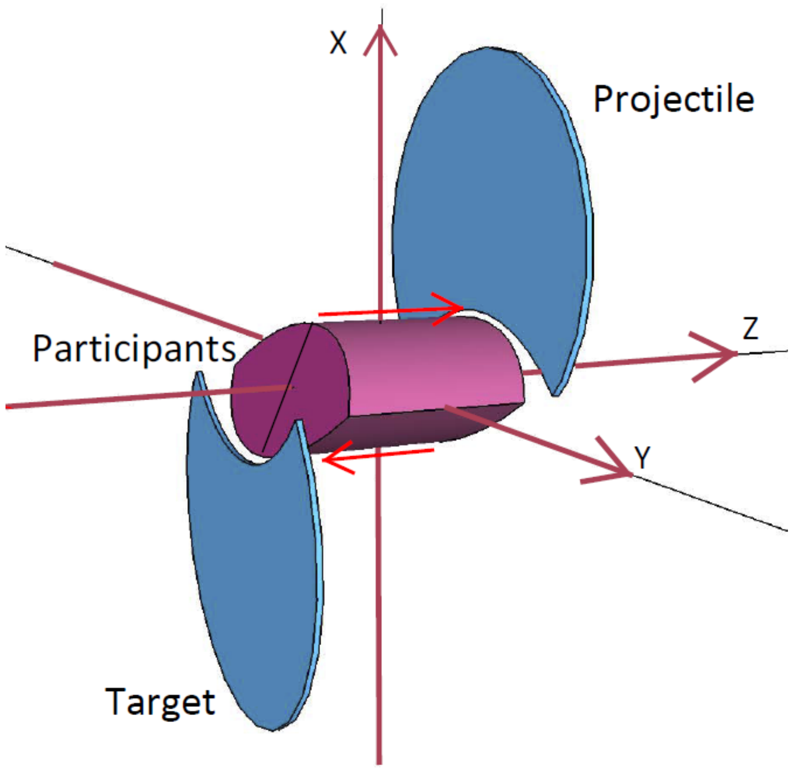
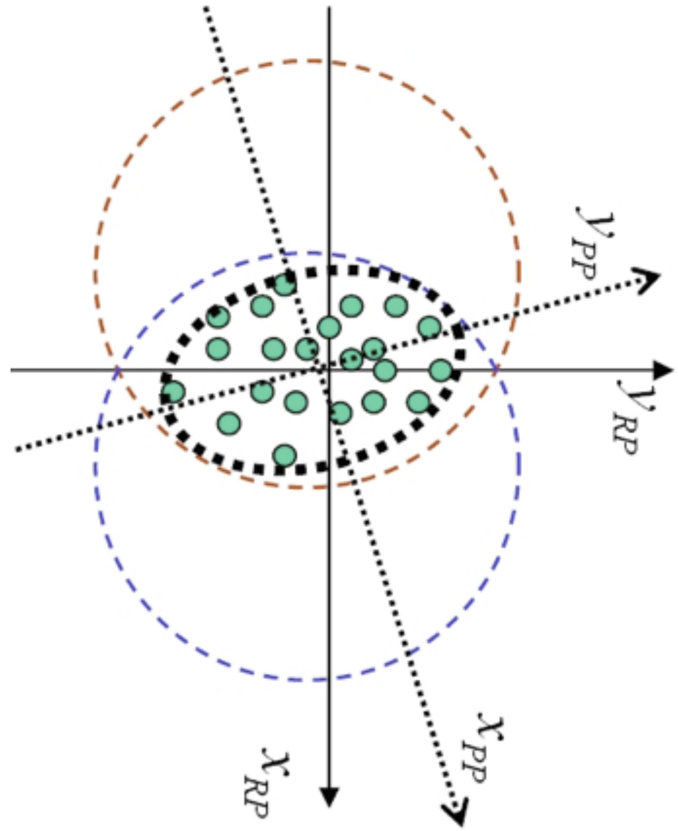
Initial state & Λ polarization

Current status of QCD from
nuclear reactions to the high energy frontier -
COST-THOR meeting – FIAS, Frankfurt am Main, Jan 19-20, 2017

Csernai, L.P.

Peripheral Collisions (A+A) → v_2 flow



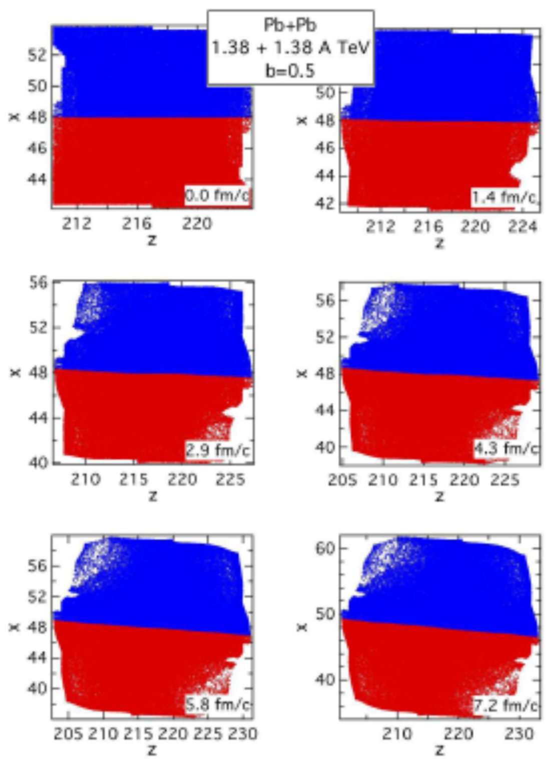


$$\frac{d^3N}{dy\,dp_t\,d\phi} = \frac{1}{2\pi}\frac{d^2N}{dy\,dp_t}\left[1 + 2v_1(y,p_t)\cos(\phi) + \underline{2v_2(y,p_t)\cos(2\phi)} + \cdots\right]$$

PICR: Shear & Turbulence → KHI

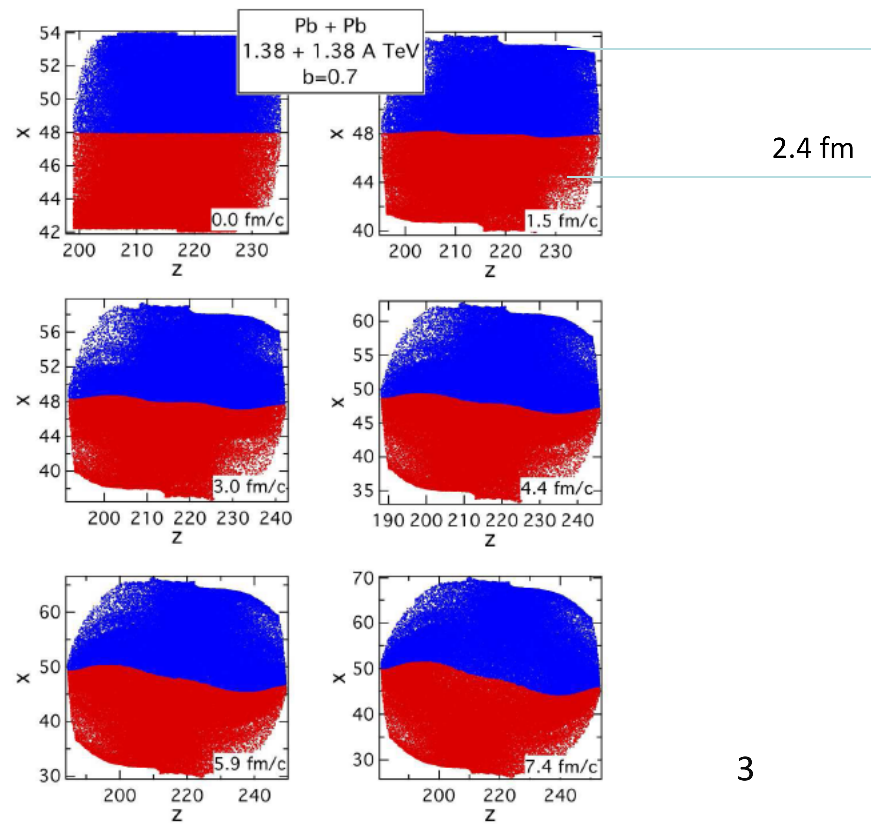
L.P. Csernai[1,2,3], D.D. Strottman[2,3], and Cs. Anderlik[4]
PHYSICAL REVIEW C **85**, 054901 (2012)

ROTATION – high η



KHI

KHI– low η



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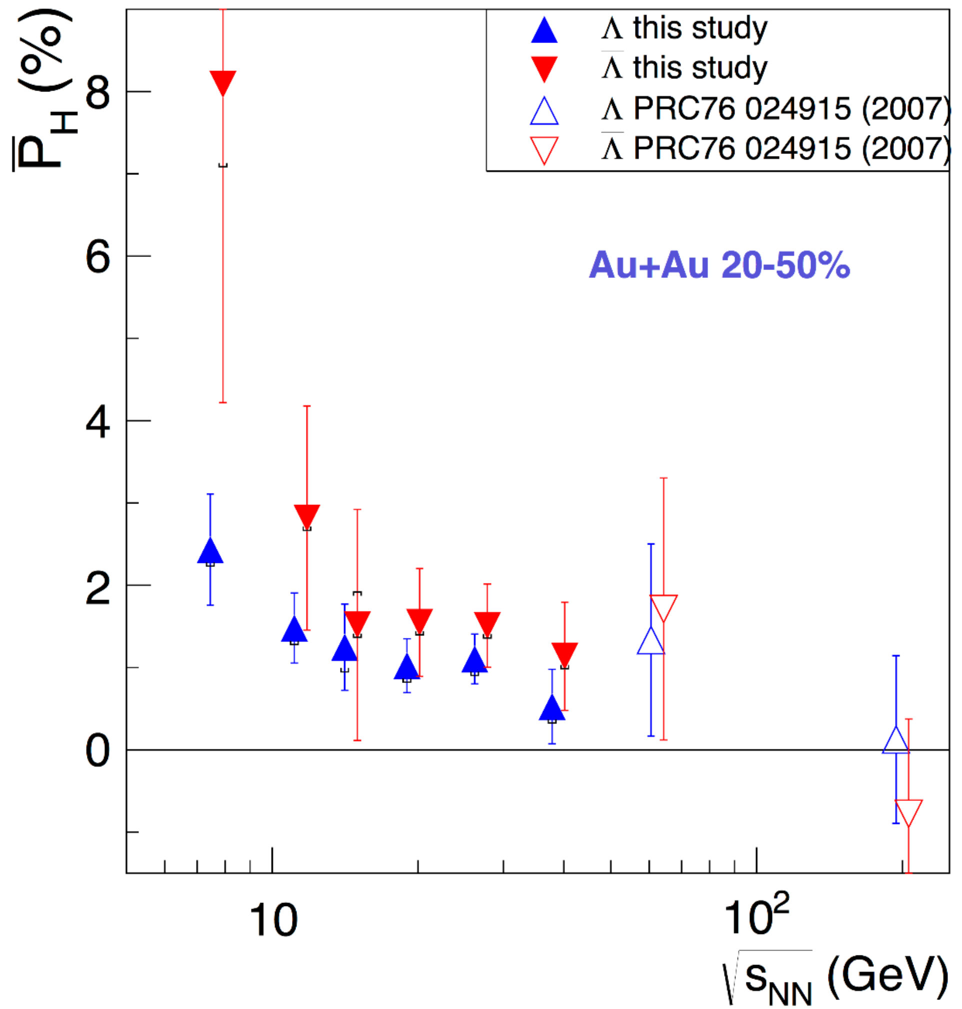
Rotation and Turbulence - (2015-16)



- STAR results

[**M.A. Lisa, et al**. (STAR Collaboration), Invited talk, QCD Chirality Workshop - UCLA, February 23-26, 2016, Los Angeles, USA.]

Observable consequences

Mike Lisa & STAR
Λ & anti- Λ polarization

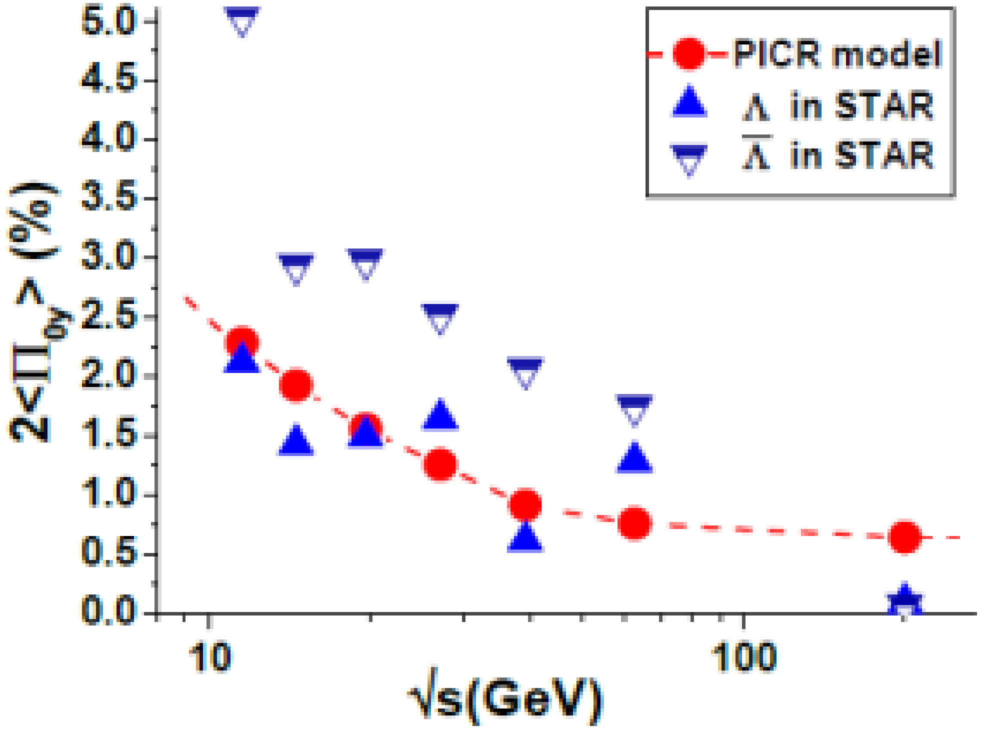
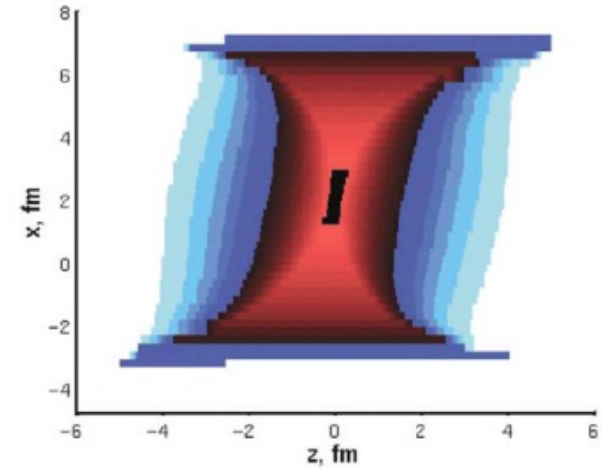
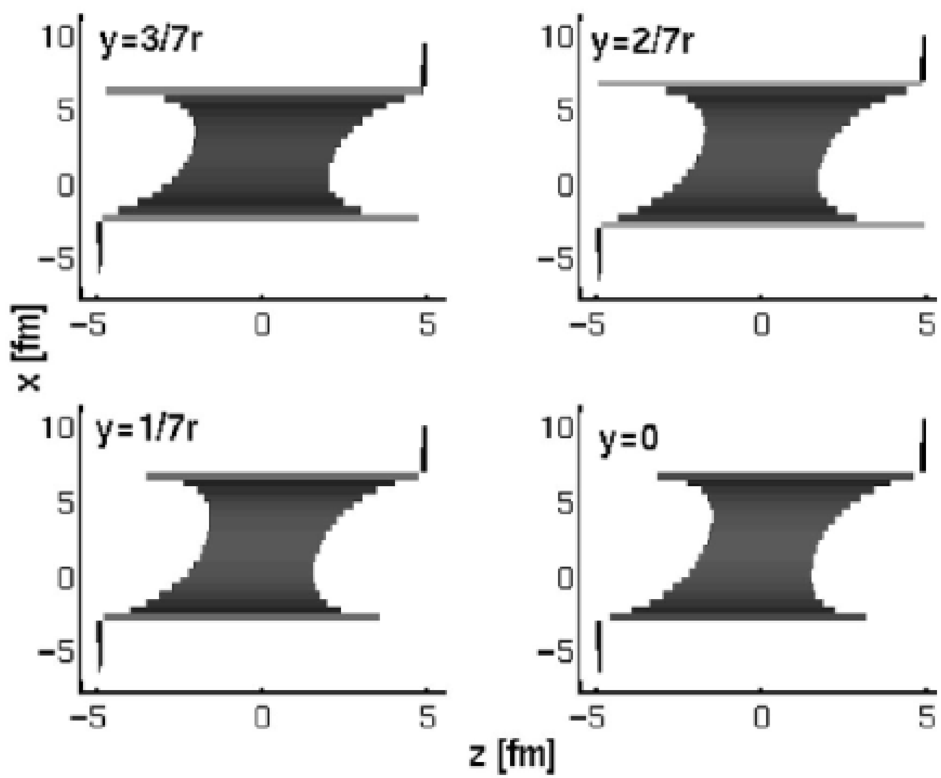


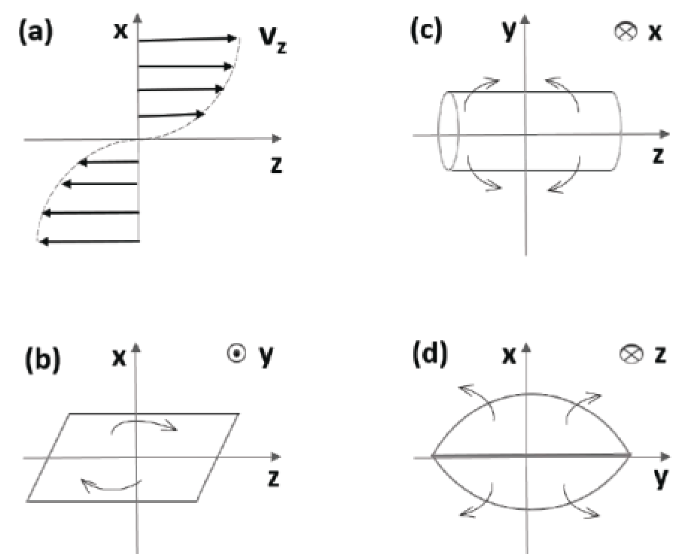
FIG. 4. (Color online) The global polarization, $2\langle\Pi_{0y}\rangle_p$, in our PICR hydro-model (red circle) and STAR BES experiments (green triangle), at energies $\sqrt{s}$ of 11.5GeV, 14.5GeV, 19.6GeV, 27GeV, 39GeV, 62.4GeV, and 200GeV. The red The experimental data were extracted from Ref[Mike Lisa], dropping the error bars.

Initial State – Peripheral reactions

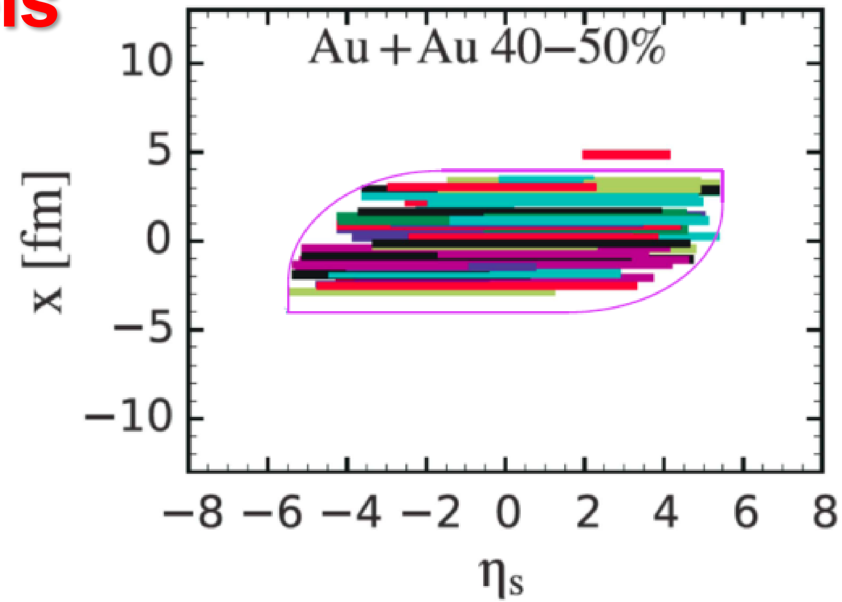
Magas, Csernai, Strottman (2001), (2002)
- Yang-Mills flux tube model for longitudinal streaks
- String tension is decreasing at the periphery
- Initial shear & vorticity is present







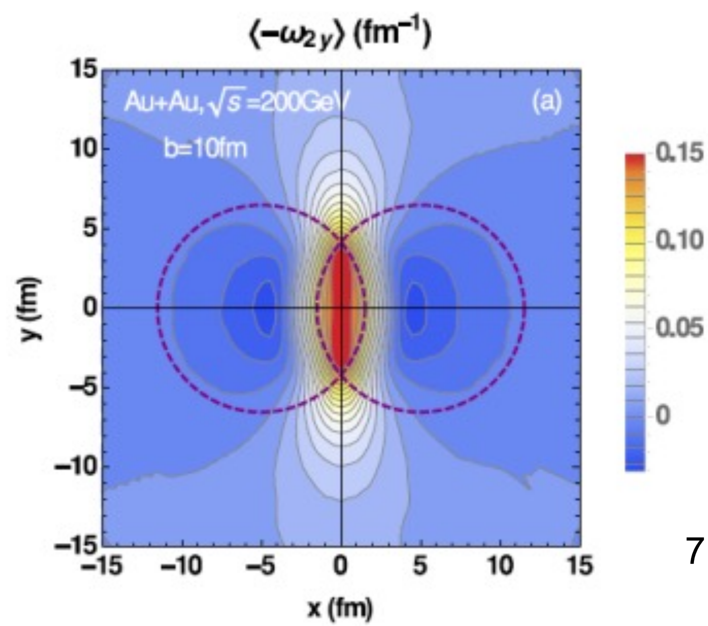
Present parton kinetic models - HIJING, AMPT, PACIAE

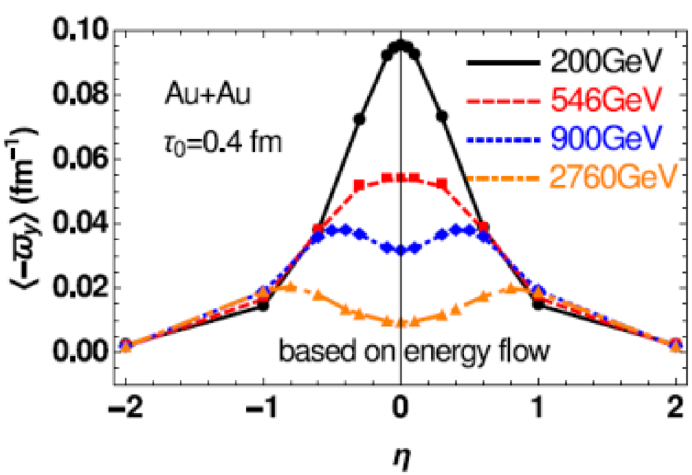


Different space-time configurations

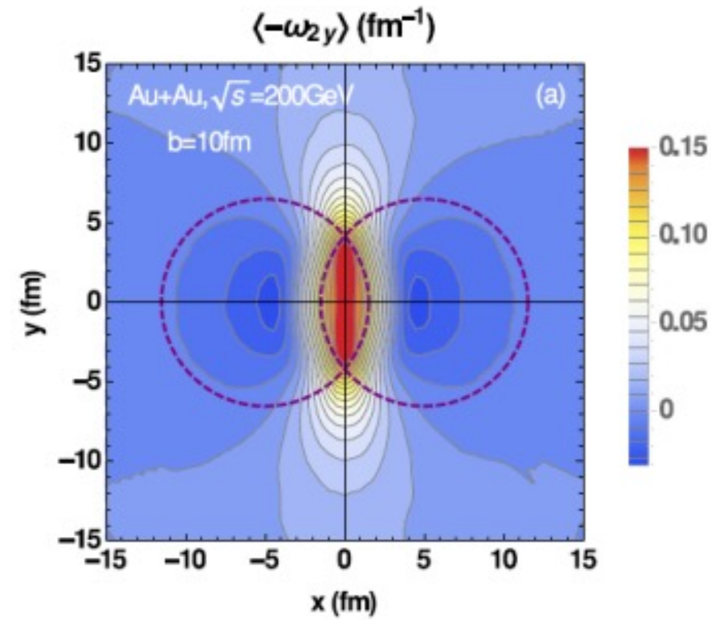
[Long-Gang Pang, Hannah Petersen, Guang-You Qin, Victor Roy and Xin-Nian Wang, 27 September - 3 October 2015, Kobe, Japan; and Long-Gang Pang, Hannah Petersen, Guang-You Qin, Victor Roy, Xin-Nian Wang, arXiv: 1511.04131]

[Wei-Tian Deng, and Xu-Guang Huang, arXiv: 1609.01801]



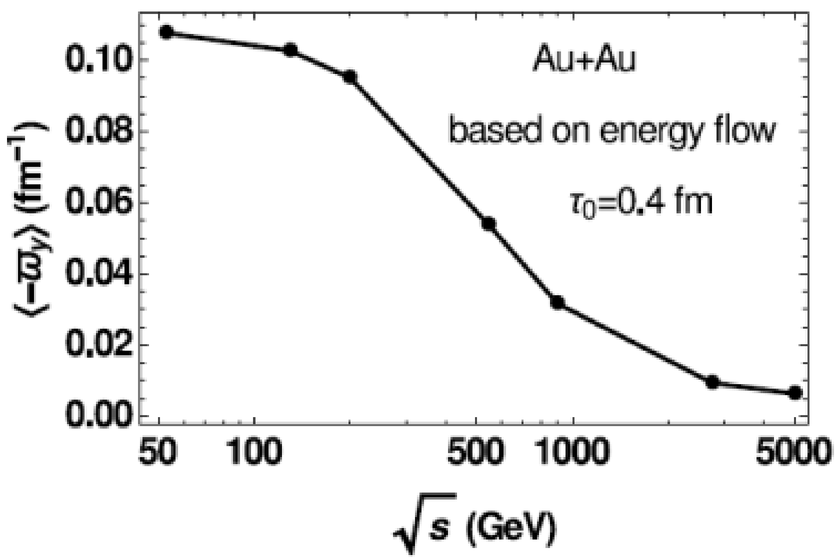


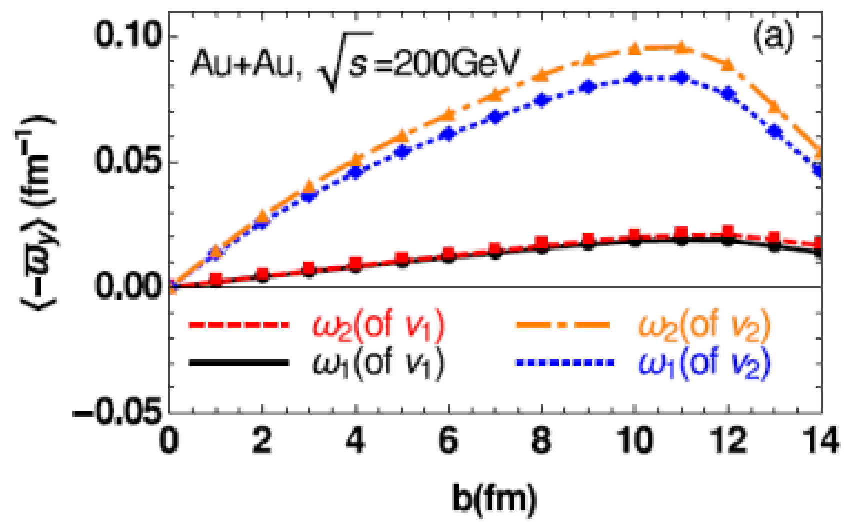
Present parton kinetic models - HIJING, AMPT, PATHIA



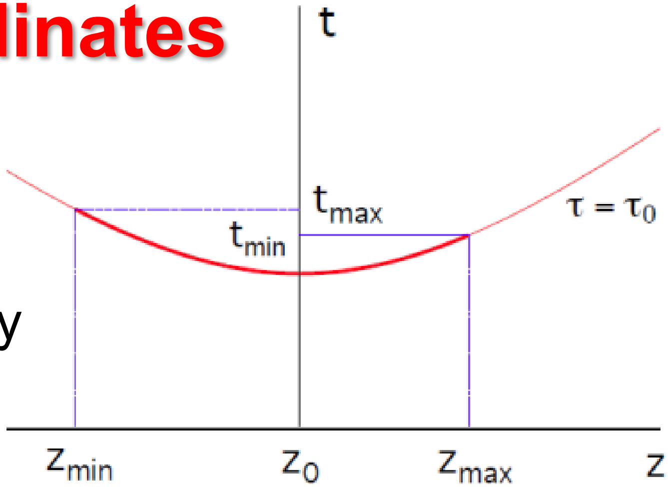
Different space-time configurations

[Wei-Tian Deng, and Xu-Guang Huang, arXiv: 1609.01801]





Initiative: new I.S. in τ, η coordinates



- Separately for each longitudinal streak
- String tension is not decreasing at the periphery
- Initial shear & vorticity is present !

The normal four vector of a hypersurface at $\tau = \text{const.}$ is

$$d\Sigma^{\mu} = A\,\tau\,u^{\mu}\,, \tag{3}$$

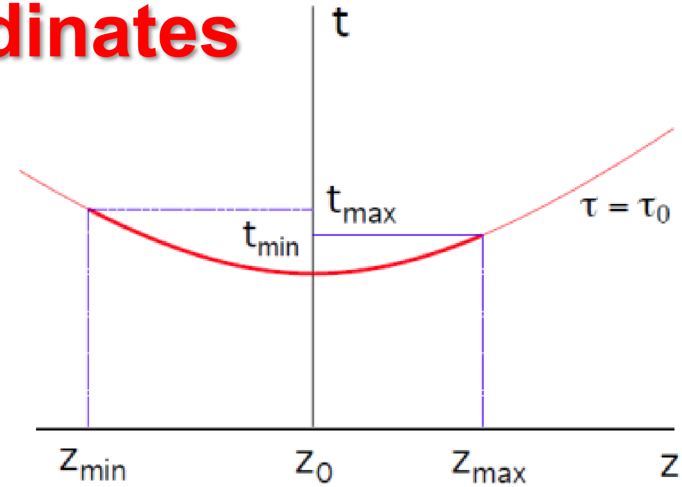
- Conservation laws: $dN = d\Sigma_{\mu} N^{\mu} = \tau A n\, u_{\mu} u^{\mu} d\eta$

$$N_i = N_1 + N_2 = \tau_0 n(\tau_0) A(\eta_{max} - \eta_{min})$$

$$E_i = E_1 + E_2 = \tau_0 e(\tau_0) A(\sinh \eta_{max} - \sinh \eta_{min})$$

$$P_{iz} = P_{1z} - P_{2z} = \tau_0 A\, e\, (\cosh \eta_{max} - \cosh \eta_{min})$$

Initiative: new I.S. in τ, η coordinates



- For the i-th streak (t,z) and (τ, η) coordinates are connected as

$$
\begin{aligned}
t - t_0 &= \tau / \sqrt{\coth^2 \eta + 1} \ , \\
z - z_0 &= \tau / \sqrt{\tanh^2 \eta + 1} \ , \\
\tau &= \sqrt{(t - t_0)^2 + (z - z_0)^2} \ , \\
\eta &= \frac{1}{2} \ln \left(\frac{t - t_0 + z - z_0}{t - t_0 - (z - z_0)} \right) \\
&= \operatorname{arctanh} \frac{z - z_0}{t - t_0} \ ,
\end{aligned}
$$

- For the central streak:

$$
\frac{1}{2} \Delta\eta_c = \operatorname{arcsinh} \left(\frac{E_c}{2\tau_0 e(\tau_0) A} \right)
$$

and

$$
\begin{aligned}
z_{c-max} &= \tau_0 / \sqrt{\tanh^2 \Delta\eta_c + 1} \ , \\
t_{c-max} &= \tau_0 / \sqrt{\tanh^{-2} \Delta\eta_c + 1}
\end{aligned}
$$

Initiative: new I.S. in τ, η coordinates

- For the i-th streak: $e(\tau_0) = E_c \Big/ \left[\tau_0\, A\, 2\, \sinh\left(\frac{1}{2}\Delta\eta_c\right)\right]$

$$\frac{1}{2}\Delta\eta_i = \operatorname{arcsinh}\left(\frac{E_i}{2\tau_0 e(\tau_0) A}\right)$$

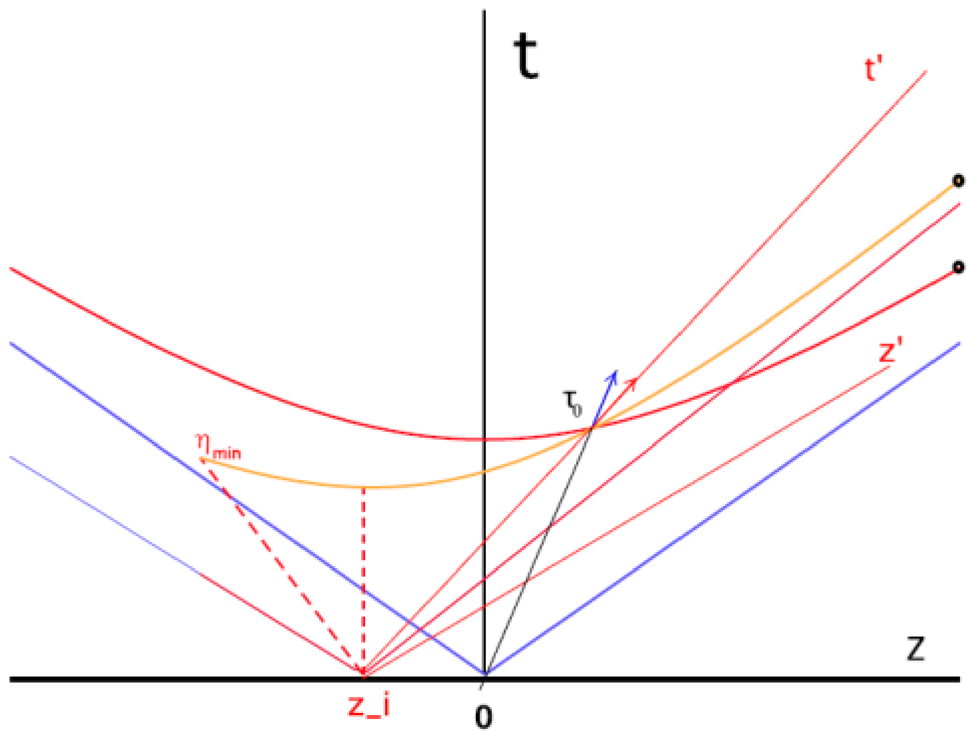
$$\eta_i = \operatorname{arctanh}\frac{P_{iz}}{E_i}\ .$$

$$\eta_{i-max_P} = \eta_i + \Delta\eta_i\ , \qquad \eta_{i-min_T}$$

$$\tau_0 = \sqrt{(t_{max} - t_{i0})^2 + (z_{max} - z_{i(}}$$

$$\eta_{i-max_P} = \operatorname{arctanh}\left(\frac{z_{max} - z_{i0}}{t_{max} - t_{i0}}\right)\ .$$

- ➔ The origin, t_{0i}, z_{0i}, will be different for each streak.



Initiative: new I.S. in τ, η coordinates

Thus for each streak, i, we can get the origin of the $\tau = \tau_0$ hyperbola, t_{i0} & z_{i0}.

from:

$$z_{i0} = z_{max} - \frac{\tau_0 \,(\tanh \eta_{i-max\,P})}{\sqrt{1 + (\tanh \eta_{i-max\,P})^2}}$$

$$\tau_0^2 = \left(t_{i0} + \frac{\tau_0}{\sqrt{\coth^2 \eta_i + 1}} \right)^2 + \left(z_{i0} + \frac{\tau_0}{\sqrt{\tanh^2 \eta_i + 1}} \right)^2 .$$

Matching I.S. to hydro

PHYSICAL REVIEW C **81**, 064910 (2010)
Matching stages of heavy-ion collision models, Yun Cheng, L. P. Csernai, V. K. Magas, B. R. Schlei, and D. Strottman

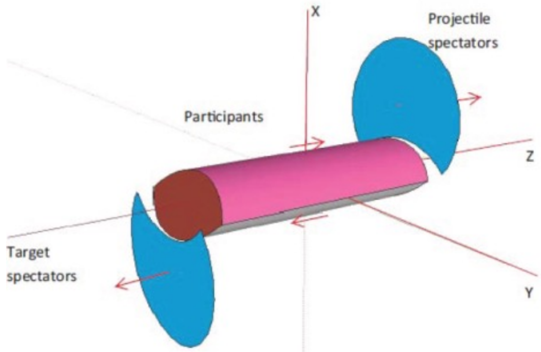
There are hydro options: Cartesian / Bjorken coordinates

Transition surface, $\tau = \text{const.}$, $t = \text{const.}$, curved $h.s$.

In all cases I.S. $T^{\mu\nu}$ → Conservation laws due to EoS.

Consequences:

- Will be similar to the 2001-2 I.S. in (t,z) coordinates
- More compact → vorticity may survive better
- The earlier results will remain qualitatively similar:



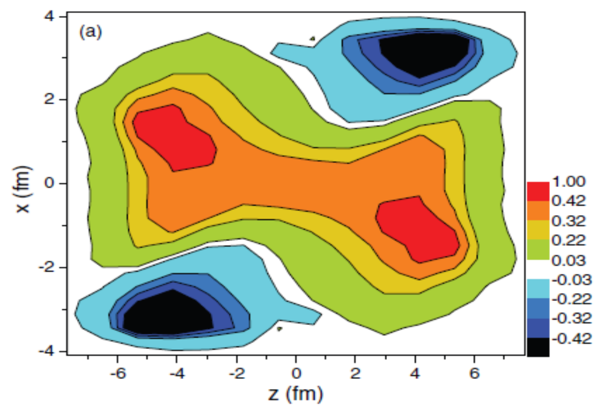


Fig. 3 The vorticity calculated in the reaction (xz) plane at t = 0.17 fm/c after the start of fluid dynamical evolution.

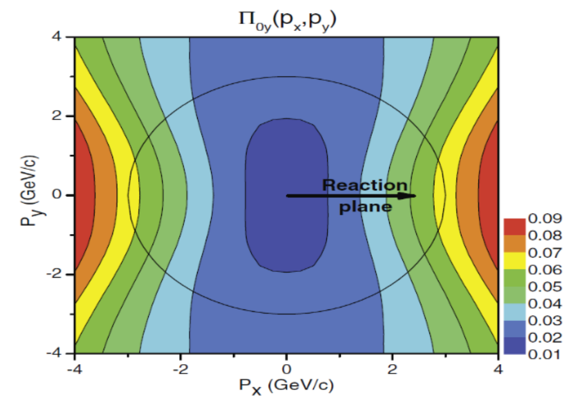


Fig. 4. The dominant y component of the observable polarization, $\boldsymbol{\Pi_0(p)}$ in the Λ's rest frame.

The initial rotation can lead to observable vorticity (Fig. 3), and polarization (Fig. 4): Leading vorticity term.
The initial angular momentum can be transferred to the polarization at final state, via spin-orbit coupling or equipartition.

[L. P. Csernai, et al, PRC **87**, 034906 (2013)]
[F. Becattini, et al. PRC **88**, 034905 (2013)]

Consequences:

Based on Ref. [Becattini, 2013], Λ polarization can be calculated as:

$$\mathbf{\Pi}(p) = \frac{\hbar\epsilon}{8m}\frac{\int dV\, n_F(x,p)\boxed{(\nabla \times \beta)}}{\int dV\, n_F(x,p)}$$

Vorticity, 1st

$$+\frac{\hbar \mathbf{p}}{8m} \times \frac{\int dV\, n_F(x,p)\boxed{(\partial_t \beta + \nabla\beta^0)}}{\int dV\, n_F(x,p)} .$$

Expansion, 2nd

where $\beta^\mu(x) = [1/T(x)]u^\mu(x)$ is the inverse temperature four-vector field. Then thermal vorticity is ω = $\nabla\times\beta$.

The polarization 3-vector in the rest frame of particle can be found by Lorentz-boosting the above four-vector:

$$\mathbf{\Pi}_0(p) = \mathbf{\Pi}(p) - \frac{\mathbf{p}}{p^0(p^0+m)}\mathbf{\Pi}(p)\cdot\mathbf{p} ,$$

[F. Becattini, L.P. Csernai, and D.J. Wang, Phys. Rev. C **88**, 034905 (2013)]

Consequences:

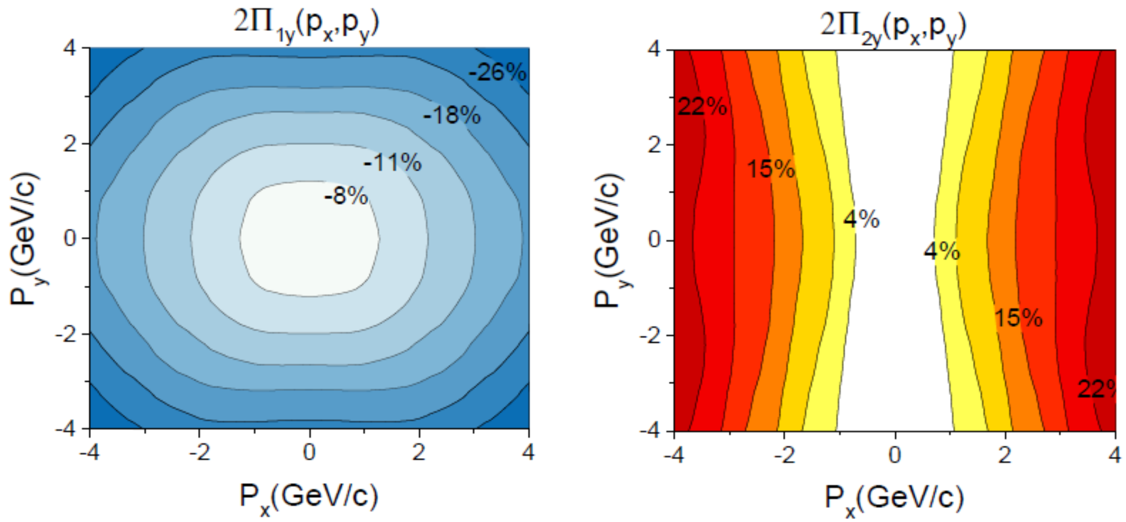
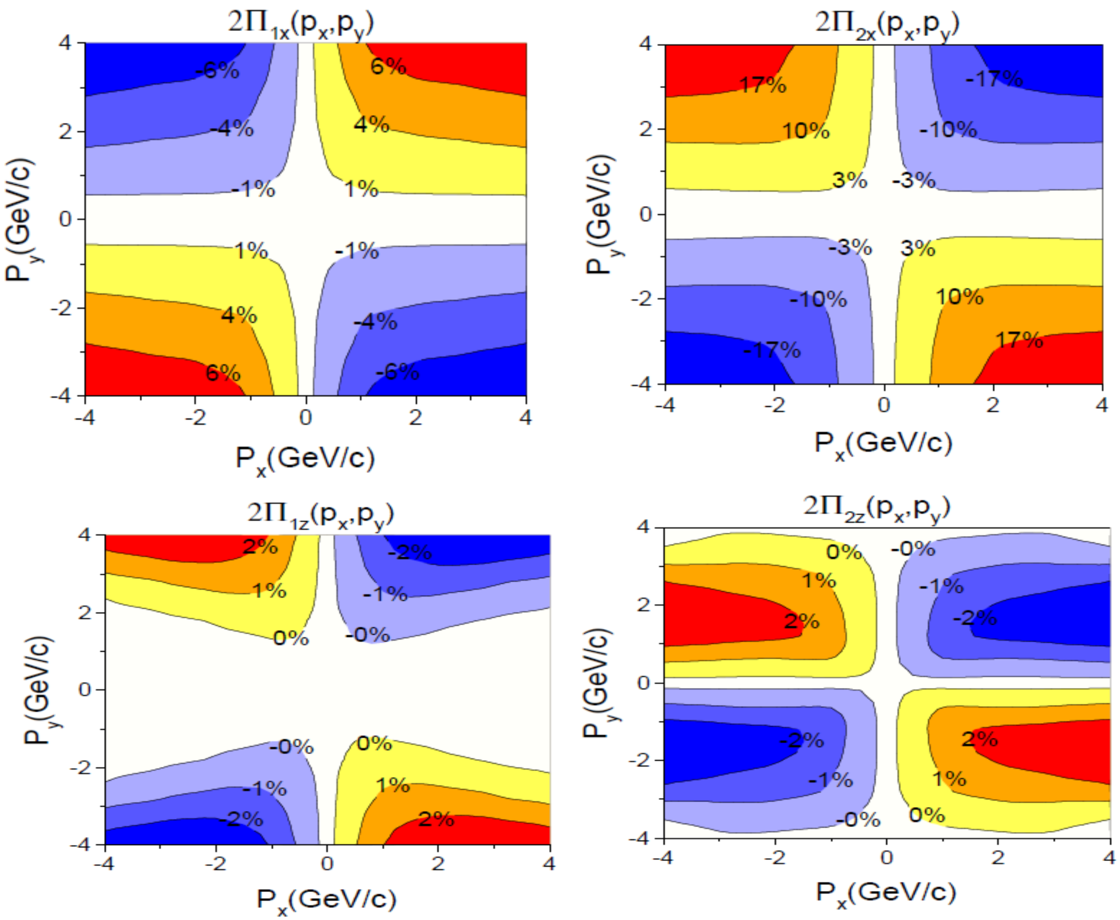


Fig. 6 The first (left) and second (right) term of the dominant y component of the Λ polarization for momentum vectors in the transverse plane at $p_z = 0$,for the FAIR U+U reaction at 8.0 GeV

- The y component is dominant, is up to ~20%, as we can compare it with x and z components later.
- 1st & 2nd terms are opposite direction. Result into a relatively smaller value of global polarization.

Consequences / c.m. !



1. Anti-symmetry

2. Trivial.

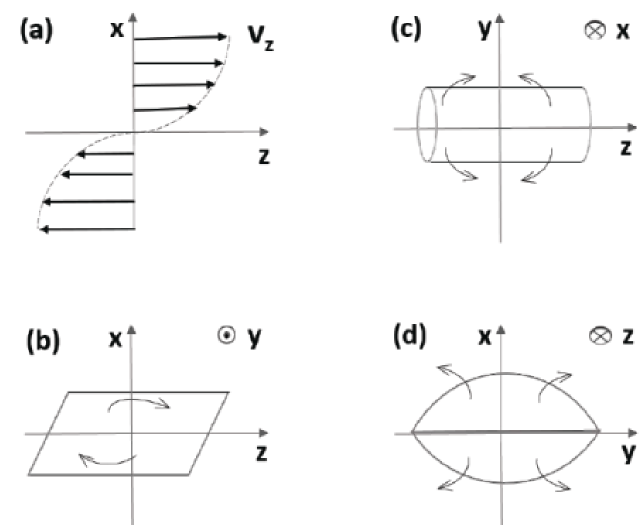
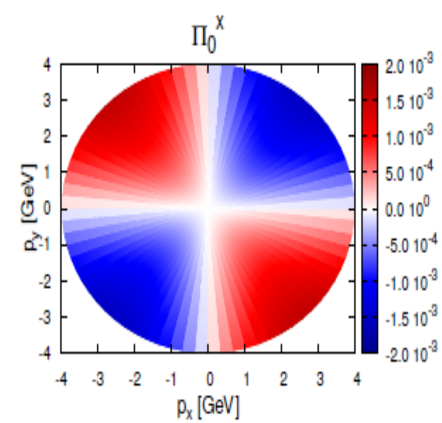


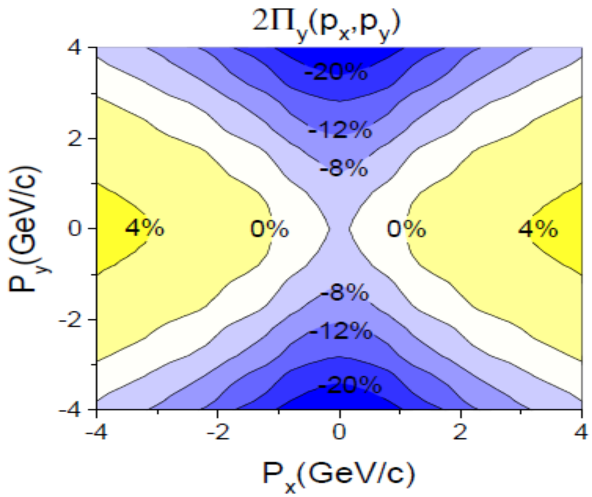
Fig. 7 The first (left) and second (right) terms of the x(up) and y(down) components of the Λ polarization for momentum vectors in the transverse plane at pz = 0,for the FAIR U+U reaction at 8.0 GeV

[Becattini, et al., Eur. Phys. J. C 75, 406 (2015).] →

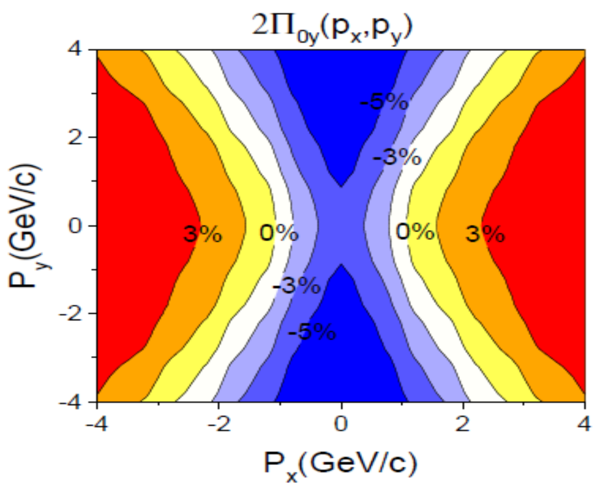


Csernai, L.P.

Consequences FAIR



- The modulus of polarization is very similar with the y component of polarization, both in magnitude and the structure. I. e. the other x and z components do not contribute to the polarization, which is in line with previous observations in this work and other papers.



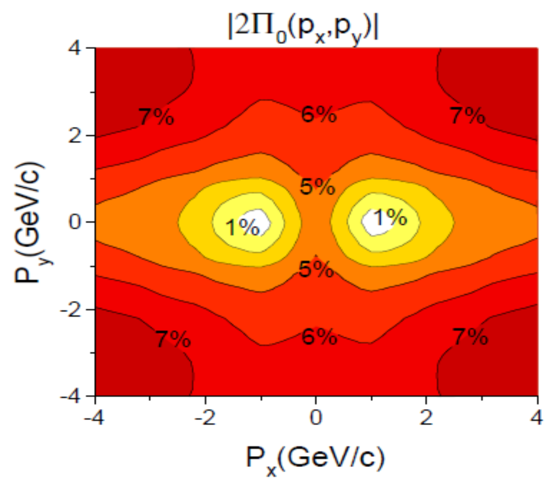


Fig. 8 The y component (left) of polarization vector in center of mass frame and Λ's rest frame. The right sub-figure are the modulus of the polarization in Λ's rest frame. At FAIR, 8.0 GeV at time 2.5+4.75 fm/c.

Csernai, L.P.

Consequences NICA

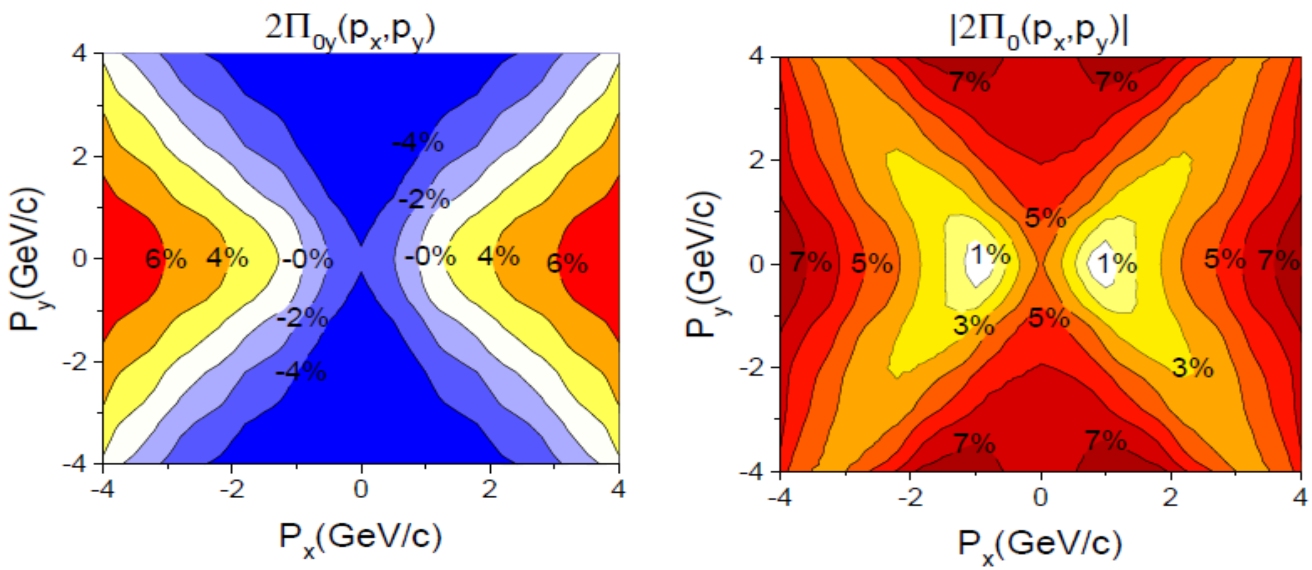


Fig. 9 The y component (left) and the modulus (right) of the polarization for momentum vectors in the transverse plane at pz = 0, for the NICA Au+Au reaction at 9.3 GeV. The figure is in the Λ's rest frame.

- Similarity between y component and modulus of Polarization, in magnitude and structure.
- Similarity between NICA and FAIR's polarization results.
- The net polarization is still negative, which means the first term is larger than the second term, at this time.

Csernai, L.P.

Consequences FAIR

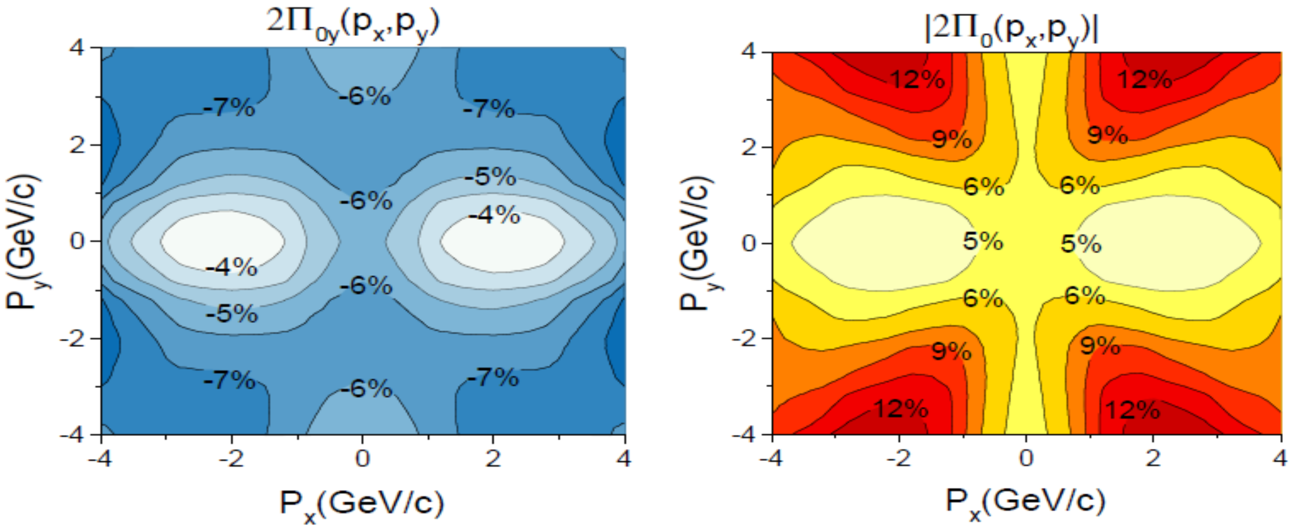


Fig. 9 The y component (left) and the modulus (right) of the polarization for momentum vectors in the transverse plane at pz = 0, for the FAIR U+U reaction at 8.0 GeV, but at an earlier time t= 2.5+1.7 fm/c. The figure is in the Λ's rest frame.

- Initially, the first term is very dominant

Conclusions

Peripheral reactions show shear, vorticity (turbulence)

I.S. can be implemented in (t, z) and (τ, η) hydro codes

Different components, $-y$, x, z, and momentum dependence do show the weight of different dynamical flow patterns.