Review of polarization at NICA energies

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Nuclotron-based Ion Collider fAcility (NICA)

Dubna 2020

MultiPurpose Detector (MPD)

Au+Au

$\sqrt{s_{NN}}$ = 4 – 11 GeV

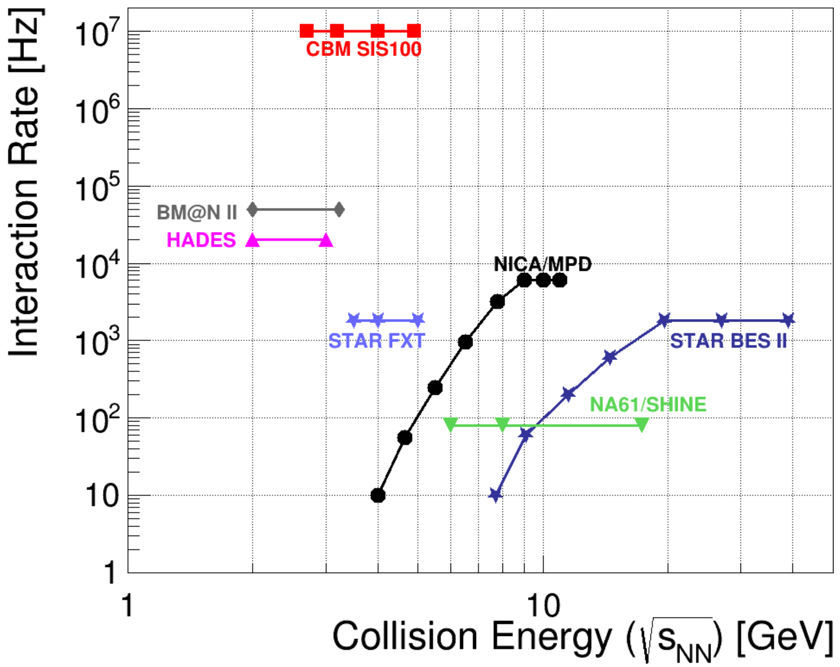
Bi(A=209) beam 2022

Au beam is planned later

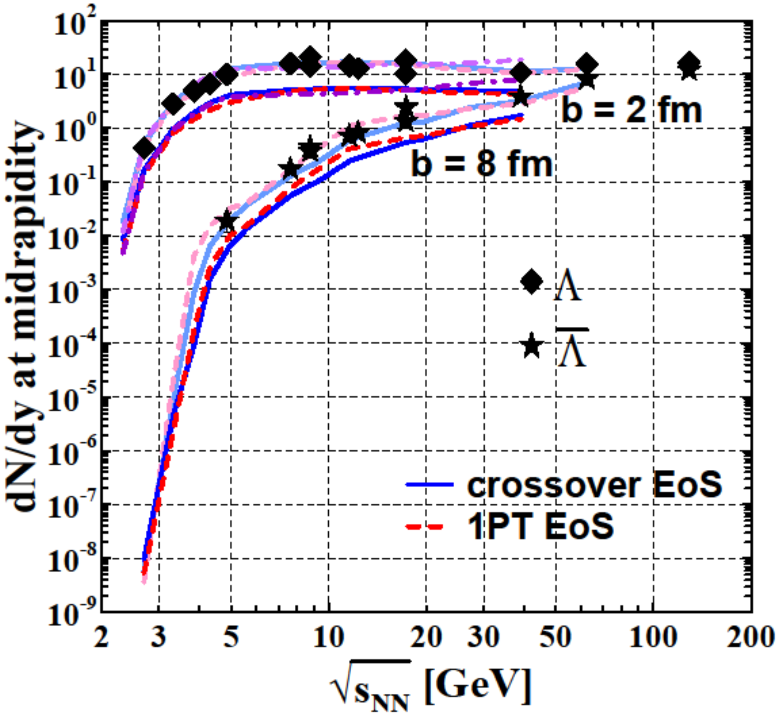
Data taking at MPD 2023

Polarization measurements are planned (approx. 2025)

Feasibility of polarization measurements at NICA



CBM, Eur.Phys.J.A 53 (2017) 3, 60



3FD simulations

STAR experience

global polarization: (dN/dy)(interaction rate) ≥ 1 s

local polarization: (dN/dy)(interaction rate) ≥ 10^4 s

Therefore, at NICA polarization measurements are feasible at

$\sqrt{s_{NN}} \geq$ 4 GeV for global Λ,

$\sqrt{s_{NN}} \geq$ 5 GeV for global $\bar{\Lambda}$,

$\sqrt{s_{NN}} \geq$ 6 GeV for local Λ,

infeasible for local $\bar{\Lambda}$

3-Fluid Dynamics (3FD)

Target-like fluid: $\partial_\mu J_t^\mu = 0$ $\quad \partial_\mu T_t^{\mu\nu} = -F_{tp}^\nu + F_{ft}^\nu$

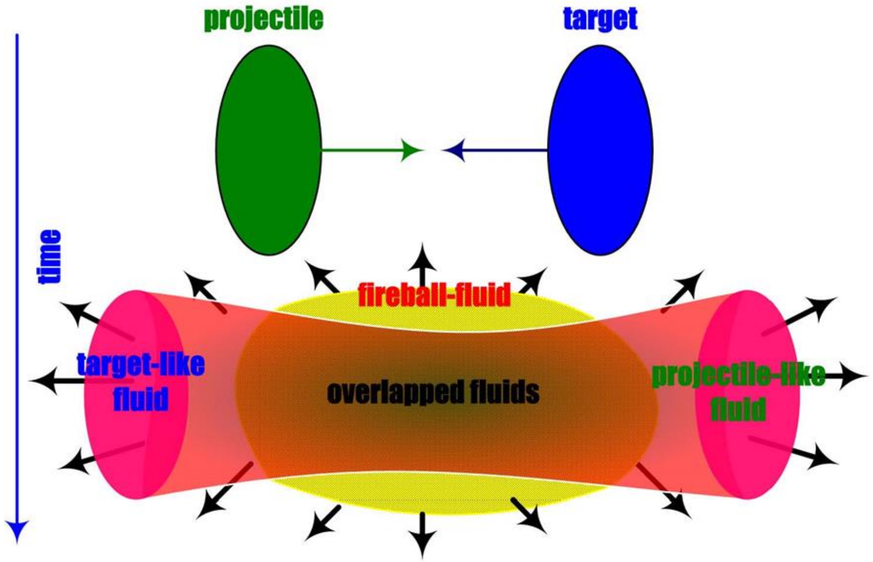
Leading particles carry bar. charge — exchange/emission

Projectile-like fluid: $\partial_\mu J_p^\mu = 0,$ $\quad \partial_\mu T_p^{\mu\nu} = -F_{pt}^\nu + F_{fp}^\nu$

Fireball fluid: $J_f^\mu = 0,$ $\quad \partial_\mu T_f^{\mu\nu} = F_{pt}^\nu + F_{tp}^\nu - F_{fp}^\nu - F_{ft}^\nu$

Baryon-free fluid — Source term — Exchange

The source term is delayed due to a formation time τ



Total energy-momentum conservation:

$$\partial_\mu (T_p^{\mu\nu} + T_t^{\mu\nu} + T_f^{\mu\nu}) = 0$$

Ivanov, Russkikh, Toneev, PRC 73, 044904 (2006)

Physical Input

- ✓ Equation of State
- ✓ Friction
- ✓ Freeze-out energy density ε_{frz} = 0.4 GeV/fm^3

Calculations of polarization at NICA energies

Only few calculations at $\sqrt{s_{NN}} <$ 7.7 GeV

✓Within thermodynamic approach by *Becattini et al.*

Deng, Huang, Ma, Zhang, PRC 101, 064908 (2020) [UrQMD, mean vorticity] [Shanghai]

Ivanov, et al., PRC 100, 014908 (2019), PRC 102, 024916 (2020) [3FD model] [Dubna]

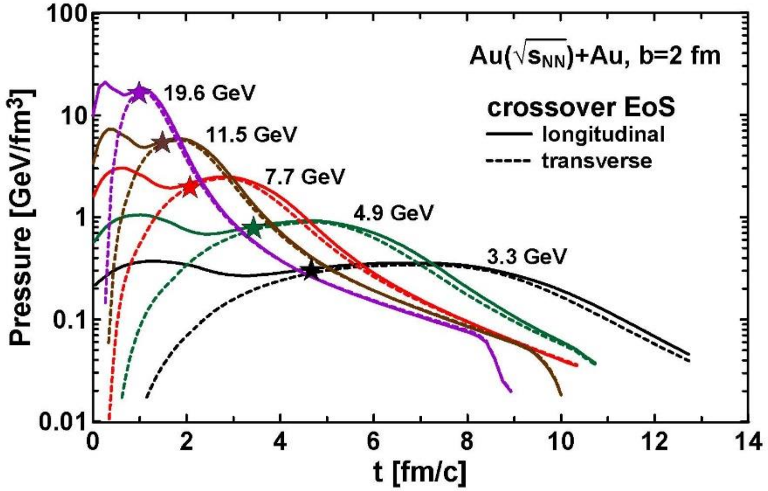
✓Within axial-vortical-effect approach *[Sorin&Teryaev, PRC 95, 011902 (2017)]*

Baznat, Gudima, Sorin, Teryaev, PRC 97, 041902 (2018) [QGSM model] [Dubna]

Ivanov, 2006.14328 [nucl-th] [3FD model] [Dubna]

Equilibration at NICA energies

Ivanov, Soldatov, PRC C 101, 024915 (2020)

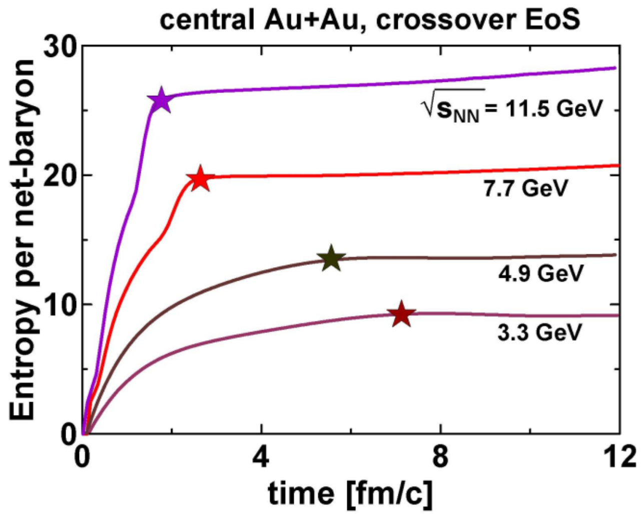


Longitudinal and transverse pressure in the center of colliding nuclei

Mechanical equilibration time is comparatively long

Freeze-out is mechanically equilibrium.
This of prime importance for the models.

Ivanov, Soldatov, EPJ A 52 (2016) 12, 367

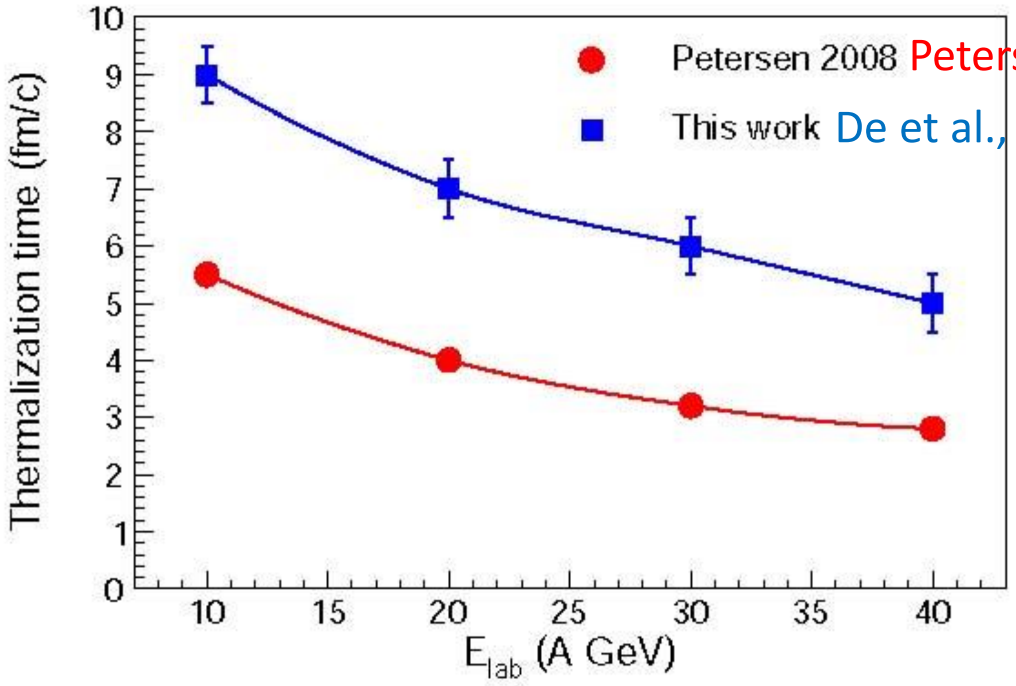


Chemical equilibration (and hence thermalization) takes longer

Thermalization at NICA energies

Other models result in similar thermalization times

Bravina et al., PRC 78, 014907 (2008); De et al., PRC 94, 054901 (2016);
Khvorostukhin, Toneev, Phys.Part.Nucl.Lett. 14 (2017), 9; Teslyk et al., PRC 101, 014904 (2020)



Petersen et al., PRC 78, 044901 (2008) [twice overlap time]

De et al., PRC 94, 054901 (2016) [UrQMD]

For comparison:
Mechanical Equilibration at 10 A GeV
≈ 3.5 fm/c

The system is thermalized at the freeze-out stage, although it can be reached right before the freeze-out

Thermodynamic approach

Relativistic Thermal Vorticity

$$\varpi_{\mu\nu} = \frac{1}{2}(\partial_\nu \hat{\beta}_\mu - \partial_\mu \hat{\beta}_\nu),$$

where $\hat{\beta}_\mu = \hbar\beta_\mu$ and $\beta_\mu = u_\nu / T$ with $T =$ the local temperature.

ϖ is related to **mean spin vector, $\Pi^\mu(p)$, of a spin 1/2 particle**
in a relativistic fluid [F. Becattini, et al., Annals Phys. **338**, 32 (2013)]

$$\Pi^\mu(p) = \frac{1}{8m} \frac{\int_\Sigma d\Sigma_\lambda p^\lambda n_F (1 - n_F)\, p_\sigma \epsilon^{\mu\nu\rho\sigma} \partial_\nu \hat{\beta}_\rho}{\int_\Sigma \Sigma_\lambda p^\lambda\, n_F},$$

n_F = Fermi-Dirac distribution function,
integration over the freeze-out hypersurface Σ.

Axial vortical effect (AVE)

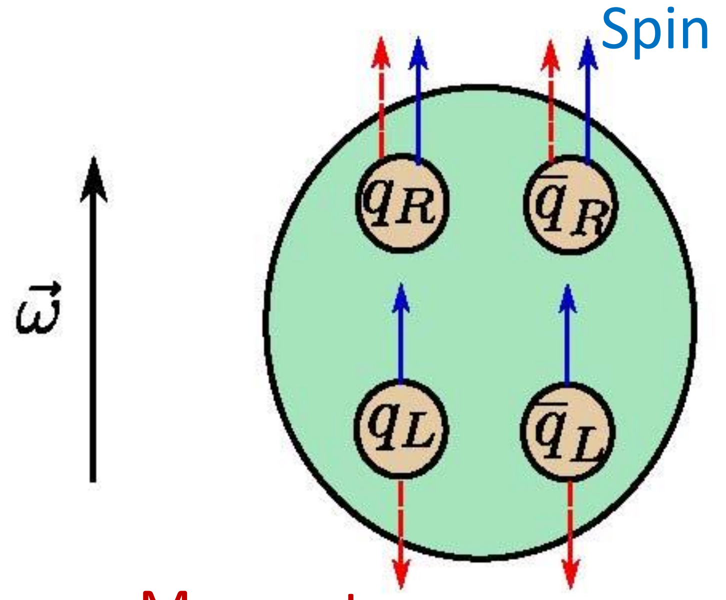
Axial current

$$J_5{}^{\nu}(x) = -N_c\left(\frac{\mu^2}{2\pi^2} + \kappa\frac{T^2}{6}\right)\epsilon^{\nu\alpha\beta\gamma}u_\alpha\omega_{\beta\gamma}$$

induced by vorticity

$$\omega_{\mu\nu} = \frac{1}{2}(\partial_\nu u_\mu - \partial_\mu u_\nu)$$

Vilenkin, PRD 20, 1807 (1979); 21, 2260 (1980).



Gao, et al., PRL 109 (2012) 232301

$\frac{\mu^2}{2\pi^2}$ = axial anomaly term is topologically protected

$\kappa\frac{T^2}{6}$ = holographic gravitational anomaly

Landsteiner, Megias, Melgar, Pena-Benitez, JHEP 1109, 121 (2011) [Gauge-gravity correspondence]

Lattice QCD results in $\kappa = 0$ in confined phase and $\kappa \leq 0.1$ in deconfined phase

[Braguta, et al., PRD 88, 071501 (2013); 89, 074510 (2014)]

AVE polarization

Assuming axial-charge conservation at hadronization

$$P_\Lambda = \int d^3x \, (J_{5s}{}^0/u_y) \, /(N_\Lambda + N_{\bar{K}^*})$$

$$P_{\bar{\Lambda}} = \int d^3x \, (J_{5s}{}^0/u_y) \, /(N_{\bar{\Lambda}} + N_{K^*})$$

u_y results from boost to the local rest frame of the matter

Sorin and Teryaev, PRC 95, 011902 (2017)

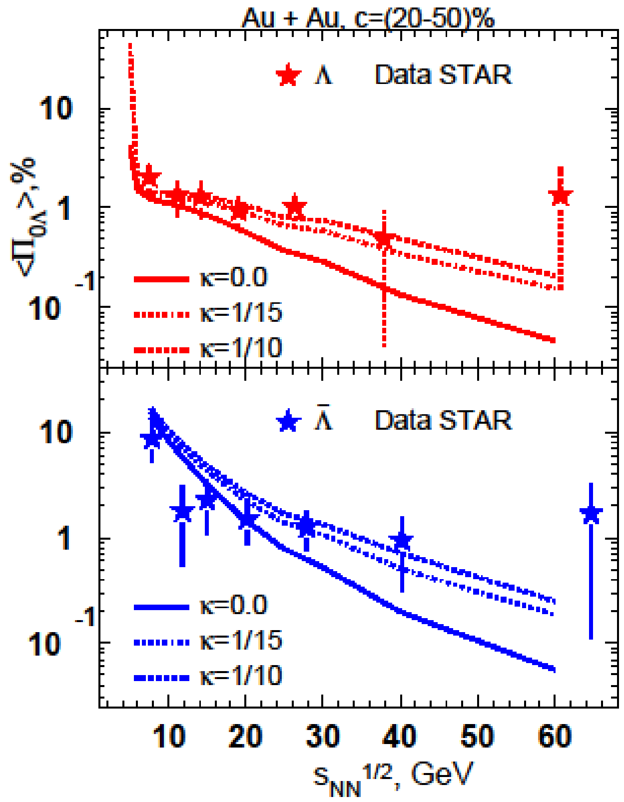
In principle, an alternative assumption is possible.

Coalescence-like hadronization: quarks coalesce into hadrons, keeping their polarization.

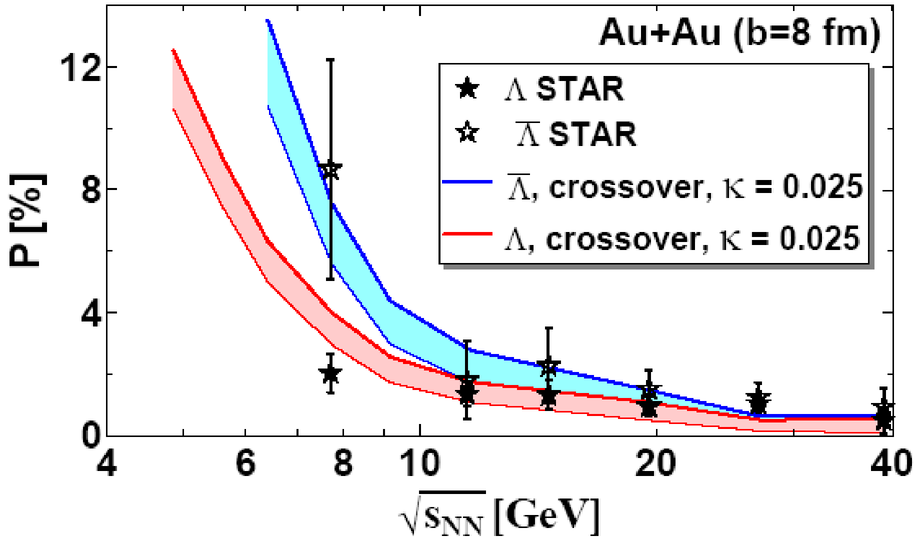
Polarization increases with $\sqrt{s_{NN}}$ decrease

AVE approach predicts higher polarization at low energies than **thermodyn. one**

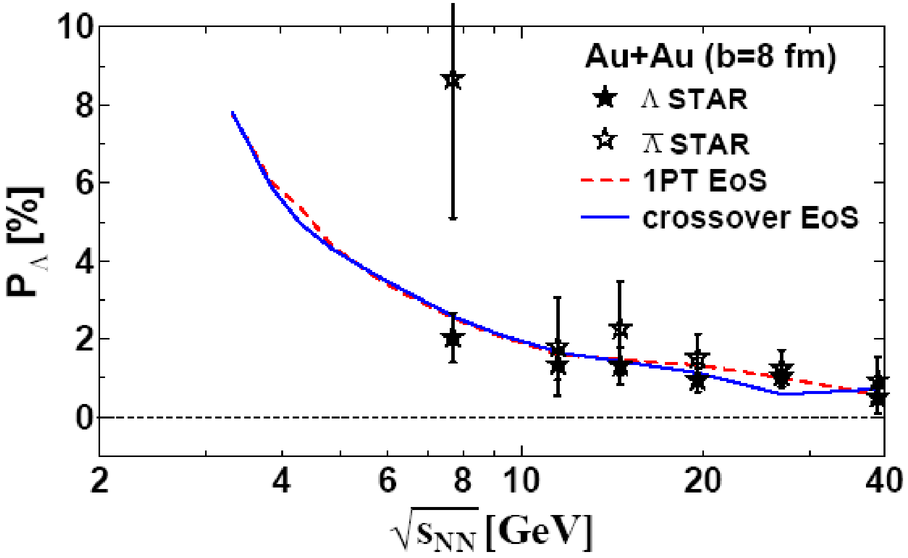
Baznat, Gudima, Sorin, Teryaev,
PRC 97, 041902 (2018)



Ivanov, 2006.14328



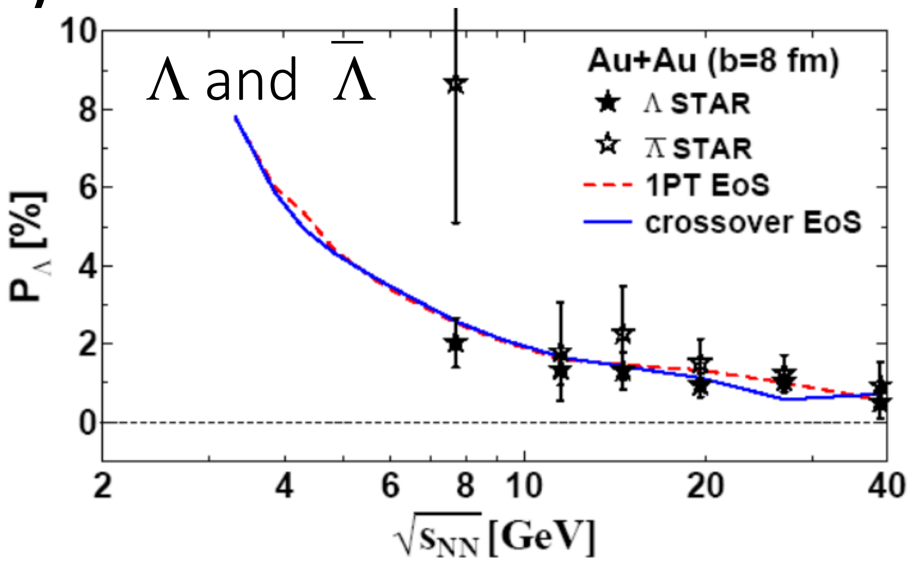
Ivanov, Soldatov, PRC 102, 024916 (2020)



NICA data will distinguish between AVE and thermodynamic predictions

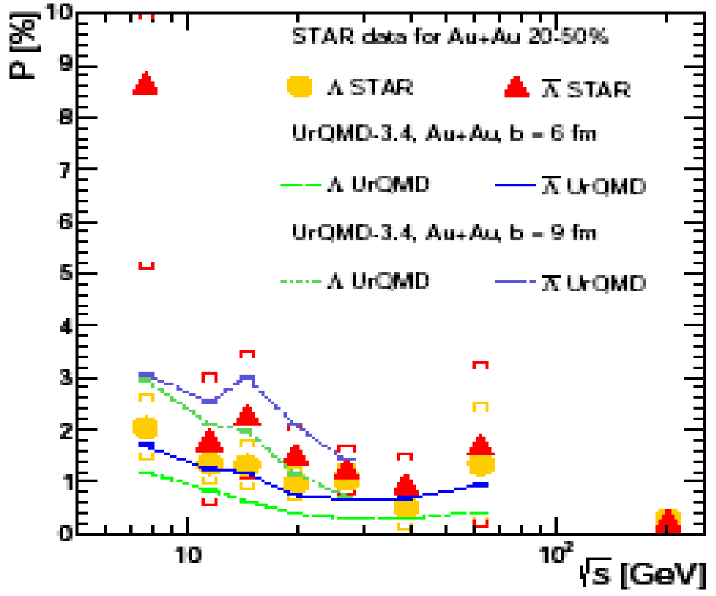
Λ -- $\bar{\Lambda}$ polarization splitting (1)

In the standard thermodynamic approach this splitting is either very small



or simply small, if different freeze-out for Λ and $\bar{\Lambda}$ is taken into account,

Vitiuk, Bravina and Zabrodin, Phys. Lett. B 803, 135298 (2020)



while exp. difference is large at 7.7 GeV, although error bars for $\bar{\Lambda}$ are also large.

Λ -- $\bar{\Lambda}$ polarization splitting (2)

A possible reason: presence of a strong electro-magnetic field:

$$\varpi_{\rho\sigma} \to \varpi_{\rho\sigma} + \frac{\mu}{S} F_{\rho\sigma}$$

Becattini, et al. PRC 95, 054902 (2017)

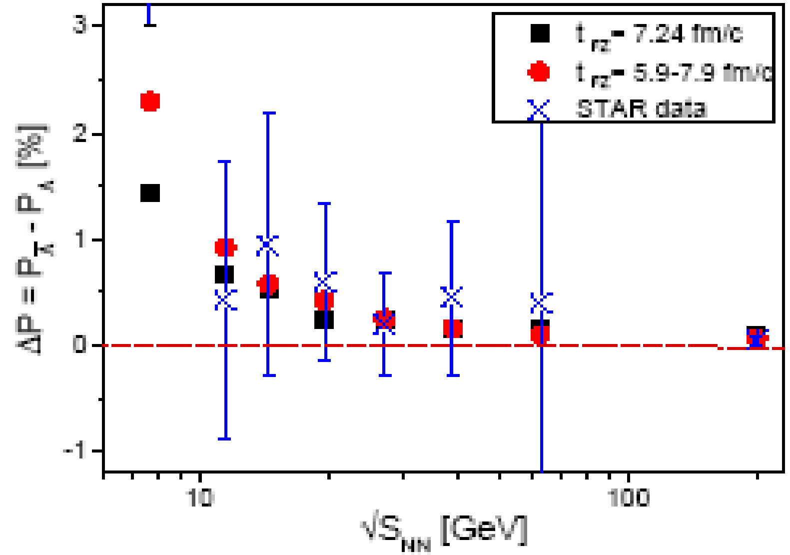
Still open question:

if required strong magnetic field is generated at freeze-out?

Discussion in [Becattini and Lisa, arXiv:2003.03640]

Λ -- $\bar{\Lambda}$ polarization splitting (3)

Xie, Chen, Csernai, arXiv:1912.00209



Interaction mediated by massive vector and scalar bosons (Walecka-like model)

Csernai, Kapusta, Welle, PRC 99, 021901 (2019)

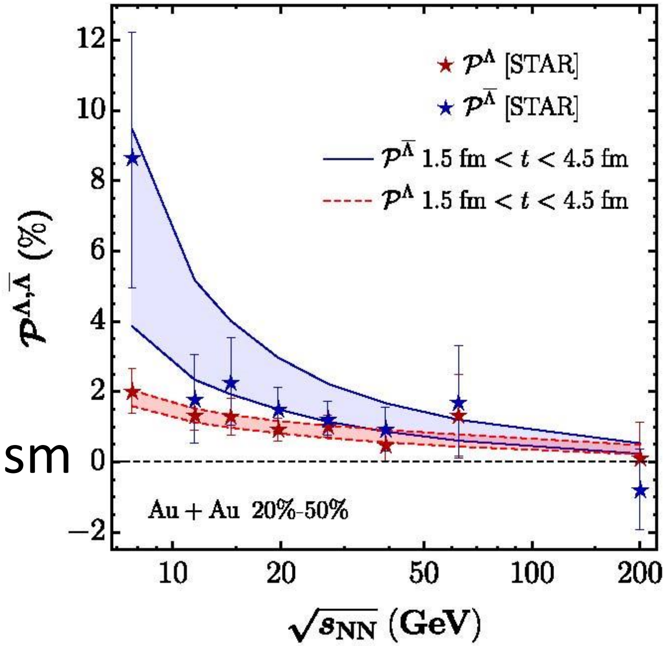
This is a dynamical (rather than thermodynamical) mechanism: polarization itself should differ from the thermodynamical one.

Glauber: More Λ's than $\bar{\Lambda}$'s are produced in corona.

Assumption: Polarization in corona is negligible.

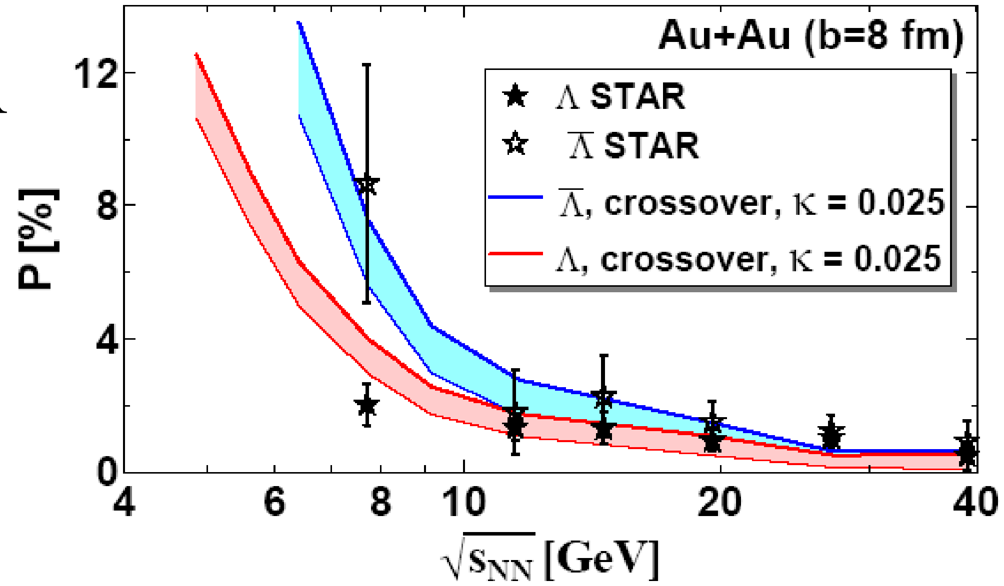
Ayala, et al., arXiv:2003.13757, PLB accepted

Also a completely dynamical (rather than thermodynamical) mechanism



Λ -- $\bar{\Lambda}$ polarization splitting (4)

AVE approach naturally predicts the Λ -- $\bar{\Lambda}$ polarization splitting



Measurements at NICA can refine the data at 7.7 GeV and extend them down to 5 GeV

and thus clarify the nature of the Λ -- $\bar{\Lambda}$ polarization splitting

Fixed-target experiments

BM@N at JINR, CBM at FAIR, STAR FXT, HADES

Rapidity dependence of polarization is still under debates
[Becattini and Lisa, arXiv:2003.03640]

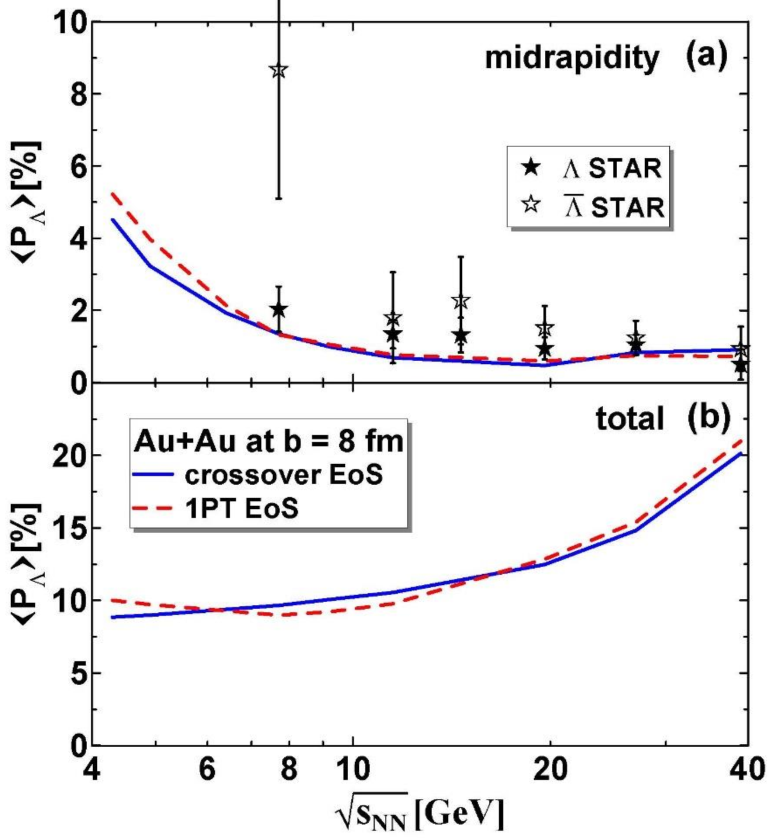
3FD: **total Λ polarization (i.e. averaged over all rapidities)** increases with collision energy rise, in contrast to **midrapidity polarization**.

In means

- ✓ Λ polarization in target fragmentation region is higher than the midrapidity one
- ✓ It increases with collision energy rise

It would be interesting to check these predictions

Ivanov, et al., PRC 100, 014908 (2019), Phys.Atom.Nucl. 83, 179 (2020)



Summary

- ✓NICA data will distinguish between AVE and thermodynamic predictions
- ✓Measurements at NICA can clarify the nature of the Λ -- $\bar{\Lambda}$ splitting
- ✓Measurements of local longitudinal Λ polarization are also possible at $\sqrt{s_{NN}} \geq 6$ GeV
- ✓Polarization measurements at NICA are planned in 2025
- ✓Fixed-target experiments will clarify rapidity dependence of the polarization