Recent results on global polarization of hyperons in Au+Au collisions at RHIC

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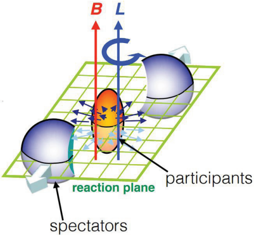
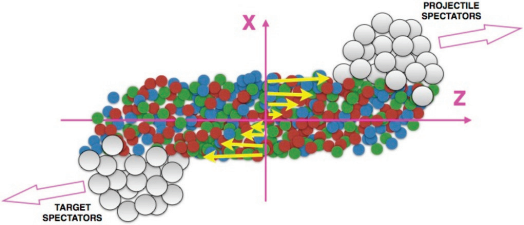
Introduction - origin of global polarization in HI collisions

- Immadiately after an A+A collision, the overlap region defined by the nuclear geometry is almond shaped, with shortest axis along the impact parameter vector.
- Multiple interactions between particles in the evolving system change the initial coordinate space asymmetry into final momentum space anisotropy, which is usually expressed as a Fourier series expansion in azimuthal angle of produced particles.
- The Fourier coefficients describing the flow of the created quasi-macroscopic system (QGP) have been studied for 20 years. In particular, the large elliptic flow indicates that the system is strongly coupled and has an extremely low viscosity to entropy ratio.



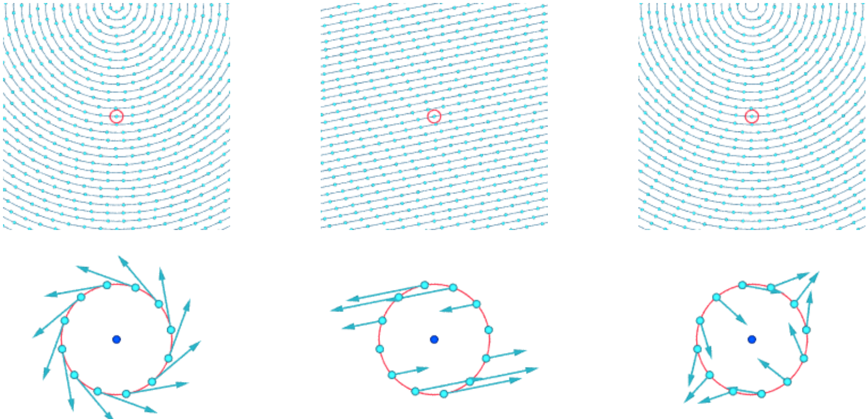


- From the very success of the hydrodynamic description of the flow, one can conclude that the system might possess an extremely high vorticity.

  Example: if the difference between the z-components of the collective velocities of the system, close to spectators is $0.1c$, and its transverse size is 5 fm, then vorticity of the system is about $0.02\ \mathrm{fm}^{-1} \approx 10^{22}\ \mathrm{s}^{-1}$.

Meaning of vorticity in classical hydrodynamics

- Vorticity is pseudovector field that describes the local spinning motion of continuum near some point, as would be seen by an observer located at that point and traveling along with the flow.
- Non-relativistic vorticity is defined as: $\vec{\omega}(\vec{r},t) = \frac{1}{2}\vec{\nabla} \times \vec{v}(\vec{r},t) \overset{\text{in 2D}}{=} \frac{1}{2}(\partial_x v_y - \partial_y v_x)\hat{z}$
- Rigid-body-like vortex ($v \propto r \;\Rightarrow\; \omega \neq 0$) | Parallel flow with shear ($\omega \neq 0$) | Irrotational vortex ($v \propto 1/r \;\Rightarrow\; \omega = 0$)



Vorticity in relativistic hydrodynamics

- There exist several approaches to define relativistic vorticity. In HI collisions most commonly used is thermal vorticity:

$$\varpi_{\mu\nu} = \frac{1}{2}(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu), \quad \text{where} \quad \beta^\mu = \frac{1}{T} u^\mu$$

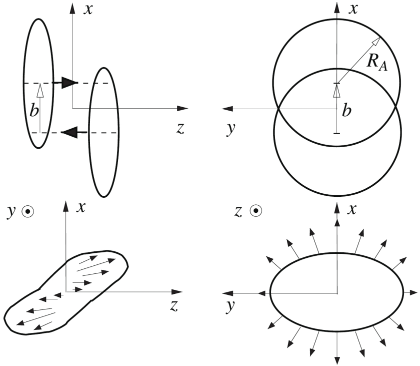
- Thermal vorticity can be used to obtain the averaged over a small region being in local equilibrium spin 4-vector $S^\mu(x,p)$ of hyperons in this region.
- The spin vector of each hyperon is measured in its rest frame ($S^{\star\mu} = (0, \vec{S}^\star)$) and then an average spin $\langle \vec{S}^\star \rangle$ of hyperons of given species in the expanding fireball is obtained.

- The OAM in non-central HI collisions:

$$\vec{J} = \vec{b} \times \vec{p}_{\text{proj}}$$

- Flow pattern of the QGP fluid is complex and any local vorticity may fluctuate as a function of position within each droplet. However, the average vorticity must be parallel to $\vec{J}$ - spin polarization projection along $\hat{J}$ is termed global polarization:

$$P = \frac{\langle \vec{S}^\star \rangle \cdot \vec{J}}{|\langle \vec{S}^\star \rangle| \, |\vec{J}|}$$

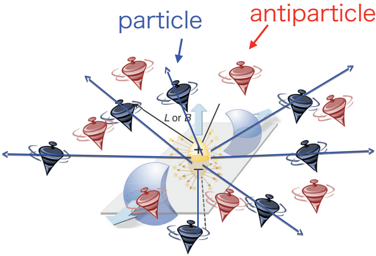


Global polarization in heavy-ion collisions

- Global polarization arises from partial conversion of the orbital angular momentum of colliding nuclei into the spin angular momentum of the produced particles.
- Global polarization in non-central HIC was predicted by Liang and Wang [PRL 94 (2005) 102301] and first observed by the STAR Collaboration [Nature 548 (2017) 62].
- Assuming local thermal equilibrium, the polarization of the produced particles is determined by the local thermal vorticity of the fluid. In non-relativistic limit ($m_h \gg T$) the polarization is given by:

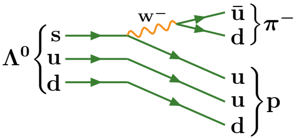
$$\vec{P} = \frac{\langle \vec{S} \rangle}{S} \approx \frac{(S+1)}{3} \frac{\vec{\omega}}{T}$$

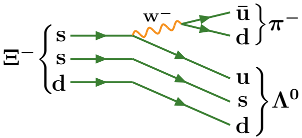
- From this equation it follows, that all particles and antiparticles of the same spin, should have the same polarization. Possible differences can arise e.g. from:
  - initial magnetic field (PRC 95 (2017) 054902),
  - the fact that different particles are produced at different times or regions as the system freezes out (PLB 803 (2020) 135298),
  - interaction of baryon spin with meson fields (PRC 99 (2019) 021901).
- To establish the global nature of the polarization, it is necessary to measure the polarization of different particles, and especially particles of different spins.

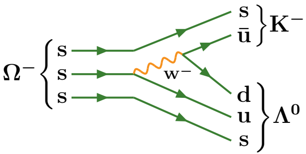


Hyperons production in Au+Au and their decay channels

- STAR has studied global polarization of Λ ($\bar{\Lambda}$) hyperons in Au+Au collisions at different $\sqrt{s_{\mathrm{NN}}}$.
- Recently STAR has also measured global polarization of Ξ^- ($\bar{\Xi}^+$) and Ω^- ($\bar{\Omega}^+$) hyperons in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV.
- Hyperon is a baryon containing one or more strange quarks, but no c, b or t quarks.
- Quark composition and decay channels of hyperons used in the presented analyses:



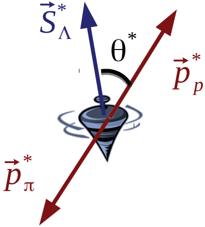




$\Lambda^0: \quad J^P = \frac{1}{2}^+$	$\Xi^-: \quad J^P = \frac{1}{2}^+$	$\Omega^-: \quad J^P = \frac{3}{2}^+$
BR 63.9%	BR 99.887%	BR 67.8%
$m = 1116$ MeV	$m = 1321$ MeV	$m = 1672$ MeV
$c\tau = 7.89$ cm	$c\tau = 4.91$ cm	$c\tau = 2.46$ cm

- The gold ion, $^{197}_{79}$**Au**, consists of 276 u and 315 d valence quarks.

Global polarization of hyperons



- In parity-violating weak decays of hyperons, the daughter particle distribution, in the rest frame of the hyperon, directly depends on the global hyperon polarization:

$$\frac{dN}{d\Omega^\star} = \frac{1}{4\pi}\left(1 + \alpha_H \vec{P}^\star_H \cdot \hat{p}^\star_B\right)$$

- The polarization along the $\vec{J}$ can be defined as:

$$P_H = \frac{8}{\pi\alpha_H}\frac{\langle \sin(\Psi_1^{\text{obs}} - \phi^\star_B)\rangle}{\text{Res}(\Psi_1^{\text{obs}})}$$

- Ξ^- (Ξ^+) decay hapens in two steps: $\Xi^- \to \Lambda + \pi^-$ and subsequently $\Lambda \to p + \pi^-$
- If the hyperon polarization is $\vec{P}_Y$, the polarization $\vec{P}_B$ of the decay baryon is (PDG):

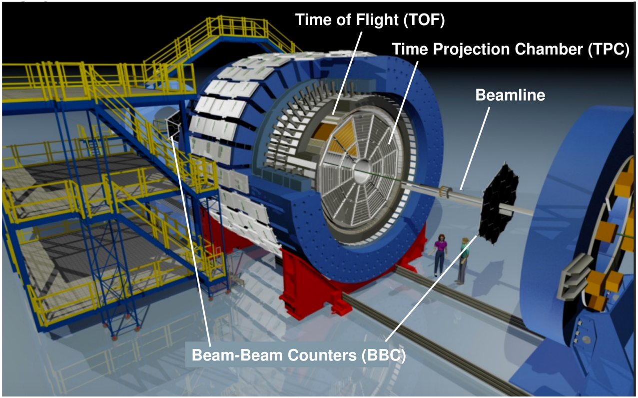
$$\vec{P}^\star_B = \frac{(\alpha_Y + \vec{P}^\star_Y \cdot \hat{p}^\star_B)\hat{p}^\star_B + \beta_Y \vec{P}^\star_Y \times \hat{p}^\star_B + \gamma_Y \hat{p}^\star_B \times (\vec{P}^\star_Y \times \hat{p}^\star_B)}{1 + \alpha_Y \vec{P}^\star_Y \cdot \hat{p}^\star_B}$$

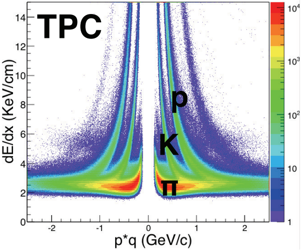
- Averaging over the angular distribution of the Λ in the rest frame of the Ξ yields:

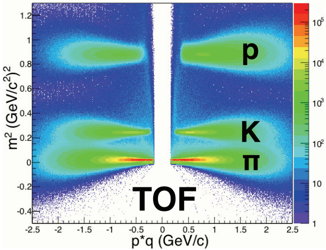
$$\vec{P}^\star_\Lambda = C_{\Xi\Lambda}\vec{P}^\star_\Xi = \frac{1}{3}(1 + 2\gamma_\Xi)\vec{P}^\star_\Xi \quad \text{with} \quad C_{\Xi\Lambda} = \frac{1}{3}(1 + 2 \times 0.916) = +0.914$$

- Similarly for the decay $\Omega^- \to \Lambda + K^-$ one gets $\vec{P}^\star_\Lambda = C_{\Omega^-\Lambda}\vec{P}^\star_\Omega = \frac{1}{5}(1 + 4\gamma_\Omega)\vec{P}^\star_\Omega$ (in this case α and β are small; this limits the unmeasured $\gamma_\Omega \approx \pm 1$)

Solenoidal Tracker At RHIC experiment

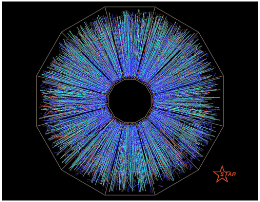






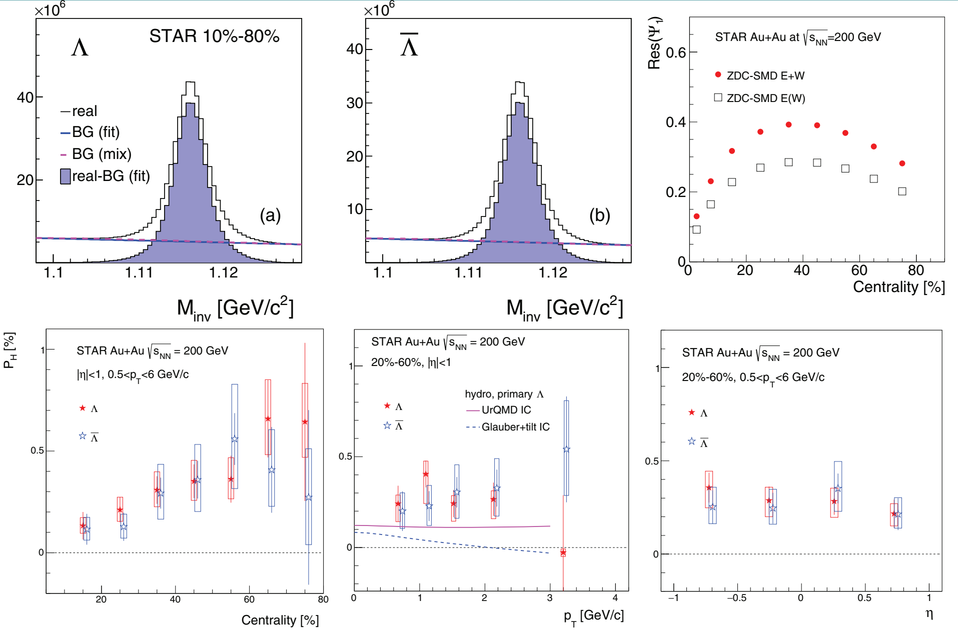
STAR detector

- TPC: dE/dx, L



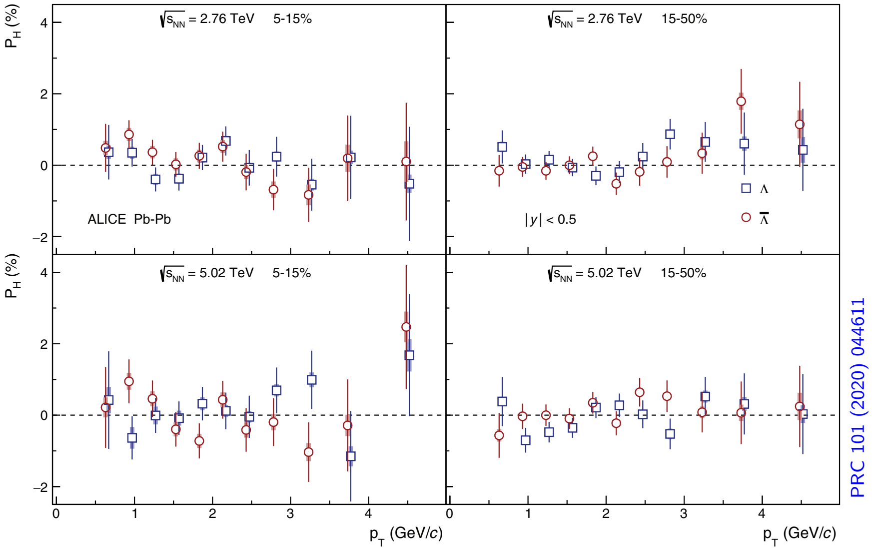
- ToF: measures $\beta = \frac{L}{ct}$, $m^2c^2 = p^2\left(1/\beta^2 - 1\right)$
- TPC and ToF coverage: $|\eta| < 1,\ 0 < \phi < 2\pi$
- BBC: Scintilator tiles located at $3.3 < |\eta| < 5$
- ZDC-SMD: Calorimeters located at $z = \pm 18$ m from IP, with position detectors inserted between the modules.

STAR results on global polarization of Λ and $\bar{\Lambda}$



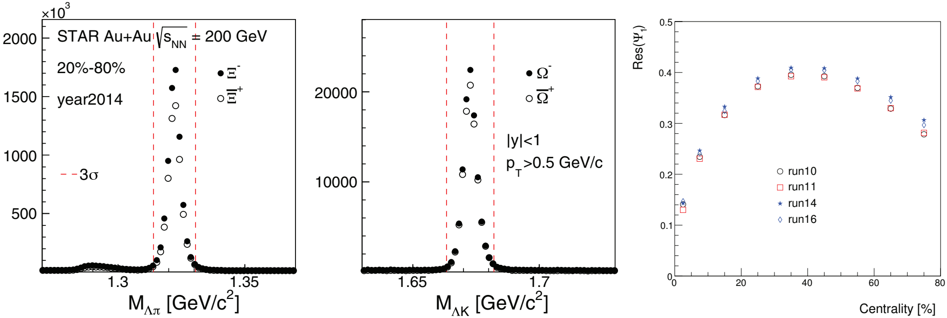
ALICE results on global polarization of Λ and $\bar{\Lambda}$

- First measurement in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ and 5.02 TeV.
- The averaged hyperon global polarization is found to be consistent with zero.



STAR results on global polarization of Ξ and Ω hyperons

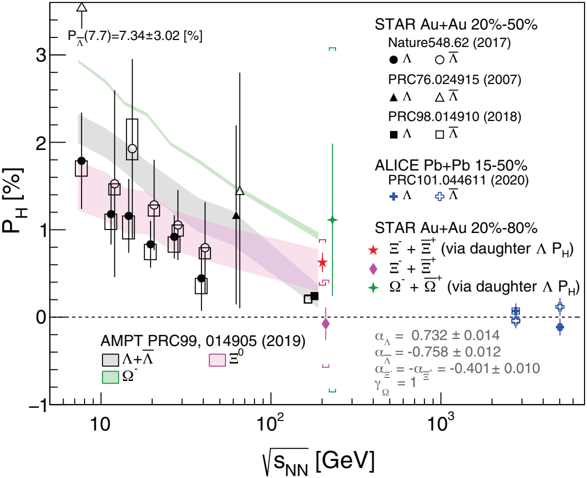
- Global polarization of Ξ and Ω hyperons has been measured for the first time in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV by STAR experiment using data collected in 2010, 2011, 2014 and 2016 [PRL 126 (2021) 162301].
- The parent $\Xi^{\mp}$ and $\Omega^{\mp}$ and their daughter $\Lambda(\bar{\Lambda})$ were reconstructed based on the ionization energy loss in the TPC gas and timing information from the ToF detector of their decay pions, kaons and protons.
- The azimuthal angle of the first-order event plane, Ψ_1^{obs}, which estimates the reaction plane, Ψ_{RP}, and its resolution $\mathrm{Res}(\Psi_1^{\mathrm{obs}})$, are obtained using the event flow vectors method [PRC 58 (1998) 1671]: $\mathrm{Res}(\Psi_1^{\mathrm{obs}}) = \langle \cos n(\Psi_1^{\mathrm{obs}} - \Psi_{\mathrm{RP}}) \rangle$



STAR results on global polarization of Ξ and Ω hyperons

- P_H for Ξ and Ω hyperons are averaged over particle and antiparticle, and integrated over centrality range $20\% - 80\%$, $p_T > 0.5$ GeV/c and $|y| < 1$.
- Measured polarizations of $\Xi^{\mp}$ hyperons using daughter Λ polarization:

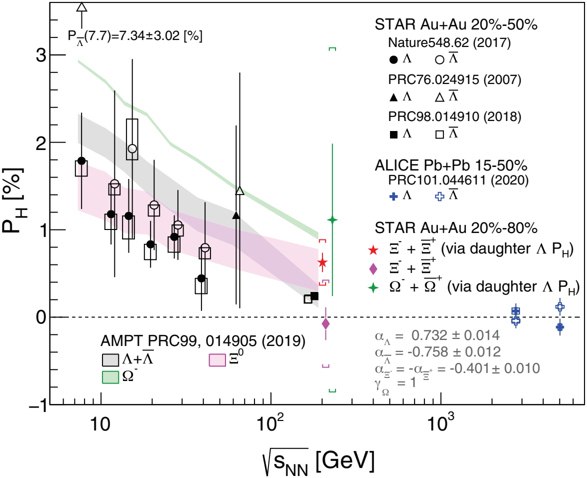
$P_{\Xi} = 0.77 \pm 0.16(\text{stat}) \pm 0.49(\text{sys})$ and $P_{\bar{\Xi}} = 0.49 \pm 0.16(\text{stat}) \pm 0.20(\text{sys})$



STAR results on global polarization of Ξ and Ω hyperons

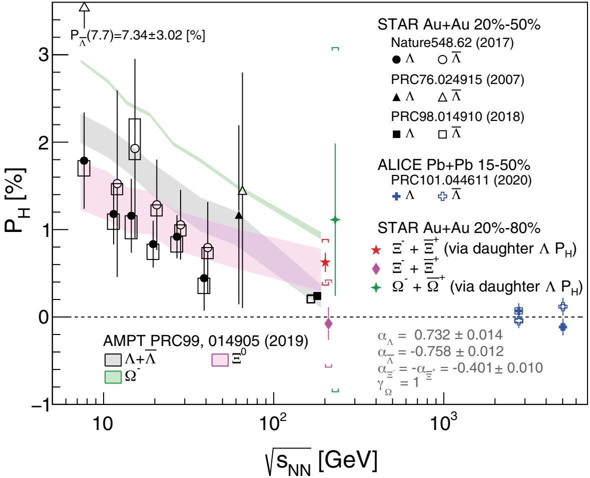
- The $\Xi^- + \Xi^+$ polarization measured via analysis of angular distribution of daughter Λ in Ξ rest frame: $\langle P_\Xi \rangle = -0.07 \pm 0.19(\text{stat}) \pm 0.50(\text{sys})$
- Global polarization for $\Omega^- + \Omega^+$ (assuming $\gamma_\Omega = 1 \;\Rightarrow\; C_{\Omega\Lambda} = 1$):

$$\langle P_\Omega \rangle = 1.11 \pm 0.87(\text{stat}) \pm 1.97(\text{sys})$$



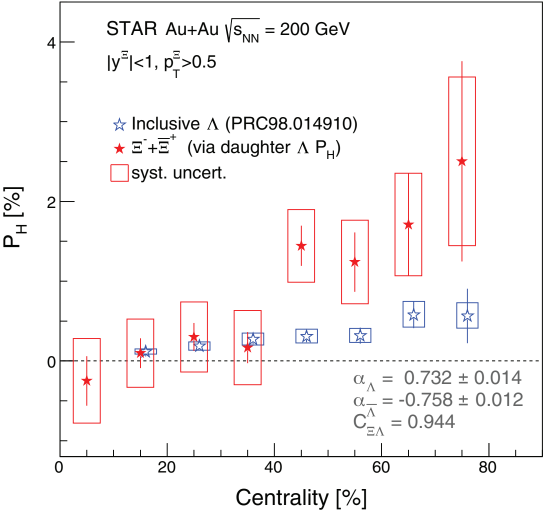
STAR results on global polarization of Ξ and Ω hyperons

- The AMPT model can describe the particle species dependence in data at 200 GeV.
- The AMPT model also describes the energy dependence of Λ polarization.
- The feed-down effect can lead to $15\% - 20\%$ reduction of the primary Λ polarization, while Ξ has less contribution from feed-down.



STAR results on global polarization of Ξ and Ω hyperons

- The hyperon polarization increases in more peripheral collisions as expected from the centrality dependence of the fluid vorticity.
- The Ξ polarization is larger than that of inclusive Λ in peripheral collisions.



Summary

- Experimental confirmation by STAR of the global polarization of hyperons (Λ, Ξ, Ω) produced in ultra-relativistic HIC opened a new way to study the properties of QGP.
- The first measurement of the global polarization for Ξ ($\bar{\Xi}$) hyperons was done in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV.
- The measurements confirm the global polarization picture based on the relativistic hydrodynamics and the system fluid vorticity.
- The average polarization of $\Xi + \bar{\Xi}$ seems to be larger than that of the inclusive Λ, which is qualitatively described by the AMPT model.
- The measured polarization seems to exhibit a centarality dependence as expected from the impact paramter dependence of the vorticity.
- Global polarization of the Ω hyperons in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV was extracted for the first time via measurements of the polarization of the the daughter Λ.
- Measurements with higher precision are needed to determine the decay parameter γ_{Ω}.
- More precise results on the global polarization of spin-$3/2$ particles are also needed to provide critical information about spin dynamics in HIC.

Backup slides

Event plane determination and resolution

- Use event plane angles ψ_n^{obs} as estimates of the angles Ψ_n (PRC 58 (1998) 1671).
- Define the components of the event flow vector Q_n as:

$$Q_{n,x} = \sum_i w_i \cos(n\phi_i) = Q_n \cos(n\psi_n^{\text{obs}}), \quad Q_{n,y} = \sum_i w_i \sin(n\phi_i) = Q_n \sin(n\psi_n^{\text{obs}})$$

where w_i is the weight for particle i ($p_{\text{T}}, E_{\text{T}}$ or ADC depending on the detector used).

- The event plane angle from Q_n reads: $\psi_n^{\text{obs}} = \frac{1}{n} \operatorname{arc\,tg}\left(\frac{Q_{n,y}}{Q_{n,x}}\right)$
- The first-order event plane for v_1 is obtained from ZDC-SMD as follows:

$\langle S \rangle = \sum_i S_i w_{S_i} / \sum_i w_{S_i}$ where $S \equiv X, Y$

$\psi_1^{\text{obs}} = \operatorname{arc\,tg}(\langle Y \rangle / \langle X \rangle)$

- Define event plane resolution as:

$$\text{Res}\{\psi_n^{\text{obs}}\} = \langle \cos n(\psi_n^{\text{obs}} - \Psi_{\text{RP}}) \rangle$$

- Event plane resolution from 2 subevent method:

$$\text{Res}\{\psi_n^{A(B)}\} = \sqrt{\langle \cos(n(\psi_n^A - \psi_n^B)) \rangle}$$

- Event plane resolution from 3 subevent method:

$$\text{Res}\{\psi_n^A\} = \sqrt{\frac{\langle \cos n(\psi_n^A - \psi_n^B) \rangle \langle \cos n(\psi_n^A - \psi_n^C) \rangle}{\langle \cos n(\psi_n^B - \psi_n^C) \rangle}}$$