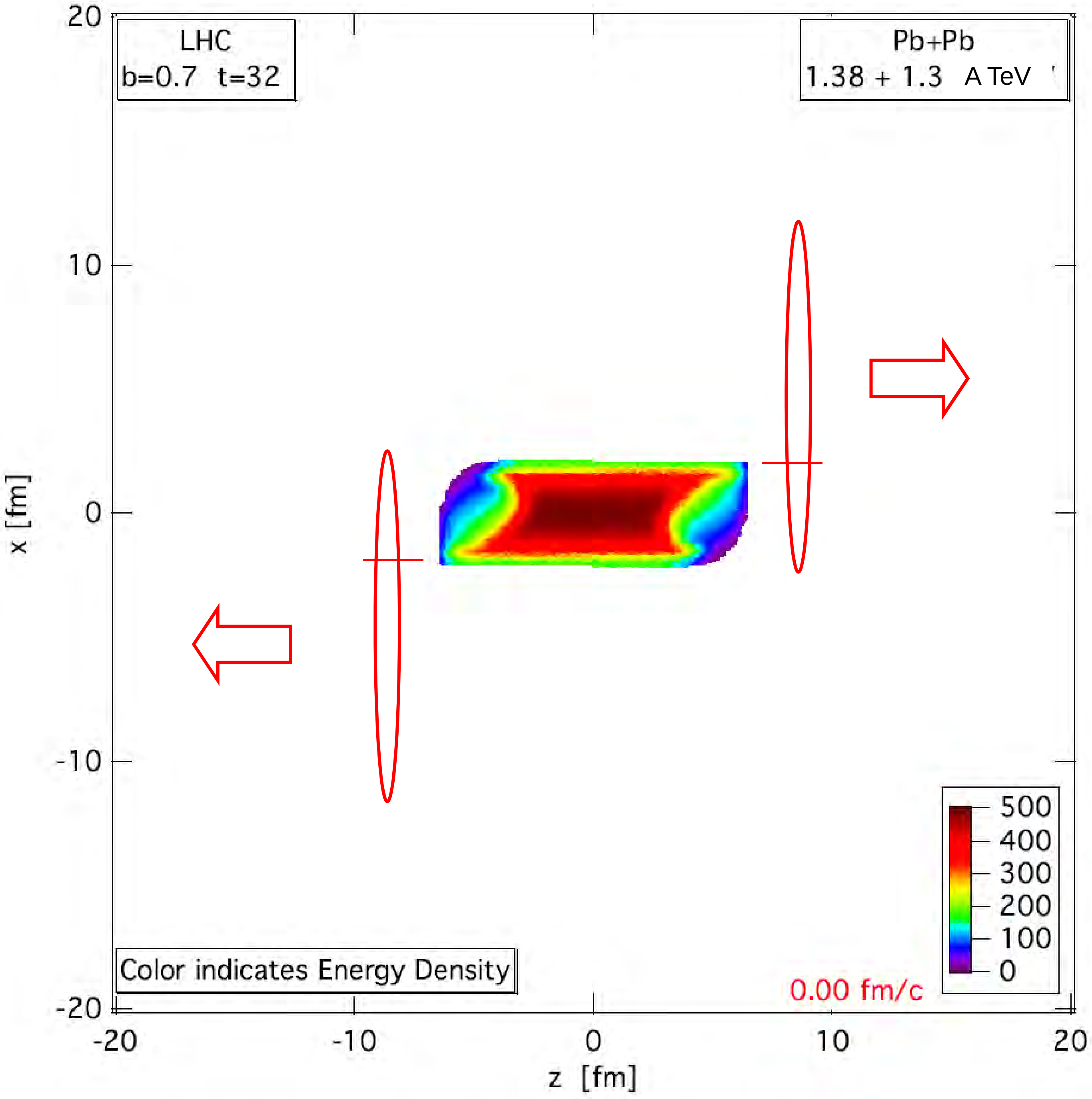
Observable signs of Rotation and Turbulence in Heavy Ion Reactions

15. Zimányi WINTER SCHOOL ON HEAVY ION PHYSICS, Dec 7-11, 2015 Budapest, Hungary

L.P. Csernai & Y.-L. Xie
University of Bergen

- Recent works with:

Dujuan Wang, Yun Cheng, Yuliang Yan, Benhao Sa, Cai Xu, Daimei Zhou, Sindre Velle, Jonas Inderhaug, Horst Stöcker, Marcus Bleicher, and Francesco Becattini



PICR-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.

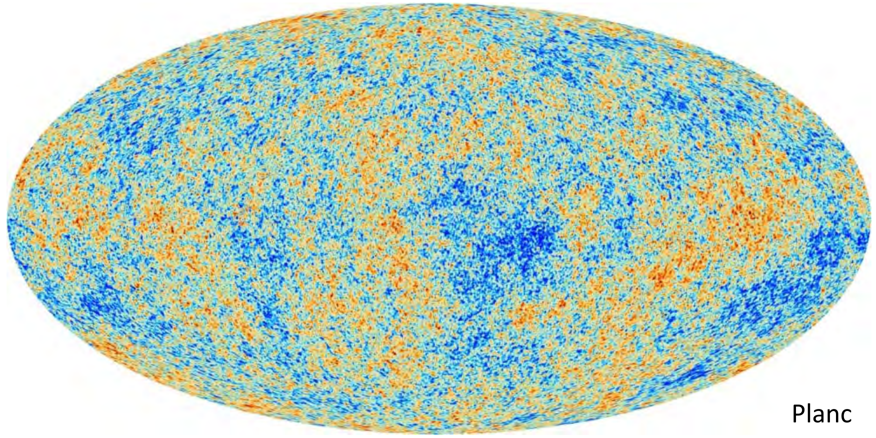
Structure and asymmetries of init. state are maintained in nearly perfect expansion.

..\zz-Movies\LHC-Ec-1h-b7-A.mov

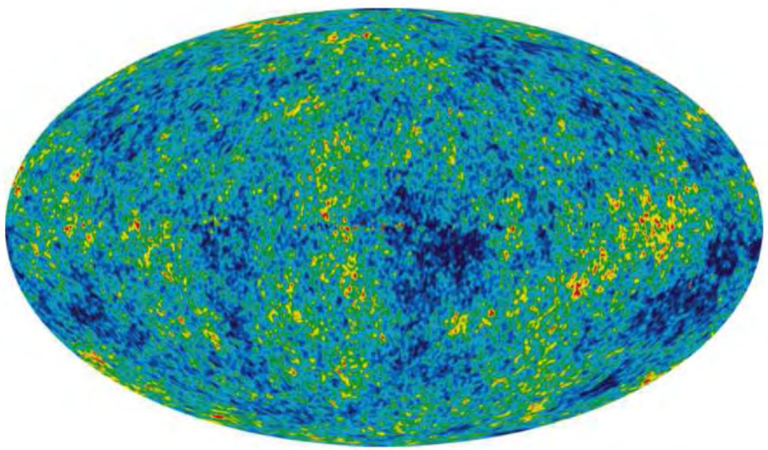
Quark – Gluon Plasma

- →
- low viscosity → strong fluctuations
- Low viscosity → dynamical instabilities

Fluctuations and polarization



Planc



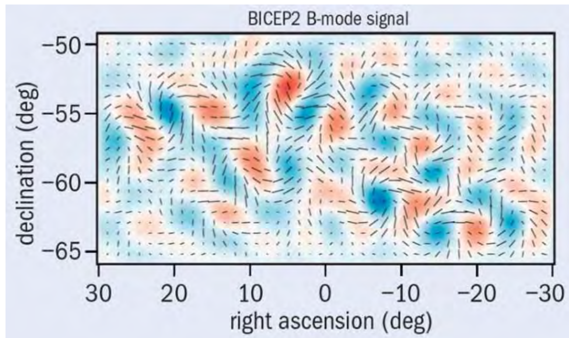
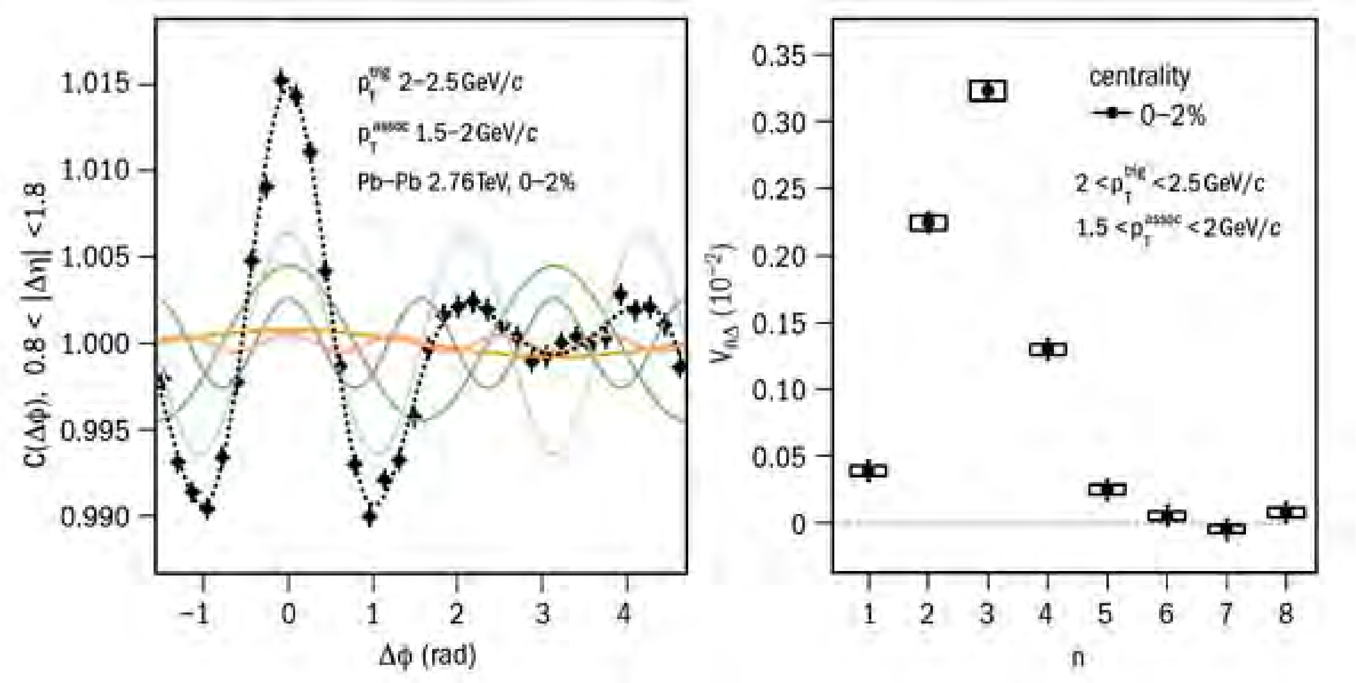


Figure 32: The CMB radiation temperature fluctuations from the 5-year WMAP data seen over the full sky. The average temperature is 2.725K, and the colors represents small temperature fluctuations. Red regions are warmer, and blue colder by about 0.0002 K.

CERN COURIER

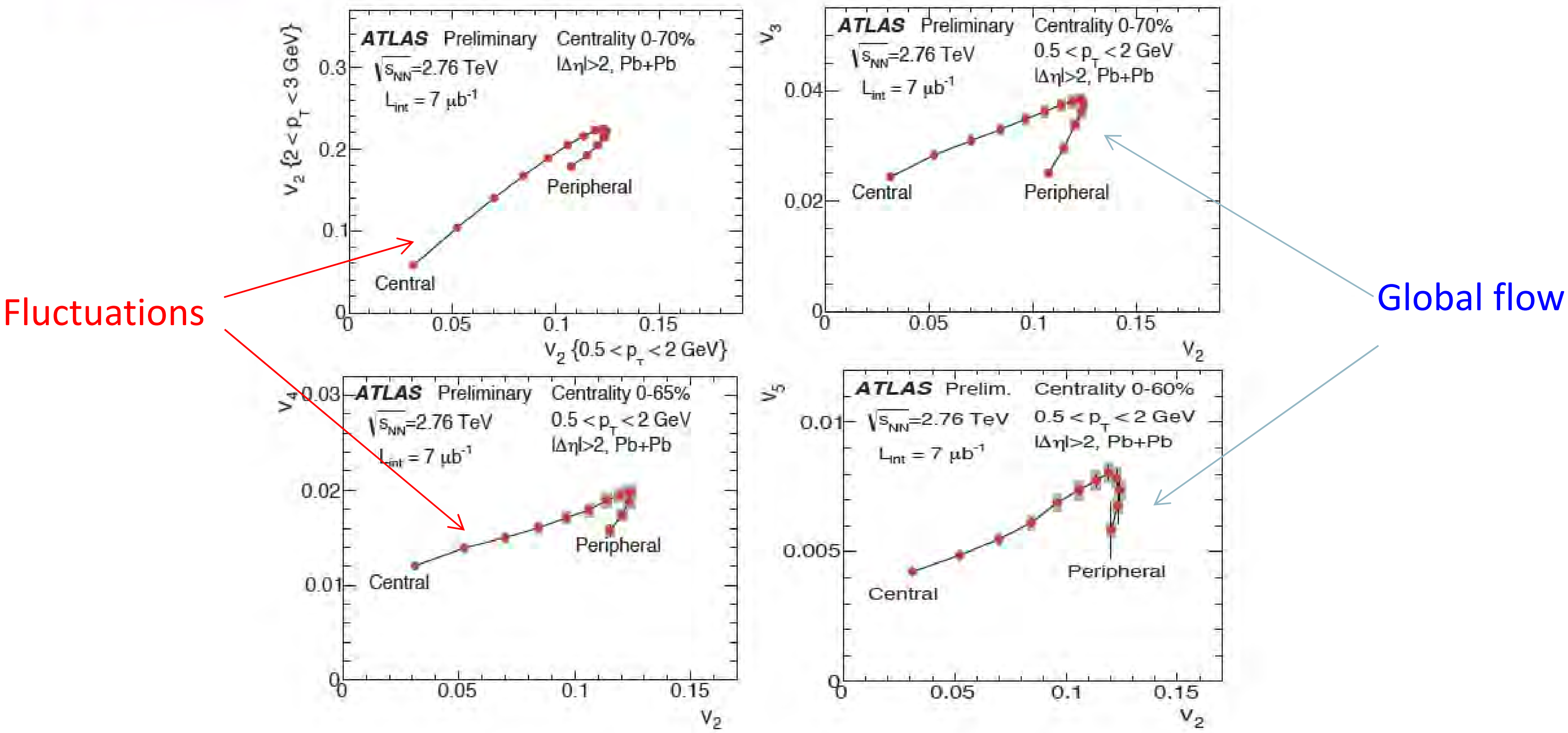
Sep 23, 2011

ALICE measures the shape of head-on lead-lead collisions



Flow originating from initial state fluctuations is significant and dominant in central and semi-central collisions (where from global symmetry no azimuthal asymmetry could occur, all Collective $v_n = 0$) !

Event-shape engineering



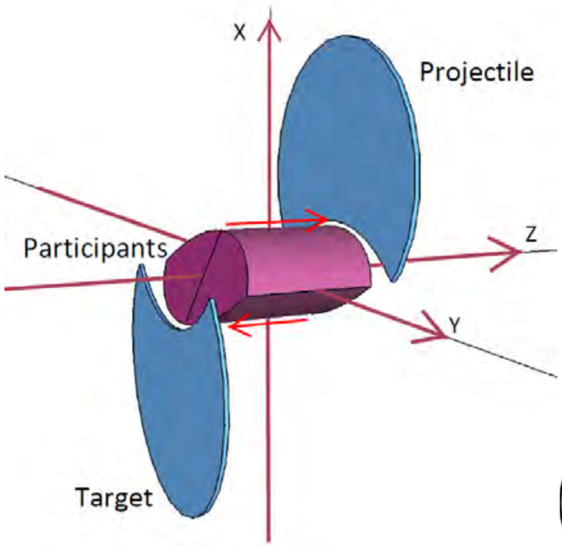
Correlation between flow coefficients:

- Non monotonic variation

ATLAS-CONF-2014-022

Two types of flow processes from: Fluctuations and/or Global Collective Flow

- How to split these two:
- In theoretical models
  - Mode-by-mode hydrodynamics, [S. Floerchinger, U.A. Wiedemann, Phys. Rev. C 88, 044906 **(2013),** Phys. Rev. C 89, 034914 (2014), Phys. Lett. B 728, 407 (2014)]
- In experiments it is more involved
  - Average many events
  - But keeping the symmetries



Method to compensate for C.M. rapidity fluctuations

1. Determining experimentally EbE the C.M. rapidity
2. Shifting each event to its own C.M. and evaluate flow-harmonics there

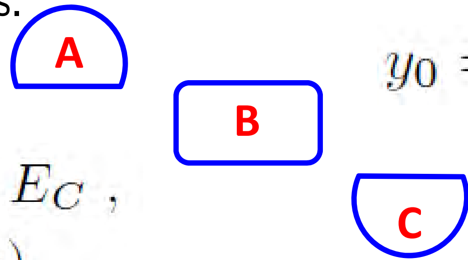
L.P. Csernai[1,2], G. Eyyubova[3] and V.K. Magas[4]

PHYSICAL REVIEW C 86, 024912 (2012)

Determining the C.M. rapidity:

The rapidity acceptance of a central TPC is usually constrained (e.g for ALICE $|\eta| < \eta_{lim} = 0.8$, and so: $|\eta_{C.M.}| \ll \eta_{lim}$, so it is not adequate for determining the C.M. rapidity of participants.

Participant rapidity from spectators



$$y_0 = 7.986$$

$$E_B = A_B\, m_{B\perp} \cosh(y^B) = E_{tot} - E_A - E_C \ ,$$
$$M_B = A_B\, m_{B\perp} \sinh(y^B) = -(M_A + M_C)$$

$$E_{tot} = 2 A_{Pb}\, m_N \cosh(y_0)$$

$$E_A = A_P\, m_N \cosh(y_0),$$
$$E_C = A_T\, m_N \cosh(-y_0),$$

give the spectator numbers, A_P and A_T, and

$$M_A = A_P\, m_N \sinh(y_0),$$
$$M_C = A_T\, m_N \sinh(-y_0),$$

$$y_E^{CM} \approx y^B = \text{artanh}\left(\frac{-(M_A + M_C)}{E_{tot} - E_A - E_C}\right)$$

[LP Csernai & H Stoecker J Phys G **41** 124001]

Azimuthal Flow analysis with Fluctuations today

In contrast to the above formulation

$$\frac{d^3N}{dy\,dp_t\,d\phi} = \frac{1}{2\pi}\frac{d^2N}{dy\,dp_t}\Big[1 + 2v_1(y,p_t)\cos(\phi - \Psi_1^{EP}) + 2v_2(y,p_t)\cos(2(\phi - \Psi_2^{EP})) + \cdots\Big],$$

Here Ψ_n^{EP} maximizes $v_n(y,p_t)$ in a rapidity range

Is this a complete ortho-normal series? Yes, if the Ψ_n^{EP} values are defined …..

We can see this by using: →

$$\cos(\alpha-\beta) = \cos\alpha\cos\beta + \sin\alpha\sin\beta,$$

[LP Csernai & H Stoecker J Phys G **41** 124001]

Azimuthal Flow analysis with Fluctuations today

Is this a complete ortho-norml series? Yes, if Ψ_n^{EP} values are defined …..

We can see this by $\cos(\alpha-\beta) = \cos\alpha\cos\beta + \sin\alpha\sin\beta,$ →

terms of the harmonic expansion

$$v_n \cos[n(\phi - \Psi_n^{EP})] = \underbrace{v_n \cos(n\Psi_n^{EP})}\ \cos(n\phi) + \underbrace{v_n \sin(n\Psi_n^{EP})}\ \sin(n\phi)$$

The angles Ψ_n^{EP} & ϕ should be measured with respect to the Reaction Plane (EbE)

$$v_{n\frac{even}{odd}}^{Coll.} \cos[n(\phi - \Psi_n^{EP})] = \frac{1}{2}\left[{}^c v_n(\mathbf{y}, p_t) \pm {}^c v_n(-\mathbf{y}, p_t)\right] \cos(n\phi)$$

$$v_{n\frac{even}{odd}}^{Fluct.} \cos[n(\phi - \Psi_n^{EP})] = \frac{1}{2}\left[{}^c v_n(\mathbf{y}, p_t) \mp {}^c v_n(-\mathbf{y}, p_t)\right] \cos(n\phi) + {}^s v_n(\mathbf{y}, p_t)\ \sin(n\phi)$$

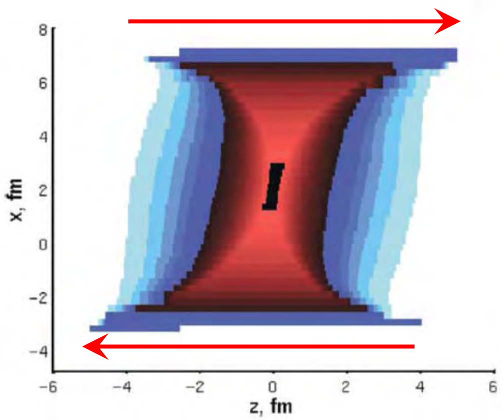
Separating Global Collective Flow & Fluctuations

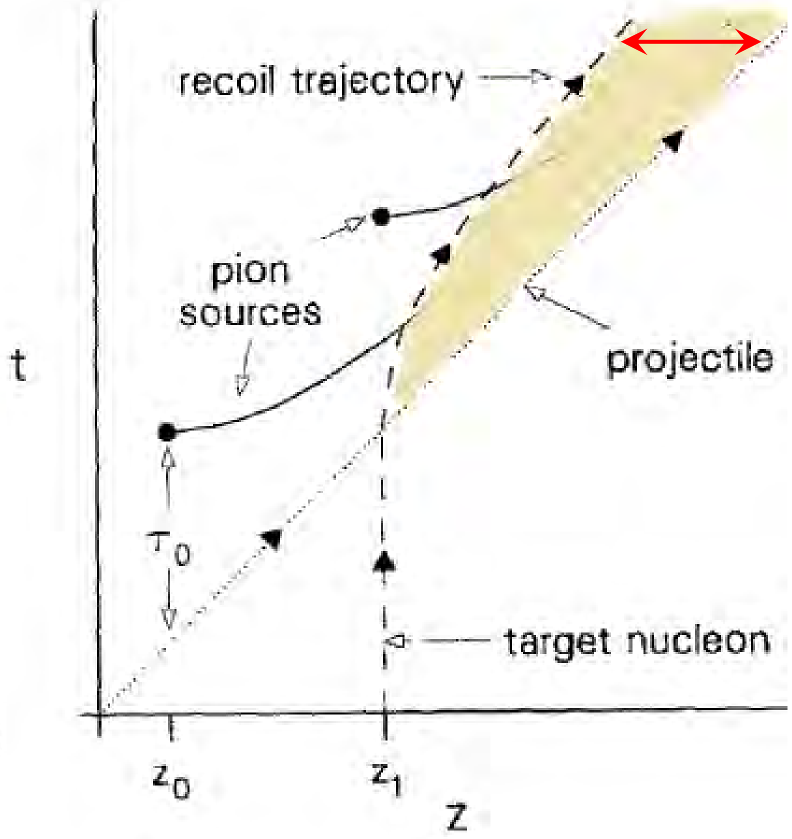
where $\mathbf{y} = y - y_{CM}$, and new coefficients

$${}^c v_n \equiv v_n \cos(n(\Psi_n^{EP})) \quad \text{and} \quad {}^s v_n \equiv v_n \sin(n(\Psi_n^{EP}))$$

Hot-Gluon Field → Compact IS, shear & vorticity

- [Gyulassy & Csernai, NPA460 (1986) 723]: Flux tube dominance →
- Flux tube, w/ large string tension →
- Longitudinal extension is limited:
- Energy & momentum conservation
- Shear flow, vorticity, rotation
- IS: 3-4 fm/c

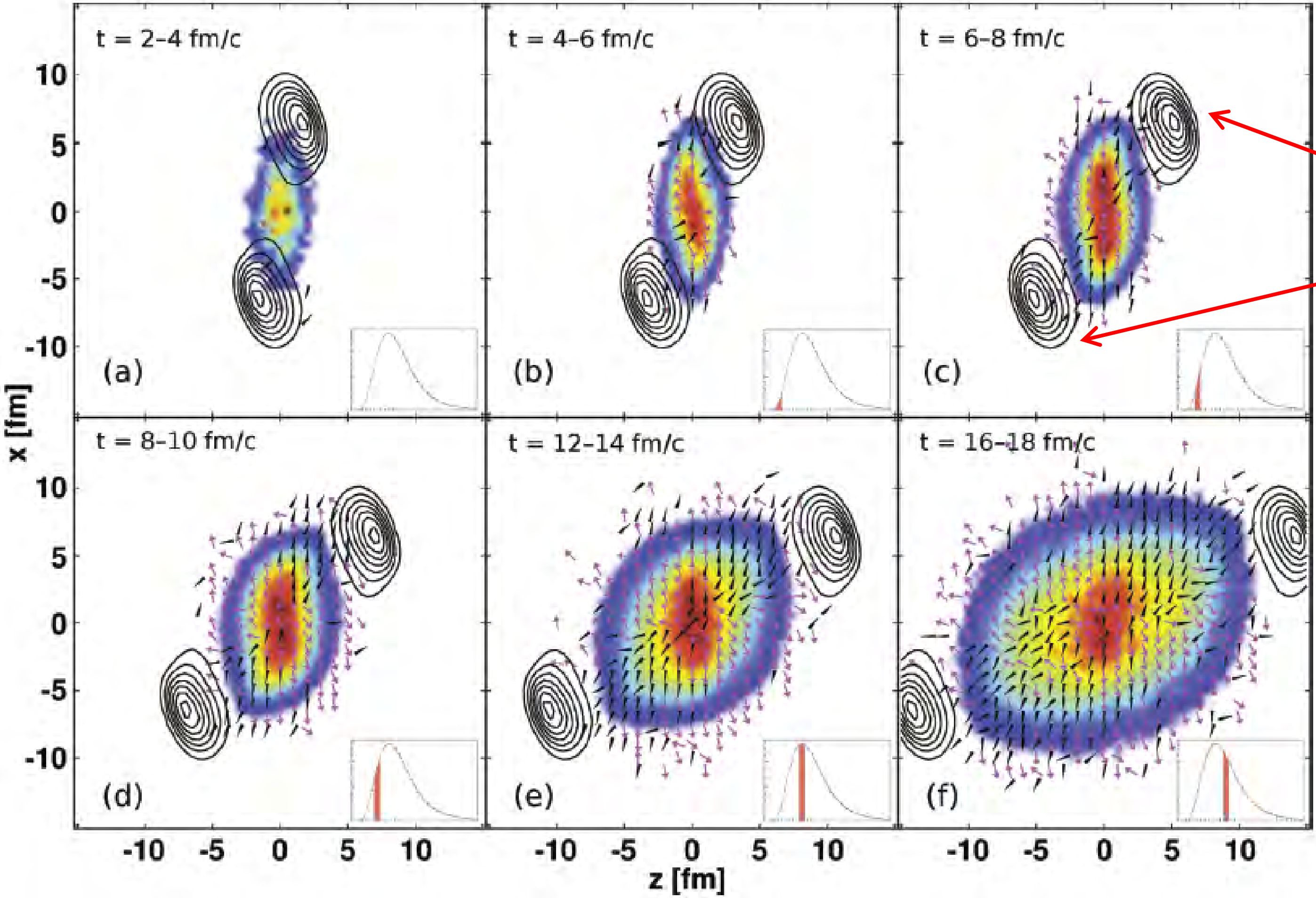




- [Magas et al., NPA 712 (2002)167]

Azimuthally sensitive Hanbury-Brown–Twiss correlations

[G. Graef, M. Bleicher, M. Lisa, Phys. Rev. C89, 014903 (2014).] UrQMD



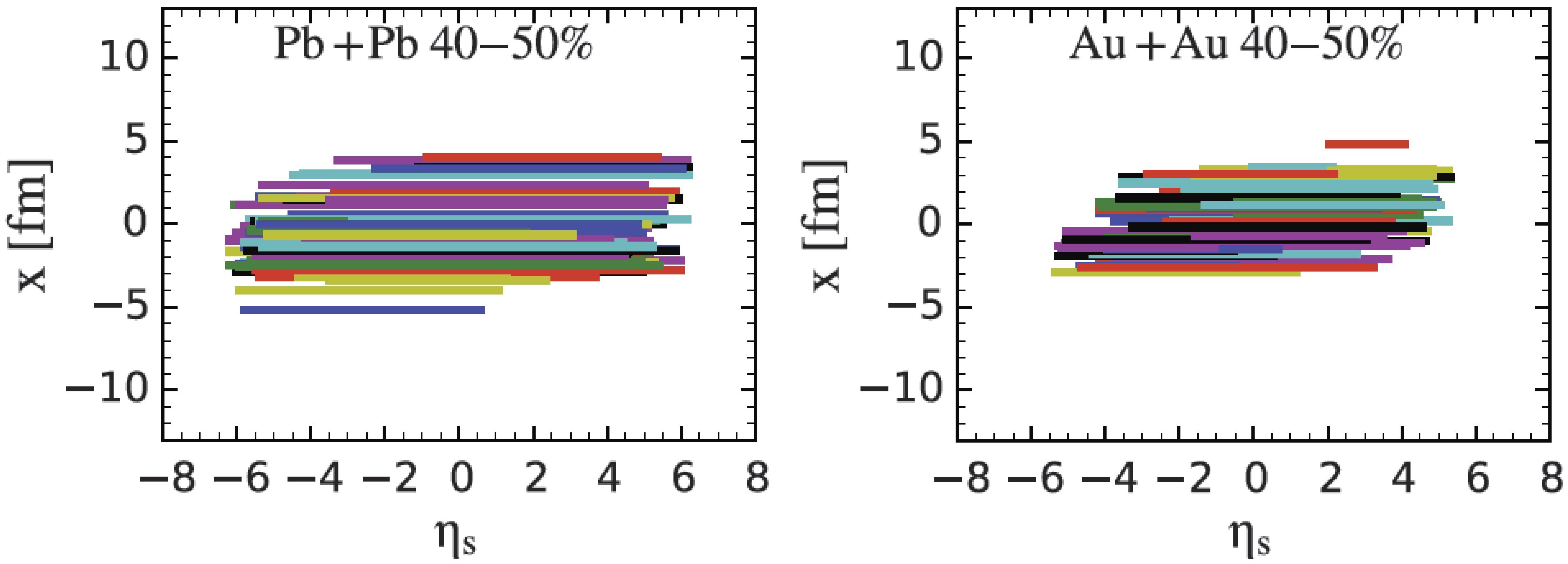
spectators

Rotation of the Initial State

$$\text{Pb} + \text{Pb at } E_{\text{lab}} = 8 \text{ GeV}, \ b = 3.4\text{–}6.8 \text{ fm},$$

Decorrelation of anisotropic flow along the longitudinal direction

[Long-Gang Pang et al., FIAS, Quark Matter 2015, Kobe, Japan]   HIJING



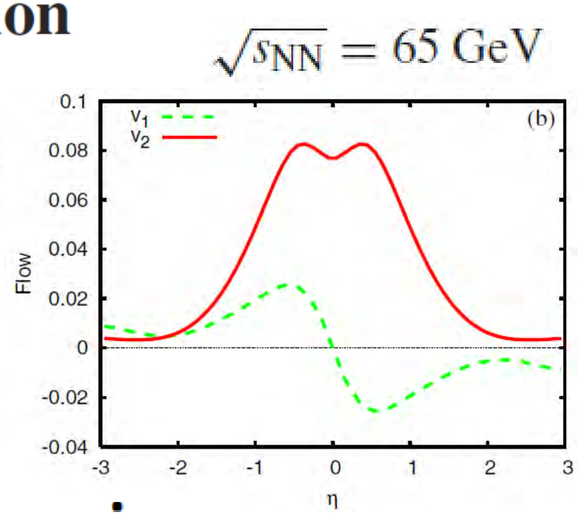
Peripheral Collisions in
rapidity coordinates

Rotation of the Initial State

Fluid dynamics as a diagnostic tool for heavy-ion collisions

Björn Bäuchle[1,2], Yun Cheng[1], László P Csernai[1,3], Volodymyr K Magas[4], Daniel D Strottman[5], Péter Ván[1,3] and Miklós Zétényi[1]

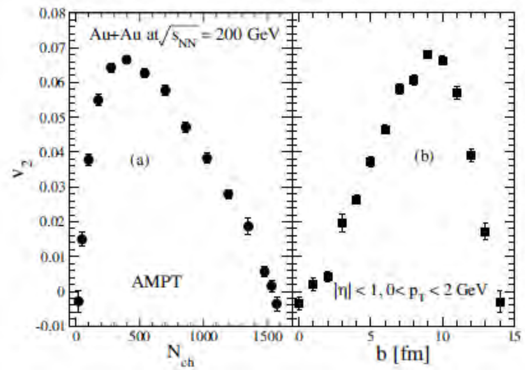
J. Phys. G: Nucl. Part. Phys. **34** (2007) S1077



Correlations among elliptic flow parameter, impact parameter, and multiplicity

Dai-Mei Zhou, Yun Cheng, Yu-Liang Yan, Bao-Guo Dong, Ben-Hao Sa and Laszlo P. Csernai

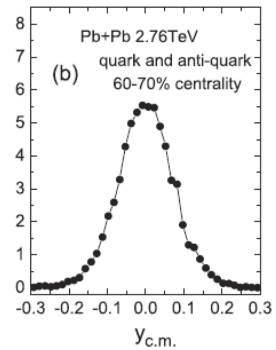
Eur. Phys. J. A **45**, 353–356 (2010)



Longitudinal fluctuations in the partonic and hadronic initial state

Yun Cheng,[1] Yu-Liang Yan,[2] Dai-Mei Zhou,[1] Xu Cai,[1] Ben-Hao Sa,[2] and Laszlo P. Csernai[3,4]

PHYSICAL REVIEW C **84**, 034911 (2011)



Development of $v_1(y)$ at increasing beam energies

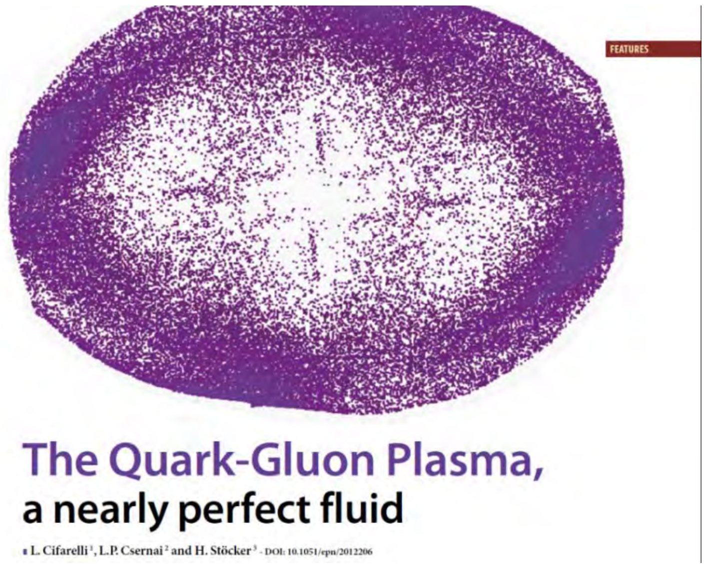
$v_1(y)$ observations show a central antiflow slope, $\partial v_1(y)/\partial y$, which is gradually decreasing with increasing beam energy [23]:

$$\frac{\partial v_1(y)_{odd}}{\partial y} = \begin{cases} -1.25\% & \text{for} \quad 62.4 \text{ GeV} \quad \text{(STAR)} \\ -0.41\% & \text{for} \quad 200.0 \text{ GeV} \quad \text{(STAR)} \\ -0.15\% & \text{for} \quad 2760.0 \text{ GeV} \quad \text{(ALICE)} \end{cases}$$

This can be attributed to smaller increase of p_t and the pressure, and the shorter interaction time, and **also to increasing rotation**.

In [Cs., Magas, Stöcker, Strottman, PRC84 (2011)] we predicted this rotation, but the turnover depends on the balance between rotation, expansion and freeze out. Apparently expansion is still faster and freeze out is earlier, so the turn over to the Positive side is not reached yet.

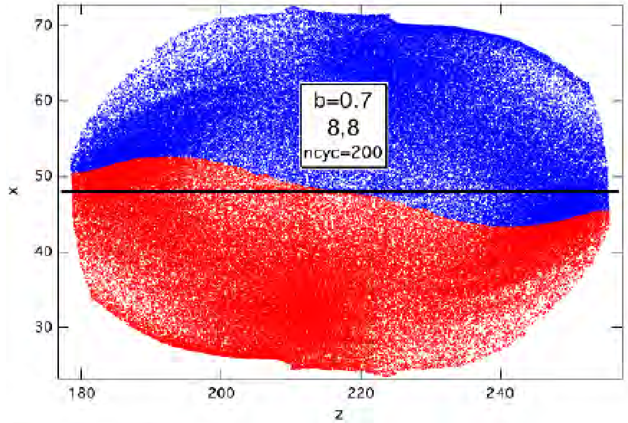
Interesting collective flow phenomena in low viscosity QGP →



Directed flow from global symmetry and initial state fluctuations

Laszlo P. Csernai[1*], Astrid Skålvik[1], D. J. Wang[1], Daniel Strottman[1], Csaba Anderlik[2], Yun Cheng[3], Yu L. Yan[4], Ben H. Sa[4]

Cent. Eur. J. Phys.
DOI: 10.2478/s11534-012-0146-4



PACIAE model capability in describing net proton moments

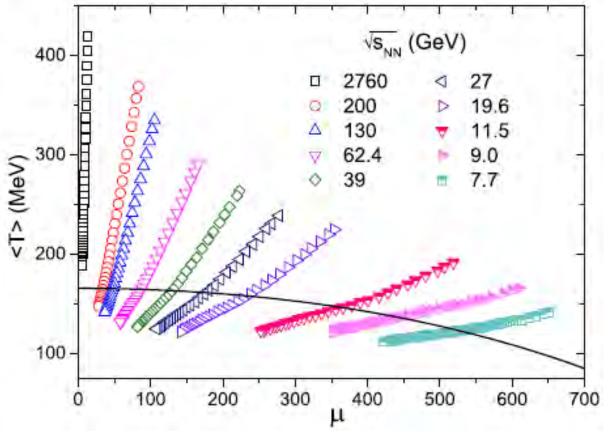
Ayut Limphirat[1,2,5*], Dai-Mei Zhou[3], Yu-Liang Yan[4], Bao-Guo Dong[4], Chinorat Kobdaj[2,5], Yupeng Yan[2,5], Laszlo P. Csernai[6,7], Ben-Hao Sa [3,4,8]

Cent. Eur. J. Phys.
DOI: 10.2478/s11534-012-0104-1

QGP flow fluctuations and the characteristics of higher moments

D.J. Wang, L.P. Csernai, D. Strottman, Cs. Anderlik, Y. Cheng, D.M. Zhou, Y.L. Yan, X. Cai and B.H. Sa

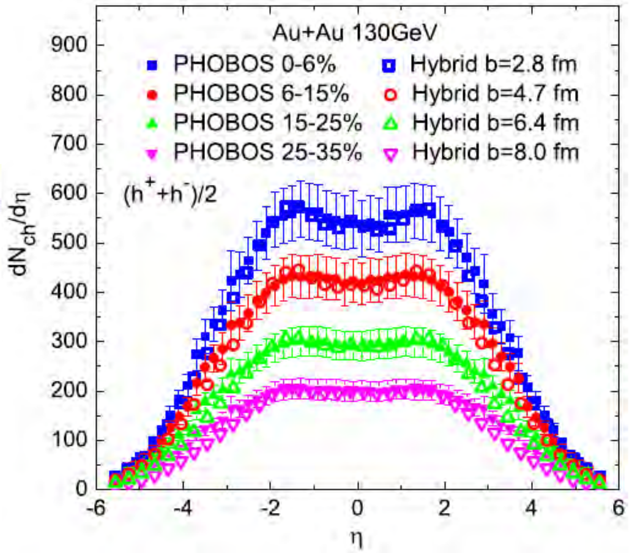
Eur. Phys. J. A (2012) 48: 168



HYDRO-PACIAE, a hydrodynamic and transport hybrid model for ultra-relativistic heavy ion collisions

Yu-Liang Yan[1], Yun Cheng[2], Dai-Mei Zhou[2], Bao-Guo Dong[1], Xu Cai[2], Ben-Hao Sa[1,2] and Laszlo P Csernai[3]

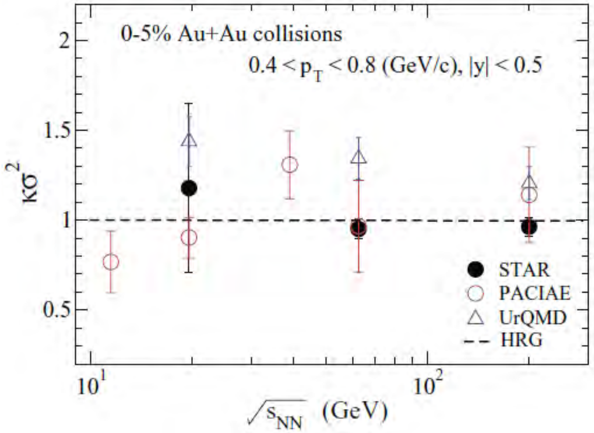
J. Phys. G: Nucl. Part. Phys. **40** (2013) 025102



Higher-moment singularities explored by net-proton nonstatistical fluctuations

Dai-Mei Zhou,[1] Ayut Limphirat,[2,5] Yu-liang Yan,[3] Cheng Yun,[1] Yu-peng Yan,[4,5] Xu Cai,[1] Laszlo P. Csernai,[6,7] and Ben-Hao Sa[1,3,4]

PHYSICAL REVIEW C **85**, 064916 (2012)



FLOW COMPONENTS AND INITIAL STATE CM FLUCTUATIONS*

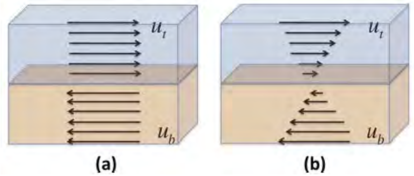
L.P. Csernai[a,b,c], A.M. Skålvik[a], D.J. Wang[a], V.K. Magas[d] H. Stöcker[c], D.D. Strottman[a,c], Y. Cheng[e], Y.L. Yan[f]

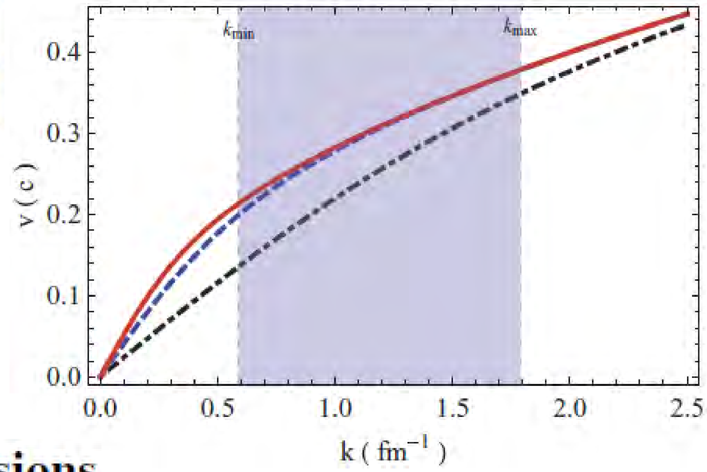
ACTA PHYSICA POLONICA B Vol. 43 (2012)

Viscous potential flow analysis of peripheral heavy ion collisions

D. J. Wang,[1] Z. Néda,[2] and L. P. Csernai[1]

PHYSICAL REVIEW C **87**, 024908 (2013)

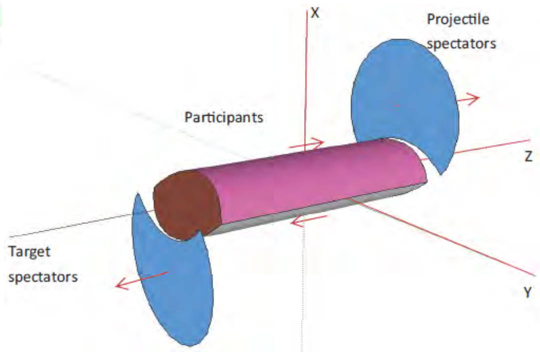


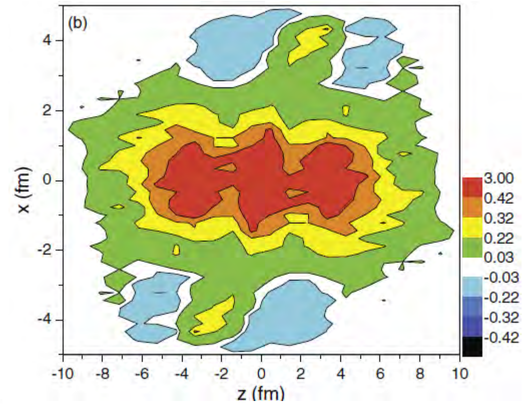


Flow vorticity in peripheral high-energy heavy-ion collisions

L. P. Csernai,[1] V. K. Magas,[2] and D. J. Wang[1]

PHYSICAL REVIEW C **87**, 034906 (2013)

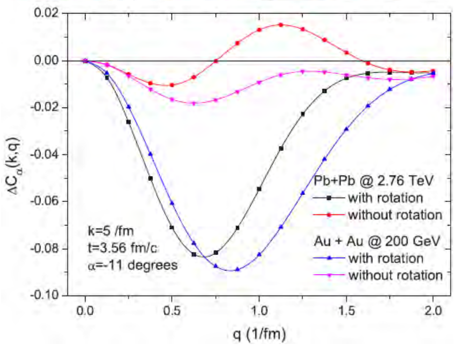




New method to detect rotation in high-energy heavy-ion collisions

L. P. Csernai,[1] S. Velle,[1] and D. J. Wang[1,2]

PHYSICAL REVIEW C **89**, 034916 (2014)



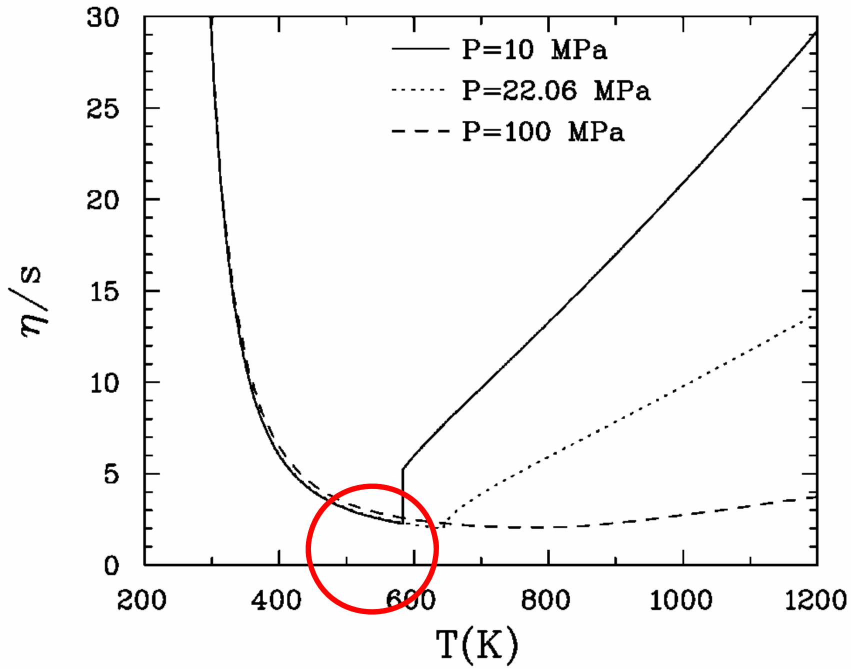
PRL 97, 152303 (2006) PHYSICAL REVIEW LETTERS week ending 13 OCTOBER 2006

Strongly Interacting Low-Viscosity Matter Created in Relativistic Nuclear Collisions

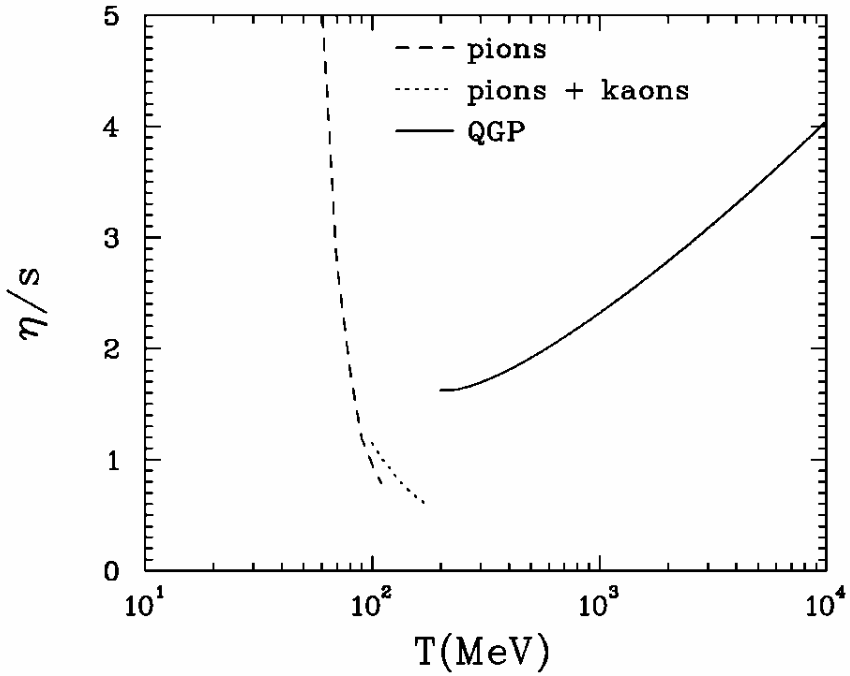
Laszlo P. Csernai,[1,2] Joseph I. Kapusta,[3] and Larry D. McLerran[4]
[1]*Section for Theoretical Physics, Department of Physics, University of Bergen, Allegaten 55, 5007 Bergen, Norway*
[2]*MTA-KFKI, Research Institute of Particle and Nuclear Physics, 1525 Budapest 114, P. O. Box 49, Hungary*
[3]*School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA*
[4]*Nuclear Theory Group and Riken Brookhaven Center, Brookhaven National Laboratory, Bldg. 510A, Upton, New York 11973, USA*
(Received 12 April 2006; published 12 October 2006)

Viscosity vs. T has a minimum at the 1st order phase transition. This might signal the phase transition if viscosity is measured. At lower energies this was done.

Water



QGP



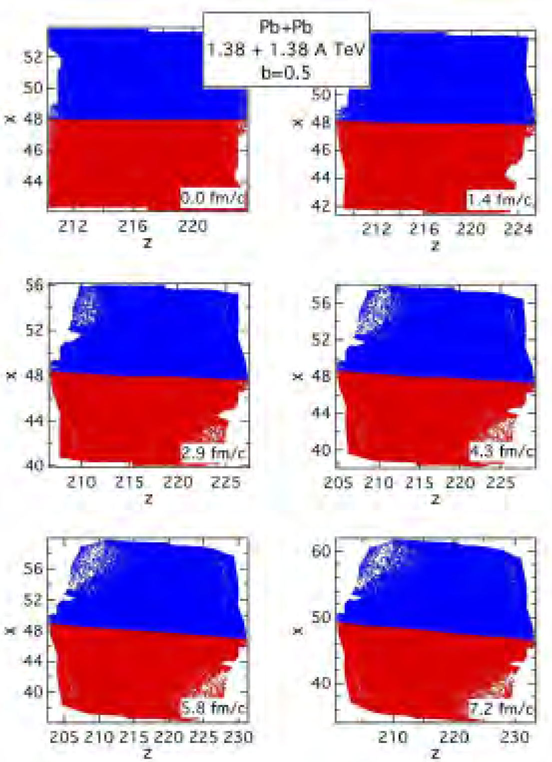
Kelvin-Helmholtz instability in high-energy heavy-ion collisions

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

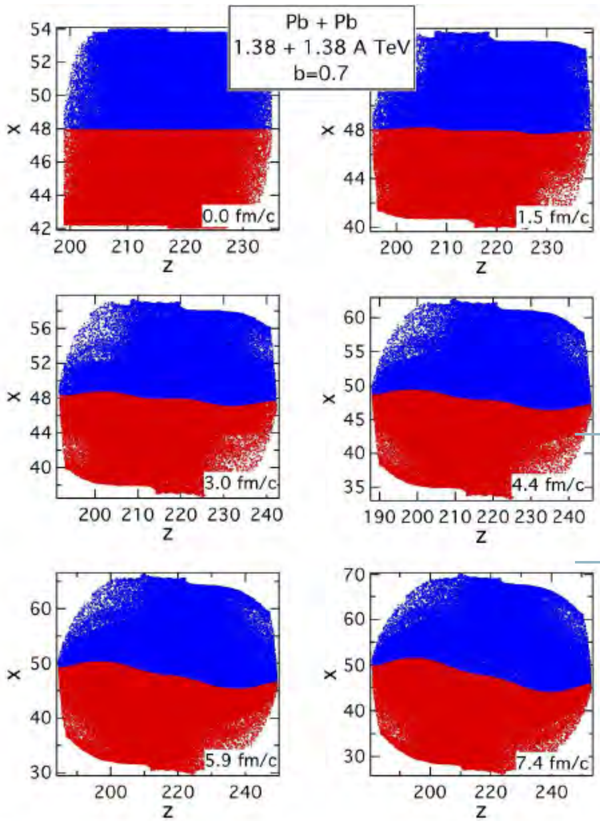
PHYSICAL REVIEW C **85**, 054901 (2012)

KHI →

ROTATION



KHI



2.4 fm

FIG. 1: (color online) Growth of the initial stage of Kelvin-Helmholtz instability in a $1.38A + 1.38A$ TeV peripheral, $b = 0.7b_{\max}$, Pb+Pb collision in a relativistic CFD simulation using the PIC-method. We see the positions of the marker particles (Lagrangian markers with fixed baryon number content) in the reaction plane. The calculation cells are $dx = dy = dz = 0.4375$fm and the time-step is 0.04233 fm/c The number of randomly placed marker particles in each fluid cell is 8^3. The axis-labels indicate the cell numbers in the x and z (beam) direction. The initial development of a KH type instability is visible from $t = 1.5$ up to $t = 7.41$ fm/c corresponding from 35 to 175 calculation time steps).

Elliptic flow and F.O.

PHYSICAL REVIEW C **81**, 064910 (2010)

Matching stages of heavy-ion collision models

Yun Cheng,[1,2,3,*] L. P. Csernai,[1,2,4] V. K. Magas,[5] B. R. Schlei,[6] and D. Strottman[2,7]

$$[N^\mu d\sigma_\mu] = 0;$$
$$[T^{\mu\nu} d\sigma_\mu] = 0;$$
$$[S^\mu d\sigma_\mu] \geqslant 0,$$

Taub adiabat [6,7], [Taub 1949, Csernai 1987] :

$$j^2 = [P](d\sigma^\mu d\sigma_\mu)/[X], \quad [P] = [(e+P)X]/(X_1 + X_0). \quad A^\mu = T^{\mu\nu} d\sigma_\nu$$

$$A_0^\mu A_{0\mu} = (e-P)A_0^\mu d\sigma_\mu + eP(d\sigma^\mu d\sigma_\mu), \qquad (18)$$

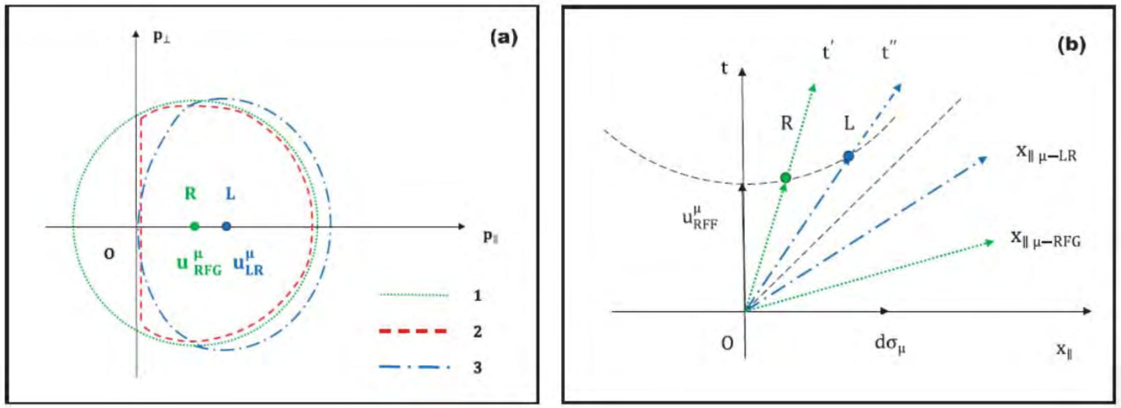
which can be solved straightforwardly if the EoS, $P = P(n, e)$,

Spec. case: with an EoS of $P = e/3$, Eq. (18) leads to a quadratic equation

$$d\hat{\sigma}^\mu d\hat{\sigma}_\mu e^2 + 2a^\mu d\hat{\sigma}_\mu e - 3a^\mu a_\mu = 0,$$

where $a^\mu \equiv A_0^\mu / D$ is the energy momentum transfer $\quad d\sigma^\mu d\sigma_\mu = \pm D^2$

CHENG, CSERNAI, MAGAS, SCHLEI, AND STROTTMAN PHYSICAL REVIEW C **81**, 064910 (2010)



FAIR

uib.no

Kelvin-Helmholtz instability in relativistic heavy ion collisions

[Chicho Nonanka, K. Okamoto, Y. Akamatsu, Quark Matter 2015, Kobe, Japan]

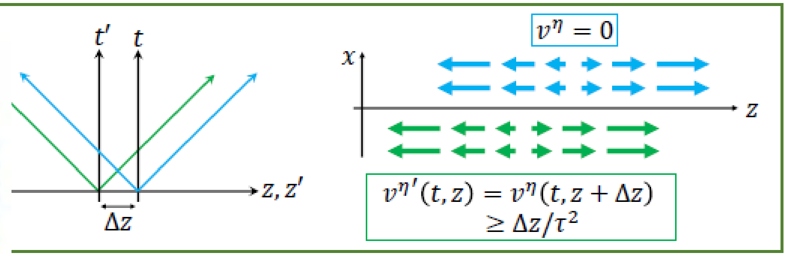
Share flow in Heavy Ion Collisions

A Lorentz contracted nuclei has finite width $\Delta z \sim 1\text{fm}$
due to the uncertainty principle

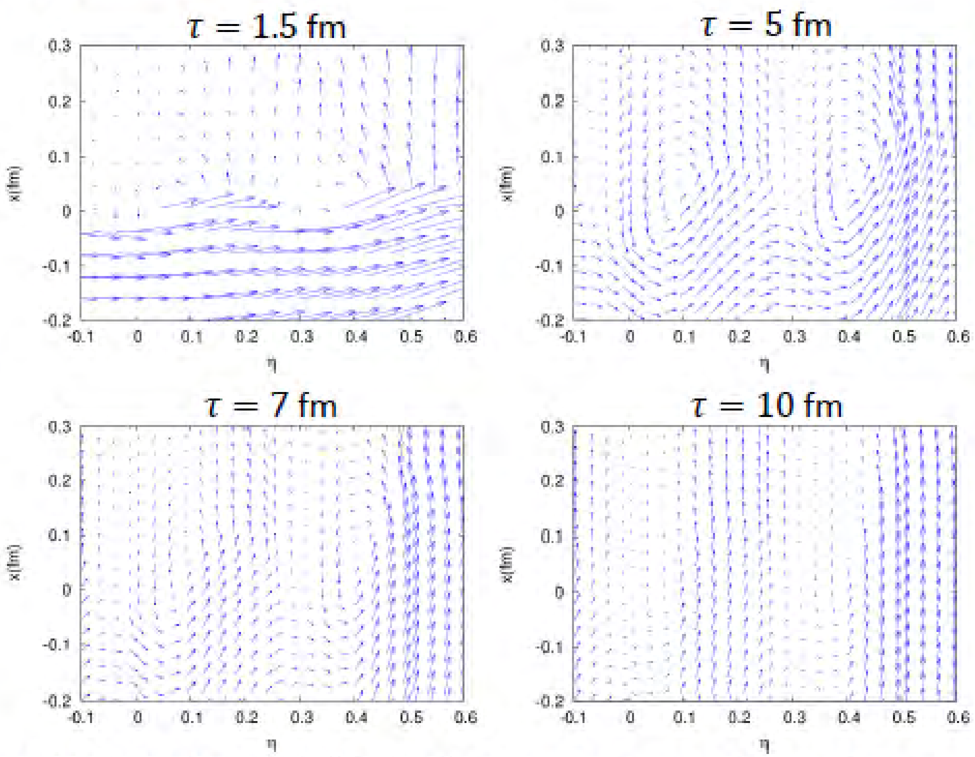
→ We assume the center position of Bjorken flow fluctuates

→ Fluid velocity v^η has a large fluctuation around $v^\eta = 0$

We consider following condition



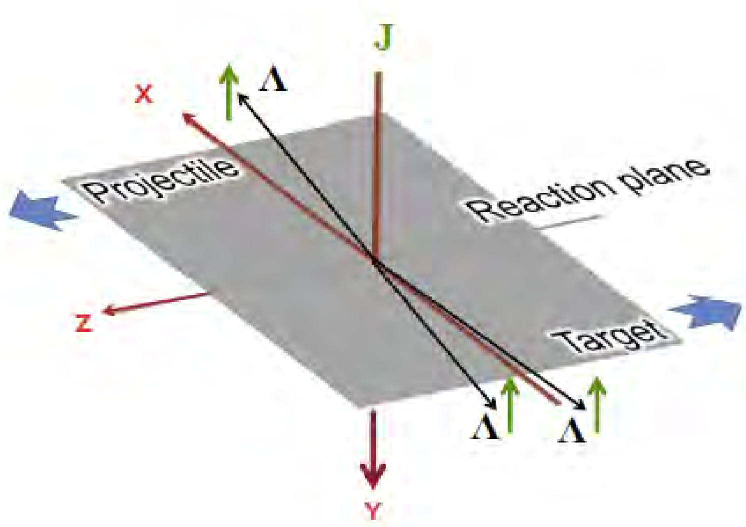
Velocity profile



- Kelvin-Helmholtz instability is observed in expanding system.
  Vortices are formed, the transvers velocity evolve.

uib.no

Detecting rotation: Lambda polarization

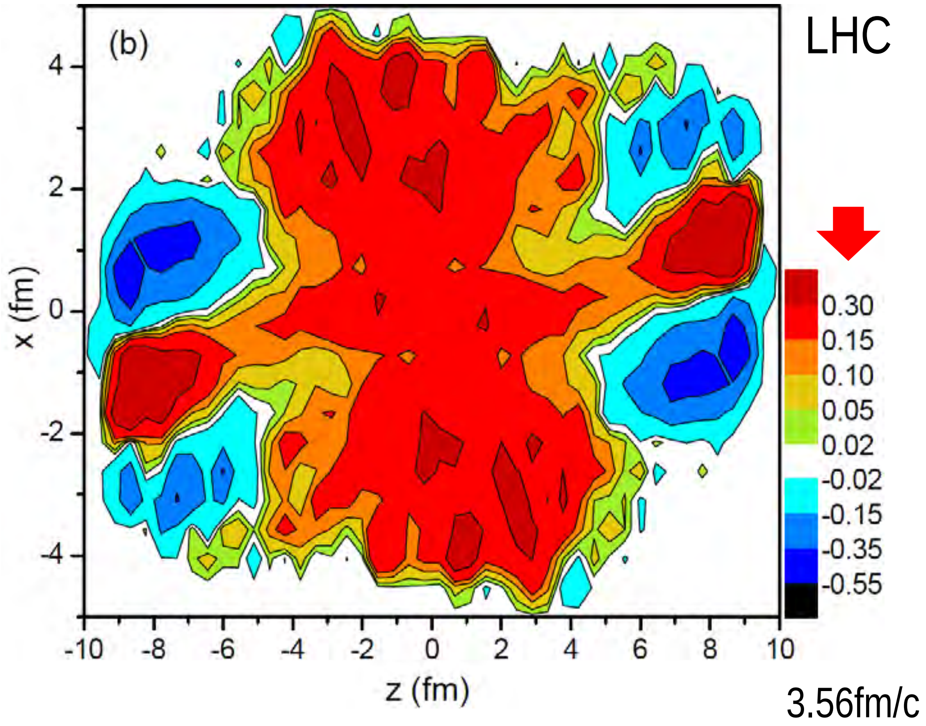


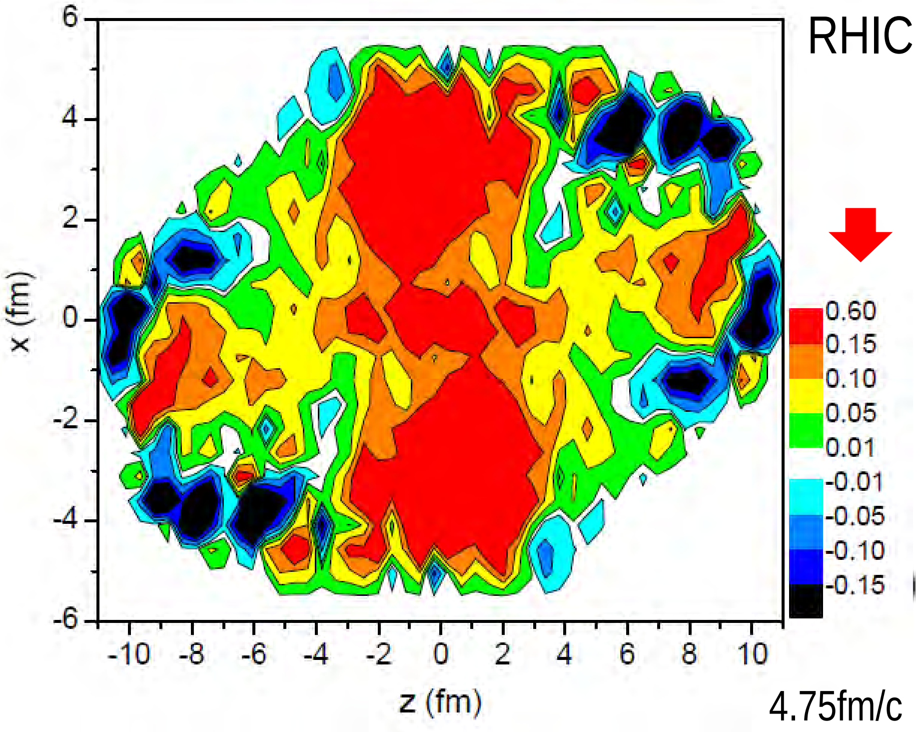
$$\mathbf{\Pi}(p) = \frac{\hbar\varepsilon}{8m}\frac{\int \mathrm{d}V\, n_F\, (\nabla \times \beta)}{\int \mathrm{d}V\, n_F}$$

$$\beta^\mu(x) = (1/T(x))u^\mu(x)$$ ← From hydro

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

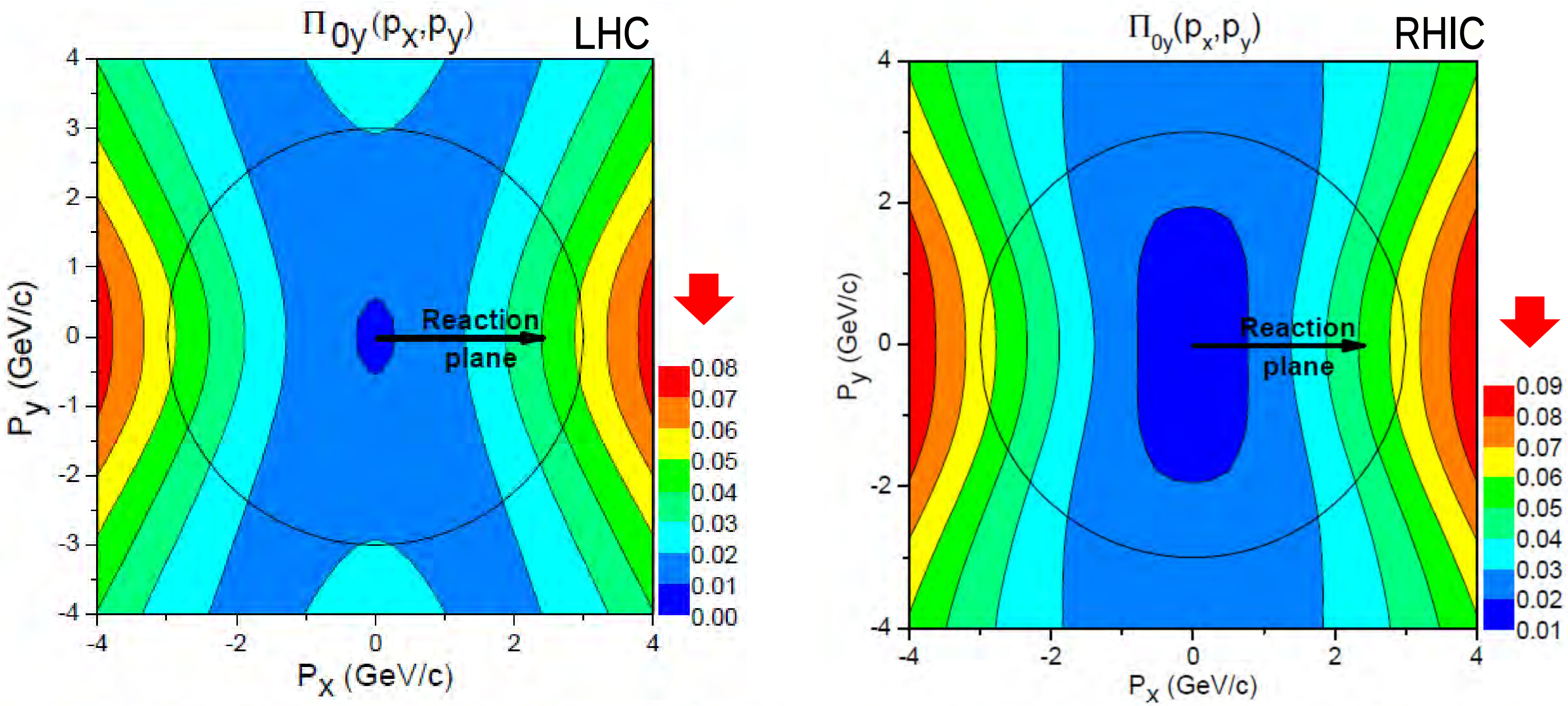
[F. Becattini, L.P. Csernai, D.J. Wang, Phys. Rev. C **88**, 034905 (2013)]





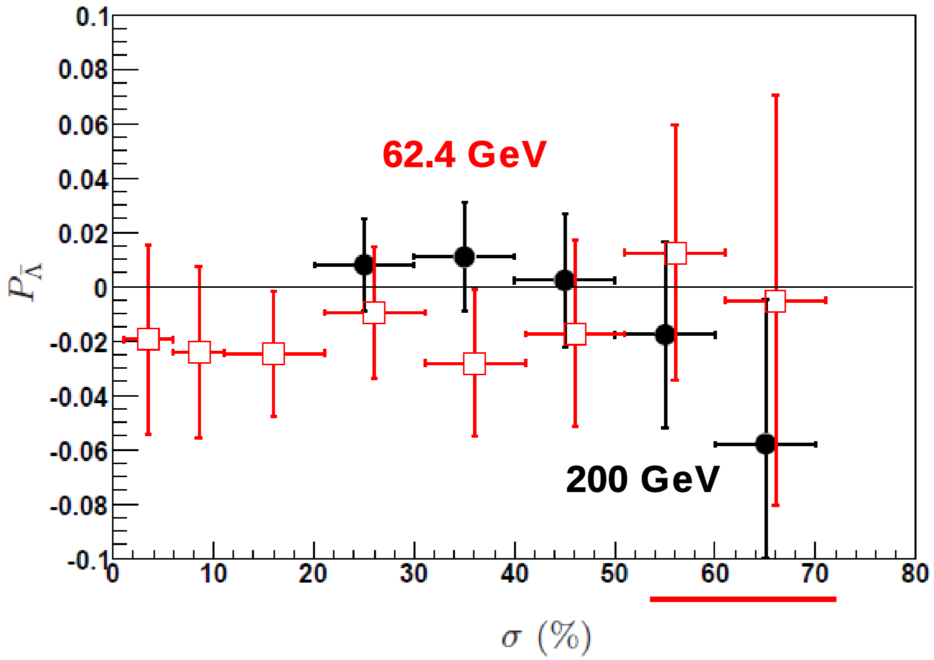
Lambda polarization

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



- **The POLARIZATION of Λ and $\bar{\Lambda}$ due to thermal equipartition with local vorticity is slightly stronger at RHIC than at LHC due to the much higher temperatures at LHC.**
- **Although early measurements at RHIC were negative, these were averaged over azimuth! We propose selective measurement in the reaction plane (in the +/- x direction) in the EbE c.m. frame. Statistical error is much reduced now, so significant effect is expected at $p_x \geq 3$ GeV/c.**

Measurements: Inconclusive (2007)



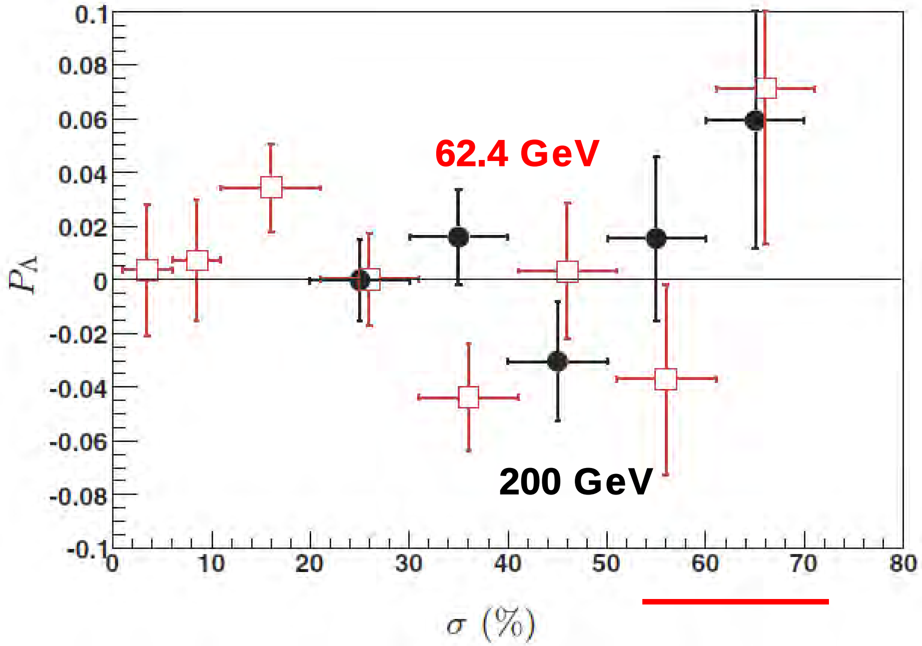


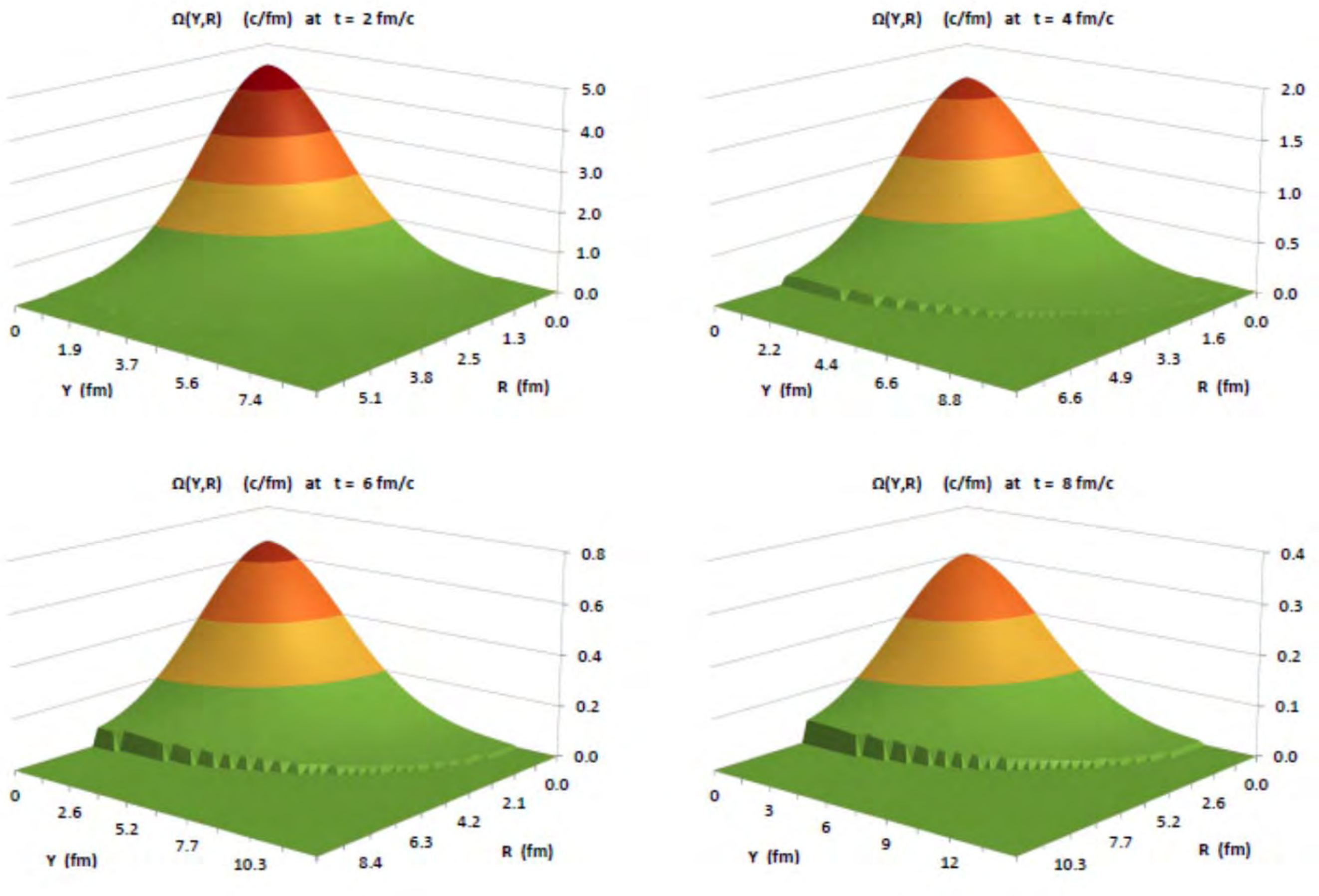
FIG. 8: (Color online) Global polarization of $\bar{\Lambda}$–hyperons as a function of centrality. Filled circles show the results for Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV (centrality region 20-70%) and open squares indicate the results for Au+Au collisions at $\sqrt{s_{NN}}$=62.4 GeV (centrality region 0-80%). Only statistical uncertainties are shown.

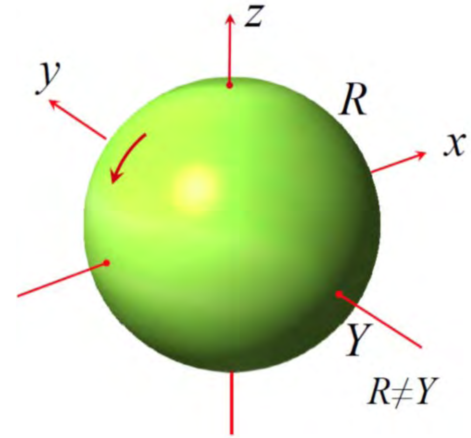
* **Azimuth averaged** ↓
* **C.M.** & **RP$_{(P/T)}$** should be precisely determined, & only at large **p$_x$** !

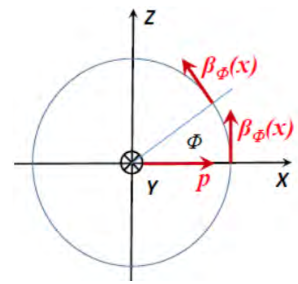
B.I. Abelev et al., (STAR) PHYSICAL REVIEW C **76**, 024915 (2007)

Exact, expanding and rotating hydro solution (E.M.)

- Exact model: T. Csörgő, M.I. Nagy, Phys. Rev. C 89, 044901 (2014).
  Hydro: L.P. Csernai, D.J. Wang, and T. Csörgő, Phys. Rev. C 90, 024901 (2014).
  Vor.: L.P. Csernai, J.H. Inderhaug, Int. J. Modern Physics E 24, 1550013 (2015).







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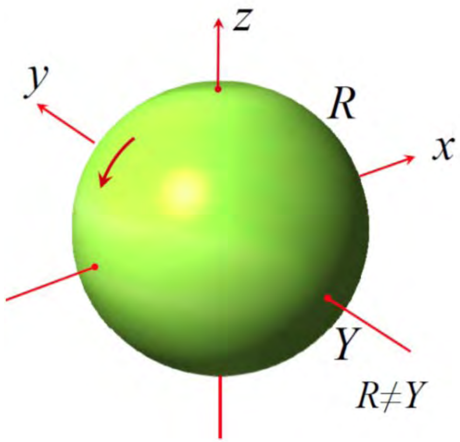
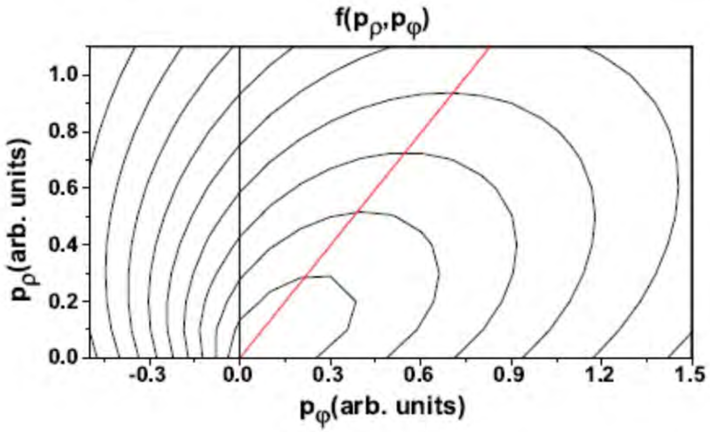
Azimuthal HBT is Changed by Rotation (E.M.)



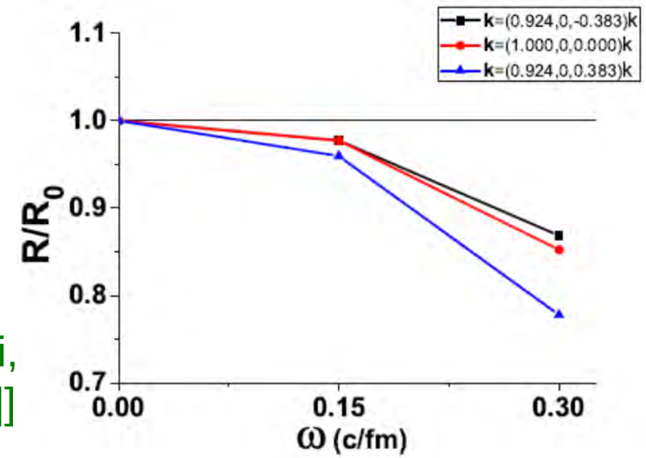
Azimuthally symmetric source but in phase space:



[Velle & Csernai,
PRC 92, 024905 (2015)]

Azimuthal HBT: $$C(q,K) = 1 + exp\left(-\sum_{i,j=o,s,l} q_i q_j R^2_{ij}(K)\right)$$

We get for azimuthal HBT, R_{oo}:



[Velle, MehrabiPari & Csernai,
arXiv: 1508.01884v1 [nucl-th]]

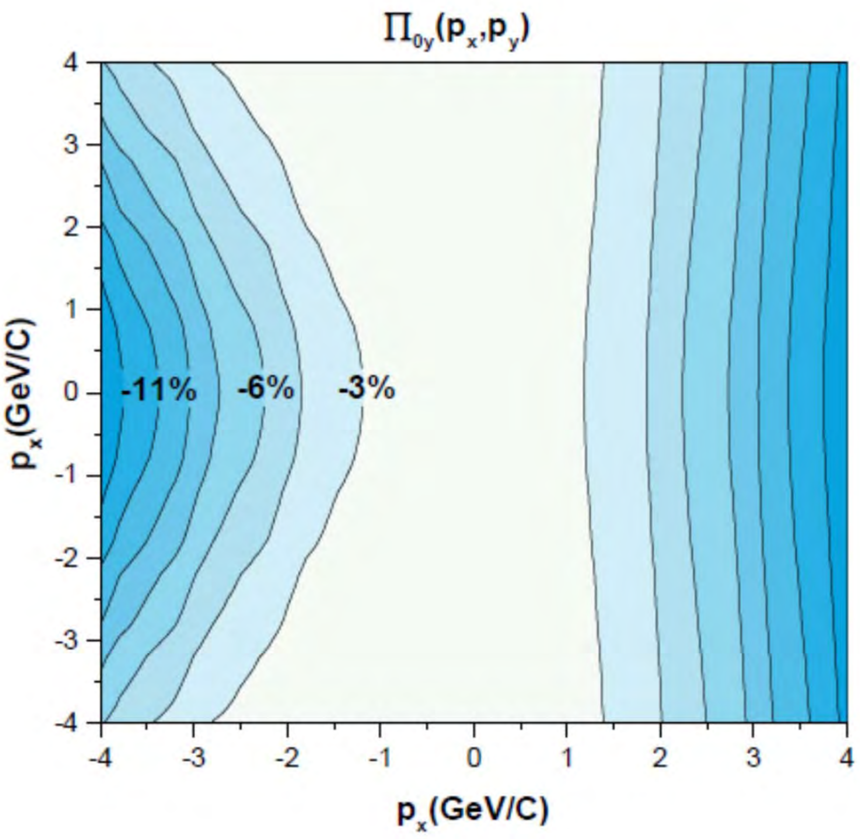
Polarization in E.M. & in ECHO-QGP hydro

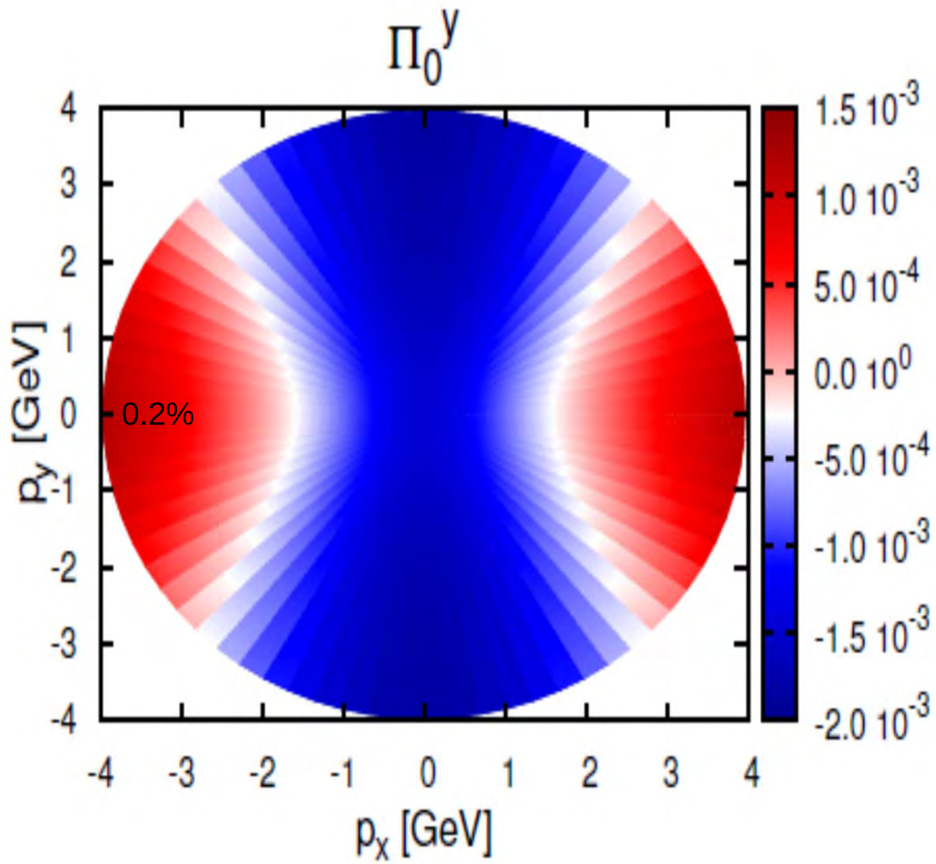
- Y-directed polarization, Π_y, is very different. In E.M. max polarization is -11%, >> in ECHO-QGP [Becattini et al.] it is -0.2%,due to lack of initial shear flow

Λ Polarization in an Exact Rotating and Expanding fluid dynamical model for peripheral heavy ion reactions

Yilong Xie, Robert C. Glastad, László P. Csernai

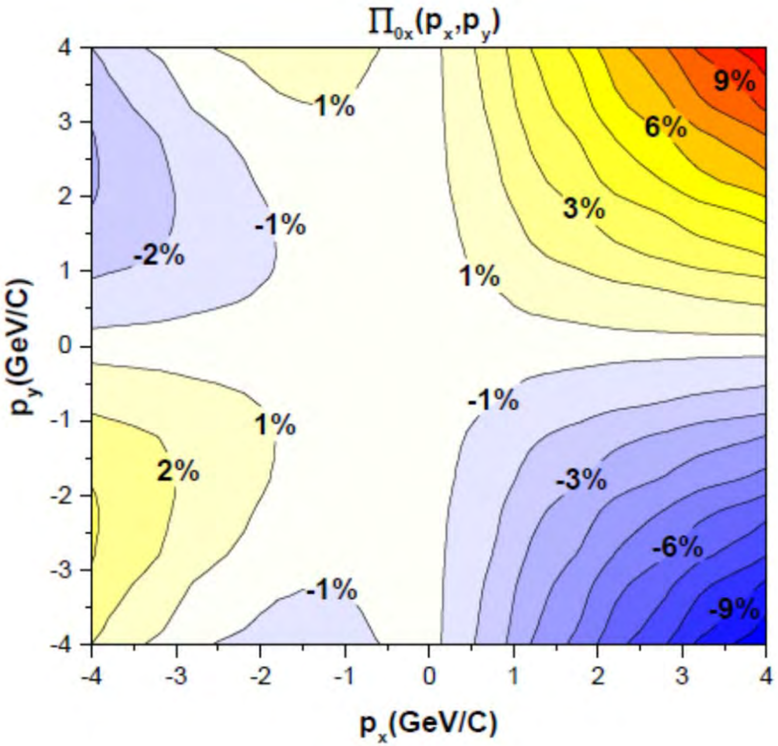
[Phys. Rev. C 92, 064901 (2015)].

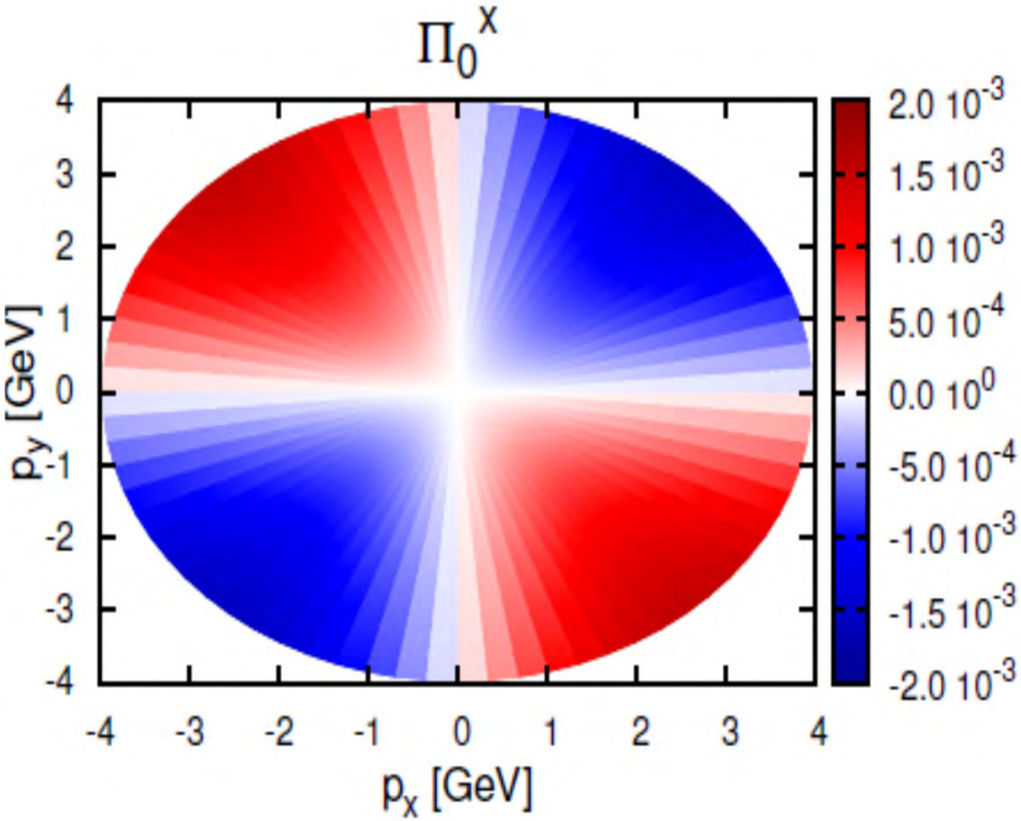




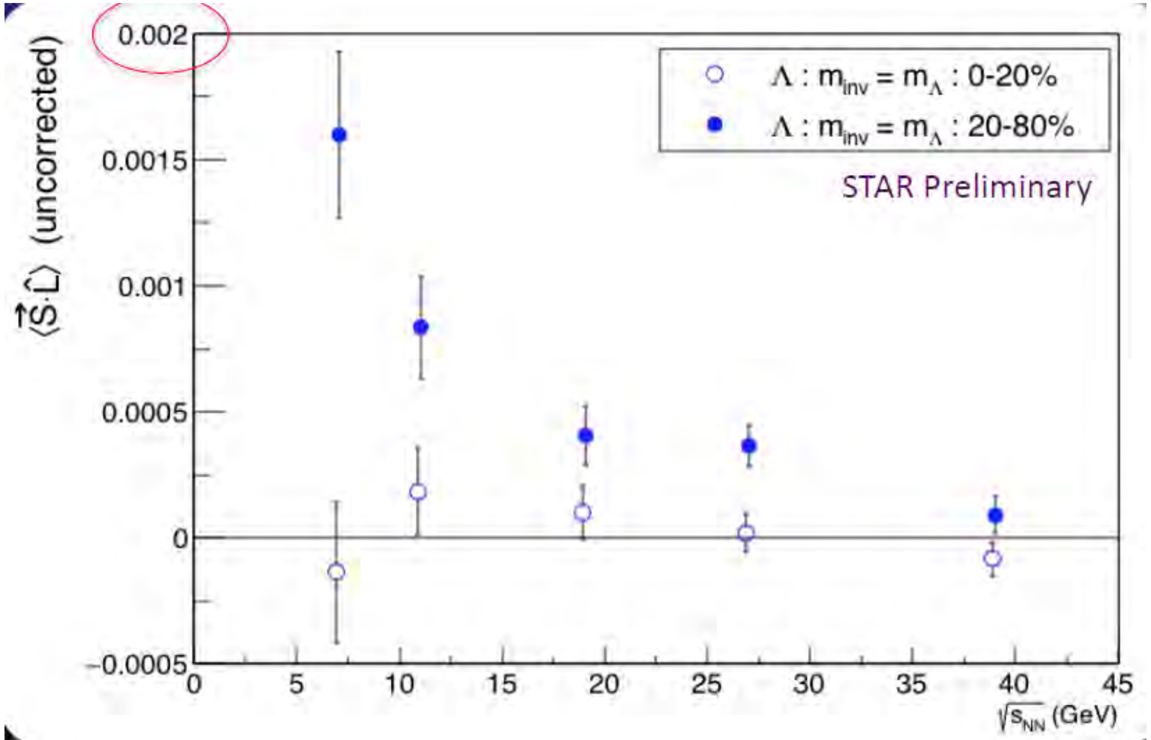
Polarization in E.M. & in ECHO-QGP hydro cont.

- In the Π_x-direction the initial shear flow has no effect.





- The structure is similar, the amplitude is different and the sign is opposite. There may be different conventions (?)

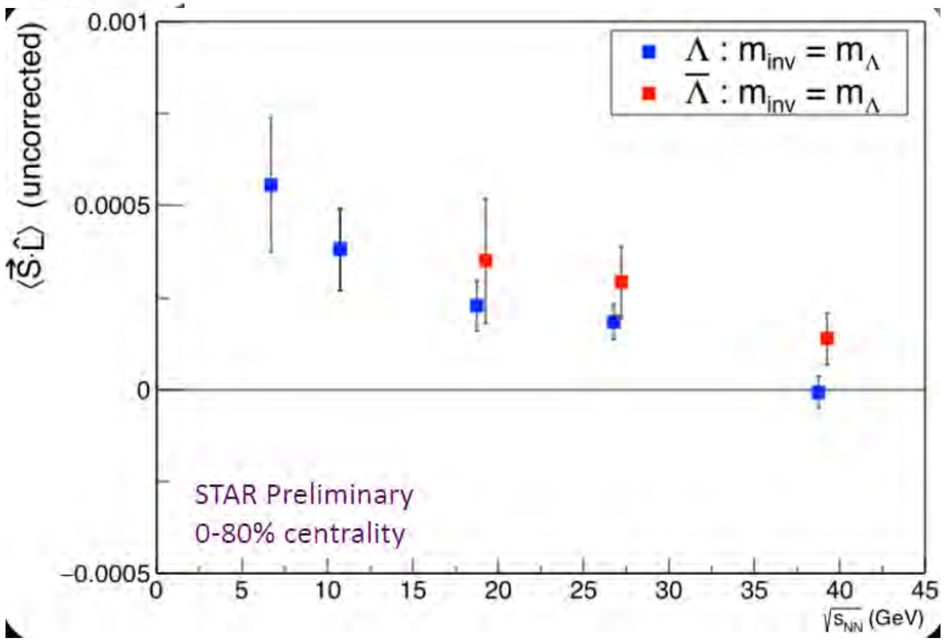


Λ polarization (prelim, a.u.) RHIC STAR – BES, **Mike Lisa**, talk at WCPF 2015, Warsaw:

(i) In peripheral HI collisions significant polarization for E = 7.7 – 39 GeV/nucl.

(ii) Λ and Λ are both polarized in the same direction → not EM but mechanical (spin-orbit) effect.

- **Reaction plane identification error is not yet corrected for**
- **EbE CM is not yet identified !**
- **All emission angles and energies are added up !!**

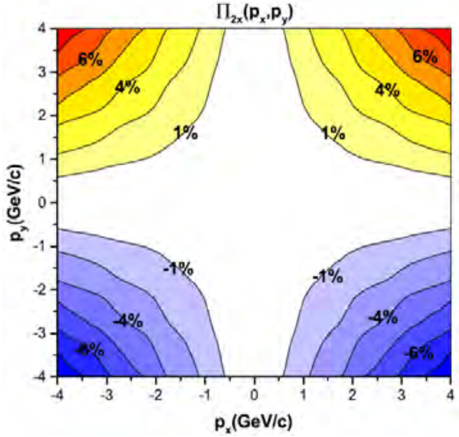


Λ polarization in an exact rotating and expanding fluid dynamical model

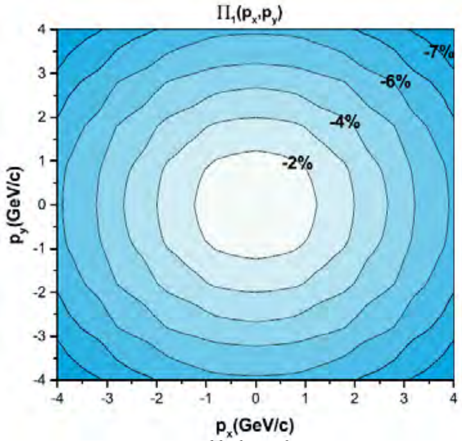
[Y.L. Xie, R.C. Glastad, L.P. Csernai, Phys. Rev. C 92, 064901 (2015).]

$$\mathbf{\Pi}(p) = \frac{\hbar\epsilon}{8m} \frac{\int dV n_F(x,p)(\nabla \times \boldsymbol{\beta})}{\int dV n_F(x,p)} \quad \text{1st}$$

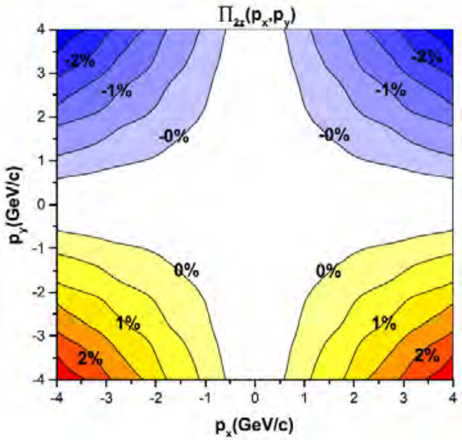
$$+ \frac{\hbar \mathbf{p}}{8m} \times \frac{\int dV n_F(x,p)(\partial_t \boldsymbol{\beta} + \nabla \beta^0)}{\int dV n_F(x,p)}, \quad \text{2nd}$$



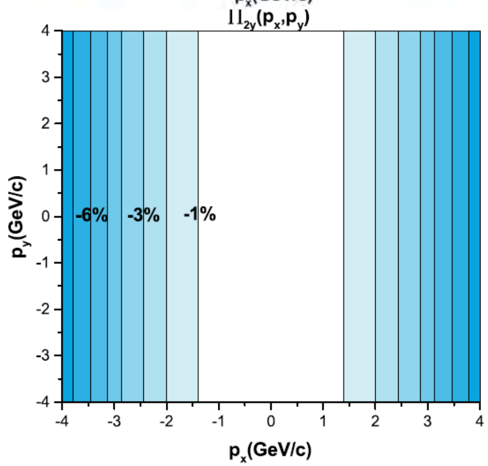
2x



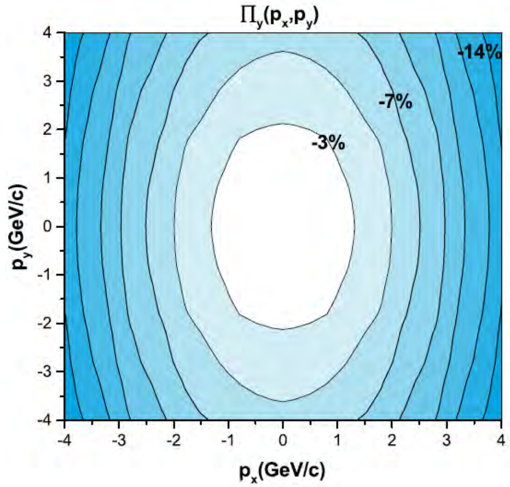
1y



2z



2y



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Conclusions

- Collective flow, Rotation, KHI, Turbulence are dominant in FD
- Dominant observables are expected, & **seen**
- QGP properties will be analyzed and Transport properties determined quantitatively.