The 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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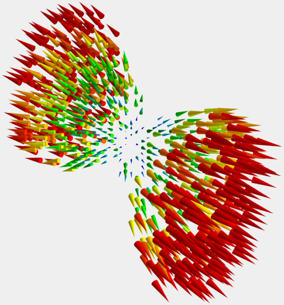


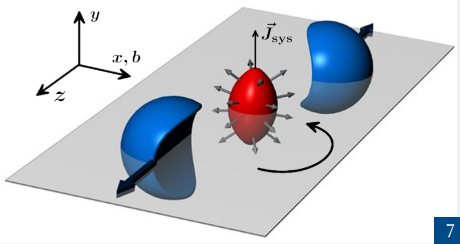
- Hot and dense created matter undergoes explosive expansion — **the Little Bang**
- Large initial orbital angular momentum is partially transferred to the medium, what leads to the non-vanishing averaged *vorticity*:

$$\vec{L} \quad \longrightarrow \quad \langle \vec{\omega} \rangle = \langle \text{rot}\, \vec{v} \rangle$$

- The vorticity is a source of the *global particle polarization*

  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 vorticity field may have *intricate space structure*
  - **Femto-vortex sheets**: *M.I. Baznat, K.K. Gudima, A.S. Sorin, and O.V. Teryaev*, Phys. Rev. C **93** (2016)
  - **Vortex rings**: *Yu.B. Ivanov, A.A. Soldatov*, Phys. Rev. C **97** (2018)

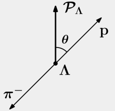


- The $\mathbf{\Lambda}$ and $\bar{\mathbf{\Lambda}}$ baryons are the *self-analyzing particles*: due to **P**-violation in weak decays, the angular distribution of final protons depends on the orientation of the $\mathbf{\Lambda}$-hyperon spin

- In the hyperon *rest frame*, the decay product distribution is

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

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



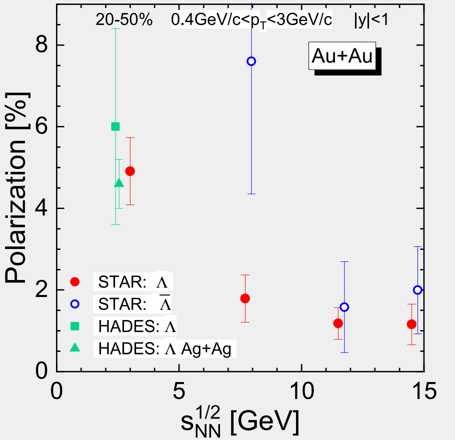
- *Rough estimate* of vorticity (**STAR**):

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

The fastest-rotating fluid?

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

- The experimental data of the global $\mathbf{\Lambda}$ and $\bar{\mathbf{\Lambda}}$ polarization



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

- 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)

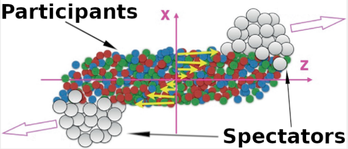
- Transition from kinetic to hydrodynamic description via *fluidization* procedure:

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

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

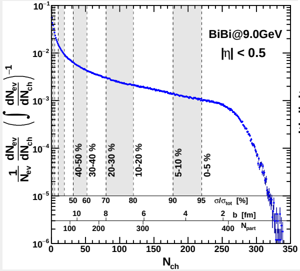
$$u_\mu T^{\mu\nu} = \boldsymbol{\varepsilon}\, u^\nu, \qquad n_B = u_\mu J^{\mu}_{B}, \qquad \longrightarrow \qquad \text{EoS}^1 \qquad \longrightarrow \qquad \text{Temperature}(\boldsymbol{\varepsilon}, n_B)$$

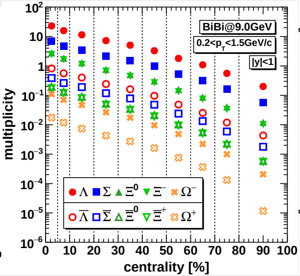
- *The fluidization criterion*: *fluidize only cells with* $\boldsymbol{\varepsilon} \geq \boldsymbol{\varepsilon}_{\mathrm{f}} \approx 0.05\,\mathrm{GeV}/\mathrm{fm}^3$*!*
- *Spectators separation*: *spectators do not interact and do not form fluid!*

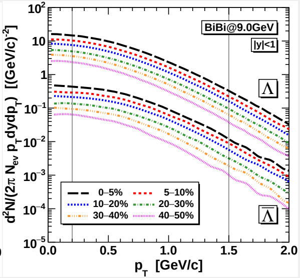


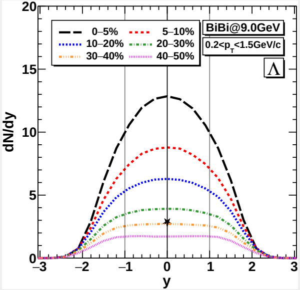
[1] **Hadron resonance gas**: *L.M. Satarov, M.N. Dmitriev, and I.N. Mishustin*, Phys. Atom. Nucl. **72** (2009)

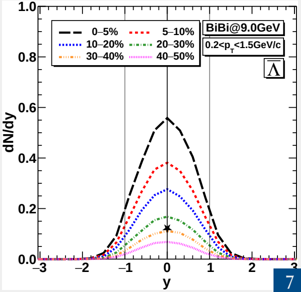
- We simulate $N_{\rm ev} \sim 2 \times 10^6$ collisions of Bi+Bi at $\sqrt{s_{NN}} = 9.0\,$GeV, define centrality classes, and calculate hyperon multiplicities and spectra:











$$p_T = \sqrt{p_x^2 + p_y^2}, \qquad y = \frac{1}{2}\log\frac{E+p_z}{E-p_z}$$

- There is a very good agreement with the STAR data[1]: Au+Au collisions at $\sqrt{s_{NN}} = 7.7 - 11.5\,$GeV with rapidity cut $|y| < 0.5$

[1] J. Adam et al. Phys. Rev. C **102**, 034909 (2020).

Polarization of particles with spin in vorticity field

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

  Relativistic thermal vorticity:

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

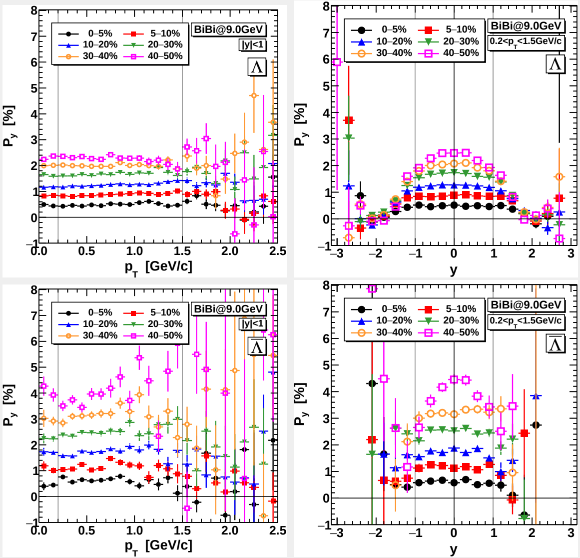
  Spin vector:

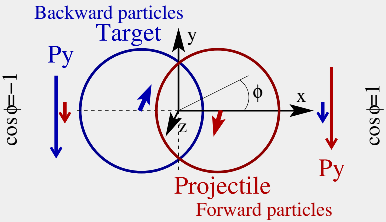
$$S^\mu(x,p) = -\frac{s(s+1)}{6m}(1 \pm n(x,p))\varepsilon^{\mu\nu\lambda\delta}\varpi_{\nu\lambda}p_\delta$$

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

  Polarization: $\mathbf{P} = \mathbf{S}^*/s$
  $\mathbf{S}^*$ spin vector in rest frame

- There is no polarization dependence on p_T.
  A plateau at medium rapidities and
  a decrease in polarization at high rapidities.





Anisotropic flows ($\Psi_{\mathrm{RP}} = 0$ in PHSD):

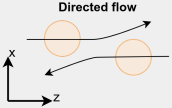
$$\frac{dN}{d\phi_{\mathrm{H}}} = \frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi_{\mathrm{H}} - \Psi_{\mathrm{RP}}))\right),$$

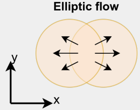
$$v_n = \langle \cos(n(\phi_{\mathrm{H}} - \Psi_{\mathrm{RP}}))\rangle,$$

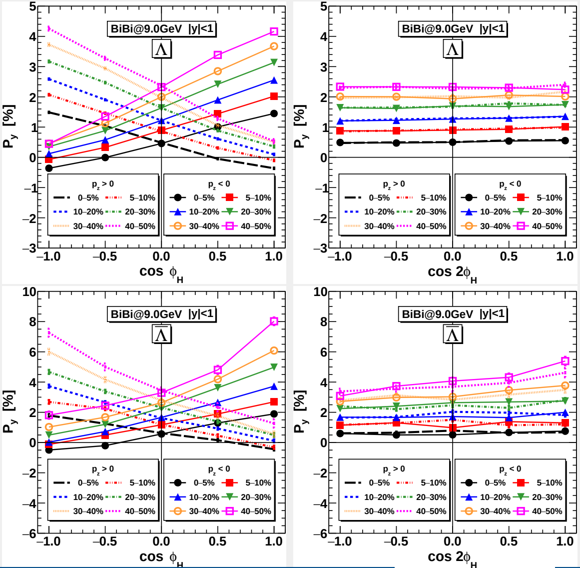
$$\phi_{\mathrm{H}} = \arctan(p_y/p_x),$$

$\cos\phi_{\mathrm{H}} \longleftrightarrow v_1$ – **directed flow**,

$\cos 2\phi_{\mathrm{H}} \longleftrightarrow v_2$ – **elliptic flow**







Summary

- We simulated $N_{\text{ev}} \sim 2 \times 10^6$ collisions of Bi+Bi at $\sqrt{s_{NN}} = 9.0\,\text{GeV}$, determined centrality classes, and calculated hyperon multiplicities and spectra. There is a very good coincidence within the STAR data.
- 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 high rapidities. The particles more sensitive for the rapidity cuts than antiparticles.
- We found correlations between directed flow and polarization. There is no correlation for elliptical flow. Selecting angle and p_z, we can probe the matter properties from the projectile and target, correspondingly.
- It was only a part of the results. A more complex analysis is being prepared for publication.

Thank You!
Questions?