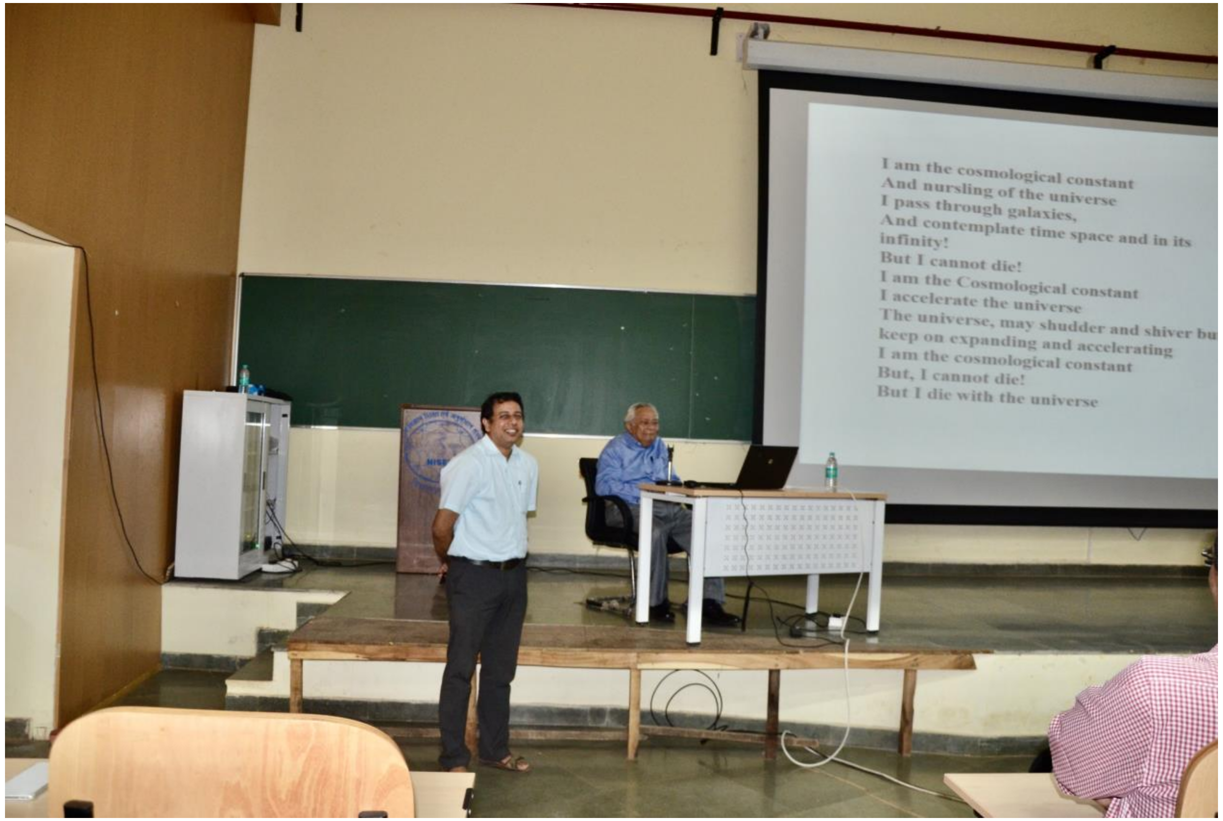
A tribute to Prof. Bikash Sinha



Prof. Sinha could traverse the canvas of nuclear physics to high energy QGP physics to early Universe cosmology with an enviable ease. He was a visionary, an institution builder, a keen and much acclaimed theoretical physicist who also built several vibrant experimental physics groups, but more so – he was a man of renaissance, large-hearted and generous.

He was a mentor and a father figure to me.

A tribute to Prof. Bikash Sinha

My pranam to Prof. Bikash Sinha, he will be remembered for pioneering contributions to several fields of science, institutions, service to the country, support for worldwide scientific programs and nurturing several young colleagues across different fields. We will miss him and may his soul rest in peace.

Observation of polarized hadrons in high energy heavy-ion collisions

Bedanga Mohanty
(NISER and CERN)

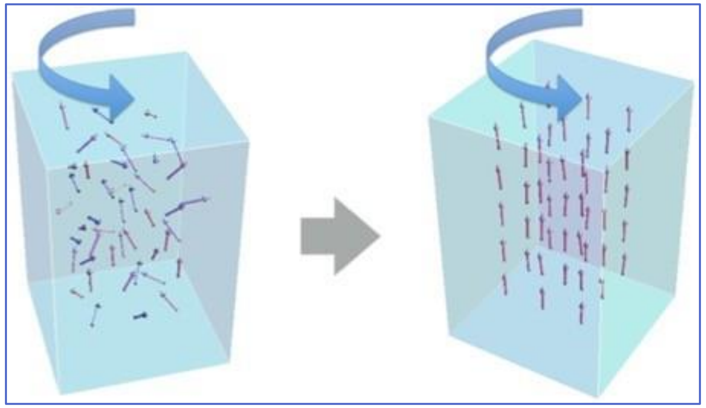
<u>Outline</u>

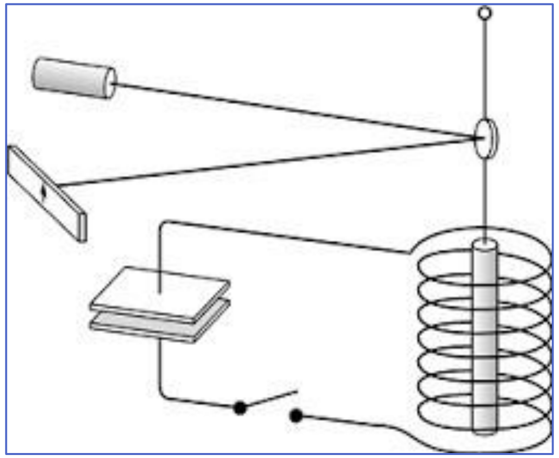
Introduction
Experimental observable
Results
- Vector meson spin alignment at RHIC & LHC
- Hyperon polarization at RHIC & LHC
- Quarkonium polarization at LHC
- Open cham polarization at LHC

Conclusions

India-ALICE-STAR Meeting
Jammu University, Jammu
November 21, 2023

Barnett Effect and Einstein-de Haas Effect





Rotation ➔ Polarization

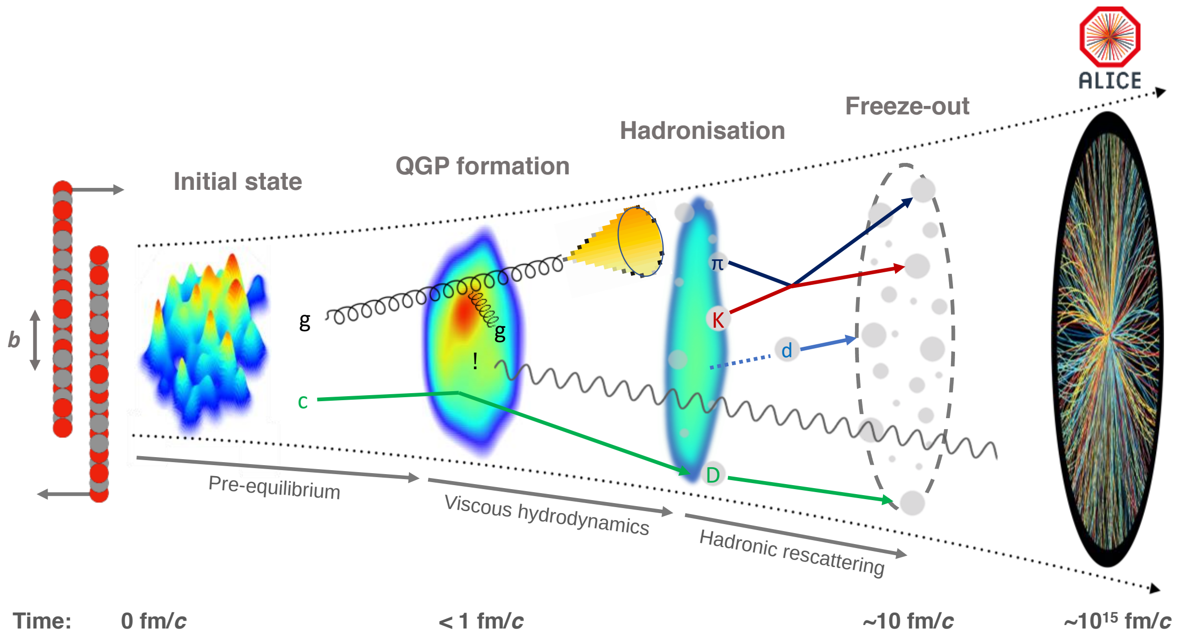
Polarization ➔ Rotation

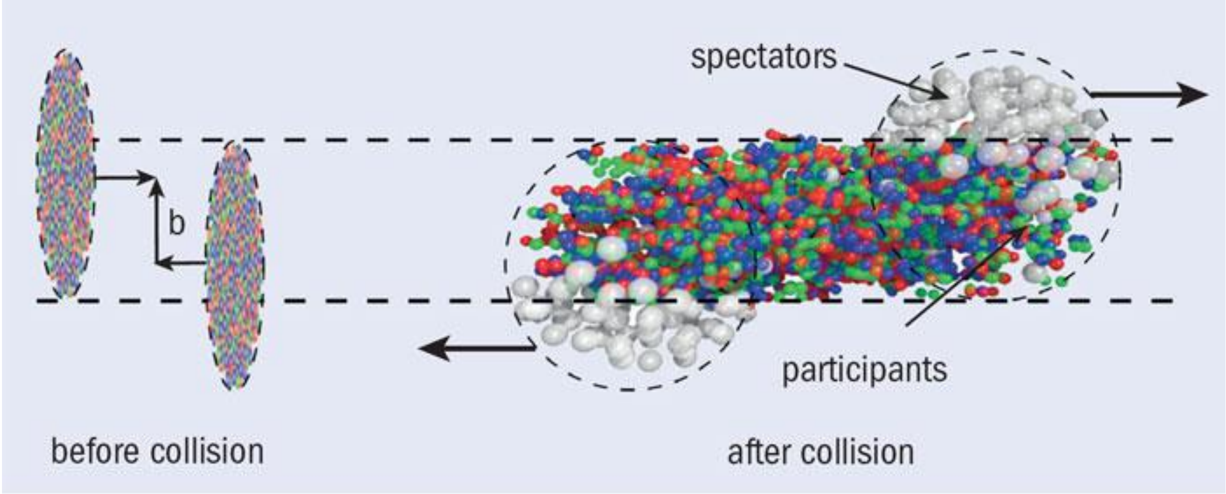
Barnett, Phys. Rev. 6 (4) 239, (1915)
Barnett, Rev. Mod. Phys. 7, 129 (1935)

Einstein, de Hass, DPG Vanhandlungen 17, 152 (1915)

Can we see any such effects in heavy-ion collisions ?

Time evolution of heavy-ion collisions

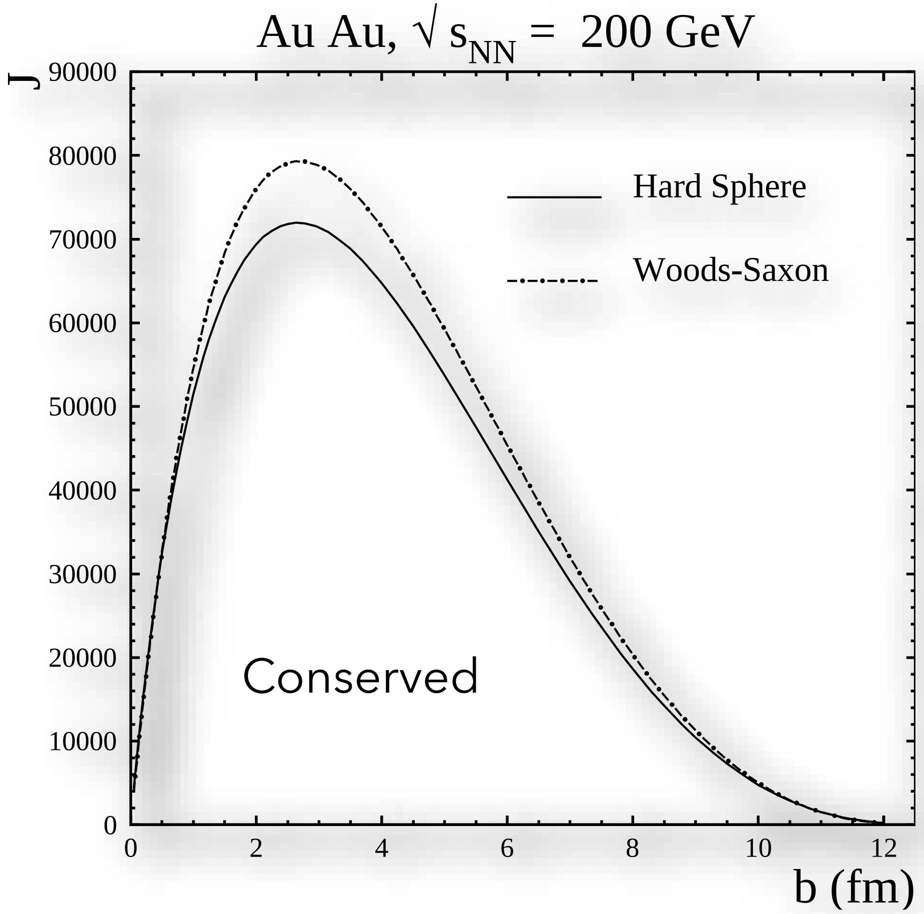


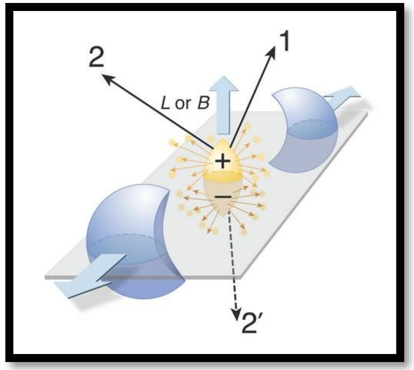


Two interesting large initial state effects

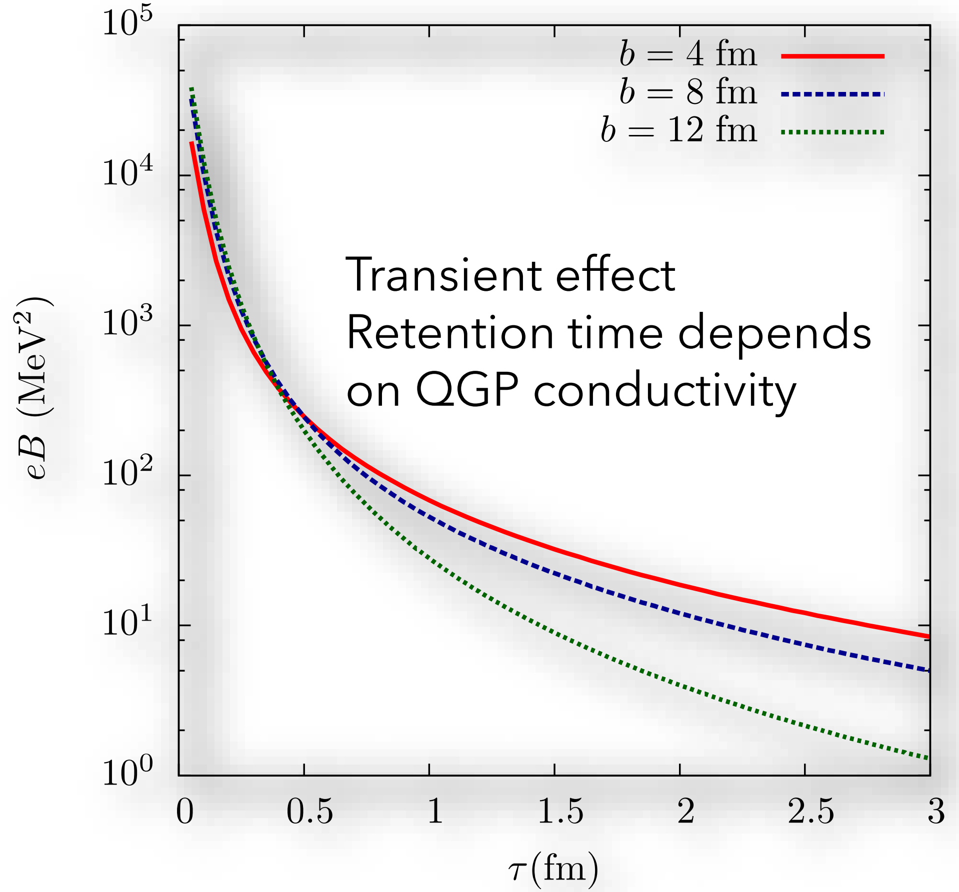
Angular momentum
Magnetic field

Angular momentum and magnetic field





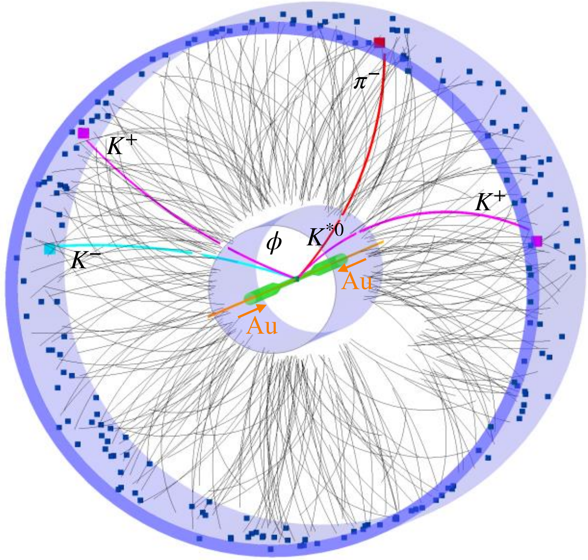
$M^2_p \sim 2 \times 10^4\ \mathrm{MeV}^2 \sim 3 \times 10^{14}$ Tesla $\sim 3 \times 10^{18}$ Gauss

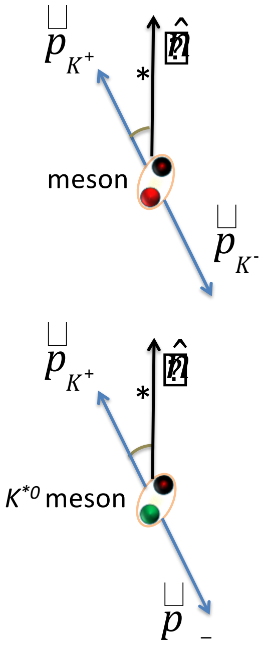


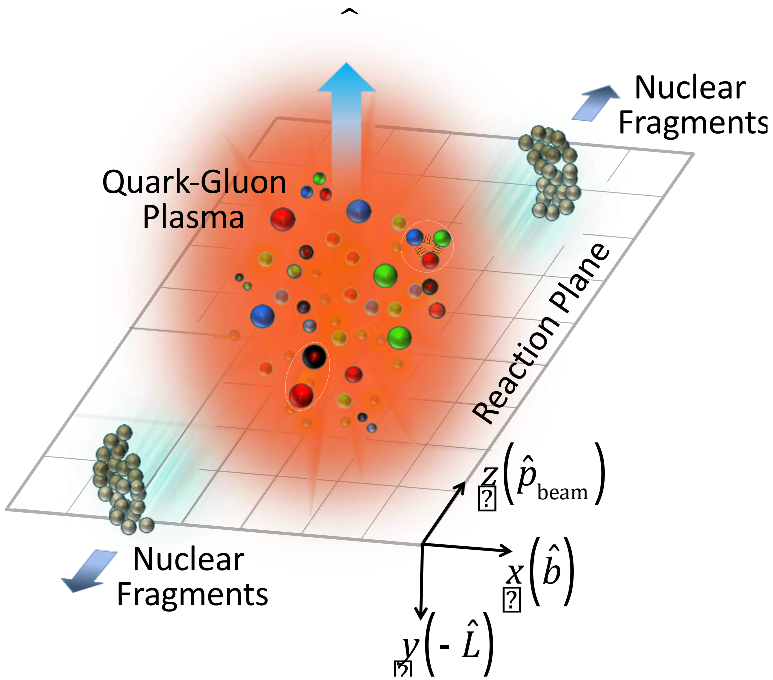
F. Becattini et al.,
Phys.Rev.C 77 (2008) 024906

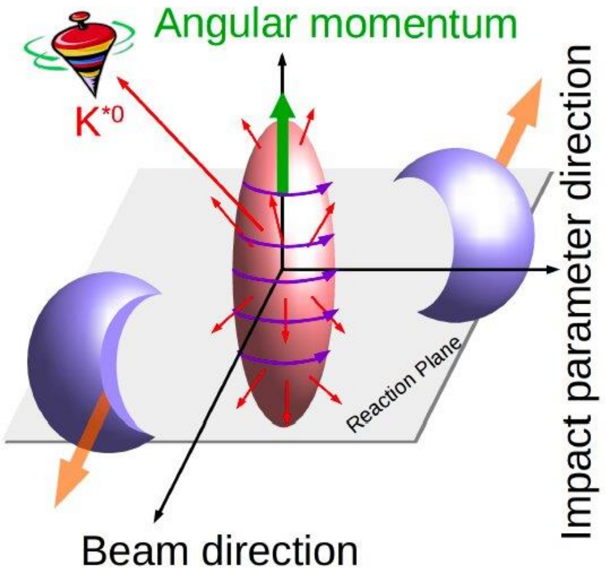
D. E. Kharzeev et al.,
Nucl.Phys.A 803 (2008) 227

Vector meson spin alignment



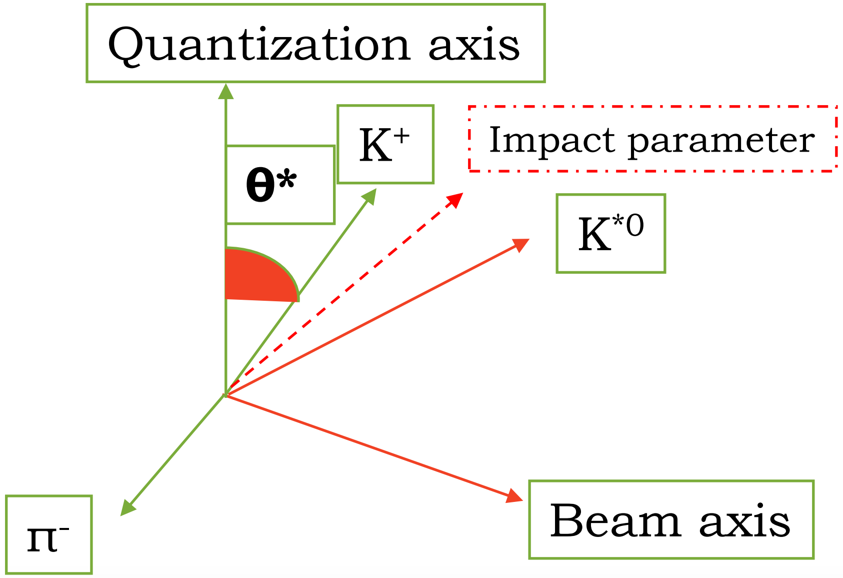






Observable: Angular distribution of vector meson

K^{*0} Vector meson
- Mass – 896 MeV/c^2
- Lifetime – 4 fm/c
- Spin 1
- Decays to K^+ and p^- (B.R – 66%)
- Quark content (d,$\overline{s}$)



K. Schilling et al., Nucl. Phys. B 15 (1970) 397

$$\frac{dN}{dcos\theta d\phi} = \langle\theta,\phi,\lambda_1,\lambda_2|M\rho M^\dagger|\theta,\phi,\lambda_1,\lambda_2\rangle$$

$$= \sum_{\lambda_V}\sum_{\lambda_{V'}}\langle\theta,\phi,\lambda_1,\lambda_2|M|\lambda_V\rangle\langle\lambda_V|\rho|\lambda_{V'}\rangle\langle\lambda_{V'}|M^\dagger|\theta,\phi,\lambda_1,\lambda_2\rangle$$

λ = Helicities
ρ = spin density matrix
M = Decay amplitude

Quantization axis
- Normal to production plane
  (Momentum of vector meson and beam axis)
- Normal to reaction plane
  (Impact parameter and beam axis)

Observable: Angular distribution of vector meson

In terms of spherical harmonics

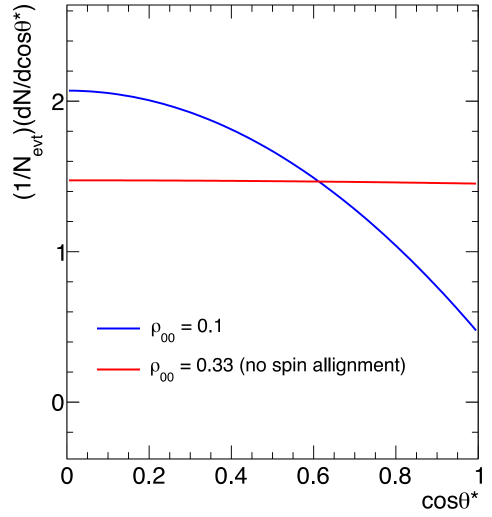
$$\frac{dN}{dcos\theta d\phi} = |C|^2 \times \sum_{m_1,m_2} Y^*_{1,m_1}(\theta,\phi) Y_{1,m_2}(\theta,\phi)\rho_{m_1,m_2}$$

Integrating over azimuthal angle

$$\frac{dN}{dcos\theta} = |C|^2 \times \frac{3}{8\pi}\left[sin^2\theta\rho_{-1,-1} + 2cos^2\theta\rho_{0,0} + sin^2\theta\rho_{1,1}\right] \times 2\pi$$
$$= |C|^2 \times \frac{3}{4}\left[sin^2\theta\left(\rho_{-1,-1} + \rho_{1,1}\right) + 2cos^2\theta\rho_{0,0}\right]$$

Normalized spin density matrix – Trace = 1

$$\frac{dN}{dcos\theta} = N_0\left[1 - \rho_{0,0} + cos^2\theta\left(3\rho_{0,0} - 1\right)\right]$$



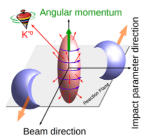
ρ_{00}: Probability vector meson is in spin state = 0

ρ_{00} = 1/3 → No spin alignment

Physics process and theory expectation

Physics process	Theory	Remarks	Reference
Vorticity (ω)	$\rho_{00}(\omega) < 1/3$	$\rho_{00}(\omega) \sim \frac{1}{3} - \frac{1}{9}(\beta\omega)^2$	*F. Becattini et al., Phys. Rev. C 95 (2017) 054902*
Magnetic field (B)	$\rho_{00}(B) > 1/3$ $\sim \frac{1}{3} - \frac{1}{9}\beta \frac{q_1 q_2}{m_1 m_2} B^2$ $\rho_{00}(B) < 1/3$	Electrically neutral vector mesons Electrically charged vector mesons	*Y. Yang et. al., Phys. Rev. C 97 (2018) 034917*
Hadronization	$\rho_{00}(rec) < 1/3$ $\sim \frac{1-P_q P_q}{3+P_q P_q}$ $\rho_{00}(frag) > 1/3$ $\sim \frac{1+\beta P_q P_q}{3-\beta P_q P_q}$	Recombination Fragmentation	*Z. Liang et. al., Phys. Lett. B 629 (2005) 20 (2005)* *Z. Liang and X. N. Wang Phys.Rev.Lett. 94 (2005) 102301*
Coherent meson field	$\rho_{00} > 1/3$	ϕ mesons	*X. L. Sheng et. al., arXiv:1910.13684*

Spin alignment of vector mesons



EDITORS' SUGGESTION

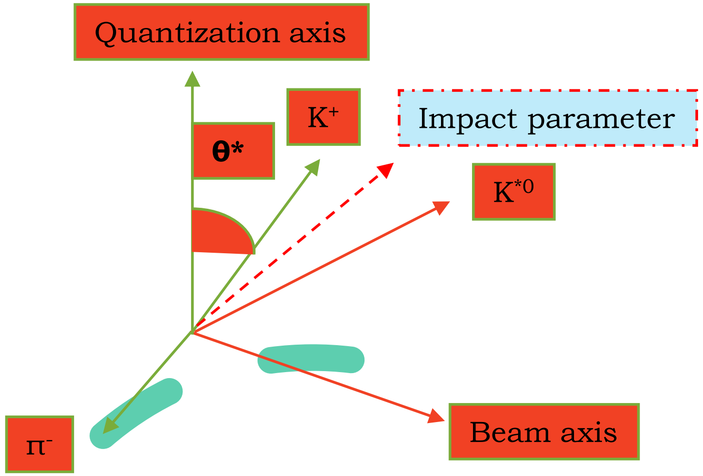
Evidence of Spin-Orbital Angular Momentum Interactions in Relativistic Heavy-Ion Collisions

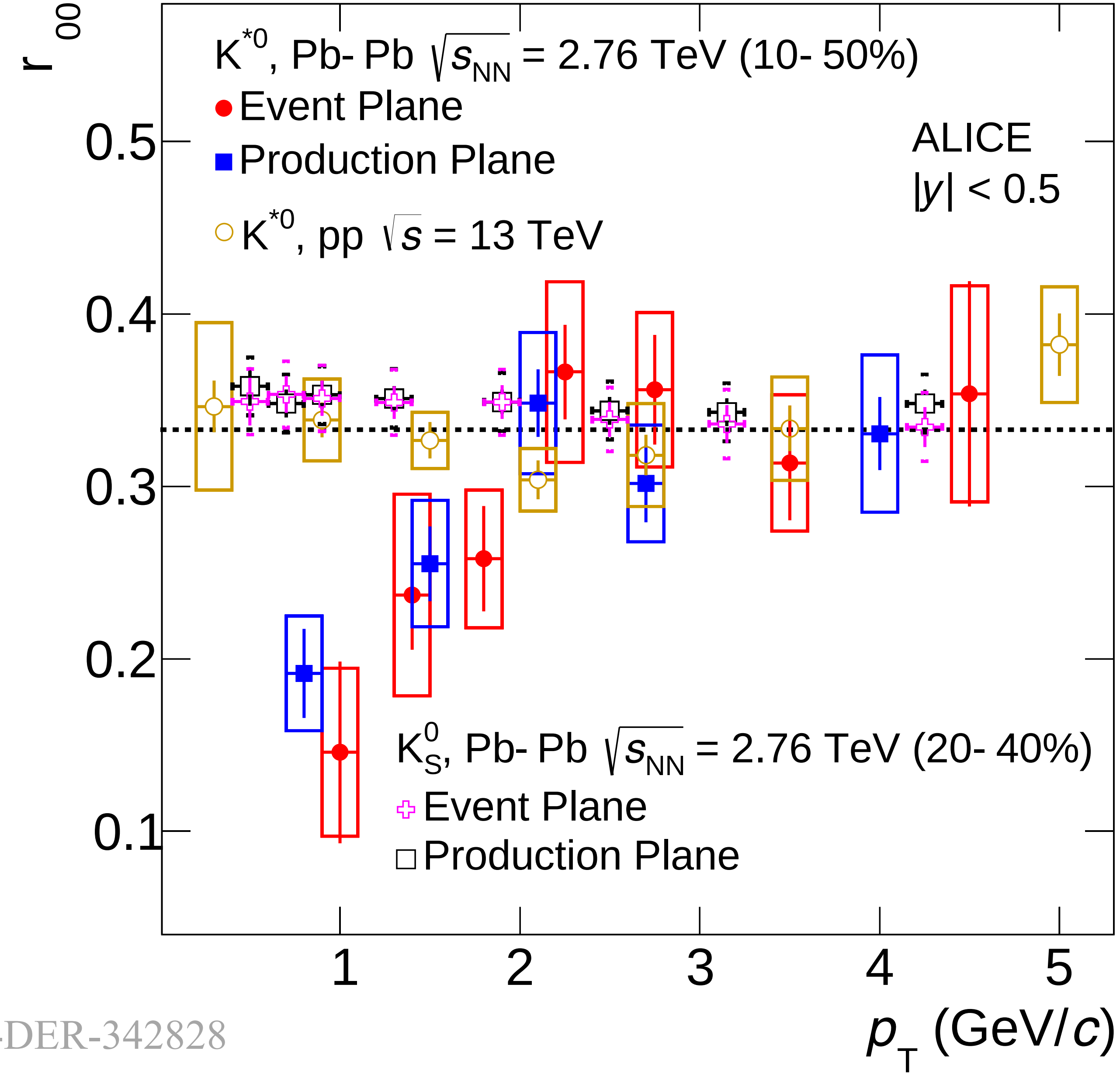
The measured spin alignment of vector mesons in heavy-ion collisions is consistent with that expected from the spin-orbit coupling of quarks with the large angular momentum of the collision.

S. Acharya *et al.* (The ALICE Collaboration)

Phys. Rev. Lett. **125**, 012301 (2020)

3σ effect

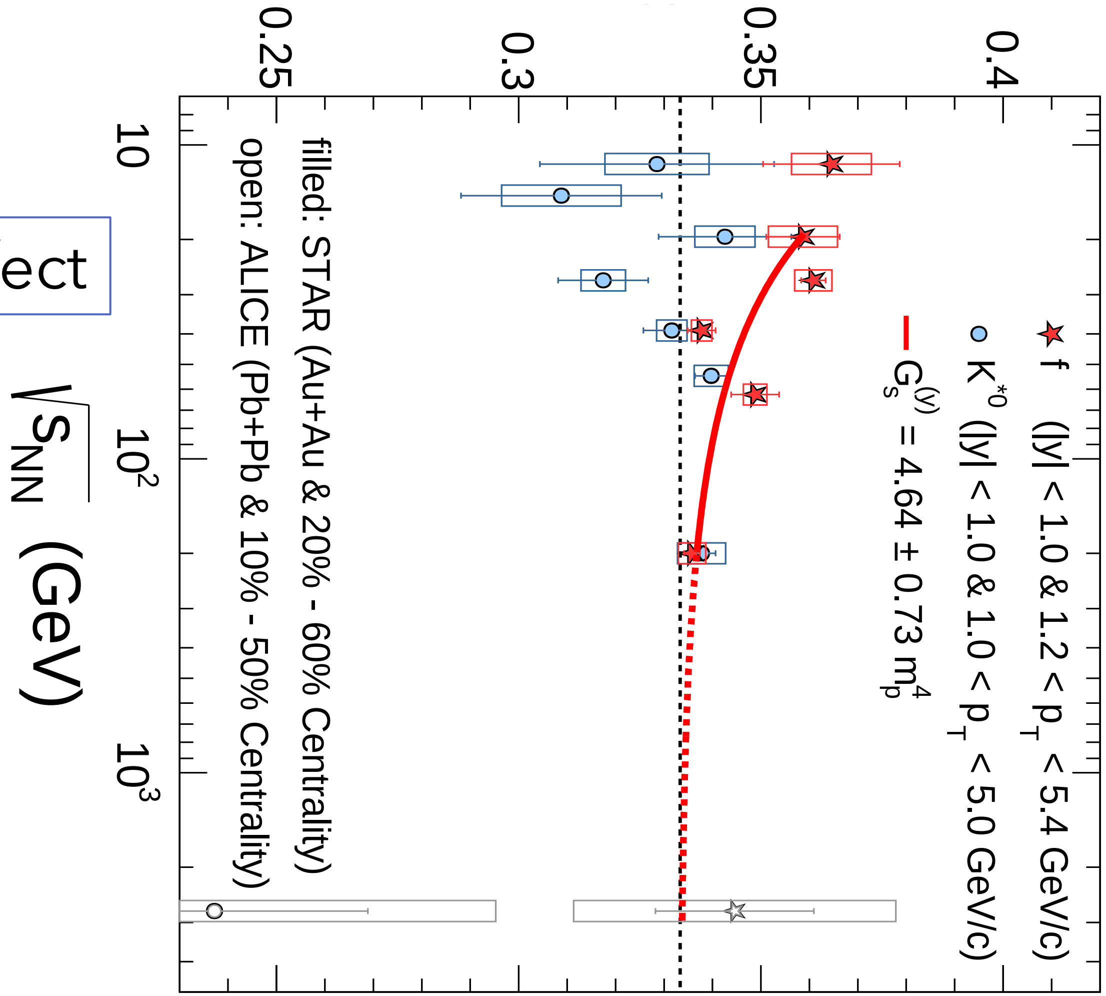




No spin alignment

Phi-meson spin alignment – RHIC and LHC

8σ effect

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Article | Published: 18 January 2023

Pattern of global spin alignment of φ and K^{*0} mesons in heavy-ion collisions

STAR Collaboration

Nature 614, 244–248 (2023) | Cite this article

$$\rho_{00}\ \phi = 1/3 + C_\Lambda + C_s + C_E + C_F + C_L + C_A + C_\phi$$

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)

Phi meson spin alignment – Physics

Requires presence of a new strong force field – **phi-meson vector field**

Like electric charges in motion can generate an EM field, *s* and *s*bar quarks in motion can generate an effective φ-meson field.

The φ-meson field can polarize *s* and *s* quarks with a large magnitude due to strong interaction, in analogy to how EM field polarize (anti)quarks.

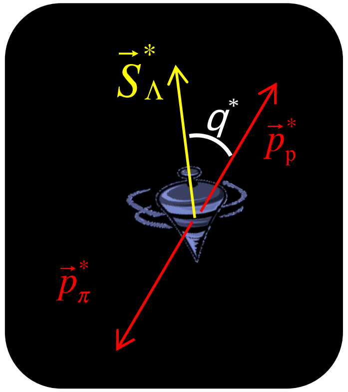
$$
\begin{aligned}
P^{y}_{s/\bar{s}}\left(t, \mathbf{x}, \mathbf{P}_{s/\bar{s}}\right) = {} & \frac{1}{2}\omega_y + \frac{1}{2m_s}\hat{\mathbf{y}}\cdot\left(\varepsilon \times \mathbf{P}_{s/\bar{s}}\right) && \Leftarrow \text{vorticity} \\
& \pm \frac{Q_s}{2m_s T} B_y \pm \frac{Q_s}{2m_s^2 T}\hat{\mathbf{y}}\cdot\left(\boldsymbol{E} \times \mathbf{P}_{s/\bar{s}}\right) && \Leftarrow \text{EM field} \\
& \pm \frac{g_\phi}{2m_s T} B_{\phi,y} \pm \frac{g_\phi}{2m_s^2 T}\hat{\mathbf{y}}\cdot\left(\boldsymbol{E}_\phi \times \mathbf{P}_{s/\bar{s}}\right) && \Leftarrow \text{strong force field}
\end{aligned}
$$

Global hyperon polarization observable

Lambdas are "self-analyzing"

- reveal polarization by preferentially emitting daughter proton in the spin direction

E. Cummins, Weak Interactions (McGraw-Hill, 1973)



$\Lambda \to p + \pi^-$

- Magneto-hydro equilibrium interpretation

$$P \sim \exp(-E/T + \mu_B B/T + \vec{\omega}\cdot\vec{S}/T + \vec{\mu}\cdot\vec{B}/T)$$

  - for small polarization:

$$P_\Lambda \approx \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T} \qquad P_{\bar{\Lambda}} \approx \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

  - vorticity from the average: $\frac{\omega}{T} = P_\Lambda + P_{\bar{\Lambda}}$

  - B-field from the difference*: $\frac{B}{T} = \frac{1}{2\mu_\Lambda}\left(P_\Lambda - P_{\bar{\Lambda}}\right)$

For an ensemble of Λs with polarization $\vec{P}$:

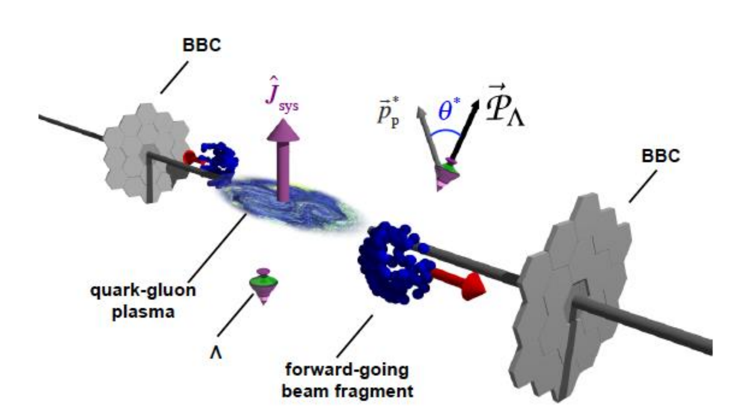
$$\frac{dW}{d\Omega^*} = \frac{1}{4\pi}\left(1+\alpha\vec{P}\cdot\hat{p}_p^*\right) = \frac{1}{4\pi}\left(1+\alpha P\cos\theta^*\right)$$

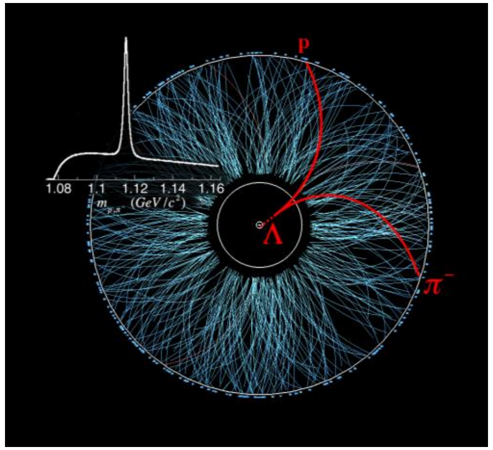
$\alpha = 0.642$ [measured]

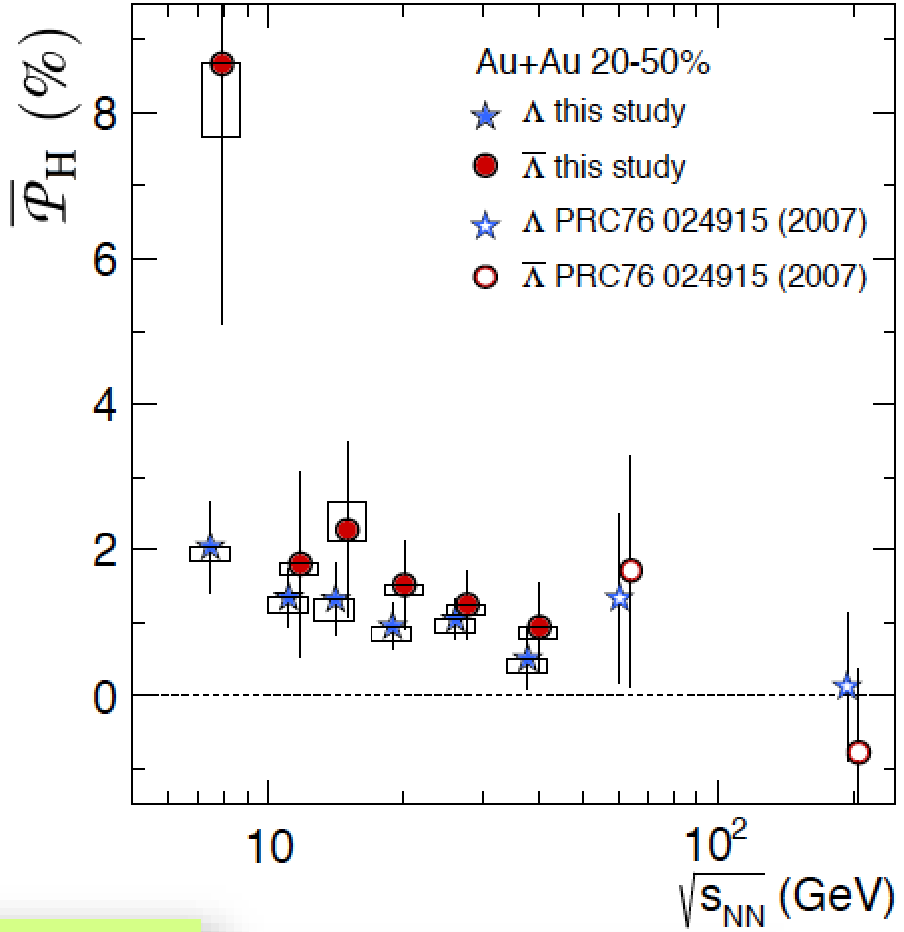
$\hat{p}_p^*$ is the daughter proton momentum direction *in* the Λ *frame*

$0 < |\vec{P}| < 1$: $\quad \vec{P} = \frac{3}{\alpha}\overline{\hat{p}_p^*}$

Hyperon polarization at RHIC and LHC







$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_H |\vec{\mathcal{P}}_H| \cos\theta^*\right)$$

decay parameter $\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013$

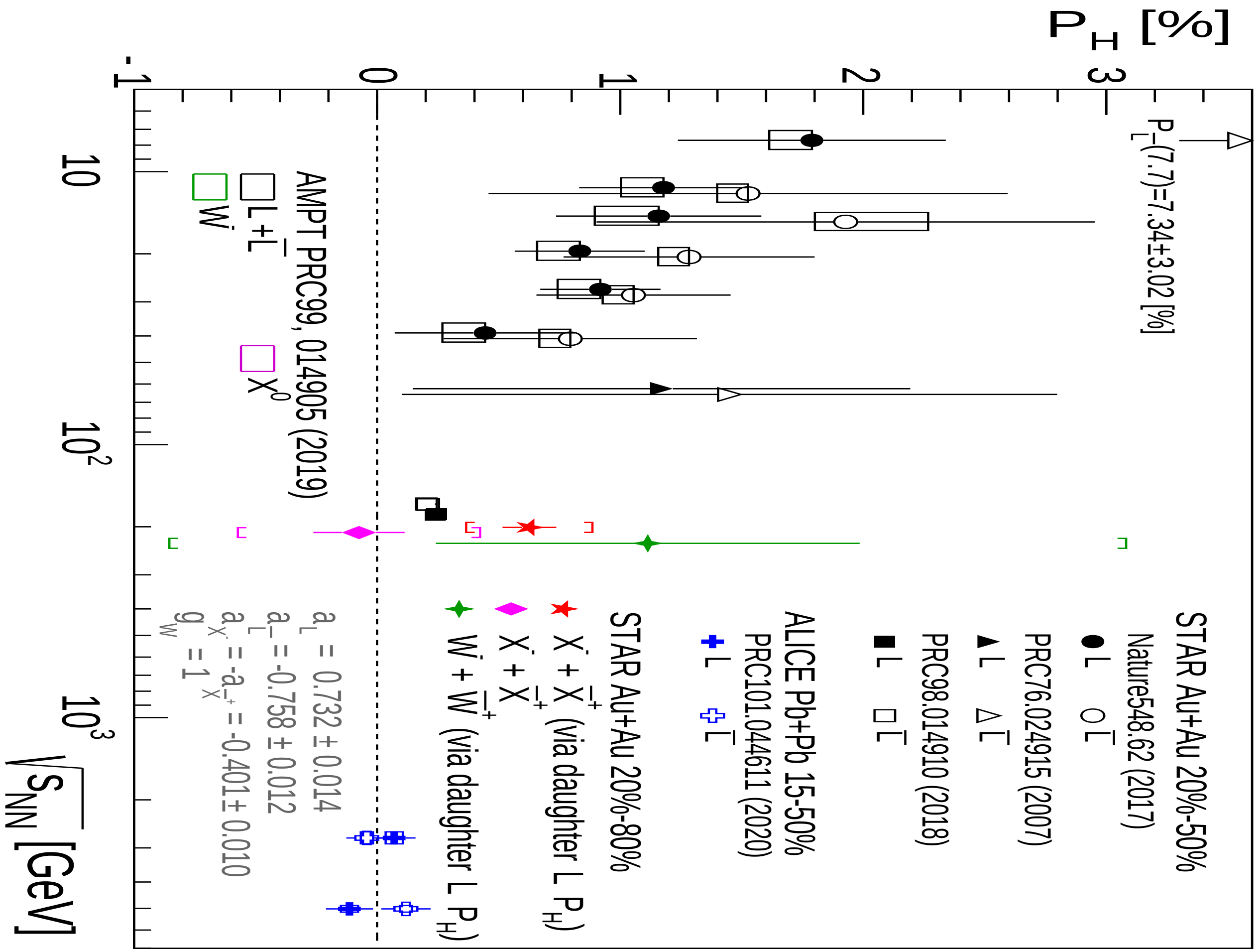
	BES average
Λ	6.8σ
anti-Λ	3.7σ

$$\omega = k_B T \left(\overline{\mathcal{P}}_{\Lambda'} + \overline{\mathcal{P}}_{\bar{\Lambda}'}\right)/\hbar$$

$$\omega \approx (9 \pm 1) \times 10^{21}\ \mathrm{s}^{-1}$$

Nature 548, 62 (2017) (STAR Collaboration)
Phys Rev C 98, 14910 (2018) (STAR Collaboration)

Hyperon polarization at RHIC and LHC



Global Polarization of Ξ and Ω Hyperons in $\mathbf{Au}+\mathbf{Au}$ Collisions at $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$

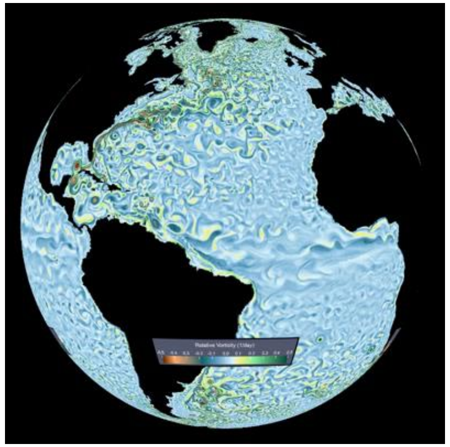
J. Adam *et al.* (STAR Collaboration)
Phys. Rev. Lett. **126**, 162301 – Published 22 April 2021; Erratum Phys. Rev. Lett. **131**, 089901 (2023)

Global polarization of Ξ and Ω hyperons

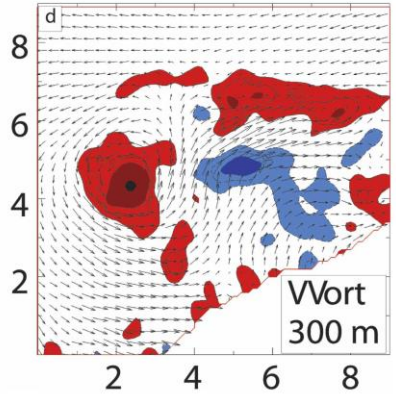
⟨PΞ⟩=0.47±0.10(stat)±0.23(syst)% for the collision centrality 20%–80%.

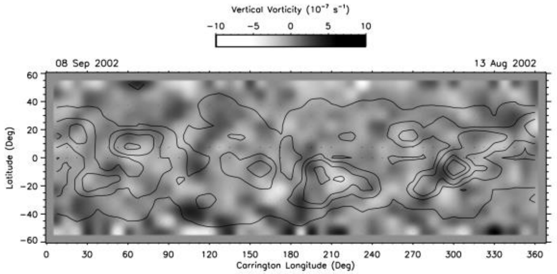
⟨PΩ⟩=1.11±0.87(stat)±1.97(syst)% was obtained by measuring the polarization of daughter Λ in the decay Ω→Λ+K, assuming the polarization transfer factor CΩΛ=1.

World data on vorticity



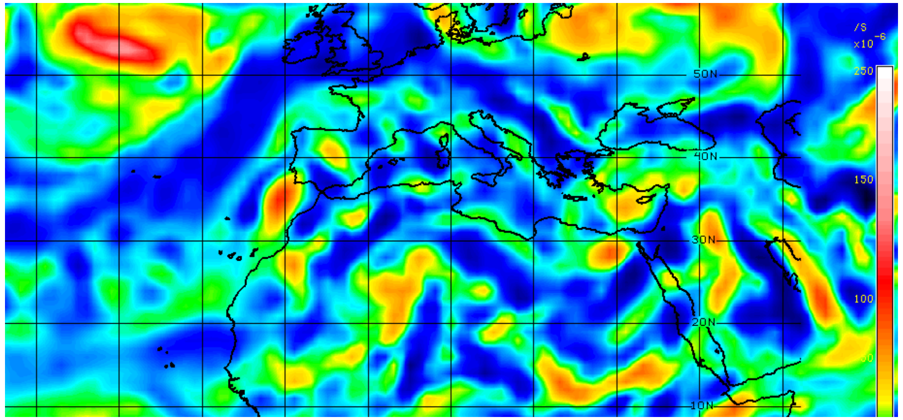
- ocean flows: $\omega \sim 10^{-5}\ s^{-1}$
- terrestrial atmosphere: $\omega \sim 10^{-4}\ s^{-1}$
- core of supercell tornado : $\omega \sim 10^{-1}\ s^{-1}$
- solar subsurface flow: : $\omega \sim 10^{-6}\ s^{-1}$
- high vorticity ($10^{-4}\ s^{-1}$) in the "collar" of Jupiter's Great Red Spot
- Heated, rotating soap bubbles ($10^{2}\ s^{-1}$)

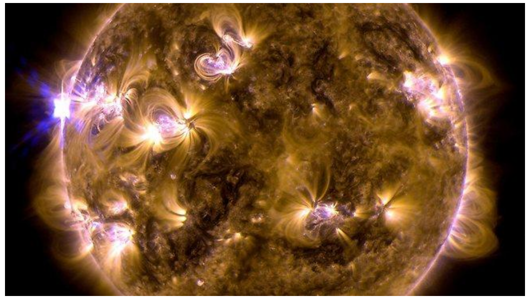


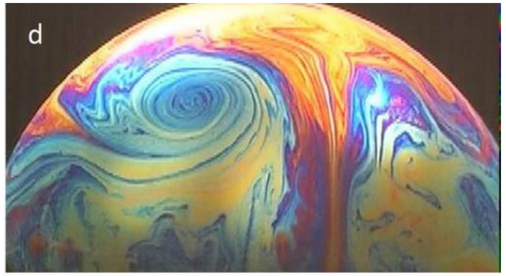


Largest values in heavy-ion collisions

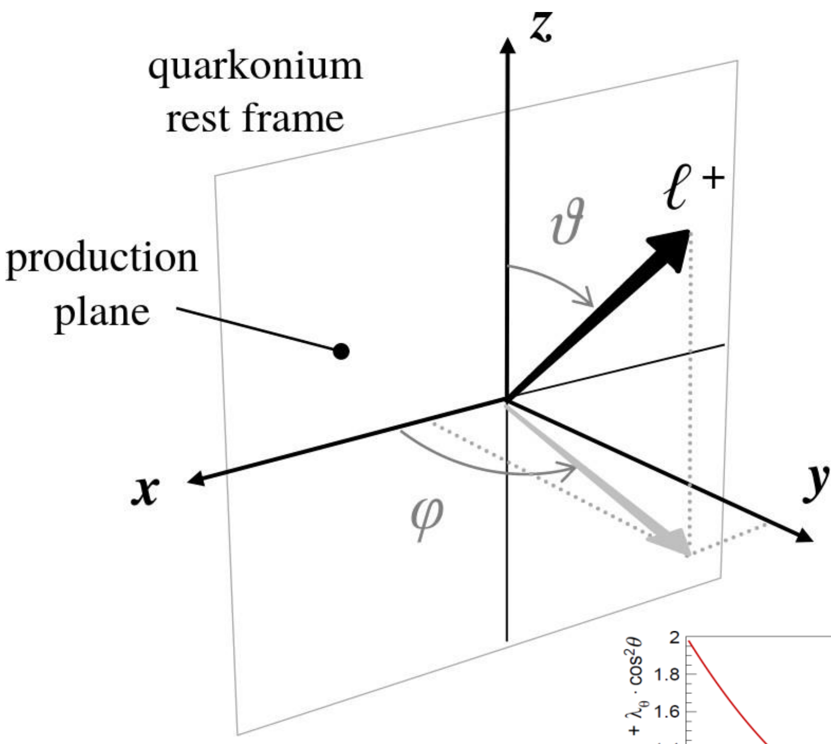
Atmospheric vorticity







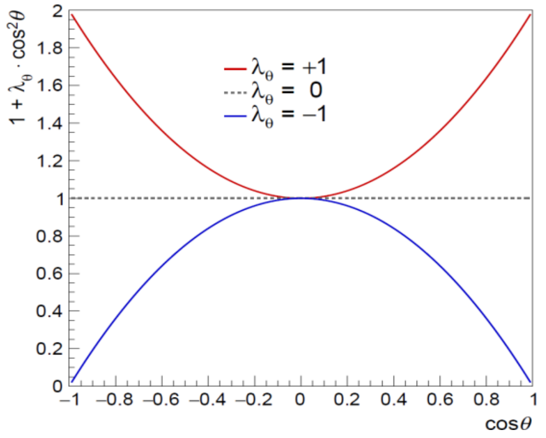
Quarkonia polarization - observable



Heavy quark pair production occurs early in the collision (t ~ 0.1 fm/c) and can experience both the short living B and the L of the rotating medium

Dilepton decay angular distribution

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



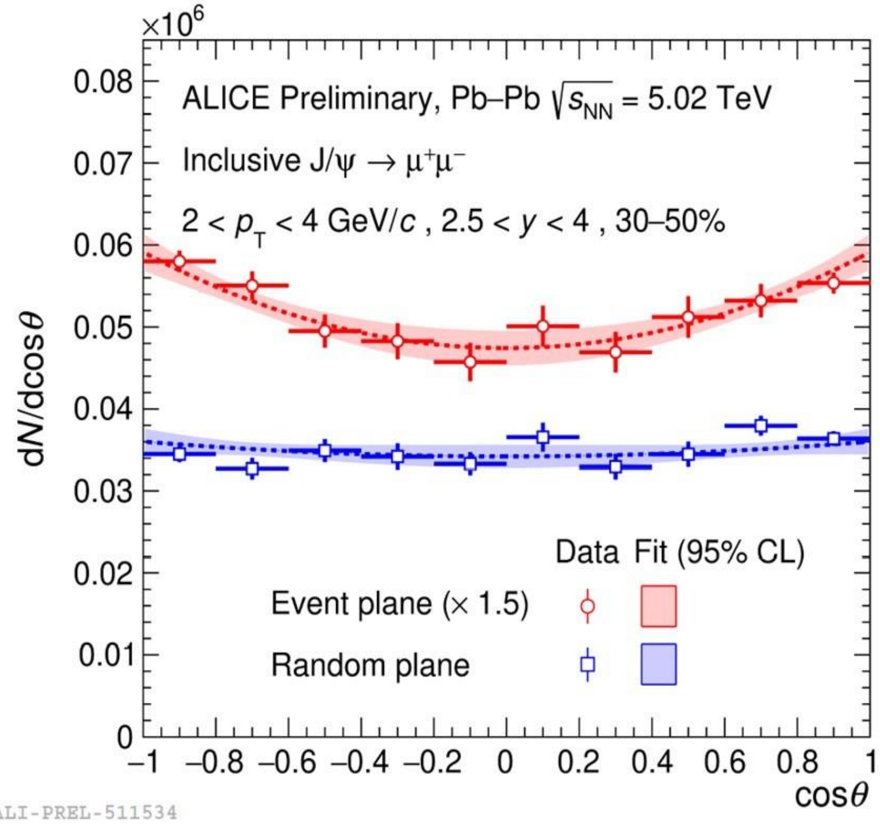
Polarization parameters

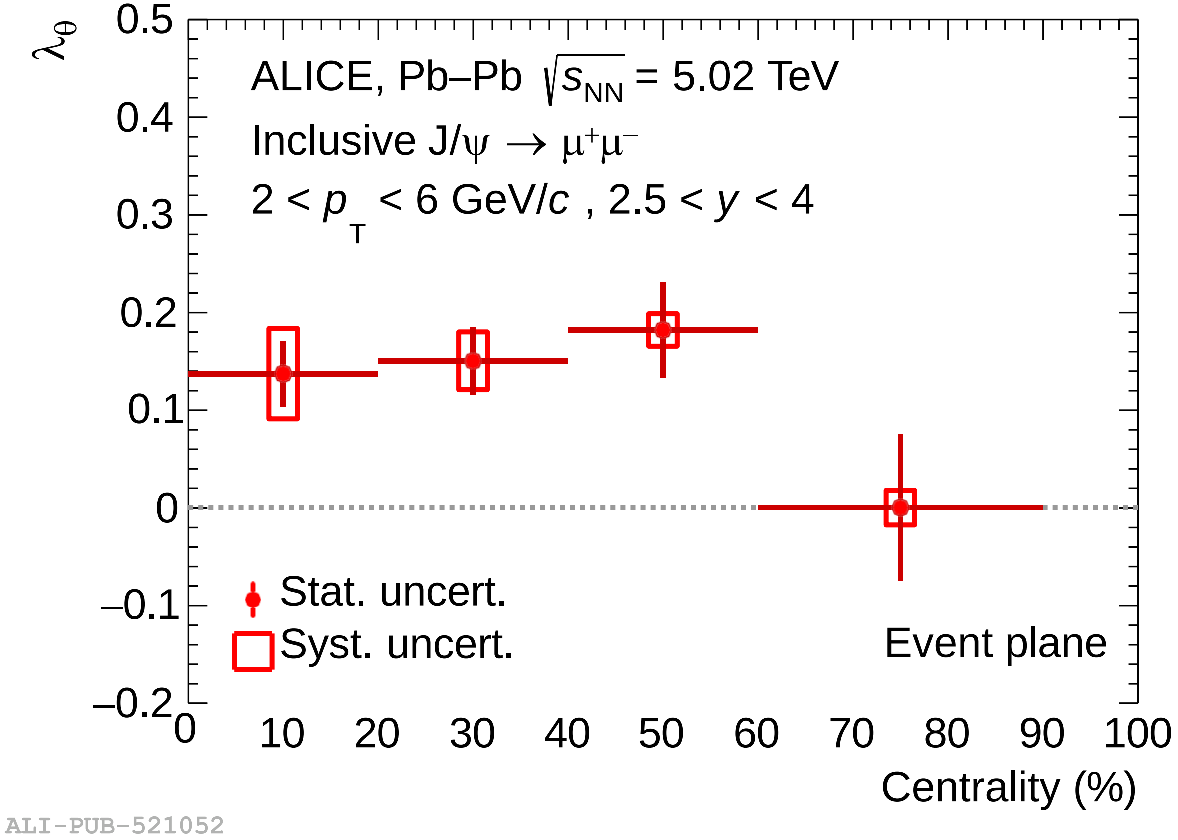
$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (0,0,0) \Rightarrow$ No polarization

$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (+1,0,0) \Rightarrow$ Transverse polarization

$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (-1,0,0) \Rightarrow$ Longitudinal polarization

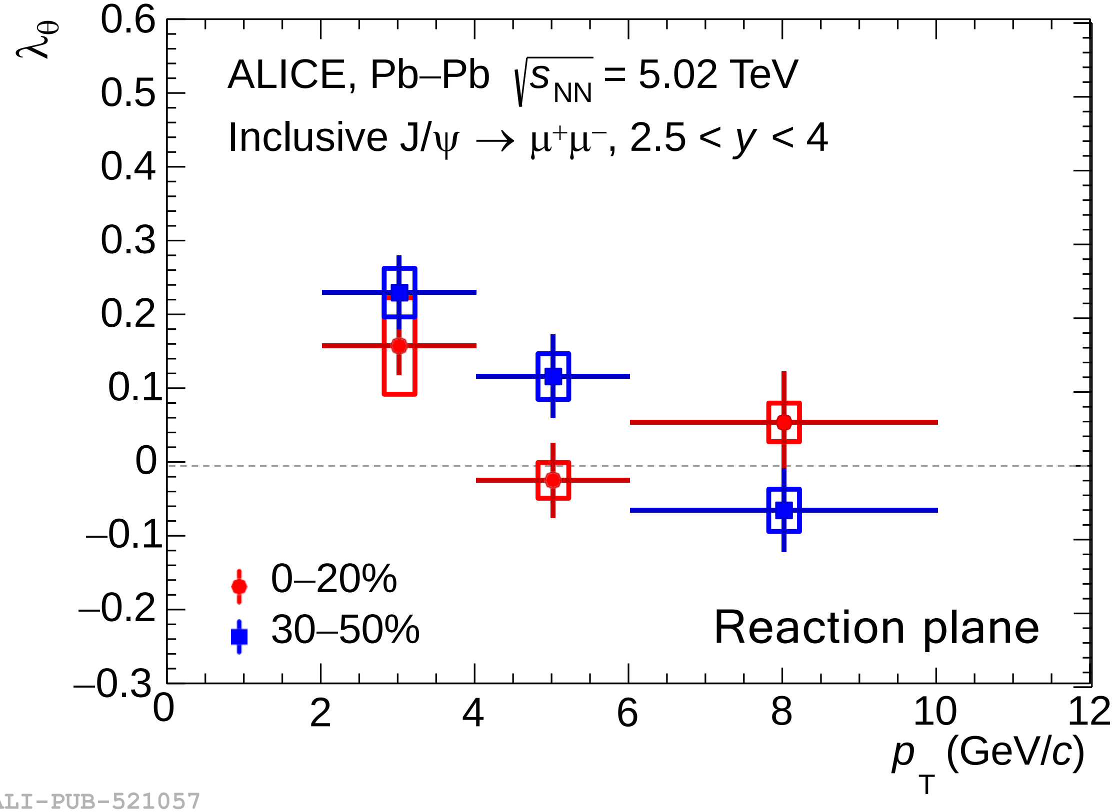
J/Ψ polarization





3.5 σ effect

J/Ψ polarization and spin alignment



ALI-PUB-521057

- In the dilepton channel:

$$\lambda_\theta = \frac{1-3\rho_{00}}{1+\rho_{00}} \qquad \begin{cases} \lambda_\theta > 0 \rightarrow \rho_{00} < 1/3 \\ \lambda_\theta < 0 \rightarrow \rho_{00} > 1/3 \end{cases}$$

Open Access

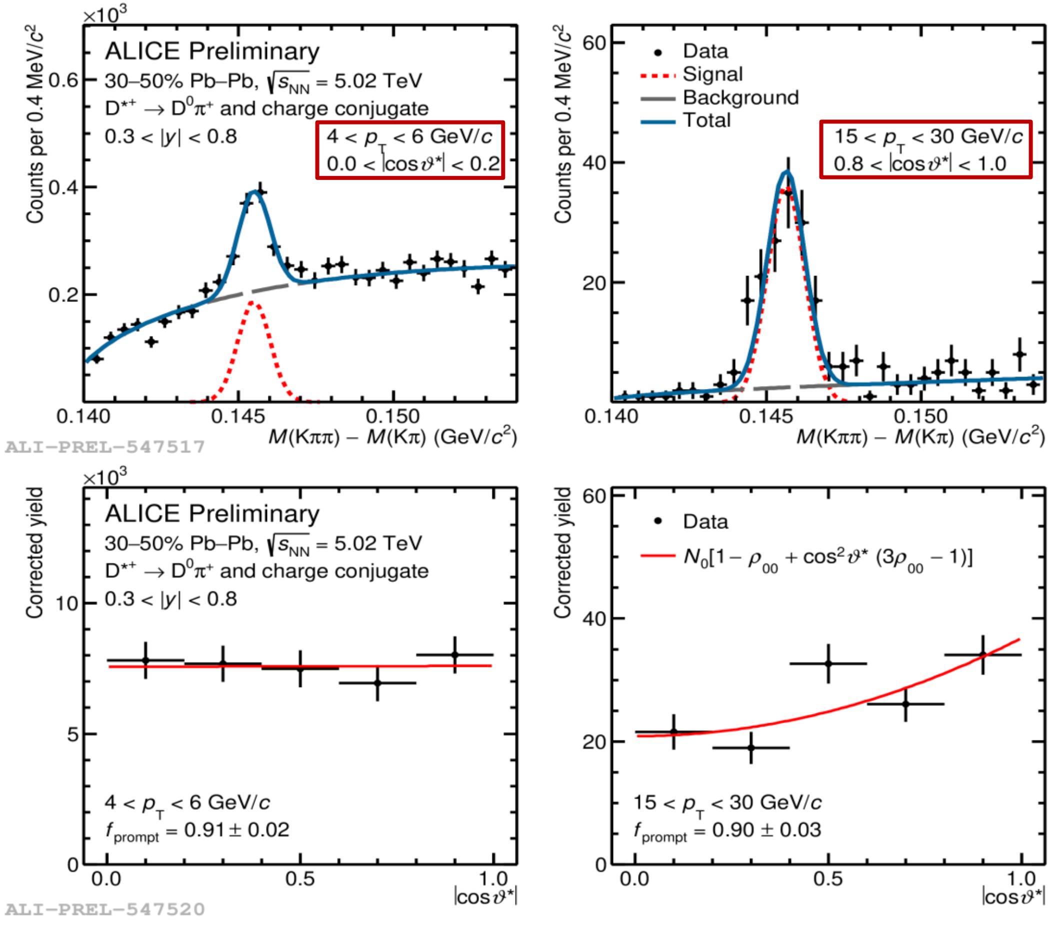
Measurement of the J/ψ Polarization with Respect to the Event Plane in Pb-Pb Collisions at the LHC

S. Acharya *et al.* (ALICE Collaboration)
Phys. Rev. Lett. **131**, 042303 – Published 25 July 2023

Open charm polarization

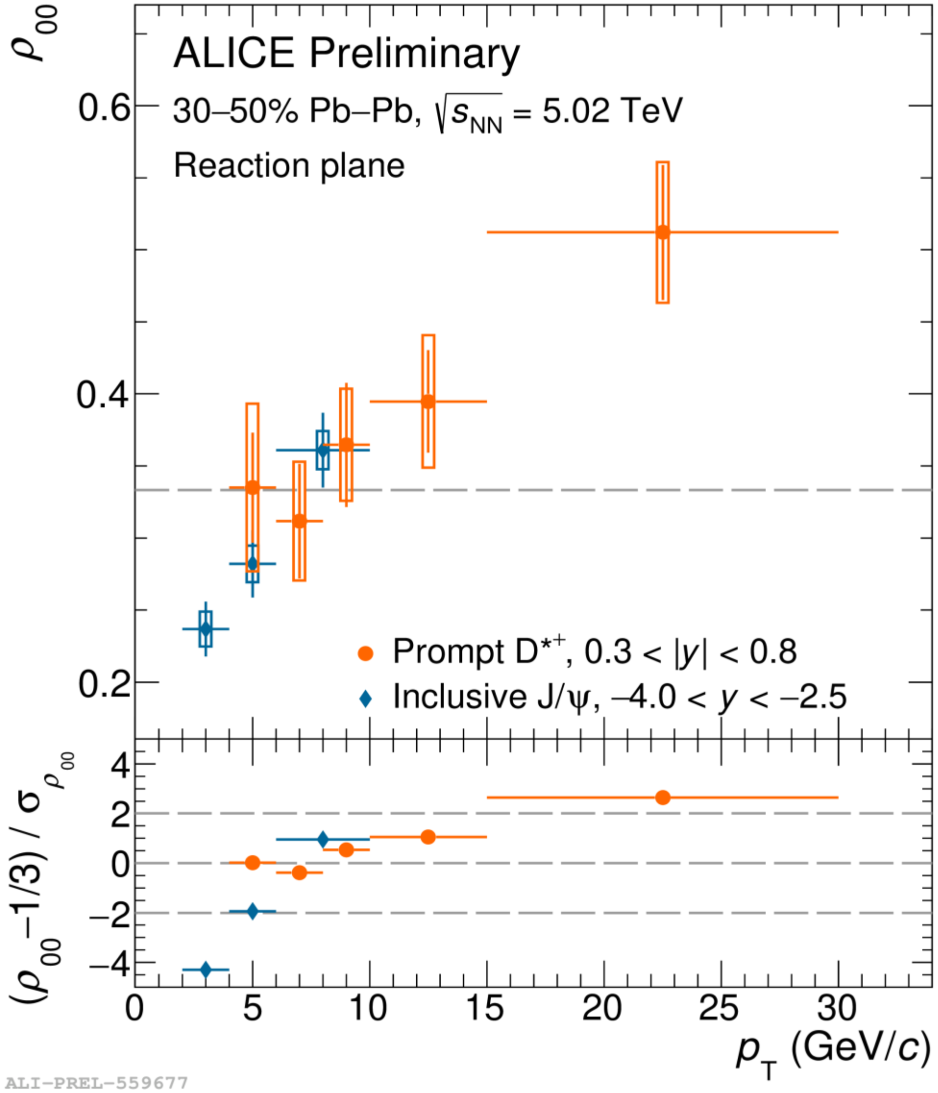
ALICE: QM2023

$$\frac{dN}{dcos\theta} = N_0\left[1 - \rho_{0,0} + cos^2\theta\,(3\rho_{0,0} - 1)\right]$$



Open charm polarization

ALICE: QM2023



First measurement of D^{*+} polarization with respect to the Reaction plane

$\rho_{00} < \frac{1}{3}$ quark recombination at low p_T

$\rho_{00} > \frac{1}{3}$ quark fragmentation at high p_T

Summary

	K^*	ϕ	D^{*a}	J/ψ	$\psi(2S)$	χ_c	$\Upsilon(nS)$
pp	ρ_{00}~1/3	ρ_{00}~1/3	ρ_{00}~1/3	ρ_{00}~1/3	ρ_{00}~1/3		
Pb-Pb	$\rho_{00} < 1/3$ low p_T	$\rho_{00} < 1/3$ low p_T $\rho_{00} > 1/3$ At RHIC	$\rho_{00} > 1/3$ high p_T	$\rho_{00} < 1/3$ low p_T			

Conclusions

- Polarization and spin alignment measurements indicate response of the medium to large initial angular momentum and magnetic fields
- Large global spin alignment for φ-meson. It cannot be explained by conventional mechanisms. However, it can be accommodated by a model with strong force field. Global spin alignment for K* meson seen at LHC
- Polarization of hyperons suggest creation of a medium with large vorticity
- Measurements have driven this area and seems to have brought new observations in the field. However, a comprehensive understanding of the underlying mechanisms at play lacking. Theory calculations required to understand these phenomena across collision energies.

Talk based on …

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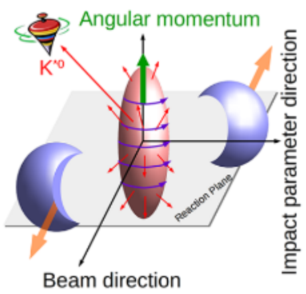
Pattern of global spin alignment of φ and K^{*0} mesons in heavy-ion collisions

STAR Collaboration

Nature **614**, 244–248 (2023) | Cite this article



EDITORS' SUGGESTION

Evidence of Spin-Orbital Angular Momentum Interactions in Relativistic Heavy-Ion Collisions

The measured spin alignment of vector mesons in heavy-ion collisions is consistent with that expected from the spin-orbit coupling of quarks with the large angular momentum of the collision.

S. Acharya *et al.* (The ALICE Collaboration)
Phys. Rev. Lett. **125**, 012301 (2020)

Thanks to experimental collaborations

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Measurement of the J/ψ Polarization with Respect to the Event Plane in Pb-Pb Collisions at the LHC

S. Acharya *et al.* (ALICE Collaboration)
Phys. Rev. Lett. **131**, 042303 – Published 25 July 2023

Global Polarization of Ξ and Ω Hyperons in $\mathrm{Au}+\mathrm{Au}$ Collisions at $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$

J. Adam *et al.* (STAR Collaboration)
Phys. Rev. Lett. **126**, 162301 – Published 22 April 2021; Erratum Phys. Rev. Lett. **131**, 089901 (2023)

Thank you