Polarization of quarks and hadrons in heavy-ion collisions

SQM-2019, Bari, Italy
June 13, 2019

Phys.Rev. C88 (2013) 061901, C93 (2016) 031902, C95 (2017) 011902, C97(2018)041902

and work in progress

Oleg Teryaev(JINR, Dubna)
in collaboration with
Mircea Baznat (IAP, Chisinau)
Alexander Sorin, Aleksei Zinchenko (JINR)

Main Topics

- Anomalous mechanism: 4-velocity as gauge field+quark-hadron duality
- Chemical potential and Energy dependence – growth for low energies –now also in other approaches
- Polarization of antibaryons: same sign (and larger magnitude)
- Quarks role: flavour dependence of size and sign
- Comparison of approaches: "hidden anomaly" for average TD polarization at m -> 0
- Rotation in heavy-ion collisions in kinetic models : helicity separation and vortical structures
- Conclusions

Global polarization

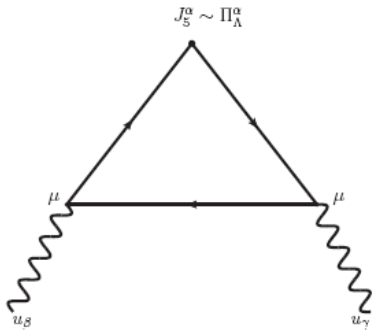
- Global polarization normal to REACTION plane
- Predictions (Z.-T.Liang et al.): large orbital angular momentum -> large polarization
- Search by STAR (Selyuzhenkov et al.'07) : polarization NOT found at % level!
- Maybe due to locality of LS coupling while large orbital angular momentum is distributed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

Anomalous mechanism – polarization –kind of anomalous transport 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 (Vilenkin, Son&Surowka, Landsteiner) 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!



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.

From (chiral) quarks to hadrons: quark-hadron duality via axial charge

- 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
- $\mu_{s(q)} \rightarrow \mu_B/3 - \mu_s$
- T-dependent term (Landsteiner's gravity anomaly); no π^2 in denominator : "hint" for role of Unruh effect ($T=a/2\pi$; poster #130 by G. Prokhorov)
- Lattice simulations: suppressed by order of magnitude due to collective effects – responsible for RHIC/LHC polarization?

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: axial charge (mediator of quark-hadron duality) -> hydrodynamical helicity
- Rapid decrease with energy
- Large chemical potential: appropriate for NICA/FAIR energies (’10)

From axial charge (analog of Cooper-Frye) to polarization and from quarks to confined hadrons (Sorin,OT'17)

- Analogy of matrix elements and classical averages

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

- Axial current: charge -> polarization vector
- Lorentz boost: requires the sign change of helicity "below" and "above" the RP

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

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

Axial charge and properties of polarization

- Antihyperons : same sign (C-even axial charge) and larger value (smaller N)
- More pronounced at lower energy. Baryon/antibaryon splitting due to magnetic field – increase (?!) with energy. Non-linear effects in H may be essential, cf vector mesons on the lattice: Luschevskaya, Solovjeva, OT: **JHEP 1709 (2017) 142**

Lambda vs Antilambda and role of vector mesons

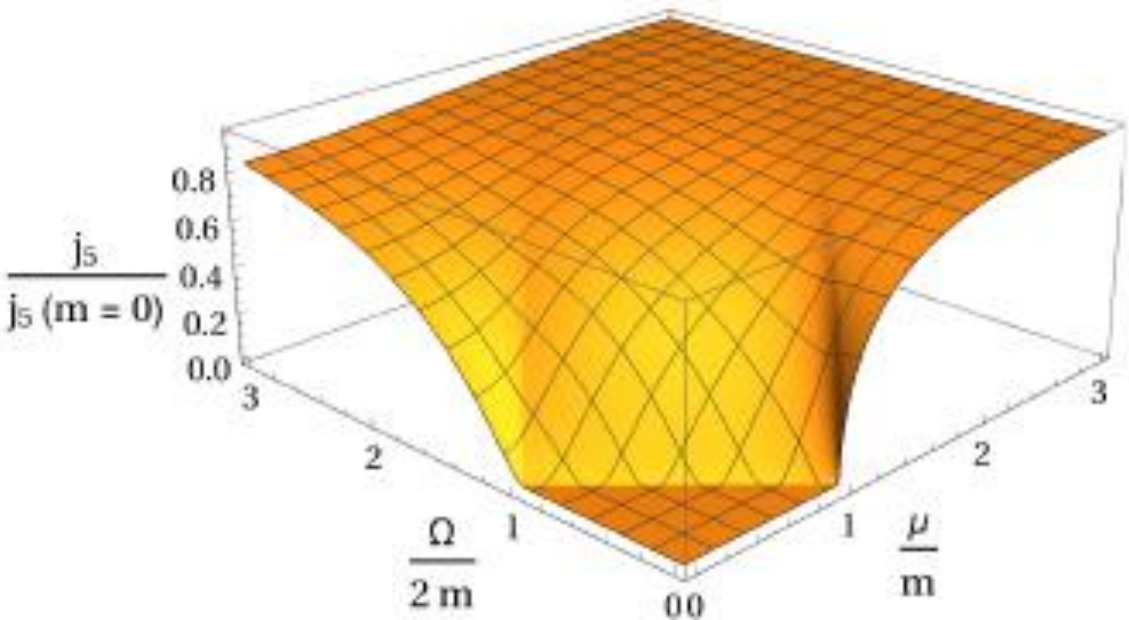
- Difference at low energies too large – same axial charge carried by much smaller number
- Strange axial charge may be also carried by K* mesons
- Λ - accompanied by (+,anti 0) K* mesons with two sea quarks – small corrections
- Anti Λ – more numerous (-,0) K* mesons with single (sea) strange antiquark
- Dominance of one component of spin results also in tensor polarization (P-even source like H^2: implied by positivityfor large polarization) –revealed in dilepton anisotropies (Bratkovskaya, Toneev,OT'95)

Chemical potential and flavour dependence

- Way via axial current/charge (TD: chemical potential) differs from "direct" TD (also for orbital/spin momentum; problems with symmetric EMT)
- TD-Universal, "flavor-blind" (only mass-dependent) polarization of universal sign
- Axial current: polarization depends on baryon structure
- Most pronounced at low energies
- Comparison of hyperons polarization (c.f. hadronic collisions)

Role of mass effects (Prokhorov, OT, Zakharov, PRD98 (2018), 071901)

- Threshold effects in chemical potential and angular velocity (acceleration – poster #130 by G. Prokhorov)



“Hidden anomaly”

- Anomalous current recovered in chiral limit and integration over all momenta
- W (x,p) ⟶ J(x)
- S(p) ⟶ <S>

Microworld: where is the fastest possible rotation?

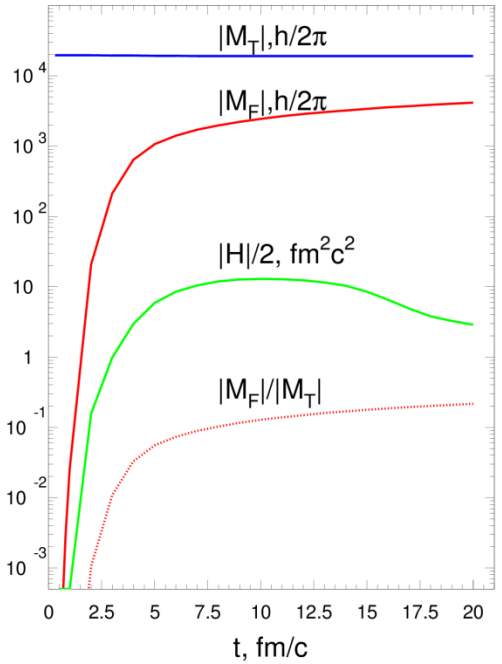
- Non-central heavy ion collisions (Angular velocity ~ c/Compton wavelength)
- ~25 orders of magnitude faster than Earth's rotation
- Calculation in kinetic quark - gluon string model (DCM/QGSM) – Boltzmann type eqns + phenomenological string amplitudes): Baznat, Gudima, Sorin, OT:
- PRC'13 (helicity separation+P@NICA~1%), 16 (femto-vortex sheets, NICA), 18 (antihyperons, gravitational anomaly, STAR)
- HSD: Usubov, OT (15); Kolomeitsev et al (18); poster # 155 by A. Zinchenko)
- UrQMD – next talk of O. Vitiuk

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 $v \parallel \mathrm{curl}\ v$

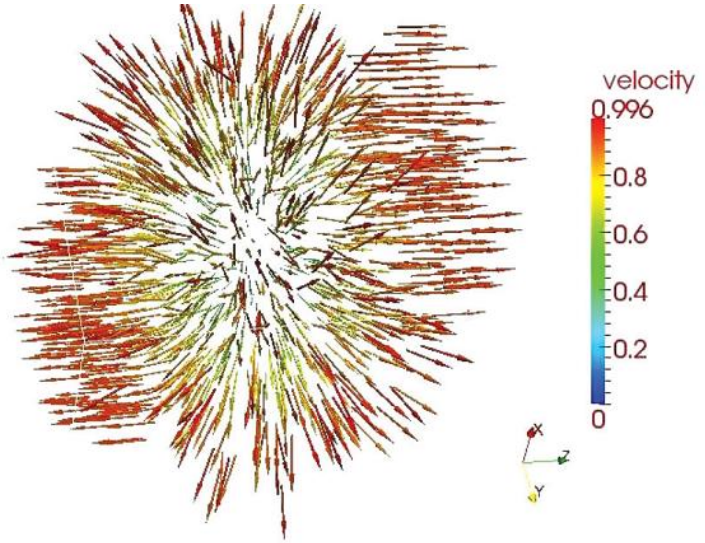
Angular momentum conservation and helicity

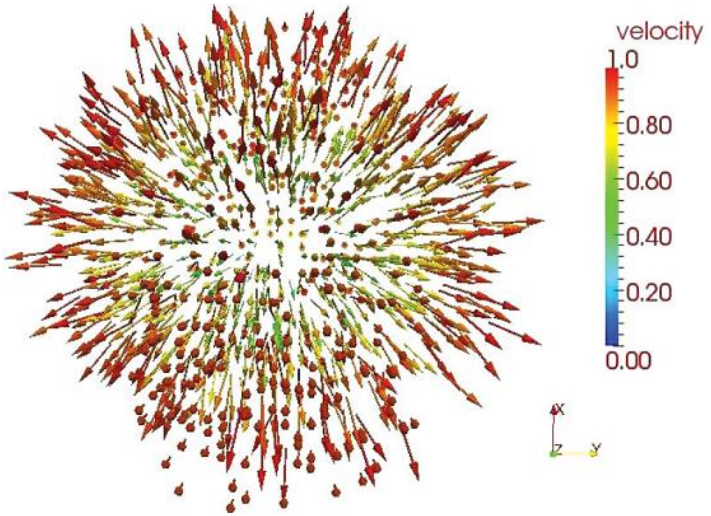
- Helicity vs orbital angular momentum (OAM) of fireball
- (~10% of total)
- Conservation of OAM with a good accuracy!



Distribution of velocity ("Little Bang")

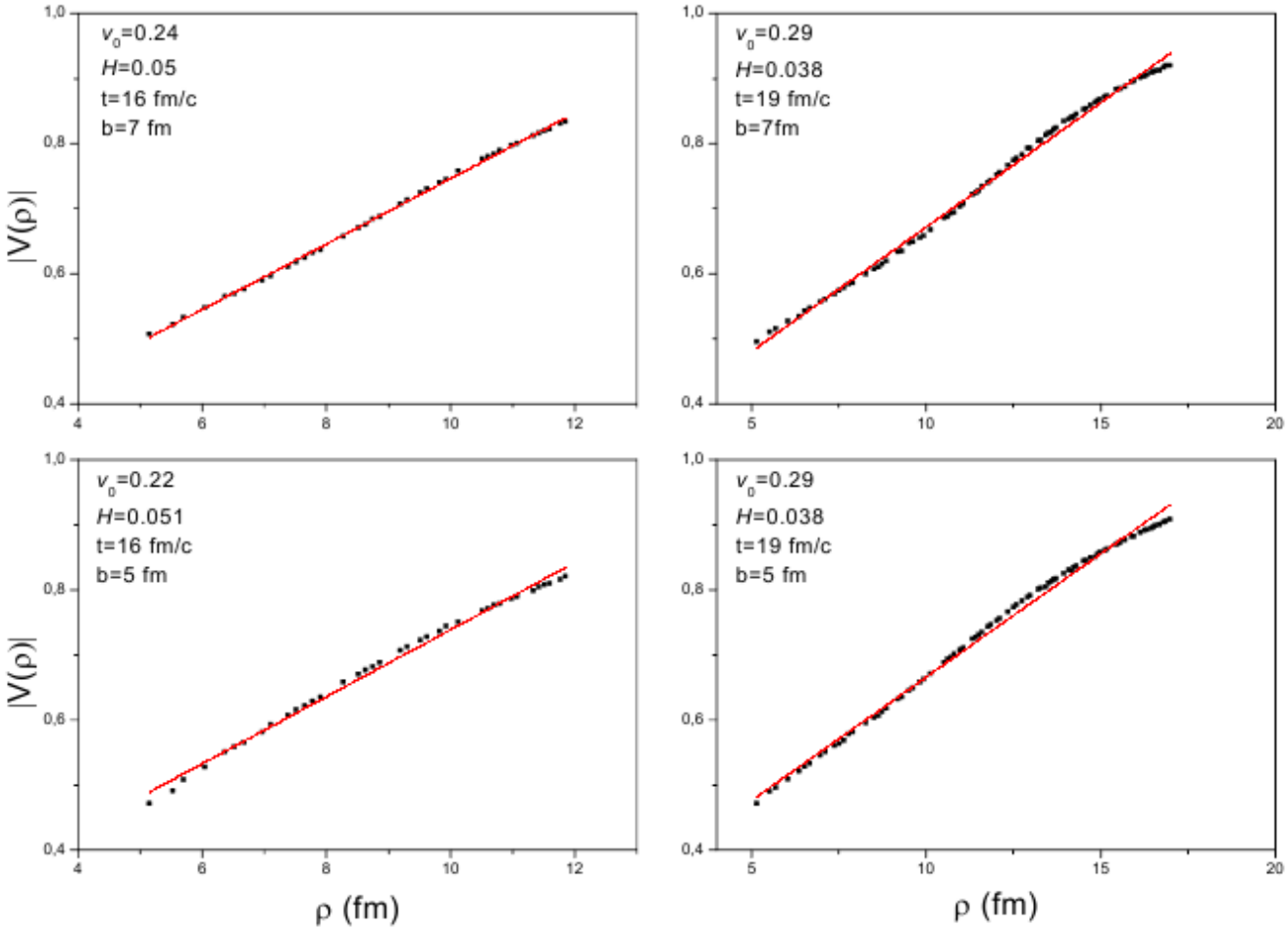
- 3D/2D projection
- z-beams direction
- x-impact paramater





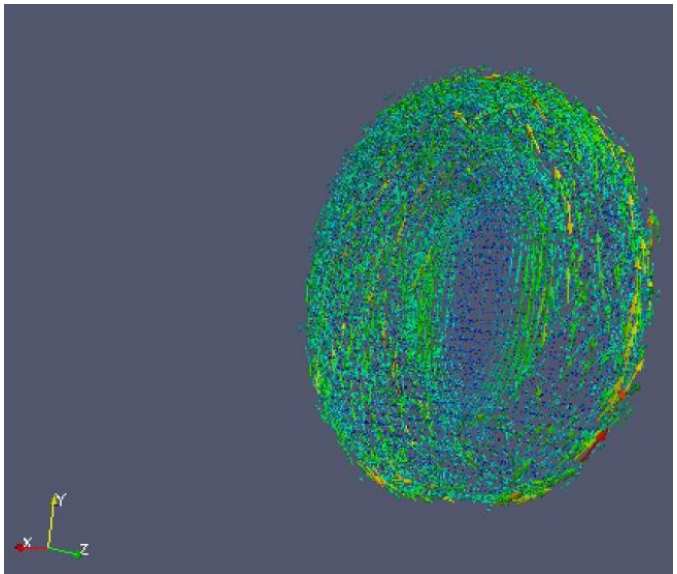
“Little Hubble” in PHSD

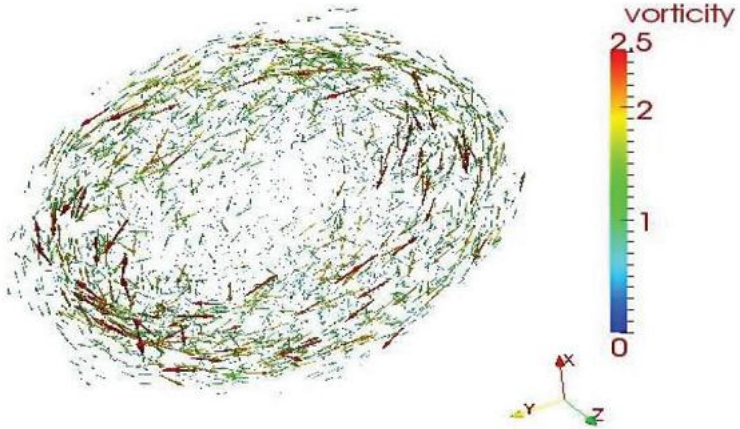
$v=v_0+H\rho$

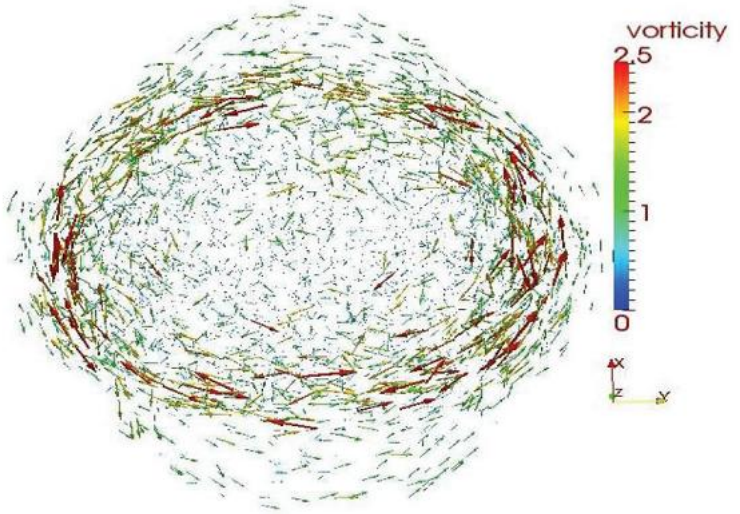


Distribution of vorticity ("Little galaxies")

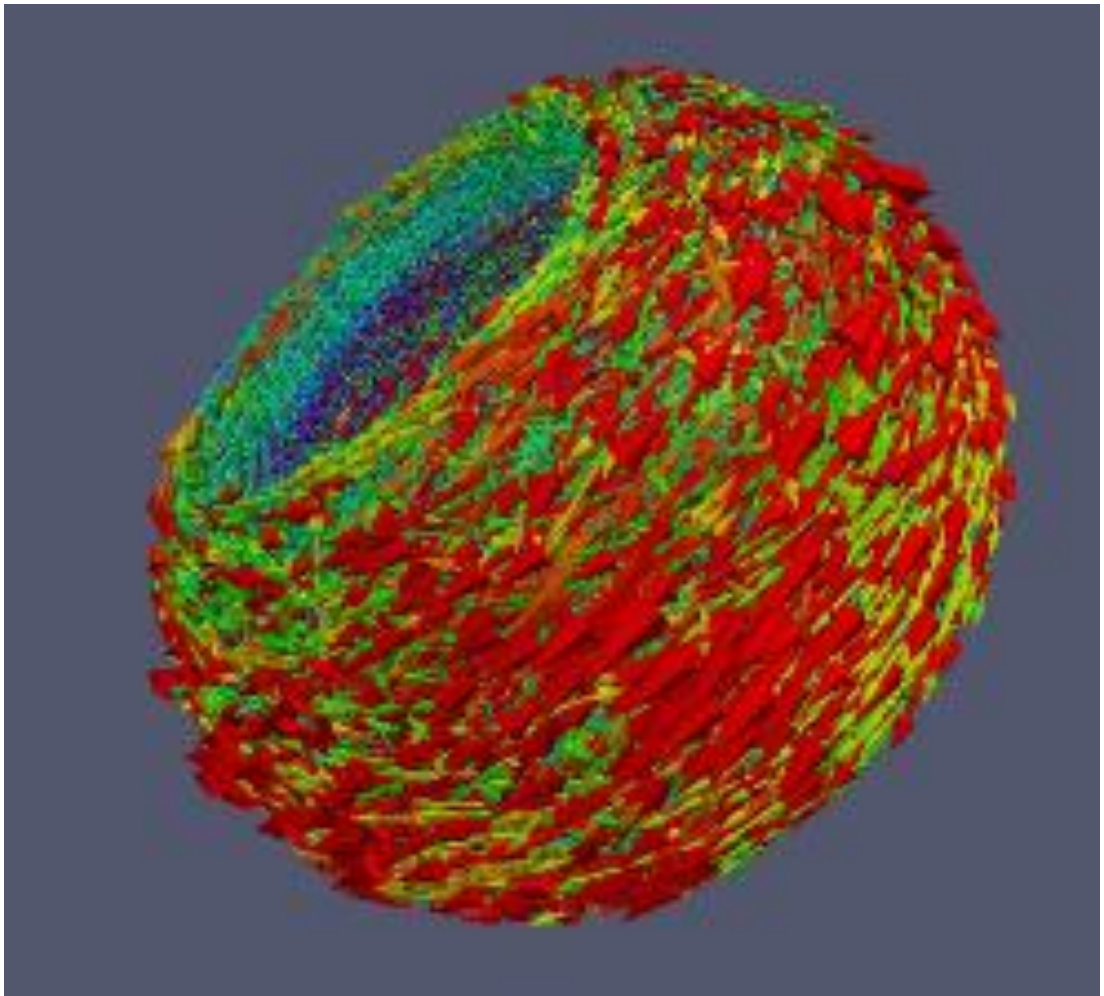
- Layer (on core - corona borderline) patterns
- Cf (anti) flow



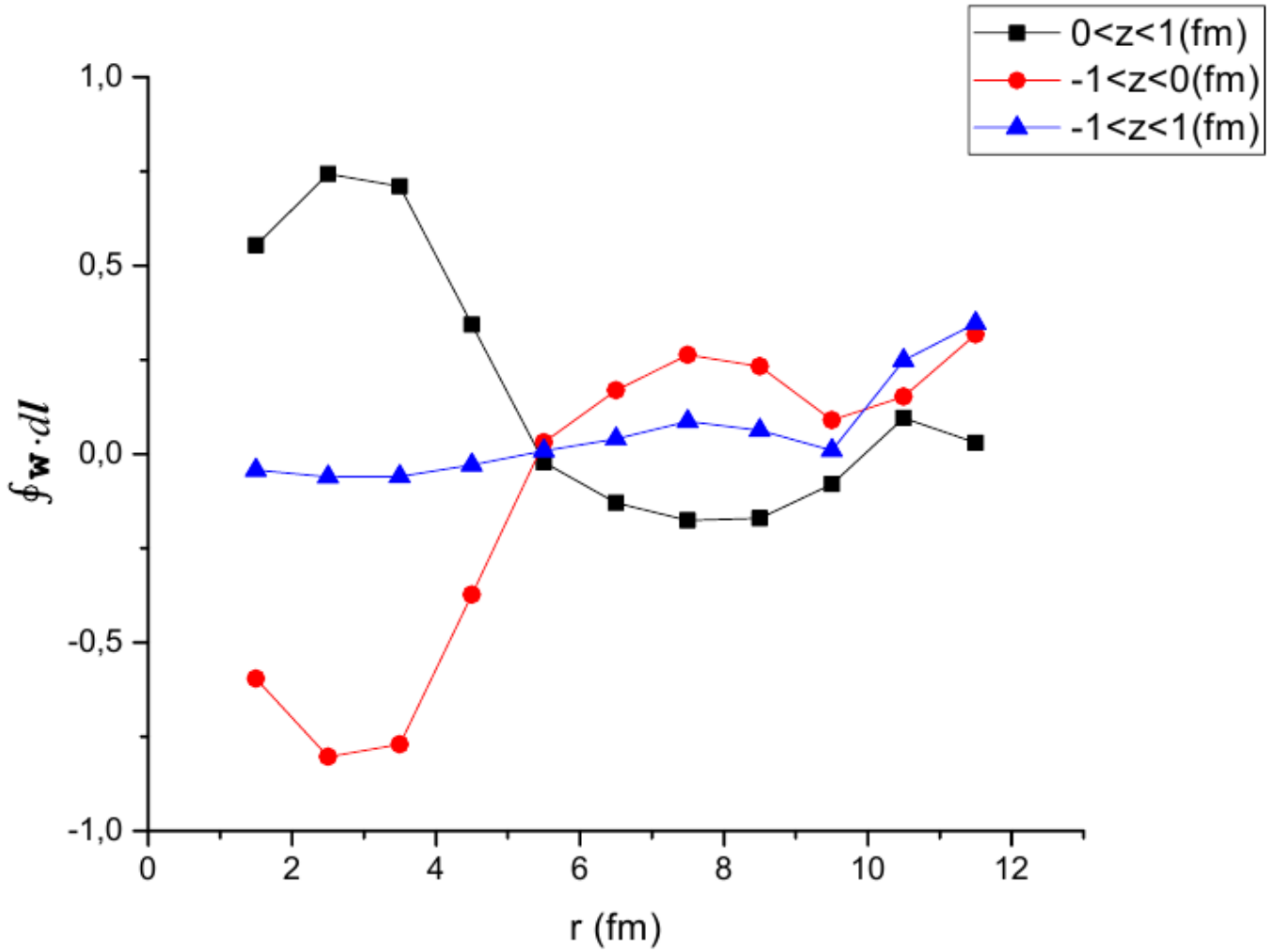




Vortex sheet

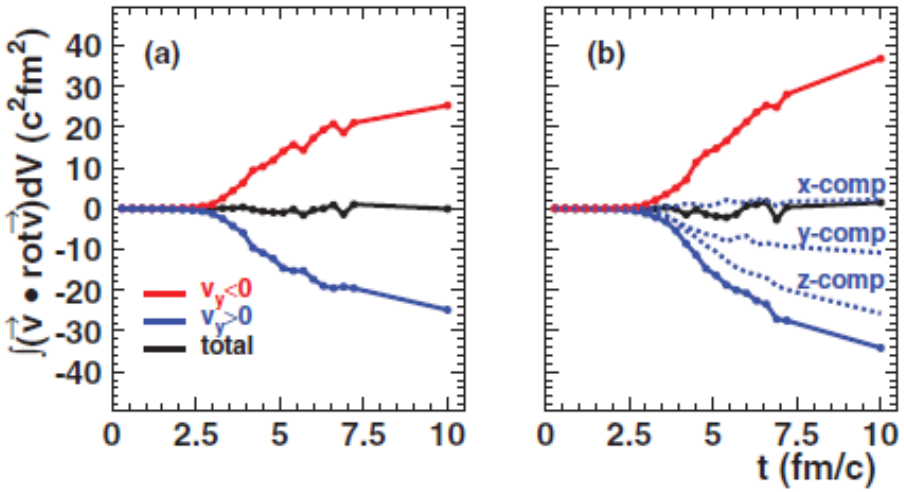


Mirror vortex rings

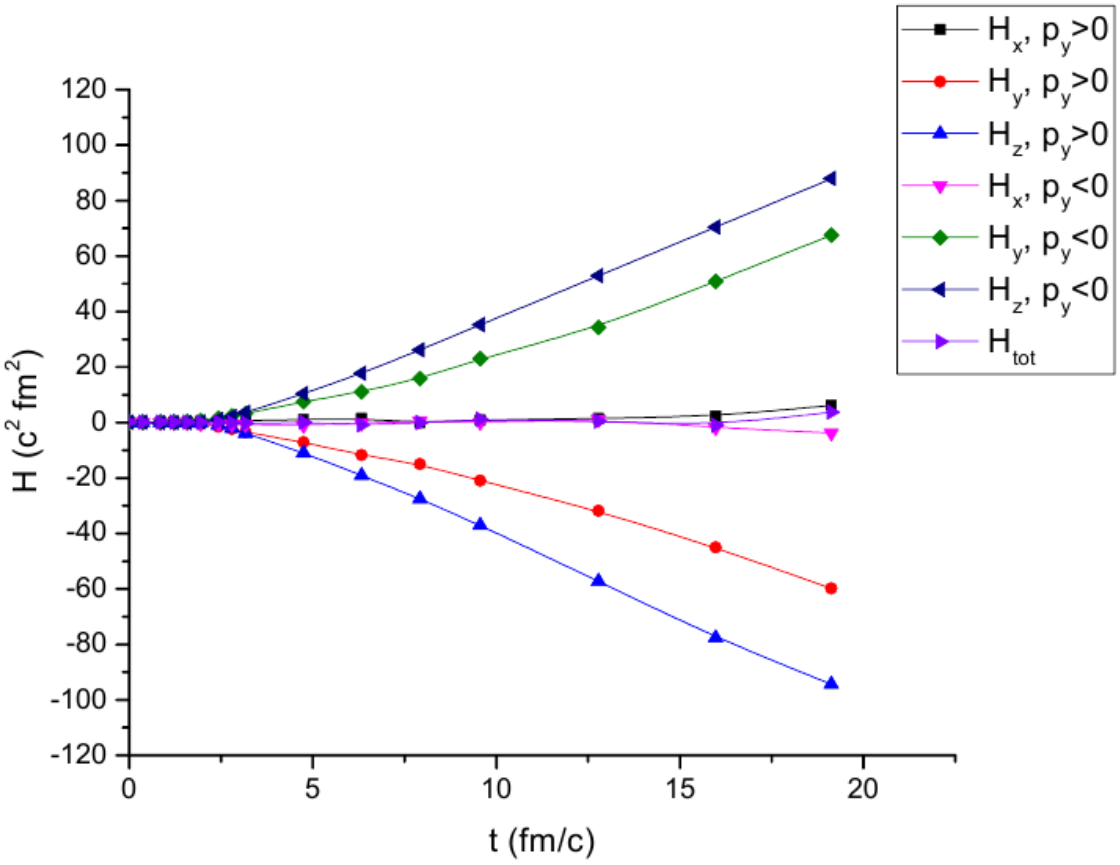


Helicity separation in QGSM **PRC88 (2013) 061901**

- Total helicity integrates to zero BUT
- Mirror helicities below and above the reaction plane – required by boost!
- Confirmed in HSD (OT, Usubov, PR**C92 (2015) 014906**
- **zz-> quadrupole structure**

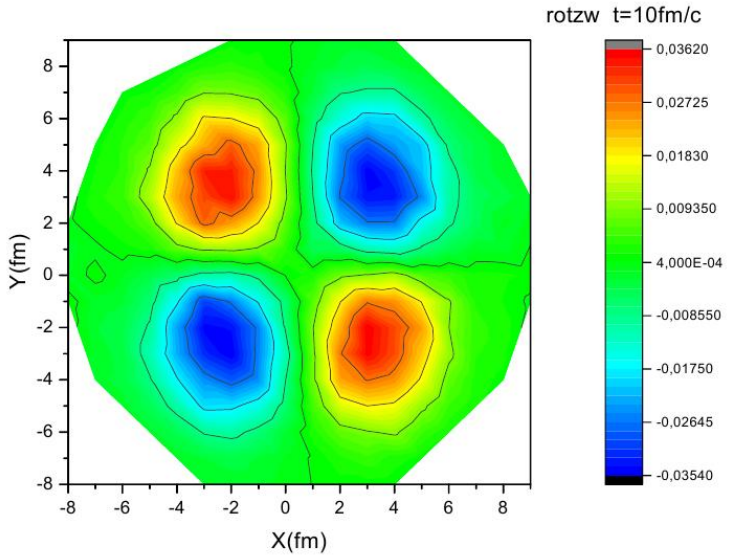


Helicity@PHSD

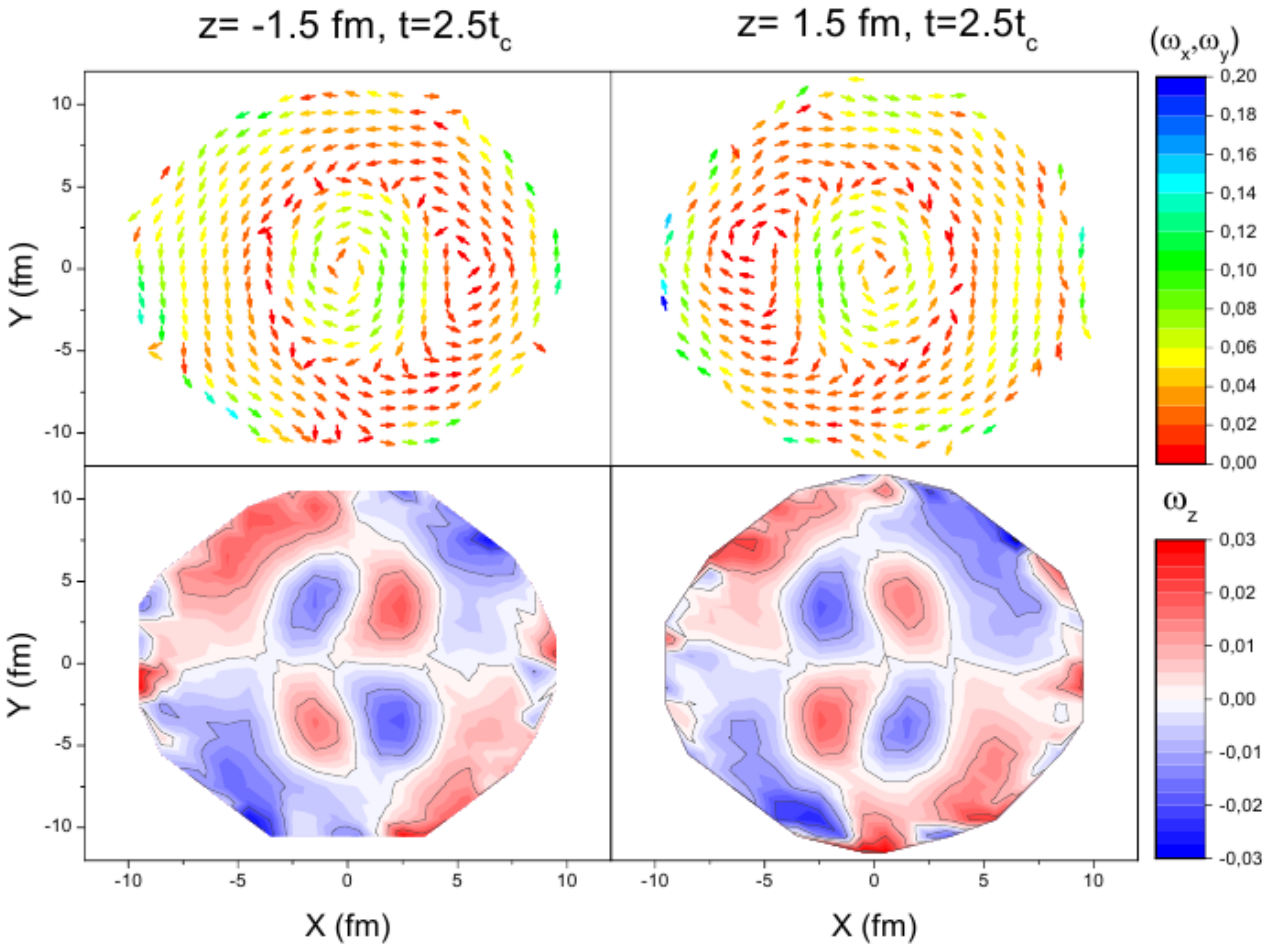


Structure of vorticity (Baznat, Gudima, Sorin, OT'17)

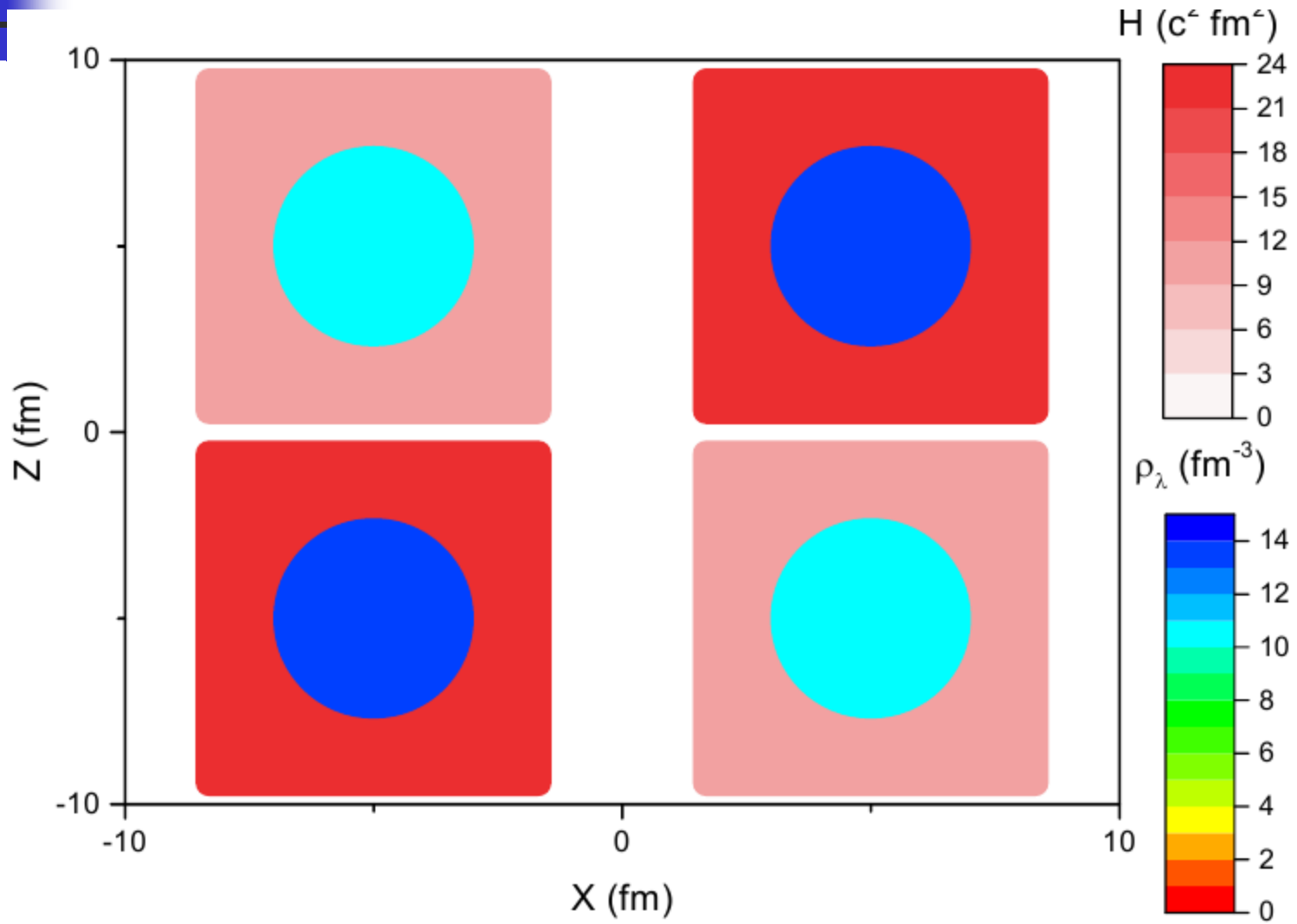
- y-component: constant vorticity, velocity changes sign
- **z-component: quadrupole structure of vorticity**



PHSD: 2nd Quadrupole Structure

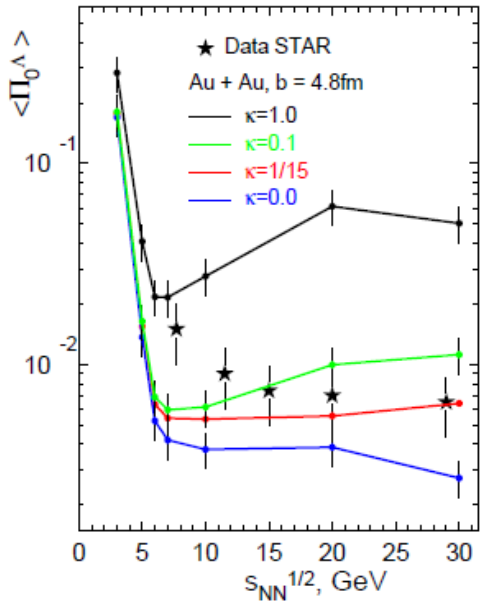


XZ- structure of helicity and polarization



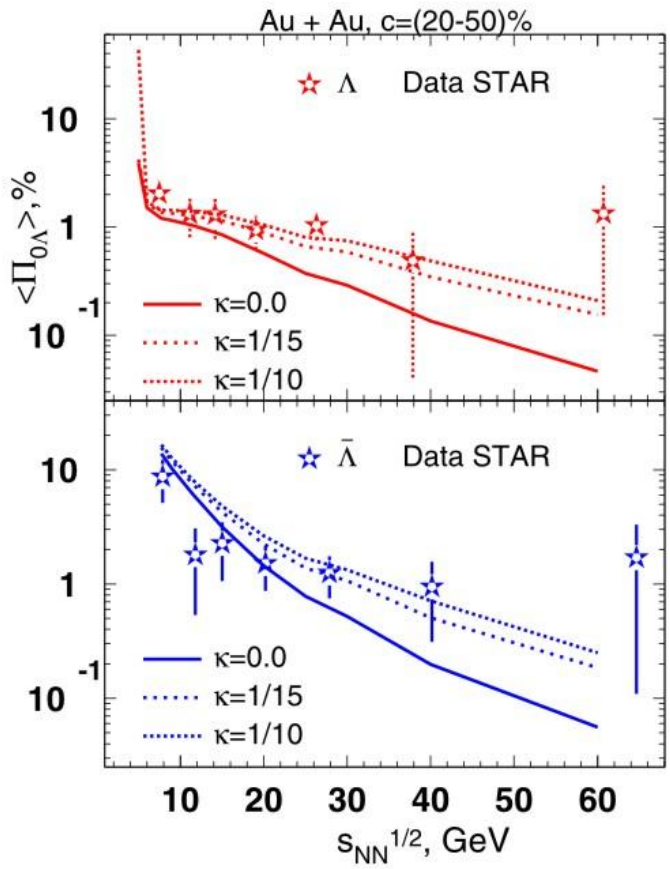
The role of (gravitational anomaly related) T^2 term

- Different values of coefficient probed



- LQCD suppression by collective effects supported; RHIC/LHC?!

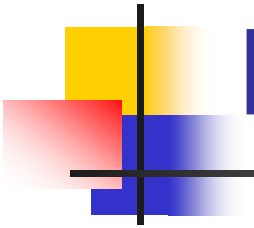
Λ vs Anti Λ


Au + Au, c=(20-50)%
Λ Data STAR
κ=0.0
κ=1/15
κ=1/10
Λ̄ Data STAR
κ=0.0
κ=1/15
κ=1/10
<Π0Λ>, %
10
1
10^-1
10 20 30 40 50 60
sNN^1/2, GeV

Conclusions/Outlook

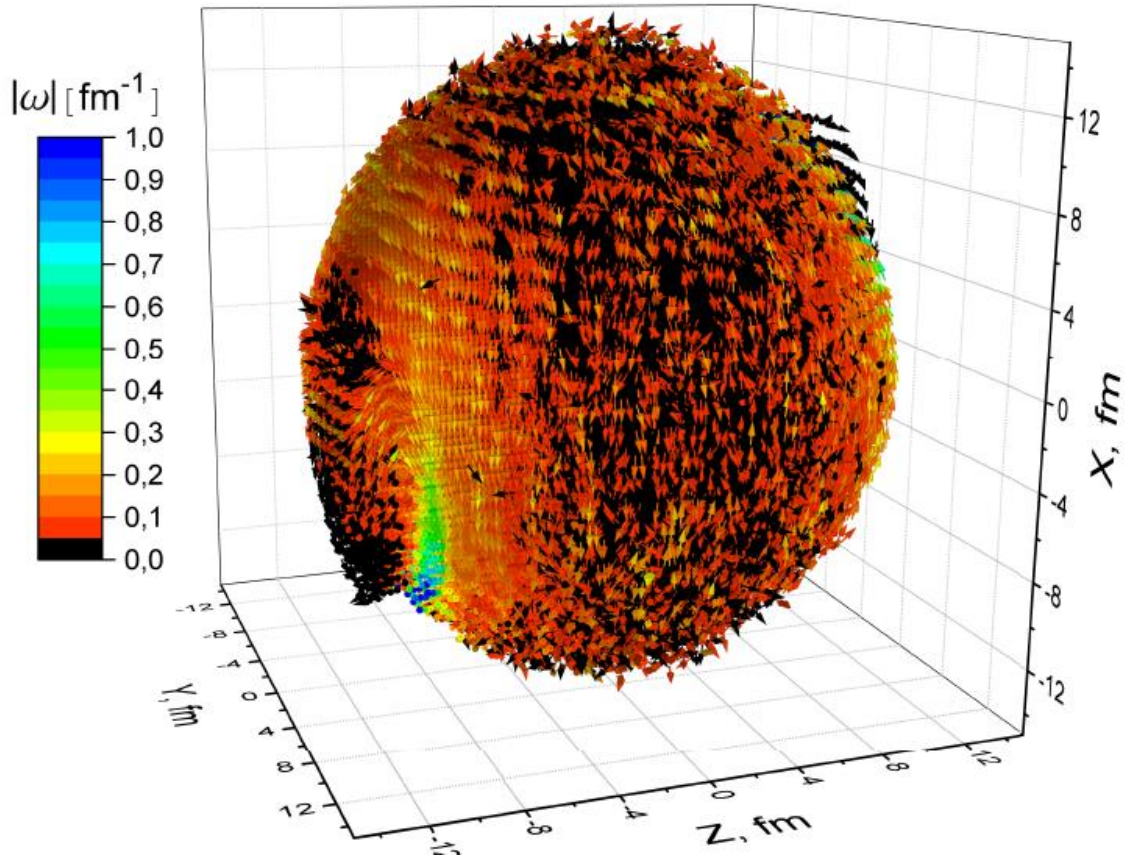
- Mechanisms of polarization: TD- for hadronic spin; Anomalous: TD for μ,T effectife field theory for chiral quarks
- Quark-hadron duality via axial charge
- Energy dependence: predicted, confirmed,
- Same sign and larger magnitude of antihyperon polarization: splitting decreases with energy
- TD+H (Becattini,Karpenko), TD+UrQMD (talk of O. Vitiuk) –complementary explanations
- Flavor dependence of size and sign of polarization as a probe of anomaly
- "Hidden anomaly" in averaged TD polarization
- To which extent duality can go?!

- A lot of femto-vortical structures



BACKUP

Vortex sheet in PHSD



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

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

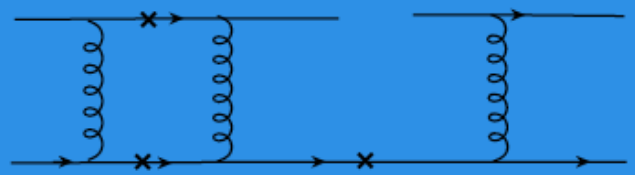
SSA - either T-violation or the phases.

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):

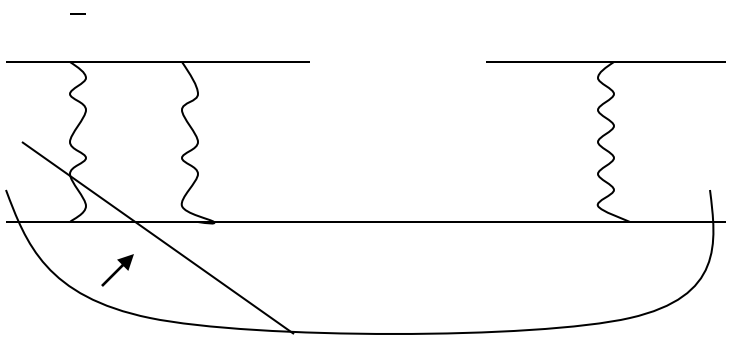


$$A \sim \frac{\alpha_S m p_T}{p_T^2 + m^2}$$

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