Quarkonium production and polarization in pp collisions with CMS

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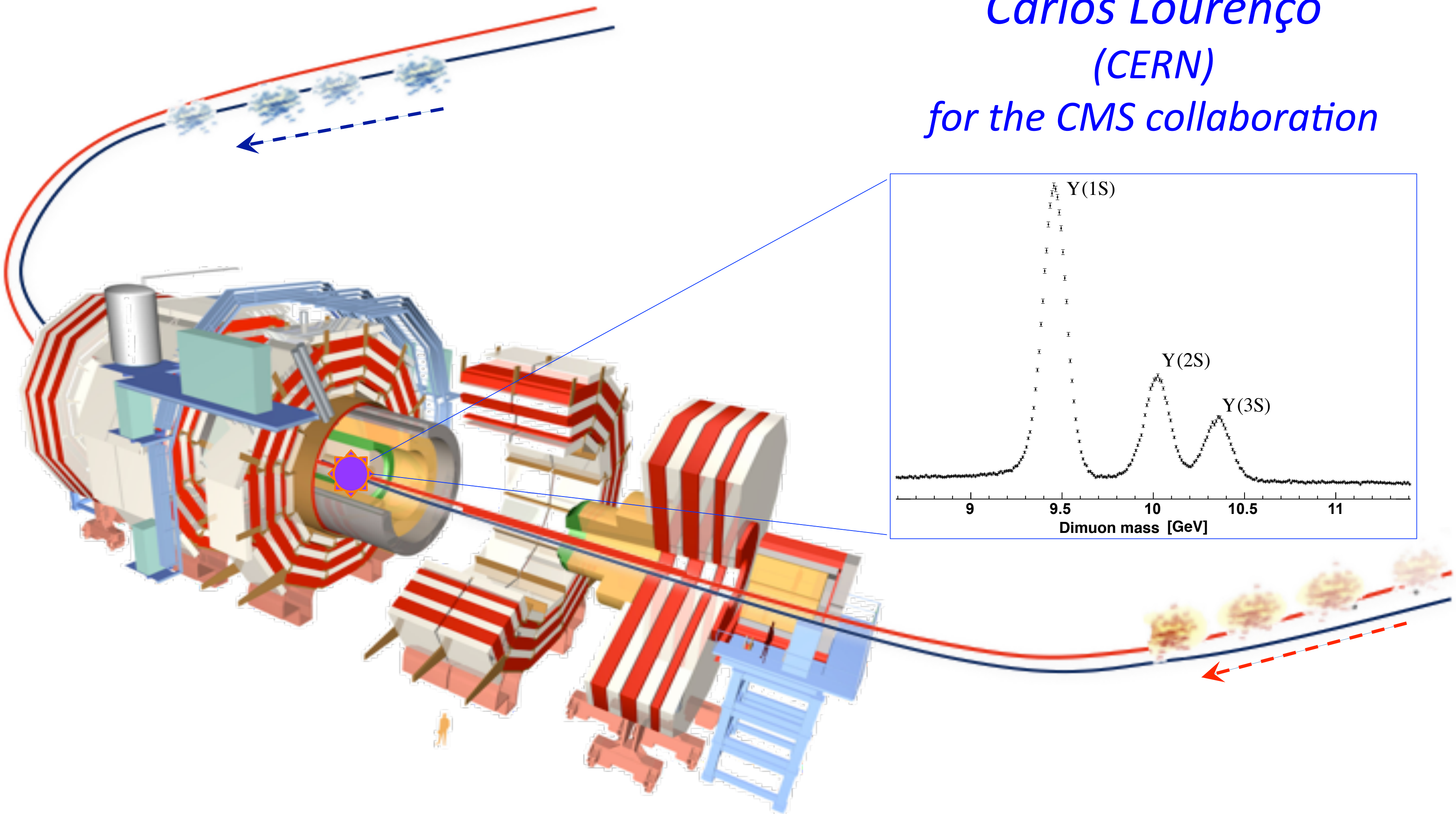
(CERN)
for the CMS collaboration



Seminar at LIP
Lisbon, 20.12.2013

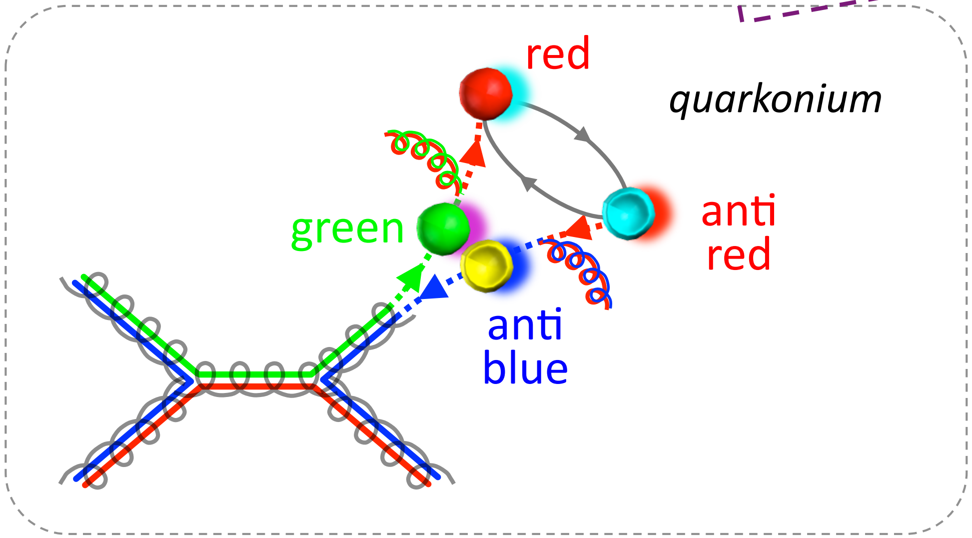
The dark side of the SM

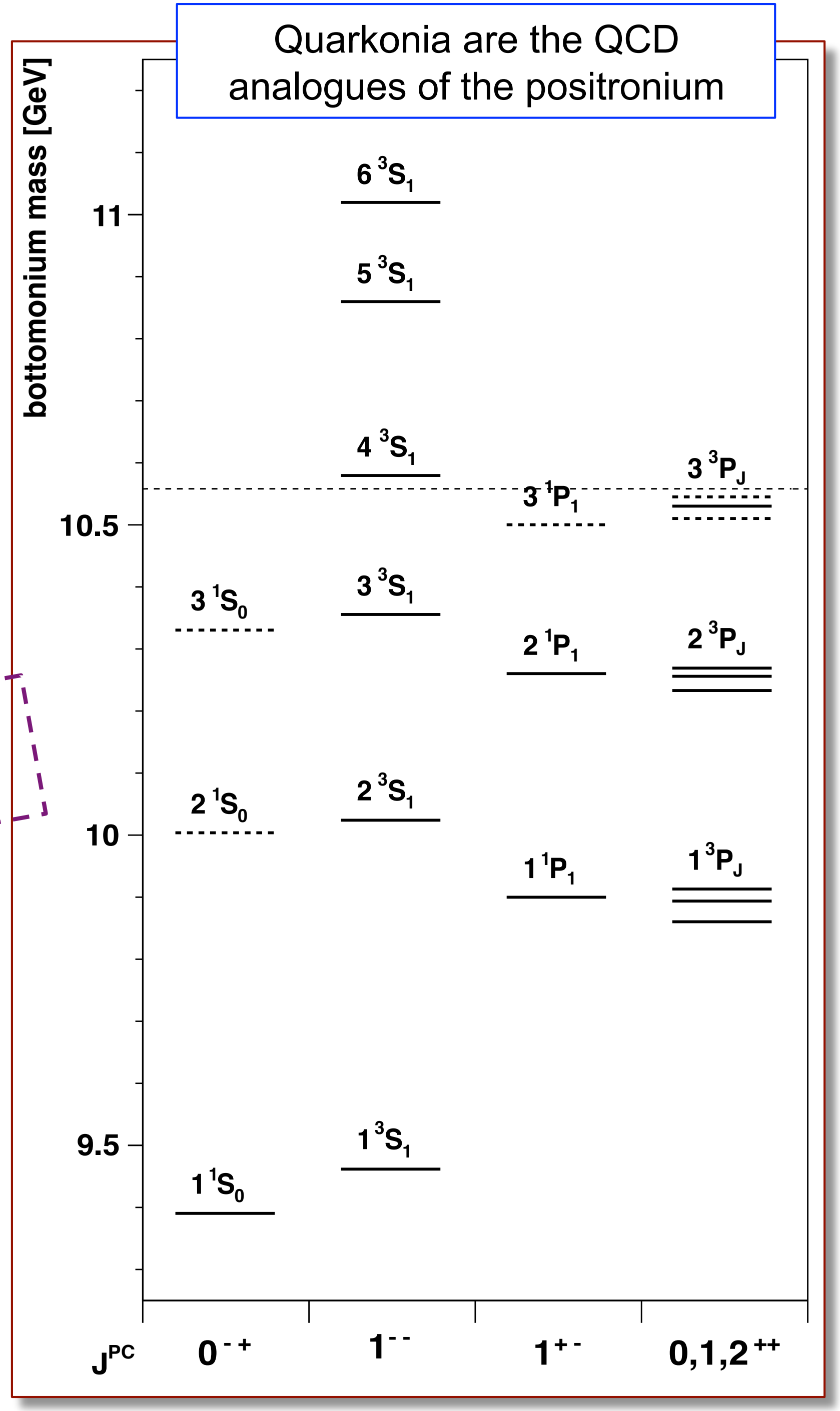
Hadron formation is a mystery within the SM;
"QCD is full of surprises and challenges"
(Joe Lykken, summary talk, LHCP 2013)

Almost all the visible matter in the universe is made of hadrons; the Higgs mechanism deals with only 0.1% of the total mass...

Quarkonium production...
is an ideal probe to study hadron formation but has been plagued with "puzzles"

see 2nd part of this seminar





The quarkonium polarization puzzle in a nutshell

In the early 90's, CDF measured a ψ(2S) cross section 50 times larger than expected in the color singlet model (CSM): "the ψ' anomaly"

In 1995, BBL gave birth to the NRQCD approach, which solved the ψ' anomaly by adding a series of color octet terms; since they had free normalizations, fitted from the data, it is not surprising to see that the data could be reproduced (within the data uncertainties)

The validity of NRQCD was probed by fixing those free parameters and then comparing a resulting prediction to independent measurements; this is where the polarization enters

The outcome is well known: NRQCD predicts transverse polarization, not observed in data

Note: Previous "equally anomalous" J/ψ measurements (by E789 and CDF) were not seen as a fundamental problem: too low p_T (E789) and too much affected by feed-down decays, of unknown fractions: the ψ(2S) was the smoking gun that killed the (LO) CSM

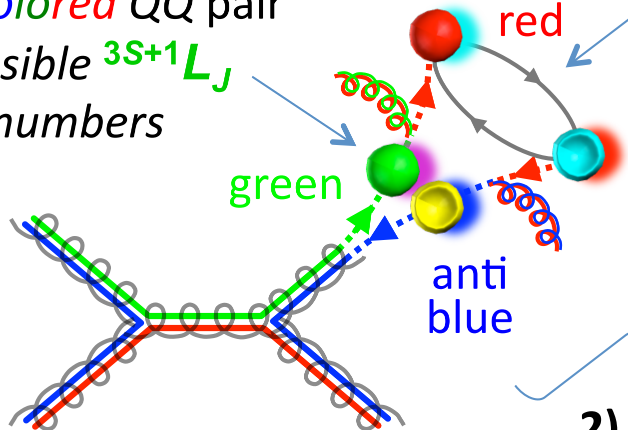
NRQCD factorization: the basic features

The heavy-quark mass provides a natural boundary between short- and long-distance QCD

Quarkonium production can be **factorized** in two distinct phases:

possibly *colored* $Q\bar{Q}$ pair *of any possible* $^{3S+1}L_J$ *quantum numbers*

quarkonium (H)



1) perturbative phase

2) non-perturbative evolution to the observed bound state *Quantum numbers change!*

1) *short-distance coefficients* (SDCs): partonic cross sections (convolved with PDFs)

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

$$\sigma(A + B \to \boldsymbol{H} + X) = \sum_{S,\,L,\,C} \sigma\{A + B \to (Q\bar{Q})_C[^{3S+1}L_J] + X\} \cdot \mathcal{P}\{(Q\bar{Q})_C[^{3S+1}L_J] \to \boldsymbol{H}\}$$

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

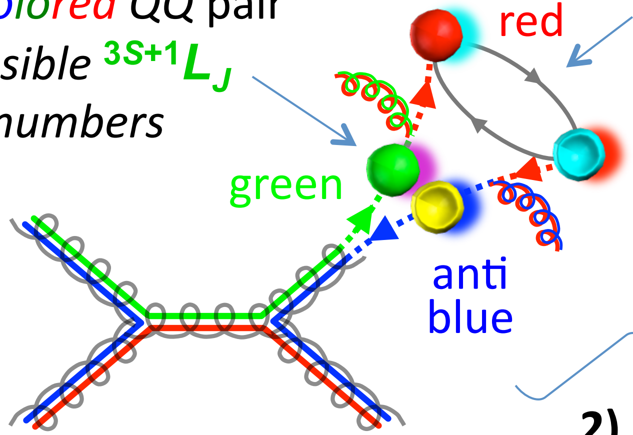
NRQCD factorization: the basic features (cont.)

The heavy-quark mass provides a natural boundary between short- and long-distance QCD

Quarkonium production can be **factorized** in two distinct phases:

possibly *colored* $Q\bar{Q}$ pair
of any possible $^{3S+1}L_J$
quantum numbers

quarkonium (*H*)



1) perturbative phase

2) non-perturbative evolution
to the observed bound state
Quantum numbers change!

1) *short-distance coefficients* (SDCs):
partonic cross sections (convolved with PDFs)

- **functions of kinematics**: p_T, y, etc
- **not universal**:
  - different in pp, e^+e^-, etc.
- calculated in pQCD, depend on α_S order; might change shapes from LO to NLO

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

- **constant**: independent of kinematics
- **universal**:
  - the same in pp, e^+e^-, etc.
  - insensitive to the "rest" of the event
- determined from fitting **data**
  → testable by over-constraining theory

The LDMEs and the v scaling

The LDMEs $\mathcal{P}\{(Q\bar{Q})_c\,[^{3S+1}L_J] \rightarrow H\}$ depend on the relative velocity v of the quark pair in the bound state, according to definite scaling rules (proportional to powers of v^2):

S-wave H : J/ψ, ψ', Υ $[^3S_1\,,\,1^{--}]$							
$^{3S+1}L_J \rightarrow$	$^1S_0$	$^3S_1$	$^1P_1$	^3P_J	^3D_J	$^1D_2$	...
Colour Singlet		1					
Colour Octet	v^4	v^4	~~v^8~~	v^4	~~v^8~~	~~v^{12}~~	~~...~~

P-wave H : $\chi_{cJ}\,,\,\chi_{bJ}$ $[^3P_J\,,\,J^{++}]$ (J = 0,1,2)							
$^{3S+1}L_J \rightarrow$	$^1S_0$	$^3S_1$	$^1P_1$	^3P_J	^3D_J	$^1D_2$	...
Colour Singlet				v^2			
Colour Octet	~~v^6~~	v^2	~~v^6~~	~~v^6~~	~~v^6~~	~~v^{10}~~	~~...~~

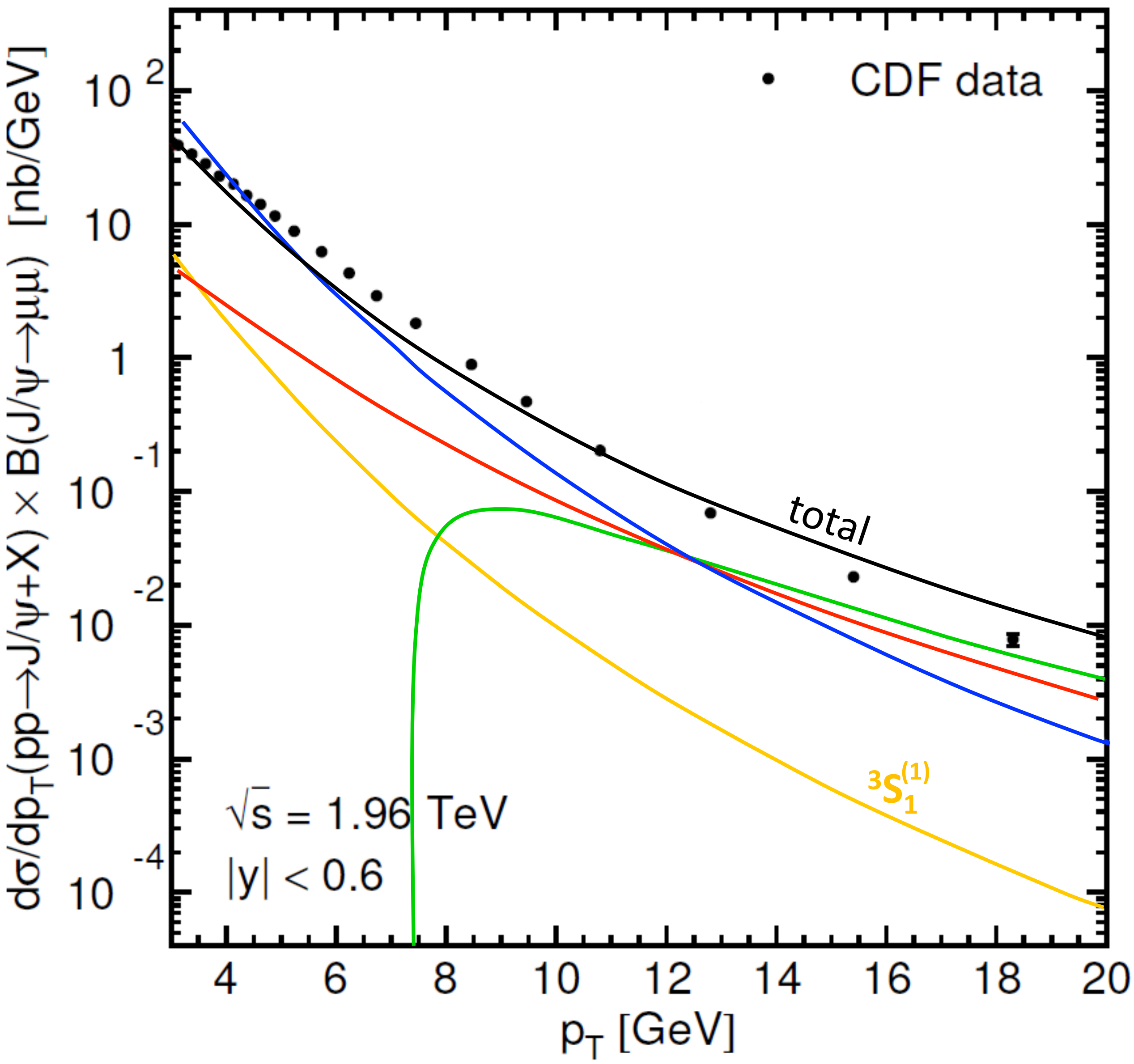
v^2 tends to be small (**non-relativistic**): $\begin{cases} \psi : \; v^2 \sim 1/3 \\ \Upsilon : \; v^2 \sim 1/10 \end{cases}$ $\Leftarrow$ $M(1P) - M(1S) \;<\; m_Q v^2 \;<\; M(2S) - M(1S)$

$\Rightarrow$ Many LDMEs can be neglected:

$\rightarrow$ fewer free parameters, determinable in well-constrained fits

NRQCD in action: a pedagogical example

The J/ψ cross section is fitted adding the (free) $^1S_0$, $^3S_1$, ^3P_J octets to the (fixed) $^3S_1$ singlet



Curves:
SDC functions at NLO by
M. Butenschön and B. Kniehl

Note:
the fit starts at p_T = 3 GeV

The $^3S_1$ and ^3P_J octet terms dominate at high p_T

What does this imply for the polarization ?

NRQCD in action: the polarization dimension

Quarkonium polarization is characterized by λ_θ, experimentally measured as the polar anisotropy of the decay dilepton angular distribution, usually in the helicity frame

The theoretical λ_θ is calculated from the transverse and longitudinal cross sections $\dfrac{\sigma_T - \sigma_L}{\sigma_T + \sigma_L}$

Each color singlet and octet term has a specific polarization associated

The $^3S_1$ singlet changes from λ_θ = +1 at LO to λ_θ = -1 at NLO (but has a relatively small impact)

The important octet terms for S-wave quarkonia are:

$^1S_0$ →	$\lambda_\vartheta = 0$	at LO, NLO, etc; isotropic wave function
$^3S_1$ →	$\lambda_\vartheta = +1$	at LO, NLO, etc, at high p_T, where the fragmenting gluon is real
^3P_J →	$\lambda_\vartheta >> +1$	at NLO, while at LO it is 0...

Dominance of the $^3S_1$ and ^3P_J octet terms → $\lambda_\vartheta \approx +1$, for high-$p_T$ S-wave quarkonia

Note: in theory, the sub-processes are not physically observable on their own, only inclusively; some calculations even give *negative* cross sections... and $\lambda_\vartheta > +1$

NRQCD vs. pre-LHC data

The NRQCD "global fits"
fit the LDMEs from p_T-differential cross sections
and then predict the quarkonium polarizations

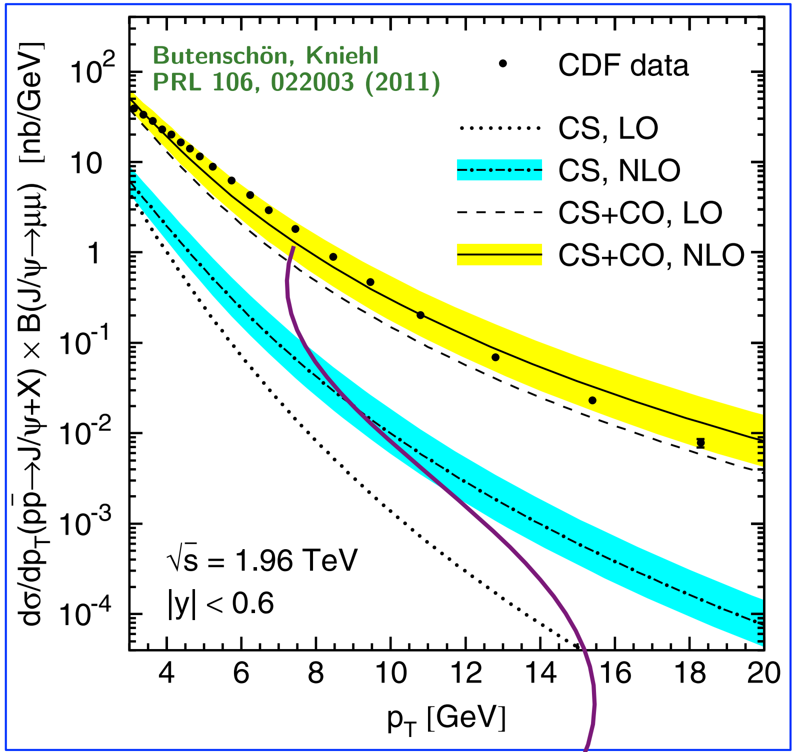
The CDF J/ψ polarization measurements
disagree with the NRQCD prediction: puzzle !

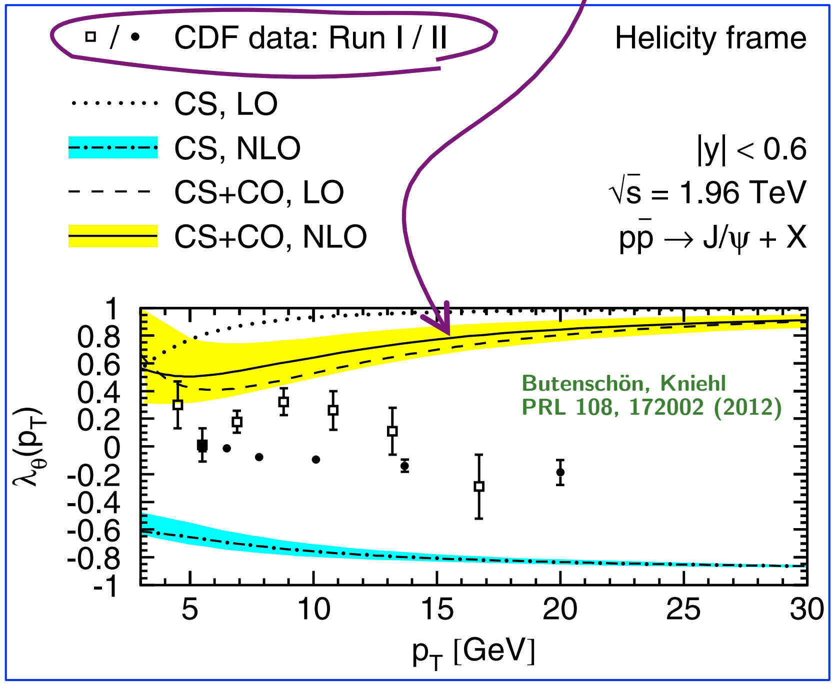
But the Run 1 and 2 results are inconsistent
(as are the CDF and D0 Υ(1S) polarizations)

Besides, feed-down effects blur the J/ψ picture
(and the CDF ψ(2S) result has poor statistics)

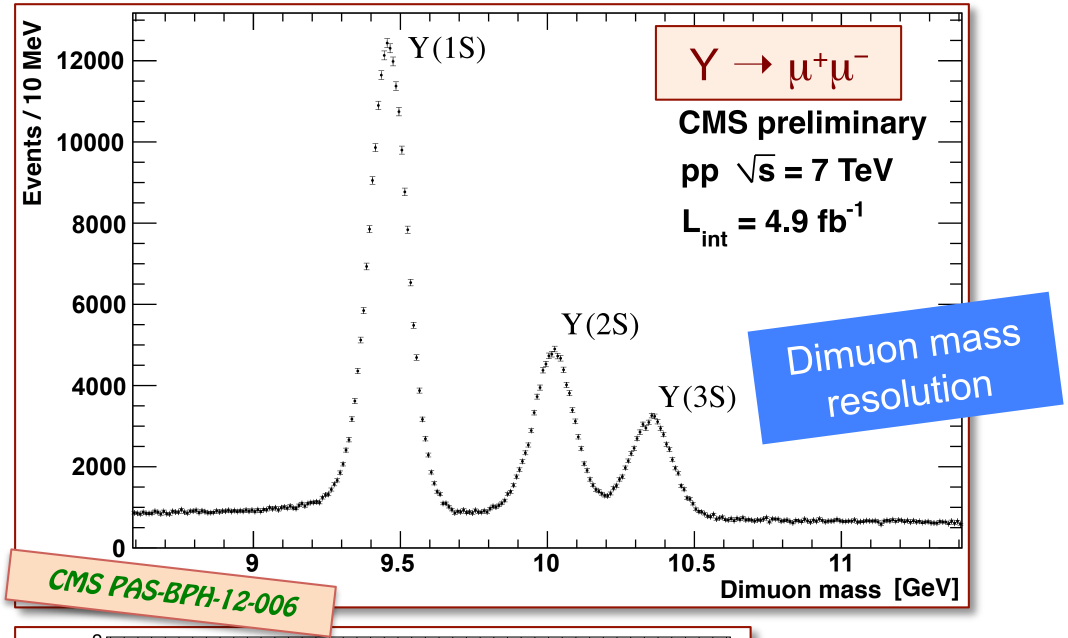
⟶ Not seen as clear-cut evidence
of a fundamental problem…

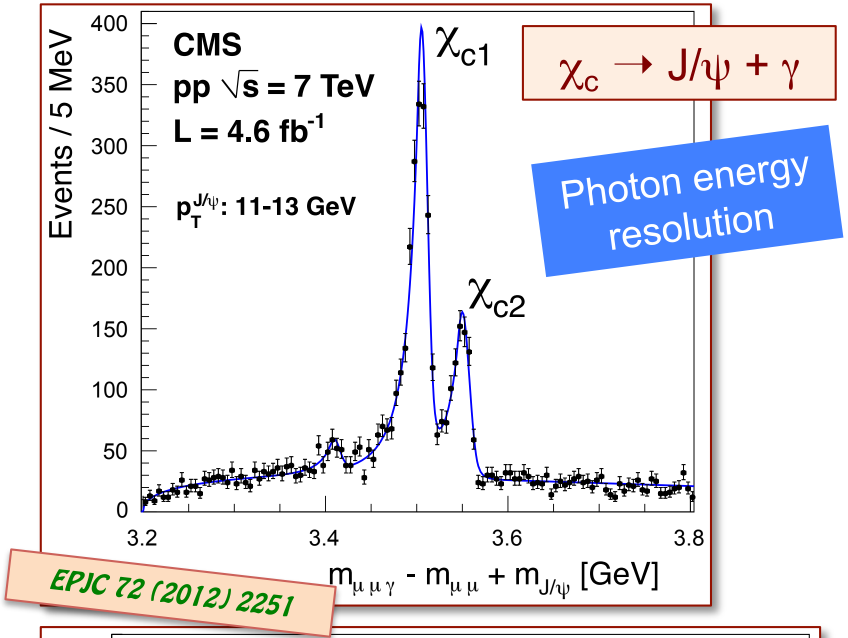
⟶ The LHC cross sections and polarizations
can provide significant improvements:
more reliable analysis methods
and higher p_T reach

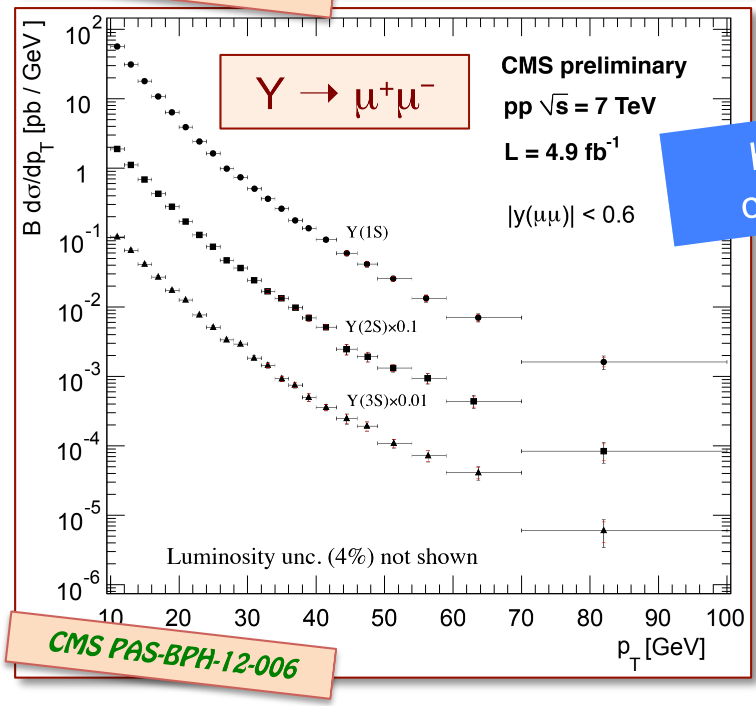




CMS: excellent performance for quarkonium studies







High-p_T coverage

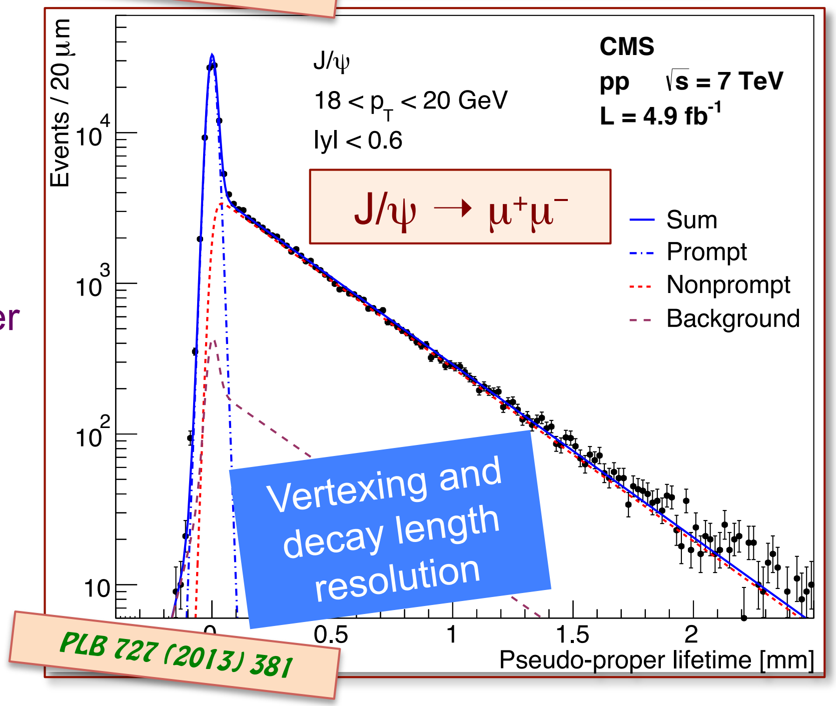
Huge silicon tracker

Very strong field

Broad acceptance

Flexible trigger

Powerful DAQ

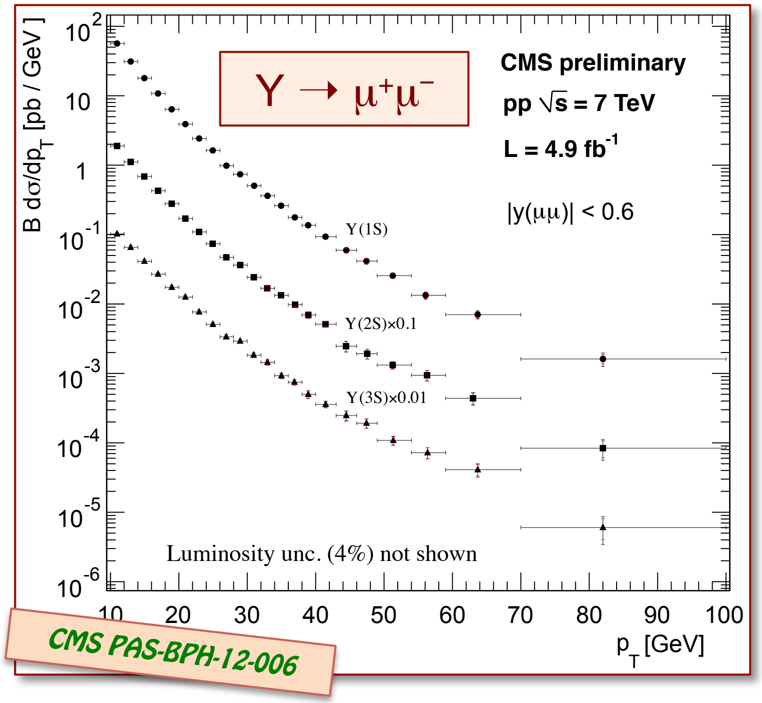


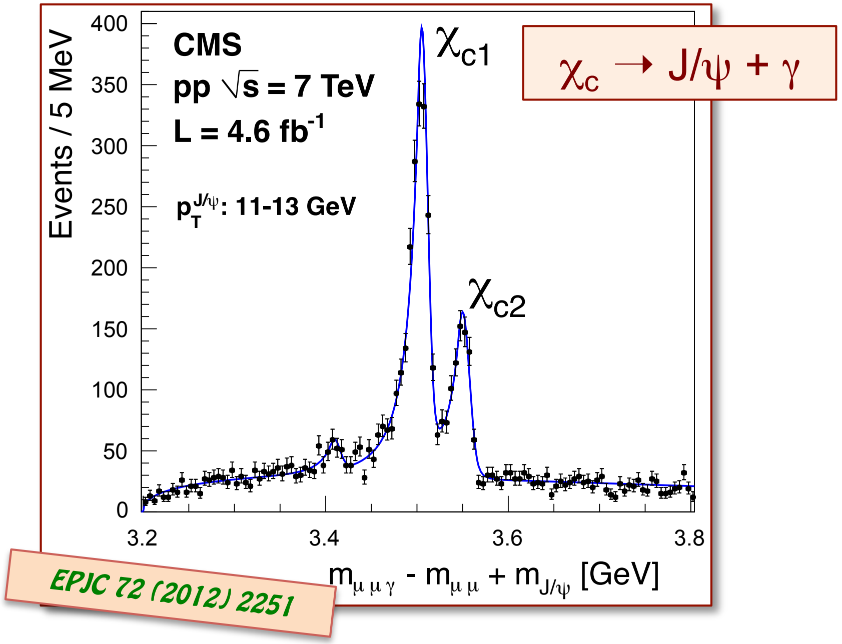
S-wave cross sections and P-wave ratios

The Υ(nS) differential cross sections were measured in the p_T range 10–100 GeV (!)

Acceptance corrections use the measured polarizations, reducing the biggest uncertainty of previous measurements

The three S states show similar patterns; P-wave feed-down contribution does not seem to significantly affect the p_T trends





The photons emitted in χ decays have ≈1% probability to convert and be reconstructed in the silicon tracker

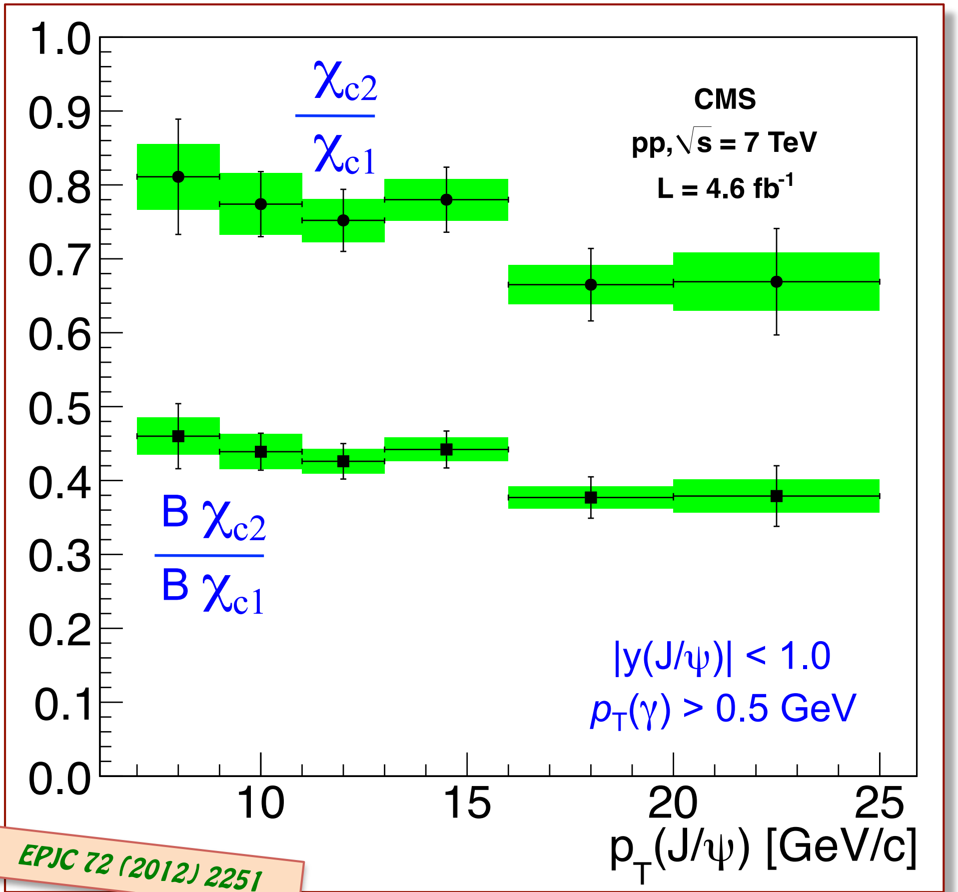
The e^+e^- tracking provides ≈5 MeV mass resolution, crucial to resolve the two states

Efficiencies cancel almost completely in the χ_{c2} / χ_{c1} cross-section ratio

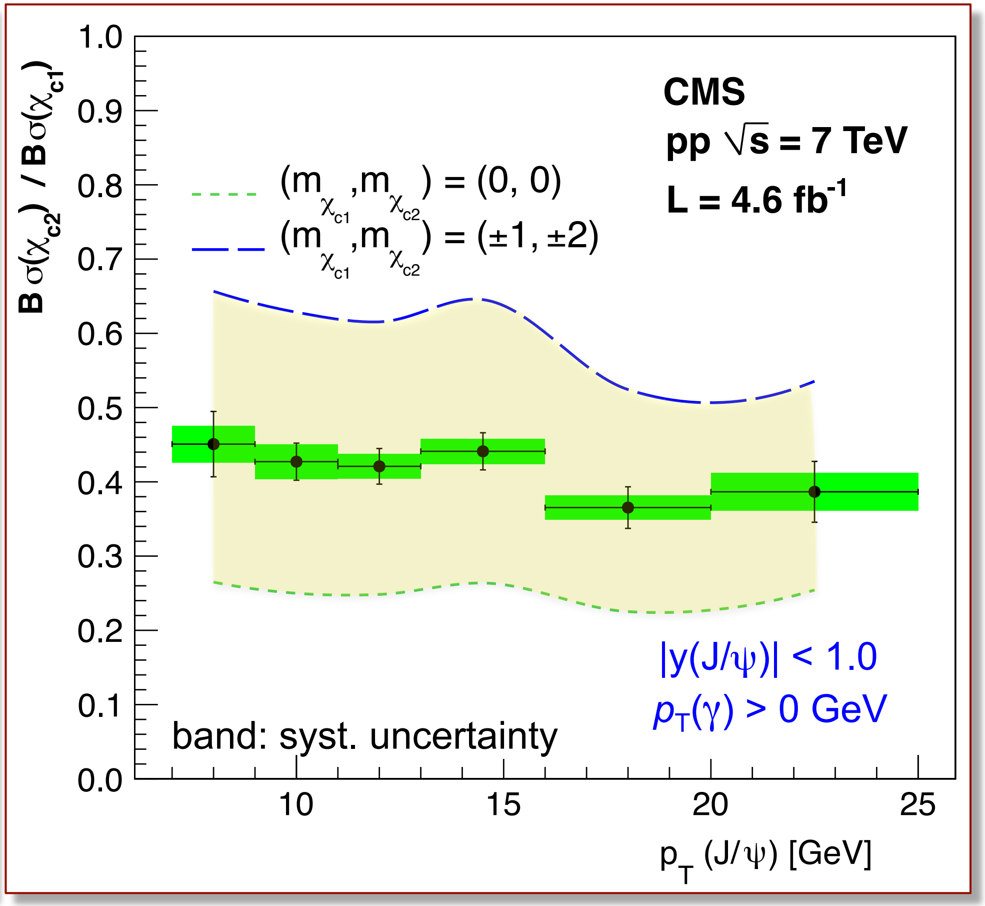
Results on P-wave charmonia

The χ_{c2} / χ_{c1} cross-section ratio was measured up to much higher p_T and with smaller errors than previous measurements; systematic errors are dominated by fit to mass distribution

To compare with theory calculations:
- the photon p_T distribution was extrapolated down to 0 GeV
- care is needed regarding assumed polarizations, that can significantly change the result



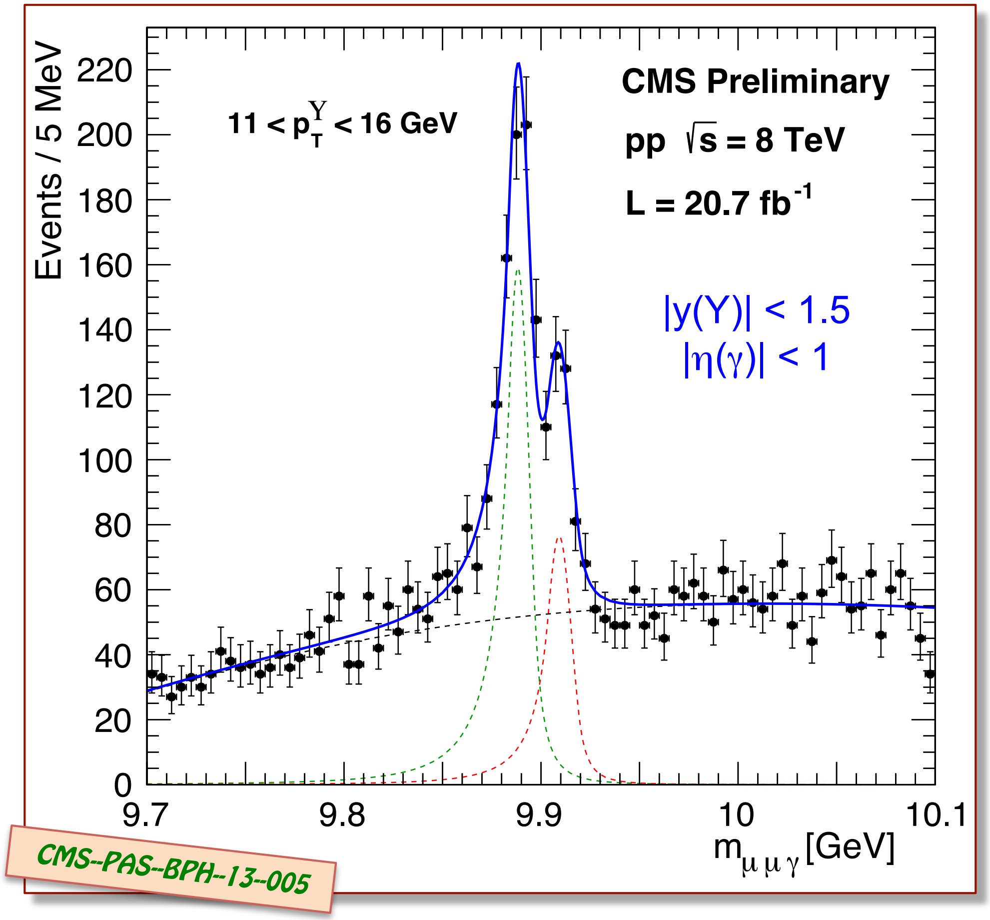
EPJC 72 (2012) 2251

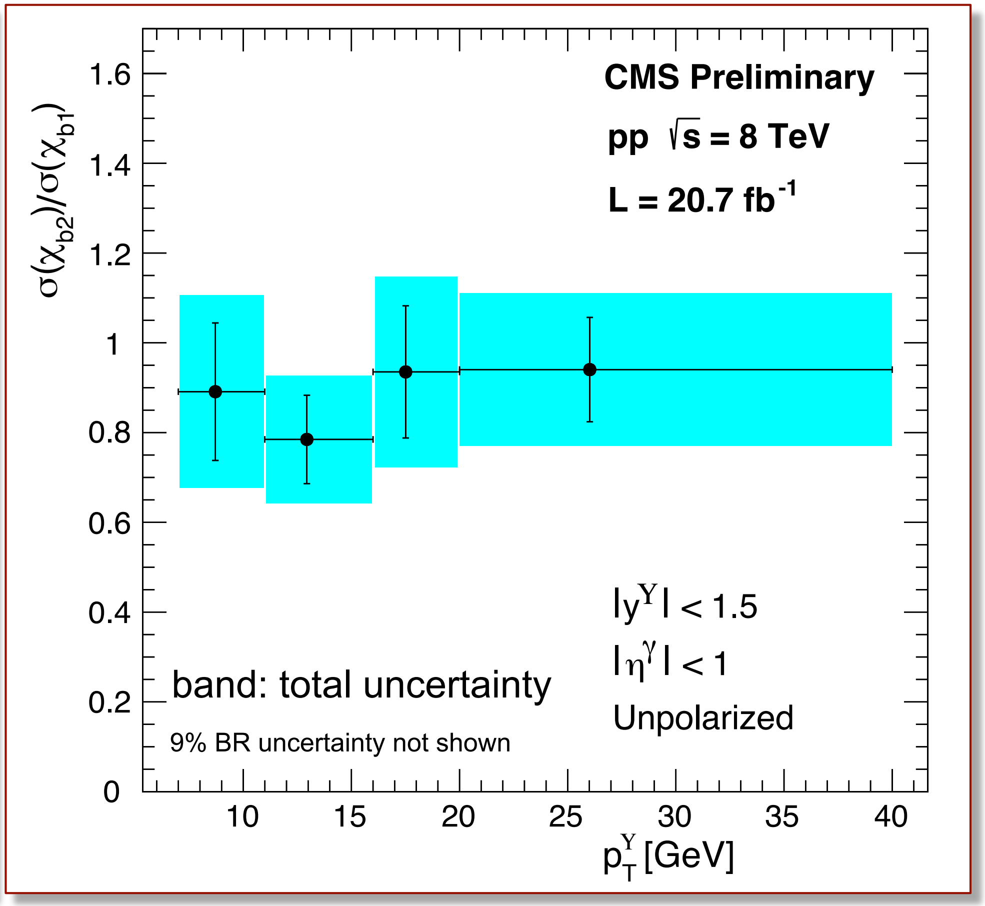


Results on P-wave bottomonia

The χ_{b2}(1P) / χ_{b1}(1P) cross-section ratio was measured for the first time in a hadron collider
Systematic uncertainties are dominated by fit to mass distribution
Mass resolution of 5 MeV resolves the two peaks, separated by only 19 MeV

Cross-section ratio seems to be rather flat with p_T





Quarkonium polarization analyses

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

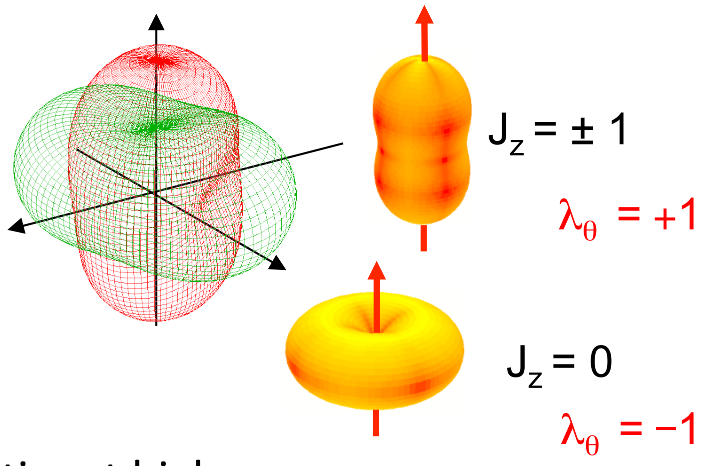
Quarkonium polarizations are measured from the angular decay distributions in dimuon decays

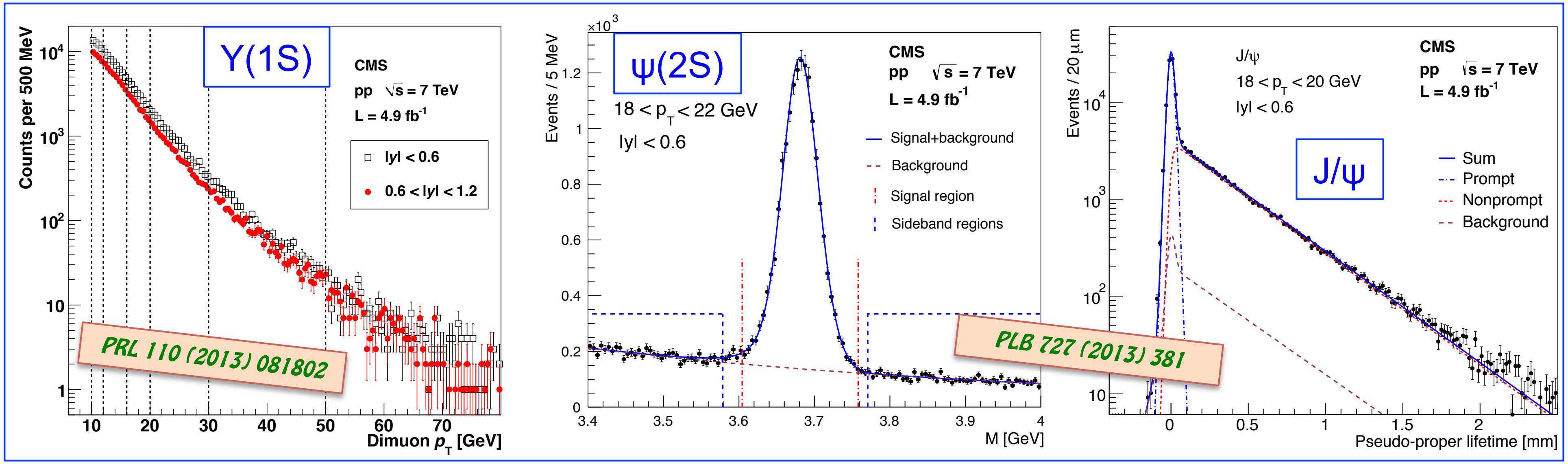
We measure the full angular distribution and report the λ_θ, λ_ϕ and $\lambda_{\theta\phi}$ polarization parameters (in 3 frames)

Continuum Bg removed using invariant mass distribution; and the non-prompt charmonia using the decay length

Challenges: precise mapping of (di)muon efficiencies (T&P) and reliable background modeling (sidebands)

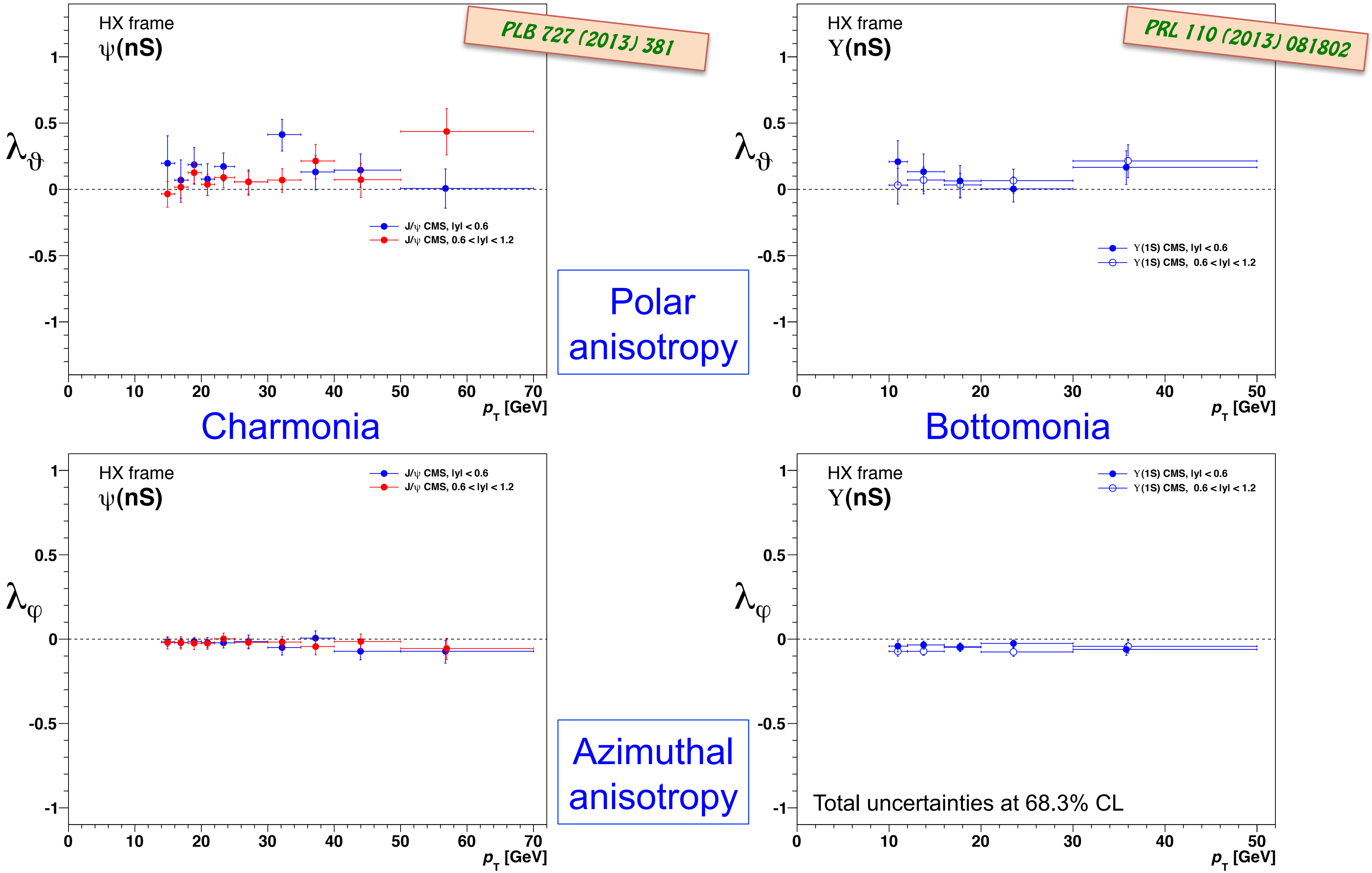
Uncertainties dominated by systematics at low p_T and statistics at high p_T





Quarkonium polarization results

No strong anisotropies seen in any of the measurements



Quarkonium polarization results

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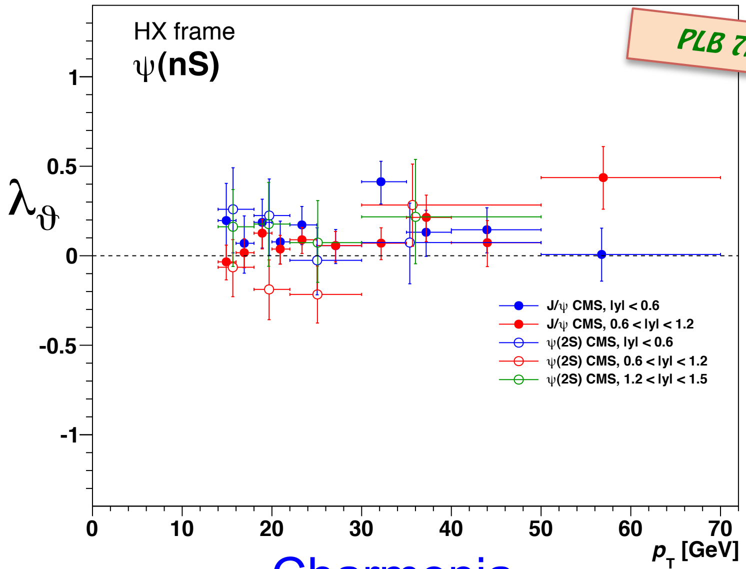
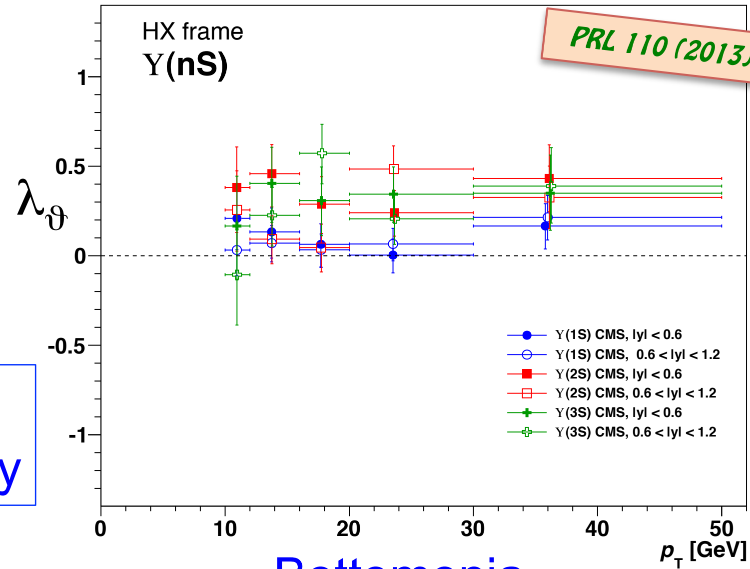
PLB 727 (2013) 381



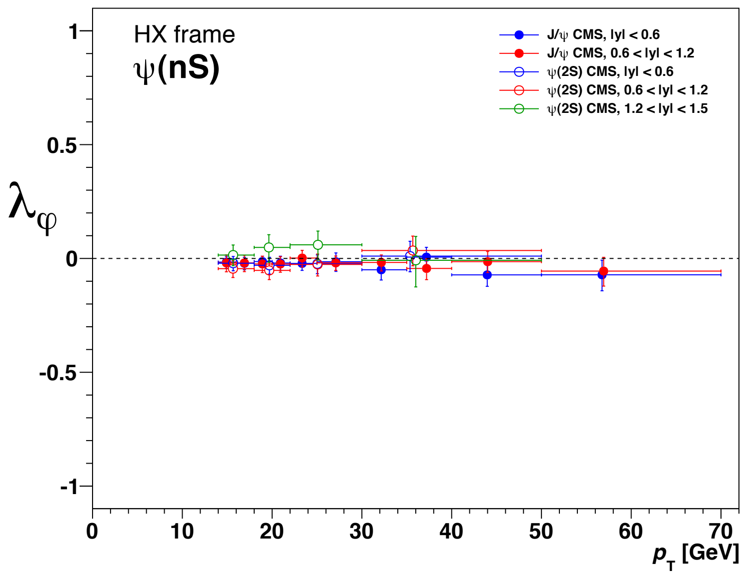
PRL 110 (2013) 081802



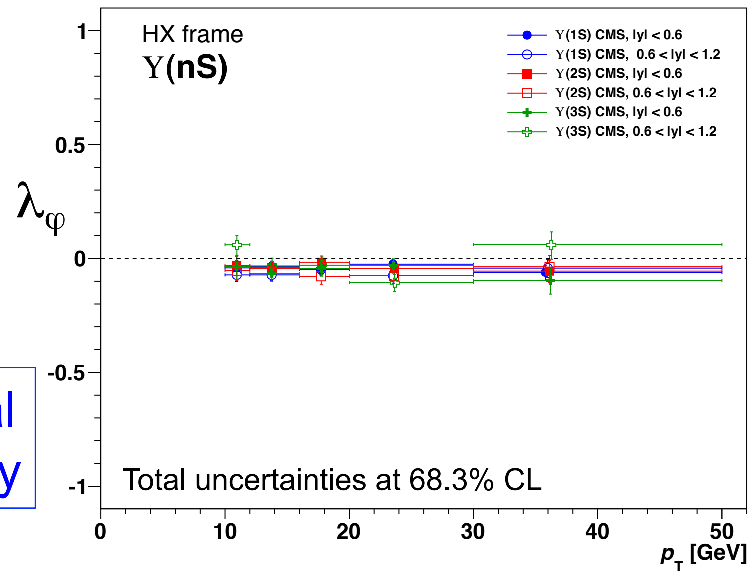
Polar anisotropy

Charmonia

Bottomonia

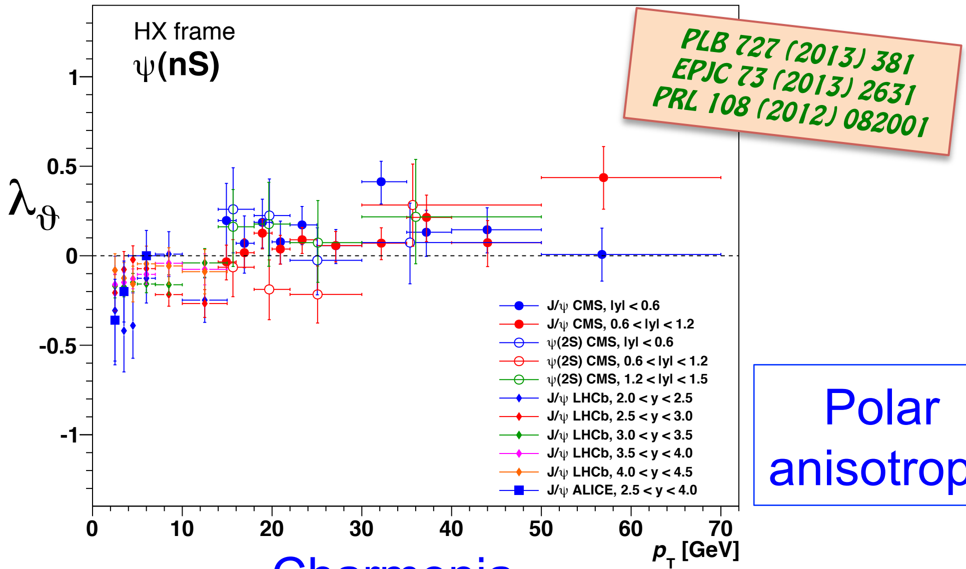


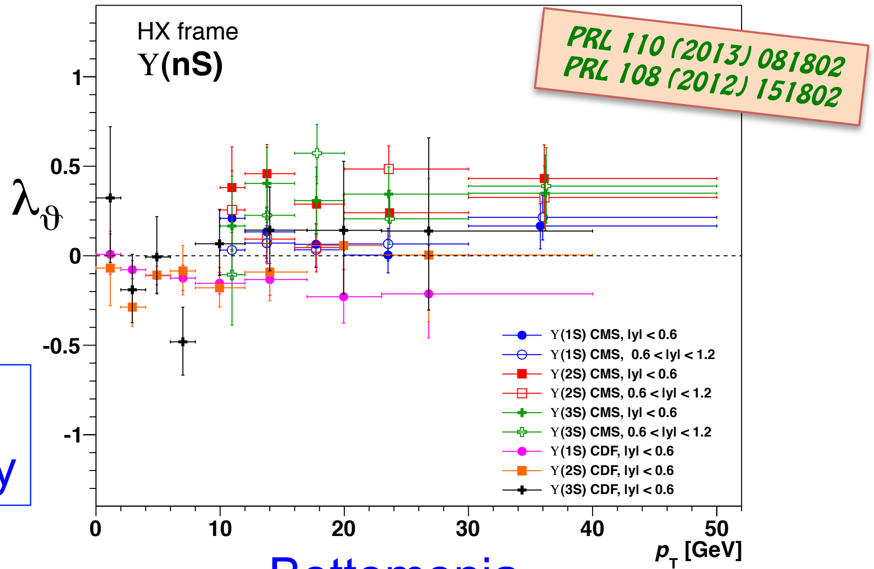
Azimuthal anisotropy



Quarkonium polarization results

No strong anisotropies seen in any of the measurements
Good consistency between CMS, LHCb, ALICE and CDF

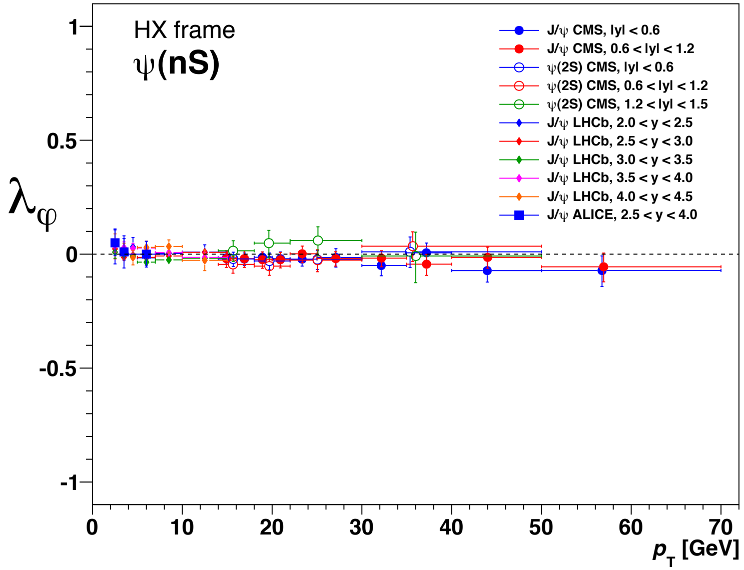




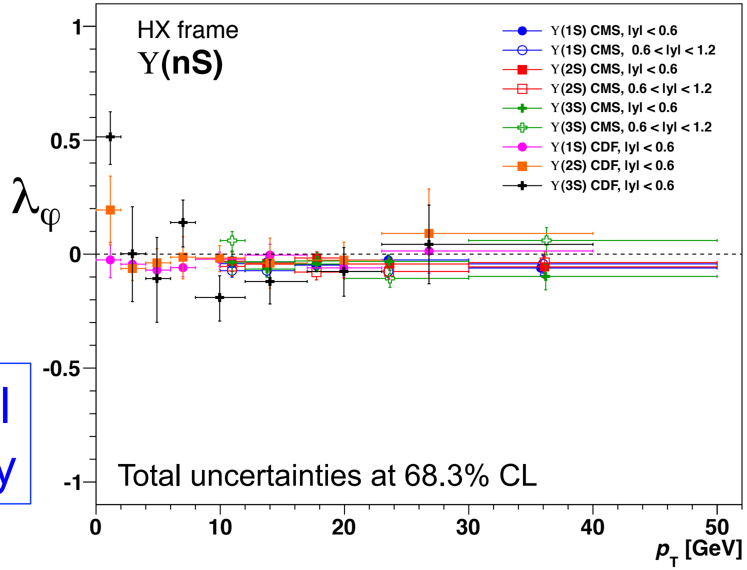
Polar anisotropy

Charmonia

Bottomonia



Azimuthal anisotropy



Summary

Cross sections and polarizations have been measured for five S-wave quarkonium states in pp collisions at $\sqrt{s}$ = 7 TeV

- ✧ Υ(1S), Υ(2S) and Υ(3S)
  - ✧ cross sections and polarizations measured with 4.9 fb^{-1} of data collected in 2011
- ✧ J/ψ and ψ(2S)
  - ✧ cross sections measured with only 37 pb^{-1} of data, collected in 2010 data
  - ✧ polarizations measured with 4.9 fb^{-1} of data collected in 2011

The χ_{c2} / χ_{c1} and χ_{b2}(1P) / χ_{b1}(1P) cross-section ratios have also been measured, at 7 and 8 TeV, respectively

The menu will "soon" be complemented with more measurements:

- ✧ J/ψ and ψ(2S) cross sections up to very high p_T
- ✧ cross sections and feed-down fractions of P-wave states (χ_c and χ_b)
- ✧ polarizations of P-wave states (χ_{c1} ; χ_{c2} ; etc)

all results are available in
twiki/bin/view/CMSPublic/PhysicsResultsBPH

Further reading

J/ψ and ψ(2S) production cross sections
CMS, EPJC 71 (2011) 1575 [L = 314 nb^{-1}, 7 TeV]
CMS, JHEP 02 (2012) 011 [L = 37 pb^{-1}, 7 TeV]

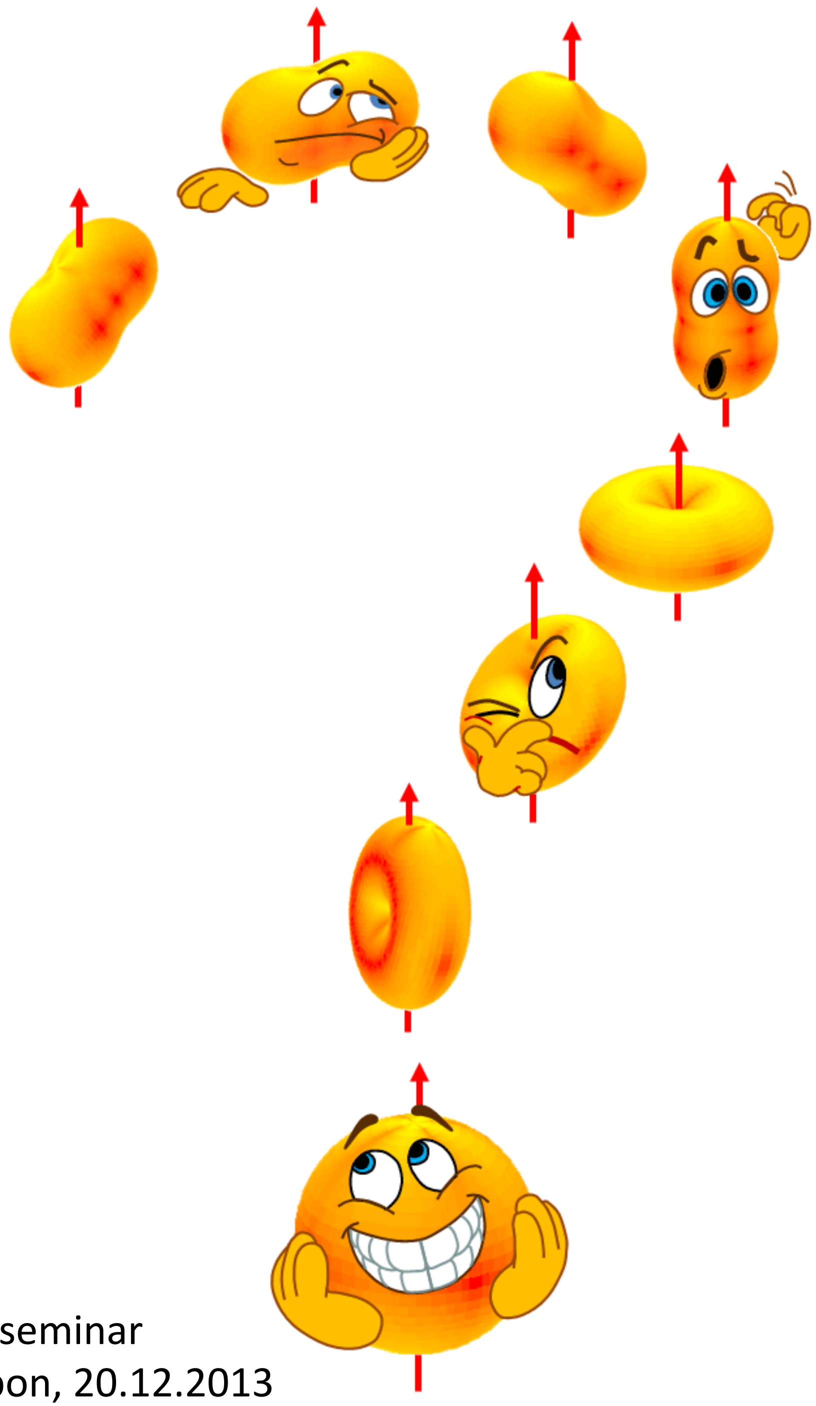
Υ(nS) production cross section
CMS, PRD 83 (2011) 112004 [L = 3 pb^{-1}, 7 TeV]
CMS, CMS PAS-BPH-12-006 [4.9 fb^{-1}, 7 TeV]

χ_{c2} over χ_{c1} cross-section ratio
CMS, EPJC 72 (2012) 2251 [4.6fb^{-1}, 7 TeV]

χ_{b2}(1P) over χ_{b1}(1P) cross-section ratio
CMS, PAS-BPH-13-005 [20.7 fb^{-1}, 8 TeV]

J/ψ and ψ(2S) polarizations
ALICE: PRL 108 (2012) 082001 [100 nb^{-1}, 7 TeV]
CMS, PLB 727 (2013) 381 [4.9 fb^{-1}, 7 TeV]
LHCb: EPJC 73 (2013) 2631 [0.37 fb^{-1}, 7 TeV]

Υ(nS) polarizations
CMS, PRL 110 (2013) 081802 [4.9 fb^{-1}, 7 TeV]
CDF, PRL 108 (2012) 151802 [6.7 fb^{-1}, 1.96 TeV]



Puzzles, achievements and perspectives in quarkonium production studies

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in collaboration with

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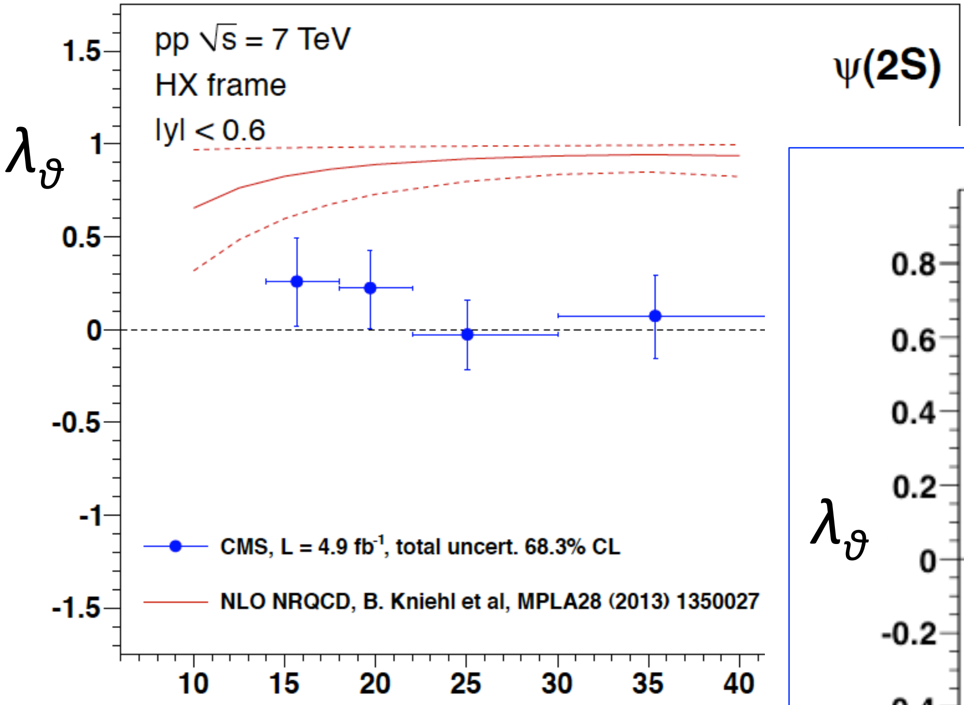
1 LIP 2 HEPHY Institute of High Energy Physics 3 CERN

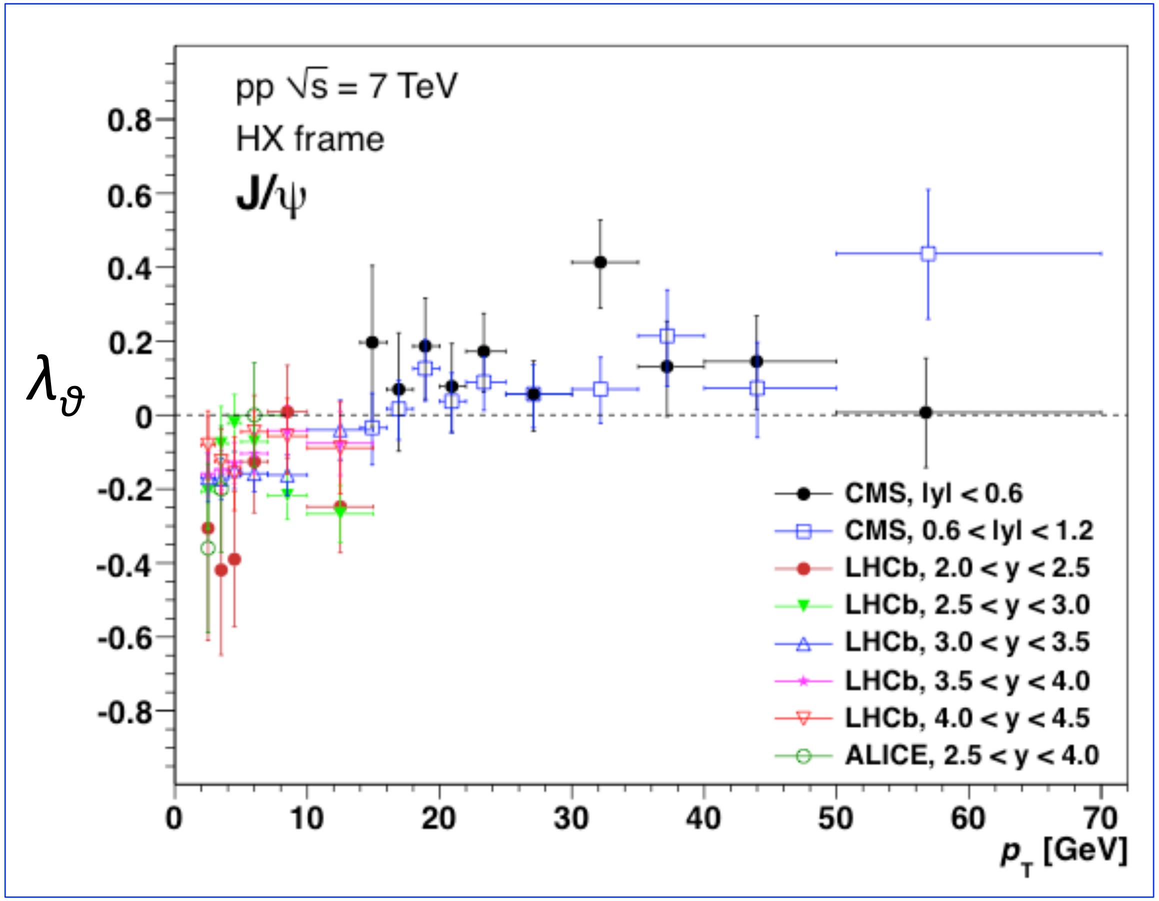
LIP seminar
Lisbon, 20.12.2013

Polarization: NRQCD vs. LHC data

CMS measured ψ(2S) polarization: no feed-down excuses…
CMS, LHCb and ALICE J/ψ results are in good agreement: no data inconsistencies
→ The puzzle is a real problem and not caused by unreliable data

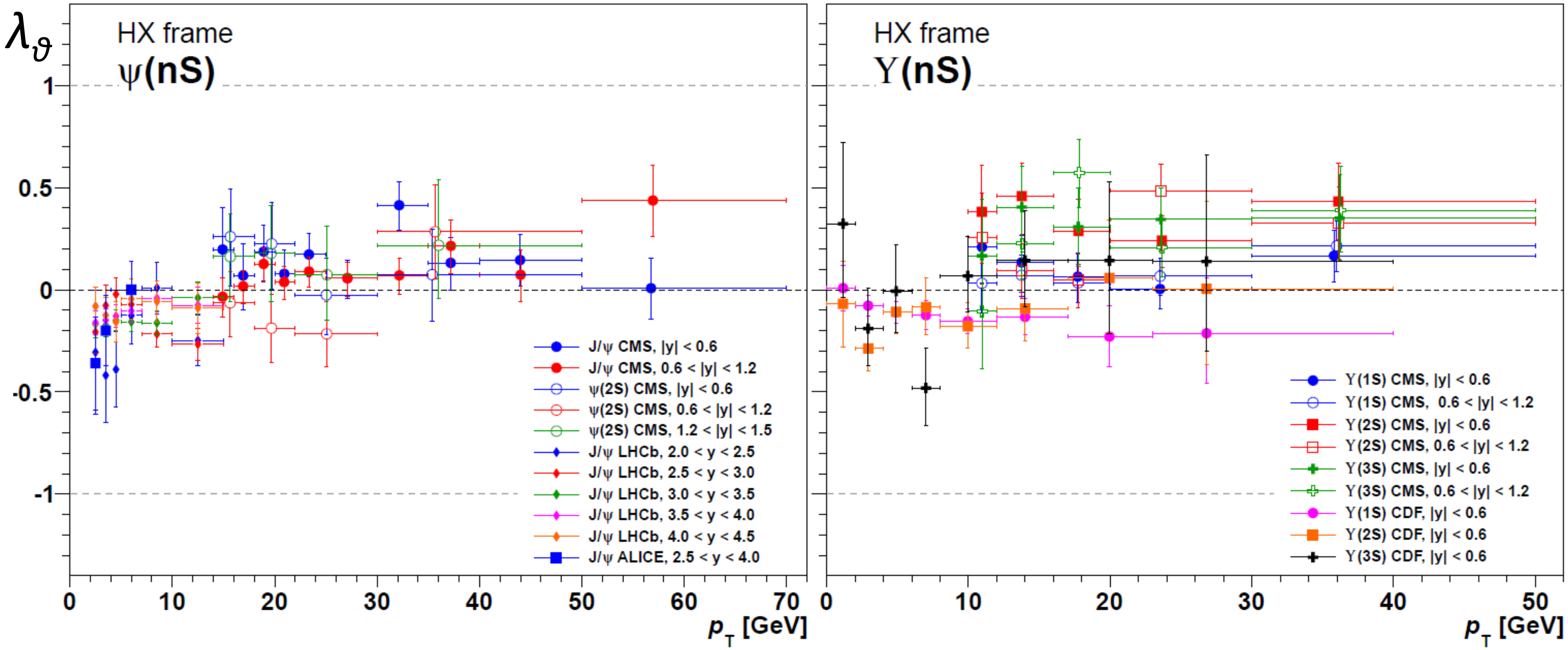


How to solve it?



A data-driven inspiration: polarization first

LHC S-wave quarkonia polarizations cluster around the unpolarized limit, with no strong changes from directly-produced states to those affected by P-wave feed-down decays

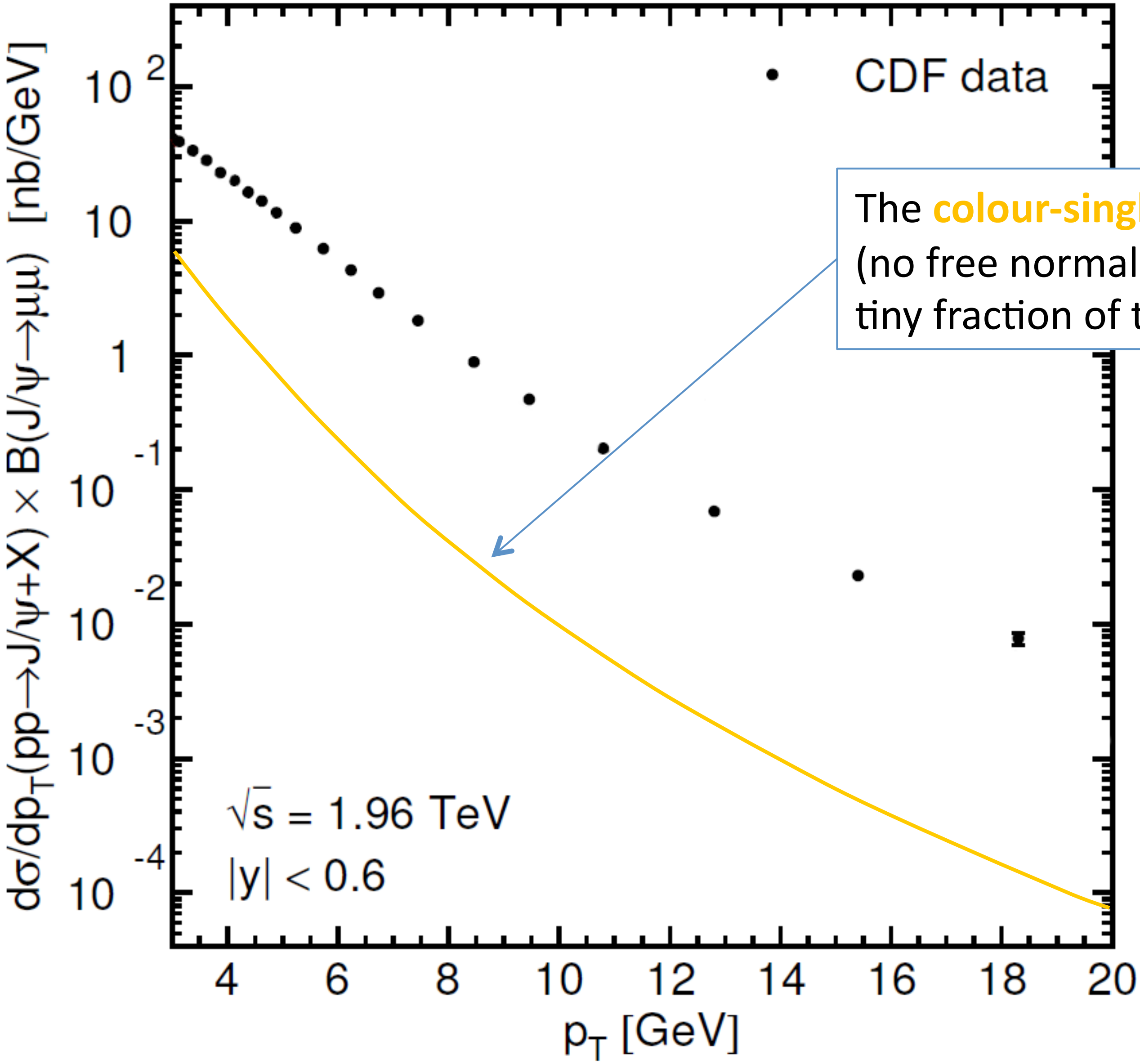


The simplest ("zero-order") explanation: all quarkonia are produced by a single mechanism, with a large contribution of the (unpolarized) $^1S_0$**-octet channel**

But we saw that this is not a dominant term in the fits to the cross sections… Right?

A second look at the NRQCD fits

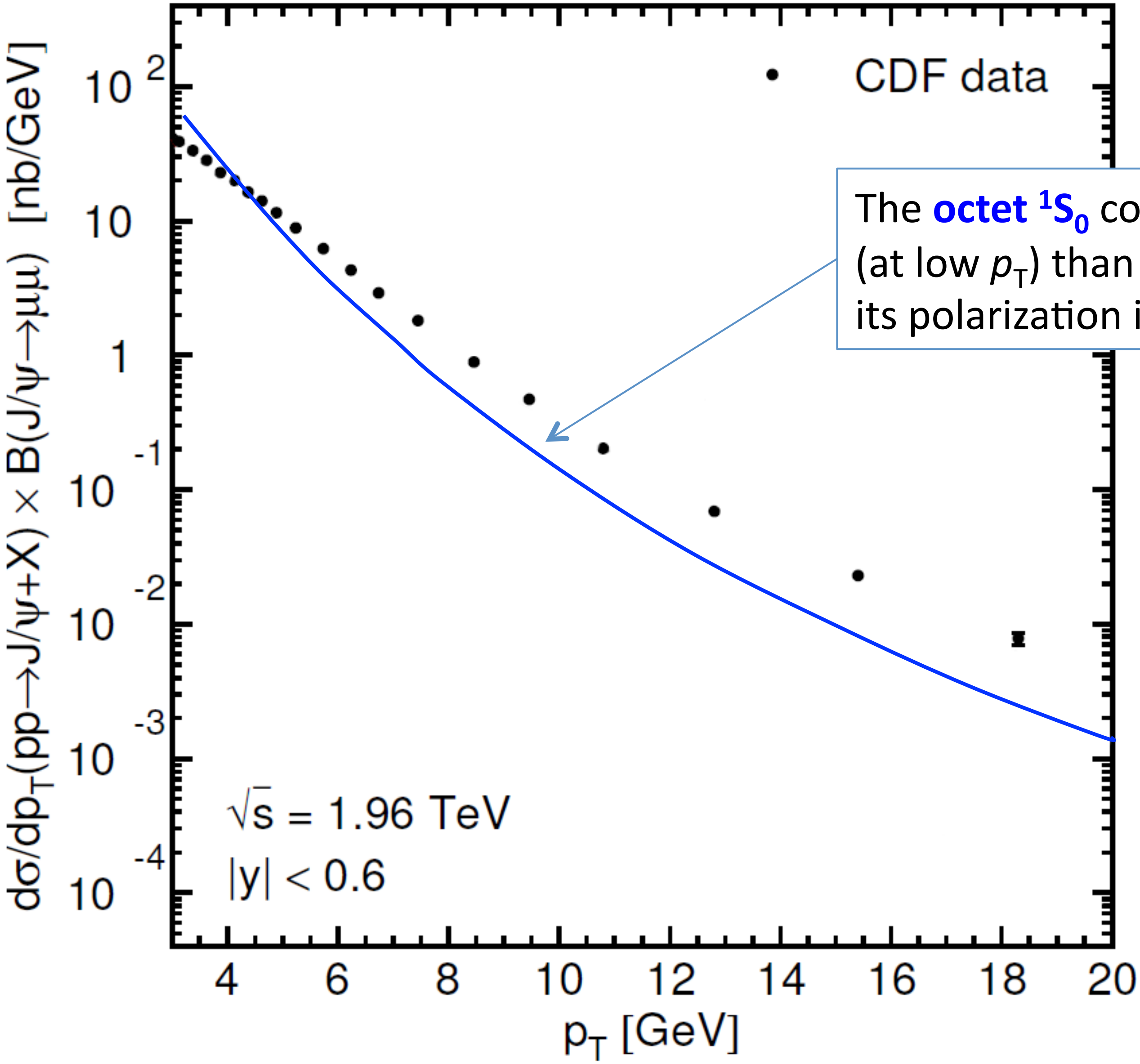
Let's consider how individual contributions in the NRQCD calculations compare to data



The **colour-singlet $^3S_1$** contribution is fixed (no free normalization) and represents a tiny fraction of the total cross section

A second look at the NRQCD fits

Let's consider how individual contributions in the NRQCD calculations compare to data

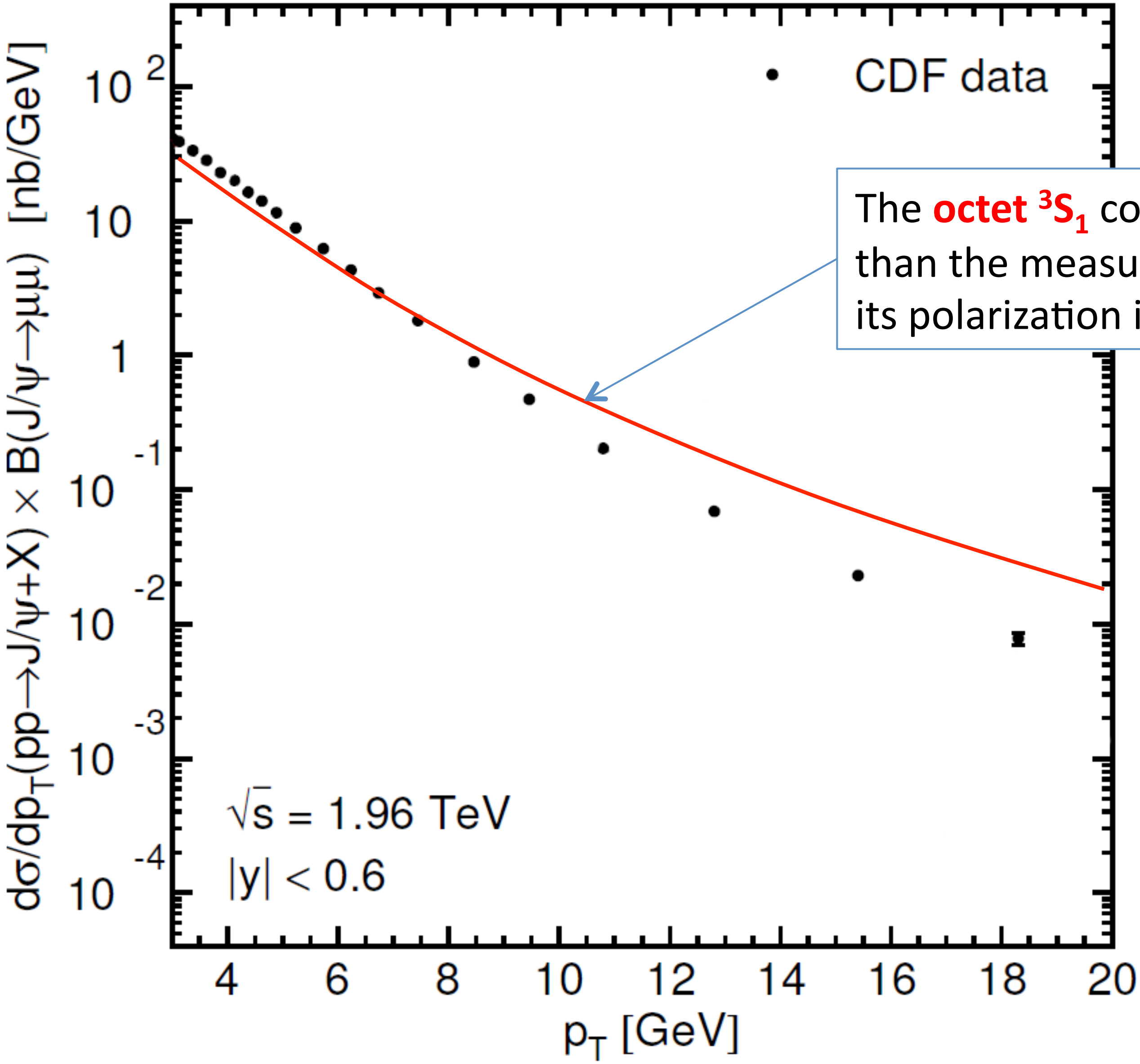


The **octet $^1S_0$** contribution alone is steeper (at low p_T) than the measured cross section; its polarization is **zero**

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

A second look at the NRQCD fits

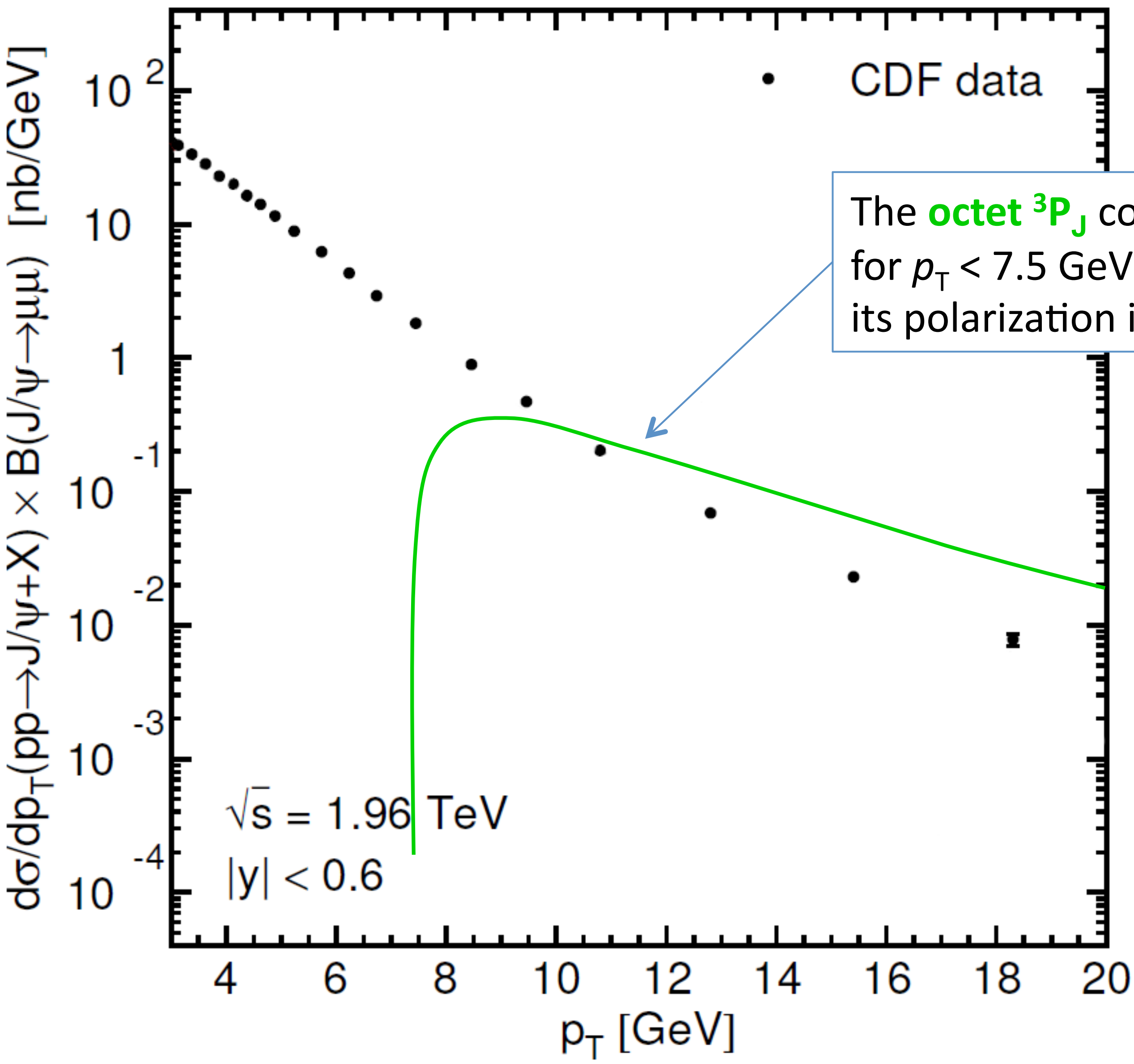
Let's consider how individual contributions in the NRQCD calculations compare to data



The **octet $^3S_1$** contribution alone is less steep than the measured cross section; its polarization is **transverse**

A second look at the NRQCD fits

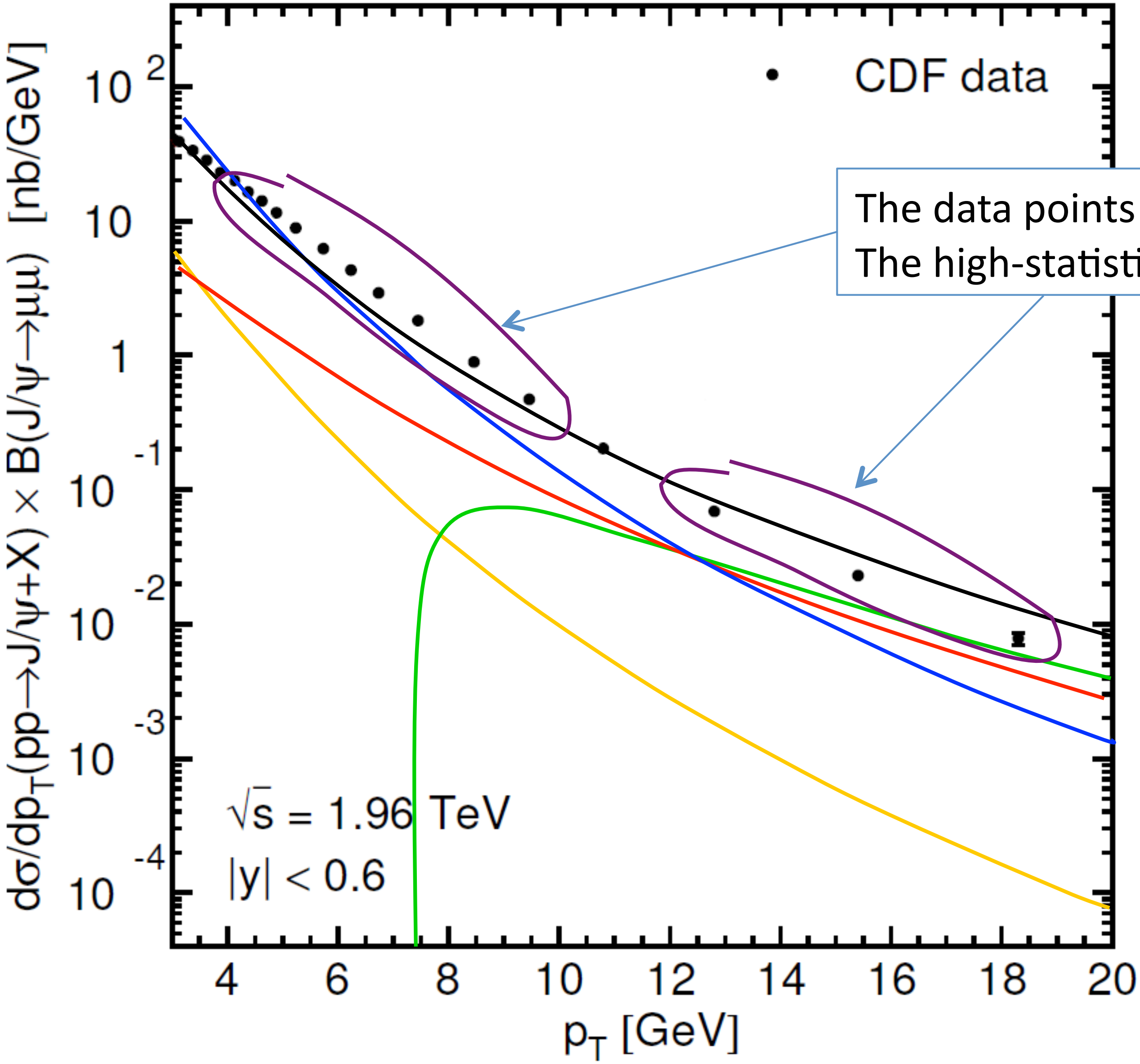
Let's consider how individual contributions in the NRQCD calculations compare to data



The **octet ^3P_J** contribution is *negative* for p_T < 7.5 GeV !
its polarization is "**hyper-transverse**"

A second look at the NRQCD fits

All together now…

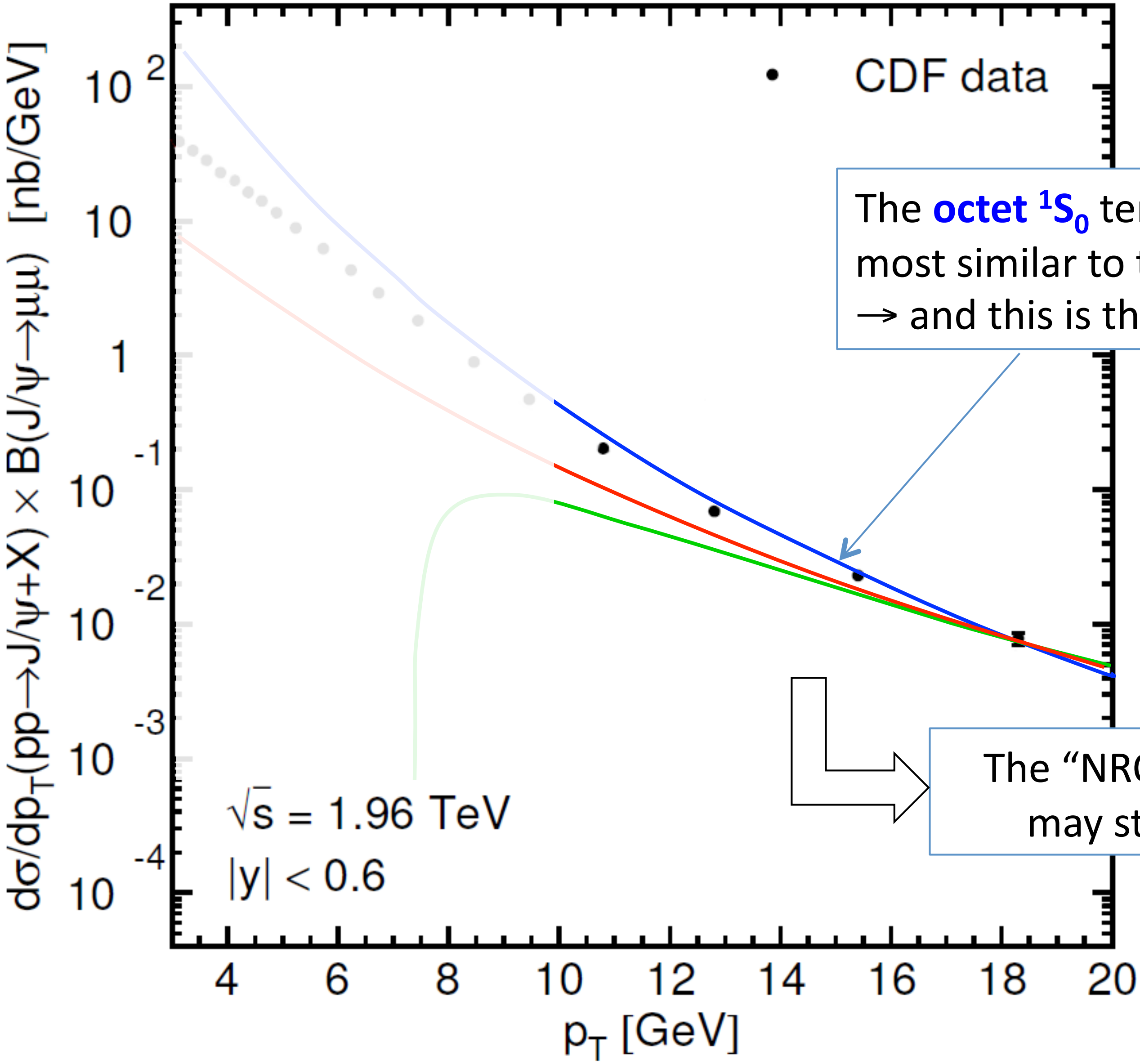


The data points are poorly fitted…
The high-statistics low-p_T points drive the fit

Reminder:
the fit starts at p_T = 3 GeV

A matter of NRQCD validity domain?

Let's isolate the high-p_T asymptotic behaviors,
by normalizing the curves to the highest-p_T CDF data point



The **octet** $^1S_0$ term has the shape most similar to the data
→ and this is the unpolarized contribution !

The "NRQCD region" may start here !

A matter of NRQCD validity domain?

- The *crucial* hypothesis of NRQCD: factorization
- A mathematical proof that it holds at all orders in α_S for quarkonium production does not exist: comparisons with data are fundamental to show the way ahead
- It is well known that it can only hold for $\boldsymbol{p_T > M}$ (and $v < 1$)
  I.e, for QQbar pairs produced at a sufficiently *short distance* $d = \max\{1/m_Q, 1/p_T\}$, significantly smaller than the bound-state size $1/(m_Q v)$
- But current analyses use data down to p_T = 3–7 GeV/c (J/ψ) and p_T = 8 GeV/c (ϒ) without systematically investigating the implications of this choice
- The lowest-p_T points drive the LDME fit results and should be gradually excluded in a search for the domain of validity of the effective theory

- The high-p_T reach of the LHC measurements can trigger a big step forward !

Towards better NRQCD global fits

We have started working on a significantly improved NRQCD fit framework:

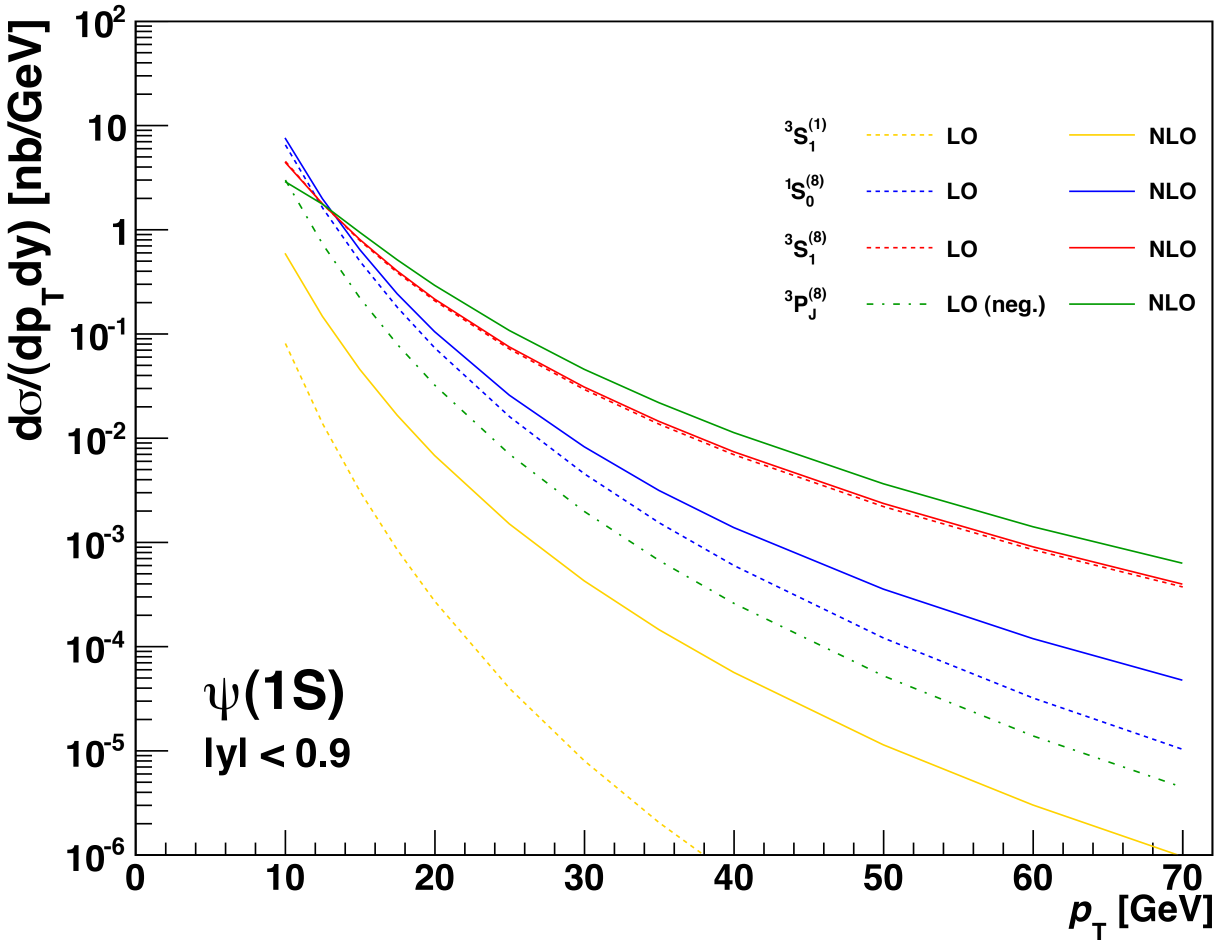
- The analysis is made as a function of thresholds in p_T / M
  to answer the basic question: has NRQCD factorization a domain of validity?
- Both cross sections and polarizations are used as *simultaneous* constraints
- Experimental correlated uncertainties (luminosity, etc) and polarization-dependent acceptances are accounted for; inconsistent measurements are not used
- Theoretical uncertainties are accounted as difference between LO and NLO calculations

Note: the bottomonium SDCs are obtained from the charmonium ones* using p_T / M scaling

*by M. Butenschön and B. Kniehl, calculated for $M = 2\, m_c$

SDCs from LO to NLO

Theoretical uncertainties (perturbative calculations) are small for the $^1S_0$ and $^3S_1$ octets, which have relatively small changes from LO to NLO
The ^3P_J contribution, instead, changes *drastically* from LO to NLO;
in cross section and in polarization



S-octet dominance would solve the problem of the slowly-converging perturbative series in NRQCD

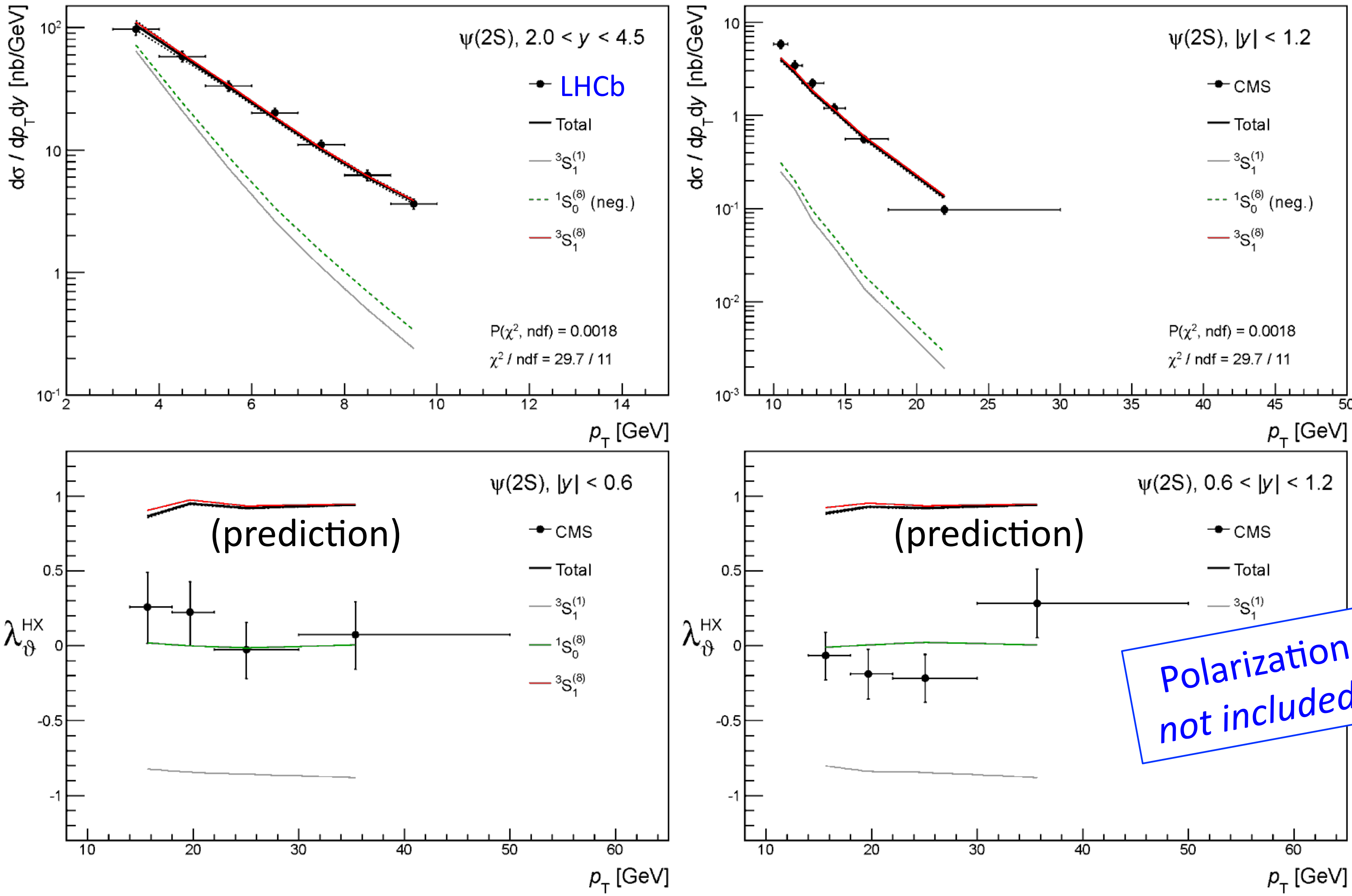
Neglecting the ^3P_J term gives much more constrained fits

→ we start with this option

The “standard” fit approach, p_T > 3 GeV

Data fitted down to lowest $p_T\,/M$, without polarization constraint

ψ(2S)



Polarization data not included in fit!

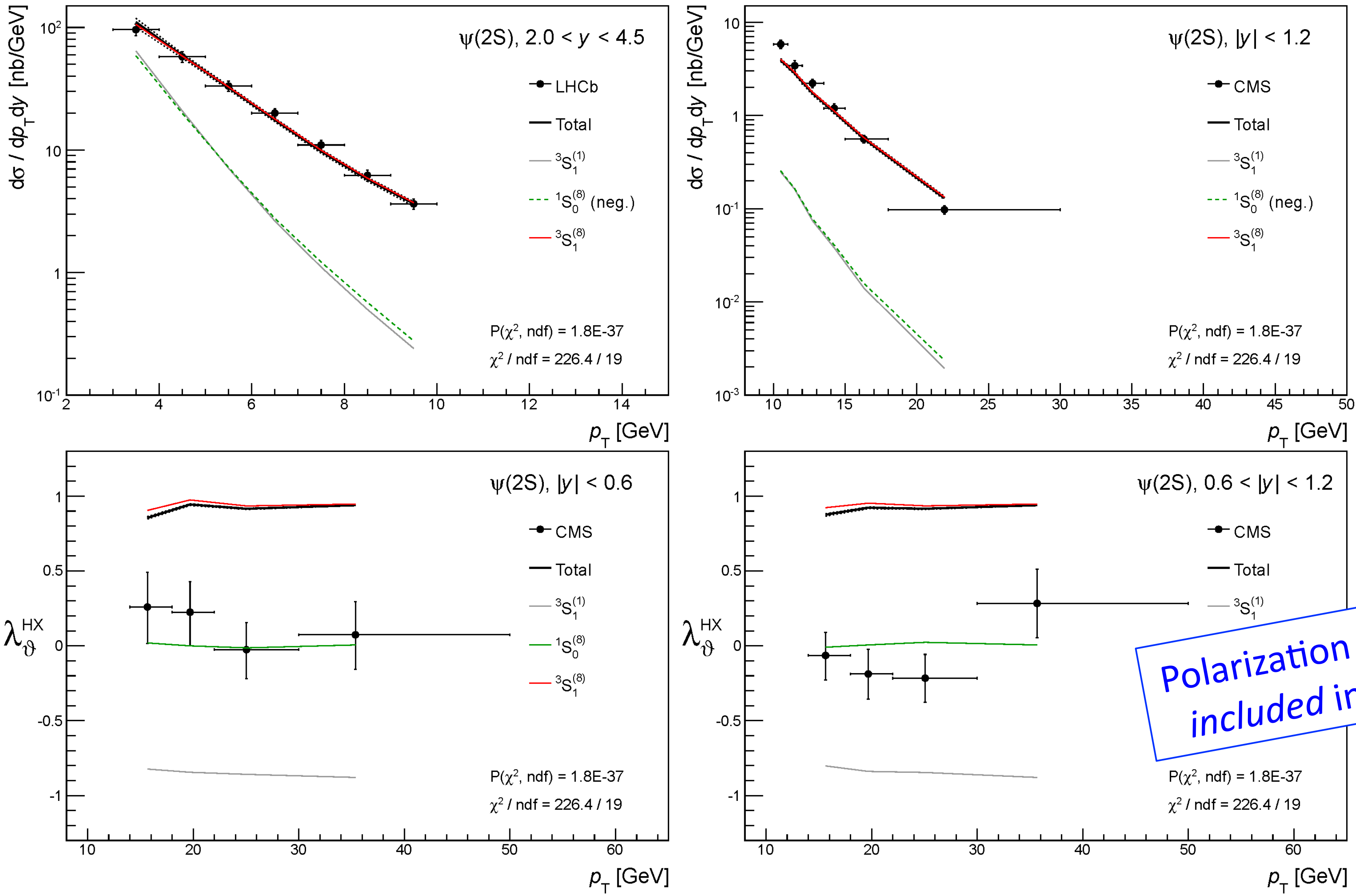
- $^{3}S_{1}^{(8)}$ dominates
- $^{1}S_{0}^{(8)}$ small and *negative*

P(χ^2)	1.8E-3

Global fit, p_T > 3 GeV

ψ(2S)

Data fitted down to lowest p_T /*M*, with polarization constraint



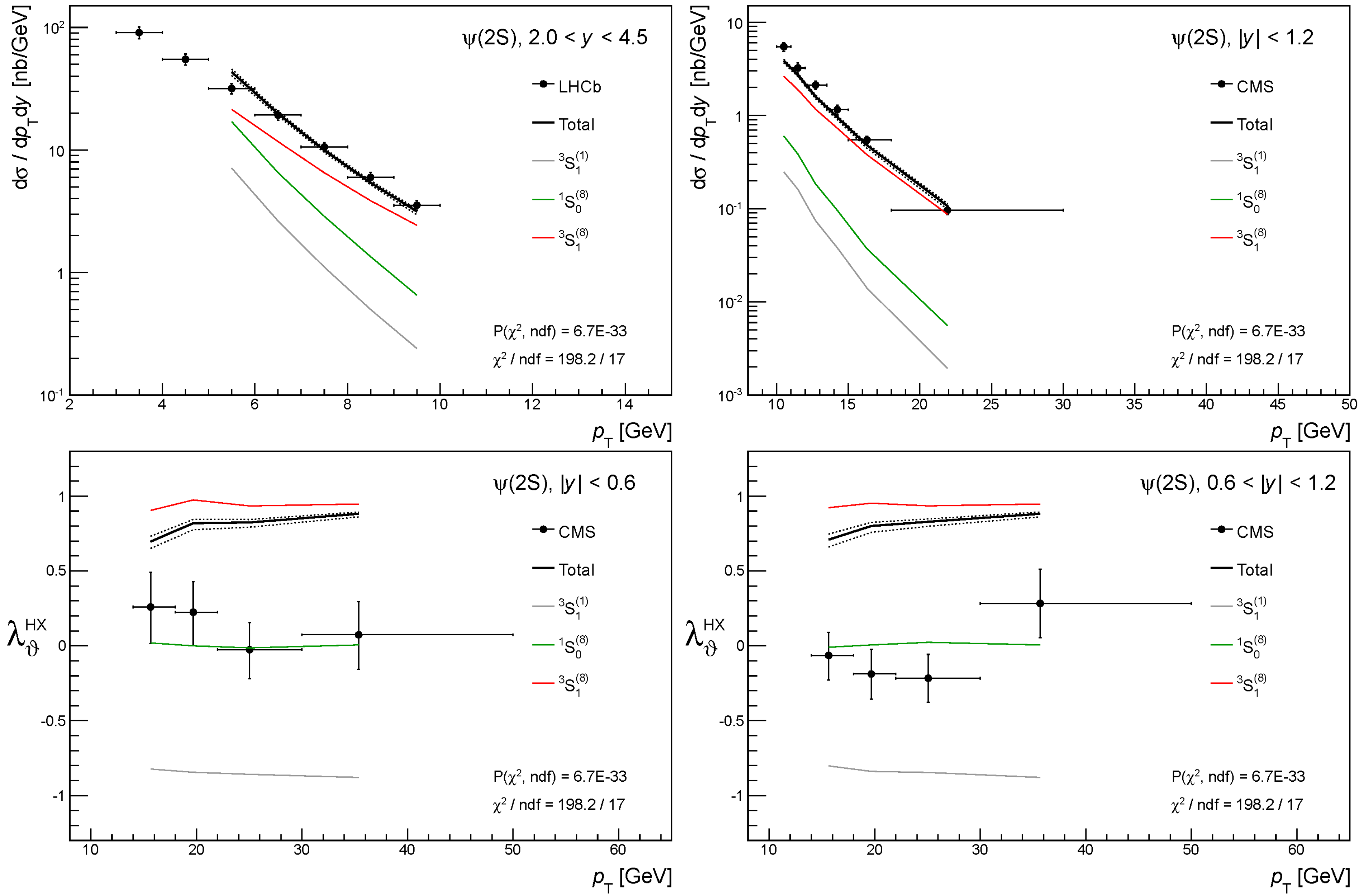
Polarization data included in fit!

- No visible change
- $^3S_1^{(8)}$ still dominates; $^1S_0^{(8)}$ still *negative*

P(χ²) 1.8E-37

Global fit, p_T > 5 GeV

ψ(2S)

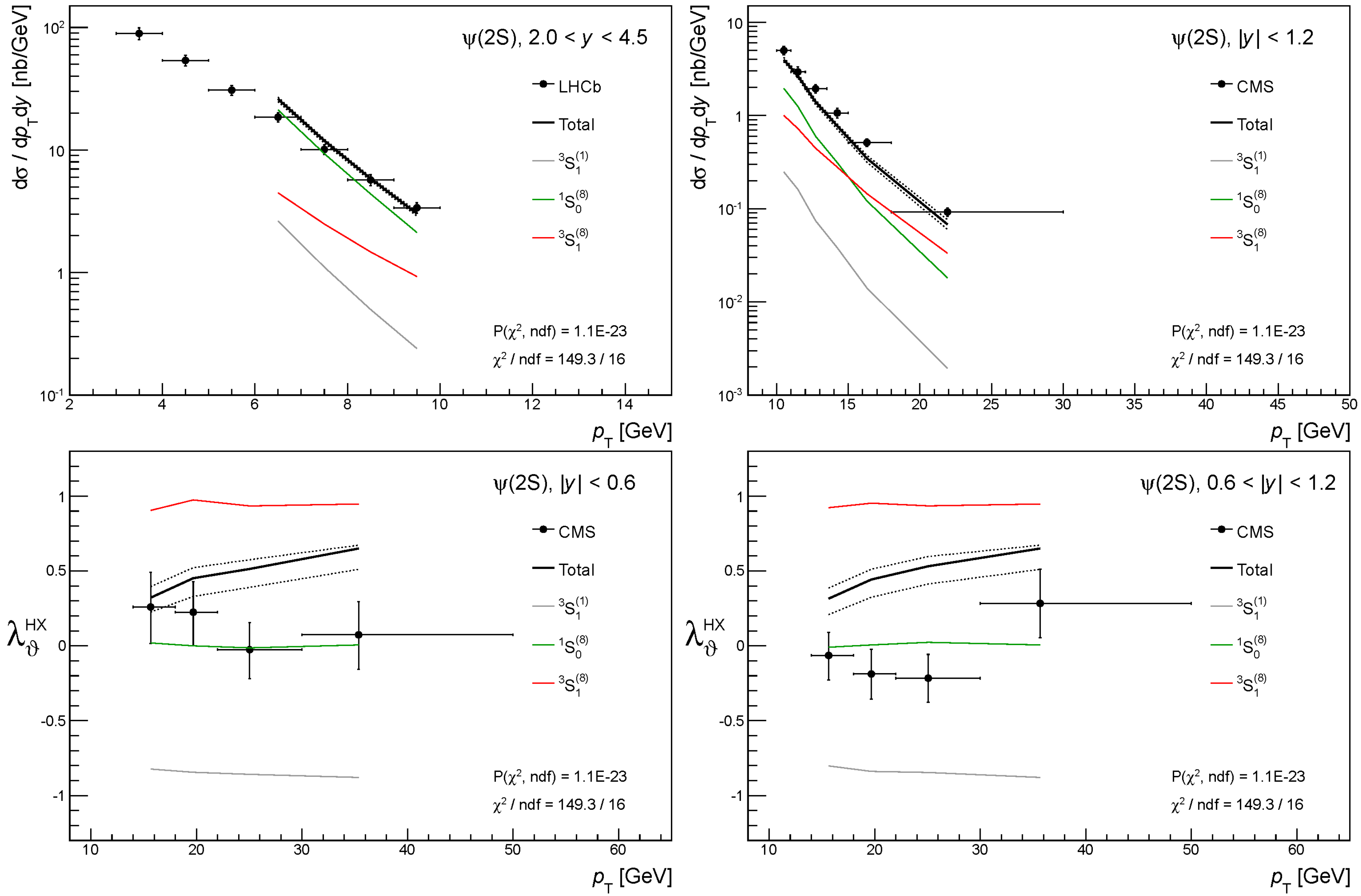


- $^3S_1^{(8)}$ decreases
- $^1S_0^{(8)}$ is positive and increases

P(χ^2) 0.67E-32

Global fit, p_T > 6 GeV

$\psi(2S)$

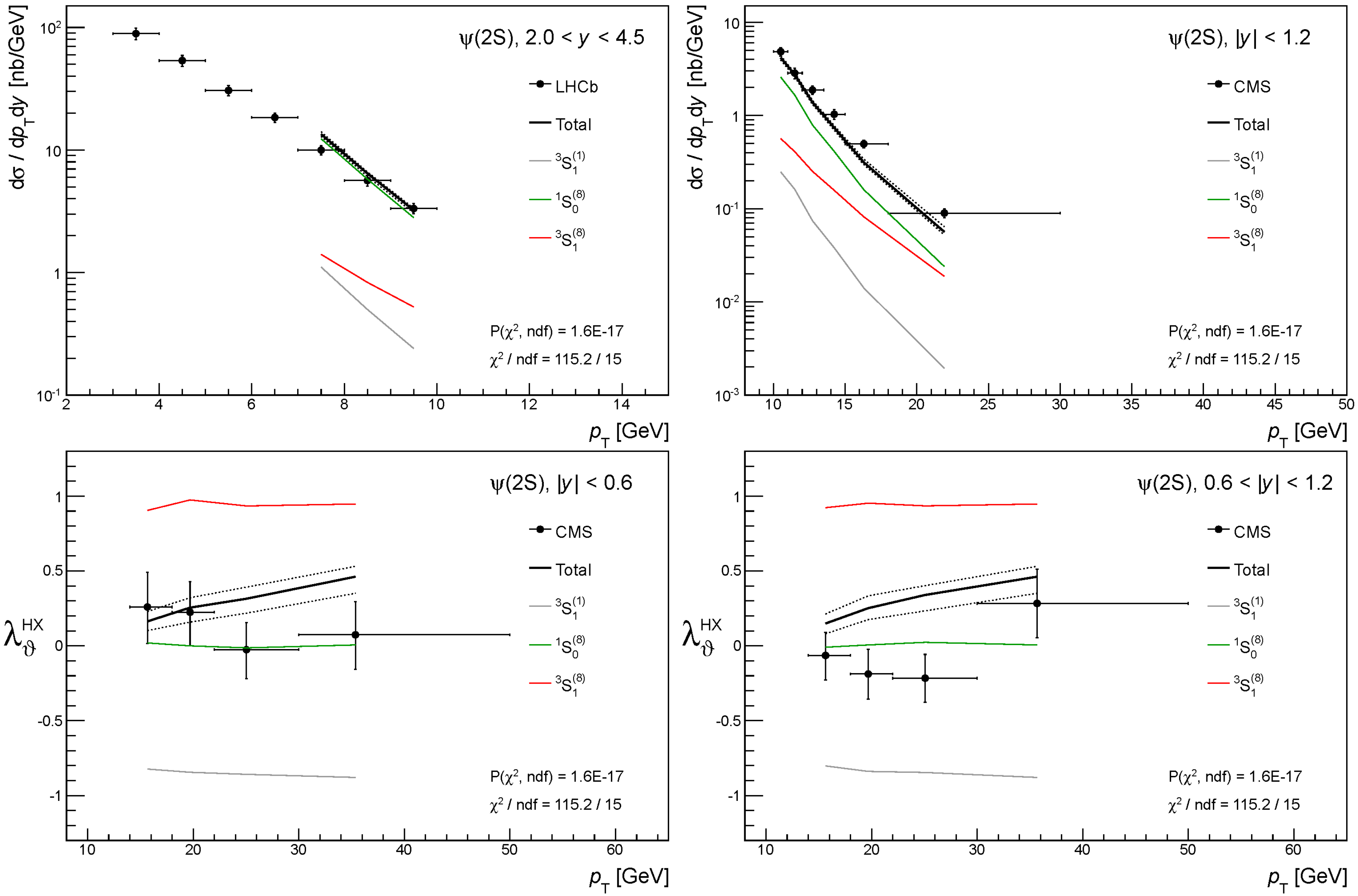


- $^3S_1^{(8)}$ and $^1S_0^{(8)}$ start exchanging their roles
- polarization is changing

$P(\chi^2)$ 1.1E-23

Global fit, p_T > 7 GeV

ψ(2S)

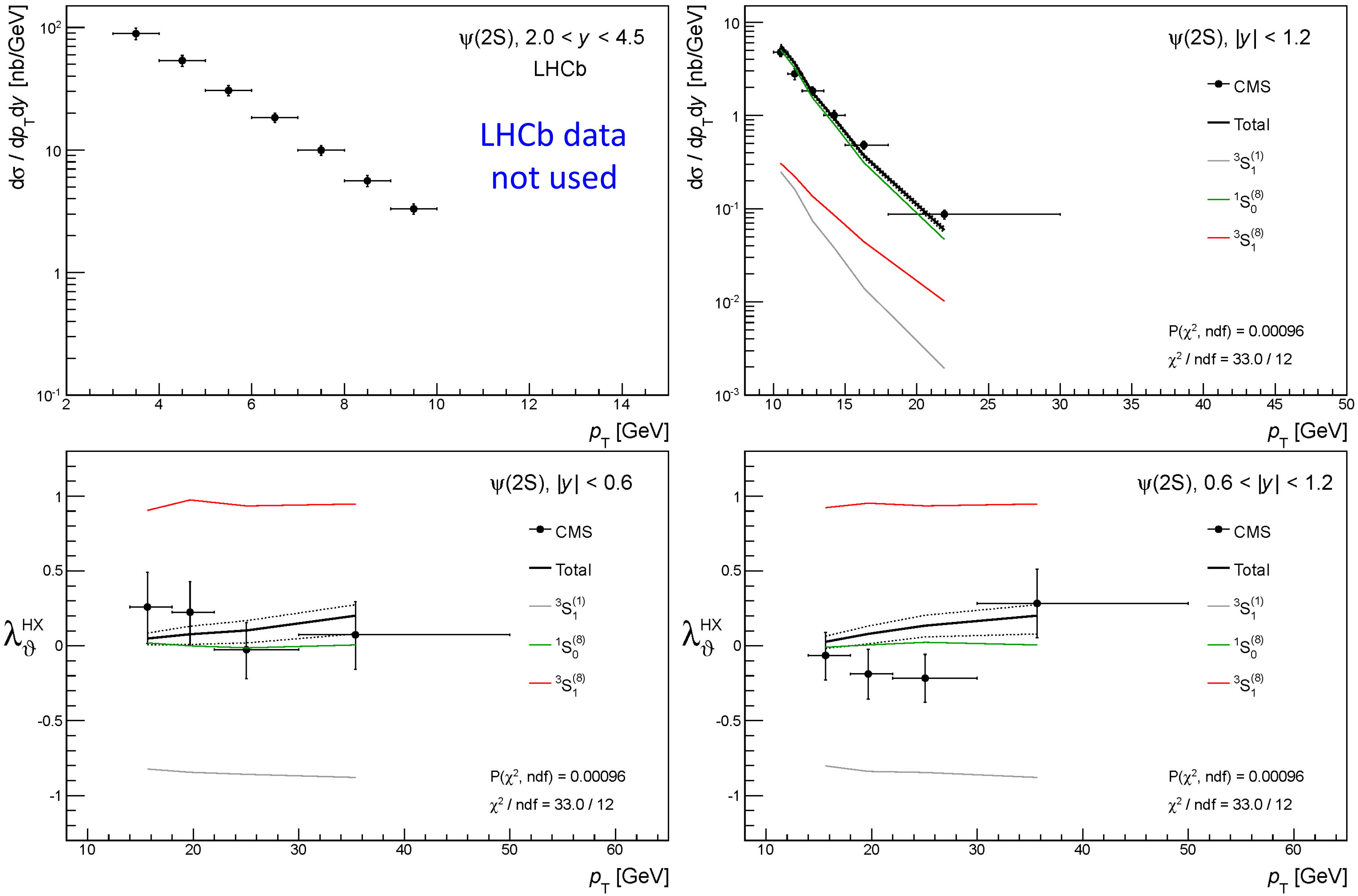


- $^1S_0^{(8)}$ is now the main contribution
- polarization closer to the data

P(χ²) 1.6E-17

Global fit, p_T > 10 GeV

$\psi(2S)$

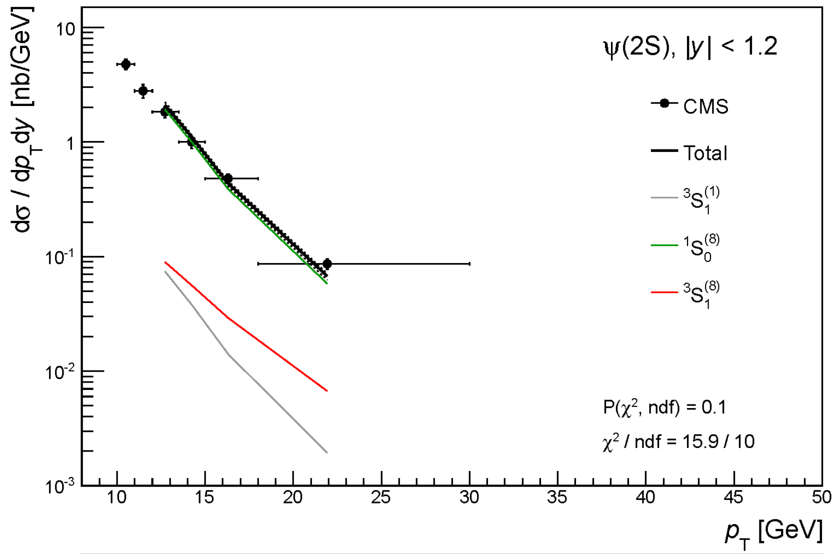


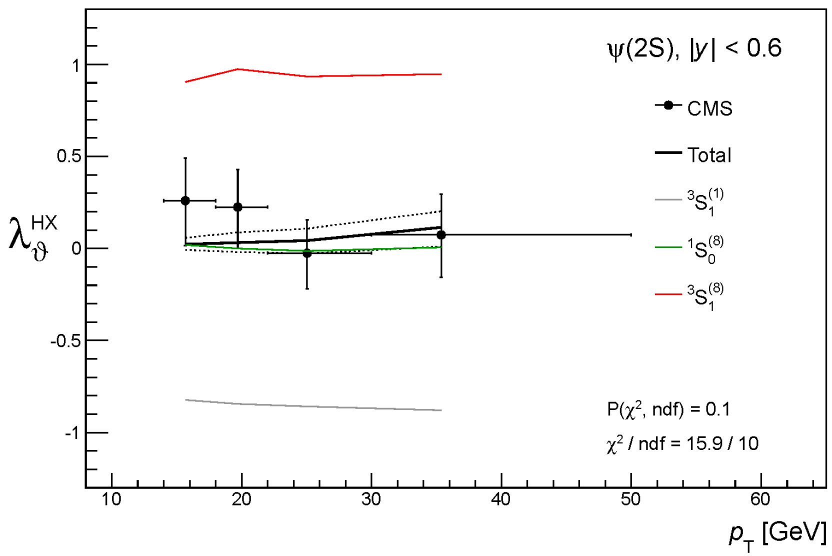
- $^1S_0^{(8)}$ dominates
- polarization quite close to the data

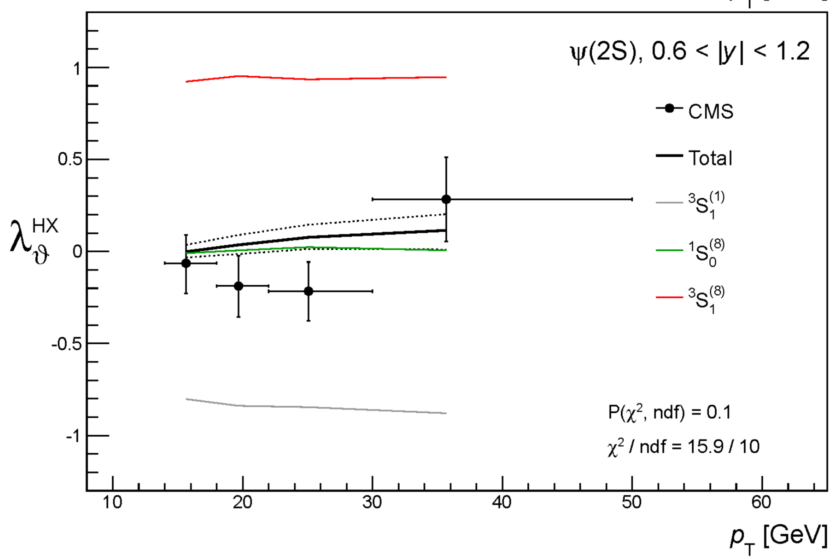
P(χ^2) 0.96E-3

Global fit, p_T > 12 GeV

$\psi(2S)$







- $^1S_0^{(8)}$ dominates
- results are stable

$P(\chi^2)$ 10%

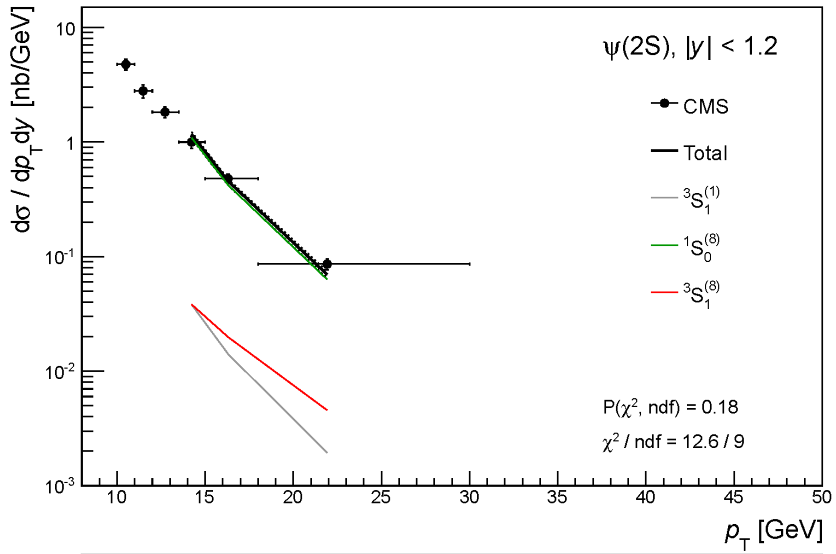
Global fit, p_T > 13 GeV

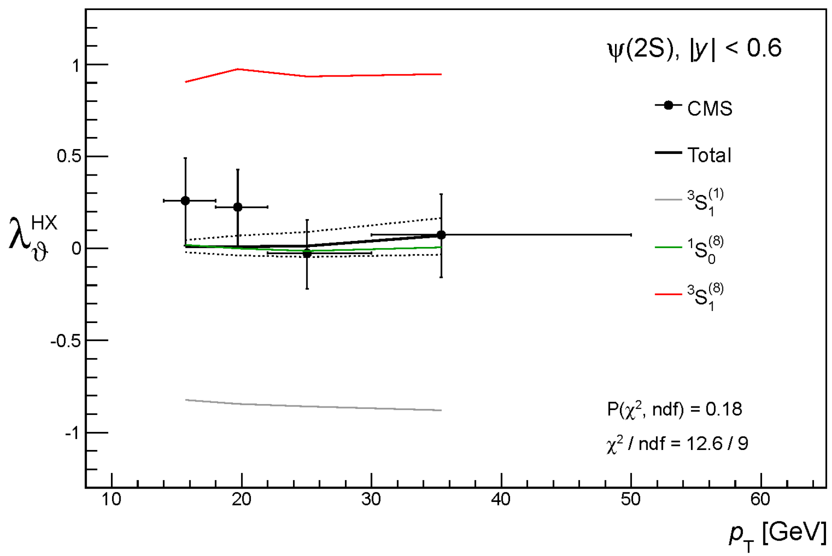
$\psi(2S)$

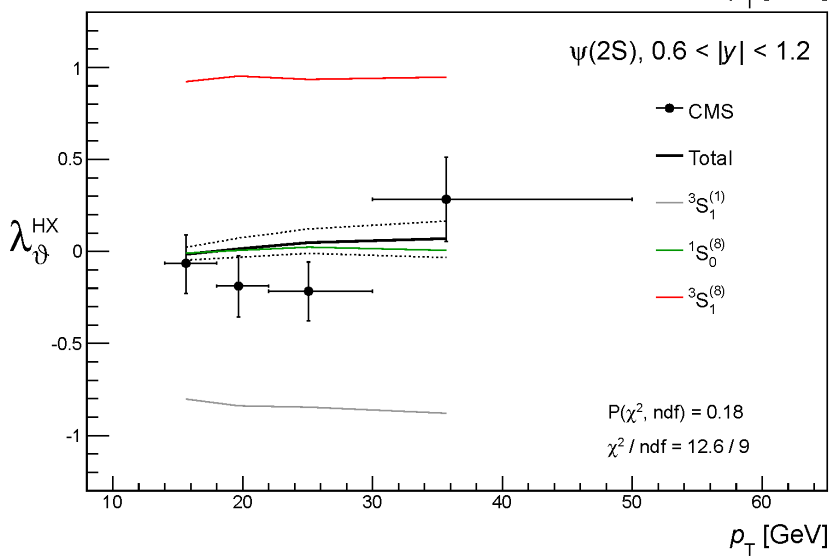
Our "best" fit so far

We deduce that
the theory describes the data when:

for the $\psi(2S)$: $p_T > 13$ GeV
more generally → $\boldsymbol{p_T / M > 3.5}$





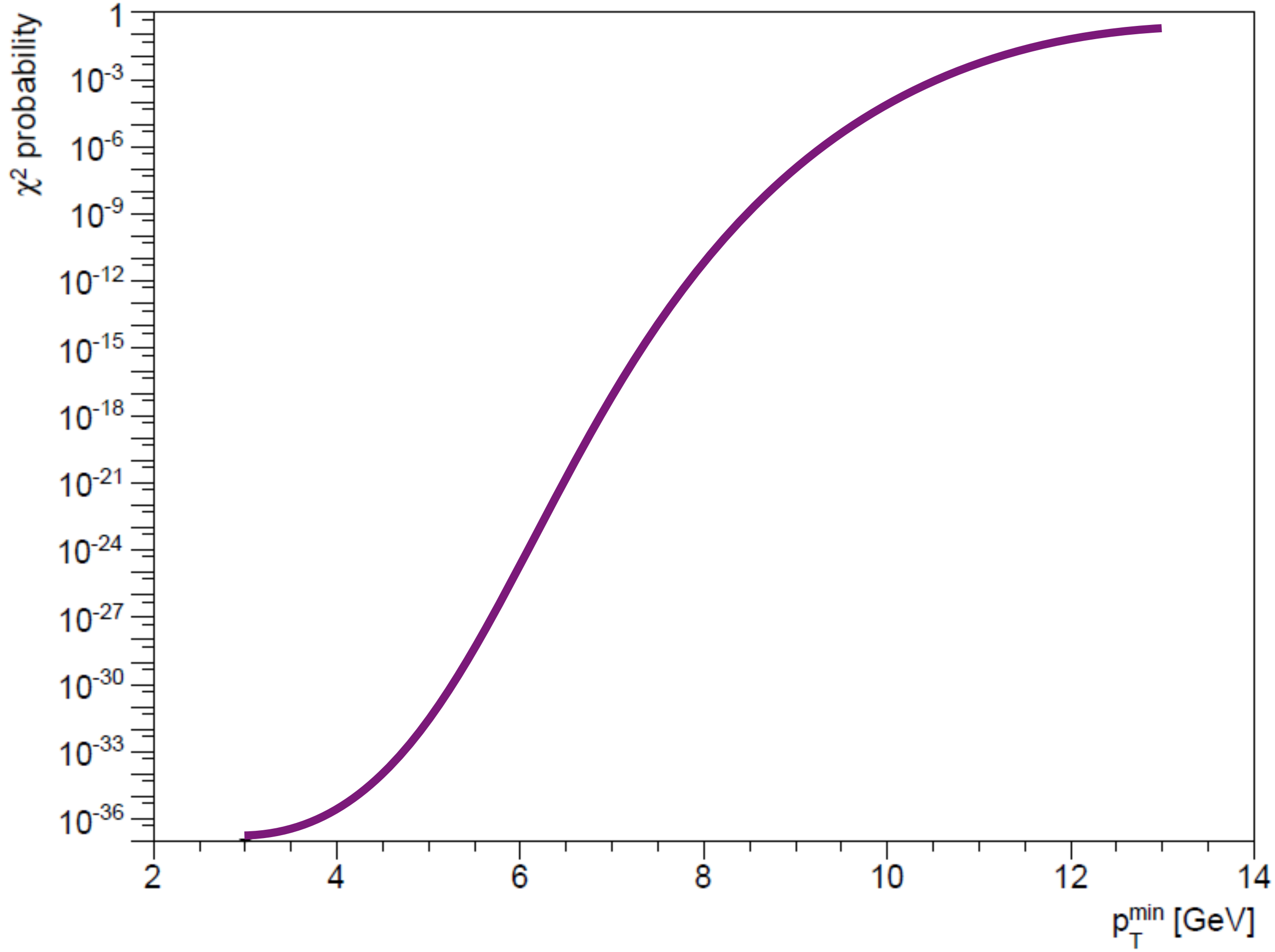


- $^1S_0^{(8)}$ dominates
- very good agreement with data

P(χ^2) 18%

ψ(2S) p_T^{min} scan summary

The search for the domain of validity of the theory framework is seemingly successful.
The χ^2 probability improved by 36 orders of magnitude !



p_T^{min} = 13 GeV

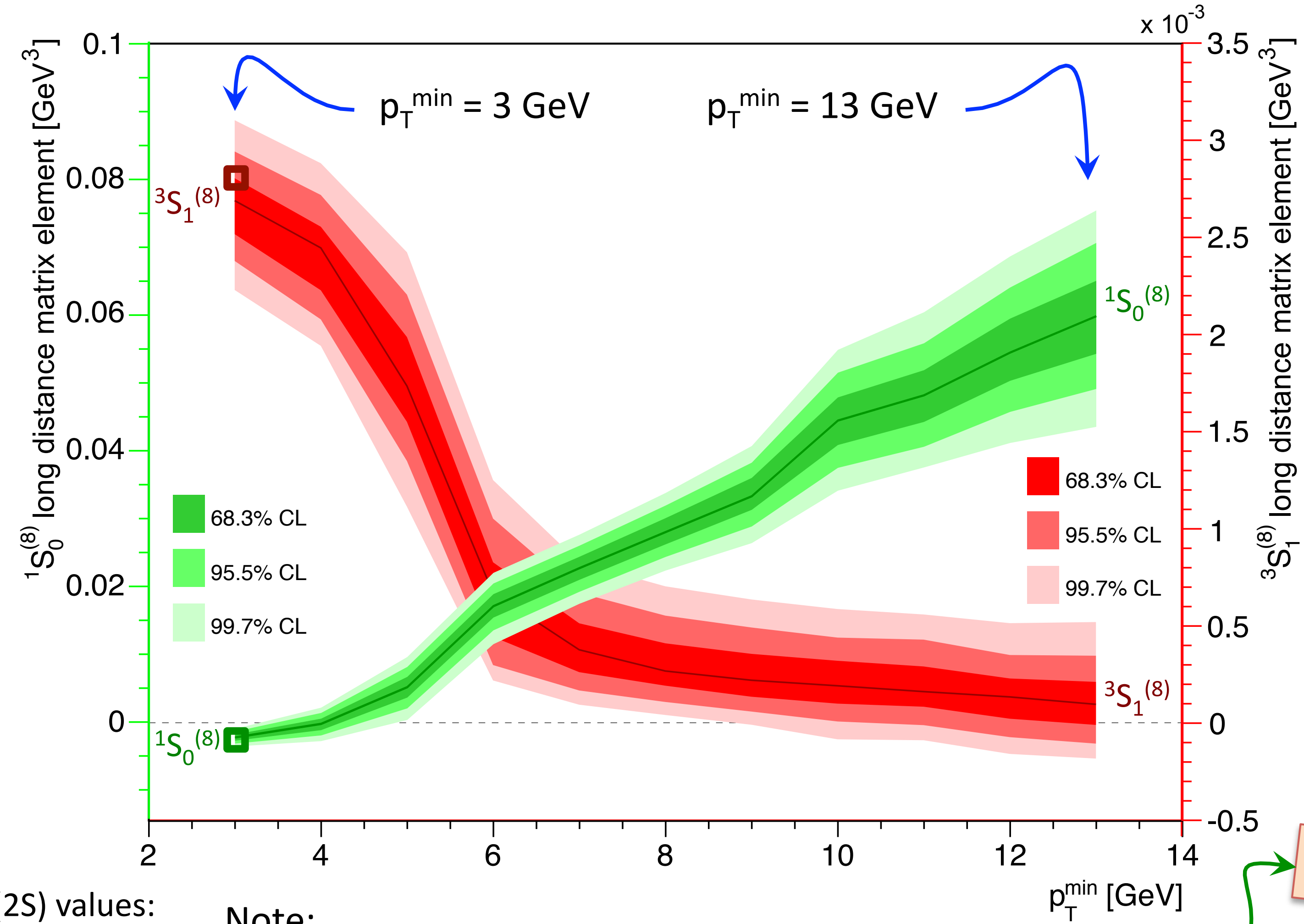
18%

p_T^{min} = 3 GeV

1.8E-37

$\psi(2S)\ p_T^{min}$ scan summary

Limiting the analysis to "NRQCD's validity domain", the $^1S_0^{(8)}$ vs. $^3S_1^{(8)}$ hierarchy is inverted: the $^1S_0^{(8)}$ octet→singlet transition matrix element dominates !



PRL 108 (2012) 172002
+ private communication

BK LDME ψ(2S) values:

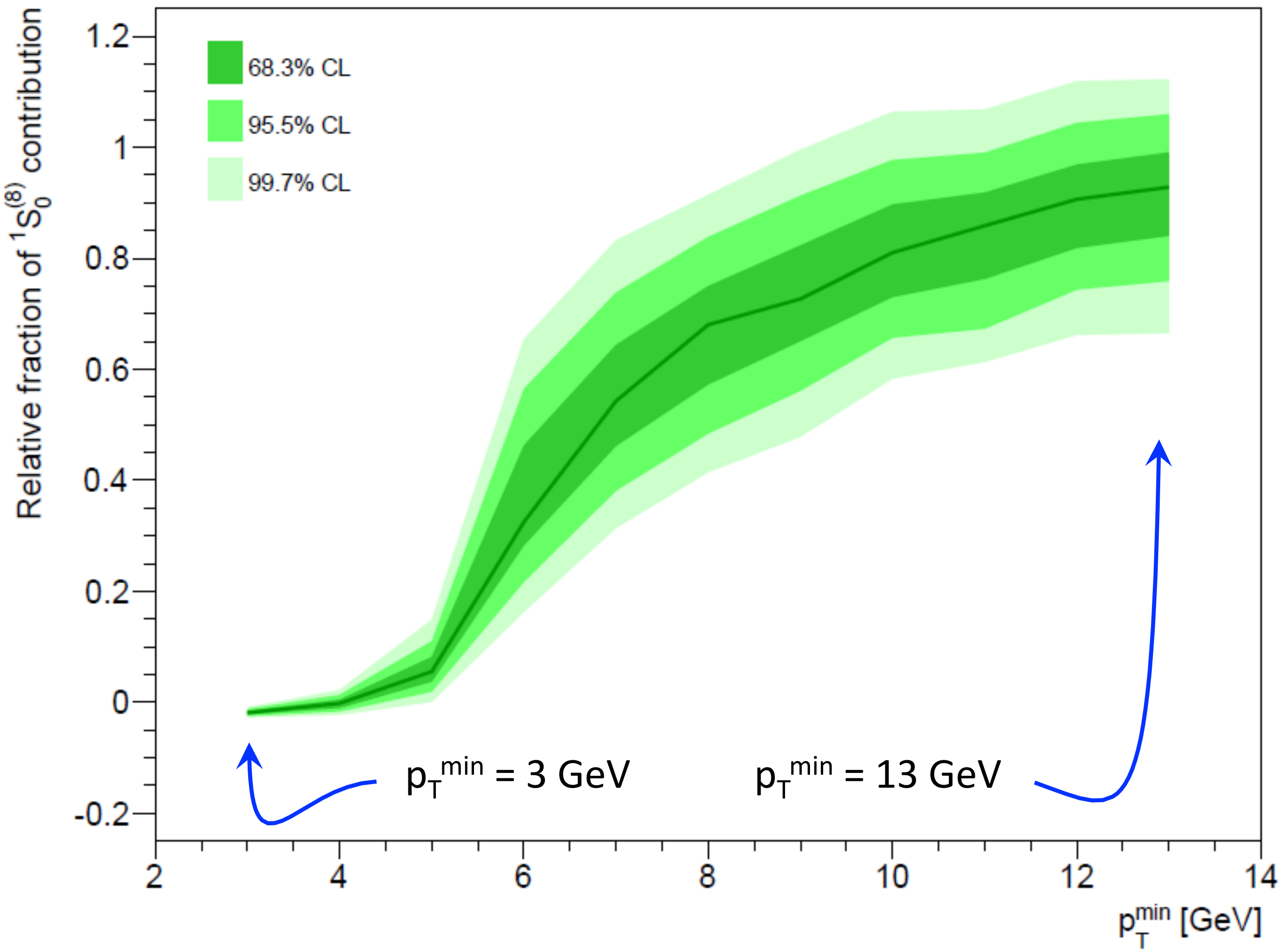
$^1S_0^{(8)}$: −0.00247 GeV^3

$^3S_1^{(8)}$: 0.00280 GeV^3

Note:
We reproduce the results of the Butenschön and Kniehl analysis, which includes photo-production data and the ^3P_J octet, and excludes the polarization results

$\psi(2S)$ p_T^{min} scan summary

The **$^1S_0$ cross-section fraction** (evaluated at $p_T / M = 6$) changes from essentially zero (or even slightly *negative*…) to become the dominant contribution

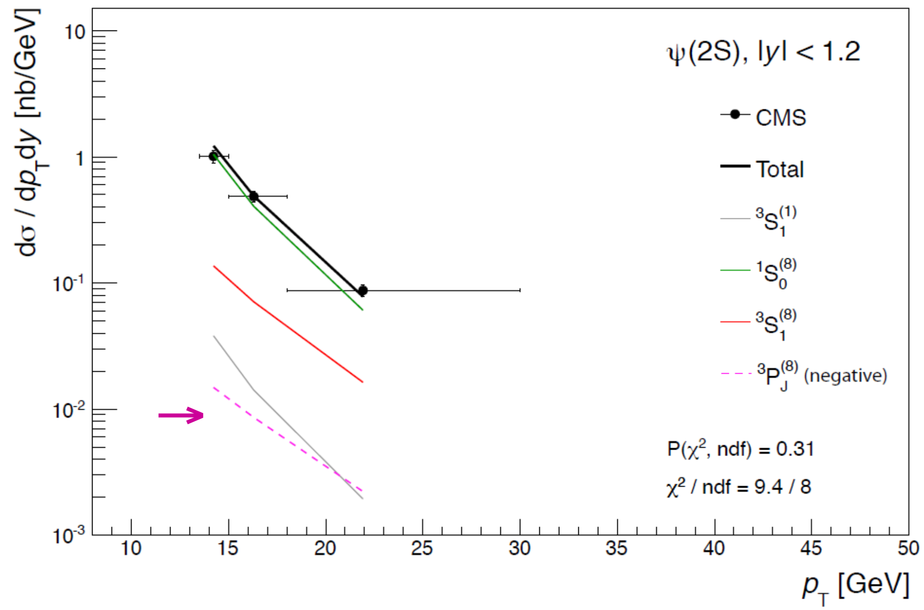


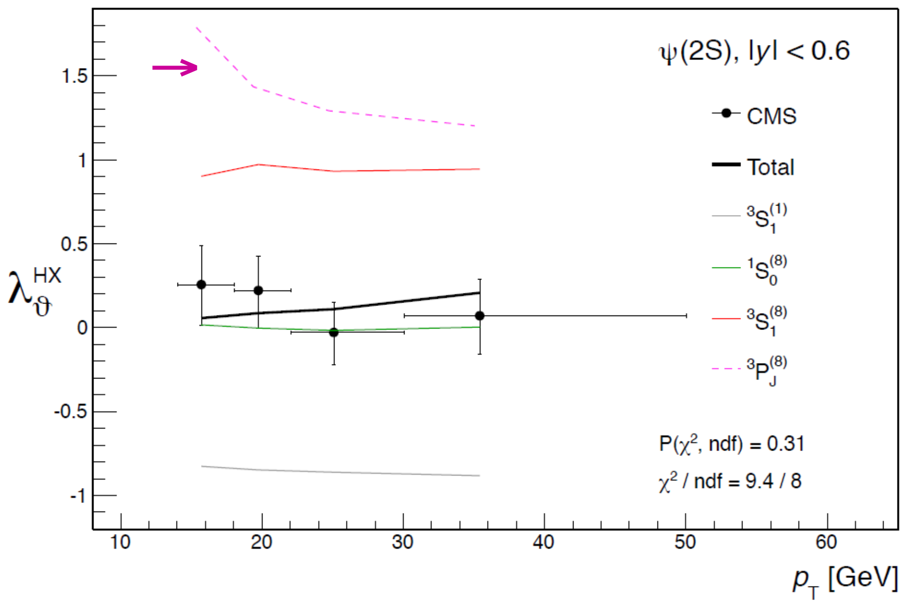
Test of the S-wave octet dominance

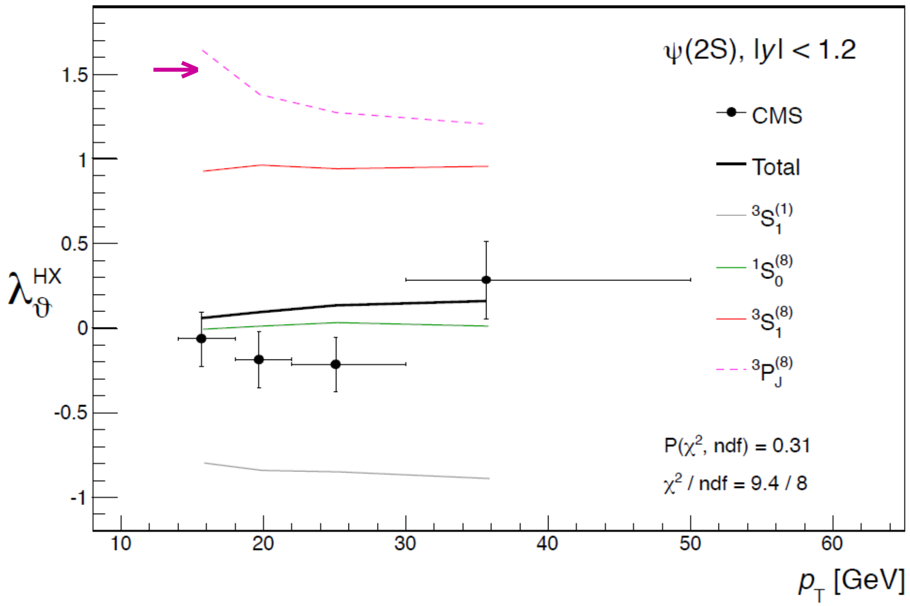
$\psi(2S)$

We now include the P-wave octet term, to check our assumption that it is negligible

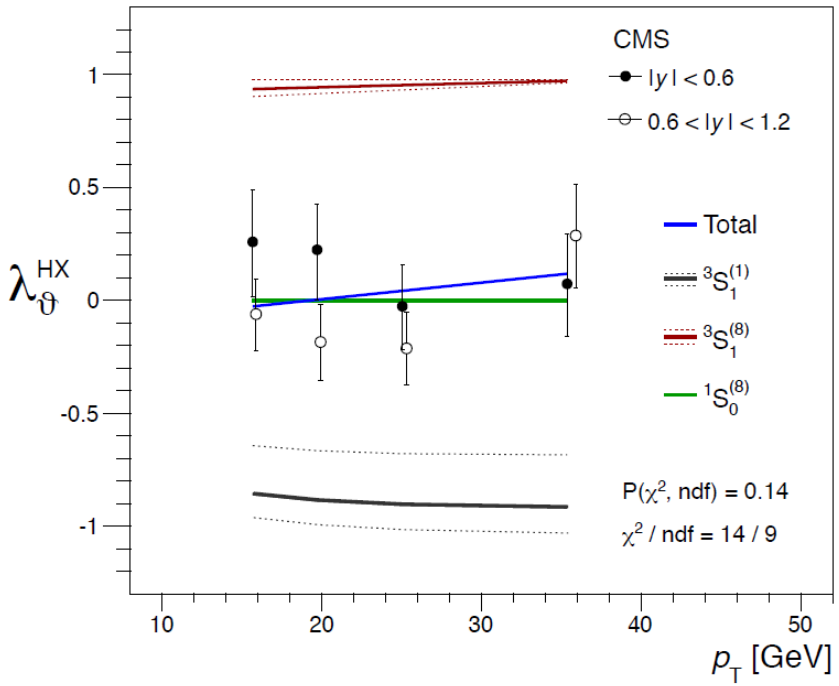
- The fit favours an extremely small (and *negative*...) value of the $^3P_J^{(8)}$ component
- Its inclusion does not improve the fit quality and does not affect the results → it is ok to leave it out ☺

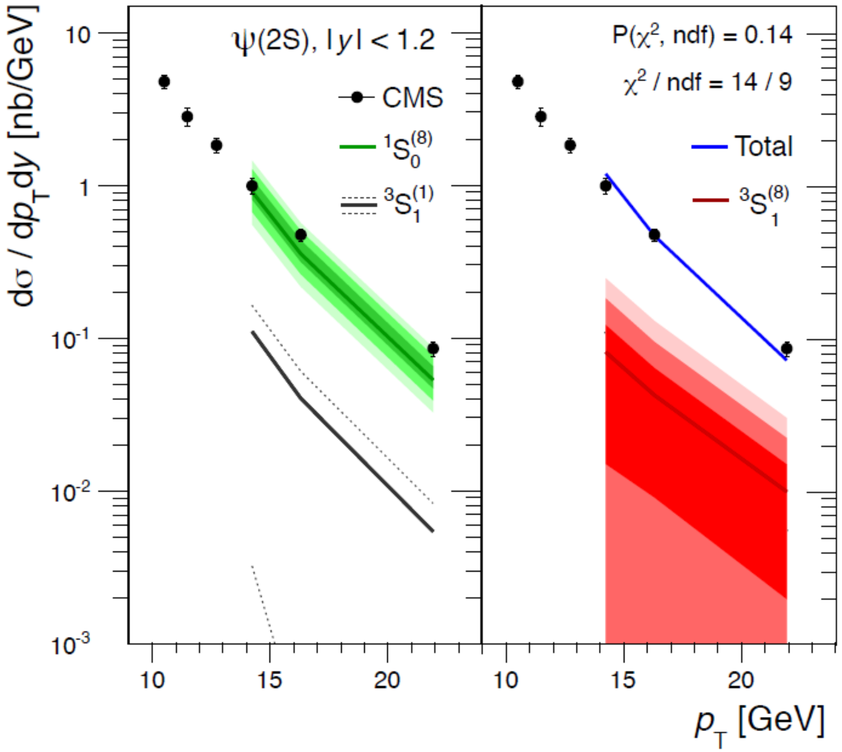






Best fit: $\psi(2S)$

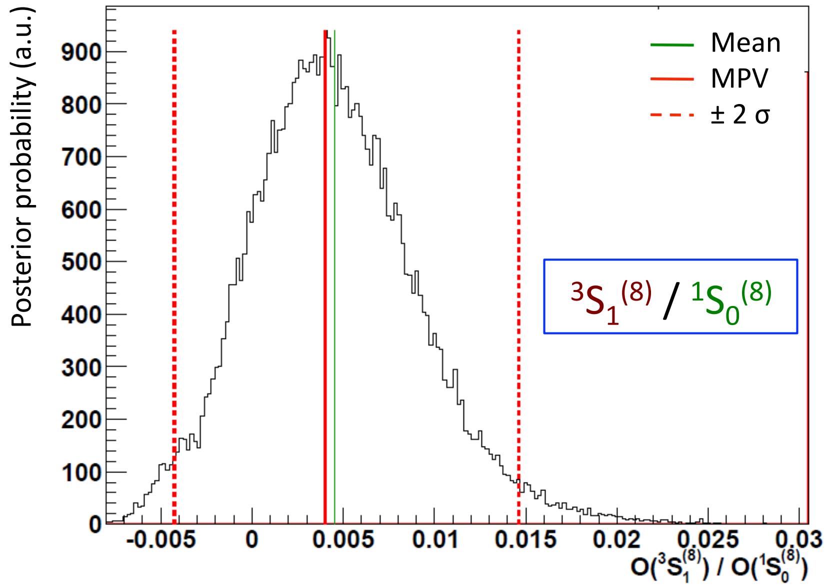




Improvements w.r.t. the previous slides:

- theoretical uncertainties (from NLO – LO)
- uncertainty bands in the $^1S_0$ and $^3S_1$ octets

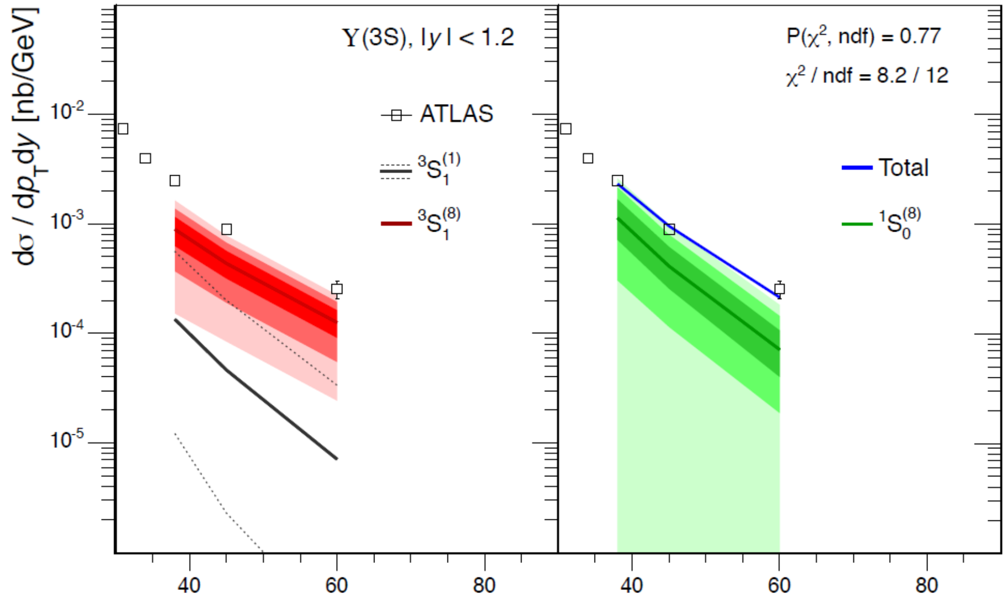
The ratio between the $^3S_1$ and $^1S_0$ LDMEs is below 2%...
The $^3S_1$ transition is practically forbidden

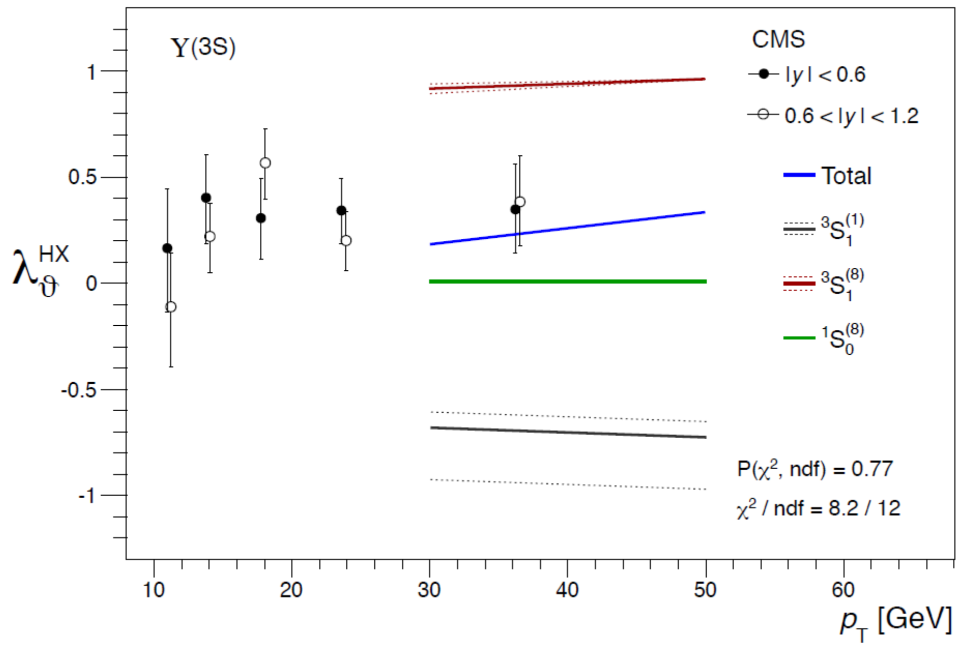


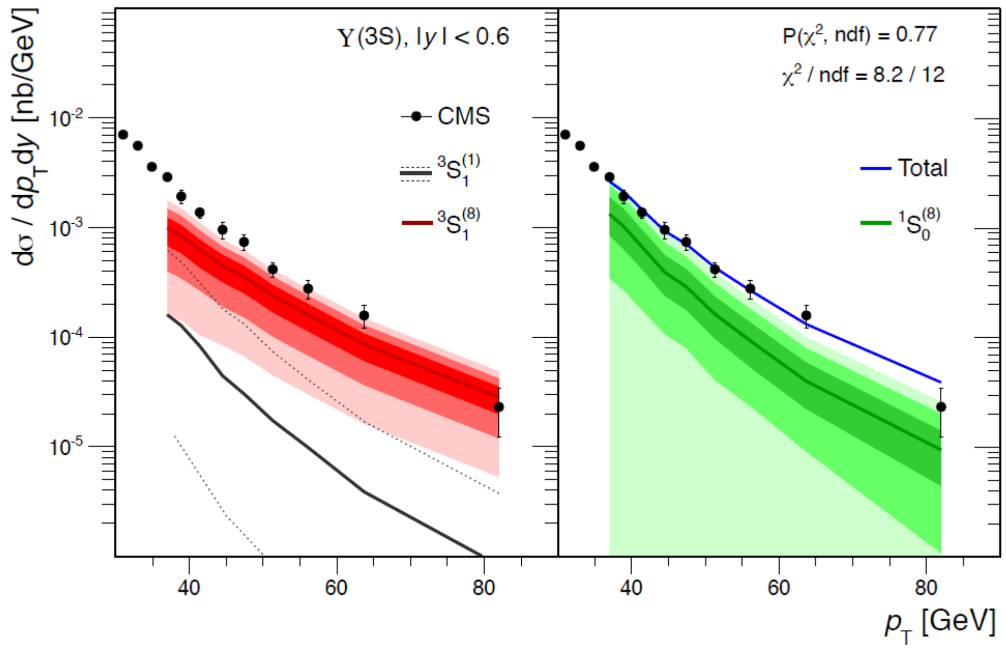
Best fit: $\Upsilon(3S)$

Same fit procedure applied to the $\Upsilon(3S)$, requiring $\boldsymbol{p_T / M > 3.5}$

- equally good fit quality: $P(\chi^2) = 77\%$
- results similar to the $\psi(2S)$ case
- we will soon add lower p_T points
- and simultaneously fit the $\psi(2S)$







An unexpected hierarchy

According to the NRQCD *v*-scaling rules we should see LDMEs of a similar magnitude for the three octet terms…

$$\mathcal{P}(^3\mathbf{P_J}) \sim \mathcal{P}(^3\mathbf{S_1}) \sim \mathcal{P}(^1\mathbf{S_0})$$

Instead, S-wave quarkonium measurements suggest a strong internal hierarchy between these three transitions:

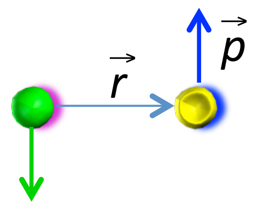
$$\mathcal{P}(^3\mathbf{P_J}) << \mathcal{P}(^3\mathbf{S_1}) << \mathcal{P}(^1\mathbf{S_0})$$

→ strong indication for the understanding of the mechanism of bound-state formation

$Q\bar{Q}$ story

First Encounter

Colour-octet pair production



$|\vec{r}| < 1/m_Q <$ quarkonium radius
(short distance interaction)

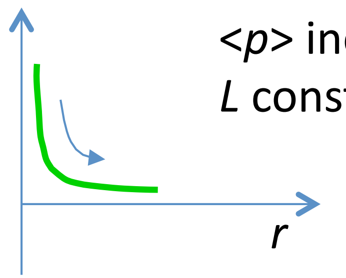
$|\vec{p}| <<<$ quarkonium lab momentum
(relative quark motion "does not exist" at perturbative level)

$\vec{L} = \vec{r} \times \vec{p}$

Not A First-Sight Attraction…

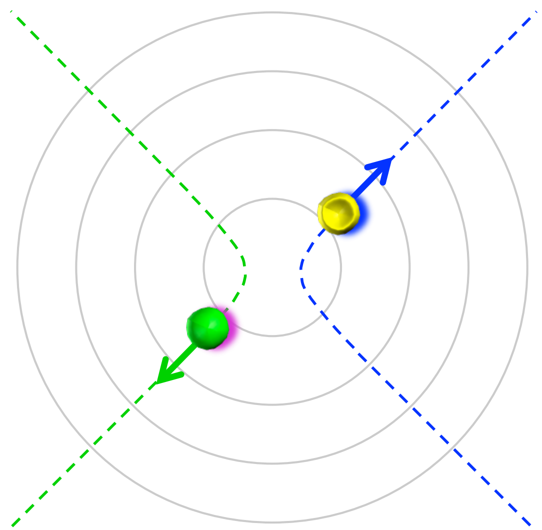
The short-distance potential between two *non-colour-conjugate* quarks is *repulsive*

$$V_{octet}(r) = +\frac{1}{6}\frac{\alpha_s}{r}$$



$\langle r \rangle$ increases
$\langle p \rangle$ increases
L constant

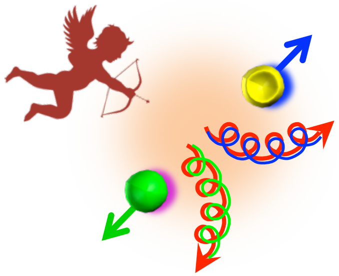
⇒



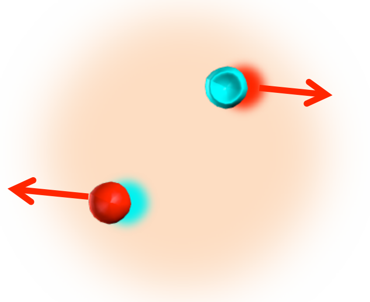
The state grows…

$Q\bar{Q}$ story

Love Strikes

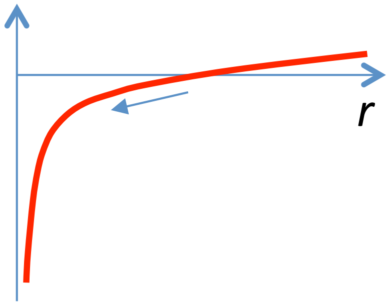


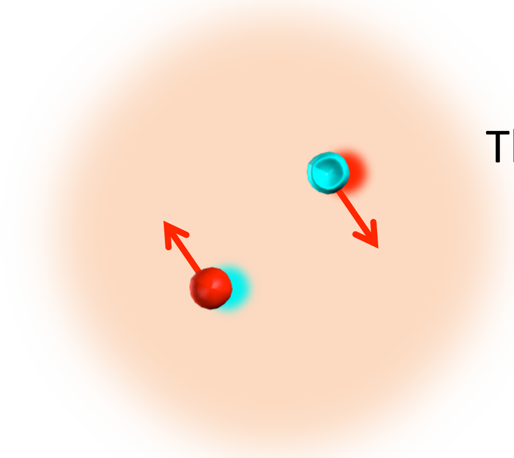
Emission/absorption of soft-gluons (at least one or two) transforms the quark-antiquark pair into a *colour-singlet* state



Since colour-conjugate quarks are *attracted*, the state growth is decelerated

$$V_{\text{singlet}}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r$$





The bound state is formed

The End

The moral

The potential energy drops from slightly positive to negative in the octet-to-singlet transition

→ On average, because of energy conservation, the kinetic energy T must increase

→ Therefore, $\Delta T \leq 0$ transitions are disfavoured or suppressed

ΔT is related to ΔL and ΔS :

The $^3\mathbf{P_J} \to \psi/\Upsilon\, g$ transition is analogous to the $\chi_{c/b} \to \psi/\Upsilon\,\gamma$ decay

$\mathbf{\Delta L = -1}$, $\Delta S = 0$

$\Delta T \sim M(\psi) - M(\chi_c) \sim -0.4$ GeV → suppressed

The $^1\mathbf{S_0} \to \psi/\Upsilon\, g$ transition is analogous to the reverse of the $\psi/\Upsilon \to \eta_{c/b}\,\gamma$ decay

$\Delta L = 0$, $\mathbf{\Delta S = +1}$

$\Delta T \sim M(\psi) - M(\eta_c) \sim +0.1$ GeV → favoured

Polarization as a crucial test

This picture favours the $^1S_0$ octet components and strongly disfavours the ^3P_J term

Together with the v-scaling rules, it implies that

- the $^1S_0$ and $^3S_1$ components dominate colour-octet production of $^3S_1$, 1^{--} quarkonia (ψ, Υ states), with $^1S_0$ favoured with respect to $^3S_1$
- the $^1S_0$ component (ΔT-favoured) and/or the $^3S_1$ component (v-favoured) dominate colour-octet production of ^3P_J, J^{++} quarkonia (χ_c, χ_b states)

These basic predictions are *suggested* by the ψ + Υ polarization measurements and should be *confirmed or falsified* by forthcoming measurements of χ polarizations

ψ, Υ:

$^1S_0 \rightarrow \lambda_\vartheta = 0$ — strongly favoured by current data

$^3S_1 \rightarrow \lambda_\vartheta = +1$

$^3P_J \rightarrow \lambda_\vartheta > +1$

χ:

$^1S_0 \rightarrow \lambda_\vartheta = 0$

$^3S_1 \rightarrow \lambda_\vartheta(\chi_1) = +1/5$

$\lambda_\vartheta(\chi_2) = +21/73$

to be measured

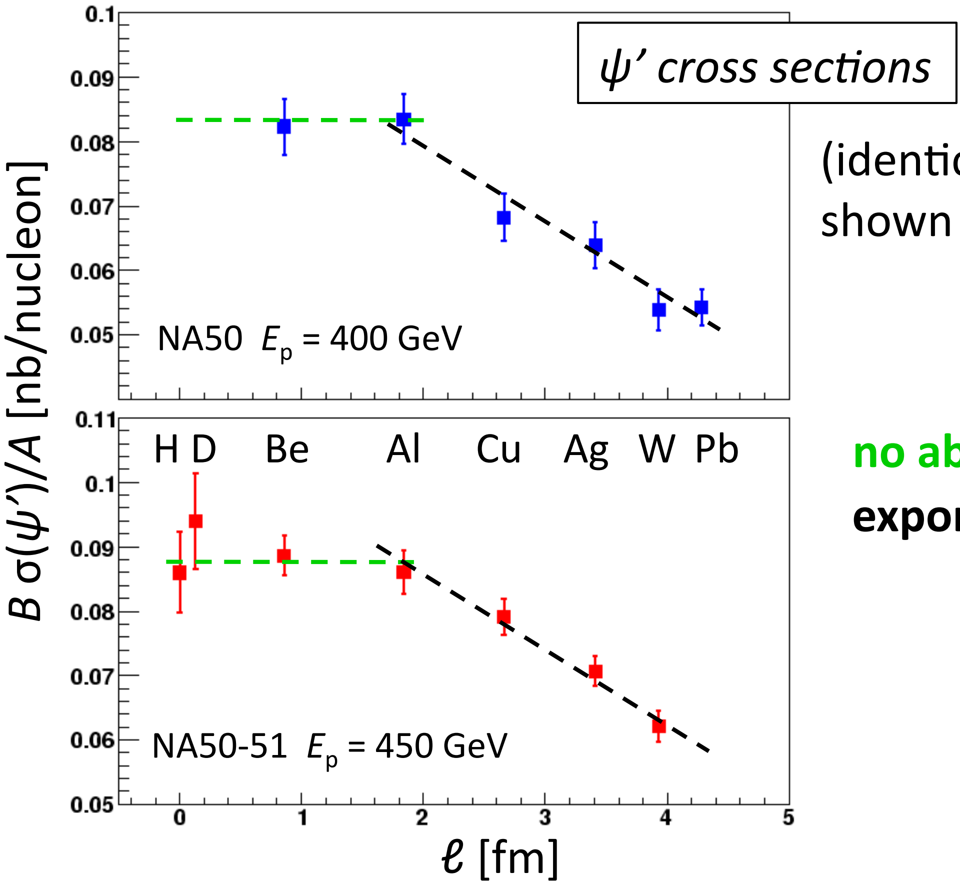
An immediate connection: p-A studies

Charmonium absorption in p-A collisions is usually parametrized as

$$\sigma(\mathrm{pA}) = \sigma_0 \cdot e^{-\rho\,\Sigma\,\ell(A)}$$
$$\sim \sigma_0\,[\,1 - \rho\,\Sigma\,\ell(A)\,]$$

ρ = density of nucleus (~ A-independent)
$\ell(A)$ = length of nuclear matter crossed by charmonium
Σ = nuclear absorption cross section

However, σ(pA) measurements do not follow this pattern down to low A:
there seems to be **no charmonium absorption in the smallest nuclei** (D, Be, Al):



(identical patterns shown by J/ψ data)

no absorption

exponential-like absorption

An immediate connection: p-A studies

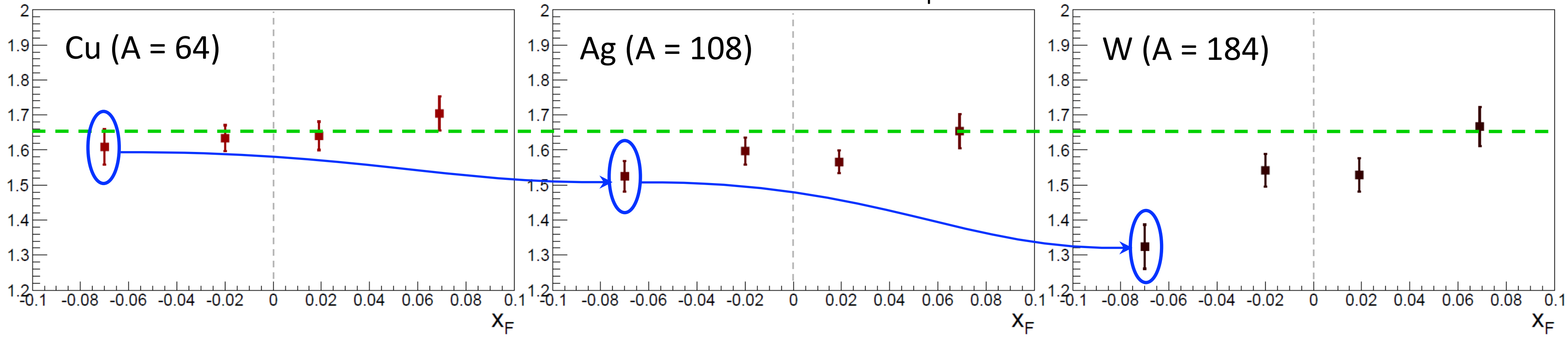
Charmonium absorption in p-A collisions is usually parametrized as

$$\sigma(\mathrm{pA}) = \sigma_0 \cdot e^{-\rho\,\Sigma\,\ell(A)}$$
$$\sim \sigma_0\,[\,1 - \rho\,\Sigma\,\ell(A)\,]$$

ρ = density of nucleus (~ A-independent)
$\ell(A)$ = length of nuclear matter crossed by charmonium
Σ = nuclear absorption cross section

Moreover, this model does not account for the asymmetry shown by the ψ'-to-J/ψ ratios between positive and negative longitudinal momentum ($x_F > 0$ / $x_F < 0$):

$B\sigma(\psi') / B\sigma(\mathrm{J}/\psi)$ [%], NA50 E_p = 450 GeV



Larger absorption difference at $x_F < 0$ (quarkonium travelling slower through the nucleus)

(similar pattern shown by E866 data at E_p = 800 GeV)

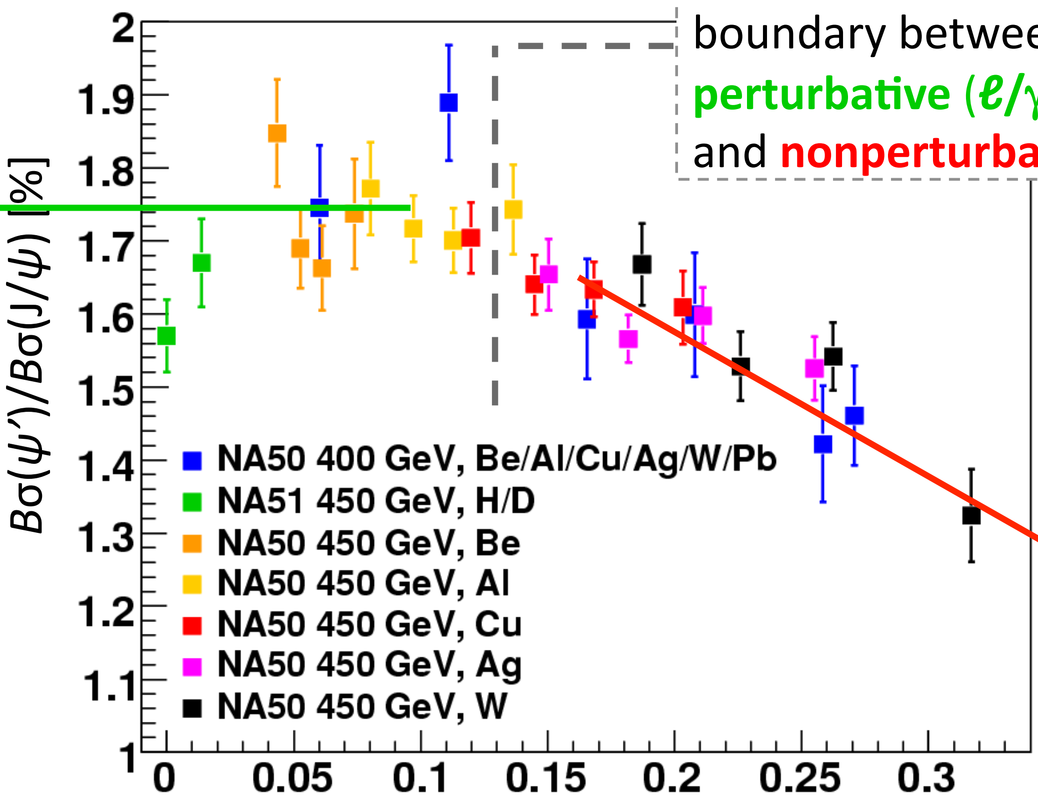
This asymmetry cannot be explained by nuclear shadowing of the parton densities (nPDFs) nor by parton energy loss, since these initial-state effects cancel in the $\sigma(\psi') / \sigma(\mathrm{J}/\psi)$ ratio

“Seeing” quarkonium formation

Putting the A and x_F dependencies together, we see, after a threshold, a monotonic scaling with the ***proper time*** $\ell(A) / \gamma(x_F)$ of quarkonium permanence inside the nucleus

quarkonium not yet absorbed, still a “point-like” object

boundary between **perturbative** ($\ell/\gamma < 1/m_Q$) and **nonperturbative** regimes!



larger absorption effects for slow quarkonium in a large nucleus

two small and very similar “pre-resonance” objects ← ℓ/γ [fm] → fully-formed J/ψ and ψ' “observable” bound states

The QQbar state grows !

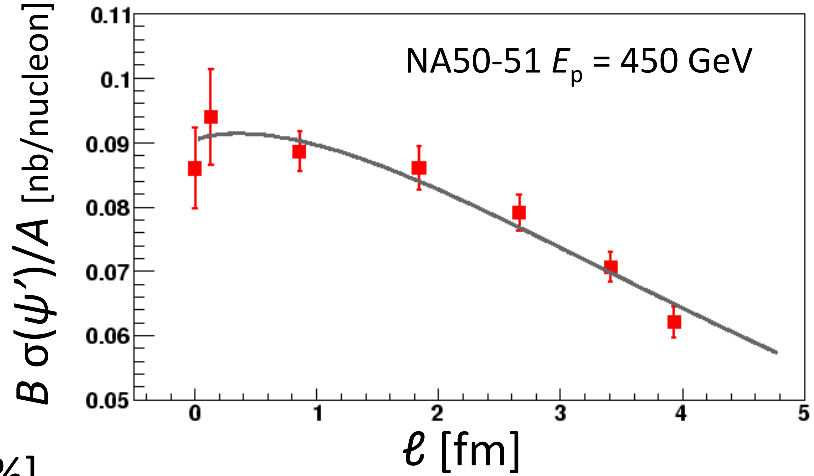
(absorption cross section proportional to object size)

→ nuclear absorption in p-A collisions as “tomography” of quarkonium formation !

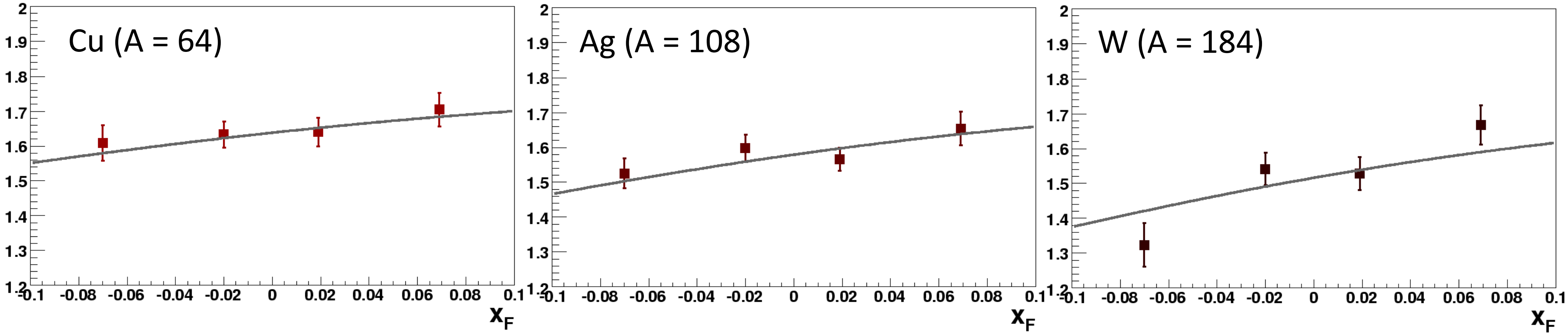
A further hint of "unified" production mechanism

Improved model including formation effects

- All charmonia come from ***one*** **"pre-ψ/χ" object** too small to be absorbed and having "lifetime" τ :
  $$dP_{formation}/d\ell = 1/(c\,\tau)$$
- Formed states are absorbed with probabilities
  $$dP_{abs}/d\ell = \rho\,\Sigma(J/\psi) \quad \text{or} \quad \Sigma(\psi') \quad \text{or} \quad \Sigma(\chi_c)$$
- Absorption cross sections scale like squared radii:
  $$\Sigma(J/\psi) : \Sigma(\chi_c) : \Sigma(\psi') = 1 : 2.1 : 3.3$$



$B\sigma(\psi') / B\sigma(J/\psi)$ [%]



The data are reproduced by a fit yielding **c τ = 0.35 ± 0.15 fm**
consistent with the formation-time expectation $h / [m_{\psi'}\,(m_{\chi c}) - m_{J/\psi}] \sim 0.3\text{-}0.5$ fm

→ scenario quantitatively consistent with all charmonia being produced by *one* mechanism

Summary

Instead of asking if NRQCD is the correct theory, we search for its domain of validity: above which p_T / M does it describe the data?

We move the polarization data from the periphery to the center of the study, realizing that it is the most stringent constraint in discriminating the theory terms

This "Copernican revolution" provides a simple solution to the polarization puzzle !

And comes together with several nice features:
- the fits are stable and the results evolve continuously with the p_T / M cut
- the results do not involve negative cross sections nor unphysical polarizations ($\lambda_\theta > 1$)
- and are insensitive to the lack of perturbative convergence of the mysterious ^3P_J octet

The path for further progress includes:
= new experimental measurements at high p_T and of the P-wave polarizations
= more theoretical efforts in understanding the P-octet term

Many thanks
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and to Sergei Baranov and Geoff Bodwin for many discussions