Vector vs tensor polarization in HIC

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ArXiv 1701.00923, 1707.02491 and work in progress

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Main Topics

- Polarization: from L to S
- Anomalous mechanism: 4-velocity as gauge field+quark-hadron duality
- Predictions:
- 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
- Rotation in heavy-ion collisions in kinetic model : helicity separation and vortical structures
- Comparison with the data
- Tensor polarization of vector mesons: polarizability vs magnetic moment
- Conclusions

Global polarization

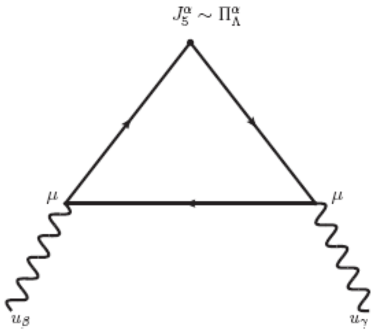
- Global polarization normal to REACTION plane
- Predictions (Z.-T.Liang et al.): large orbital angular momentum -> large polarization
- Search by STAR (Selyuzhenkov et al.'07) : polarization NOT found at % level!
- Maybe due to locality of LS coupling while large orbital angular momentum is distributed
- 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
- T-dependent term - related to gravitational anomaly
- Lattice simulations: 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 energies

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

- Analogy of matrix elements and classical averages

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

- Axial current: charge = projection of Pauli-Lubansky 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

- Polarization is 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
- Baryon/antibaryon splitting due to magnetic field – increase (?!) with energy

- Relation to thermal vorticity mechanism (Talks of I. Karpenko, E. Kolomeitsev) – axial current from Wigner function (talk of G. Prokhorov)

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)

Tensor polarization

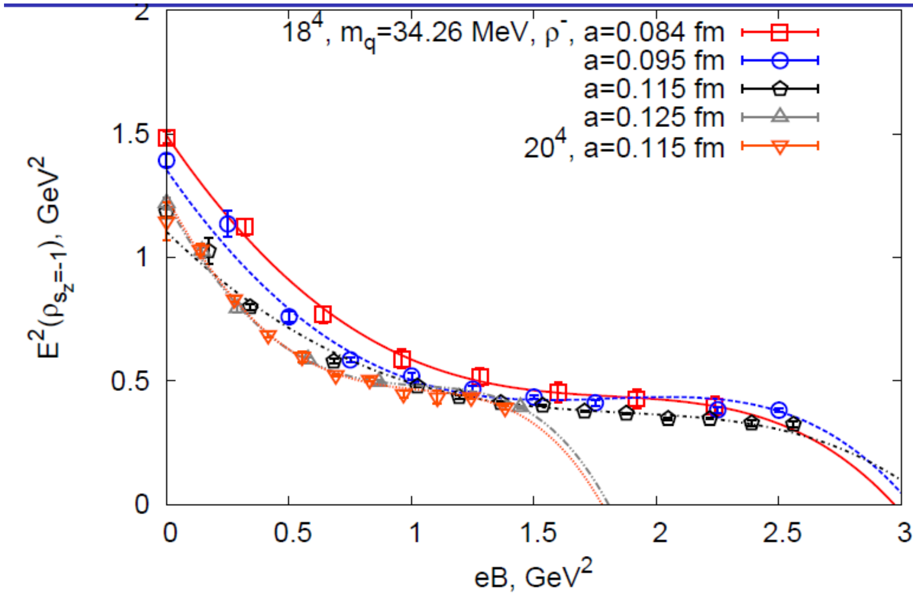
- Spin 1
- Vector: P= (N(+)-N(-))/(N(+)+N(-))
- Tensor: A= (N(+)+N(-)-2N(0))/ (N(+) + N(-) + N (0))
- P-even
- Dominance of one (+,-) component – both vector and tensor

Vector vs tensor polarization

- Tensor – not generated by linear effects of vorticity and magnetic field
- Quadratic effects required
- Magnetic field polarizability vs magnetic moment (may contribute to splitting of baryon and antibaryon polarizations)
- Lattice calculations (Luschevskaya,Solovjeva,OT)

Energy of charged meson in magnetic field JHEP 1709 (2017) 142

- g~2 for small fields BUT
- No tachyonic mode



$$E^2 = |qH| - gs_z qH + m^2 - 4\pi m\beta(qH)^2 + k(qH)^4, \quad H = eB$$

Magnetic field effect on tensor polarization (preliminary)

- Tensor polarizability

$$\beta_{tensor} = \frac{\beta_{s=+1}+\beta_{s=-1}-2*\beta_{s=0}}{\beta_{s=+1}+\beta_{s=-1}+\beta_{s=0}} = 2\frac{\beta_{s=|1|}-\beta_{s=0}}{2\cdot\beta_{s=|1|}+\beta_{s=0}}$$

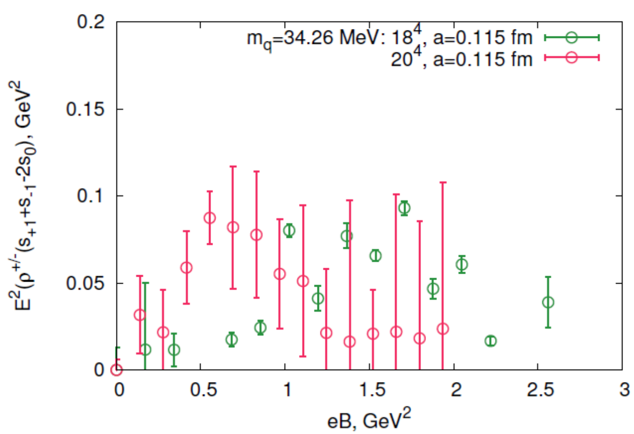
1. lattice 18^4, b=8.2 or a= 0.115 fm $M_\pi = 541 \pm 3MeV$

$$\beta_{tensor} = 2.22 \pm 0.48$$

2. lattice 18^4, b=8.2 or a=0.115 fm $M_\pi = 535 \pm 4MeV$

$$\beta_{tensor} = 1.87 \pm 0.44$$

- May be modified at higher fields



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)

Other approach to baryons in confined phase: vortices in pionic superfluid (V.I. Zakharov, OT:1705.01650;PRD96,09623)

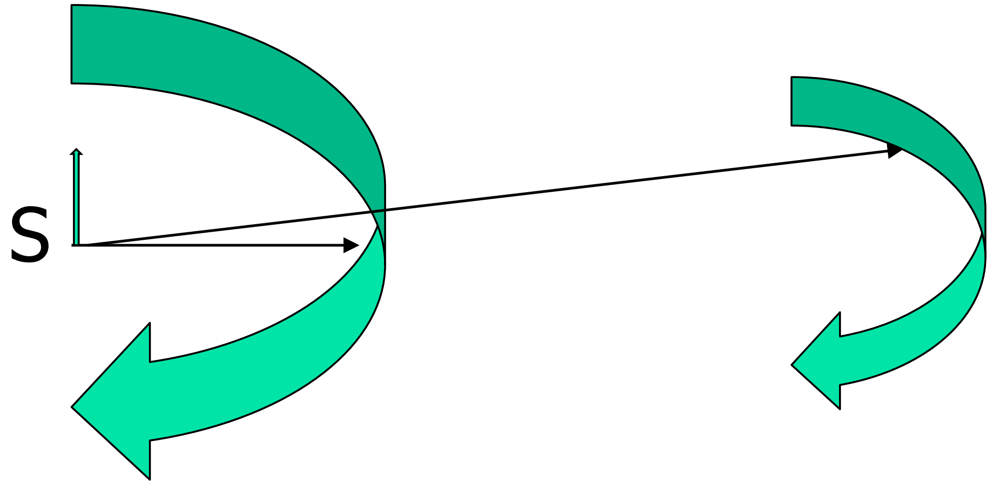
- Pions may carry the axial current due to quantized vortices in pionic superfluid (Kirilin,Sadofyev,Zakharov'12)

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

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

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

Core of quantized vortex

- Constant circulation – velocity increases when core is approached
- 

- Helium ($v < v_{sound}$) bounded by intermolecular distances
- Pions ($v<c$) –> (baryon) spin in the center

Microworld: where is the fastest possible rotation?

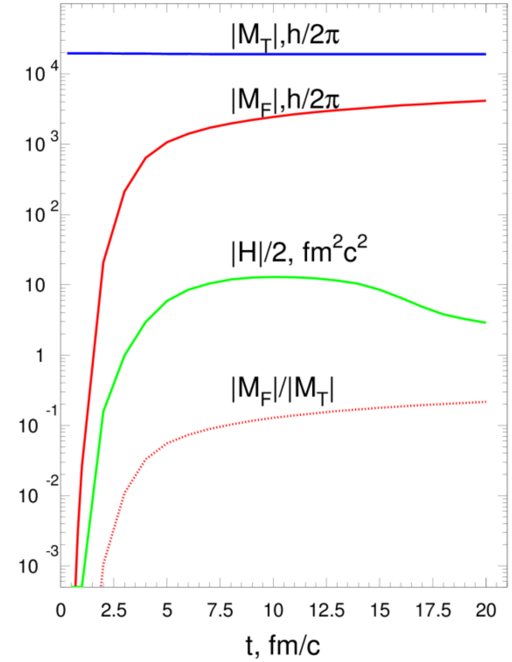
- Non-central heavy ion collisions (Angular velocity ~ c/Compton wavelength)
- ~25 orders of magnitude faster than Earth's rotation
- Calculation in kinetic quark - gluon string model (DCM/QGSM) – Boltzmann type eqns + phenomenological string amplitudes): Baznat, Gudima, Sorin, OT,
- PRC'13 (helicity separation+P@NICA~1%), 16 (femto-vortex sheets), 17 (antihyperons, gravitational anomaly)

Rotation in HIC and related quantities

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

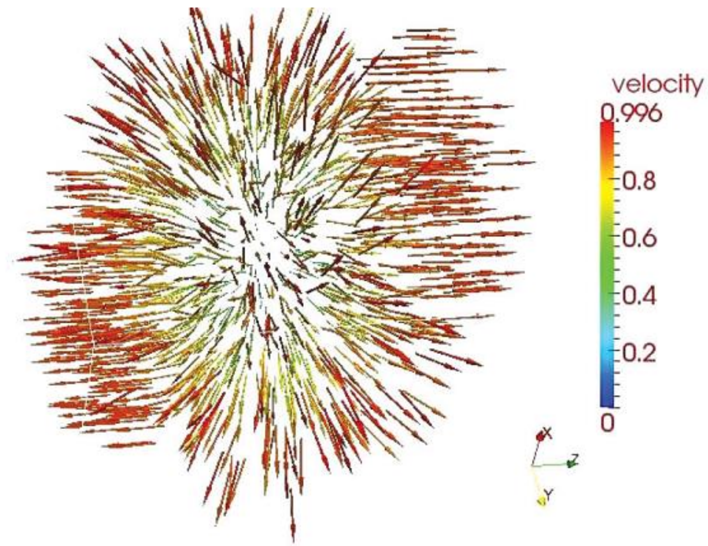
Angular momentum conservation and helicity

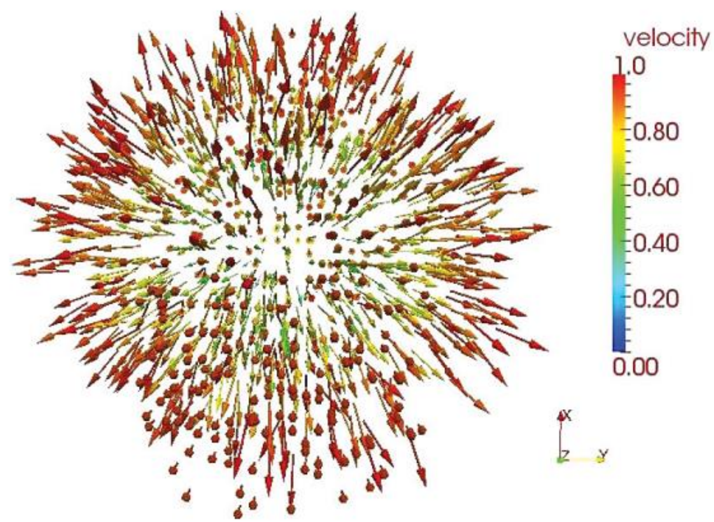
- Helicity vs orbital angular momentum (OAM) of fireball
- (~10% of total)
- Conservation of OAM with a good accuracy!



Distribution of velocity ("Little Bang")

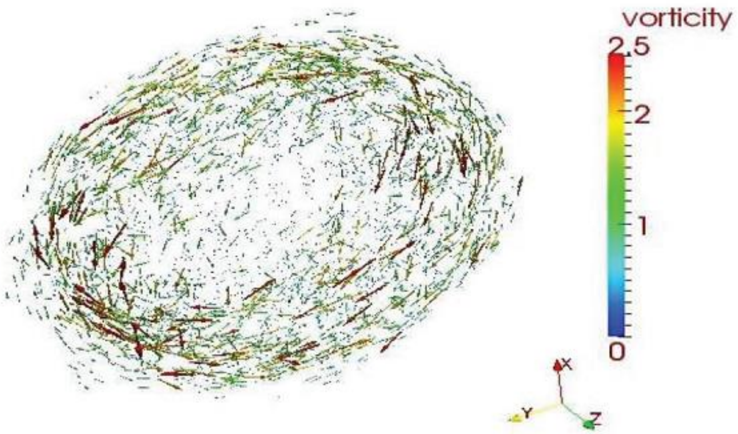
- 3D/2D projection
- z-beams direction
- x-impact paramater

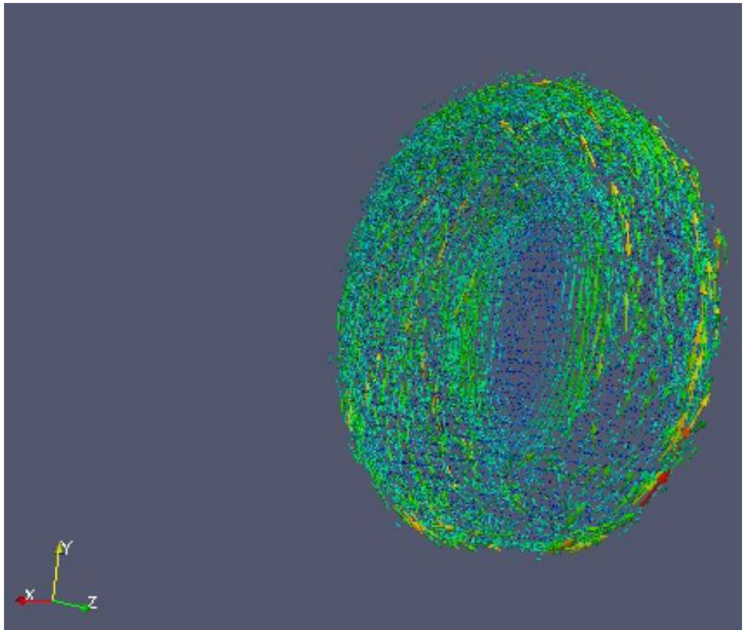


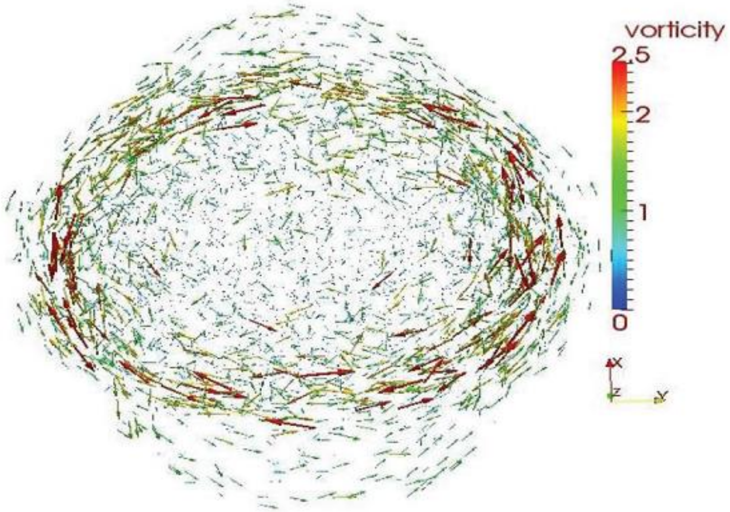


Distribution of vorticity ("Little galaxies")

- Layer (on core - corona borderline) patterns

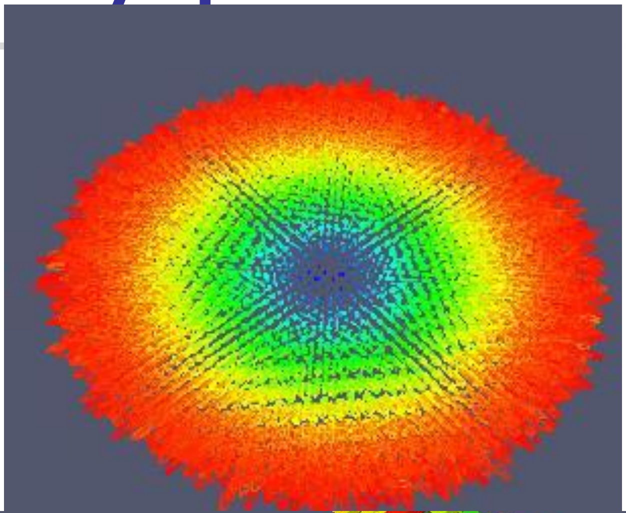




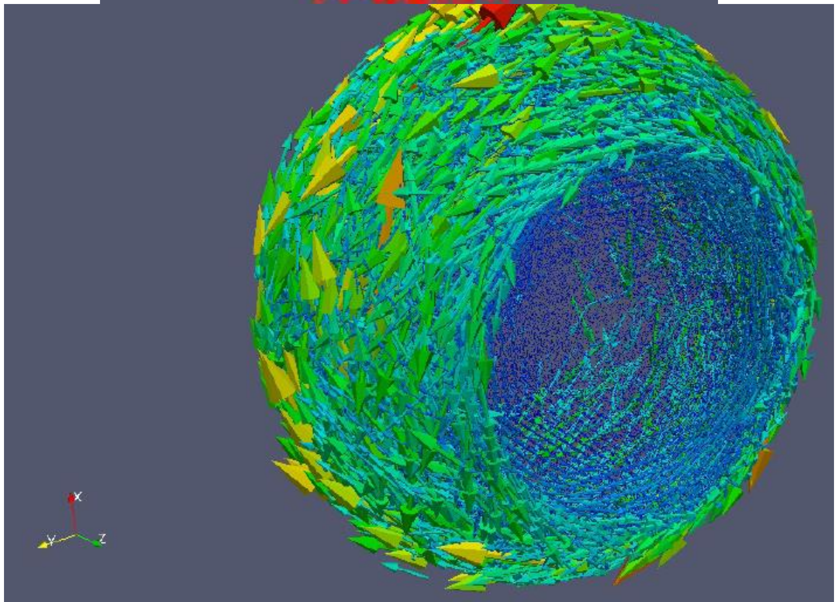


Velocity and vorticity patterns

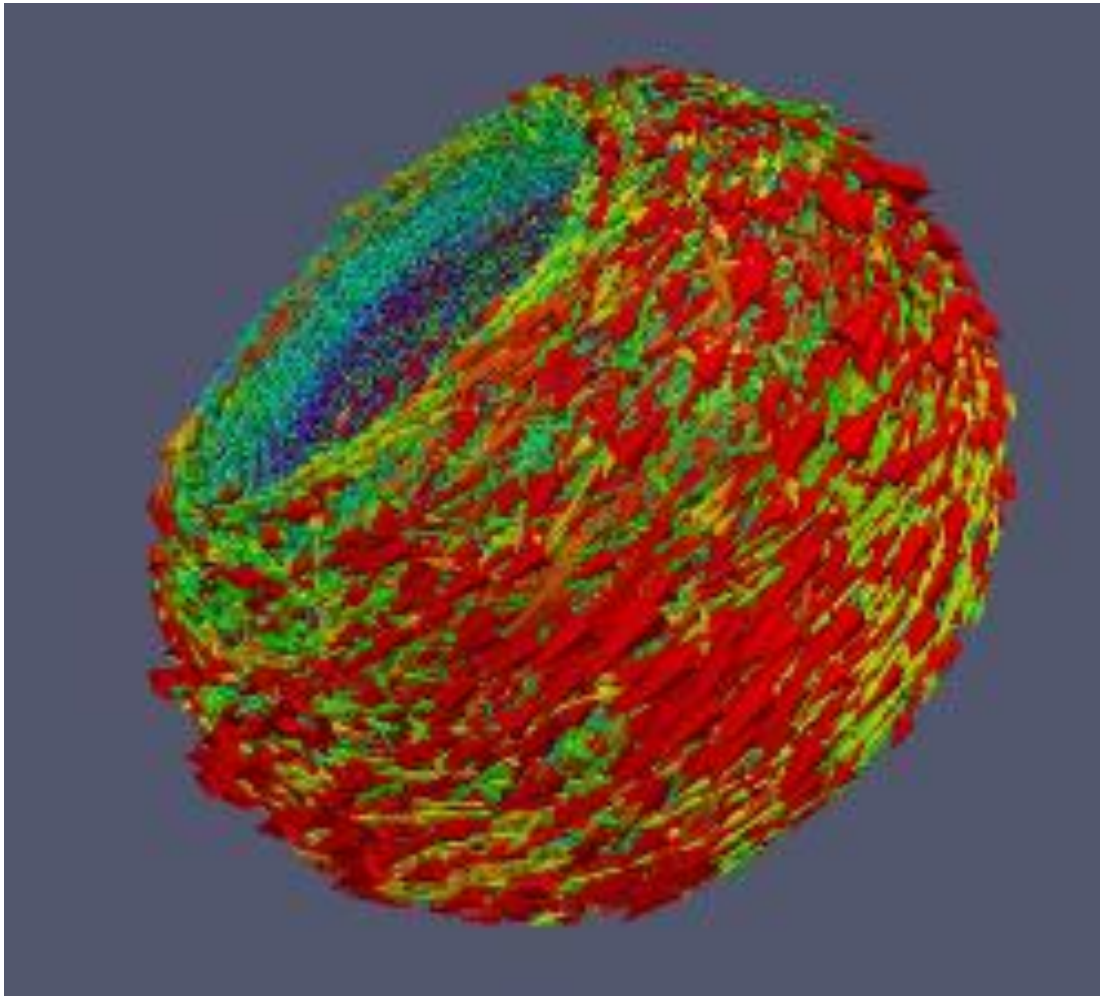
- Velocity



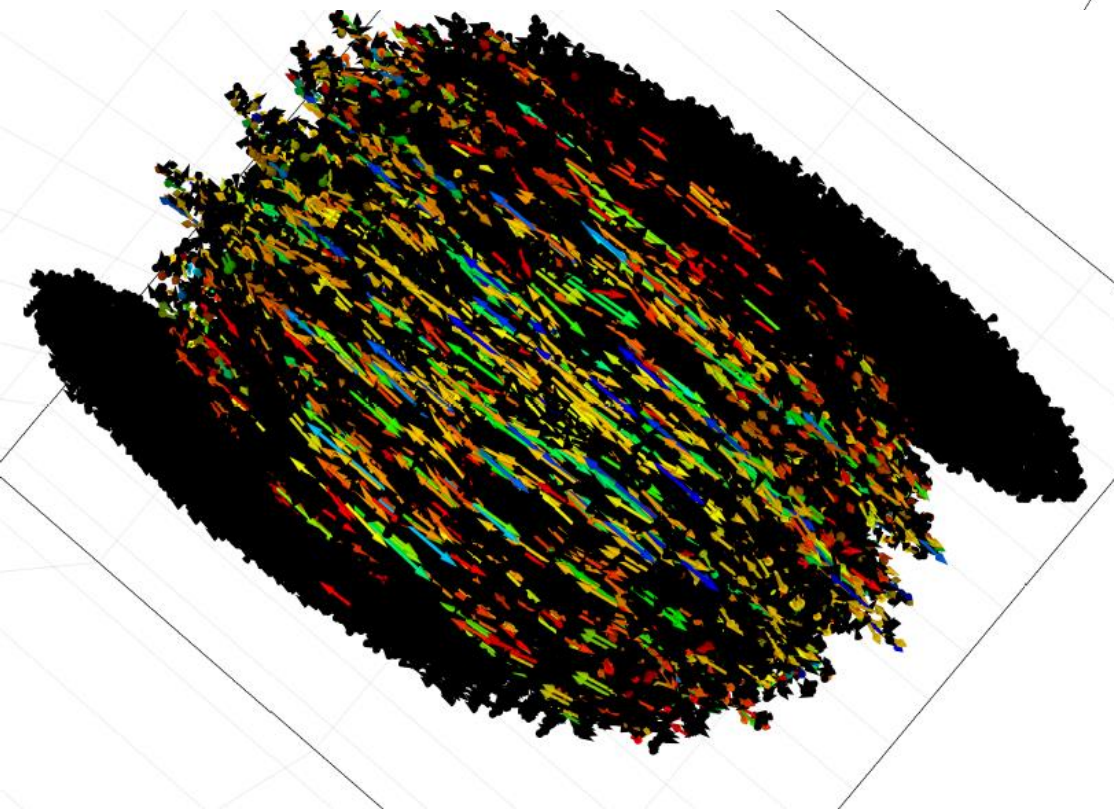
- Vorticity pattern – vortex sheets

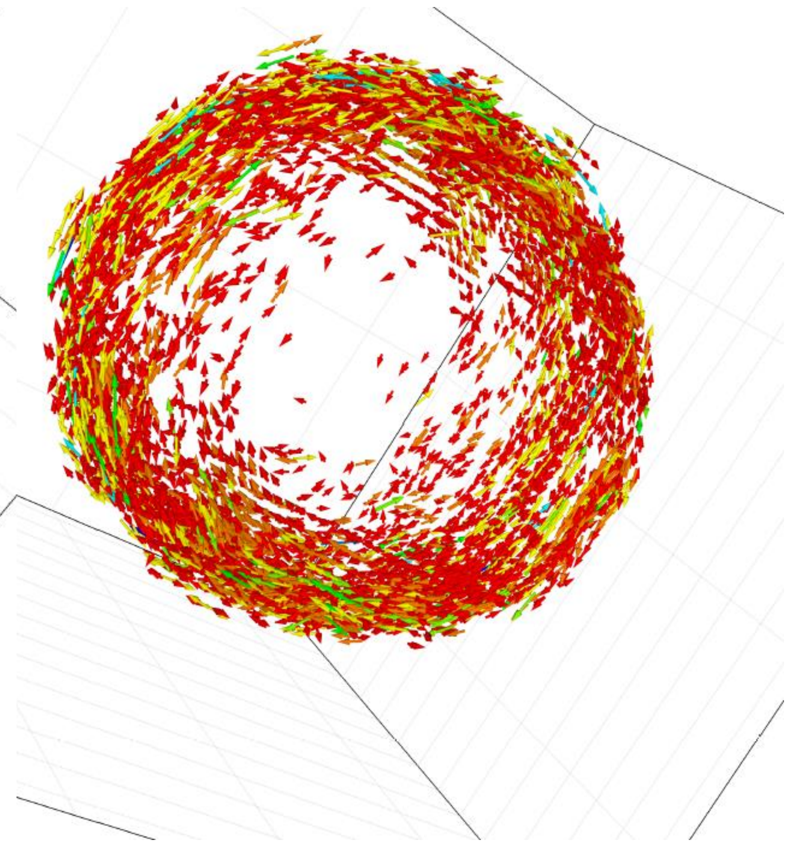


Vortex sheet



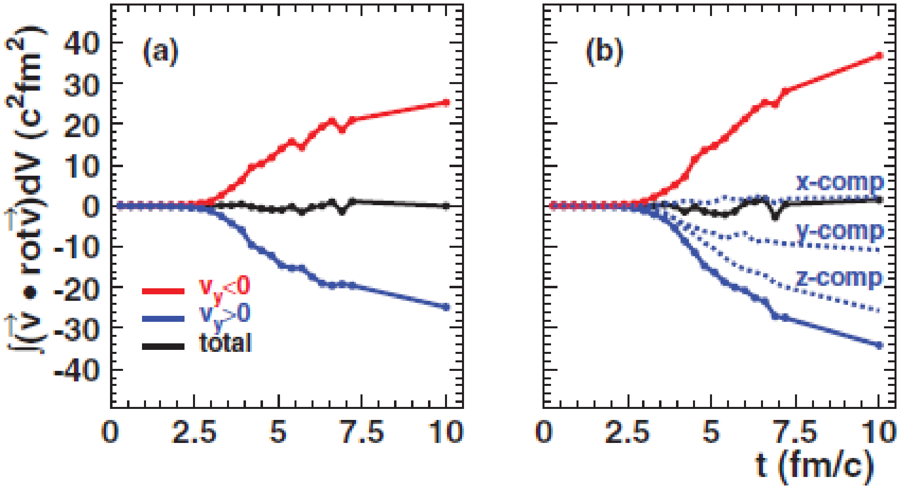
Vortex sheet formation in PHSD model (preliminary)





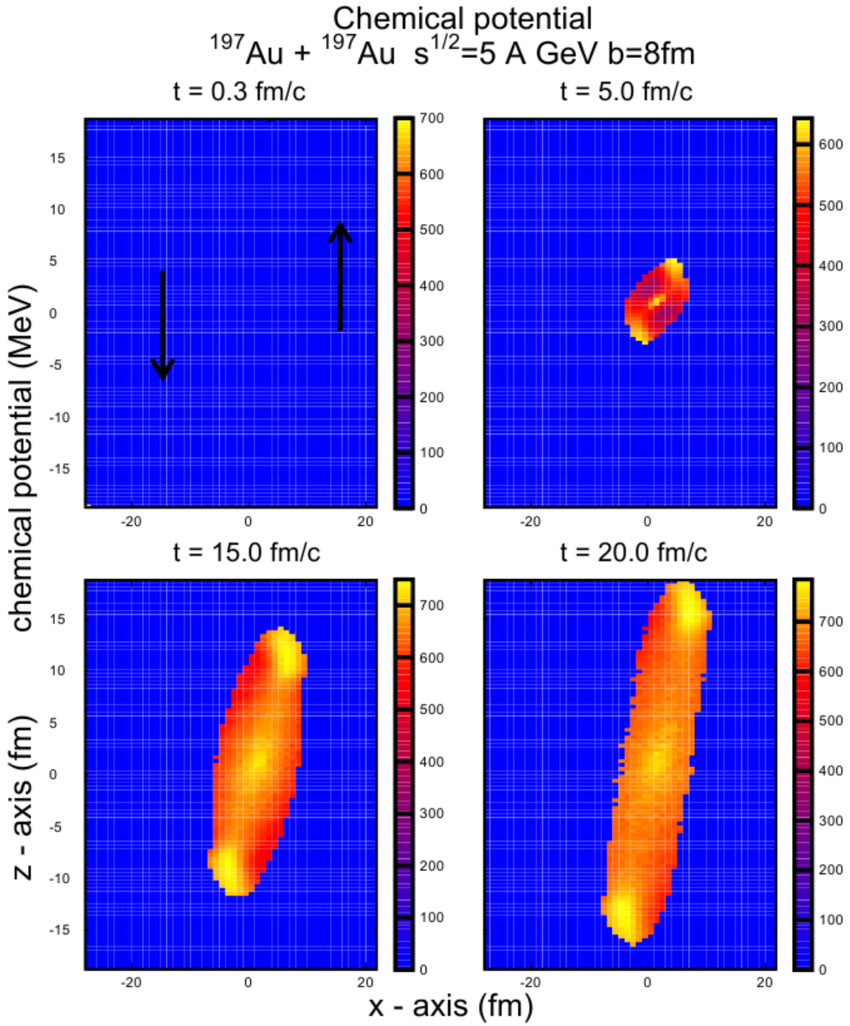
Helicity separation in QGSM **PRC88 (2013) 061901**

- 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**



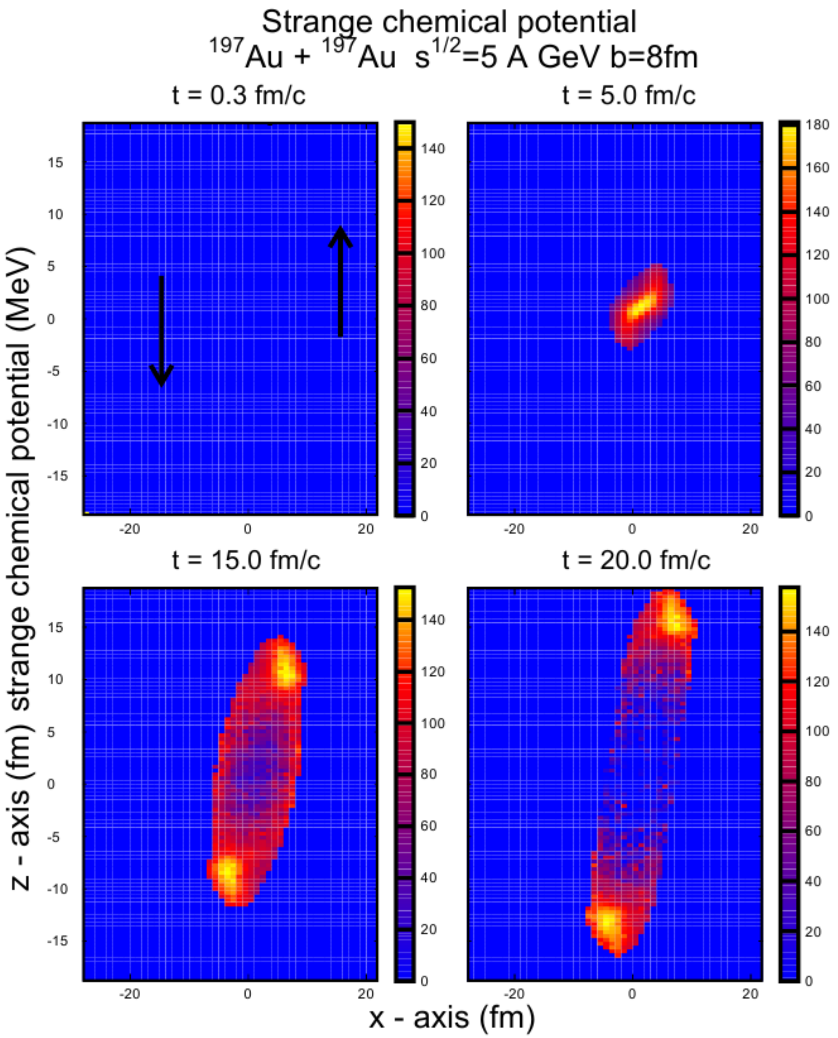
Chemical potential : Kinetics -> TD

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

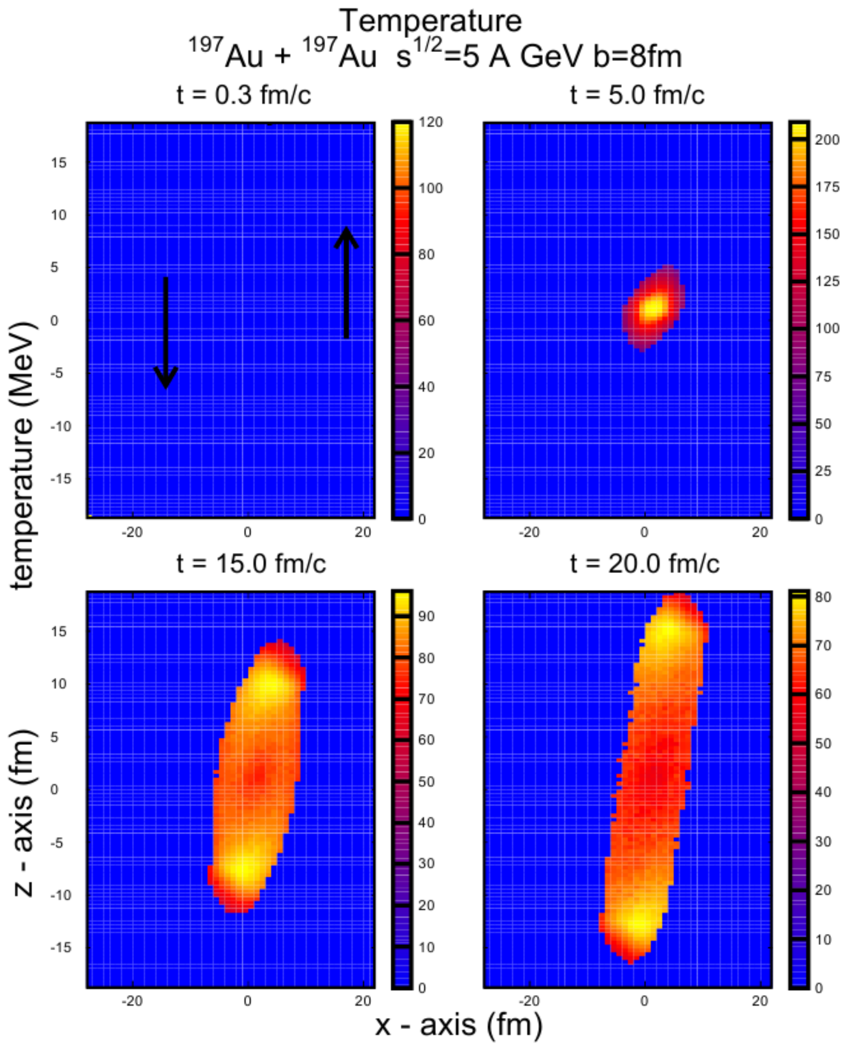


Strange chemical potential (polarization of Lambda is carried mostly by strange quark!)

- Non-uniform in space and time



Temperature

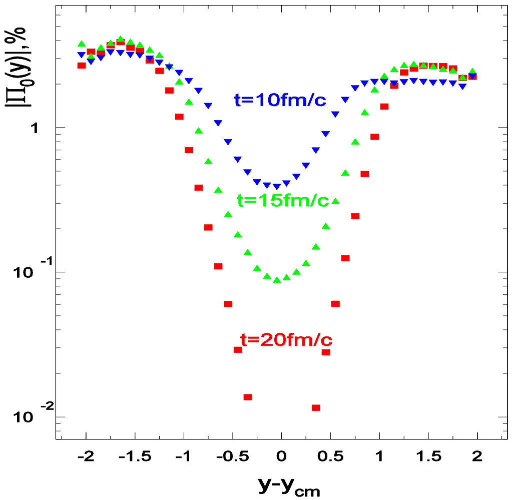


QGSM numerics for polarization

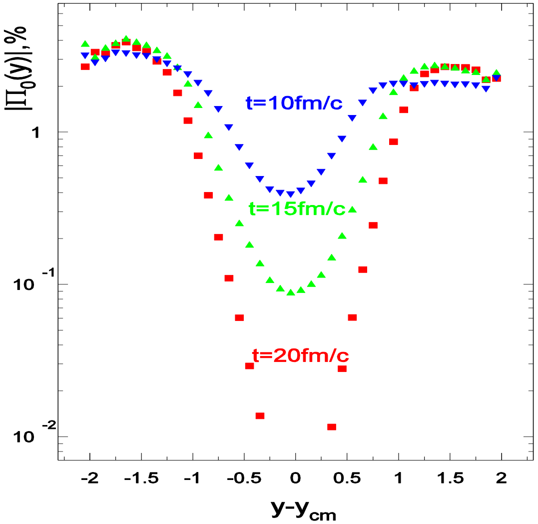
- Helicity ~ 0th component of polarization in lab. frame + effect of boost to Lambda rest frame

$$\Pi_0(y)=1/(4\pi^2)\int \gamma^2(x)\mu_s^2(x)\,|v\cdot rot(v)|\,n_\Lambda(y,x)w_1d^3x \Big/ \int n_\Lambda(y,x)w_2d^3x$$

$w_1=1$, $w2=1$

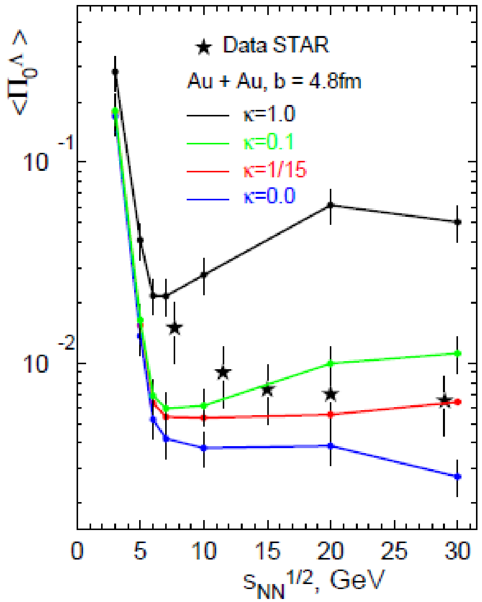


$w_1=1$, $w_2=p_y/m$



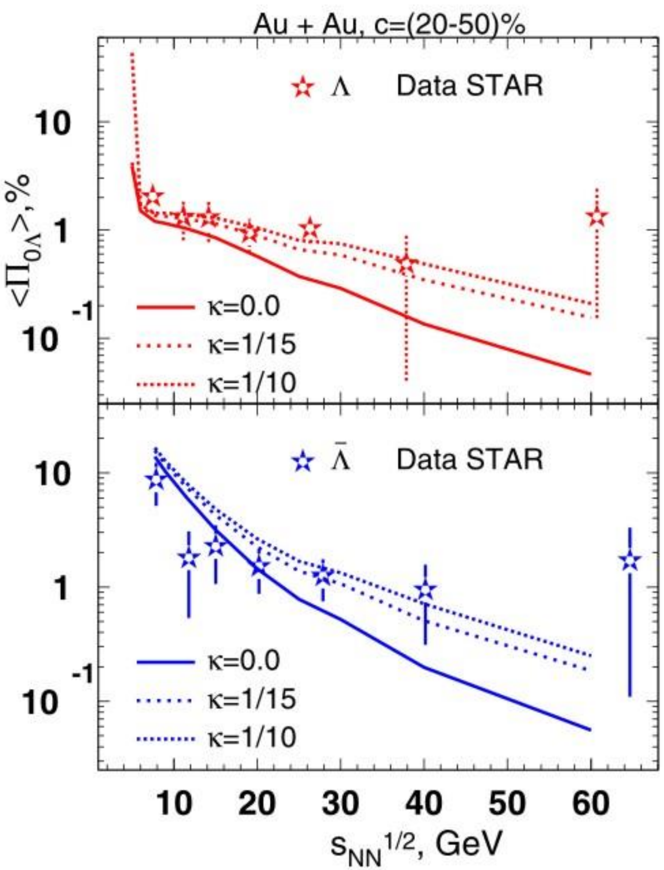
The role of (gravitational anomaly related) T^2 term

- Different values of coefficient probed



- LQCD suppression by collective effects supported

Λ vs Anti Λ (preliminary, in preparation)



Conclusions/Outlook

- Polarization – new probe of anomaly in quark-gluon matter (to be studied at NICA!)
- Quark-hadron duality via axial charge
- 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
- Flavor dependence of size and sign of polarization as a probe
- Tensor polarization – from polarizability in large magnetic fields

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

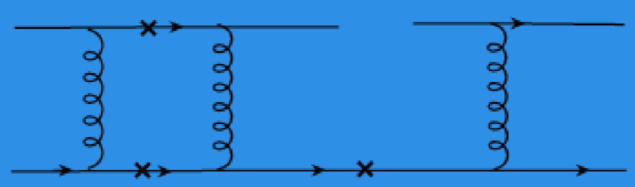
SSA - either T-violation or the phases.

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):

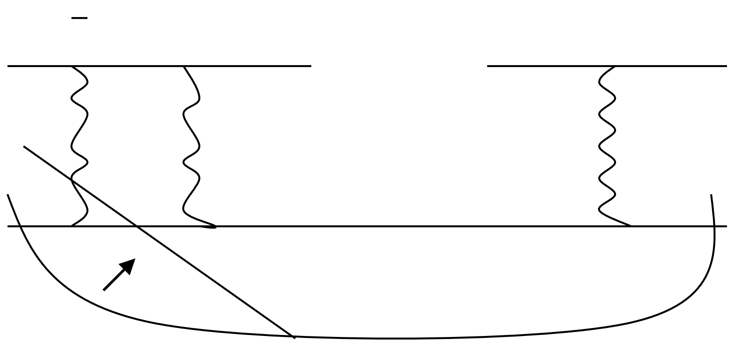


$$A \sim \frac{\alpha_S m p_T}{p_T^2 + m^2}$$

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