Particle polarization in heavy-ion collisions at moderately relativistic energies

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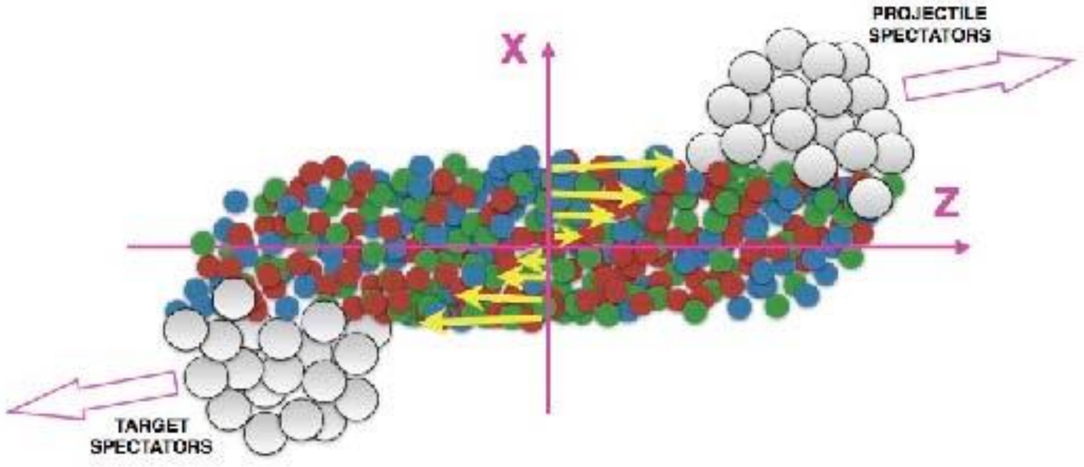
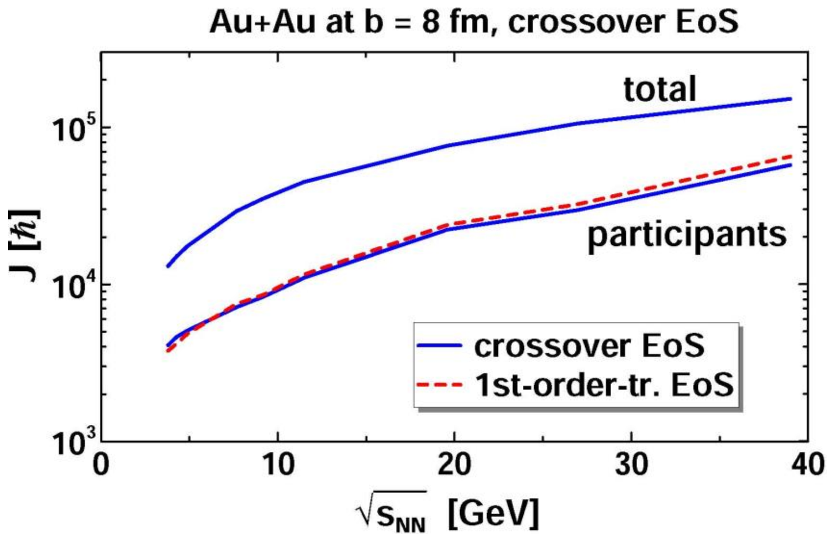
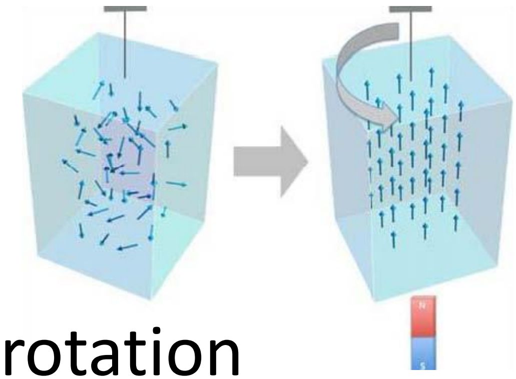
Vortical motion of nuclear matter





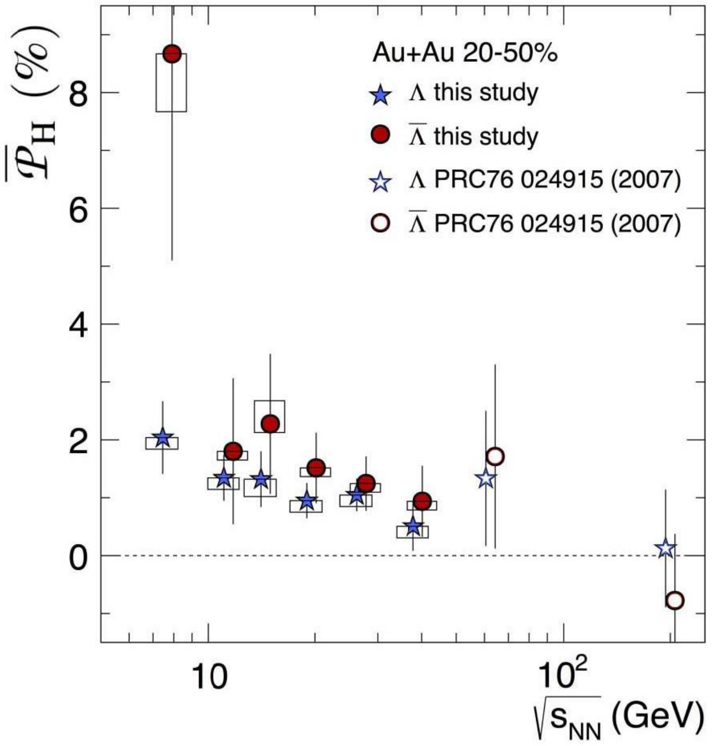
Vortical motion: $\boldsymbol{\omega} = (1/2)\ \boldsymbol{\nabla} \times \mathbf{v}$ = **Vorticity**

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: in progress
- NICA: planned in approx. 2025

Motivations

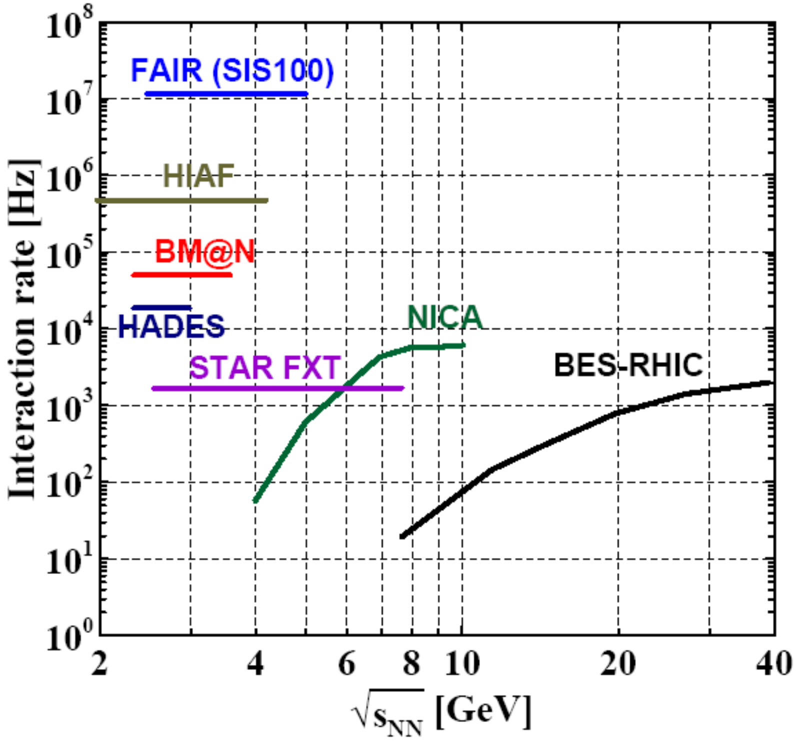
Study of

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

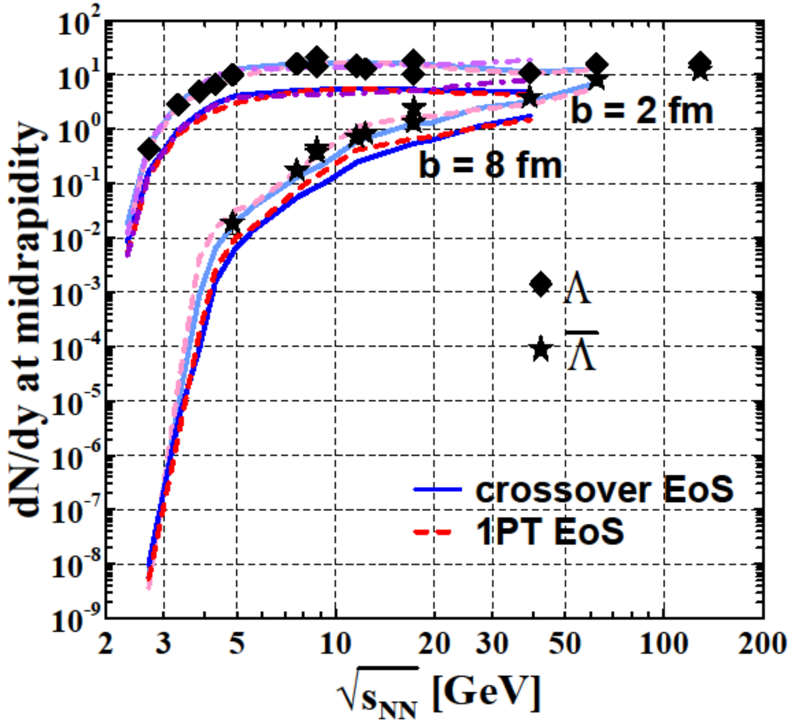
✓**mechanism of angular-momentum transfer from orbital one to spin**

- Thermodynamic approach
- Chiral Vortical Effect
- …

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

Threshold collision energies, above which measurements are feasible.

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

3-Fluid Dynamics (3FD)

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

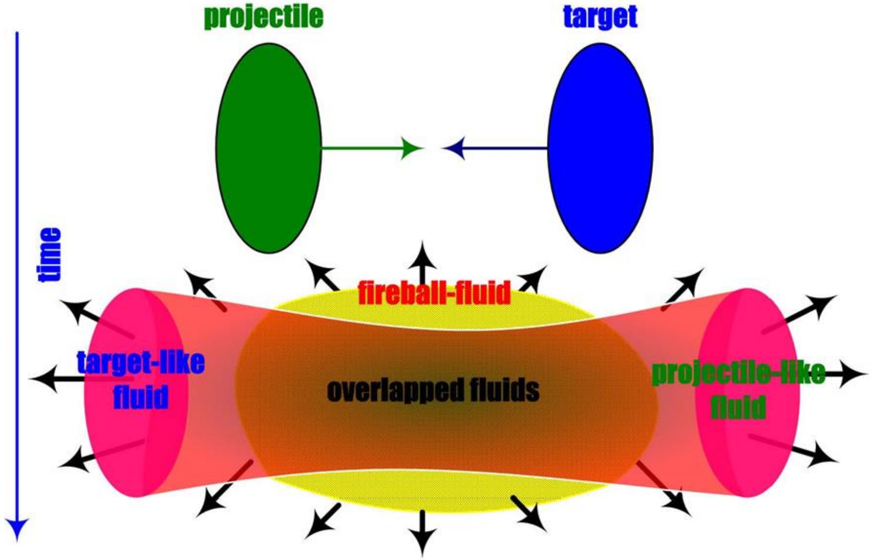
Leading particles carry bar. charge — exchange/emission

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 — Source term — 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)

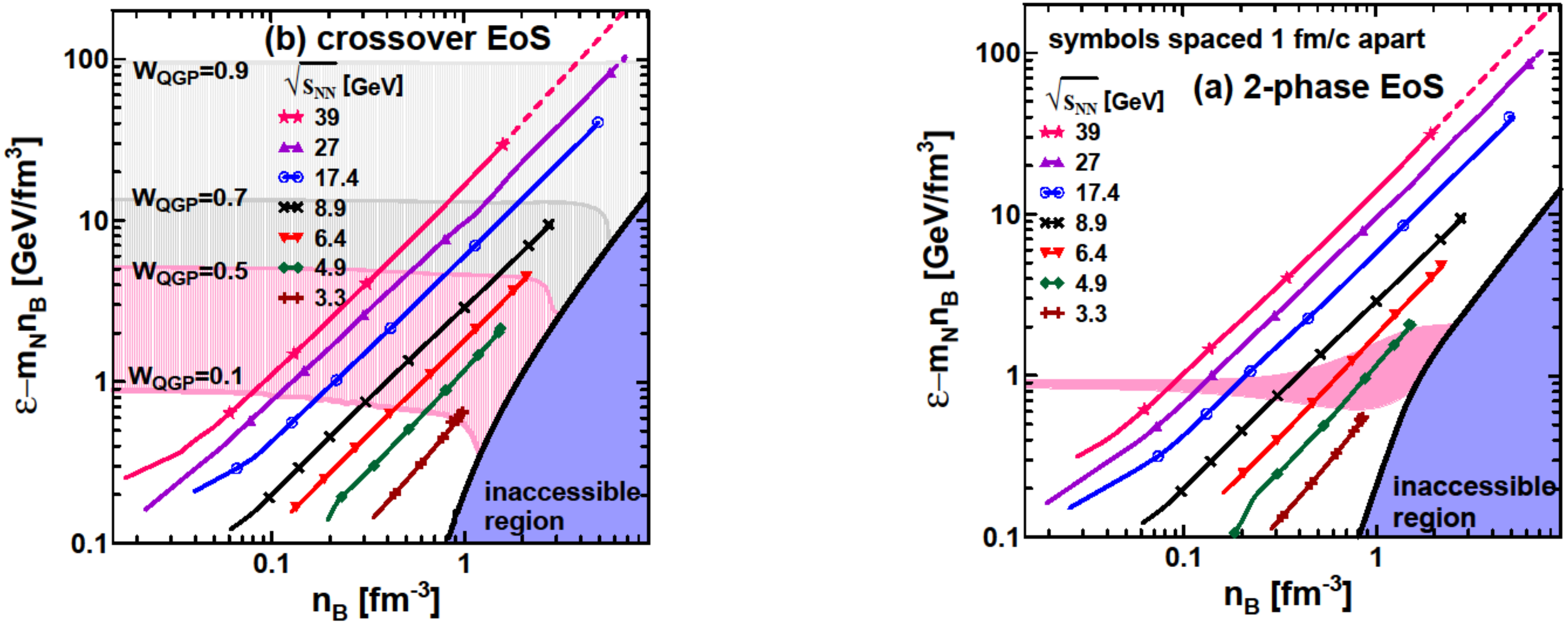
Physical Input

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

QGP Transition in 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)

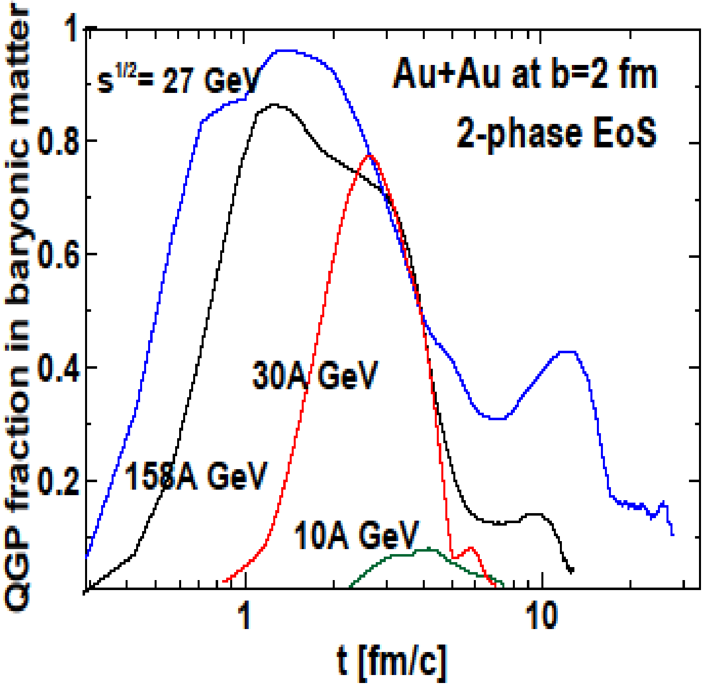


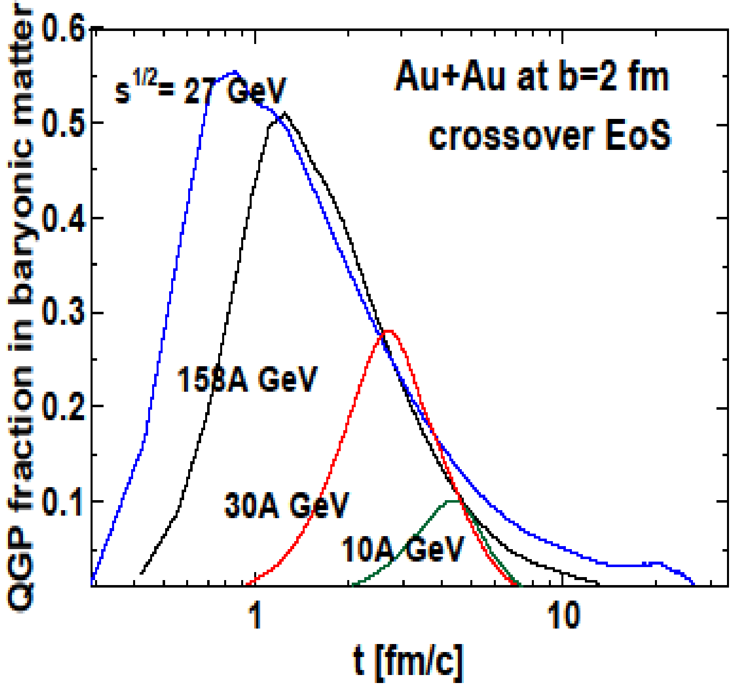
Slow crossover EoS

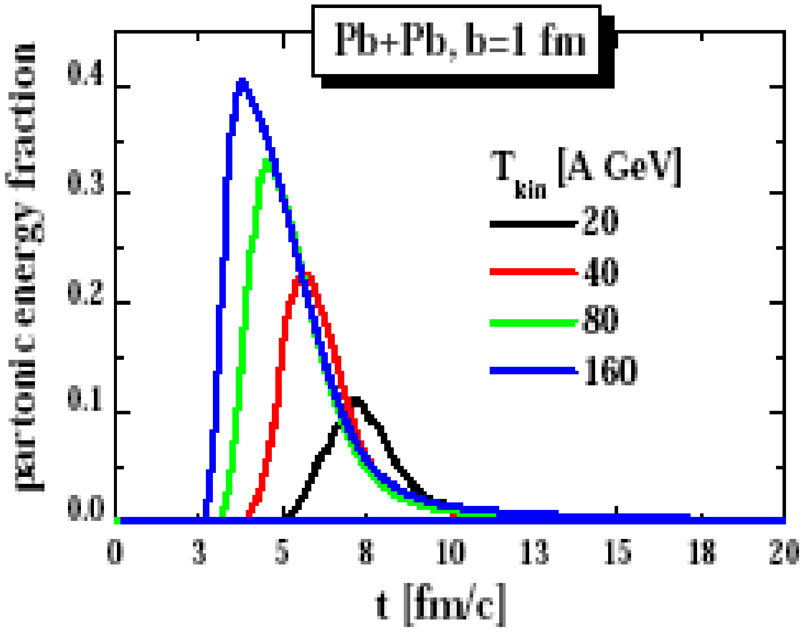
lattice QCD: fast crossover

deconfinement transition starts at top AGS energies in both cases.

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.

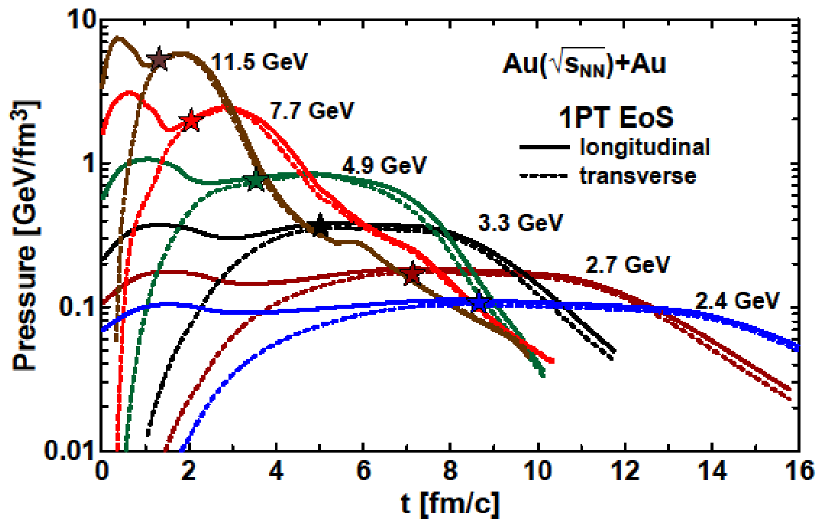
Equilibration at low energies

- Thermodynamic approach
- Chiral Vortical Effect

→ Require equilibrium

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

Longitudinal and transverse pressure in the center →

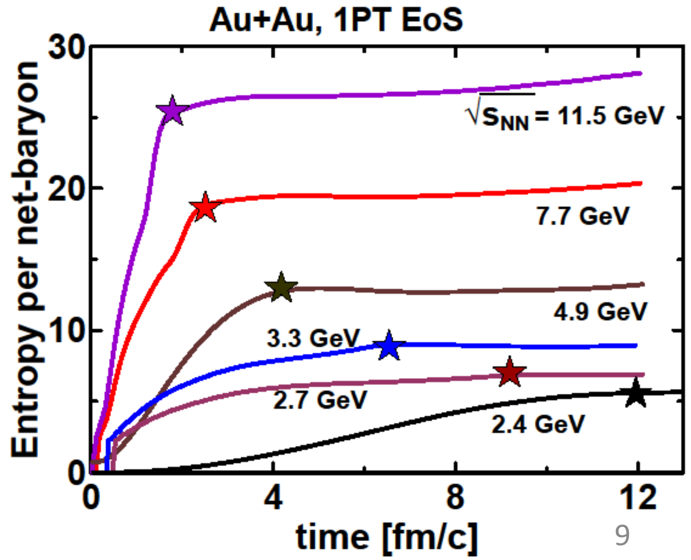


Mechanical equilibration time (★) is comparatively long

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

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

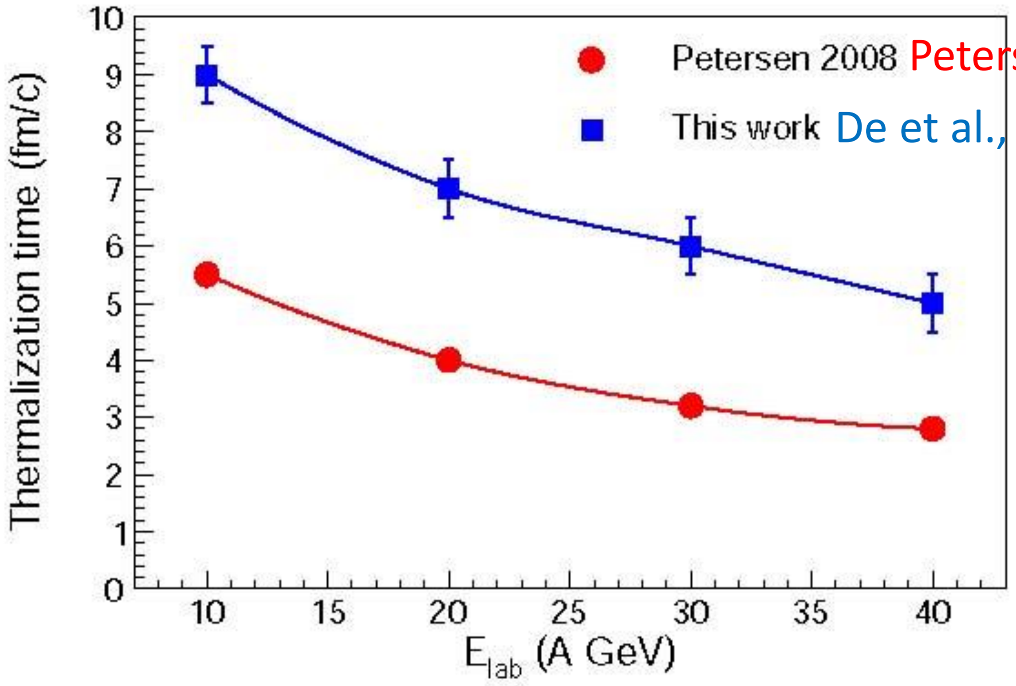
Chemical equilibration (★)
(and hence thermalization) takes longer →



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
$\approx$ 3.5 fm/c

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

Chiral vortical effect (CVE)

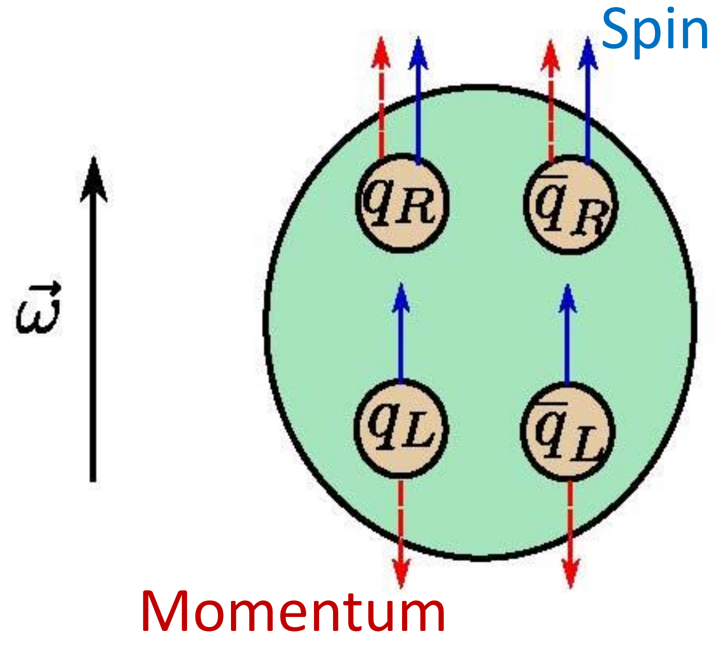
Axial current

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

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

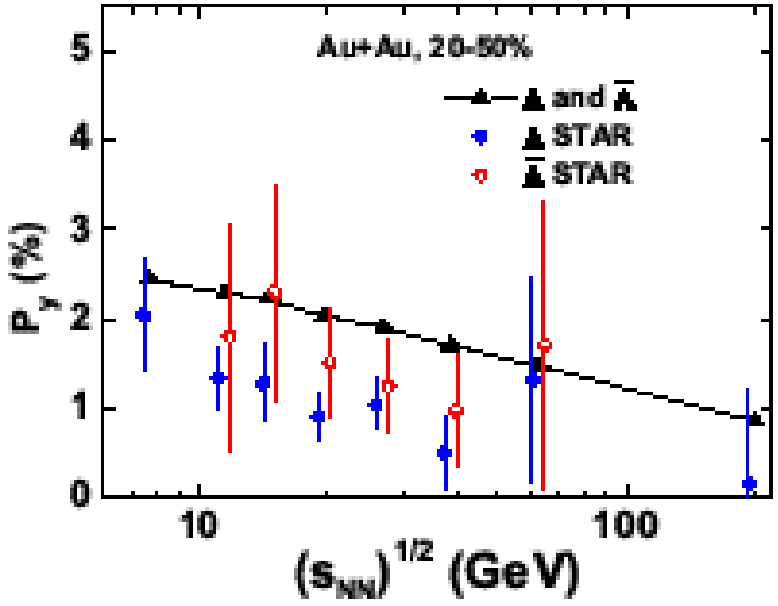
Landsteiner, Megias, Melgar, Pena-Benitez, JHEP 1109, 121 (2011) [Gauge-gravity correspondence]

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

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

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

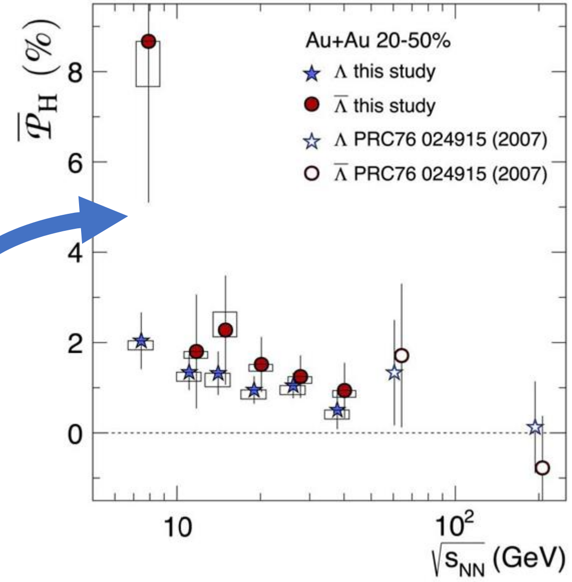
u_y results from boost to the local rest frame of the matter

Sorin and Teryaev, PRC 95, 011902 (2017)

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

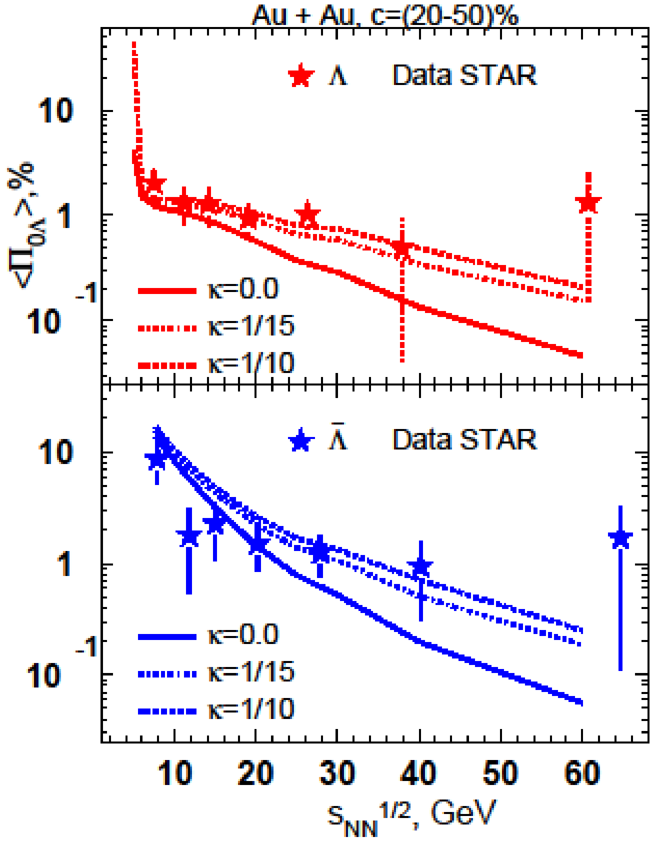
Therefore,

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

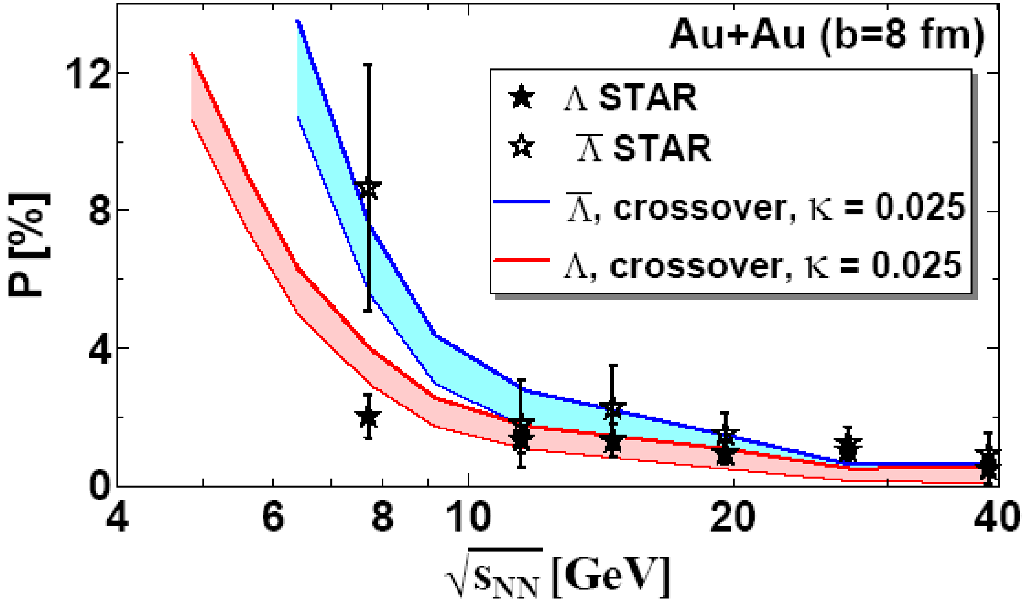


Axial-vortical-effect (AVE) polarization

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.

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!

Thermodynamic global polarization in 3FD

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

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

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

Approximation 1: Averaging of (…) and ϖ_{zx} are decoupled $$\mathbf{P}_\Lambda \simeq \frac{\langle \varpi_{zx} \rangle}{2} \left(1 + \frac{2}{3} \frac{\langle E_\Lambda \rangle - m_\Lambda}{m_\Lambda} \right)$$

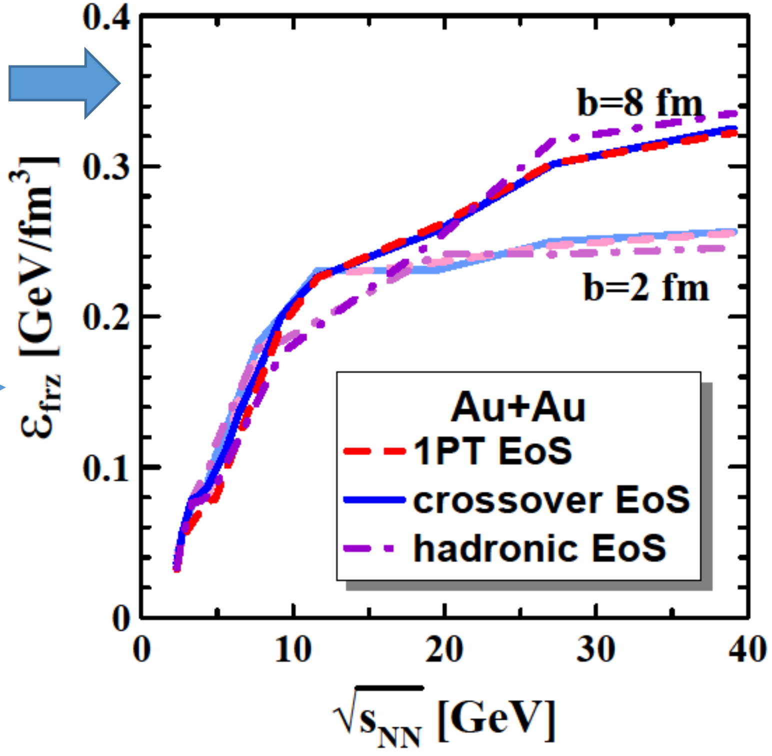
Approximation 2: Averaging over central region [z_{left},z_{right}] confined by |y|< $\Delta y_h/2$

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

Calculations of polarization below BES-RHIC energies

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

✓Within thermodynamic approach *[Becattini et al., Ann. Phys. 338, 32 (2013)]*

YI, et al., PRC 100, 014908 (2019); PRC 102, 024916 (2020); ***YI, PRC 103, L031903 (2021)*** [3FD model]

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

below NICA energies

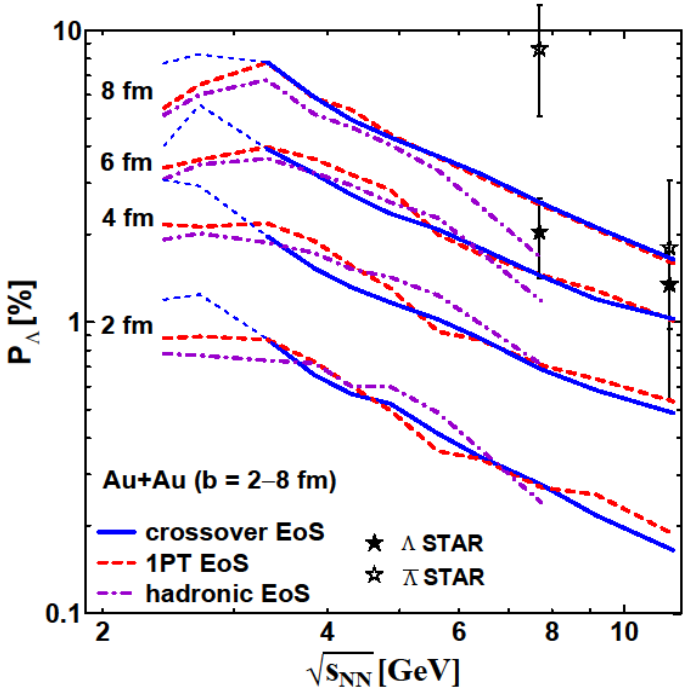
✓Within axial-vortical-effect approach *[Sorin&Teryaev, PRC 95, 011902 (2017)]*

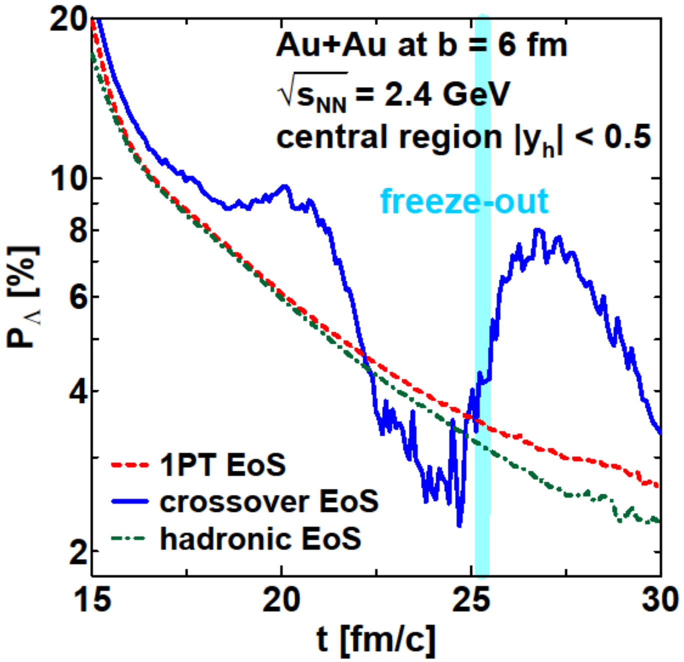
Baznat, Gudima, Sorin, Teryaev, PRC 97, 041902 (2018) [QGSM model]

YI, PRC 102 (2020) 4, 044904 [3FD model]

Thermodynamic polarization at moderate energies

YI, PRC **103**, L031903 (2021)



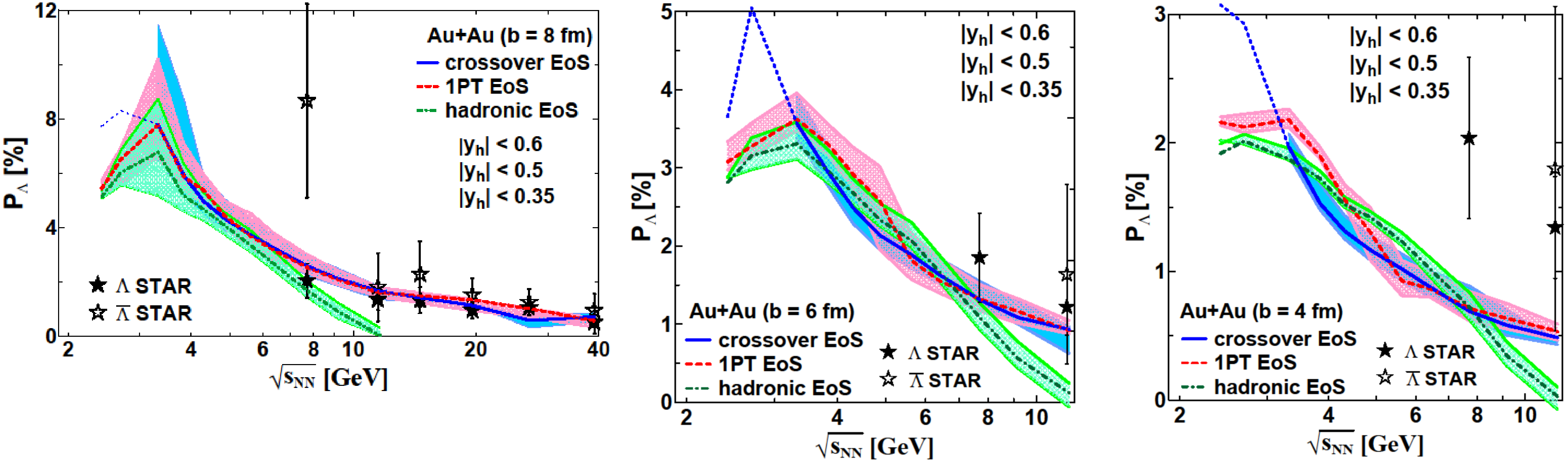


Unstable numerics for crossover EoS

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



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

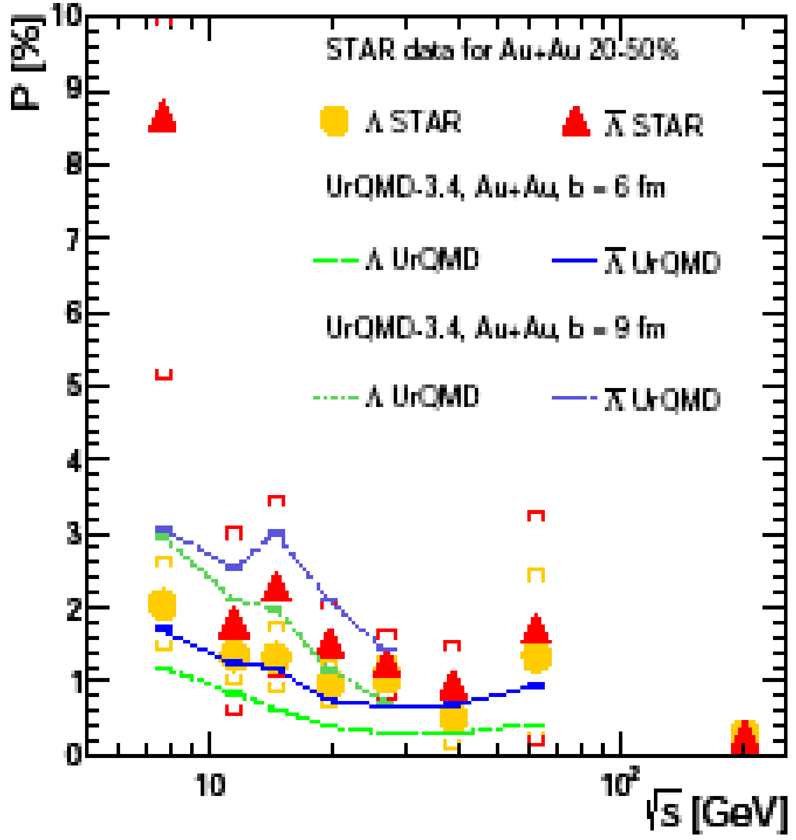
Problem: Λ -- $\bar{\Lambda}$ polarization splitting

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.

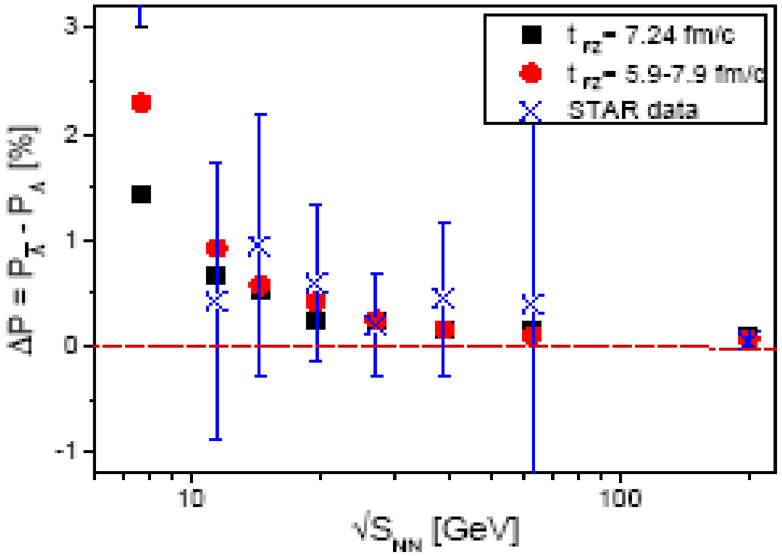


Λ -- $\bar{\Lambda}$ polarization splitting: possible solutions

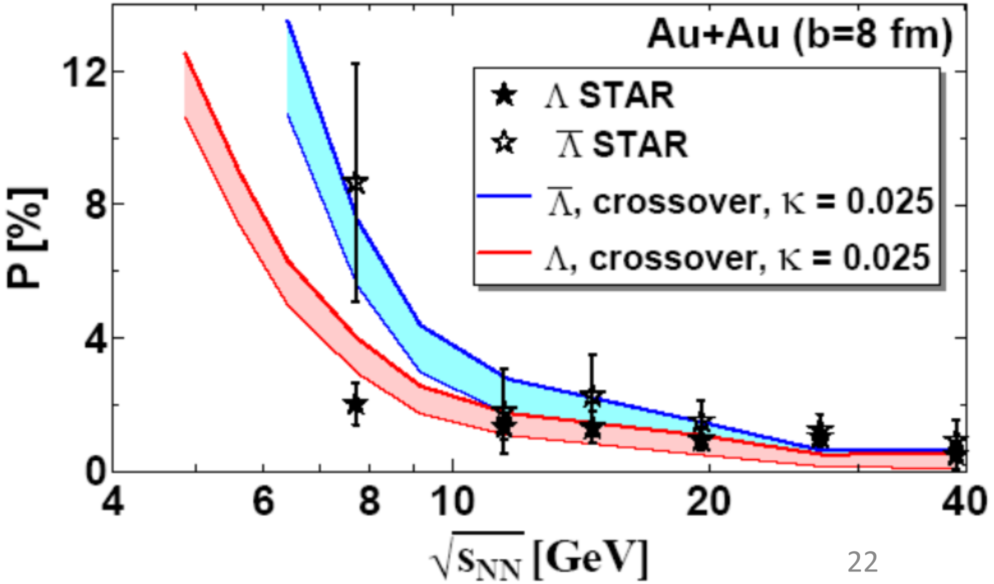
Interaction mediated by massive vector and scalar bosons (Walecka-like model)

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

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



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



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]

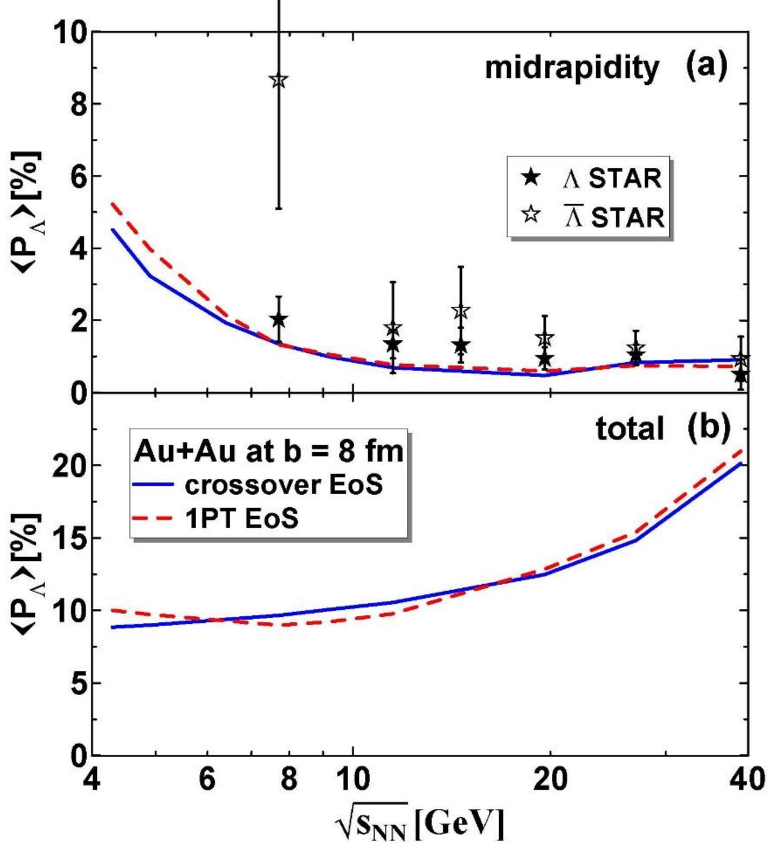
3FD: **total Λ polarization (i.e. averaged over all rapidities)** increases with collision energy rise, in contrast to **midrapidity polarization**.

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

YI, et al., PRC 100, 014908 (2019)



Summary

✓Prerequisite for polarization models:
The system is thermalized at the freeze-out stage

✓Prediction: **Λ polarization rises with collision energy decrease at $\sqrt{s_{NN}} \leq 7.7$ GeV**

✓Prediction: **Λ polarization reaches a maximum or a plateau at $\sqrt{s_{NN}} \leq 3$ GeV**

✓Prediction: **Λ polarization increases from midrapidity to forward/backward rapidities**

✓Measurements at moderate energies can clarify the nature of the Λ -- $\bar{\Lambda}$ splitting

Other problems related to Polarization

- Thermodynamic approach predicts **the wrong sign of the local longitudinal popularization** as compared with that measured by STAR

It seems to be resolved [Becattini et al., 2103.10917, 2103.14621] two days ago.

Additional shear term resolves the problem and also contributes to global polarization

- **Spin alignment of vector mesons (ϕ and K*):** it is large as compared to the tiny alignment predicted by the thermodynamic model.

- Conceptual problems

Additional shear term

[F. Becattini, M. Buzzegoli, A. Palermo. 2103.10917;
F. Becattini, M. Buzzegoli, A. Palermo, G. Inghirami, I. Karpenko, 2103.14621]

$$\beta_\nu(y) \simeq \beta_\nu(x) + \partial_\lambda \beta_\nu(x)(y-x)^\lambda$$

and replacing into the (5), with $\zeta = 0$ which is a good approximation for the purpose of this work:

$$\hat\rho_{\rm LE} \simeq \frac{1}{Z_{\rm LE}} \exp\left[-\beta_\nu(x)\hat P^\nu + \right. \tag{7}$$
$$\left. - \partial_\lambda \beta_\nu(x) \int_\Sigma {\rm d}\Sigma_\mu(y)(y-x)^\lambda \hat T^{\mu\nu}(y)\right],$$

Standard vortical term

$$S^\mu_\varpi(p) = -\frac{1}{8m}\epsilon^{\mu\rho\sigma\tau} p_\tau \frac{\int_\Sigma {\rm d}\Sigma \cdot p\, n_F(1-n_F)\varpi_{\rho\sigma}}{\int_\Sigma {\rm d}\Sigma \cdot p\, n_F}, \tag{1}$$

where thermal vorticity is defined as the anti-symmetric derivative of the four-temperature field:

$$\varpi_{\mu\nu} = -\frac{1}{2}\left(\partial_\mu \beta_\nu - \partial_\nu \beta_\mu\right). \tag{2}$$

additional shear term

$$S^\mu_\xi(p) = -\frac{1}{4m}\epsilon^{\mu\rho\sigma\tau} \frac{p_\tau p^\lambda}{\varepsilon} \frac{\int_\Sigma {\rm d}\Sigma \cdot p\, n_F(1-n_F)\hat t_\rho \xi_{\sigma\lambda}}{\int_\Sigma {\rm d}\Sigma \cdot p\, n_F} \tag{3}$$

where $\varepsilon = \sqrt{m^2 + {\rm p}^2}$, $\hat t$ is the time direction in the QGP or center-of-mass frame, and ξ is the symmetric derivative of the four-temperature, defined as *thermal shear tensor*:

$$\xi_{\mu\nu} = \frac{1}{2}\left(\partial_\mu \beta_\nu + \partial_\nu \beta_\mu\right). \tag{4}$$

Plans

- **Effect of the additional shear term on** the global polarization

- **Nature of the Λ -- $\bar{\Lambda}$ splitting** (interaction mediated by massive vector and scalar bosons)

- **Rapidity dependence** of the global polarization

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)