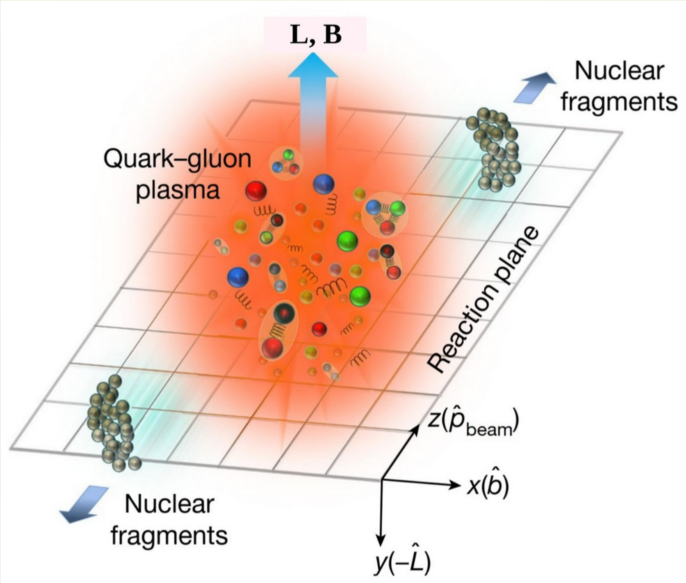
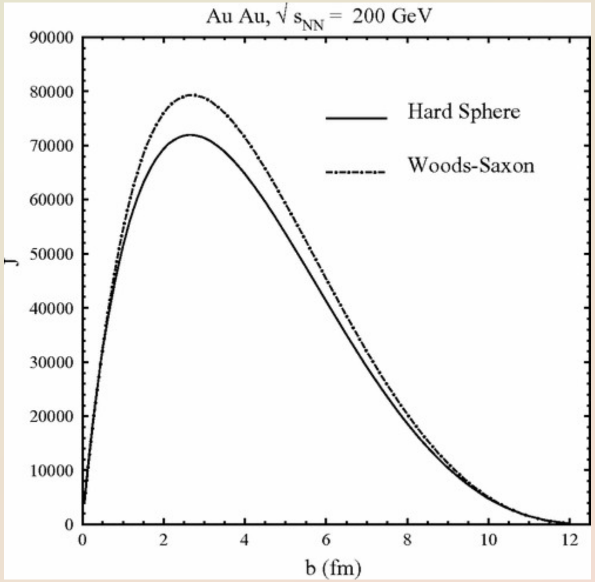
Global polarization and Vector meson production with ALICE

Prottay Das (for the ALICE Collaboration)
CERN
Geneva, Switzerland

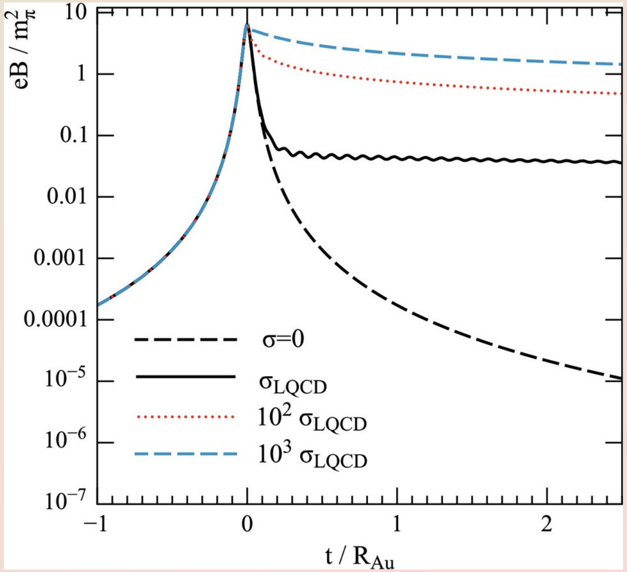
Initial conditions of heavy-ion collisions



STAR Collaboration,
Nature volume 614, pages 244–248 (2023)



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

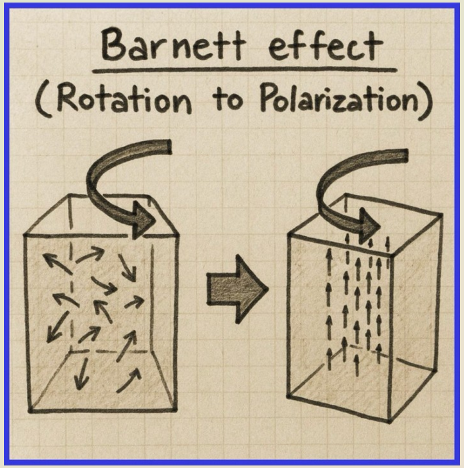


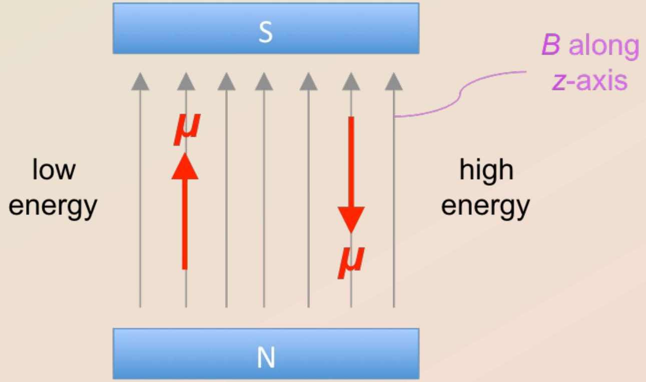
McLerran and Skokov,
Nucl.Phys.A 929 (2014) 184-190

- ✓ Large orbital angular momentum (vorticity) perpendicular to reaction plane (y axis), of the order of $10^4\ \hbar$
- ✓ Intense initial magnetic field (**B**) along the system orbital angular momentum direction is theorized (O~ 10^{19} Gauss)
- ✓ Retention of **B** depends on medium conductivity

Liang and Wang, PRL94 102301 (2005)
Voloshin, nucl-th/0410089
Liang et al., Phys.Rev.Lett 94 (2008) 102301
Jiang et al., Phys. Rev. C 94 (2016) 044910

Polarization in heavy-ion collisions





https://monomole.com/nuclear-magnetic-dipole-moment-nmr/

Barnett effect

(Rotation to polarization)

- ✓ Spontaneous magnetization
- ✓ Polarization (spin-orbital coupling)

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

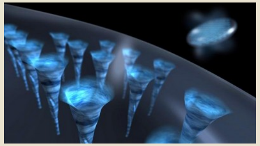
- ✓ Magnetic field polarizes particles based on their magnetic moment

<u>Take home message:</u> Large Angular Momentum (vorticity) -> Polarization of quarks (independent of their charge)
Large Magnetic Field -> Polarization of quarks (charge dependent)

Vorticity at different scales (s^{-1})

Nano droplets of superfluid He

Science, 345(6199)

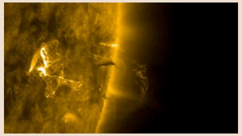


10^{6}

10^{-1}

Tornadoes

Solar winds



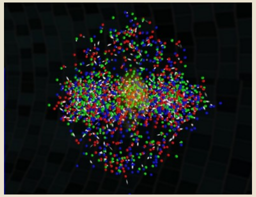
10^{-4}

10^{-5}

Ocean flows

Vorticity at different scales (s^{-1})

10^{21}



QGP at RHIC

STAR Collaboration,
Nature volume 548, pages 62–65 (2017)

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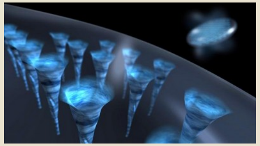
Science, 345(6199)



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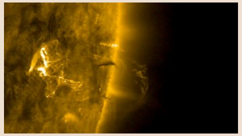

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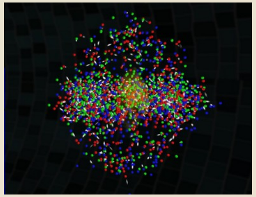

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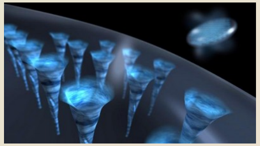


10^{6}

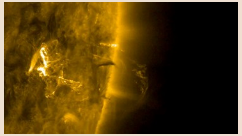
How fast QGP rotates at LHC??

Useful ingredient for developing spin-hydro models

10^{-1}

Tornadoes

Solar winds



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Experimental signatures

Polarization of hyperons

Experimental signatures

Polarization of hyperons

Spin-alignment of vector mesons

Experimental signatures

Polarization of hyperons

$$P_H = \frac{-8}{\pi \alpha_H} \frac{\langle \sin(\phi^*_p - \Psi_{SP}) \rangle}{R^1_{SP}}$$

Spin-alignment of vector mesons

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ALICE

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$$\frac{dN}{d\cos\theta} = N_0 [1 - \rho_{00} + \cos^2\theta (3\rho_{00} - 1)]$$

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

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ALICE

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$\rho_{00} = 1/3$ ⇒ No spin alignment

Thermal estimates →

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

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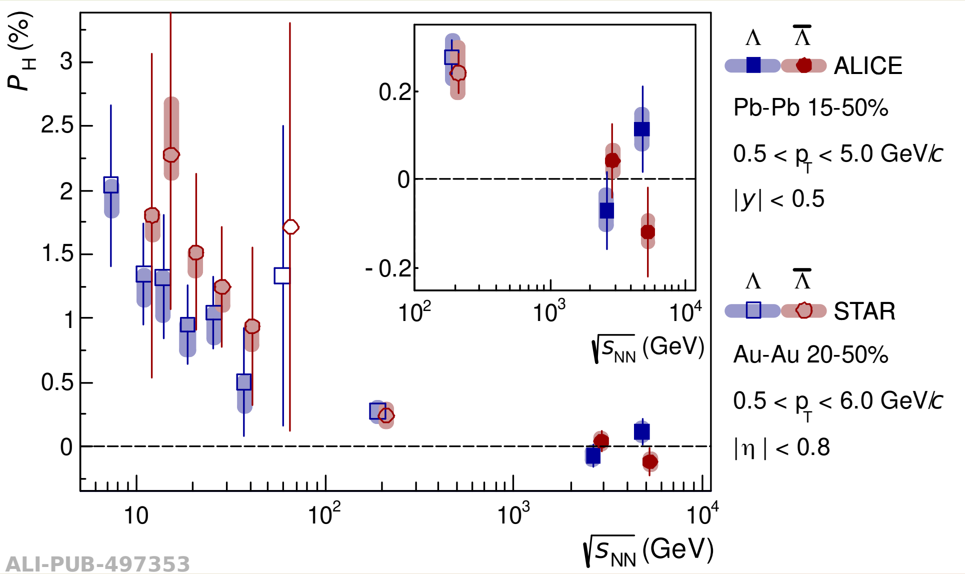
Becattini et al., Phys. Rev. C 95 (2017) 054902

Experimental puzzle

Hyperon polarization



ALICE Collaboration,
Phys. Rev. C101 (2020) 044611

✓ $P_H \sim 0$ within uncertainties at LHC

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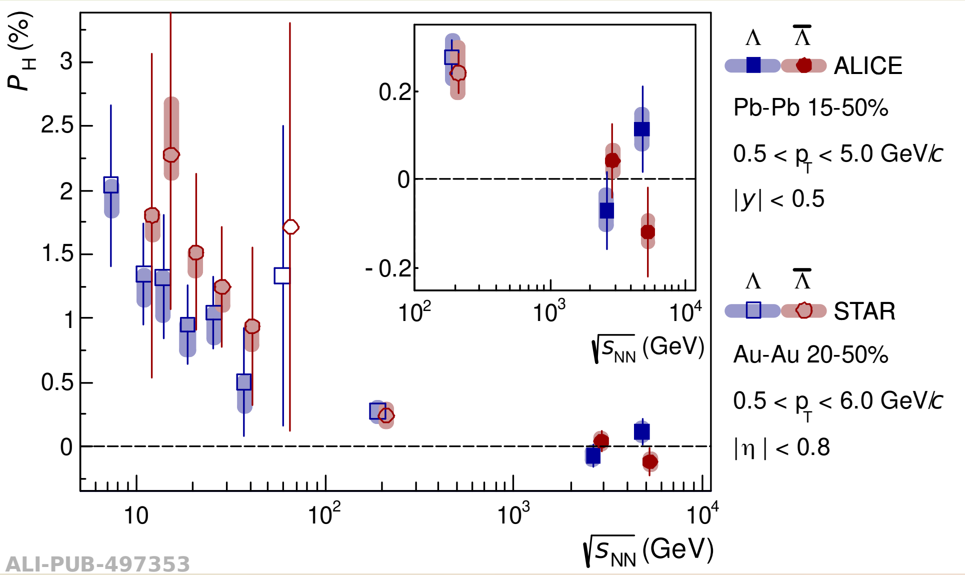

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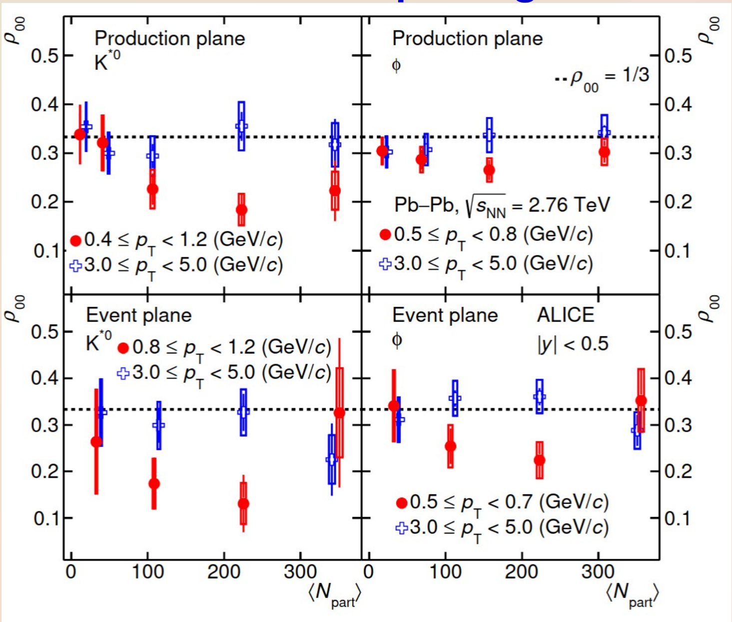
Vector meson spin-alignment



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Phys. Rev. Lett. 125 (2020) 012301

✓ $\rho_{00} < 1/3$ (significant deviation)

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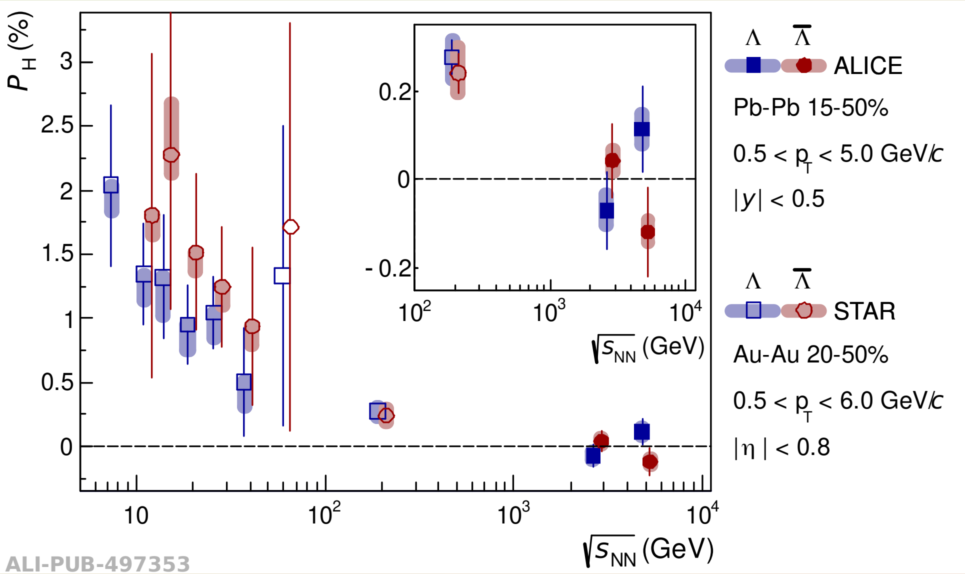
ALICE

Hyperon polarization



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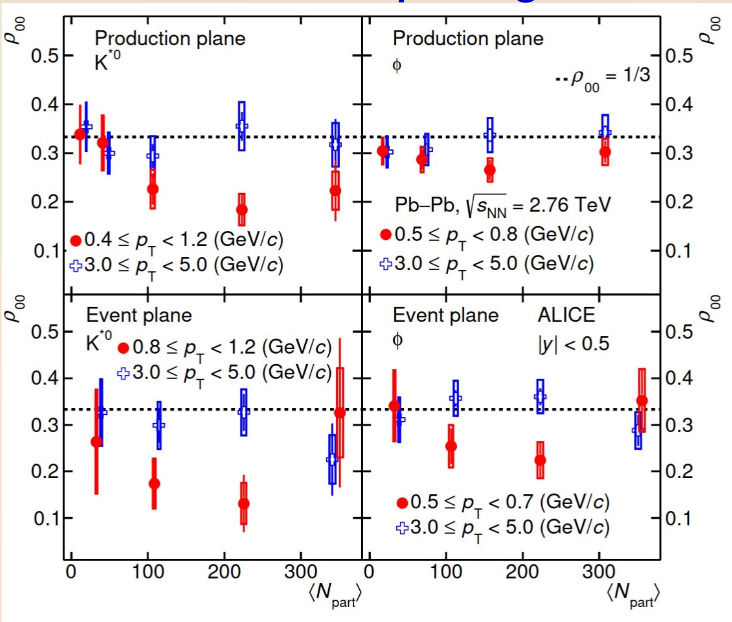

ALICE Collaboration,
Phys. Rev. Lett. 125 (2020) 012301

$$\rho_{00} - \frac{1}{3} \sim 4\, P_H^2 / 9$$

Thermal estimate

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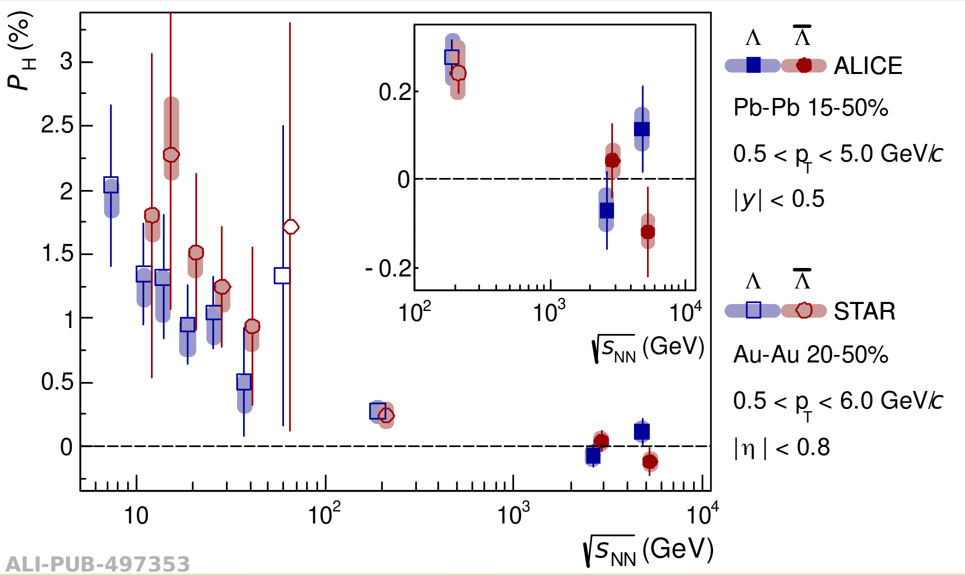

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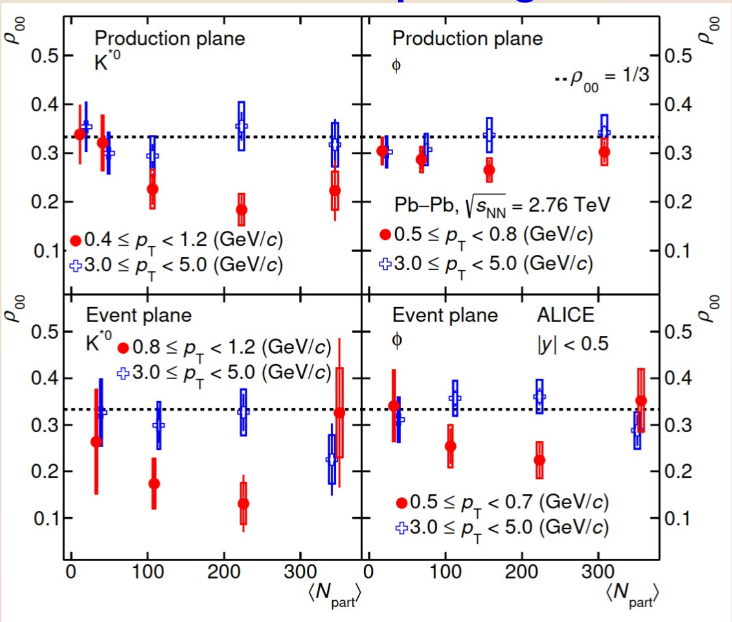

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Thermal estimate

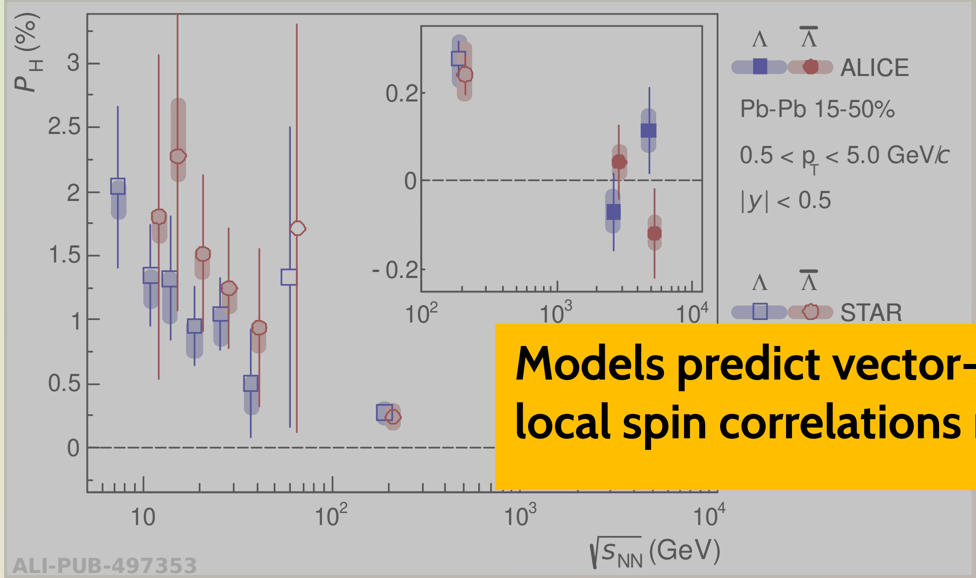
✓ $P_H \sim 0$ within uncertainties at LHC

✓ $\rho_{00} < 1/3$ (significant deviation)

✓ **Expectation:** $P_H \sim 0 \Rightarrow \rho_{00} \approx 1/3$
✓ **Observation:** $P_H \sim 0$, large deviation in ρ_{00}

Experimental puzzle

Hyperon polarization



ALICE Collaboration,
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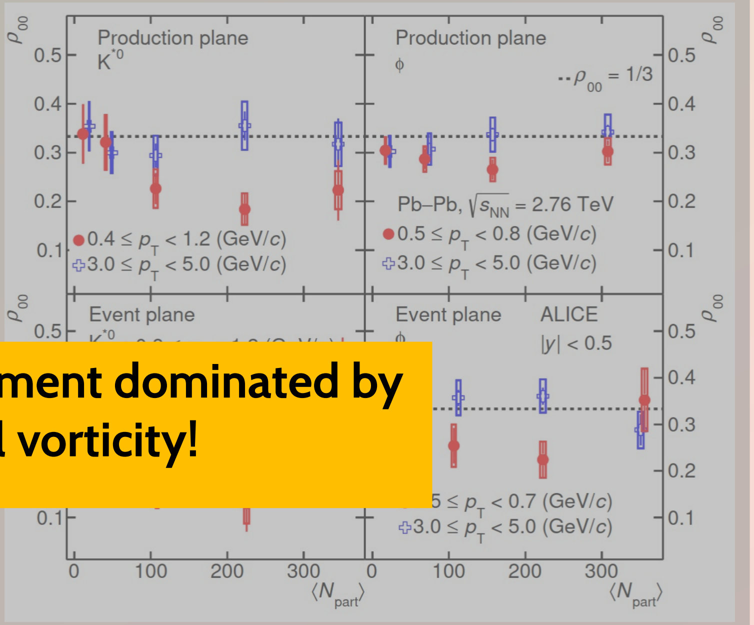
Vector meson spin-alignment



ALICE Collaboration,
Phys. Rev. Lett. 125 (2020) 012301

$$\rho_{00} - \frac{1}{3} \sim 4\,P_H^2/9$$

Models predict vector-meson spin alignment dominated by local spin correlations rather than global vorticity!

- ✓ P_H ~ 0 within uncertainties at LHC
- ✓ ρ_{00} < 1/3 (significant deviation)

- ✓ **Expectation:** P_H ~ 0 => $\rho_{00} \approx 1/3$
- ✓ **Observation:** P_H ~ 0, large deviation in ρ_{00}

Resolving puzzle

- ✓ **Possible mechanisms:** Strong fields, hydrodynamic gradients, holographic

Avdesh et al., Phys. Rev. D 108 (2023) 016020
Becattini et al., Phys. Rev. D 110 (2024) 056047
Avdesh et al., Phys. Rev. D 109 (2024) 054038

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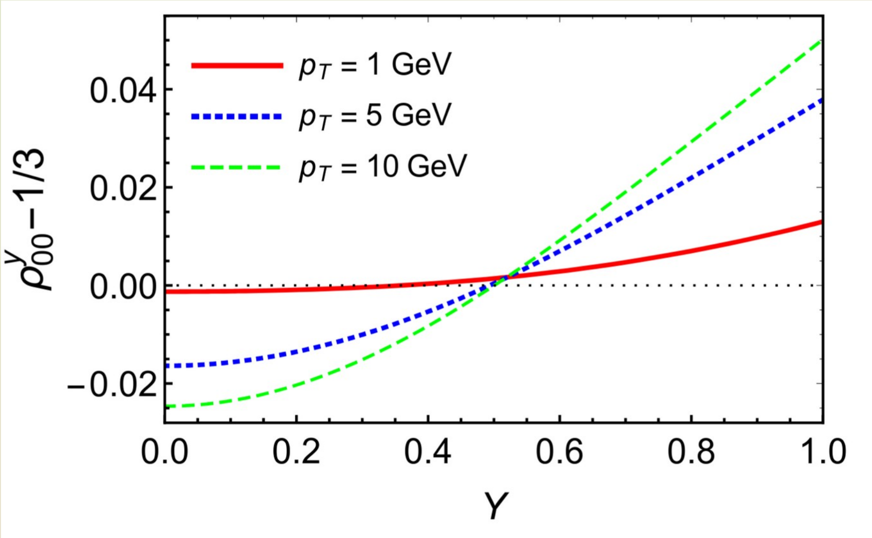

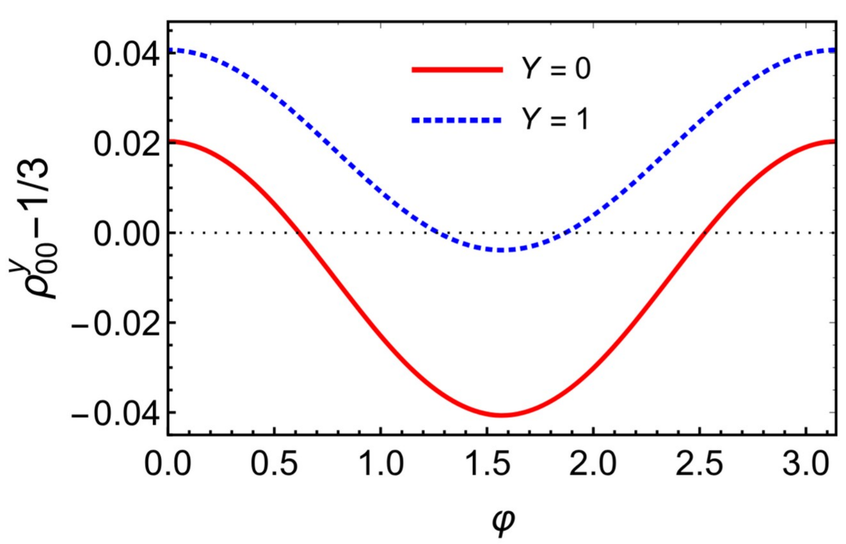

✓ **Predictions:** Strong rapidity dependence and azimuthal modulation of ρ_{00}

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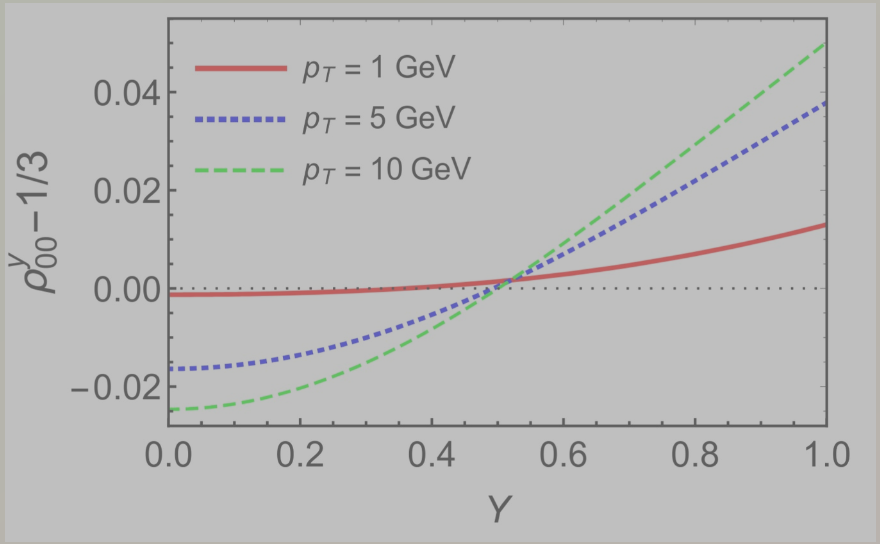

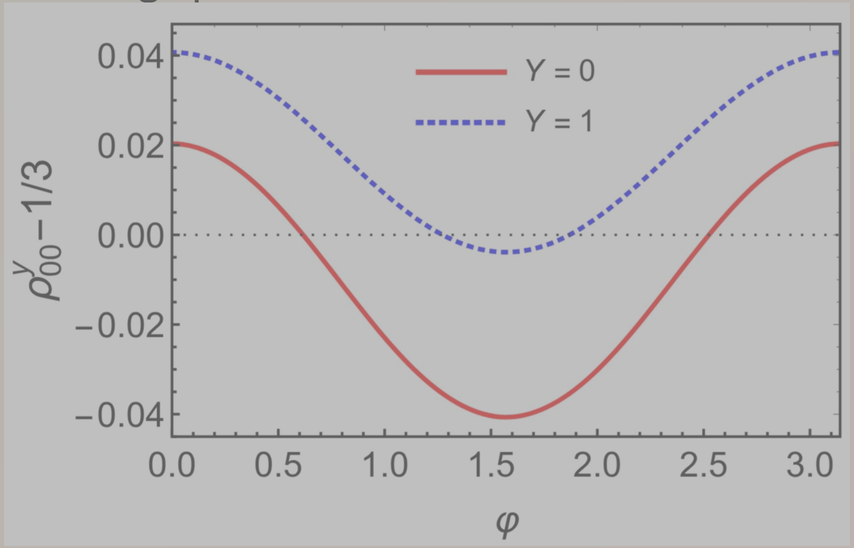

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High statistics Run3 ALICE measurement will:

- Test rapidity and azimuthal dependence of spin alignment

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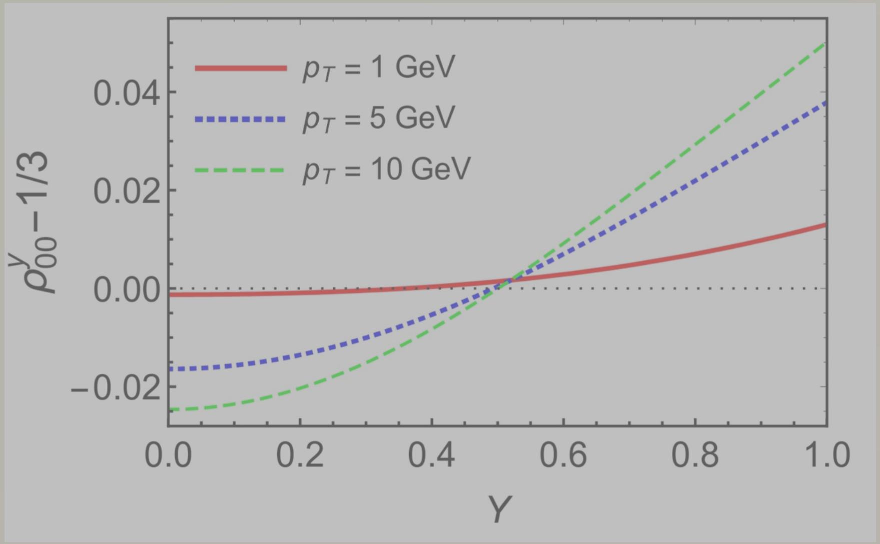

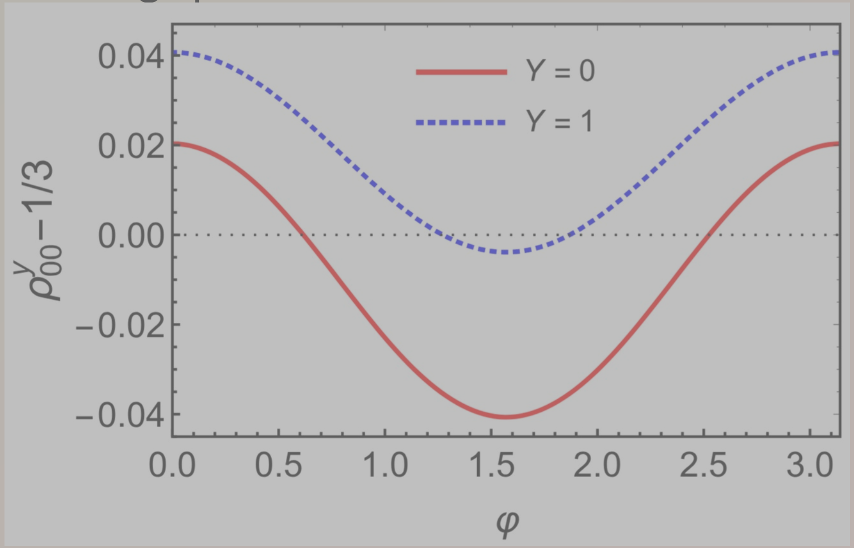

✓ **Predictions:** Strong rapidity dependence and azimuthal modulation of ρ_{00}

High statistics Run3 ALICE measurement will:

- ✓ Test rapidity and azimuthal dependence of spin alignment
- ✓ Constrain competing spin-alignment mechanisms

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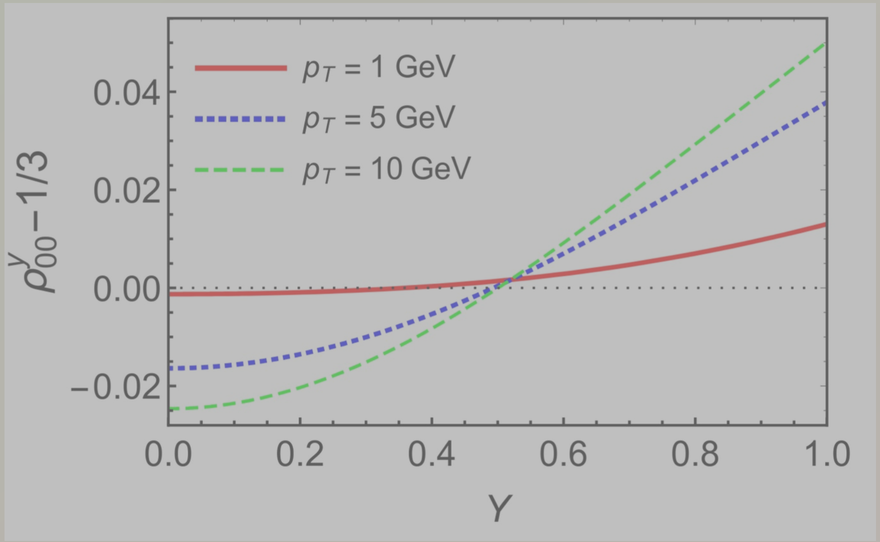
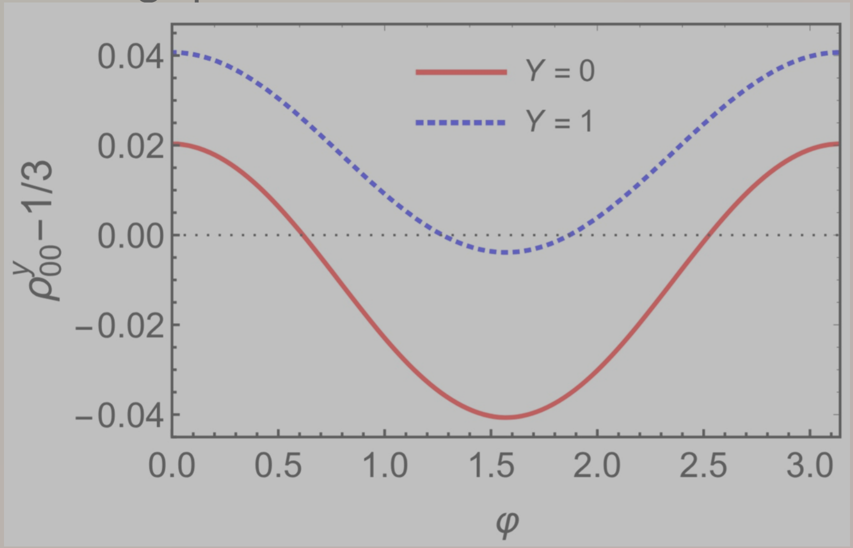
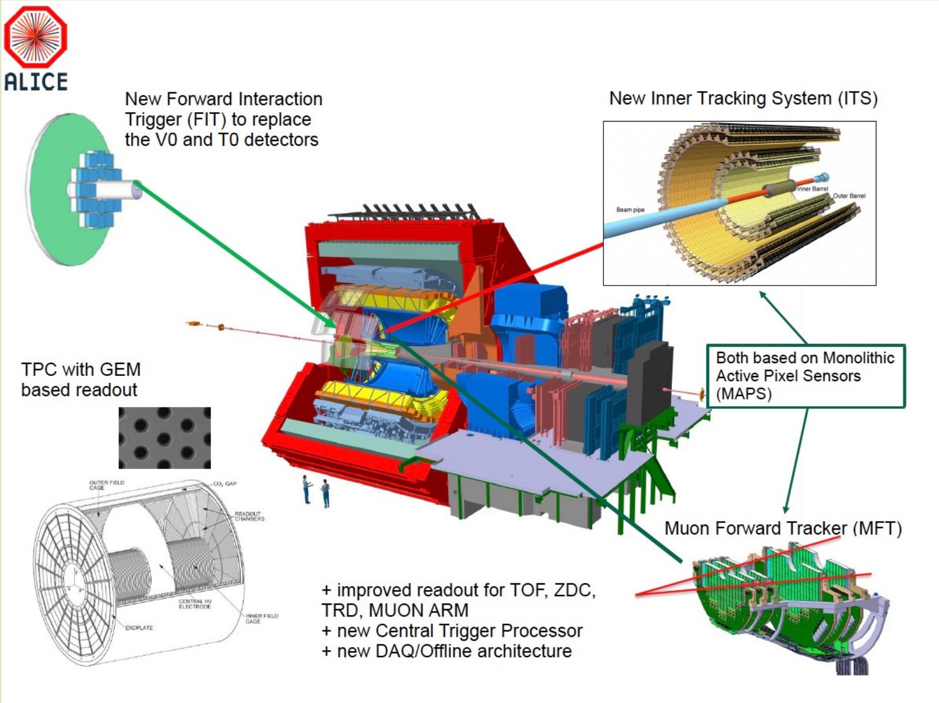




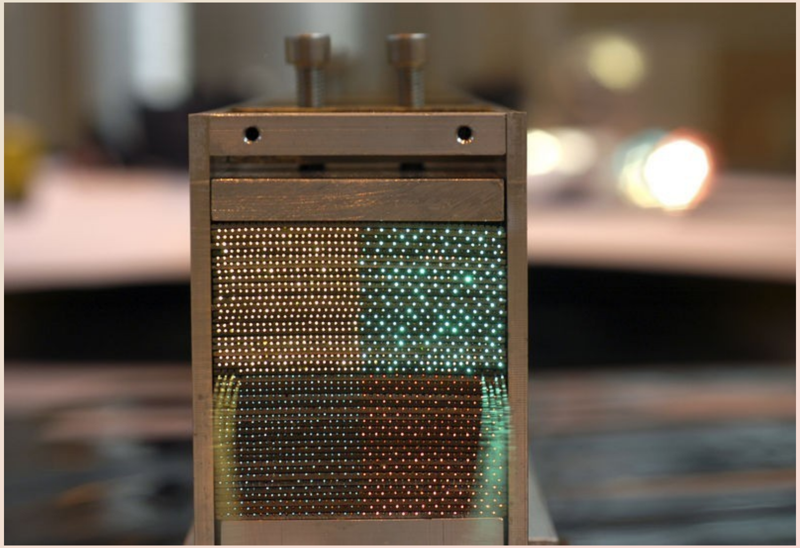
- **Predictions:** Strong rapidity dependence and azimuthal modulation of ρ_{00}

High statistics Run3 ALICE measurement will:
- Test rapidity and azimuthal dependence of spin alignment
- Constrain competing spin-alignment mechanisms
- Precise estimation of P_H and vorticity at LHC energy

ALICE detector

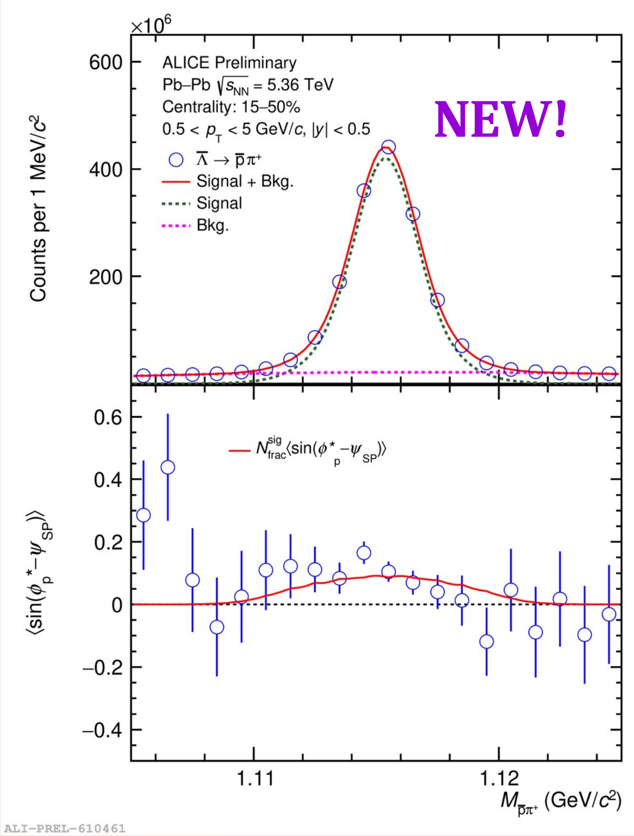


ZDC ($|\eta| > 8.78$)



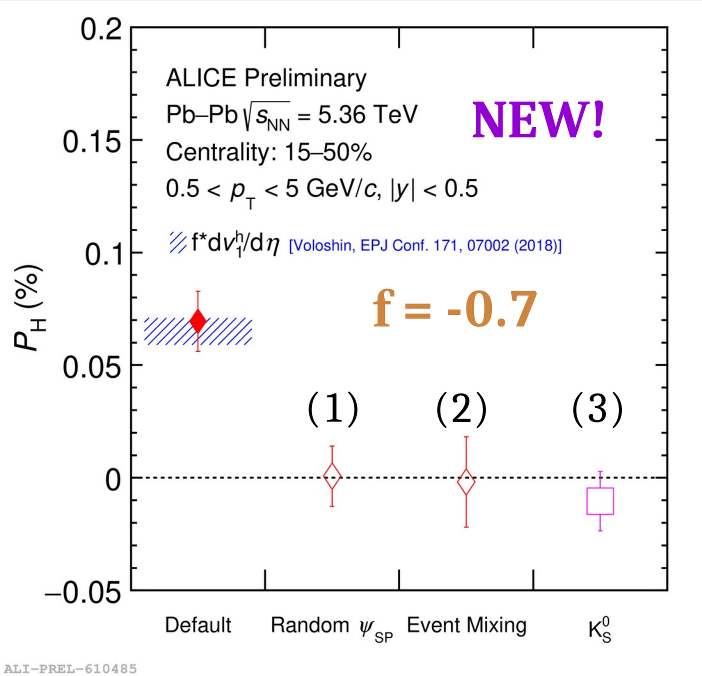
- ✓ Dataset: 2023 Pb-Pb $\sqrt{s_{NN}} = 5.36$ TeV (~6 billion events)
- ✓ FIT: Event selection, centrality estimation
- ✓ TPC: Particle reconstruction
- ✓ ZDC: Spectator plane Ψ_{SP} reconstruction (R^1_{SP} ~ 25%)

Global polarization measurement at LHC

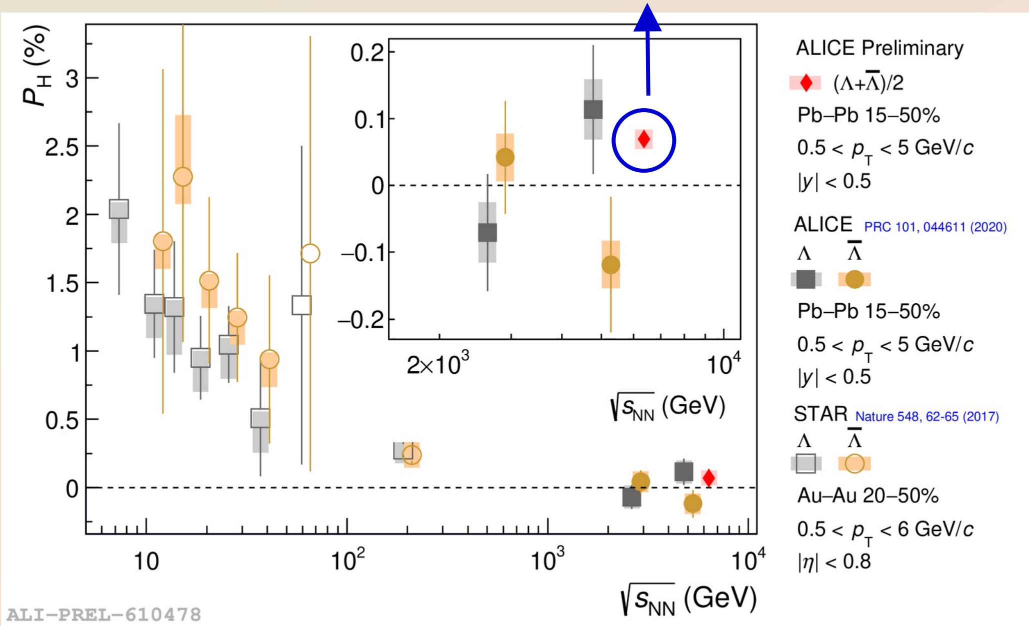


- ✓ P_H measured from the simultaneous fit to invariant mass and polarization variable distribution
- ✓ Non zero average polarization is observed

Global polarization measurement



NEW!



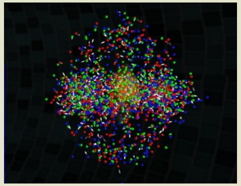
- ✓ Average polarization consistent with the empirical prediction based on directed flow slope at mid-rapidity
- ✓ Several null hypothesis tests (1, 2, 3) performed succesfully
- ✓ **First observation of non-zero polarization of hyperons at LHC energies with 5σ significance**

Revisiting vorticity at different scales (s^{-1})

ALICE

$$\frac{\omega}{T} = P_{\Lambda} + P_{\bar{\Lambda}}$$

QGP at RHIC



STAR Collaboration,
Nature volume 548, pages 62–65 (2017)

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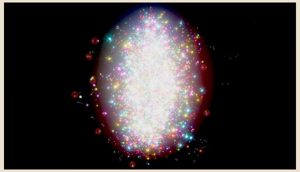
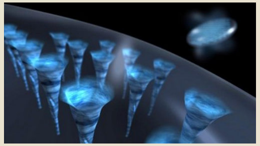
10^{20}



QGP at LHC → **NEW ALICE DATA!**

Nano droplets of superfluid He



Science, 345(6199)

10^{6}

10^{-1}

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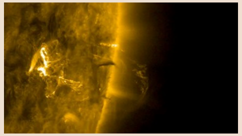
Solar winds

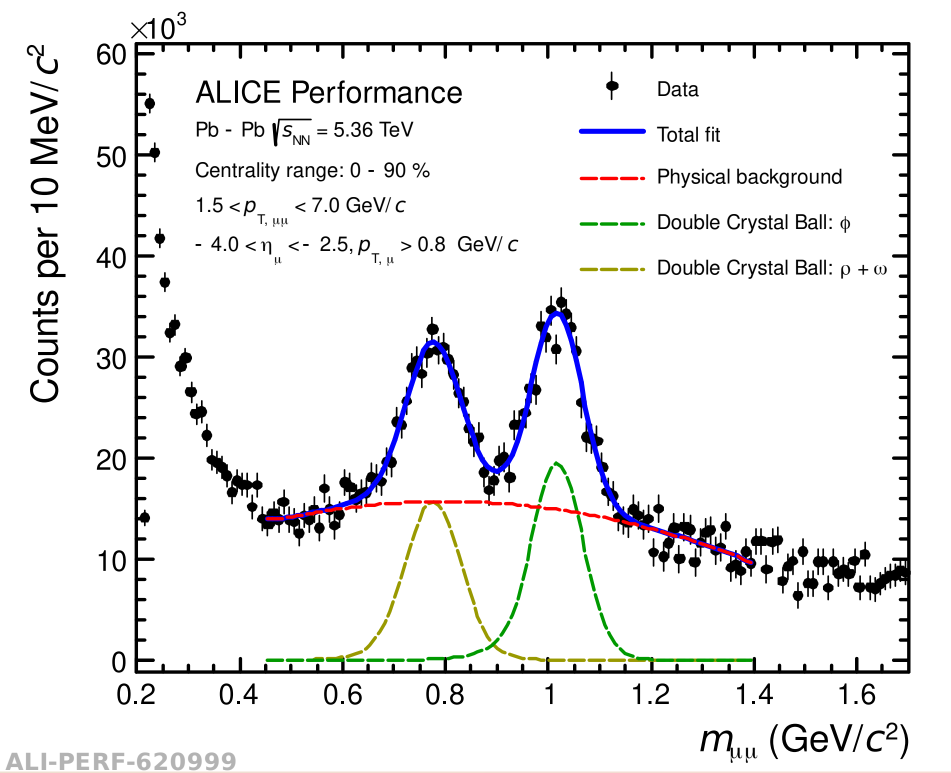


10^{-4}

10^{-5}

Ocean flows

Vector meson signal at forward rapidity



- ✓ Clear Φ meson signal at forward rapidity in Pb-Pb collisions
- ✓ Enables measurement of spin alignment at forward rapidity
- ✓ Key ingredient to test predicted rapidity dependence of spin alignment

Summary

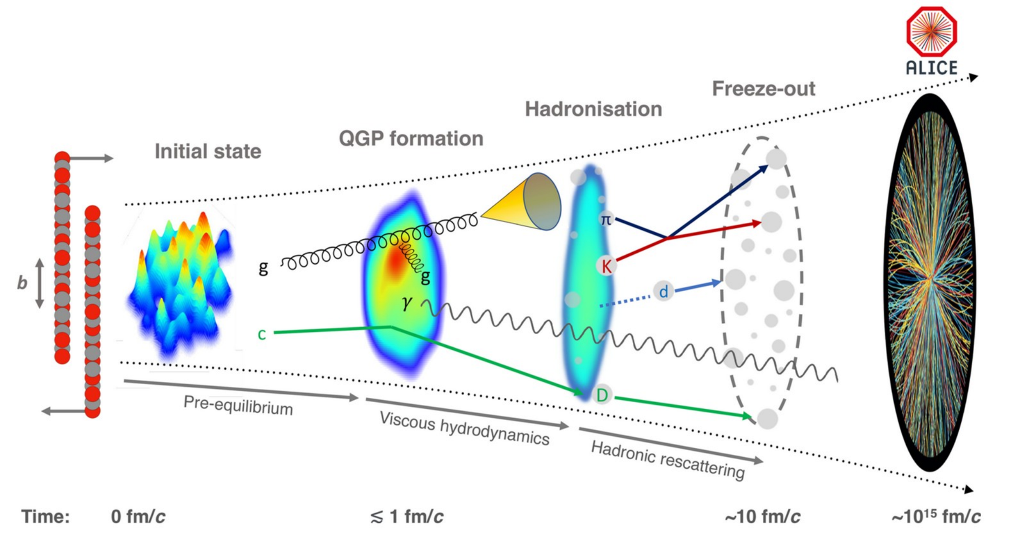
- **Global polarization:** first observation at the LHC with 5σ significance -> access to QGP vorticity
- **QGP vorticity:** order 10^{20} s^{-1}, the second most vortical fluids observed in nature after RHIC
- **Spin alignment puzzle:** small P_H but significant deviation of ρ_{00} from 1/3
- **Foward rapidity:** clear signal of Φ meson -> enables spin-alignment measurement beyond midrapidity

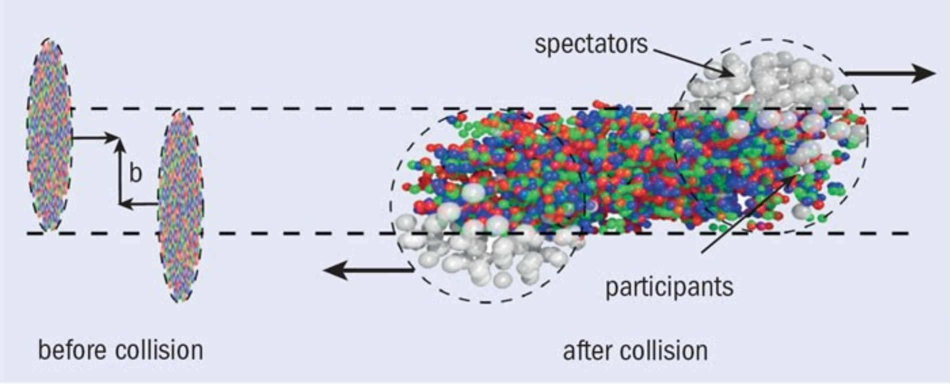
Outlook

- More Run3 data -> precision and differential measurements of P_H and ρ_{00}
- Constrain magnetic fields at LHC energy
- Test rapidity and azimuthal dependence of ρ_{00} for various species

Backup

Evolution of heavy-ion collisions

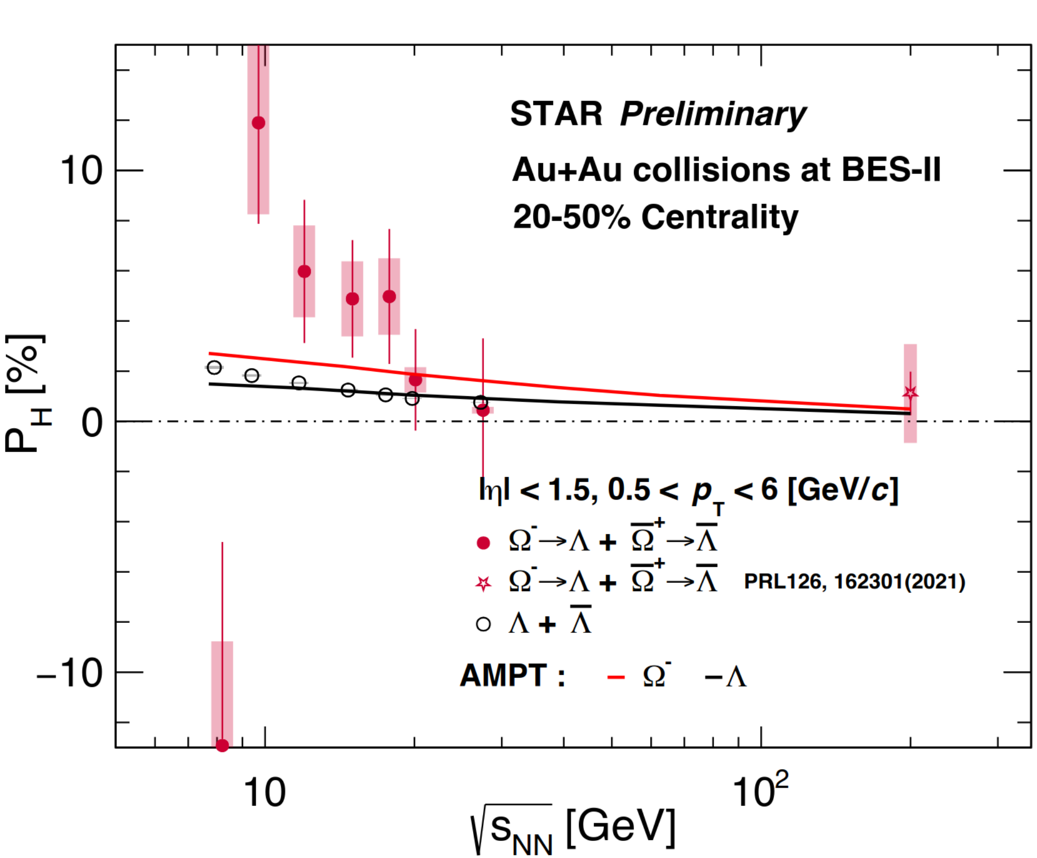




Two interesting large initial state effects

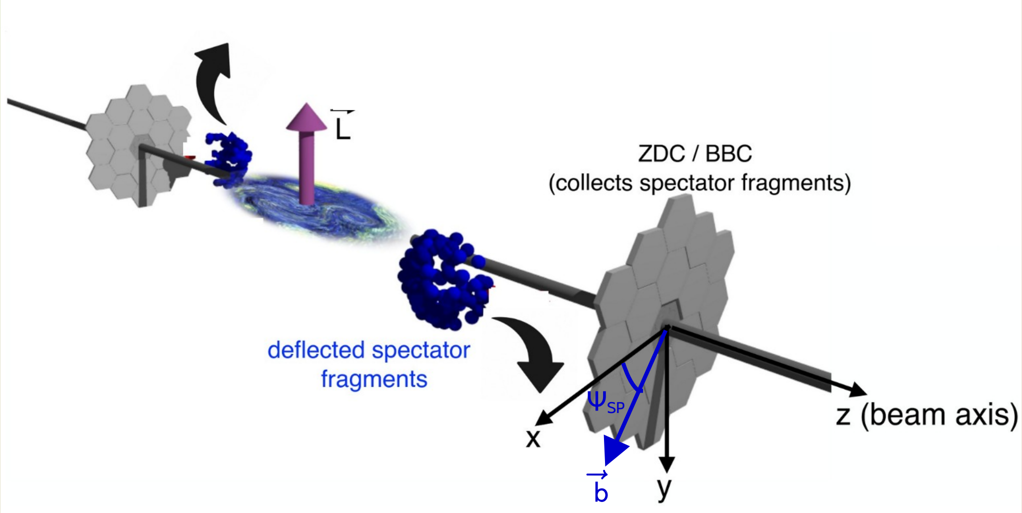
- ✓ (1) Angular momentum
- ✓ (2) Magnetic field

ALICE Collaboration,
Eur. Phys. J. C 84 (2024) 813



STAR Preliminary
Au+Au collisions at BES-II
20-50% Centrality
|η| < 1.5, 0.5 < p_T < 6 [GeV/c]
$\Omega^- \to \Lambda + \overline{\Omega}^+ \to \overline{\Lambda}$
$\Omega^- \to \Lambda + \overline{\Omega}^+ \to \overline{\Lambda}$ PRL126, 162301(2021)
$\Lambda + \overline{\Lambda}$
AMPT : Ω^- Λ
P_H [%]
$\sqrt{s_{NN}}$ [GeV]
10
0
−10
10
10^2

Global hyperon polarization measurement procedure



STAR Collaboration, Nature volume 548, pages 62–65 (2017)

- ✓ Deflection of the spectators determines the direction of angular momentum
- ✓ On average spectators deflect outwards

S. Voloshin and T. Niida; Phys. Rev. C 94, 021901(R) (2016)

Experimental observable

✓ Global hyperon polarization (along y axis)

$$P_H = \frac{-8}{\pi \alpha_H} \frac{\langle \sin(\phi^*_p - \Psi_{SP}) \rangle}{R^1_{SP}}$$

STAR Collaboration, Nature volume 548, pages 62–65 (2017)

✓ Thermal limit

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

- Vorticity : $\frac{\omega}{T} = P_\Lambda + P_{\bar{\Lambda}}$
- B-field : $\frac{B}{T} = \frac{1}{2\mu_\Lambda}\left(P_\Lambda - P_{\bar{\Lambda}}\right)$

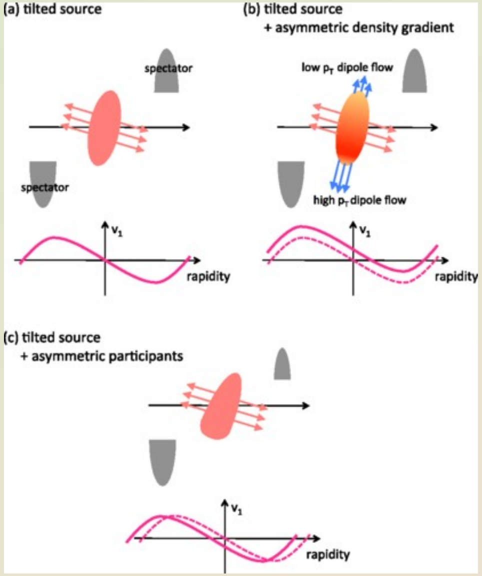
Becattini et al., Phys. Rev. C 95 (2017) 054902

φ^*_p = azimuthal angle of daughter proton in hyperon rest frame

Ψ_{SP} = spectator plane angle

R^1_{SP} = resolution correction factor of spectator plane

Vorticity and directed flow



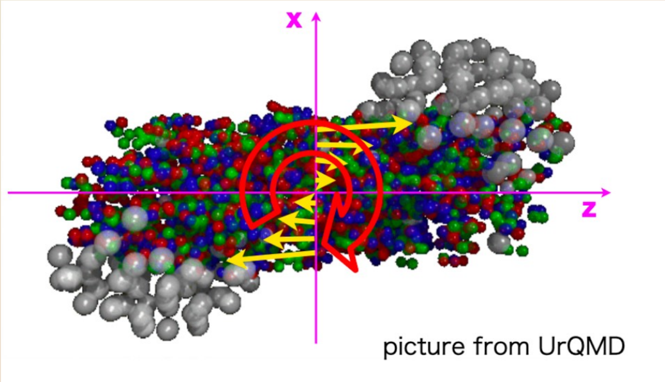
STAR Collaboration, Phys. Rev. C 98, 014915

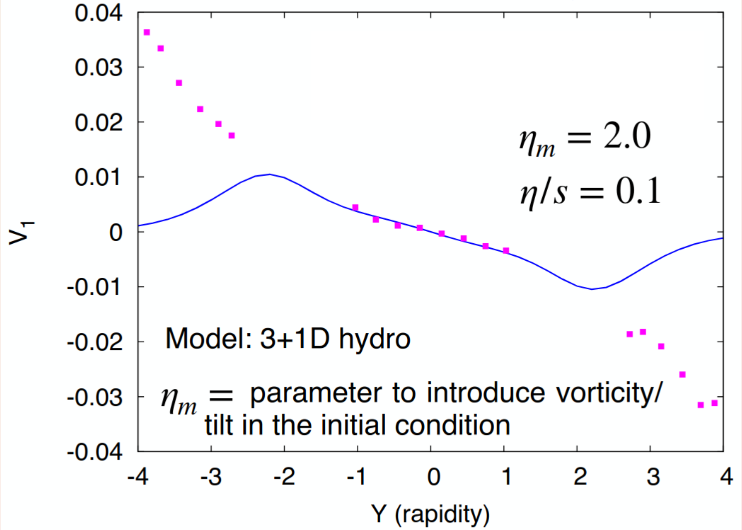
- ✓ Asymmetries in the initial velocity field generate vorticity (tilt) in the system -> generates directed flow

S. A. Voloshin, EPJ Web Conf., 171 (2018) 07002

- ✓ To describe directed flow (v_1) in heavy-ion collisions -> vorticity (tilt) has to be taken into account

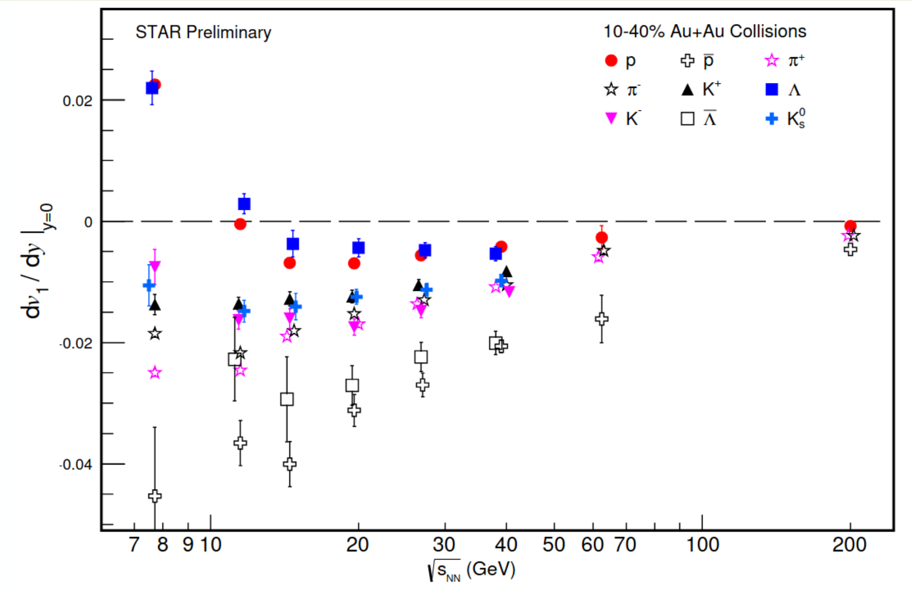
$$\omega_y = \frac{-1}{2}\frac{\partial v_z}{\partial x}$$



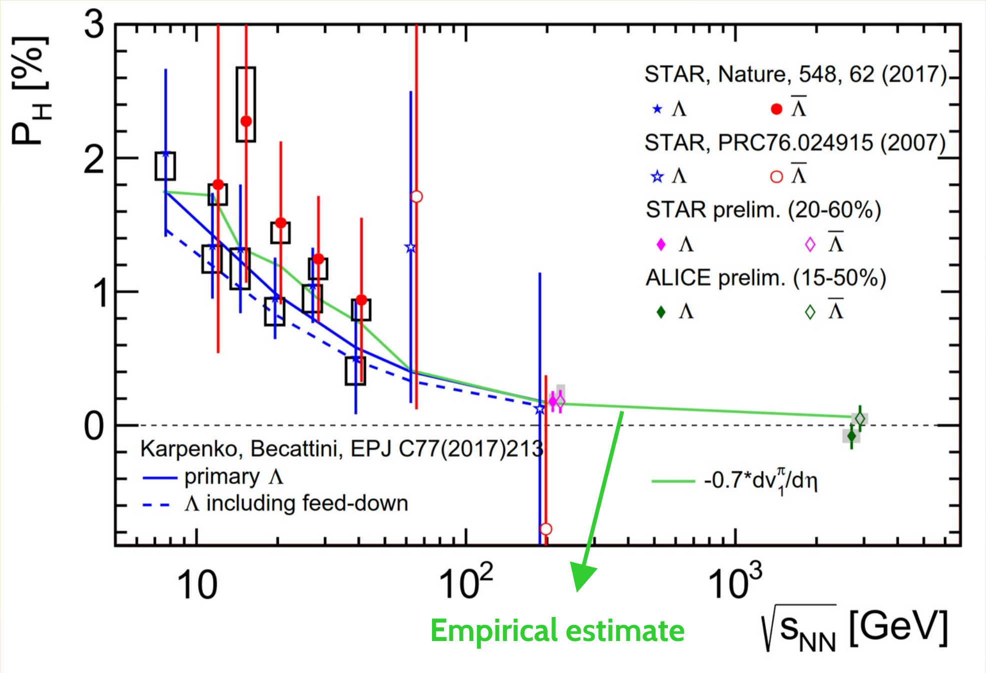


Becattini et al, Eur. Phys. J. C 78, 354 (2018)

Vorticity and directed flow



S. Singha, P. Shanmuganathan and D. Keane, Adv. High Energy Phys. 2016, 2836989 (2016)



S. Voloshin, EPJ Web Conf., 171 (2018) 07002

- ✓ Polarization and dv_1/dy are strongly correlated -> decreases with increase in collision energy
- ✓ v_1 at the LHC three times smaller than v_1 at top RHIC energy

ALICE Collaboration, Phys. Rev. Lett. 111 (2013) 232302

- ✓ Expect P_H at LHC atleast three times smaller than at RHIC