Relativistic Heavy-Ion Collisions within Three-Fluid Dynamics (3FD)

predictions for NICA

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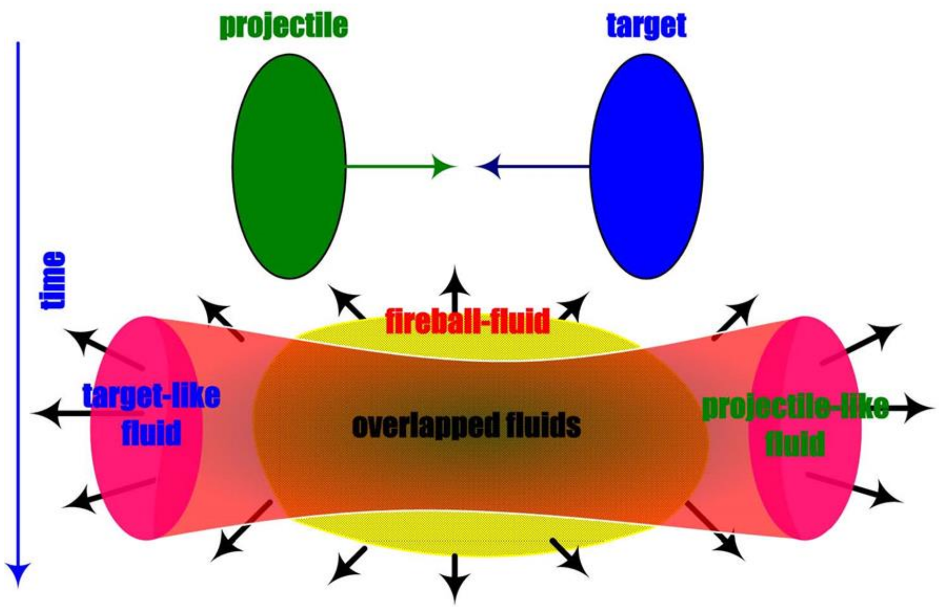
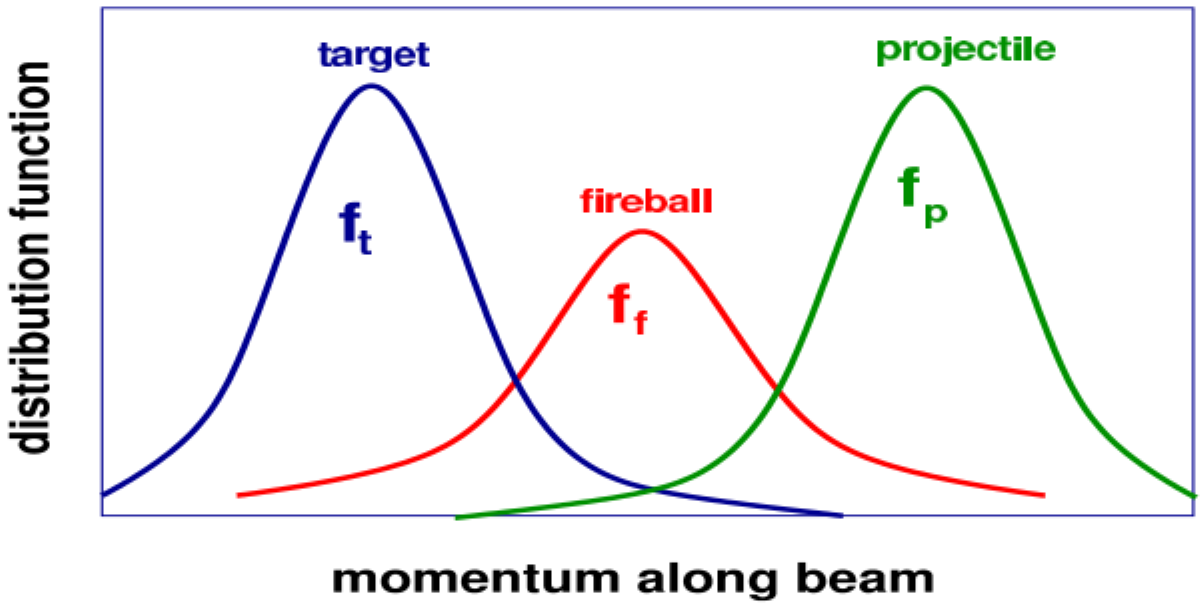
Three-fluid dynamics (3FD) model

The 3FD approximation simulate the early, nonequilibrium stage of the 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: $\partial_\mu J_t^\mu = 0$ $\quad$ $\partial_\mu T_t^{\mu\nu} = -F_{tp}^\nu + F_{ft}^\nu$

Leading particles carry bar. charge $\quad$ 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 $\quad$ Source term $\quad$ 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 (no phase transition)

Mishustin, Russkikh and Satarov,

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

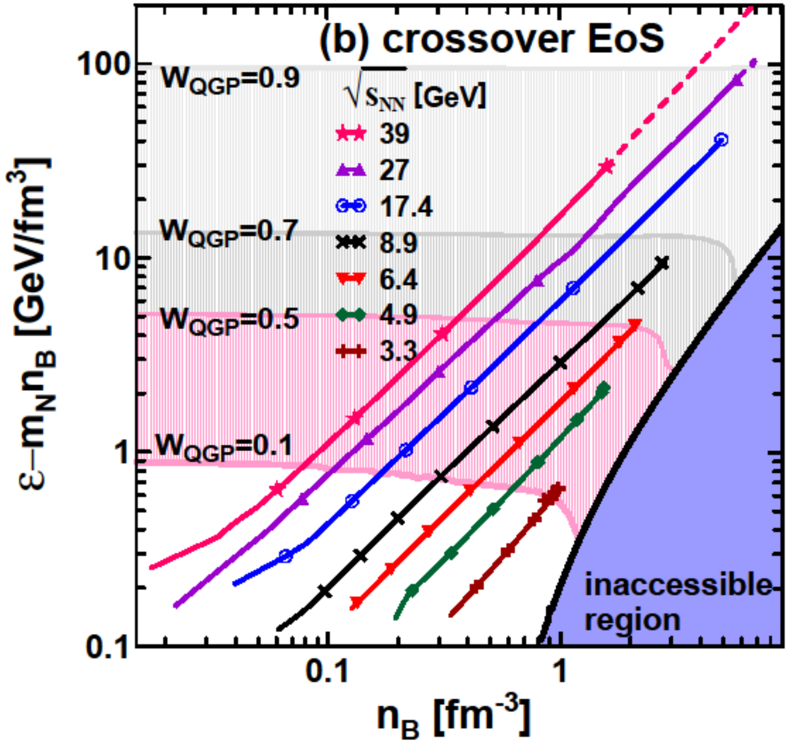
- hadronic+QGP EoS with 1st-order PT
- hadronic+QGP EoS with crossover

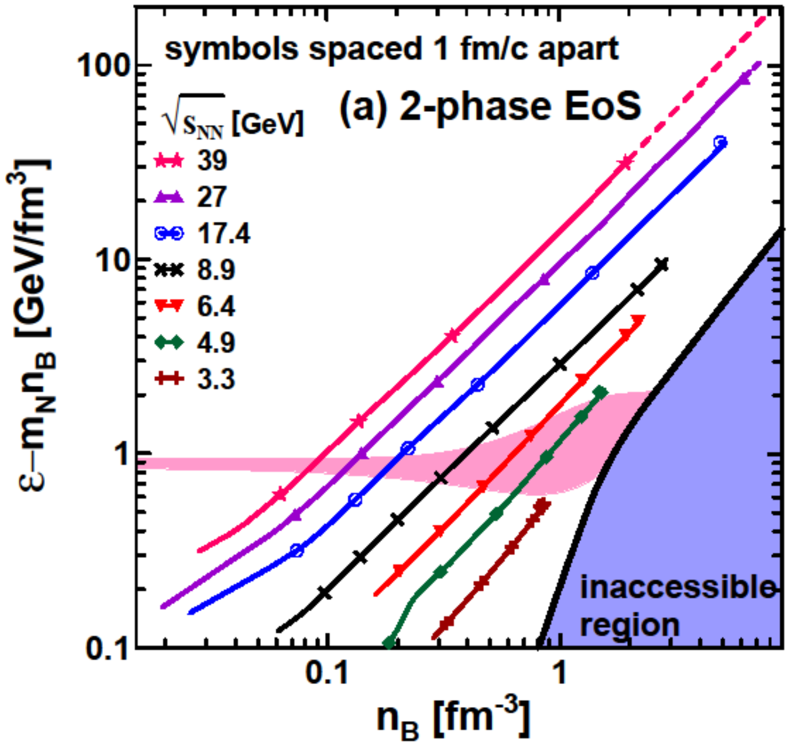
EoS: Khvorostukhin, Skokov, Toneev, Redlich, EPJ C48, 531 (2006)

QGP Transition in central region [Y.I., PRC 87 (2013) 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 **$\sqrt{s_{NN}} \geq 5$ GeV** .

Multiple 3FD applications at ASG, SPS, BES-RHIC, NICA and FAIR energies

- Bulk observables → crossover EoS is slightly preferable
- Flow observables → crossover EoS is strongly preferable
- Global Λ polarization (discussed below)
- Hadronic EoS fails at **$\sqrt{s_{NN}} \geq 5$ GeV**

THESEUS event generator

3FD:

- The output = Lagrangian test particles (i.e. fluid droplets)
- Fluid droplet = element of freeze-out surface
- Observables = integration of hadron distribution functions over freeze-out surface

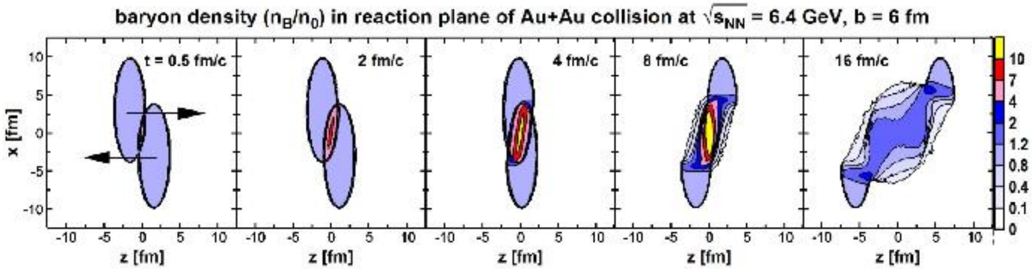
This is inconvenient for application of experimental acceptance

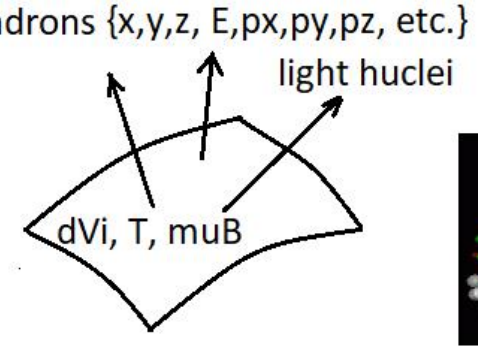
- In 2016 the THESEUS event generator was introduced.

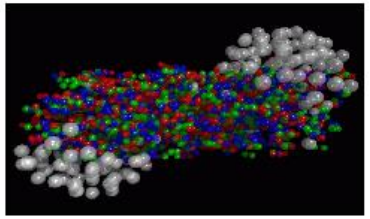
(3FD+Particlization+UrQMD): P. Batyuk et al., PHYSICAL REVIEW C 94, 044917 (2016)

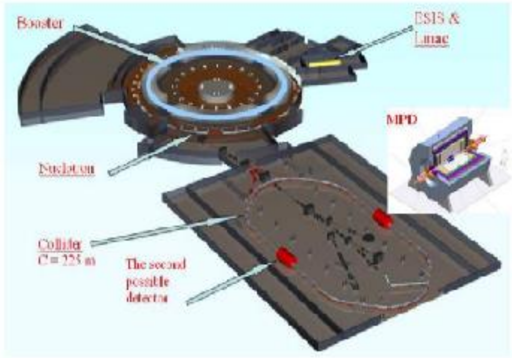
- **THESEUS = 3FD + Monte Carlo hadron sampling + afterburner via UrQMD**
- THESEUS presents the 3FD output in terms of a set of observed particles.

Hydrodynamic modelling of nuclear collisions for NICA / FAIR









Initial state → hydrodynamic evolution → particlization → afterburner → detector response

3-fluid hydrodynamical model (Y.Ivanov et al.)

THESEUS generator

(optionally) UrQMD, etc. (Iu. Karpenko, H.Elfner)

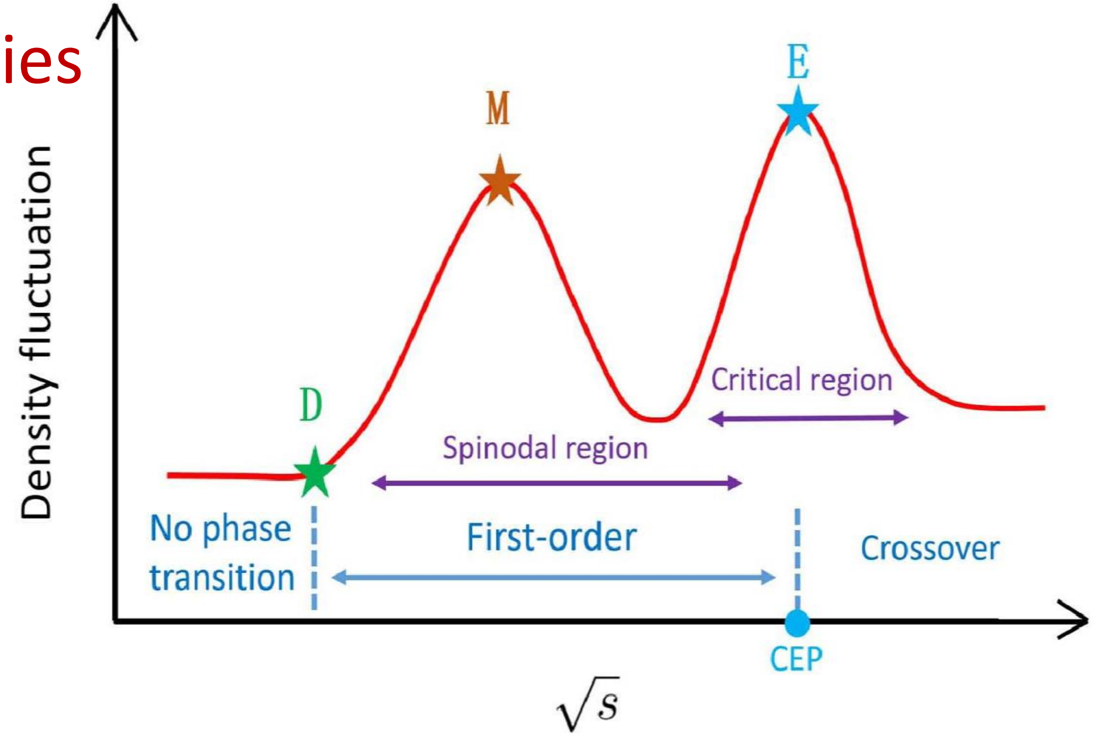
GEANT, MPD,BM@N (O.Rogachevsky, P.Batuyk, S.Merts et al.)

courtesy of M. Kozhevnikova

Light nuclei in heavy-ion collisions

Why are they interesting?

- Abundant production at NICA and FAIR energies
- Very scarce data at NICA and FAIR energies
- Signal of spinodal instability
- Signal of critical endpoint (CEP)
- Medium effects



Kai-Jia Sun, et al., PLB 781 (2018) 499

Updated THESEUS event generator

- There are no light nuclei in 3FD and **THESEUS**, but only primordial nucleons
- Light nuclei are done by means of coalescence that requires additional parameters
- Updated THESEUS (THESEUS-v2):

  The light-nuclei are treated thermodynamically, on equal basis with hadrons

Kozhevnikova, Ivanov, Karpenko, Blaschke, Rogachevsky, PRC 103 (2021) 4, 044905

THESEUS-v2: updates

Recalculation of baryon chemical potential taking into account light nuclei production:

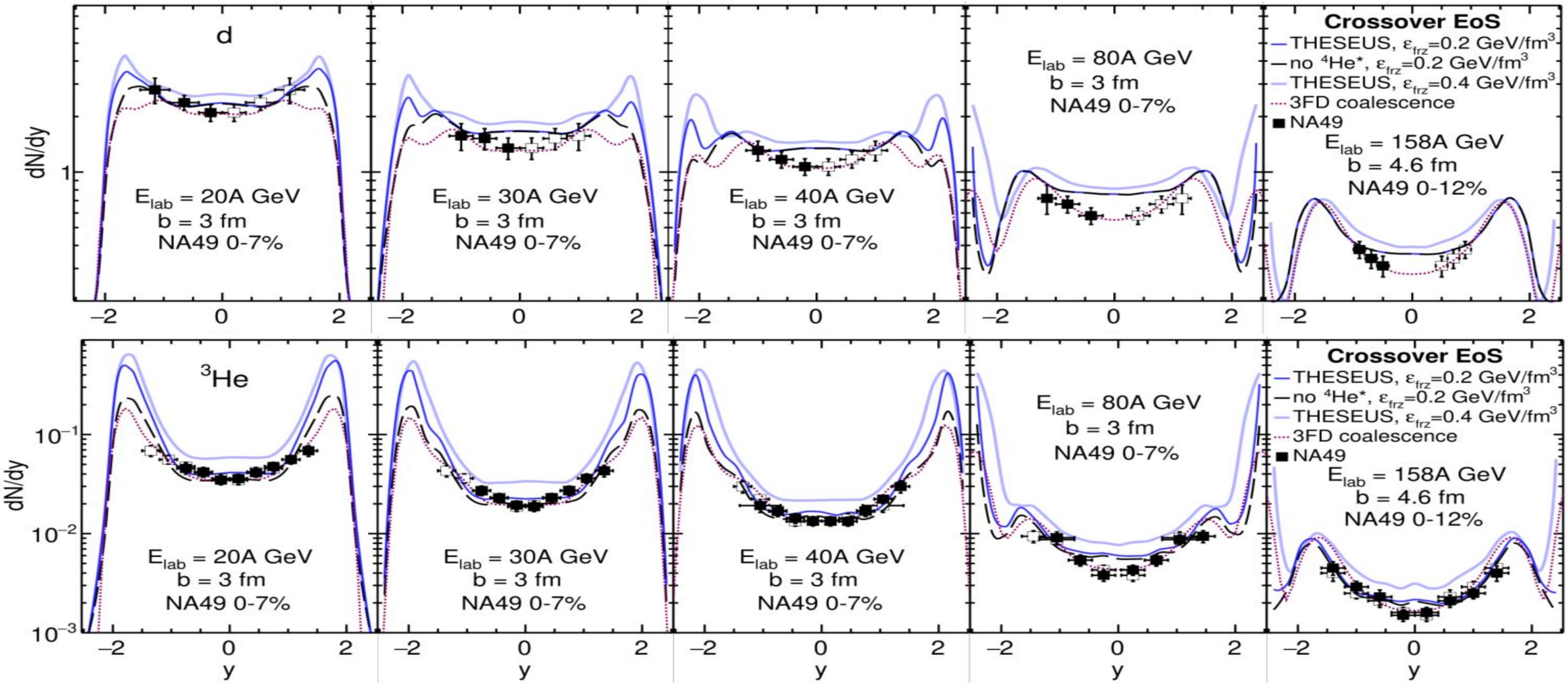
$$
\begin{aligned}
& n_{\text{primordial } N}(x;\mu_B,T) + \sum_{\text{hadrons}} n_i(x;\mu_B,\mu_S,T) \\
= {} & n_{\text{observable } N}(x;\mu'_B,T) + \sum_{\text{hadrons}} n_i(x;\mu'_B,\mu_S,T) \\
& + \sum_{\text{nuclei}} n_c(x;\mu'_B,\mu_S,T).
\end{aligned}
$$

'hadrons' = baryon resonances

Nucleus(E[MeV])	J	decay modes, in %
d	1	Stable
t	1/2	Stable
^{3}He	1/2	Stable
^{4}He	0	Stable
^{4}He(20.21)	0	$p = 100$
^{4}He(21.01)	0	$n = 24,\ p = 76$
^{4}He(21.84)	2	$n = 37,\ p = 63$
^{4}He(23.33)	2	$n = 47,\ p = 53$
^{4}He(23.64)	1	$n = 45,\ p = 55$
^{4}He(24.25)	1	$n = 47,\ p = 50,\ d = 3$
^{4}He(25.28)	0	$n = 48,\ p = 52$
^{4}He(25.95)	1	$n = 48,\ p = 52$
^{4}He(27.42)	2	$n = 3,\ p = 3,\ d = 94$
^{4}He(28.31)	1	$n = 47,\ p = 48,\ d = 5$
^{4}He(28.37)	1	$n = 2,\ p = 2,\ d = 96$
^{4}He(28.39)	2	$n = 0.2,\ p = 0.2,\ d = 99.6$
^{4}He(28.64)	0	$d = 100$
^{4}He(28.67)	2	$d = 100$
^{4}He(29.89)	2	$n = 0.4,\ p = 0.4,\ d = 99.2$

Stable light nuclei and low-lying resonances of the ^{4}He.

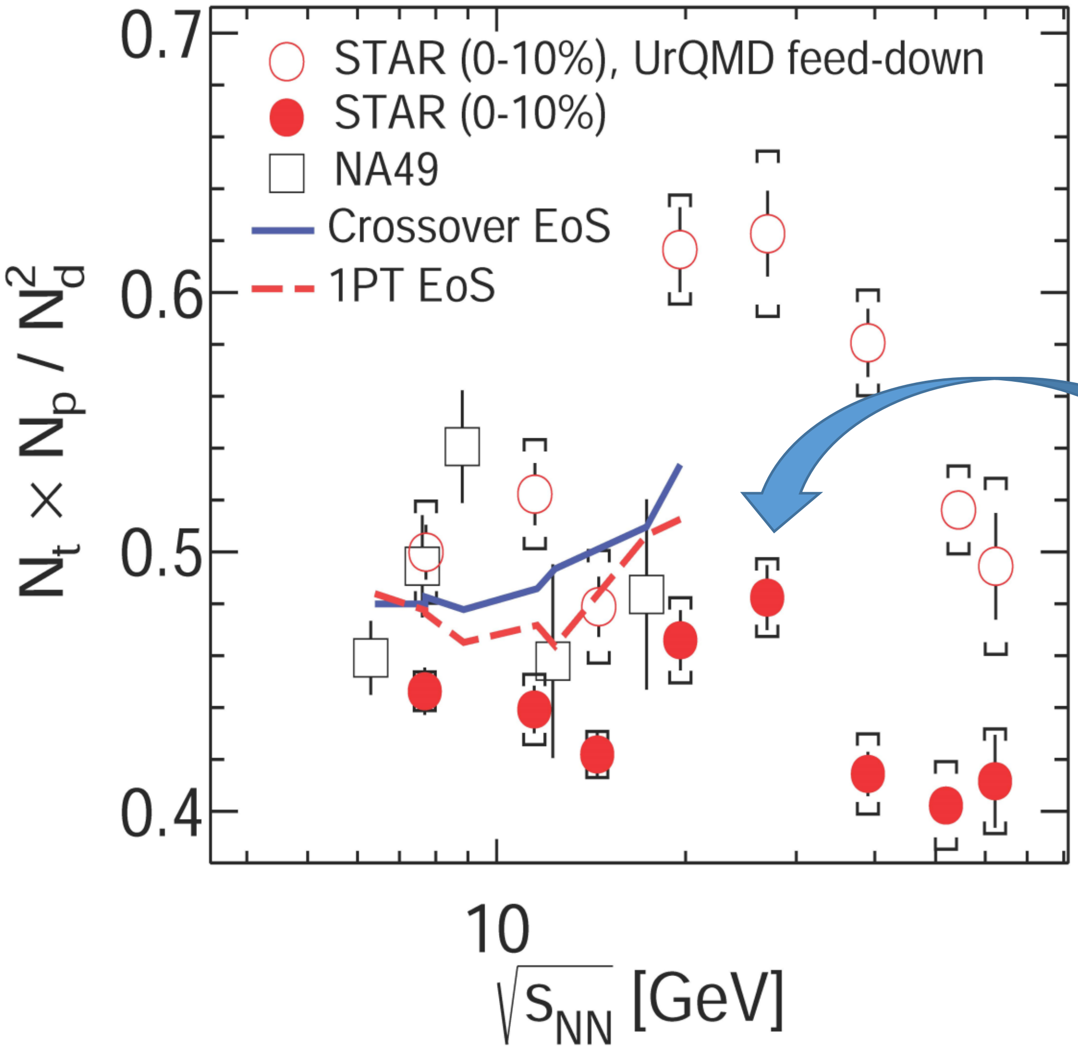
THESEUS-v2: rapidity distributions



Resonances of ^{4}He are unimportant in midrapidity at SPS energies.
Puzzle: reproduction of the 3He data is better than that of deuterons.

Kozhevnikova, YI, arXiv:2210.07334 [nucl-th]

$N(t) \times N(p)/N^2(d)$ ratio



Kozhevnikova, YI, arXiv:2210.07334 [nucl-th]

CEP? Spinodial instability?

THESEUS models growth to energies of 20–30 GeV, although there is neither CEP nor spinodial instability?

Accurate subtraction of weak-decays feed-down from proton yield is important

Polarization in heavy-ion collisions

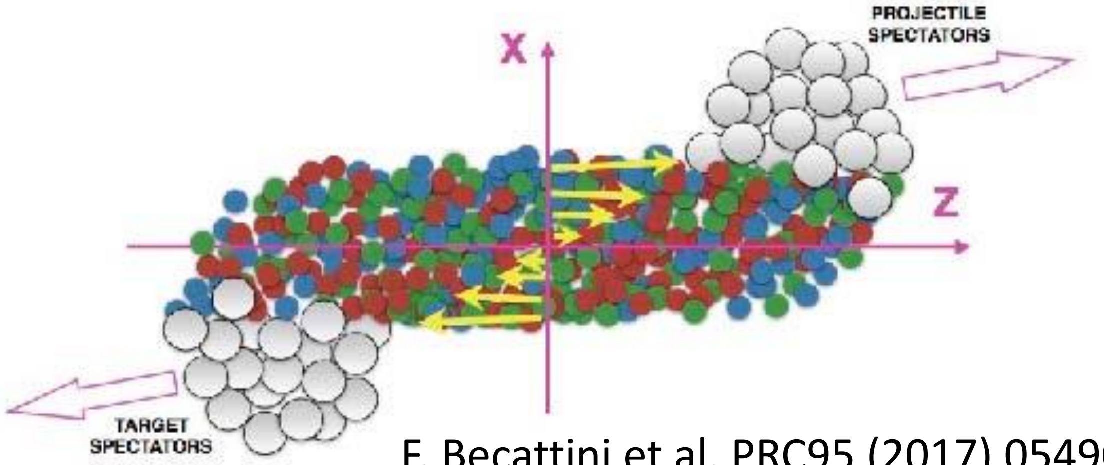
Motivations: Study of

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

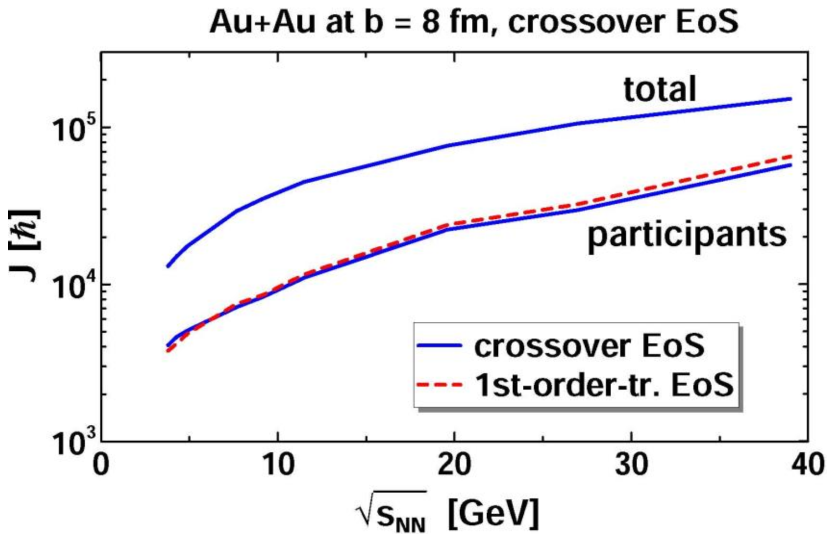
✓**mechanism of angular-momentum transfer from orbital one to spin**

- **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)]

Vortical motion of nuclear matter

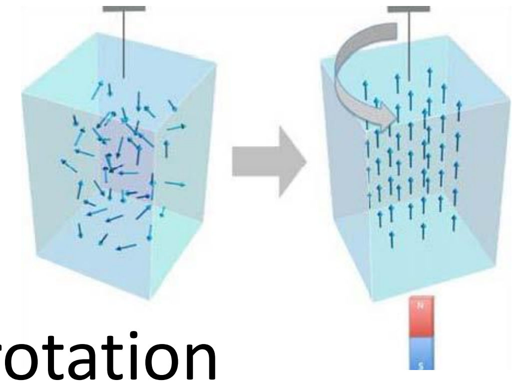


F. Becattini et al. PRC95 (2017) 054902



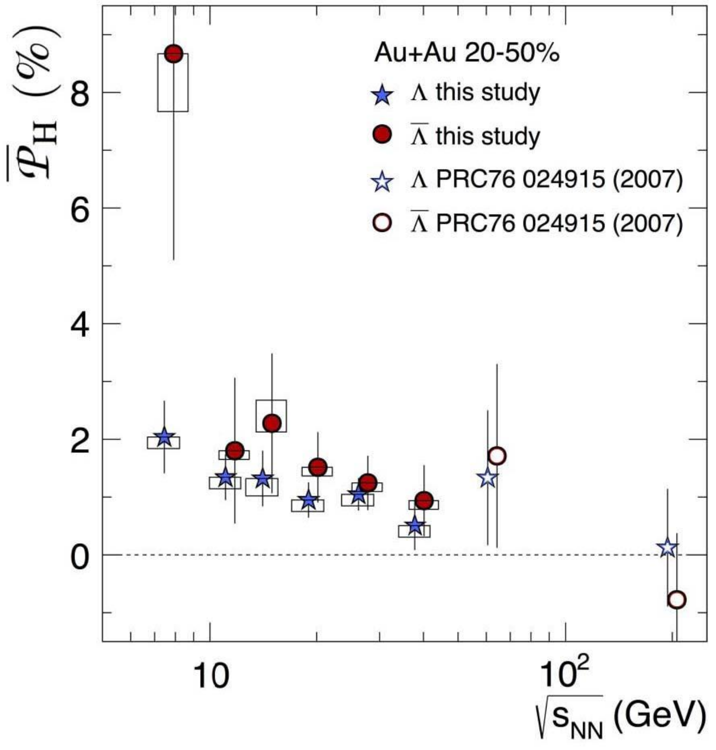
Vortical motion: $\boldsymbol{\omega} = (1/2)\ \nabla \times \mathbf{v}$ = **Vorticity**

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

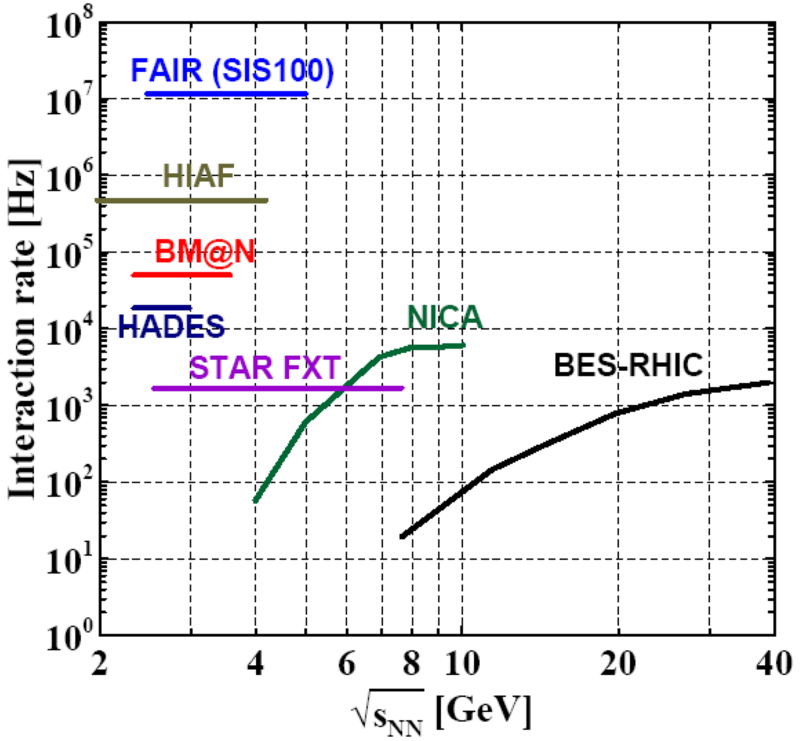
- ✓ Global Λ and anti-Λ polarization [Nature 548, 62 (2017)]
- ✓ Local polarization of hyperons along the beam direction [PRL 123, 132301 (2019)]
- ✓ Measurement of global spin alignment of vector Mesons [NPA 1005 (2021) 121733]
- ✓ Global polarization of Ξ and Ω hyperons at 200 GeV
- ✓ [PRL 126 (2021) 16, 162301]

At NICA and FAIR energies, data are still very scarce

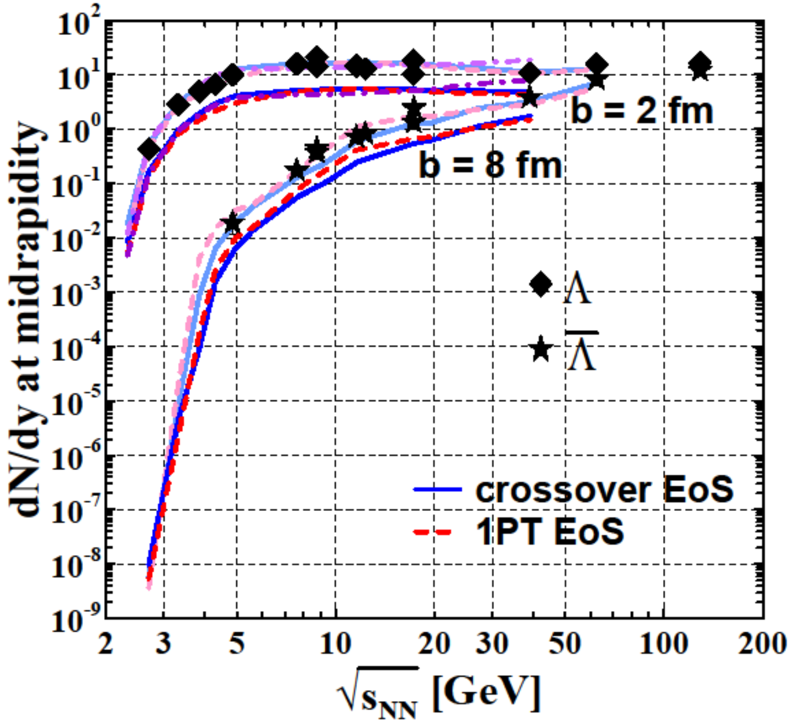
- ➢ HADES: Λ Polarization at 2.4 GeV [PLB 835 (2022) 137506]
- ➢ STAR-FXT: Λ Polarization at 3 and 7.2.GeV

PRC 104 (2021) L061901; EPJ Web Conf. 259, 06003 (2022).

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

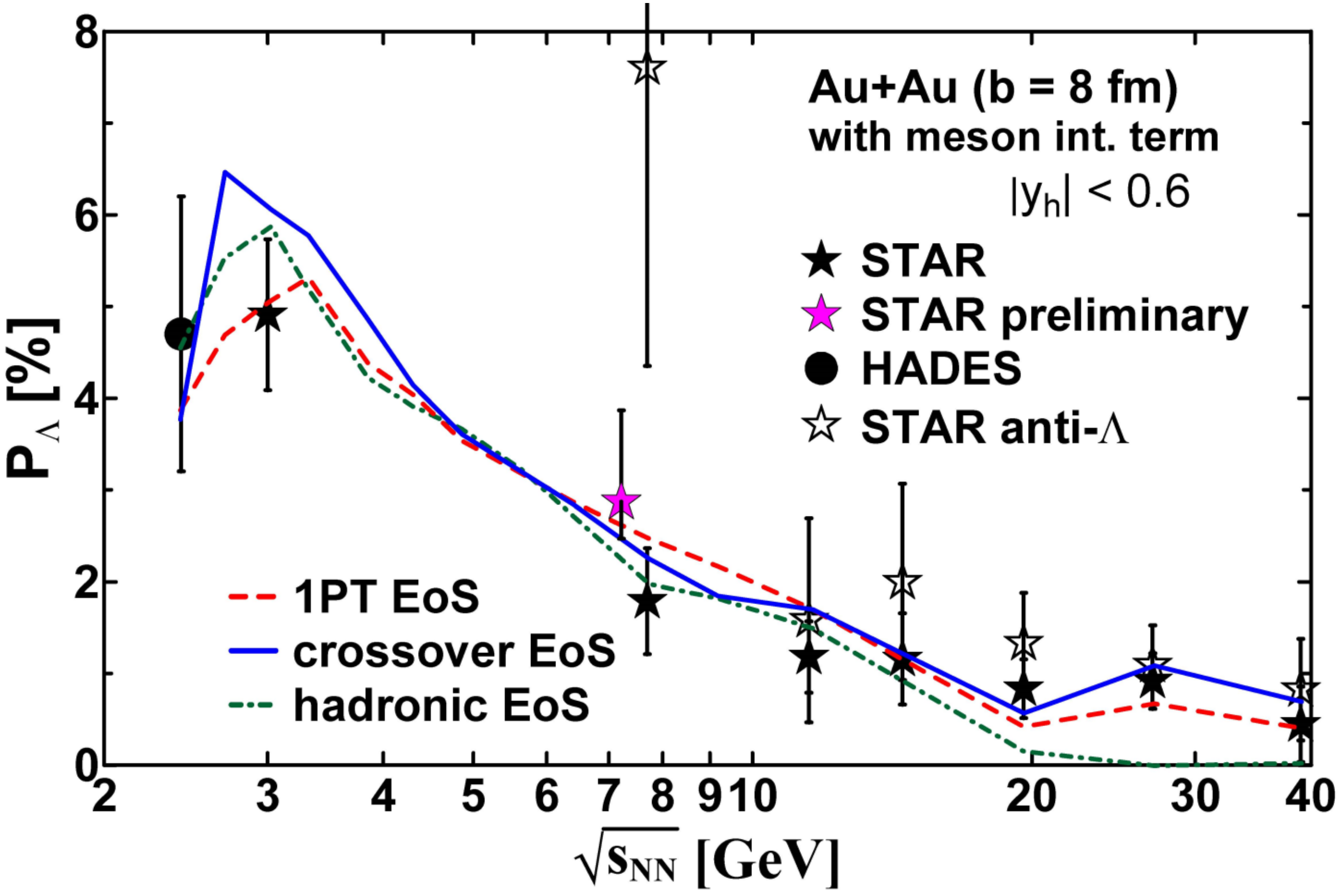
Threshold collision energies, above which measurements are feasible.

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

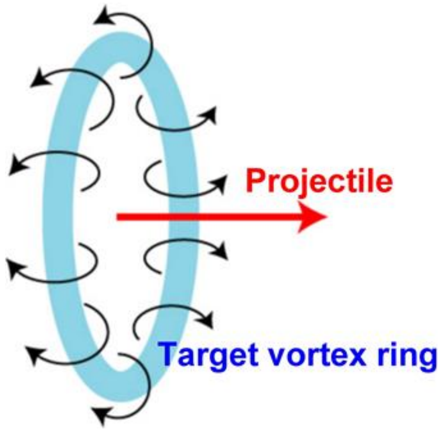
Polarization at $3 < \sqrt{s_{NN}} < 11$ GeV

- ✓ **There are no data at $3 < \sqrt{s_{NN}} < 7$ GeV**
- ✓ **Where is maximum of P_Λ?**
- ✓ **Is difference between P_Λ and $P_{anti\text{-}\Lambda}$ that huge as at 7.7 GeV?**
- ✓ **Local polarization of hyperons along the beam direction at 5 -- 11 GeV?**
- ✓ **Global spin alignment of vector mesons at 5 -- 11 GeV?**

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



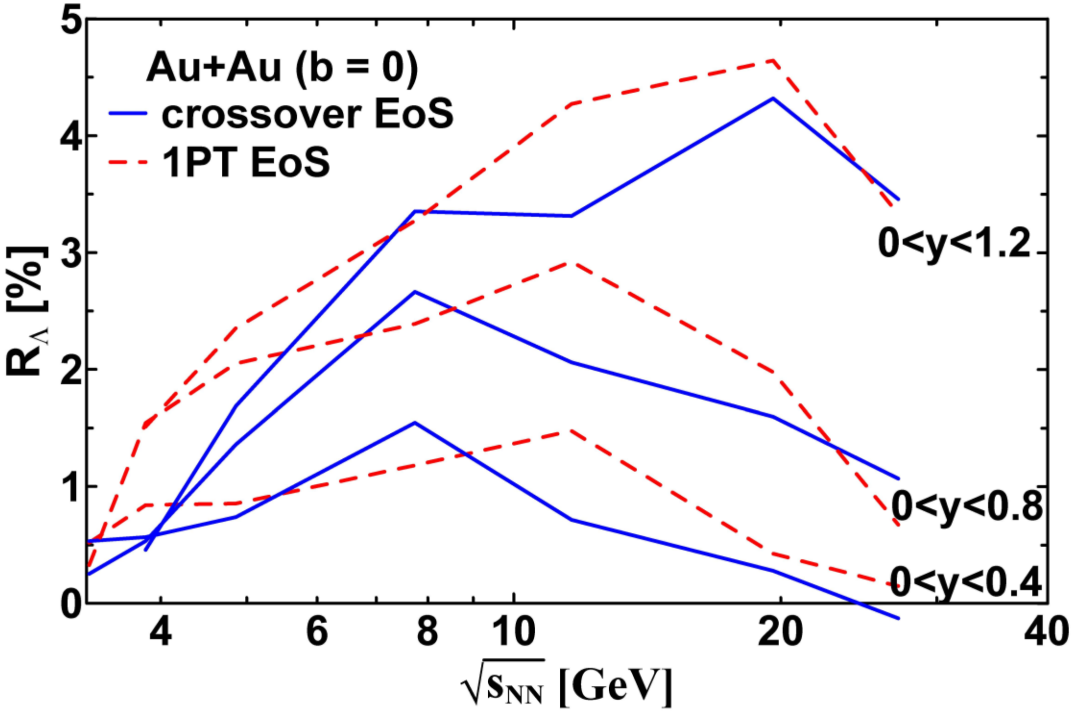
Vortex rings



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

The matter rotation is opposite in this two rings.

3FD prediction: These smoke rings can be observed even in midrapidity at 5 < √sNN < 11 GeV



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

$P_\Lambda(\mathbf{p})$ is polarization of the Λ hyperon,
p is its spacial momentum, and
$\mathbf{e}_z$ is the unit vector along the beam.

Collective transverse flow

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_{RP}))\right)$$

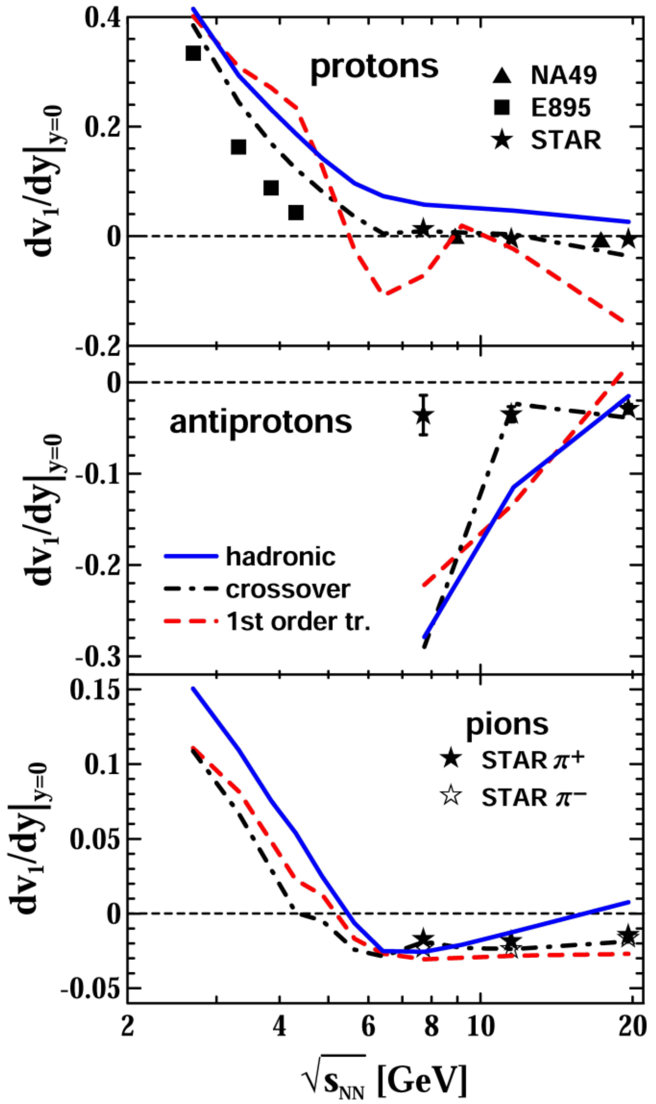
ϕ = azimuthal angle

v_1 = directed flow
v_2 = elliptic flow

Directed flow (v_1)

YI and Soldatov, PRC 91 (2015) 2, 024915

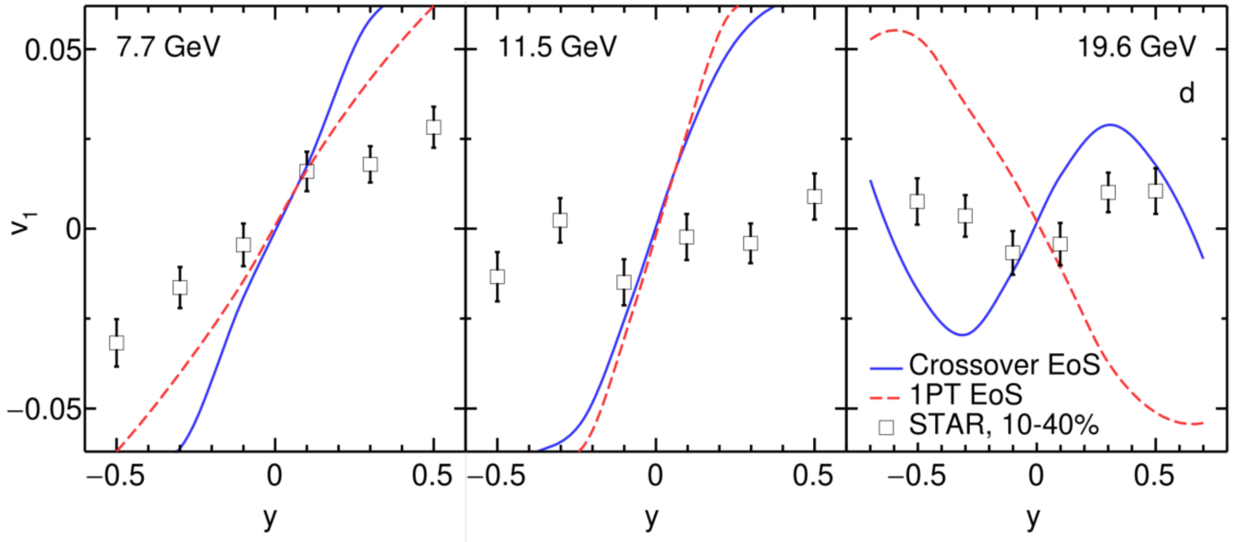
- ✓ v_1, especially the proton one, is very sensitive to onset of the deconfinement transition.
- ✓ The deconfinement transition happens in the NICA energy range.
- ✓ Crossover EoS is preferable.
- ❖ Proton directed flow at √sNN < 7 GeV (AGS) is well reproduced in terms of <P_x>, but not in terms of v_1. Why?
- ❖ Pion v_1 data are absent at √sNN < 7.7 GeV



Directed flow (further questions)

- ✓ Kaon v_1 data [STAR, PRL 120, 062301 (2018)] are still not explained.
- ✓ Kaon v_1 data are absent at √sNN < 7.7 GeV

- ❖ Deuteron v_1 data [STAR, PRC 102, 044906 (2020)] are still not explained.
- ❖ Deuteron v_1 data are absent at 3 < √sNN < 7.7 GeV



Kozhevnikova, YI, arXiv:2210.07334 [nucl-th]

Summary

✓THESEUS event generator is very suitable for simulating heavy-ion collisions at NICA energies

✓THESEUS also provides predictions for light nuclei

It is interesting to measure at NICA:

✓Light nuclei production

✓Polarization

✓Directed and elliptic flow

Thank you
for your attention!

Backup

Chiral vortical effect (CVE)

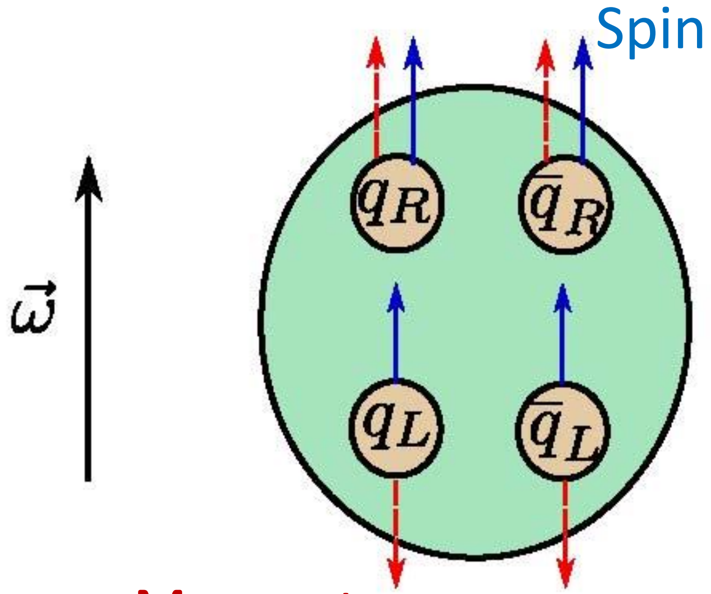
Axial current

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

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

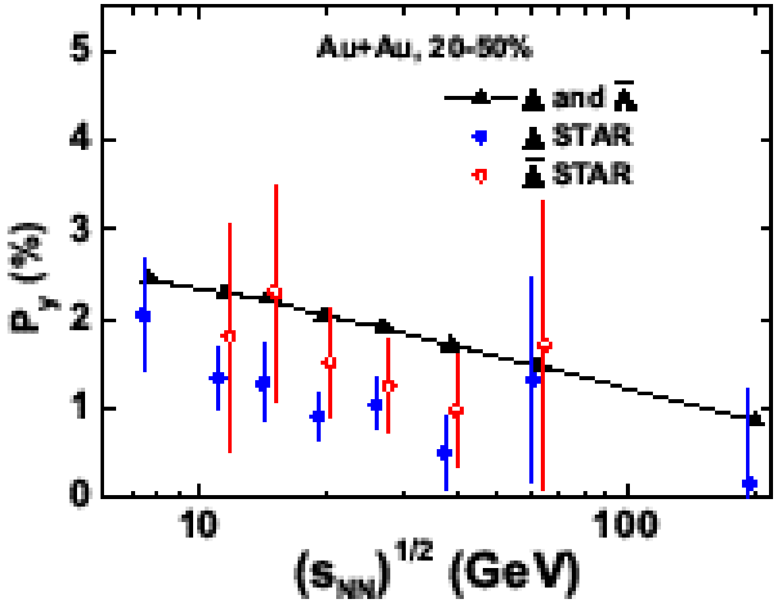
Landsteiner, Megias, Melgar, Pena-Benitez, JHEP 1109, 121 (2011) [Gauge-gravity correspondence]

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

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

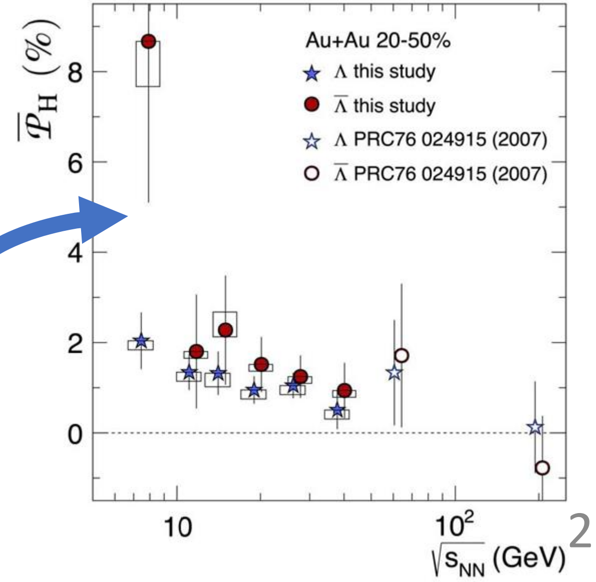
u_y results from boost to the local rest frame of the matter

Sorin and Teryaev, PRC 95, 011902 (2017)

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

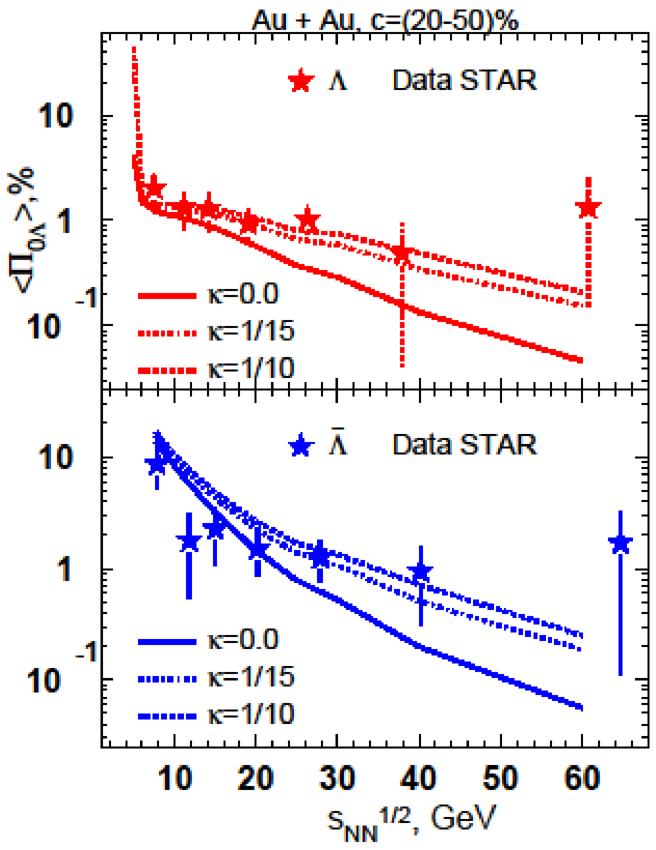
Therefore,

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

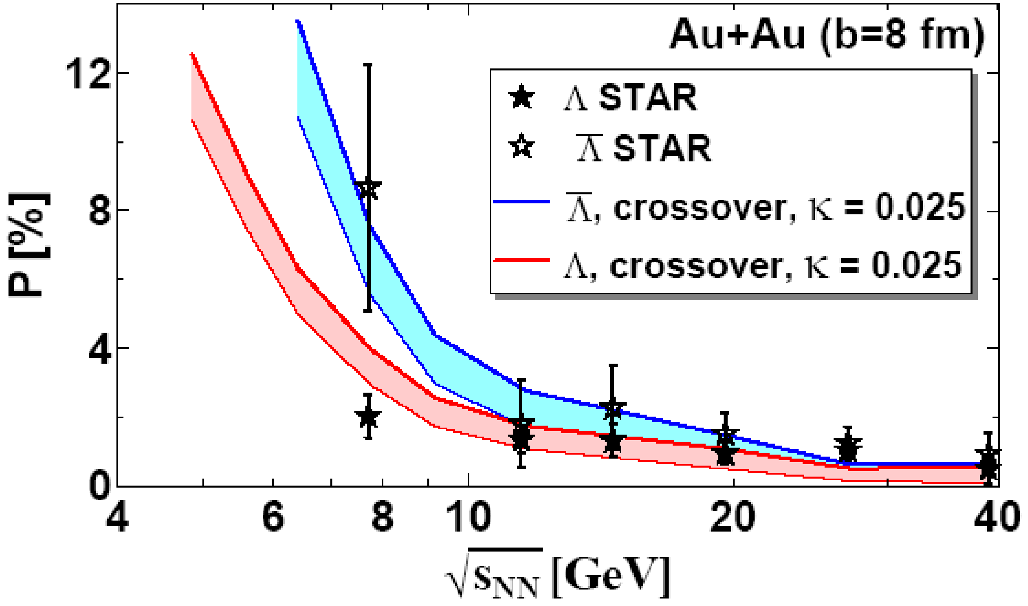


Axial-vortical-effect (AVE) polarization

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.