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

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BLTP

*Global hyperon polarization on MPD*

25 June 2024

# Outline

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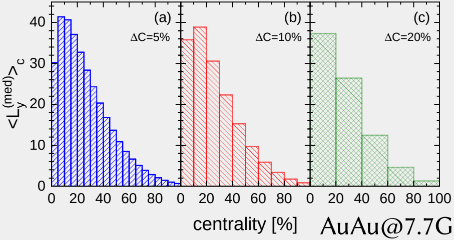
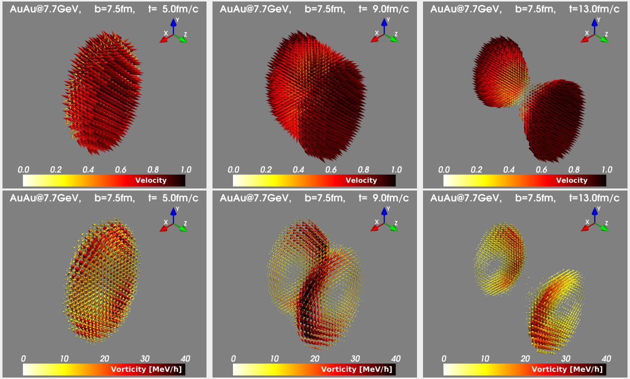
# Non-central heavy-ion collisions

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

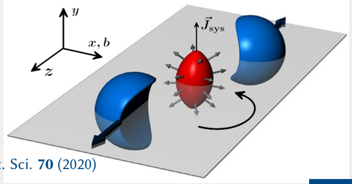
$$\vec{L} \quad \longrightarrow \quad \langle \vec{\omega} \rangle = \langle \mathrm{rot}\, \vec{v} \rangle \neq 0$$




AuAu@7.7GeV




- 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))

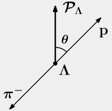
[2] **vortex rings** (*Yu.B. Ivanov, A.A. Soldatov*, Phys. Rev. C **97** (2018); *Yu.B. Ivanov*, Phys. Rev. C **107** (2023))

[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 $\Lambda$ 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 $\Lambda$-hyperon spin
- In the hyperon *rest frame*, the decay product distribution is

$$\frac{dN}{d\cos\theta} = \frac{1}{2}(1 + \alpha_H|\vec{\mathcal{P}}_H|\cos\theta)$$

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



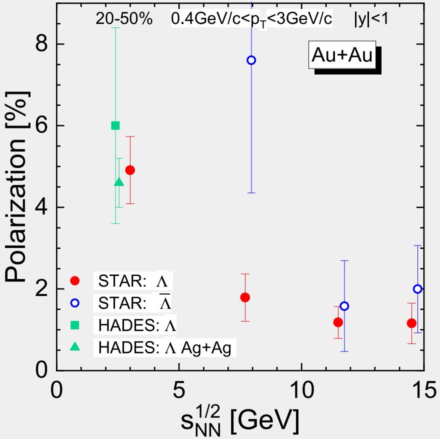

- *Rough estimate* of vorticity (**STAR**):

$$\omega \approx \left\langle \frac{k_B T}{\hbar}(\overline{\mathcal{P}}_\Lambda + \overline{\mathcal{P}}_{\bar{\Lambda}}) \right\rangle_{\sqrt{s_{NN}}} \approx 10^{22}\,\mathrm{s}^{-1} \approx 6\mathrm{MeV}/\hbar$$

*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 $\Lambda$ and $\bar{\Lambda}$ 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)

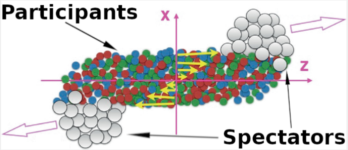
- Transition from kinetic to hydrodynamic description via *fluidization* procedure:

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

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

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

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

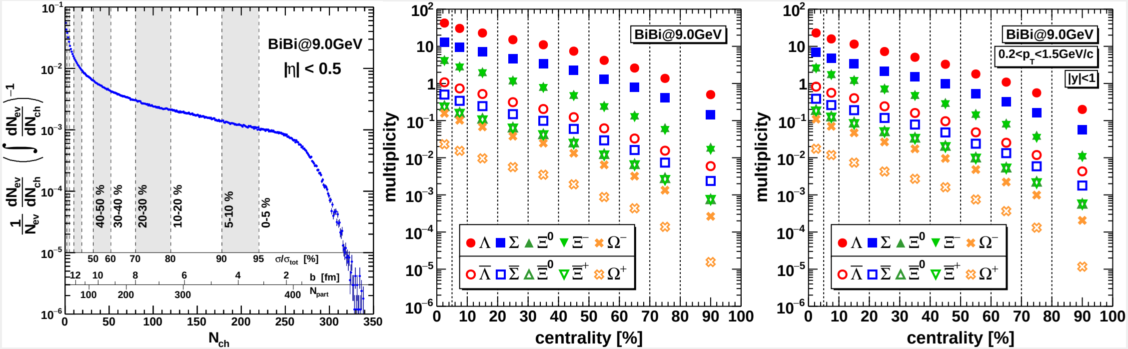



[1] **Hadron resonance gas**: *L.M. Satarov, M.N. Dmitriev, and I.N. Mishustin*, Phys. Atom. Nucl. **72** (2009)

# Outline

# Centrality determination

- We simulate $N_{\text{ev}} \approx 2 \times 10^6$ collisions of Bi+Bi at $\sqrt{s_{NN}} = 9.0\,\text{GeV}$.
- Then, we define a centrality class as a fraction of the cross section $\sigma/\sigma_{\text{tot}}$.
- Finally, we evaluate multiplicities with/without acceptance.

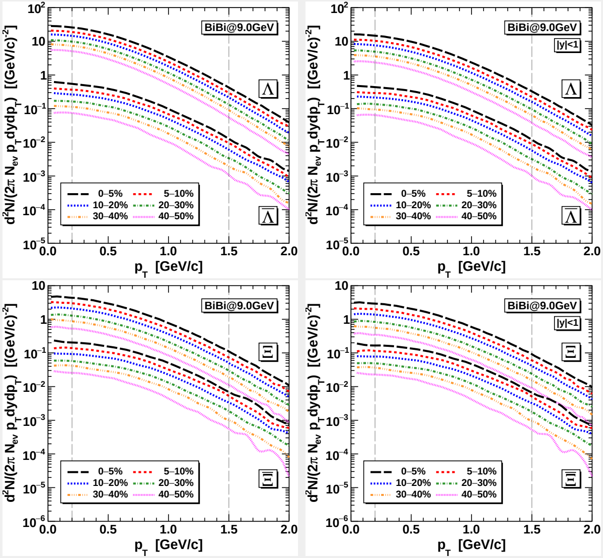



- *The minimum bias collisions approximately coincide with the 30-40% centrality class.*
- $\dfrac{\text{multiplicity without cuts}}{\text{multiplicity with cuts}} \approx 2 \div 2.5$
- Good agreement with the NA49 data[1].

[1] PRL **94**, 192301 (2005); PRC **78**, 034918 (2008)

# Hyperon spectra: $\frac{d^2N}{dy\,dp_T}$

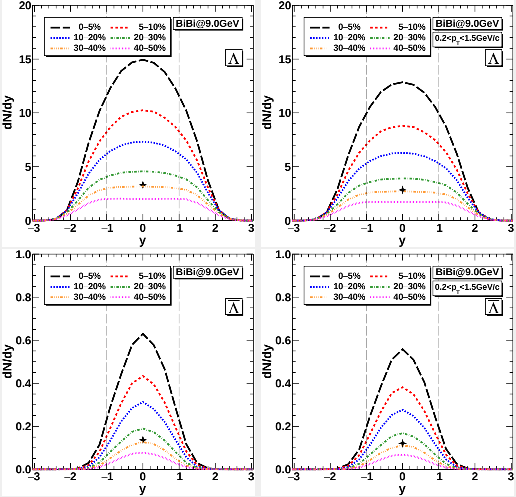
- Good agreement with the STAR data[1].
- The **blast-wave model** for arbitrary velocity field of the fireball (*including flow effects*) is currently under development. The spectrum will be a benchmark for the model.



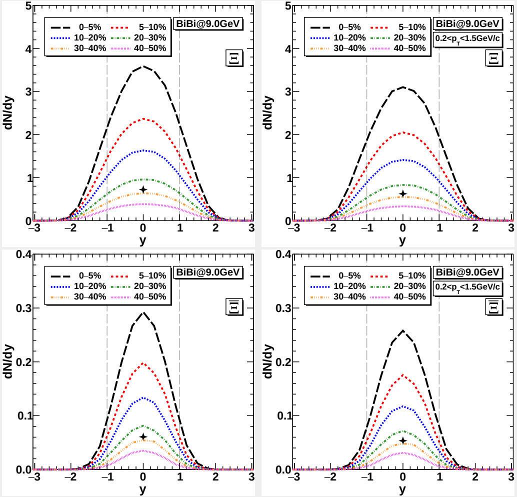

[1]Au+Au collisions at $\sqrt{s_{NN}} = 7.7 - 11.5$ GeV with rapidity cut $|y| < 0.5$; *J. Adam et al.* Phys. Rev. C **102**, 034909 (2020).

# Hyperon spectra: $\frac{dN}{dy}$

## $\Lambda$ and $\overline{\Lambda}$




## $\Xi^0 + \Xi^-$ and $\overline{\Xi}^0 + \overline{\Xi}^+$




- *Particles are more sensitive to cut by high rapidities!*
- Min bias values are denoted by markers.

- **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, $p_\delta$ – 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:*

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

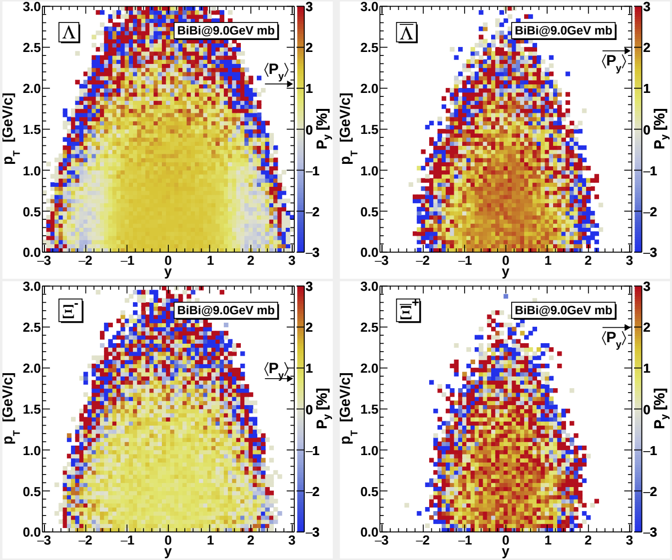
- **Our algorithm:**
  1. At each time step we fluidize the system (*excluding spectators*) and calculate vorticity.
     *Medium*: $\varepsilon > \varepsilon_{\rm f} \approx 0.05\,{\rm GeV/fm^3}$ and $\varpi_{\mu\nu} \neq 0$ .
     *Out of medium*: $\varepsilon \leq \varepsilon_{\rm f} \approx 0.05\,{\rm GeV/fm^3}$ 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 map

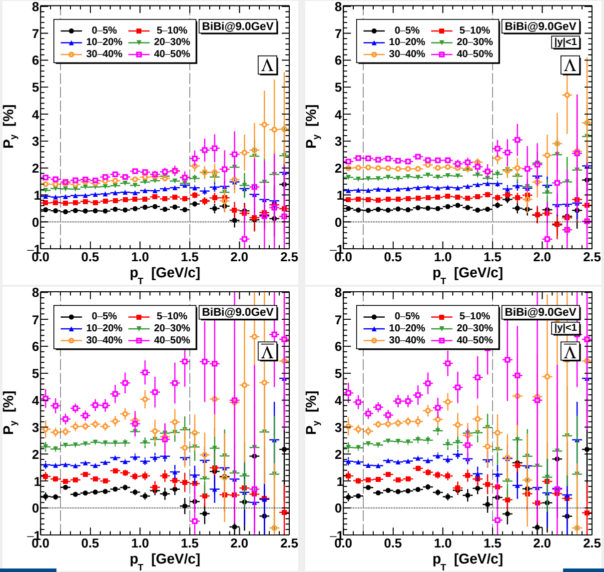
- Plateau in midrapidity and small momentum — *homogeneous medium?*
- Large fluctuations at high rapidities and momenta.
- *Core-corona*[1]*?*
- Distributions for $\Xi^-$ and $\Xi^0$ (for $\overline{\Xi}^+$ and $\overline{\Xi}^0$) are almost identical.




[1] *A. Ayala, I. Domínguez, I. Maldonado, M.E. Tejeda-Yeomans*, $\Lambda$ and $\overline{\Lambda}$ global polarization from the core-corona model. Rev. Mex. Fis. Suppl. 2022, 3, 040914

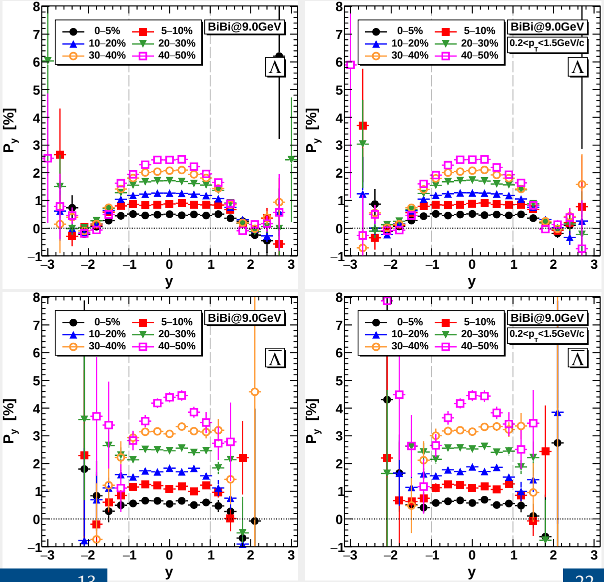
# Polarization vs momentum

- Plateau at small momenta.
- Large fluctuations at high momenta.
- Similar behavior for different centrality classes.
- Cut by rapidity *increases* the polarization signal for hyperons, but *not for antihyperons.*

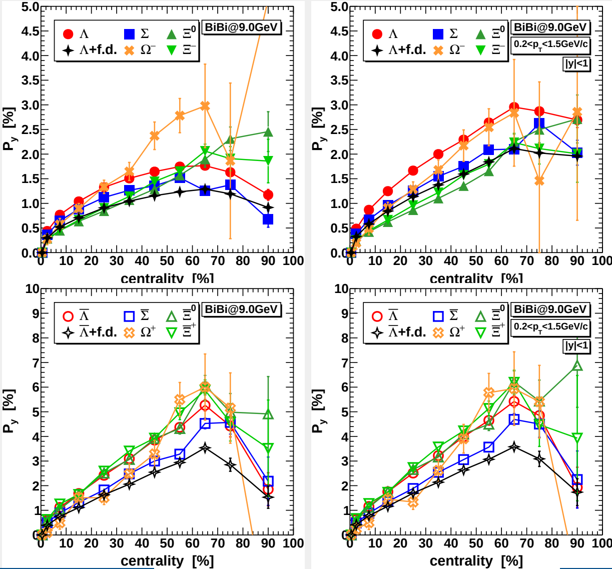


# Polarization vs rapidity

- Plateau for central and hump for non-central collisions in midrapidity — *(in)homogeneity or size of fireball?*
- Polarization decreases at intermediate rapidities.
- Large fluctuations at high rapidities.
- *Cut by momentum does not affect the global polarization!*



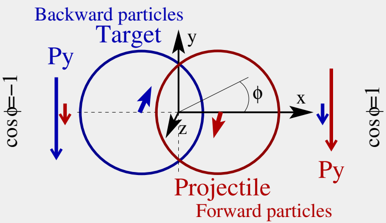
- Polarization *increases* until the 60 – 70% centrality class and then *decreases* for all the hyperon species.
- Feed-down contribution *decreases* the total polarization of $\Lambda$ and $\overline{\Lambda}$ by $\lesssim 30\%$. The contamination comes from $\Sigma^0$ and $\overline{\Sigma}^0$!
- We must consider the *feed-down procedure before cuts* by rapidity and momentum!
- *Cuts increase polarization for hyperons, but not for antihyperons!*



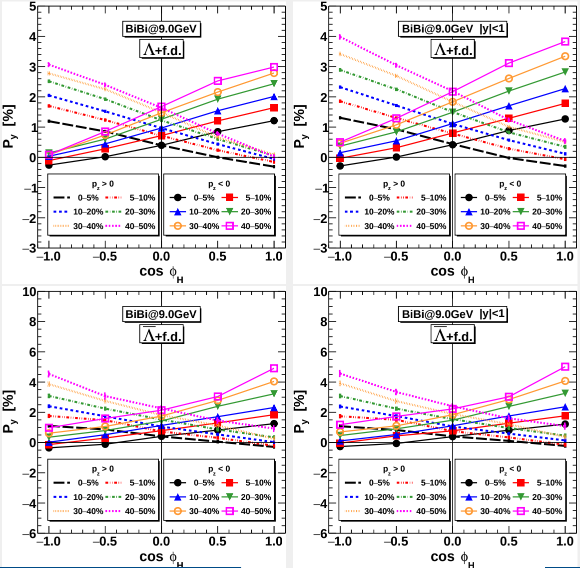
| | $\Lambda$ | | $\Lambda$+f.d. | | $\overline{\Lambda}$ | | $\overline{\Lambda}$+f.d. | |
|---|---|---|---|---|---|---|---|---|
| centrality | $N$ | $P_y, \%$ | $N$ | $P_y, \%$ | $N$ | $P_y, \%$ | $N$ | $P_y, \%$ |
| $10-50\%$ | **6.76** | **1.60** | **10.13** | **1.09** | **0.23** | **2.43** | **0.43** | **1.62** |
| $10-60\%$ | **5.77** | **1.67** | **8.63** | **1.14** | **0.19** | **2.55** | **0.36** | **1.70** |
| $20-50\%$ | **5.20** | **1.86** | **7.73** | **1.28** | **0.17** | **2.98** | **0.32** | **1.99** |
| $20-60\%$ | **4.35** | **1.94** | **6.46** | **1.34** | **0.14** | **3.13** | **0.26** | **2.08** |
| $30-50\%$ | **4.18** | **2.08** | **6.19** | **1.43** | **0.13** | **3.50** | **0.25** | **2.32** |
| $30-60\%$ | **3.39** | **2.17** | **5.00** | **1.50** | **0.10** | **3.70** | **0.19** | **2.44** |
| $40-50\%$ | **3.28** | **2.25** | **4.84** | **1.56** | **0.10** | **3.99** | **0.18** | **2.63** |
| $40-60\%$ | **2.54** | **2.37** | **3.73** | **1.65** | **0.07** | **4.22** | **0.14** | **2.78** |

- *Narrowing* the centrality bin we can *increase* the polarization signal, but it *decreases* the multiplicity! *The most optimal binning is* $30-50\%$*!*
- It is better to use $20-50\%$ than $10-60\%$, $30-50\%$ than $20-60\%$, and $40-50\%$ than $30-60\%$ due to *approximately the same multiplicity but larger polarization!*

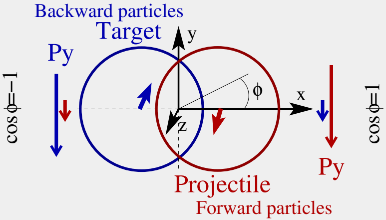
# The polarization-flow correlations: "directed" flow for $\Lambda$

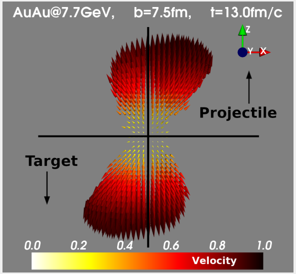


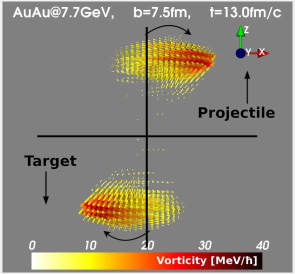

- Before drawing we reflect the polarization sign $P_y \to -P_y$ for clarity.
- The highest polarization corresponds to the particles *moving in the same direction as the projectile* (target), which *are mostly born from the matter of the projectile* (target)!
- *We can increase the polarization signal by selecting particles by angle!*

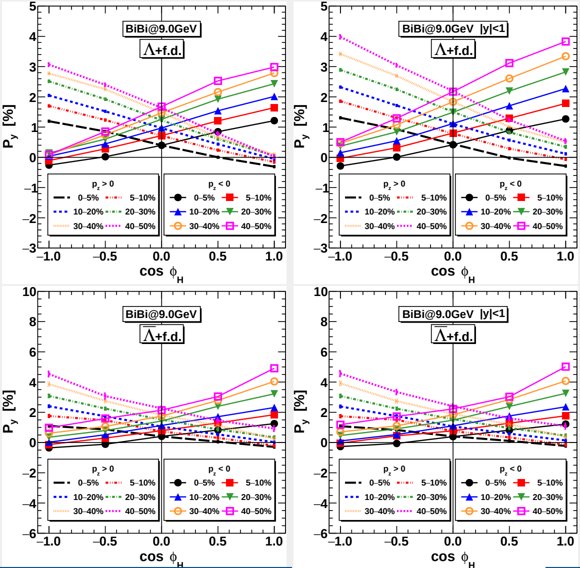


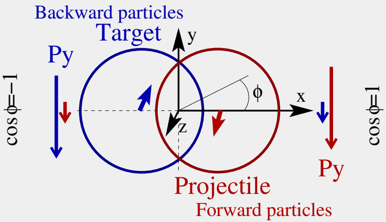
# The polarization-flow correlations: "directed" flow for Λ






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

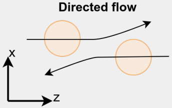
$$\frac{dN}{d\phi_{\mathrm{H}}} = \frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi_{\mathrm{H}} - \Psi_{\mathrm{RP}}))\right),$$

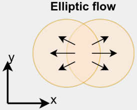
$$v_n = \langle \cos(n(\phi_{\mathrm{H}} - \Psi_{\mathrm{RP}}))\rangle,$$

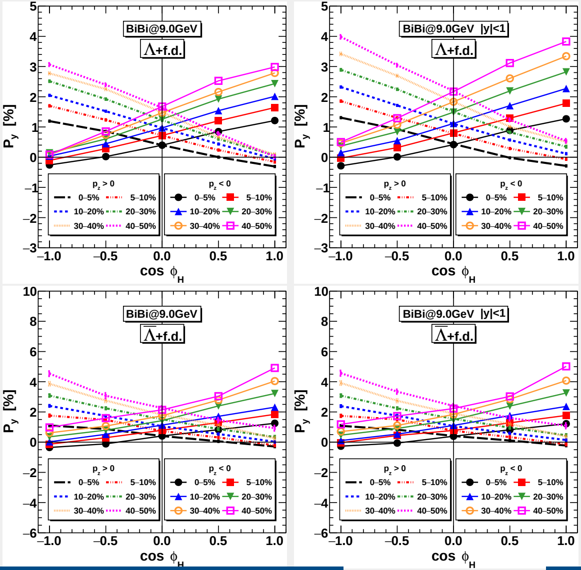
$$\phi_{\mathrm{H}} = \arctan(p_y/p_x),$$

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

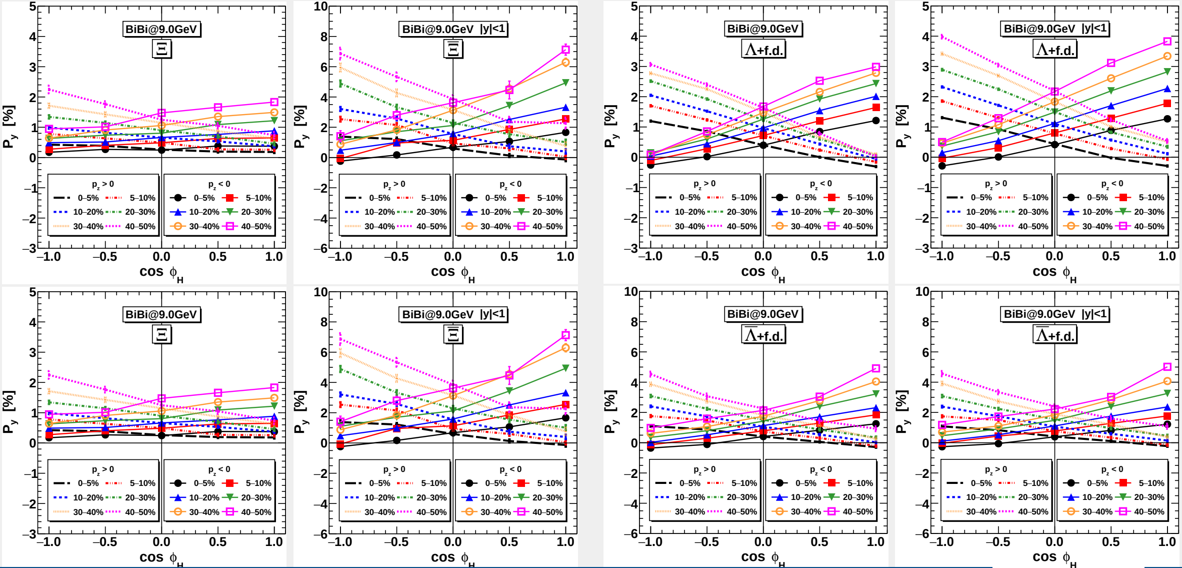
$\cos 2\phi_{\mathrm{H}} \longleftrightarrow v_2$ – **elliptic flow**



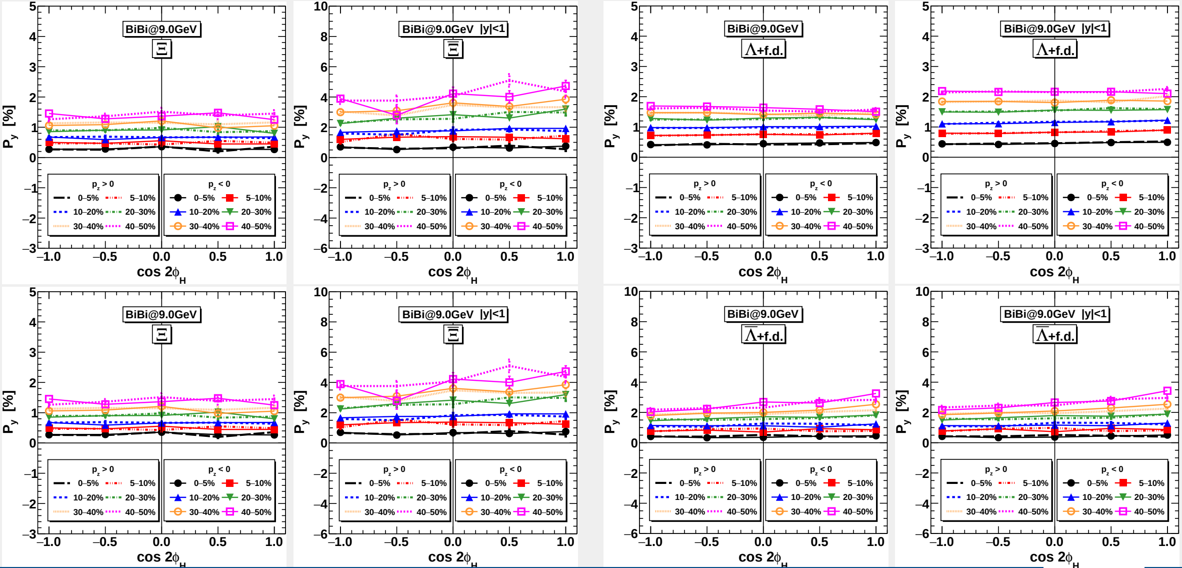



# The polarization-flow correlations: "directed" flow for Ξ



# The polarization-flow correlations: "elliptic" flow



# Outline

- We simulated $N_{\text{ev}} \approx 2 \times 10^6$ 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 and NA49 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 higher rapidities. The particles more sensitive for the rapidity cuts than antiparticles.*
- We analyzed different centrality binning. There are optimal ones between multiplicities and the global polarization.
- We found *correlations between "directed" flow and polarization*. There is no correlation for "elliptical" flow. *Selecting angle and $p_z$, we can increase the polarization signal.*

Thank You!
Questions?