Hyperon Production, Vortex Rings, and Angular Dependence of Hyperon Spin Polarization at NICA complex energies

Phys.Rev. C 107 (2023) 3, Particles 6 (2023), arXiv:2305.10792, Particles 7 (2024)

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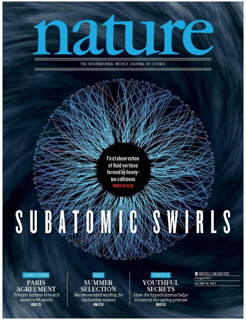
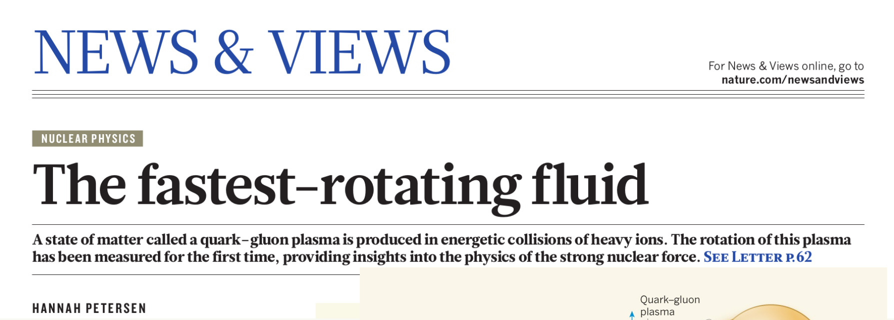
Introduction





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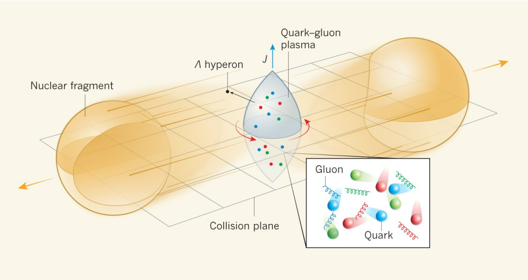
NUCLEAR PHYSICS

The fastest-rotating fluid

A state of matter called a quark–gluon plasma is produced in energetic collisions of heavy ions. The rotation of this plasma has been measured for the first time, providing insights into the physics of the strong nuclear force. SEE LETTER P.62

HANNAH PETERSEN



- The polarization experiments provide new insights into deep physical nature.
- The global polarization of Λ and $\overline{\Lambda}$ in heavy-ion collisions leads to the hypothesis that *a quark-gluon plasma is the fastest rotating fluid*.

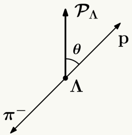
Why Λ hyperons and where does rotation come from?

The global polarization of Λs and vorticity

- The Λs 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

$$\frac{dN}{d\cos\theta} = \frac{1}{2}(1 + \alpha_{\rm H}|\boldsymbol{\mathcal{P}}_{\rm H}|\cos\theta)$$

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

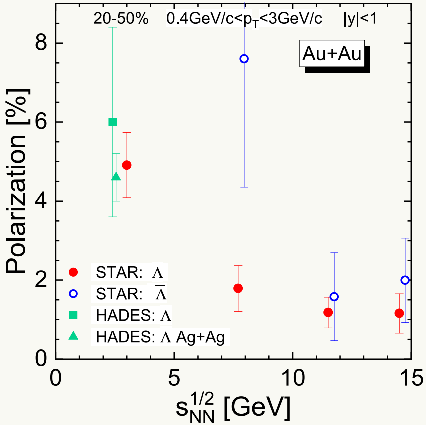


- *Rough estimate* of vorticity (**STAR**):

$$\omega_{\rm STAR} \approx \left\langle \frac{k_B T}{\hbar}(\overline{\mathcal{P}}_\Lambda + \overline{\mathcal{P}}_{\bar\Lambda}) \right\rangle_{\sqrt{s_{NN}}} \approx 10^{22}\,\mathrm{s}^{-1}$$

The fastest-rotating fluid?

pulsar PSR J1748–2446ad	$\omega \sim 5 \times 10^3\,\mathrm{s}^{-1}$
superfluid He II nanodroplets	$\omega \sim 10^7\,\mathrm{s}^{-1}$



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

Why the polarization decreases with an energy increase?

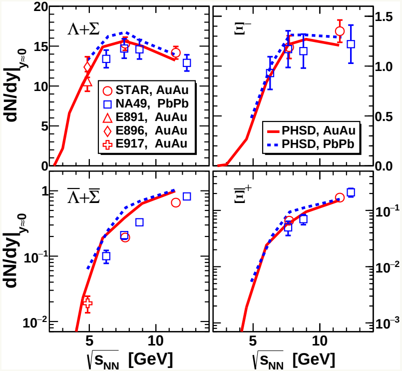
Why the polarization for $\overline{\Lambda}$ is higher than Λ?

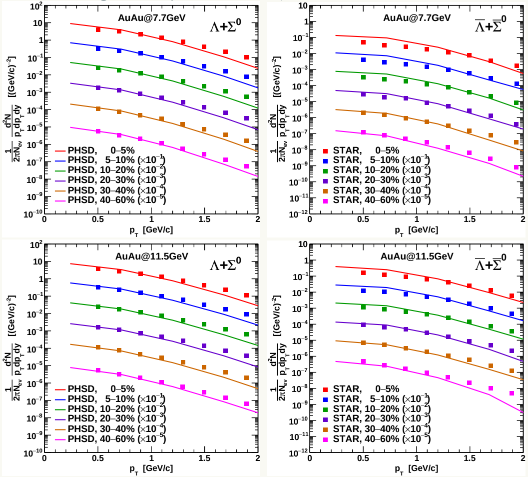
Is vorticity actually a source of the observed polarization?

How big is the rotation in reality?

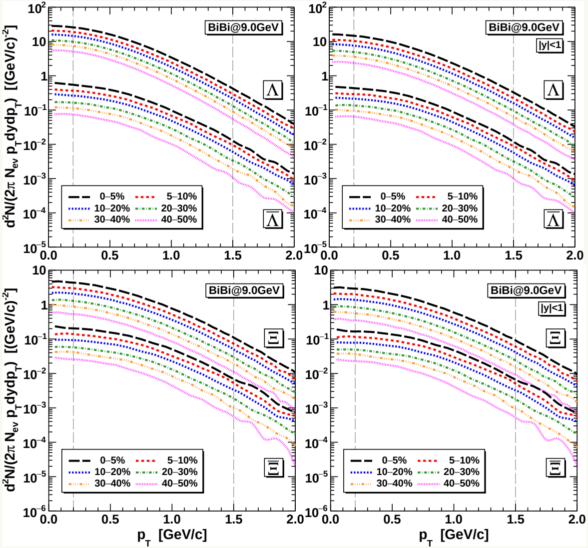
- The **PHSD transport model** as a heavy-ion collisions framework: **Kadanoff-Baym equations** (on-shell and off-shell dynamics, first gradient expansion, test particles ansatz), **DQPM** (parton phase), **FRITIOF Lund** (hard scattering), **Chiral Symmetry Restoration** (strangeness production), ...

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



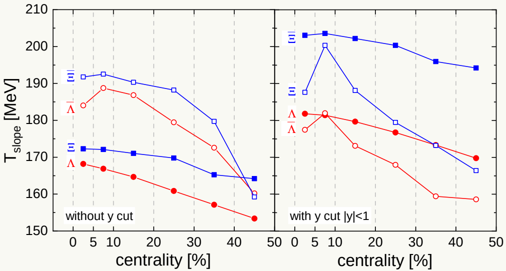


Transverse momentum spectra



- To find the slopes we fit the distributions with the blast-wave formula ($0.5 \leq p_T \leq 1.5$ GeV):

$$\frac{dN}{2\pi p_T dp_T} = A m_T K_1\left(\frac{m_T}{T_{\text{slope}}}\right), \quad m_T = \sqrt{m_H^2 + p_T^2}.$$



- *For hyperons T_{slope} shows weak dependence* on the centrality decreasing by $\sim 5 - 15$ MeV. *For anti-hyperons a decrease is stronger* (by ~ 30 MeV).
- *The cut $|y| < 1$ leads to an increase of T_{slope}* by $13 - 17$ MeV for Λs and by 30 MeV for Ξs.

The slopes of the p_T-spectra indicate that anti-hyperons decouple from the fireball at an earlier stage than hyperons!

Let’s analyze the medium properties.

The fluidization procedure

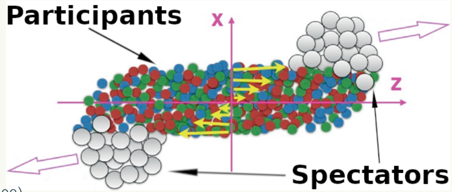
- *The main feature*: we investigate the medium properties using *a fully microscopic approach!*
- Transition from particles to continuous medium via the *“continuization”* procedure:

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

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

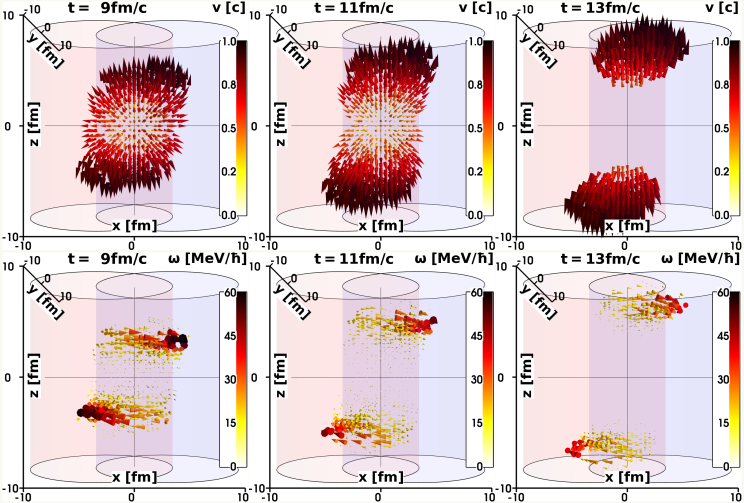
$$u_\mu T^{\mu\nu} = \varepsilon\, u^{\nu}, \qquad n_B = u_\mu J^{\mu}_{B}, \qquad \longrightarrow \qquad \text{EoS}^{a} \qquad \longrightarrow \qquad \text{Temperature}(\varepsilon, n_B)$$

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



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

The velocity and vorticity fields for BiBi@9.0GeV, b=8.5fm



- The fireball velocity $\boldsymbol{v}$ consists of **the irrotational Hubble part** and *a small admixture leading to the vorticity* $\boldsymbol{\omega} = \boldsymbol{\nabla} \times \boldsymbol{v}$.
- **Two deformed elliptical vortex rings** move and rotate in opposite directions along the collision axis.
- The ring deformation depends on the impact parameter.

- The vorticity magnitude reaches $\sim 80\ MeV/\hbar \sim 10^{23}\ s^{-1}$ in dynamics!

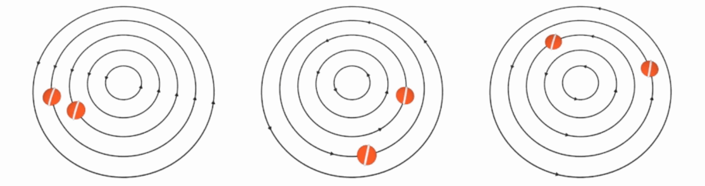
But vorticity is a dimensional and ambiguous quantity, so how big is the rotation in reality?

- Irrotational vortex:

$$\boldsymbol{\Omega} = (0, 0, \alpha r^{-2})$$

$$\boldsymbol{v} = \boldsymbol{\Omega} \times \boldsymbol{r} = (-\frac{\alpha y}{r^2}, \frac{\alpha x}{r^2}, 0)$$

$$\boldsymbol{\omega} = \nabla \times \boldsymbol{v} = 0$$

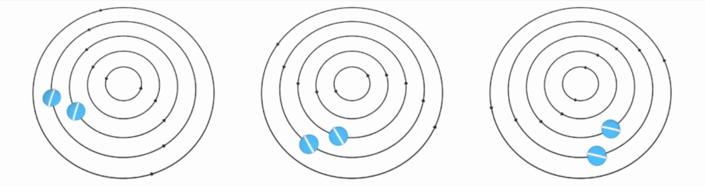


- Rigid-body rotation:

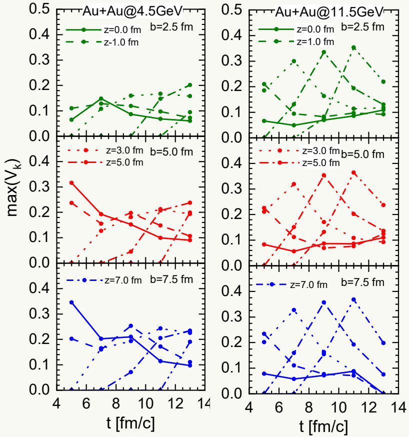
$$\boldsymbol{\Omega} = (0, 0, \Omega)$$

$$\boldsymbol{v} = \boldsymbol{\Omega} \times \boldsymbol{r} = (-\Omega y, \Omega x, 0)$$

$$\boldsymbol{\omega} = (0, 0, 2\Omega) = 2\boldsymbol{\Omega}$$



The kinematic vorticity number $\mathfrak{W}_k$ as a measure of rotationality



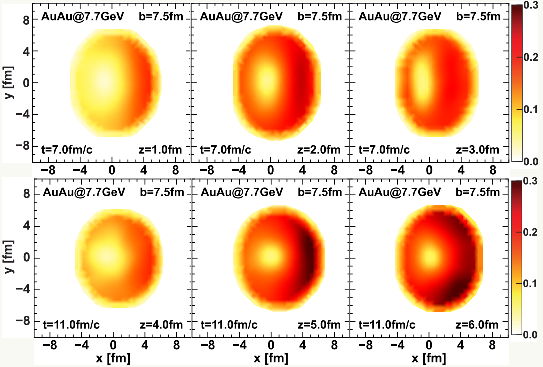
$$\partial_i v_j = \xi_{ij,+} + \xi_{ij,-}$$

$$\xi_{+,ij} = \frac{1}{2}(\partial_i v_j + \partial_j v_i)$$

$$\xi_{-,ij} = \frac{1}{2}(\partial_i v_j - \partial_j v_i)$$

$$\xi_+^2 = \xi_+^{ij}\xi_{ij,+}$$

$$\xi_-^{ij}\xi_{ij,-} = \omega^2/2$$



$$\mathfrak{W}_k = \sqrt{\frac{\xi_-^{ij}\xi_{ij,-}}{\xi_+^{kl}\xi_{kl,+}}} = \frac{|\omega|}{\sqrt{2}\xi_+}$$

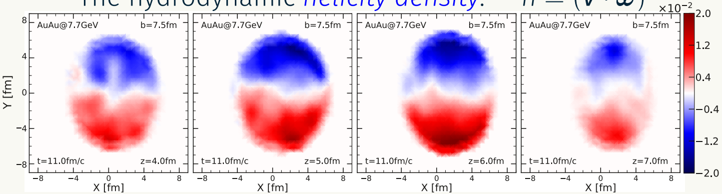
$$V_k = \frac{2}{\pi}\arctan \mathfrak{W}_k$$

- $0 \le V_k \le 1$: $V_k = 0$ for *irrotational shear motion*, $V_k = 1$ for *pure rigid-body rotation*.
- $\max(V_k) < 1/2 =$ **Poiseuille flow** $\longrightarrow$ ***shear motion, almost irrotational!***
- $\mathfrak{W}_k$ was firstly proposed in *C. Truesdell*, J. Rational Mech. Anal. 2, **173** (1953).

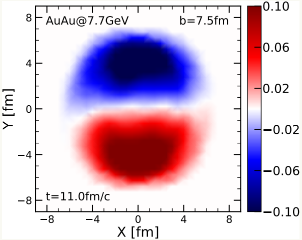
The hydrodynamic helicity $h = \mathbf{v} \cdot \boldsymbol{\omega}$

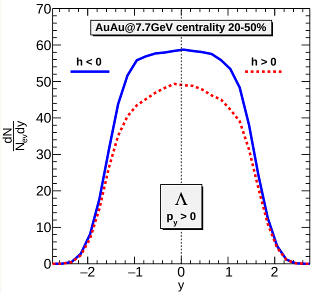
- **The axial vortex effect:** polarization due to the *helicity* [*A. Sorin, O. Teryaev*, Phys. Rev. C **95** (2017)]
- **The helicity separation effect** [*M. Baznat, O. Teryaev, A. Sorin, K. Gudima*, Phys. Rev. C **88** (2013)]

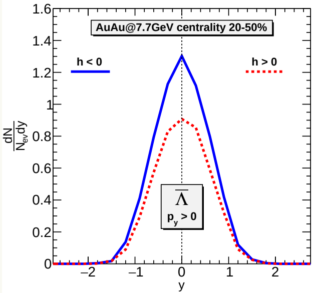
The hydrodynamic *helicity density*: $h = (\mathbf{v} \cdot \boldsymbol{\omega})$



$\widetilde{h}(x, y) = \int h(x, y, z)\, dz$







- In the semi-plane $h < 0$ ($h > 0$) there are *more particles with* $p_y > 0$ ($p_y < 0$)!
- Zones with *negative* and *positive* helicities can be probed by selection of Λs and $\bar{\Lambda}$s with *positive* and *negative* p_y.

Let's move on to polarization analysis.

Polarization of particles with spin in a vorticity field

- **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:

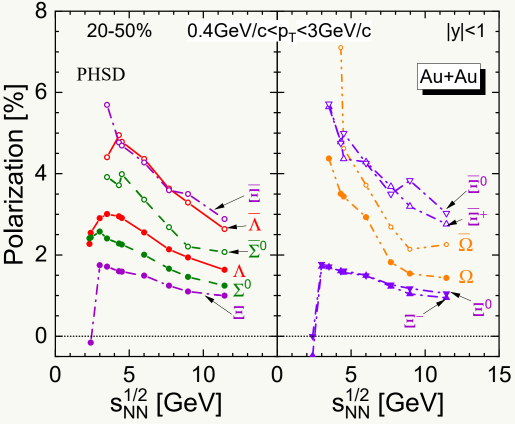
$$\mathbf{S}^* = \mathbf{S} - \frac{(\mathbf{S}\cdot\mathbf{p})\mathbf{p}}{E(E+m)}$$

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

- **Our algorithm:**

1. At each time step we fluidize the system (*excluding spectators*) and calculate vorticity.
   Medium: $\varepsilon > \varepsilon_f \approx 0.05$ GeV/fm^3 and $\varpi_{\mu\nu} \neq 0$.
   Out of medium: $\varepsilon \leq \varepsilon_f \approx 0.05$ GeV/fm^3 and $\varpi_{\mu\nu} = 0$.
2. After any collision (elastic or inelastic) particle is polarized by $\varpi_{\mu\nu}$. *In out of medium the polarization is zero due to $\varpi_{\mu\nu} = 0$.*
3. **Feed-down:**
   Strong decays: $\Sigma^* \to \Lambda + \pi, \quad \Xi^* \to \Xi + \pi$
   are already taken into account in the PHSD dynamic ($C_{\Lambda\Sigma^*} = C_{\Xi\Xi^*} = 1/3$).
   EW decays: $\Xi \to \Lambda + \pi, \quad \Sigma \to \Lambda + \gamma$
   we consider *by hand* with $C_{\Lambda\Sigma^0} = -1/3$, $C_{\Lambda\Xi^0} = 0.914$, and $C_{\Lambda\Xi^0} = 0.943$.

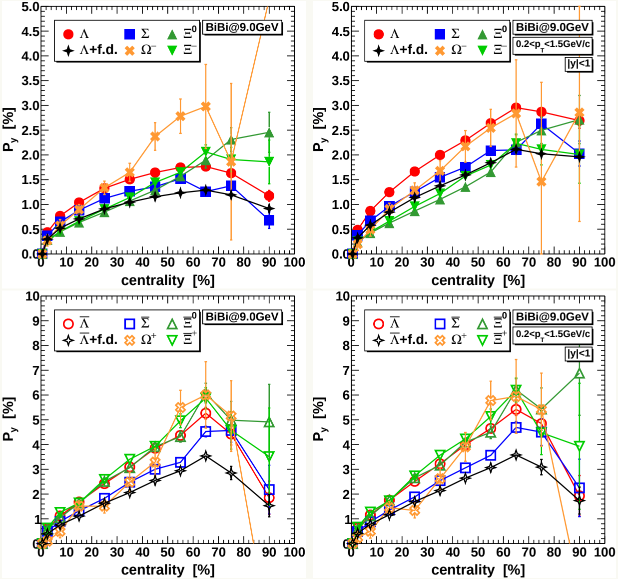
Polarization vs. collision energy



- There is ***a different polarization for particles and antiparticles*** for all the hyperon species.
- The polarization of all the hyperon kinds ***decreases with an energy increase*** for $\sqrt{s_{NN}} > 3 - 5$ GeV.
- The *strongest decrease* and *smallest difference* is for Ω and $\overline{\Omega}$.
- *The biggest difference is for Ξ and $\overline{\Xi}$.*
- The maximum of Λ and $\overline{\Lambda}$ polarization occurs at $\sqrt{s_{NN}} \approx 4$ GeV.
- The following polarization hierarchy holds for the energy range $\sqrt{s_{NN}} = 3.5 - 11.5$ GeV:

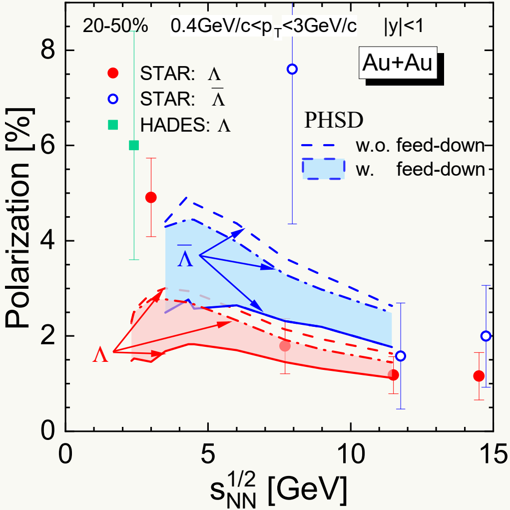
$$P_{\overline{\Xi}} \approx P_{\overline{\Lambda}} > P_{\overline{\Sigma}^0} > P_{\Lambda} > P_{\Sigma^0} > P_{\Xi}.$$

Polarization vs. centrality



- There is a ***different polarization for particles and antiparticles*** for all the hyperon species.
- ***The polarization increases with an centrality class increase*** (up to $60-70\%$) and then *decreases* for all the hyperon species. Is is also an experimental trend!
- *The cuts increase polarization for hyperons*, *but not for anti-hyperons!*
- The feed-down contribution *decreases* the total polarization of Λ and $\overline{\Lambda}$ by $\lessapprox 30\%$. The contamination mostly comes from Σ^0 and $\overline{\Sigma}^0$!

- The filled area reflects uncertainty between ratio of Λ and Σ. The limiting case, where all Σs are considered as Λs, is depicted via a dash-dotted line.



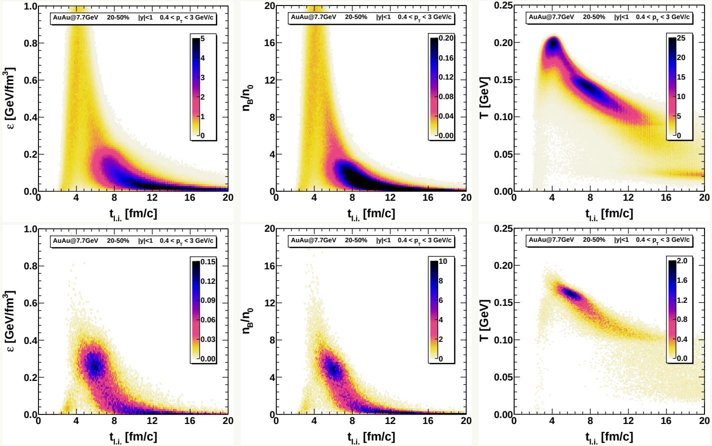
- The polarization of Λ hyperons *agrees* with experimental data, *except low energies.* The polarization of $\bar{\Lambda}$ is *larger in $1.5 - 2$ times* than Λ.
- ***It looks more attractive to consider the global polarization of Ξ hyperons***, which experimentally could be *clearly identified* and would carry ***direct information about the spin polarization of the fireball***.
- Moreover, a part of Ξ comes from Ξ^* decays and *carries by factor 5/3 stronger polarization than primary Ξs.*

In fact, the vorticity is the only one *dynamical* mechanism which results in different polarization *without* any distinctions between particles and anti-particles!

But what is a source of the difference?

Particle distributions at the moment of its last interaction

$$\frac{d^2N}{d\varepsilon\, dt_{\mathrm{l.i.}}} \qquad \frac{d^2N}{dn_B\, dt_{\mathrm{l.i.}}} \qquad \frac{d^2N}{dT\, dt_{\mathrm{l.i.}}}$$



- Hyperons: *two broad temperature peaks* from smooth and broad density distributions
- Anti-hyperons: *one narrow temperature peak* from more localized (in 2-D sense) distributions

- *Different thermodynamic conditions for particles and anti-particles* ⟶ *different polarization!*

Can we find an imprint of the vorticity mechanism?

Can we find an imprint of the vorticity mechanism?

YES!

Can we find an imprint of the vorticity mechanism?

YES!

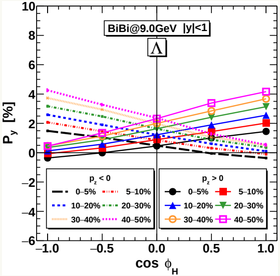
Let’s look at the angular dependence of polarization.

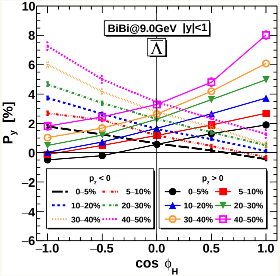
The angular dependence of the hyperon polarization

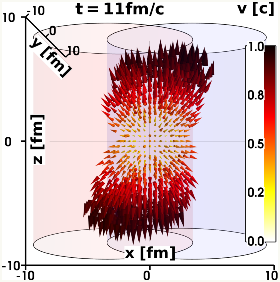
$$\phi_{\mathrm{H}} = \mathrm{atan}(p_y/p_x)$$

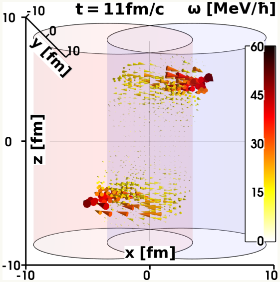
$$\cos\phi_{\mathrm{H}} = p_x/p_T$$

- 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.*
- *The imprint of the vorticity mechanism is the angular dependence of the polarization!*









Conclusions

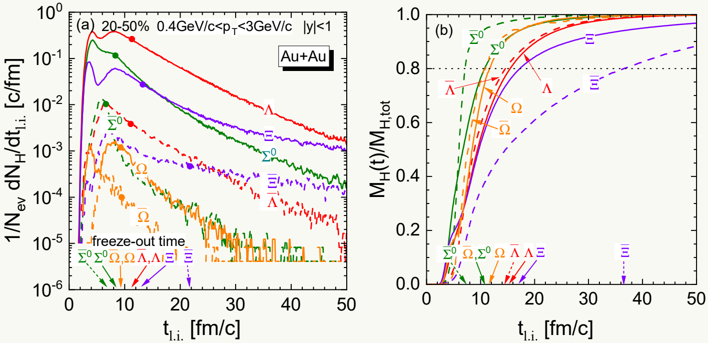
- We compare the yields and spectra received within **PHSD** with experimental data. There is a good correspondence.
- The spectra suggest that *anti-hyperons decouple from the fireball earlier than hyperons.*

- We developed a transition from kinetic to hydrodynamic description via *fluidization* procedure.
- We analyzed the angular momentum transfer from the ions to the medium. The maximum of the transfer for $\mathrm{Au}+\mathrm{Au}$ at $\sqrt{s_{NN}} = 4.5 - 11.5$ GeV is reached at $b \approx 5$ fm.
- We observed *two deformed elliptic vortex rings*. The deformation depends on the impact parameter.
- We analyzed a measure of the rotationality and concluded that *the flow is mostly irrotational*.
- We observed *the helicity separation effect* and found that zones with *negative* and *positive* helicities can be probed by selection of Λs and $\overline{\Lambda}$s with *positive* and *negative* p_y.

- We found that *polarization for anti-particles is larger than for particles* and *the polarization decrease with an energy increase* for all the hyperon species. *The most contamination in the feed-down account comes from Σ^0 and $\overline{\Sigma}^0$*.
- We observed that *the polarization increases with centrality* up to $60 - 70\%$ centrality class and then decreases.
- We investigated the polarization sources and confirmed that the anti-hyperons and hyperons have *different thermodynamic conditions at freeze-out*, what *leads to different polarizations*.
- We found that *the angular dependence of the polarization is an imprint of the vorticity mechanism*. *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.*

Backup

Freeze-out time



- $\sqrt{s_{NN}} = 7.7$ GeV
- There are *two main sources* of hyperons and *only one of anti-hyperons*.
- The freeze-out times relation is

$$t^{(\text{f.o.})}_{\Lambda} \approx t^{(\text{f.o.})}_{\overline{\Lambda}}, \qquad t^{(\text{f.o.})}_{\Omega} \approx t^{(\text{f.o.})}_{\overline{\Omega}}$$

$$t^{(\text{f.o.})}_{\Sigma} > t^{(\text{f.o.})}_{\overline{\Sigma}}, \qquad t^{(\text{f.o.})}_{\Xi} < t^{(\text{f.o.})}_{\overline{\Xi}}$$

particle	Λ	$\overline{\Lambda}$	Σ	$\overline{\Sigma}$	Ξ^-	$\overline{\Xi}^+$	Ξ^0	$\overline{\Xi}^0$	Ω	$\overline{\Omega}$
$t^{(\text{f.o.})}$, fm/c	11.36	11.09	8.25	6.67	13.69	21.97	12.85	21.47	9.33	9.14

- There is *no direct connection between the freeze-out time and polarization* in opposite to **UrQMD** (*O. Vitiuk, L.V. Bravina, E.E. Zabrodin*, PLB**803**, (2020)).

In comparison with calculations in PLB803, we find a smaller difference in the mean freeze-out times for $\Lambda(\overline{\Lambda})$ hyperons:

$$t_{\Lambda}^{(\mathrm{f.o.})} - t_{\overline{\Lambda}}^{(\mathrm{f.o.})} \approx 0.27\,\mathrm{fm}/c \ \text{ against } \approx 1.5\,\mathrm{fm}/c,$$

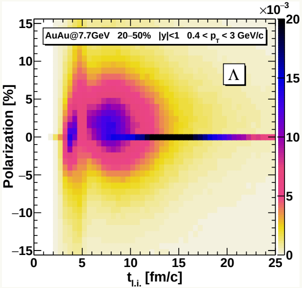
whereas the mean time itself is twice as short:

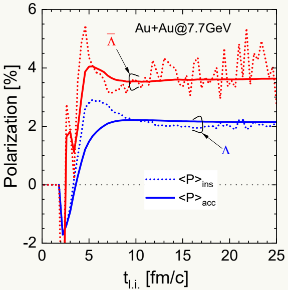
$$t_{\Lambda(\overline{\Lambda})}^{(\mathrm{f.o.})} \approx 11.2\,\mathrm{fm}/c \ \text{ vs. } \approx 19.8 - 21.3\ \mathrm{fm}/c.$$

In general, the interacting phase of the nucleus-nucleus collision last in the UrQMD model longer than in PHSD:

$$\sim 300\ \mathrm{fm}/c \ \text{ vs. } \sim 50\ \mathrm{fm}/c.$$

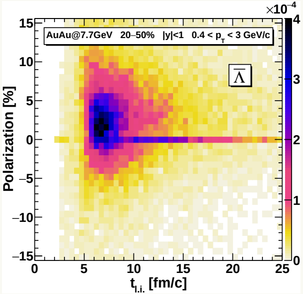
Polarization vs. time of the last interaction





- There are *two main sources* of hyperons and *only one of anti-hyperons*.
- The following relation holds for both instantaneous and accumulated polarizations for $t_{\mathrm{l.i.}} \gtrsim 3\,\mathrm{fm/c}$:

$$P_y(\overline{\Lambda}) > P_y(\Lambda).$$



- The vast amount of Λs is released *with zero polarization due to rescattering processes* occurring in *the dilute matter with vanishing vorticity* $(\sim 10 - 20\,\mathrm{fm}/c)$.
- For $t \gtrsim 10\,\mathrm{fm}/c$ the accumulated polarization stays *approximately constant*. The instant polarization is not zero due to decays of the resonances.
- *The polarization changes the sign* at the moment of full overlap.