Λ polarization in heavy-ion collisions at moderately relativistic energies

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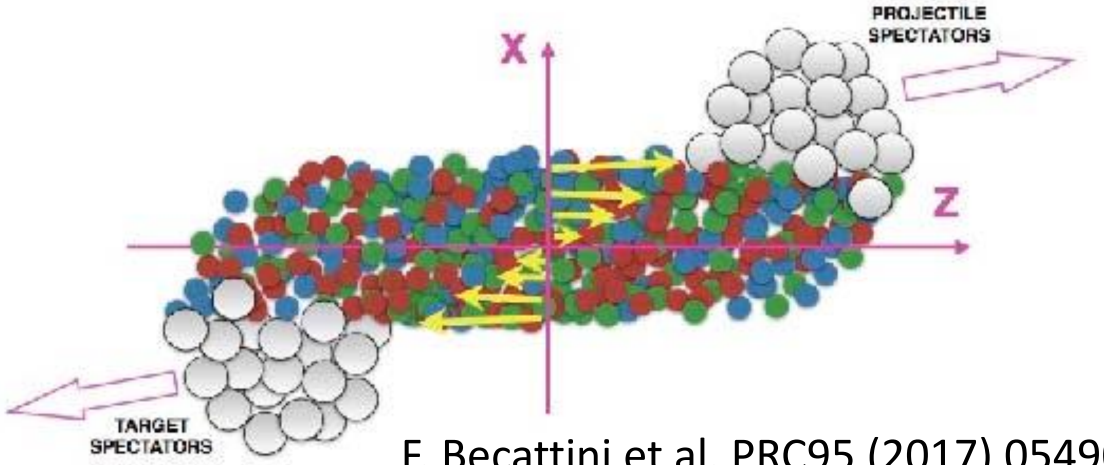
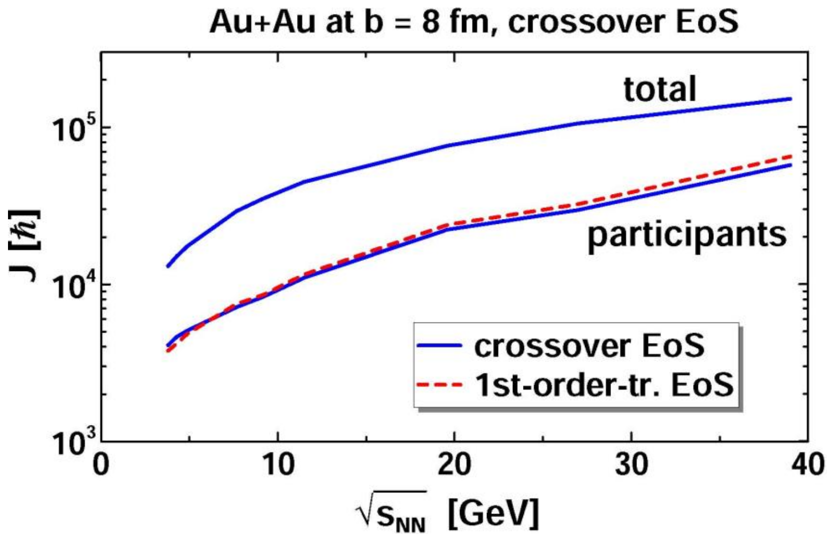
Vortical motion of nuclear matter

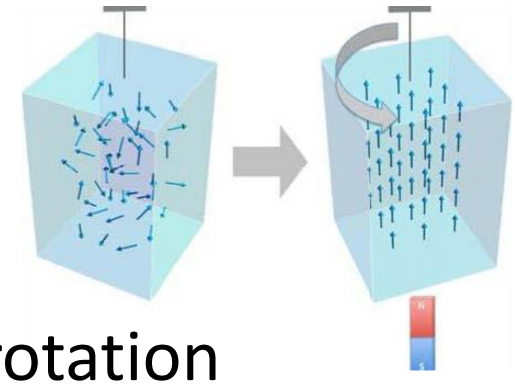


F. Becattini et al. PRC95 (2017) 054902



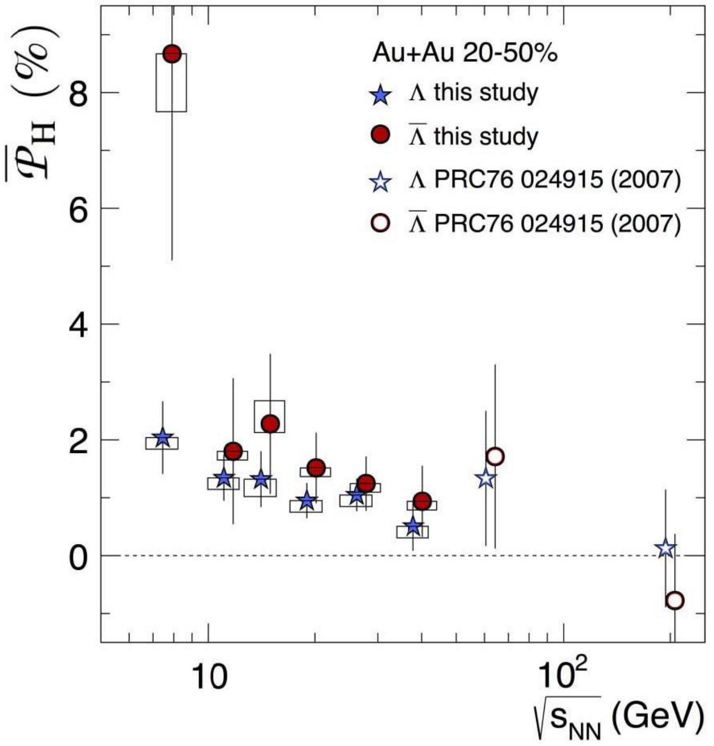
Vortical motion: $\boldsymbol{\omega} = (1/2)\ \boldsymbol{\nabla} \times \mathbf{v}$ = **Vorticity**

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



- Angular momentum → spin polarization
- Similarly to Barnett effect (1915): magnetization by rotation

Polarization Measurements



STAR

- ✓ Global Λ and anti-Λ polarization [Nature 548, 62 (2017)]
- ✓ Local polarization of hyperons along the beam direction [PRL 123, 132301 (2019)]
- ✓ Measurement of global spin alignment of vector Mesons [NPA 1005 (2021) 121733]
- ✓ Global polarization of Ξ and Ω hyperons at 200 GeV [2012.13601]

At moderately relativistic energies

- ➢ HADES: Λ Polarization at 2.4 GeV [Springer Proc.Phys. 250 (2020) 435]
- ➢ STAR-FXT: Λ Polarization at 3 GeV [2108.00044 [nucl-ex]]
- ➢ NICA: planned in approx. 2025

Motivations

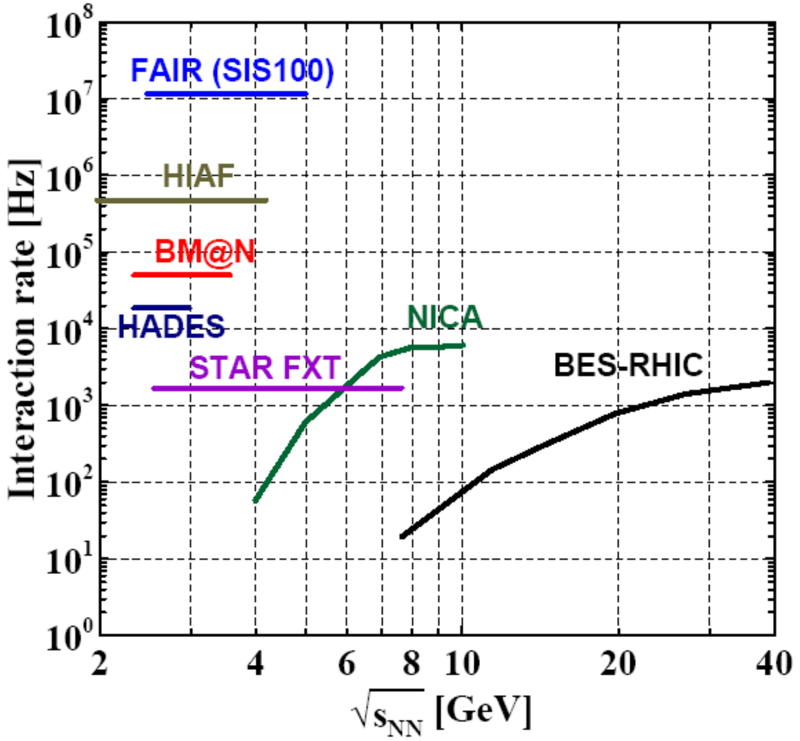
Study of

✓ **vortical motion in heavy-ion collisions**

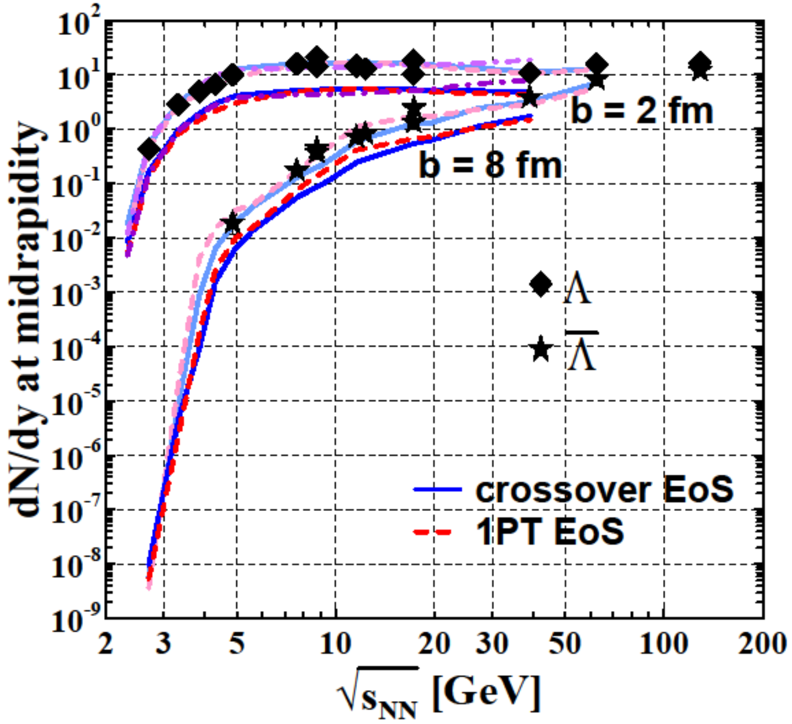
✓ **mechanism of angular-momentum transfer from orbital one to spin**

- **Thermodynamic approach** [F. Becattini, et al.] ➡ *Discussed below*
- Chiral Vortical Effect [Vilenkin (1979); Son and Zhitnitsky (2004)]
- “Lagrangian approach” [D. Montenegro, L. Tinti and G. Torrieri]

Feasibility of polarization measurements



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



STAR and HADES experience

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

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

3FD simulations

Facility	BM@N	HIAF	FAIR	NICA
$\sqrt{s_{NN}}$ [GeV]	2.3 – 3.5	2.3 – 4	2.7 – 4.9	4 – 11
global Λ, $\sqrt{s_{NN}} \gtrsim$	2.3 GeV	2.3 GeV	2.7 GeV	4 GeV
global $\bar{\Lambda}$, $\sqrt{s_{NN}} \gtrsim$	no	3.5 GeV	3 GeV	5 GeV
local Λ, $\sqrt{s_{NN}} \gtrsim$	2.7 GeV	2.5 GeV	2.7 GeV	6 GeV
local $\bar{\Lambda}$, $\sqrt{s_{NN}} \gtrsim$	no	no	4 GeV	no

Threshold collision energies, above which measurements are feasible.

3-Fluid Dynamics (3FD)

Target-like fluid: $\partial_\mu J^\mu_t = 0$ $\quad$ $\partial_\mu T^{\mu\nu}_t = -F^\nu_{tp} + F^\nu_{ft}$

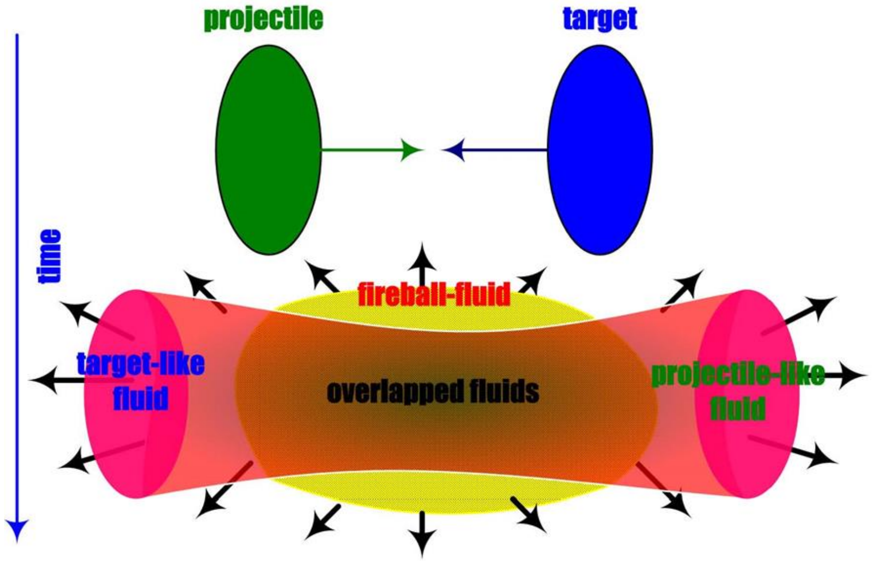
Leading particles carry bar. charge $\quad$ exchange/emission

Projectile-like fluid: $\partial_\mu J^\mu_p = 0,$ $\quad$ $\partial_\mu T^{\mu\nu}_p = -F^\nu_{pt} + F^\nu_{fp}$

Fireball fluid: $J^\mu_f = 0,$ $\quad$ $\partial_\mu T^{\mu\nu}_f = F^\nu_{pt} + F^\nu_{tp} - F^\nu_{fp} - F^\nu_{ft}$

Baryon-free fluid $\quad$ Source term $\quad$ Exchange

The source term is delayed due to a formation time τ



Total energy-momentum conservation:

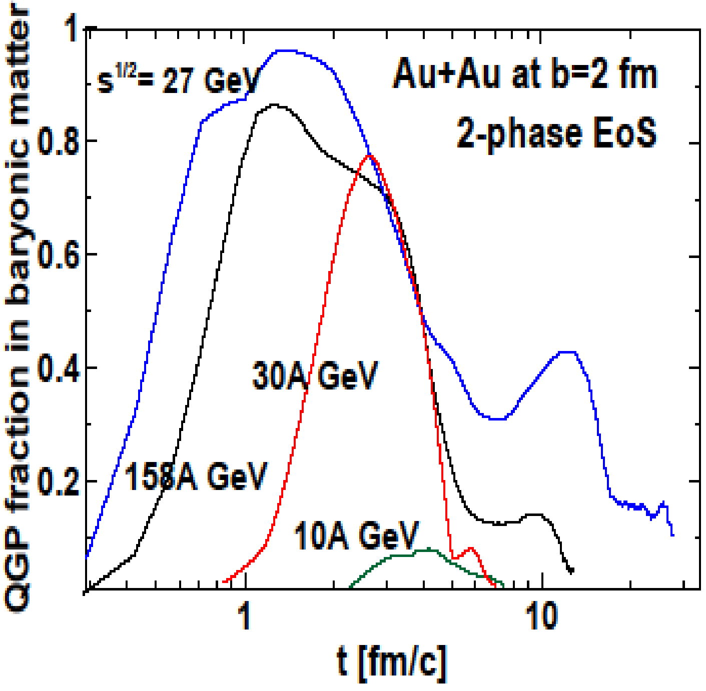
$$\partial_\mu (T^{\mu\nu}_p + T^{\mu\nu}_t + T^{\mu\nu}_f) = 0$$

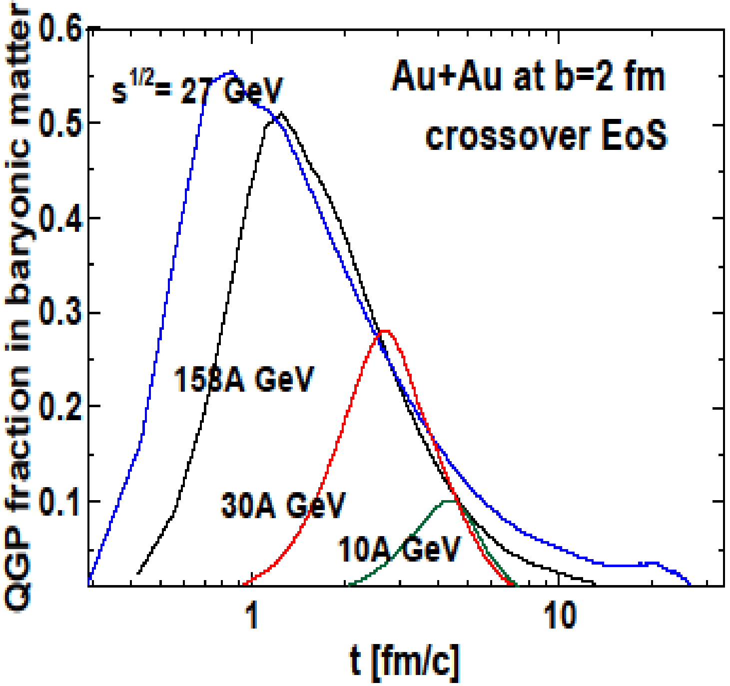
YI, Russkikh, Toneev, PRC 73, 044904 (2006)

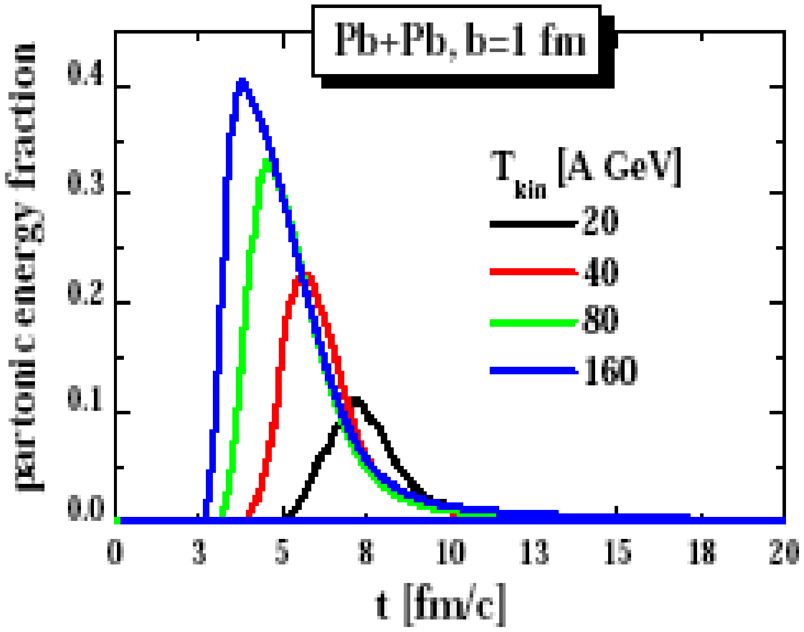
Physical Input

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

QGP Transition in bulk







PHSD: Cassing&Bratkovskaya, NPA 831, 215 (2009).

Deconfinement transition starts at top AGS energies.

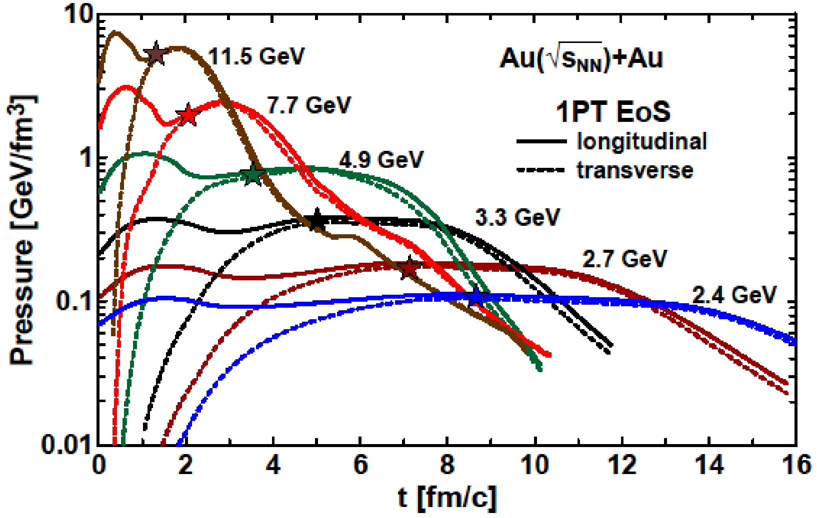
Alternative viewpoint: Seck, Galatyuk, et al., arXiv:2010.04614 [nucl-th]
Dilepton Signature of a First-Order Phase Transition already at 1-2A GeV.

Equilibration at low energies

- Thermodynamic approach
- Chiral Vortical Effect

→ Require equilibrium

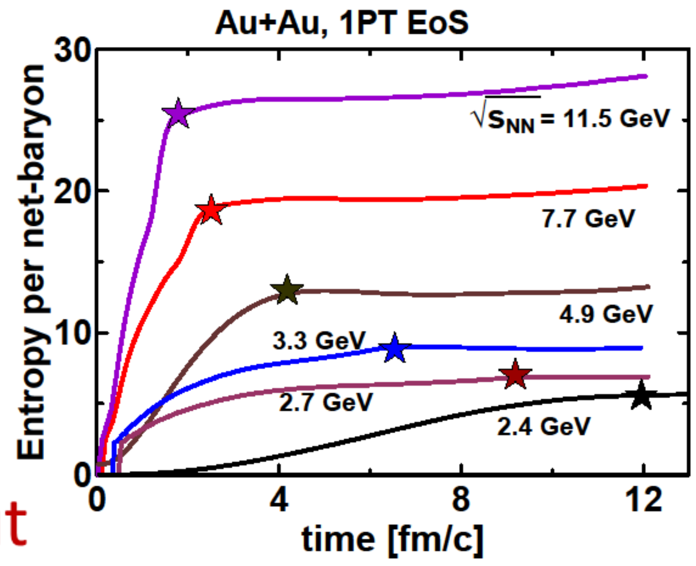
YI, Soldatov, PRC C 101, 024915 (2020)



Longitudinal and transverse pressure in the center
Mechanical equilibration time (★) is comparatively long

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

YI, Soldatov, EPJA 52 (2016) 12, 367



Chemical equilibration (★)
(and hence thermalization) takes longer

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

Thermodynamic approach to polarization

Spin is in thermal equilibrium with other degrees of freedom

[F. Becattini, et al., Ann. Phys. 338, 32 (2013)]

Chemical potential for angular momentum $\varpi_{\mu\nu} = \frac{1}{2}(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu)$ =Thermal Vorticity

$\beta_\mu = u_\mu / T$ = 4-velocity/Temperature

Mean spin vector of a spin of Λ particle in a relativistic fluid

$$S^\mu = \frac{1}{8m_\Lambda} \frac{\int d\Sigma_\lambda p^\lambda n_\Lambda p_\sigma \varepsilon^{\mu\nu\rho\sigma} \varpi_{\rho\nu}}{\int d\Sigma_\lambda p^\lambda n_\Lambda}$$

n_Λ = Fermi-Dirac distribution function, integration over freeze-out hypersurface

Formulation in terms of frozen-out hadronic matter!

Observable global polarization

$$\mathrm{P}_{\Lambda}^{\mu} = \left\langle \mathrm{S}_{\Lambda}^{\mu} \right\rangle / \mathrm{S}_{\Lambda}$$ Polarization of Λ particle, S_Λ=1/2

Polarization is measured **in the rest frame (*)** of Λ particle $$\mathbf{S}_{\Lambda}^{*} = \mathbf{S}_{\Lambda} - \frac{\mathbf{p}_{\Lambda} \cdot \mathbf{S}_{\Lambda}}{E_{\Lambda}\left(E_{\Lambda} + m_{\Lambda}\right)} \mathbf{p}_{\Lambda}$$

$$\mathrm{P}_{\Lambda} = \frac{1}{2m_{\Lambda}} \left\langle \left(E_{\Lambda} - \frac{1}{3} \frac{\mathbf{p}_{\Lambda}^{2}}{E_{\Lambda} + m_{\Lambda}} \right) \varpi_{zx} \right\rangle$$ Global polarization is directed along the y axis

Thermodynamic global polarization in 3FD

$$P_\Lambda = \frac{1}{2m_\Lambda}\left\langle\left(E_\Lambda - \frac{1}{3}\frac{\mathbf{p}_\Lambda^2}{E_\Lambda + m_\Lambda}\right)\varpi_{zx}\right\rangle$$

averaging with Λ distribution function, n_Λ

Approximations made in [YI, PRC 103, L031903 (2021)]:

Approximation 1: feed-down from decays of Σ^0 , Σ^* , … is neglected

Approximation 2: Averaging with energy density, ε, in stead of n_Λ

Approximation 3: Averaging of (…) and ϖ_{zx} are decoupled

$$\mathbf{P}_\Lambda \simeq \frac{\langle\varpi_{zx}\rangle}{2}\left(1 + \frac{2}{3}\frac{\langle E_\Lambda\rangle - m_\Lambda}{m_\Lambda}\right)$$

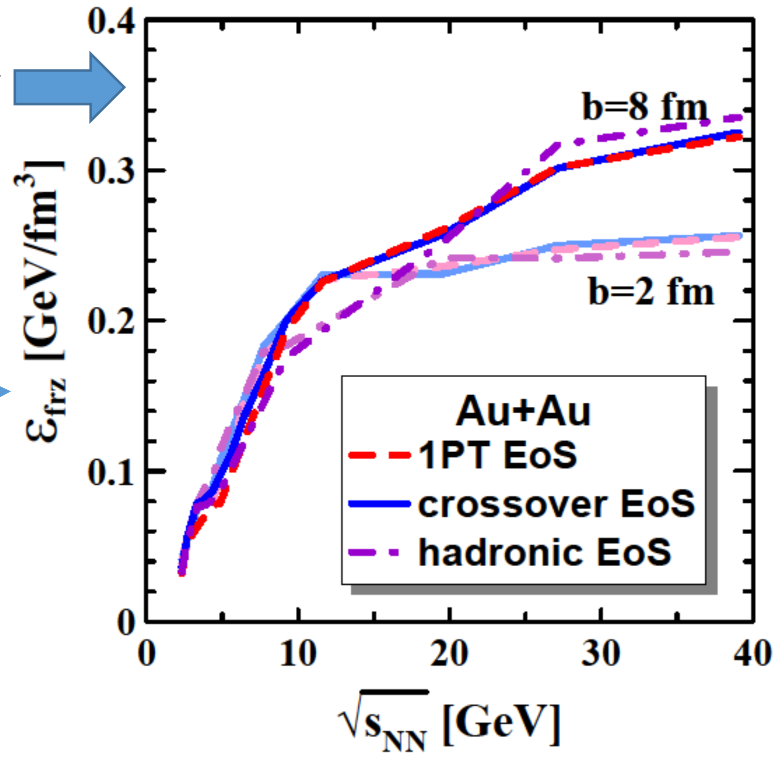
Approximation 4: Averaging over central region [z_{left},z_{right}] confined by $|y| < \Delta y_h/2$

Hydrodynamical rapidity: $y_h(z,t) = \frac{1}{2}\ln\frac{\langle u^0 + u^3\rangle}{\langle u^0 - u^3\rangle}$ $\quad \Delta y_h(t) = y_h(z_{\rm right},t) - y_h(z_{\rm left},t)$.

Freeze-out for polarization calculation

Usually it is a local freeze-out , i.e. cell-by-cell.
The freeze-out procedure starts when the local energy density < 0.4 GeV/fm^3:
(1) This criterion should be met in the cell and in eight surrounding cells.
(2) At least one of the surrounding cells is empty (border with vacuum).

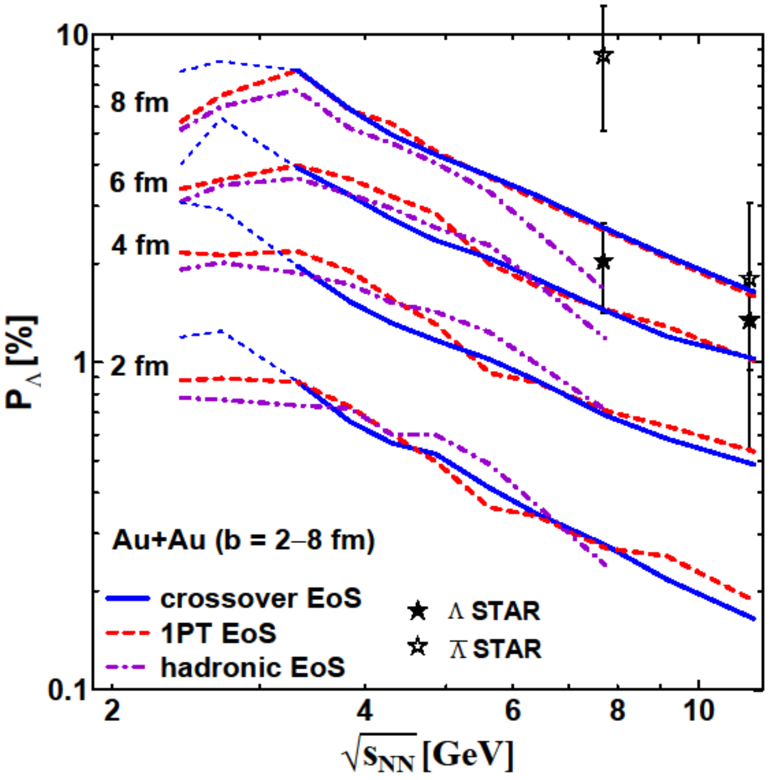
Therefore, the actual mean freeze-out energy density



For the polarization calculation global freeze-out at ε_{frz} in the central region

Thermodynamic polarization at moderate energies

YI, PRC 103, L031903 (2021)

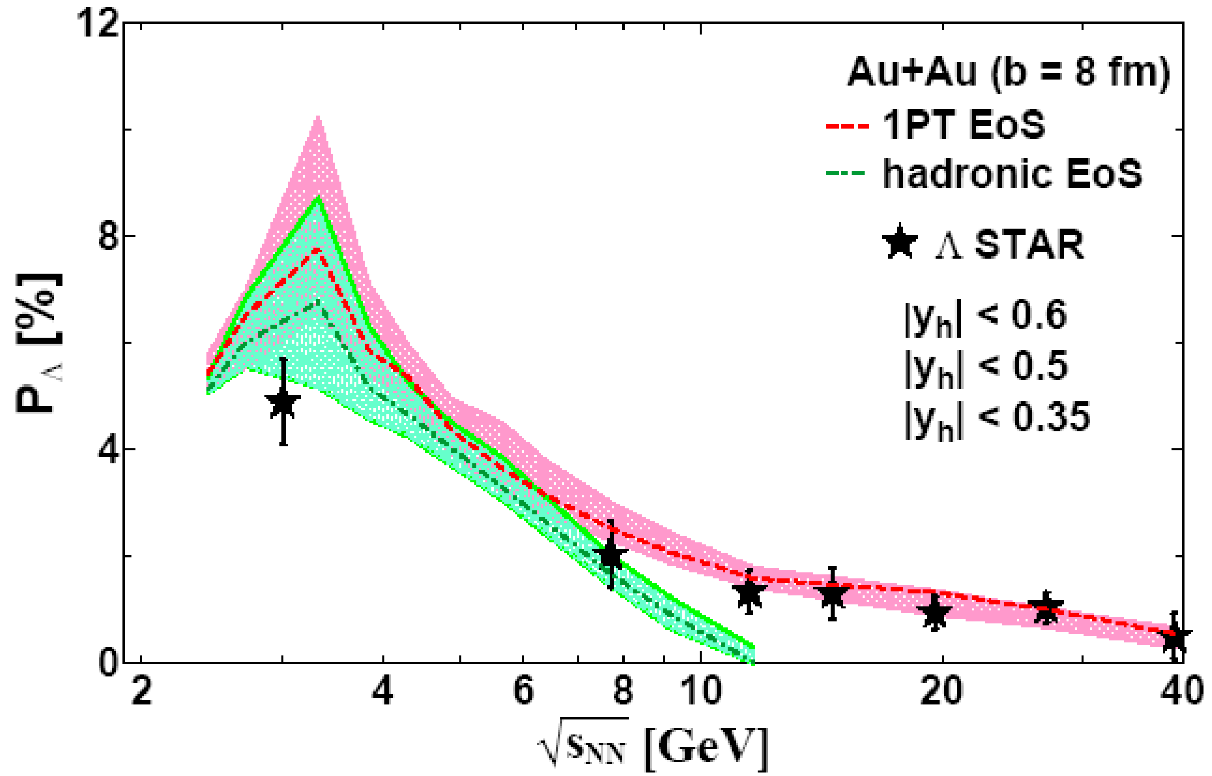


Polarization reaches a maximum or a plateau (depending on EoS and centrality) at $\sqrt{s_{NN}} \approx 3$ GeV.

Rapidity window dependence

$|y_h| < 0.6$ upper border, $|y_h| < 0.5$ center line, $|y_h| < 3.5$ lower border

YI, PRC 103, L031903 (2021)



Global polarization increases with increasing width of rapidity window around the midrapidity

Thermodynamic global polarization in 3FD

$$P_\Lambda = \frac{1}{2m_\Lambda}\left\langle\left(E_\Lambda - \frac{1}{3}\frac{\mathbf{p}_\Lambda^2}{E_\Lambda + m_\Lambda}\right)\varpi_{zx}\right\rangle$$ averaging with Λ distribution function, n_Λ

Approximations made in new run of calculations:

Approximation 1: feed-down from decays of **Σ^0** and **Σ^*** is **taken into account**

Approximation 2: Averaging with **Λ density, ρ_Λ ,** in stead of n_Λ . This is better than ε.

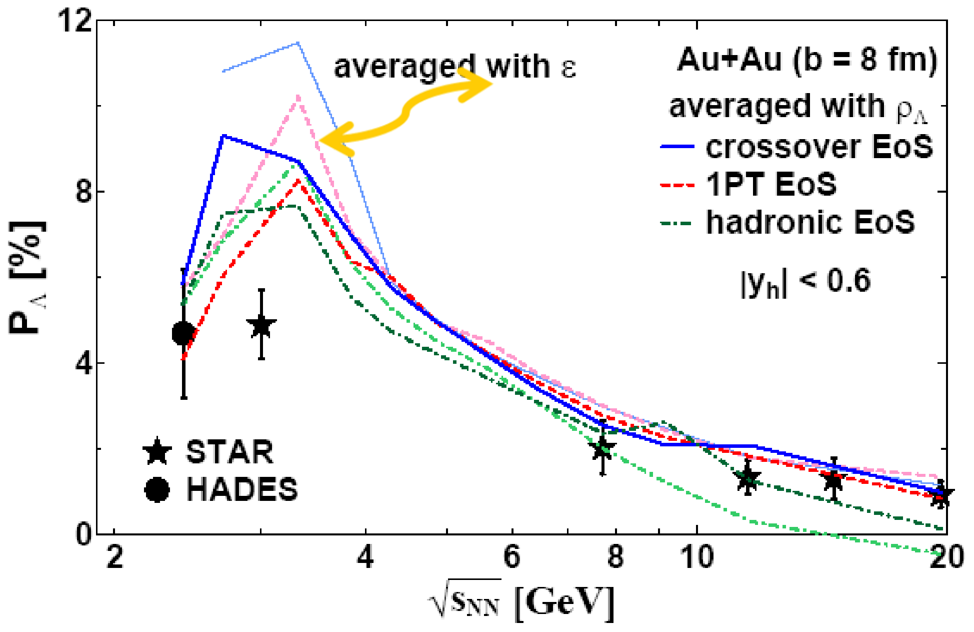
Approximation 3: Averaging of (…) and ϖ_{zx} are **not decoupled in P_Λ**

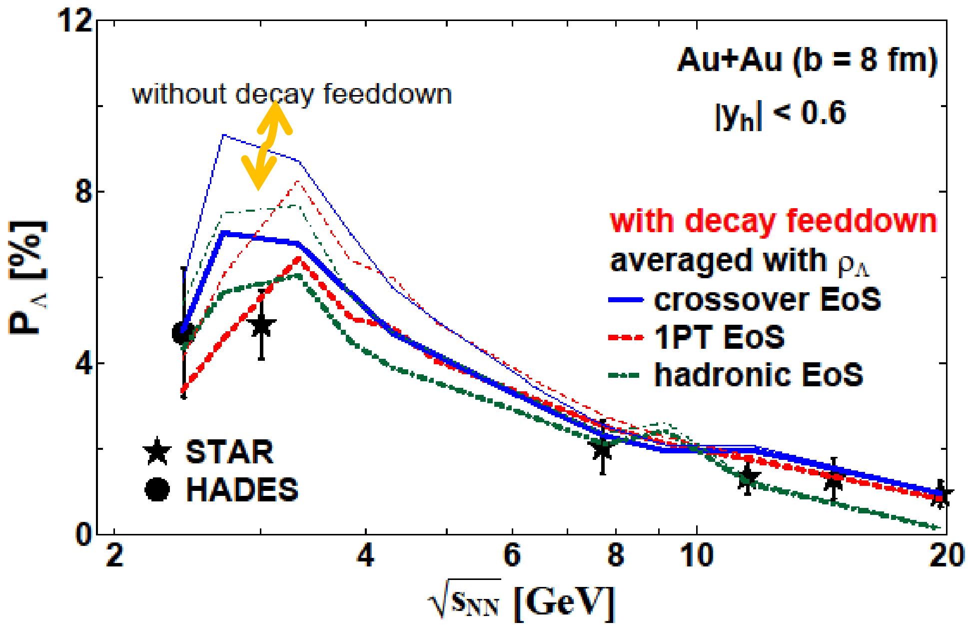
Approximation 4: Averaging over central region $[z_{left}, z_{right}]$ confined by $|y| < \Delta y_h/2$

Hydrodynamical rapidity: $y_h(z,t) = \frac{1}{2}\ln\frac{\langle u^0 + u^3\rangle}{\langle u^0 - u^3\rangle}$ $\quad \Delta y_h(t) = y_h(z_{\rm right}, t) - y_h(z_{\rm left}, t)$,

Global polarization in new run of 3FD calculations

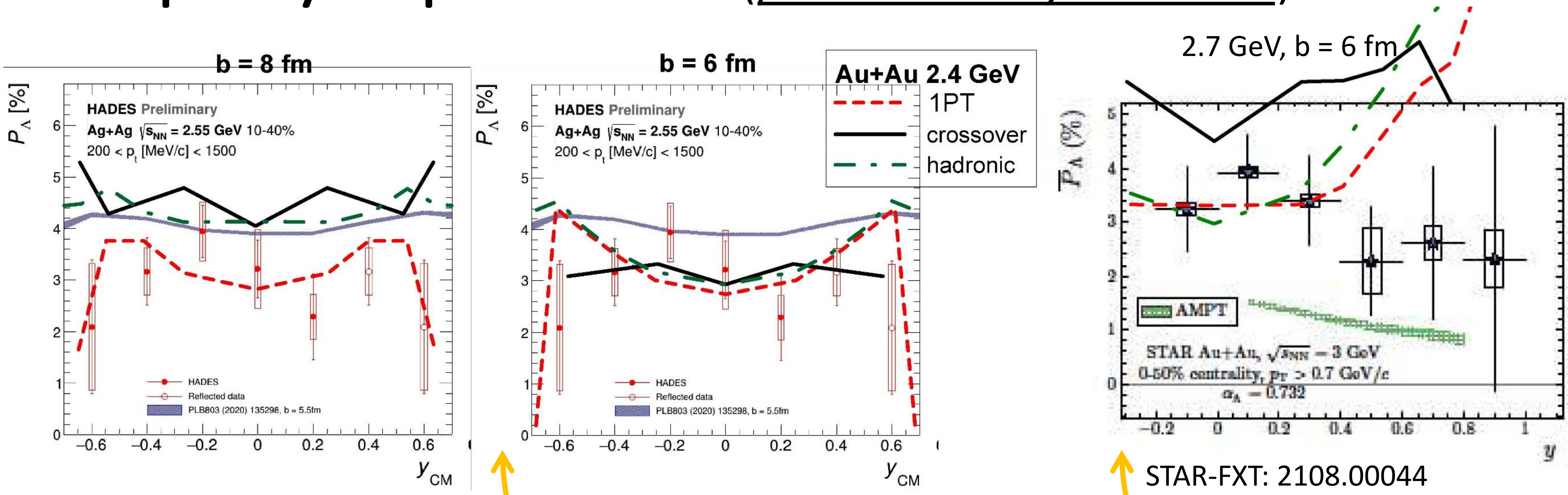
preliminary results





- ✓ **Averaging with Λ density, ρ_Λ in stead of ε, noticeably reduces P_Λ at $\sqrt{s_{NN}} < 4$ GeV**
- ✓ **Decay feed-down noticeably reduces P_Λ**

Rapidity dependence (*preliminary results*)



STAR-FXT: 2108.00044

https://indico.cern.ch/event/985652/contributions/4305142/attachments/2246397/3812486/SQM2021-Kornas.pdf

- ✓ 3FD: **Λ polarization increases from midrapidity to forward/backward rapidities**
- ✓ **3FD does not contradict HADES data, but contradicts to STAR-FXT data.** **acceptance???**

Summary

- ✓ Prerequisite for polarization models: **freeze-out stage is thermalized**

- ✓ 3FD: Λ **polarization rises with collision energy decrease at $\sqrt{s_{NN}} \leq$ 7.7 GeV** (experimentally observed)

- ✓ 3FD: Λ **polarization reaches a maximum at $\sqrt{s_{NN}} \leq \approx$ 3 GeV** (experimentally looks like a plateau; acceptance?)

- ✓ 3FD: Λ **polarization increases from midrapidity to forward/backward rapidities** (STAR-FXT: experimentally decreases; acceptance?)

- ✓ **Decay feeddown noticeably reduces P_Λ at $\sqrt{s_{NN}}$ < 8 GeV**

Backup

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

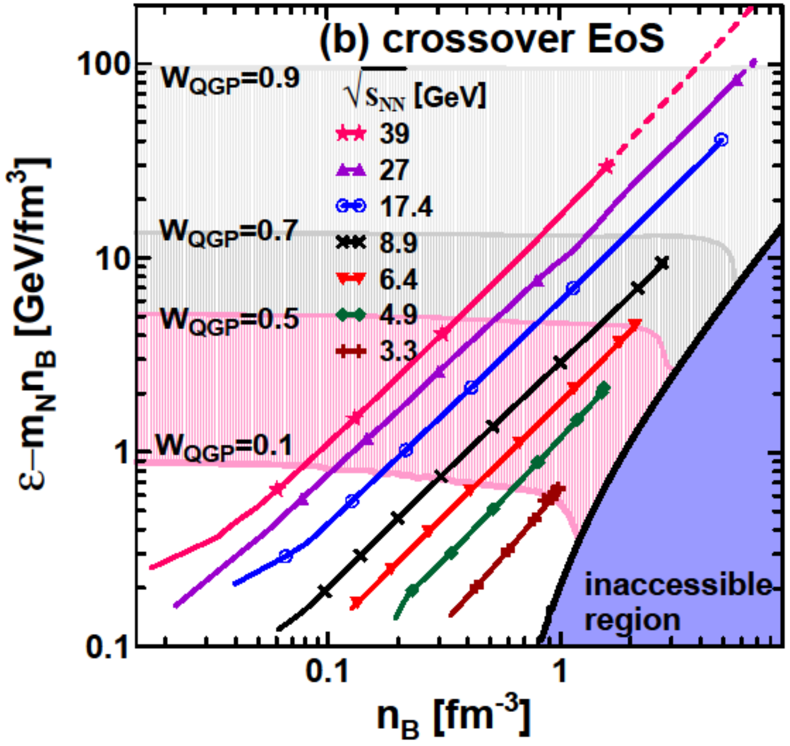
Data taking at MPD 2023

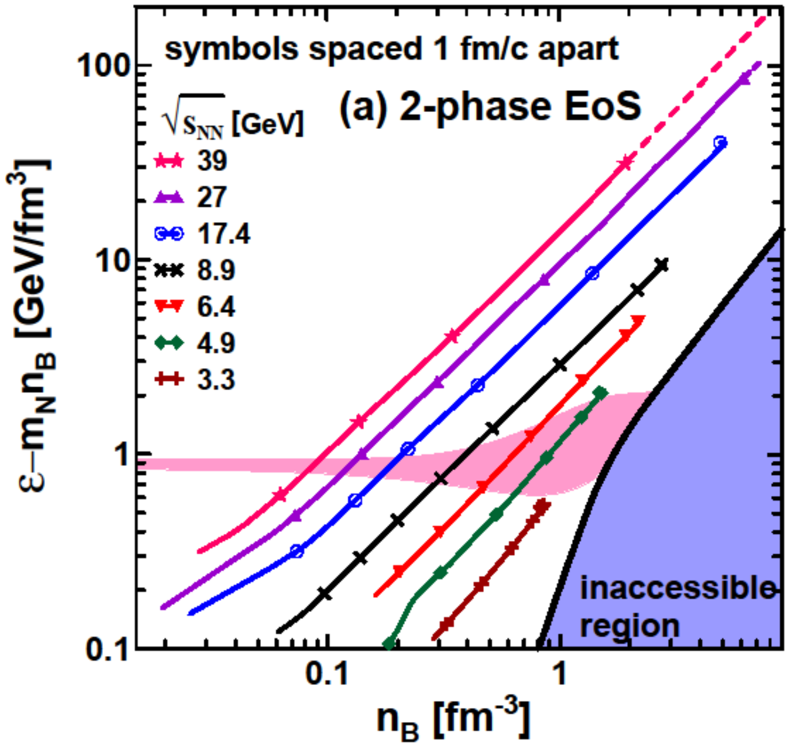
Polarization measurements are planned (approx. 2025)

QGP Transition in central region [Y.I., Phys.Rev.C 87 (2013) 6, 064904]

$|x| \leq 2$ fm, $|y| \leq 2$ fm and $|z| \leq \gamma_{cm}$ 2 fm, γ_{cm} = Lorentz factor of initial motion in cm frame

EoS's: Khvorostukhin, Skokov, Redlich, Toneev, EPJ C48, 531 (2006)





Slow crossover EoS
lattice QCD: fast crossover

deconfinement transition starts at top AGS energies in both cases.

Chiral vortical effect (CVE)

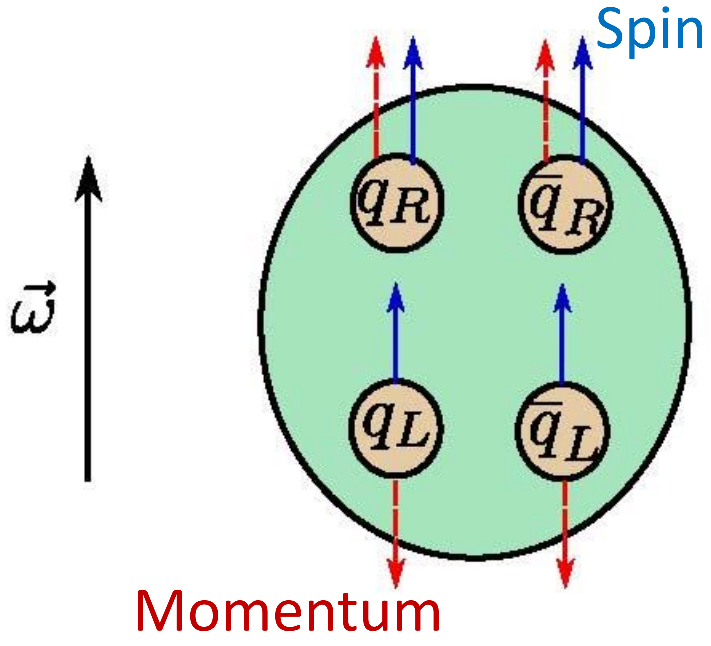
Axial current

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

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).

Son and Zhitnitsky, PRD 70, 074018 (2004)



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

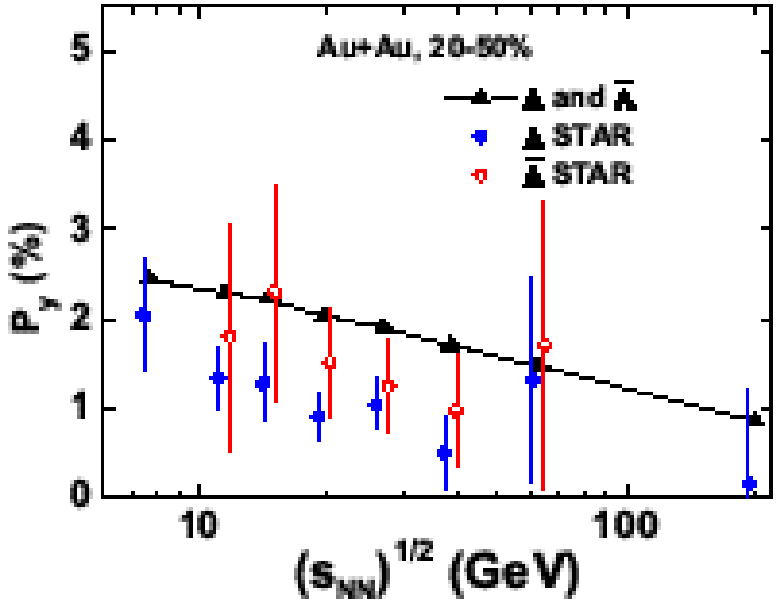
Landsteiner, Megias, Melgar, Pena-Benitez, JHEP 1109, 121 (2011) [Gauge-gravity correspondence]

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)]

Chiral vortical effect (CVE): Coalescence

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



Sun and Ko, PRC 96, 024906 (2017)

Λ -- $\bar{\Lambda}$ **polarization** splitting is not explained

Only BES-RHIC energies were studied

Axial-vortical-effect (AVE):

Axial-charge conservation at hadronization

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

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

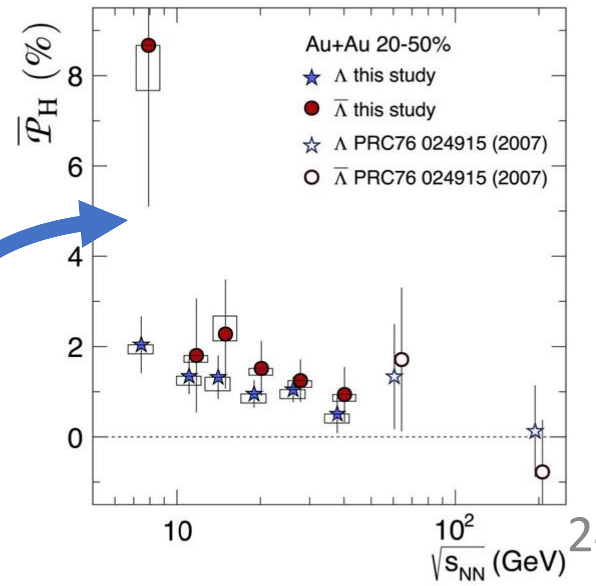
u_y results from boost to the local rest frame of the matter

Sorin and Teryaev, PRC 95, 011902 (2017)

P_{Λ} and $P_{anti-\Lambda}$ are quite different

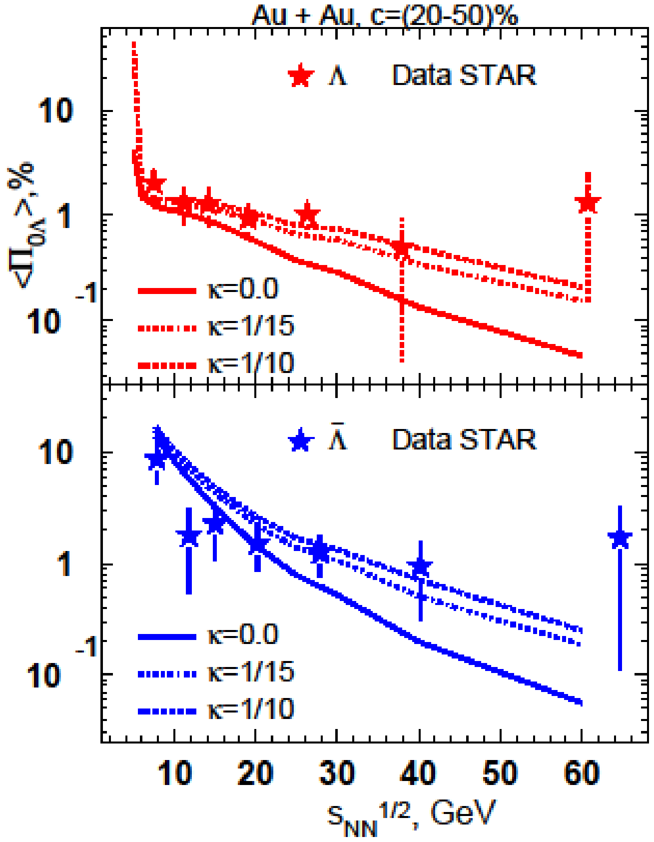
Therefore,

Λ -- $\bar{\Lambda}$ splitting can be addressed

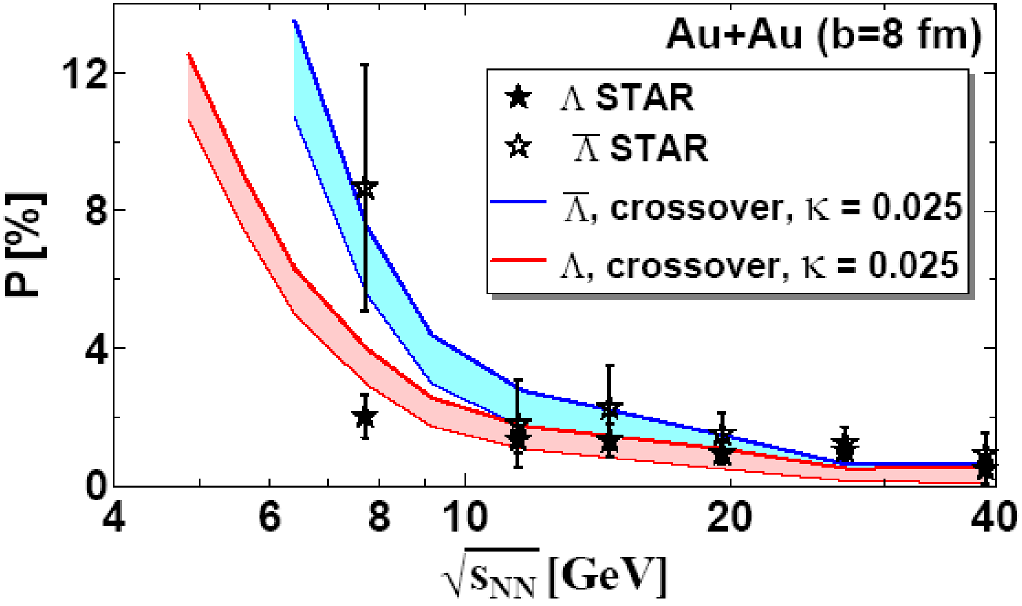


Axial-vortical-effect (AVE) polarization

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



YI, PRC 102 (2020) 4, 044904



Λ -- $\bar{\Lambda}$ splitting is explained

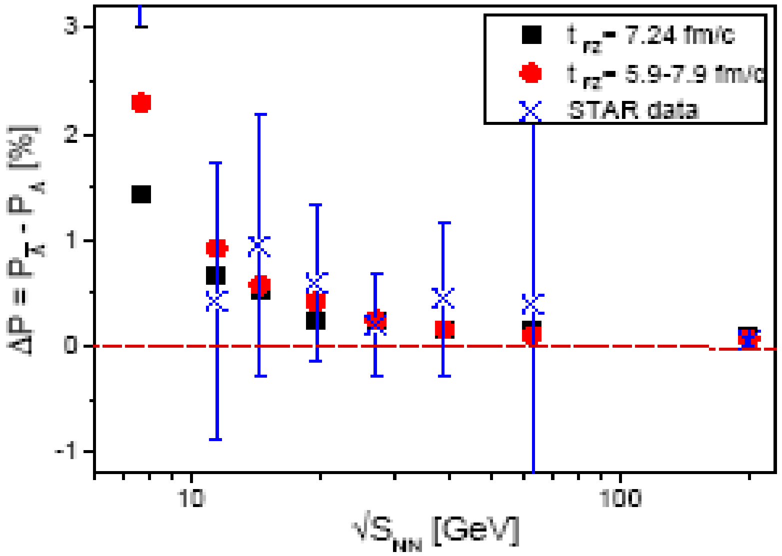
- **CVE and AVE are hardly applicable below NICA range**
- because the chiral symmetry is spontaneously broken.

Λ -- $\bar{\Lambda}$ polarization splitting: possible solutions

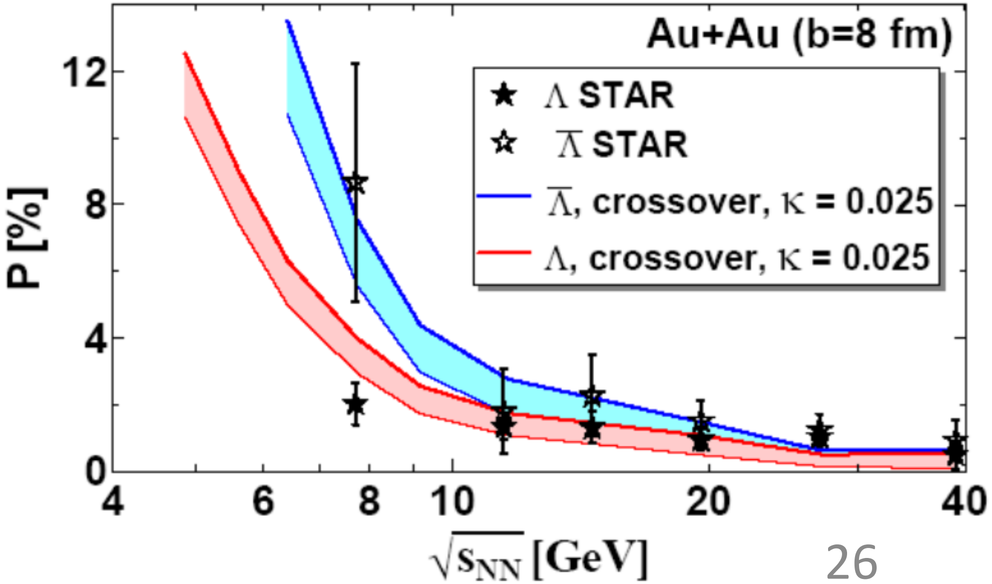
Interaction mediated by massive vector and scalar bosons (Walecka-like model)

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

Xie, Chen, Csernai, EPJC 81, 12 (2021)



AVE naturally explains the Λ -- $\bar{\Lambda}$ splitting



Problem: Λ -- $\bar{\Lambda}$ polarization splitting

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.