Lambda polarization in peripheral heavy ion collisions

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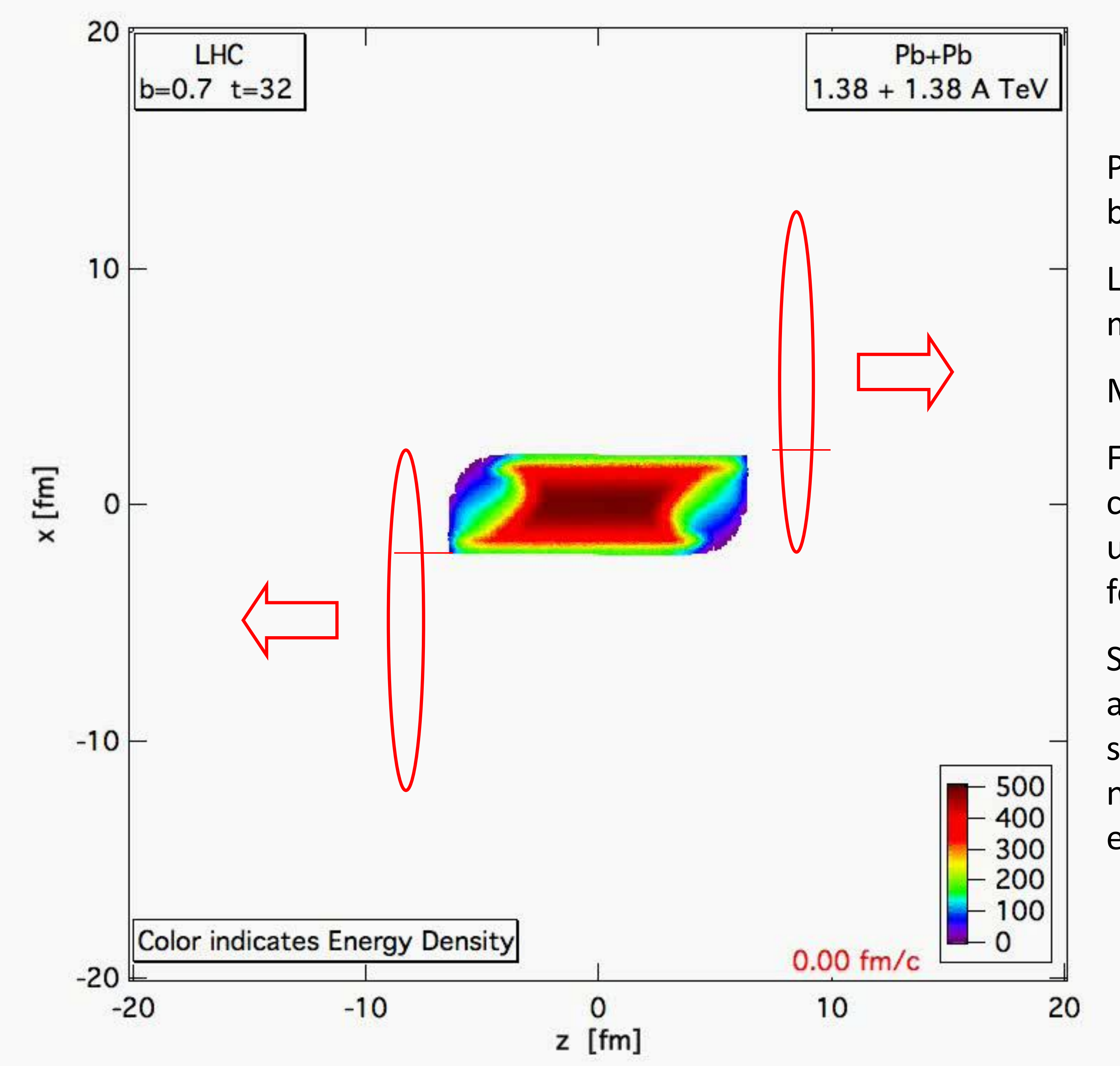
Workshop on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions,
19-22 March 2018, Galileo Galilei Institute, Firenze



PIC-
hydro

Pb+Pb 1.38+1.38 A TeV, b= 70 % of b_max

Lagrangian fluid cells, moving, ~ 5 mill.

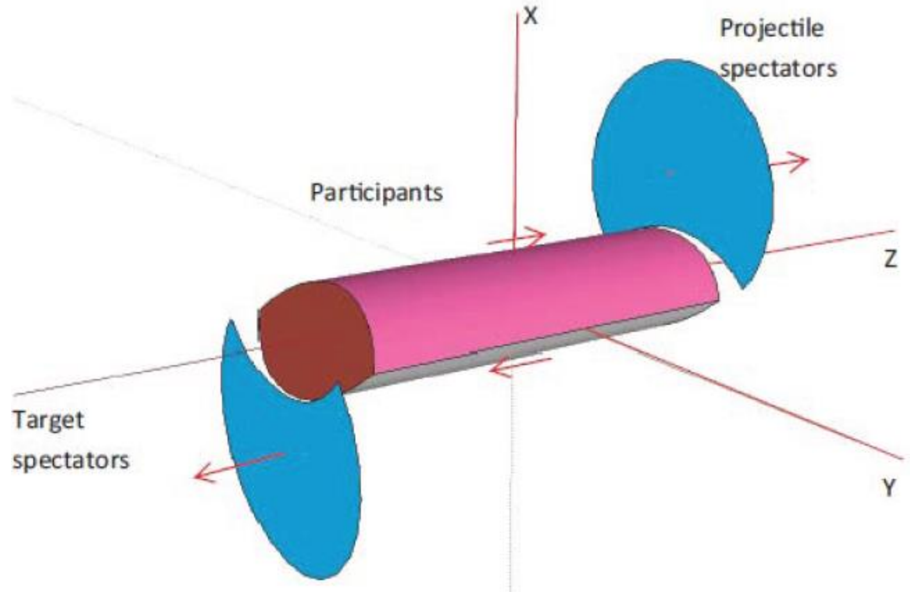
MIT Bag m. EoS

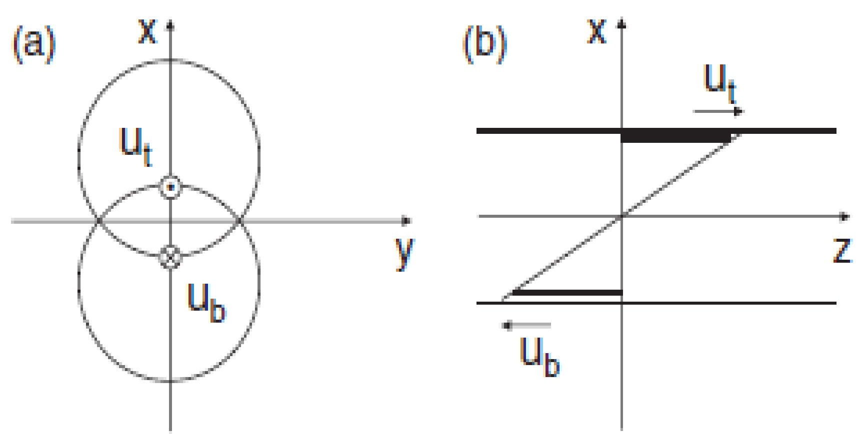
FO at T ~ 200 MeV, but calculated much longer, until pressure is zero for 90% of the cells.

Structure and asymmetries of init. state are maintained in nearly perfect expansion.

Periheral Collisions - Initial State

- Peripheral reactions
- ∃ Shear ➔ vorticity ➔
- L: in -y direction



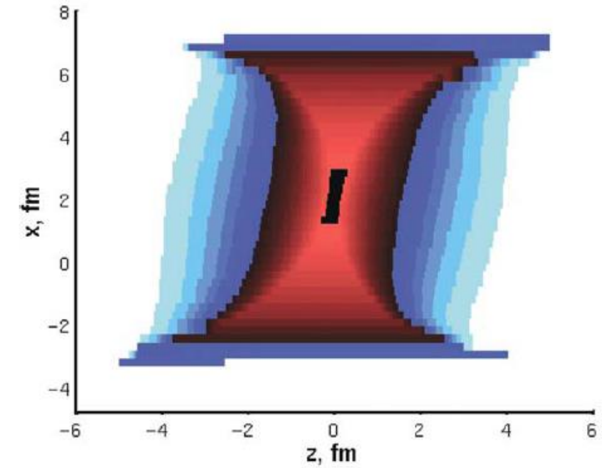


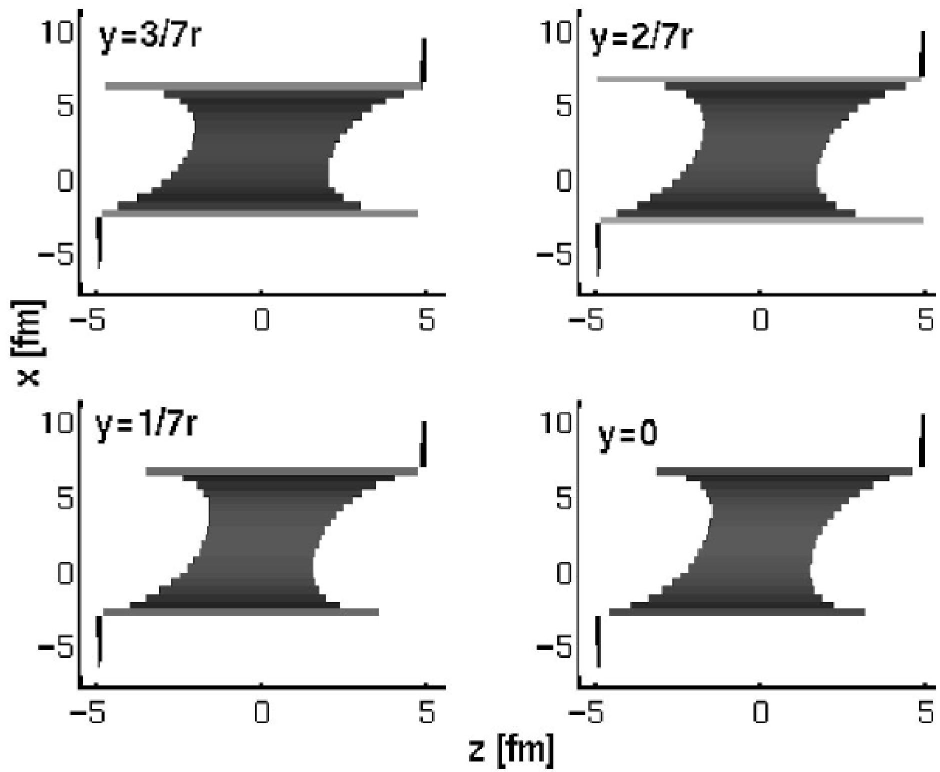
Hw P: L = ?

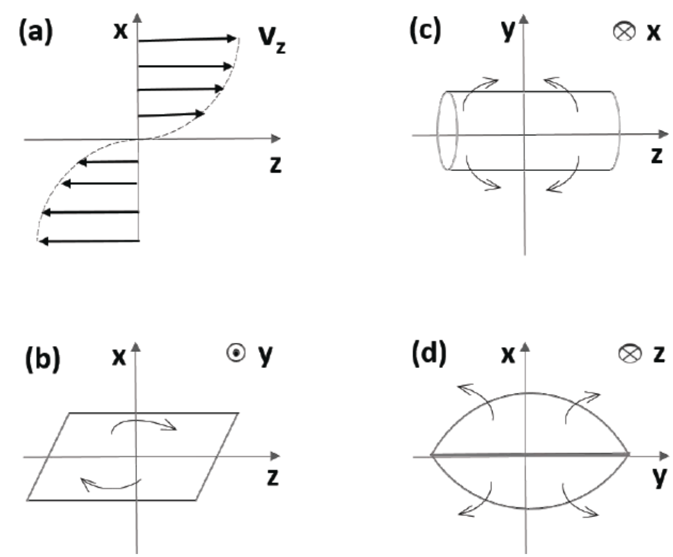
Initial State – Peripheral reactions

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





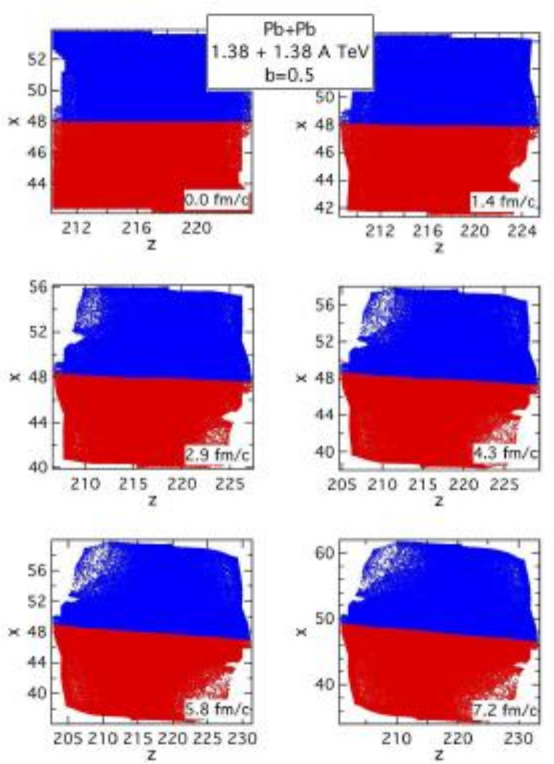


Shear & Turbulence → KHI

L.P. Csernai[1,2,3], D.D. Strottman[2,3], and Cs. Anderlik[4]

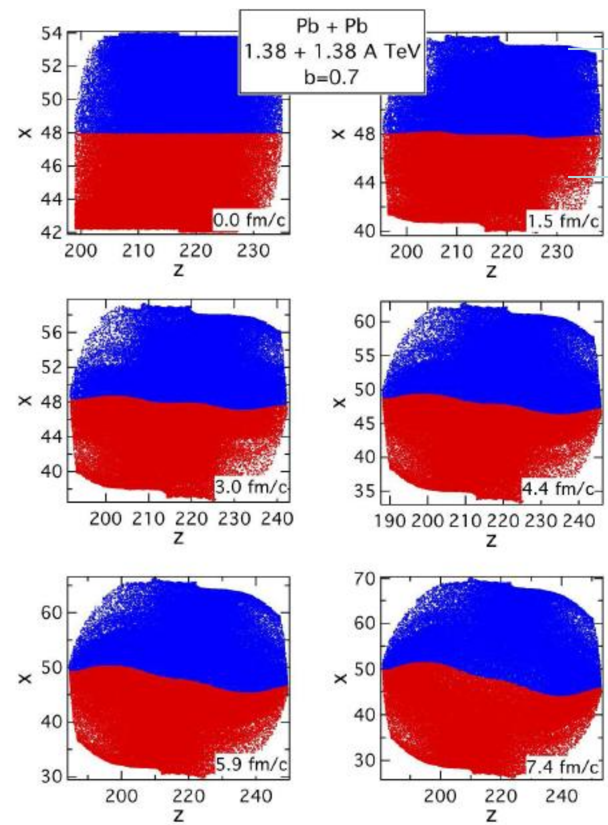
PHYSICAL REVIEW C **85**, 054901 (2012)

ROTATION – high η

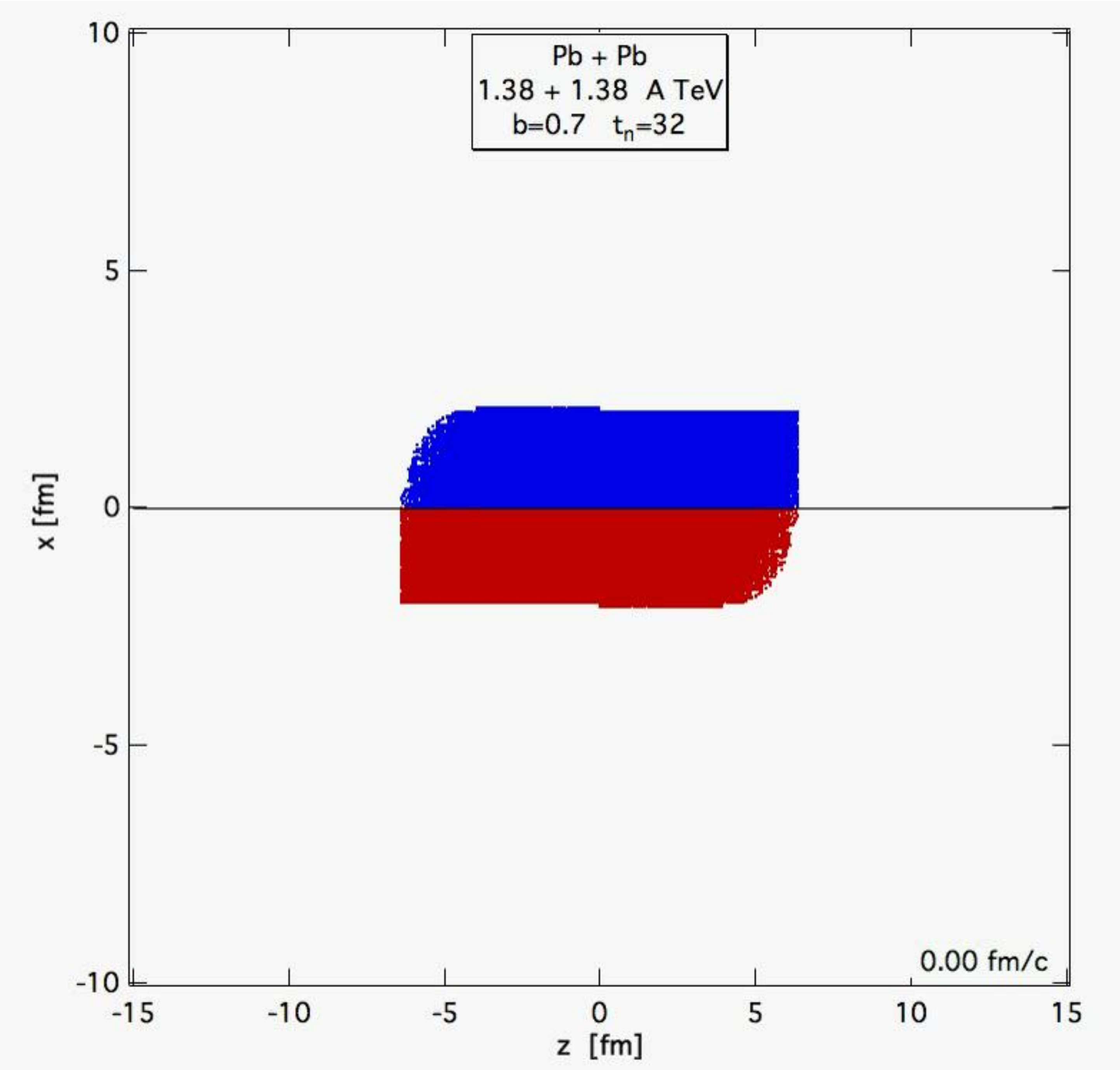


KHI

KHI– low η



2.4 fm



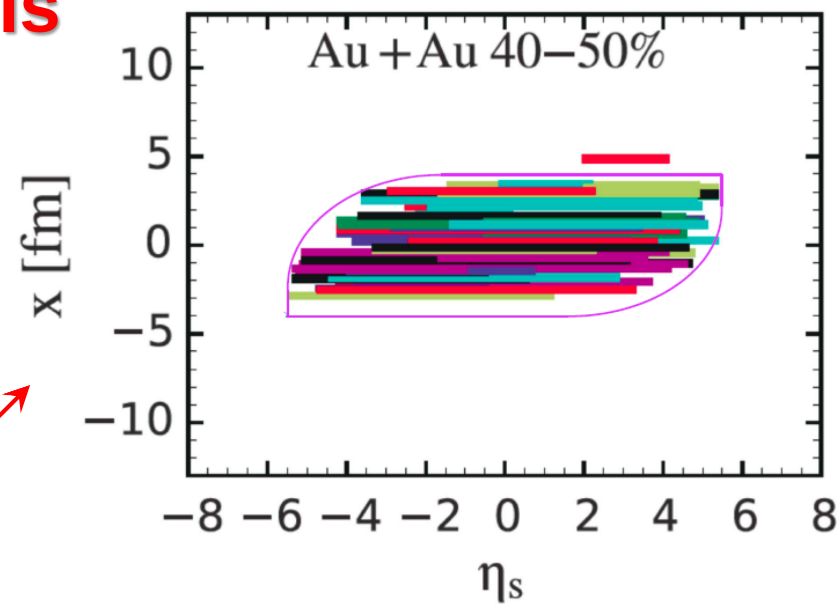
Kelvin – Helmholtz Instability

PICR Hydro (2012)

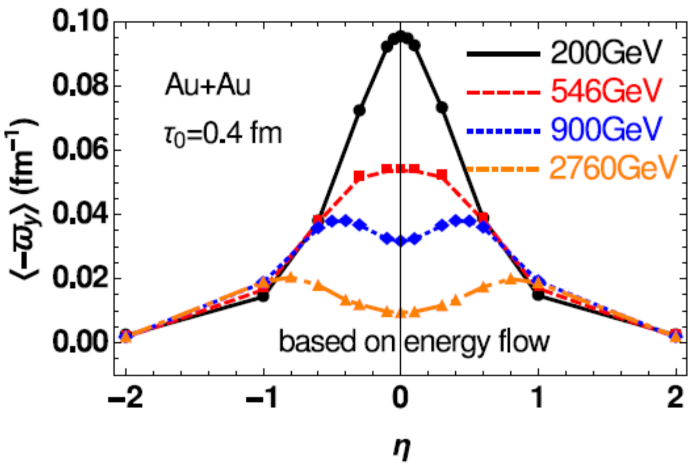
Present parton kinetic models - HIJING, AMPT, PACIAE

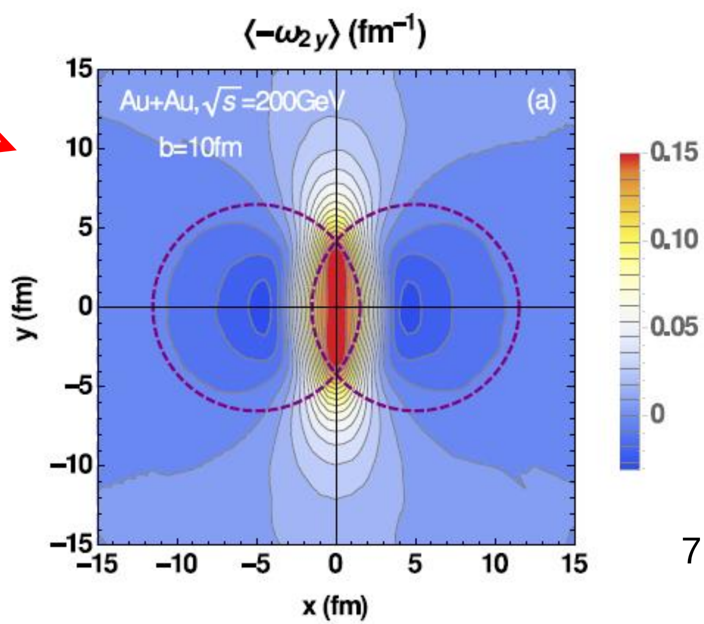
Different space-time configurations

[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: **15**11.04131]

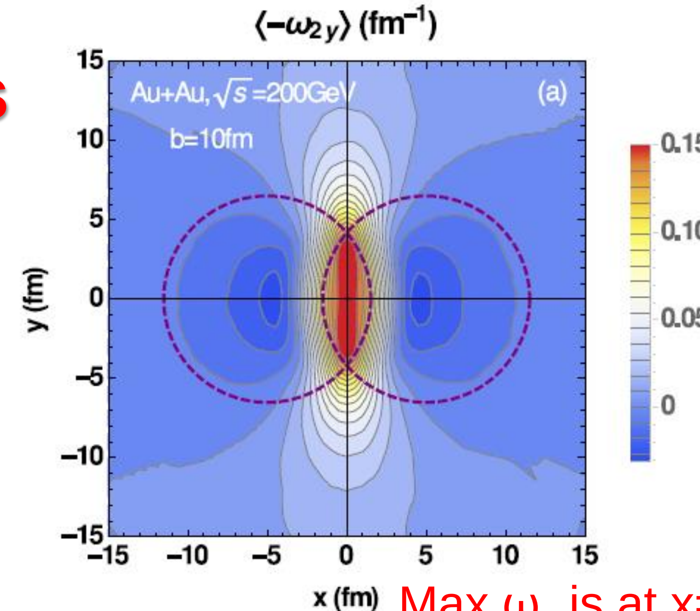


[Wei-Tian Deng, and Xu-Guang Huang, arXiv: **16**09.01801]





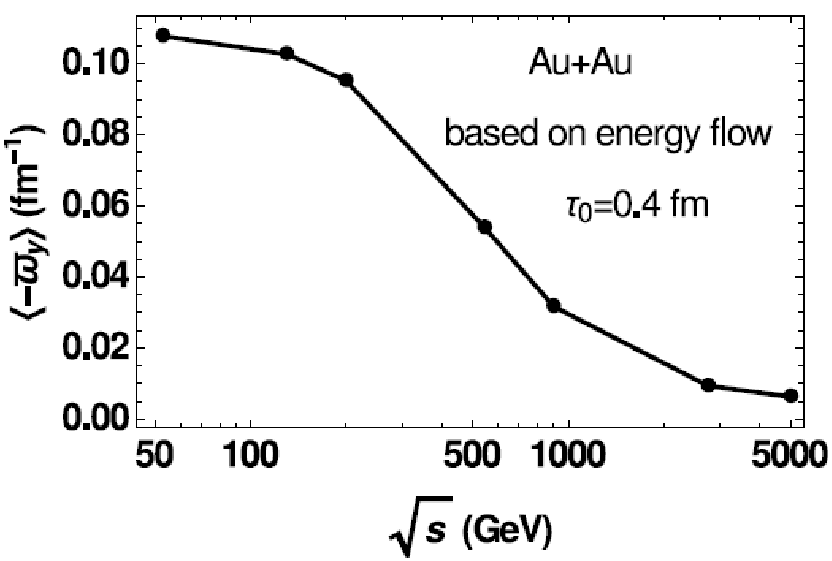
Present parton kinetic models
- HIJING, AMPT, PATHIA

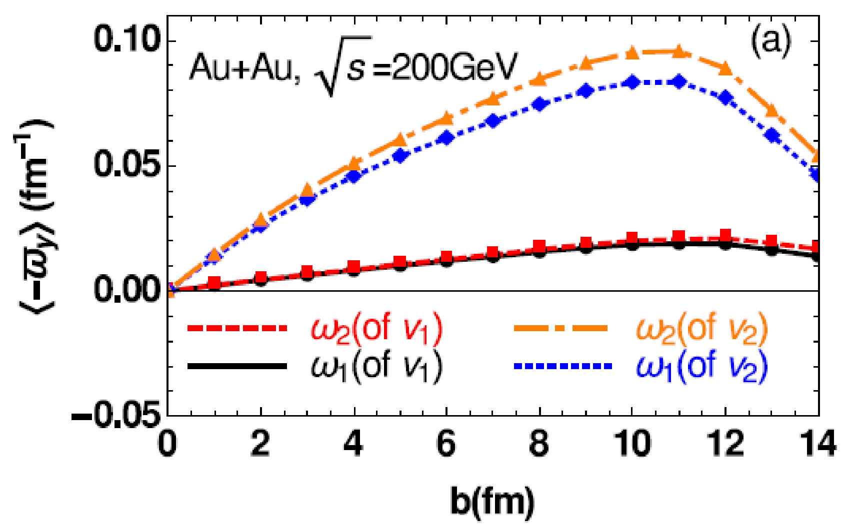


Max ω_y is at x=0 !!!

Different space-time configurations

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

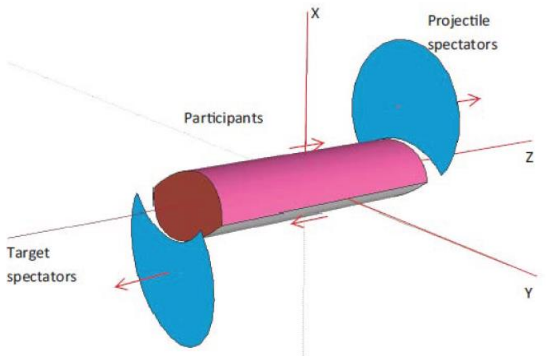




ε flow

ρ flow

Consequences – vorticity (2013):



- 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:

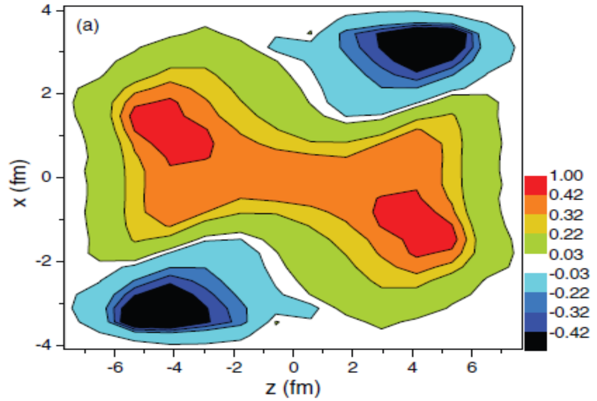


Fig. 3 The vorticity calculated in the reaction (xz) plane at t = 0.17 fm/c after the start of fluid dynamical evolution.

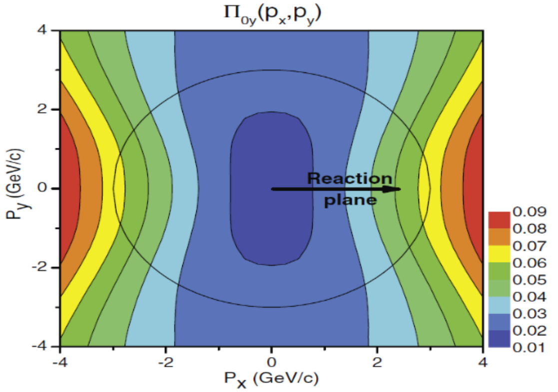


Fig. 4. The dominant y component of the observable polarization, $\boldsymbol{\Pi_0(p)}$ in the Λ's rest frame.

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

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)**]

Y. L. Xie,[1] M. Bleicher,[2,3] H. Stöcker,[2,3] D. J. Wang,[4] and L. P. Csernai[1]

Λ polarization in peripheral collisions at moderately relativistic energies

Consequences:

PHYSICAL REVIEW C 94, 054907 (2016)

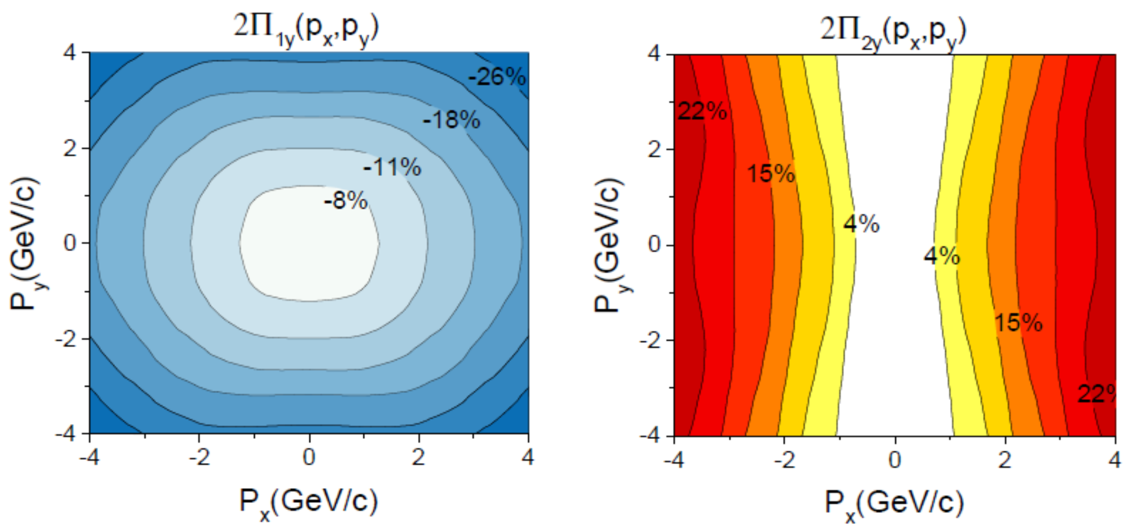


Fig. 6 The first (left) and second (right) term of the dominant y component of the Λ polarization for momentum vectors in the transverse plane at $p_z = 0$,for the FAIR U+U reaction at 8.0 GeV

- 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. !

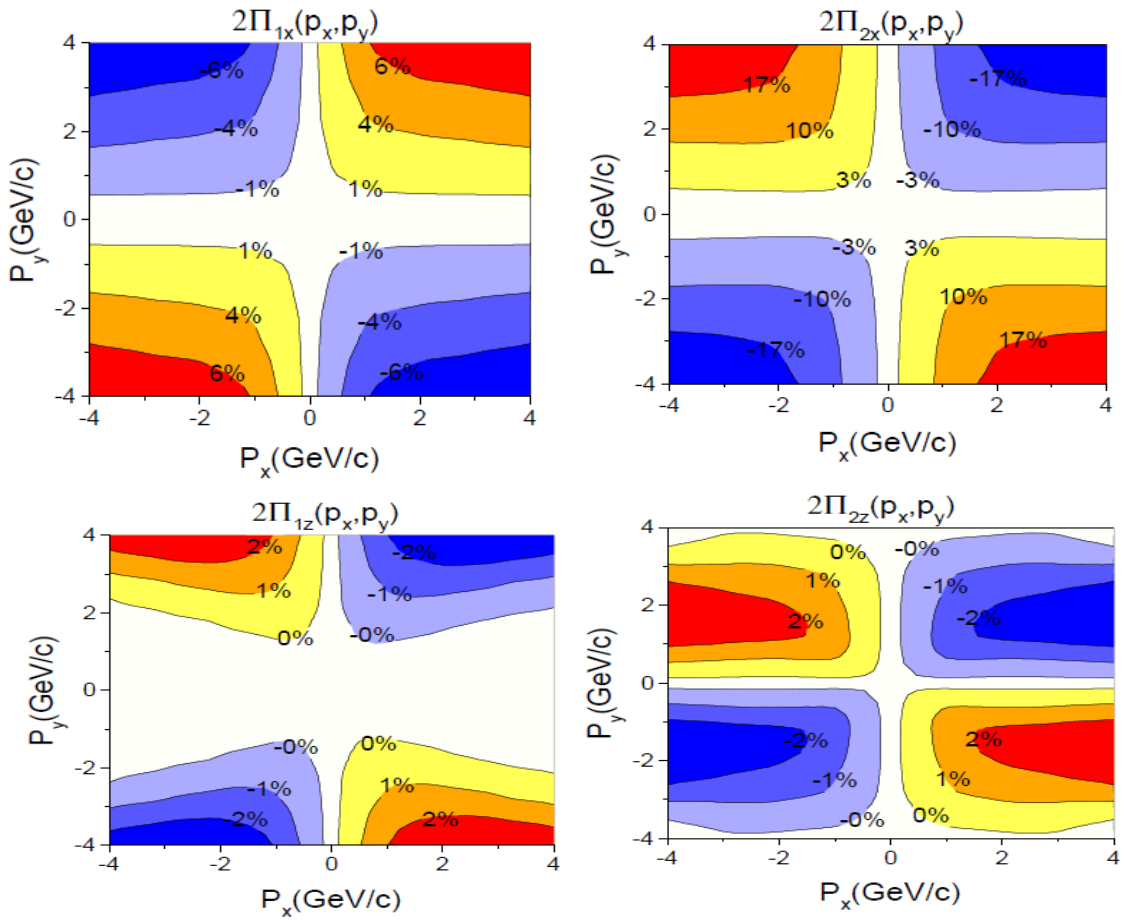
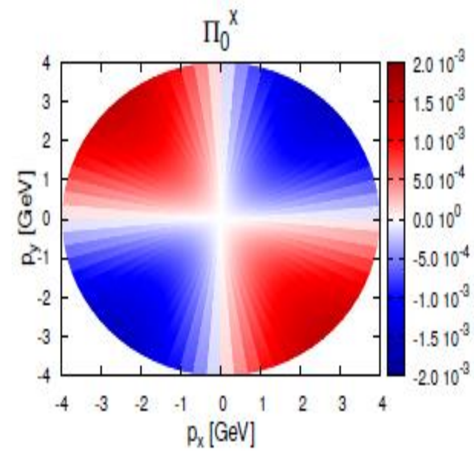


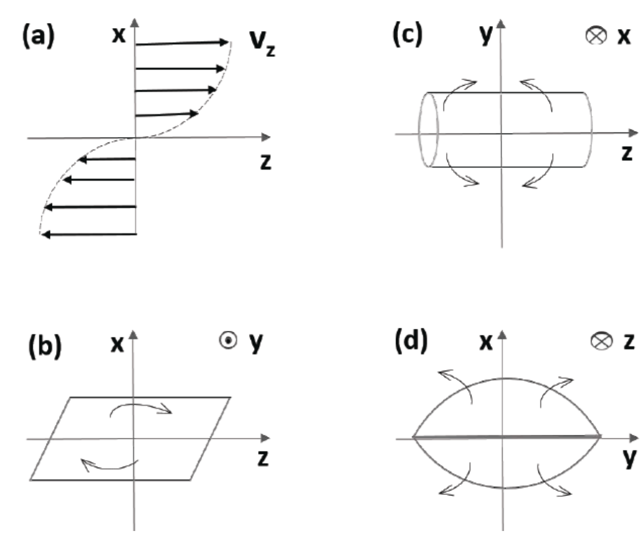
Fig. 7 The first (left) and second (right) terms of the x(up) and y(down) components of the Λ polarization for momentum vectors in the transverse plane at pz = 0,for the FAIR U+U reaction at 8.0 GeV

[Xie, Bleicher, Stoecker, Wang, Csernai, PRC **94**, 054907 (**2016**).]



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

1. Anti-symmetry



At the highest energies / Rel. Hydro.

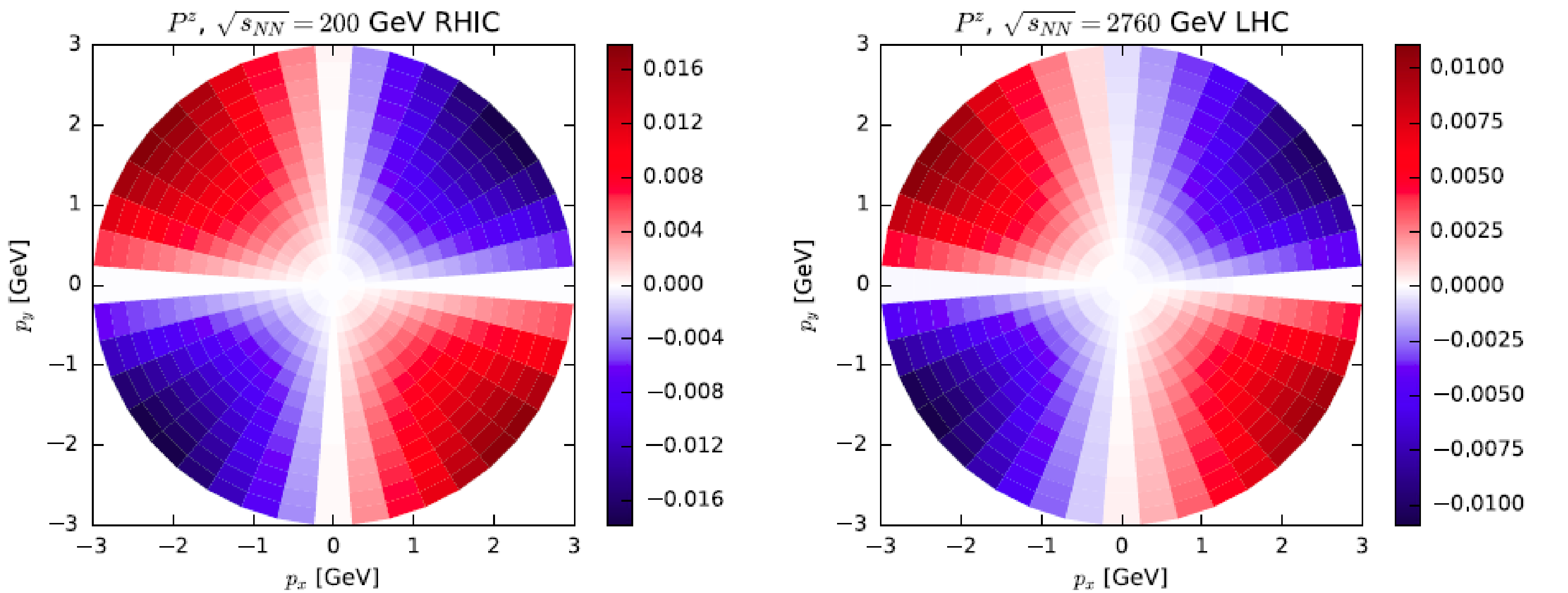
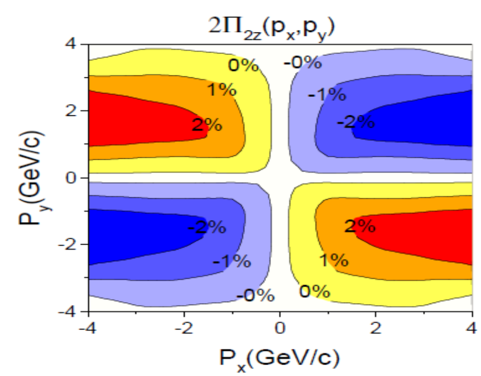


FIG. 2. Map of longitudinal component of polarization of midrapidity Λ from a hydrodynamic calculation corresponding to 20%–50% central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV (left) and 20%–50% central Pb-Pb collisions at $\sqrt{s_{NN}} = 2760$ GeV (right).

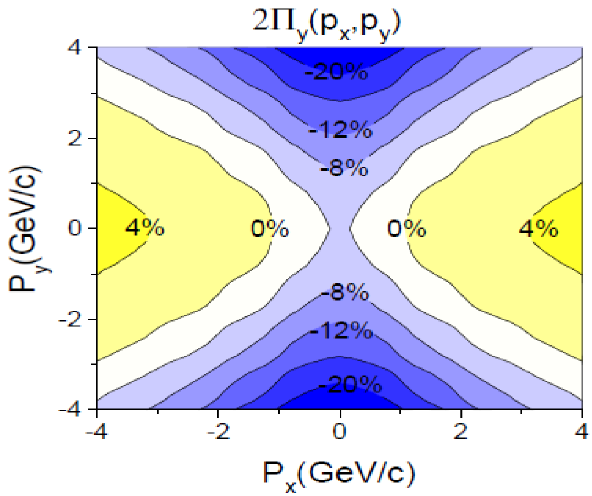
F. Becattini and Iu. Karpenko

PHYSICAL REVIEW LETTERS **120,** 012302 (2018)

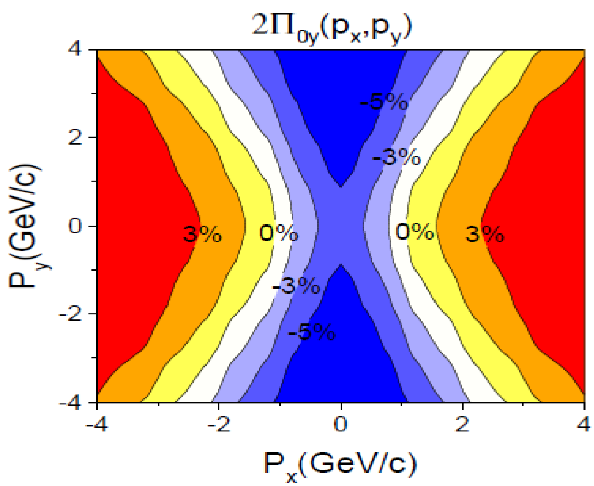


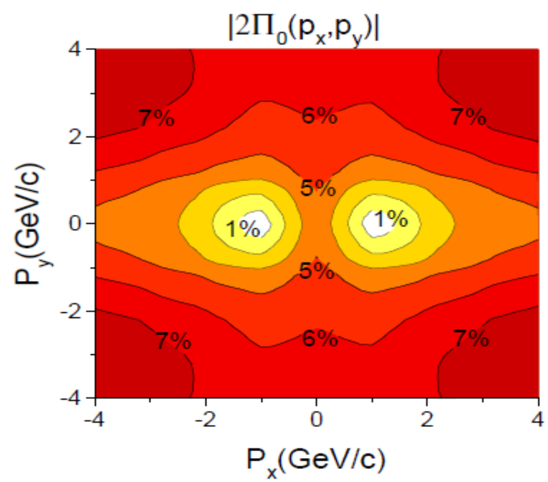
[Xie et al., PRC **94**, 054907 (**2016**)]

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.





[Xie et al., PRC **94**, 054907 (**2016**)]

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.

Consequences NICA

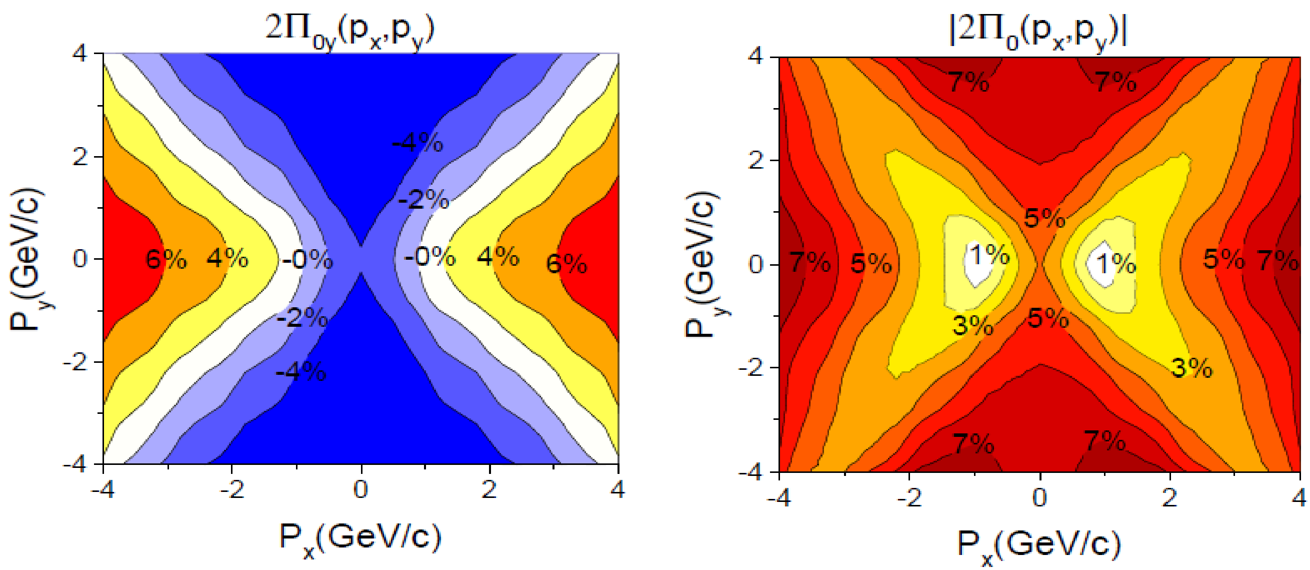
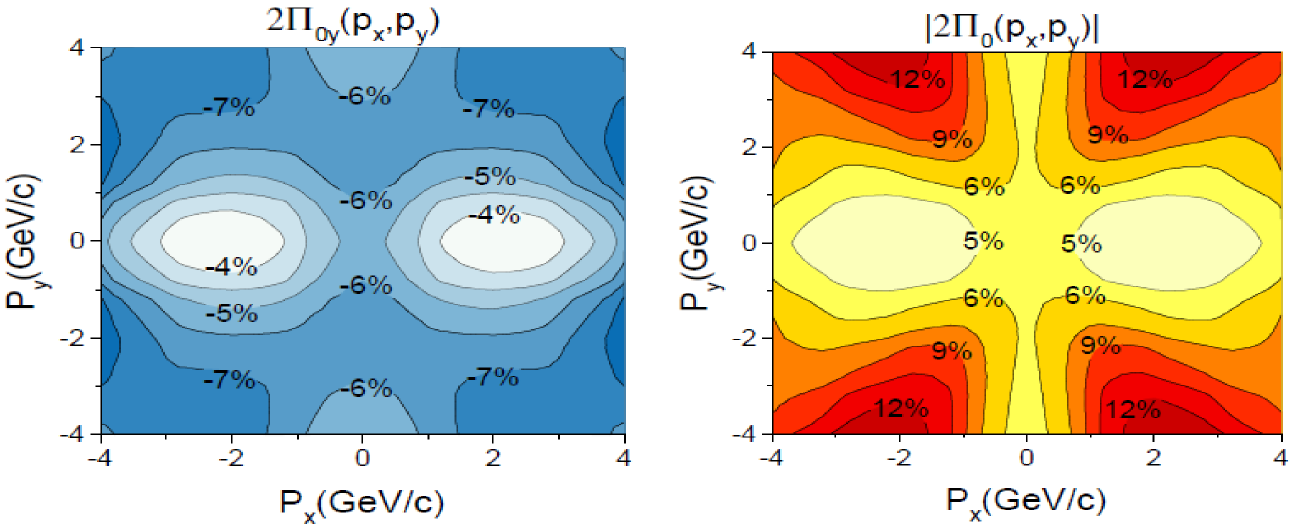


Fig. 9 The y component (left) and the modulus (right) of the polarization for momentum vectors in the transverse plane at pz = 0, for the NICA Au+Au reaction at 9.3 GeV. The figure is in the Λ's rest frame.

[Xie et al., PRC **94**, 054907 (**2016**)]

- 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.

Consequences FAIR



[Xie et al., PRC **94**, 054907 (**2016**)]

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.

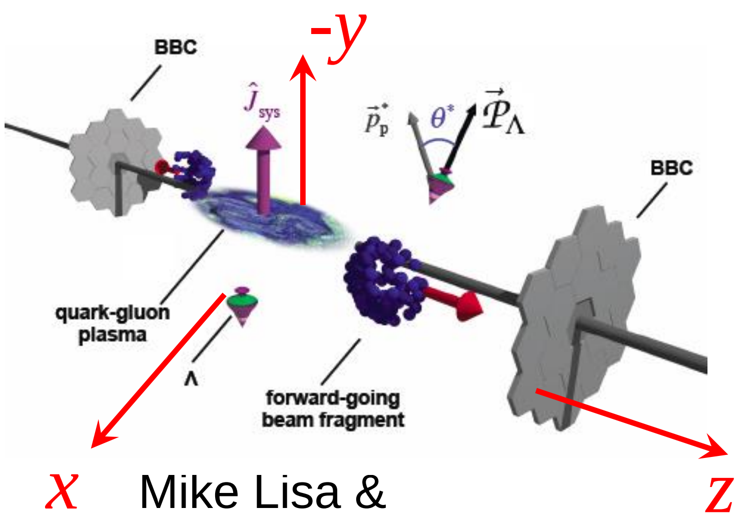
- Initially, the first term is very dominant

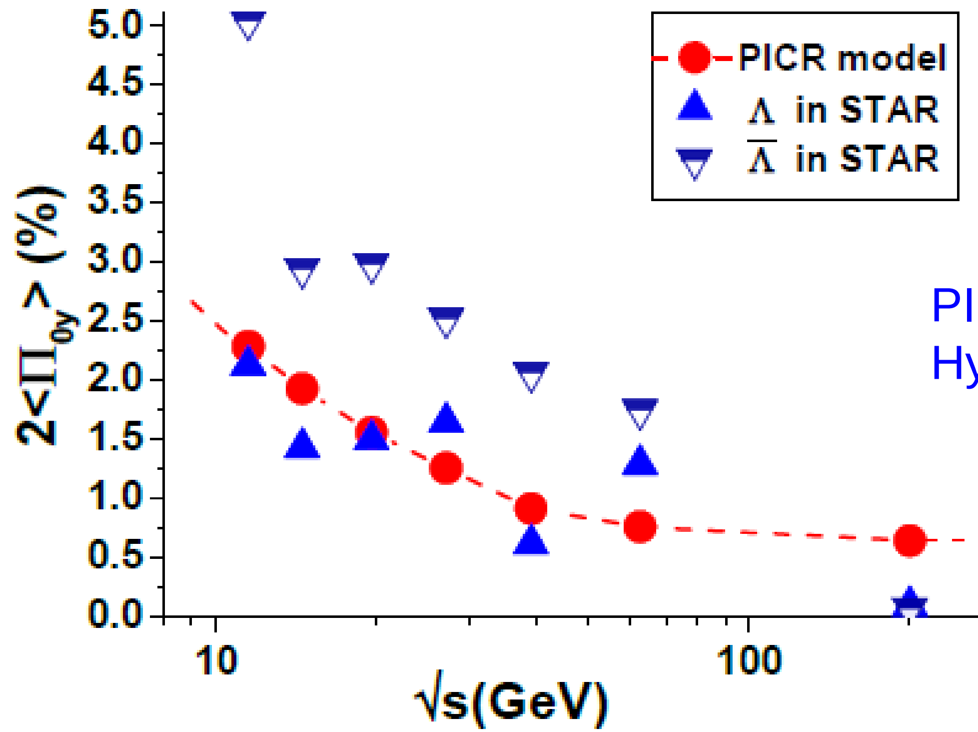
Polarization and EbE c.m. determination

- Earlier EbE c.m. determination ➔ increased V_1 by a factor of 2 [Cs.,E.,M., (2012)].
- Now polarization in x and z directions is symmetric in EbE c.m. frame!!!
- ➔ integrated x & z polarizations vanish (except random fluct.)
- ➔ finding EbE c.m. is possible by
  - Minimizing integrated Π_x & Π_z
  - Maximizing integrated $-\Pi_y$

Observable consequences

[Yilong Xie, Dujuan Wang, and Laszlo P. Csernai[1]
PHYSICAL REVIEW C **95**, 031901(R) (2017)]





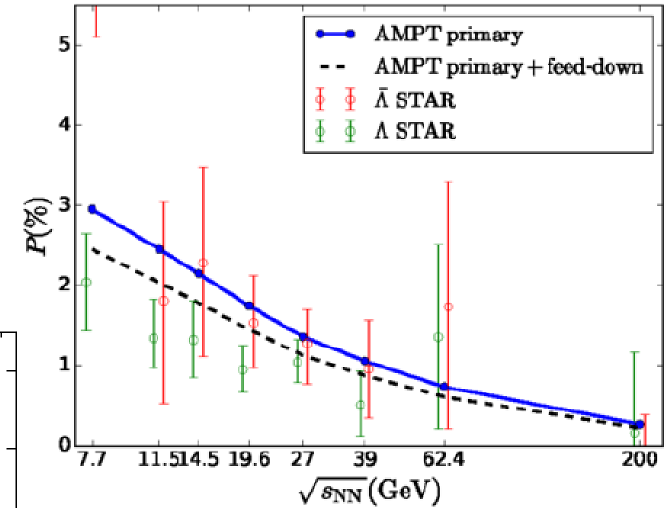
PICR
Hydro

Mike Lisa & STAR:
Angular mom.→
Vorticity (**rot** v)→
Λ & anti- Λ polarization

[Xie et al., PRC 94, 054907 (2016).]

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.

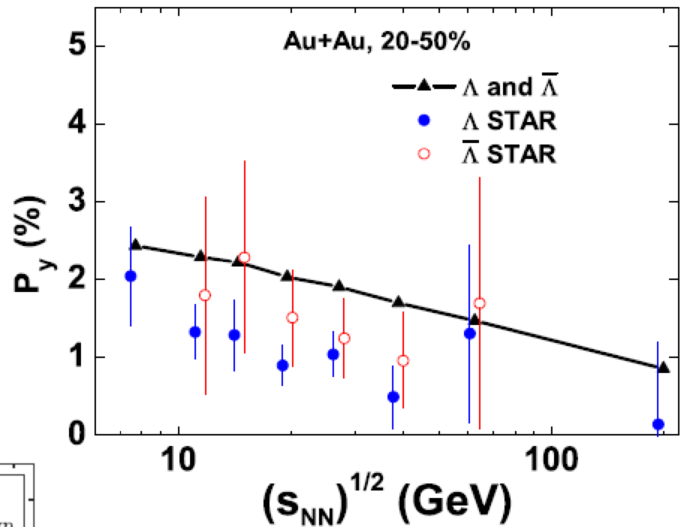
Λ & Anti-Λ Polarization



[Li, Petersen, et al., NPA 967 (2017) 772.]

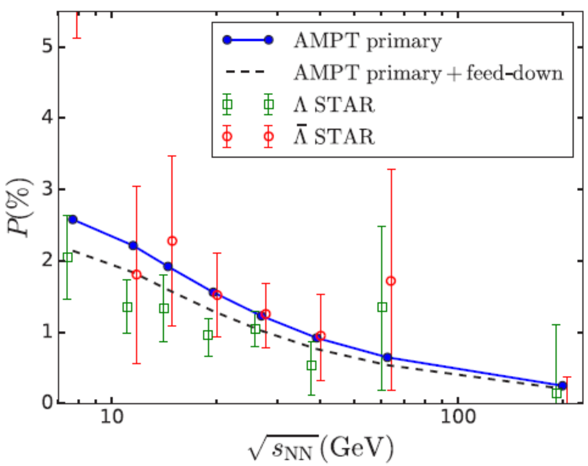
AMPT

AMPT



[Sun & Ko, PRC 96, 024906 (2017).]

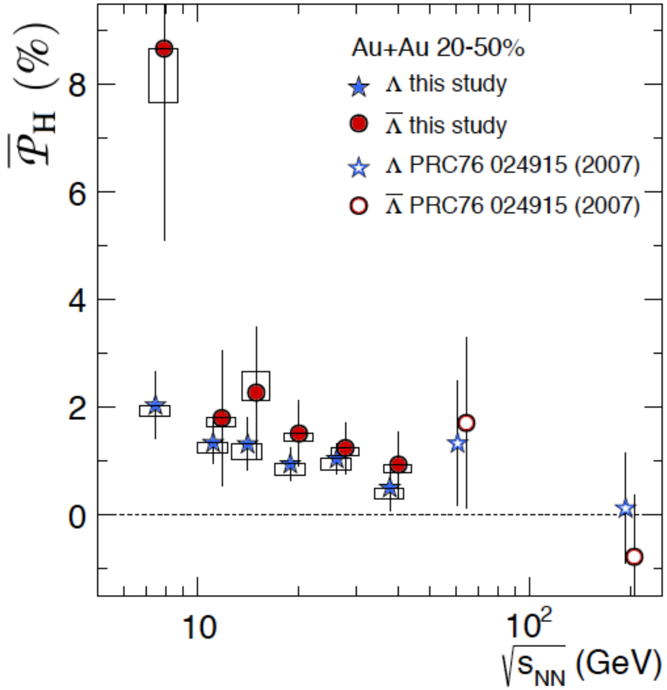
AMPT



[Li, Pang et al., PRC 96, 054908 (2017).]

Global Λ Polarization

$\Lambda \to p\pi$



[Global Λ hyperon polarization in nuclear collisions, STAR Collaboration Nature Letters -548, 62 (2017).]

- Positive Λ signal → positive vorticity
- **First time non-zero signal observed!**
- $\bar{\Lambda}$ > Λ (?) → magnetic coupling
- First measurement on ϕ meson spin alignment

arXiv:1701.06657

Λ & Anti-Λ Coupling to Nucleons

Difference based on Hypernuclei:
1.0 – 1.5 MeV i.e. ~ 20% of nuclear binding energy !!!

∃ ~ 20 Λ-hypernuclei ($T_{1/2} = 10^{-10}$s) 1953-1995

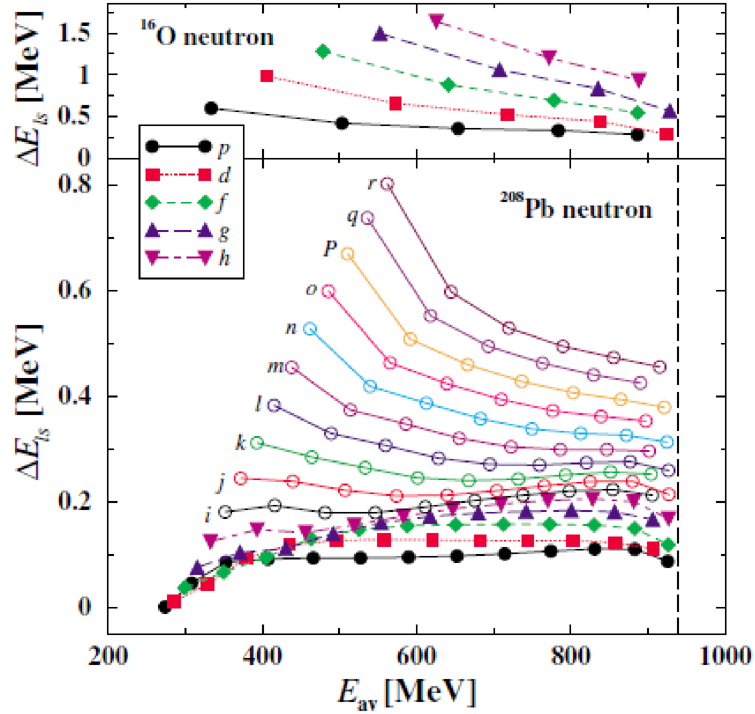


FIG. 2 (color online). Spin-orbit splitting $\epsilon_A(nl_{l-1/2}) - \epsilon_A(nl_{l+1/2})$ in antineutron spectra of ^{16}O and ^{208}Pb versus the average energy of a pair of spin doublets. The vertical dashed line shows the continuum limit.

[ZhouSG-etal-PhysRevLett.91(2003)262501]

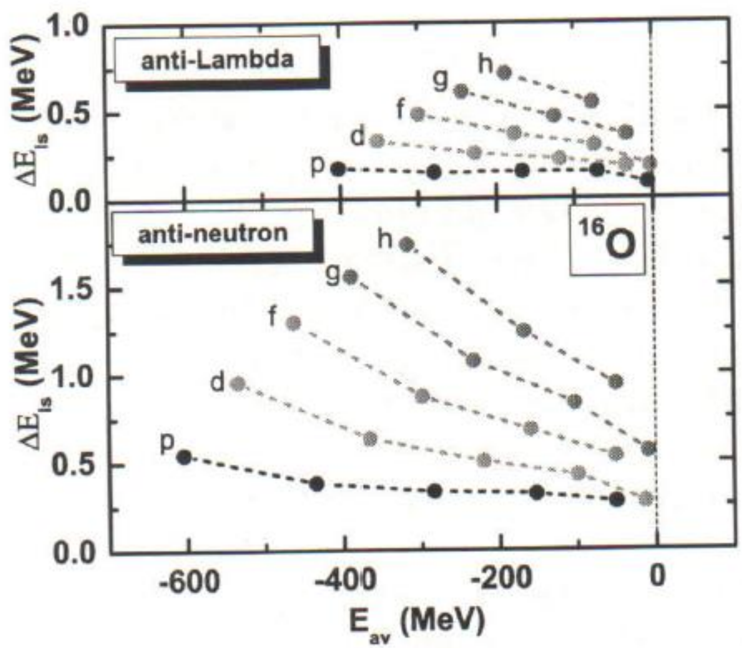


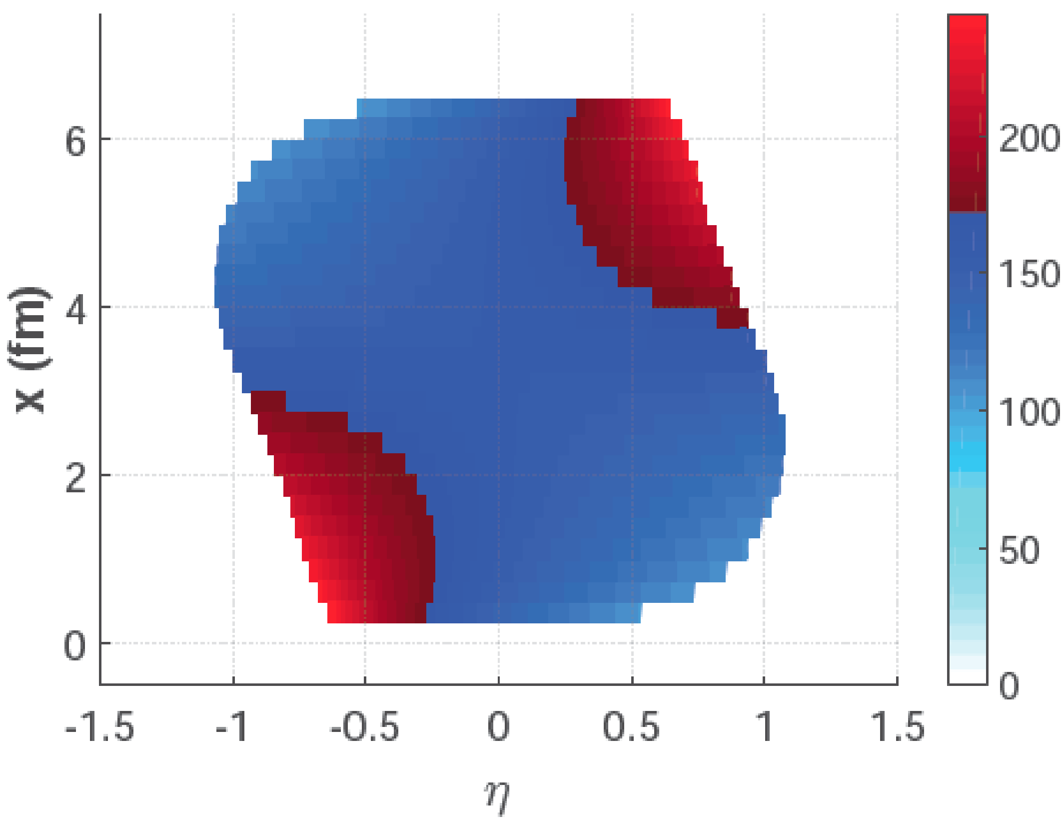
Fig. 2. Spin-orbit splitting $\epsilon_A(nl_{l-1/2}) - \epsilon_A(nl_{l+1/2})$ in the spectra of anti-Lambda and anti-neutron in ^{16}O versus the average energy of a pair of spin doublets. The vertical dashed line shows the continuum limit.

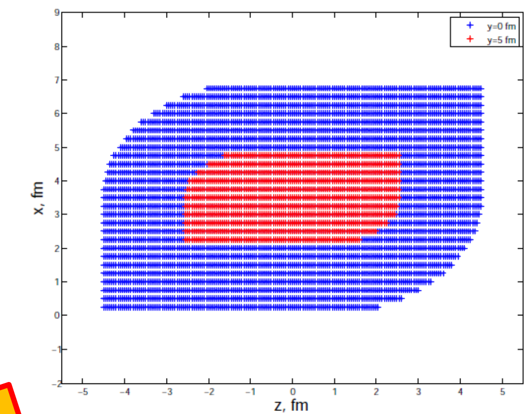
[SongCY-etal-IJMPE19(2010)2538]

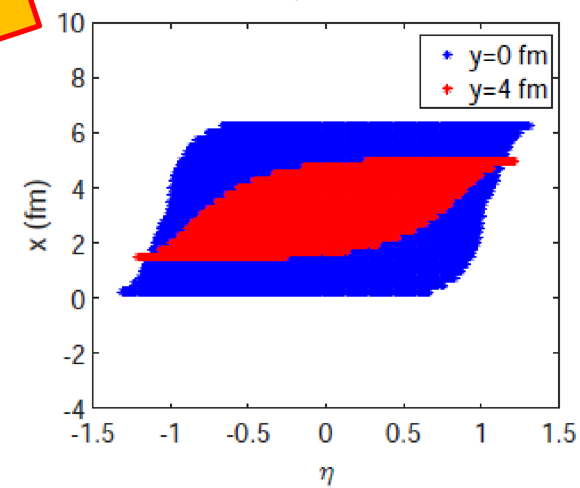
Initiative: new I.S. in τ, η coordinates → x,y,z,t

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

Energy density GeV/fm^3
propagated to the c.m. hyperbola

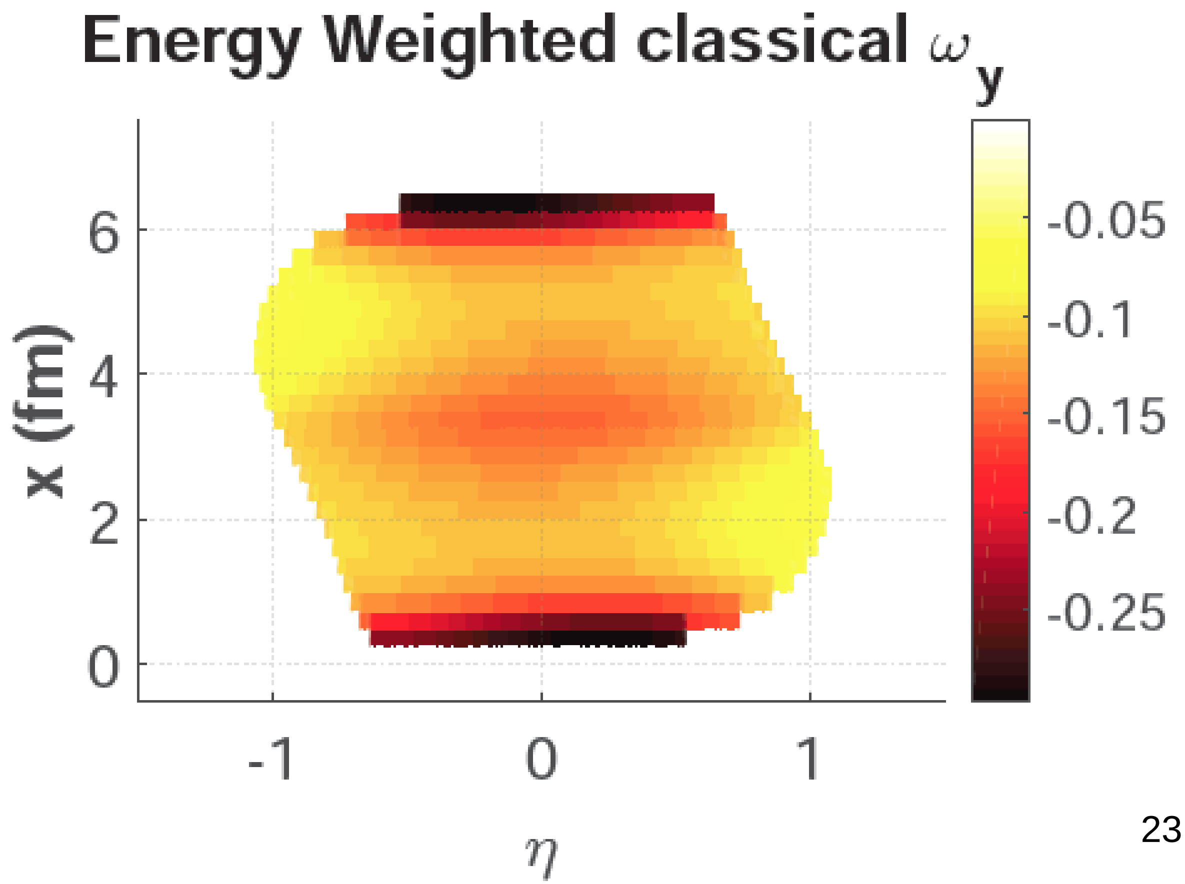






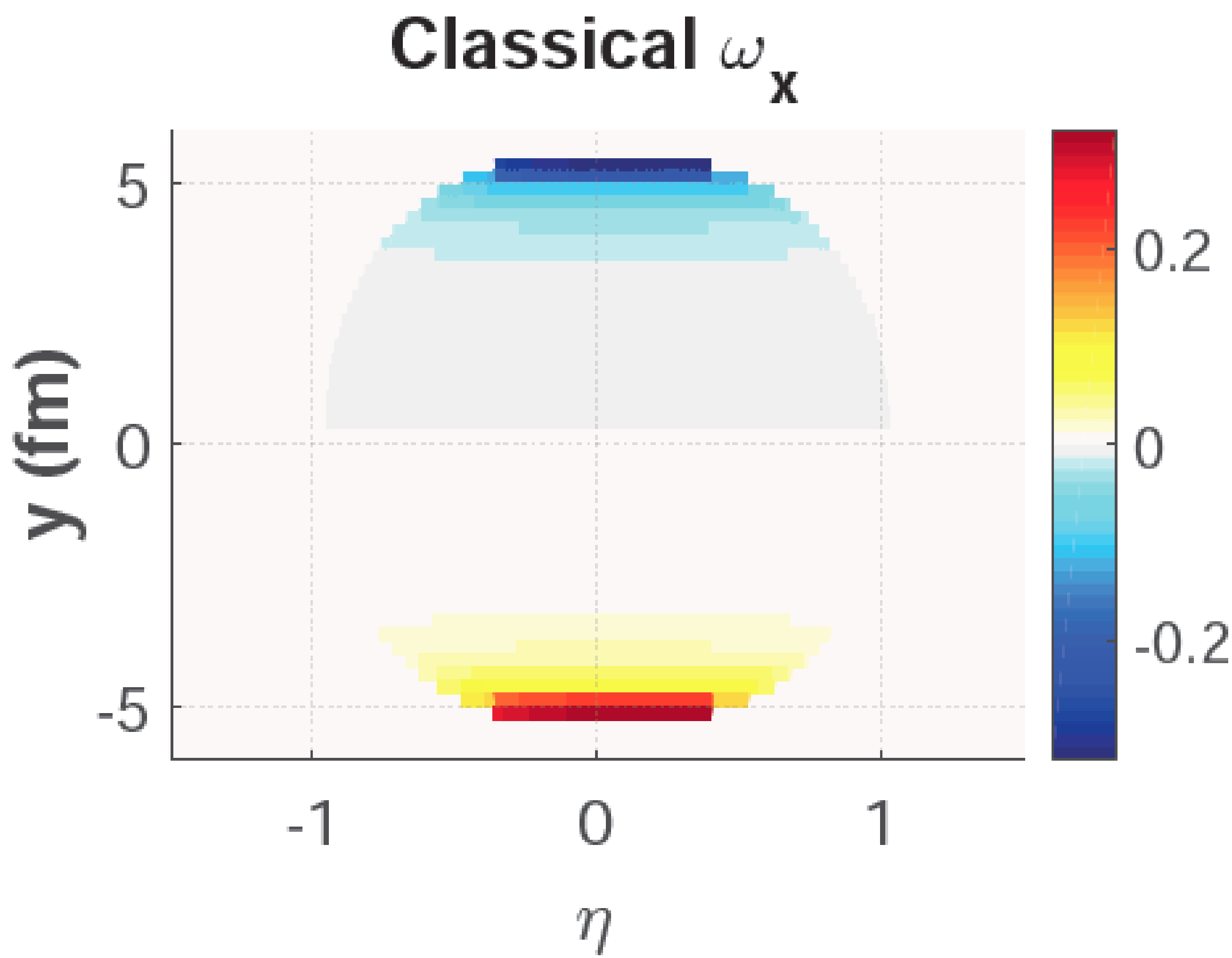
Consequences – vorticity (2017):

- Vorticity is max. at the edges, at high +/- X
- Consequence of the Bjorken type model
- Contradicts to AMPT and parton cascade results of [Wei-Tian Deng, and Xu-Guang Huang, arXiv: 1609.01801], where max. is at x=0.



Consequences – vorticity (2017):

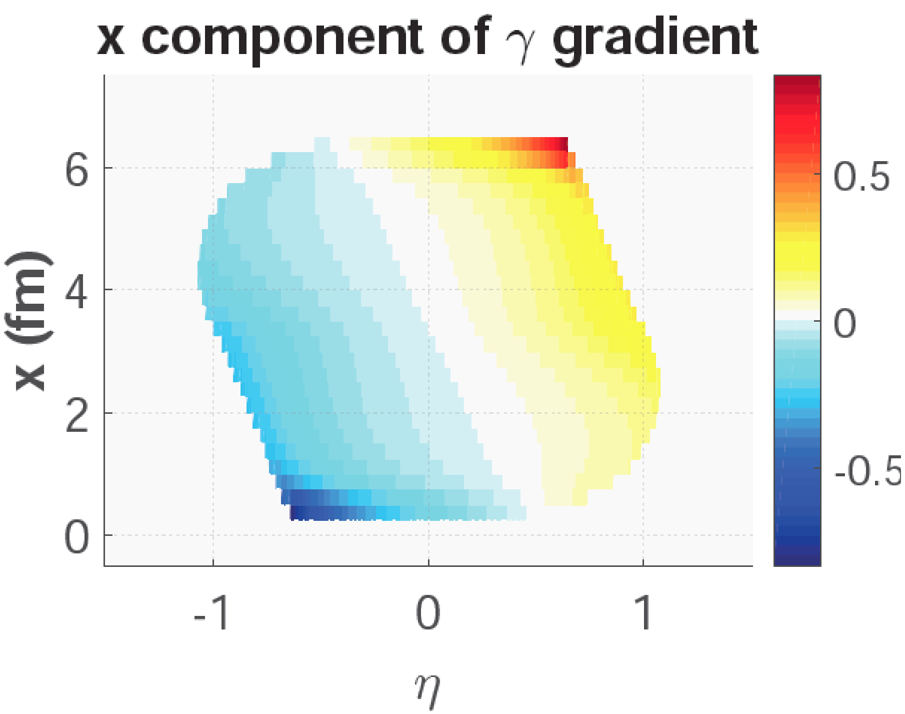
- Vorticity in x direction is max. at the edges, at high +/- y
- The two edges point to opposite directions, +/- x, i.e. cancel in total ω_x

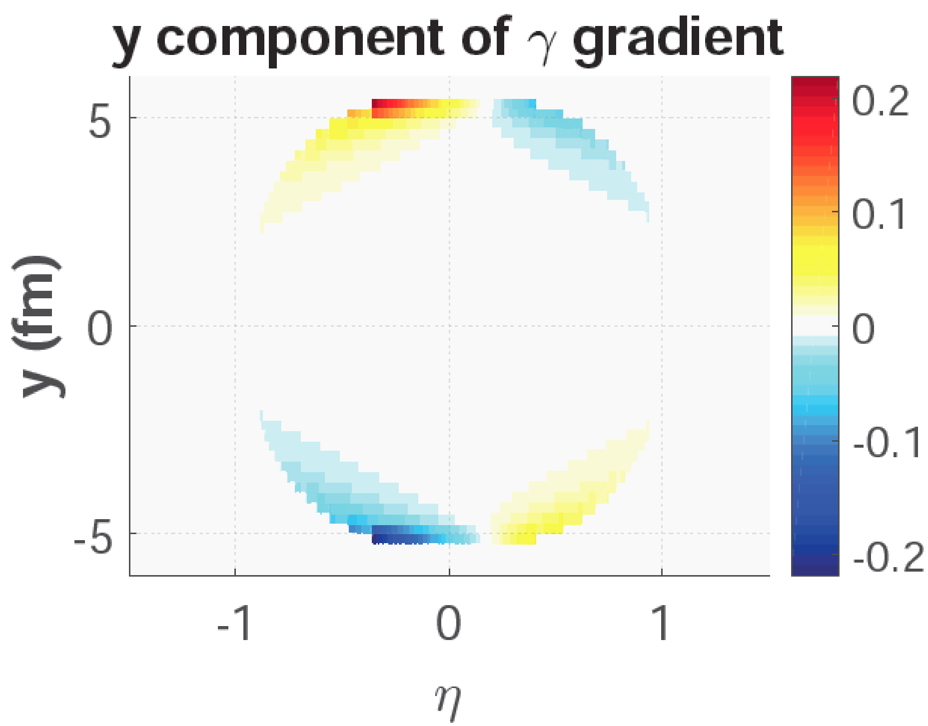


Relativistic corrections in the new I.S. :

The time derivative $\partial_t \boldsymbol{\beta}$ is not included in the I.S. but the gradient term,

$\nabla \beta^0$, has finite contribution (on τ =0 hypersurface):





New Initial State – 2017/8

- **z-directed vorticity**
- I.S. : v_x & v_y vanish everywhere, β_x & β_y *too*
- → **Initial** $\omega_z = 0$ → init. class. $\Pi_z = 0$.
- (except surface effects)
- **y-directed vorticity**
- →Classical polarization, Π_y , is negative (-y directed),
- →Rel. polarization, Π_y , may have small negative domains
- **x-directed vorticity**
- Integrated $\omega_x = 0$, → integrated class. Π_x vanishes, p-dependence is symmetric.

Summary

- Collective flow is the most dominant collective feature of HI reactions.
- Peripheral reactions show shear, vorticity (turbulence) for small transport coefficients ➔ exp. Λ-Polarization
- I.S. is of utmost importance, it 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.

- ➔ **Λ-Polarization is highly sensitive diagnostic tool**

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