Hyperon polarization in Heavy-Ion collisions

STUDY OF HIGH-DENSITY NUCLEAR MATTER WITH HADRON BEAMS

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Main Topics

- Polarization: from nucleons to ions

- Anomalous mechanism: 4-velocity as gauge field

- Chemical potential and Energy dependence

- Rotation in heavy-ion collisions: Vortiex sheets

- Polarization of hyperons: comparison of approaches

- Conslusions

Single Spin Asymmetries (vector polarization)

Simplest example - (non-relativistic) elastic pion-nucleon scattering $\pi \vec{N} \to \pi N$
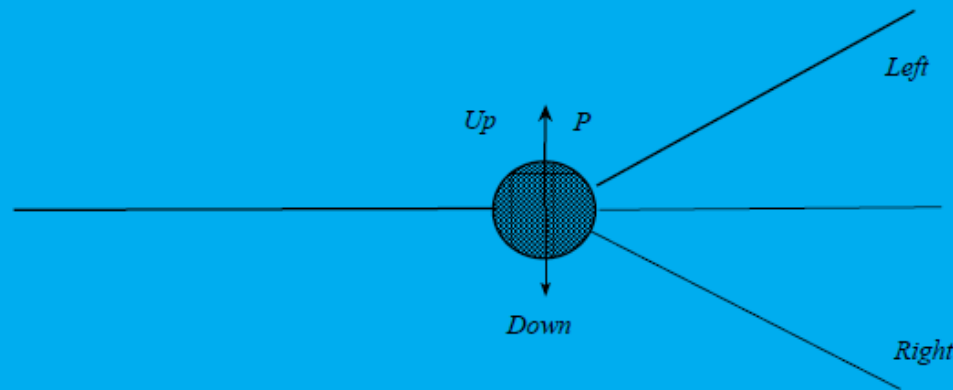
$M = a + ib(\vec{\sigma}\vec{n})$ $\vec{n}$ is the normal to the scattering plane.

Density matrix: $\rho = \frac{1}{2}(1 + \vec{\sigma}\vec{P})$,

Differential cross-section: $d\sigma \sim 1 + A(\vec{P}\vec{n})$, $A = \frac{2Im(ab^*)}{|a|^2 + |b|^2}$

Λ-polarisation

- Self-analyzing in weak decay
- Directly related to s-quarks polarization: complementary probe of strangeness
- Widely explored in hadronic processes
- Disappearance-probe of QCD matter formation (Hoyer; Jacob, Rafelsky: '87): Randomization – smearing – no direction normal to the scattering plane
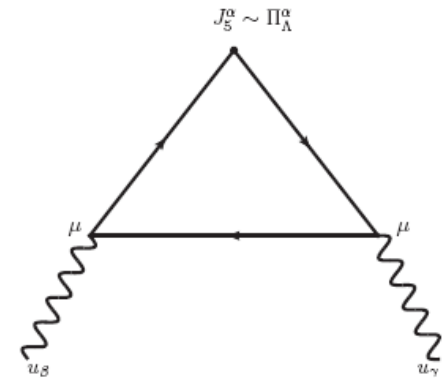
Global polarization

- Global polarization normal to REACTION plane

- Predictions (Z.-T.Liang et al.): large orbital angular momentum -> large polarization

- Search by STAR (I. Selyuzhenkov et al.'07) : polarization NOT found at % level!

- Maybe due to locality of LS coupling while large orbital angular momentum is distributed

- How to transform rotation to spin?

Anomalous mechanism – polarization similar to CM(V)E

- 4-Velocity is also a GAUGE FIELD

$$e_j A_\alpha J^\alpha \Rightarrow \mu_j V_\alpha J^\alpha$$

- Triangle anomaly leads to polarization of quarks and hyperons (Rogachevsky, Sorin, OT '10)

- Analogous to anomalous gluon contribution to nucleon spin (Efremov,OT'88)

- 4-velocity instead of gluon field!

Anomaly for polarization

- Induced axial charge

$$c_V = \frac{\mu_s^2 + \mu_A^2}{2\pi^2} + \frac{T^2}{6}, \quad Q_5^s = N_c \int d^3x \, c_V \gamma^2 \epsilon^{ijk} v_i \partial_j v_k$$

- Neglect axial chemical potential
- T-dependent term - related to gravitational anomaly
- Lattice simulation: suppressed due to collective effects

Energy dependence

- Coupling -> chemical potential

$$Q_5^s = \frac{N_c}{2\pi^2} \int d^3x \, \mu_s^2(x) \gamma^2 \epsilon^{ijk} v_i \partial_j v_k$$

- Field -> velocity; (Color) magnetic field strength -> vorticity;

- Topological current -> hydrodynamical helicity

- Large chemical potential: appropriate for NICA/FAIR energies

One might compare the prediction below with the right panel figures

O. Rogachevsky, A. Sorin, O. Teryaev
Chiral vortaic effect and neutron asymmetries in heavy-ion collisions
PHYSICAL REVIEW C 82, 054910 (2010)

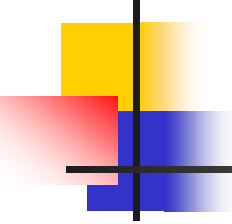One would expect that polarization is proportional to the anomalously induced axial current [7]

$$j_A^\mu \sim \mu^2 \left(1 - \frac{2\mu n}{3(\epsilon + P)} \right) \epsilon^{\mu\nu\lambda\rho} V_\nu \partial_\lambda V_\rho, \qquad (6)$$

where n and ϵ are the corresponding charge and energy densities and P is the pressure. Therefore, the μ dependence of polarization must be stronger than that of the CVE, leading to the effect's increasing rapidly with decreasing energy.

This option may be explored in the framework of the program of polarization studies at the NICA [17] performed at collision points as well as within the low-energy scan program at the RHIC.

Raw

All corrected
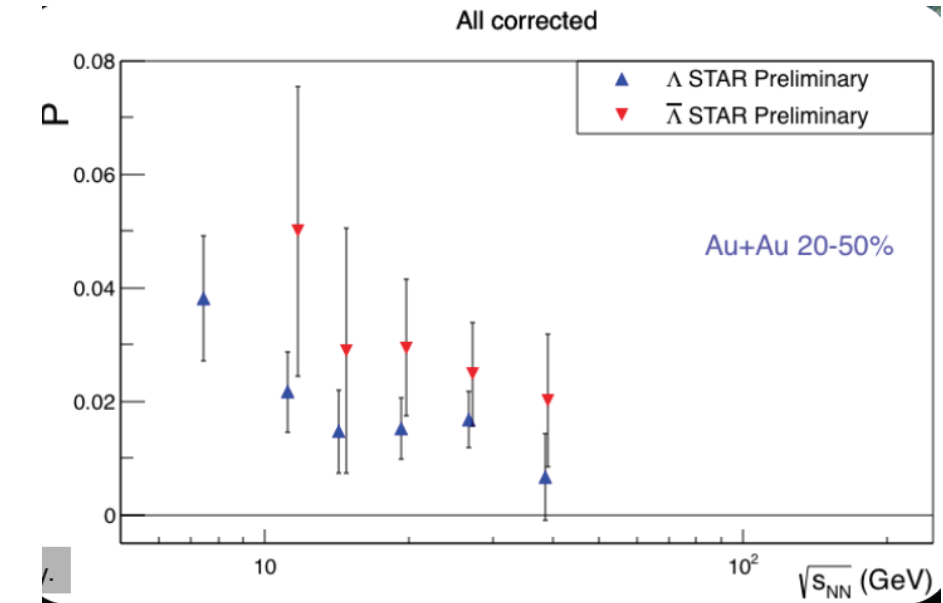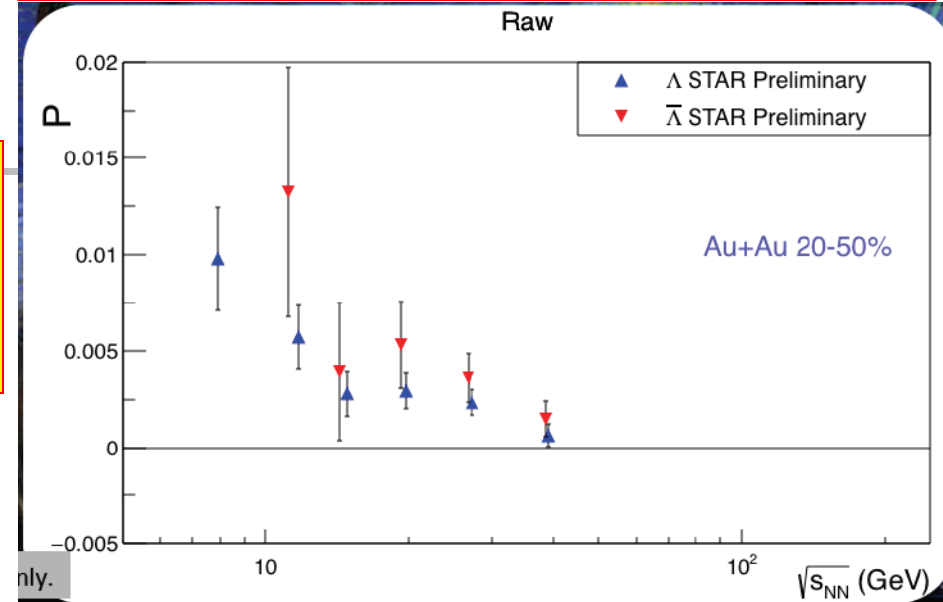
Microworld: where is the fastest possible rotation?

- Non-central heavy ion collisions (Angular velocity ~ c/Compton wavelength)
- ~25 orders of magnitude faster than Earth's rotation
- Differential rotation – vorticity
- P-odd :May lead to various P-odd effects
- Calculation in kinetic quark - gluon string model (DCM/(LA)QGSM) – Boltzmann type eqns + phenomenological string amplitudes)

Rotation in HIC and related quantities

- Non-central collisions – orbital angular momentum
- $L = \Sigma\ r \times p$
- Differential pseudovector characteristics – vorticity
- $\omega = \mathrm{curl}\ v$
- Pseudoscalar – helicity
- $H \sim \langle (v\ \mathrm{curl}\ v) \rangle$
- Maximal helicity – Beltrami chaotic flows $v\ ||\ \mathrm{curl}\ v$

Simulation in QGSM (Kinetics -> HD)

$$50 \times 50 \times 100 \text{ cells} \qquad dx = dy = 0.6 \text{ fm}, \, dz = 0.6/\gamma \text{ fm}$$

- Velocity

$$\vec{v}(x, y, z, t) = \frac{\sum_i \sum_j \vec{P}_{ij}}{\sum_i \sum_j E_{ij}}$$
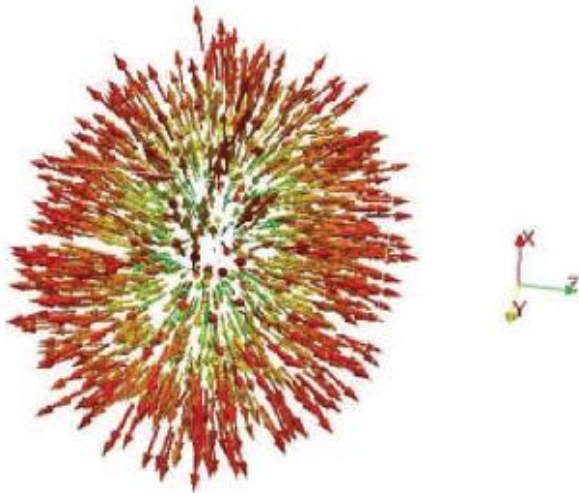
- Vorticity – from discrete partial derivatives

Angular momentum conservation and helicity

- Helicity vs orbital angular momentum (OAM) of fireball
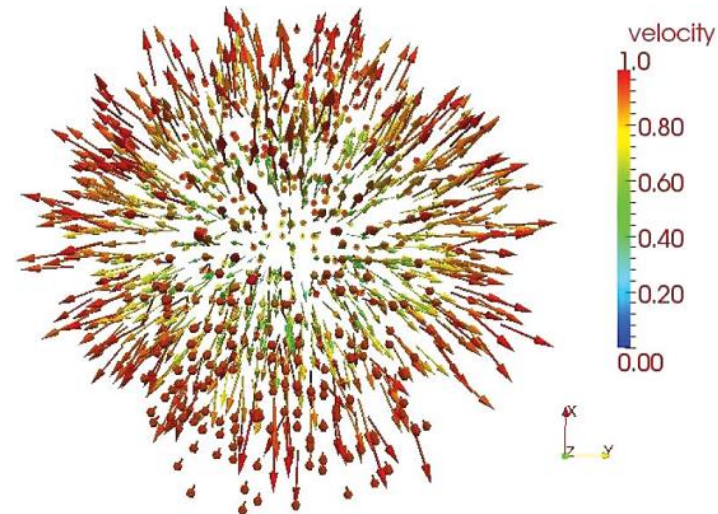- (~10% of total)

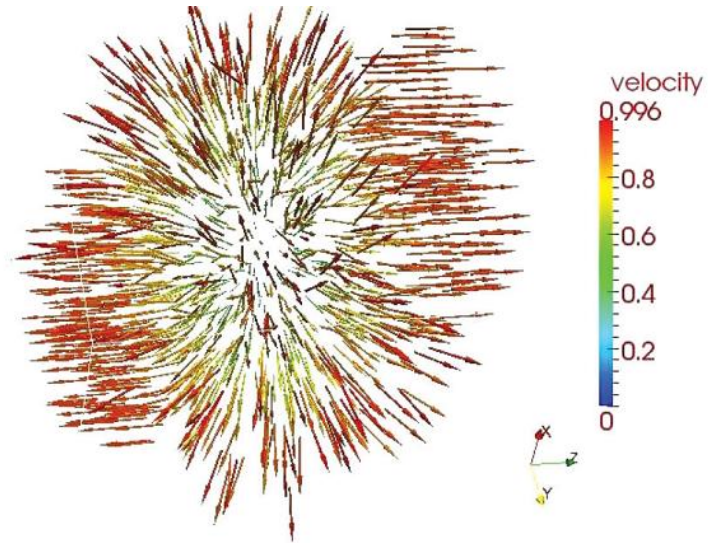- Conservation of OAM with a good accuracy!
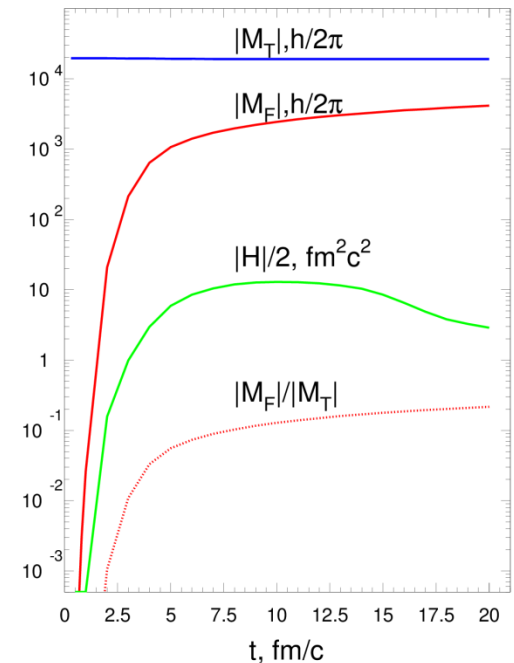
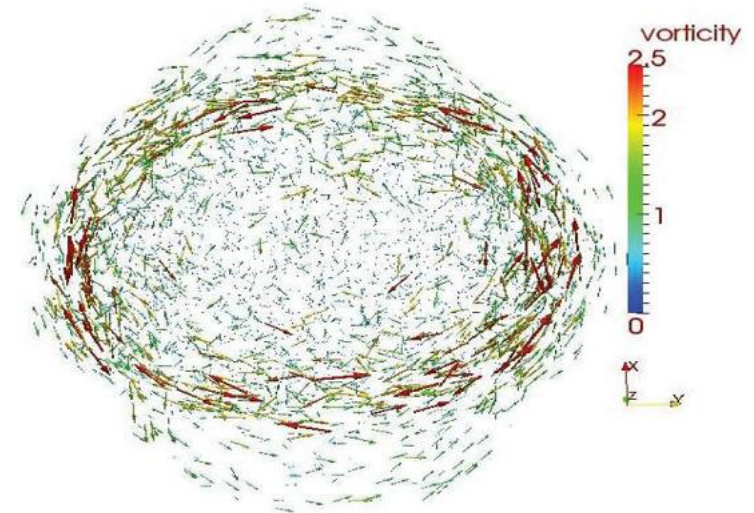# Structure of velocity and vorticity fields (NICA@JINR-5 GeV/c)
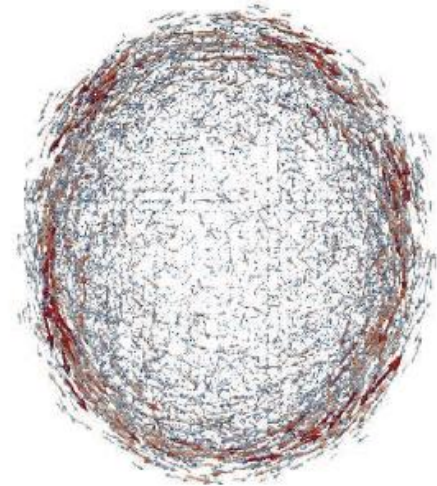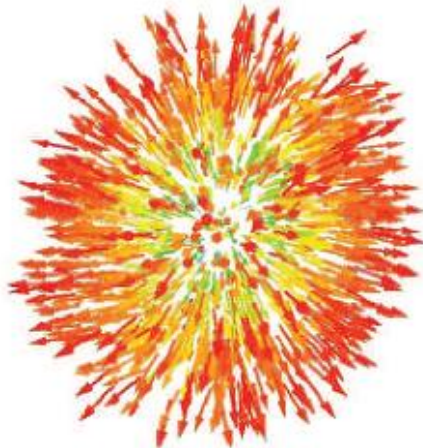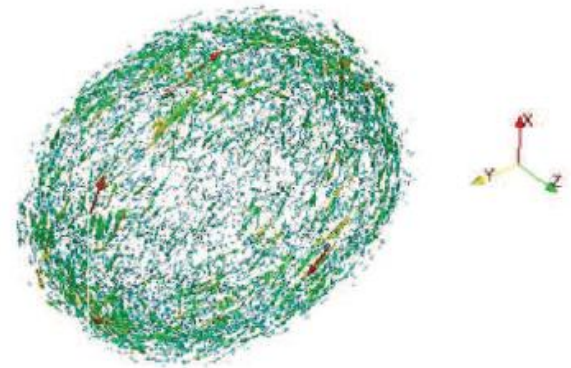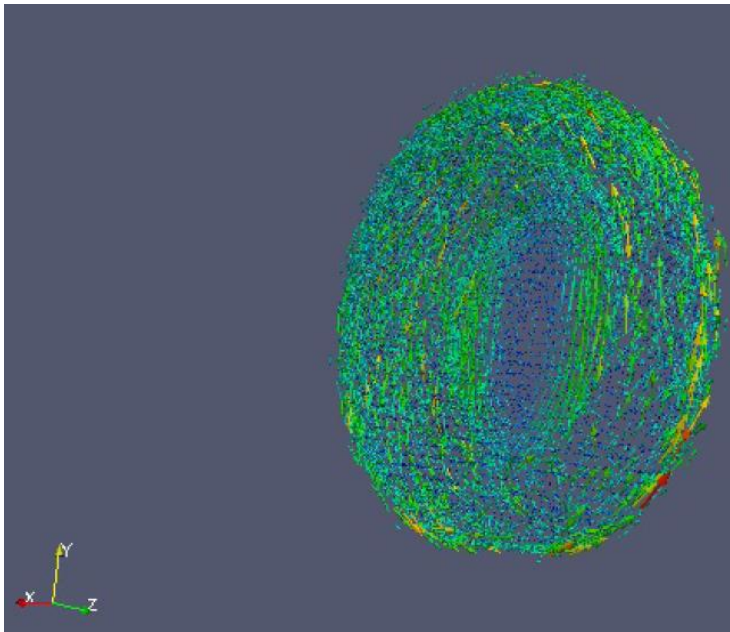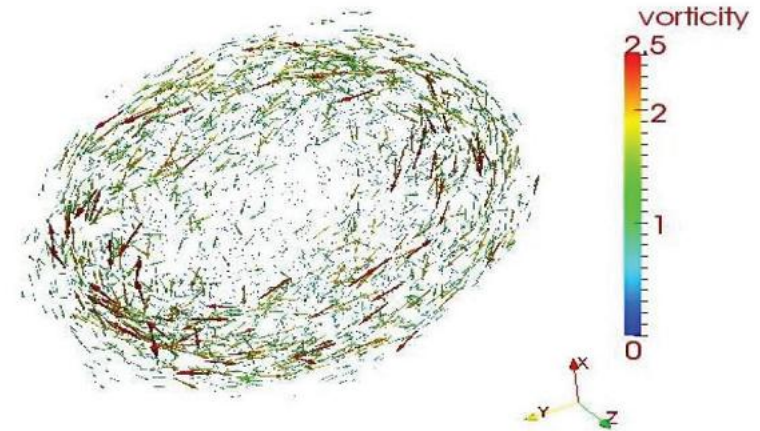
Distribution of velocity ("Small Bang")

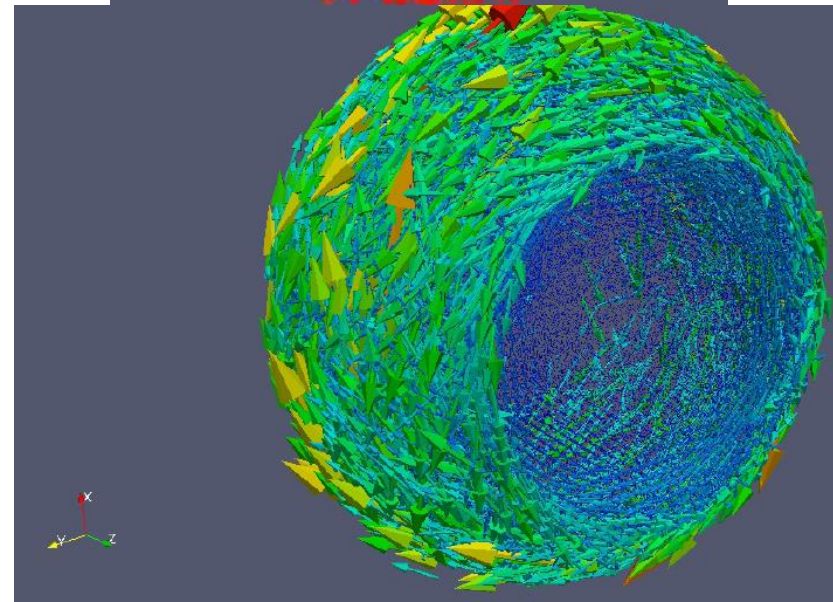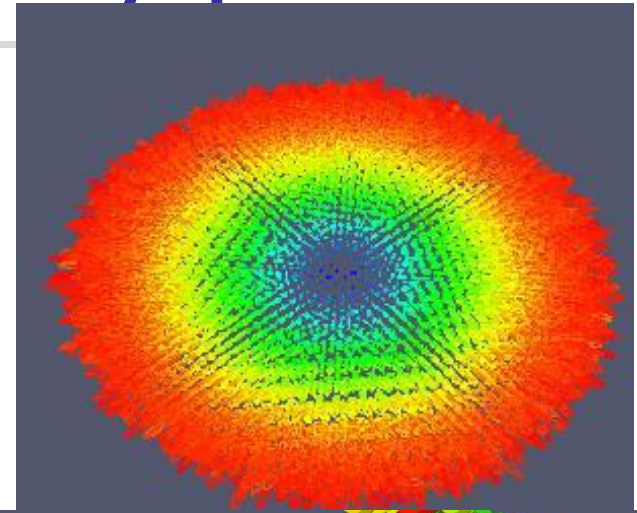- 3D/2D projection

- z-beams direction

- x-impact paramater

Distribution of vorticity ("small galaxies")

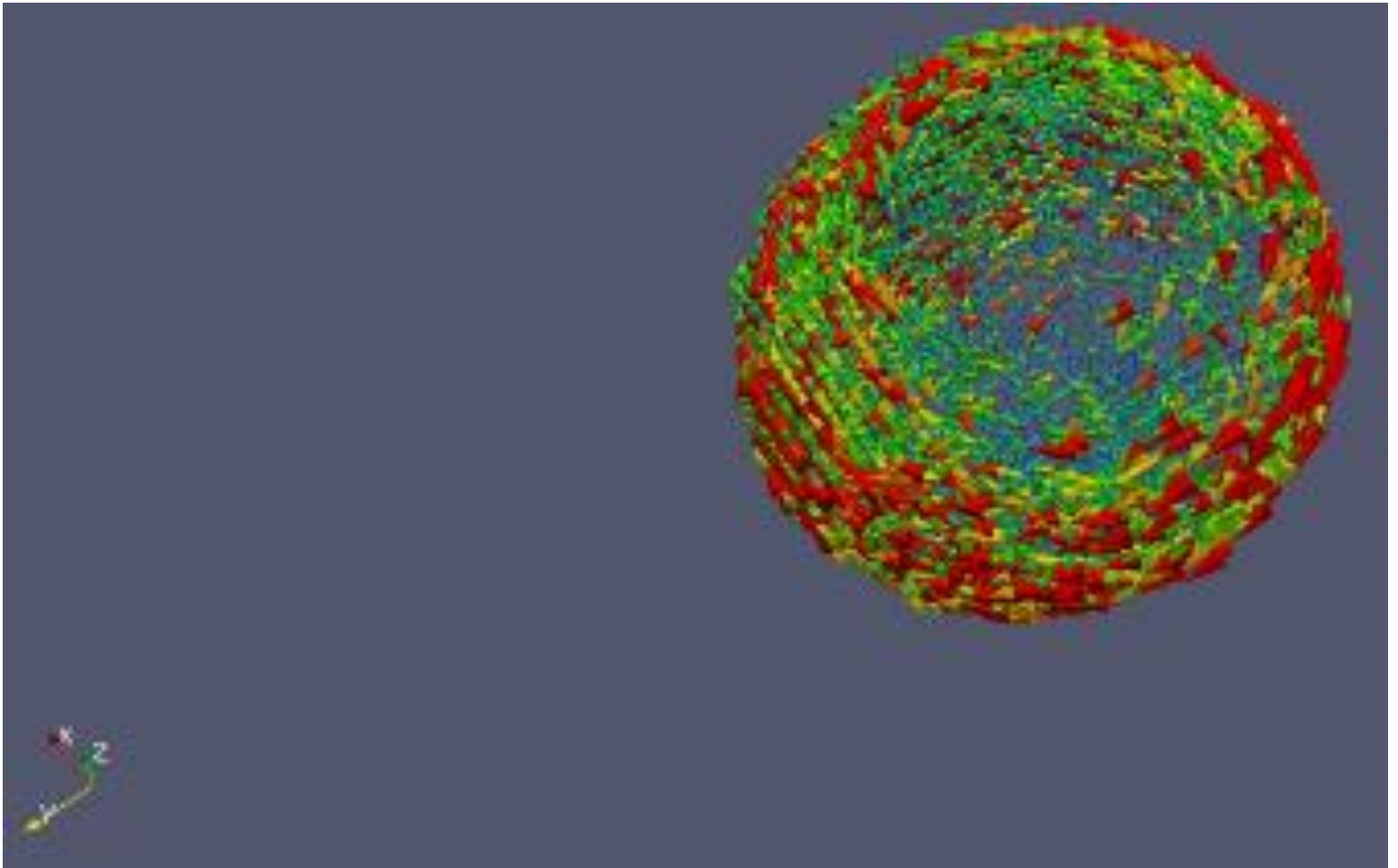- Layer (on core - corona borderline) patterns
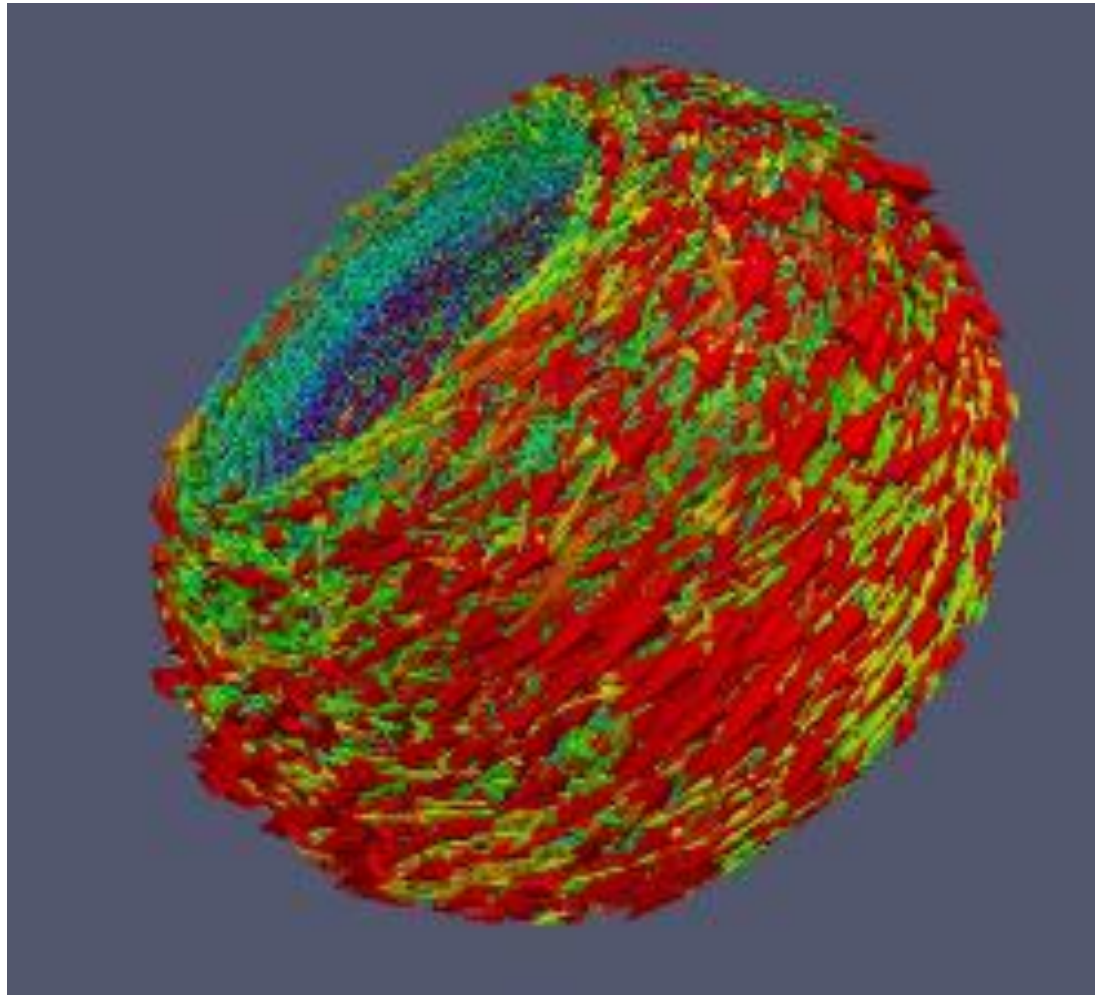
Velocity and vorticity patterns

- Velocity

- Vorticity pattern – vortex sheets - due to L   BUT cylinder symmetry!
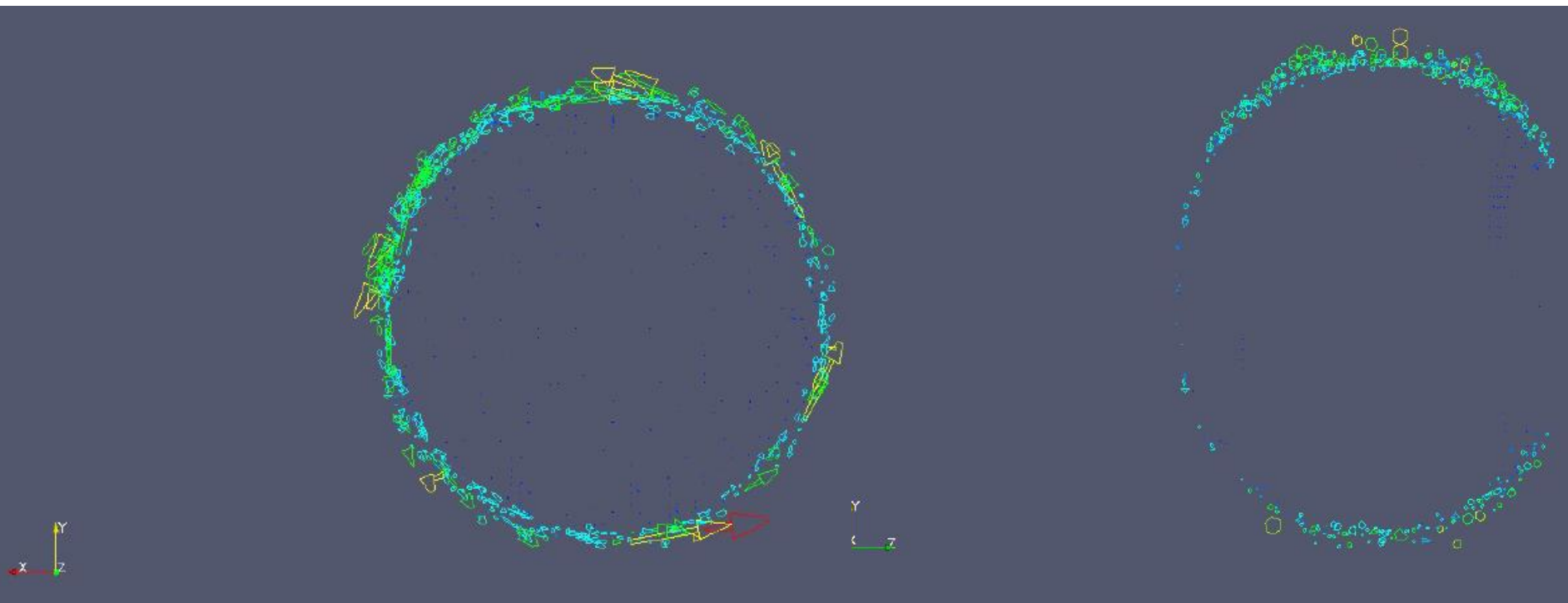
Vortex sheet (fixed direction of L)

Vortex sheet （Average over L directions ）

Sections of vorticity patterns

- Front and side views
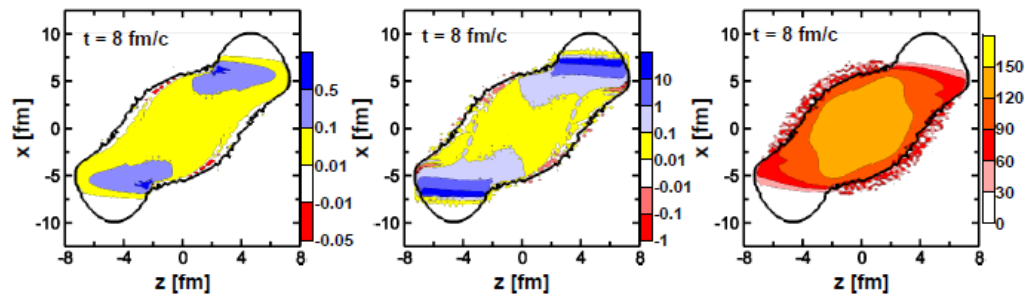
Vortex sheets

- Naturally appears in kinetic models
- Absent in viscous HD (L. Csernai et al)
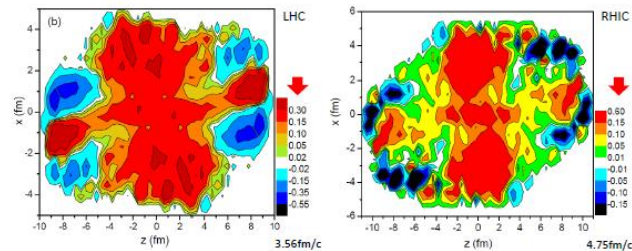
- Appears in 3 fluid dynamics model (Yu. Ivanov, A. Soldatov, **arXiv:1701.01319**)

Helicity separation in QGSM
PRC88 (2013) 061901

- Total helicity integrates to zero BUT
- Mirror helicities below and above the reaction plane
- Confirmed in HSD (OT, Usubov, PR**C92 (2015) 014906**
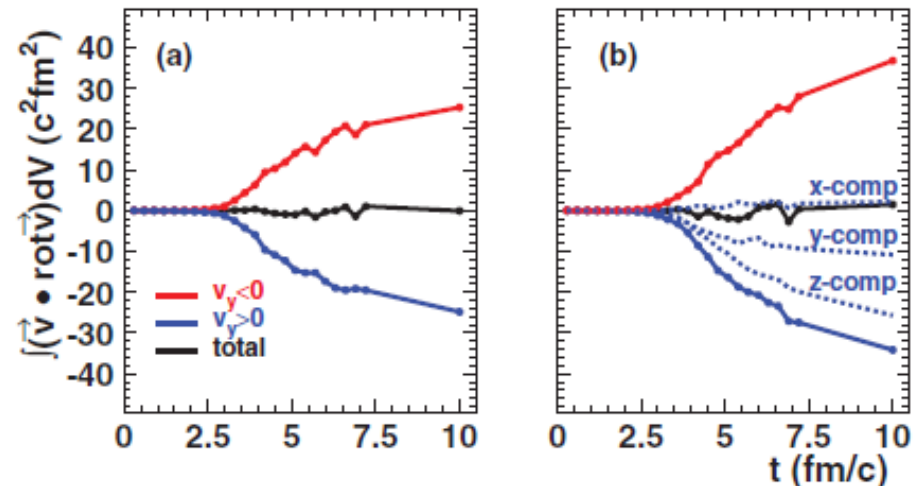
What is the relative orientation of velocity and vorticity?

- Measure – Cauchy-Schwarz inequality
- Small but non-negligible correlation
- Maximal correlation - Beltrami flows

PHYSICAL REVIEW C 88, 061901(R) (2013)
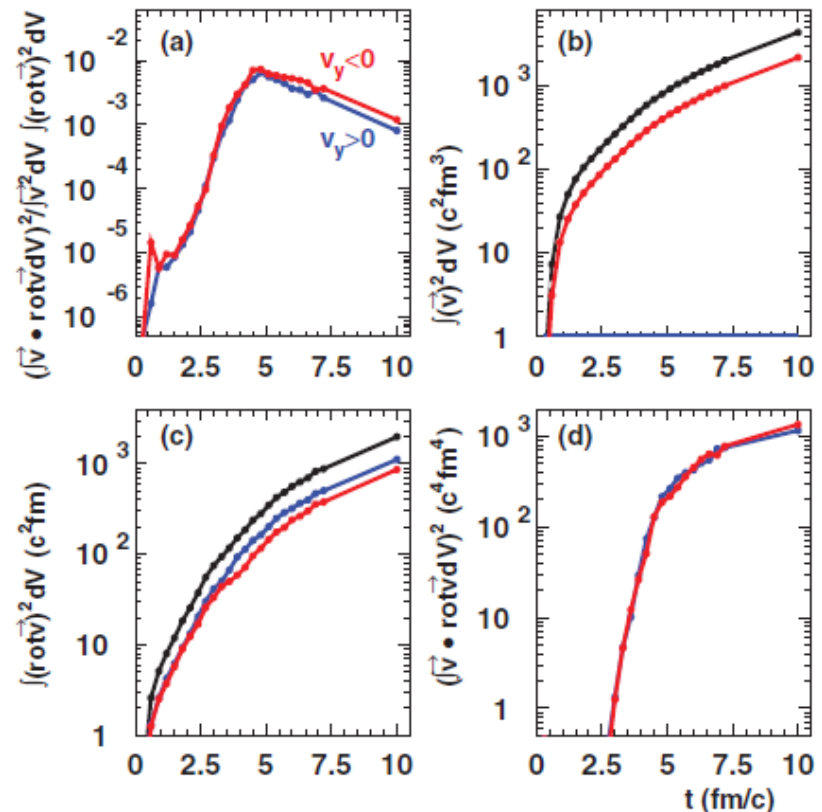
Chemical potential : Kinetics -> TD

- TD and chemical equilibrium
- Conservation laws
- Chemical potential from equilibrium distribution functions
- 2d section: y=0

Chemical potential
^{197}Au + ^{197}Au $s^{1/2}$=5 A GeV b=8fm
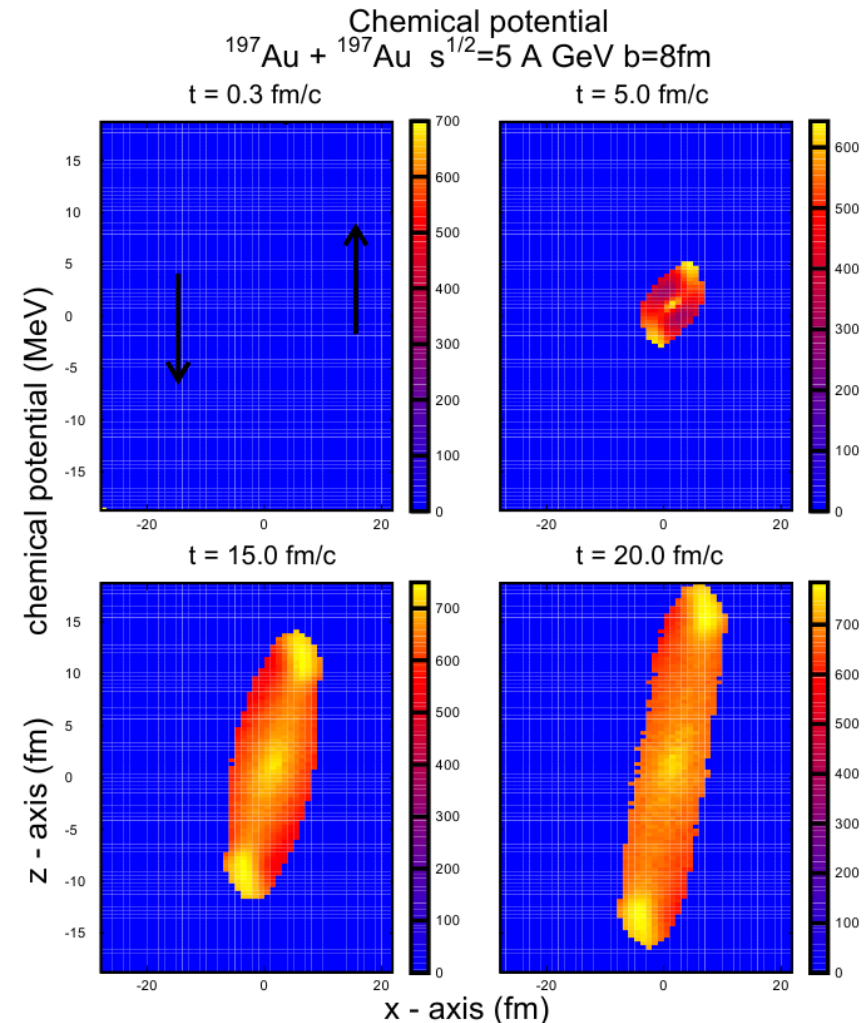
Strange chemical potential (polarization of Lambda is carried by strange quark!)

- Non-uniform in space and time

Strange chemical potential
$^{197}Au + ^{197}Au \ s^{1/2}=5 \ A \ GeV \ b=8fm$

Temperature

Temperature
$^{197}Au + ^{197}Au \ s^{1/2}=5$ A GeV b=8fm
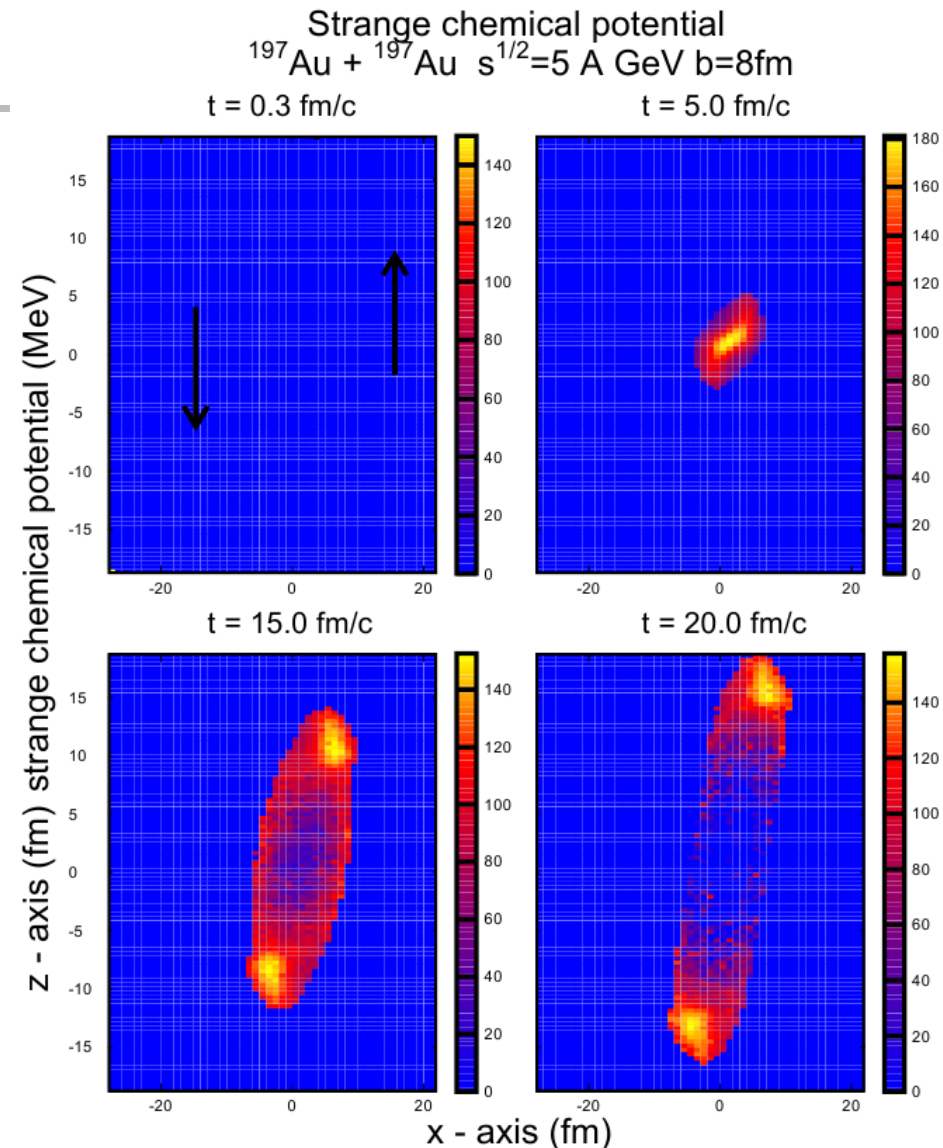
From axial charge to polarization

- Analogy of matrix elements and classical averages

$$< p_n|j^0(0)|p_n >= 2p_n^0 Q_n \qquad < Q > \equiv \frac{\sum_{n=1}^{N} Q_n}{N} = \frac{\int d^3x\, j^0_{class}(x)}{N}$$

- Lorentz boost: compensate the sign of helicity

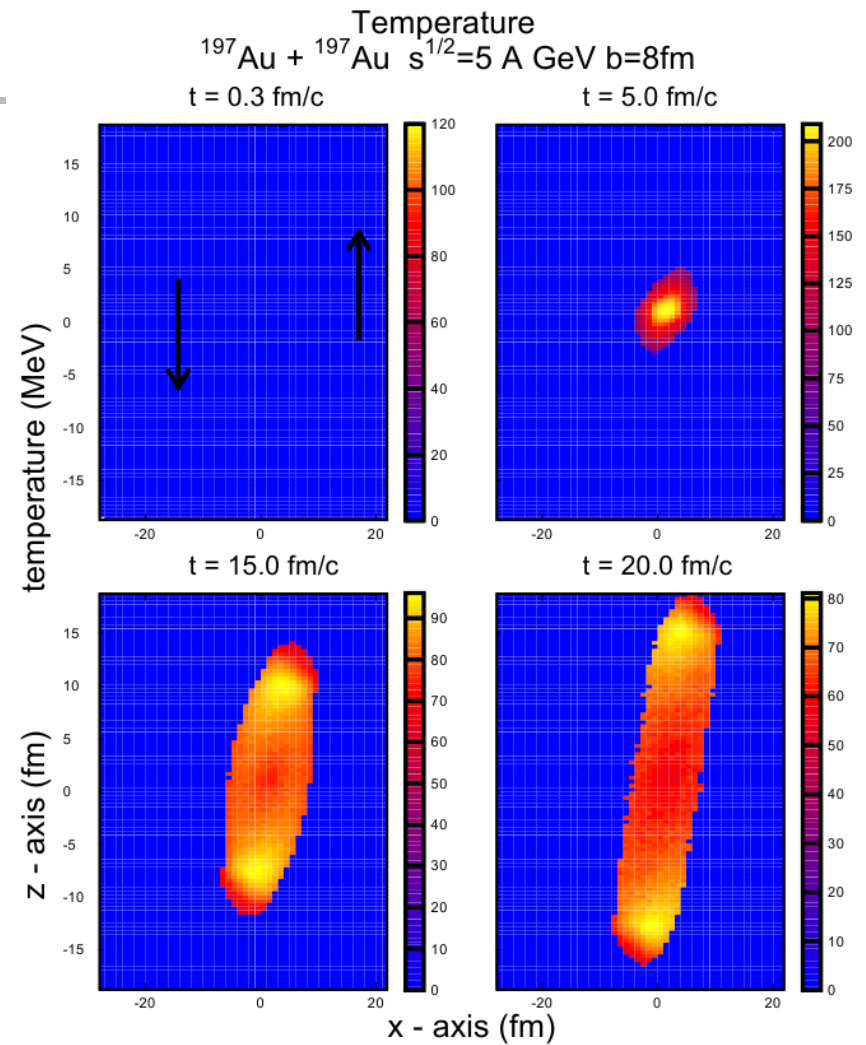$$\Pi^{\Lambda,lab} = (\Pi_0^{\Lambda,lab}, \Pi_x^{\Lambda,lab}, \Pi_y^{\Lambda,lab}, \Pi_z^{\Lambda,lab}) = \frac{\Pi_0^{\Lambda}}{m_\Lambda}(p_y, 0, p_0, 0)$$

$$< \Pi_0^{\Lambda} > = \frac{m_\Lambda\, \Pi_0^{\Lambda,lab}}{p_y} = < \frac{m_\Lambda}{N_\Lambda\, p_y} > Q_5^s \equiv < \frac{m_\Lambda}{N_\Lambda\, p_y} > \frac{N_c}{2\pi^2} \int d^3x\, \mu_s^2(x)\gamma^2 \epsilon^{ijk} v_i \partial_j v_k$$

- Antihyperons (smaller N) : same sign and larger value (confirmed by STAR)

Helicity -> rest frame polarization

- Helicity ~ 0th component of polarization in lab. frame – effect of boost to Lambda rest frame – various options

$$\Pi_0(y) = 1/(4\pi^2) \int \gamma^2(x)\mu_s^2(x) |v \cdot rot(v)| n_\Lambda(y,x) w_1 d^3x \Big/ \int n_\Lambda(y,x) w_2 d^3x$$

$w_1 = 1, \quad w_2 = 1$ $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad w_1 = 1, \quad w_2 = p_y/m$
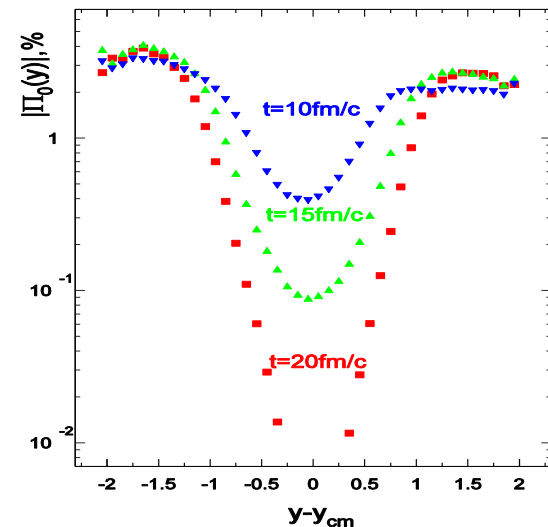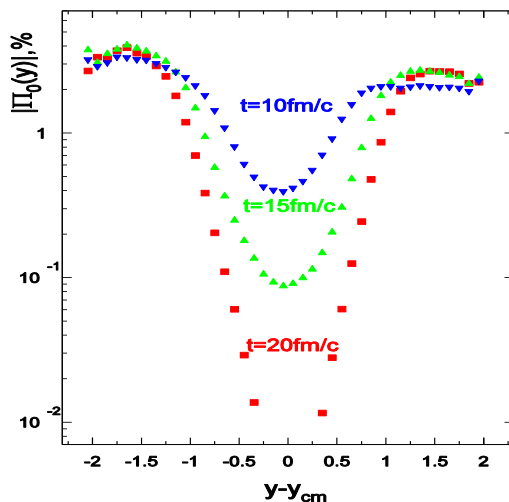
Various methods of boost implementation
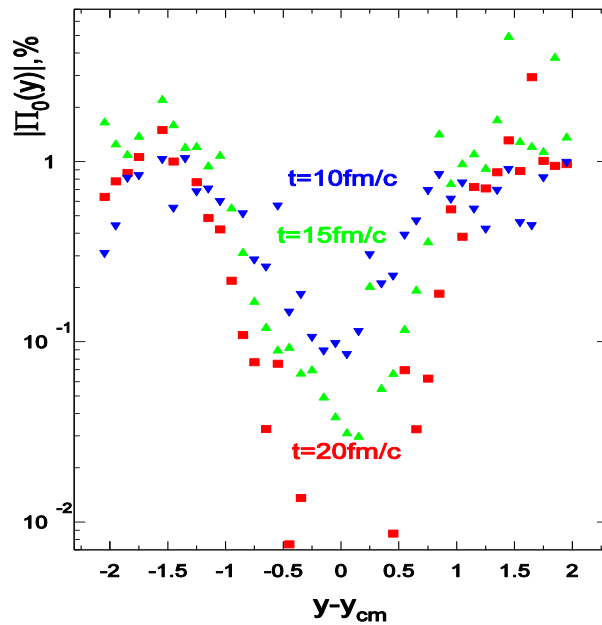
- $w_1 = m/p_y,$ $w_2 = 1$ $w_1 = m/p_y,$ $w_2 = p_y/m$
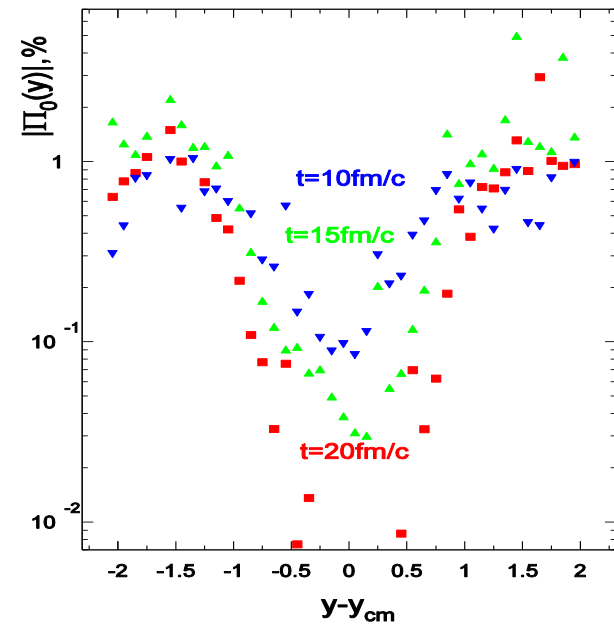
Combining QGSM (thermal)vorticity with TD mechanism (F. Becattini et al., talk of S. Voloshin)

- Temperature – calculated analogously to chemical potential

Plot legend: $t= 5 \times 6$ (black circles), $t=10 \times 4$ (blue triangles), $t=15 \times 2$ (green triangles), $t=20$ fm/c (red squares). Y-axis: $|\Pi_0|$ (%). X-axis: $y - y_{c.m.}$
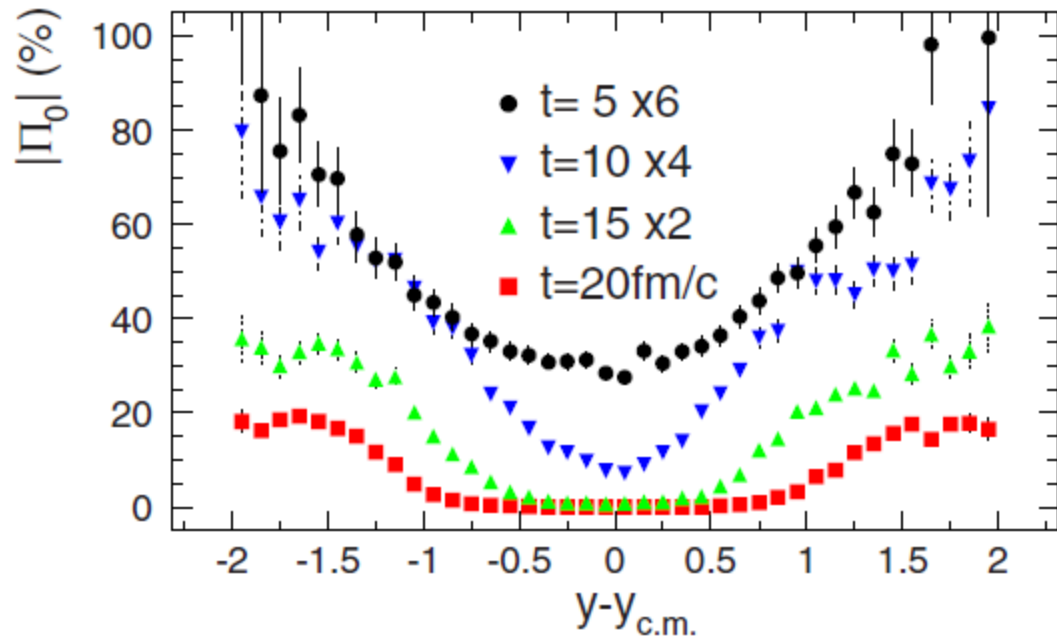
- Similar polarization pattern

Energy dependence

- Growth at low energy

- Surprisingly close to STAR data!

- Structure – may be due to fluctuation for low particles number
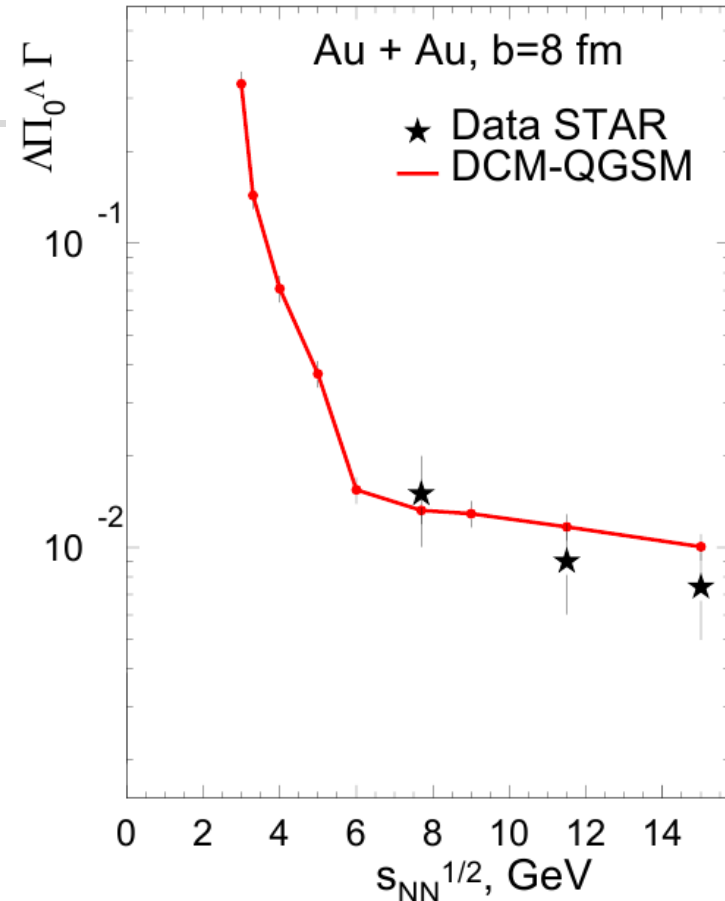
The role of (gravitational anomaly related) T^2 term

- Different values of coefficient probed
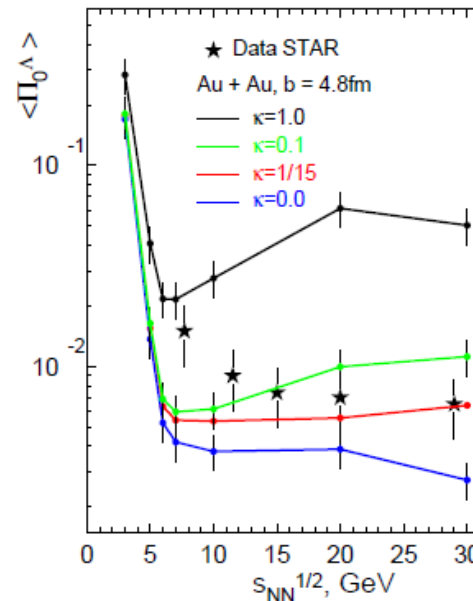
- LQCD suppression by collective effects supported

Polarization at NICA/MPD (A. Kechechyan)

- QGSM Simulations and recovery accounting for MPD acceptance effects

AuAu (LAQGSM)

Role of vector mesons

- Strange axial charge may be also carried by K* mesons
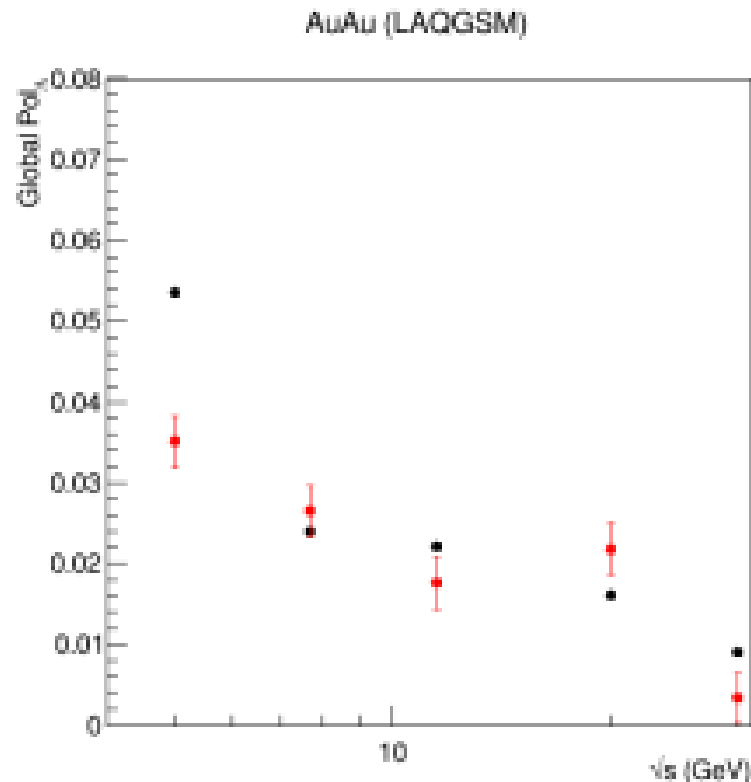
- Λ - accompanied by (+,anti 0) K* mesons with two sea quarks – small corrections

- Anti Λ – more numerous (-,0) K* mesons with single (sea) strange antiquark – makes polarization enhancement smaller and better compatible to the data (work in progress)

- Vector polarization implies also tensor polarization (HIC – Bratkovskaya, OT, Toneev, **Phys.Lett. B348 (1995) 283-289**) – measurable in decay (dilepton) angular distributions

Conclusions/Outlook

- Polarization – new probe of anomaly in quark-gluon matter (to be studied at NICA/FAIR)

- Generated by femto-vortex sheets

- Energy dependence predicted and confirmed

- Same sign and larger magnitude of antihyperon polarization

- T-dependent term due to gravitational anomaly may be extracted from the data

- Anomalous mechanism may be combined with other models for calculation of velocity/vorticity/helicity

- QGSM may be conbined with other mechanisms of polarization generation

BACKUP

Properties of SSA

The same for the case of initial or final state polarization.

Various possibilities to measure the effects: change sign of $\vec{n}$ or $\vec{P}$: left-right or up-down asymmetry.

Qualitative features of the asymmetry

Transverse momentum required (to have $\vec{n}$)

Transverse polarization (to maximize $(\vec{P}\vec{n})$)

Interference of amplitudes

IMAGINARY phase between amplitudes - absent in Born approximation

Phases and T-oddness

Clearly seen in relativistic approach:

$\rho = \frac{1}{2}(\hat{p} + m)(1 + \hat{s}\gamma_5)$

Than: $d\sigma \sim Tr[\gamma_5 ....] \sim im\varepsilon_{sp_1p_2p_3}...$

Imaginary parts (loop amplitudes) are required to produce real observable.

$\varepsilon_{abcd} \equiv \varepsilon^{\alpha\beta\gamma\delta} a_\alpha b_\beta c_\gamma d_\delta$ each index appears once: $P-$ (compensate S) and $T-$ odd.

However: no real $T-$violation: interchange $|i> \leftrightarrow |f>$ is the nontrivial operation in the case of nonzero phases of $<f|S|i>^* = <i|S|f>$.
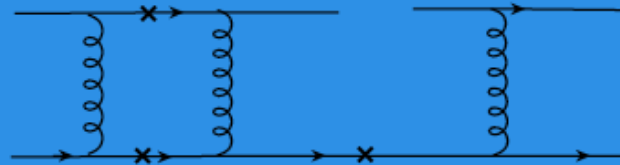
SSA - either T-violation or the phases.

DIS - no phases ($Q^2 < 0$)- real T-violation.

Perturbative PHASES IN QCD

QCD factorization: where to borrow imaginary parts?
Simplest way: from short distances - loops in partonic subprocess. Quarks elastic scattering (like $q - e$ scattering in DIS):
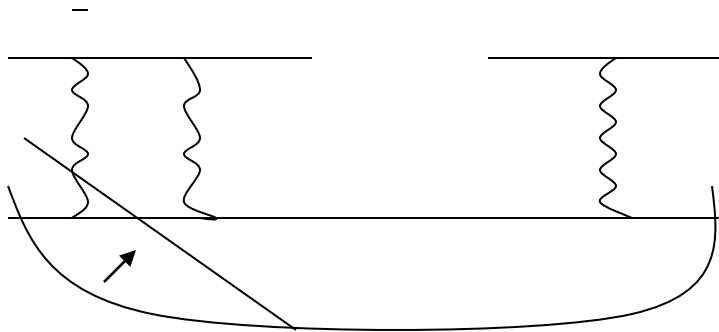

$$A \sim \frac{\alpha_S m p_T}{p_T^2 + m^2}$$

Large SSA "...contradict QCD or its applicability"

Short+ large overlap– twist 3

- Quarks – only from hadrons
- Various options for factorization – shift of SH separation

- New option for SSA: Instead of 1-loop twist 2 – Born twist 3 (quark-gluon correlator): Efremov, OT (85, Fermionic poles); Qiu, Sterman (91, GLUONIC poles)
- Further shift to large distances – T-odd fragmentation functions (Collins, dihadron, handedness)