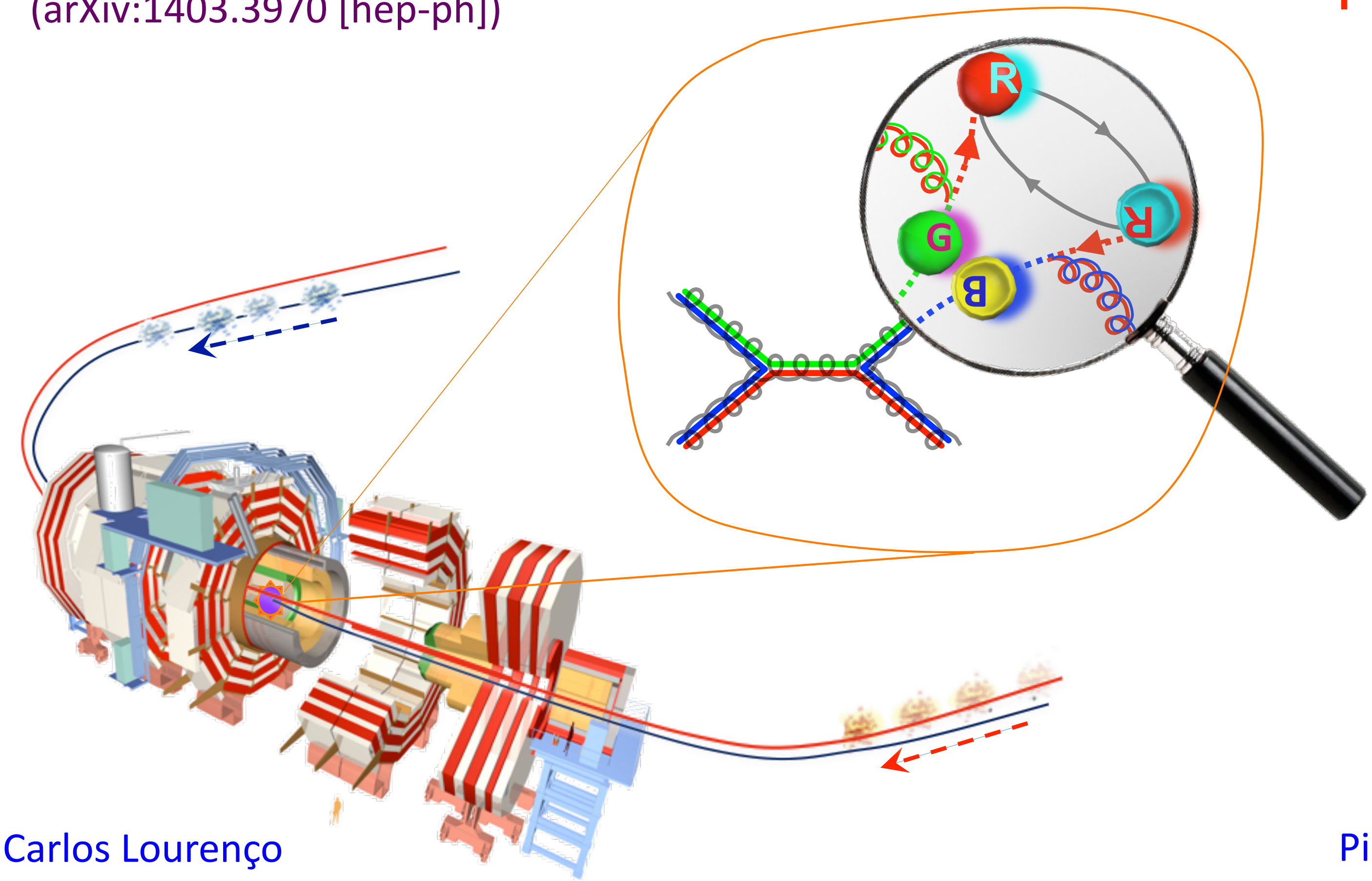
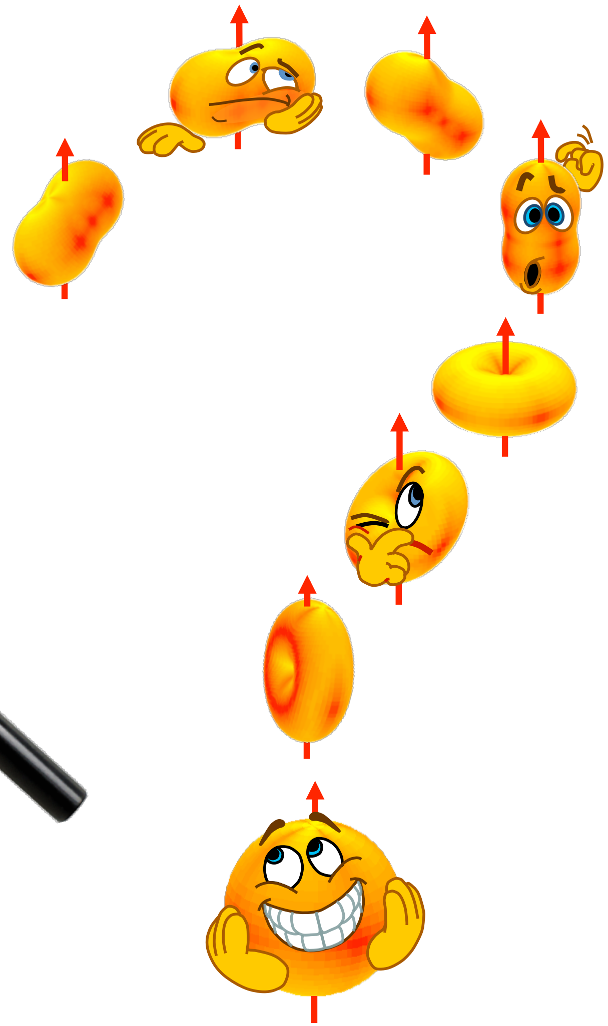
Quarkonium production in the LHC era
A polarized perspective

A data driven analysis of quarkonium production measurements

All the details can be found in
Physics Letters B 736 (2014) 98–109
(arXiv:1403.3970 [hep-ph])





Carlos Lourenço
QWG 2014, 14.11.2014

In collaboration with
Pietro Faccioli, Valentin Knünz,
João Seixas and Hermine Wöhri

The take home message

Q: Can the measured $\psi(2S)$ cross section and polarization, vs. p_T and y, be described as a superposition of NLO singlet and octet contributions?

A: Yes ! With good accuracy, for $p_T > 10$ GeV

Q: What is the relative importance of the octet terms considered?

A: The $^1S_0^{[8]}$ dominates; the $^3S_1^{[8]}$ is small (few %); the $^3P_J^{[8]}$ is negligible.

The "quarkonium polarization puzzle" has a simple solution, inspired by the patterns seen in the data

The basic inputs

1) We start from the singlet ($^3S_1^{[1]}$) and octets ($^1S_0^{[8]}$, $^3S_1^{[8]}$, $^3P_J^{[8]}$) NLO SDCs of Butenschön & Kniehl (*)
for the cross sections and polarizations: $\sigma = 2\sigma_T + \sigma_L$ and $\lambda_\vartheta = (\sigma_T - \sigma_L) / (\sigma_T + \sigma_L)$

Other octets can be neglected: $v^2 < 1$ and LDMEs are proportional to powers of v^2

S-wave quarkonia : J/ψ, ψ(2S), 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	$v^{3\text{-}4}$	v^4	v^8	v^4	v^8	v^{12}	...

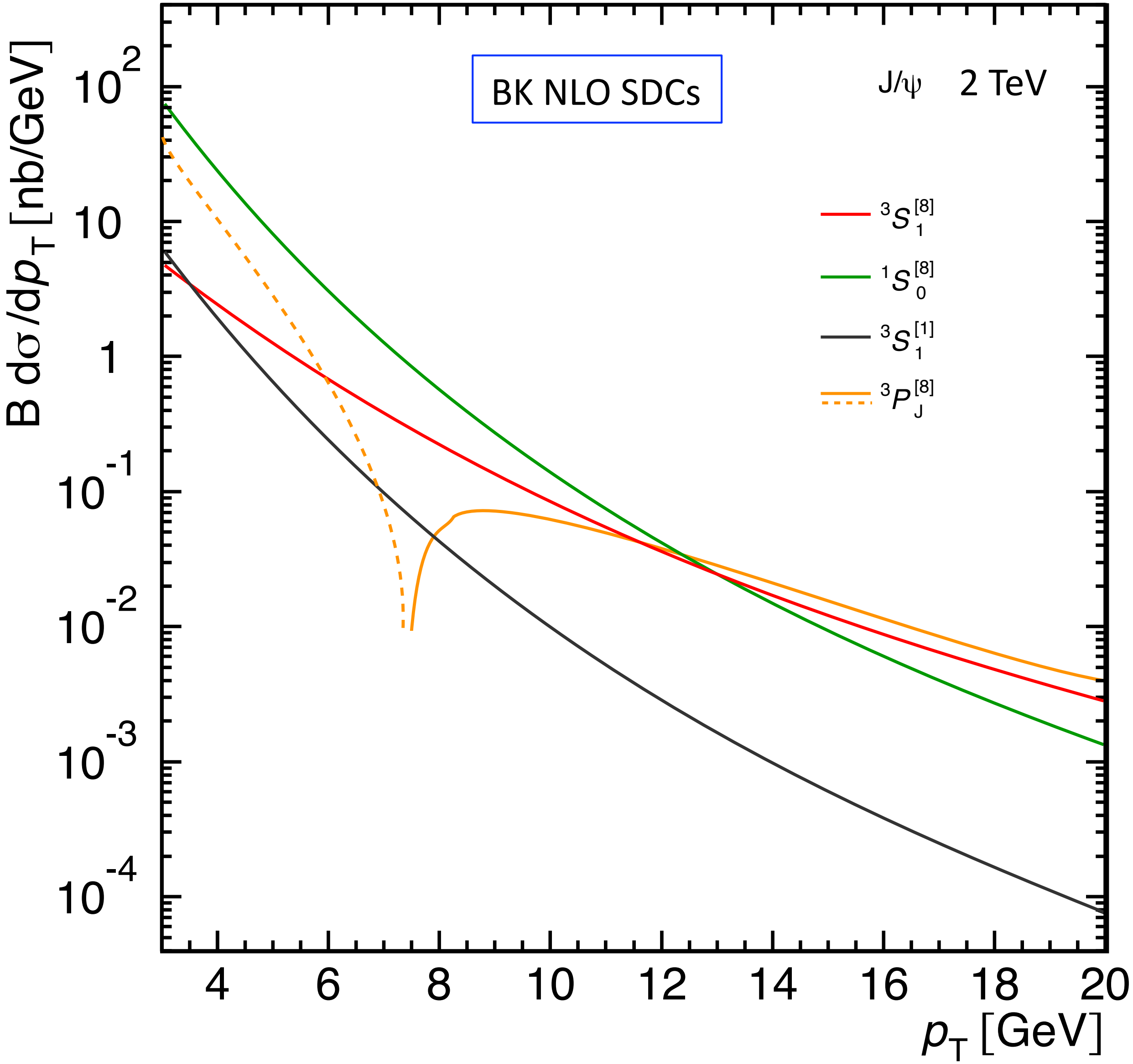
2) We concentrate on the ψ(2S) because it is not affected by P-wave feed-down decays
It is good to start with the simplest case; less "freedom" in the fits → more reliable results

We also looked at the ϒ(3S); our paper was finished before the χ_b(3P) feed-down was known...

3) We place considerable care in the treatment of uncertainties and correlations,
when fitting the data with a superposition of theory functions

(*) M. Butenschön & B. Kniehl, PRL 108, 172002 (2012)
Many thanks to Mathias and Bernd for sending us their data files

The SDCs in the cross section dimension



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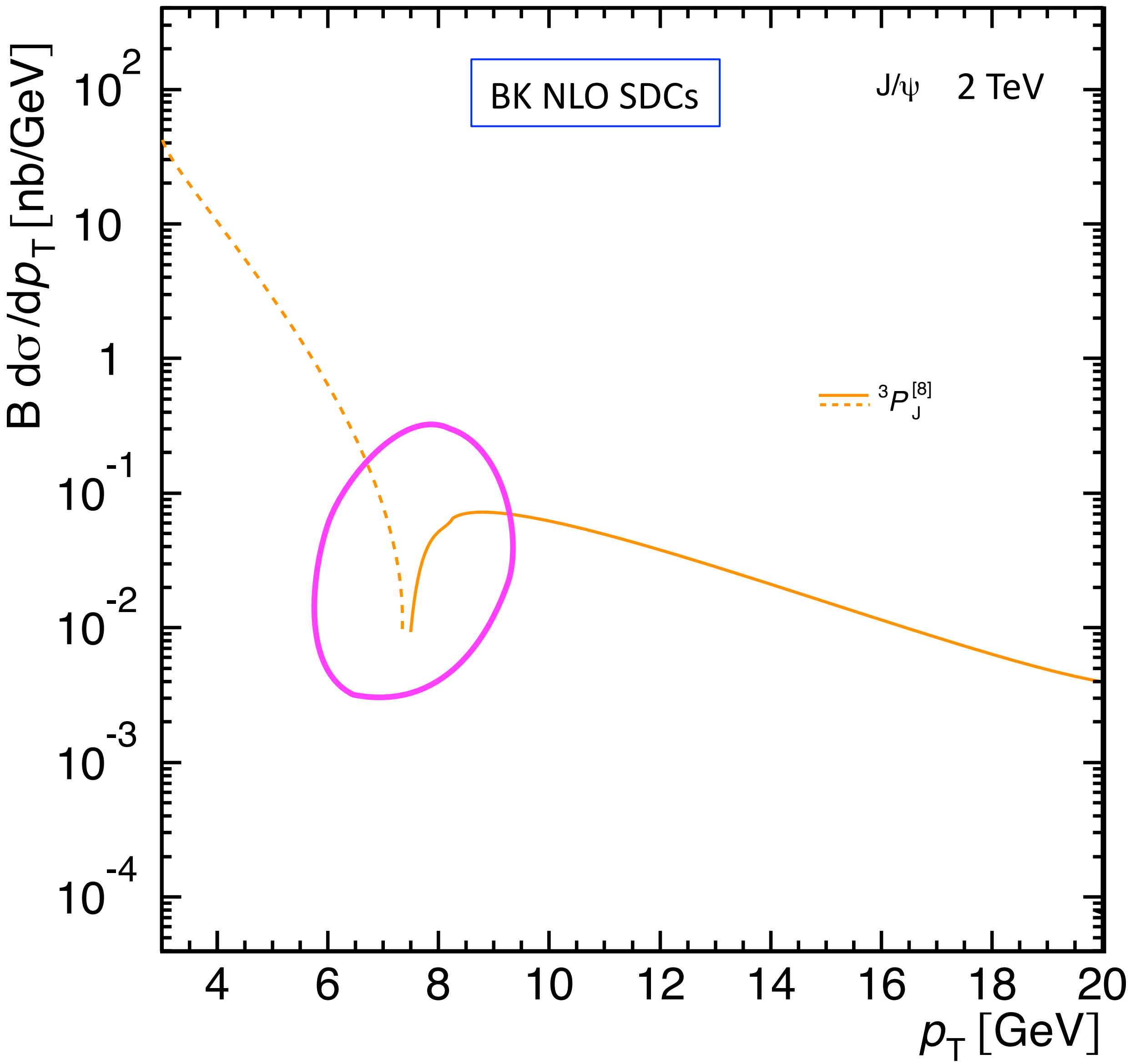
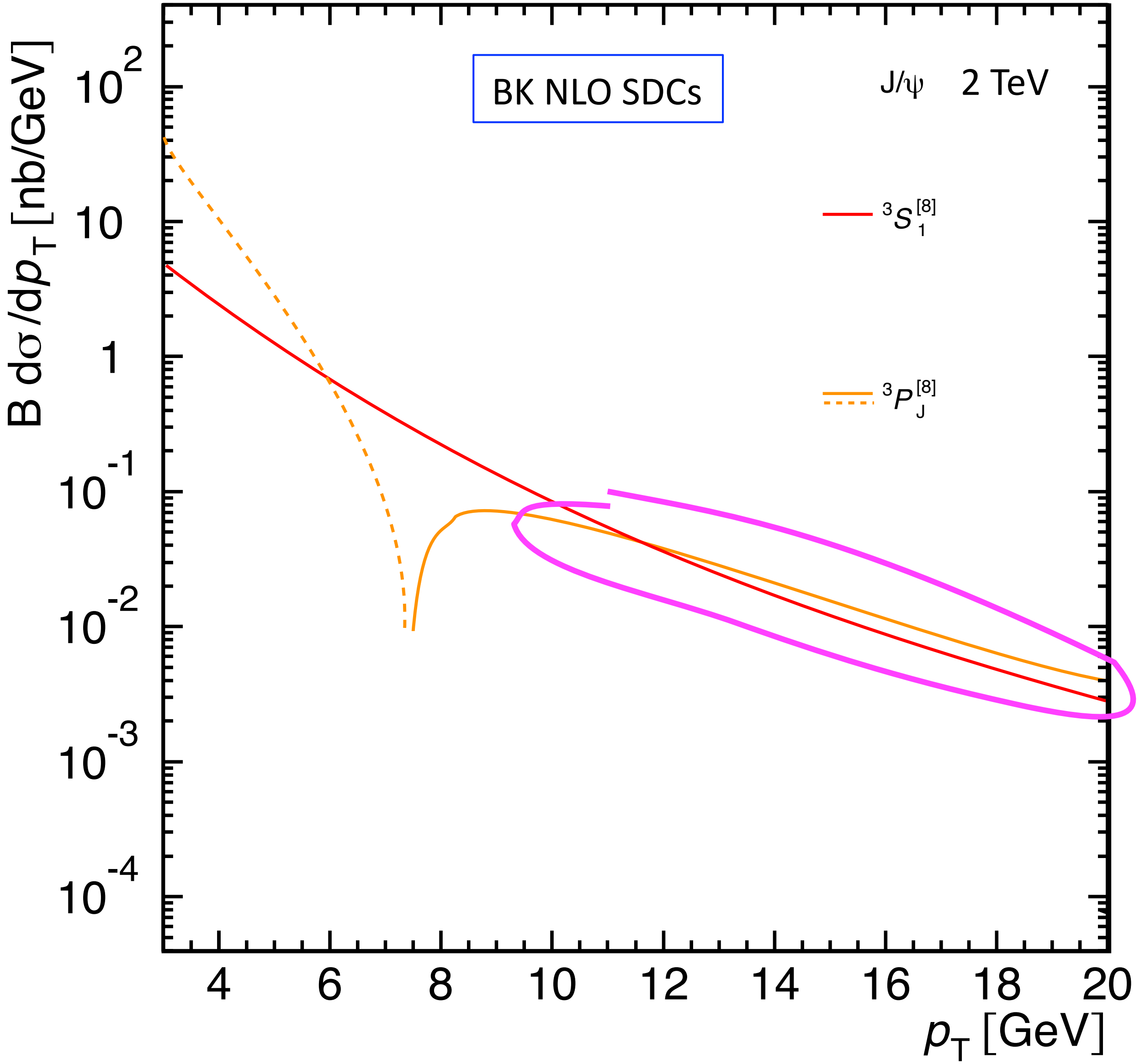


At p_T = 7.5 GeV,
the $^3P_J^{[8]}$ SDC changes sign

→ *negative cross section…*
at low or high p_T
(dep. on LDME sign)

The SDCs in the cross section dimension



For p_T > 10 GeV, the $^3S_1^{[8]}$ and $^3P_J^{[8]}$ SDCs are *parallel to each other*

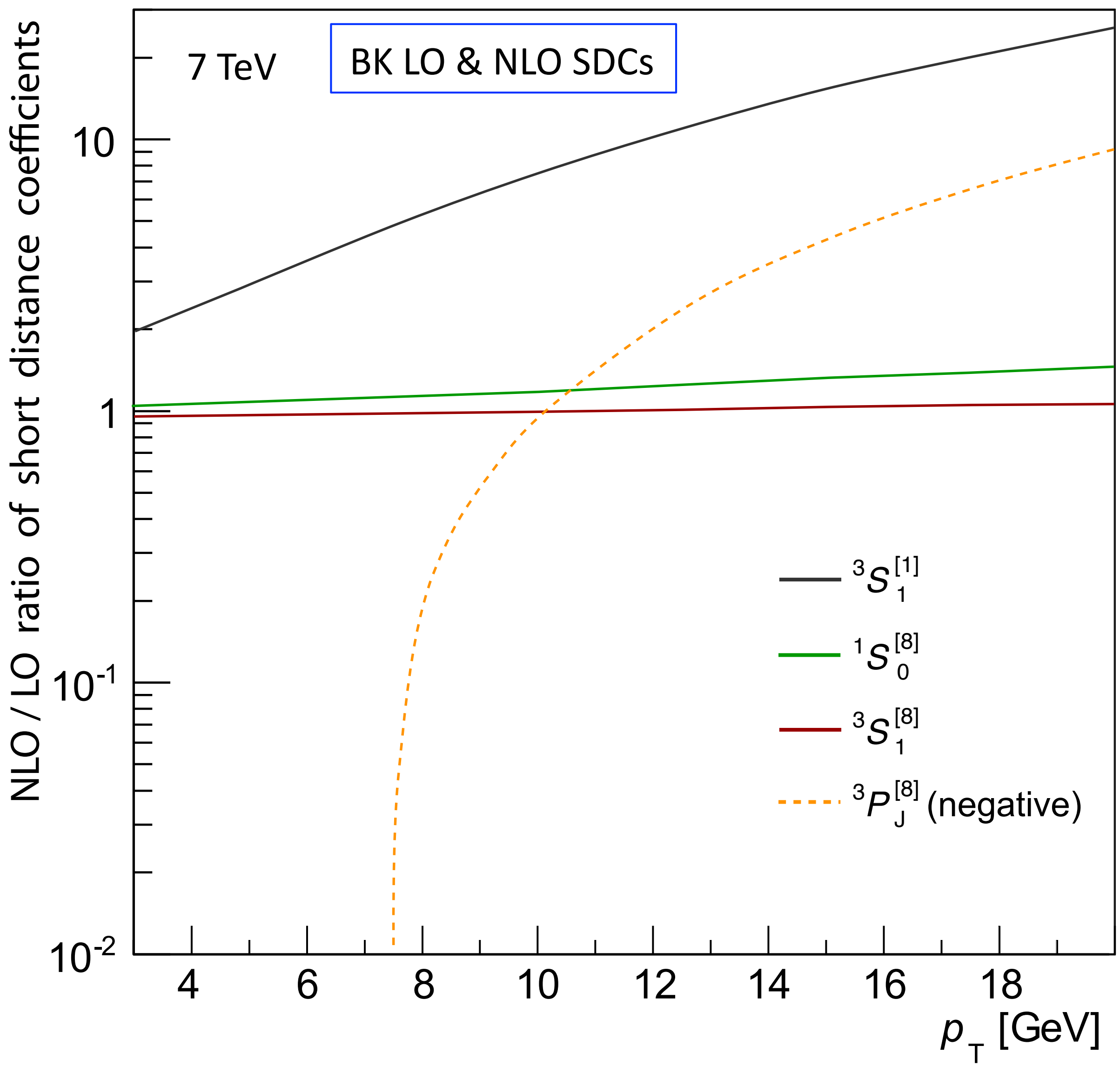
→ cross sections cannot discriminate their individual contributions

Data can be described equally well by setting $^3P_J^{[8]}$ to zero and only fitting the $^3S_1^{[8]}$ LDME

Otherwise, the fit is under-constrained: many solutions give the same result because these two terms annihilate each other

Less "freedom" in the fits → more reliable results

The SDCs in the cross section dimension: LO vs. NLO



From LO to NLO,
the $^1S_0^{[8]}$ and $^3S_1^{[8]}$ octets
change very little

→ pQCD works ☺

But the $^3P_J^{[8]}$ octet changes a lot,
even the sign ☹

“Higher order” corrections
will surely have a strong impact
in this octet SDC

The uncertainty on the $^3P_J^{[8]}$ SDC
(NLO-LO) is so large that it does
not constrain the fit to the data

Less “freedom” in the fits
→ more reliable results

The SDCs in the polarization dimension

Quarkonium polarization is characterized by λ_θ :

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

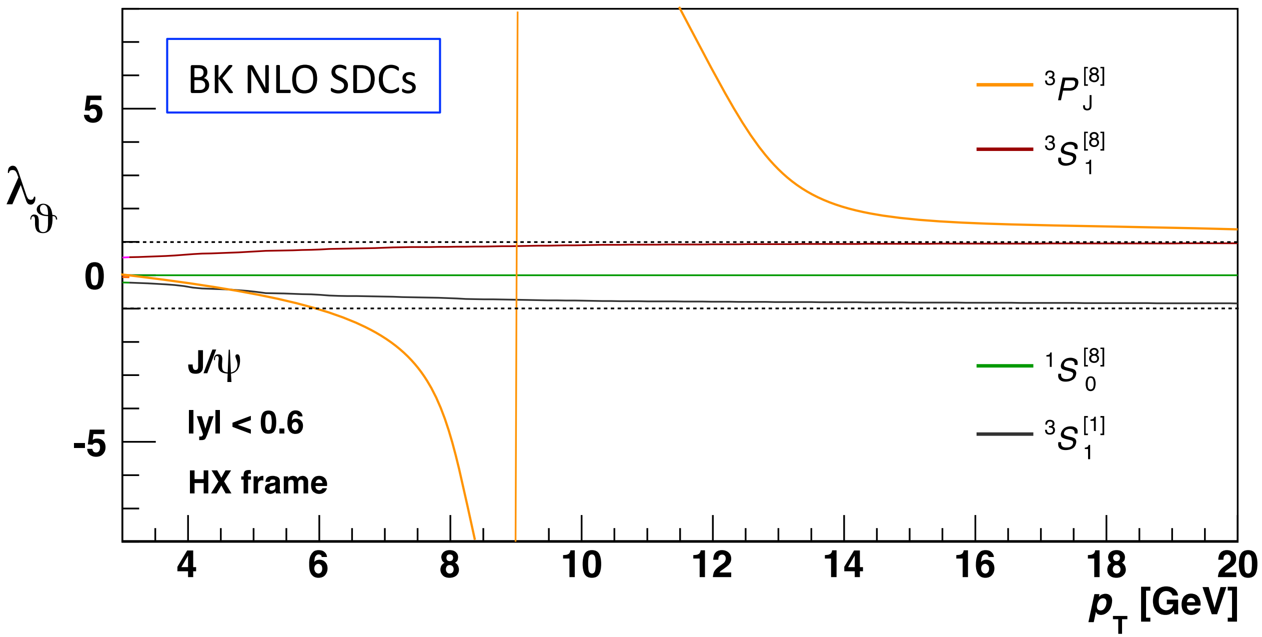
Each colour singlet and octet has a specific polarization associated (values in the helicity frame):

${}^3S_1^{[1]} \rightarrow \lambda_\vartheta \sim -0.9$ at NLO and high p_T (it is ≈ +1 at LO… but has a small contribution)

${}^1S_0^{[8]} \rightarrow \lambda_\vartheta = 0$ at LO, NLO, etc; isotropic wave function

${}^3S_1^{[8]} \rightarrow \lambda_\vartheta = +1$ at LO, NLO, etc; at high p_T, where the fragmenting gluon is "real"

${}^3P_J^{[8]} \rightarrow \lambda_\vartheta$ changes from $-\infty$ to $+\infty$ at $p_T \approx 9$ GeV ! It remains $> +1$ at high p_T

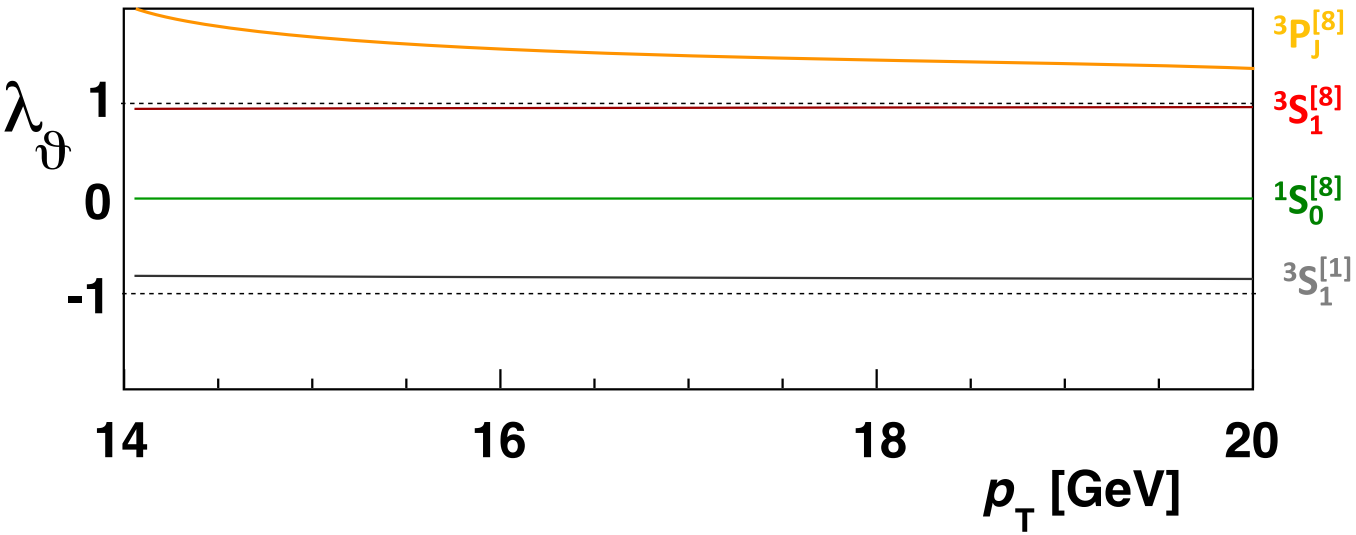


Conceptually:
the function $\lambda_\vartheta({}^3P_J^{[8]})$
looks unphysical

Technically:
should we fit measured data
with discontinuous functions?

The SDCs in the polarization dimension

To discriminate between the several (singlet and octet) terms, the polarization has a *much higher* discrimination power. The differential cross sections have very similar ("exponential") shapes while the polarizations could not be more different from each other ☺



Fitting LDMEs from cross sections and then predicting the polarizations is a historical heritage from times when the measured polarizations were inconsistent and ambiguous

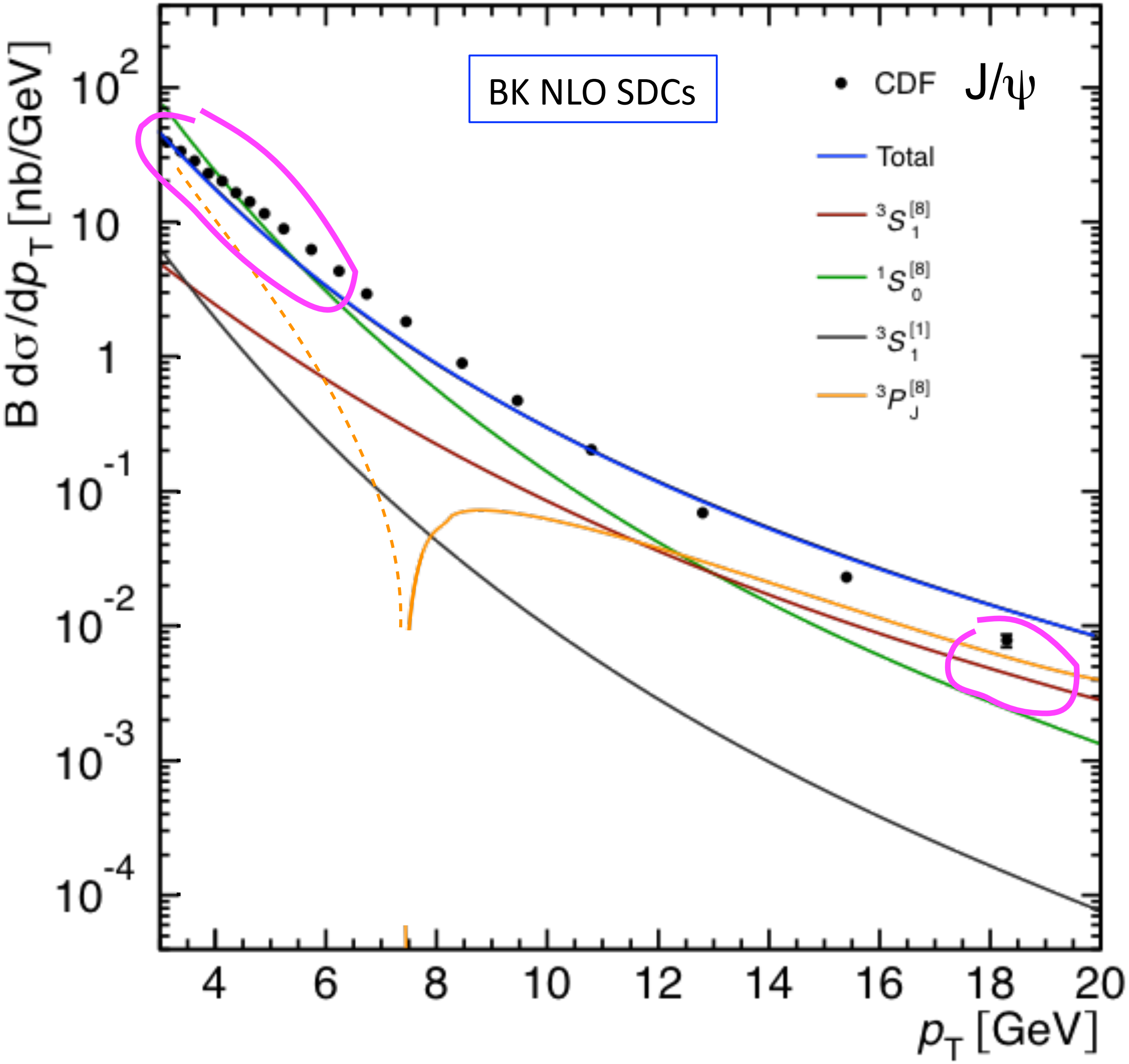
Conceptually, the polarization measurements must be at the centre of the analyses !

Furthermore, *fixed-order* calculations are expected to *fail* reproducing the low-p_T cross sections, which have the smallest uncertainties → the extracted LDMEs will be biased

Instead, the $\lambda_\vartheta(^1S_0^{[8]}) = 0$ and $\lambda_\vartheta(^3S_1^{[8]}) \approx +1$ polarizations can be deduced independently of pQCD and p_T

The "quarkonium polarization puzzle"

The J/ψ cross section is fitted to the (fixed) singlet ($^3S_1^{[1]}$) plus the (free) octets ($^1S_0^{[8]}$, $^3S_1^{[8]}$, $^3P_J^{[8]}$)



The fit is determined by the low-p_T data (down to 3 GeV !)

The $^3S_1^{[8]}$ and $^3P_J^{[8]}$ SDCs dominate at high p_T

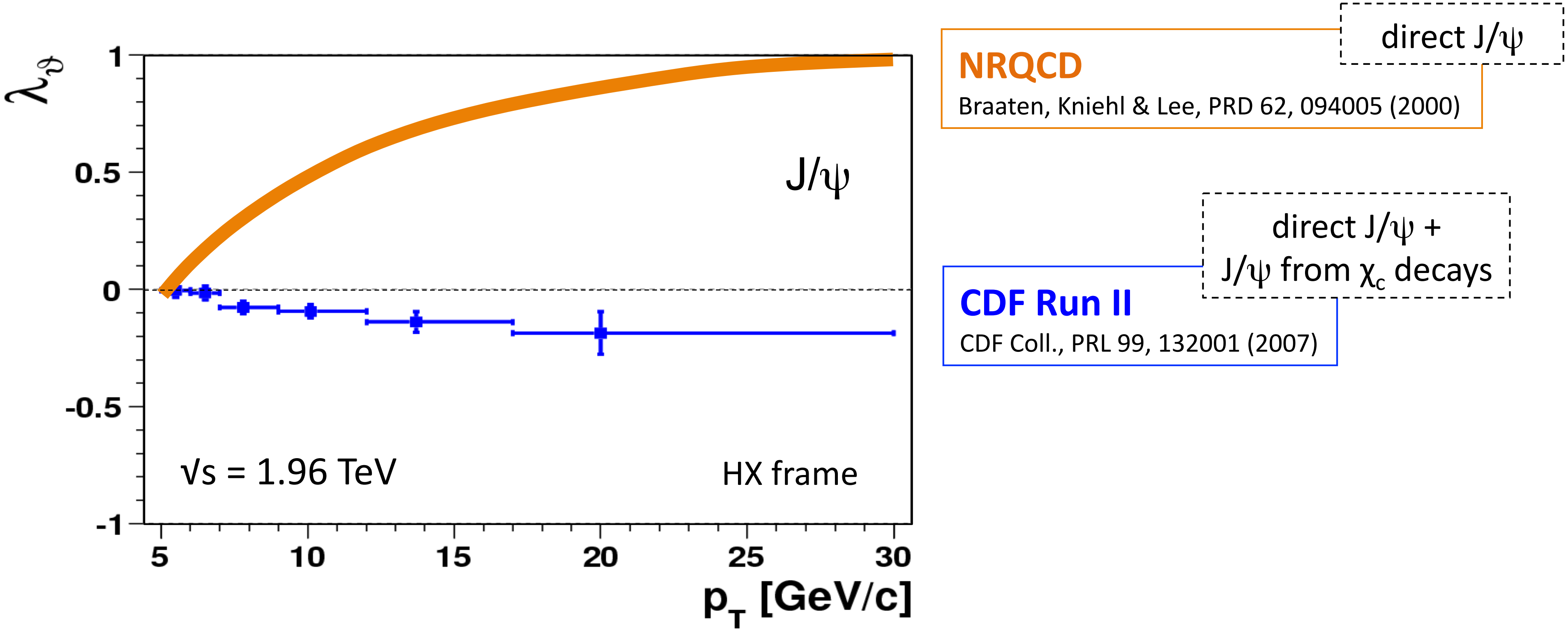
$\lambda_\vartheta \rightarrow \approx 1$

a famous "NRQCD prediction"

The “quarkonium polarization puzzle”

NRQCD predicts transverse polarization at high p_T, not observed in the data

The CDF J/ψ data ruled out the $\lambda_\vartheta \to \approx 1$ “NRQCD prediction”



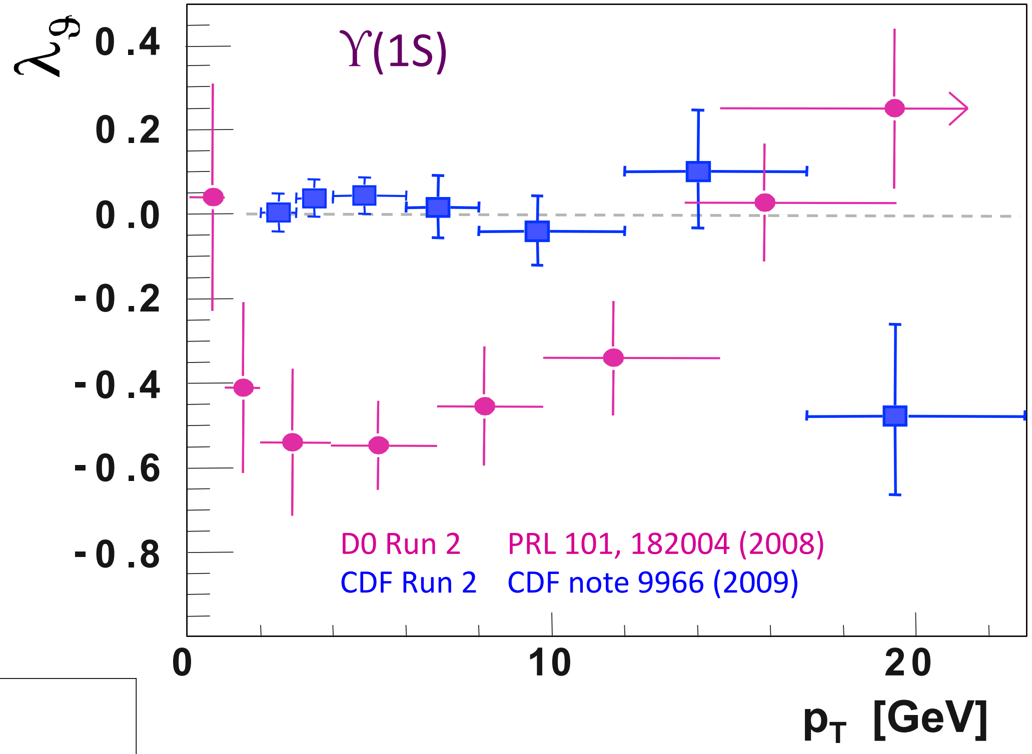
The “quarkonium polarization puzzle”

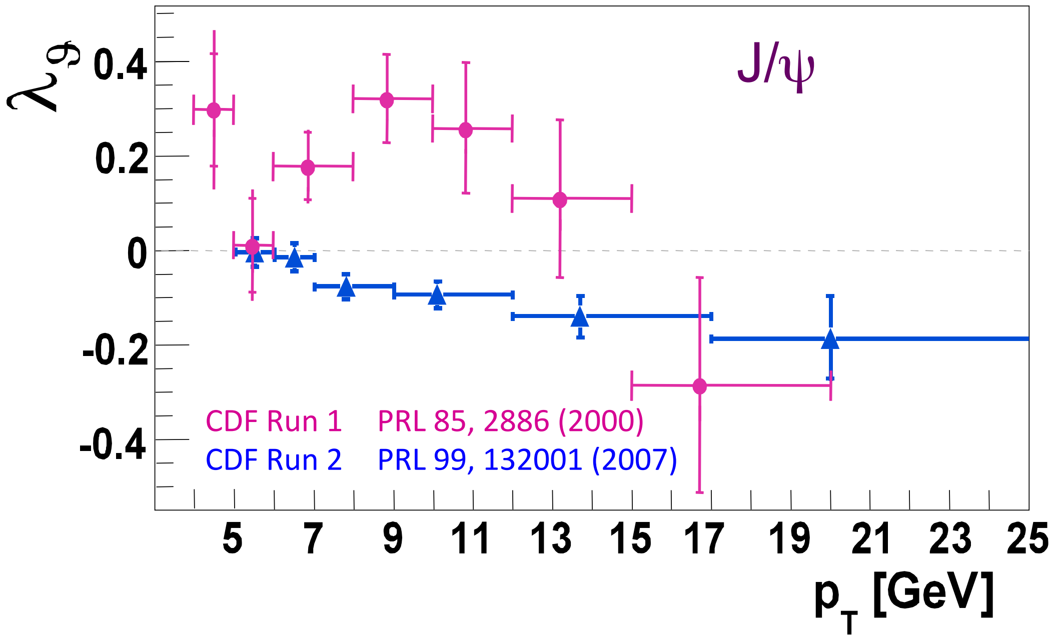
However, people remained doubtful:

Tevatron data might not reach high enough p_T

CDF Run 1 and Run 2 :
→ J/ψ polarizations disagree

CDF and D0 :
→ ϒ(1S) polarizations disagree

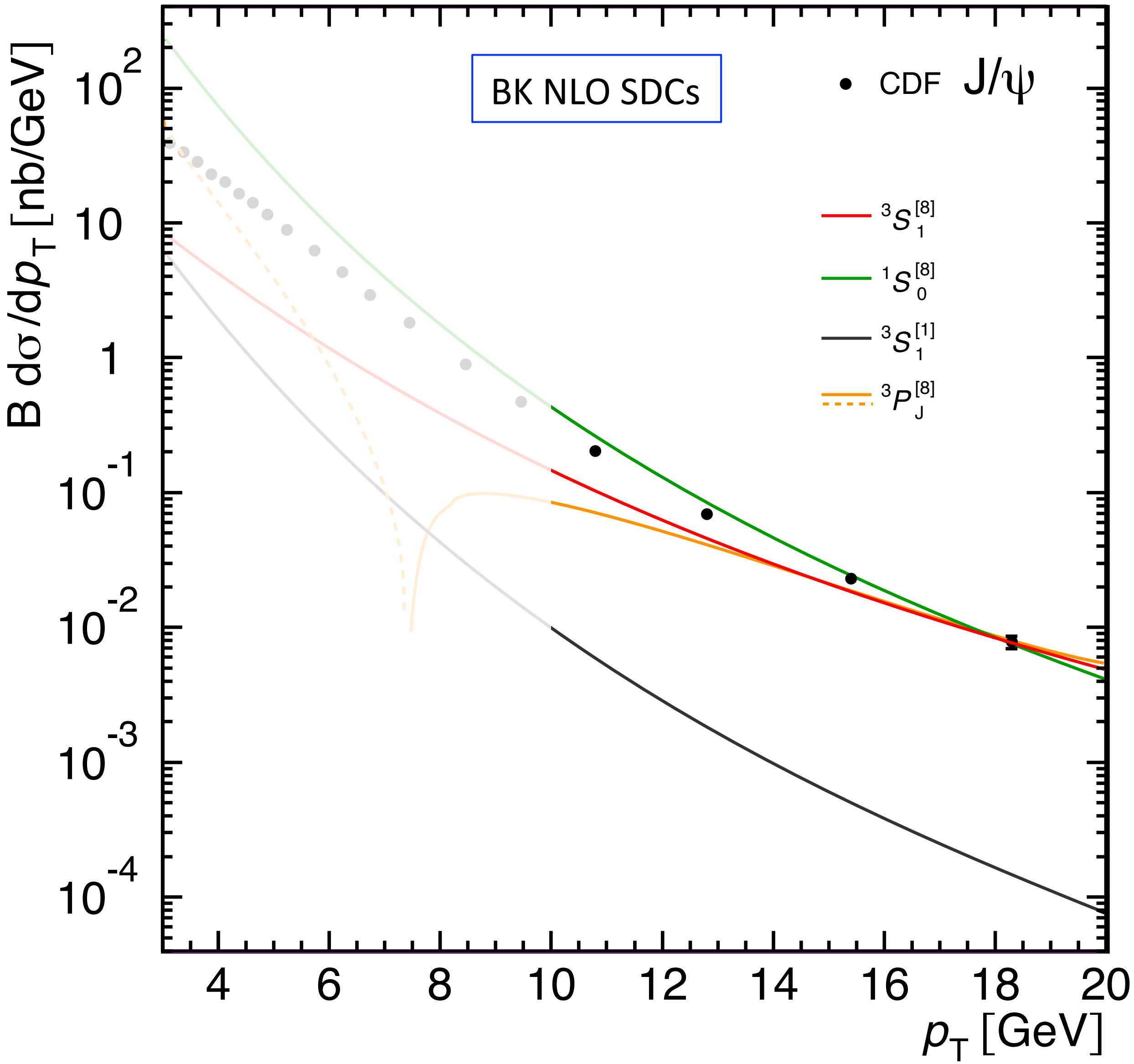




LHC data eagerly awaited ☺

The "quarkonium polarization puzzle" revisited

The high p_T shapes of the octets (${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, ${}^3P_J^{[8]}$) can be compared by normalizing them at $p_T \approx 18$ GeV



If the fit would start at high p_T, the ${}^1S_0^{[8]}$ term would dominate and the "prediction" would be that quarkonia should be dominantly unpolarized

$\lambda_\vartheta \rightarrow \approx 0$

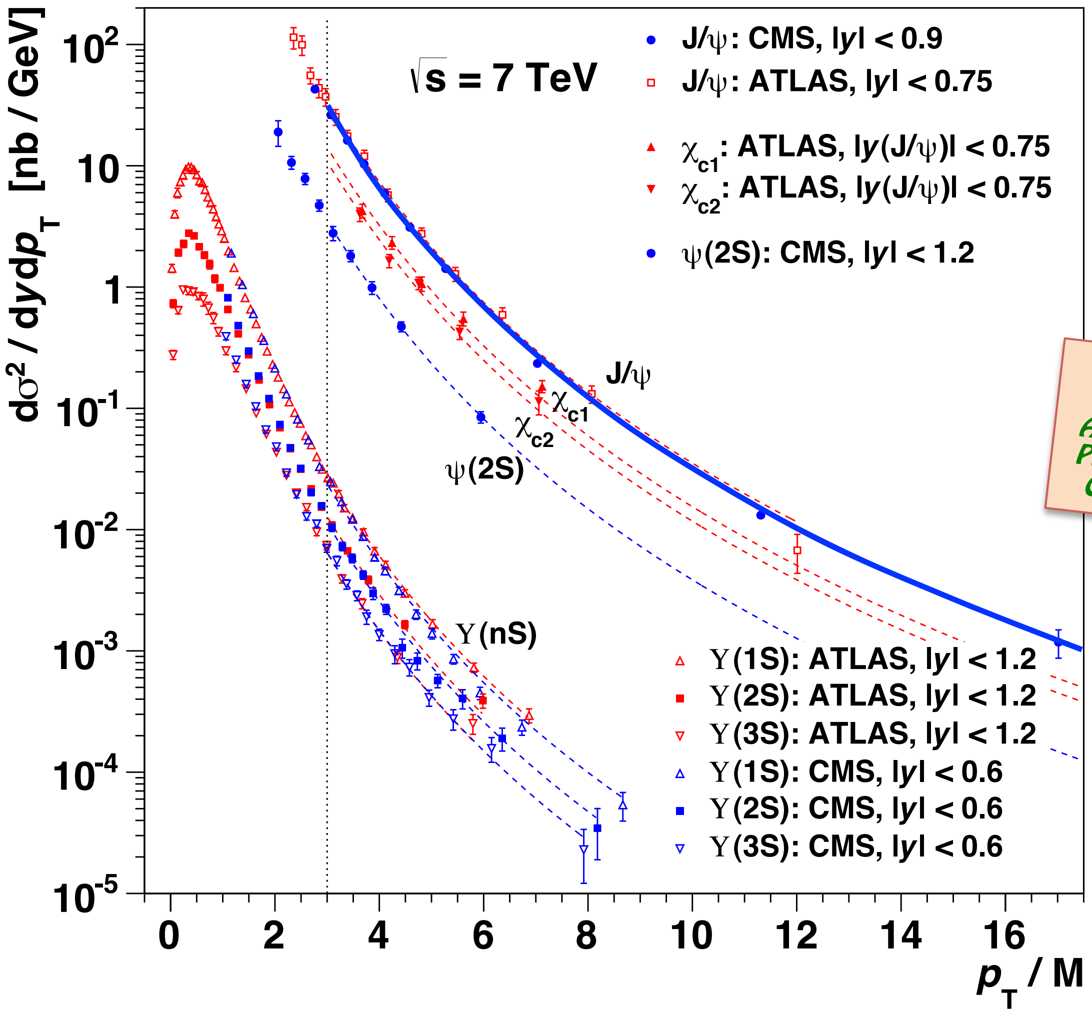
"High p_T quarkonia should be transversely polarized"

is not a *fundamental* prediction but simply the result of a fit to cross sections, including very low p_T data, where the (NLO) SDCs are unreliable

Cross sections at the LHC

All differential cross sections at mid-rapidity, for 7 quarkonia, show identical p_T / M shapes, for $p_T / M > 3$

Occam's explanation: all quarkonia are dominantly produced by a single (colour octet) process

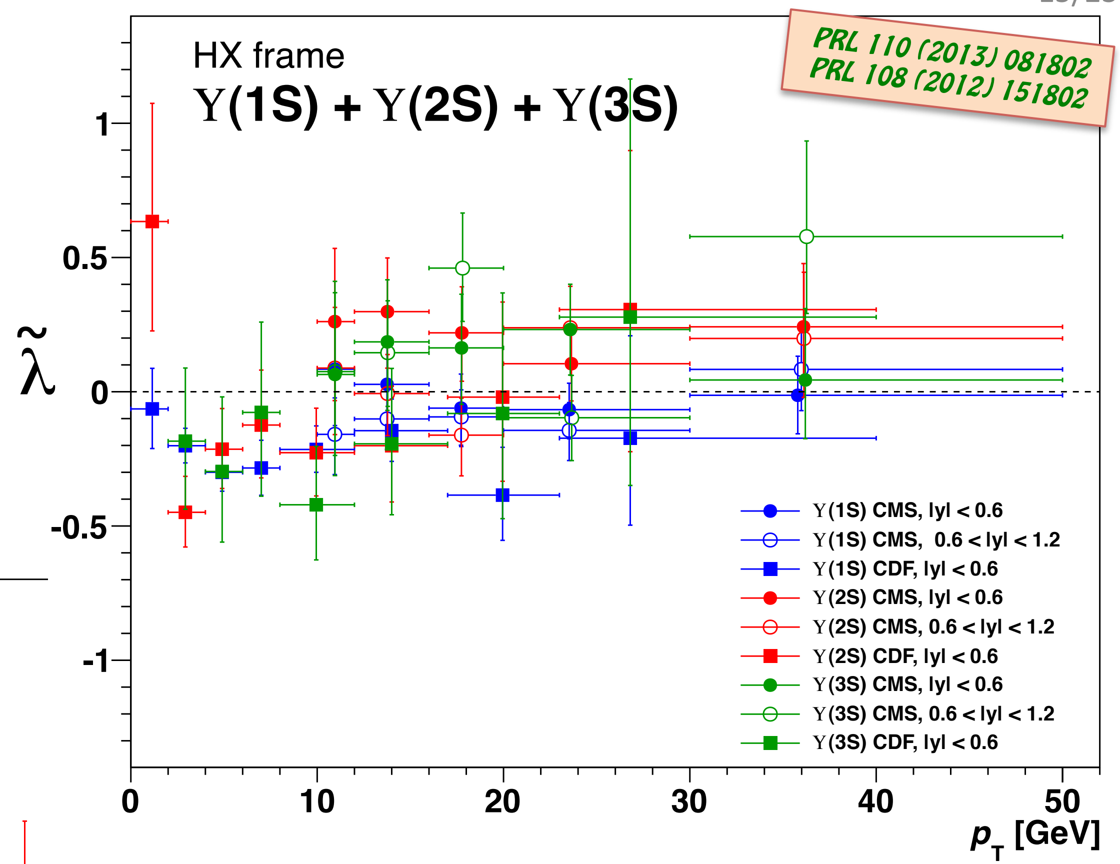


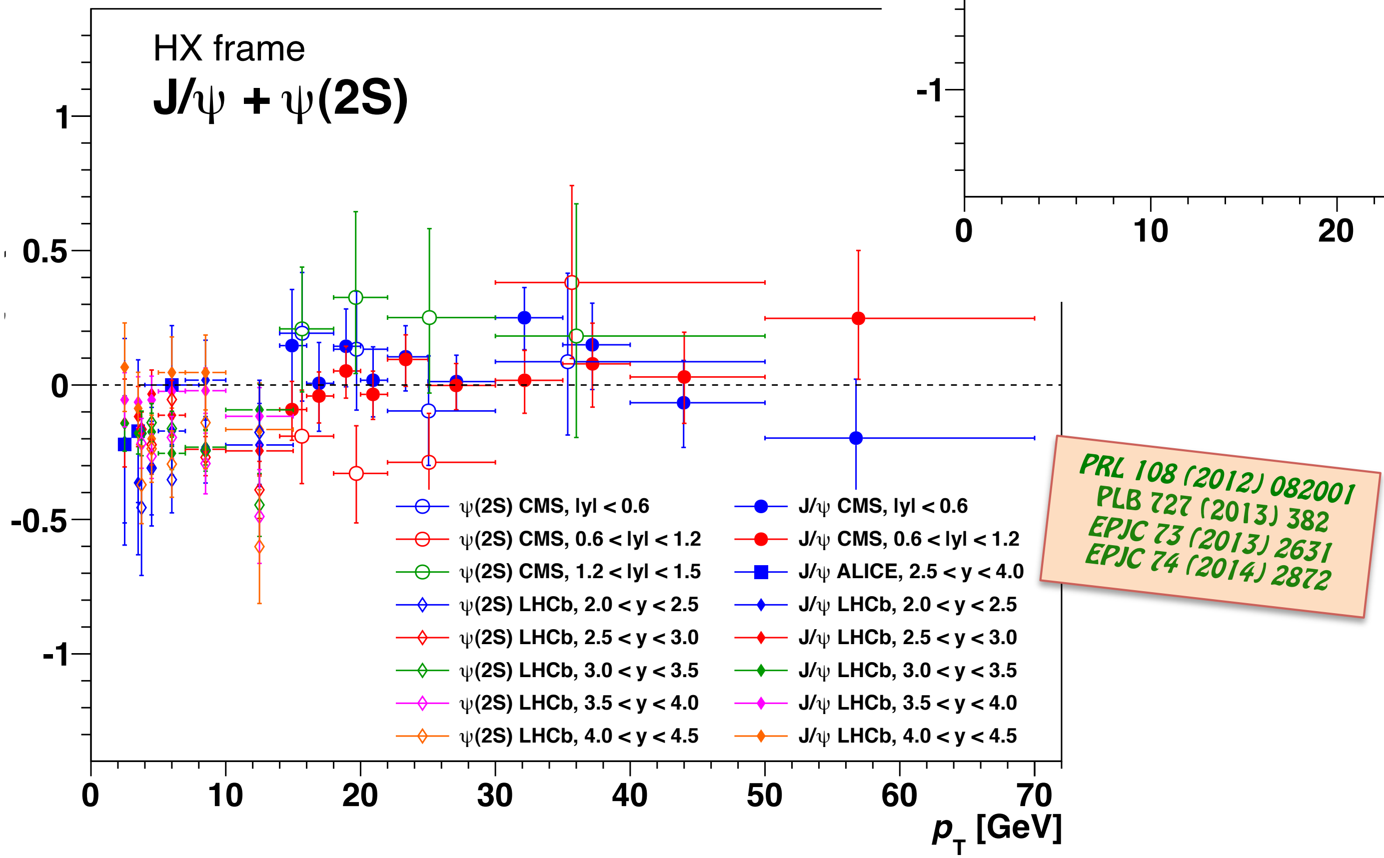
JHEP 02 (2012) 011
NPB 850 (2011) 387
ATLAS, CONF-2013-095
PRD 87 (2013) 052004
CMS PAS-BPH-12-006

Polarizations at the LHC

All measurements cluster around the unpolarized limit

Occam's explanation:
the dominating colour-octet process is the unpolarized $^1S_0^{[8]}$

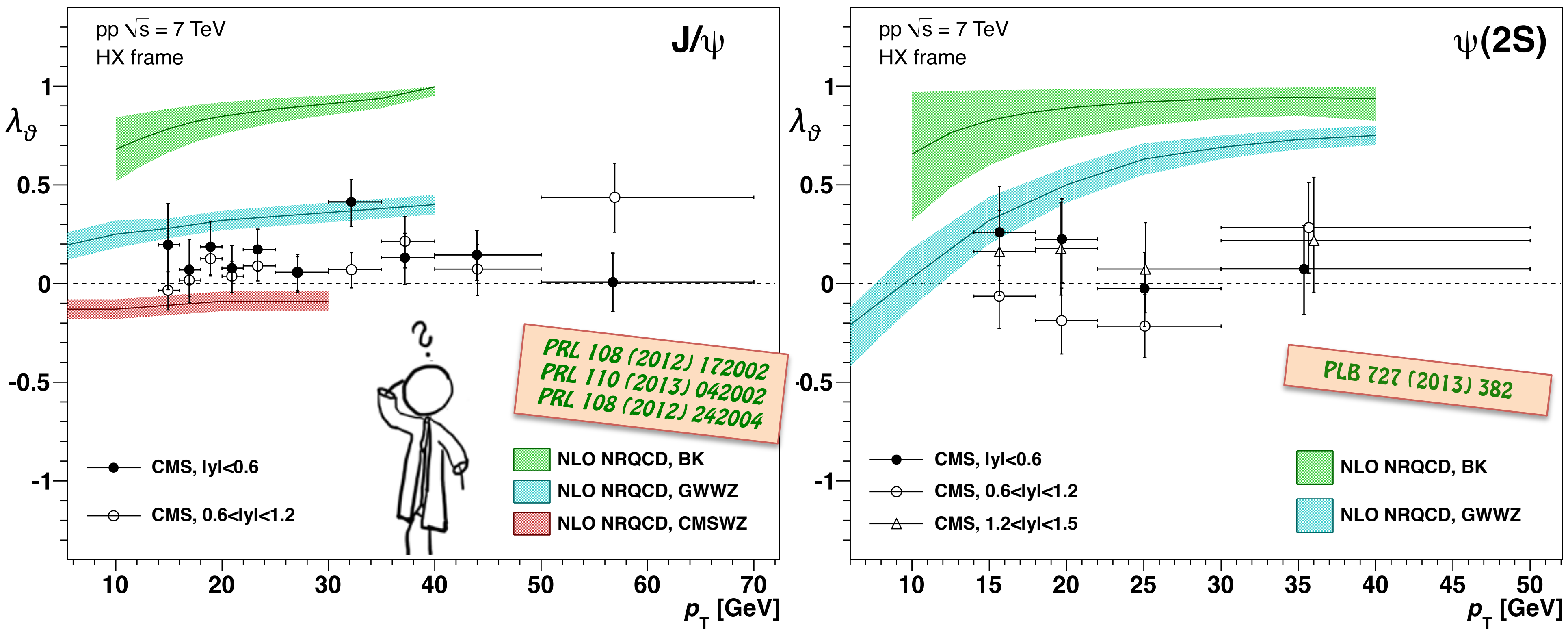




NRQCD analyses of LHC data

Three NRQCD analyses (BK, GWWZ, CMSWZ) start from similar SDCs and get very different LDMEs

	hadroproduction data	photoproduction data	feed-down decays	**polarization data**	**p_T min. (GeV)**
BK	Yes	Yes	No	No	1 or 3
GWWZ	Yes	No	Yes	No	**7**
CMSWZ	Yes	No	No	Yes	**7**



NRQCD analyses of LHC data

Four NRQCD analyses (BK, GWWZ, CMSWZ, FKLSW) start from similar SDCs and get very different LDMEs

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BK	Yes	Yes	No	No	1 or 3
GWWZ	Yes	No	Yes	No	**7**
CMSWZ	Yes	No	No	Yes	**7**
FKLSW	Yes	No	No(*)	**Yes**	**$p_T/M > 3$**

(*) Not needed for the $\psi(2S)$ analysis

	are the fits made consistently ?	are the resulting LDMEs reliable ?	strategy
BK	No	No	theory driven
GWWZ	No	No	theory driven
CMSWZ	No	No	theory driven
FKLSW	**Yes**	Yes	data driven

A data-driven global fit of quarkonium measurements

PLB 736 (2014) 98

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

In each fit step, the probed LDME values are used to compute the *theoretical* λ_ϑ and $d\sigma/dp_T$ functions, as well as the *measured* $d\sigma/dp_T$ spectra, recalculating the acceptance for the polarization under test

All other analyses compare *unpolarized data points* to *transversely polarized theory curves* !!!

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

Theoretical uncertainties are included, evaluated as the difference between LO and NLO calculations

As input SDCs (T and L) we use the BK NLO pQCD calculations

Only LHC measurements are used; earlier results were ambiguous, incomplete or at too low p_T

The analysis is restricted to the $\psi(2S)$ and $\Upsilon(3S)$ data, to minimise the number of free parameters; the $\chi_b(3P)$ feed-down contamination in the $\Upsilon(3S)$ is neglected

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

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

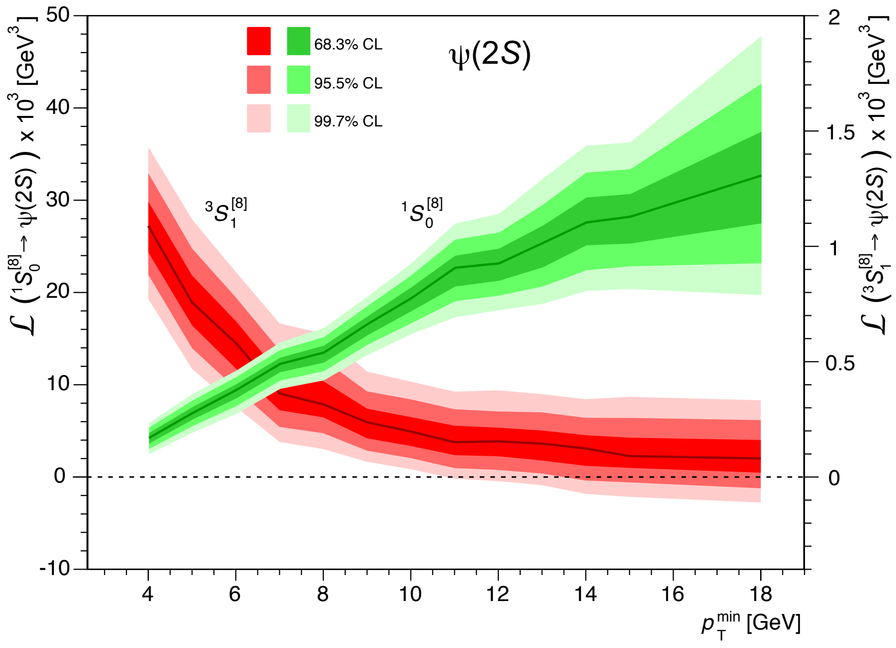
*by M. Butenschön and B. Kniehl, calculated for $M = 2\ m_c$

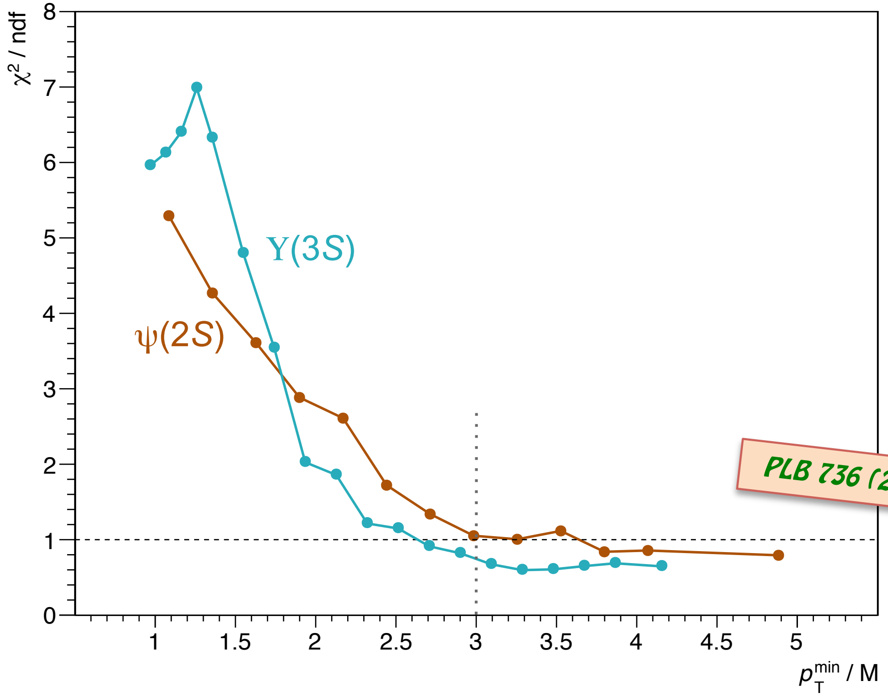
All data are equal but some are more equal than others

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





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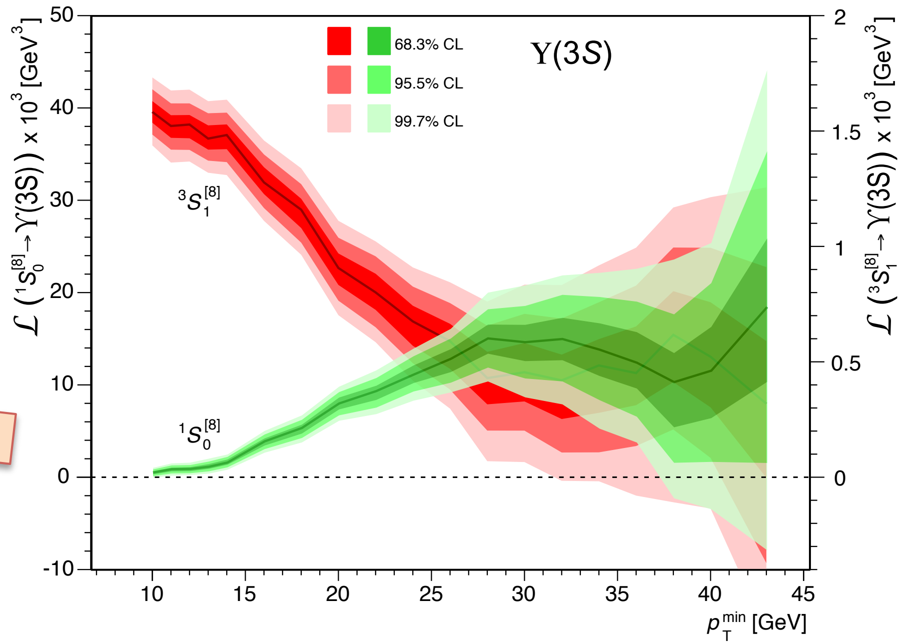
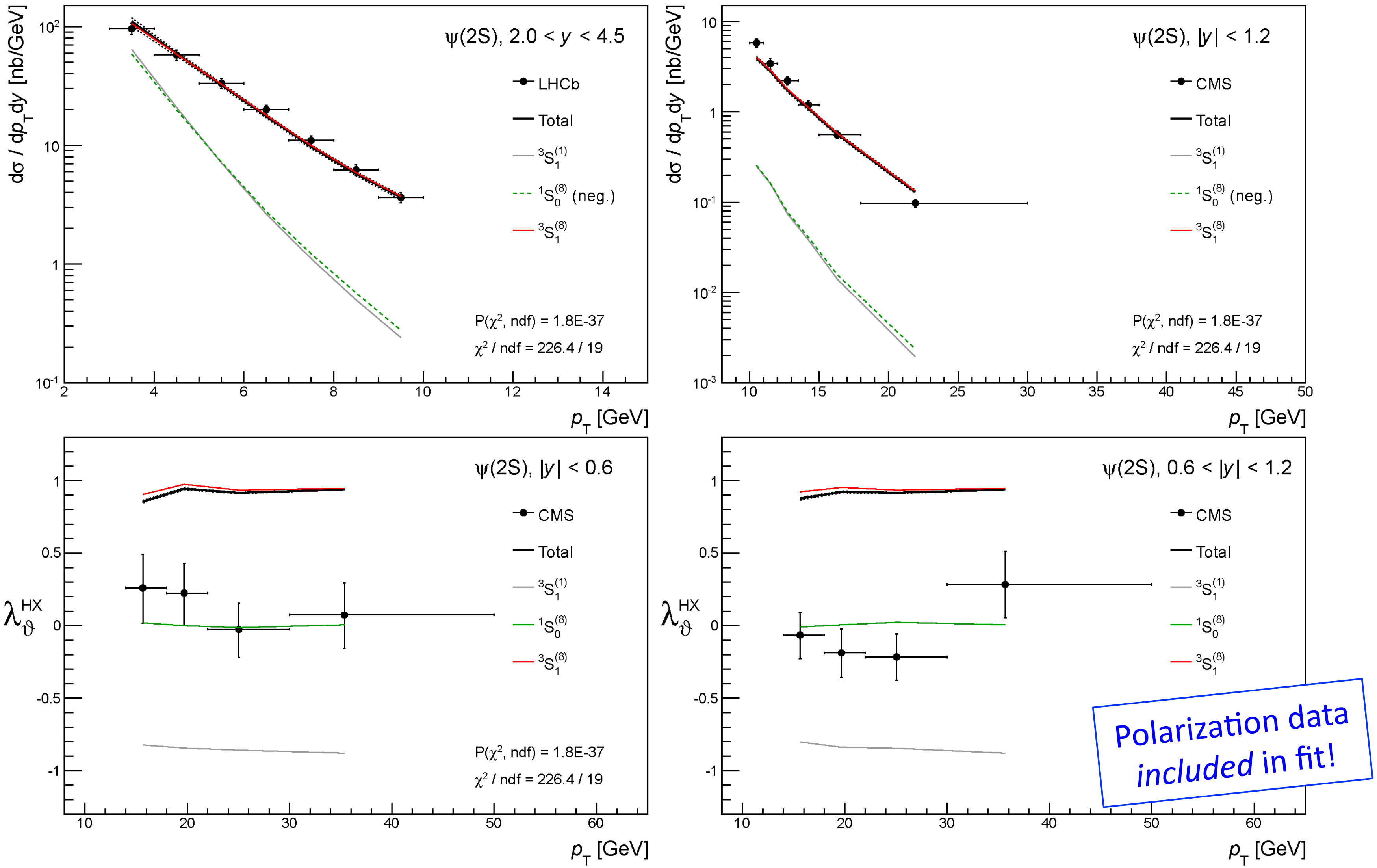


Illustration of a $\psi(2S)$ fit, using p_T > 3 GeV data



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

P(χ^2) 1.8E-37

The solution of the quarkonium polarization puzzle

The ψ(2S) and Υ(3S) cross sections and polarizations
can be simultaneously described
as a superposition of singlet and octet SDCs

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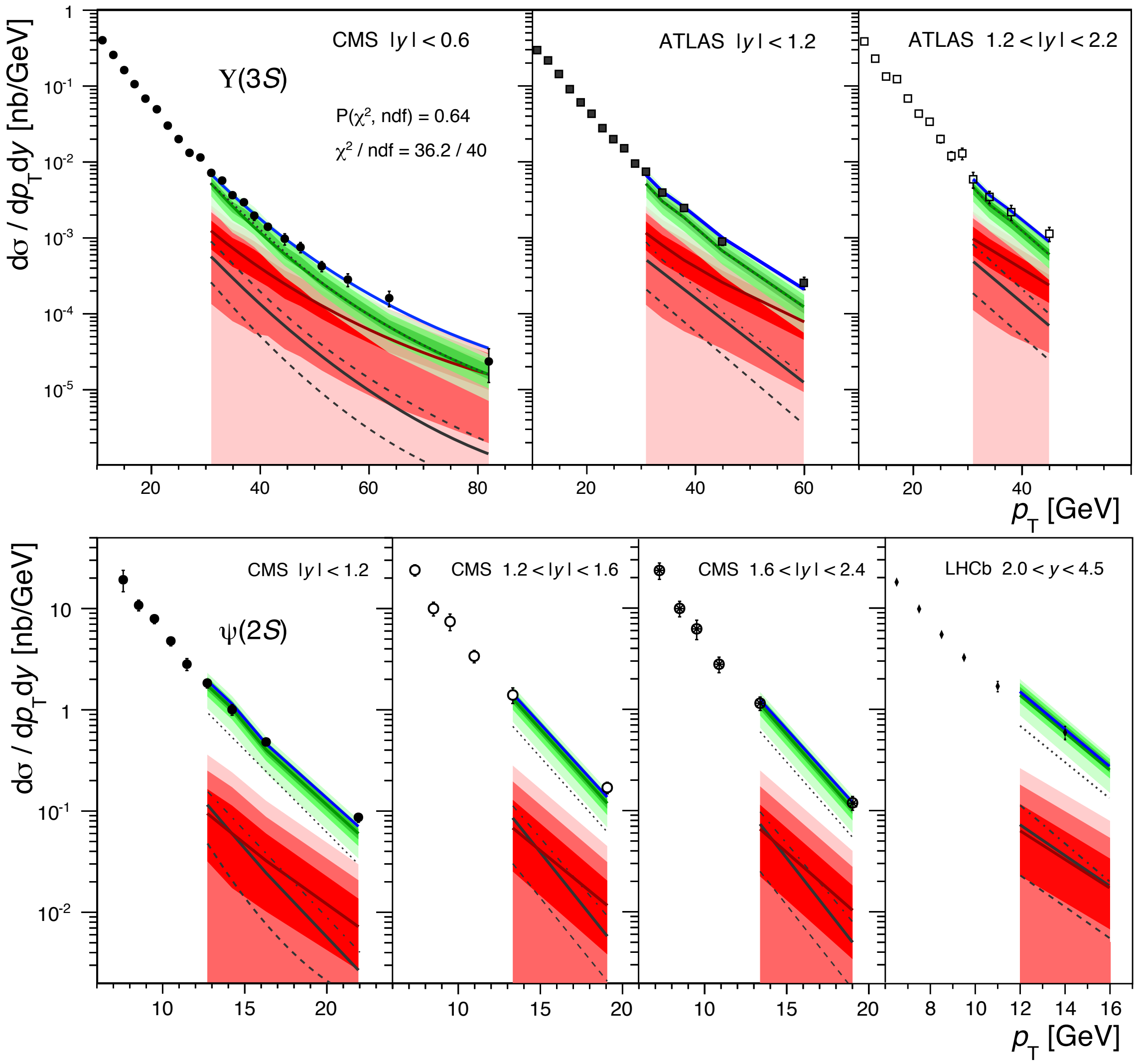
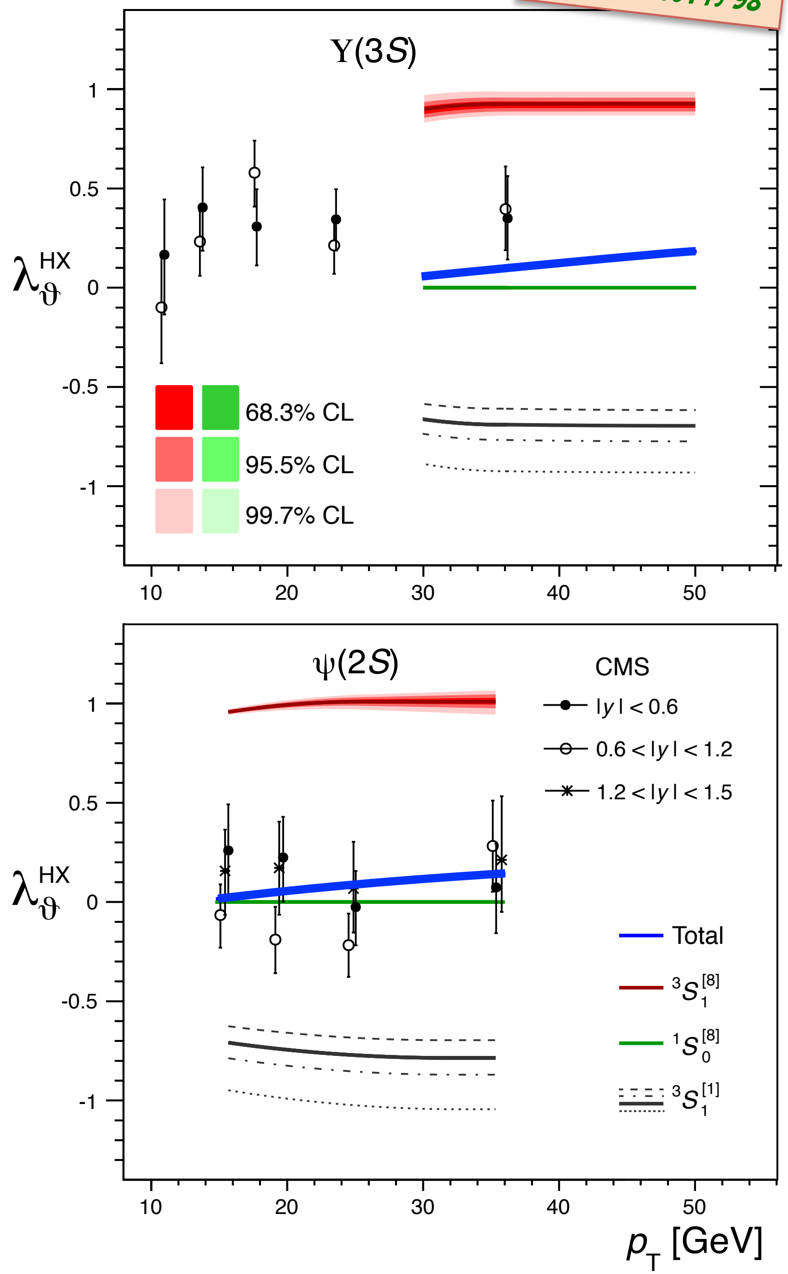




Comments on the LDMEs

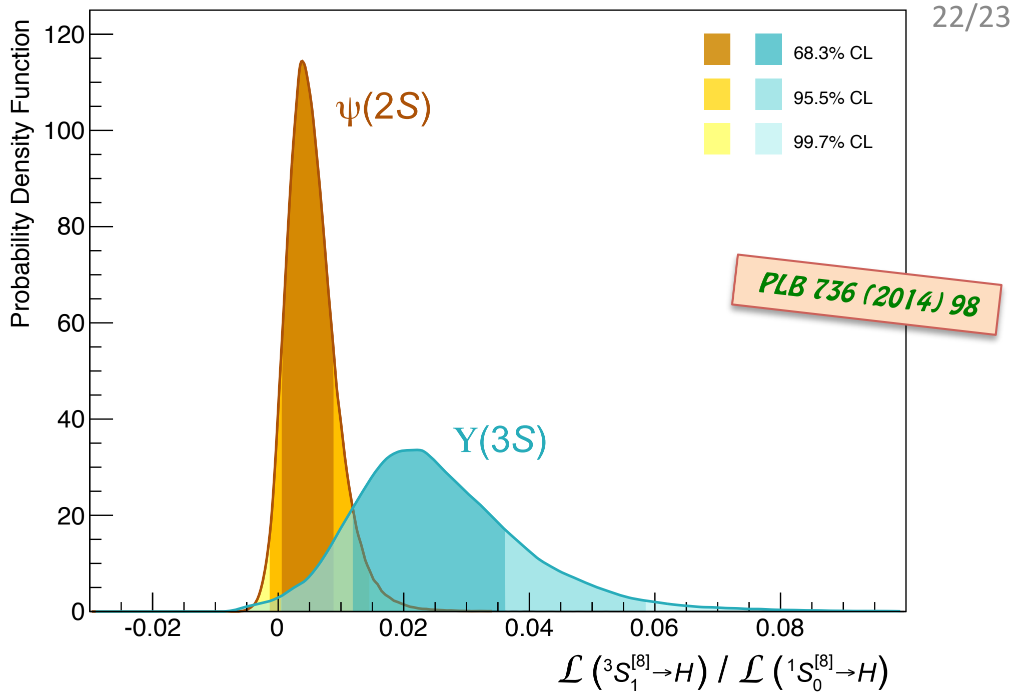
The ${}^3S_1^{[8]}$ LDME is < 6% of the ${}^1S_0^{[8]}$ LDME, at 95% CL
→ the ${}^3S_1^{[8]}$ transition is suppressed

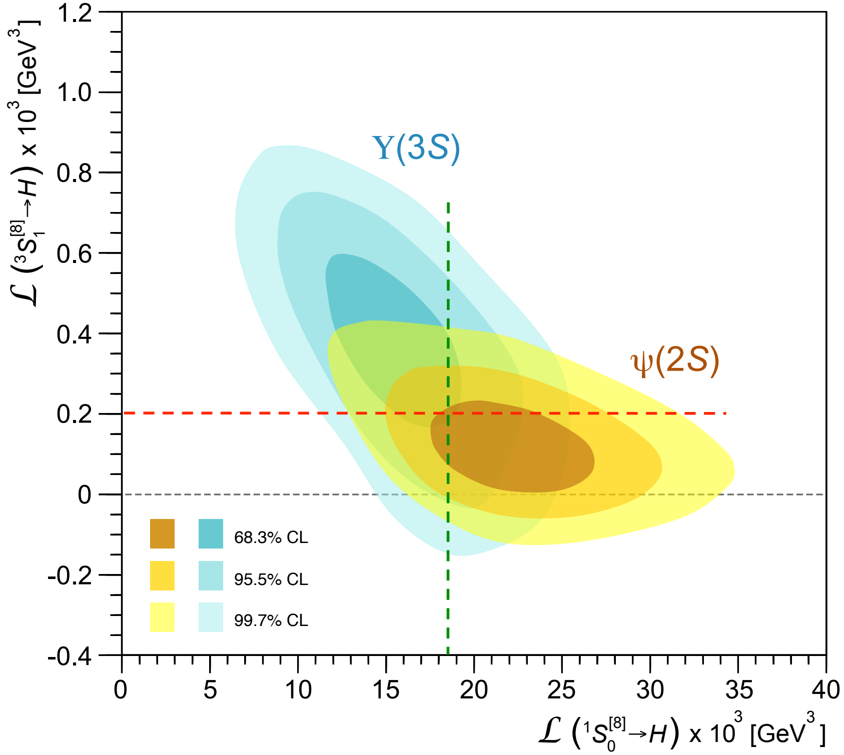
Redoing the fits including the ${}^3P_J^{[8]}$ term leads to a small (and *negative*) contribution
→ the ${}^3P_J^{[8]}$ transition can be neglected

The $\psi(2S)$ and $\Upsilon(3S)$ LDMEs, independent free parameters in the fit, might be identical...

$$O({}^1S_0^{[8]}, \psi(2S)) = O({}^1S_0^{[8]}, \Upsilon(3S)) = 0.0185 \text{ GeV}^3$$
$$O({}^3S_1^{[8]}, \psi(2S)) = O({}^3S_1^{[8]}, \Upsilon(3S)) = 0.0020 \text{ GeV}^3$$

an important indication that the ${}^3S_1^{[8]}$ and ${}^1S_0^{[8]}$ LDMEs are physical observables (hadron formation probabilities)





What have we learnt so far?

The p_T /*M* scaling between 7 quarkonia, from pure S-wave states to pure P-wave states, indicates that all quarkonia are similarly produced
→ all quarkonia seem to be dominantly produced by a single (colour octet) process

The polarizations of *all* five S-wave states indicate that the dominant process is unpolarized
→ the $^1S_0^{[8]}$ octet dominates quarkonium production (at least up to some p_T value)

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These non-trivial observations help understanding how the quarks interact with each other
→ the QQbar bound states are preferably formed from two quarks of:
1) different colours (rather than in an already neutral configuration)
2) smaller relative angular momentum and spin than the ones of the bound state

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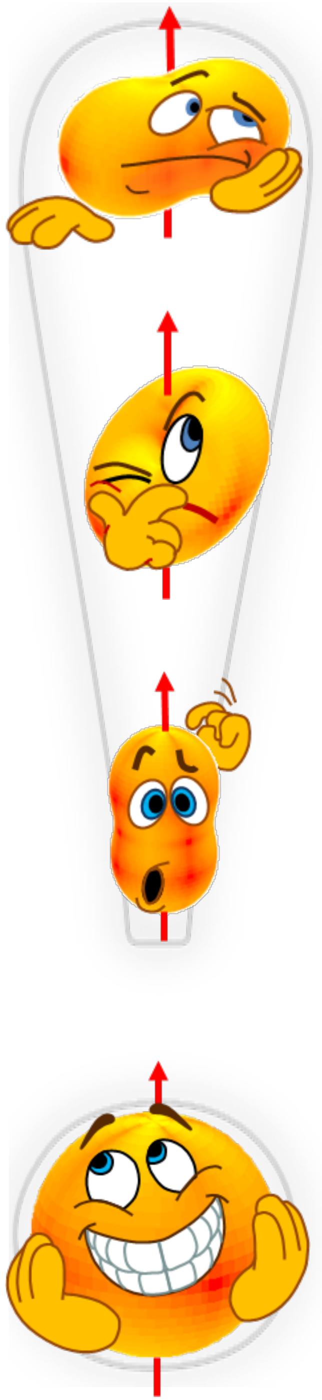
The data can be described as a superposition of *physical* processes, without mathematical entities of negative cross sections and unphysical/discontinuous polarizations ($\lambda_\vartheta > 1$)
→ useful to understand quark confinement : how hadrons form in pp collisions
→ and quark deconfinement : how *physically meaningful objects* evolve in nuclear matter

There is no “quarkonium polarization puzzle”…

Do not try and bend the spoon. That’s impossible.
Instead… only try to realize the truth.

There is no spoon

Then you’ll see that it is not the spoon that bends, it is only yourself



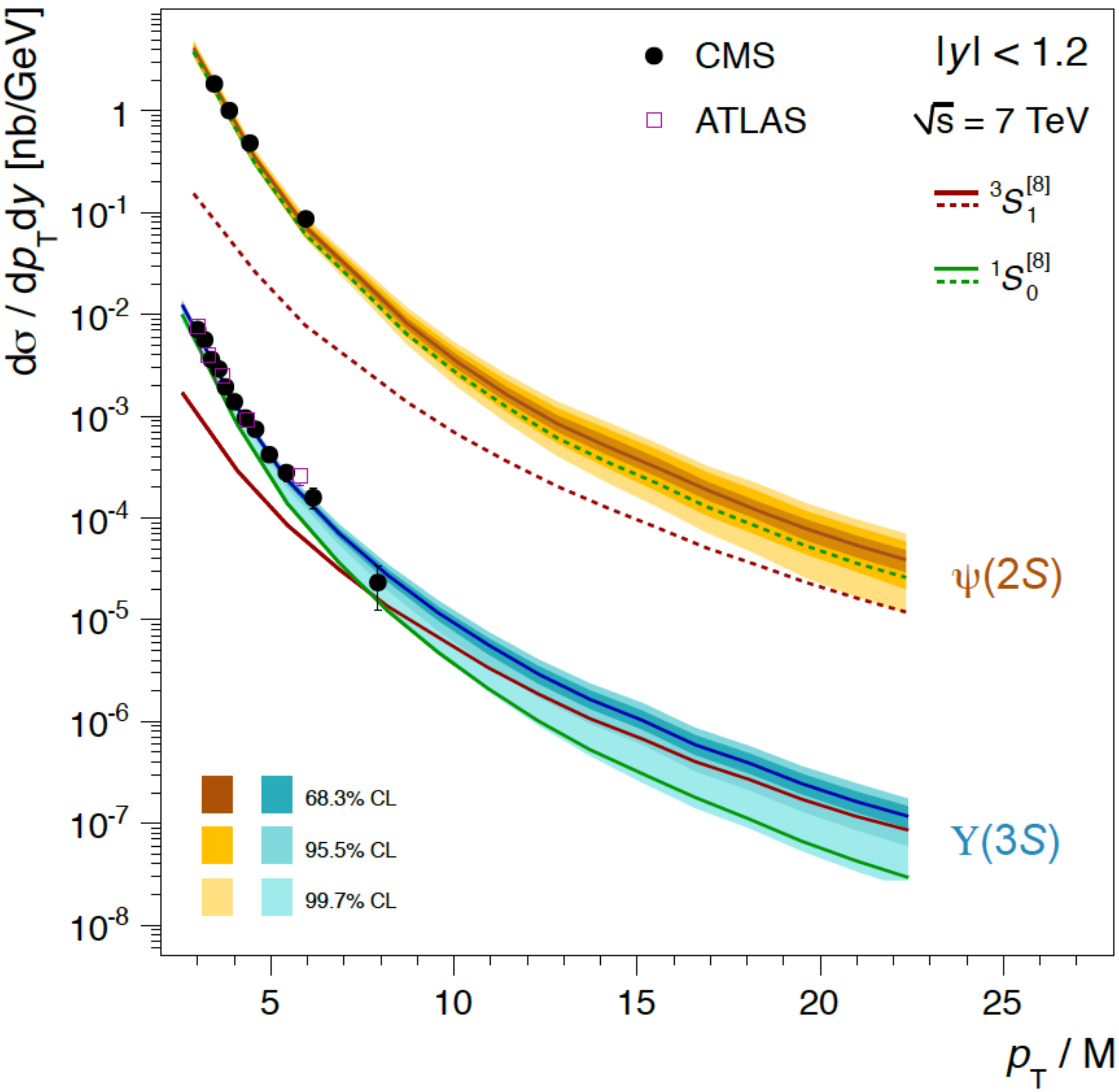
Back up !!!

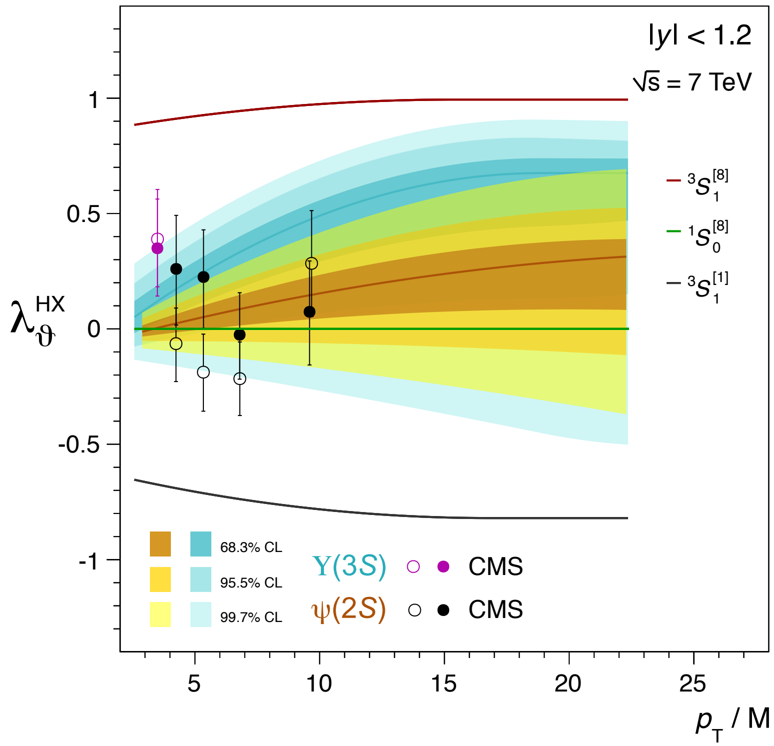
Further reading on quarkonium polarization

- P. Faccioli, C. Lourenço and J. Seixas, *Rotation-invariant relations in vector meson decays into fermion pairs*, Phys. Rev. Lett. 105, 061601 (2010)
- P. Faccioli, C. Lourenço and J. Seixas, *New approach to quarkonium polarization studies*, Phys. Rev. D 81, 111502(R) (2010)
- P. Faccioli, C. Lourenço, J. Seixas and H.K. Wöhri, *Towards the experimental clarification of quarkonium polarization*, Eur. Phys. J. C 69, 657 (2010)
- P. Faccioli, *Questions and prospects in quarkonium polarization measurements from proton-proton to nucleus-nucleus collisions*, Mod. Phys. Lett. A 27, 1230022 (2012)
- CDF Collaboration*, Measurements of the Angular Distributions of Muons from Y Decays in ppbar Collisions at sqrt(s) = 1.96 TeV,* Phys. Rev. Lett. 108, 152802 (2012)
- CMS Collaboration*, Measurement of the Y(1S), Y(2S) and Y(3S) polarizations in pp collisions at sqrt(s) = 7 TeV*, Phys. Rev. Lett. 110, 081802 (2013)
- CMS Collaboration*, Measurement of the prompt* J/ψ *and* $\psi(2S)$ *polarizations in pp collisions at sqrt(s) = 7 TeV*, Phys. Lett. B 727, 381 (2013)
- LHCb Collaboration*, Measurement of* J/ψ *polarization in pp collisions at sqrt(s) = 7 TeV,* Eur. Phys. J. C 73, 2631 (2013)
- P. Faccioli, Valentin Knünz, C. Lourenço, J. Seixas and H.K. Wöhri, *Quarkonium production in the LHC era: a polarized perspective*, arXiv:1403.3970 [hep-ph]
- LHCb Collaboration*, Measurement of* $\psi(2S)$ *polarization in pp collisions at sqrt(s) = 7 TeV,* Eur. Phys. J. C 74, 2872 (2014)

What happens at higher p_T?

Maybe the $^3S_1^{[8]}$ term is dominant at higher p_T/M values than currently covered
If so, $\Upsilon(3S)$ of p_T > 100 GeV should tend to be transversely polarized



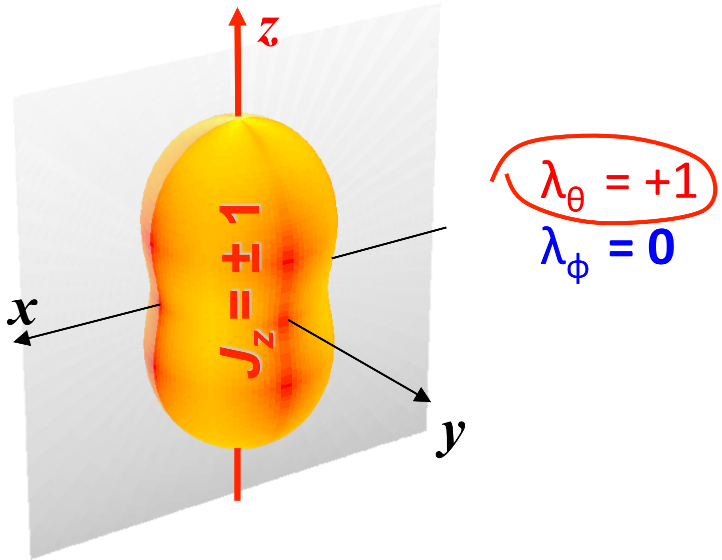


Measurements with 2012 data needed to vastly improve the accuracy of the results and extend their p_T reach

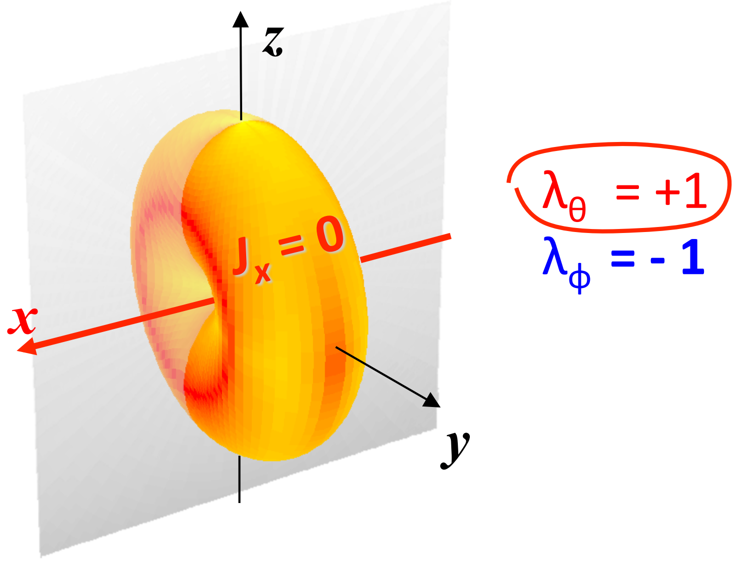
The azimuthal anisotropy is not a minor detail

Almost all the pre-LHC measurements ignored the azimuthal component of the distribution (λ_ϕ)
This “simplification” leads to ambiguous and meaningless results

Case 1: transverse polarization



Case 2: longitudinal polarization, observation frame ⊥ to the ‘natural’ one



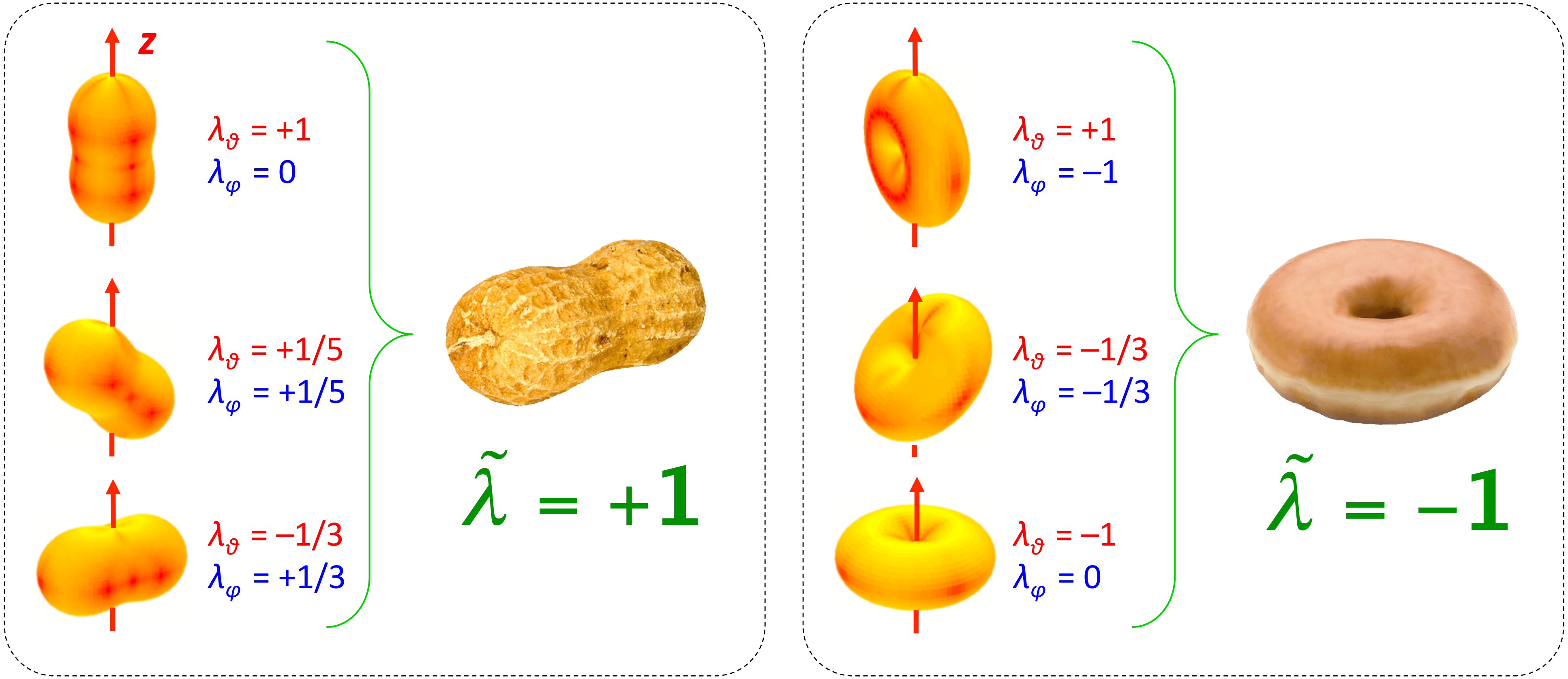
- Two very different (opposite) physical cases, with same λ_θ
- Only distinguishable by measuring λ_ϕ (no integration over ϕ !)

The frame-independent polarization parameter $\tilde{\lambda}$

The *shape* of the distribution is (obviously) frame-invariant (= invariant by rotation)

It can be characterized by a frame-independent parameter: $\tilde{\lambda} = \dfrac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}$

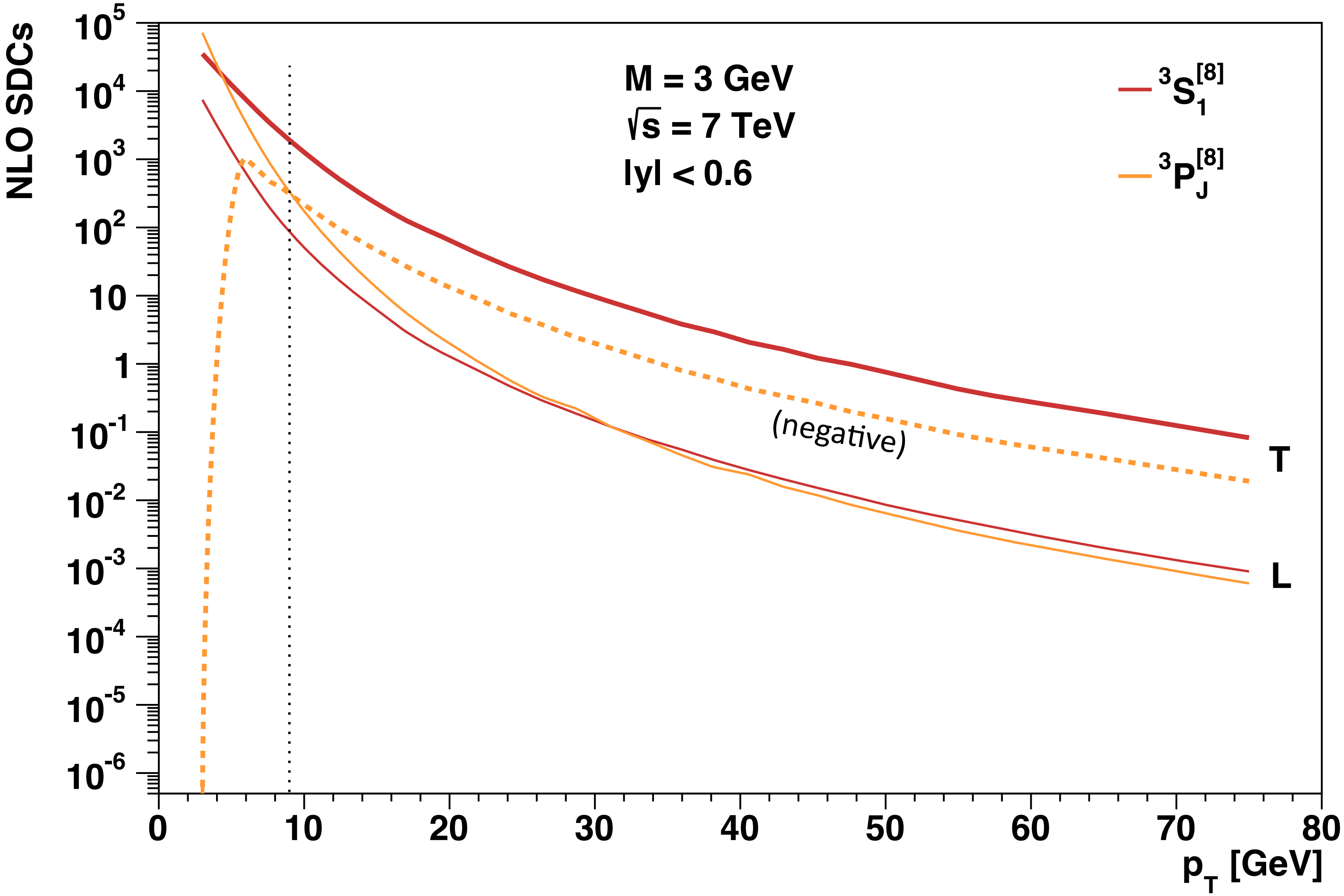
Comparing the values measured in several different frames allows us to search for biases in the analyses



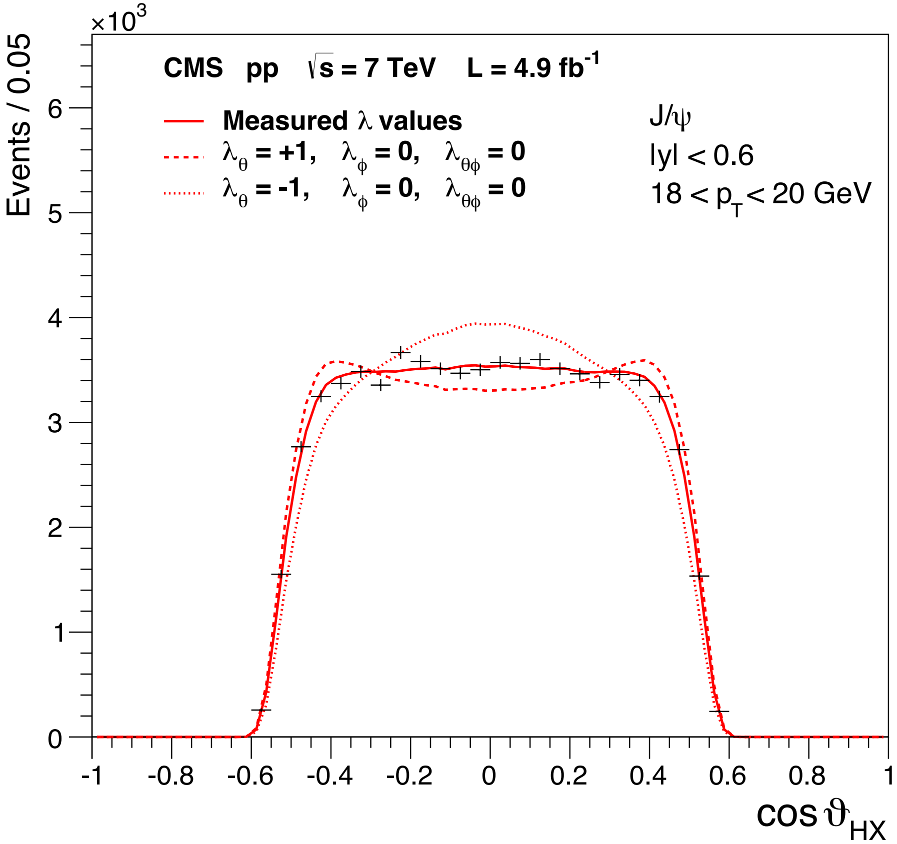
The mysterious ^3P_J octet

Exceptionally, the ^3P_J octet SDC ($\sigma_T + \sigma_L$) changes sign between low and high p_T :
it is positive for $p_T < 9$ GeV, where $\sigma_T < \sigma_L$ and negative for higher p_T values, where $\sigma_T > \sigma_L$

This means that $\lambda_\theta = (\sigma_T - \sigma_L) / (\sigma_T + \sigma_L)$ diverges at $p_T = 9$ GeV, where it changes from $-\infty$ to $+\infty$!



The *measured* cross sections crucially depend on the polarization assumed when computing the acceptance correction !
Not only in normalization but also in terms of shape



Quarkonium Production in pp and pA collisions
"Quarkonium 2010", Paris, July 2010