Vorticity and Lambda polarization in baryon rich matter

Strangeness in Quark Matter

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Oleg Teryaev(JINR)

in collaboration with

Mircea Baznat, Konstantin Gudima (IAP, Chisinau)

George Prokhorov, Alexander Sorin (JINR)

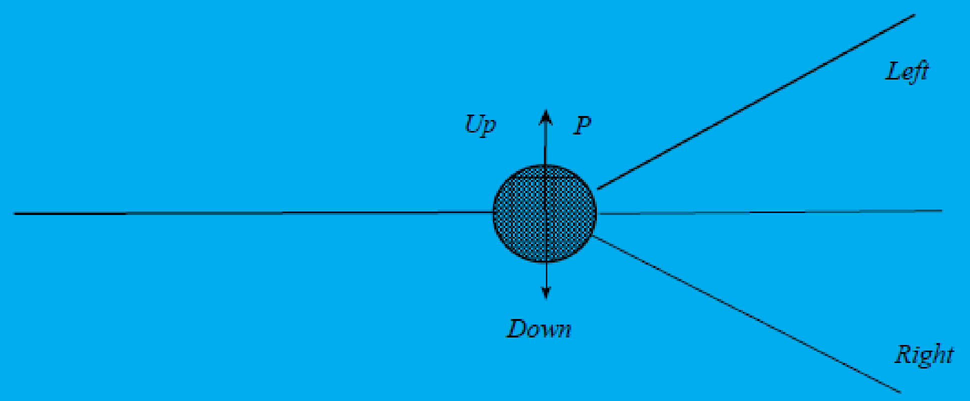
Valentin Zakharov (ITEP)

Main Topics

- Polarization: from nucleons to ions
- Anomalous mechanism: 4-velocity as gauge field
- Chemical potential and Energy dependence
- Rotation in heavy-ion collisions: Vortical structures
- Baryons vs antibaryons
- Comparison of approaches
- Conclusions

Single Spin Asymmetries

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

SSA

- Parity conservation – normal to scattering plane
- Interference – LS coupling
- QCD for hadrons – quark-gluon correlations : twist 3 (fermionic poles: Efremov, OT'85; gluonic poles: Qiu,Sterman'91)

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
- But is the randomization complete (smoothly from hadrons to ions)?!

Global polarization

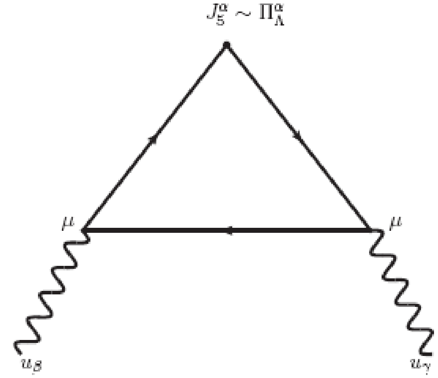
- Global polarization normal to REACTION plane
- Predictions (Z.-T.Liang et al.): large orbital angular momentum -> large polarization
- Search by STAR (Selyuzhenkov et al.'07) : polarization NOT found at % level!
- Maybe due to locality of LS coupling while large orbital angular momentum is distributed
- How to transform rotation to spin?

Anomalous mechanism – polarization similar to CM(V)E

- 4-Velocity is also a GAUGE FIELD (V.I. Zakharov et al)

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

- 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
- Rapid decrease with energy
- 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)

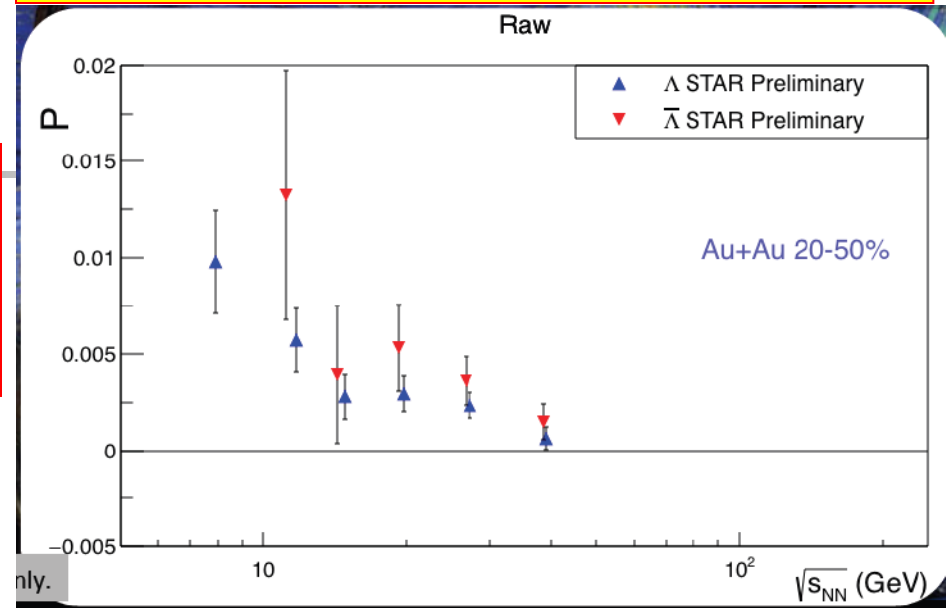
One would expect that polarization is proportional to the anomalously induced axial current [7]

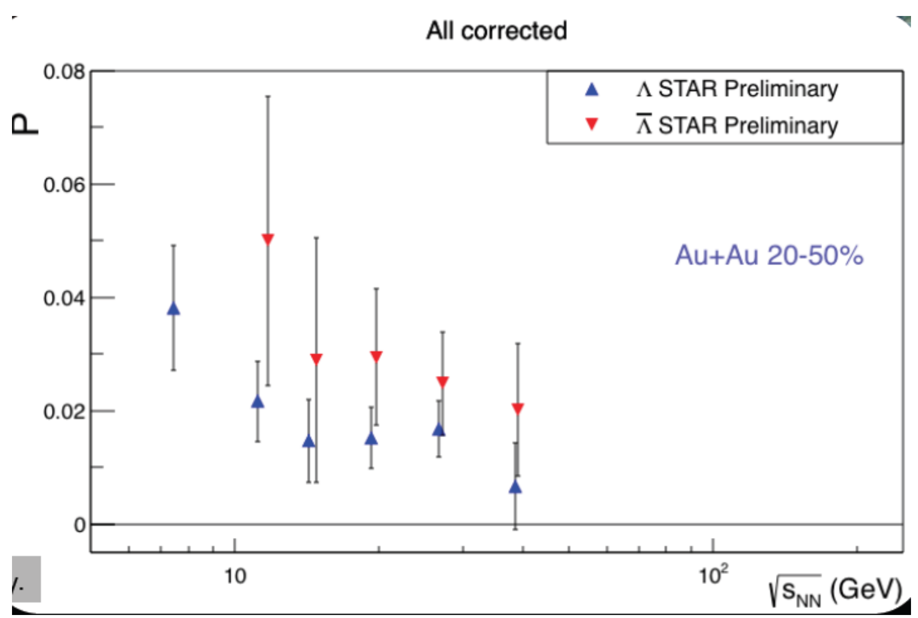
$$j_A^{\mu} \sim \mu^2 \left(1 - \frac{2\mu n}{3(\epsilon + P)}\right) \epsilon^{\mu\nu\lambda\rho} V_\nu \partial_\lambda V_\rho, \quad (6)$$

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.

M. Lisa, for the STAR collaboration , QCD Chirality Workshop, UCLA, February 2016;
SQM2016, Berkeley, June 2016





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/QGSM) – Boltzmann type eqns + phenomenological string amplitudes): Baznat,Gudima,Sorin,OT, PRC'13,16

Rotation in HIC and related quantities

- Non-central collisions – orbital angular momentum
- L=Σ r x p
- Differential pseudovector characteristics – vorticity
- ϖ = curl v
- Pseudoscalar – helicity
- H ~ <(v curl v)>
- Maximal helicity – Beltrami chaotic flows v || curl v

Simulation in QGSM (Kinetics -> HD)

$50 \times 50 \times 100$ cells $\quad dx = dy = 0.6$ fm, $dz = 0.6/\gamma$ fm

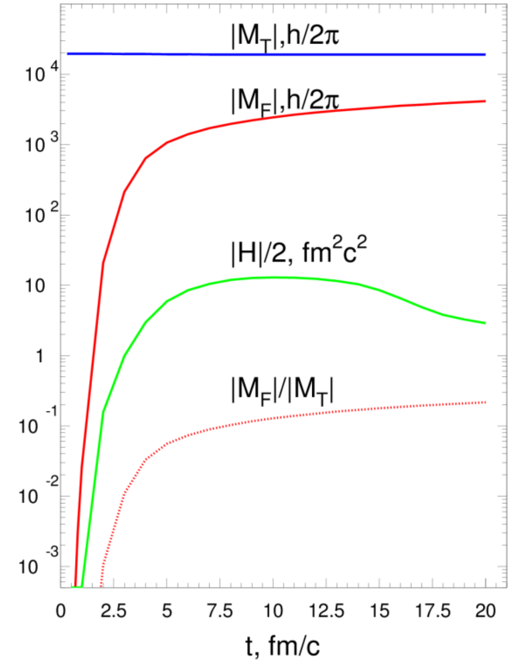
- Velocity

$$\vec{v}(x, y, z, t) = \frac{\sum_i \sum_j \vec{P}_{ij}}{\sum_i \sum_j E_{ij}}$$

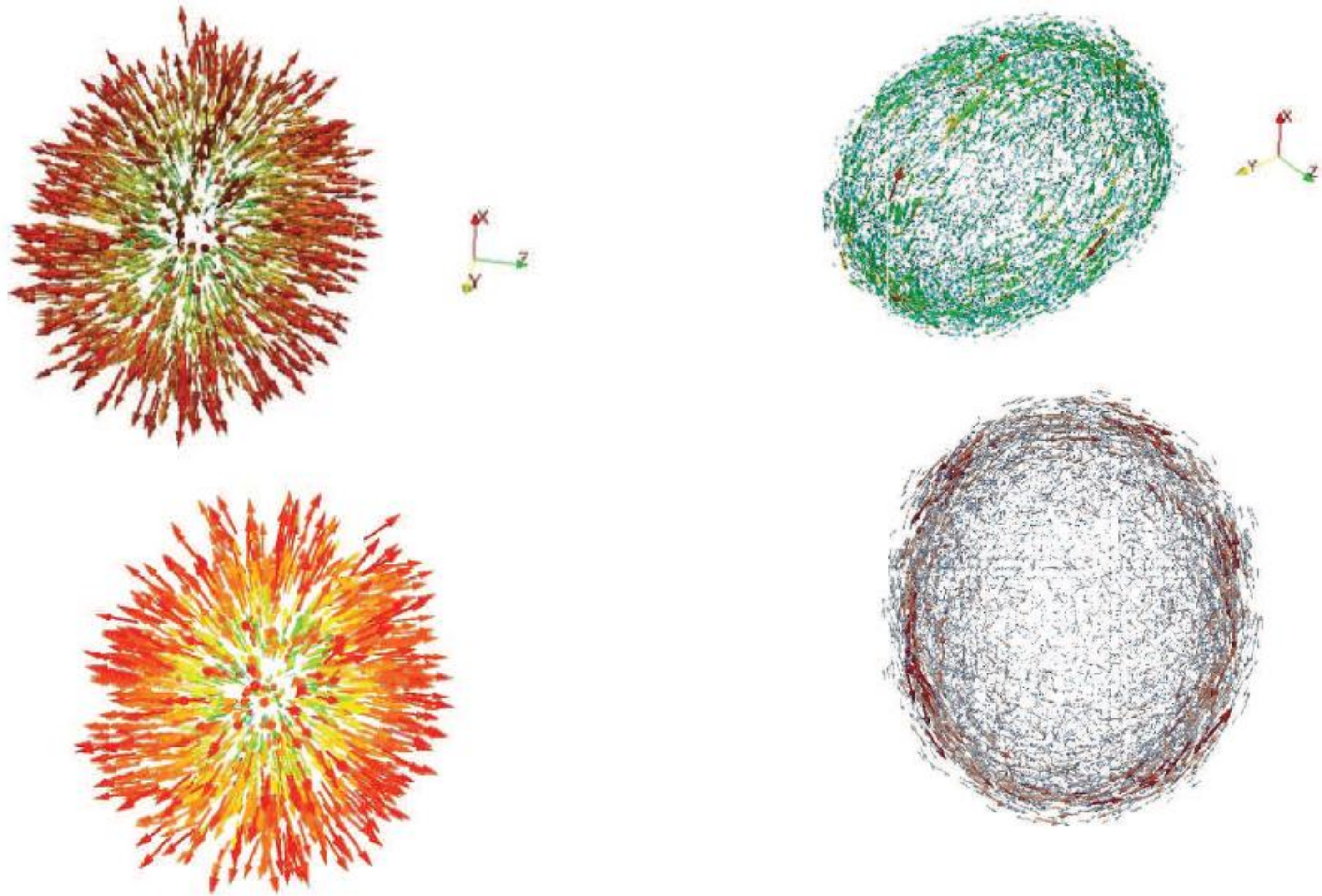
- Vorticity – from discrete partial derivatives

Angular momentum conservation and helicity

- Helicity vs orbital angular momentum (OAM) of fireball
- (~10% of total)
- Conservation of OAM with a good accuracy!

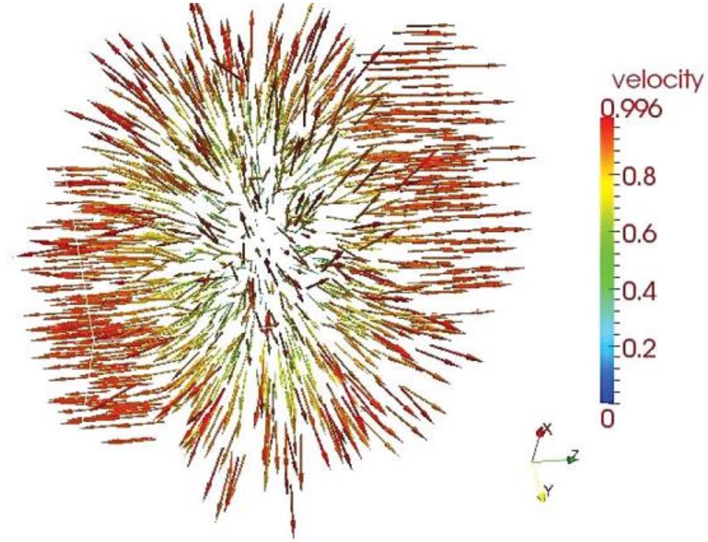


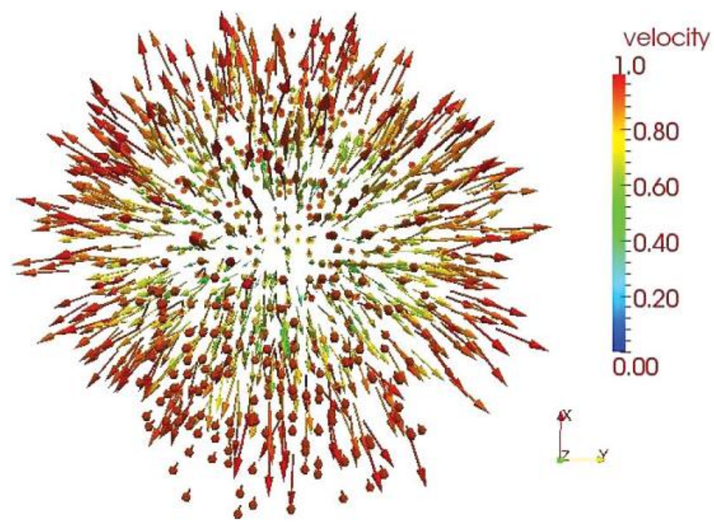
Structure of velocity and vorticity fields (NICA@JINR-5 GeV/c)



Distribution of velocity ("Little Bang")

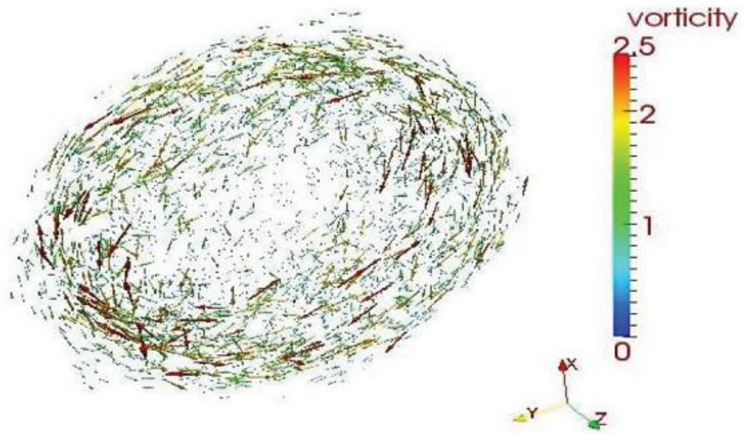
- 3D/2D projection
- z-beams direction
- x-impact paramater

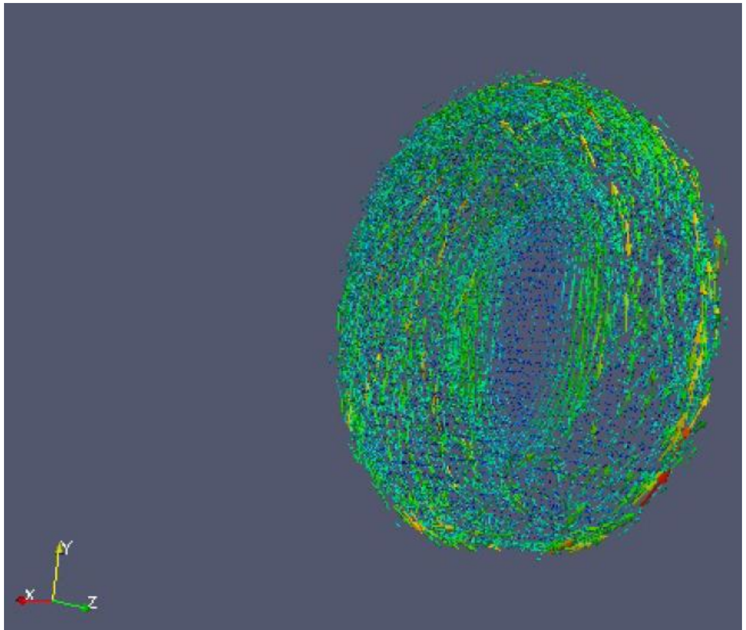


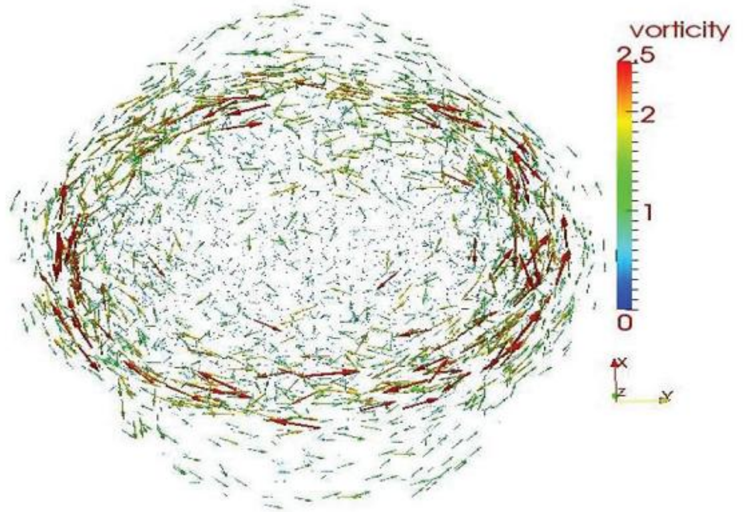


Distribution of vorticity ("Little galaxies")

- Layer (on core - corona borderline) patterns

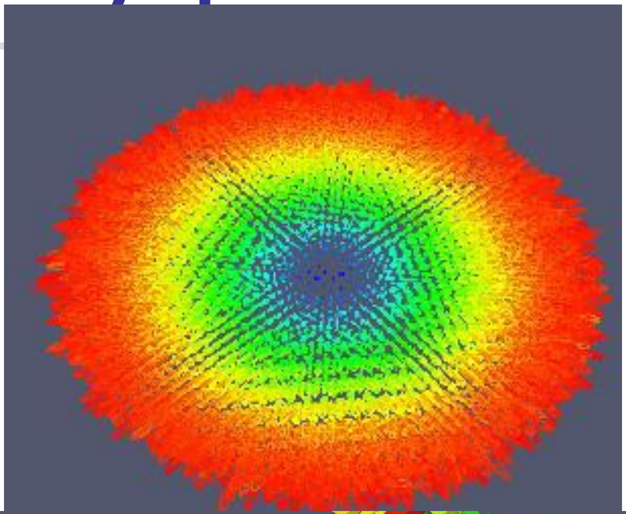




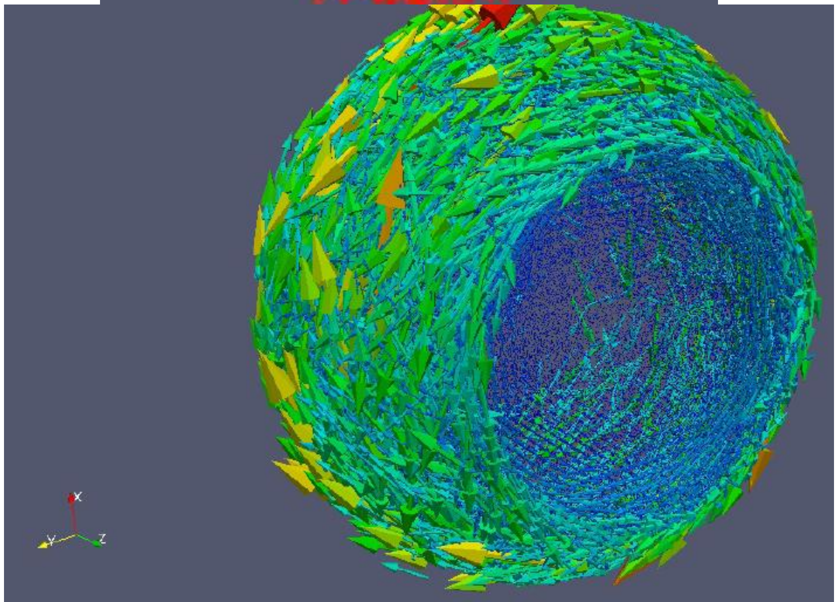


Velocity and vorticity patterns

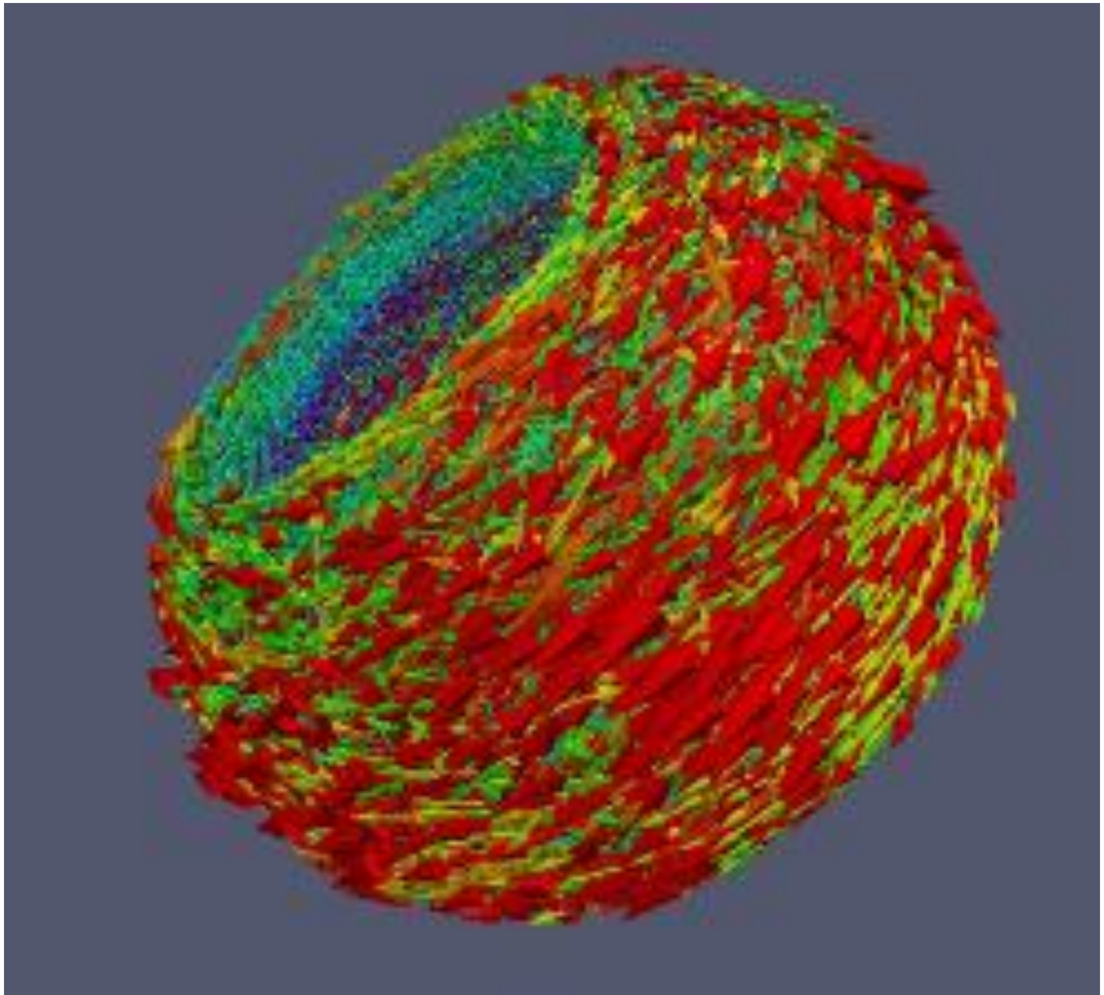
- Velocity



- Vorticity pattern – vortex sheets

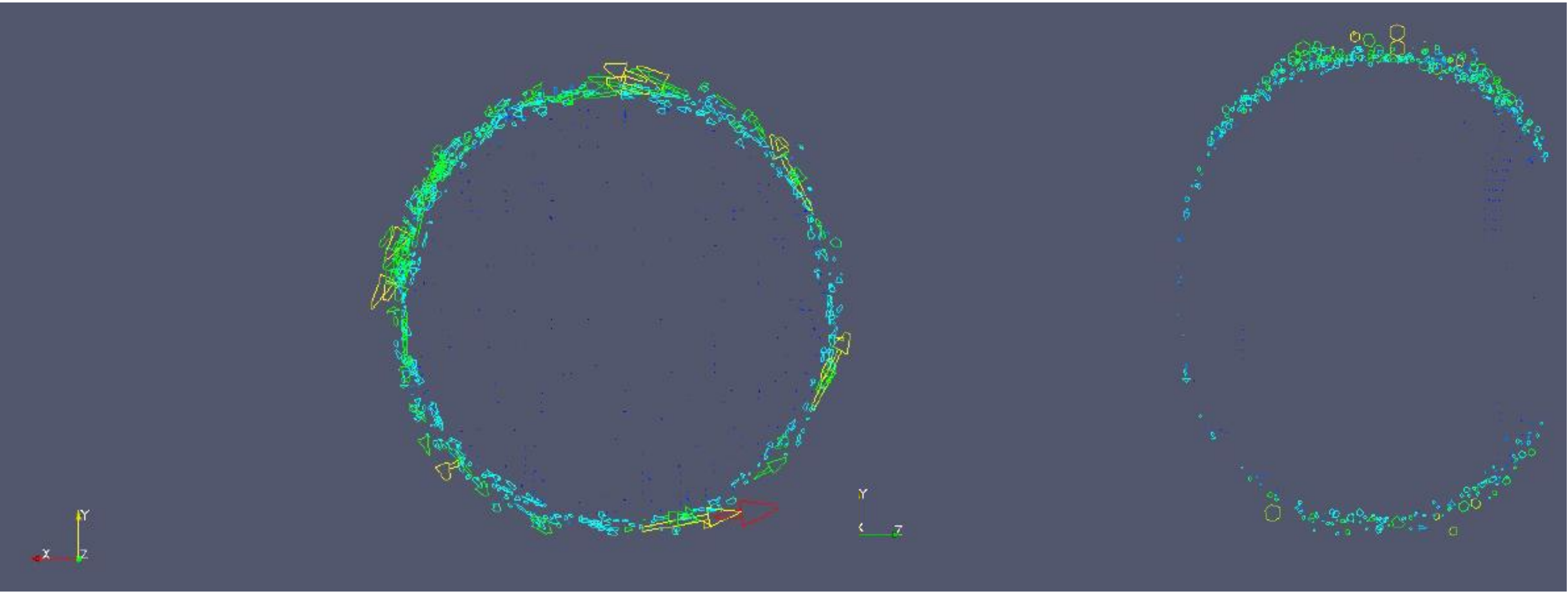


Vortex sheet



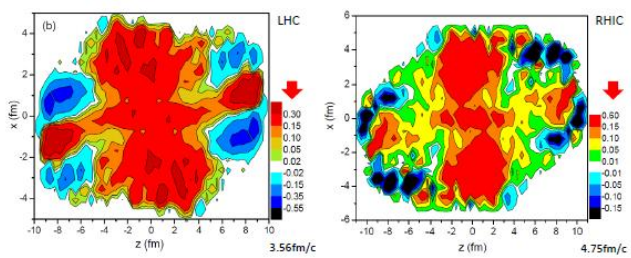
Sections of vorticity patterns

- Front and side views

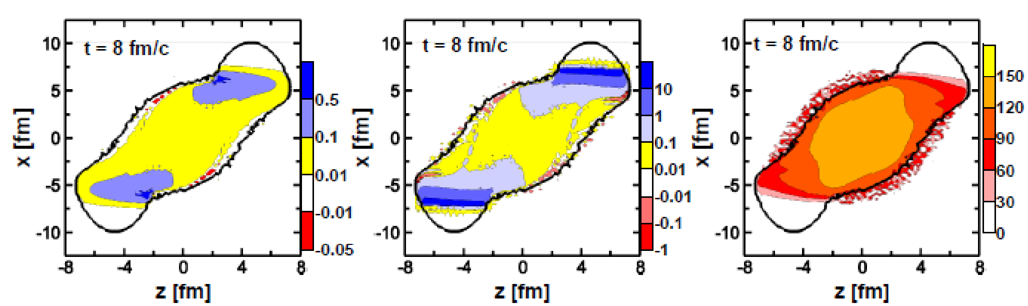


Vortex sheets

- Naturally appears in kinetic models
- Absent in viscous HD (L. Csernai et al)

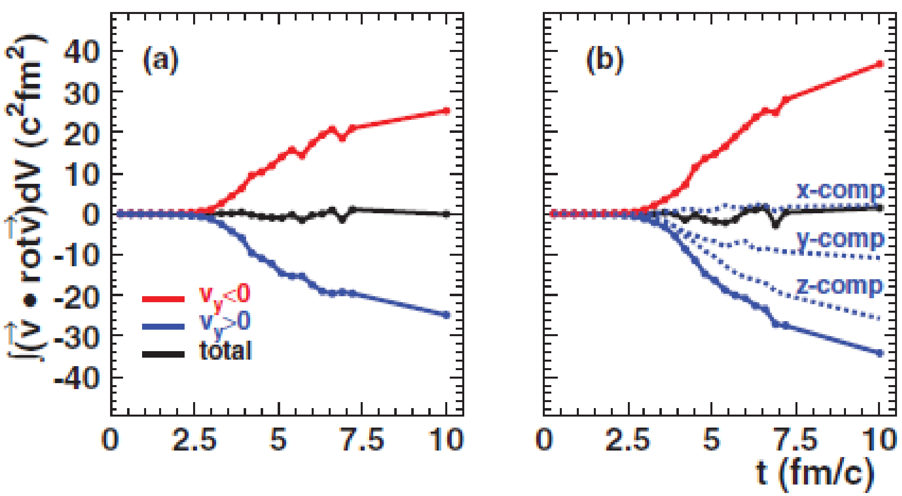


- Appears in 3 fluid dynamics model (Yu. Ivanov, A. Soldatov, **arXiv:1701.01319**)



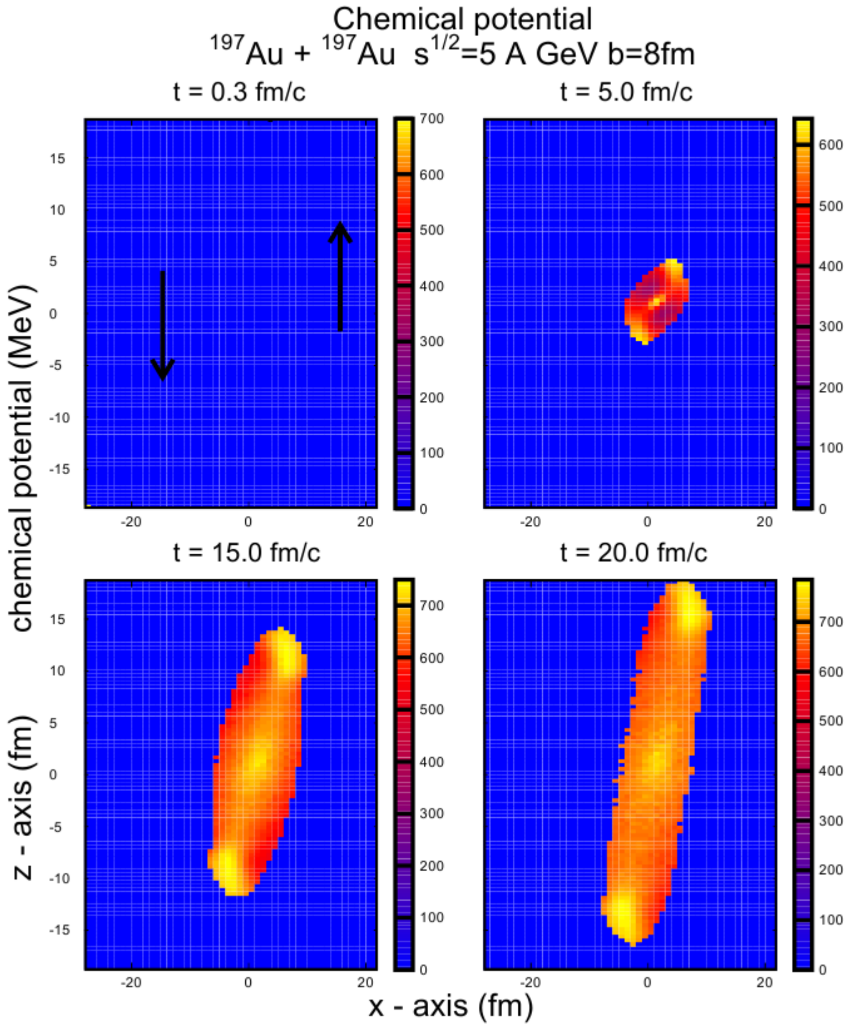
Helicity separation in QGSM **PRC88 (2013) 061901**

- Total helicity integrates to zero BUT
- Mirror helicities below and above the reaction plane
- Confirmed in HSD (OT, Usubov, PR**C92 (2015) 014906**



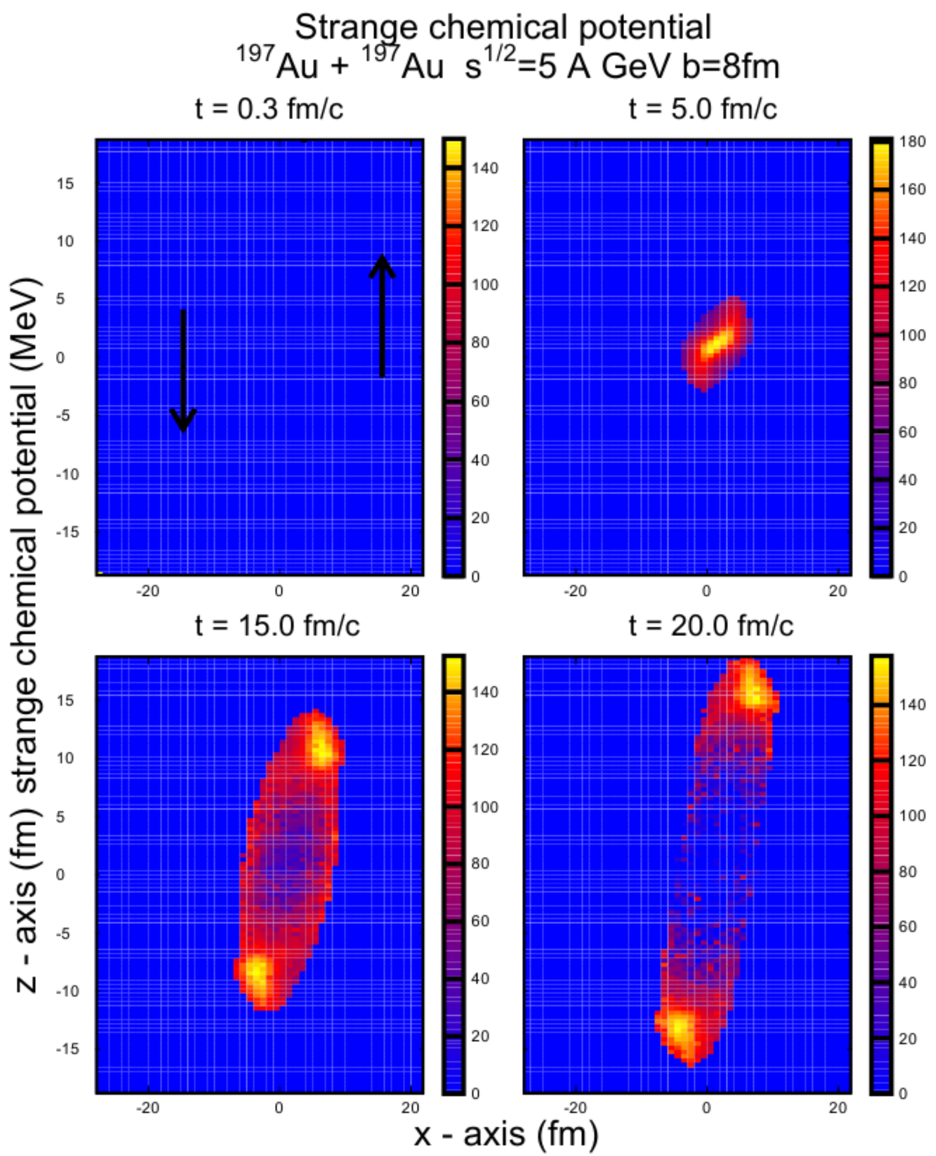
Chemical potential : Kinetics -> TD

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

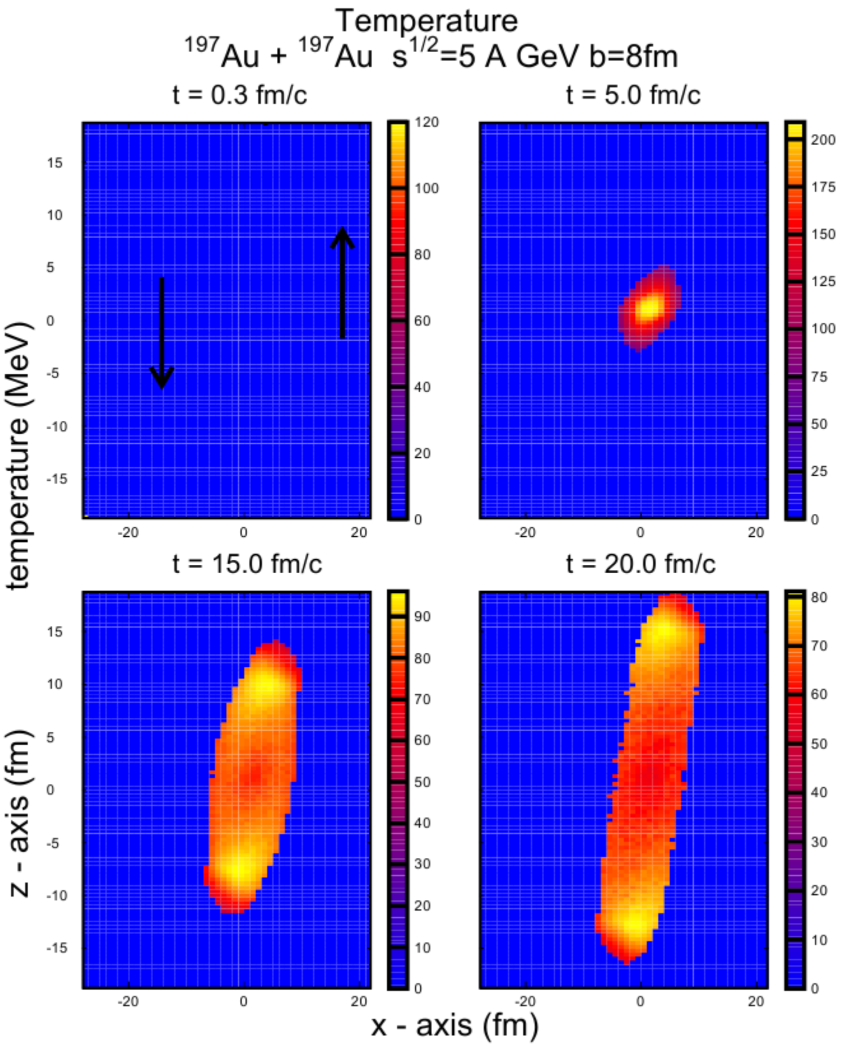


Strange chemical potential (polarization of Lambda is carried by strange quark!)

- Non-uniform in space and time



Temperature



From axial charge to polarization (and from quarks to confined hadrons) – analog of Cooper-Frye

- 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

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

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

Axial charge and properties of polarization

- Polarizationis enhanced for particles with small transverse momenta – azimuthal dependence naturally emerges
- Antihyperons : same sign (C-even axial charge) and larger value (smaller N)
- More pronounced at lower energy BUT
- Baryon/antibaryon splitting due to magnetic field – increase with energy
- Recent STAR data (talks of W. Zha, S. Voloshin) support polarization for particles with angles close to reaction plane and closeness of baryons and antibaryons polarization at 200 GeV

Other approach to baryons in confined phase: vortices in pionic superfluid (V.I. Zakharov, OT:1705.01650)

- Pions may carry the axial current due to quantized vortices in pionic superfluid (Kirilin,Sadofyev,Zakharov'12)

$$j_5^\mu = \frac{1}{4\pi^2 f_\pi^2}\epsilon^{\mu\nu\rho\sigma}(\partial_\nu\pi^0)(\partial_\rho\partial_\sigma\pi^0) \qquad \frac{\pi_0}{f_\pi} = \mu \cdot t + \varphi(x_i) \qquad \oint \partial_i\varphi dx_i = 2\pi n$$

$$\partial_i\varphi = \mu v_i$$

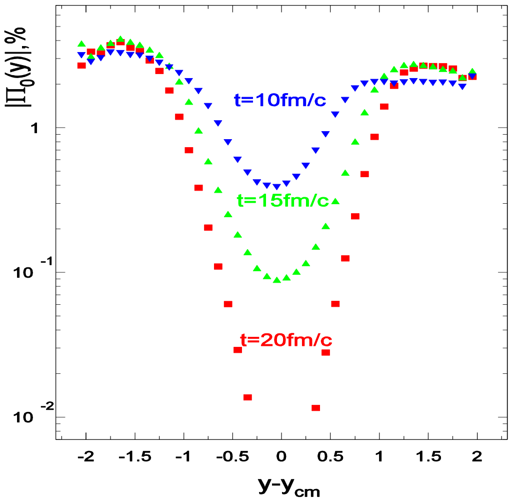
- Suggestion: core of the vortex- baryonic degrees of freedom- polarization

QGSM numerics for polarization

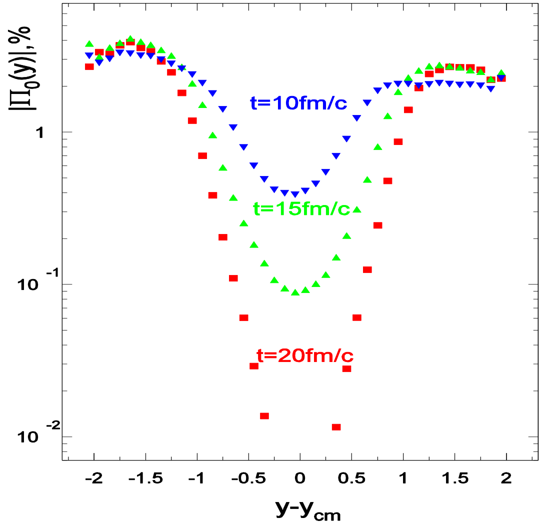
- Helicity ~ 0th component of polarization in lab. frame + effect of boost to Lambda rest frame

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

$w_1=1$, $w2= 1$

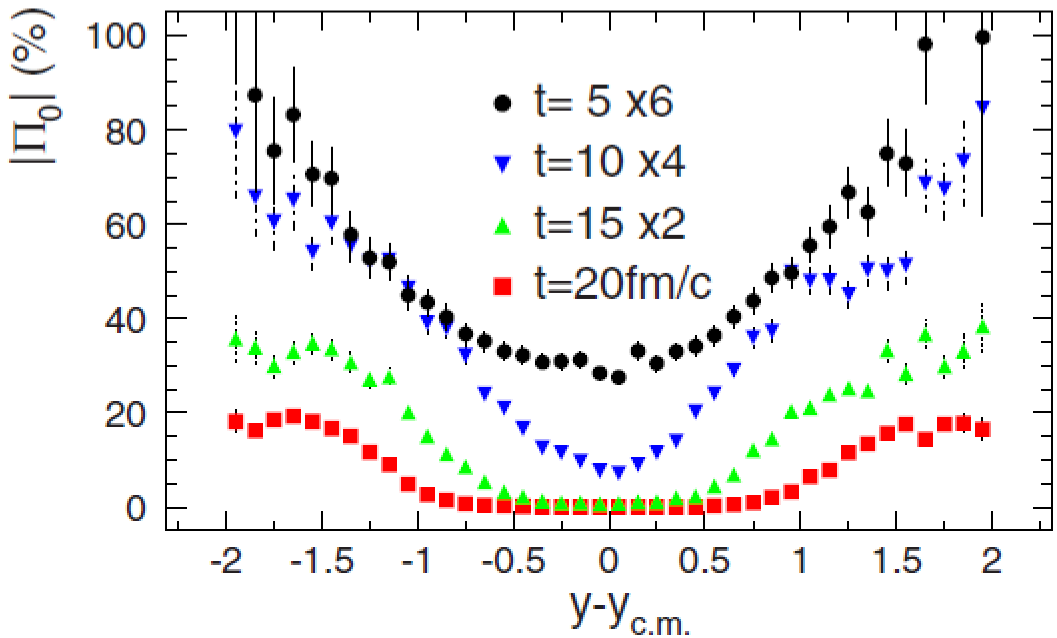


$w_1=1$, $w_2=p_y/m$



Combining QGSM (thermal)vorticity with TD mechanism (talks of F. Becattini, S. Voloshin)

- Thermal vorticity + axial charge



- Similar polarization pattern

Comparison of methods

- Wigner function – induced axial current (triangle diagram– V.I. Zakharov) – Prokhorov (poster), OT,1707.02491

$$\alpha_\mu = \frac{1}{T} u^\nu \partial_\nu u_\mu = \frac{a_\mu}{T}, \quad w_\mu = \frac{1}{2T} \epsilon_{\mu\nu\alpha\beta} u^\nu \partial^\alpha u^\beta = \frac{\omega_\mu}{T}$$

$$\langle : j_\mu^5 : \rangle = \Big(\frac{1}{6} \big[T^2 + \frac{a^2 - \omega^2}{4\pi^2} \big] + \frac{\mu^2}{2\pi^2} \Big) \omega_\mu + \frac{1}{12\pi^2} (\omega \cdot a) \, a_\mu$$

$$\langle : j_\mu^5 : \rangle = 2\pi \, \mathrm{Im} \Big[\big(\frac{1}{6} (T^2 + \varphi^2) + \frac{\mu^2}{2\pi^2} \big) \varphi_\mu \Big] \qquad \varphi_\mu = \frac{a_\mu}{2\pi} + \frac{i\omega_\mu}{2\pi}$$

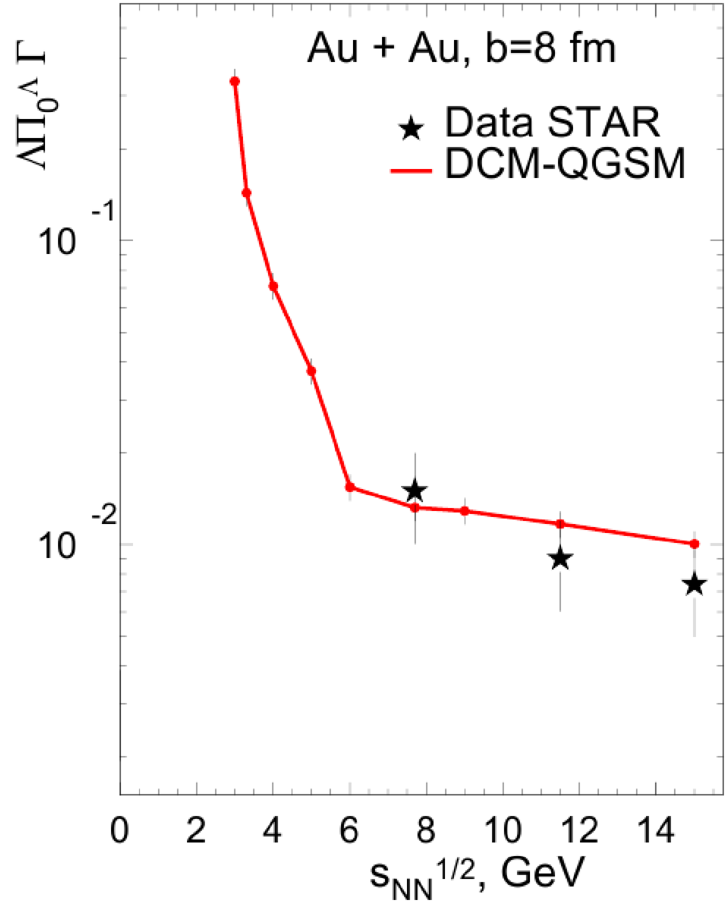
- New terms of higher order in vorticity
- Topological universal acceleration-directed term

Chemical potential and flavour dependence

- Way via axial current/charge differs from direct TD
- TD-Universal (only mass-dependent)polarization(?!)
- Axial current: polarization depends on baryon structure
- Most pronounced at low energies
- Comparison of hyperons polarization (problem for hadronic collisions)

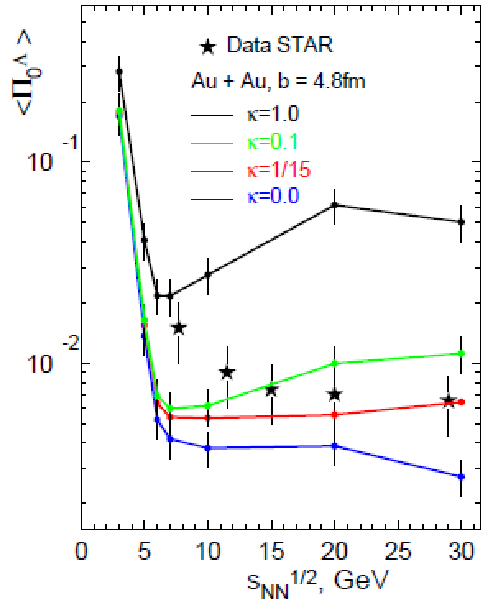
Energy dependence

- Growth at low energy
- Close to STAR data
- Structure – due to low number of Lambdas



The role of (gravitational anomaly related) T^2 term

- Different values of coefficient probed

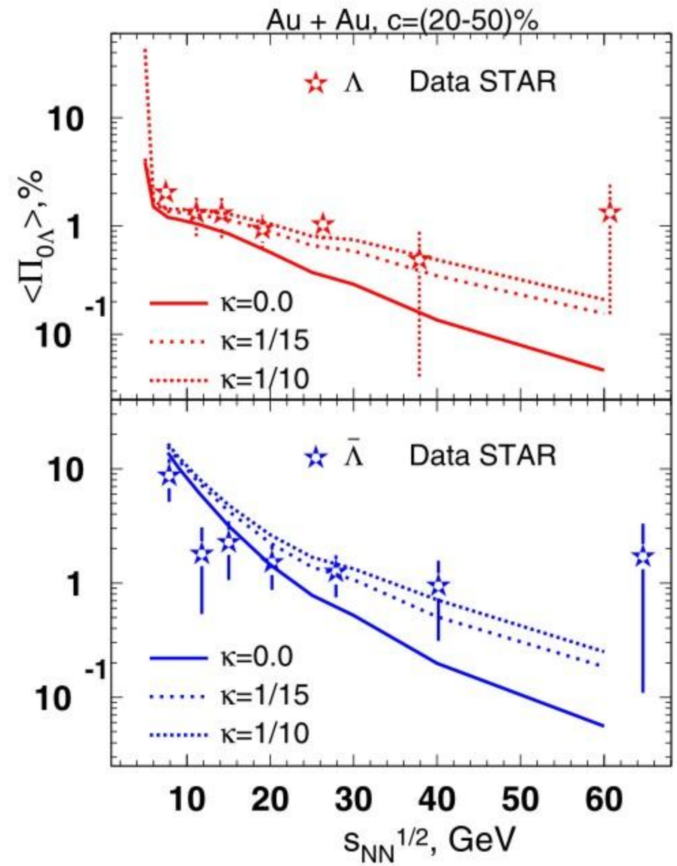


- LQCD suppression by collective effects supported

Lambda vs Antilambda and role of vector mesons

- Difference at low energies too large – same axial charge carried by much smaller number
- 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
- Dominance of one component of spin results also in tensor polarization –revealed in dilepton anisotropies (Bratkovskaya, Toneev,OT'95)

Λ vs Anti Λ (preliminary, in preparation)



Conclusions/Outlook

- Polarization – new probe of anomaly in quark-gluon matter (to be studied at NICA!?)
- Generated by femto-vortex sheets
- Energy dependence predicted and confirmed
- Same sign and larger magnitude of antihyperon polarization: splitting decreases with energy
- T-dependent term due to gravitational anomaly may be extracted from the data
- Induced extra current (with new topological term) from Wigner functions
- Polarization - from core of vortices in pionic superfluid

THANK YOU FOR ATTENTION! WELCOME TO DUBNA!

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 $< f|S|i >^* = < i|S|f >$.

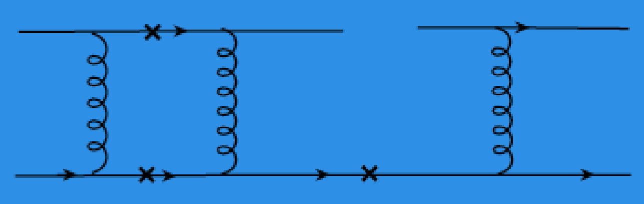
SSA - either T-violation or the phases.

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):

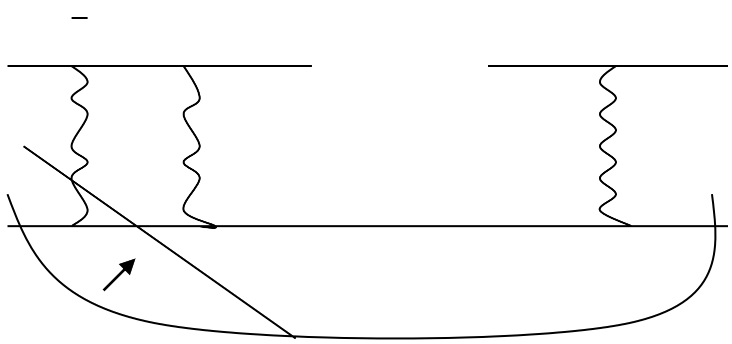


$$A \sim \frac{\alpha_S m p_T}{p_T^2 + m^2}$$

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)

Polarization at NICA/MPD (A. Kechechyan)

- QGSM Simulations and recovery accounting for MPD acceptance effects