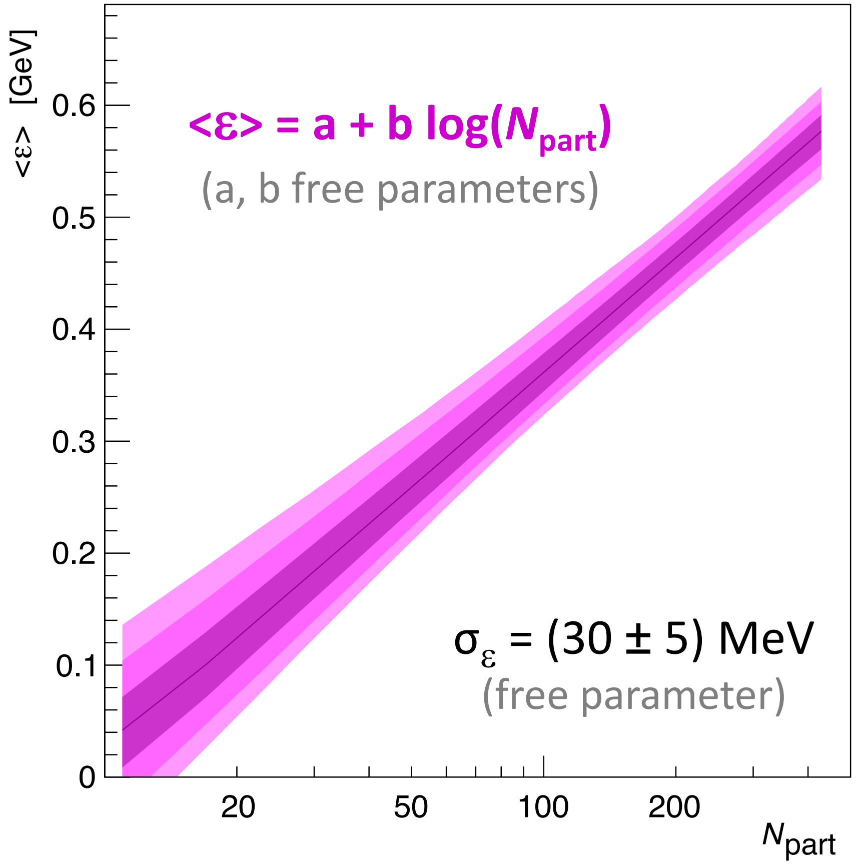
σ_ε = 30 MeV

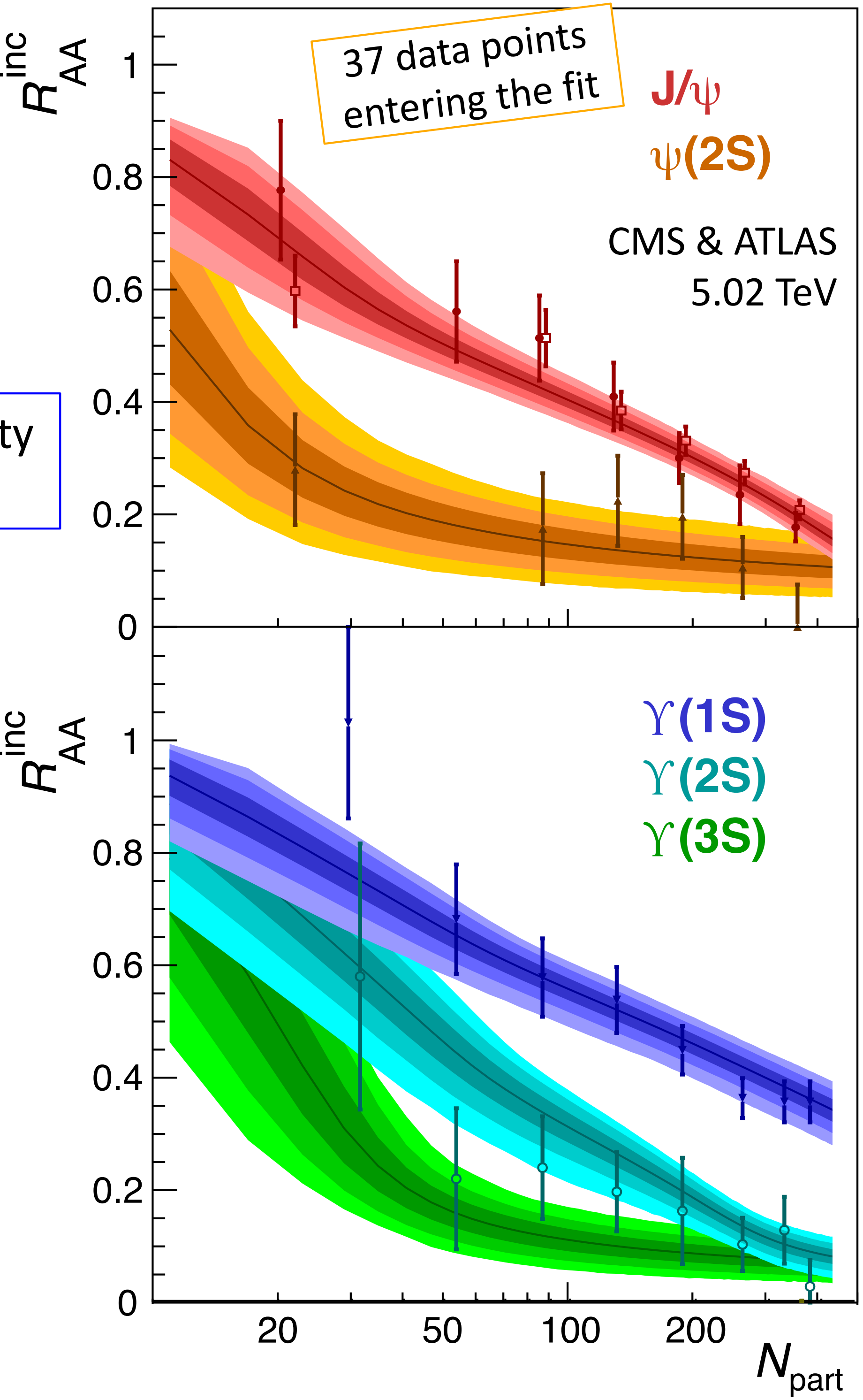
$\delta = 0.63 \pm 0.04$

Global fit of R_{AA} data vs. centrality (Npart)

- 37 data points
- 3 free parameters
- 70 nuisance parameters (BFs, pp cross sections, global uncertainties)

Good fit quality
$P(\chi^2) = 22\%$





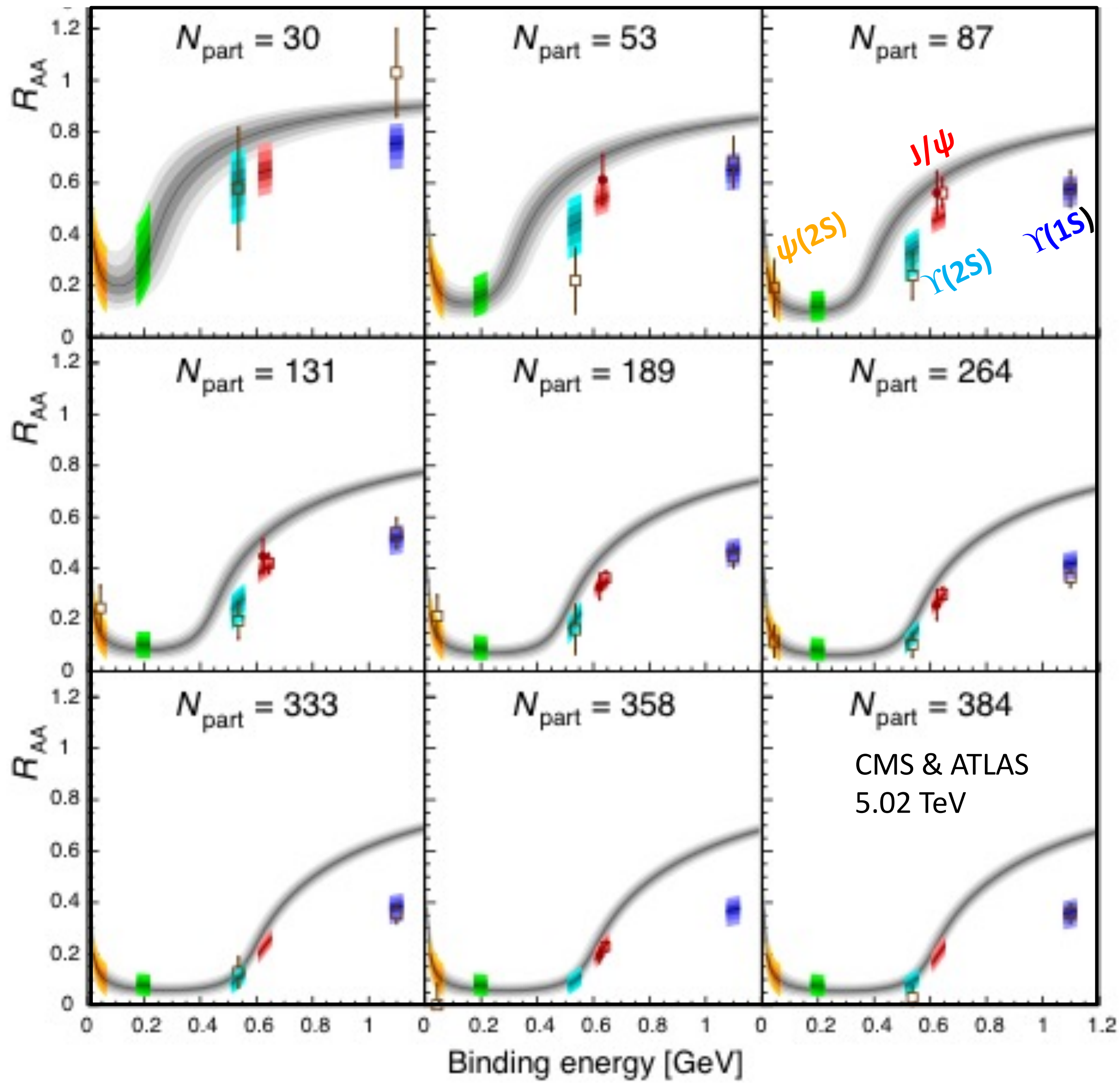
Global fit of R_{AA} data vs. binding energy

Experimental evidence of *sequential nuclear suppression*, increasingly penalizing the more weakly bound states

as foreseen in the case of quark gluon plasma screening

gray: direct production
coloured: inclusive

- ψ(2S)
- ϒ(3S)
- ϒ(2S)
- J/ψ
- ϒ(1S)



Summary: 1) NRQCD vs. LHC ; 2) Pb-Pb vs. pp

Long-lasting experimental and theoretical polarization puzzles have been solved:
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1. **shapes of the p_T distributions** → $\boldsymbol{p_T/M}$ short distance
2. **cross-section scaling with mass** → $\boldsymbol{E_b}$ long distance

This parametrization mirrors well the general idea of **factorization**

Also the Pb-Pb data (for S-wave states) show a surprisingly simple pattern:
R_{AA} can be parametrized assuming a shift of the binding-energy,
equal in magnitude for all charmonia and bottomonia (at least in first approximation)

3. **centrality dependence** → $\boldsymbol{E_b - \varepsilon}$

Further reading

- P. Faccioli, C. Lourenço and J. Seixas,
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  Phys. Rev. Lett. 105, 061601 (2010)

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  New approach to quarkonium polarization studies,
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  Towards the experimental clarification of quarkonium polarization,
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  Questions and prospects in quarkonium polarization measurements from proton-proton to nucleus-nucleus collisions,
  Mod. Phys. Lett. A 27, 1230022 (2012)

- P. Faccioli, V. Knünz, C. Lourenço, J. Seixas and H.K. Wöhri,
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  Phys.Lett. B736 (2014) 98

- P. Faccioli, C. Lourenço, M. Araújo, J. Seixas, I. Krätschmer and V. Knünz,
  Quarkonium production at the LHC: a data-driven analysis of NRQCD's predictions,
  Phys. Lett. B773 (2017) 476

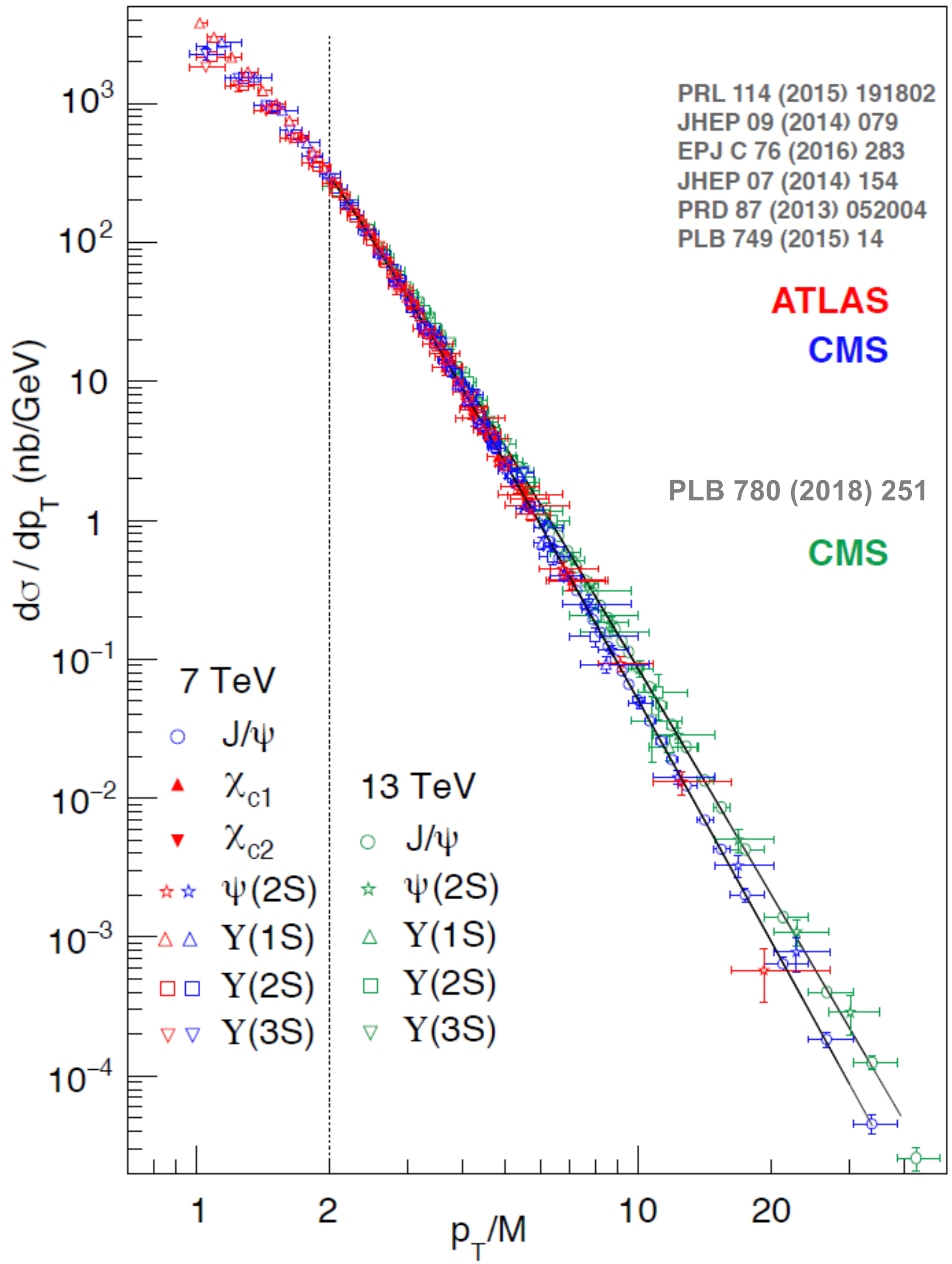
- P. Faccioli, C. Lourenço, M. Araújo, J. Seixas, I. Krätschmer and V. Knünz,
  From identical S- and P-wave p_T spectra to maximally distinct polarizations: probing NRQCD with χ states,
  Eur. Phys. J. C78 (2018) 268

- P. Faccioli, C. Lourenço, M. Araújo and J. Seixas,
  Universal kinematic scaling as a probe of factorized long-distance effects in high-energy quarkonium production,
  Eur. Phys. J. C78 (2018) 118

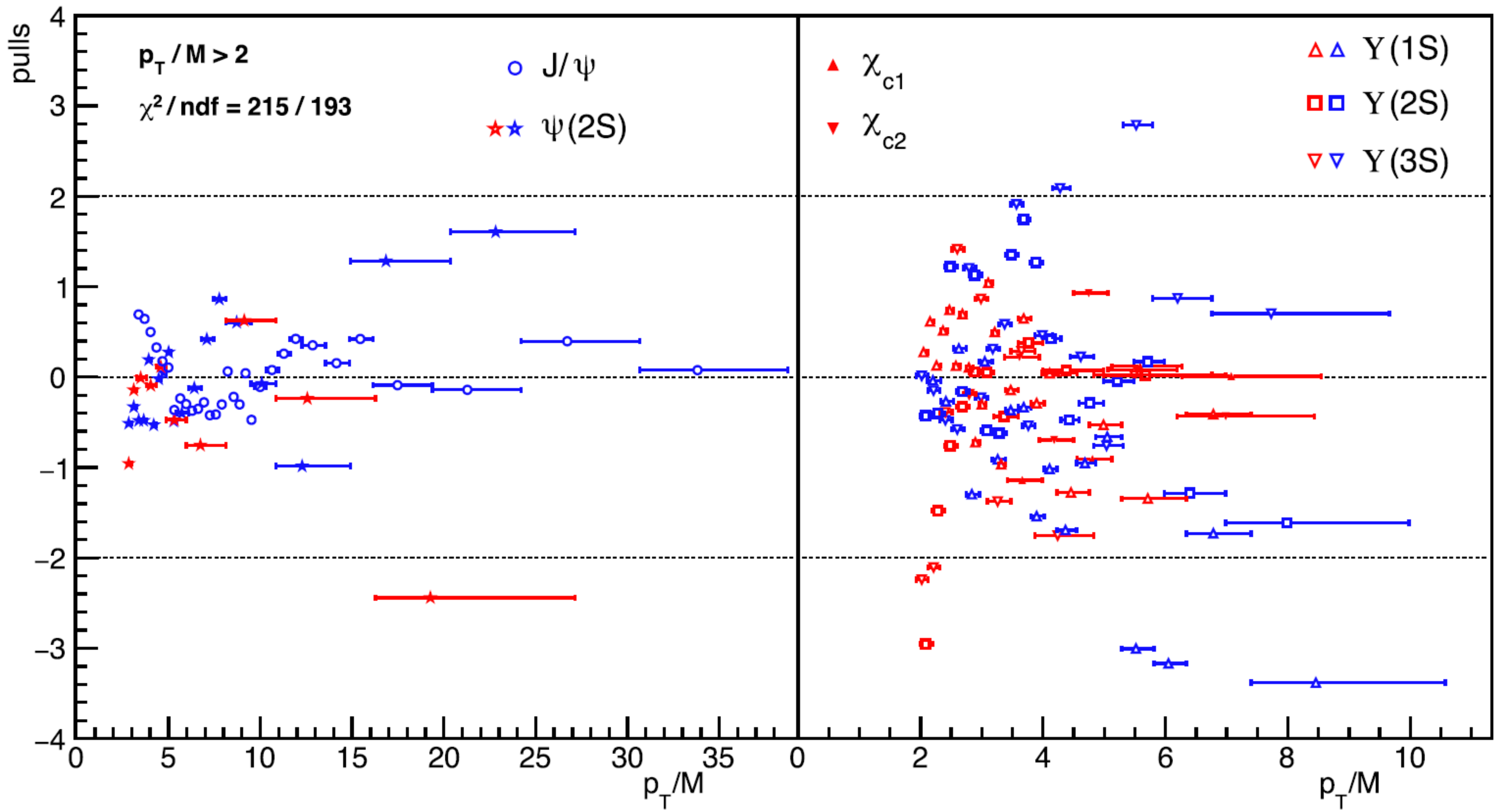
- P. Faccioli and C. Lourenço,
  The fate of quarkonia in heavy-ion collisions at LHC energies: a unified description of the sequential suppression patterns,
  Submitted to EPJC

Backup

Higher energy, broader distribution

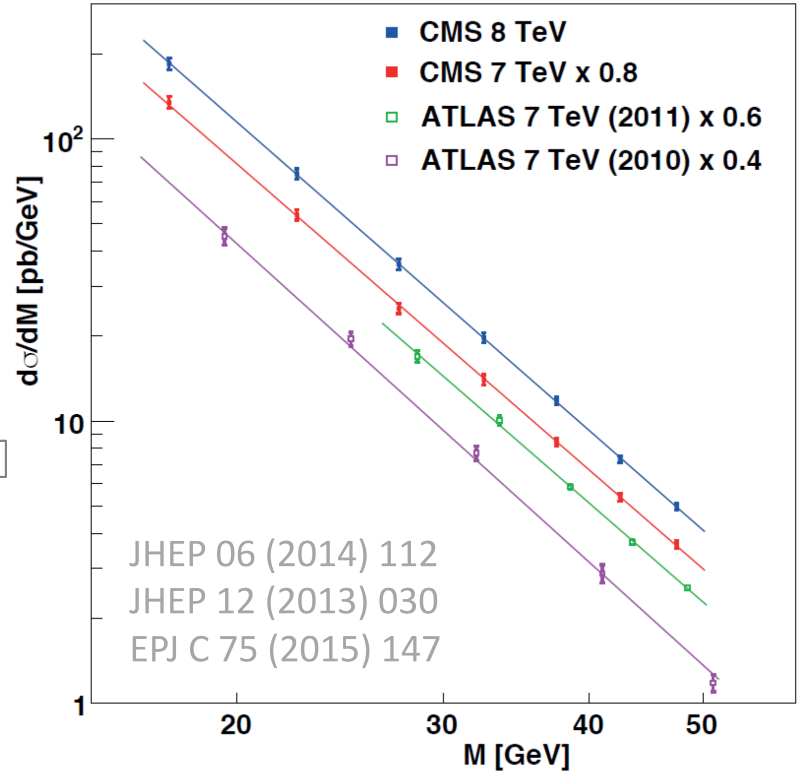


Distribution of pulls (7 TeV fit)



quarkonium, 7 TeV:

$$\frac{d\sigma/dp_T(\Upsilon(1S))}{d\sigma/dp_T(J/\psi)} = \left(\frac{m_b}{m_c}\right)^{-(6.6 \pm 0.1)}$$



Drell-Yan at 7|8 TeV for $M < M_Z$:

$$\frac{d\sigma/dM\,(M_2)}{d\sigma/dM\,(M_1)} = \left(\frac{M_2}{M_1}\right)^{-(3.63 \pm 0.03)}$$

From dimensional analysis:

$$\frac{d\sigma^{DY}}{dM} \propto M^{-3}$$ at partonic level

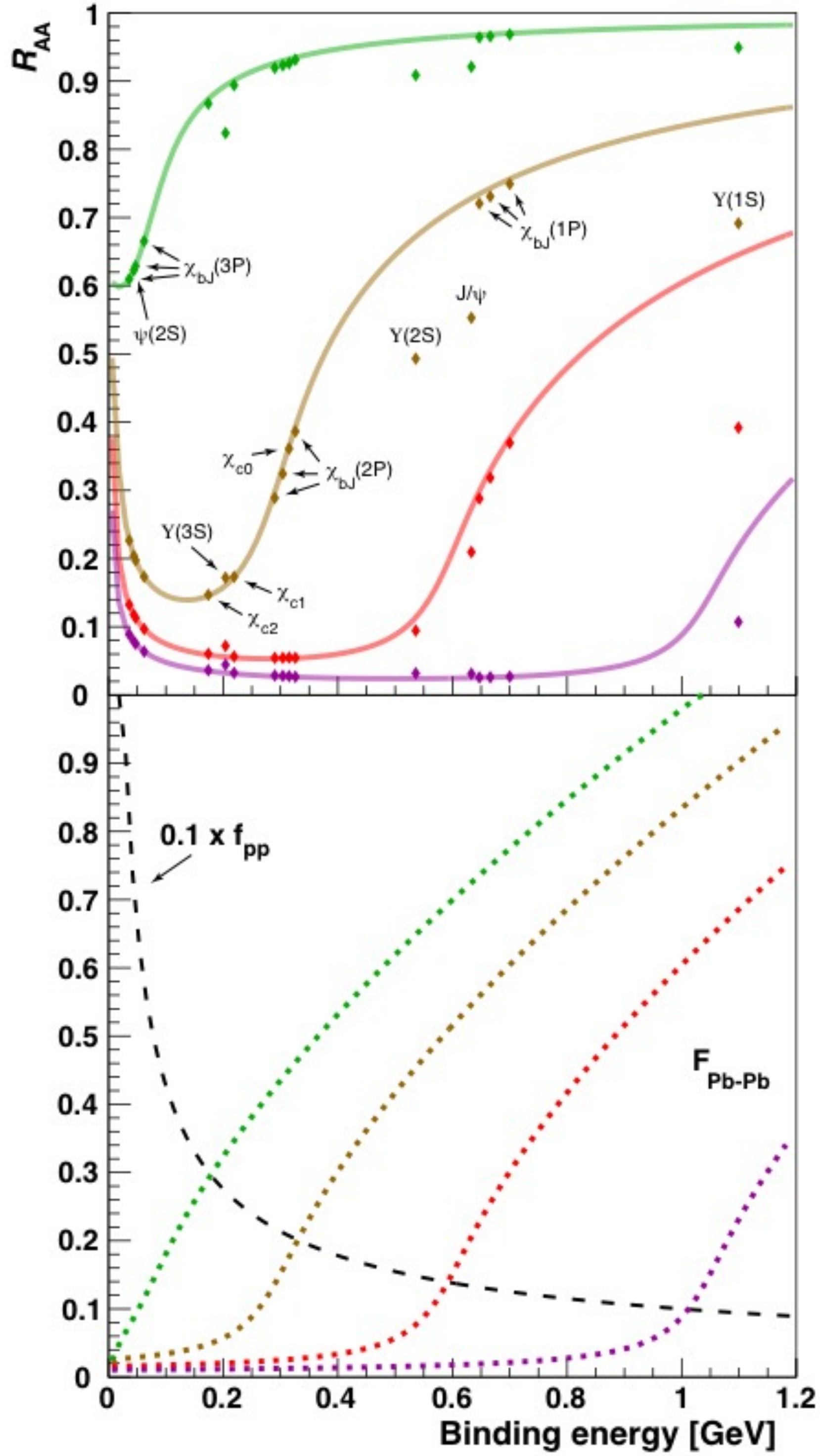
$$\frac{d\sigma^{DY}}{dM} \propto M^{-(3+\beta)}$$ including parton-luminosity factor $\approx(\sqrt{s}/M)^{\beta}$, common to all processes

$\Rightarrow$ **$\beta = 0.63 \pm 0.03$**

$\Rightarrow$ the "PDF-undressed" quarkonium cross section goes like $m_Q^{-(6.0 \pm 0.1)}$

quarkonium: m_Q^{-6} $\Leftrightarrow$ DY: M^{-3}

the difference seems to be just the $[m_Q^{3}]$-dimensional bound-state wave function!



R_{AA}
$\chi_{bJ}(3P)$
$\psi(2S)$
$\chi_{bJ}(1P)$
$\Upsilon(1S)$
J/ψ
$\Upsilon(2S)$
χ_{c0}
$\chi_{bJ}(2P)$
$\Upsilon(3S)$
χ_{c1}
χ_{c2}
$0.1 \times f_{pp}$
$F_{Pb\text{-}Pb}$
Binding energy [GeV]