Quarkonium polarisation in (p-A and) nucleus-nucleus collisions from SPS to the LHC

- A long standing puzzle
- General remarks on the measurement method
- A rotation-invariant formalism to measure vector polarizations and parity asymmetries
- Quarkonium polarization
- Heavy Ion applications

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New Observables in Quarkonium Production
ECT* Trento, 28 Fev-4 Mar 2016

LIP

INSTITUTO SUPERIOR TÉCNICO

A varied menu for the LHC (and AFTER)

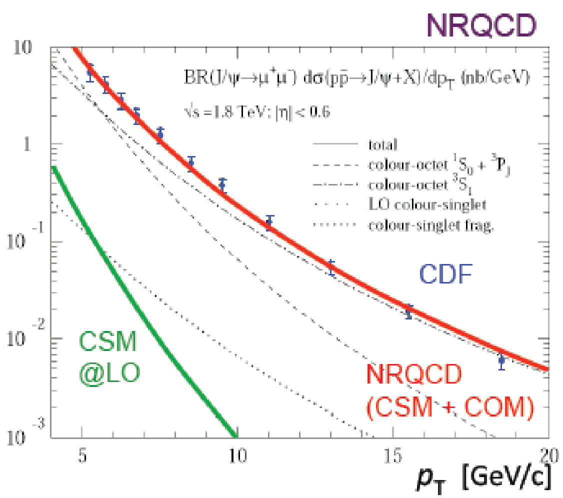
- Measure polarization = determine average angular momentum composition of the particle, through its decay angular distribution
- It offers a much closer insight into the quality/topology of the contributing production processes wrt to decay-averaged production cross sections
- Polarization analyses are particularly important to (for example):
  - understand still unexplained production mechanisms [$\boldsymbol{J/\psi, \chi_c, \psi', \Upsilon, \chi_b}$]
  - characterize the spin of newly (eventually) discovered resonances [***X*(3872)**, Higgs, *Z'*, graviton, ...]
  - Understand the properties of dense and hot matter

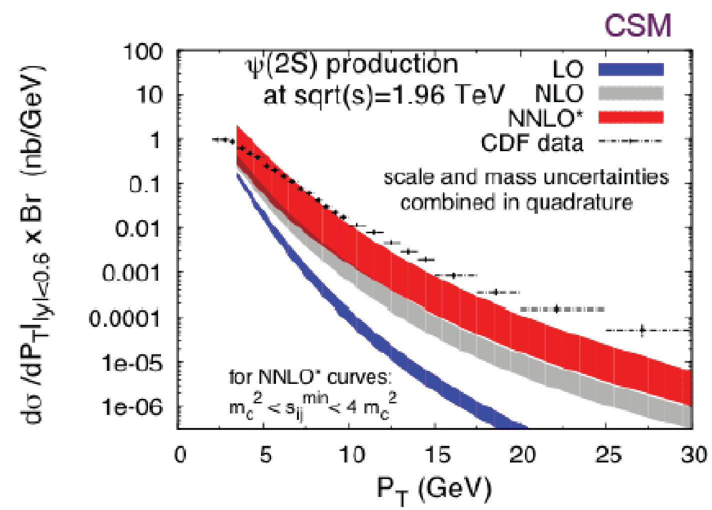
Task list

One assumes that the production of **quark-antiquark states** can be described using **perturbative QCD**, as long as we "**factor out**" long-distance bound-state effects

A seemingly inescapable prediction of NRQCD approach is that "high" p_T quarkonia come from fragmenting gluons and are fully tranversely polarized

However, despite good success in describing cross sections...





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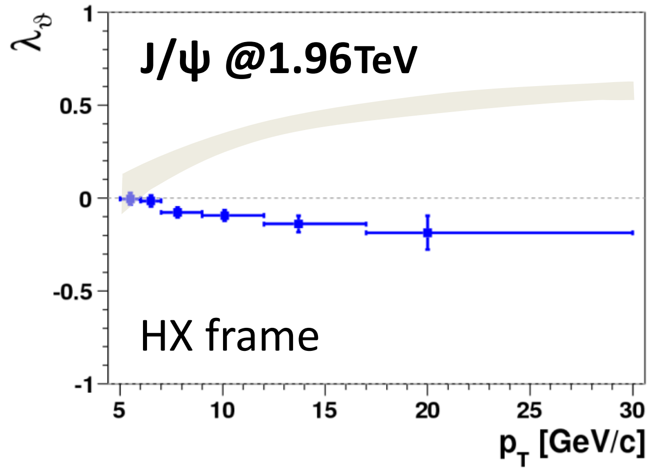
One assumes that the production of **quark-antiquark states** can be described using **perturbative QCD**, as long as we "**factor out**" long-distance bound-state effects

A seemingly inescapable prediction of NRQCD approach is that "high" p_T quarkonia come from fragmenting gluons and are fully tranversely polarized

the first comparisons with polarization data were not promising…



NRQCD factorization
Braaten, Kniehl & Lee, PRD62, 094005 (2000)

CDF Run II
CDF Coll., PRL 99, 132001 (2007)

But:

- Until recently the experimental situation was contradictory and incomplete, as it was emphasized in Eur. Phys. J. C69, 657 (2010)
  → improve drastically the quality of the experimental information
- maybe the theory is only valid at asymptotically high p_T
  → extend measurements to $p_T >> M$
- contributions of intermediate *P*-wave states have not been fully calculated yet and are still unknown experimentally (remember Ilse's talk)
  → measure polarizations of *directly* produced states, ψ' and $\Upsilon(3S)$
  → measure polarizations of *P*-wave states, χ_c and χ_b, and their feeddown to *S* states

Task list

There are problems actually on the theory side which are becoming quite evident

Remember that in NRQCD the factorization hypothesis implies that the cross-section for the inclusive production of a meson H in a A+B collision is

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

SDC LDME

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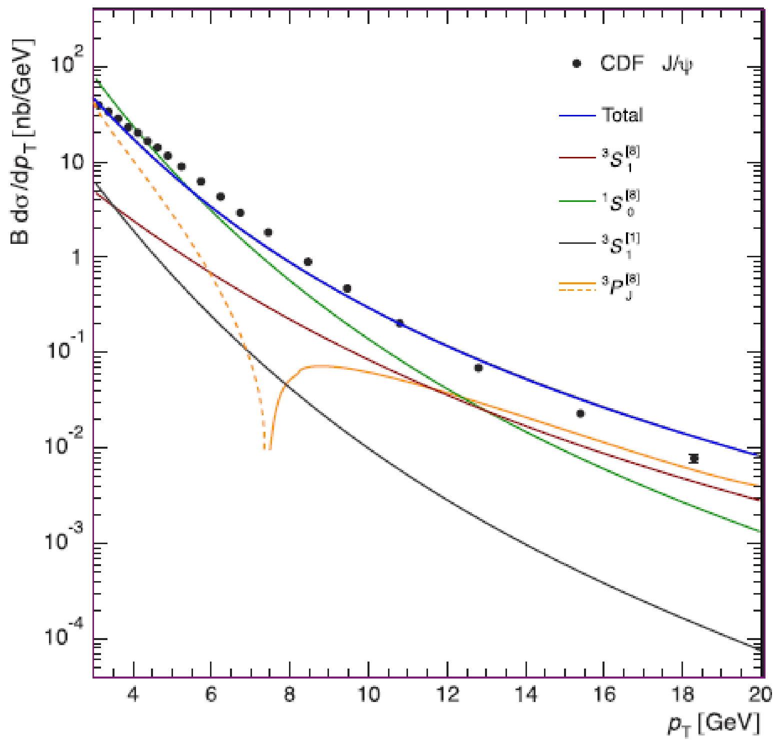

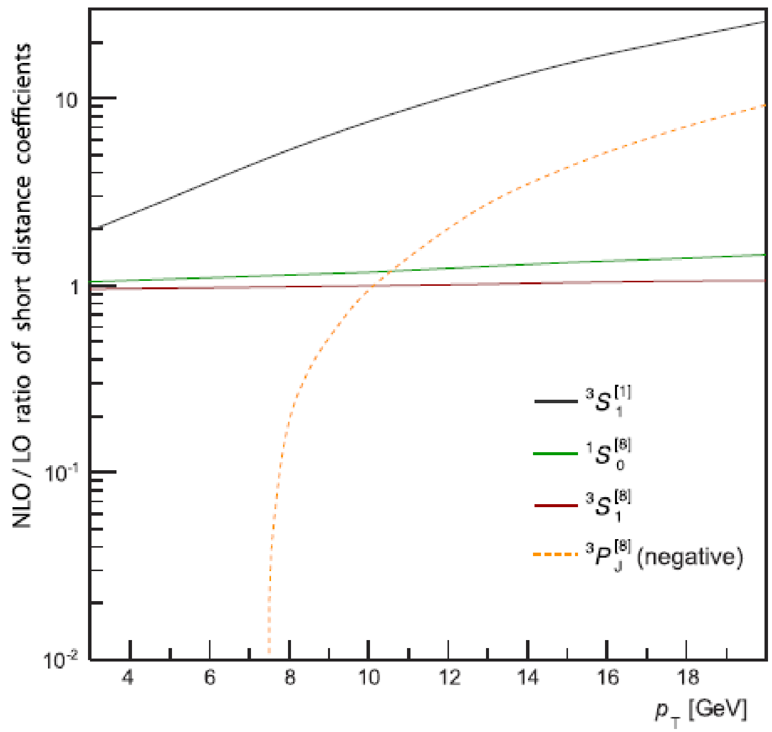

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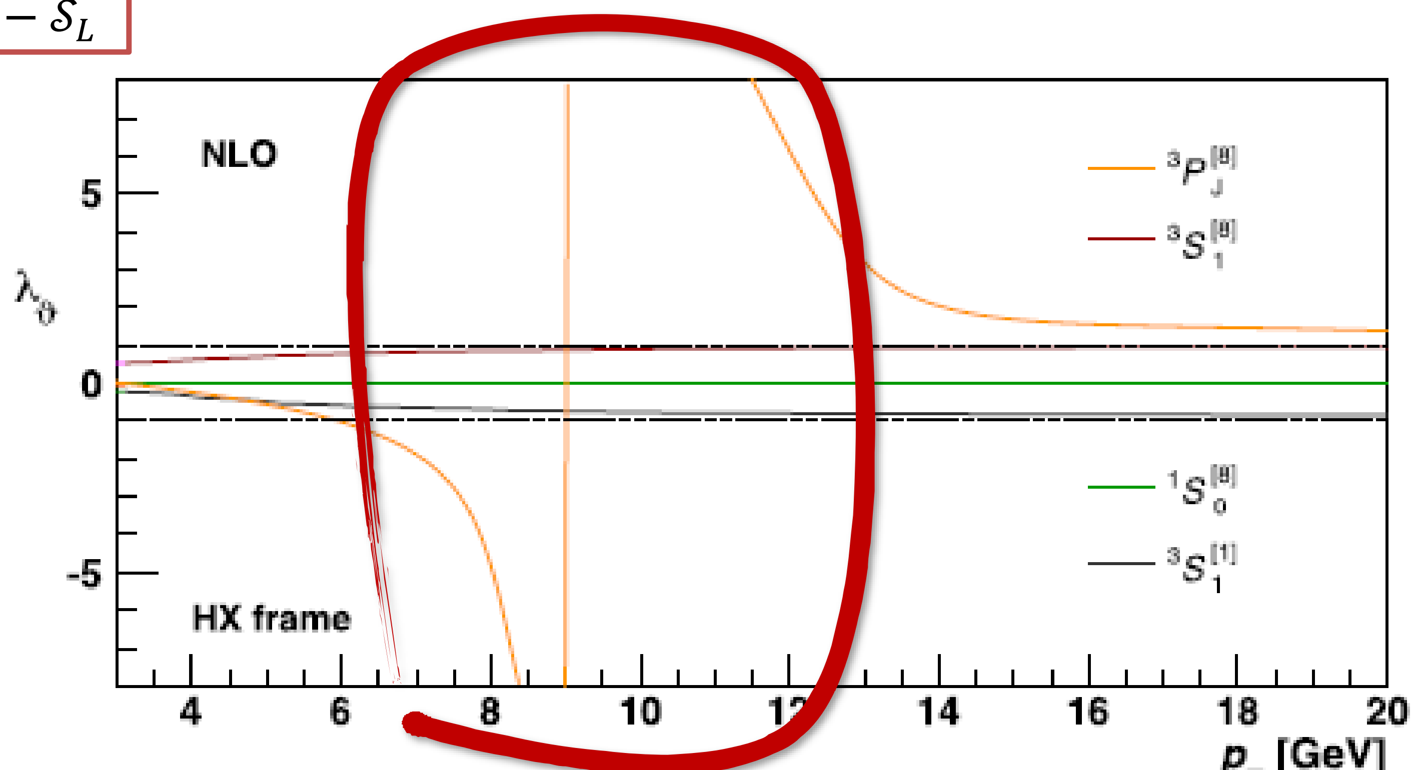
SDC LDME

$$\lambda_\theta=\frac{\mathcal{S}_T+\mathcal{S}_L}{\mathcal{S}_T-\mathcal{S}_L}$$



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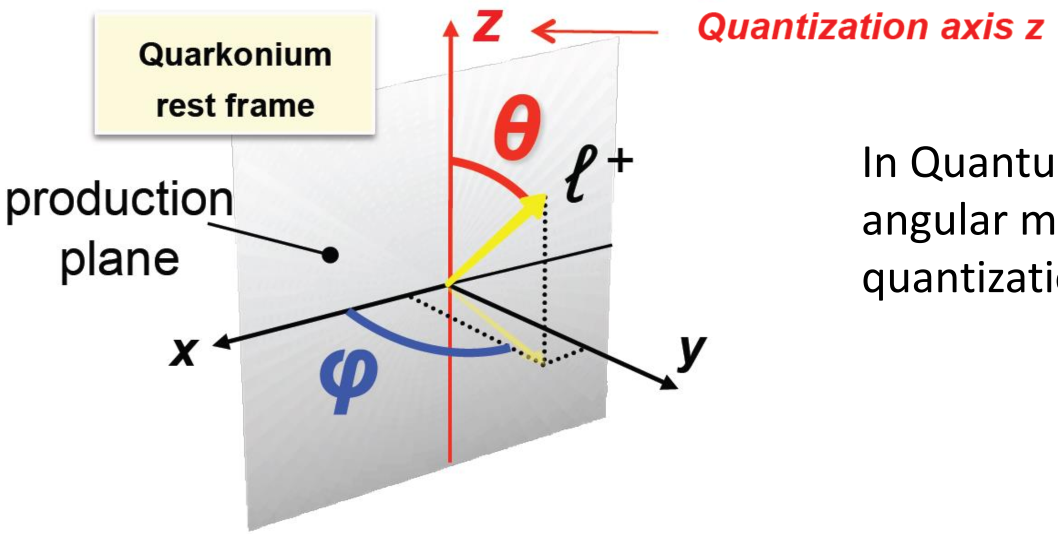
SDC LDME

IT IS possible to define kinematic discriminants to distinguish $^3P_J^{[8]}$ on a statistical basis from the other terms. One could then identify regions of phase space where the quarkonia would have **negative cross sections** and decay distributions **violating angular momentum conservation**!

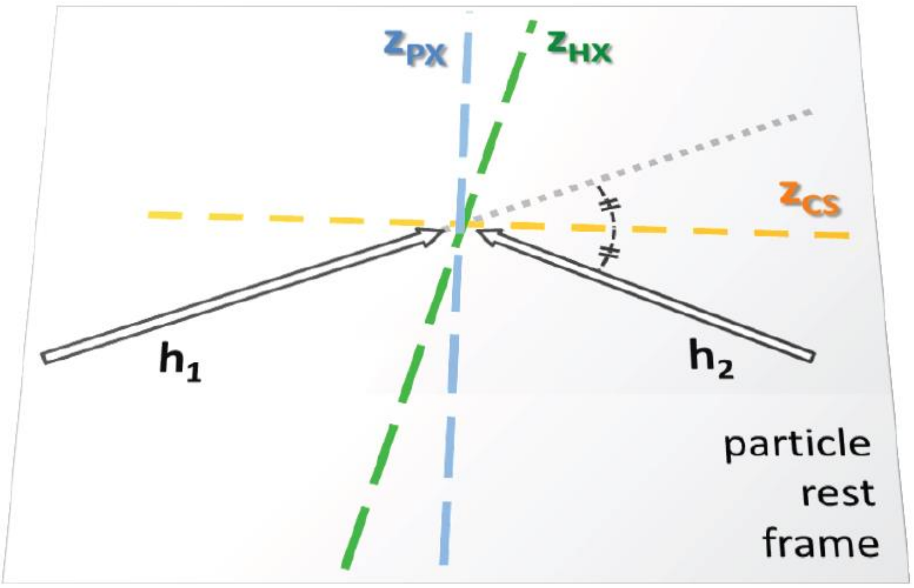
Definition of observables



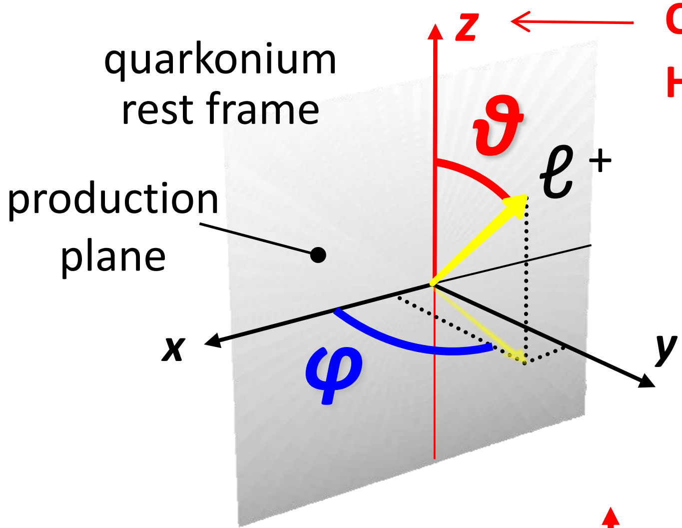
In Quantum Mechanics the study of angular momentum requires a quantization axis (aka *"z-axis"*)

Many possible (known) choices:

- Gottfried-Jackson (GJ)
- Collins-Soper (CS)
- Helicity (HX)
- Perpendicular Helicity (PX)



Frames and parameters



Collins-Soper axis (CS): ≈ dir. of colliding partons

Helicity axis (HX): dir. of quarkonium momentum

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

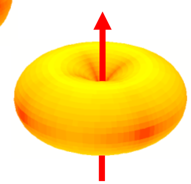
$\lambda_\vartheta = +1$

$\lambda_\varphi = \lambda_{\vartheta\varphi} = 0$

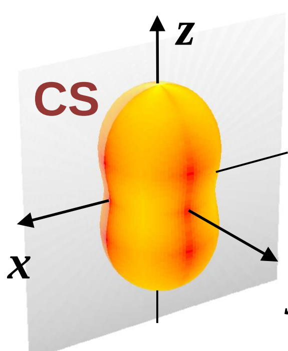
$J_z = \pm 1$ → $\lambda_\vartheta = +1$: **"transverse"** (= photon-like) pol.

$\lambda_\vartheta = -1$

$\lambda_\varphi = \lambda_{\vartheta\varphi} = 0$



$J_z = 0$ → $\lambda_\vartheta = -1$: **"longitudinal"** pol.

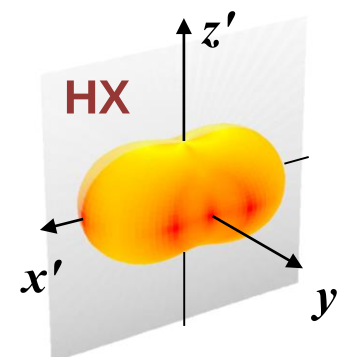


CS ⊥ HX for mid rap. / high p_T

$\lambda_\vartheta = +1$
$\lambda_\varphi = 0$

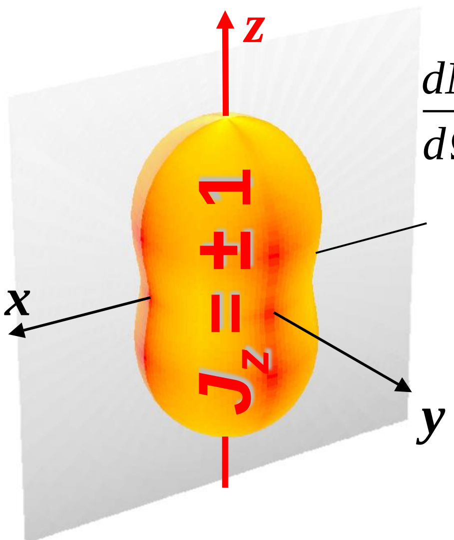
90º

$\lambda_\vartheta = -1/3$
$\lambda_\varphi = +1/3$



The azimuthal anisotropy is not a detail

Case 1: natural transverse polarization

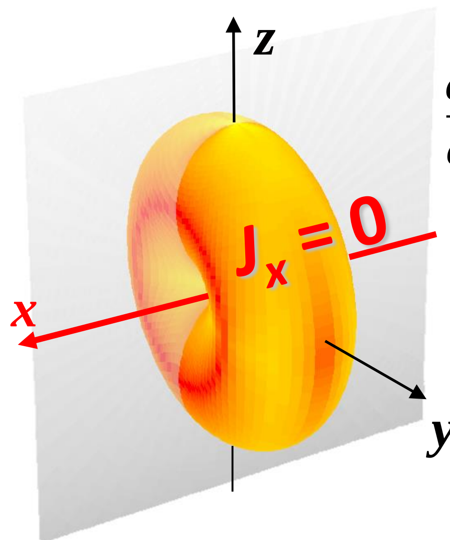


$$\frac{dN}{d\Omega} \propto 1 + \cos^2\theta$$

$\lambda_\vartheta = +1$

$\boldsymbol{\lambda_\varphi} = \mathbf{0}$

Case 2: natural longitudinal polarization, observation frame $\perp$ to the natural one



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

$\lambda_\vartheta = +1$

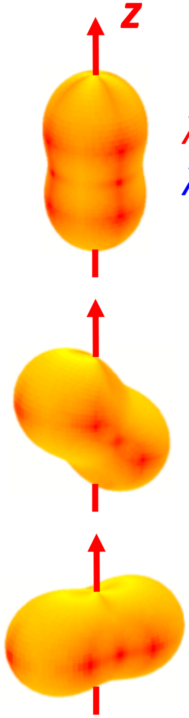
$\boldsymbol{\lambda_\varphi} = \mathbf{-1}$

- Two very different physical cases
- Indistinguishable if $\boldsymbol{\lambda_\varphi}$ is not measured (integration over $\boldsymbol{\varphi}$)

Frame-independent polarization

The ***shape*** of the distribution is obviously frame-invariant.
→ it can be characterized by a frame-independent parameter, e.g. $\tilde{\lambda} = \dfrac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}$

Note: $\tilde{\lambda} = 1$ means Lam-Tung relation

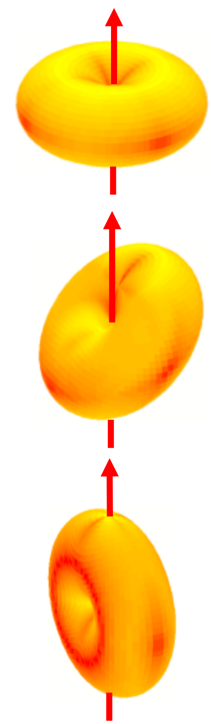


$\lambda_\vartheta = +1$, $\lambda_\varphi = 0$

$\lambda_\vartheta = +1/5$, $\lambda_\varphi = +1/5$

$\lambda_\vartheta = -1/3$, $\lambda_\varphi = +1/3$

$$\tilde{\lambda} = +1$$



$\lambda_\vartheta = -1$, $\lambda_\varphi = 0$

$\lambda_\vartheta = -1/3$, $\lambda_\varphi = -1/3$

$\lambda_\vartheta = +1$, $\lambda_\varphi = -1$

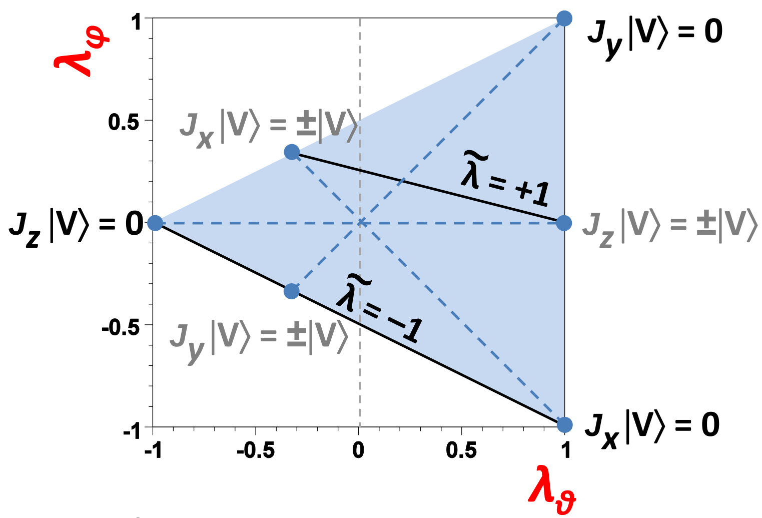
$$\tilde{\lambda} = -1$$

P. Faccioli, C. Lourenço, J.S., PRL 105, 061601; PRD 82, 096002; PRD 83, 056008

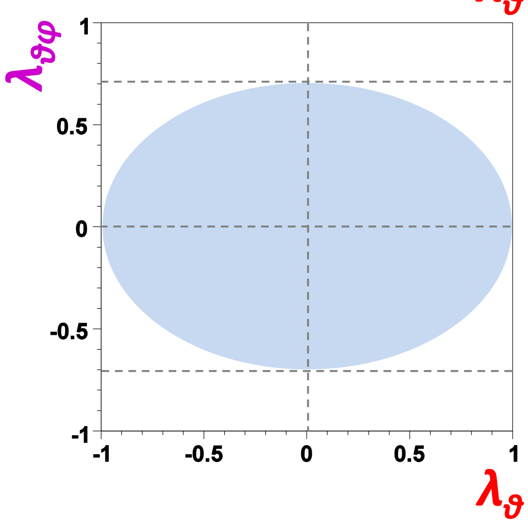
Positivity constraints for dilepton distributions

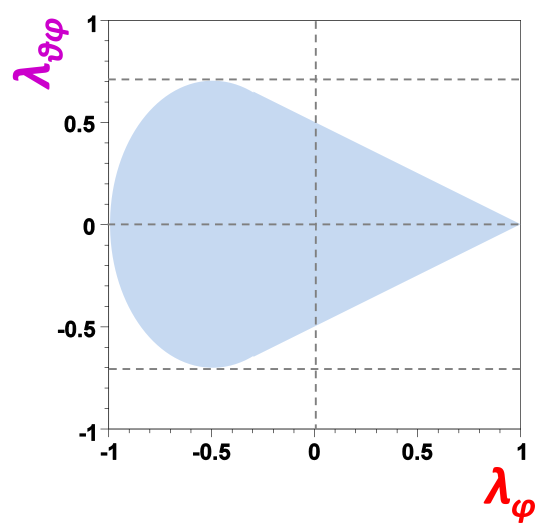
P. Faccioli, C.Lourenço, J.S., PRL 105, 061601 (2010); PRD 83, 056008 (2011)

- General and frame-independent constraints on the anisotropy parameters of vector particle decays



$$|\lambda_\varphi| \leq \frac{1}{2}(1+\lambda_\vartheta)\,, \quad \lambda_\vartheta^2 + 2\lambda_{\vartheta\varphi}^2 \leq 1\,,$$
$$|\lambda_{\vartheta\varphi}| \leq \frac{1}{2}(1-\lambda_\varphi)\,,$$
$$(1+2\lambda_\varphi)^2 + 2\lambda_{\vartheta\varphi}^2 \leq 1 \quad \text{for} \quad \lambda_\varphi < -1/3$$





physical domain

Positivity constraints for dilepton distributions

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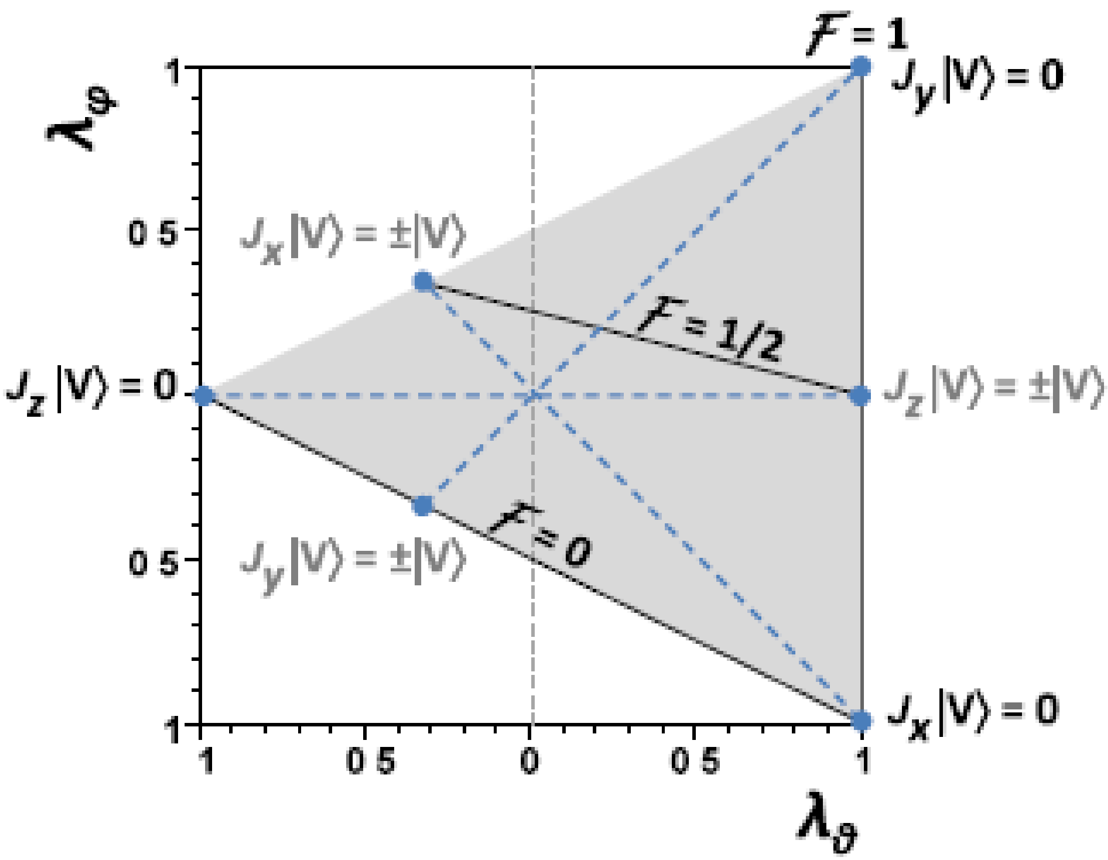
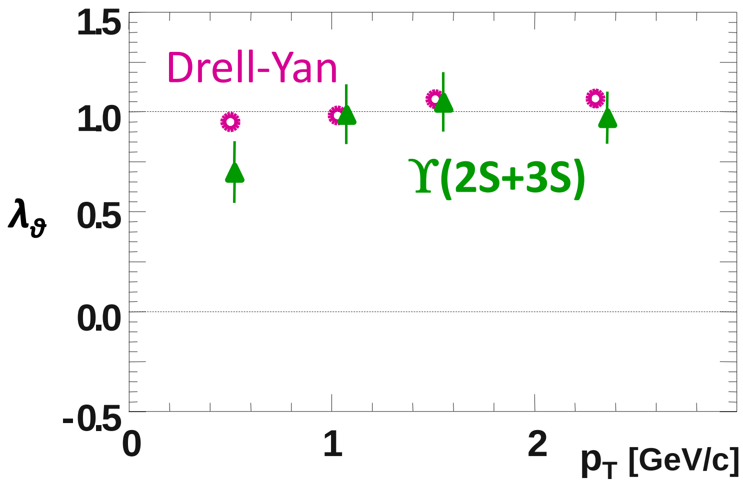


$$\mathcal{F} = \frac{1+\tilde{\lambda}}{3+\tilde{\lambda}}$$

physical domain

What polarization axis?

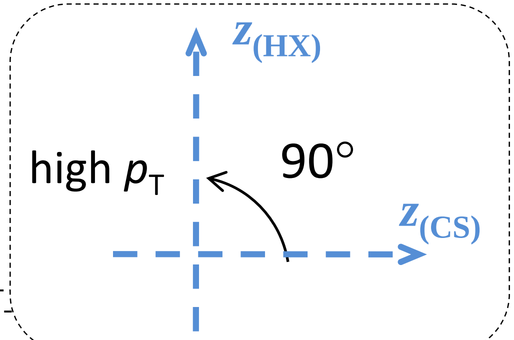
1) helicity conservation (at the *production* vertex)
→ J =1 states produced in *fermion-antifermion annihilations* (q-$\bar{q}$ or e^+e^-) at Born level have transverse polarization along the ***relative direction of the colliding fermions*** ***(Collins-Soper axis)***



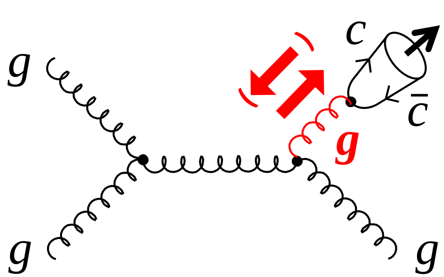
Drell-Yan is a paradigmatic case
but not the only one

Remember: DY for Y is a background to deal with

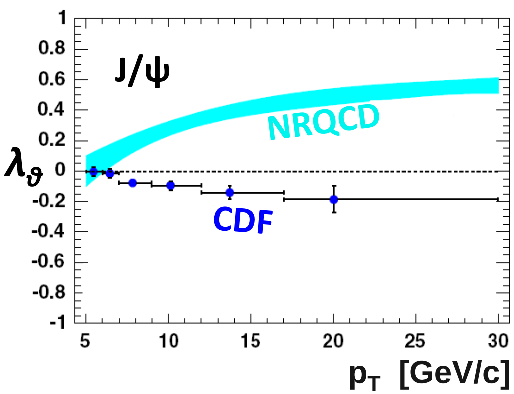
E866 (p-Cu)
Collins-Soper frame



2)



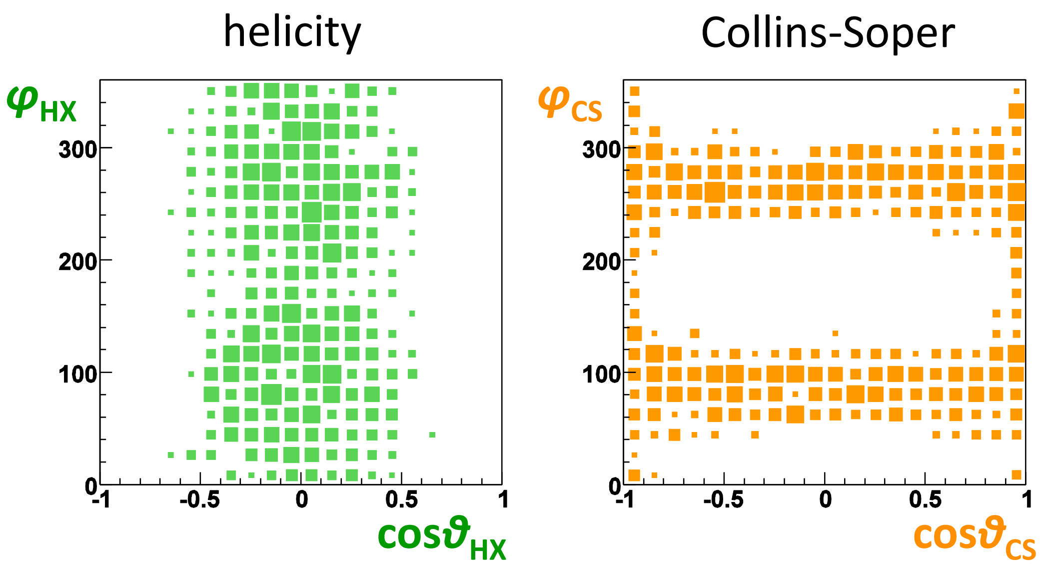
NRQCD → at *very large* p_T, quarkonium produced from the fragmentation of an on-shell gluon, inheriting its natural spin alignment



→ large, transverse polarization along the ***$Q\bar{Q}$*** *(=gluon)* ***momentum*** ***(helicity axis)***

Some remarks on methodology

- Measurements are challenging
  - A typical collider experiment imposes p_T cuts on the single muons; this creates zero-acceptance domains in decay distributions from “low” masses:



Toy MC with
$p_T(\mu) > 3$ GeV/c (both muons)

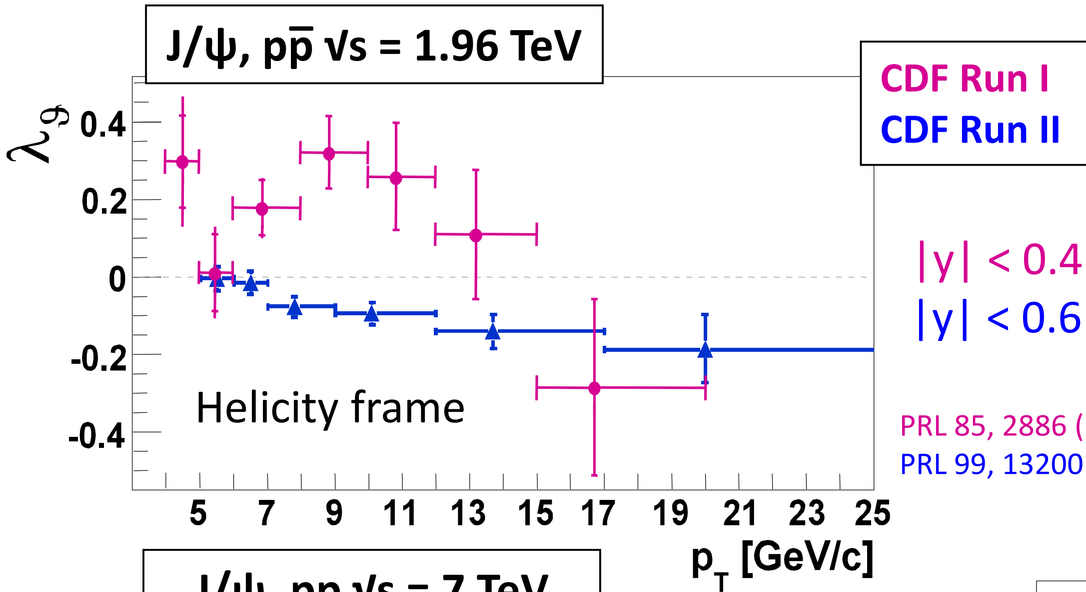
Reconstructed
unpolarized Υ(1S)

$p_T(\Upsilon) > 10$ GeV/c, $|y(\Upsilon)| < 1$

  - This spurious “polarization” must be accurately taken into account.
  - Large holes strongly reduce the precision in the extracted parameters

Quarkonium polarization: a “puzzle”

- J/ψ: Measurements at Tevatron , LHC (ALICE)



|y| < 0.4

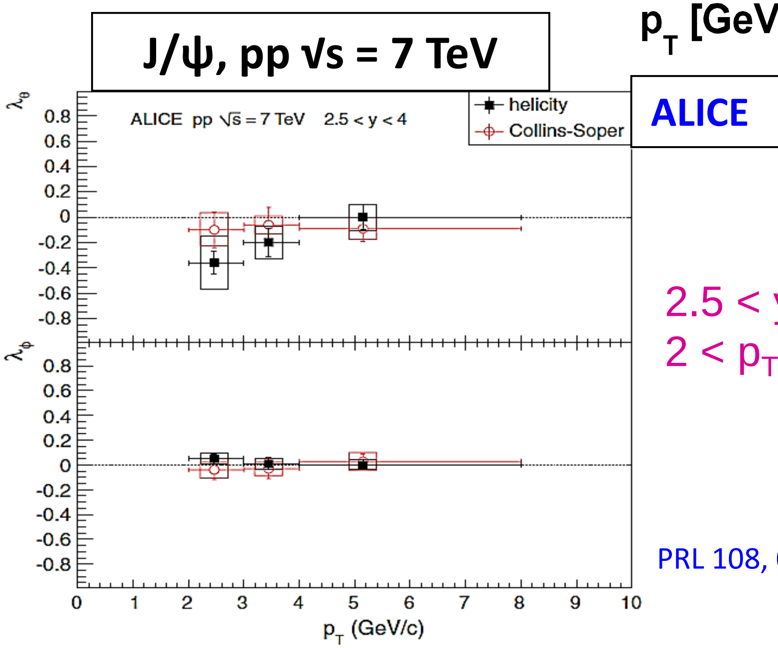
|y| < 0.6

PRL 85, 2886 (2000)

PRL 99, 132001 (2007)

- Only λ_θ measured
- Only one frame used (**HX**)

- **CDF II** vs **CDF I**
  → not known what caused the change



2.5 < y < 4,
2 < p_T < 8 GeV/c

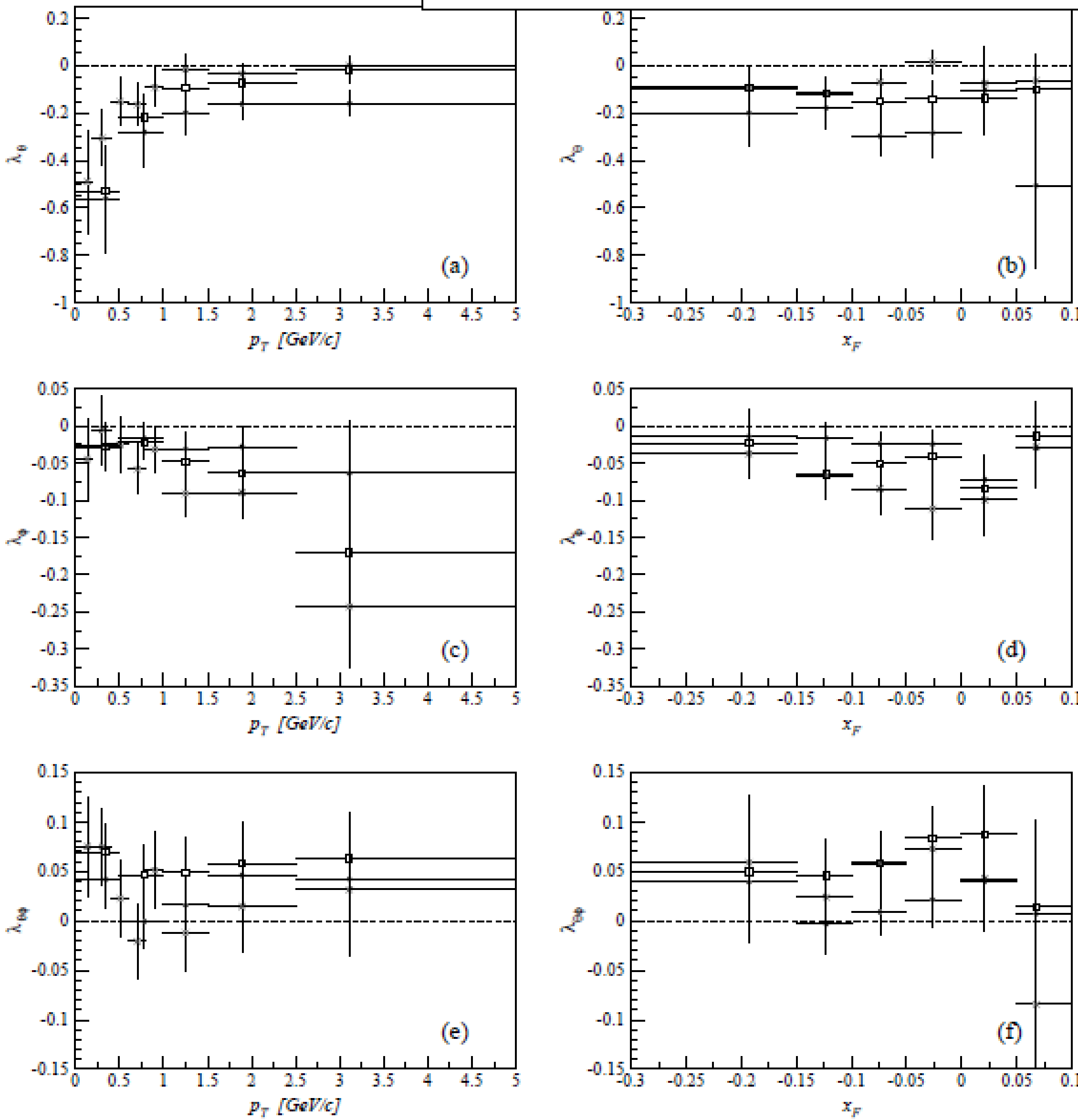
PRL 108, 082001 (2012)

- λ_θ and λ_ϕ separately measured
- Two frames used (**HX & CS**)
- $|\cos\theta|$ & $|\phi|$ dist. fit imposing $\tilde{\lambda}$ to be invariant in the two frames ⚠

Quarkonium polarization: a "puzzle"

- J/ψ: HERA-B

J/ψ, p-Cu and p-W √s = 41.6 GeV



- λ_θ, λ_ϕ and $\lambda_{\theta\phi}$ measured by single variable projections
- Three frames used (**HX, GJ & CS**)

$-1.5 < y < 0.8$
$-0.34 < x_F < 0.14$
$0 < p_T < 5.4$ GeV/c

EPJ C60 517 (2009)

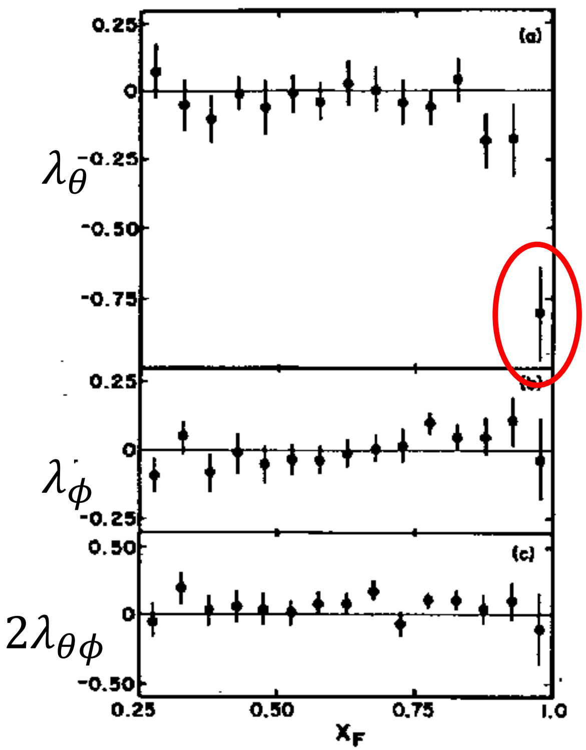
Quarkonium polarization: a “puzzle”

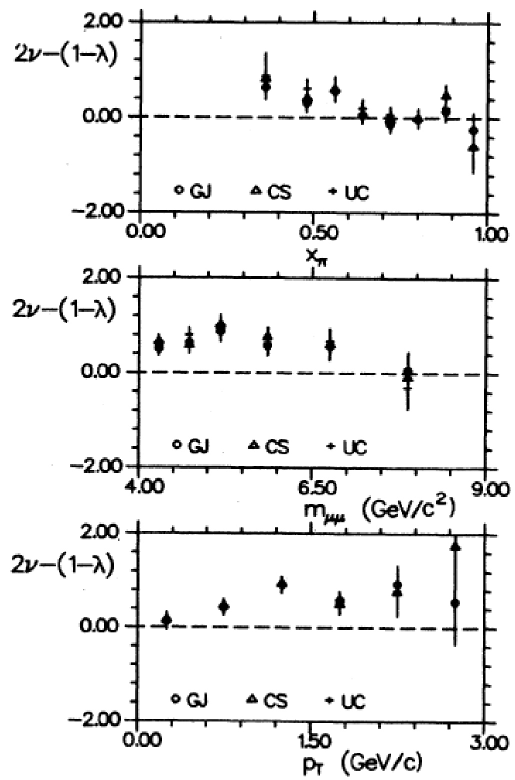
- J/ψ: Other fixed target experiments

Experiment	reaction	$\sqrt{S}$	x_F range	λ_θ
E537	$\overline{p}$ + W	15.3 GeV	$x_F > 0$	-0.115 ± 0.061
E537	π^- + W	15.3 GeV	$x_F > 0$	0.028 ± 0.004
E672/706	π^- + Be	31.5 GeV	$0.1 < x_F < 0.8$	-0.01 ± 0.08
E771	p + Si	38.8 GeV	$-0.05 < x_F < 0.25$	-0.09 ± 0.12
E866	p + Cu	38.8 GeV	$0.25 < x_F < 1.0$	$0.069 \pm 0.004 \pm syst.$

J/ψ, 252 GeV π on W

Chicago-Iowa-Princeton Coll (E615).





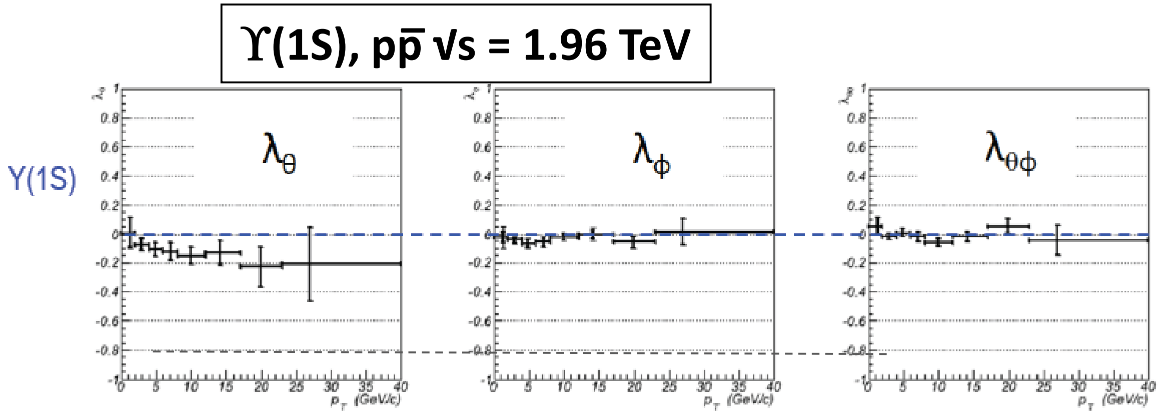
- λ_θ, λ_ϕ and $\lambda_{\theta\phi}$ measured
- Three frame used (**GJ, CS, UC**)
- Violates Lam-Tung relation

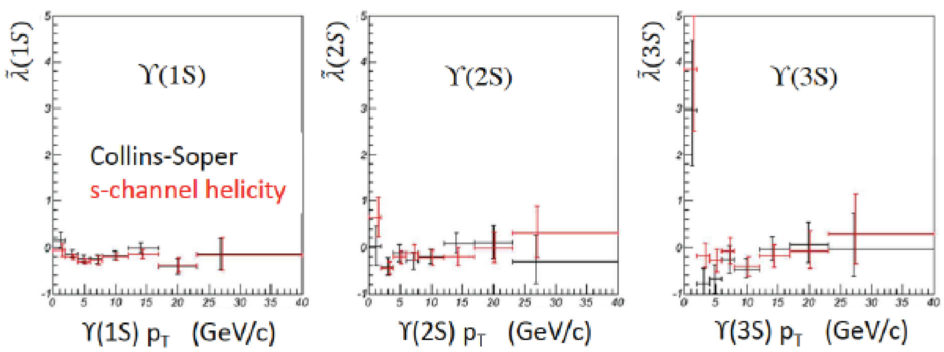
PRL 58, 2523 (1987)

PRD 39, (1989)

Quarkonium polarization: a "puzzle"

- Υ(nS): Measurements at Tevatron (**2002-2012**)



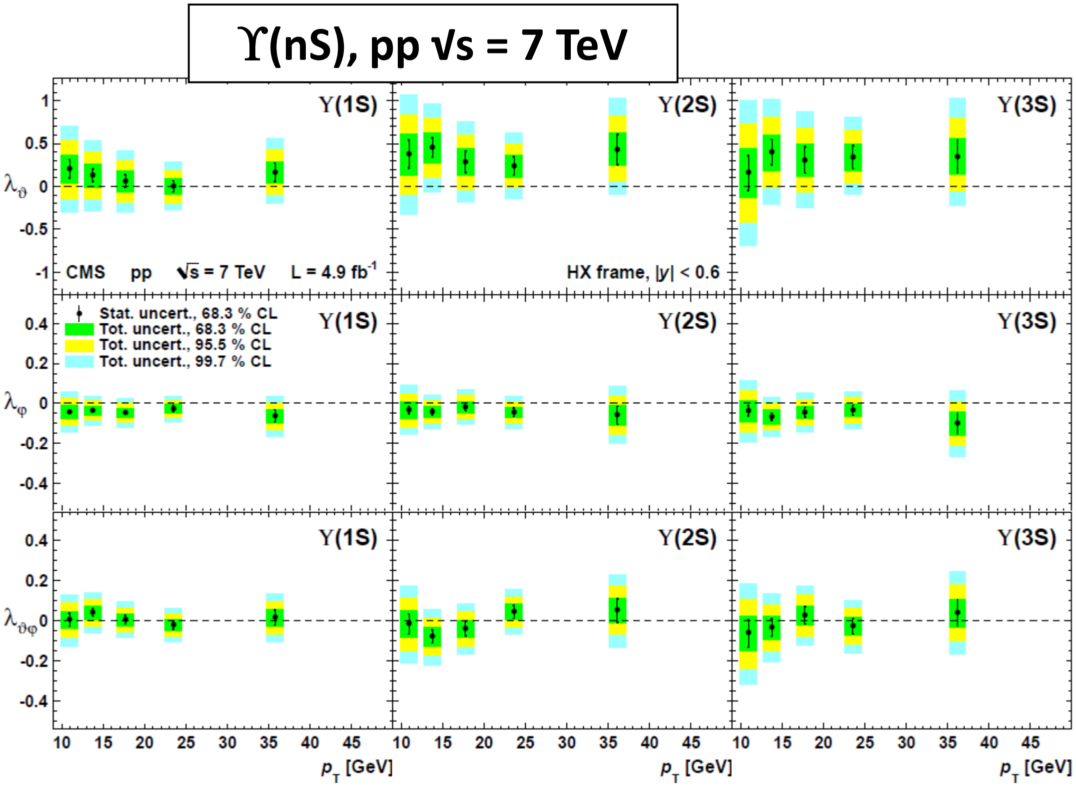


CDF+D∅ (2002)
- Only λ_θ measured
- Only one frame used (**HX**)

CDF (2012)
- λ_θ, λ_ϕ and $\lambda_{\theta\phi}$ measured
- $\tilde{\lambda}$ checked
- Two frames used (**HX & CS**)

Quarkonium polarization: a "puzzle"

- Υ(nS): Measurements at LHC (**CMS**)



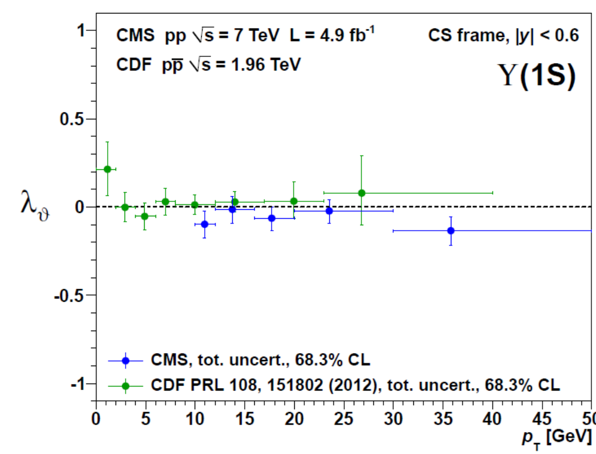
Phys. Rev. Lett. 110, 081802

- λ_θ, λ_ϕ and $\lambda_{\theta\phi}$ measured
- Three frames used (**HX, CS, PX**)
- $\tilde{\lambda}$ checked
- Fully multidimensional

|y| < 0.6

0.6<|y| < 1.2

10 <p_T< 40 GeV/c



Comparison with CDF results

Quarkonium polarization: a "puzzle"

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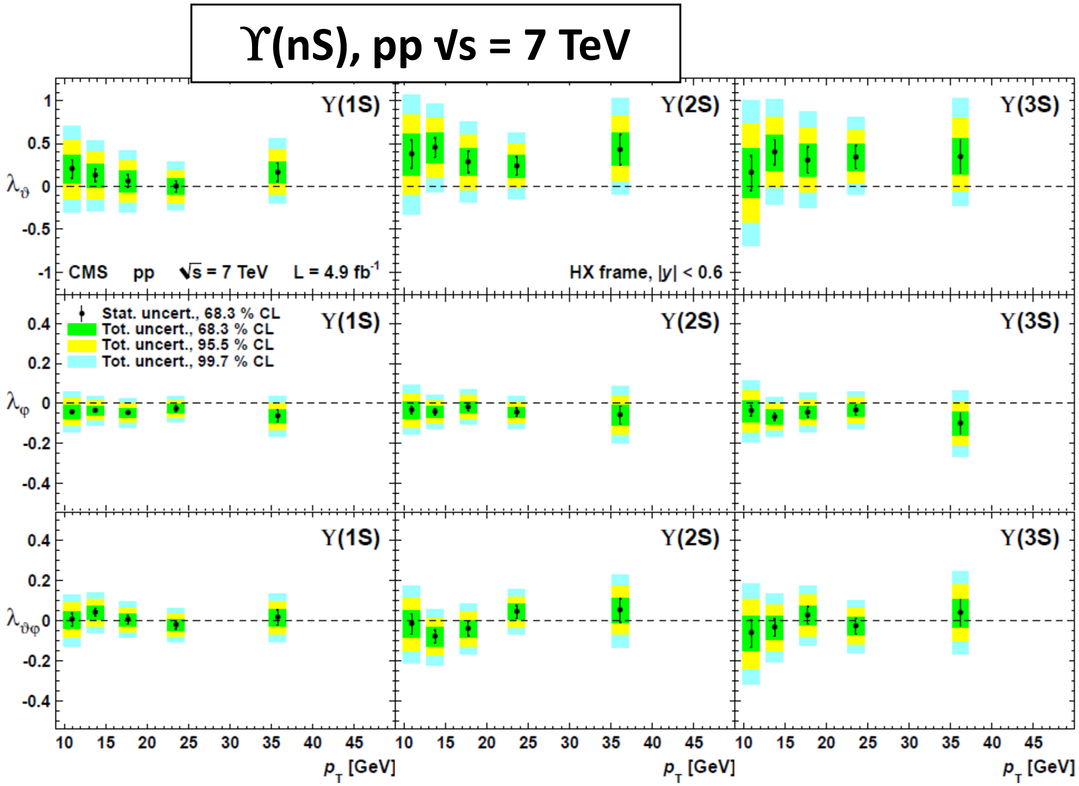

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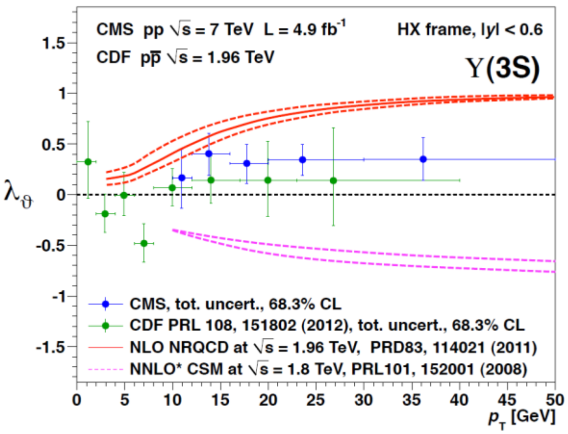
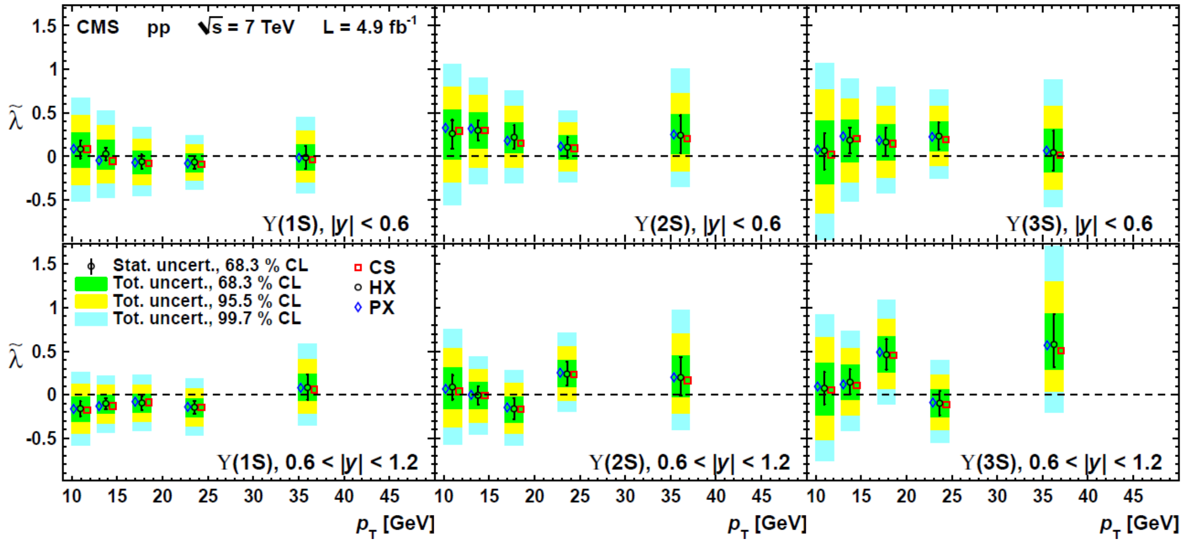


Comparison with CDF results

Quarkonium polarization: a “puzzle”

- Υ(nS): Measurements at LHC (**CMS**)

Υ(nS), pp √s = 7 TeV



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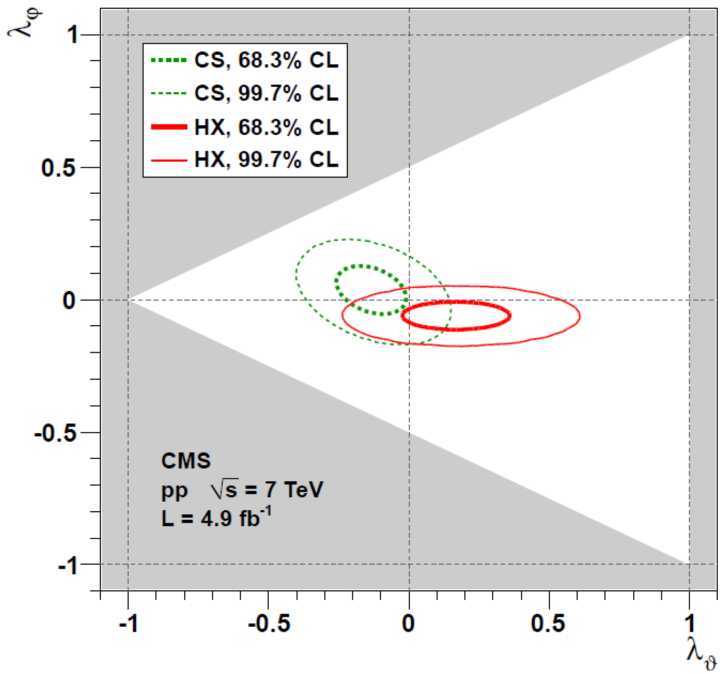
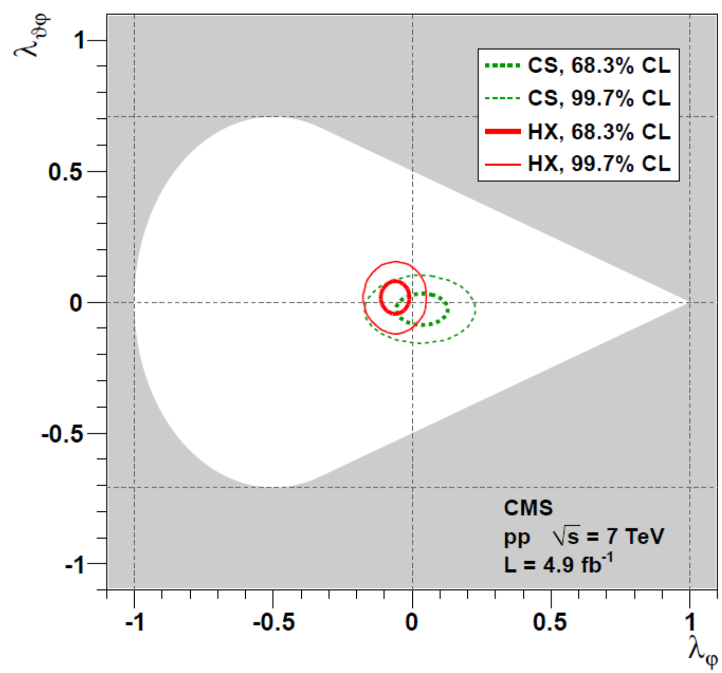




- λ_θ, λ_ϕ and $\lambda_{\theta\phi}$ measured
- Three frames used (HX, CS, PX)
- $\tilde{\lambda}$ checked
- Fully multidimensional

Phys. Rev. Lett. 110, 081802

A lot of measurements to do...

- Measurement of χ_{c0}(1P), χ_{c1}(1P) and χ_{c2}(1P) production cross sections
- Measurement of χ_b (1P), χ_b(2P) and χ_b(3P) production cross sections;
- Measurement of the relative production yields of J = 1 and J = 2 χ_b states
- Measurement of the χ_{c1} (1P) and χ_{c2}(1P) polarizations versus p_T and rapidity
- Measurement of the χ_b (1P) and χ_b (2P) polarizations
- …

…and a series of questions to answer

- Is there a simple composition of processes, probably dominated by one single mechanism, that is responsible for the production of all quarkonia?

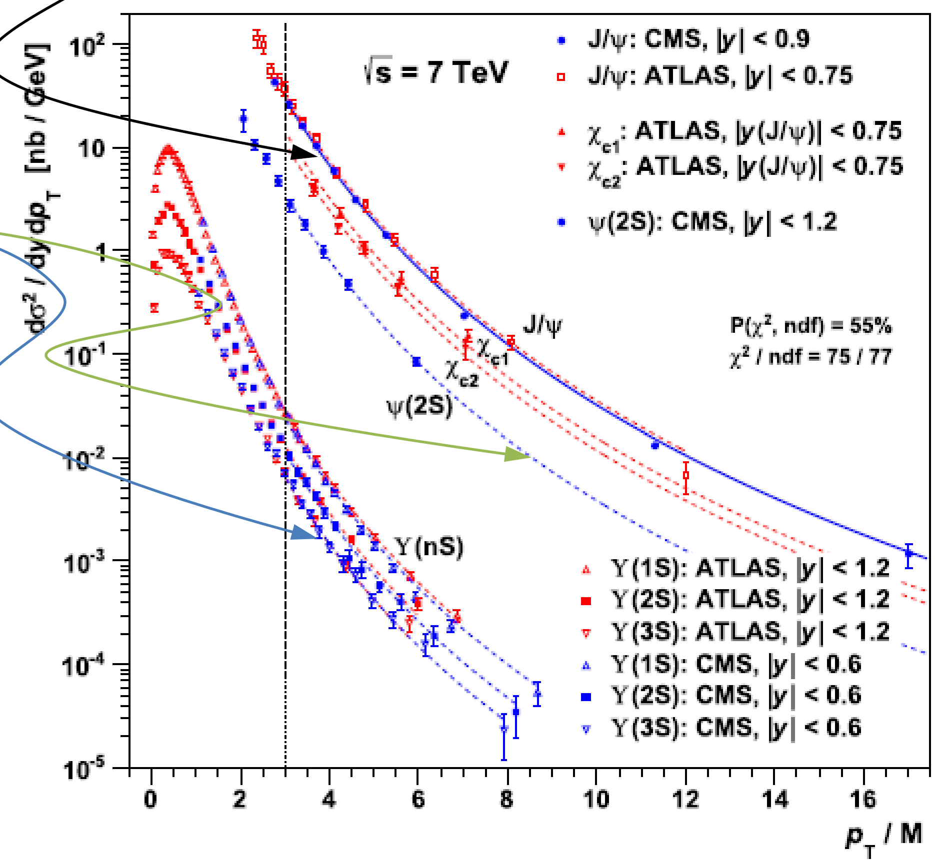
Solid curve is a fit to the *J/ψ* CMS data ($p_T/M>3$)

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

Remaining curves are replicas with normalizations adjusted to the individual datasets

$$f\left(\frac{p_T}{M}\right) = \left(1 + \frac{1}{\beta - 2} . \frac{\left(\frac{p_T}{M}\right)^2}{\gamma}\right)^{-\beta}$$

$$\beta = 3.62 \pm 0.07$$
$$\gamma = 1.29 \pm 0.32$$



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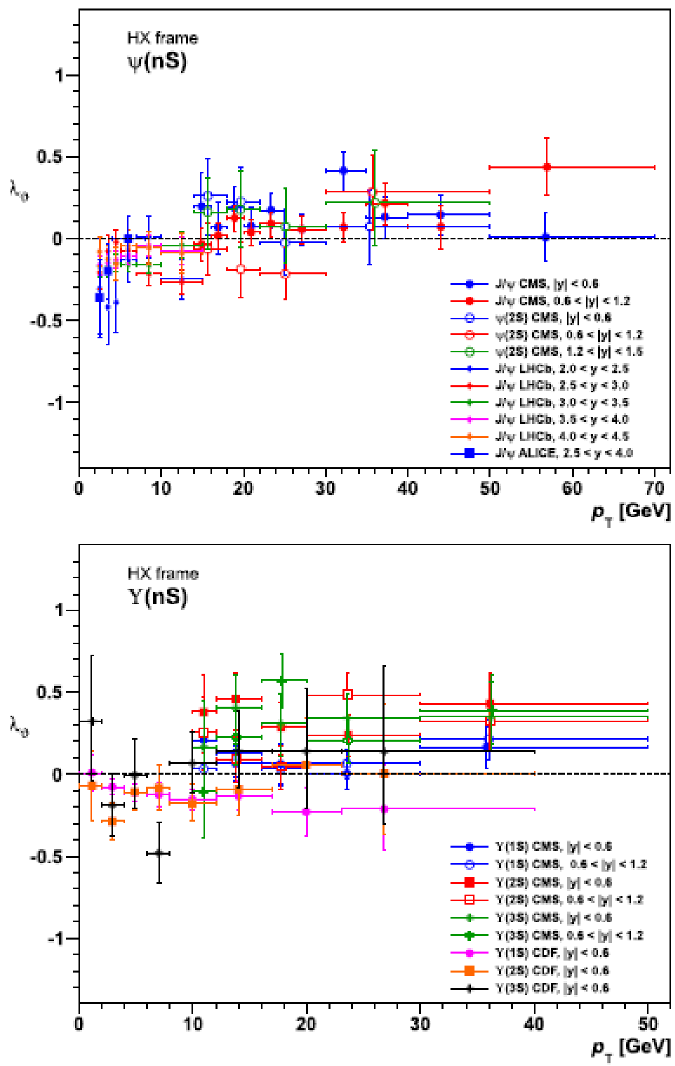
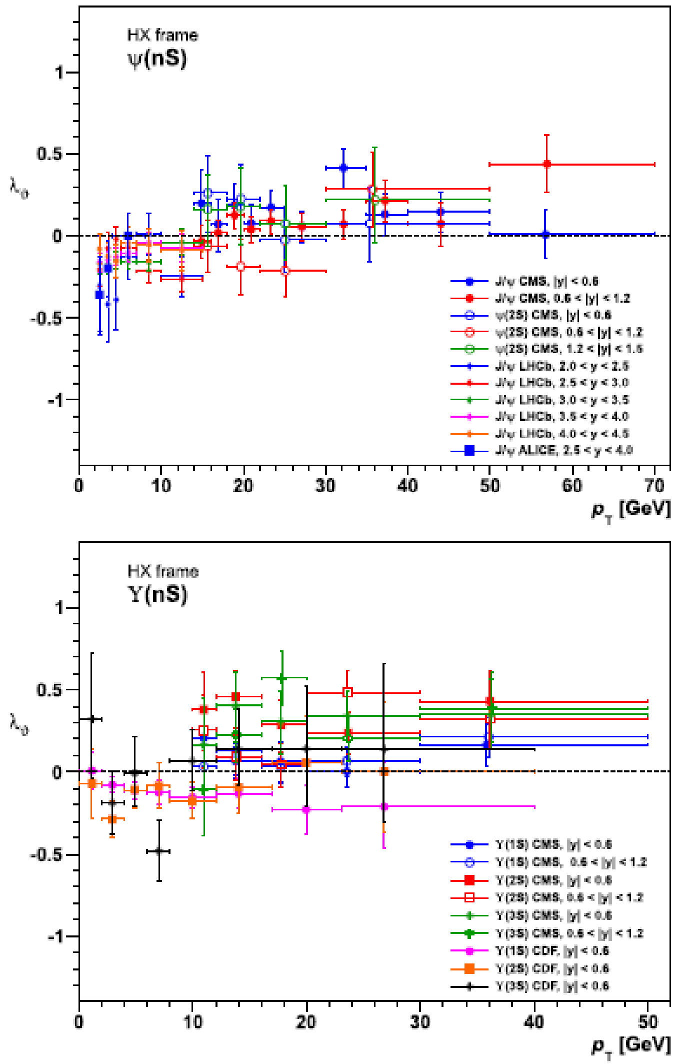


P. Faccioli *et al, PLB 736(2014) 98*

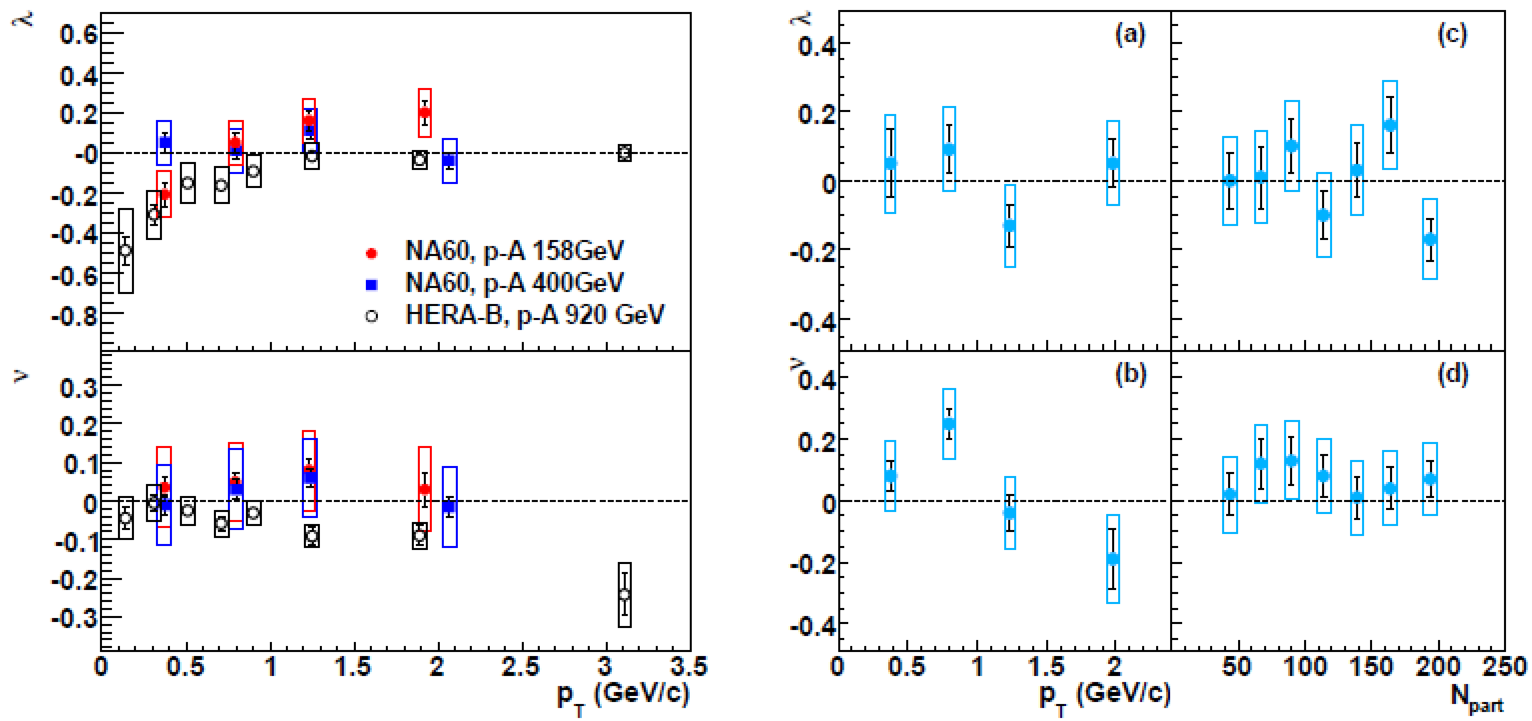
…and a series of questions to answer

- **Is this mechanism perturbed in the presence of matter at high density and high temperature?**



Pioneering measurements at SPS: NA60

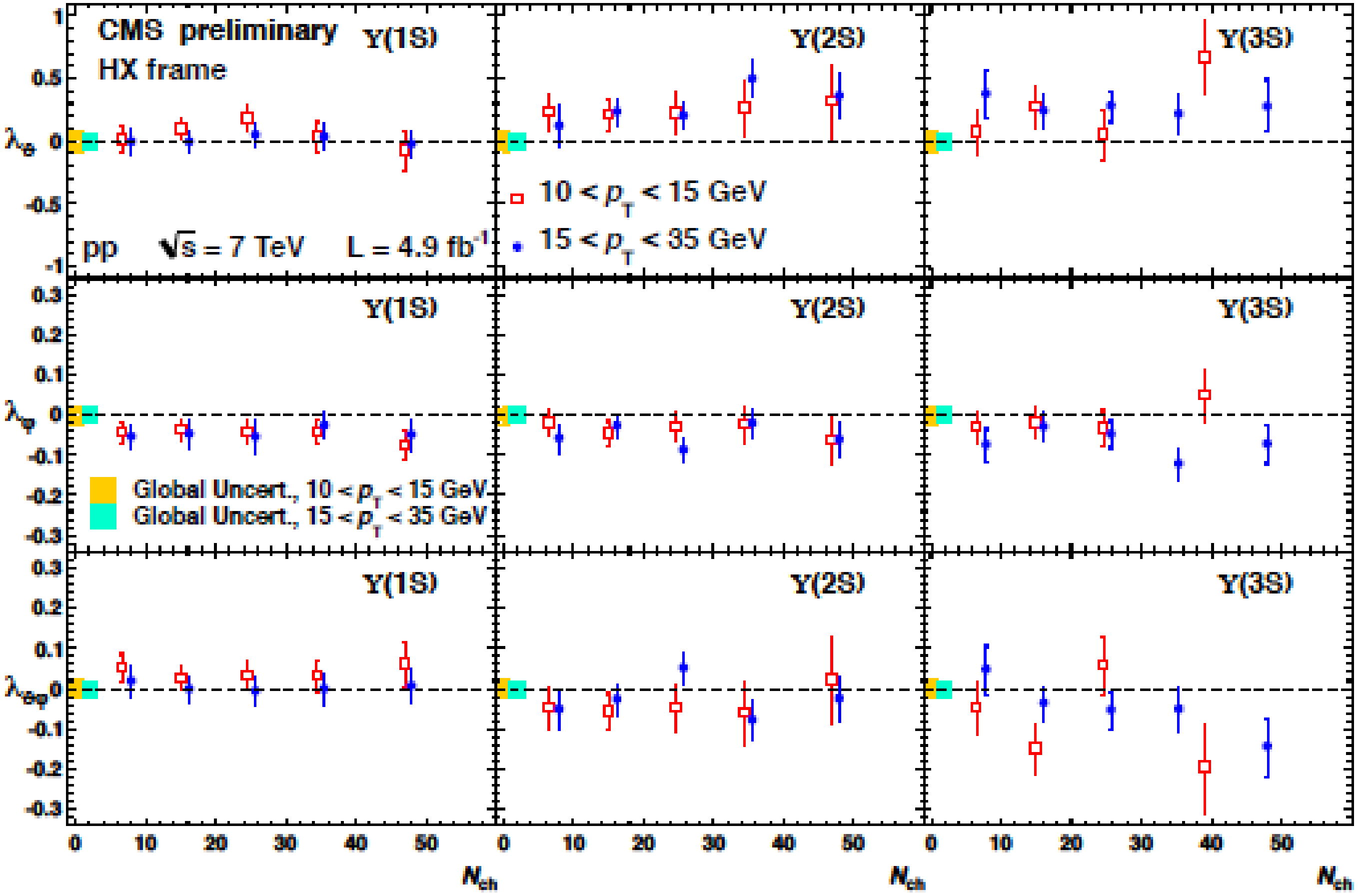
- λ_θ and λ_φ measured (p-A); HX and CS frames used.



http://arxiv.org/abs/0907.5004
http://arxiv.org/abs/0907.3682

A first step in this program at LHC: polarization as a function of multiplicity

CMS p-p



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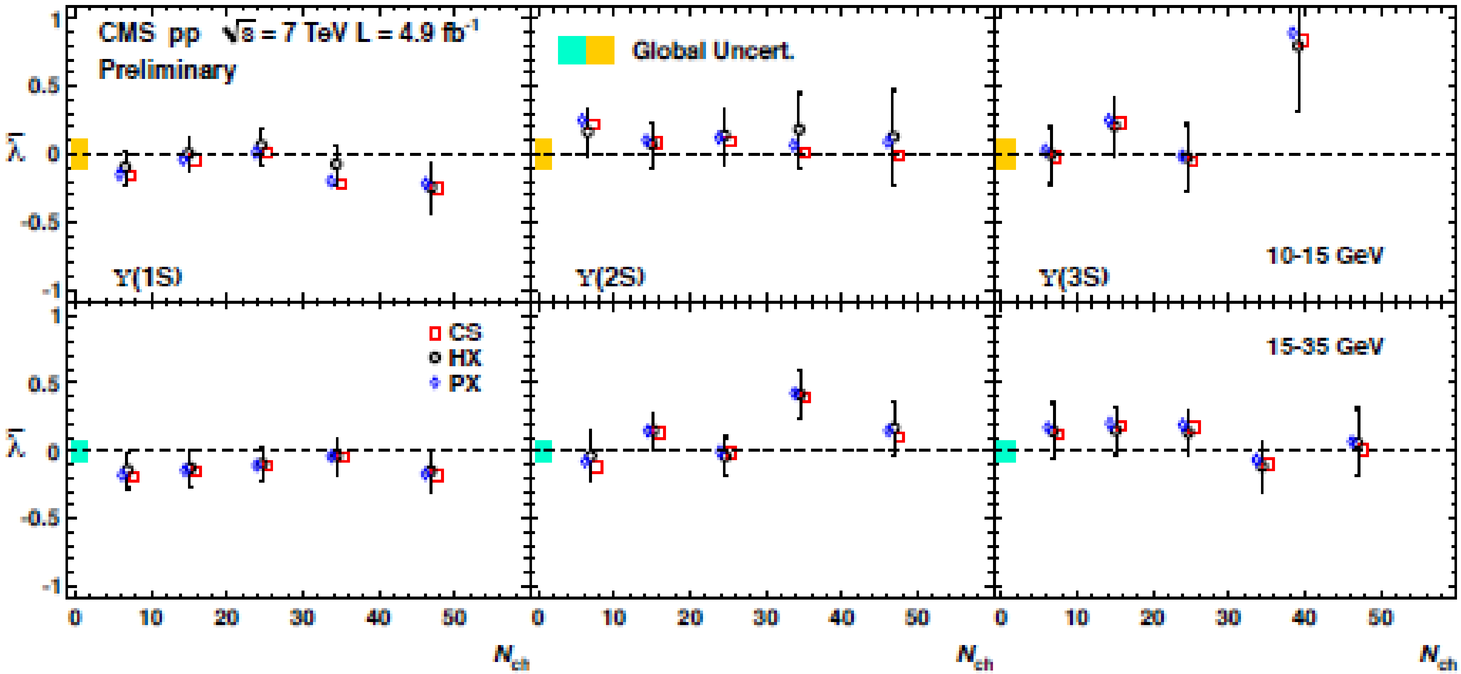


Summary

- The new quarkonium polarization measurements have many improvements with respect to previous analyses and shed, when combined with cross-section data, a new light on quarkonium production

  Will we (finally) manage to solve an old puzzle?

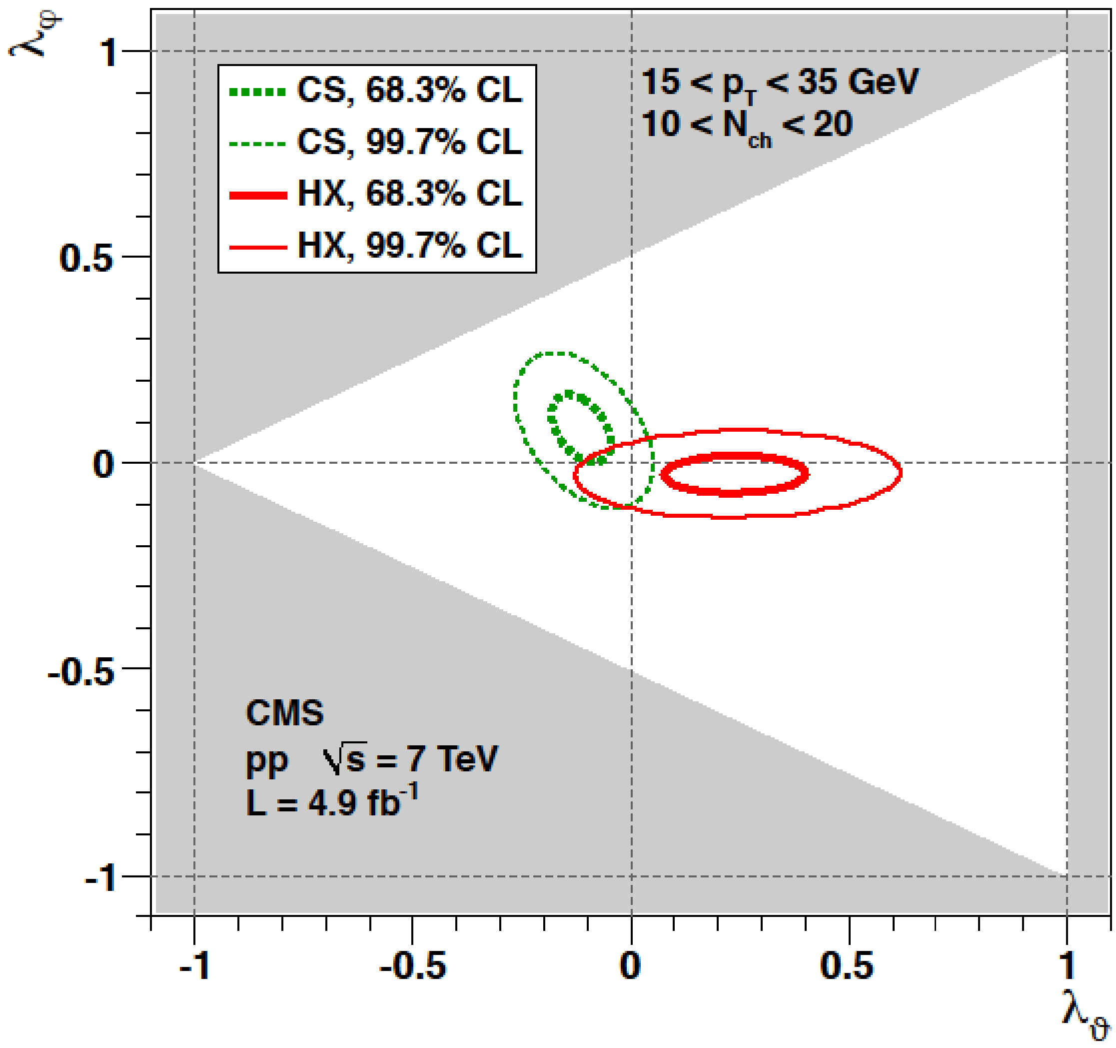
- General advice: do not throw away physical information!
  (azimuthal-angle distribution, rapidity dependence, ...)

- A new method based on rotation-invariant observables gives several advantages in the measurement of decay distributions and in the use of polarization information

- Quarkonium polarization could be used to probe hot and dense matter. A complete program is under way.

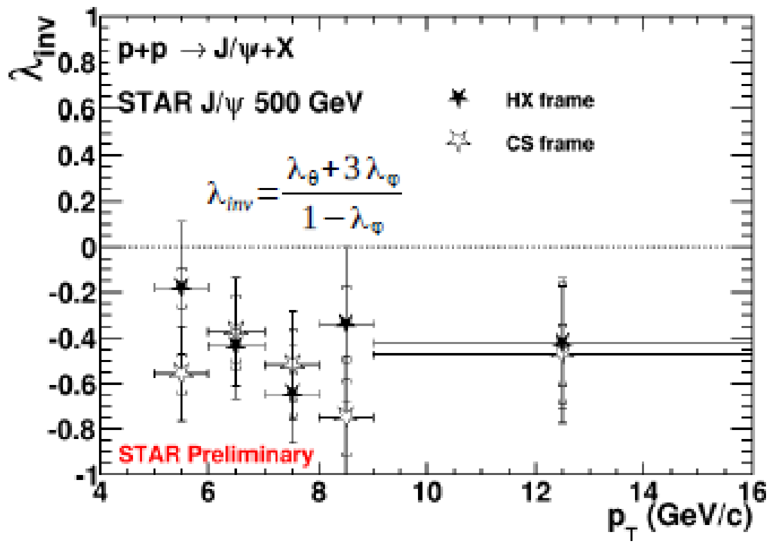
Backup slides

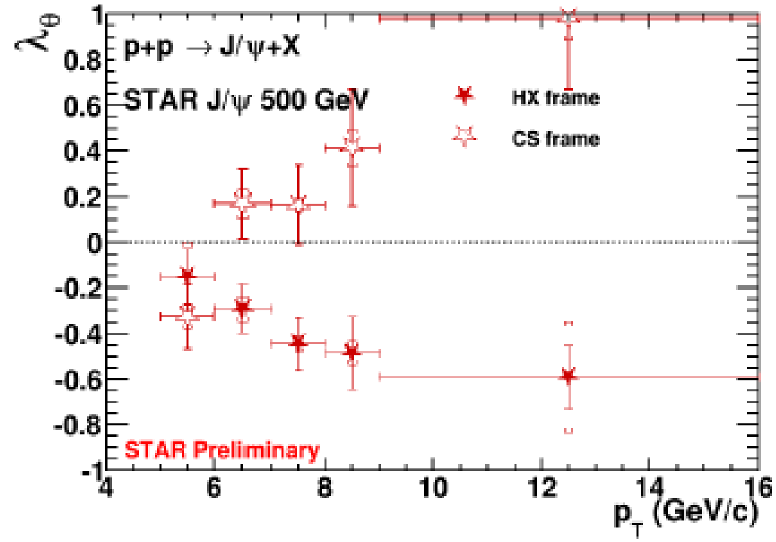
A first step in this program: polarization as a function of multiplicity

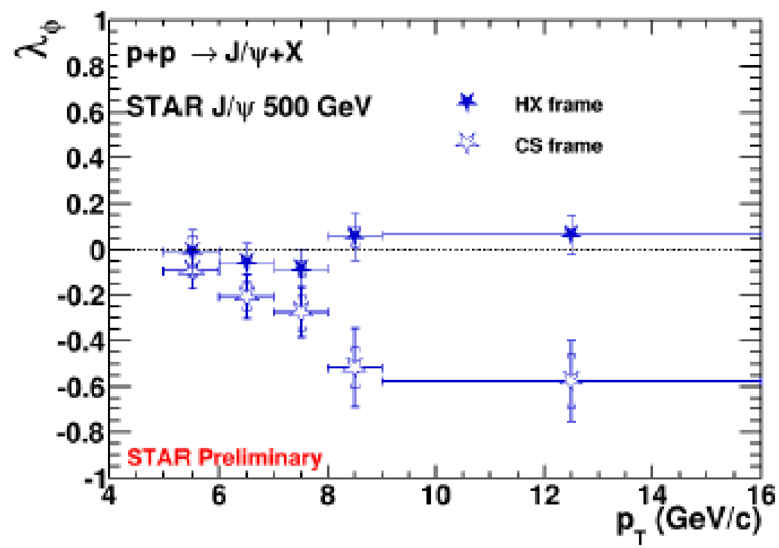


J/ψ polarization at √s = 500 GeV

- λ_θ, λ_φ and λ_{inv} and in the HX and CS frames
  - → λ_{inv} *vs* p_T consistent between both frames
  - → trend towards longitudinal polarization



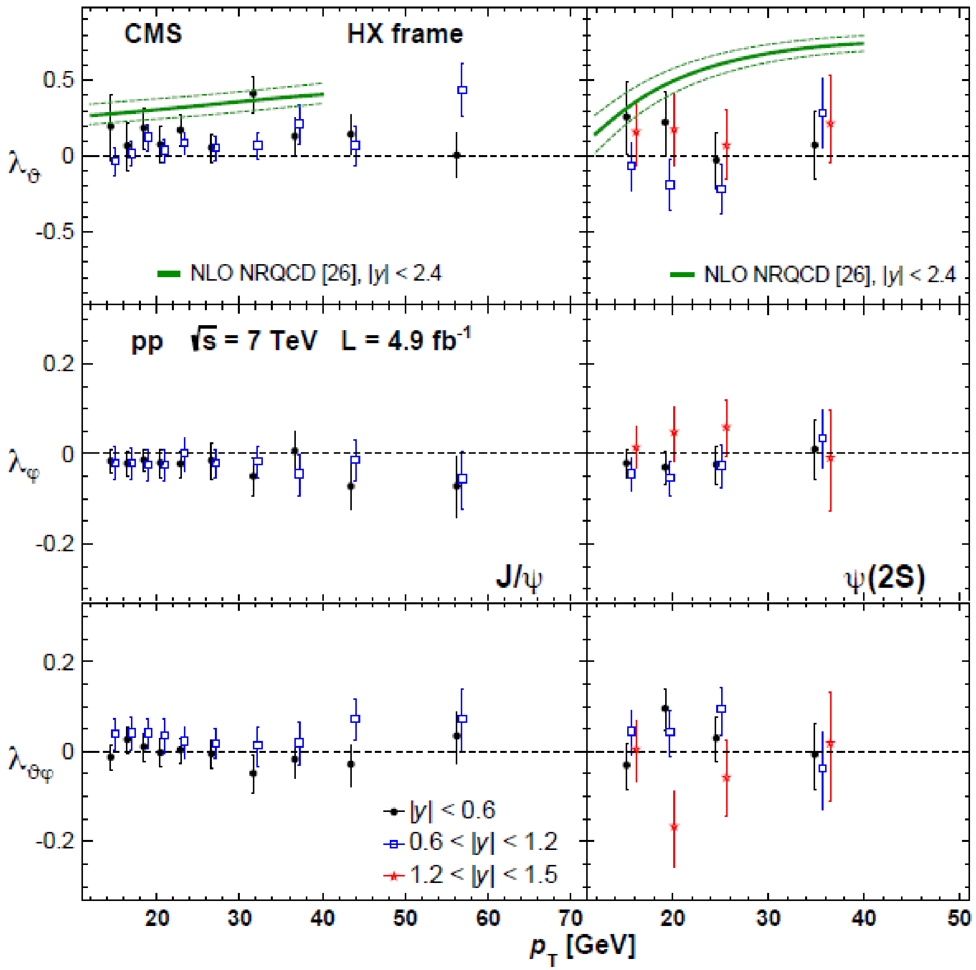




Quarkonium polarization: a "puzzle"

- ψ(nS): Measurements at LHC (**CMS**)

ψ(nS), pp √s = 7 TeV



- λ_θ, λ_ϕ and $\lambda_{\theta\phi}$ measured
- Three frames used (**HX, CS, PX**)
- $\tilde{\lambda}$ checked
- Fully multidimensional

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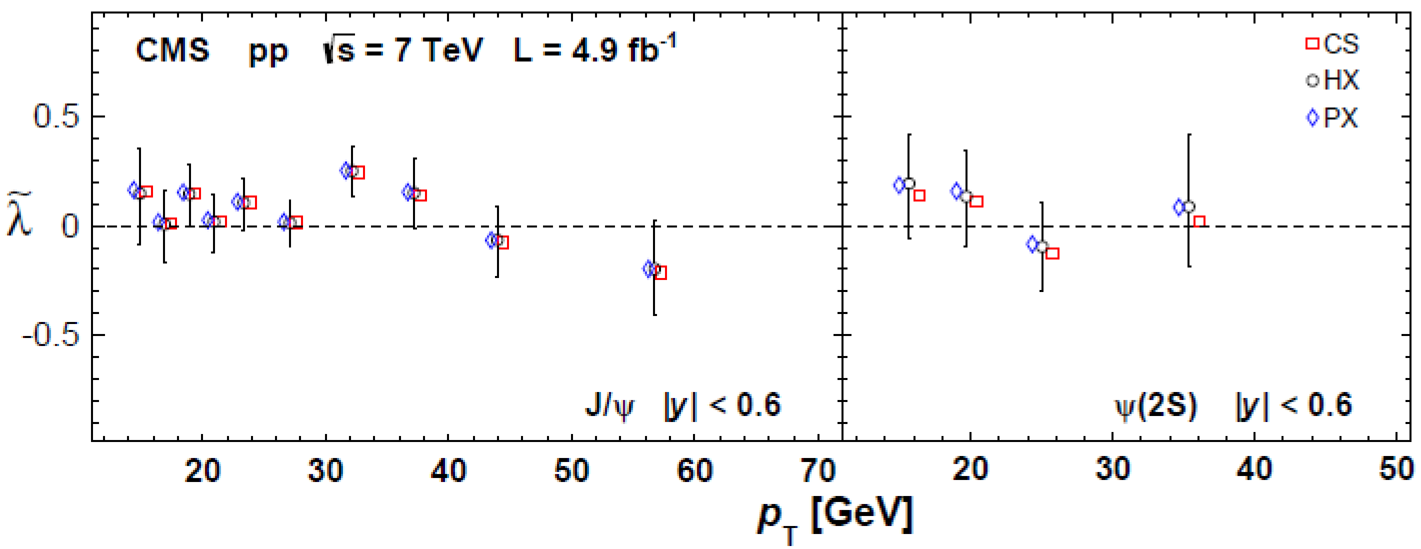

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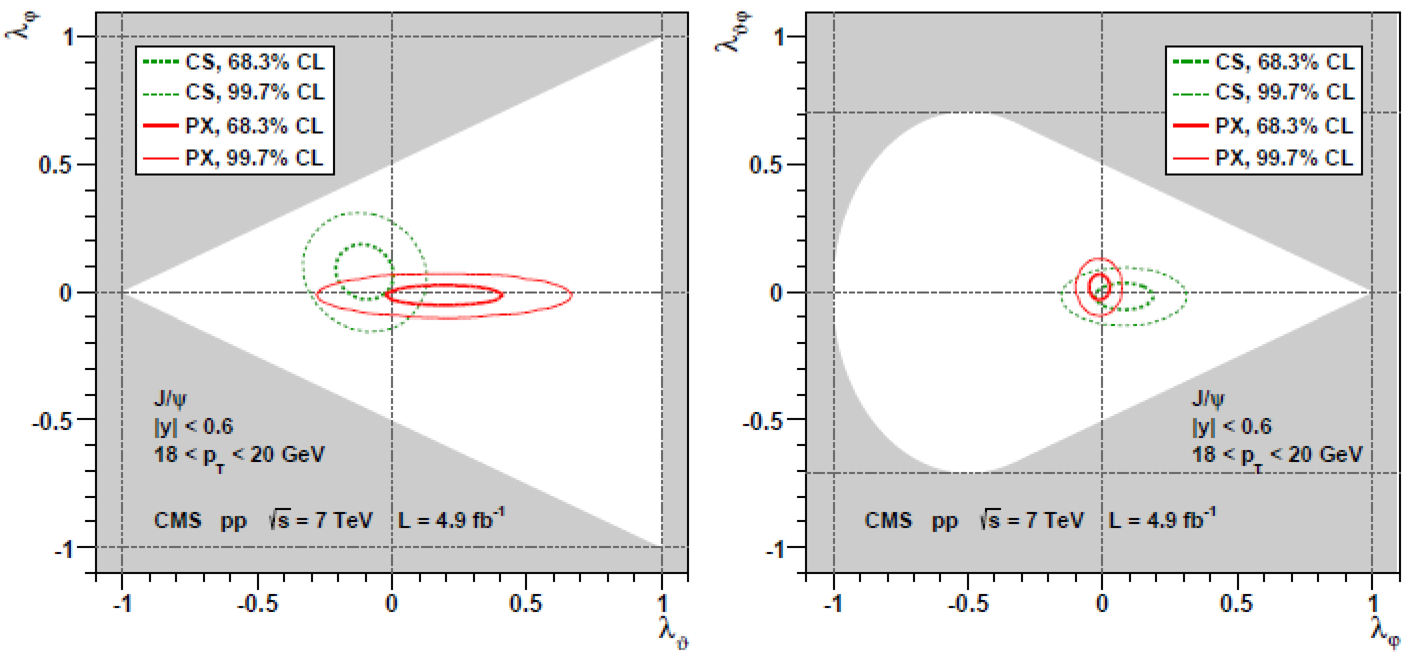
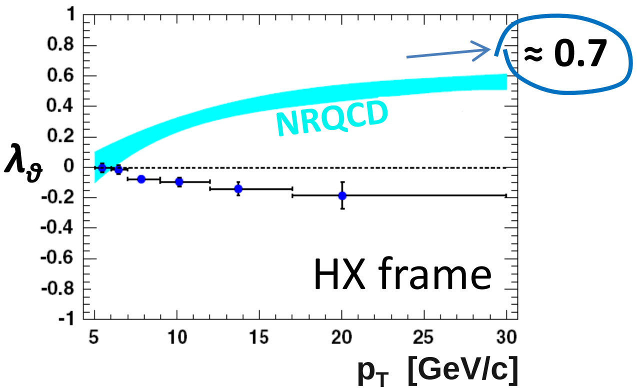
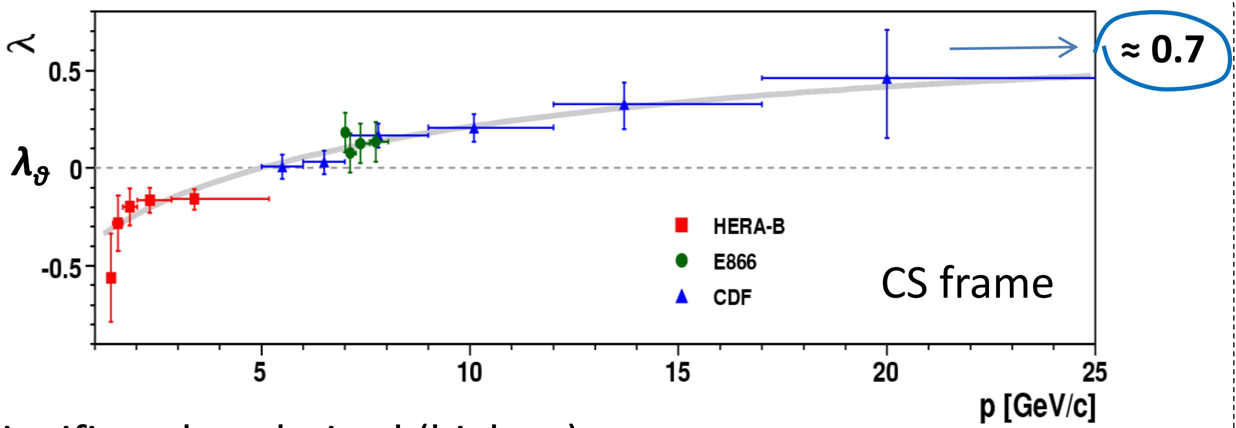


J/ψ polarization as a signal of colour deconfinement?





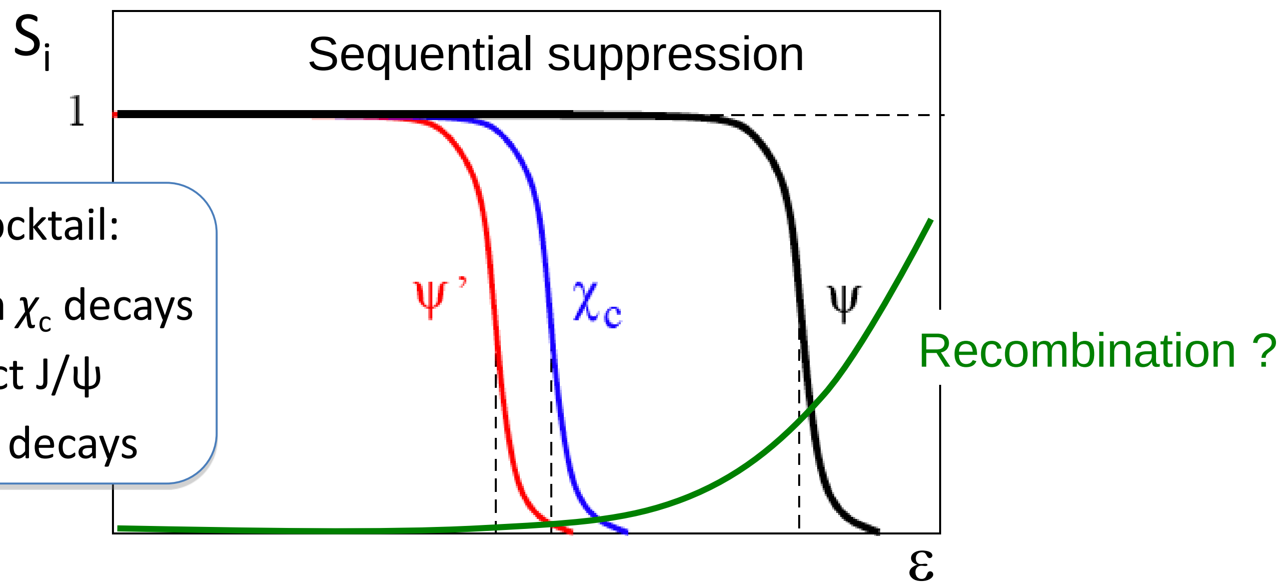
Starting "pp" scenario:
- J/ψ significantly polarized (high p_T)
- feeddown from χ_c states (≈ 30%) smears the polarizations

J/ψ cocktail:

≈ 30% from χ_c decays

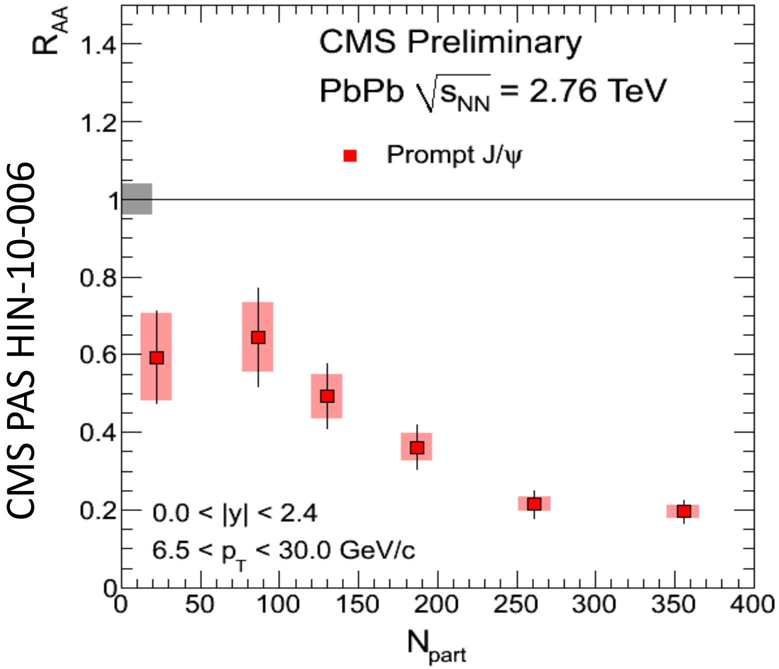
≈ 70% direct J/ψ

\+ ψ' decays



- As the χ_c (and ψ') mesons get dissolved by the QGP, λ_ϑ should *change to its direct value*

J/ψ polarization as a signal of sequential suppression?



P. Faccioli, JS, PRD 85, 074005 (2012)
B.L. Ioffe and D.E. Kharzeev *PRC* **68** (2003) 061902.

CMS data:

- up to 80% of J/ψ's disappear from pp to Pb-Pb
- more than 50%
  (≳ fraction of J/ψ's from ψ' and χ_c)
  disappear from peripheral to central collisions

→ **sequential suppression** gedankenscenario:
in central events ***ψ' and χ_c are fully suppressed***
and all J/ψ's are *direct*

It may be impossible to test this directly:
measuring the χ_c yield (reconstructing χ_c radiative decays) in PbPb collisions is prohibitively difficult due to the huge number of photons

However, a ***change of prompt-J/ψ polarization*** must occur from pp to central Pb-Pb!

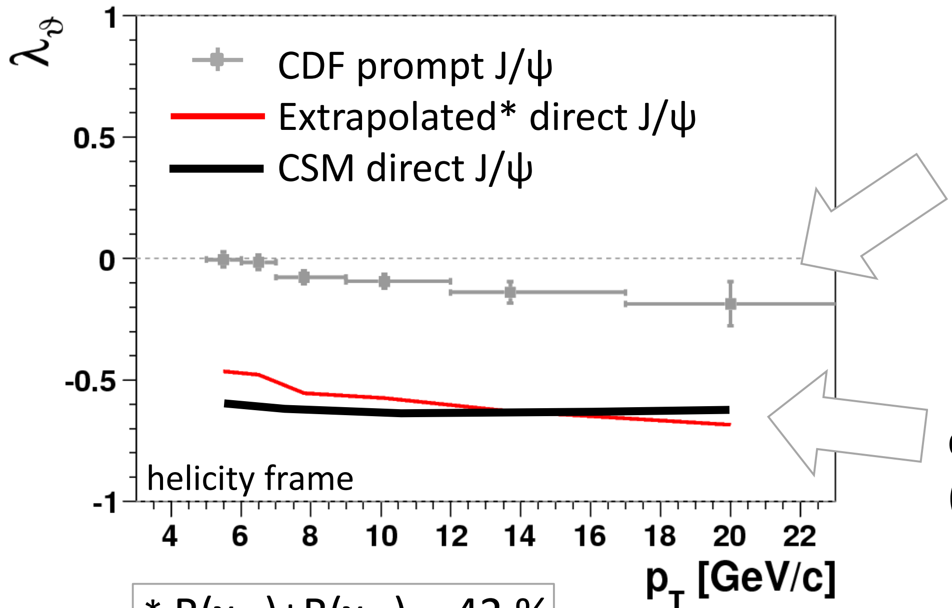
Reasonable sequence of measurements:

1) prompt J/ψ polarization in pp
2) χ_c-to-J/ψ fractions in pp
3) χ_c polarizations in pp
4) prompt J/ψ polarization in PbPb

→ χ_c suppression in PbPb!

J/ψ polarization as a signal of sequential suppression?

Example scenario:



prompt-J/ψ polarization in pp: $\lambda_\vartheta \cong -0.15$

direct-J/ψ polarization: $\lambda_\vartheta \cong -0.6$
(assumed to be the same in pp and PbPb)

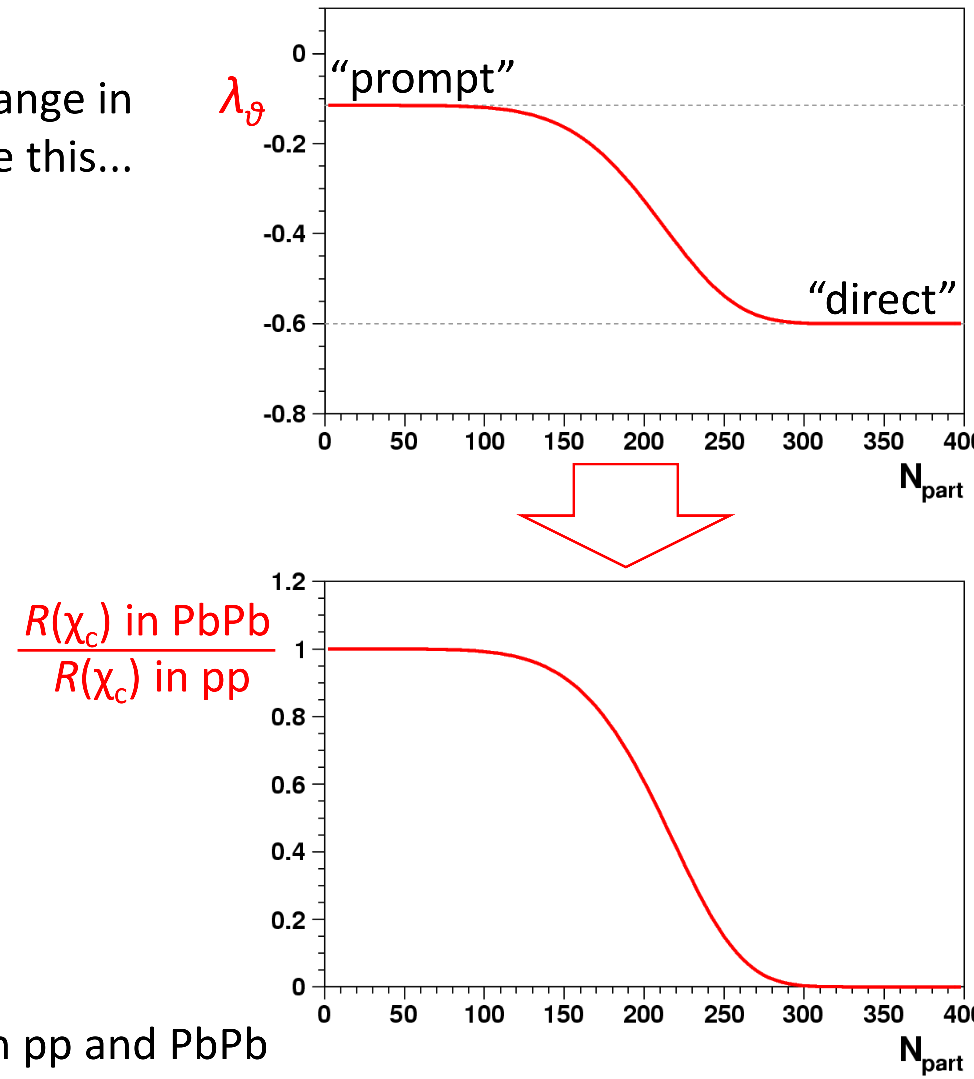
* $R(\chi_{c1})+R(\chi_{c2}) = 42\ \%$
$R(\chi_{c2})/R(\chi_{c1}) = 38\ \%$
$h(\chi_{c1}) = 0$
$h(\chi_{c2}) = \pm 2$

$$\vec{\lambda}^{\,\mathrm{prt}} = \frac{\frac{[1-R(P_1)-R(P_2)]\vec{\lambda}^{\mathrm{dir}}}{3+\lambda_\vartheta^{\mathrm{dir}}} + \frac{R(P_1)\vec{\lambda}^{P_1}}{3+\lambda_\vartheta^{P_1}} + \frac{R(P_2)\vec{\lambda}^{P_2}}{3+\lambda_\vartheta^{P_2}}}{\frac{[1-R(P_1)-R(P_2)]}{3+\lambda_\vartheta^{\mathrm{dir}}} + \frac{R(P_1)}{3+\lambda_\vartheta^{P_1}} + \frac{R(P_2)}{3+\lambda_\vartheta^{P_2}}}$$

J/ψ polarization as a signal of sequential suppression?

If we measure a change in prompt polarization like this...

... we are observing the disappearance of the χ_c relative to the J/ψ



Simplifying assumptions:

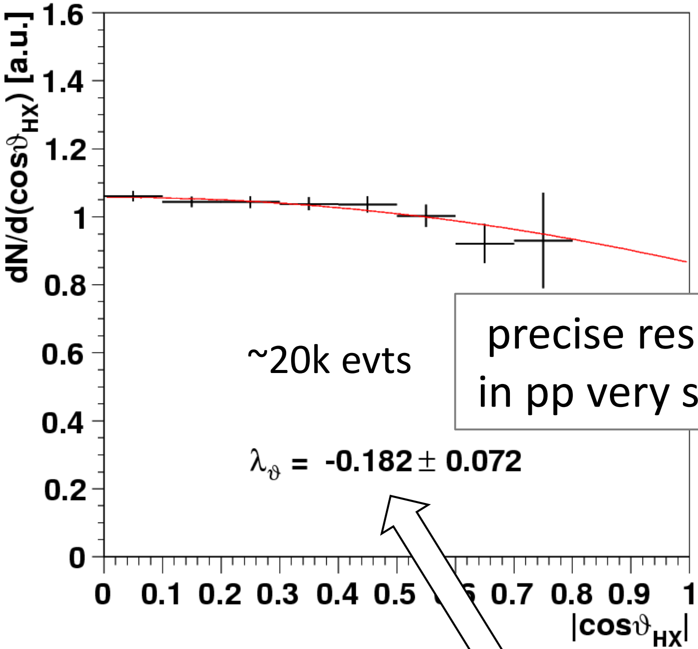
- direct-J/ψ polarization is the same in pp and PbPb
- *normal* nuclear effects affect J/ψ and χ_c in similar ways
- χ_{c1} and χ_{c2} are equally suppressed in PbPb

J/ψ polarization as a signal of sequential suppression?

When will we be sensitive to an effect like this?

CMS-like toy MC with $p_T(\mu) > 3$ GeV/c, $6.5 < p_T < 30$ GeV/c, $0 < |y| < 2.4$

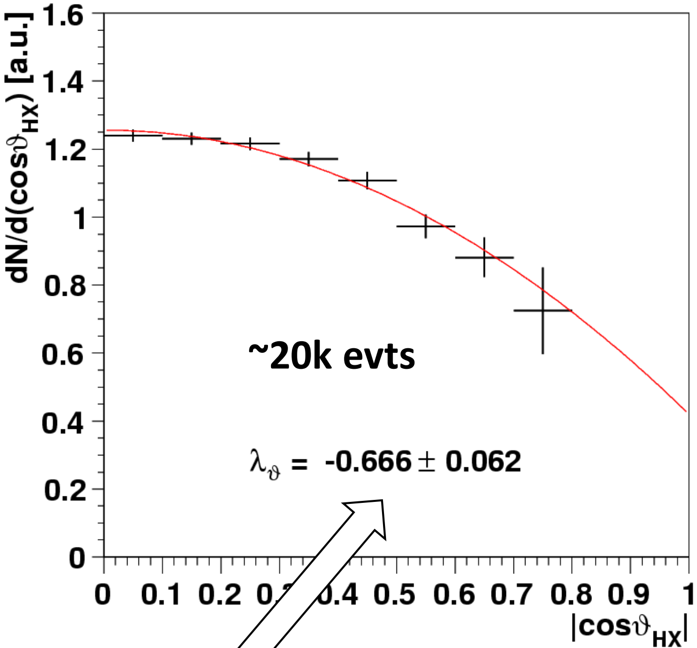
prompt-J/ψ polarization as observed in **pp** (and peripheral PbPb)



precise results in pp very soon

efficiency-corrected $|\cos\vartheta_{HX}|$ distribution

prompt-J/ψ polarization as observed in **central PbPb**



In this scenario, the χ_c disappearance is measurable at ~5σ level with ~20k J/ψ's in central Pb-Pb collisions

J/ψ polarization as a signal of sequential suppression?

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CMS-like toy MC