ROTATING QCD MATTER

Dubna International Advanced School of Theoretical Physics

Helmholtz International Summer School

Lattice QCD, Hadron Structure and Hadronic Matter

JINR, Dubna, August 25, 2014

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Outline

Lecture 1

Rotation in heavy-ion collisions

From rotation to polarization: Axial anomaly

Anomaly in nucleon and hadronic matter: vorticity vs gluon polarization

Exploration of Spin effects at JINR

Lecture 2

Rotation and gravity

Gravitational formfactors

Equivalence principle and its extenstion

Rotation and lattice

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)

Model calculations@BLTP

Baznat, Gudima, Sorin, OT PHYSICAL REVIEW C **88**, 061901(R) (2013)

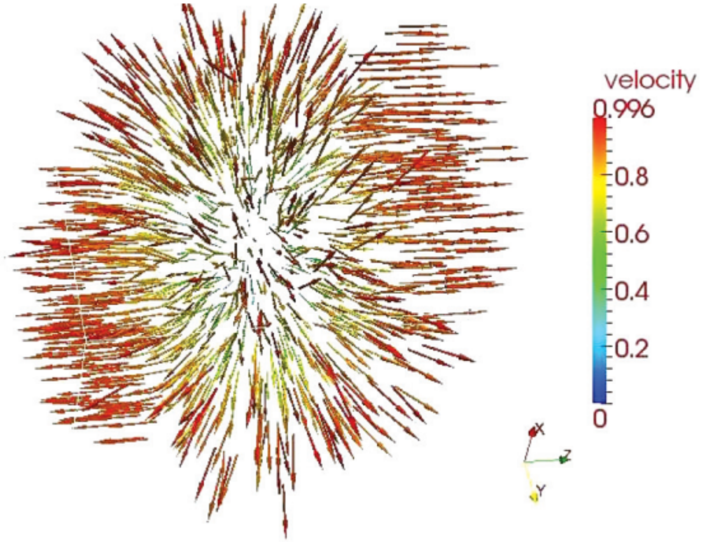
- Kinetic model (Quark-Gluon String Model) – output - particle momenta

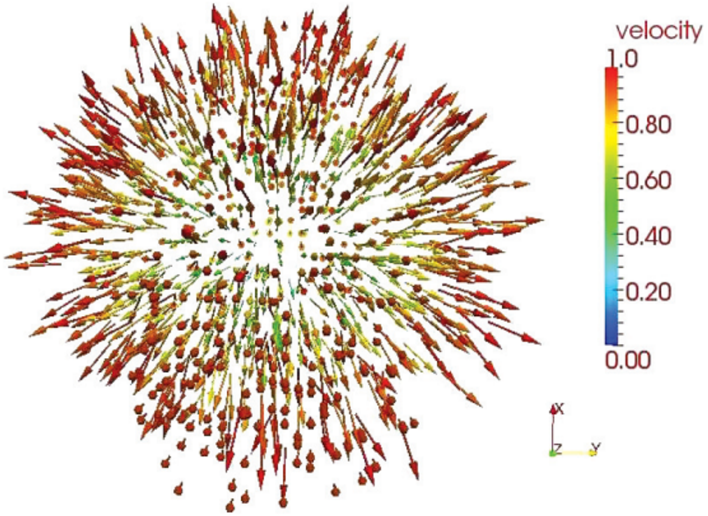
- Velocity $$\vec{v}(x,y,z,t) = \frac{\sum_i \sum_j \vec{P}_{ij}}{\sum_i \sum_j E_{ij}}$$

- i – particles, j – (1-10000) events

Distribution of velocity ("Small Bang")

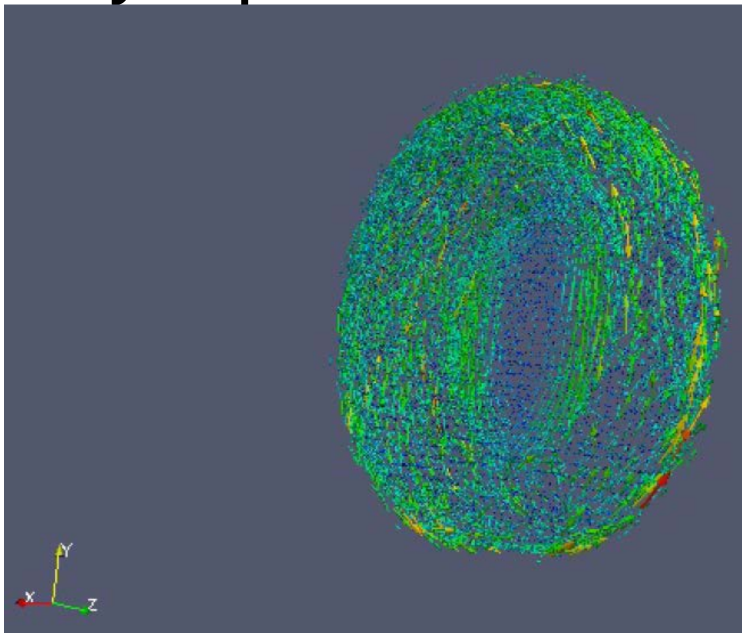
- 3D/2D projection
- z-beams direction
- x-impact paramater



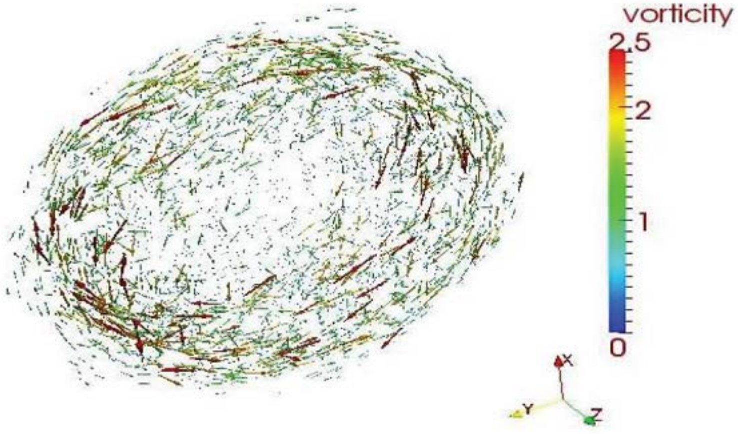


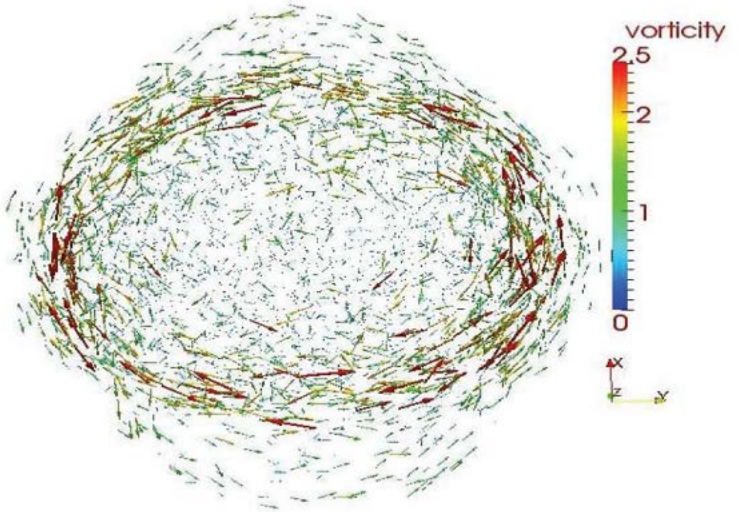
Distribution of vorticity ("small galaxies")

- Layer patterns –



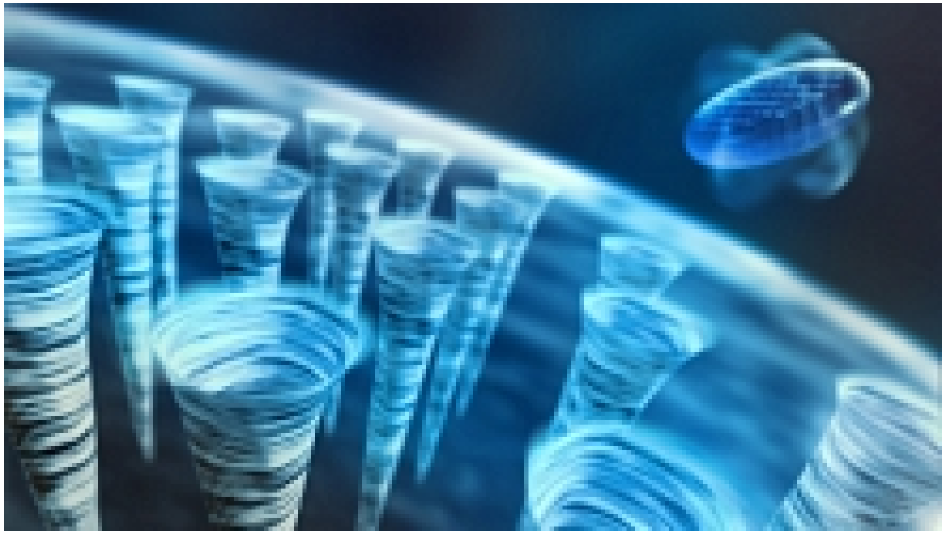
- (preliminary)





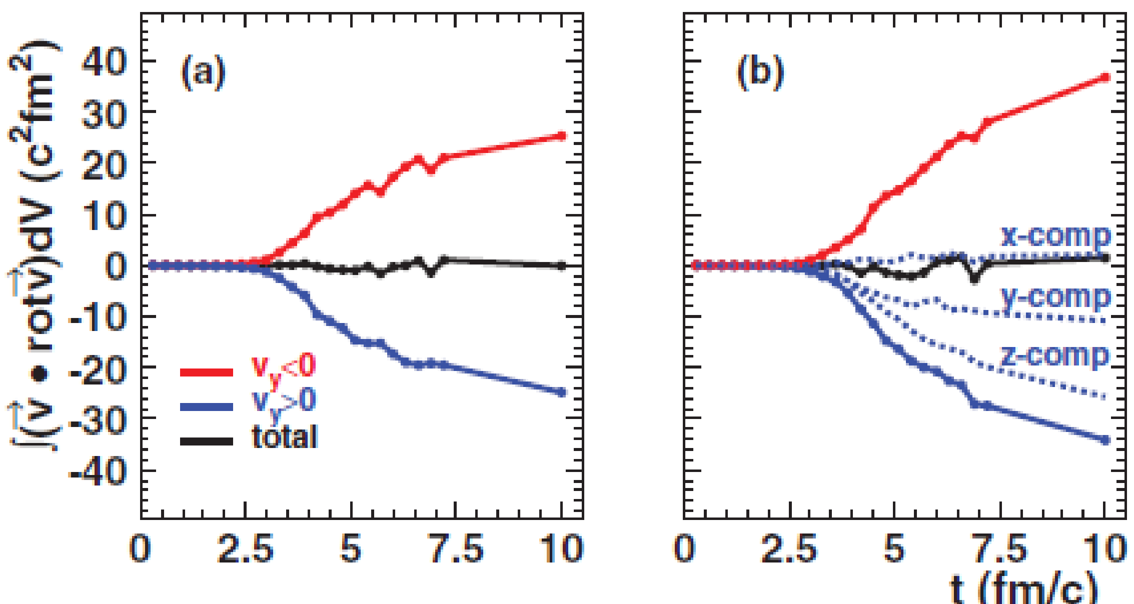
Liquid helium

- Recent observation of “mini-tornadoes”
- Science 22 August 2014:
  Vol. 345 no. 6199 pp. 906-909
  DOI: 10.1126/science.1252395
- **REPORT**
- **Shapes and vorticities of superfluid helium nanodroplets**
- **Cf “femtodroplets” in HIC**



Helicity separation

- Total helicity integrates to zero BUT
- Mirror helicities below and above the reaction plane



What is the relative orientation of velocity and vorticity?

- Measure – Cauchy-Schwarz inequality
- Small but non-negligible correlation

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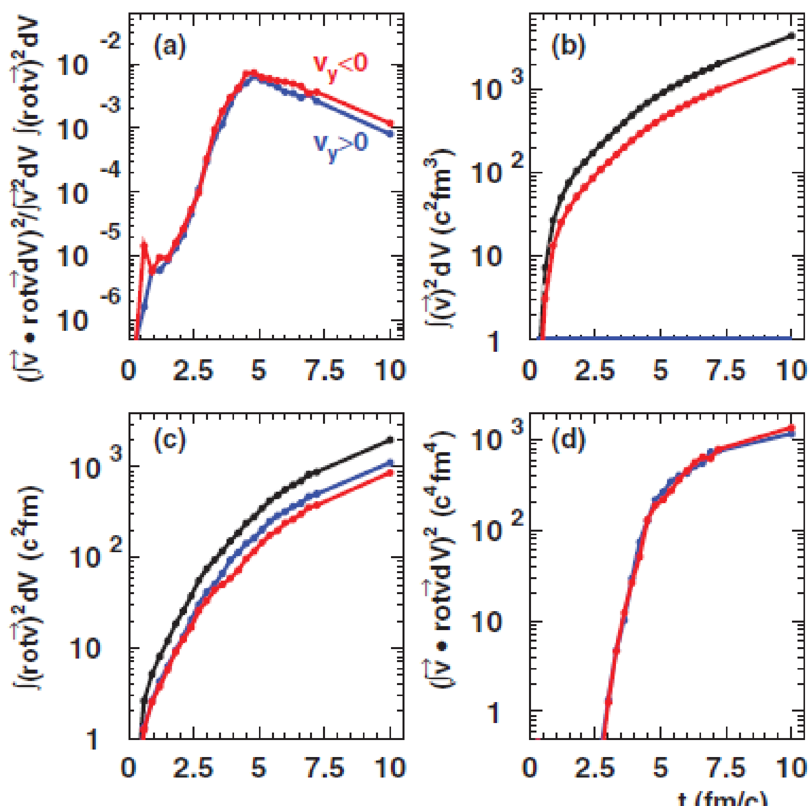


How robust is the prediction?

- Similar results:
- UrQMD model
- HSD model (poster presentation of R. Usubov)

How to observe this effect?

- Coupling of HD helicity to quark axial current via axial anomaly
- May lead to POLARIZATION of hyperons

Symmetries and conserved operators

- (Global) Symmetry -> conserved current ($\partial^\mu J_\mu = 0$)
- Exact:
- U(1) symmetry – charge conservation - electromagnetic (vector) current
- Translational symmetry – energy momentum tensor $\partial^\mu T_{\mu\nu} = 0$

Massless fermions (quarks) – approximate symmetries

- Chiral symmetry (mass flips the helicity)

$$\partial^{\mu} J^{5}{}_{\mu} = 0$$

- Dilatational invariance (mass introduce dimensional scale – c.f. energy-momentum tensor of electromagnetic radiation)

$$T_{\mu\mu} = 0$$

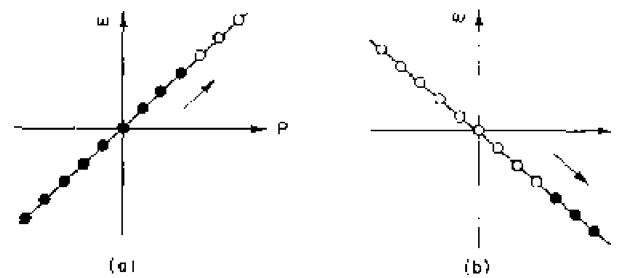
Quantum theory

- Currents -> operators
- Not all the classical symmetries can be preserved -> anomalies
- Enter in pairs (triples?...)
- Vector current conservation <-> chiral invariance
- Translational invariance <-> dilatational invariance

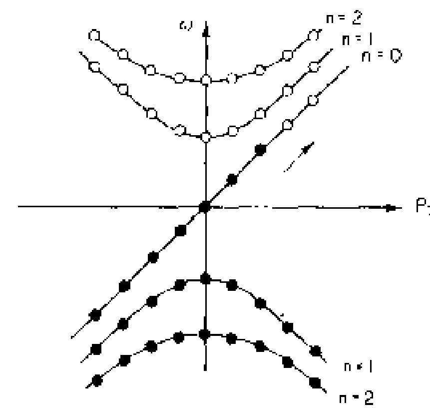
Calculation of anomalies

- Many various ways (VVA diagram)
- All lead to the same operator equation

$$\partial^{\mu} j^{(0)}_{5\mu} = 2i\sum_{q} m_q \bar{q}\gamma_5 q - \left(\frac{N_f \alpha_s}{4\pi}\right) G^{a}_{\mu\nu}\tilde{G}^{\mu\nu,a}$$



- UV vs IR languages- understood in physical picture (Gribov, Feynman, Nielsen and Ninomiya) of Landau levels flow (E||H)



Counting the Chirality

- Degeneracy rate of Landau levels
- “Transverse” HS/(1/e) (Flux/flux quantum)
- “Longitudinal” Ldp= eE dt L (dp=eEdt)
- Anomaly – coefficient in front of 4-dimensional volume - e^2 EH

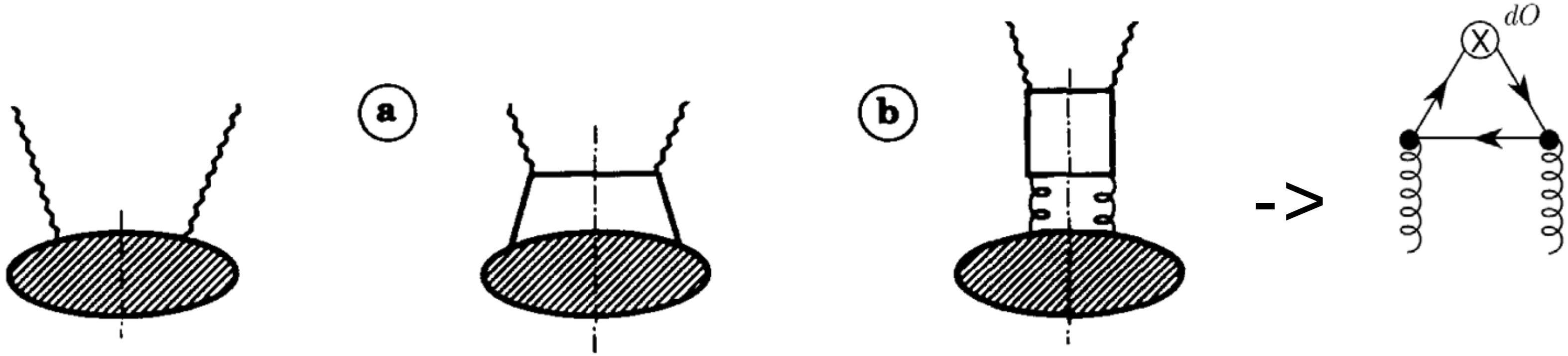
Anomaly and nucleon spin structure

- Transmits (leading twist) circular polarization of gluons to that of light quarks

- Transmits (high twist) quark-gluon correlations to polarization of heavy (strange may be considered heavy sometimes!) quarks

Gluon Anomaly and spin structure

- Gluon contribution to DIS



- Taking the 1st moment (integral over x): box -> triangle
- Gluon polarization – numerically small

Massive quarks

- One way of calculation – finite limit of regulator fermion contribution (to TRIANGLE diagram) in the infinite mass limit
- The same (up to a sign) as contribution of REAL quarks
- For HEAVY quarks – cancellation!
- Anomaly – violates classical symmetry for massless quarks but restores it for heavy quarks

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Heavy quarks polarisation

- Non-complete cancellation of mass and anomaly terms (97)

$$\partial^\mu j^c_{5\mu} = \frac{\alpha_s}{48\pi m_c^2}\partial^\mu R_\mu ,$$

$$\langle N(p,\lambda)|j^{(c)}_{5\mu}(0)|N(p,\lambda)\rangle$$

$$= \frac{\alpha_s}{12\pi m_c^2}\langle N(p,\lambda)|g \sum_{f=u,d,s} \bar{\psi}_f \gamma_\nu \tilde{G}_\mu{}^\nu \psi_f|N(p,\lambda)\rangle$$

$$R_\mu = \partial_\mu (G^a_{\rho\nu}\tilde{G}^{\rho\nu,a}) - 4(D_\alpha G^{\nu\alpha})^a \tilde{G}^a_{\mu\nu}$$

$$= \frac{\alpha_s}{12\pi m_c^2} 2m_N^3 s_\mu f_S^{(2)} .$$

- Gluons correlation with nucleon spin – twist 4 operator NOT directly related to twist 2 gluons helicity BUT related by QCD EOM to singlet twist 4 correction (colour polarisability) f2 to g1
- “Anomaly mediated” polarisation of heavy quarks

Numerics

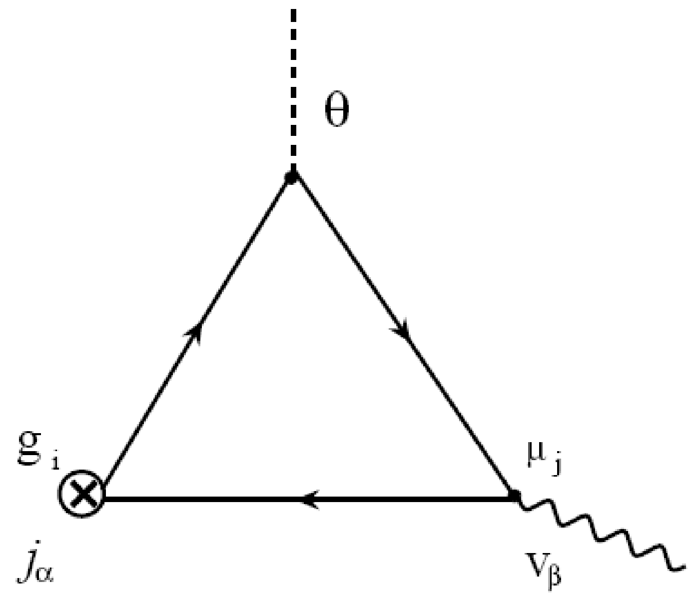
- Small (intrinsic) charm polarisation

$$\overline{G}_A^c(0) = -\frac{\alpha_s}{12\pi} f_S^{(2)} \left(\frac{m_N}{m_c}\right)^2 \approx -5 \times 10^{-4}$$

- Consider STRANGE as heavy! – CURRENT strange mass squared is 100 times larger – -5% - reasonable compatibility to the data! (But problem with DIS and SIDIS)

Anomaly in medium – new external lines in VVA graph

- Gauge field -> velocity
- CME -> CV(ortical)E
- Kharzeev, Zhitnitsky (07) – EM current
- Straightforward generalization: any (e.g. baryonic) current – neutron asymmeries@NICA - Rogachevsky, Sorin, OT - **Phys.Rev.C82:054910,2010**.



Baryon charge with neutrons – (Generalized) Chiral Vortical Effect
(Anomalous transport on the lattice –M. Polikarpov and collaborators; lectures of P. Buividovich)

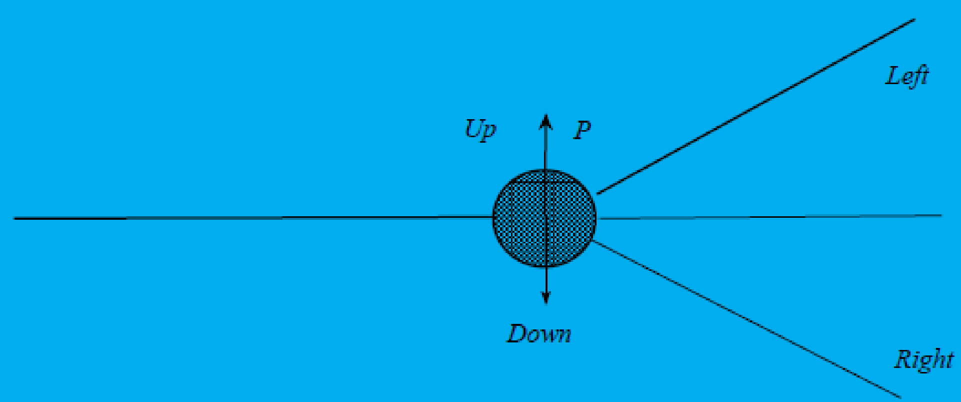
- Coupling: $e_j A_\alpha J^\alpha \Rightarrow \mu_j V_\alpha J^\alpha$

- Current: $J_e^\gamma = \frac{N_c}{4\pi^2 N_f} \varepsilon^{\gamma\beta\alpha\rho} \partial_\alpha V_\rho \partial_\beta (\theta \sum_j e_j \mu_j)$
- \- Uniform chemical potentials: $J_i^\nu = \frac{\sum_j g_{i(j)} \mu_j}{\sum_j e_j \mu_j} J_e^\nu$
- \- Rapidly (and similarly) changing chemical potentials:

$$J_i^0 = \frac{|\vec{\nabla} \sum_j g_{i(j)} \mu_j|}{|\vec{\nabla} \sum_j e_j \mu_j|} J_e^0$$

Single Spin Asymmetries (vector polarisation)

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

Polarization of hyperons in HIC

- Hyperons (in particular, Λ) polarization (self-analyzing in weak decay)
- Normal to scattering plane - smearing in HIC-rotation in reaction plane
- Searched at RHIC (S. Voloshin et al.) – oriented plane (slow neutrons) - no signal observed

Why polarization is not seen?

- Possible origin – distributed orbital angular momentum and local spin-orbit coupling
- Only small amount of collective OAM is coupled to polarization

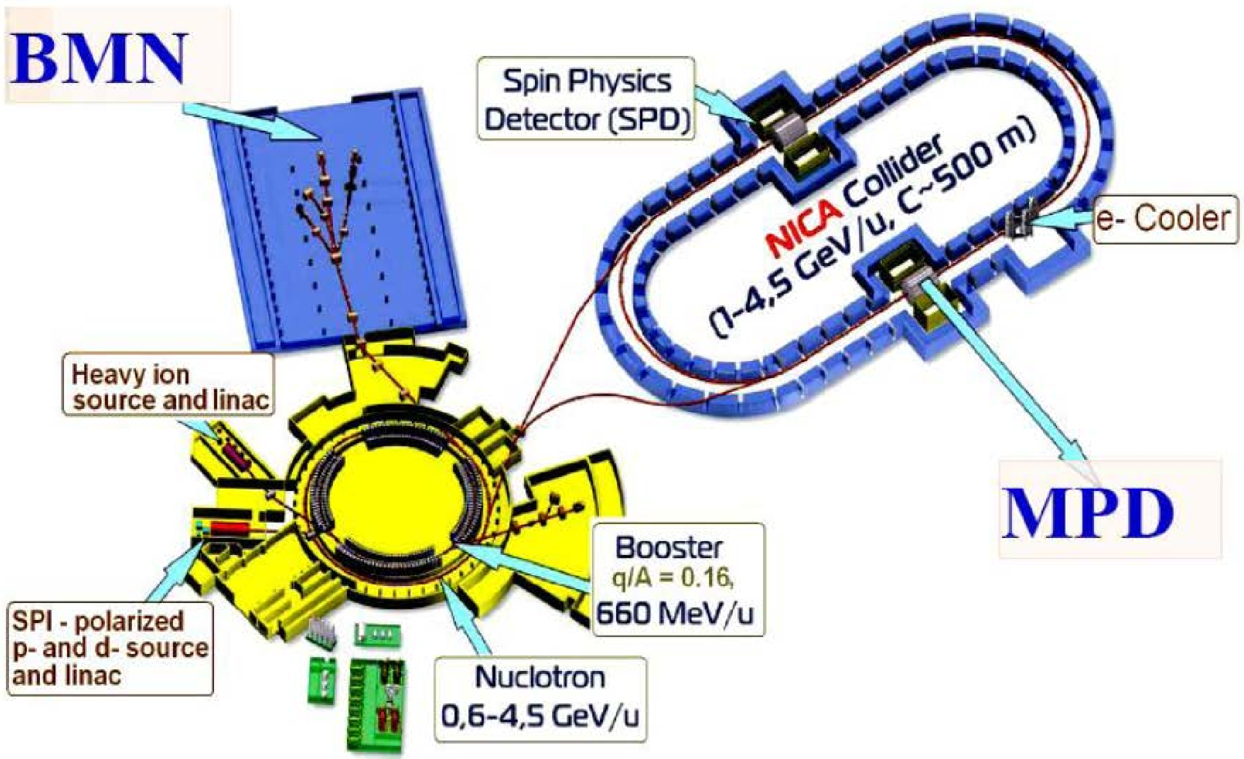
New source of Λ polarization: coupling to rotation

- Bilinear effect of vorticity – generates quark axial current (Son, Surowka'09)
- Strange quarks - should lead to Λ polarization (Rogachevsky,Sorin,OT'10)
- Proportional to square of chemical potential – small at high energies (RHIC) – may be probed at moderate ones (FAIR & NICA)
- Also maximal helicity!

How large is the polarization?

- Induced current $j_A^\mu \sim \mu^2 \left(1 - \frac{2\,\mu\,n}{3\,(\epsilon + P)}\right) \epsilon^{\mu\nu\lambda\rho}\, V_\nu\, \partial_\lambda V_\rho$
- Axial charge $Q_5^s = \frac{N_c}{2\pi^2} \int d^3x \mu^2(x) \epsilon^{ijk} u_i \partial_j u_k = \frac{\langle \mu^2 \rangle\, N_c H}{2\pi^2},$
- Polarization $\langle P_\Lambda \rangle \sim \frac{\langle \mu^2 \rangle N_c H}{2\pi^2 \langle N_\Lambda \rangle}.$ ~1%

Where to study it? – NICA - (lectures of G. Trubnikov, O.Rogachevsky, excursion 3.09)



Spin@NICA

- Λ-hyperons polarization – MPD and BM@N detectors

- Gluon polarization in nucleon and other spin (and transverse momentum) dependent distribution – SPD detector

Conclusions/Discussion - I

- Vorticity emerges in collisions of heavy ions
- May be transmitted to quark polarization analogously to case of gluon polarization in nucleon
- New source of hyperon polarization in heavy ions collisions
- Quark masses may (partially) screen anomaly effects