Λ polarization and vortex rings in heavy-ion collisions at NICA energies

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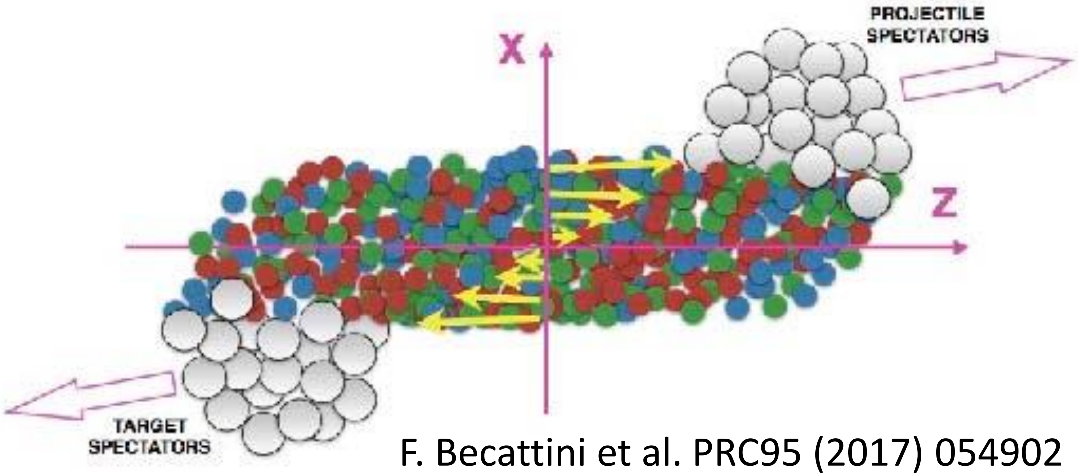
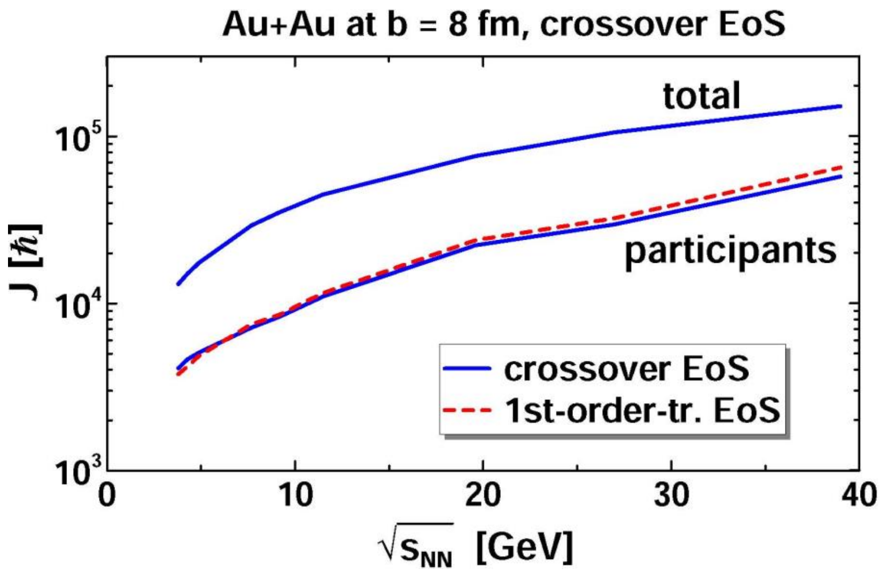
INFINUM-2023, 27 February 2023 to 3 March 2023, BLTP JINR

Vortical motion of nuclear matter



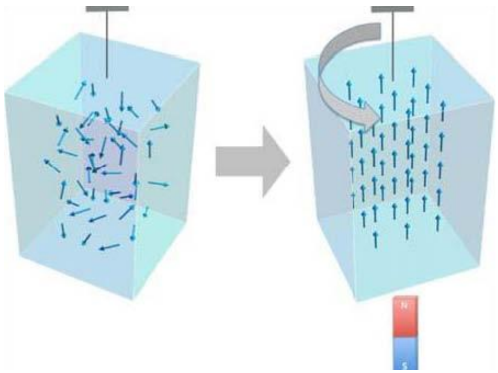
F. Becattini et al. PRC95 (2017) 054902



Vortical motion: **ω** = $(1/2)$ **∇ × 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 in heavy-ion collisions

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); Rogachevsky&Sorin&Teryaev (2010)]
- Phenomenological models [A. Ayala et al., PRC (2022)]

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

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

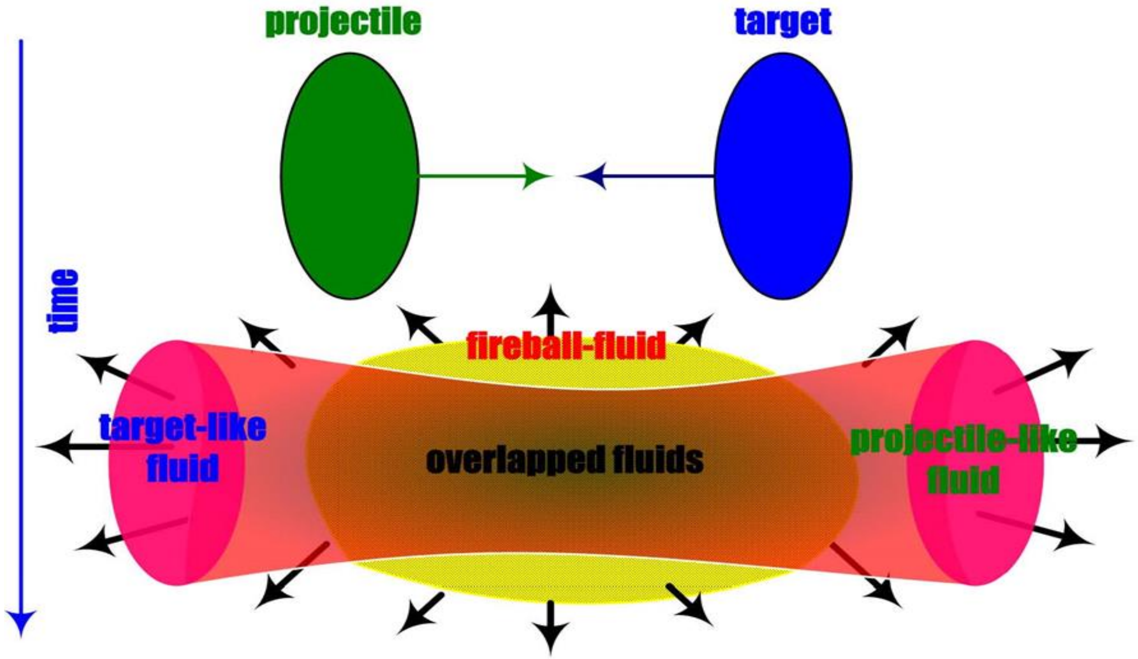
n_Λ = Λ distribution function, integration over freeze-out hypersurface

Formulation in terms of frozen-out hadronic matter!

Three-fluid dynamics (3FD) model

The 3FD approximation simulate the early, nonequilibrium stage of strongly-interacting matter:

- ✓ baryon-rich fluids: nucleons of the projectile (p) and the target (t) nuclei.
- ✓ fireball (f) fluid: newly produced particles which dominantly populate the midrapidity region.



3FD model

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

Leading particles carry bar. charge exchange/emission

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

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

Baryon-free fluid Source term Exchange

The source term is delayed due to a formation time τ

Total energy-momentum conservation:

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

Physical Input

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

3FD: YI, Russkikh, Toneev, PRC 73, 044904 (2006)

EoS:

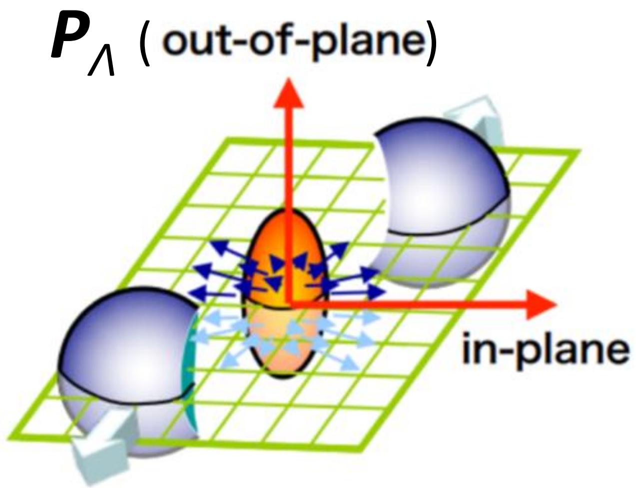
- hadronic EoS

Mishustin, Russkikh , Satarov,

Sov. J. Nucl. Phys. 54, 260 (1991)

- EoS with 1st-order PT
- EoS with crossover

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



Shi Pu, Chirality, vorticity, and magnetic field in heavy ion collisions, UCLA 2022

Global Polarization at NICA energies

$$P_\Lambda^\mu = \langle S_\Lambda^\mu \rangle / S_\Lambda$$ Polarization of Λ particle, $S_\Lambda=1/2$

Global polarization is directed along the global angular momentum

Approximations made [YI&Soldatov, PRC 105 (2022) 3, 034915]:

Appr. 1: isochronous freeze-out $(d^3p/p_0)\, d\Sigma_\lambda p^\lambda = d^3p\, d^3x$

Appr. 2: **Hydrodynamical rapidity**: in stead of true rapidity *y(p)*

$$y_h(z,t) = \frac{1}{2} \ln \frac{\langle u^0 + u^3 \rangle}{\langle u^0 - u^3 \rangle}$$

Approximated Global Polarization

Replacing true rapidity by the hydro one allows to perform momentum integration first

$$P_\Lambda^{\varpi} = \frac{1}{6}\frac{\int_{\Sigma(y_h)} d^3x\,\left(\rho_\Lambda + 2T^{00}_\Lambda/m_\Lambda\right)\varpi_{zx}}{\int_{\Sigma(y_h)} d^3x\,\rho_\Lambda}$$

where integration runs over cells $\Sigma(y_h)$ with fixed hydro rapidity y_h and

$$T^{00}_\Lambda = (\varepsilon_\Lambda + p_\Lambda)u^0u^0 - p_\Lambda$$

is 00 component of partial energy-momentum tensor related to the Λ contribution

Advantage of the approximations is that P_Λ is expressed only in terms hydro quantities

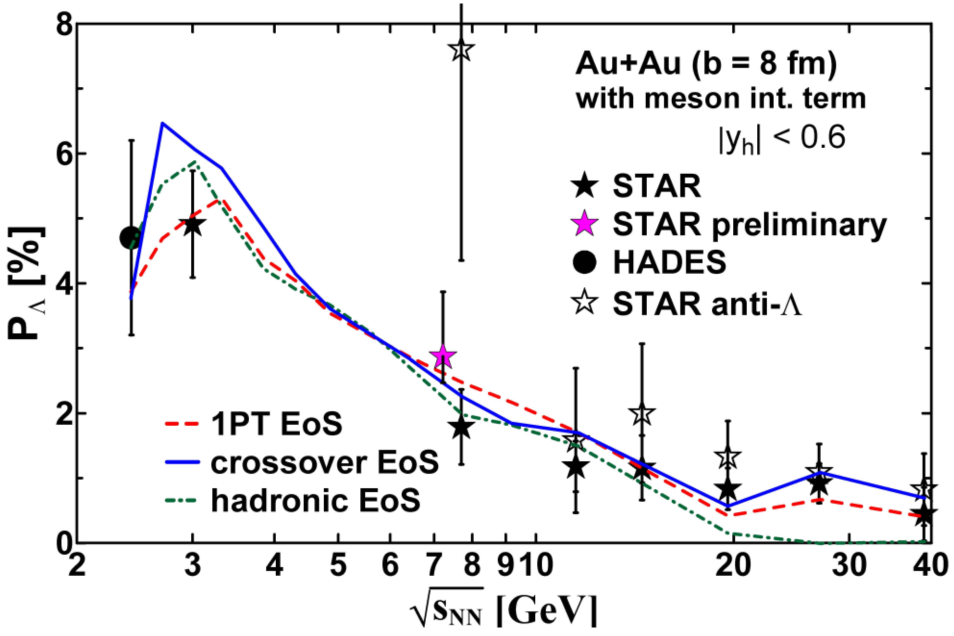
Polarization at $3 < \sqrt{s_{NN}} < 11$ GeV

YI&Soldatov, PRC 105 (2022) 3, 034915

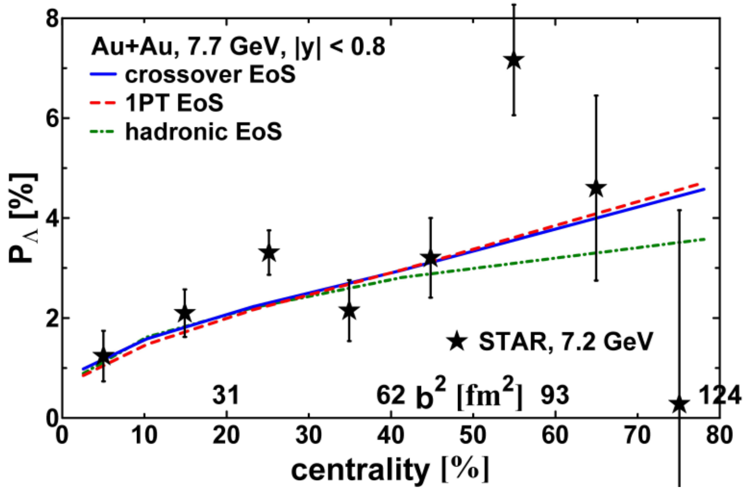
With account for

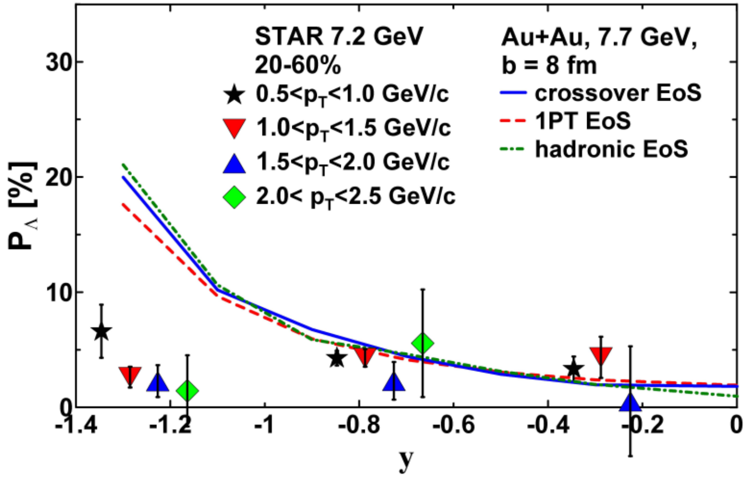
- Feed-down from decays of **Σ^0 and Σ^***
- Meson-field induced contribution
  [Csernai, Kapusta, Welle, PRC 99, 021901 (2019)]

Not perfect, but a reasonable reproduction of data

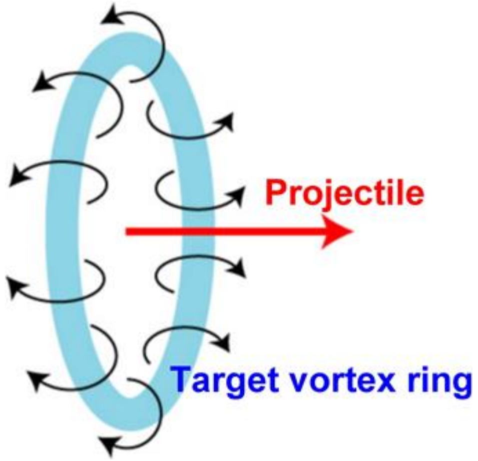


- ✓ 3FD has an advantage at moderately relativistic energies.
- ✓ The best reproduction of low-energy polarization so far.





Vortex rings



Like smoke rings

M. Lisa, Chirality, vorticity, and magnetic field in heavy ion collisions, UCLA 2022

Partial transparency of colliding nuclei at high energies.

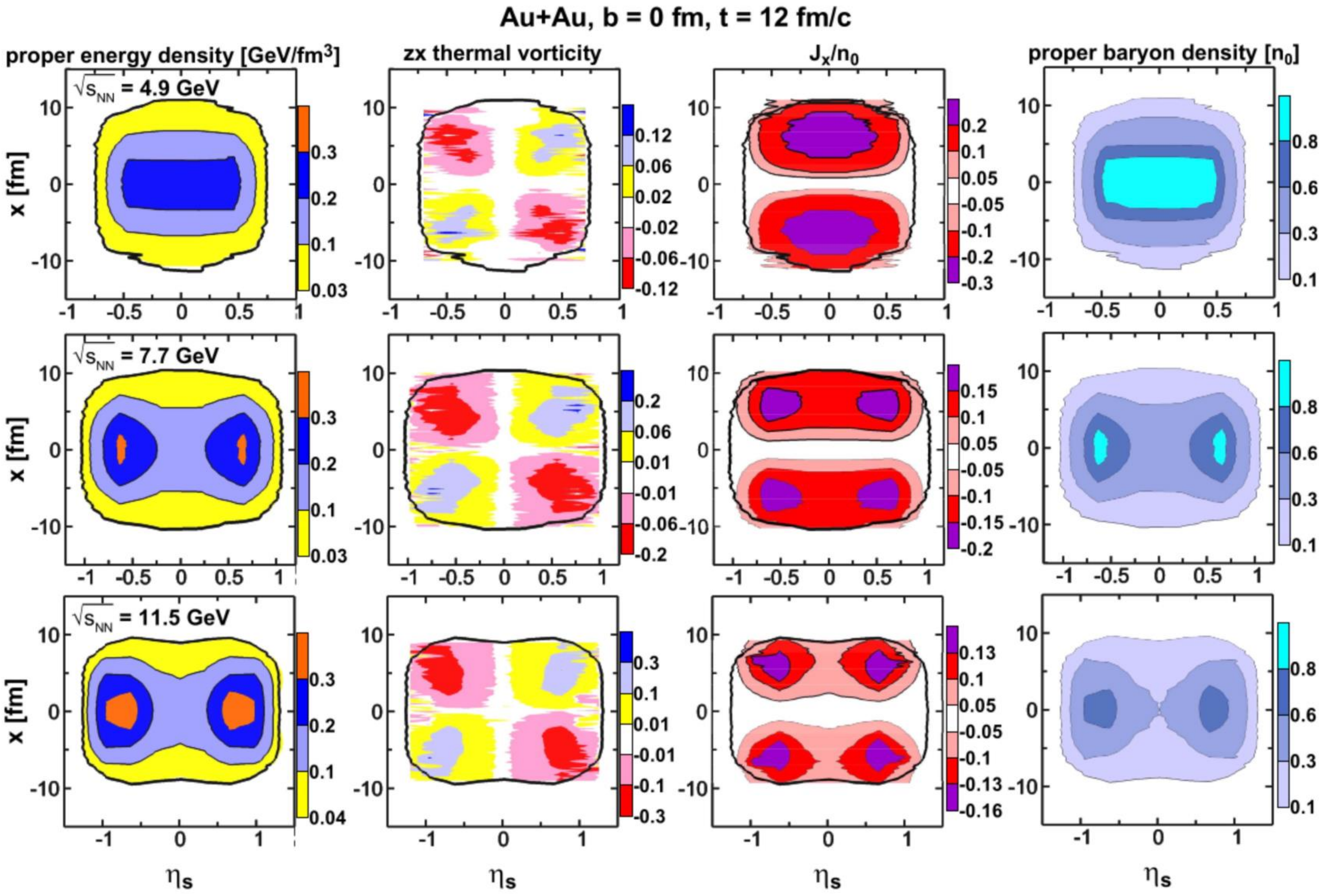
The matter in the central region is stronger decelerated.
The peripheral matter acquires a rotational motion.

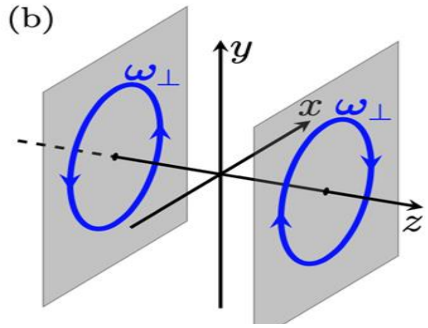
Two vortex rings are formed at the periphery of the stronger stopped matter in the central region, i.e. at forward/backward rapidities.

Matter rotation is opposite in these two rings.

Predicted by YI, Soldatov, Toneev, Fu, Xu, Huang, Song, Baznat, Gudima, Sorin, Teryaev, Usubov, Deng, Wei, Xia, Li, Tang, Wang, Zinchenko, Tsegelnik, Kolomeitsev, Voronyuk, Lisa, Barbon, Chinellato, Serenone, Shen, Takahashi, Torrieri within different models

Vortex rings in ultra-central Au+Au collisions





Xia, et al., PRC 98, 024905 (2018)

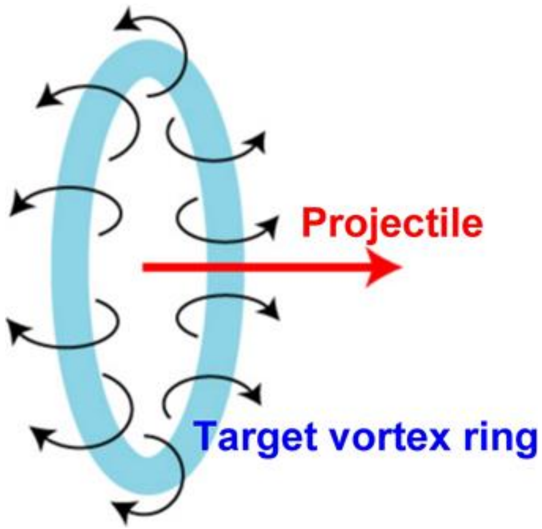
Two vortex rings at forward (projectile) and backward (target) rapidities.

The matter rotation is opposite in this two rings.

Vortex rings correlate with baryon current because of their origin from incomplete baryon stopping

$\eta_s = (1/2) \ln [(t + z)/(t - z)]$

Ring observable



$$R_\Lambda(y) = \left\langle \frac{\mathbf{P}_\Lambda \cdot (\mathbf{e}_z \times \mathbf{p})}{|\mathbf{e}_z \times \mathbf{p}|} \right\rangle_y$$

$P_\Lambda(\mathbf{p})$ = polarization of the Λ hyperon

p = its spacial momentum

$\mathbf{e}_z$ = unit vector along the beam

Proposed in [Lisa, et al., PRC 104, 011901 (2021)]

Non-collective background: the same ring observable is nonzero in even *pp* collisions, where there is no collective ring structure **discussed below**

Ring observable in 3FD terms

Within the same (and few extra) approximations as those for global $\mathbf{P}_\Lambda$

$$R_\Lambda(y_h) \approx \int_{\Sigma(y_h)} d^3x \, \rho_\Lambda(x) \frac{\mathbf{P}_\Lambda \cdot (\mathbf{u} \times \mathbf{e}_z)}{(\mathbf{u}_T^2 + 2T/m_\Lambda)^{1/2}} \Big/ \int_{\Sigma(y_h)} d^3x \rho_\Lambda(x)$$

$\mathbf{P}_\Lambda(\boldsymbol{x})$ = local polarization of Λ hyperon averaged over p

$\rho_\Lambda(\boldsymbol{x})$ = local density of Λ hyperon

$\mathbf{u}$ = local velocity

$\mathbf{u}_T$ = local transverse velocity

$\mathbf{e}_z$ = unit vector along the beam

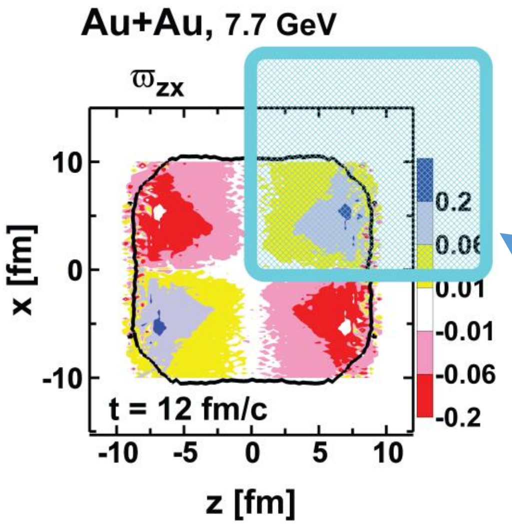
Integration runs over cells $\Sigma(y_h)$ with fixed hydro rapidity y_h

Simplification for ultra-central collision

✓Let $y_h>0$, then integration is confined by z>0

✓Axial symmetry

$$\int d^3x\ldots = \int d\varphi \int_0^\infty rdr \int_0^\infty dz\ldots = 2\pi \int_0^\infty rdr \int_0^\infty dz\ldots \Rightarrow 2\pi \int_0^\infty xdx \int_0^\infty dz\ldots$$

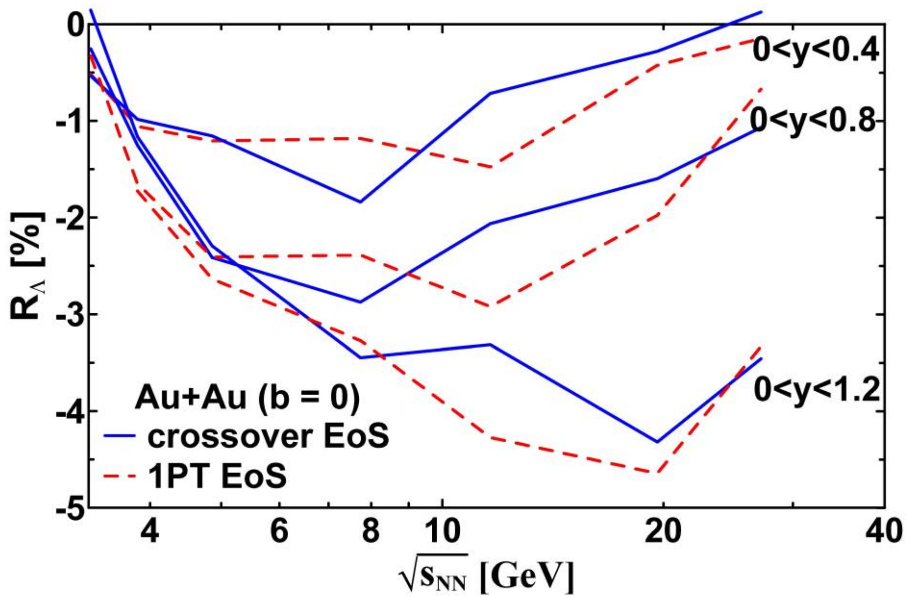


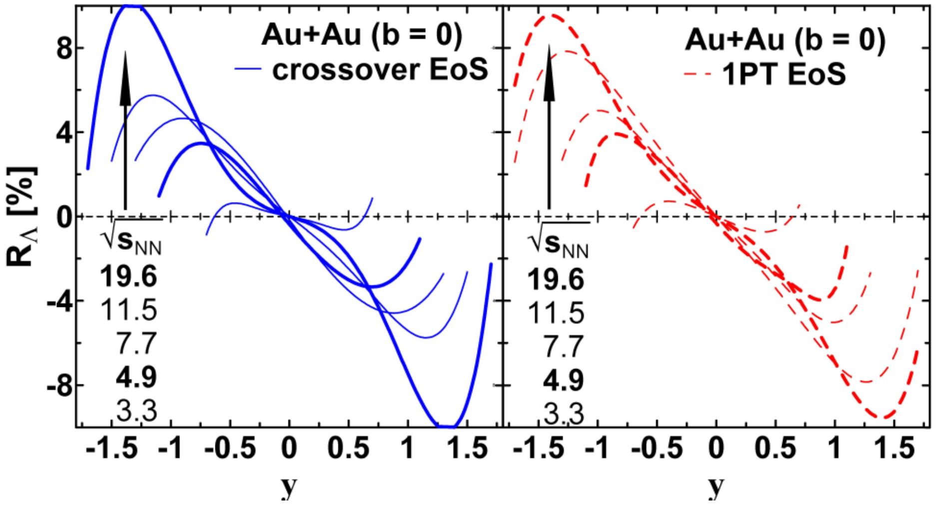
calculation is similar to that of the global polarization only in the **quadrant (x > 0; z > 0)** and with additional weights

$$R_\Lambda \approx \int_0^\infty x dx \int_0^\infty dz \rho_\Lambda P_y^\Lambda \frac{u_x}{(u_x^2 + 2T/m_\Lambda)^{1/2}} / \int_0^\infty x dx \int_0^\infty dz \rho_\Lambda$$

Ring observable at 3 < $\sqrt{s_{NN}}$ < 30 GeV

YI, *PRC* 107 (2023) 2, L021902





Vortex rings are formed at $\sqrt{s_{NN}}$ > 4 GeV

They can be observed in midrapidity 0<y<0.4 (or -0.4<y<0) at 4 < $\sqrt{s_{NN}}$ < 20 GeV

Predictions of different EoS's strongly differ at 7 < $\sqrt{s_{NN}}$ < 12 GeV

This range correlates with that of the irregularity in the baryon stopping, where results of different EoS's also strongly differ [YI, PLB 721, 123 (2013); YI&Blaschke, PRC 92, 024916 (2015)].

Early-stage incomplete baryon stopping is the driving forth of the vortex-ring formation.

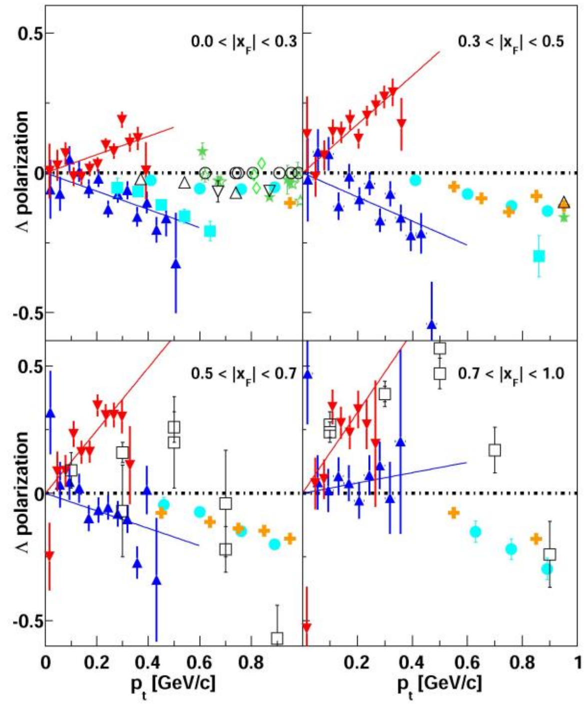
Background of direct Λ production with polarization correlated with beam direction

- ***R_Λ* is nonzero in *pp* collisions, where there is no collective ring structure**
- It is referred as transverse polarization in *pp* collisions
- This transverse polarization is expected to be diluted due to rescatterings in AA collisions
- Any case, calculations of ***R_Λ*** the due to vortex rings should be complemented by simulations of this transverse polarization similarly to that done in [Nazarova, et al., Phys. Part. Nucl. Lett. 18 (2021) 429]
- **There is a possibility to measure *R* for anti-Λ. Anti-Λ transverse polarization in pp collisions is consistent with zero.**

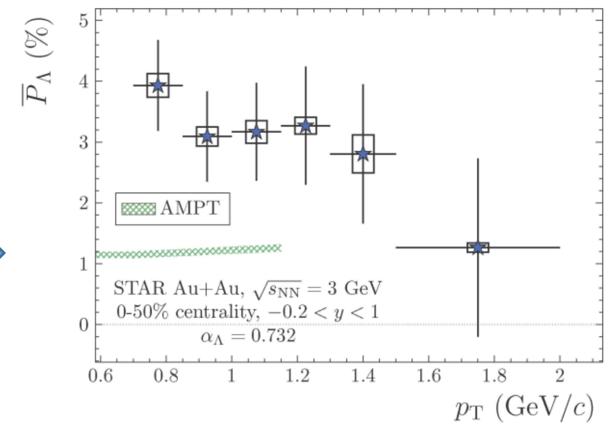
limiting the p_T of Λ from above

- **Another possibility is to reduce background of the transverse polarization by limiting the p_T of Λ from above.**

- While the magnitude of the transverse Λ polarization linearly rises with p_T,
- COSY-TOF, EPJA 52, 337 (2016)



- low-pT Λ's should dominate in the vortex-rings $\boldsymbol{R_\Lambda}$ because these rings are collective phenomena.
- STAR, PRC 104, L061901 (2021)



Summary

- ✓Global Λ polarization is predicted for the NICA energy range

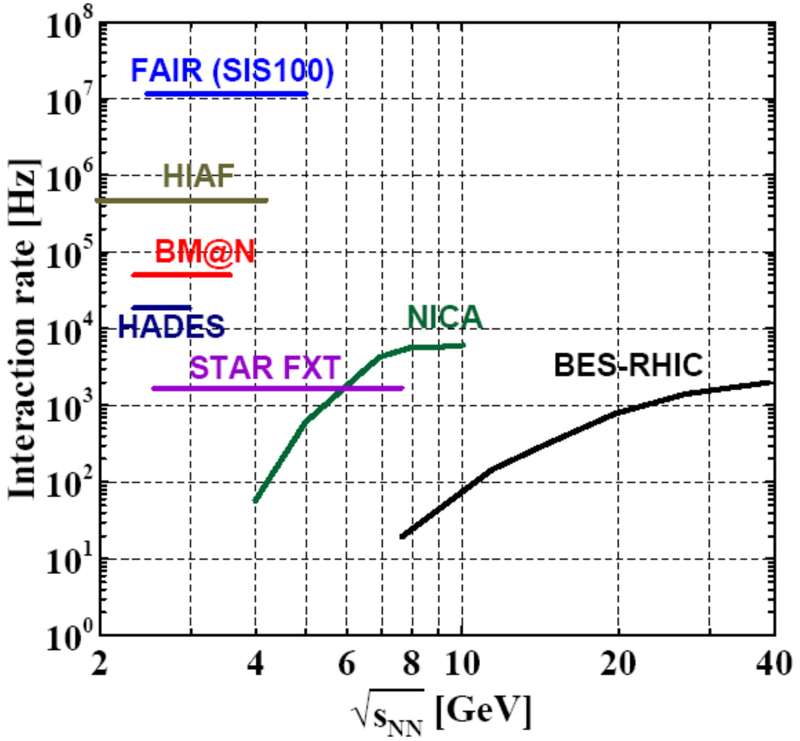
- ✓**New phenomenon: Vortex rings** that carry information about early nonequilibrium stage of nuclear collision, in particular, about baryon stopping.
- ✓**Vortex rings can be observed in midrapidity at NICA energies**
- ✓Background of direct Λ production with polarization correlated with beam direction should be taken into account
- ✓ It looks like the **vortex-ring** structures are also common for the nuclear excited states [Nesterenko, Repko, Kvasil, Reinhard PRL 120 (2018) 18, 182501]

Thank you

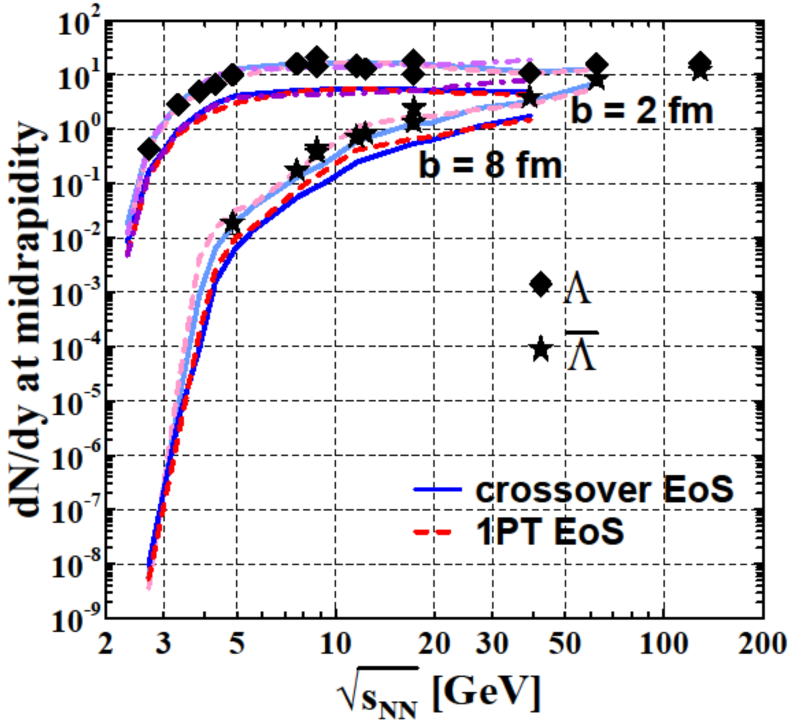
for your attention!

Backup

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

Chiral vortical effect (CVE)

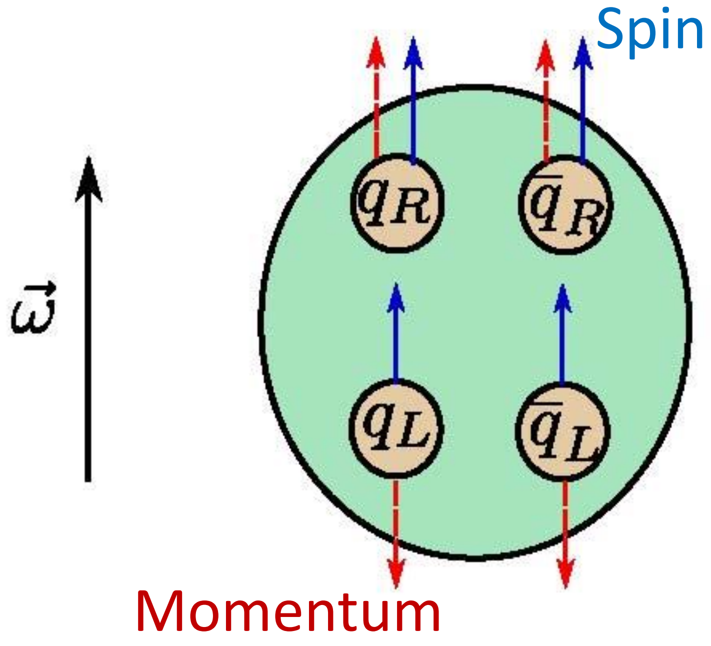
Axial current

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

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

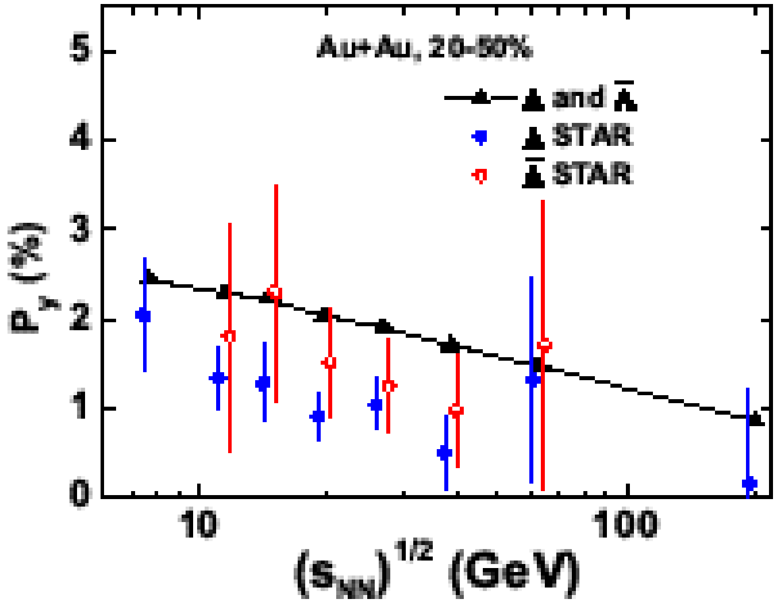
Landsteiner, Megias, Melgar, Pena-Benitez, JHEP 1109, 121 (2011) [Gauge-gravity correspondence]

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.



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

Only BES-RHIC energies were studied

Sun and Ko, PRC 96, 024906 (2017)

Axial-vortical-effect (AVE):

Axial-charge conservation at hadronization

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

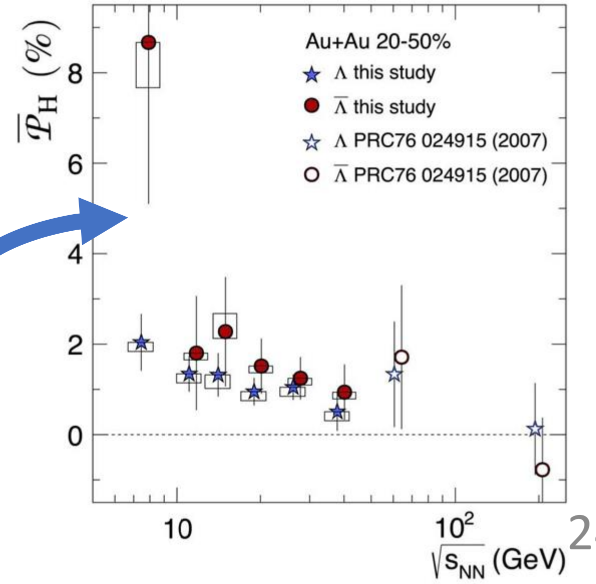
u_y results from boost to the local rest frame of the matter

Sorin and Teryaev, PRC 95, 011902 (2017)

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

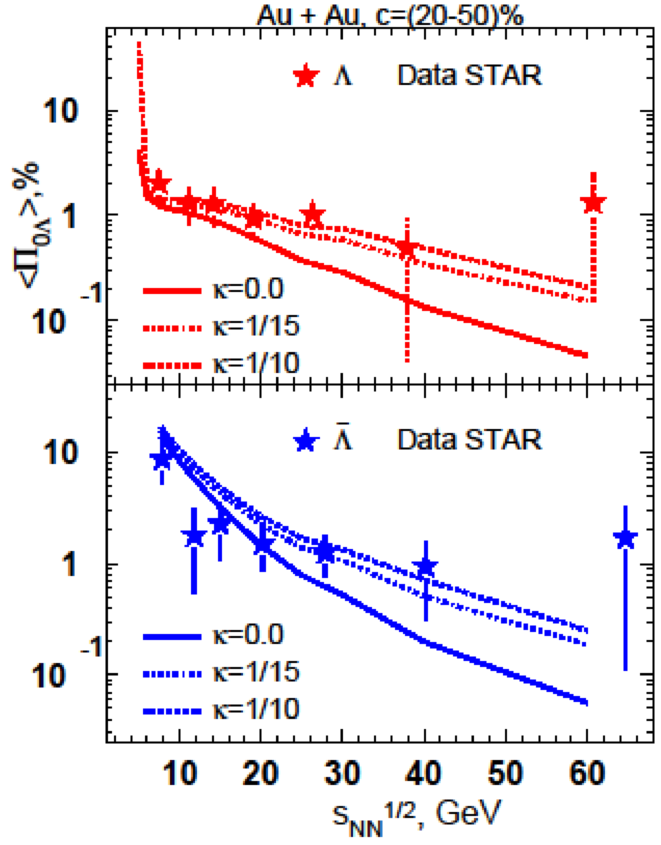
Therefore,

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

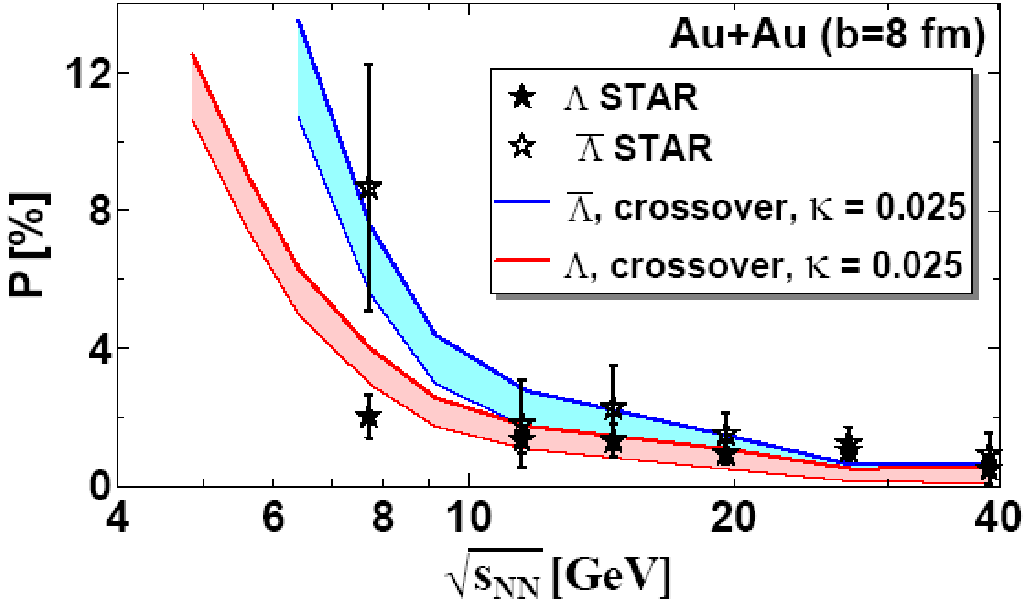


Axial-vortical-effect (AVE) polarization

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.