Quarkonium polarization in *pp* collisions: a long-standing puzzle

Livio Bianchi

Probing the strong interaction at AFTER

Les Houches – France

12-17 January 2014

Heavy quarkonium production

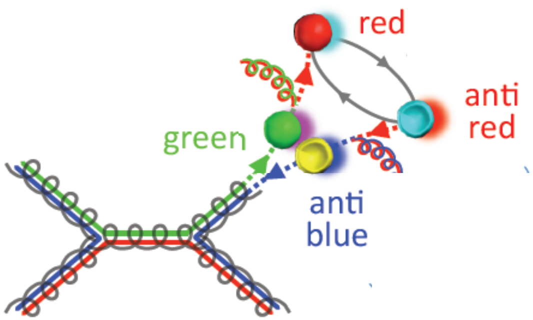
Quarkonium production involves different energy scales: the $q\bar{q}$ formation is a hard process, while the binding of the constituents and the evolution of the bound state occur at softer scales.

Theoretical models assume factorization:

$$\sigma[H] = \sum_n \sigma_n(\Lambda) \langle 0|\mathcal{O}_n^H|0\rangle$$

Cross section for the production of the quarkonium H

Short distance coefficients: perturbative cross sections (+PDF) for the production of a $q\bar{q}$ pair in a given quantum state *n*

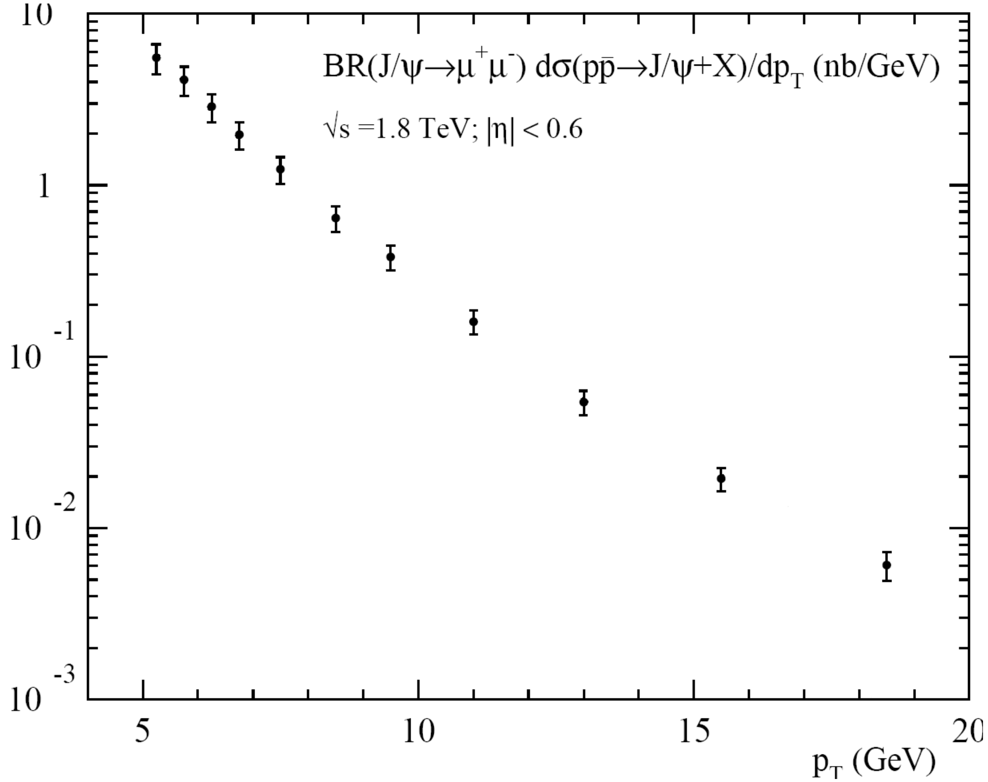


Long distance matrix elements: embed the non-perturbative part. **THEY ARE ASSUMED TO BE UNIVERSAL**

Different implementations of the factorization formula:

- **Color Singlet Model (CSM)**: the color of the $q\bar{q}$ pair neutralizes in the hard process
- **Nonrelativistic QCD (NRQCD)**: the color can be neutralized also in the long distance part $\rightarrow$ the perturbative cross section can create singlet and octet $q\bar{q}$ systems. The **color octet matrix elements** are estimated through a **fit to the p_t-differential J/ψ cross sections**

Trying to describe CDF results

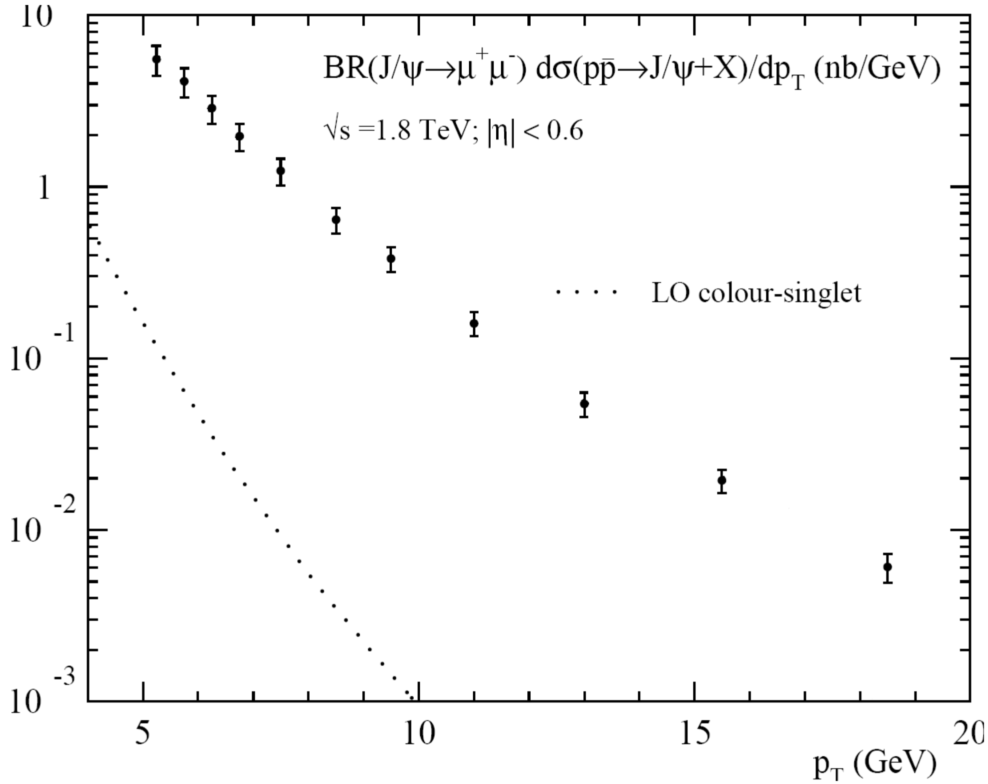


The J/ψ production mechanism in hadronic collisions is still an open issue.

CDF results on p_t-differential cross section for (e.g.) direct J/ψ: important testing ground.

N. Brambilla *et al.*, arXiv:hep-ph/0412158v2

Trying to describe CDF results



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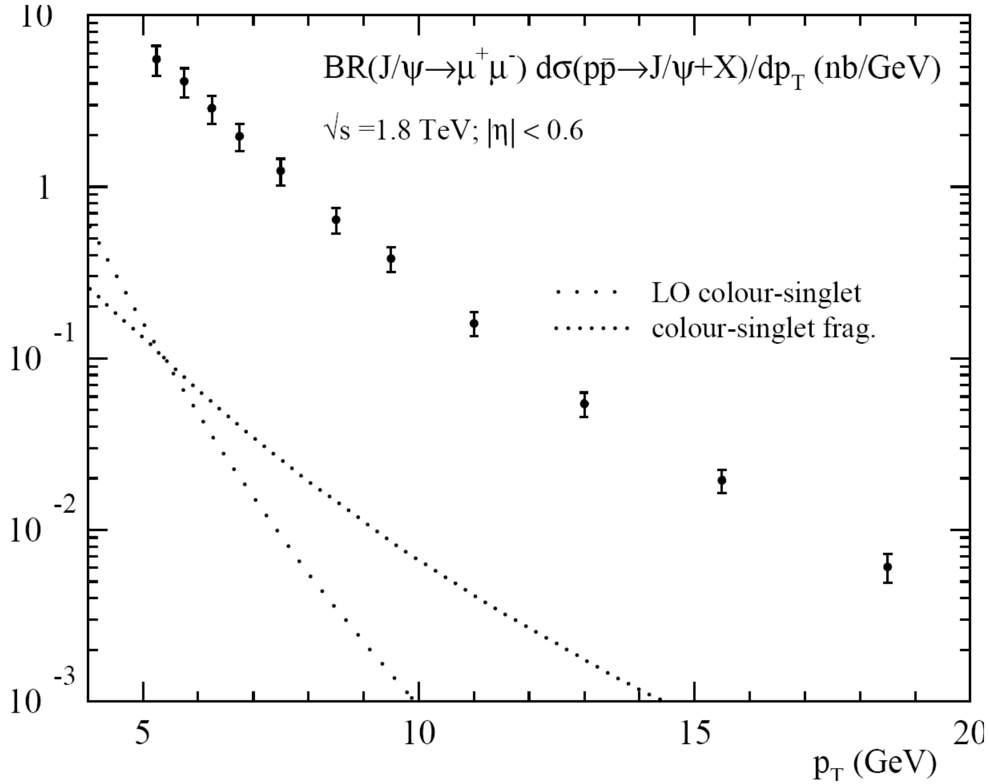

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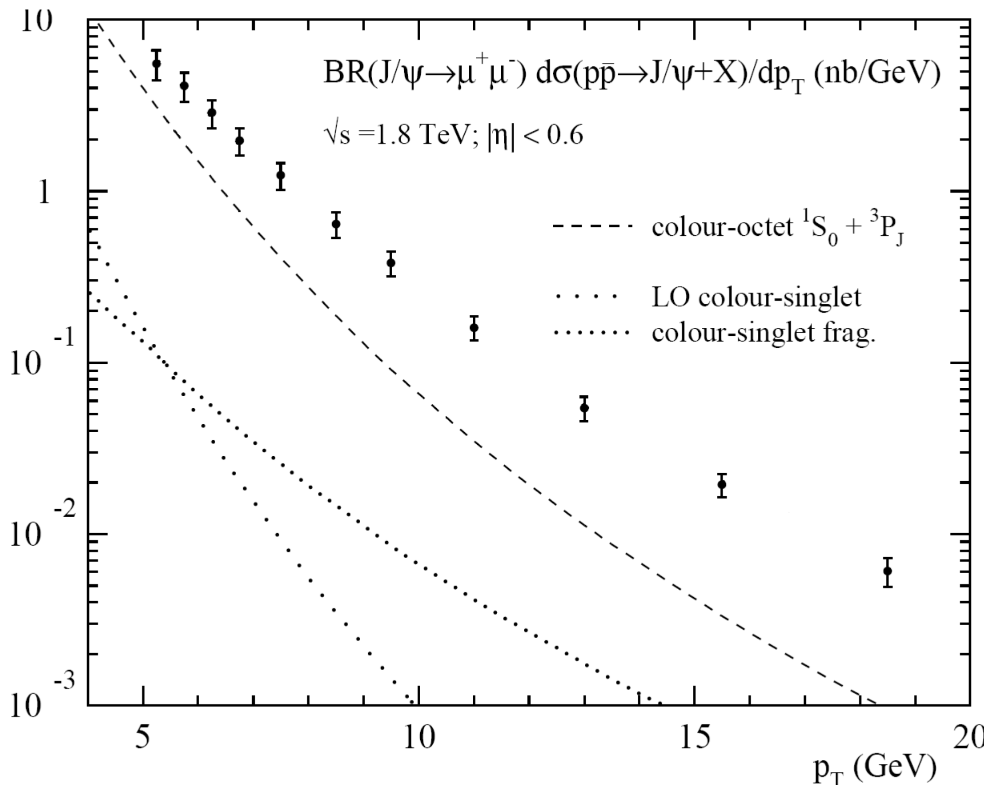

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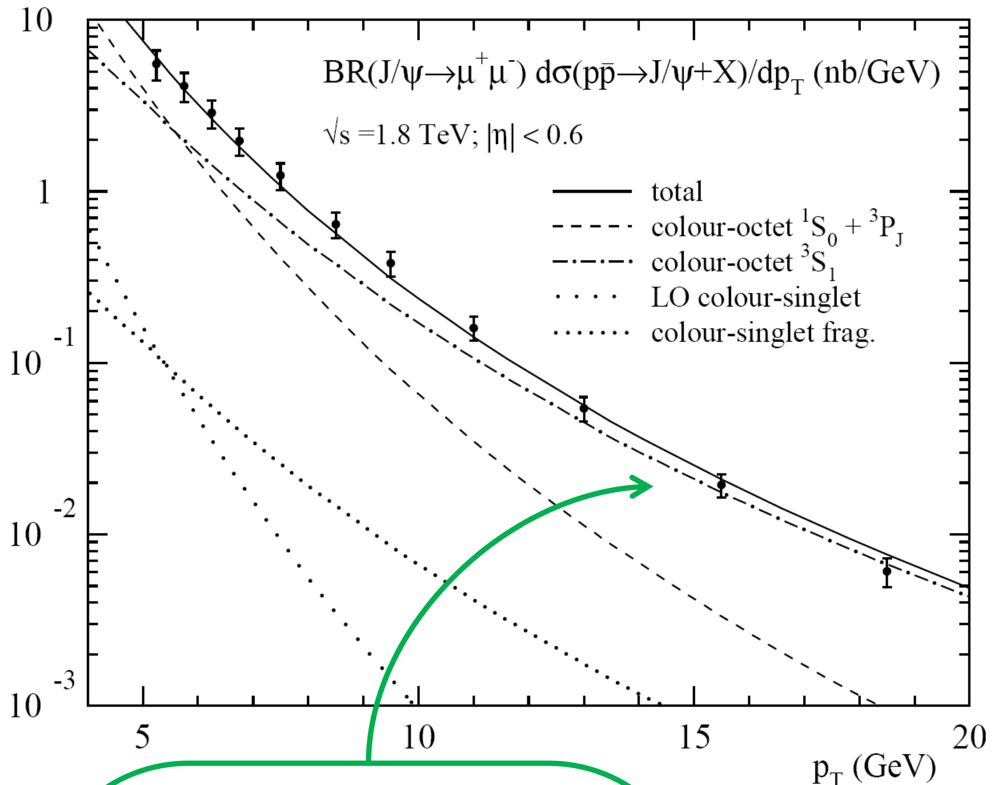

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LO CS + LO CO + gluon fragment. (LO NRQCD): perfect agreement

Gluon fragmentation dominant mechanism at high p_t

gluons almost on shell → transversely polarized

The long distance coefficients do not dilute $c\bar{c}$ polarization

⇒ **LO NRQCD prediction:**
Transverse polarization for high-p_t J/ψ

N. Brambilla *et al.*, arXiv:hep-ph/0412158v2

How to experimentally study polarization

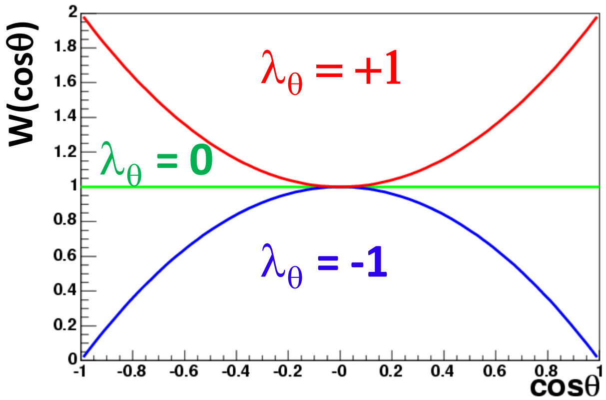
How to study quarkonium polarization

In a two-body decay quarkonium polarization is measured through the extraction of the anisotropies in the angular distribution of its daughter particles.
Taking as a reference the μ^+(conventionally), the angular distribution can be expressed as:

$$\boxed{W(\cos\theta,\phi) \propto \frac{1}{3+\lambda_\theta} \cdot (1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi)}$$

θ and ϕ are the polar and azimuth angles of the μ^+ momentum in a given reference frame.

$|\Psi\rangle = a_{+1}\,|+1\rangle + a_0\,|0\rangle + a_{-1}\,|-1\rangle \;\rightarrow\; \lambda$ parameters can be expressed in terms of a_i

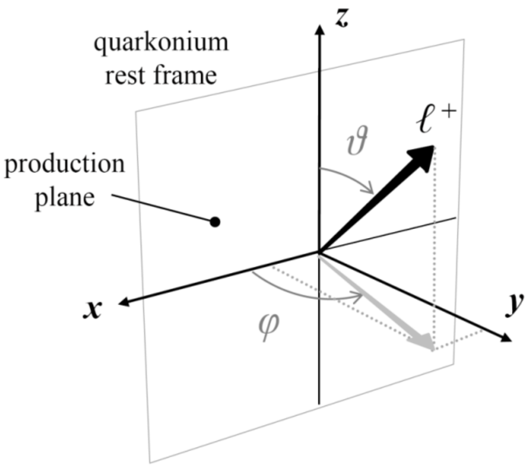


λ_θ is the fundamental parameter, directly affected by polarization:

$\lambda_\theta = +1 \;\rightarrow$ **transverse polarization**

$\lambda_\theta = \;\; 0 \;\rightarrow$ **no polarization**

$\lambda_\theta = -1 \;\rightarrow$ **longitudinal polarization**



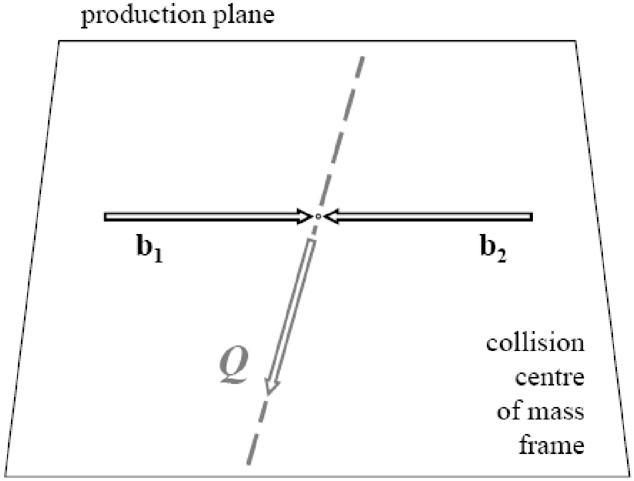
P. Faccioli *et al.*, EPJ C**69** (2010) 657673

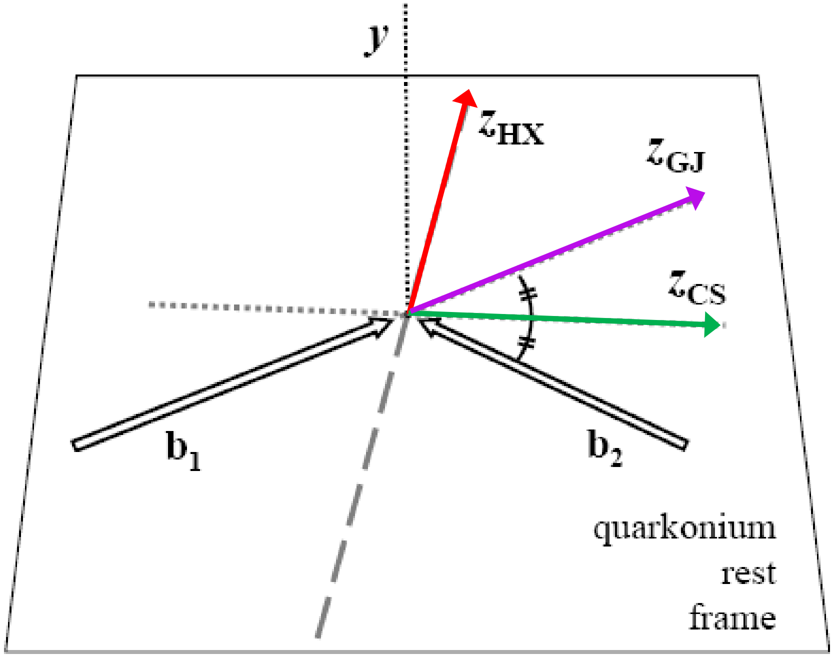
Polarization is extracted in the quarkonium rest frame.

Several possible definitions of the *z*-axis (always contained in the production plane):

- **helicity**: quarkonium momentum direction in the collision's reference frame;
- **Collins-Soper**: bisector of the angle between one beam and the opposite of the other beam in the quarkonium rest frame;
- **Gottfried-Jackson**: direction of one beam in the quarkonium rest frame (mostly used in fixed target experiments)

For this analysis the helicity and Collins-Soper definitions were used





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From the definition of the λ parameters and considering rotations among the reference frames it is possible to define a class of invariant quantities:

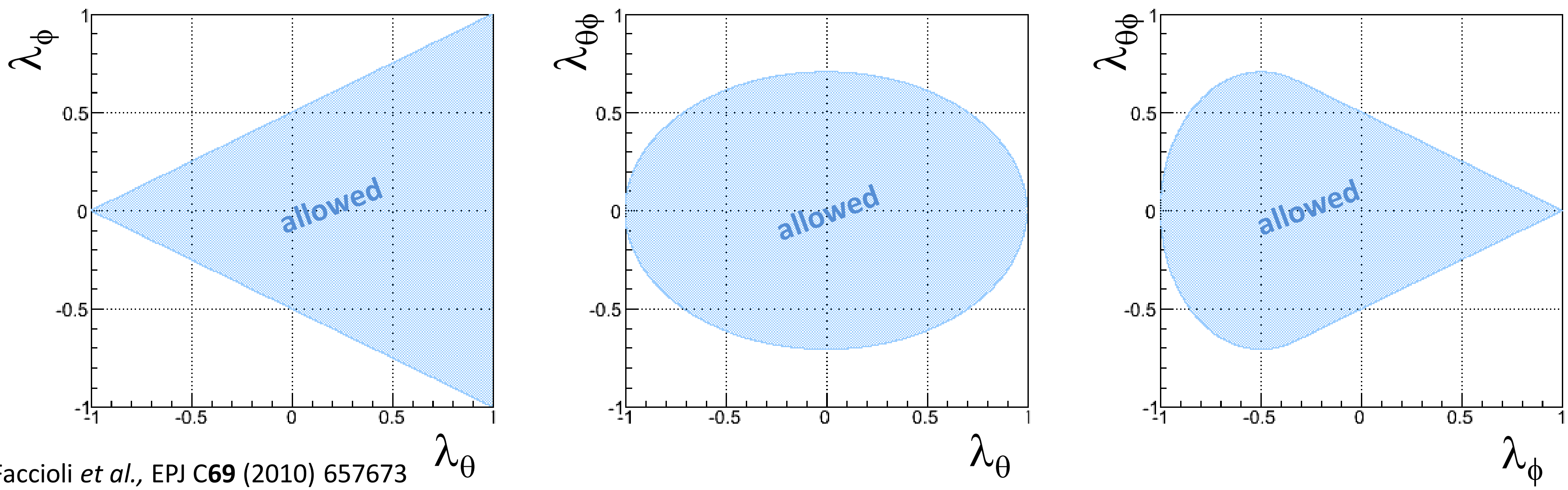
For each combination of integer numbers (c_1, c_2, c_3), it must be the same for all the reference frames

$$\mathcal{F}_{c_1,c_2,c_3} = \frac{(3+\lambda_\theta) + c_1(1-\lambda_\phi)}{c_2(3+\lambda_\theta) + c_3(1-\lambda_\phi)}$$

If the analysis is performed in more than one frame this quantity can be used as a check

Moreover, it is possible to define a 3D region in the [λ_θ, λ_ϕ, $\lambda_{\theta\phi}$] space that corresponds to the variability domain of the parameters.

The projections of this 3D figure on the 2D plots [λ_θ, λ_ϕ], [λ_θ, $\lambda_{\theta\phi}$] and [λ_ϕ, $\lambda_{\theta\phi}$] are:



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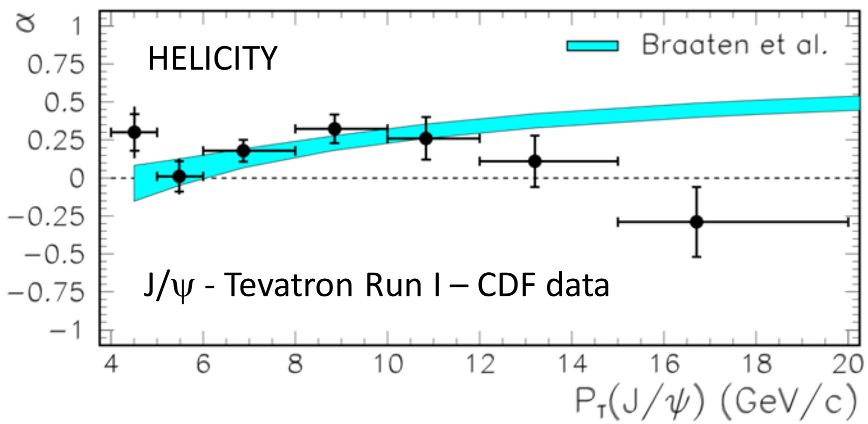
Results

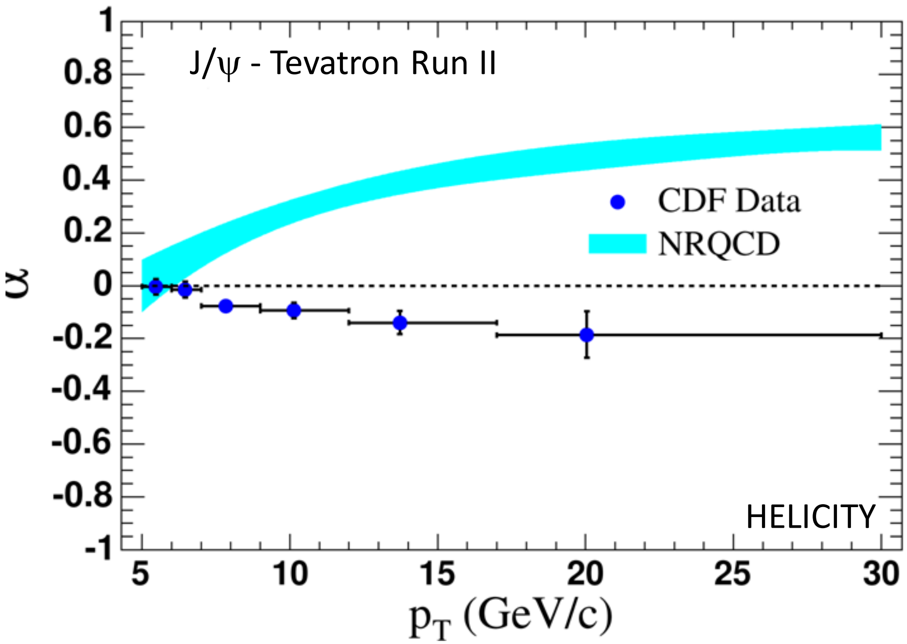


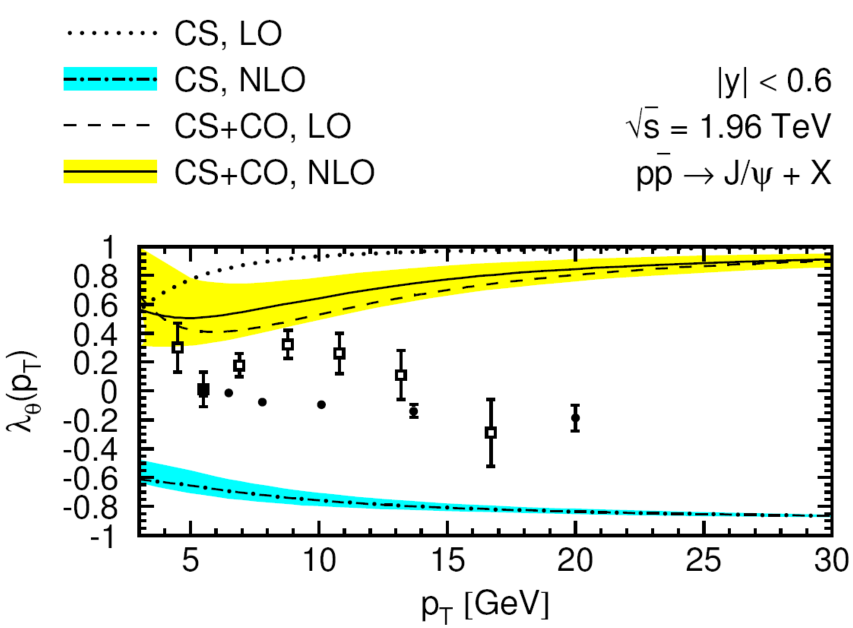
The CDF experiment measured the λ_θ (=α) parameter for prompt J/ψ hadroproduction

Only the cosθ part of the full angular distribution analyzed (no estimation of λ_ϕ and $\lambda_{\theta\phi}$)

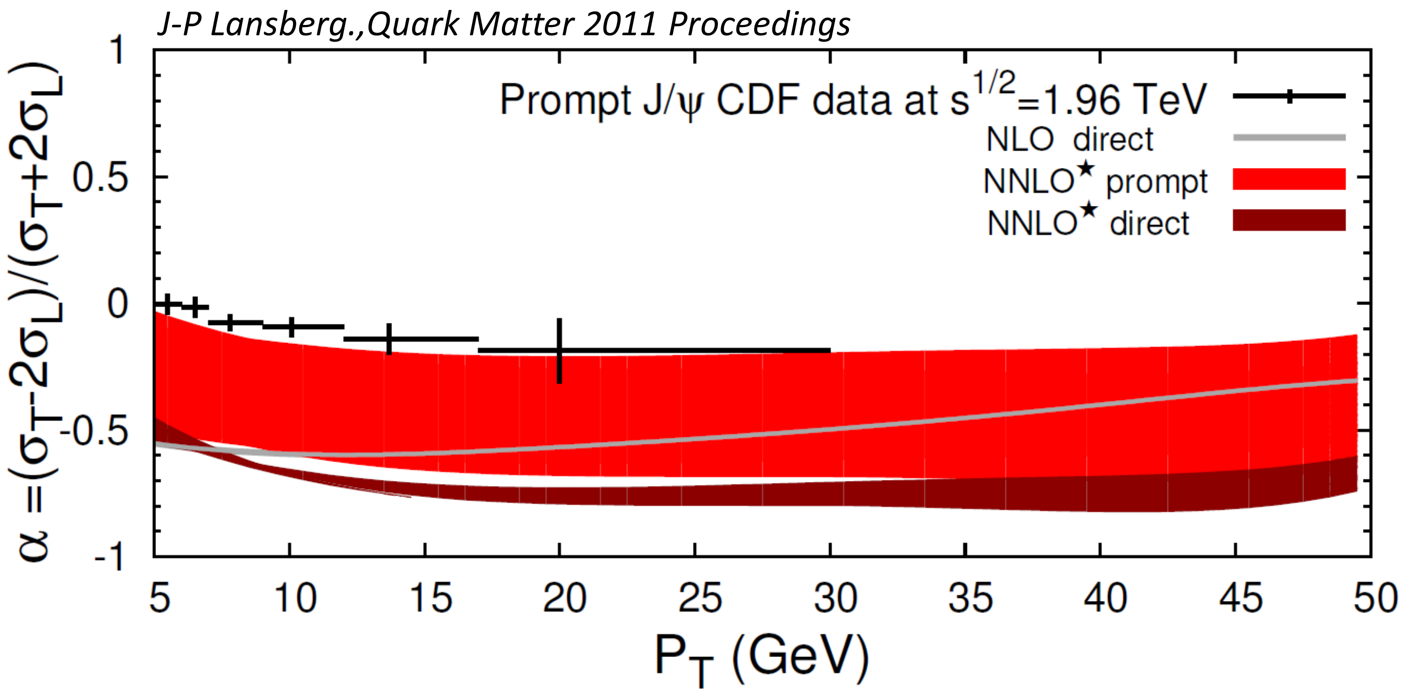
Results from Run I and Run II of the Tevatron:

no consistency between the two
not in agreement with LO and NLO NRQCD





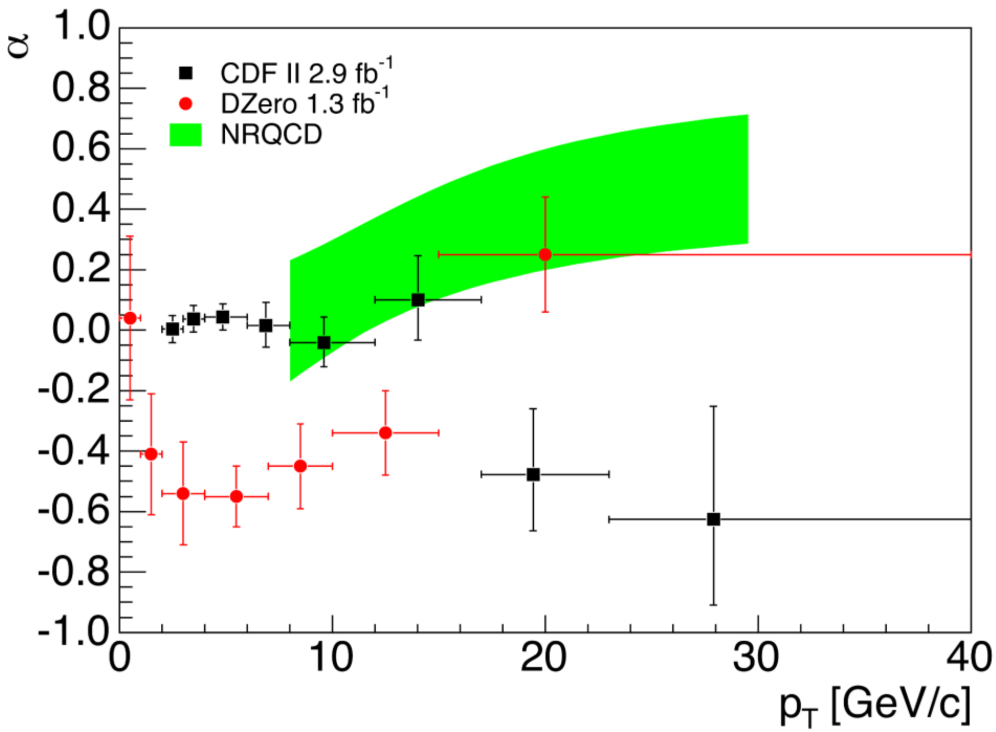
J/ψ polarization from CDF



The disagreement of NRQCD with data triggered strong efforts from the CSM side

More detailed calculations at higher order (NLO, NNLO*) showed a better agreement with polarization data, despite the huge uncertainty bands

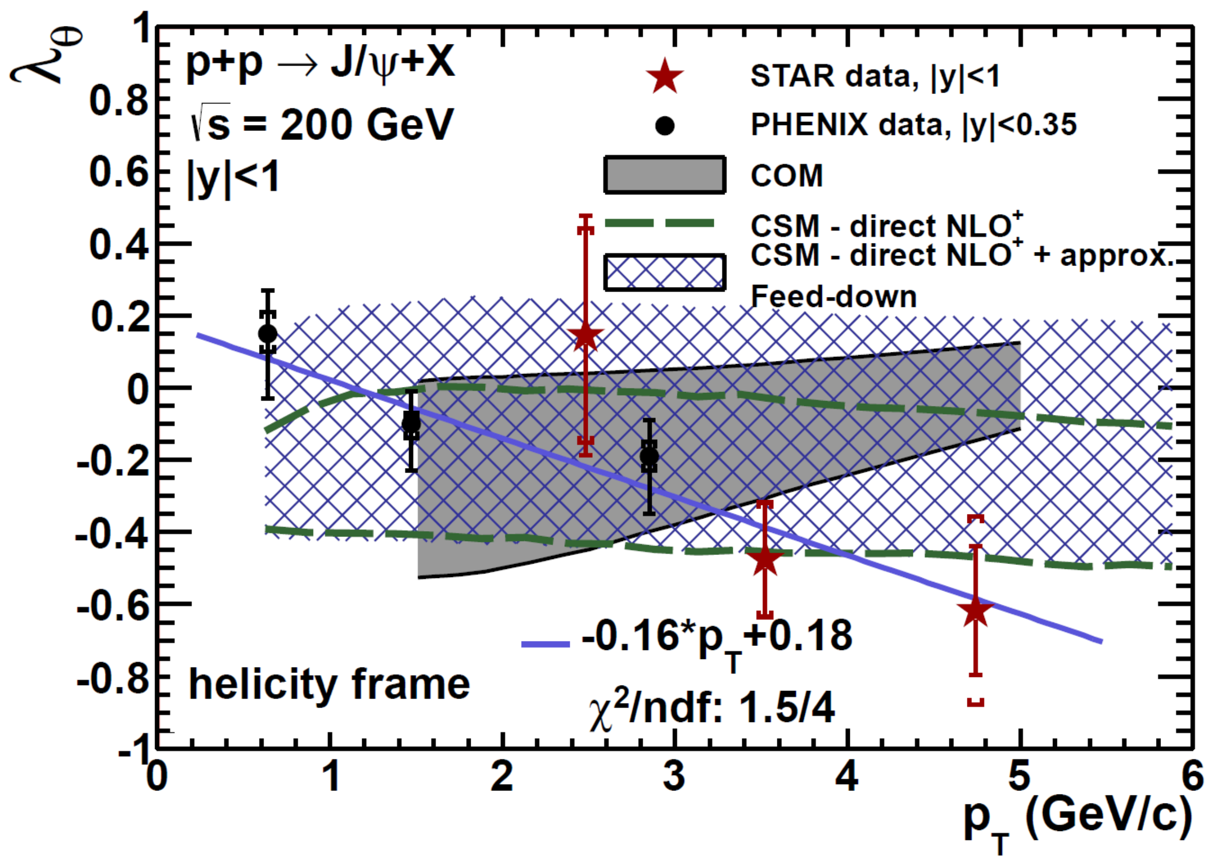
Υ polarization from CDF and D0



$\Upsilon(1S)$ polarization measurement from the two experiments (Run II) in disagreement

Still puzzling

PHENIX and STAR

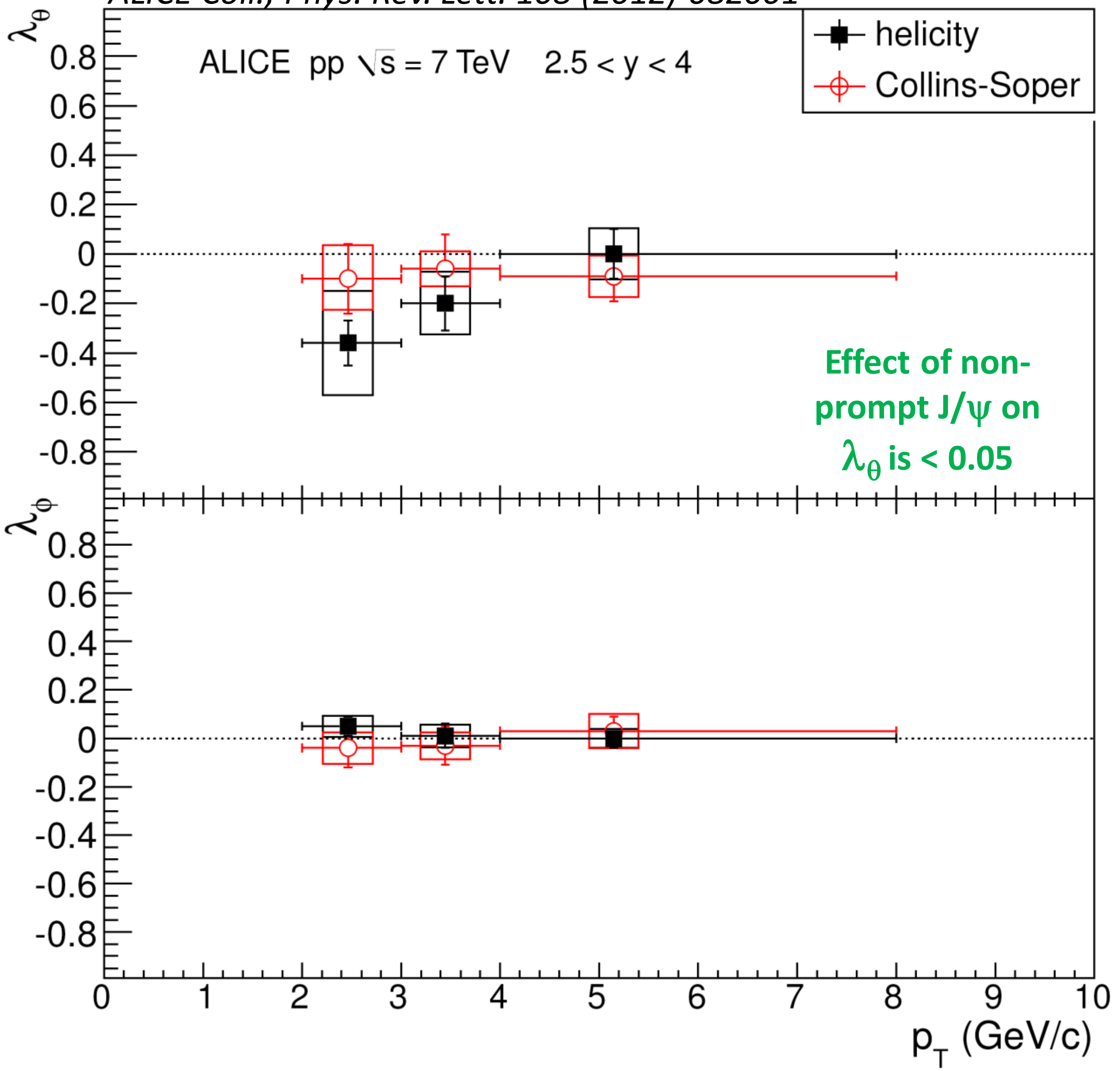


Also PHENIX and STAR measured J/ψ polarization in pp collisions at √s = 200 GeV

Agreement between the two experiments, but too low p_T to perform a real comparison with theory

J/ψ polarization with ALICE (2.5 < y < 4)

ALICE Coll., Phys. Rev. Lett. 108 (2012) 082001



No significant polarization observed in all the p_t range

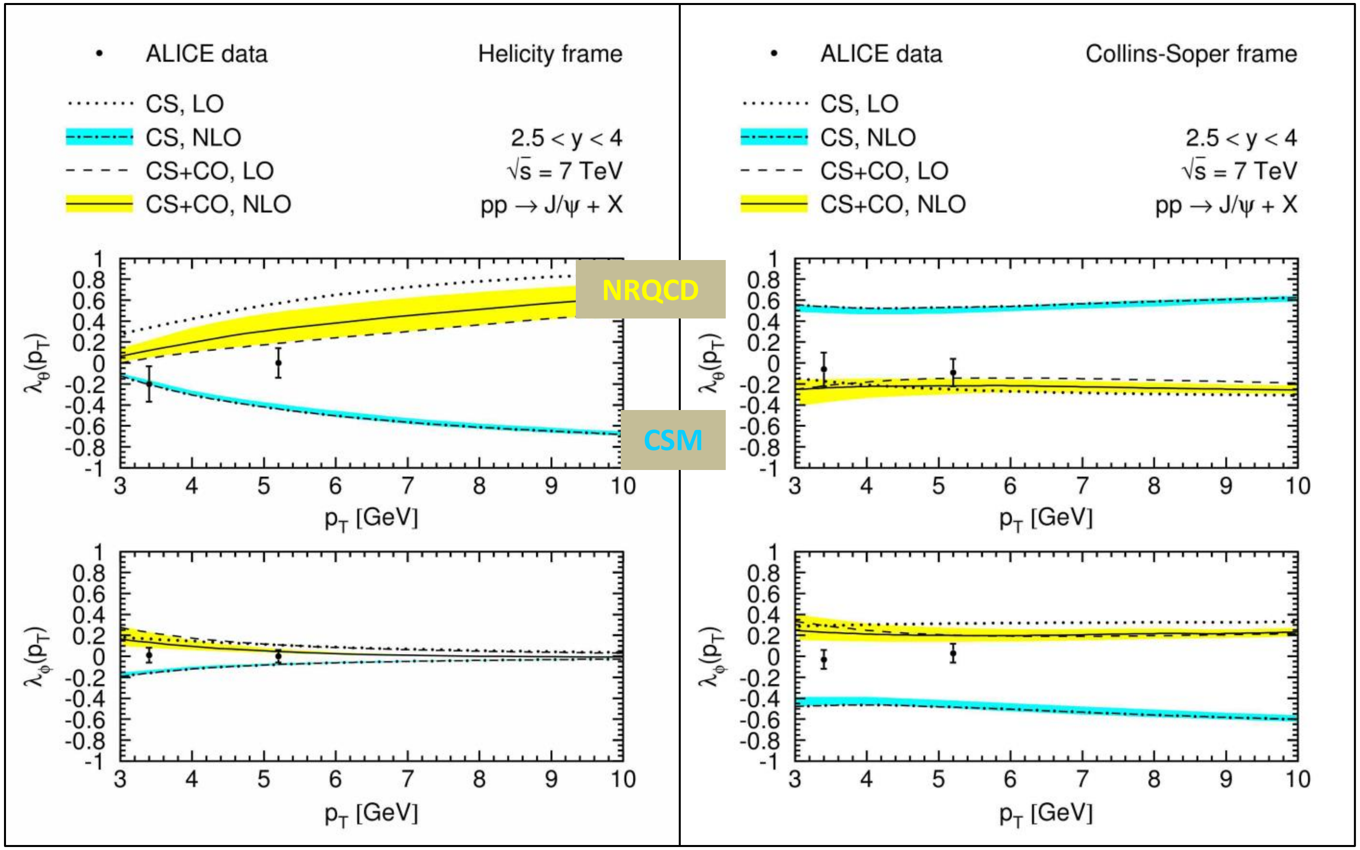
Hint for longitudinal polarization at low p_t in the helicity frame which vanishes at higher p_t

In the Collins-Soper reference frame λ_θ always compatible with (but sistematically lower than) zero

λ_ϕ always compatible with zero in both the reference frames.

Also $\lambda_{\theta\phi}$ checked to be compatible with zero

ALICE results compared with LO and NLO NRQCD and CSM predictions
(M. Butenschön B.A. Kniehl, PRL 106 (2011) 022003), obtained making use of the non perturbative coefficients extracted from a global fit to the differential cross sections measured in hadron-hadron, lepton-hadron and lepton-lepton collisions

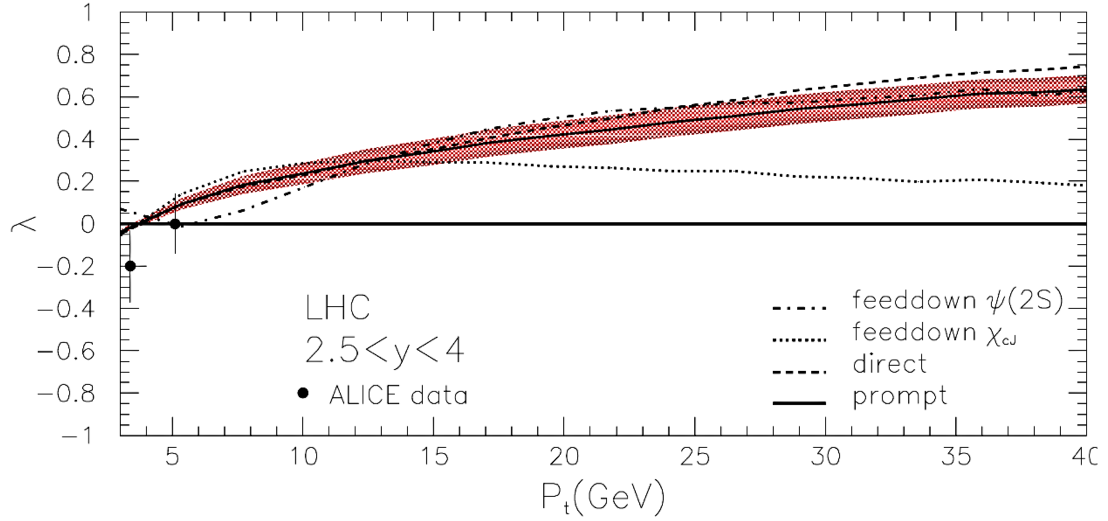


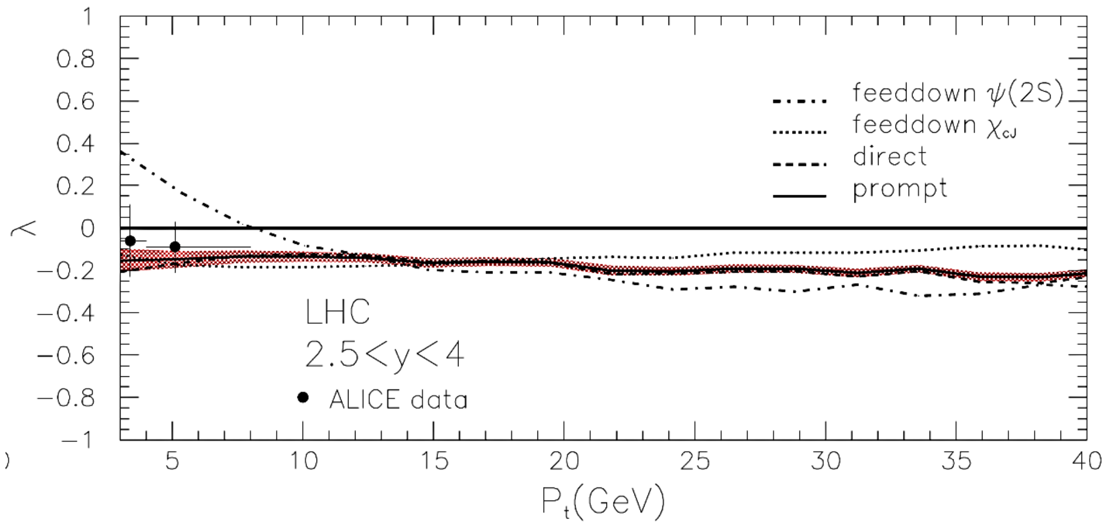
None of the two curves can perfectly describe the data

NRQCD slightly favored, in particular in the Collins-Soper frame

M. Butenschön B.A. Kniehl, PRL 108(2011) 172002

J/ψ polarization with ALICE: comparison with theory (II)





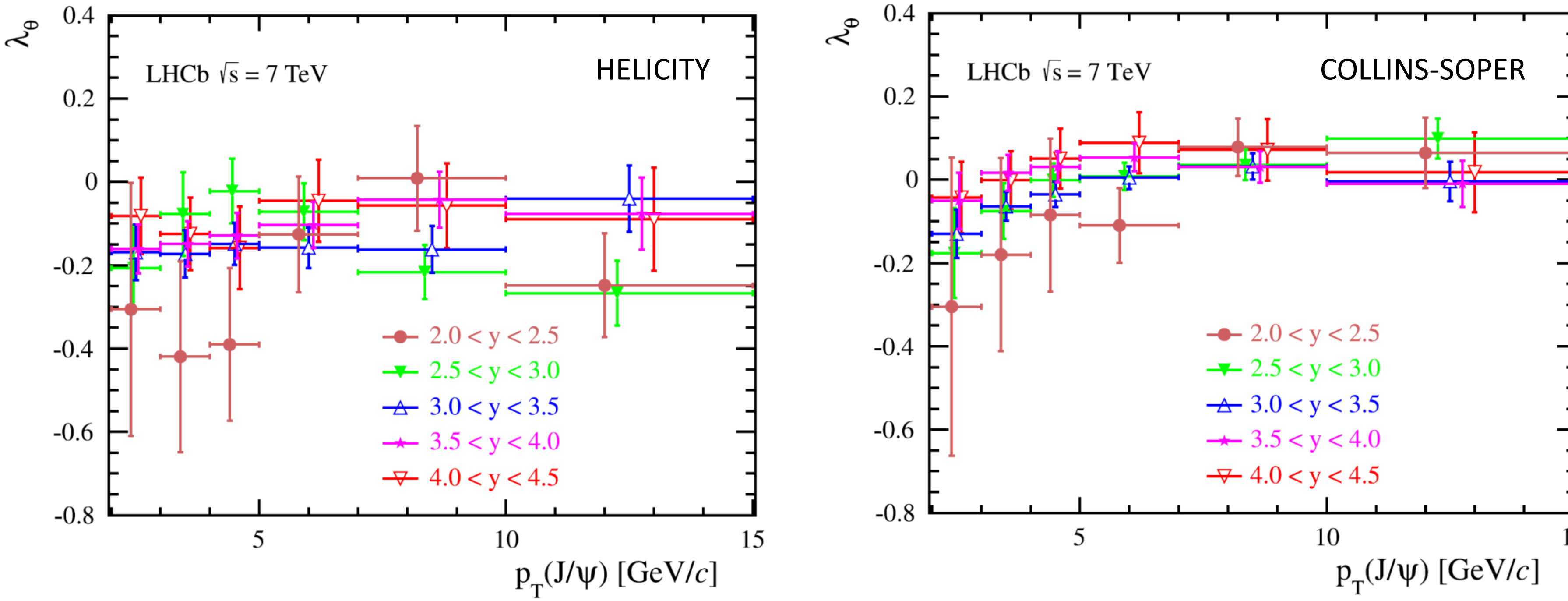
Also another theory group made a comparison with ALICE's results (B. Gong at al., arXiv:1205.6682).

The theoretical curves (NLO NRQCD) were in this case obtained for prompt J/ψ production and only the λ_θ parameter was considered.

In order to make the comparison data-theory more conclusive need to reach higher p_t

B. Gong at al., PRL 110, 042002 (2013)

J/ψ polarization with LHCb

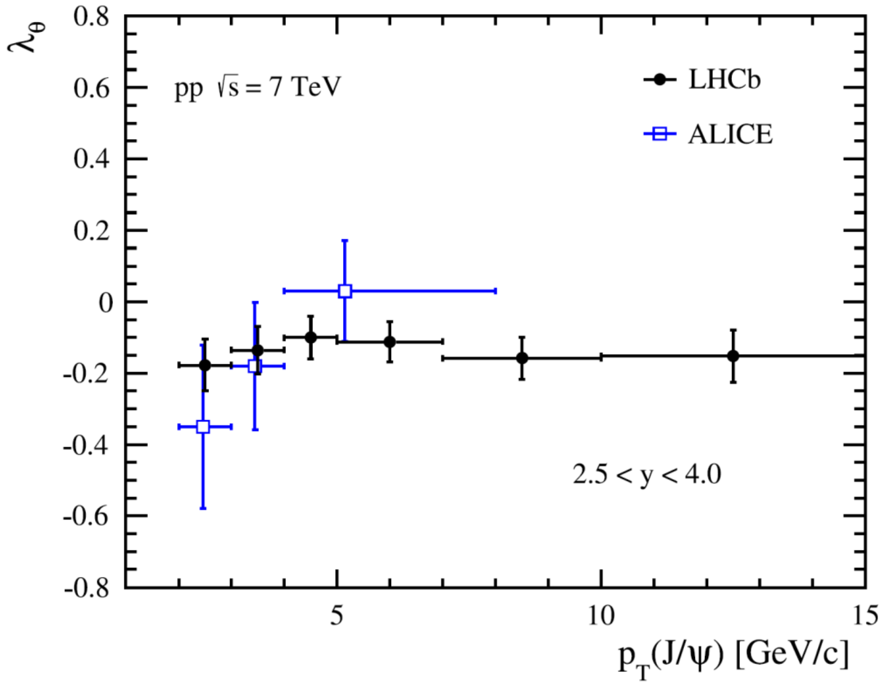


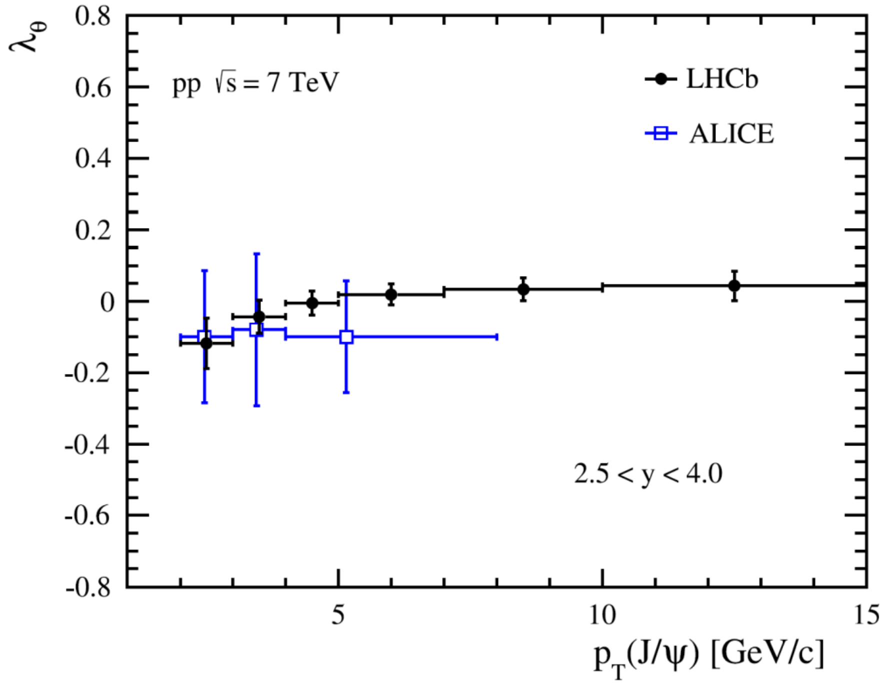
Multi-differential measurement performed up to 15 GeV/c in the range 2 < y < 4.5

In the helicity reference frame slightly longitudinal polarization observed.
In the Collins-Soper reference λ_θ goes to zero at high p_T.
All the other parameters consistent with zero.

LHCb Coll., Eur. Phys. J. C (2013)73:2631

J/ψ polarization with LHCb: comparison with ALICE

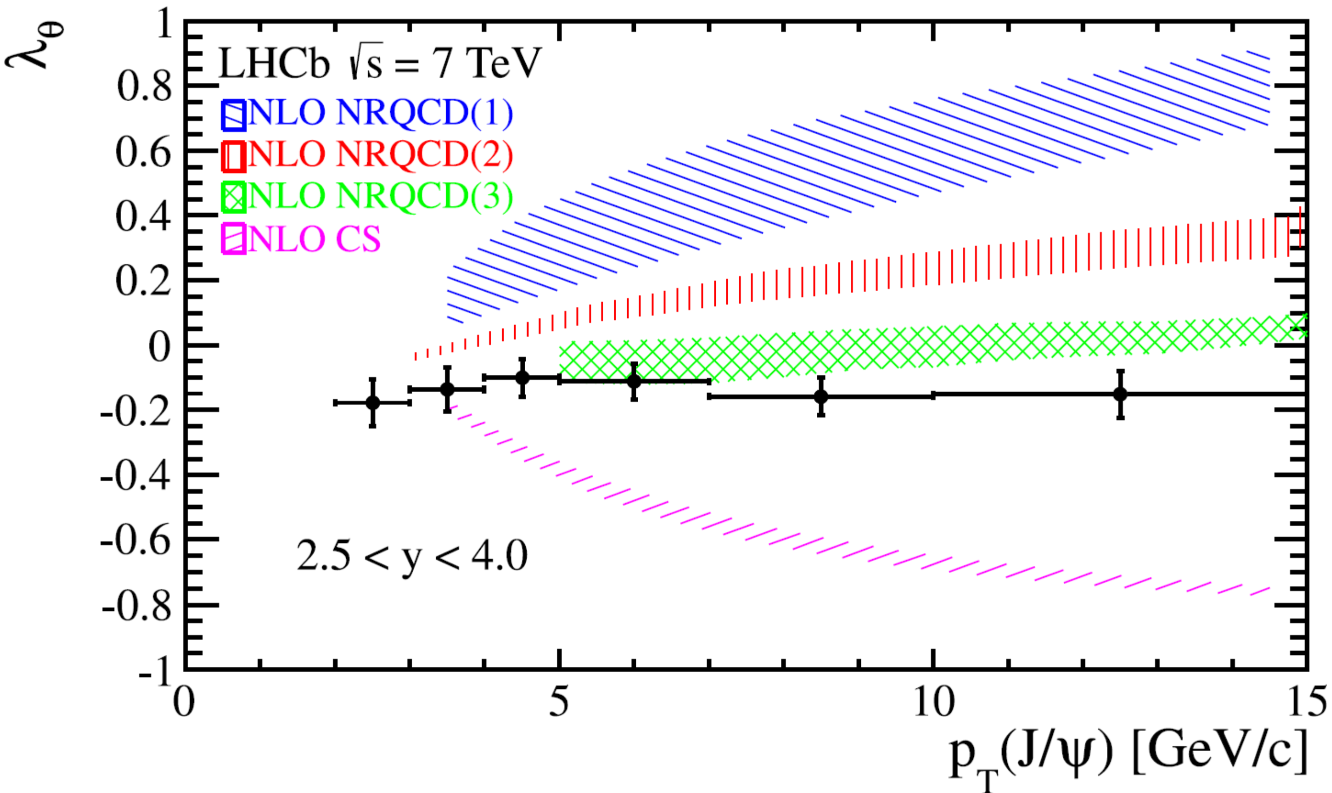




The comparison between ALICE and LHCb shows a very good agreement in the common y region for both the reference frames

LHCb Coll., Eur. Phys. J. C (2013)73:2631

LHCb



The comparison data/theory is still puzzling.

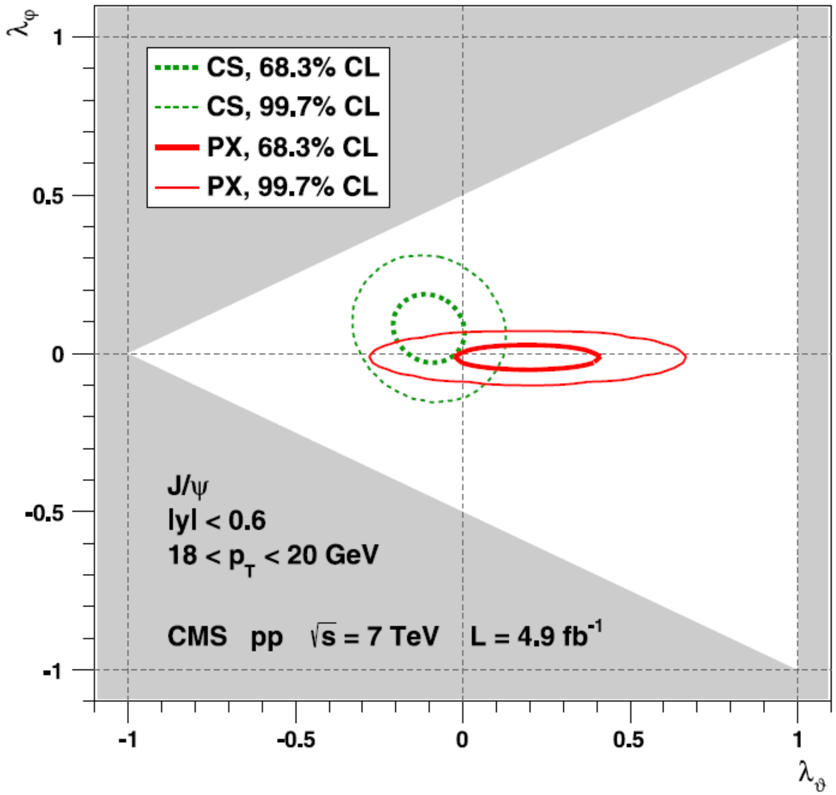
A better agreement is achieved when polarization measurements are used for the global fit (green band)

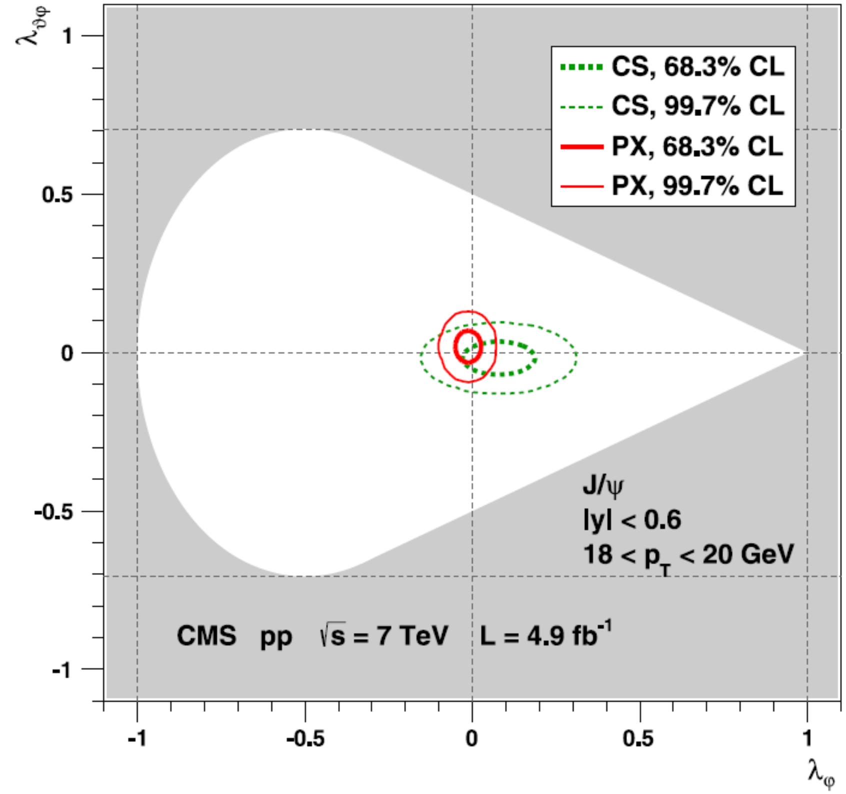
M. Butenschön B.A. Kniehl, PRL 108(2011) 172002
M. Butenschön B.A. Kniehl, PRL 108(2011) 172002
B. Gong at al., PRL 110(2013) 042002
K.-T. Chao et al., PRL 108(2012) 242004

LHCb Coll., Eur. Phys. J. C (2013)73:2631

Charmonium polarization from CMS (I)

Livio Bianchi
AFTER Workshop
13^{th} Jan 2014



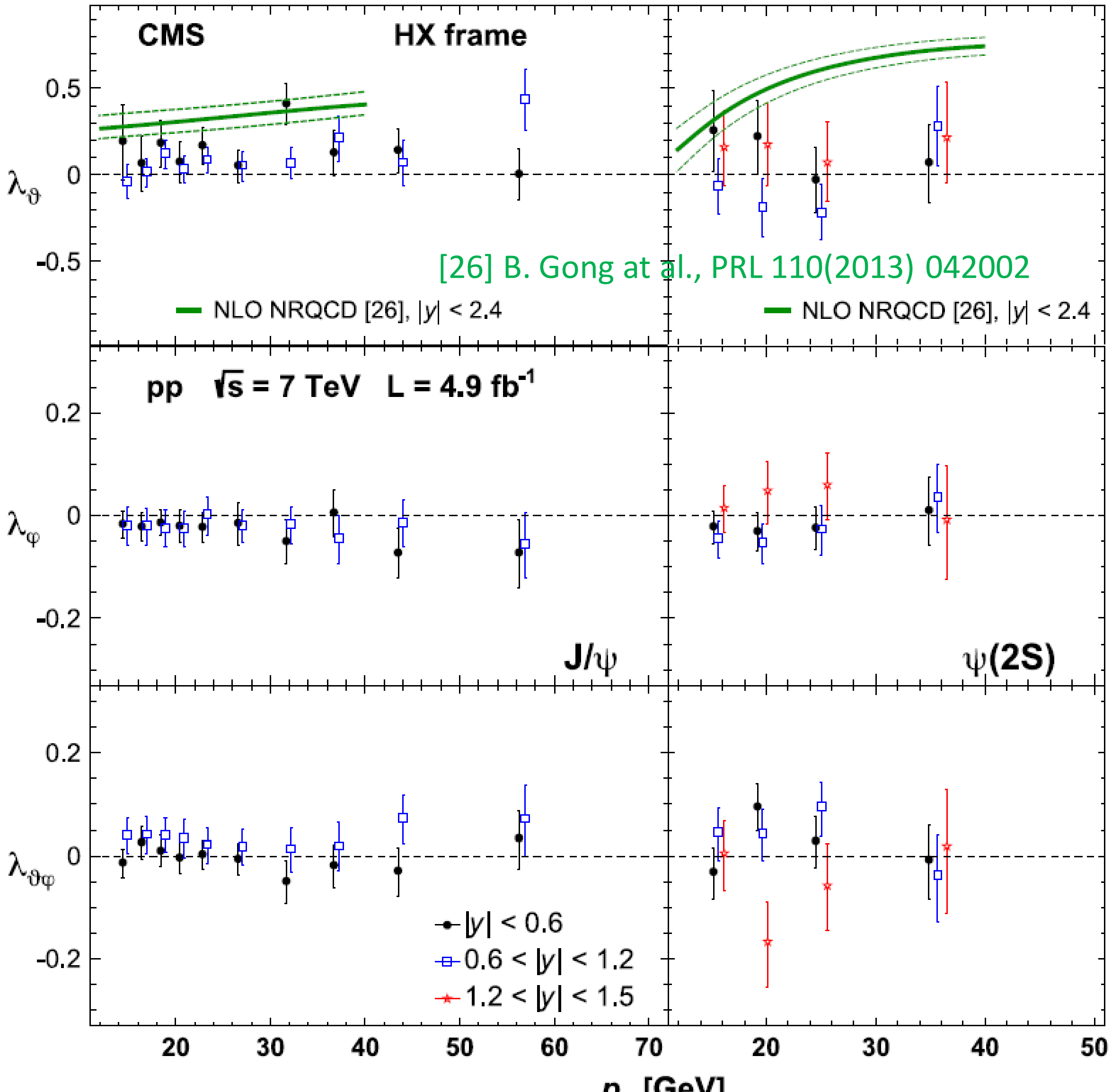


CMS measured J/ψ and ψ(2S) polarization in a large p_T domain (up to 70 GeV/c) and in three different rapidity ranges ($|y|<0.6$, $0.6 < y < 1.2$ and $1.2 < y < 1.5$).

Multi-dimensional analyses performed in different reference frames: λ_ϕ and $\lambda_{\theta\phi}$ found to be everywhere compatible with zero.

CMS Coll., Physics Letters B 727 (2013) 381–402

Charmonium polarization from CMS (II)



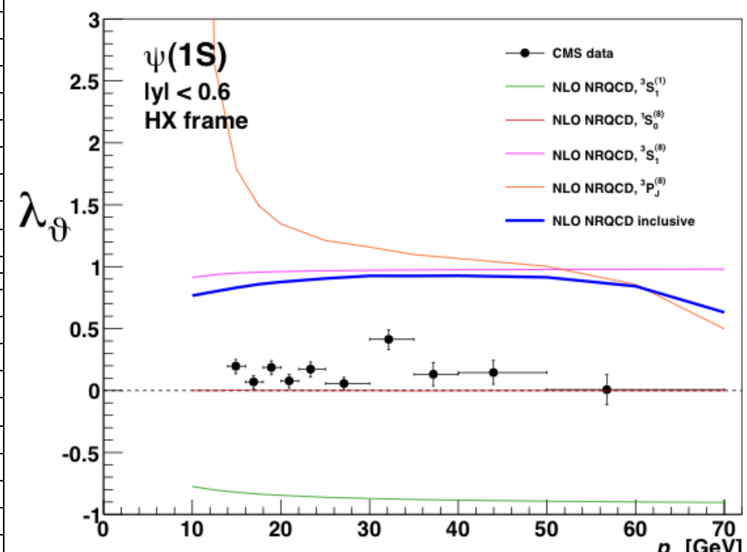
[26] B. Gong at al., PRL 110(2013) 042002

CMS Coll., Physics Letters B 727 (2013) 381–402

Parameterscompatible with zero, both for J/ψ and ψ(2S)

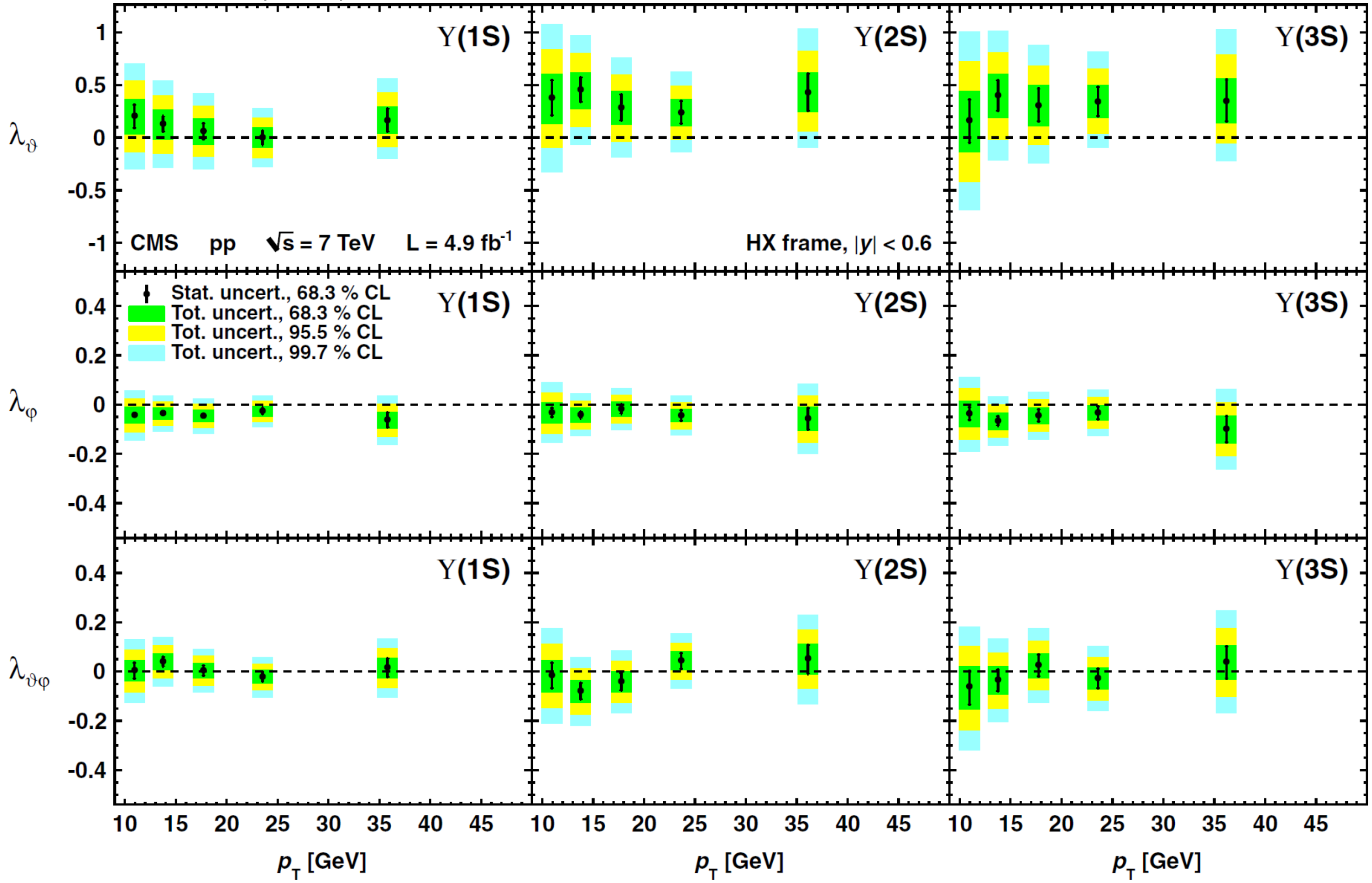
No significant dependence on the charmonium rapidity

The comparison with NLO NRQCD is again not satisfactory



Bottomonium polarization from CMS

CMS Coll., PRL 110, 081802 (2013)

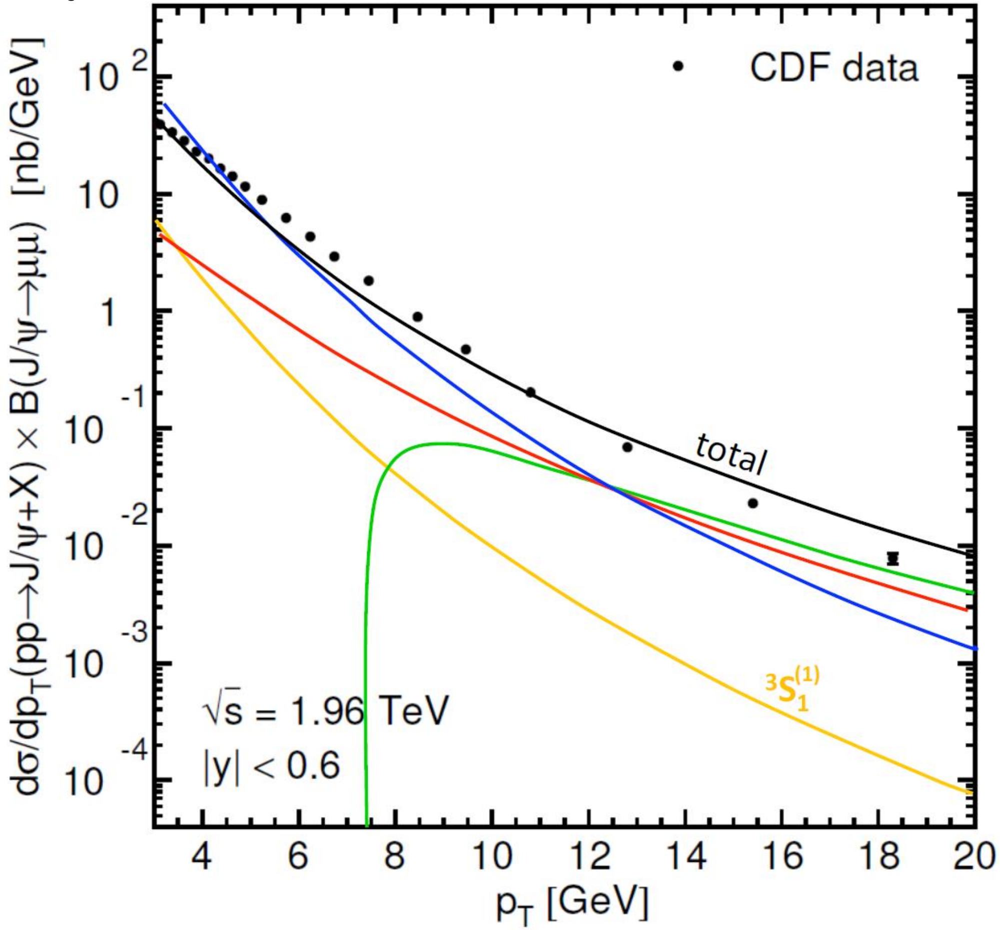


Multi-dimensional analysis performed on the three Υ resonances up to large p_T and in two rapidity bins (|y|<0.6 and 0.6 < y < 1.2).

Hint for non-zero λ_θ for Υ(2S) and Υ(3S)

Change of perspective

C. Lourenço et al., Hard Probes 2013



Summing-up theoretical procedure:

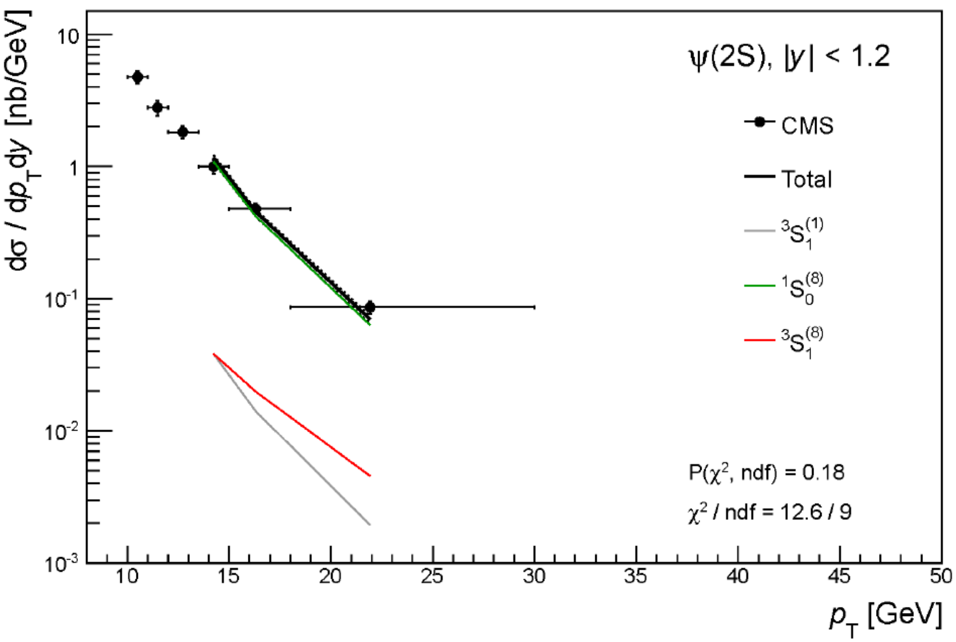
- Take all the cross-section data for a given quarkonium production (hadro, photo, etc.) and fit them leaving the LDMEs free
- Use the estimated LDMEs to predict the degree of polarization (**FAIL**)

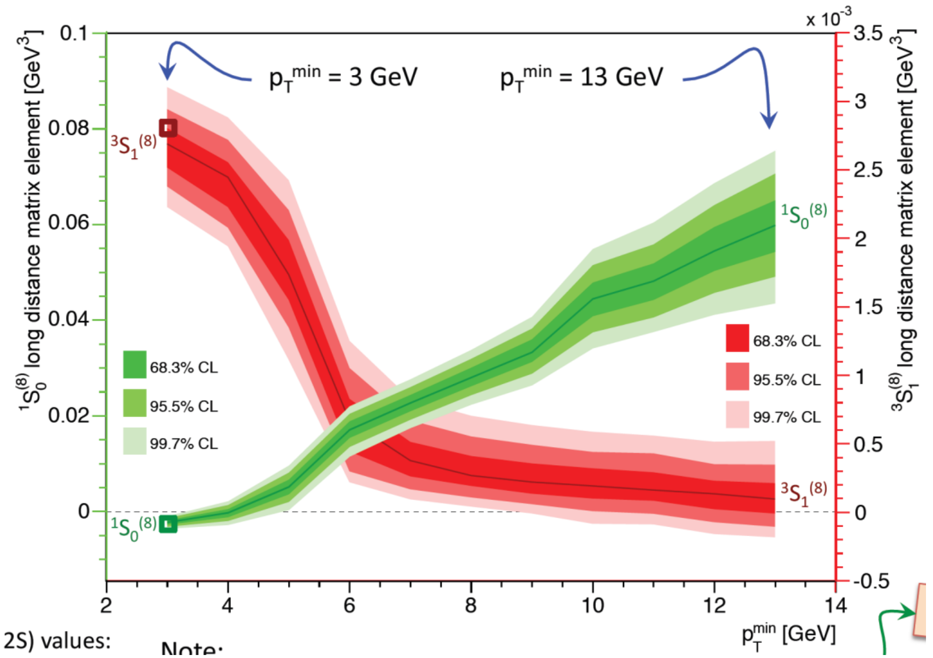
BUT
In this way the fit to the cross-section data is describing the trend JUST QUALITATIVELY and tends to be constrained by low-pt data points!

Possible different approach:
Let's assume NRQCD is valid, but we need to understand what is the validity domain!
We concentrate on a single set of data and we try to fit the cross section from a certain p_T onwards:
we **try to define a minimum p_T value from which NRQCD correctly predicts polarization**

Change of perspective: example on $\psi(2S)$

C. Lourenço et al., Hard Probes 2013





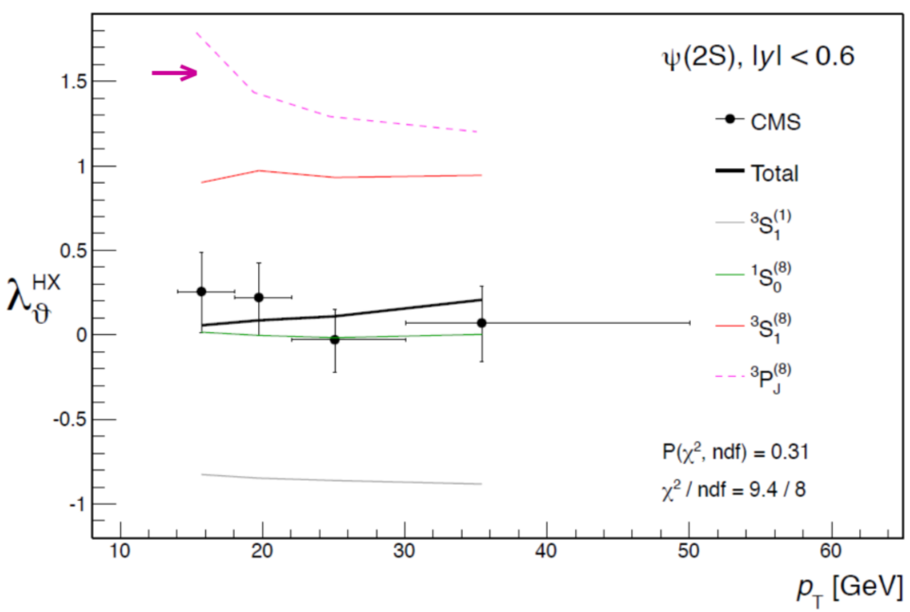
Considering CMS data on $\psi(2S)$, one sees that the fit to the p_T-differential cross-section gives the best χ^2 for p_T>13GeV/c

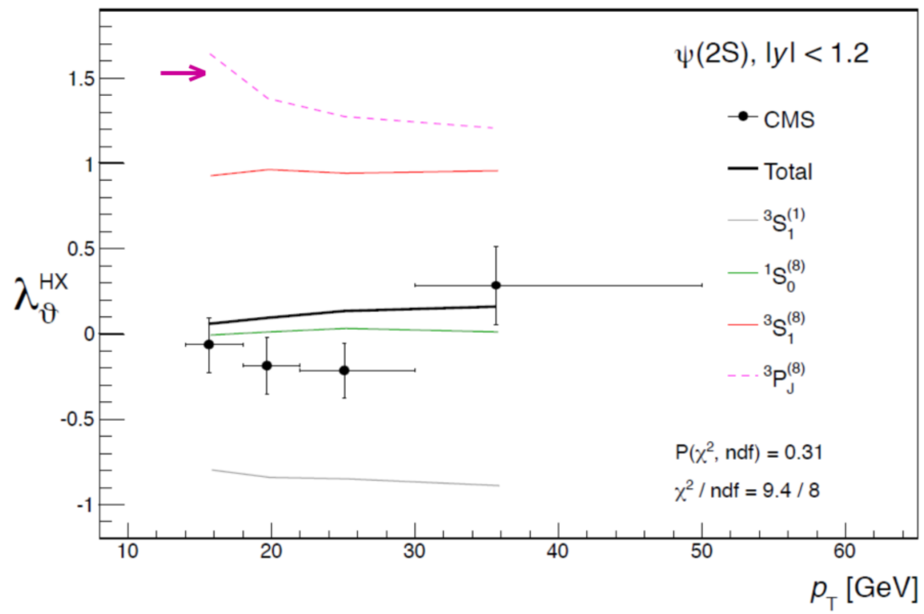
While p_T increases, the different LDMEs evolve and the relative importance of them changes!

For p_T>13GeV/c the dominant contribution is from $^1S_0$

Change of perspective: what happens to polarization

C. Lourenço et al., Hard Probes 2013





$^1S_0$ is the LDME which carries the zero-polarization contribution!!

Fitting ψ(2S) data for p_T higher than 13 GeV/c,
one can correctly provide predictions on the degree of polarization.

Is this the correct way to proceed?
Need large data samples from the same experiment for different quarkonia
in the p_T range 5-50 GeV/c

Conclusions and outlook

The degree of polarization of hadro-produced quarkonia is a key-observable

Tevatron experiments measured it, but the disagreement between CDF and D0 on Υ and the internal disagreement between CDF Run I and Run II on J/ψ made the comparison with theory less meaningful

J/ψ polarization has also been studied at RHIC at very low p_T

LHC experiments have been delivering high-precision results for J/ψ, $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$. The agreement among the experiment is very good.

The comparison of LHC results with theoretical predictions is still giving no satisfying answers and a new approach seem to emerge in order to understand the origin of the discrepancy.

The need of a theoretical effort is clear,
but still need very precise data for different quarkonia
in the intermediate and large p_T regions

$\downarrow$

AFTER?

Thank you