The Global Hyperon Polarization and the Forward-Backward Flow in the Bi+Bi collisions at the NICA energies

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BLTP

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- The **PHSD transport model** as a heavy-ion collisions framework: *Kadanoff-Baym equations, DQPM, FRITIOF Lund, Chiral Symmetry Restoration, ...*

  W. Cassing, E.L. Bratkovskaya, Phys. Rev. C **78** (2008), Nucl. Phys. A **831** (2009)

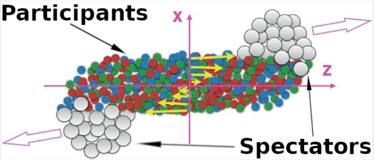
- Transition from kinetic to hydrodynamic description via *fluidization* procedure:

$$T^{\mu\nu}(\boldsymbol{x},t) = \frac{1}{\mathcal{N}} \sum_{a,i_a} \frac{p^{\mu}_{i_a}(t)\, p^{\nu}_{i_a}(t)}{p^{0}_{i_a}(t)} \Phi\left(\boldsymbol{x}, \boldsymbol{x}_{i_a}(t)\right), \qquad \mathcal{N} = \int \Phi\left(\boldsymbol{x}, \boldsymbol{x}_i(t)\right)\, d^3x,$$

$$J^{\mu}_{B}(\boldsymbol{x},t) = \frac{1}{\mathcal{N}} \sum_{a,i_a} B_{i_a} \frac{p^{\mu}_{i_a}(t)}{p^{0}_{i_a}(t)} \Phi\left(\boldsymbol{x}, \boldsymbol{x}_{i_a}(t)\right), \qquad \Phi\left(\boldsymbol{x}, \boldsymbol{x}_i(t)\right) - \text{smearing function},$$

$$u_\mu T^{\mu\nu} = \varepsilon\, u^{\nu}, \qquad n_B = u_\mu J^{\mu}_{B}, \qquad \longrightarrow \qquad \text{EoS}^{1} \qquad \longrightarrow \qquad \text{Temperature}(\varepsilon, n_B)$$

- *The fluidization criterion*: *only cells with* $\varepsilon \geq \varepsilon_{\mathrm{f}} \approx 0.05\,\mathrm{GeV}/\mathrm{fm}^3$!
- *Spectators separation*: *spectators do not interact and do not form fluid!*

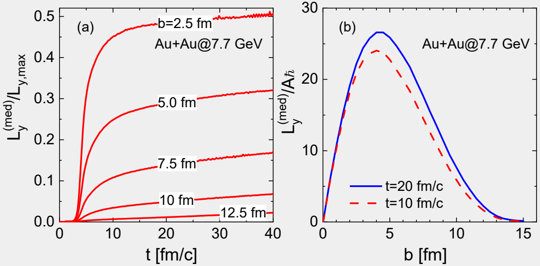


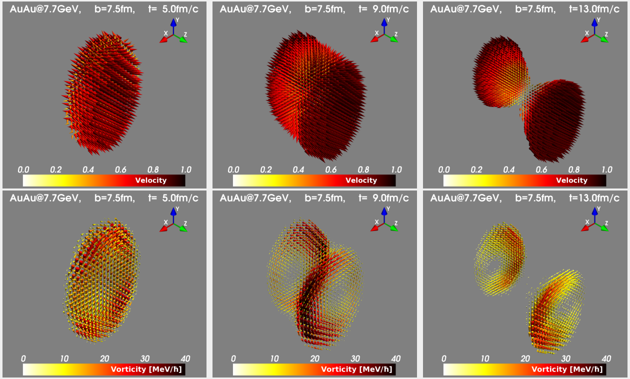
[1] **Hadron resonance gas**: *L.M. Satarov, M.N. Dmitriev, and I.N. Mishustin*, Phys. Atom. Nucl. **72** (2009)

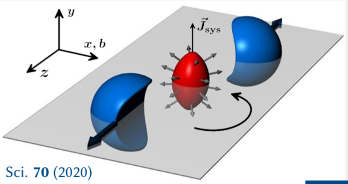
Non-central heavy-ion collisions

- Initial angular momentum of ions is partially transferred to the medium, what leads to the non-vanishing averaged *vorticity*:

$$\vec{L} \quad \longrightarrow \quad \langle\vec{\omega}\rangle = \langle \mathrm{rot}\, \vec{v}\rangle \neq 0$$







- The vorticity field may have *intricate space structure*[1,2]
- The vorticity is a source of the *global particle polarization*[3]

[1] **vortex sheets** (*M.I. Baznat, K.K. Gudima, A.S. Sorin, and O.V. Teryaev*, Phys. Rev. C **93** (2016))

[2] **vortex rings** (*Yu.B. Ivanov, A.A. Soldatov*, Phys. Rev. C **97** (2018); *Yu.B. Ivanov*, Phys. Rev. C **107** (2023))

[3] *F. Becattini, V. Chandra, L. Del Zanna, and E. Grossi*, Annals Phys. **338** (2013); *F. Becattini, M.A. Lisa*, Annu. Rev. Nucl. Part. Sci. **70** (2020)

The thermodynamic approach

F. Becattini, V. Chandra, L. Del Zanna, E. Grossi, Annals Phys. **338** (2013)

Relativistic thermal vorticity:

$$\varpi_{\mu\nu} = \frac{1}{2}(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu), \quad \beta_\nu = \frac{u_\nu}{T}$$

Spin vector:

$$S^\mu(x,p) = -\frac{s(s+1)}{6m}(1 \pm n(x,p))\varepsilon^{\mu\nu\lambda\delta}\varpi_{\nu\lambda}p_\delta$$

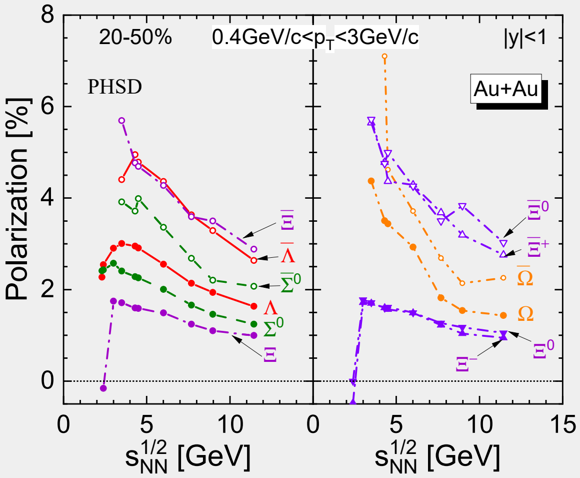
$n(x,p)$ – distribution function, s – spin, m – mass, p_δ – 4 momentum of particle

Spin vector in the particle rest frame:

$$\mathbf{S}^* = \mathbf{S} - \frac{(\mathbf{S}\cdot\mathbf{p})\mathbf{p}}{E(E+m)}$$

Polarization:

$$\mathbf{P} = \mathbf{S}^*/s$$

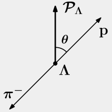


- The polarization for particles and antiparticles is *different!*
- The polarization *decreases* with an energy *increase!*

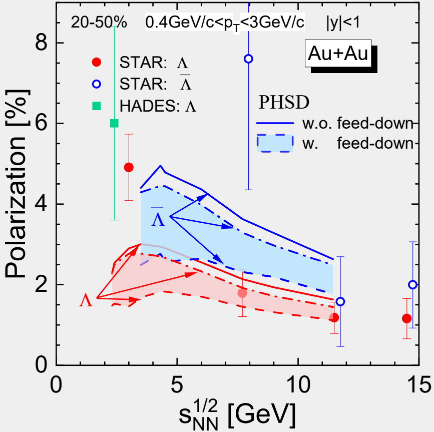
- The Λ and $\bar{\Lambda}$ baryons are the *self-analyzing particles*: due to **P**-violation in weak decays, the angular distribution of final protons depends on the orientation of the Λ-hyperon spin.
- In the hyperon *rest frame*, the decay product distribution is

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta} = \frac{1}{2}(1 + \alpha_{\mathrm{H}}|\vec{\mathcal{P}}_{\mathrm{H}}|\cos\theta)$$

$$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.732 \pm 0.014$$



- The global polarization for particles and antiparticles is *different!*
- The global polarization *decreases* with an *increase* of energy!
- *Good agreement* with the experimental data except low energies.



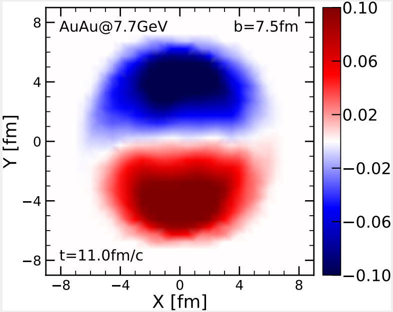
L. Adamczyk et al., Nature **548** (2017)
R.A.Yassine et al. (HADES Coll.), Phys.Lett.B **835** (2022)

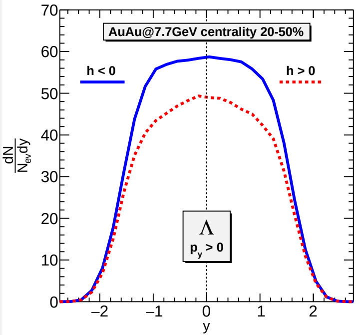
What about other mechanisms?

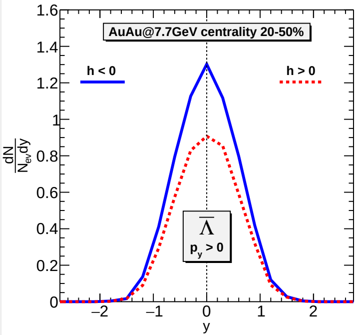
Hydrodynamic helicity

- **The axial vortex effect:** polarization via *helicity* $h = (\vec{v} \cdot \vec{\omega})$ [*A. Sorin, O. Teryaev*, Phys. Rev. C **95** (2017)]
- **The helicity separation effect:** [*M. Baznat, O. Teryaev, A. Sorin, K. Gudima*, Phys. Rev. C **88** (2013)]

$$\widetilde{h}(x, y) = \int h\, dz = \int (\vec{v} \cdot \vec{\omega})\, dz$$



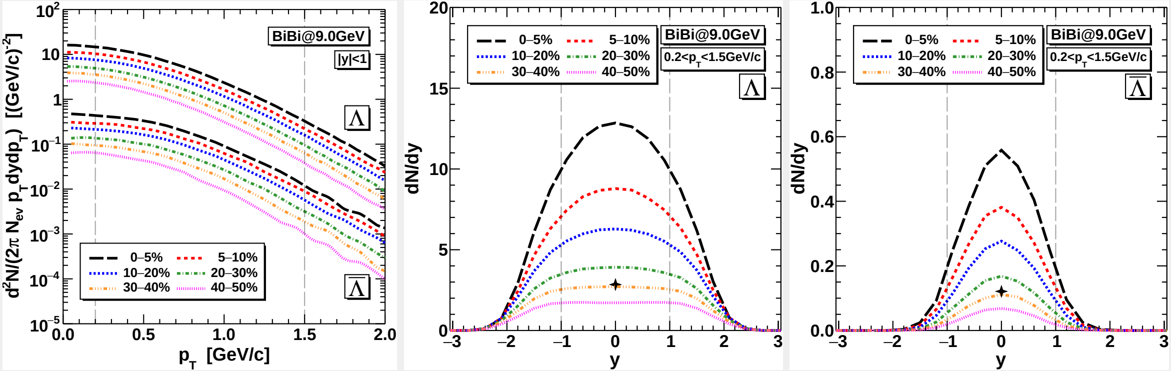




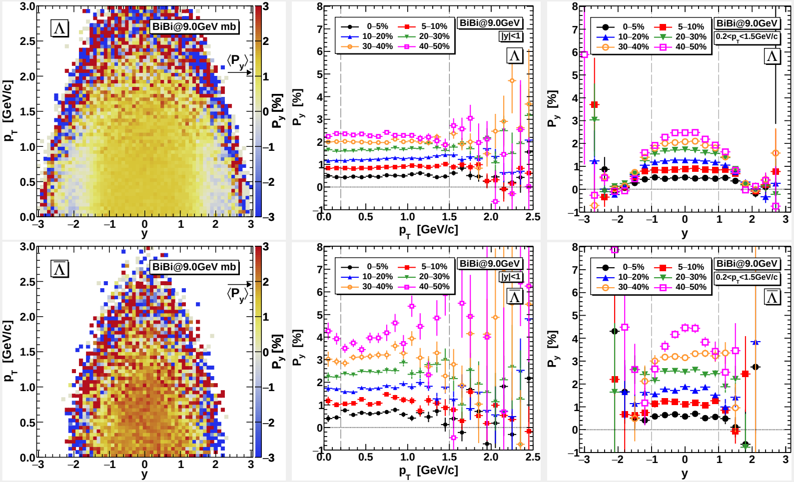
- In the upper semi-plane *with* $h < 0$ there are *more particles with* $p_y > 0$ than with $p_y < 0$!
- Zones with $h < 0$ and $h > 0$ can be probed by selection of Λ's and $\overline{\Lambda}$'s with $p_y > 0$ and $p_y < 0$!
- There is *no difference in the polarization* for particles and antiparticles!

Can we distinguish the vorticity mechanism of global polarization from others?

Hyperon spectra



- The **blast-wave model** for arbitrary velocity field of the fireball (*including flow effects*) is currently under development. The spectrum will be a benchmark for the model.
- Good agreement with the STAR data [*J. Adam et al.* Phys. Rev. C **102**, 034909 (2020)].
- Particles have *broader rapidity distributions* than antiparticles $\longrightarrow$ *rapidity cut is more significant!*



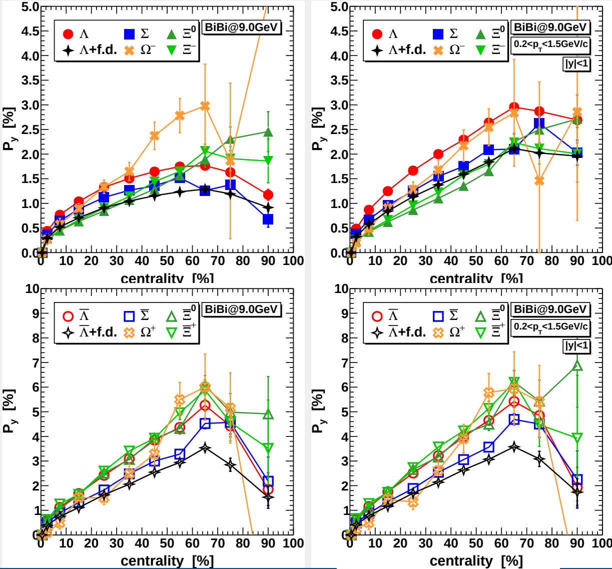
- Plateau in midrapidity and small momentum — *homogeneous medium?*
- Large fluctuations at high rapidities and momenta ⟶ *zero averaged polarization* for these zones.
- Cut by momentum *does not affect* the global polarization.
- Cut by rapidity *increases* the polarization signal for hyperons, but *not for antihyperons*.

Polarization vs centrality

- Polarization *increases* until the $60 - 70\%$ centrality class and then *decreases* for all the hyperon species. The trend is consistent with experimental data[1].

- Feed-down contribution[2] *decreases* the total polarization of Λ and $\overline{\Lambda}$ by $\lesssim 30\%$. The contamination comes from Σ^0 and $\overline{\Sigma}^0$!

- *Cuts increase polarization for hyperons, but not for antihyperons!*



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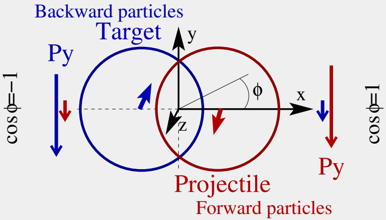
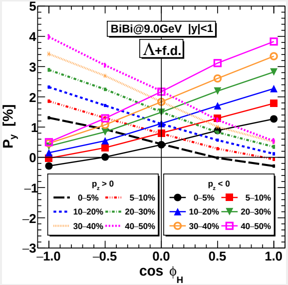
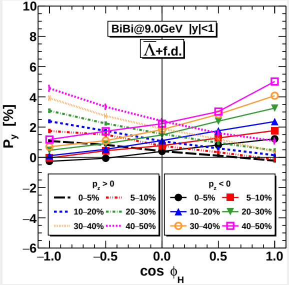
[1] *K. Okubo*, Web Conf. **2022**, 259, 06003.

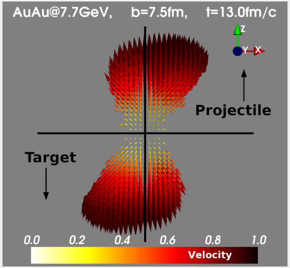
[2] Account of the secondary Λ's from EW decays; strong decays are already taken into account dynamically.

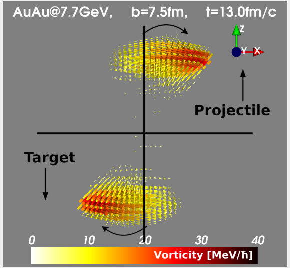
- The highest polarization corresponds to the particles *moving in the same direction as the projectile* (target), which *are mostly born from the matter of the projectile* (target)!
- *We can increase the polarization signal by selecting particles by angle and momentum!*











- We analyzed the angular momentum transfer from the ions to the medium. We observed *two elliptic vortex rings*.
- We found that *polarization for particles and antiparticles is different* and *the polarization decrease with an energy increase* for all the hyperon species. *The polarization of* Λ *and* $\overline{\Lambda}$ *agrees with the experimental data* except low energies. *The most contamination comes from* Σ^0 *and* $\overline{\Sigma}^0$.
- We analyzed the dependence of polarization on momentum and rapidity. There is *no clear dependence for the transverse momentum*, whereas we observed *a plateau at medium rapidities* and *a decrease in polarization at higher rapidities. The particles are more sensitive for the rapidity cuts than antiparticles.*
- We analyzed the centrality dependence of the global polarization. It agrees with the experimental trend.
- We found *correlations between forward-backward flows and polarization. Selecting particles by angles and the sign of* p_z*, we can increase the polarization signal.*
- *The vorticity mechanism leads to different polarizations of particles and antiparticles without any additional assumption of different effects on them. The polarization trends are consistent with the experimental data.*

Thank You!
Questions?