Global polarization of hyperons from PHSD point of view.

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MPD Collaboration meeting 20.04.2023

Heavy-ion collisions

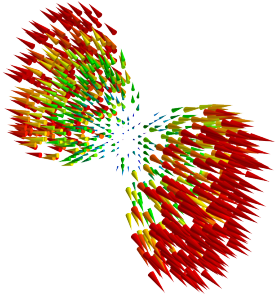
- Hot and dense created matter undergoes explosive expansion — **the Little Bang**
- Large initial orbital angular momentum is partially transferred to the medium, what leads to the non-vanishing averaged *vorticity*:

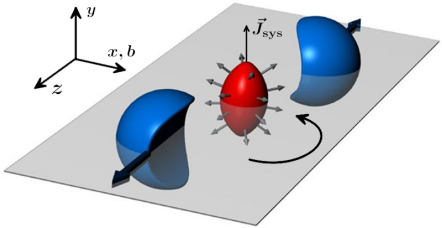
$$\boldsymbol{L} \quad \longrightarrow \quad \langle \boldsymbol{\omega} \rangle = \langle \mathrm{rot}\, \boldsymbol{v} \rangle$$

- The vorticity leads to 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 *rich space-time 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)





Global Λ and $\bar{\Lambda}$ polarization

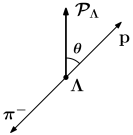
- The $\boldsymbol{\Lambda}$ and $\bar{\boldsymbol{\Lambda}}$ are the *self-analyzing particles*: due to **P**-violation in weak decays, the angular distribution of final protons depends on the orientation of the $\boldsymbol{\Lambda}$-hyperon spin

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

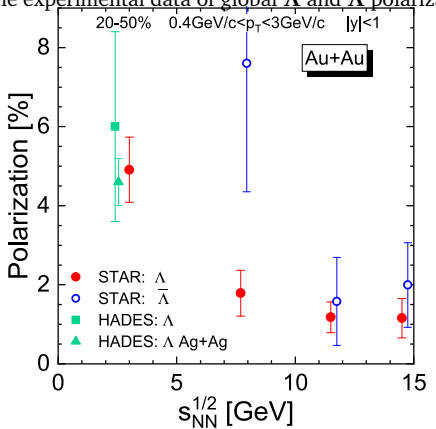
$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta} = \frac{1}{2}(1 + \alpha_{\mathrm{H}}\cos\theta)$$

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

according to direction $\mathcal{P}_{\mathrm{H}}$



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



L. Adamczyk et al., Nature **548** (2017)
R.A.Yassine et al. (HADES Coll.) arXiv:2207.05160

PHSD

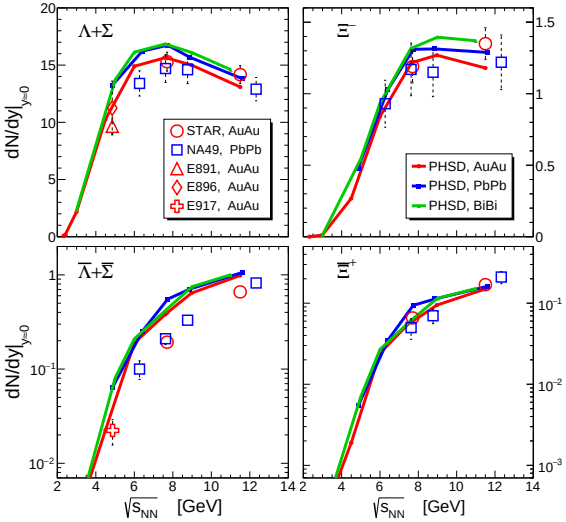
- The **PHSD transport model** as a heavy-ion collisions framework

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

- Good description of a large number of experimental observables

  O. Linnyk, E.L. Bratkovskaya, W .Cassing,
  Prog. Part. Nucl. Phys. **87** (2016)

- The **PHSD** performance test



Polarization of particles with spin in vorticity field

- **The thermodynamic approach**

  F. Becattini, V. Chandra, L. Del Zanna, E. Grossi,
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  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:

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

  s – spin, p_δ – 4 momentum of particle
  We assume the Boltzmann limit $(1 \pm n(x,p)) \approx 1$

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

- Not yet included in this calculations: the thermal shear, spin-Hall and electro-magnetic terms.

The fluidization procedure: Landau frame

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

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

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

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

- Equation of State: **Hadron resonance gas**
  L.M. Satarov, M.N. Dmitriev, and I.N. Mishustin, Phys. Atom. Nucl. **72** (2009)

- *The fluidization criterion*: ***fluidize only cells with*** $\varepsilon > 0.05\,\mathbf{GeV/fm^3}$**!**

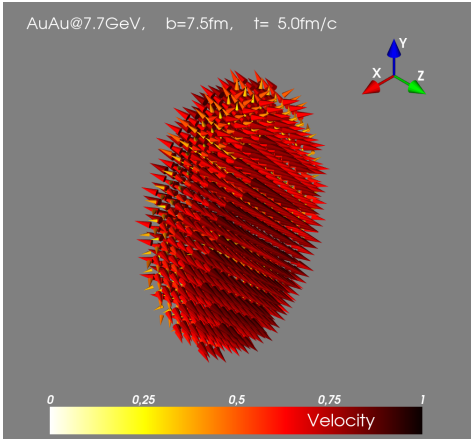
- *Spectators separation*: spectators moves with approximately beam rapidity $||y| - y_{\rm b}| \leq 0.27$
  Spectator nucleons do not form fluid!

- *Propagation of hadrons in mean field is switched off.*

Velocity and vorticity fields

$\omega_{\mathrm{STAR}} \approx 10^{22}\,\mathrm{s}^{-1} \approx 6.6\,\mathrm{MeV}/\hbar$

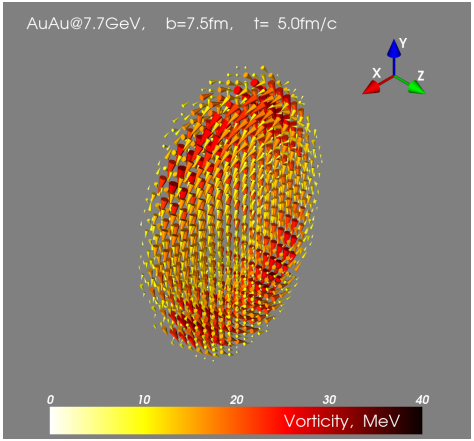
Phys.Rev.C 107 (2023) 3, 034906, e-Print: 2211.09219



Hydrodynamic velocity field

$\varepsilon > 0.05\,\mathrm{GeV}/\mathrm{fm}^3$

$\boldsymbol{v} \approx \boldsymbol{v}_{\mathrm{Hubble}} = (\alpha_T\, x, \alpha_T\, y, \alpha_z\, z)$



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$\boldsymbol{\omega} = \mathrm{rot}\,\boldsymbol{v}$

for clarity draw only $|\boldsymbol{\omega}| > 5\,\mathrm{MeV}/\hbar$

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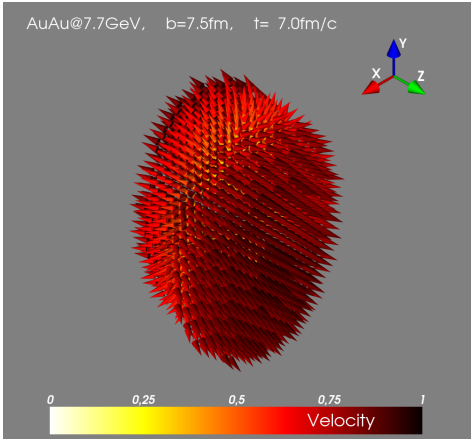

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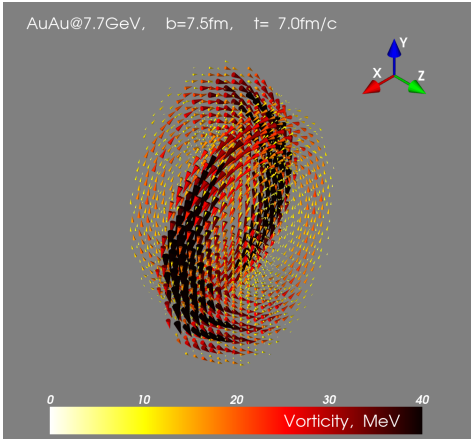

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$\boldsymbol{\omega} = \mathrm{rot}\,\boldsymbol{v}$

$|\boldsymbol{\omega}|_{\max} \approx 67.1\,MeV/\hbar!$

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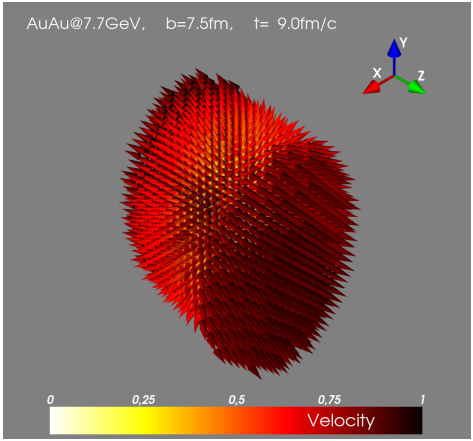

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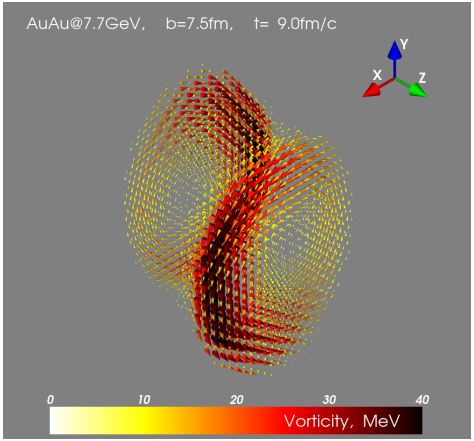

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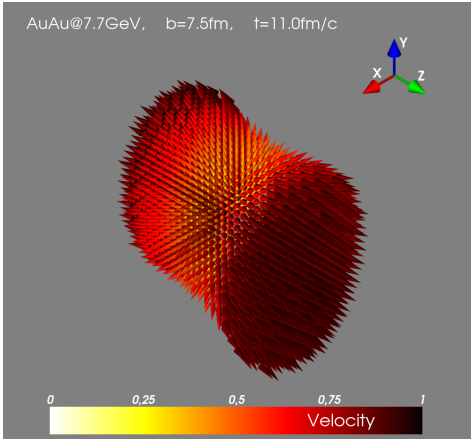

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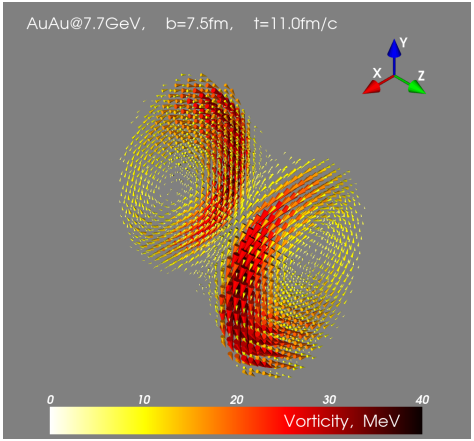

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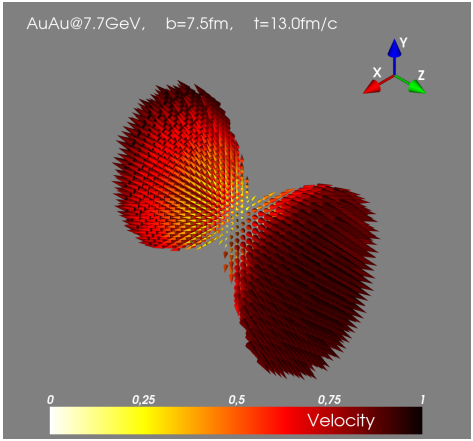

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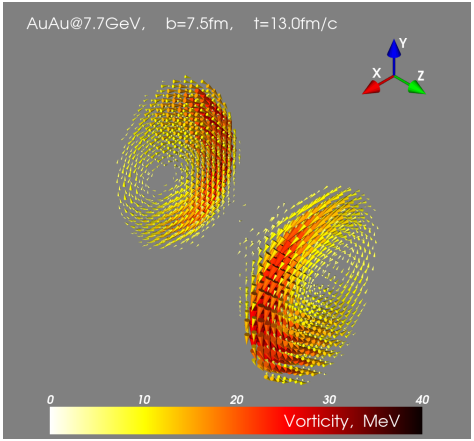

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  Polarization: $\mathbf{P} = \mathbf{S}^*/s$
  $\mathbf{S}^*$ spin vector in rest frame

- **Our statements**

  ☞ *Hydro velocity.* ☞ *No spectators.*

- **Interaction/production point**

  ☞ *No "Medium":* $\varepsilon < 0.05\mathrm{GeV/fm}^3$
  $\Rightarrow$ *No thermal vorticity* $\varpi_{\mu\nu} = 0$

  Elastic or inelastic process:
  "Medium": particle is polarized.
  No "Medium": zero polarization.

  Strong decays:
  $\Sigma^* \to \Lambda + \pi, \quad \Xi^* \to \Xi + \pi$
  spin transfer $C_{\Lambda\,\Sigma^*} = C_{\Xi\,\Xi^*} = 1/3$

  $$S_{Doughter} = C_{D\,P}\, S_{Parent}$$

- **Λ, Σ^0, Ξ, Ω are stable in PHSD.**

The Λ and $\bar{\Lambda}$ polarization

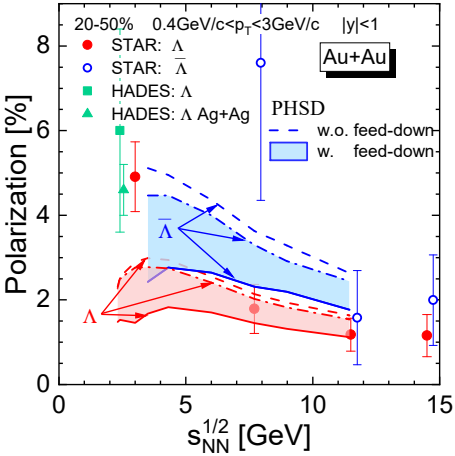
- *The feed-down effects*

strong: *is already included*

weak: $\Xi \to \Lambda + \pi \quad c\tau = 4.91 - 8.71\,cm$

EM: $\Sigma^0 \to \Lambda + \gamma \quad c\tau = 2.2 \times 10^4\,fm$

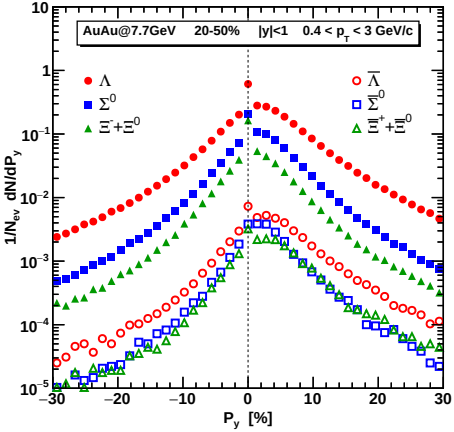
Spin transfer coefficients:
$C_{\Lambda\,\Xi^-} = 0.927$, $C_{\Lambda\,\Xi^0} = 0.900$,
$C_{\Lambda\,\Sigma^0} = -1/3$



- The polarization of $\mathbf{\Lambda}$ hyperons *agrees* with experimental data, *except low energies* $\sqrt{s_{NN}} \leq 3$ GeV. The *maximum* of the $\mathbf{\Lambda}$ polarization at $\sqrt{s_{NN}} \approx 4$ GeV
- The polarization of $\bar{\mathbf{\Lambda}}$ *larger in* $1.5 - 2$ *times* than $\mathbf{\Lambda}$.
At $\sqrt{s_{NN}} \geq 11.5$ GeV *agrees* with experimental data, but at $\sqrt{s_{NN}} \leq 7.7$ GeV *less*

Polarization of different species of hyperons

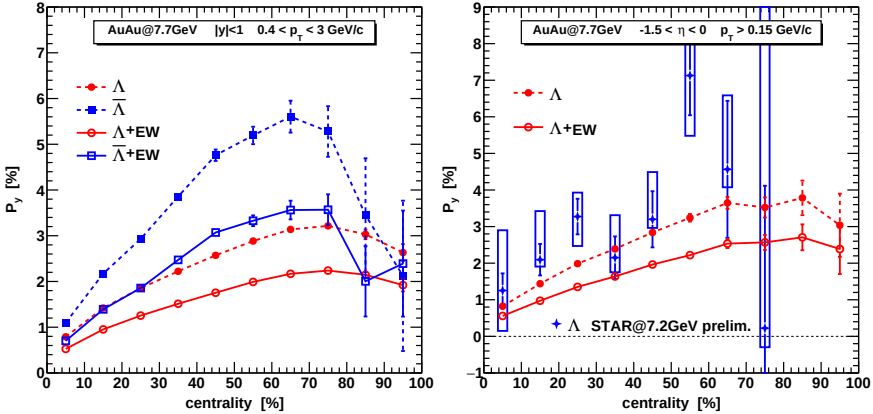
Particles 2023, 6(1), 373-384



- The feed-down reduces strongly the particle polarization.
- Polarization linearly increases with the collision centrality.
- Maximum is about 60-70%

Polarization of different species of hyperons

Particles 2023, 6(1), 373-384



STAR: EPJ Web Conf. 2022, 259, 06003

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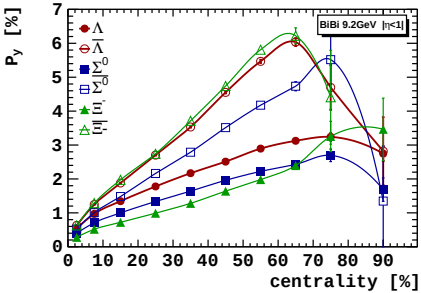
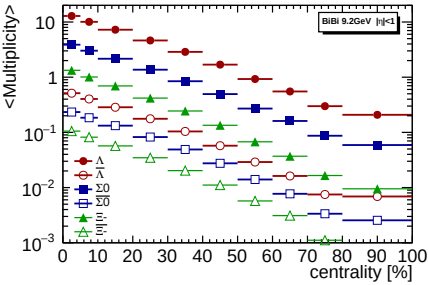
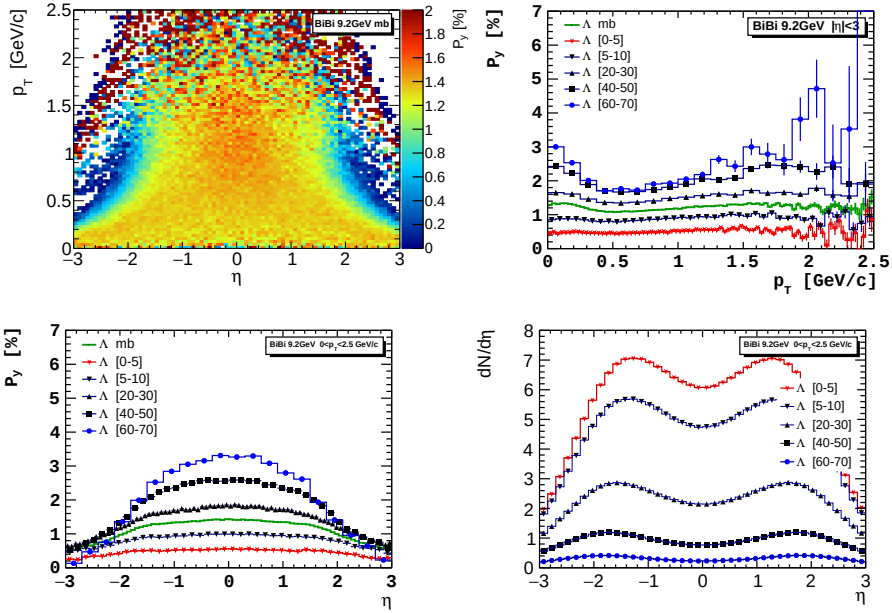
Centrality dependence of different species of hyperons





- Anti-hyperons are always more polarized then hyperons.
- Polarization linearly increases with the collision centrality up to diffusion area of the nuclei. Maximum is about 60-70% (in contrast with other models).
- Difference $P_y(\overline{\Xi^-}) - P_y(\Xi^-)$ is the biggest.

$\Lambda^{primary}$



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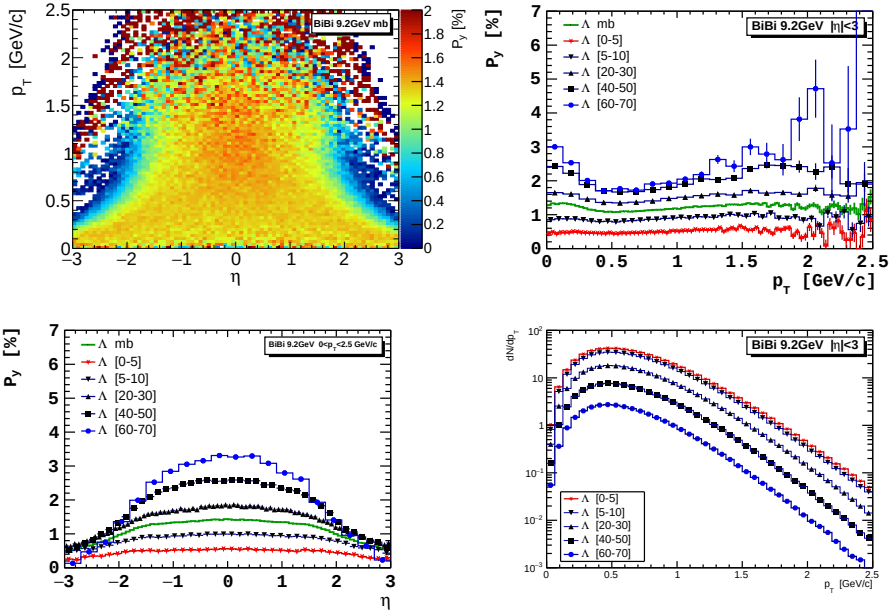

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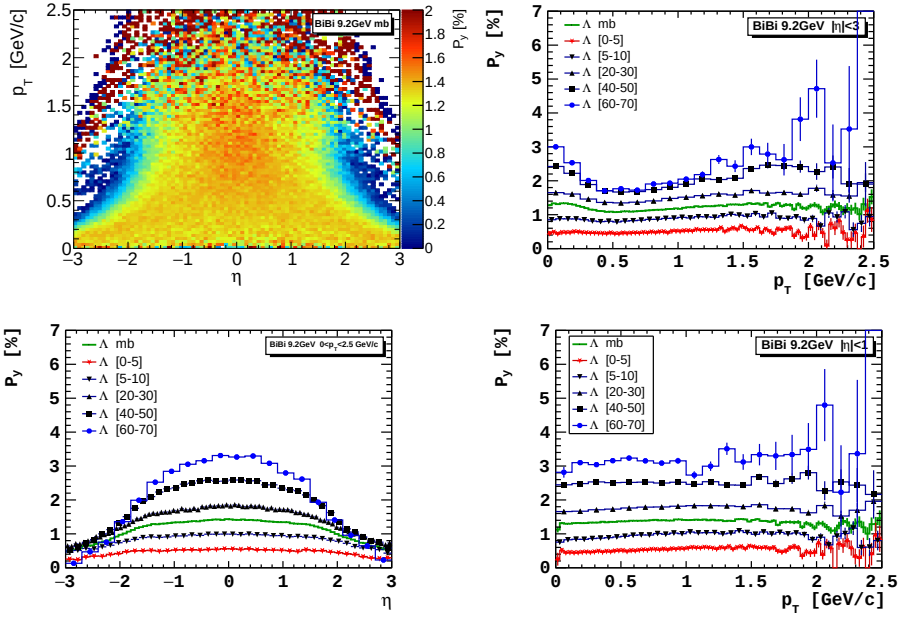
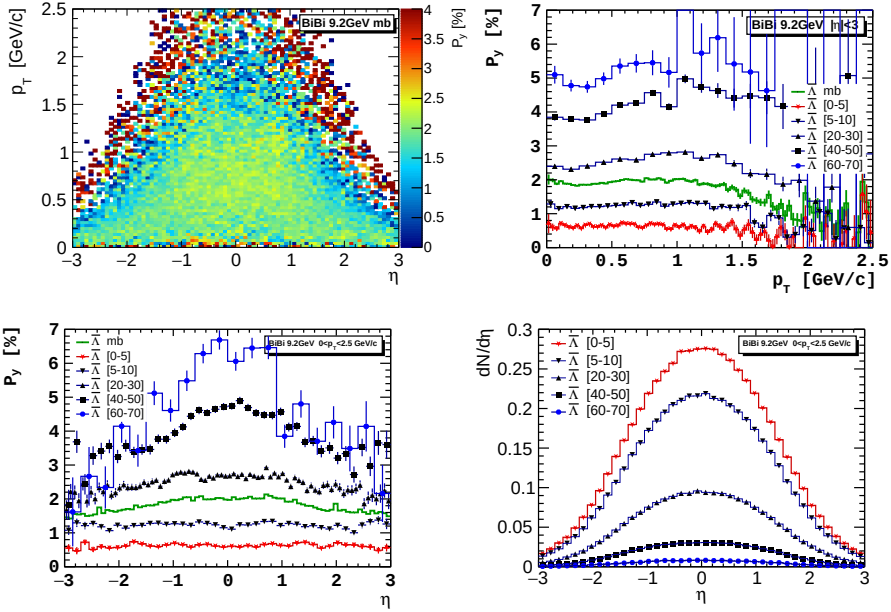


$\bar{\Lambda}^{primary}$



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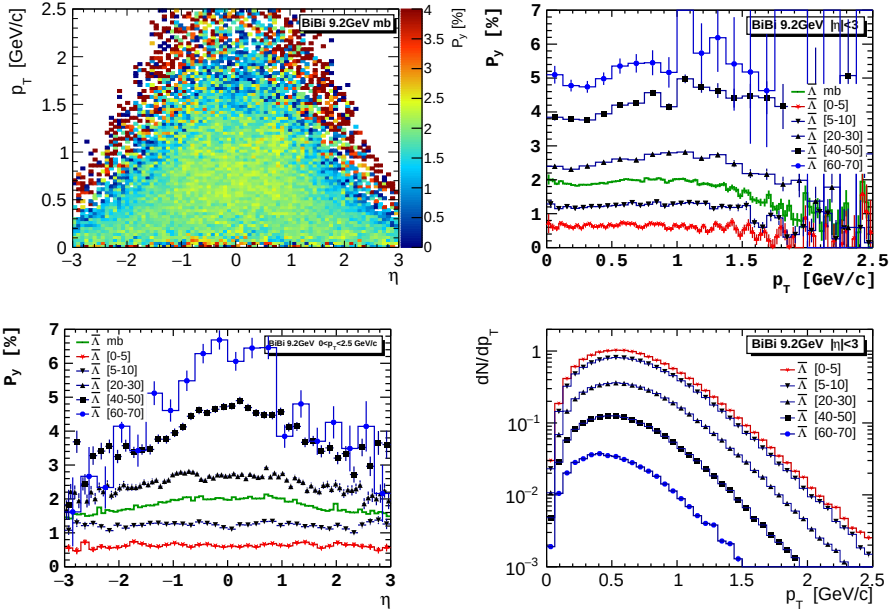

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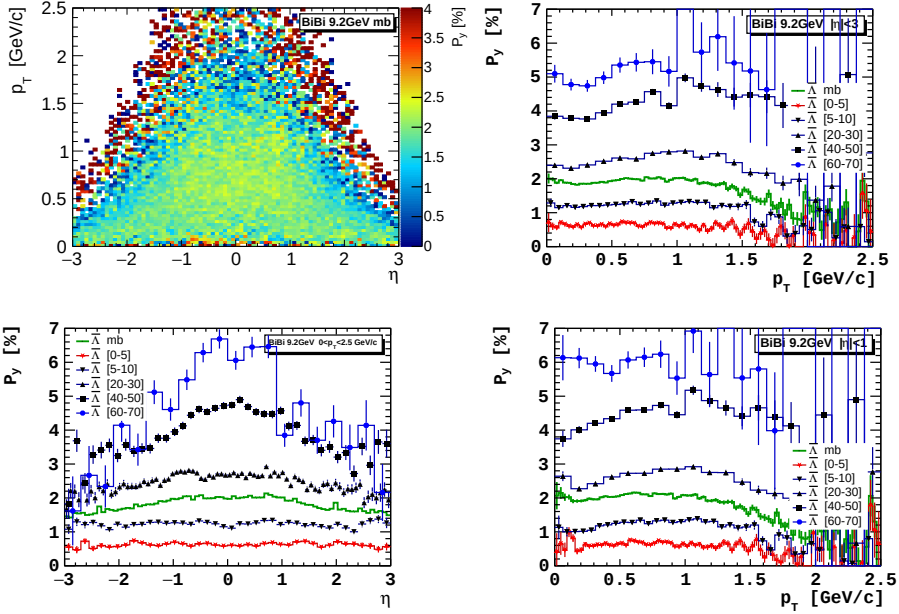
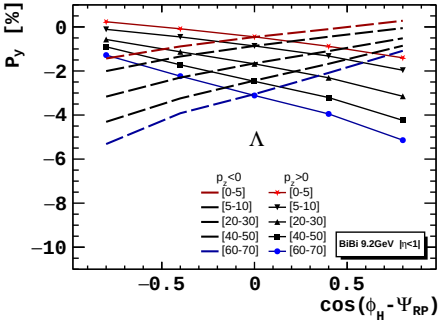
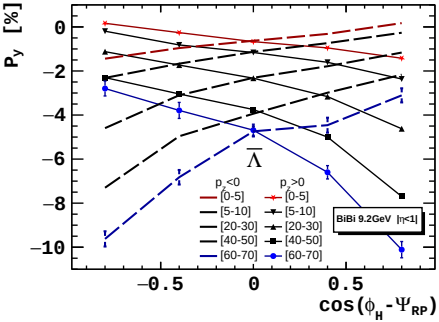


Polarization and Forward-Backward flow

Primary Λ and $\bar{\Lambda}$ (without feed-down).

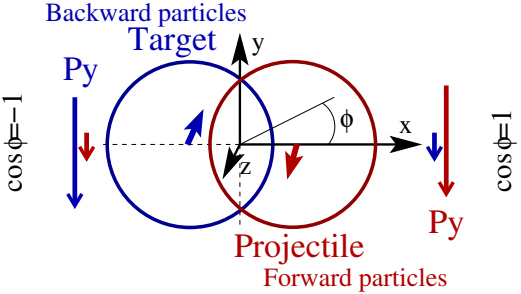




- No correlations for: P_y vs v_2, P_z vs v_1, P_z vs v_2.
- **PHSD default:** Reaction plane $\Psi_{RP} = 0$ – from projectile $\Longrightarrow$ angular momentum $J_y < 0$ and polarization $P_y < 0$.
- **MPD default:** Reaction plane from target $\Longrightarrow J_y > 0, P_y > 0$

Polarization and Forward-Backward flow

PHSD



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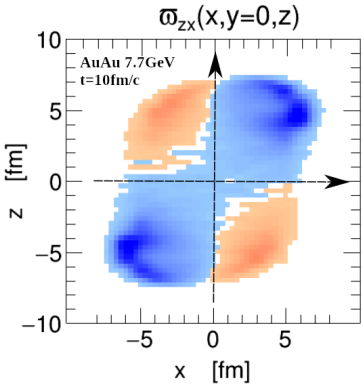
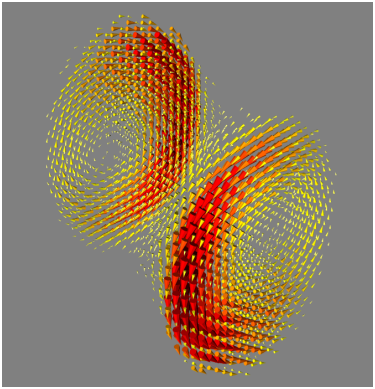
Polarization and Forward-Backward flow

$$P_y \sim \varpi_{zx}$$





- Two vortex rings.
- The origin of correlations is quadrupole structure and directed flow.

Polarization and Forward-Backward flow

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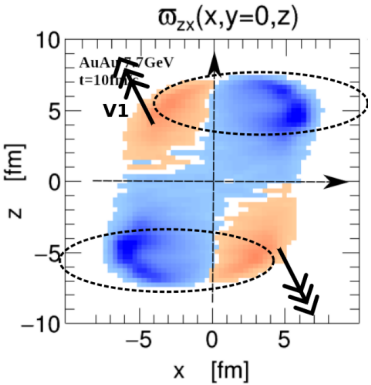

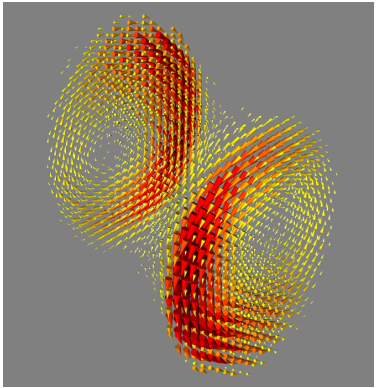

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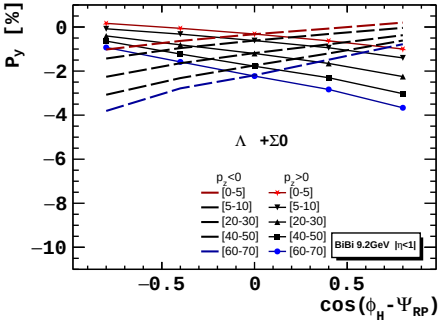
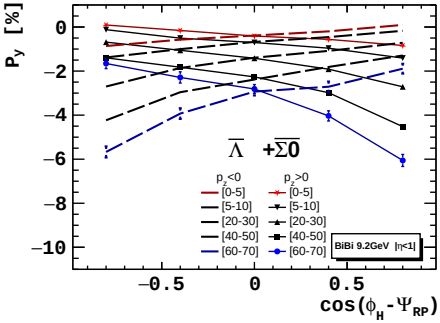
Polarization and Forward-Backward flow

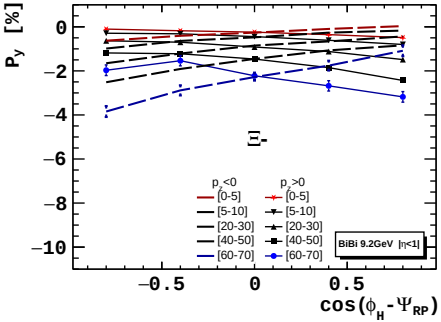
Estimation of Λ ($\bar{\Lambda}$) polarization with feed-down from Σ^0 ($\bar{\Sigma}^0$).

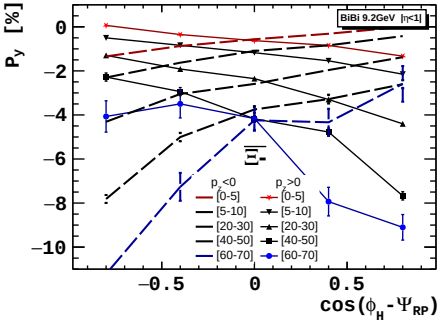




- Correlation is interplay of emission areas according to vortex rings.
- The feed-down reduces strongly the particle polarization.
- **PHSD default:** Reaction plane $\Psi_{RP} = 0$ – from projectile $\Longrightarrow$ angular momentum $J_y < 0$ and polarization $P_y < 0$.

Polarization and Forward-Backward flow





- Correlation is just interplay of emission areas according to vorticity rings.
- No feed-down is required for Ξ

Conclusions

- The polarization of the $\mathbf{\Lambda}$ hyperons agrees with experimental data, except low energies $\sqrt{s_{NN}} \leq 3\,\text{GeV}$. The maximum of the $\mathbf{\Lambda}$ polarization at $\sqrt{s_{NN}} \approx 4\,\text{GeV}$. The polarization of $\bar{\mathbf{\Lambda}}$ larger in $1.5 - 2$ times than $\mathbf{\Lambda}$. It agrees with experimental data at $\sqrt{s_{NN}} = 11.5\,\text{GeV}$, but is less at $\sqrt{s_{NN}} = 7.7\,\text{GeV}$.
- Strong polarization suppression is caused by the *feed-down from* $\mathbf{\Sigma^0}$ *and* $\bar{\mathbf{\Sigma}}^{\mathbf{0}}$ hyperons.
- Uncertainty in ratio of $\mathbf{\Sigma}^0$ to $\mathbf{\Lambda}$ production leads to big uncertainty in measured global polarization of $\mathbf{\Lambda}$ hyperons.
- Polarization only slightly depends on η and p_T at mid pseudo-rapidity region.
- Polarization depends linear on centrality and achieves maximum at centrality $[60 - 70\%]$.
- The consequence of vortical rings is correlation of P_y with directed flow of hyperon. Good check for global polarization mechanism.
- The experimental study of global polarization of Ξ (maybe Ω) looks as the best probe for the Λ polarization.

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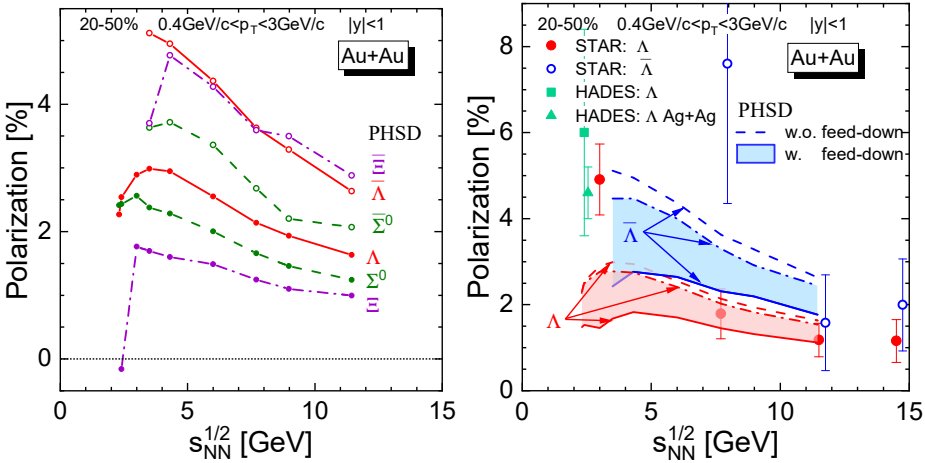
THANK YOU!

The Ξ polarization (Λ from Ξ)?!

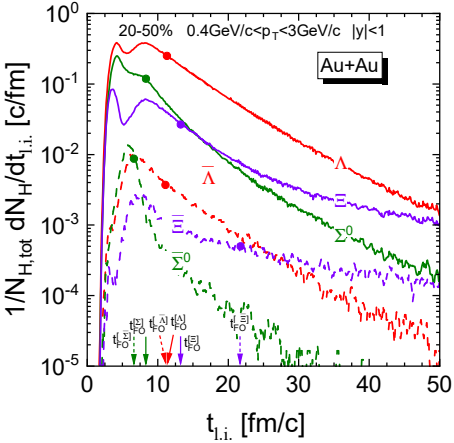


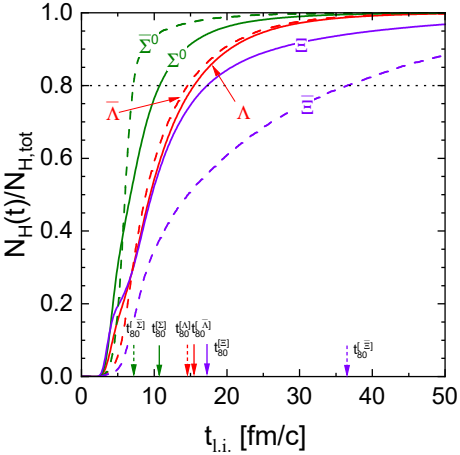
weak decay: $\Xi \to \Lambda + \pi \quad c\tau = 4.91 - 8.71cm$

no contamination from Σ^0

Rates of final hyperon production

- **Trace to time of the last interaction, AuAu@7.7GeV**





Strong decays are already naturally included.

Different freeze-out can lead to different polarization.