Livio Bianchi *
Università & INFN Torino

Experimental overview of vector mesons spin alignment

Zimányi School

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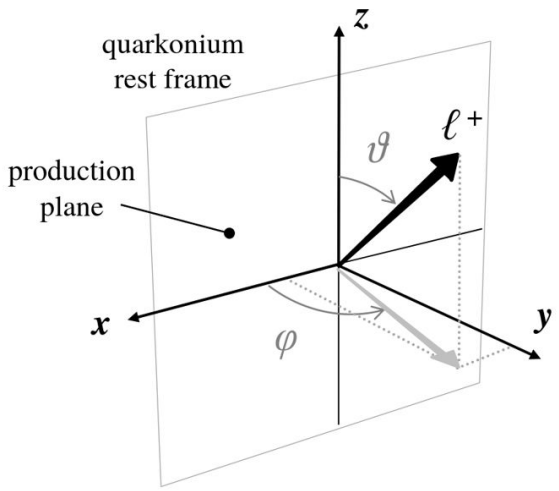
* Livio.Bianchi@cern.ch

Vector meson polarization: intro



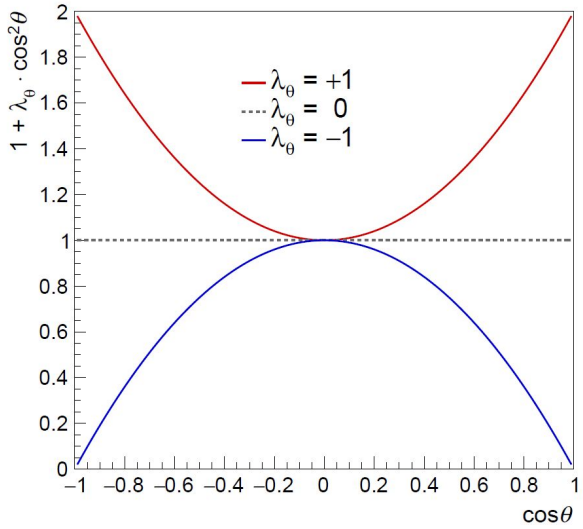
A vector meson Ψ can be characterized by its total angular momentum state:

$$|\Psi\rangle = b_{+1}\,|1,+1\rangle + b_0\,|1,0\rangle + b_{-1}\,|1,-1\rangle$$

Coefficients *b* weight the possible values of the third component J_z which for a *L*=0 state correspond to the third component of the spin with respect to a given quantization axis

Angular momentum conservation in the vector meson decay leads to a non-isotropic daughter's angular distribution:

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



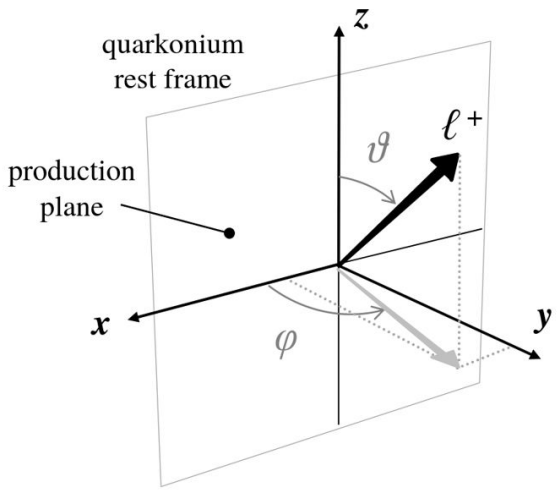
θ and φ: polar and azimuthal angles of decay daughter with respect to a chosen reference axis

For a 2-prong leptonic decay:

λ_θ = +1 : transverse polarization

λ_θ = -1 : longitudinal polarization

Vector meson polarization: intro



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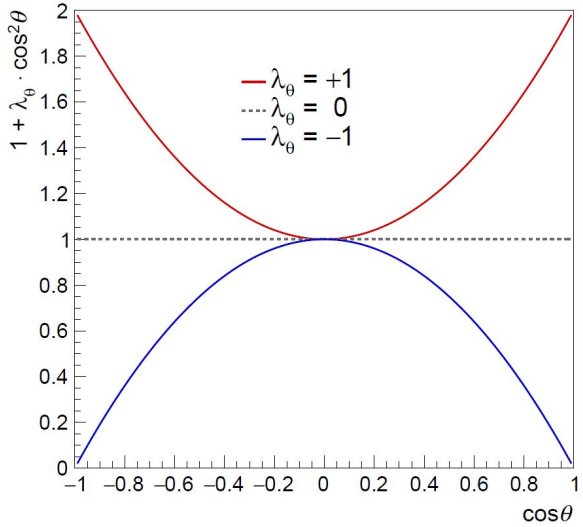

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For a 2-prong leptonic decay:

λ_θ = +1 : transverse polarization

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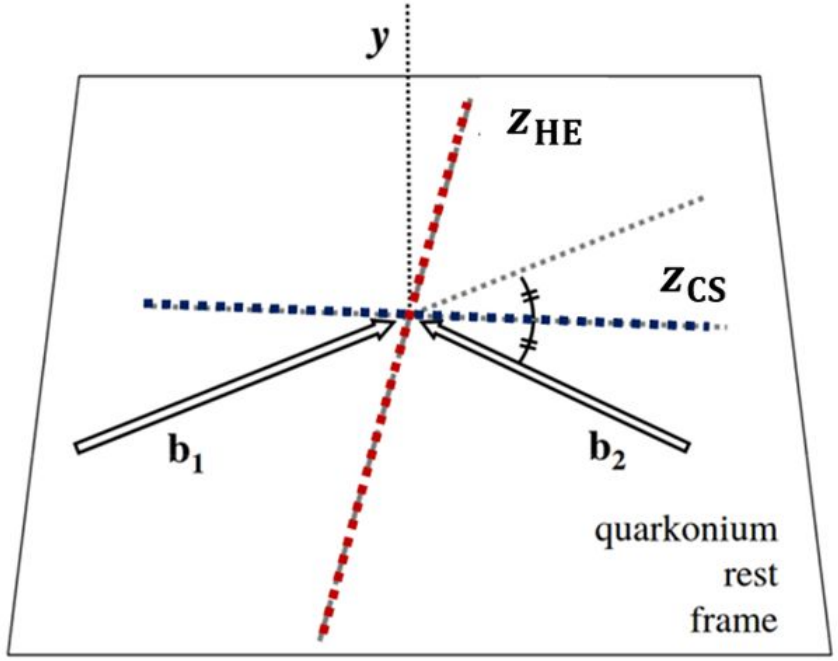
NOTE: λ_θ embeds information on the total angular momentum of the final state (space angular momentum & spin of the products)

If two leptons are produced in the final state

$$\lambda_\theta = \frac{1-3\rho_{00}}{1+\rho_{00}}$$

where ρ_{00} is the spin density matrix element ($\neq \frac{1}{3} \rightarrow$ polarization)

Reference frames



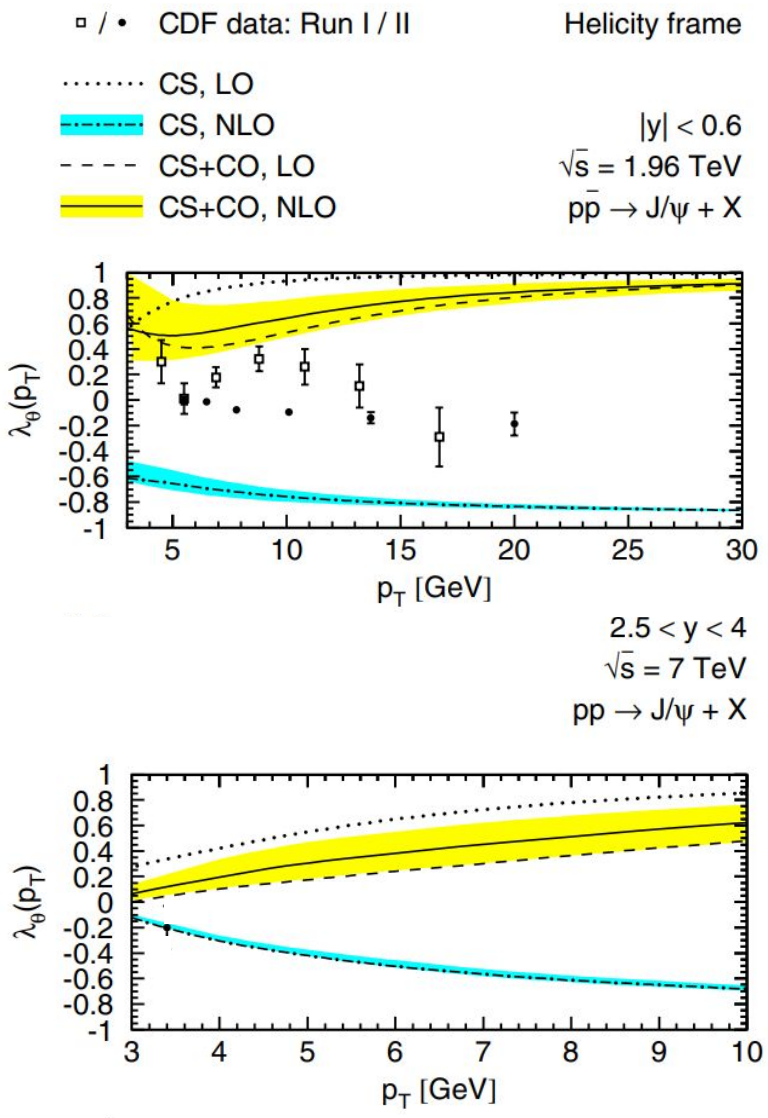
The choice of the polarization axis is key:

- Best axis: aligned to the quantization axis
- Experimentally one can have several choices:
  - HELICITY: flight direction of the vector meson in the collision rest frame
  - COLLINS SOPER: bisector of the angle between the two colliding beams as seen from the meson rest frame
  - EVENT PLANE: used in heavy ion collisions and connected to global properties of the event (see later)
- relations among polarization parameters extracted in different frames exist and can be used to remove systematic biases

Faccioli et al., EPJC 69 (2010) 657

Polarization in pp collisions

Physics motivation in pp



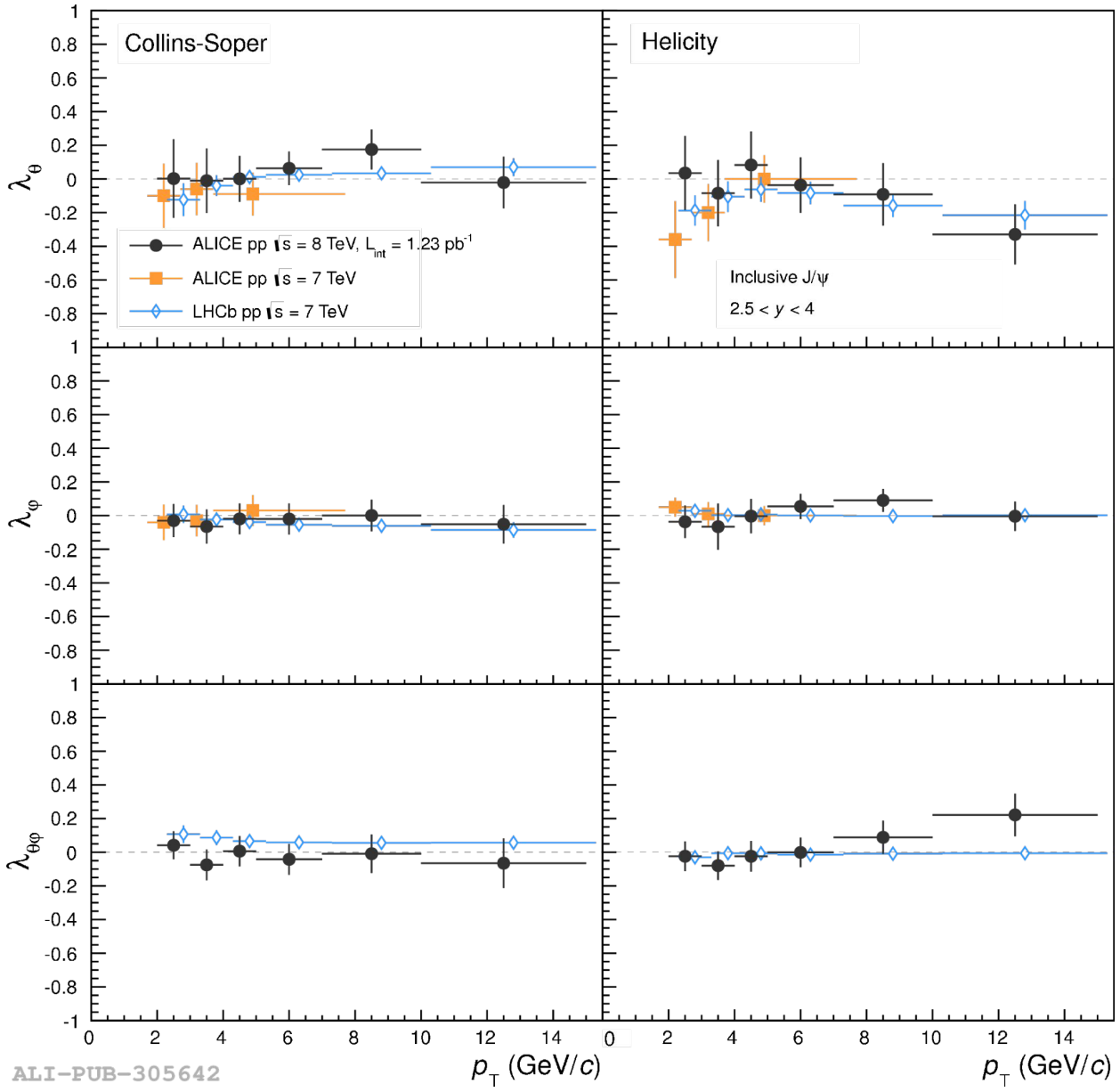
Butenschoen et al., Phys. Rev. Lett. 108, 172002

Quarkonia polarization sensitive to the production mechanism

Before LHC start:

- Opposite pre(post)dictions for Color Singlet Model and NRQCD at NLO
- Large difference between LO and NLO calculations
- Thevatron: CDF-D0 Run1 puzzle and CDF Run1-Run2 tension
- Predictions for LHC experiments: awaited results to discriminate among production mechanisms

J/ψ polarization in pp (I)

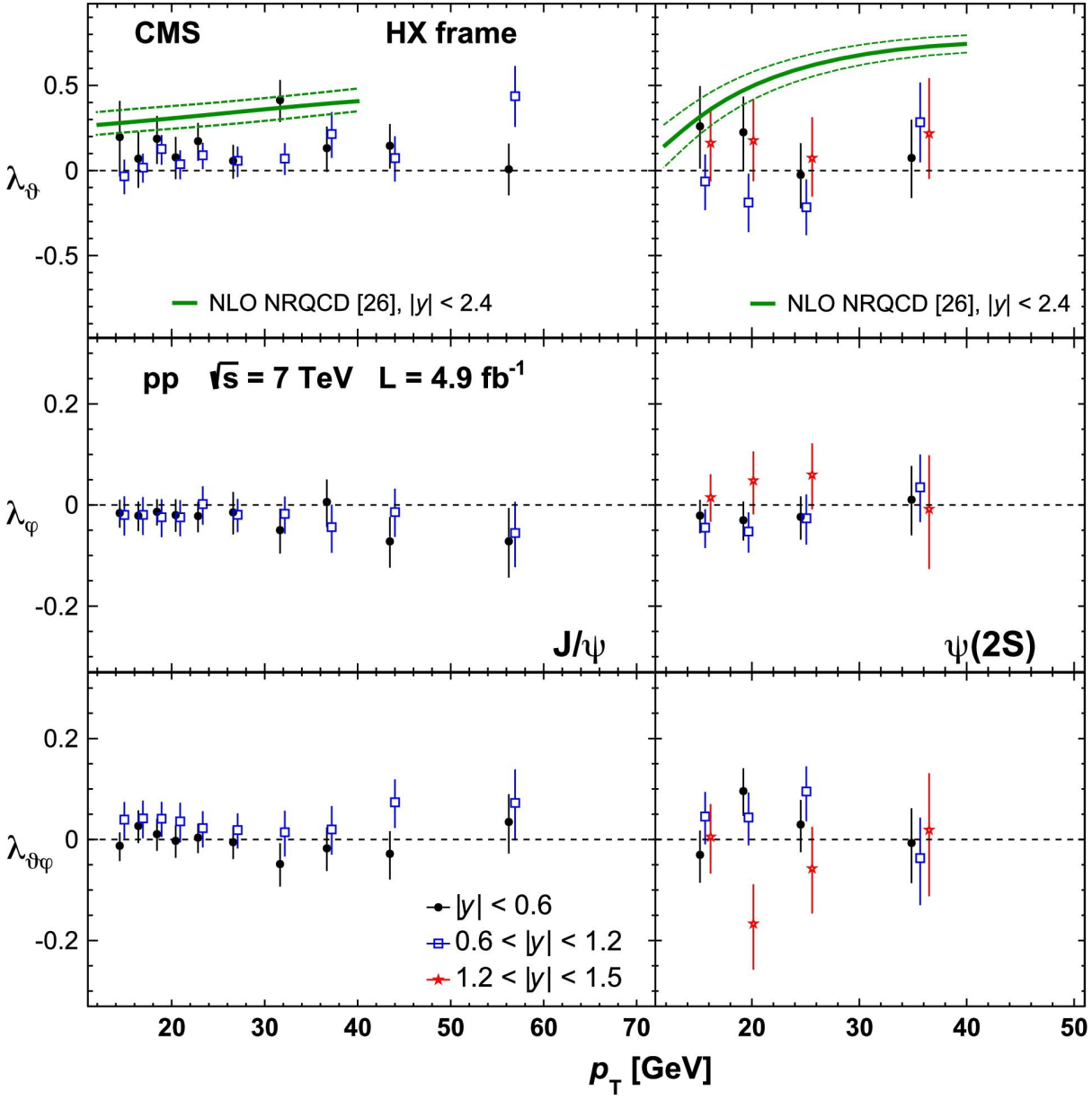


FORWARD RAPIDITY:

- No strong J/ψ polarization observed by ALICE and LHCb (large p_T range up to 15 GeV/c)
- Results for prompt (LHCb) and inclusive (ALICE) J/ψ production do not differ significantly

ALICE, PRL 108 (2012) 082001 ALICE, EPJC 78 (2018) 562 LHCb, EPJC 73 (2013) 11

J/ψ polarization in pp (II)



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ALICE, PRL 108 (2012) 082001 ALICE, EPJC 78 (2018) 562 LHCb, EPJC 73 (2013) 11

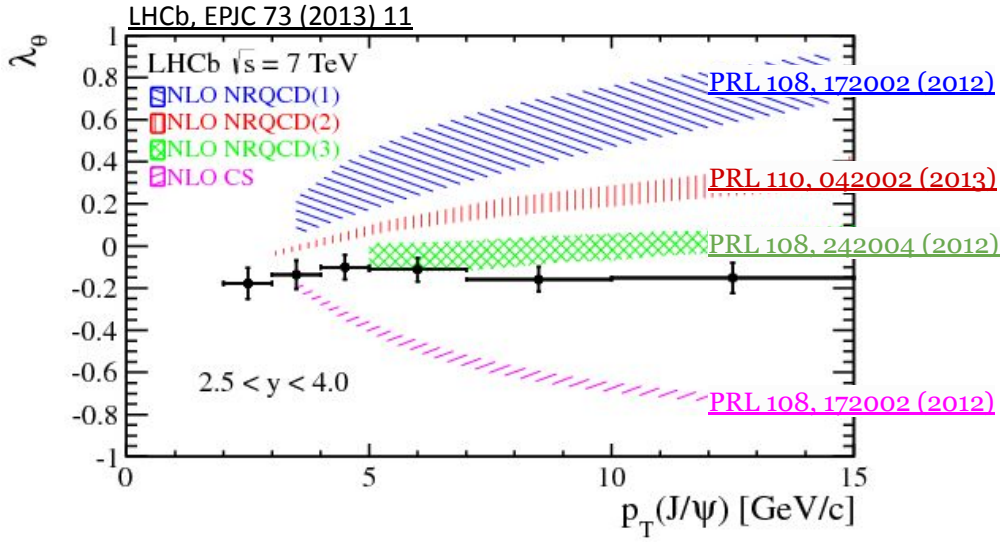
CENTRAL RAPIDITY:

- No strong J/ψ and ψ(2S) polarization observed by CMS (three ranges in $|y|$<1.5)

CMS, PLB 727 (2013) 381

J/ψ polarization: models getting closer (?)

LHCb, EPJC 73 (2013) 11



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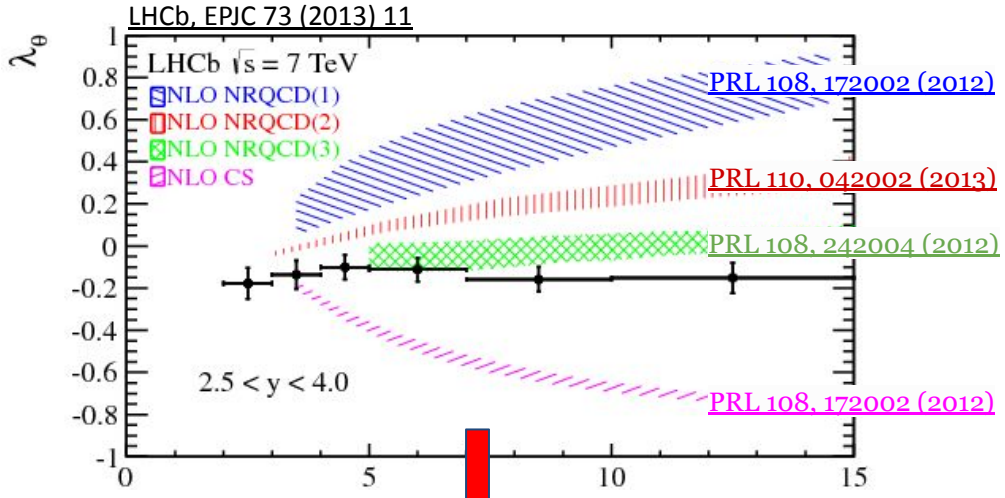
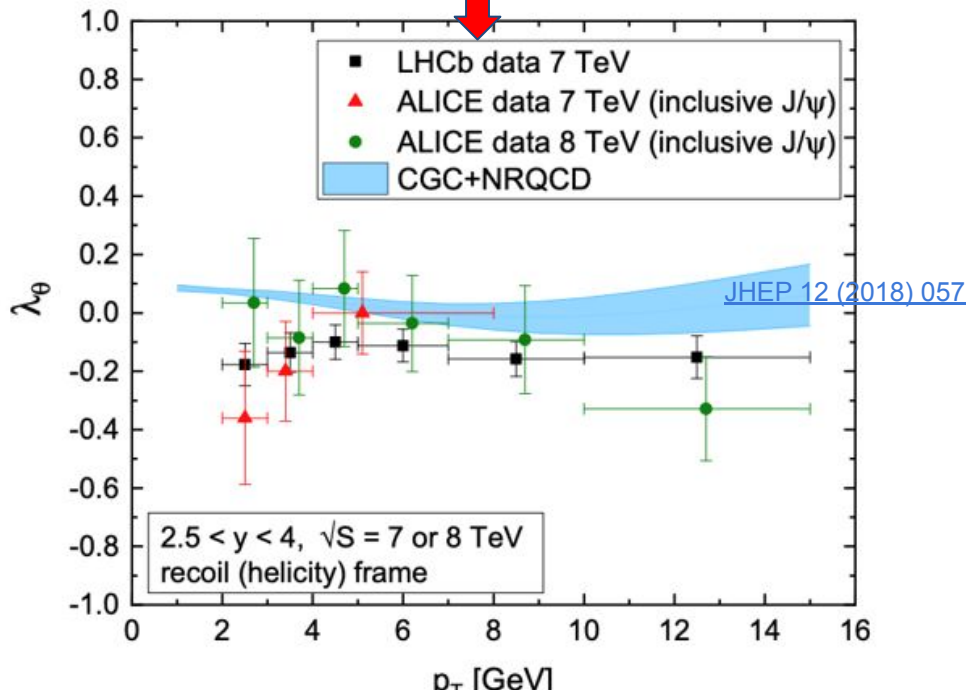


PRL 108, 172002 (2012)

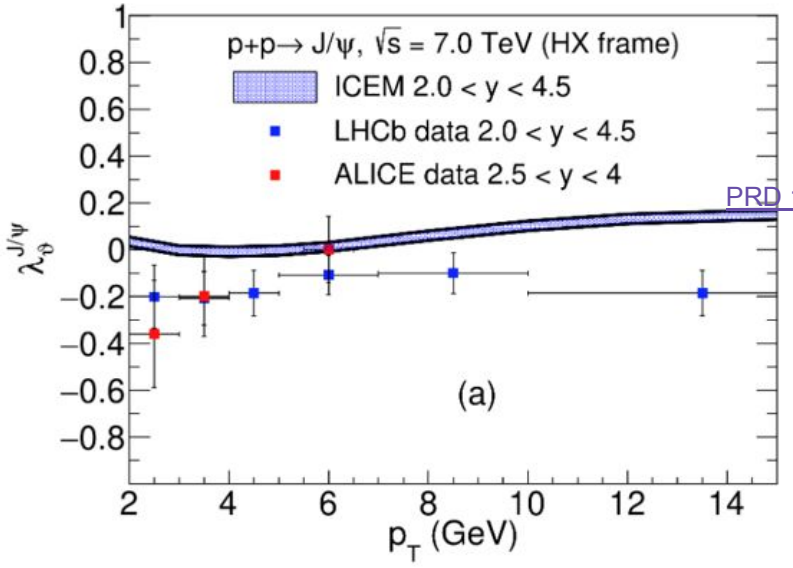
PRL 110, 042002 (2013)

PRL 108, 242004 (2012)

PRL 108, 172002 (2012)



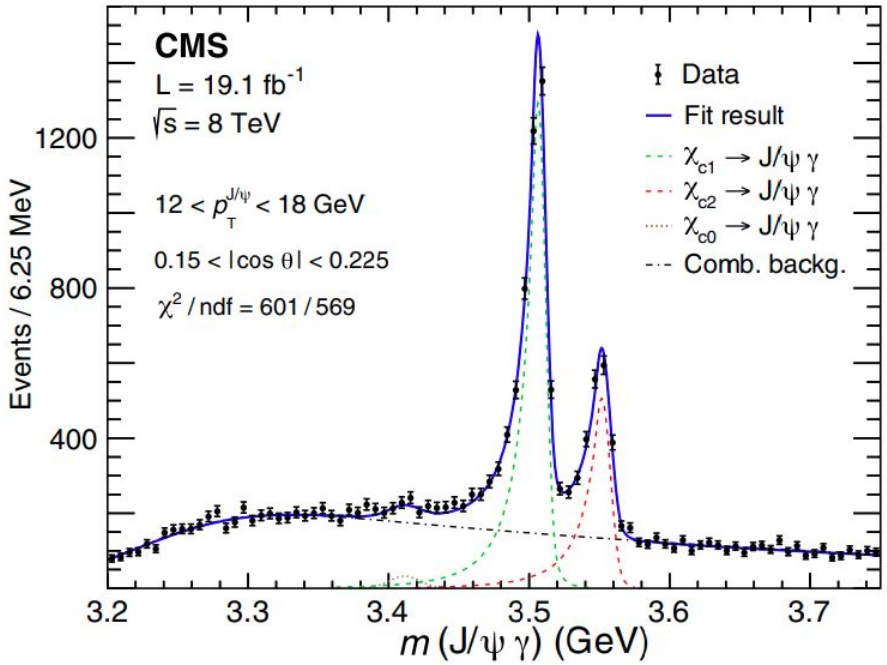
JHEP 12 (2018) 057



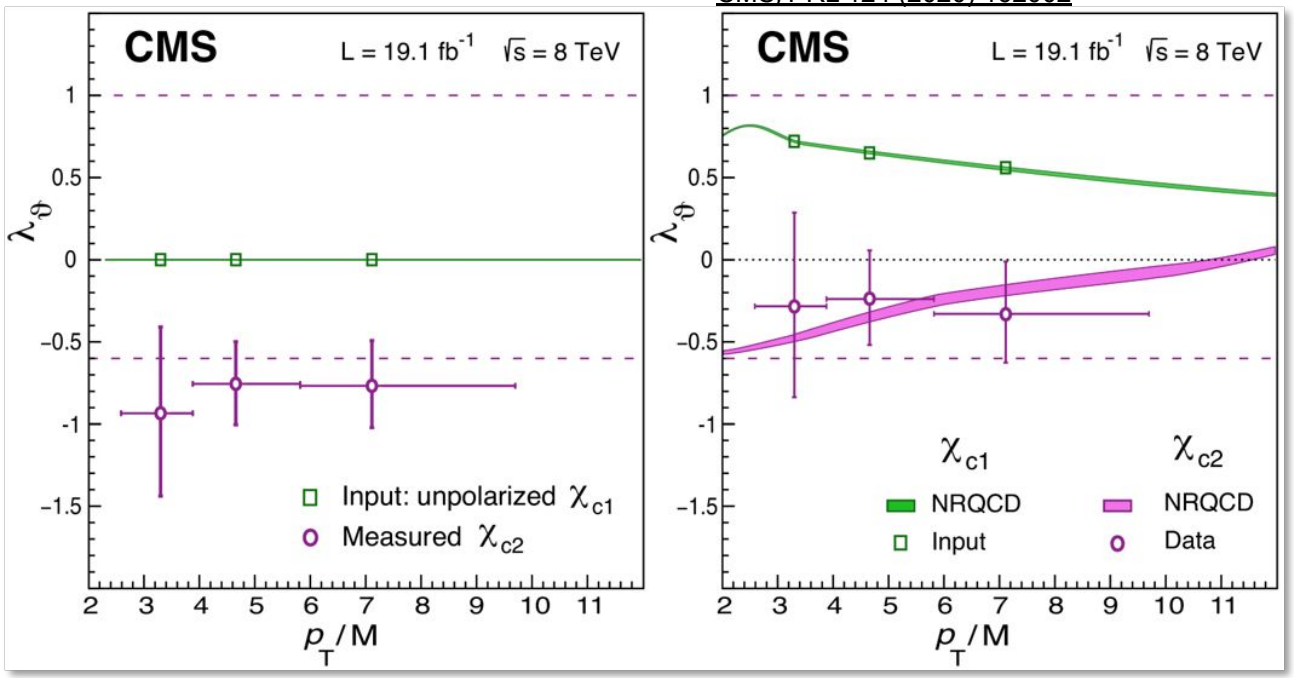
PRD 104 (2021) 9

- Models getting closer to polarization results
- Mostly thanks to the inclusion of polarization results in the fit of LDME in NRQCD
- Polarization puzzle experimentally solved (no incoherences among results from different experiments at high energy)

$\lambda_\vartheta(\chi_{c2})/\lambda_\vartheta(\chi_{c1})$



CMS, PRL 124 (2020) 162002

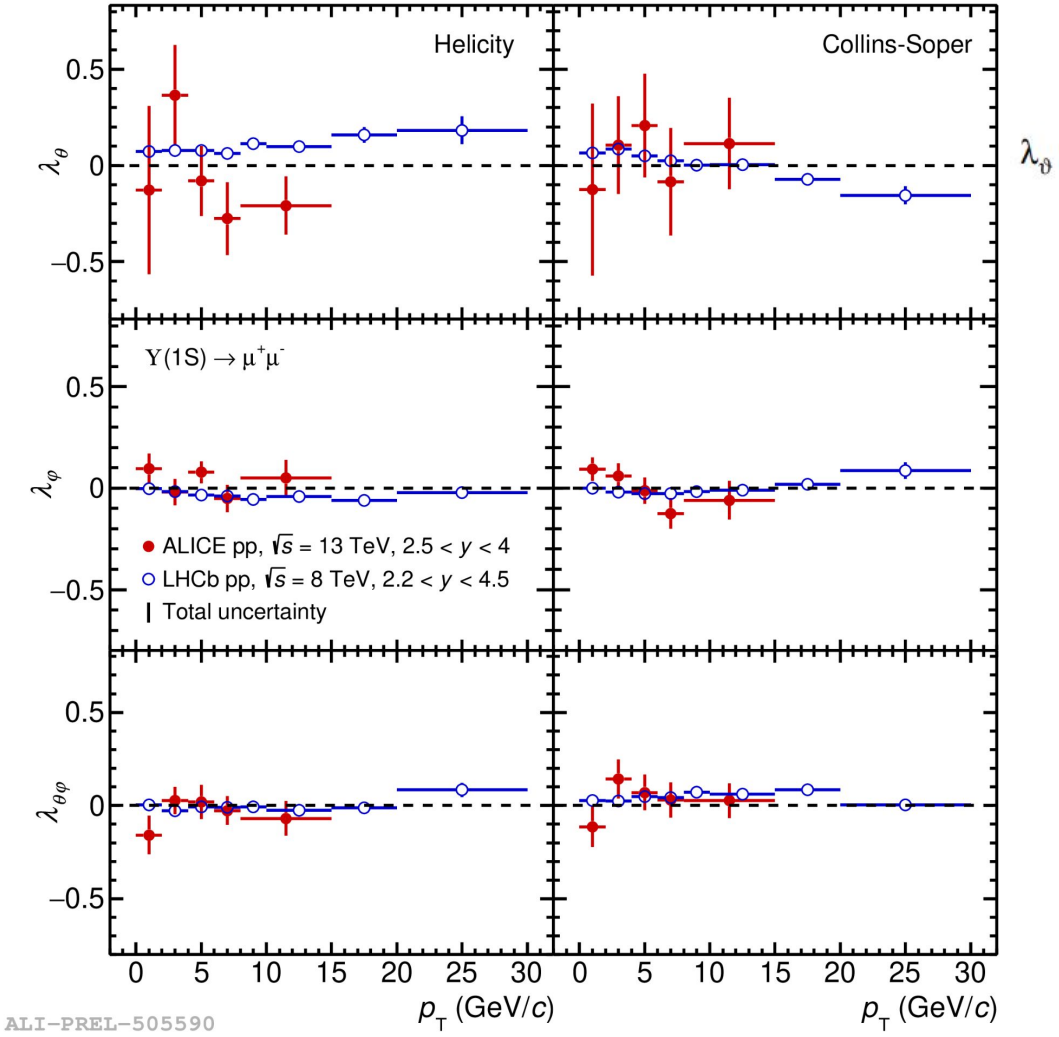


- $\lambda_\vartheta(\chi_{c2})/\lambda_\vartheta(\chi_{c1})$ measured from $\mu\leftarrow J/\psi$ angular distribution in the Helicity frame
- χ_{c2} λ_ϑ estimated fixing χ_{c1} λ_ϑ to zero or to the NRQCD expectation
- first evidence of non-zero polarization of quarkonia at the LHC

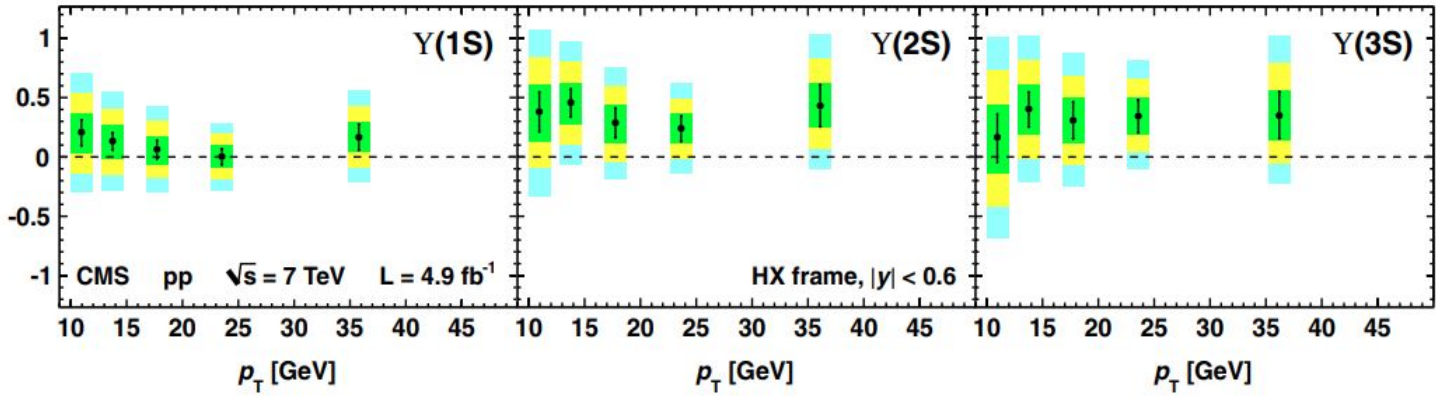
A direct measurement would be very interesting!
What is the impact on the measured λ_ϑ of the J/ψ?

Υ polarization in pp

LHCb, JHEP 12 (2017) 110

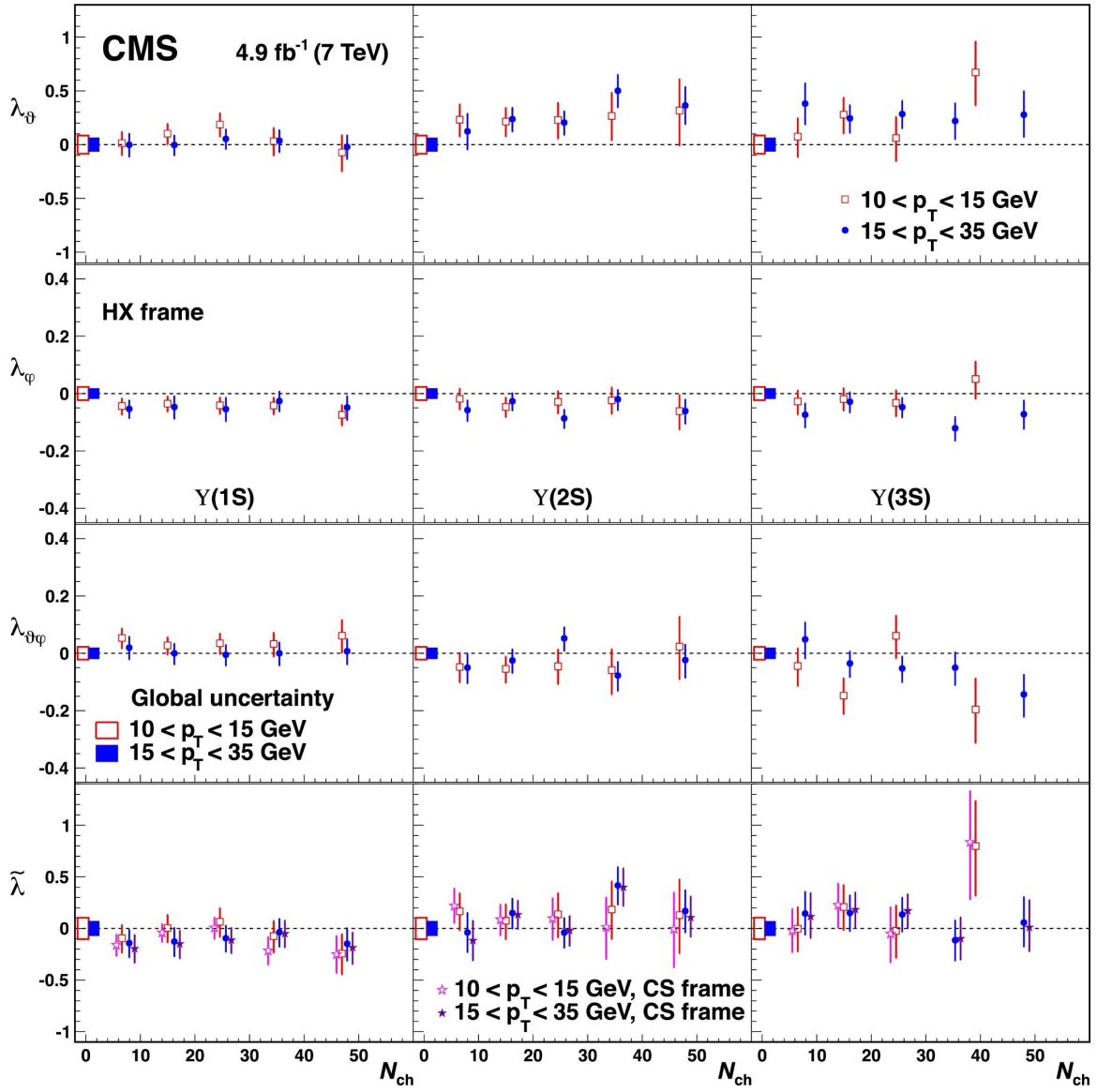


CMS, PRL 110 (2013) 081802



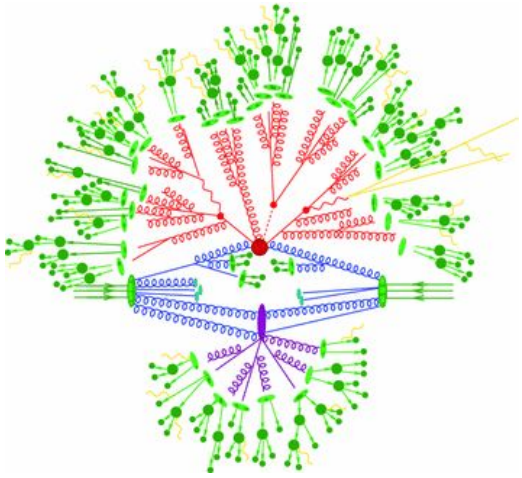
- Υ(1S) polarization measured at forward and central rapidity in pp at different $\sqrt{s}$ → very mild polarization found
- Excited states measured by CMS at central rapidity. Large uncertainties → no significant polarization measured

Υ polarization in pp VS multiplicity



- Study of Υ(nS) polarization as a function of multiplicity in pp collisions at $\sqrt{s}$ = 7 TeV
- First attempt in checking if the QCD environment during hadronization can affect bottomonia polarization
- not strongly affected by the medium
- no significant polarization measured

CMS, PLB 761 (2016) 31



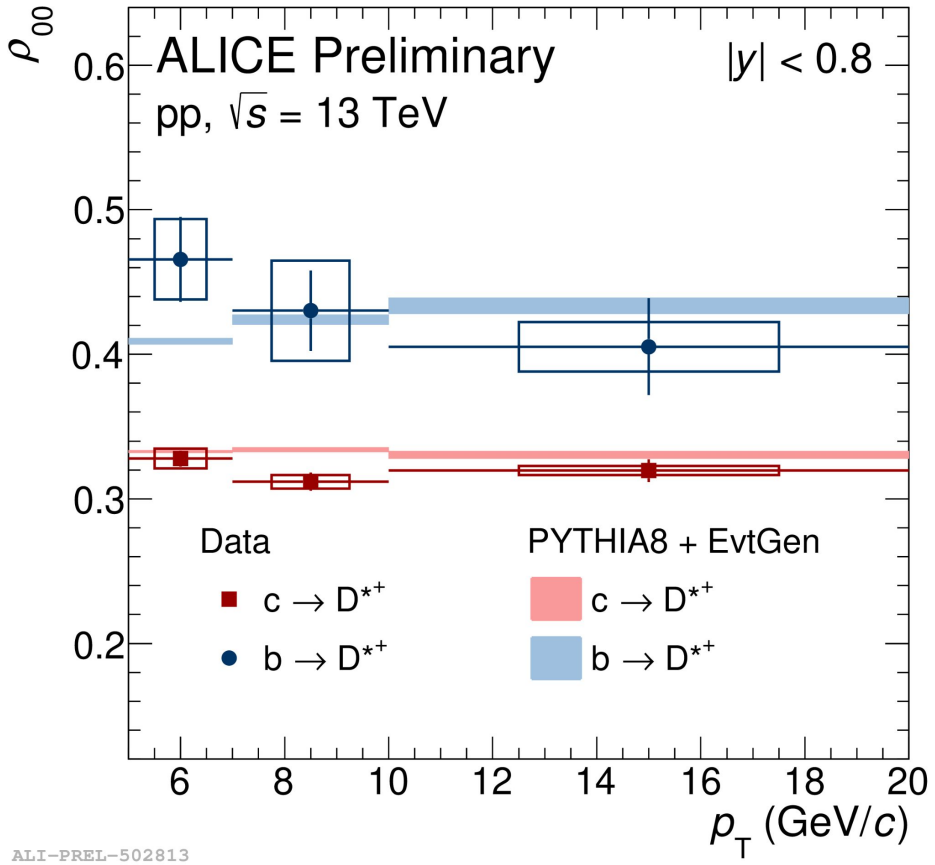
D^{*+} polarization in pp

- First measurement of D^{*+} ($\rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$) polarization in pp collisions at $\sqrt{s}$ = 13 TeV
- Spin density matrix element ρ_{00} measured through the analysis of the angular distribution of D^{*+} daughters

$$\frac{dN}{d\cos\theta} \propto (1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2\theta$$

$$\begin{cases} \rho_{00} = 1/3 \rightarrow \text{no spin alignment} \\ \rho_{00} \neq 1/3 \rightarrow \text{spin alignment} \end{cases}$$

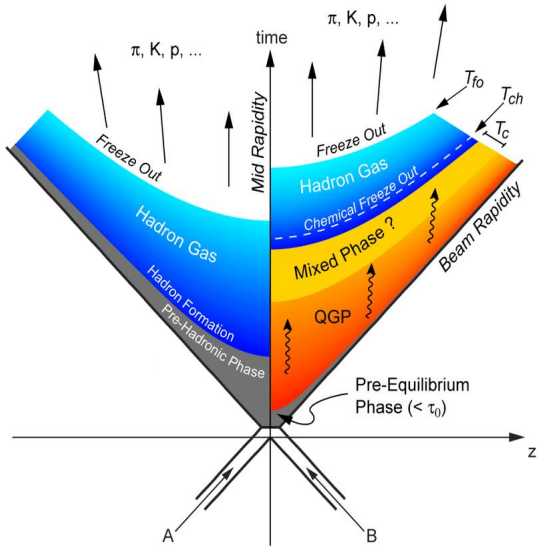
- useful reference for studies in A-A (see later)
- No significant polarization observed for prompt D^{*+}. Non-prompt D^{*+} feature longitudinal polarization (as expected)
- comparison to PYTHIA8+EvtGen simulation → good agreement

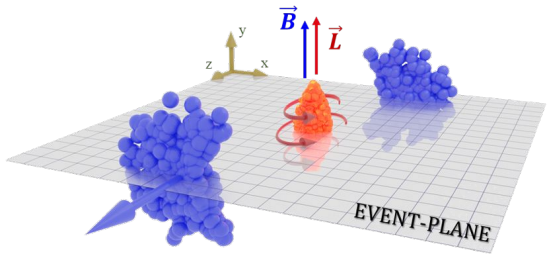


D. Lange, Nucl. Instrum. Meth. A 462 (2001) 707

Results in A-A collisions

A-A collisions: a conspiracy for potential polarization





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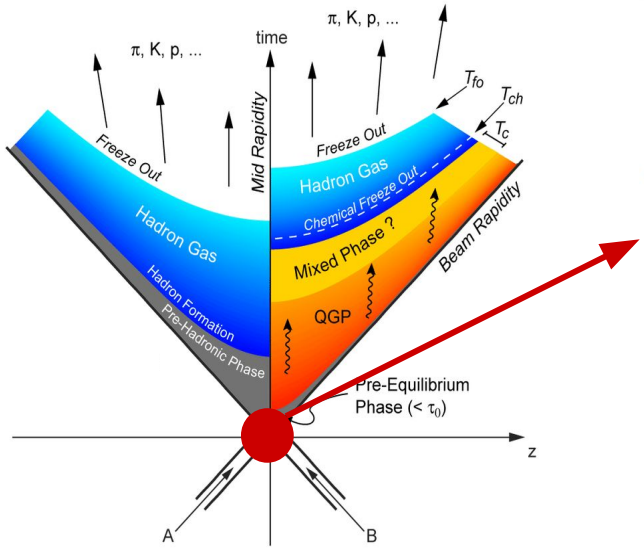
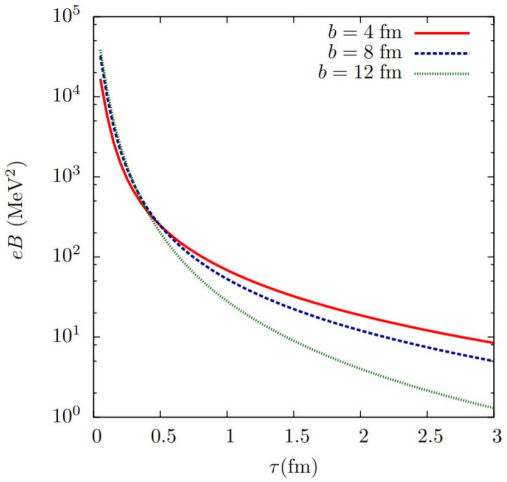
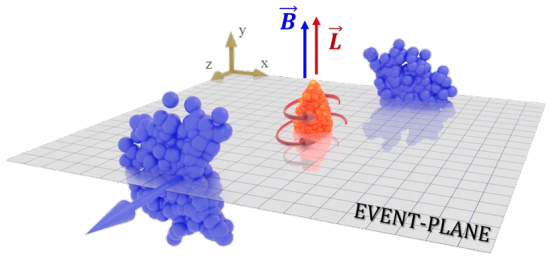




Strong B (~10^{14} T) due to beam currents

- decaying in τ~1fm
- no strong centrality dependence
- possibly affecting high-Q^2 processes $\rightarrow \psi$ polarization?



Kharzeev et al., NPA 803 (2008)

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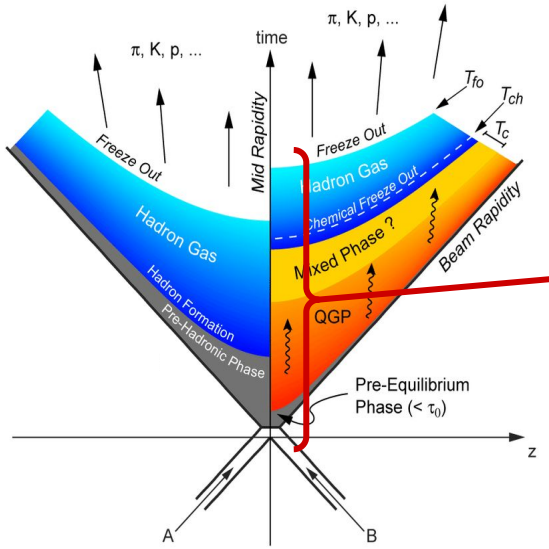

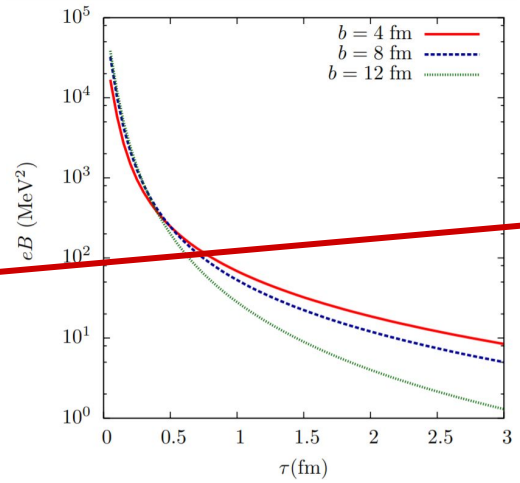

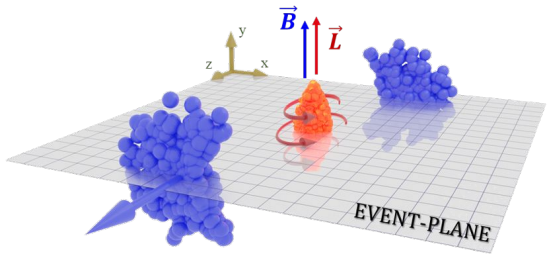

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Large angular momentum

- conserved (no time dependent)
- centrality dependent
- strong vorticity in the partonic fluid
- can affect processes throughout the whole system evolution

Becattini et al.,
Phys. Rev. C 77 (2008) 024906

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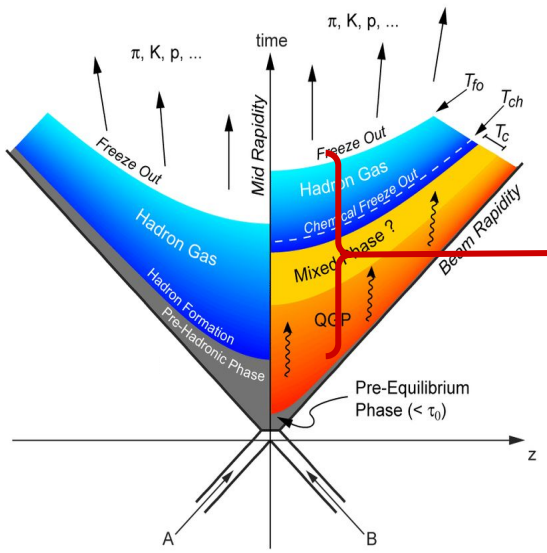

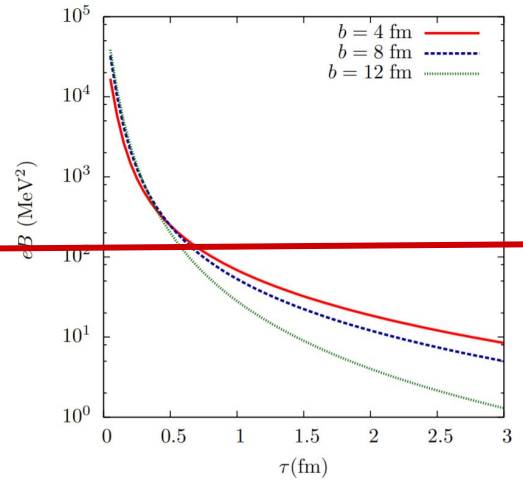

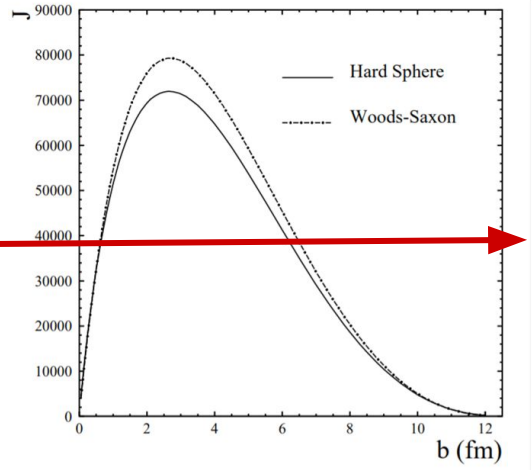

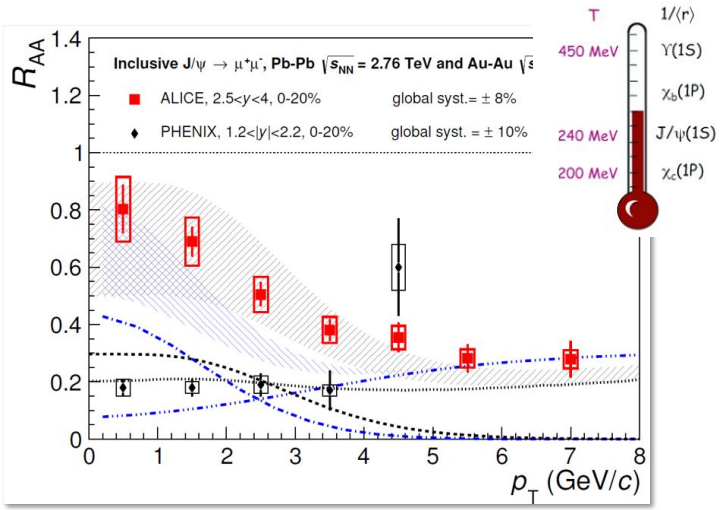

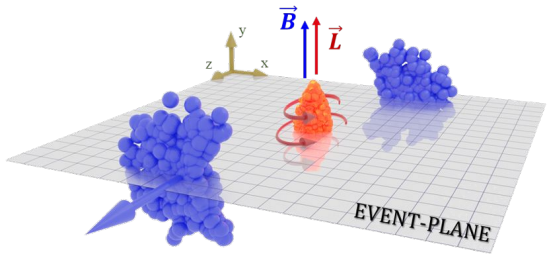

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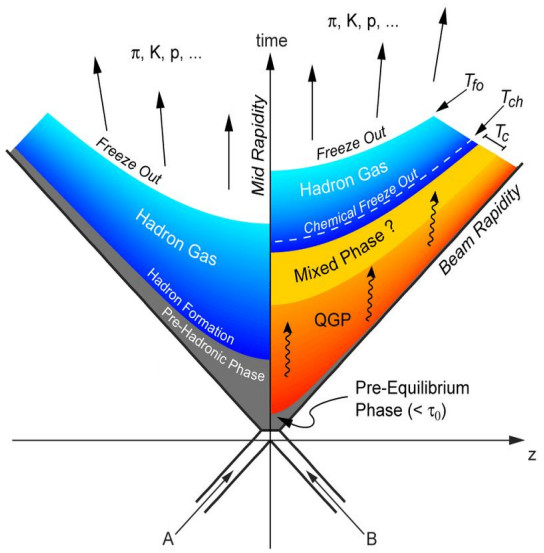
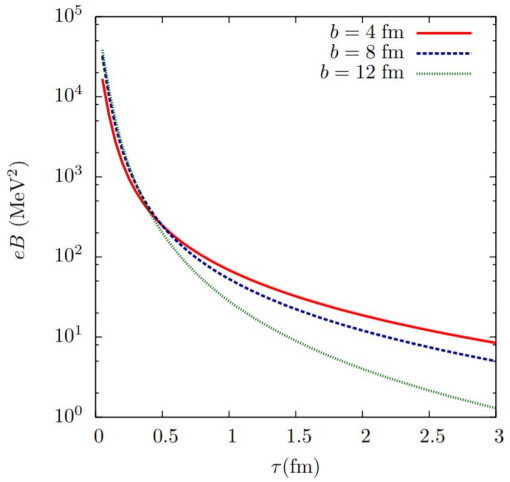
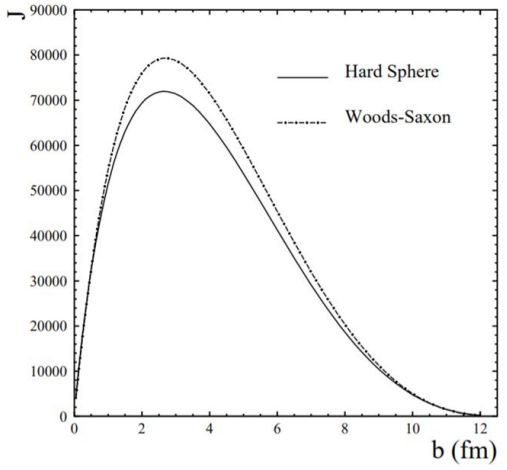
Medium effects

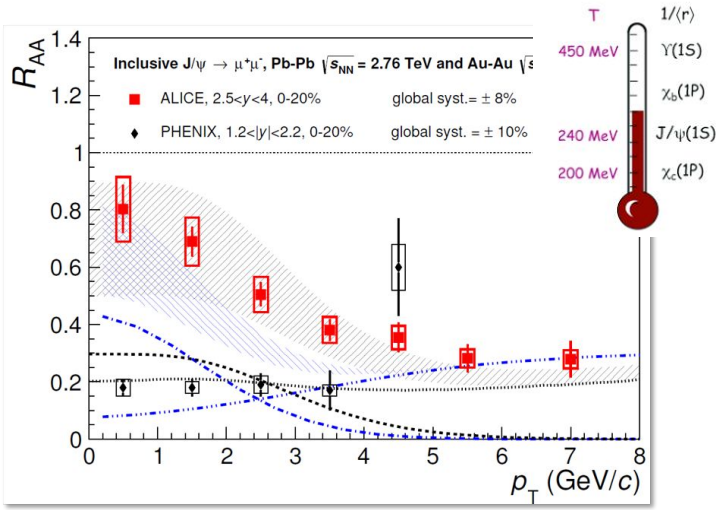
- quarkonia suppression $\rightarrow$ different mix of direct, prompt and non-prompt states (different dissociation temperatures)
- J/ψ regeneration at low p_T
- collective partonic motion
- Effective mesonic fields due to net flavour currents (e.g. ϕ-meson field)

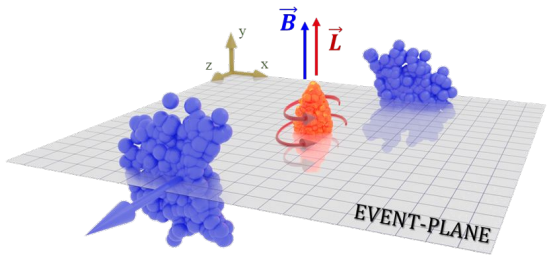
A-A collisions: a conspiracy for potential polarization











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Phenomenological background

Theoretical framework to study polarization in A-A improved significantly in the last two decades.

e.g. ρ_{00} parameter for ϕ production affected by several effects:

$$\rho_{00} = \frac{1}{3} + c_{\Lambda} + c_{\varepsilon} + c_{E} + c_{F} + c_{L} + c_{A} + c_{\phi}$$

- some of them leading to $\rho_{00} > \frac{1}{3}$, others to $\rho_{00} < \frac{1}{3}$
- some of them can be constrained by measurements on different baryon/meson states
- each one depending on different quantities (charge, mass, etc.)

Polarization measurements for different states are a precise test of the theoretical framework

⤸

novel study of medium properties in a quantitative way across energies

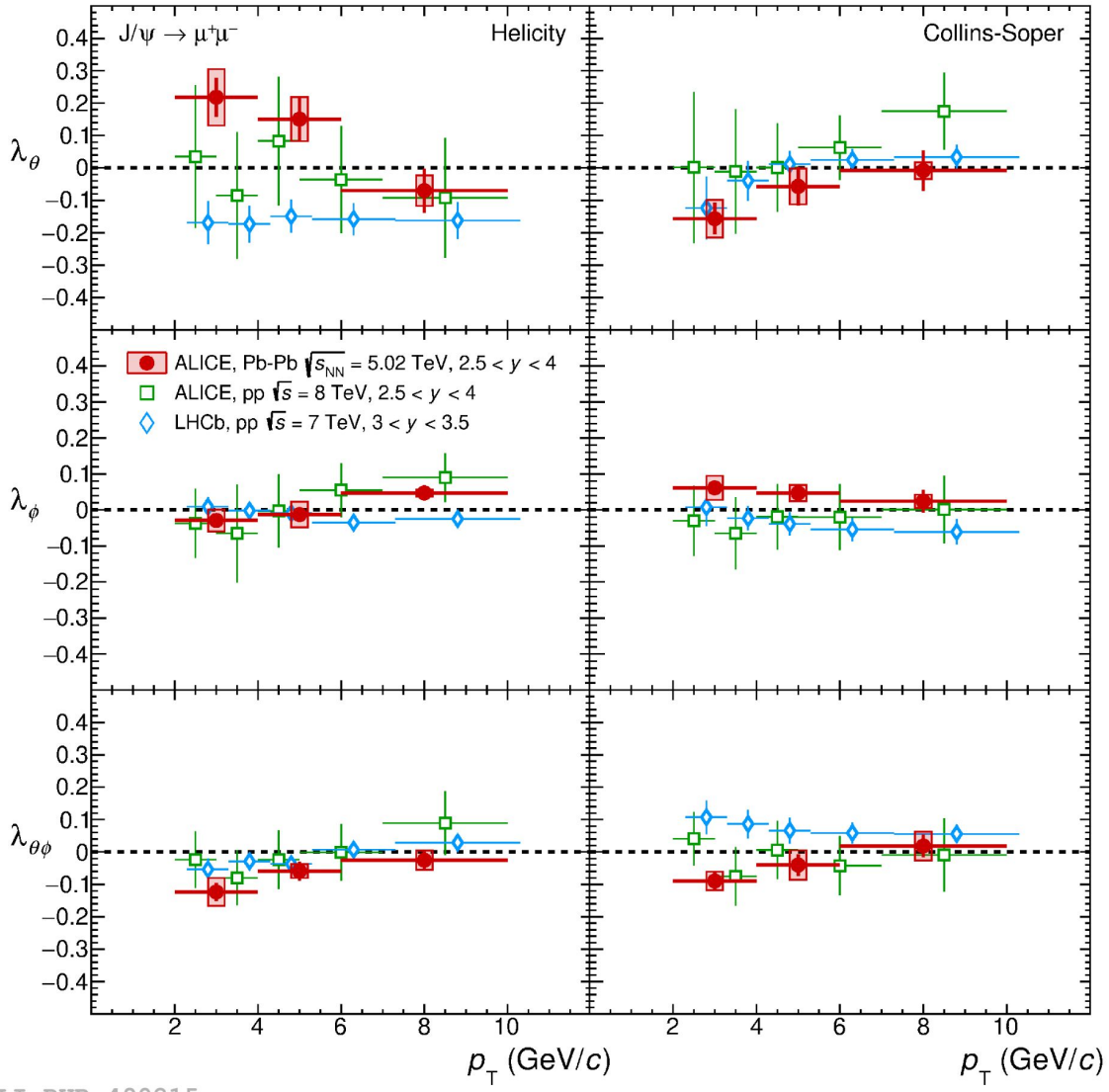
[1]. Liang et., al., Phys. Lett. B 629, (2005);
Yang et., al., Phys. Rev. C 97, 034917 (2018);
Xia et., al., Phys. Lett. B 817, 136325 (2021);
Beccattini et., al., Phys. Rev. C 88, 034905 (2013)
[2]. Sheng et., al., Phys. Rev. D 101, 096005 (2020);
Yang et., al., Phys. Rev. C 97, 034917 (2018)
[3]. Liang et., al., Phys. Lett. B 629, (2005)
[4]. Xia et., al., Phys. Lett. B 817, 136325 (2021);
Gao, Phys. Rev. D 104, 076016 (2021)
[5]. Muller et., al., Phys. Rev. D 105, L011901 (2022)
[6]. Sheng et., al., Phys. Rev. D 101, 096005 (2020);
Phys. Rev. D 102, 056013 (2020);
arXiv:2205.15689 (2022); arXiv:2206.05868 (2022)

From Aihong Tang's talk at the Chirality Workshop (UCLA Dec. 2022)

Physics Mechanisms	(ρ_{00})
c_{Λ}: Quark coalescence vorticity & magnetic field[1]	< 1/3 (Negative ~ 10^{-5})
c_{ε}: E-comp. of Vorticity tensor[1]	< 1/3 (Negative ~ 10^{-4})
c_{E}: Electric field[2]	> 1/3 (Positive ~ 10^{-5})
c_{F}: Fragmentation[3]	> or, < 1/3 (~ 10^{-5})
c_{L}: Local spin alignments[4]	< 1/3
c_{A}: Turbulent color field[5]	< 1/3
c_{ϕ}: Vector meson strong force field[6]	> 1/3 (Can accommodate large positive signal)

J/ψ polarization in Pb-Pb: "production" frames

ALICE, PLB 815 (2021) 136146



ALI-PUB-490215

ALICE measurement of J/ψ polarization at forward rapidity in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV:

- λ_θ: 2σ difference with respect to 0 in HE and CS frames at low p_T
- consistent with pp results by ALICE…
- …but 3σ tension wit LHCb result in pp!

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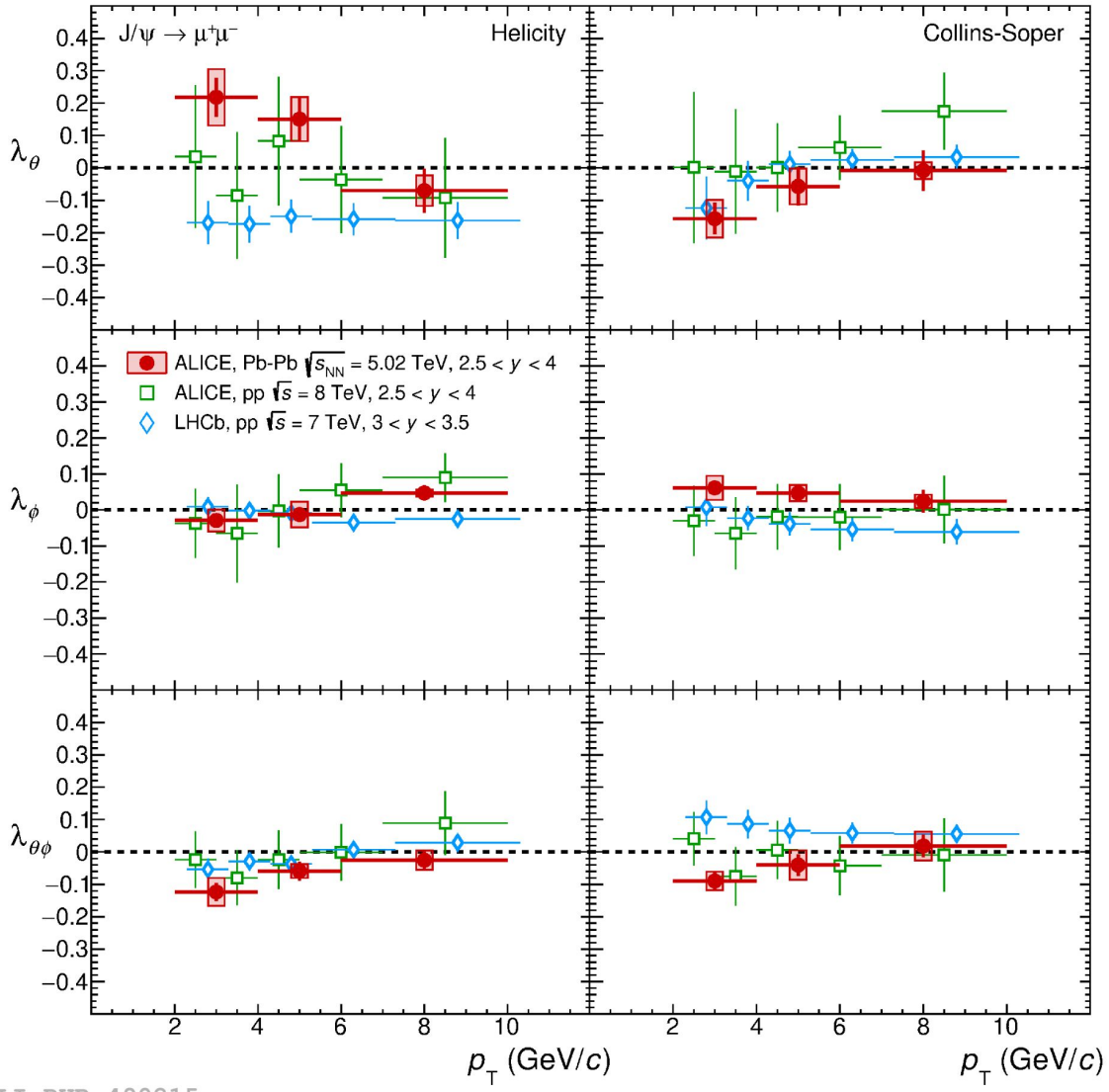

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- what is the role of *B*?
- can *L* conservation play a role? Are regenerated J/ψ polarized due to *c*-quark participation to the vortical collective motion?

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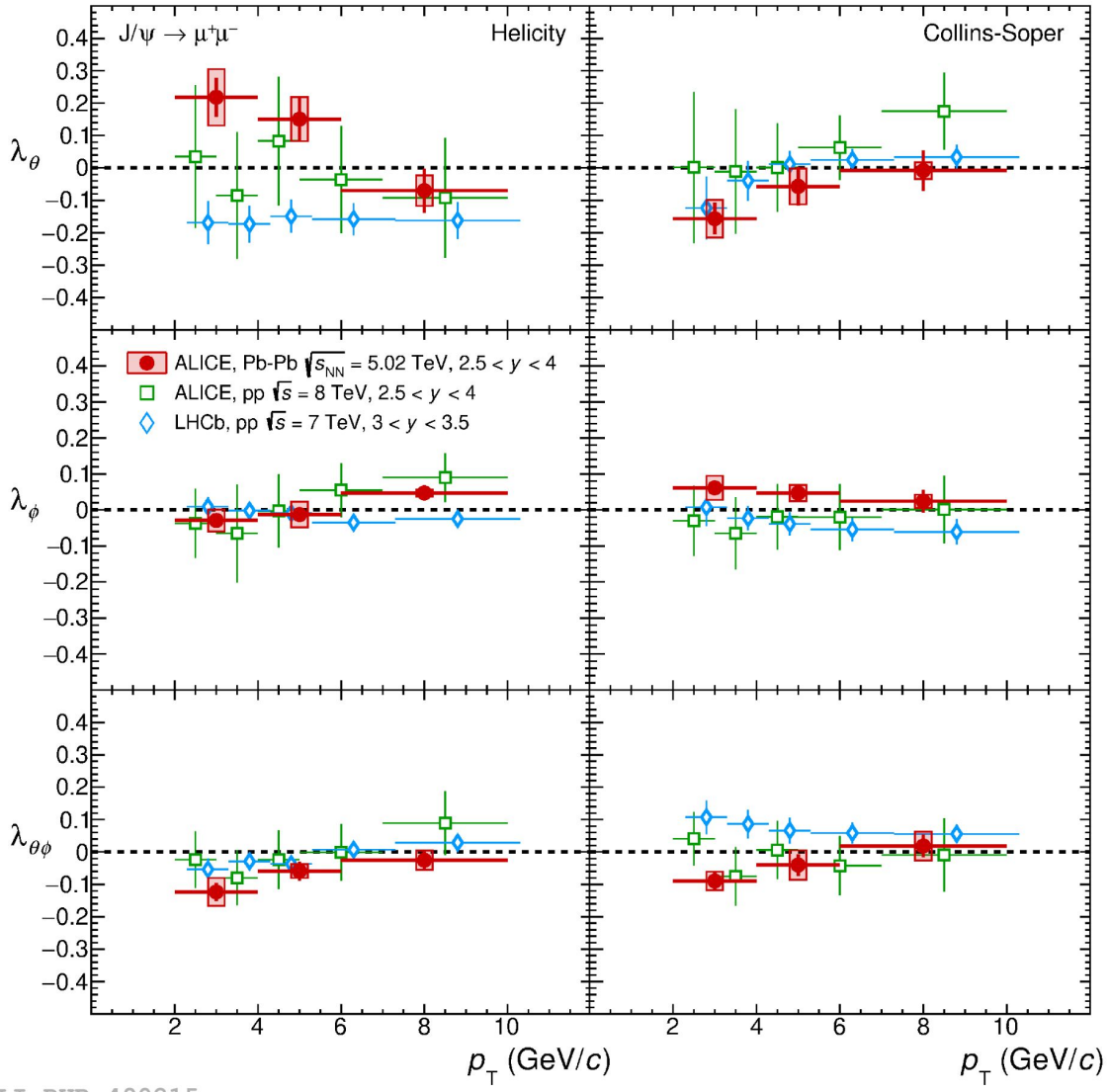

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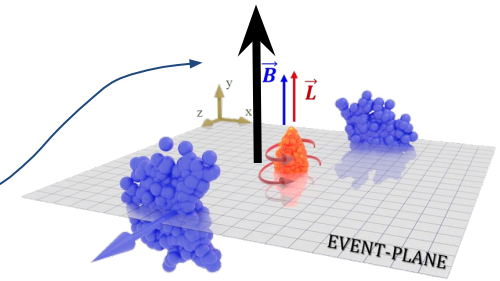
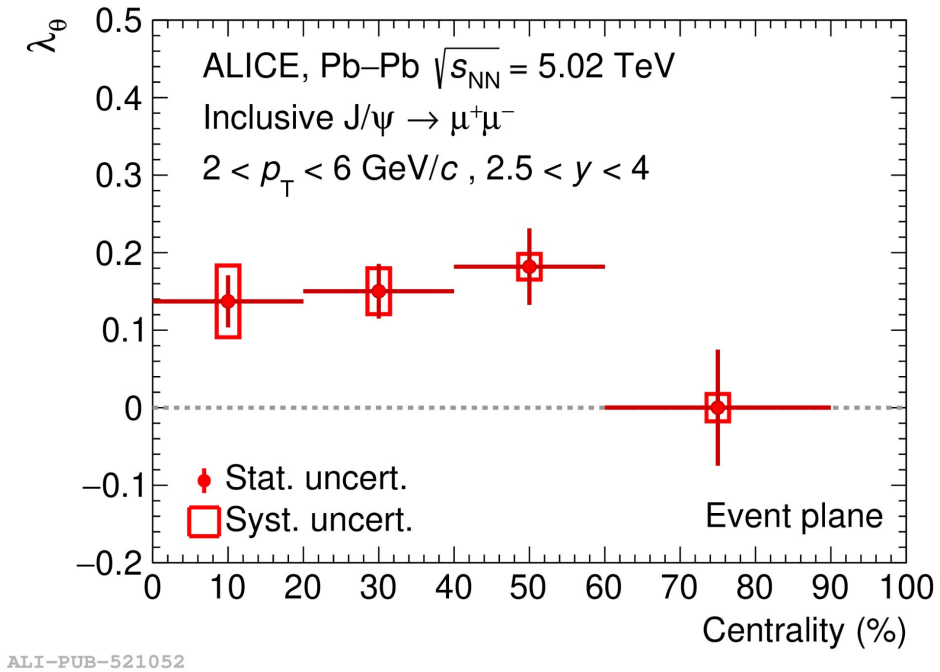
Need to change reference frame!

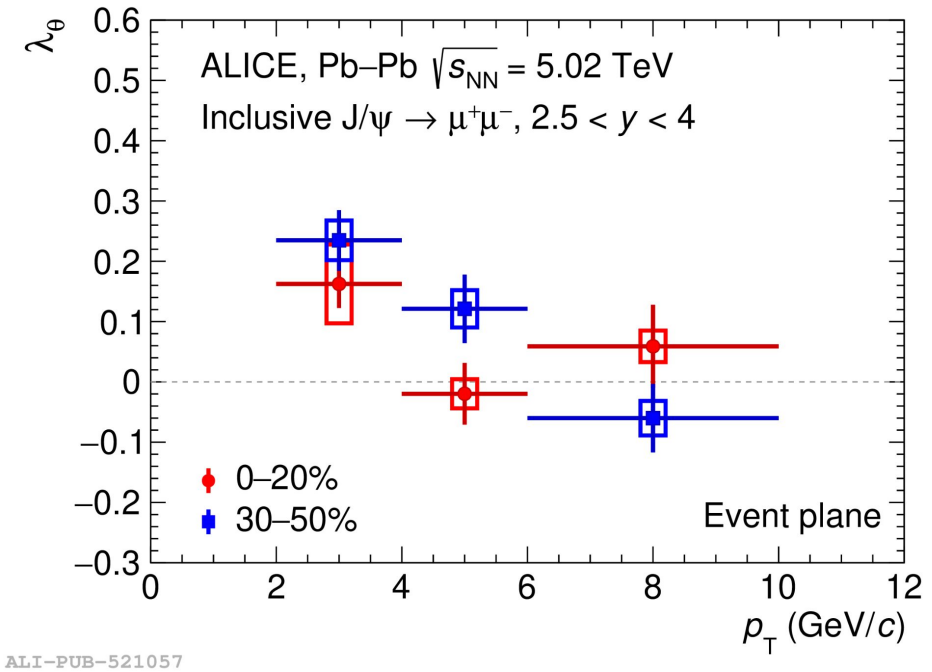
POLARIZATION AXIS: NORMAL TO THE EVENT PLANE



J/ψ polarization in the Event Plane frame

ALICE, arXiv:2204.10171





First measurement of J/ψ polarization in the EP frame:

- Small but significant polarization observed (3.5σ in 40-60%)
- No significant centrality dependence in 0-60% range
- in semi-peripheral collisions (30-50%) the effect is 3.9σ significant at lowest p_T, while λ_θ reaches zero at high p_T

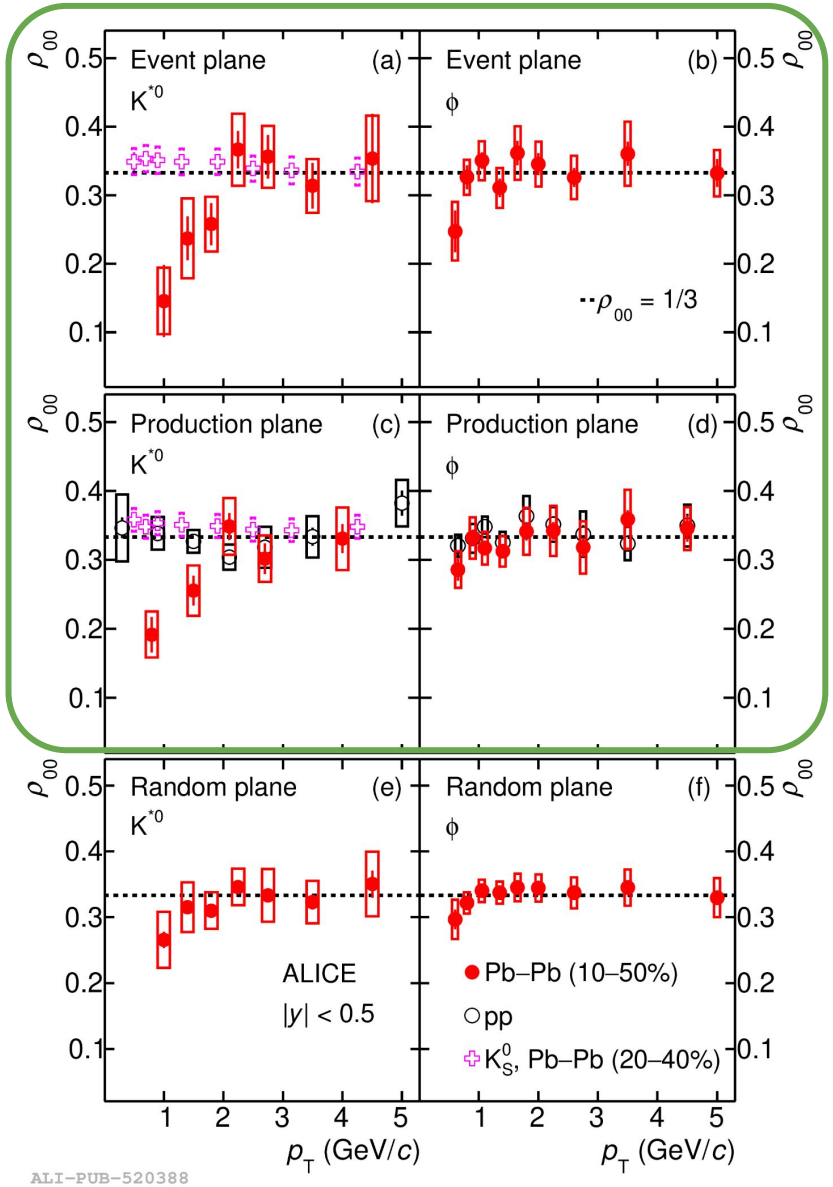
more connected to the late stage evolution of the system?

Difficult to draw conclusions without a solid phenomenological framework. Work ongoing from theorists

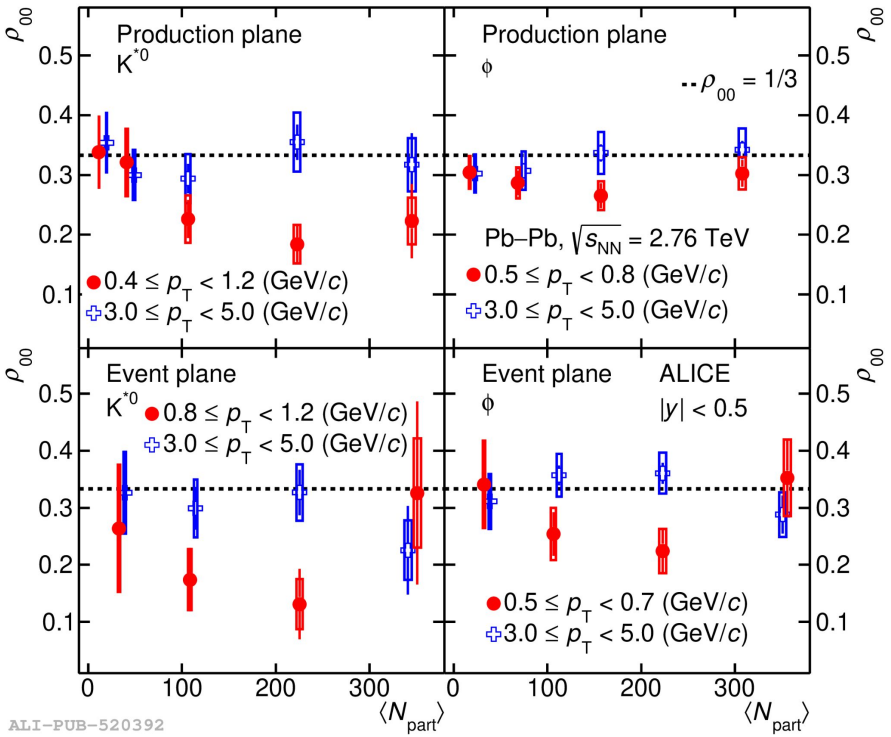
Ioffe & Kharzeev, Phys. Rev. C, 68 (2003) 061902

Sheng, Oliva et al., arXiv:2205.15689

Results for K*^{0} and ϕ: ALICE



$$\frac{dN}{d\cos\theta} \propto (1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2\theta$$



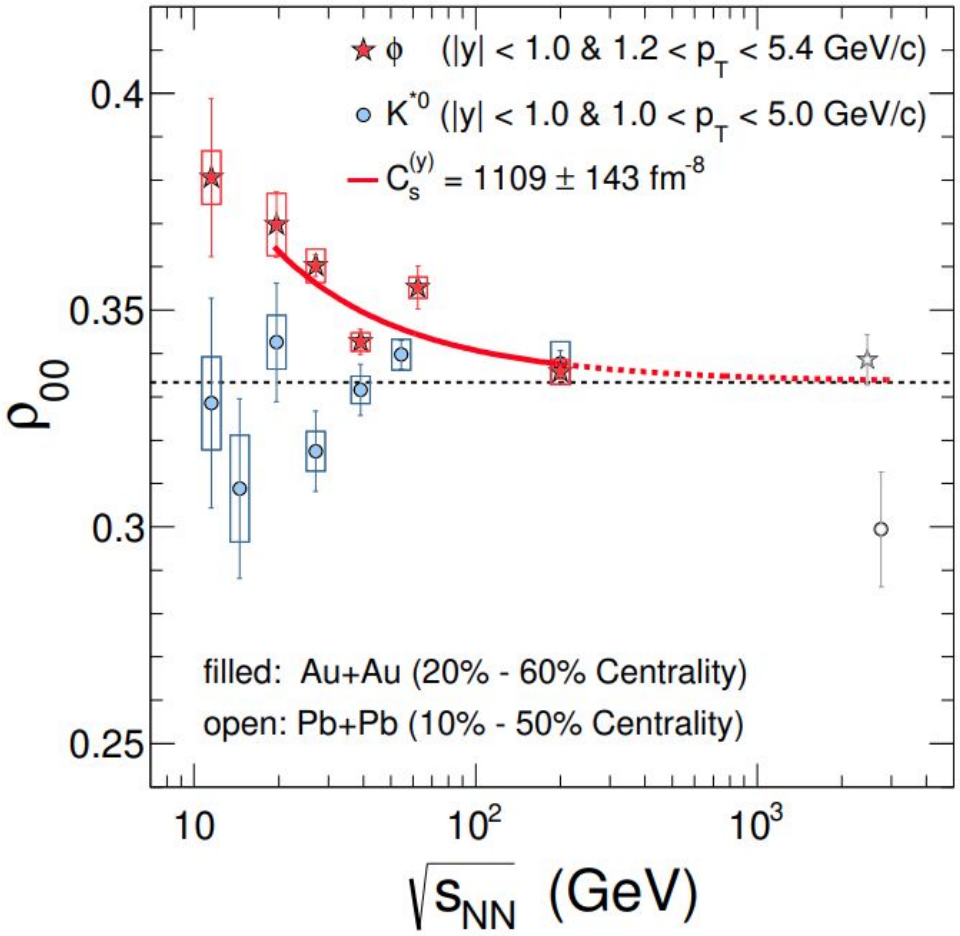
ALICE, PRL 125 (2020) 012301

ρ_{00} = ⅓ → no spin alignment
ρ_{00} ≠ ⅓ → spin alignment

- Significant deviation of ρ_{00} from ⅓ at low p_T in EP and PP
- more significant for K*^{0} than for ϕ (though consistent between the two)
- for p_T > 2 GeV/c no polarization
- the effect is maximum in semi-central collisions where it reaches 3.2 (2.6) σ and 2.1 (1.9) σ for K*^{0} and ϕ mesons in PP(EP) respectively

Results for K* and ϕ: STAR

STAR, arXiv:2204.02302



- Significant deviation of ρ_{00} from ⅓ to higher values for ϕ. Deviation vanishes at high center-of-mass energies
- no deviation observed for K^{*0}
- Compatibility to ALICE result for K^{*0} is questionable
- invoking effective ϕ-field contribution would explain the trend for ϕ. Difficult to extend the same argument to K^{*0}

Sheng, Oliva et al., arXiv:2205.15689

Wrap-up

Conclusions and outlook

Polarization studies in pp:

- Useful tool to discriminate among heavy quarkonia production mechanisms
- reference for polarization studies in A-A
- No significant polarization measured for J/ψ, ψ (2S), Υ(1-2-3S) at the LHC in different rapitity and transverse momentum ranges
- prompt D*+ not polarized. D*+ from B hadron decay shows the expected large (inherited) polarization. Will serve as reference for A-A measurements
- large ratio in λ_θ for χ_{c1} and χ_{c2}

Polarization studies in A-A:

- unique tool to study the properties of the partonic medium
- Hint for J/ψ polarization in semi-peripheral collisions at low p_T in the EP reference frame
- Polarization (ρ_{00}<⅓) observed for K*^{0} and ϕ at low p_T in the PP and EP reference frames by ALICE. Significance is larger for K*^{0} in semi-peripheral collisions
- STAR results show a significant ϕ polarization (ρ_{00}>⅓) at low $\sqrt{s}$, vanishing at top RHIC energy. Points to an important contribution of the effective ϕ-field