What can we learn from NICA?

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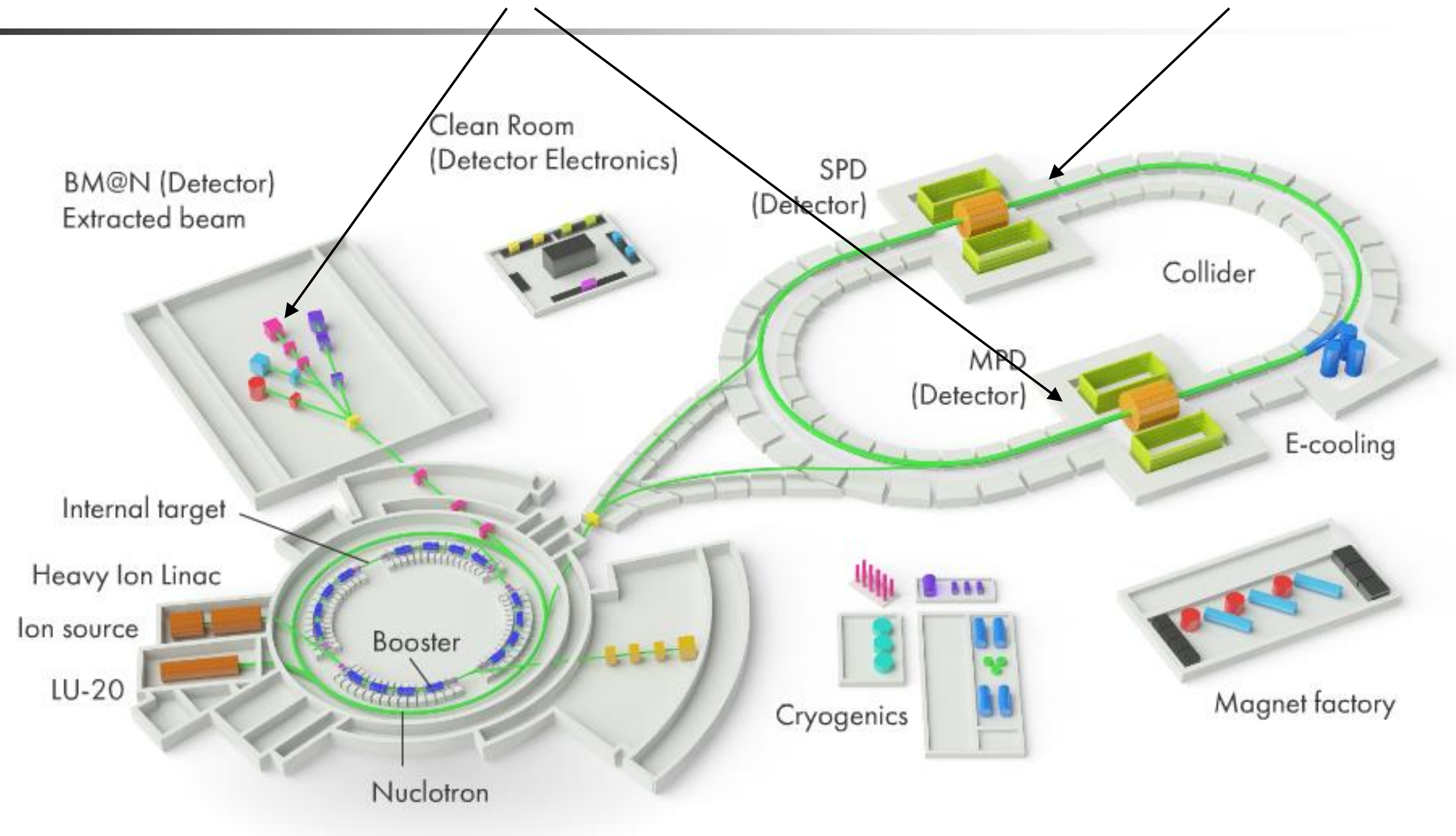
Outline

- NICA: Heavy Ion and Hadronic collisions
- Heavy Ions vs hadrons: specifics vs similarity
- Small systems: “statistical” and “dynamical” description
- Axial anomaly and anomalous transport
- Polarization in hadronic and heavy-ion collisions

NICA: heavy ions and hadrons

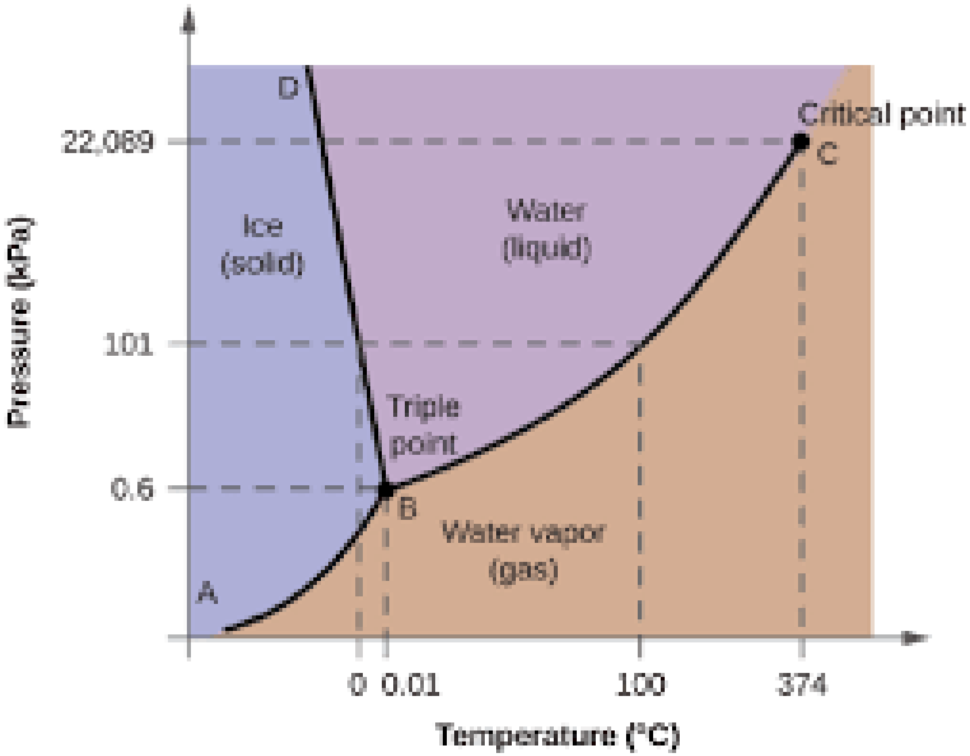


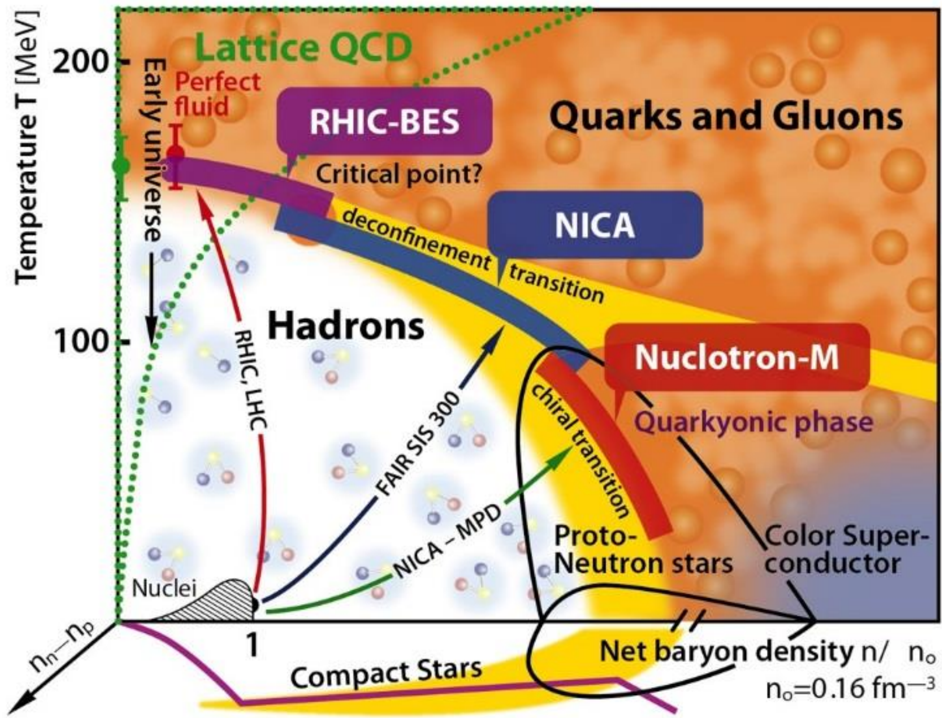
Theory: based on QCD but seemingly rather different

- Hadrons – QCD factorization
- Partonic hard scattering
- Parton distributions -> ("3D") Wigner functions

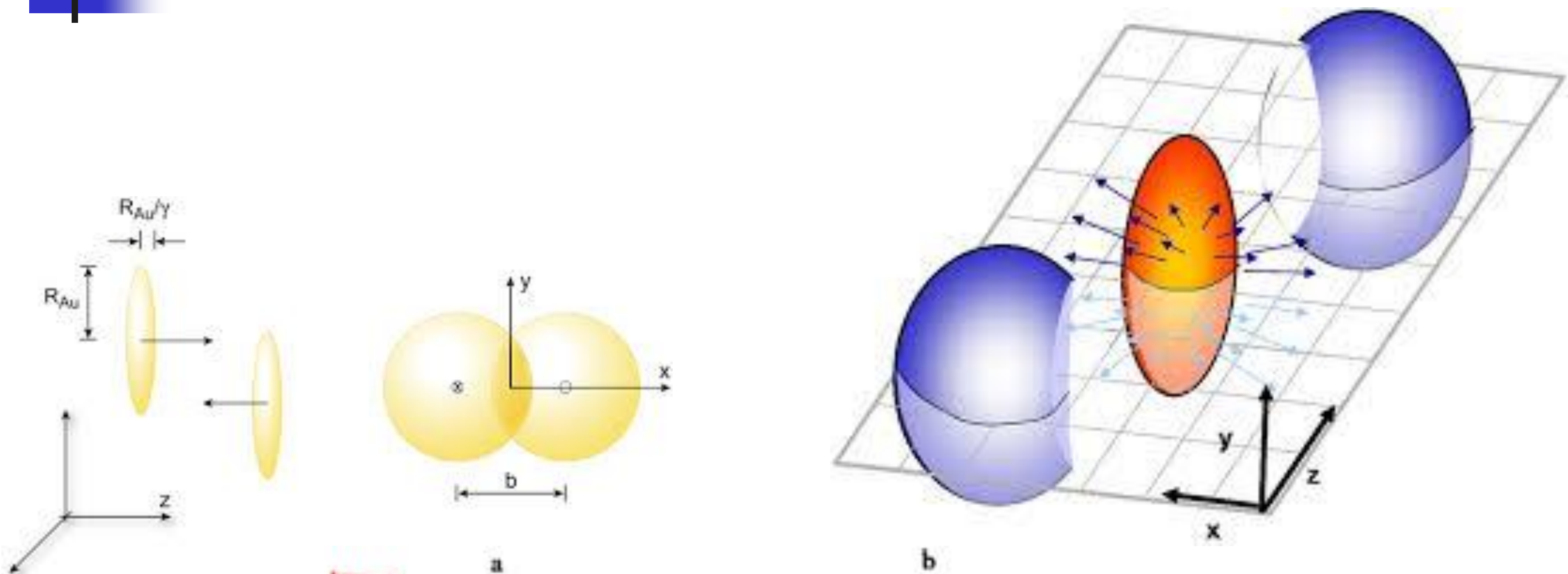
- Heavy ions: QCD phase diagram
- Statistical description (T, μ)
- Collective effects – flows, fluctuations

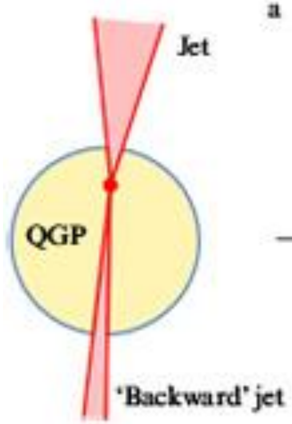
Phase diagram: Macro- ~10^{23}; Micro- ~ 10^{3-5}

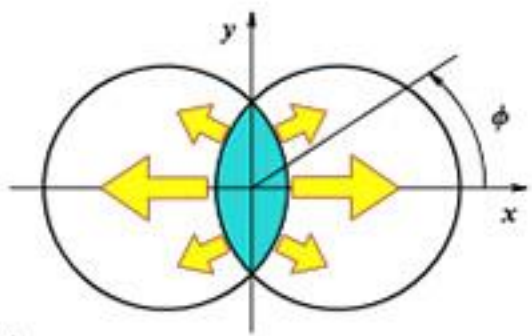




Collective effects: reaction plane and flows: $N \sim (1 + 2 \sum v_n \cos(n\Phi))$



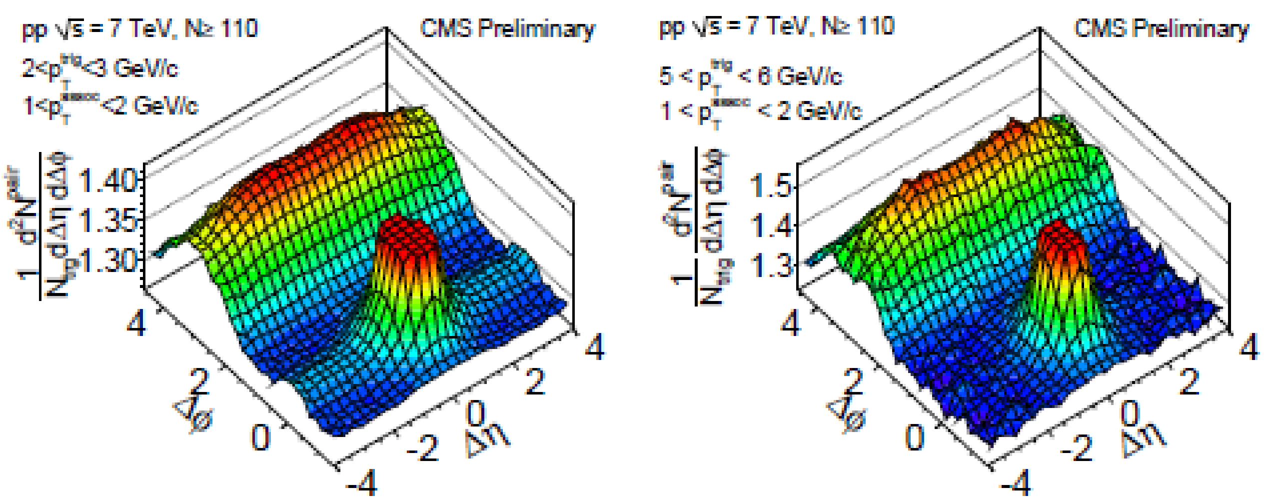




Unexpected: ridge in pp

- Naturally emerges due to reaction plane
- May be explained dynamically (Regge cuts ("duality")

Ridge correlation structure in high multiplicity pp collisions with CMS 2



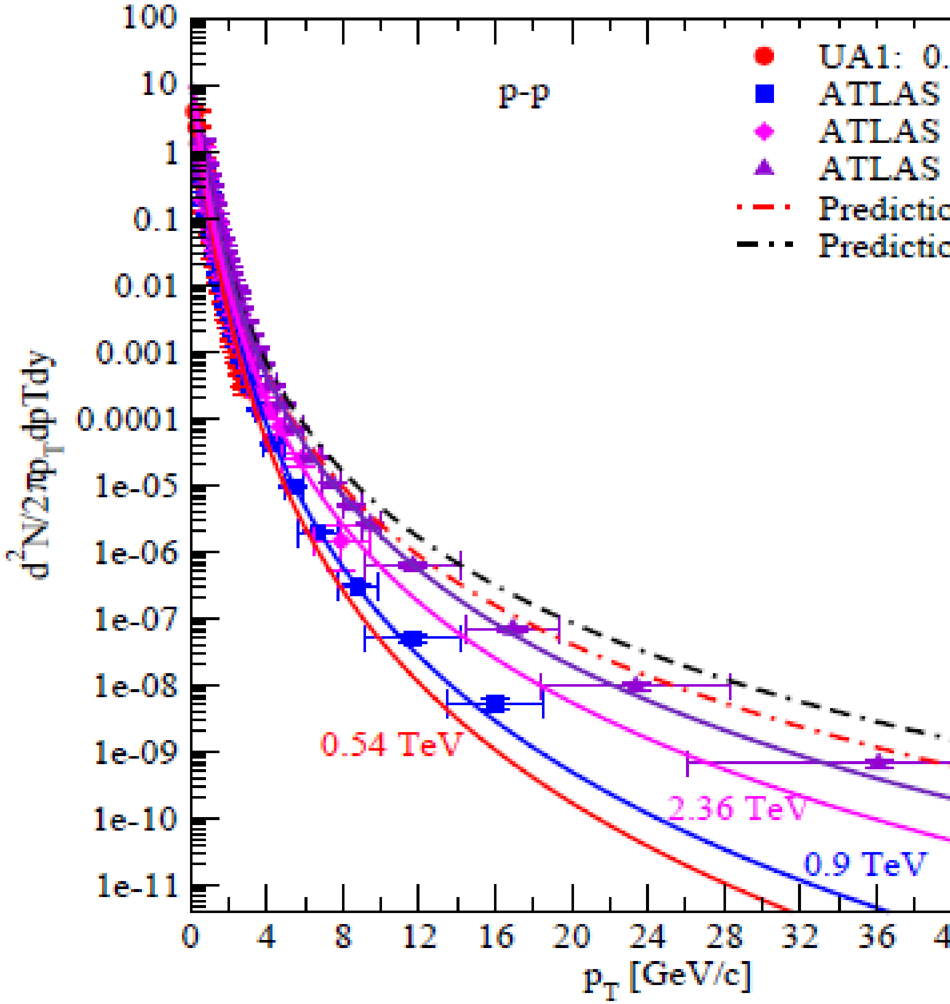
Statistics in pp collisions – Levy-Tsallis distribution

- Wide range
- Power-law

$$\left.\frac{d^2N}{dp_T\ dy}\right|_{y=0} = gV\frac{p_T m_T}{(2\pi)^2}\left[1+(q-1)\frac{m_T}{T}\right]^{-q/(q-1)}$$

- Boltzmann limit

$$\lim_{q\to 1}\frac{d^2N}{dp_T\ dy} = gV\frac{p_T m_T \cosh y}{(2\pi)^2}\exp\left(-\frac{m_T\cosh y-\mu}{T}\right)$$



Scale invariance

- $y = f(x)$
- Dimensionfull quantities: $y = y_0\, f(x/x_0)$
- $y=e^{az}$ -> depends on x_0 , y_0
- $y = z^a$ - invariant for $x_0 \to \lambda x_0$, $y_0 \to \lambda^a y_0$
- In QCD- approximately at large (pQCD) scale and small (coupling freezing, conformal window) scale
- Tsallis effective theory for QCD
- Duality of statistical and dynamical description

Polarization data has often been the graveyard of fashionable theories.
If theorists had their way, they might just ban such measurements altogether out of self-protection.
J.D. Bjorken
St. Croix, 1987

- Axial anomaly and transport in hadronic media
- Vorticity and hyperon polarization

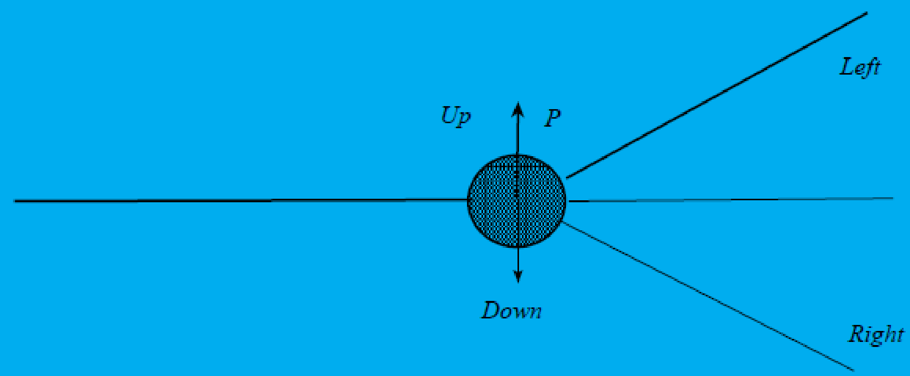
Appeared in Nature

Global Λ hyperon polarization in nuclear collisions: evidence for the most vortical fluid

The extreme temperatures and energy densities generated by ultra-relativistic collisions between heavy nuclei produce a state of matter with surprising fluid properties[1]. Non-central collisions have angular momentum on the order of $1000\hbar$, and the resulting fluid may have a strong vortical structure[2–4] that must be understood to properly describe the fluid. It is also of particular interest because the restoration of fundamental symmetries of quantum chromodynamics is expected to produce novel physical effects in the presence of strong vorticity[15]. However, no experimental indications of fluid vorticity in heavy ion collisions have so far been found. Here we present the first measurement of an alignment between the angular momentum of a non-central collision and the spin of emitted particles, revealing that the fluid produced in heavy ion collisions is by far the most vortical system ever observed. We find that Λ and $\overline{\Lambda}$ hyperons show a positive polarization of the order of a few percent, consistent with some hydrodynamic predictions[5]. A previous measurement[6] that reported a null result at higher collision energies is seen to be consistent with the trend of our new observations, though with larger statistical uncertainties. These data provide the first experimental access to the vortical structure of the "perfect fluid"[7] created in a heavy ion collision. They should prove valuable in the development of hydrodynamic models that quantitatively connect observations to the theory of the Strong Force. Our results extend the recent discovery[8] of hydrodynamic spin alignment to the subatomic realm.

Simple example

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

Single Spin Asymmetries and Spin-Orbital Interactions

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 $(\vec{P}\vec{n})$)

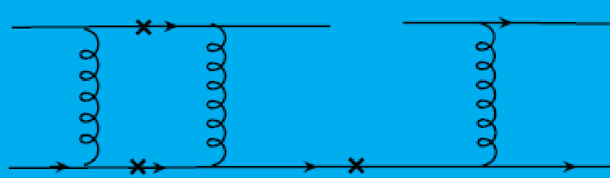
Interference of amplitudes

IMAGINARY phase between amplitudes - absent in Born approximation

Single Spin Asymmetries in pQCD

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):

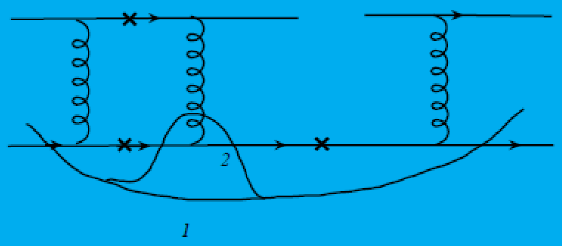


$$A \sim \frac{\alpha_S m p_T}{p_T^2 + m^2}$$

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

NPQCD: twist 3 and T-odd distributions

Escape: QCD factorization - possibility to shift the borderline between large and short distances



At short distances - Loop $\longrightarrow$ Born diagram

At Large distances - quark distribution $\longrightarrow$ quark-gluon correlator.

Physically - process proceeds in the external gluon field of the hadron.

Leads to the shift of α_S to non-perturbative domain AND

"Renormalization" of quark mass in the external field up to an order of hadron's one

$$\frac{\alpha_S m p_T}{p_T^2 + m^2} \to \frac{M b(x_1, x_2) p_T}{p_T^2 + M^2}$$

Further shift of phases completely to large distances - T-odd fragmentation functions. Leading twist transversity distribution - no hadron mass suppression.

Theory of spin: axial anomalies

- Quantum anomalies
- Anomaly and Landau levels flow
- Dispersive approach to anomaly and t’Hooft principle
- Induced currents from anomaly

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)

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

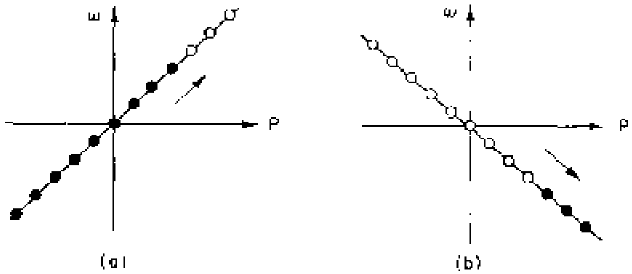
Quantum theory

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

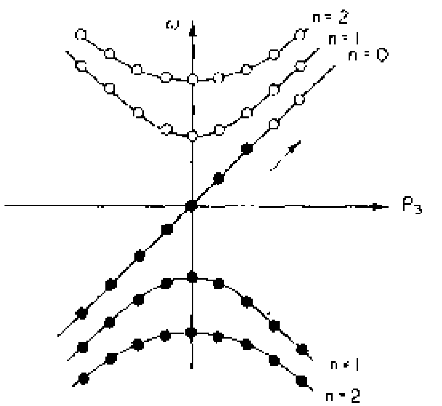
Calculation of anomalies

- Many various ways
- 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)



Degeneracy of Landau levels and 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

Topological current

- Anomaly implies new current conservation
- $\partial_\mu (J-K)^\mu=0$
- Preserved by QCD evolution
- Controls the anomalous gluon contributions to nucleon spin structure (Lecture 1)

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

Dilatational anomaly

- Classical and anomalous terms

$$\theta_{\mu\mu} = [\beta(\alpha_s)/4\alpha_s]\, G^a_{\mu\nu} G^a_{\mu\nu}$$

$$+ m_u \bar{u}u + m_d \bar{d}d + m_s \bar{s}s + \sum_{h=c,b,\ldots} m_h \bar{h}h$$

- Beta function – describes the appearance of scale dependence due to renormalization
- For heavy quarks – cancellation of classical and quantum violation -> decoupling

Anomaly and virtual photons

- Often assumed that only manifested in real photon amplitudes
- Not true – appears at any Q^2
- Natural way – dispersive approach to anomaly (Dolgov, Zakharov'70) - anomaly sum rules
- One real and one virtual photon – Horejsi,OT'95
- where $$\int_{4m^2}^{\infty} A_3(t;q^2,m^2)dt = \frac{1}{2\pi}$$

$$F_j(p^2) = \frac{1}{\pi}\int_{4m^2}^{\infty}\frac{A_j(t)}{t-p^2}dt, \qquad j=3,4$$

$$\begin{aligned} T_{\alpha\mu\nu}(k,q) &= F_1\,\varepsilon_{\alpha\mu\nu\rho}k^\rho + F_2\,\varepsilon_{\alpha\mu\nu\rho}q^\rho \\ &+ F_3\,q_\nu\varepsilon_{\alpha\mu\rho\sigma}k^\rho q^\sigma + F_4\,q_\nu\varepsilon_{\alpha\mu\rho\sigma}k^\rho q^\sigma \\ &+ F_5\,k_\mu\varepsilon_{\alpha\nu\rho\sigma}k^\rho q^\sigma + F_6\,q_\mu\varepsilon_{\alpha\nu\rho\sigma}k^\rho q^\sigma \end{aligned}$$

Dispersive derivation

- Axial WI $$F_2 - F_1 = 2mG + \frac{1}{2\pi^2}$$
- GI $$F_2 - F_1 = (q^2 - p^2)F_3 - q^2 F_4$$
- No anomaly for imaginary parts

$$(q^2 - t)A_3(t) - q^2 A_4(t) = 2mB(t)$$

$$F_j(p^2) = \frac{1}{\pi}\int_{4m^2}^{\infty} \frac{A_j(t)}{t - p^2} dt, \qquad j = 3, 4$$

- Anomaly as a finite subtraction

$$F_2 - F_1 - 2mG = \frac{1}{\pi}\int_{4m^2}^{\infty} A_3(t)dt$$

$$\int_{4m^2}^{\infty} A_3(t; q^2, m^2)dt = \frac{1}{2\pi}$$

Properties of anomaly sum rules

- Valid for any Q^2 (and quark mass)
- No perturbative QCD corrections (Adler-Bardeen theorem)
- No non-perturbative QCD correctioons ('t Hooft consistency principle)
- Massless pole in quark triangle – massless pion (complementary to CSB)

Mesons contributions

- Pion – saturates sum rule for real photons $ImF_3 = \sqrt{2} f_\pi \pi F_{\pi\gamma\gamma*}(Q^2)\delta(s - m_\pi^2)$ $F_{\pi\gamma^*\gamma}(0) = \frac{1}{2\sqrt{2}\pi^2 f_\pi}$
- For virtual photons – pion contribution is rapidly decreasing $F^{\mathrm{asymp}}_{\pi\gamma\gamma^*}(Q^2) = \frac{\sqrt{2} f_\pi}{Q^2} + \mathcal{O}(1/Q^4)$
- This is also true also for axial and higher spin mesons (longitudianl components are dominant)
- Heavy PS decouple in a chiral limit

Content of Anomaly Sum Rule ("triple point")

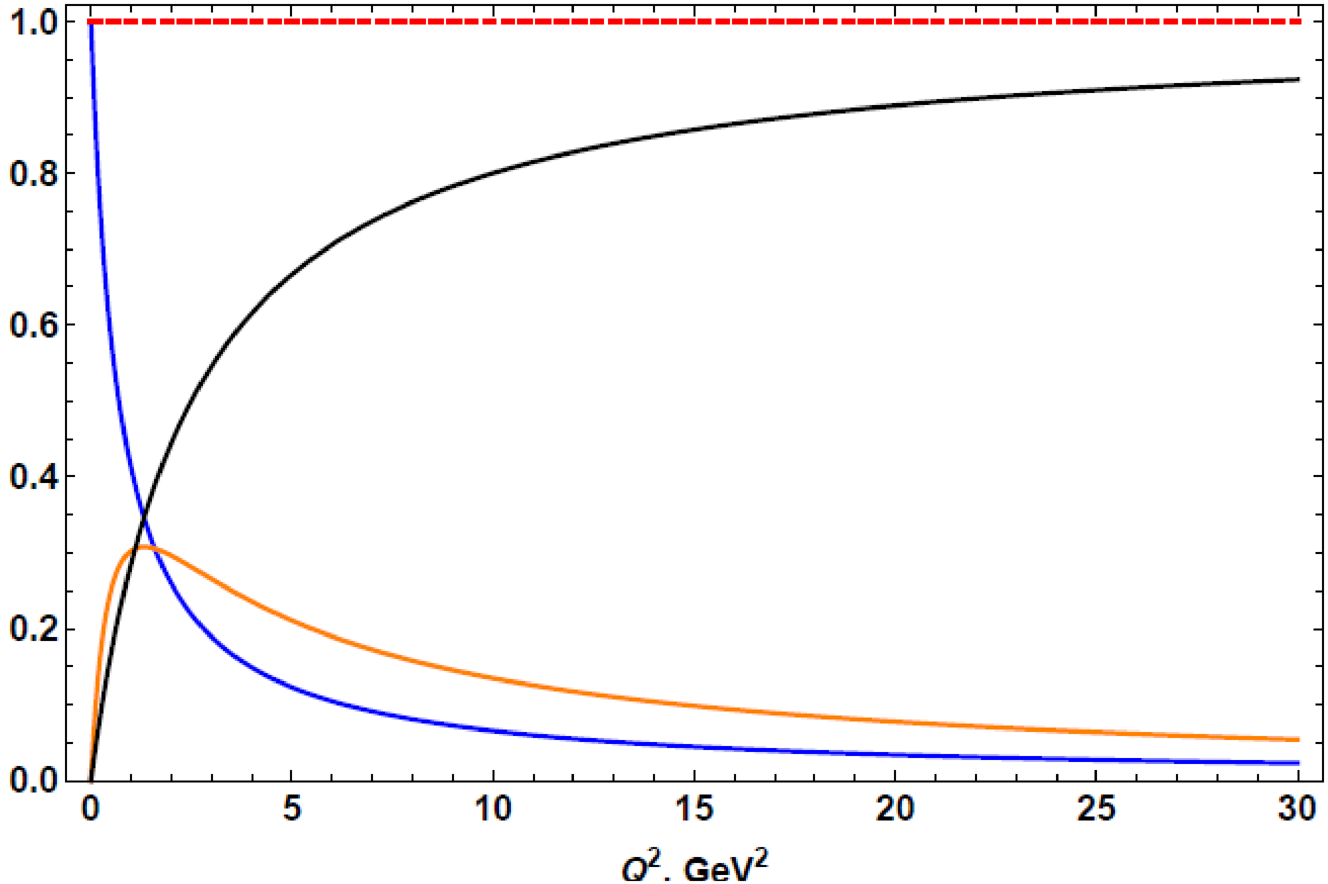


Figure 1: Relative contributions of π (blue line) and a_1 (orange line) mesons, intervals of duality are $s_0 = 0.7\ GeV^2$ and $s_1 - s_0 = 1.8\ GeV^2$ respectively, and continuum (black line), continuum threshold is $s_1 = 2.5\ GeV^2$

Anomaly as a collective effect

- One can never get constant summing finite number of decreasing function
- Anomaly at finite Q^2 is a collective effect of meson spectrum
- General situation –occurs for any scale parameter (playing the role of regulator for massless pole)
- Chemical potential?! Quarkyonic phase?!

Anomaly in Heavy Ion Collisions - Chiral Magnetic Effect (D. Kharzeev)

From QCD back to electrodynamics: Maxwell-Chern-Simons theory

$$\mathcal{L}_{\rm MCS} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - A_\mu J^\mu + \frac{c}{4} \, P_\mu J^\mu_{CS}.$$

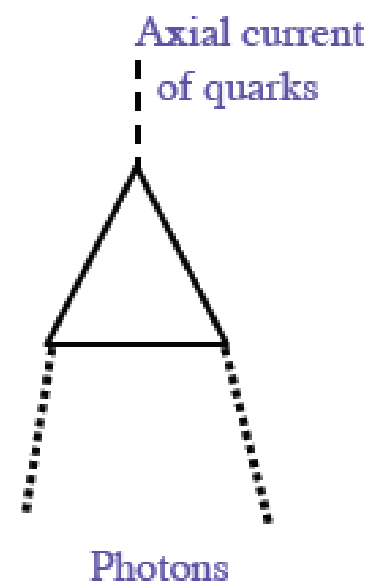
$$J^\mu_{CS} = \epsilon^{\mu\nu\rho\sigma} A_\nu F_{\rho\sigma} \qquad P_\mu = \partial_\mu \theta = (M, \vec{P})$$

$$\vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = \vec{J} + c\left(M\vec{B} - \vec{P} \times \vec{E}\right),$$

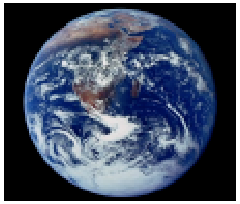
$$\vec{\nabla} \cdot \vec{E} = \rho + c\vec{P} \cdot \vec{B},$$

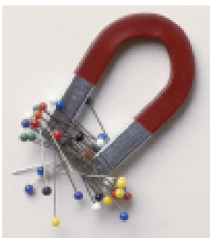
$$\vec{\nabla} \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0,$$

$$\vec{\nabla} \cdot \vec{B} = 0,$$



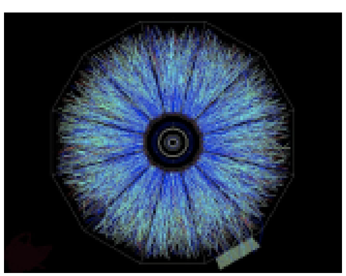
Comparison of magnetic fields





The Earths magnetic field	0.6 Gauss
A common, hand-held magnet	100 Gauss
The strongest steady magnetic fields achieved so far in the laboratory	4.5×10^5 Gauss
The strongest man-made fields ever achieved, if only briefly	10^7 Gauss
Typical surface, polar magnetic fields of radio pulsars	10^{13} Gauss
Surface field of Magnetars	10^{15} Gauss

http://solomon.as.utexas.edu/~duncan/magnetar.html



At BNL we beat them all!

Off central Gold-Gold Collisions at 100 GeV per nucleon

$$e\,B(\tau = 0.2\,\mathrm{fm}) \;=\; 10^3 \sim 10^4\ \mathrm{MeV}^2 \sim 10^{17}\,\mathrm{Gauss}$$

Induced current for (heavy - with respect to magnetic field strength) strange quarks

- Effective Lagrangian

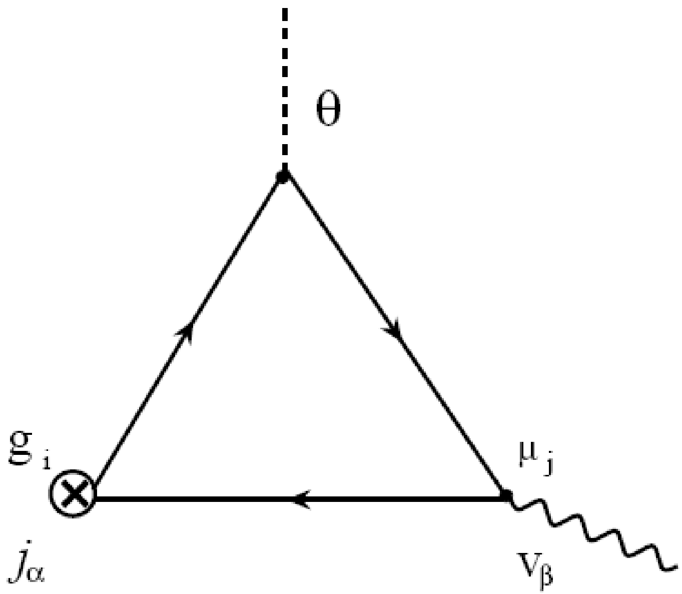
$$L = c(F\tilde{F})(G\tilde{G})/m^4 + d(FF)(GG)/m^4$$

- Current and charge density from c (~7/45) – term $j^\mu = 2c\tilde{F}^{\mu\nu}\partial_\nu(G\tilde{G})/m^4$
- $\rho \sim \vec{H}\vec{\nabla}\theta$ (multiscale medium!)

  $\theta \sim (G\tilde{G})/m^4 \to \int d^4x G\tilde{G}$
- Light quarks -> matching with D. Kharzeev et al'

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

- 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:

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

Dissipationless transport

- Time reversal: E -> E, H-> -H, j -> -j

- Electric Conductance: $j = \sigma_E E$
- Change sign under time reversal -> (anti)dissipation

- Magnetic Conductance: $j = \sigma_H H$
- Stable under time reversal – no dissipation!

Anomaly

- Anomaly – quantum violation of classical symmetries
- Many derivations – Landau level flow: UV and IR faces
- Dispersive approach and ‘tHooft principle: collective effect for extra parameter(virtuality, chemical potential…)
- Dissipationless transport in HIC

Back to polarization

- Polarization: from nucleons to ions
- Anomalous mechanism: 4-velocity as gauge field
- Chemical potential and Energy dependence
- Rotation in heavy-ion collisions: Vortical structures
- Vortices in pionic superfluid
- Conclusions

Λ-polarisation

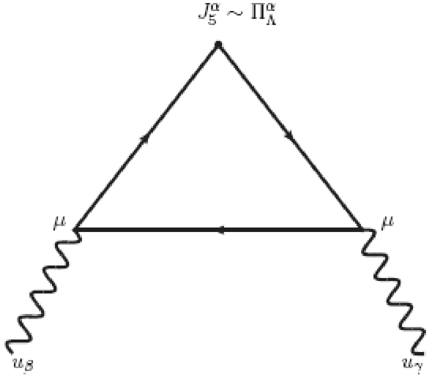
- Self-analyzing in weak decay
- Directly related to s-quarks polarization: complementary probe of strangeness
- Widely explored in hadronic processes
- Disappearance-probe of QCD matter formation (Hoyer; Jacob, Rafelsky: ’87): Randomization – smearing – no direction normal to the scattering plane

Global polarization

- Global polarization normal to REACTION plane
- Predictions (Z.-T.Liang et al.): large orbital angular momentum -> large polarization
- Search by STAR (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). Magnetic field -> VORTICITY
- $e_j A_\alpha J^\alpha \Rightarrow \mu_j V_\alpha J^\alpha$ rot A -> rot V
- Triangle anomaly (Axial Vortical Effect) 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!



Momentum and spin – Axial Anomaly appears

$\int dxx...$ - current operator with derivative - energy momentum tensor; physically - weighting with momentum fraction

$$\int_0^1 dxx(\sum[q(x)+\bar{q}(x)]+G(x))=1 \quad (7)$$

Experimentally quark contribution ~ 0.5 - historically the first evidence for gluon existence.

What about spin-dependent distributions? $\int dx$-axial current. Some matrix elements are known from $\beta-$decay. $<p|J_5^\mu|n>$-due to isospin invariance $\rightarrow <p|J_5^\mu|p> - <n|J_5^\mu|n>$ - Bjorken sum rule.

$$\int_0^1 dx(\Delta u(x)+\Delta\bar{u}(x)-\Delta d(x)-\Delta\bar{d}(x))=\frac{1}{6}g_A \quad (8)$$

Is there any sum rule similar to momentum sum rule (polarized partons should carry total nucleon spin. like spin-averaged partons carry its momentum)

Feynman: Is there any constraint...?

Total angular momentum conservation

$$\int_0^1 dx(\sum(\Delta q(x)+\Delta\bar{q}(x))+\Delta G(x)+L_q(x)+L_G(x))=\frac{1}{2} \quad (9)$$

However: Orbital angular momenta are nonlocal Do not appear in inclusive processes cross-sections. Require non-forward matrix elements for its measurement (Lecture 3)

Another conserved operator - quark-gluon current (due to axial anomaly)

$$\int_0^1 dx(\sum(\Delta q(x)+\Delta\bar{q}(x))+N_f\frac{\alpha_S}{2\pi}\Delta G(x))=const \quad (10)$$

Two faces of nucleon spin structure

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 (Braguta et al.) using similarity to Axial Magnetic Effect: 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

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

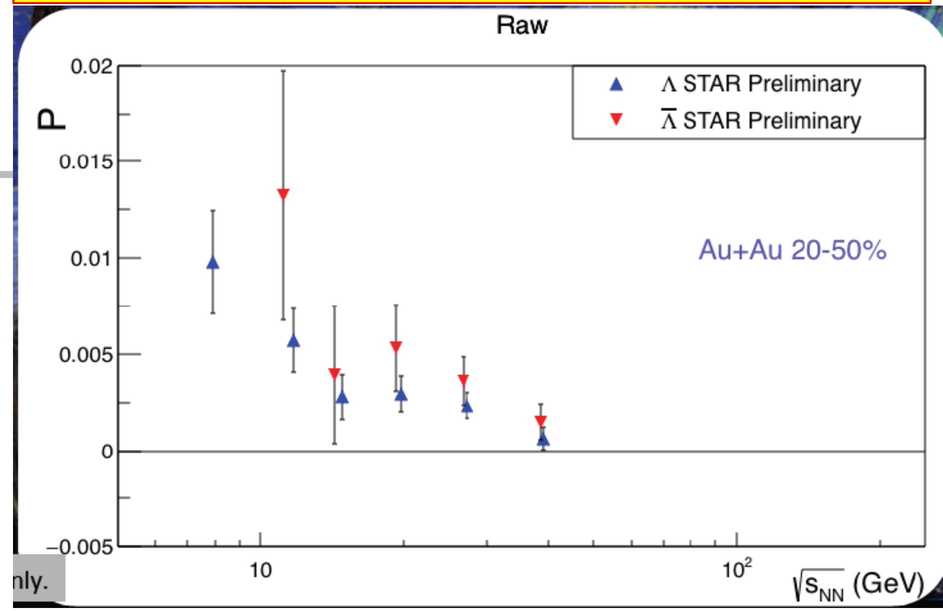
O. Rogachevsky, A. Sorin, O. Teryaev
Chiral vortaic effect and neutron asymmetries in heavy-ion collisions
PHYSICAL REVIEW C 82, 054910 (2010)

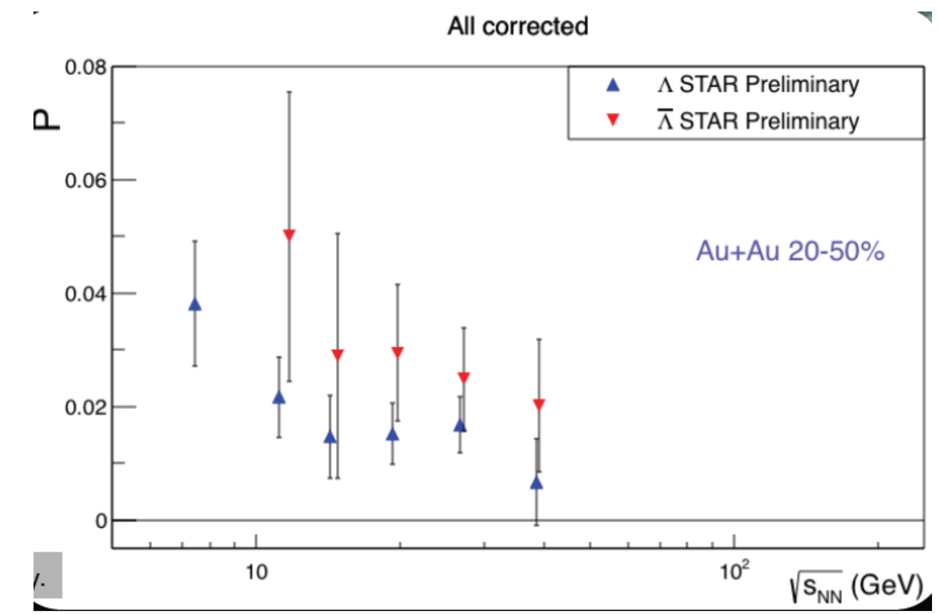
One would expect that polarization is proportional to the anomalously induced axial current [7]

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

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.





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

Simulation in QGSM (Kinetics -> HD)

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

- Velocity

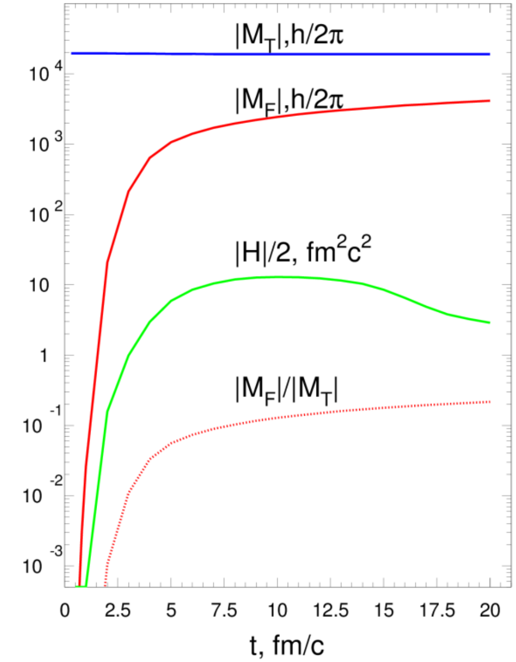
$$\vec{v}(x, y, z, t) = \frac{\sum_i \sum_j \vec{P}_{ij}}{\sum_i \sum_j E_{ij}}$$

- Vorticity – from discrete partial derivatives

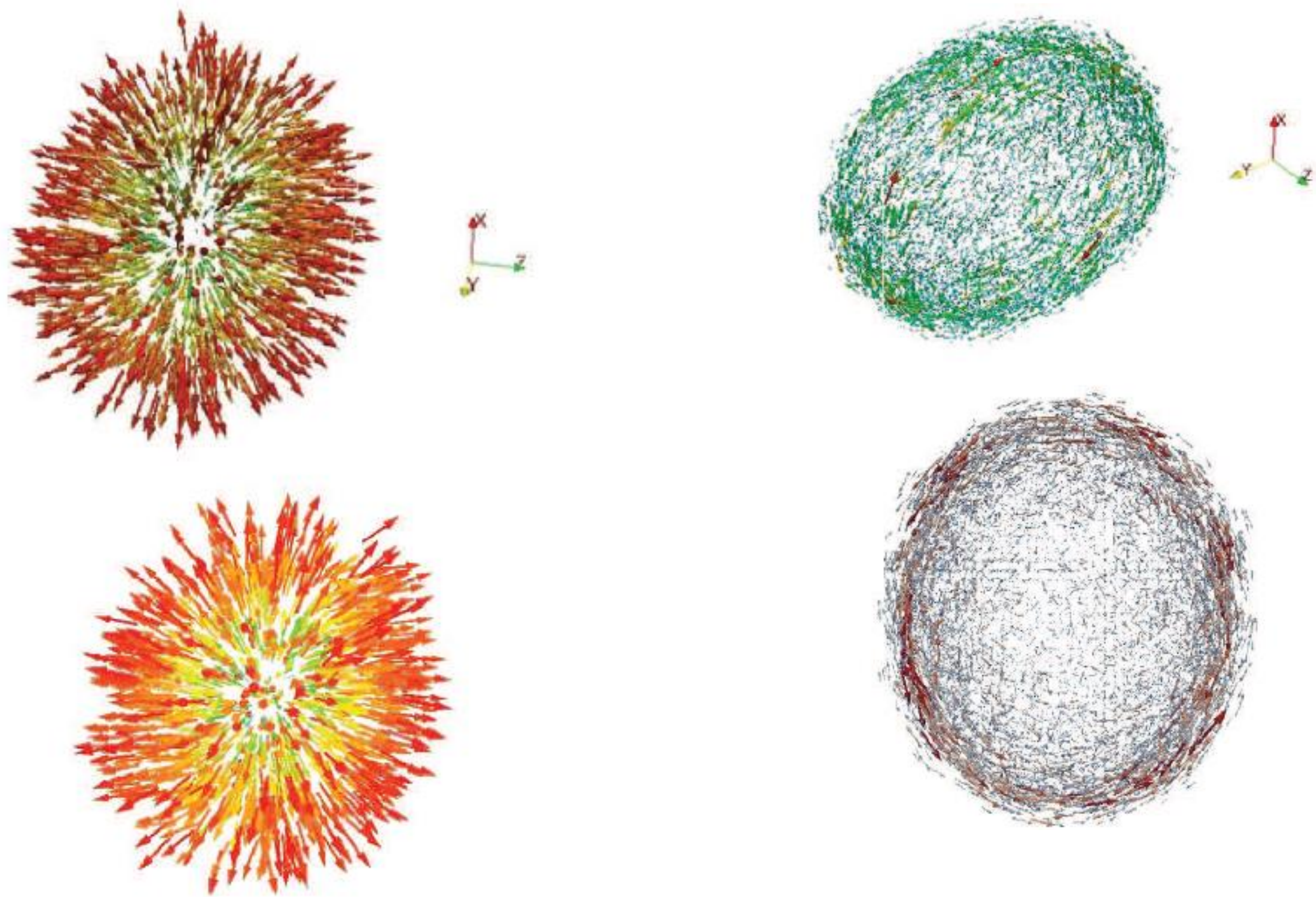
Angular momentum conservation and helicity

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

- Conservation of OAM with a good accuracy!

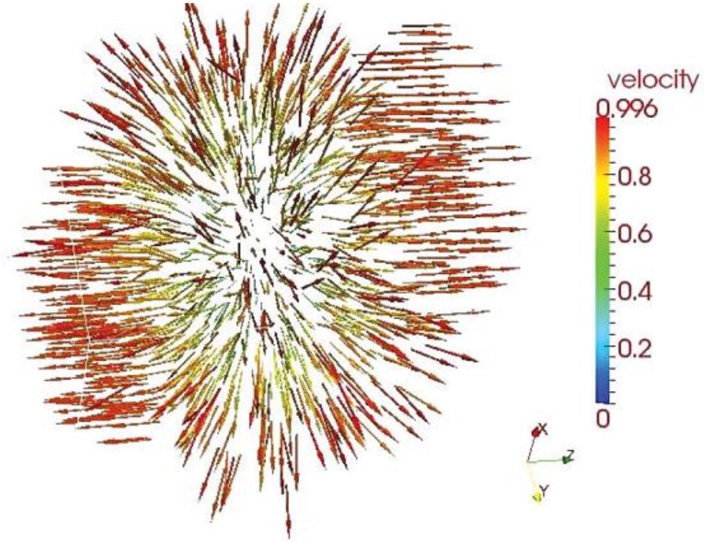


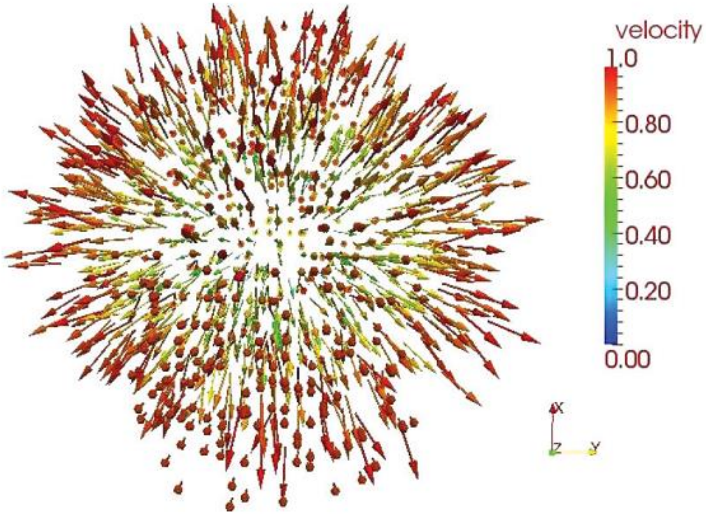
Structure of velocity and vorticity fields (NICA@JINR-5 GeV/c)



Distribution of velocity ("Little Bang")

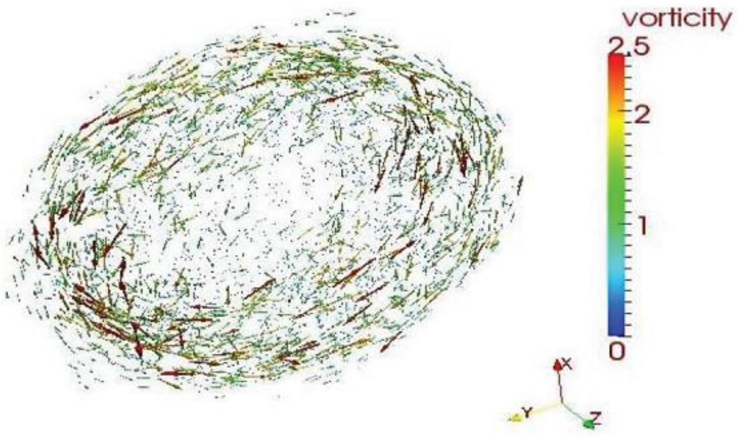
- 3D/2D projection
- z-beams direction
- x-impact paramater

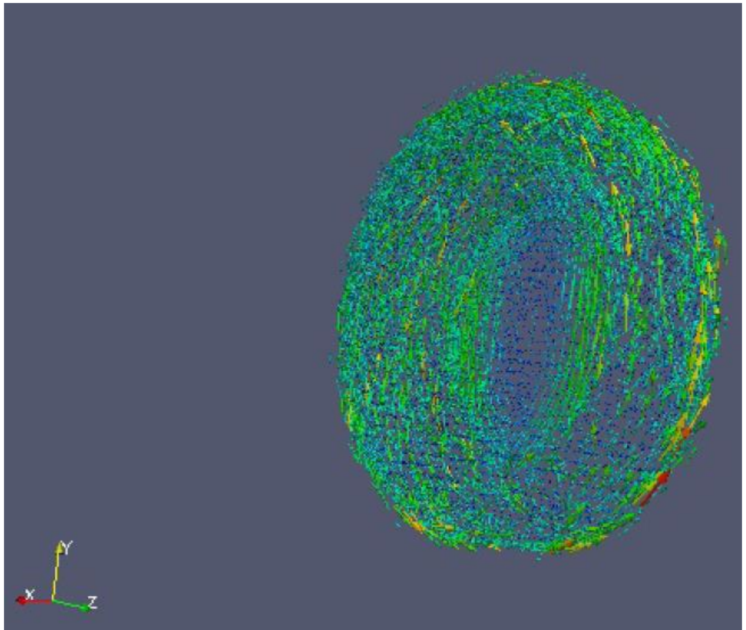


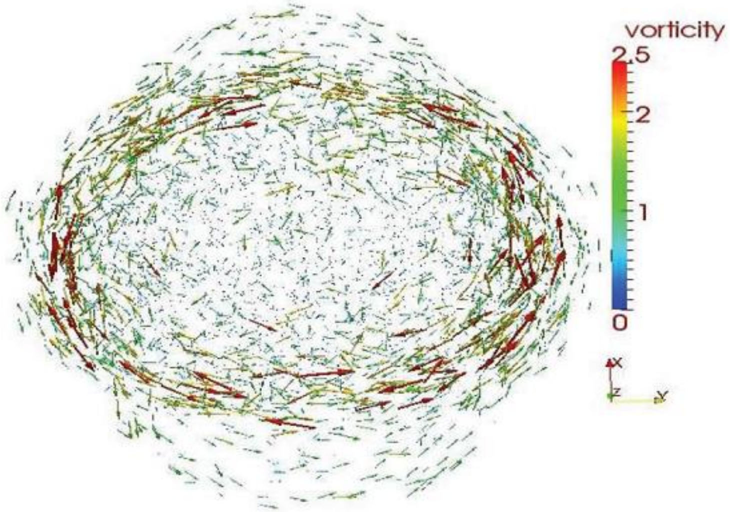


Distribution of vorticity ("Little galaxies")

- Layer (on core - corona borderline) patterns

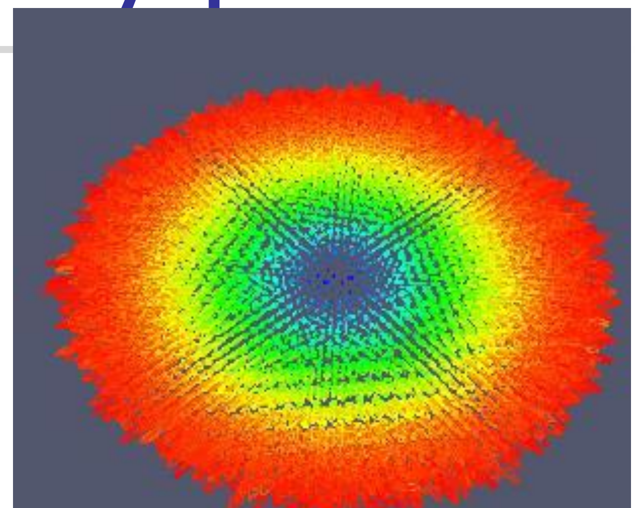




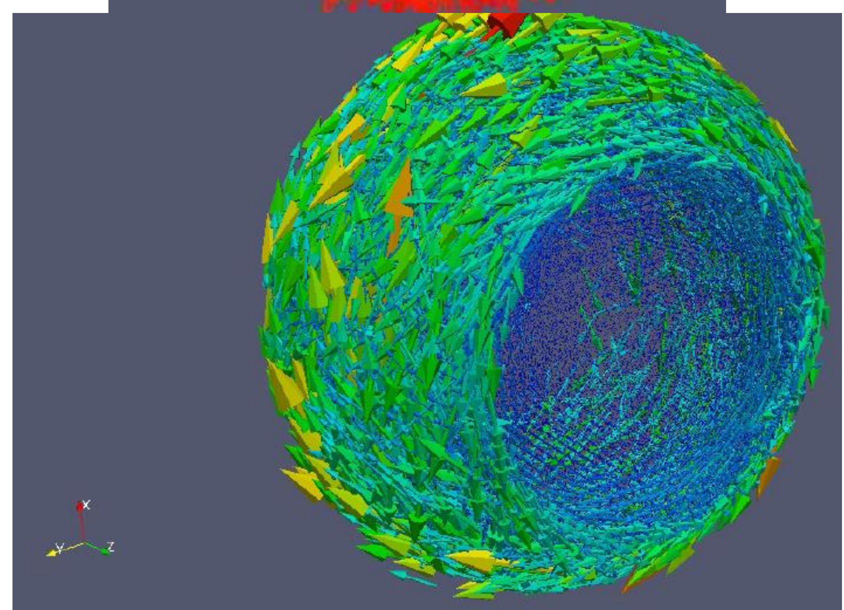


Velocity and vorticity patterns

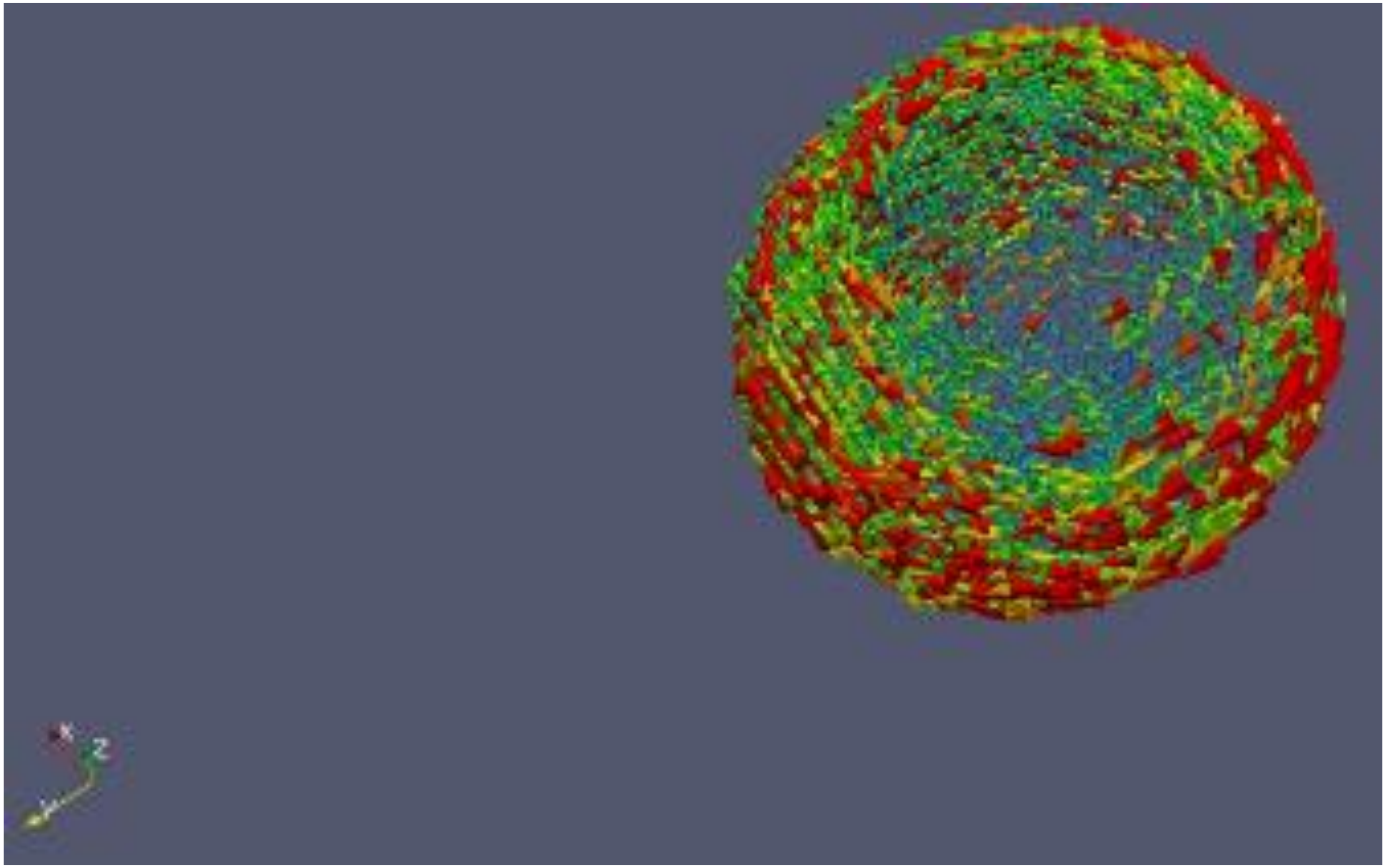
- Velocity



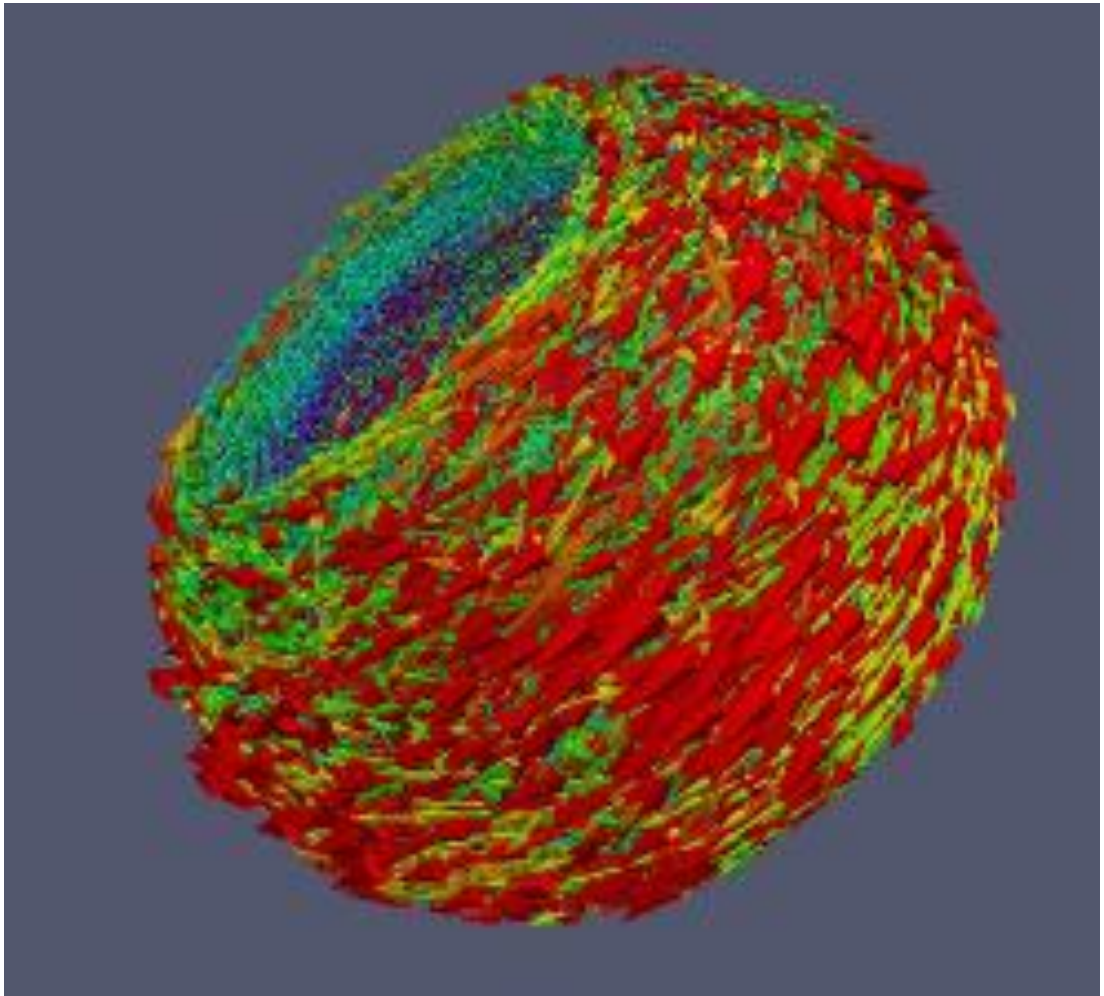
- Vorticity pattern – vortex sheets - due to L BUT cylinder symmetry!



Vortex sheet (fixed direction of L)

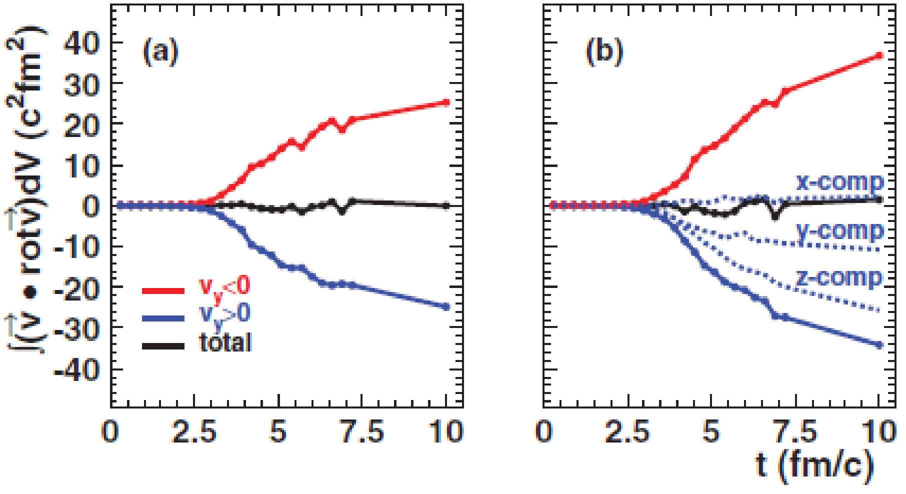


Vortex sheet （ Average over L directions ）



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

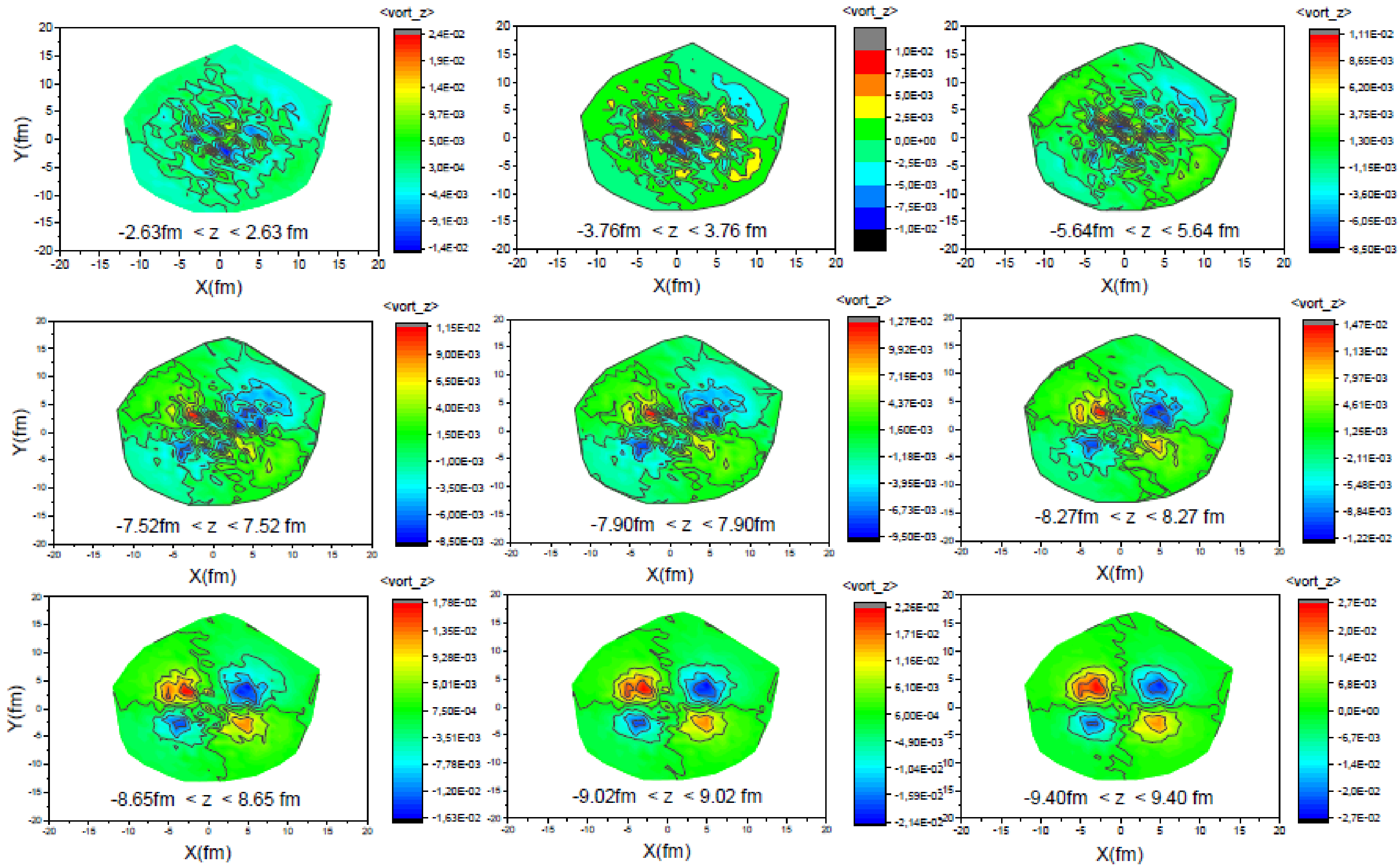
- Total helicity integrates to zero BUT
- Mirror helicities below and above the reaction plane
- Confirmed in HSD (OT, Usubov, PR**C92 (2015) 014906**



Structure of vorticity

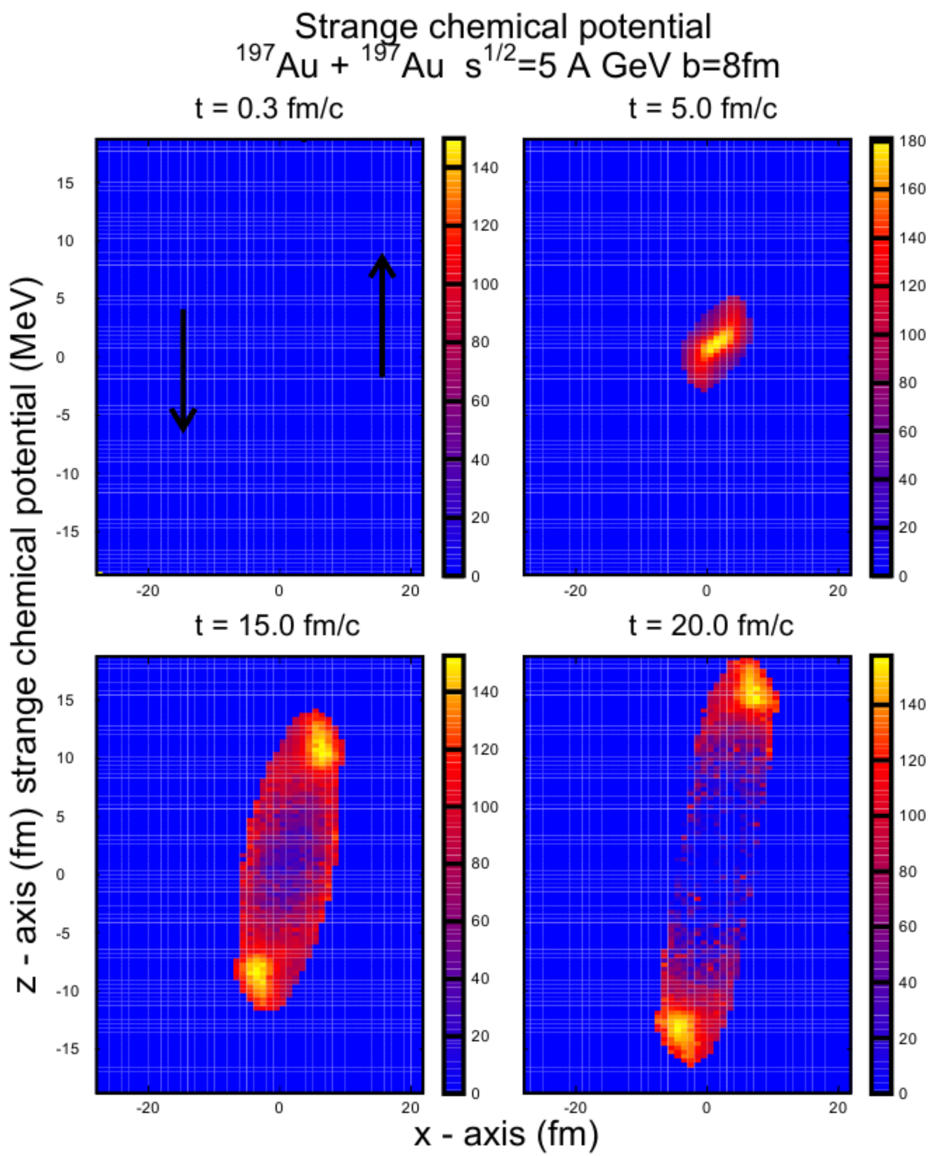
- y-component: constant vorticity, velocity changes sign
- z-component: quadrupole structure of vorticity

Quadrupole structure of longitudinal vorticity

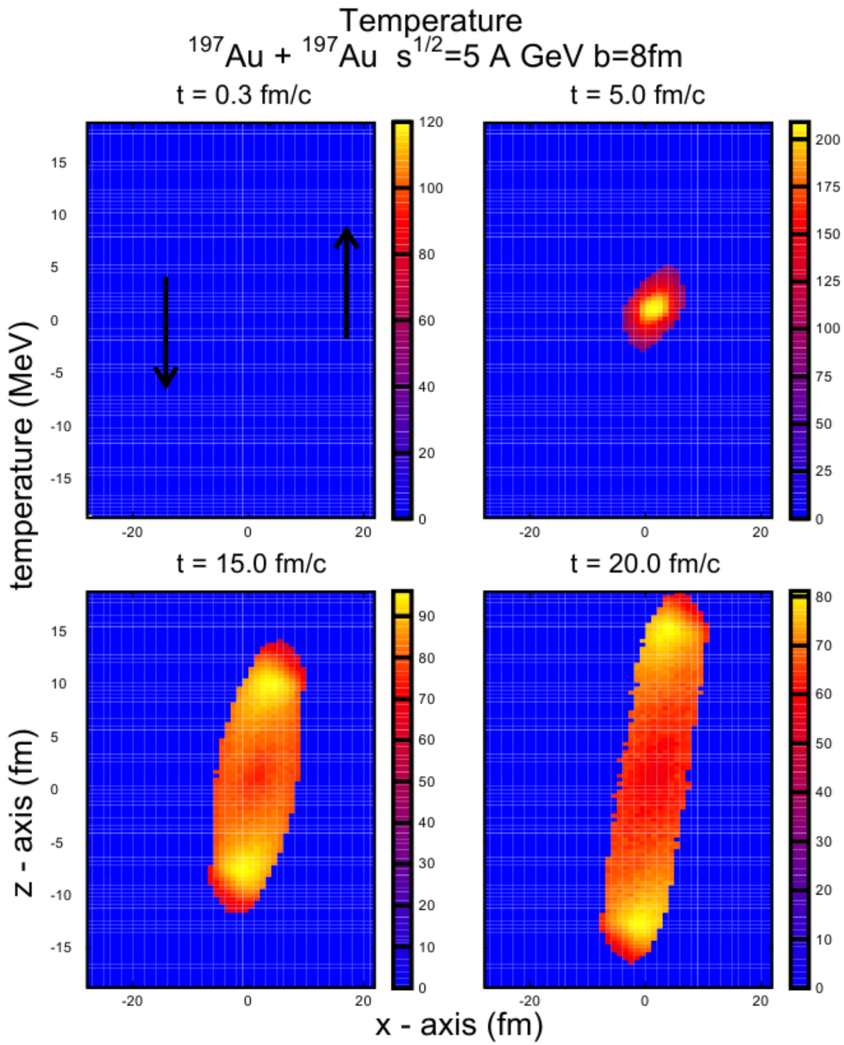


Strange chemical potential (polarization of Lambda is carried by strange quark!)

- Non-uniform in space and time



Temperature



From axial charge to polarization (and from quarks to confined hadrons)

- 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 (more pronounced at lower energy; EM difference-decrease)

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

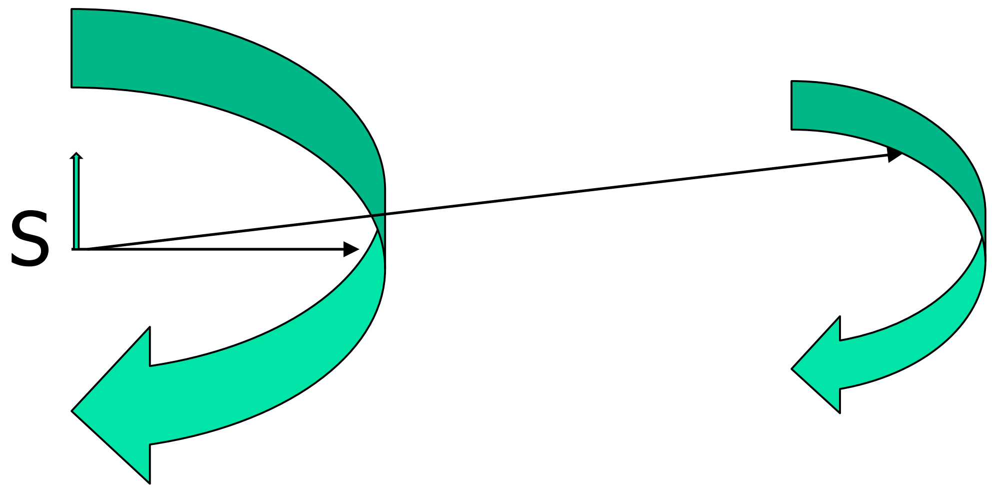
- Pions may carry the axial current due to quantized vortices in pionic superfluid (Kirilin,Sadofyev,Zakharov'12)

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

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

- Suggestion: core of the vortex-baryonic degrees of freedom- polarization
- Dissipation – analog of loop effects for hadrons

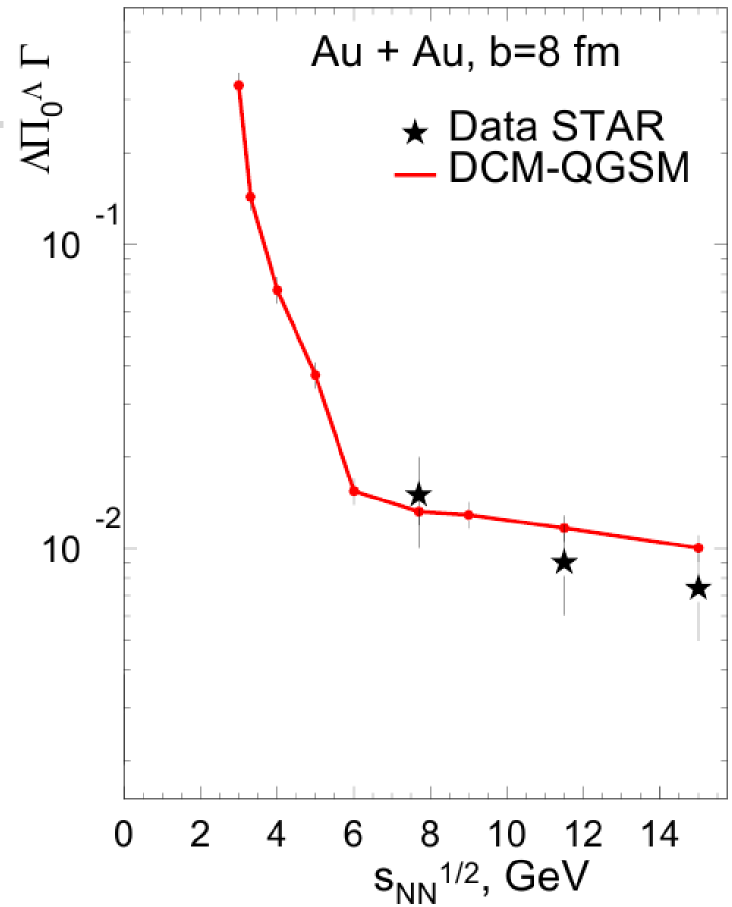
Core of quantized vortex

- Constant circulation – velocity increases when core is approached
- 

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

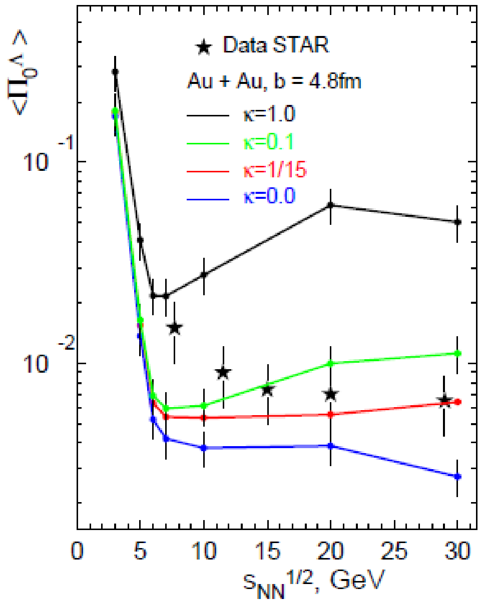
Energy dependence

- 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

Conclusions

- Hadronic and heavy ion collisions – different aspects of QCD
- Deep relation possible
- Polarization – interesting case study
- We can learn (among other things) something about fastest ever possible rotation from NICA

QCD

Why QCD?

Major scientific problem - mass of the Universe

$\sim$ 70% - Dark Energy

$\sim$ 25% - Dark Matter

$\sim$ 5% - Visible Matter

almost all of which is due to QCD!

1. Almost all of visible matter = protons.

Binding energy of nuclei and electrons in atoms - negligible.

Binding energy of nucleons in nuclei - dominant (current quark mass/proton mass $\sim$ 1%) (Current=fundamental) quarks are very light - chiral symmetry.

2. Fundamental theory of strong interaction - responsible for nuclear phenomena;

3. However - currently directly applicable only at large energy/momenta transfer - "hard" processes. Also very important - background for any search of new physics at hadronic colliders.

QCD like QED

What is QCD?

1. Local gauge theory (like QED)

Global phase transformation of Dirac electron field

$$\Psi(x) \rightarrow e^{i\alpha}\Psi(x) \qquad (1)$$

Invariance -(Charge) conservation law

Local phase transformation

$$\Psi(x) \rightarrow e^{i\alpha(x)}\Psi(x) \qquad (2)$$

Invariance - (Minimal)interaction with photon field.

$$\bar{\psi}\hat{A}\psi; \quad A^{\mu}(x) \rightarrow A^{\mu}(x) + \partial^{\mu}\alpha(x) \qquad (3)$$

QCD unlike QED

2. Non-abelian (unlike QED)

Dirac quark field - intrinsic degree of freedom (colour) First evidence - from baryon spectroscopy: Δ^{++} - 3 quarks of different colours.

Global transformation

$$\Psi_{\rho}(x) \rightarrow e^{it_{\rho\beta}\alpha}\Psi_{\beta}(x) \tag{4}$$

(t-Gell Mann matrices) - Colour charge conservation. Moreover, all observed hadrons are colour singlet.

Local transformation invariance - (minimal interaction with gluon filed)

$$\bar{\psi}_{\alpha}\hat{A}^{a}t^{a}_{\alpha\beta}\psi_{\beta}; \tag{5}$$

$N = 3$ quark colours - $(N^2 - 1)/2 = 8$ gluon colours.

New ingredient - self interaction of gluons. Dramatic effect for charge renormalization. RG - invariant (μ) - running (Q^2) coupling.

QED - screening - growing with Q^2, or in back direction - zero charge.

QCD - decreasing with Q^2 (asymptotic freedom) - growing in back direction - confinement.

Many reasons (but no rigorous proof - worth $\$10^6$) that it is absolute. Explains the non existence of free coloured particles. Nuclear forces - remnant of strong colour forces like van der Vaals forces. Unlike to them - short distance rather than long distance - mass gap - crucial ingredient of confinement,

Applying Asymptotic Freedom

How to explore the asymptotic freedom?

Processes typically contain hadrons on-shell.

The main tool -QCD factorization

Separate perturbatively calculable "hard" subprocesses and non-perturbative "soft" distribution/fragmentation functions.

Due to confinement problem - uncalculable BUT

1. Good objects for Non-perturbative methods (Lattice) and models

2. Universal = process independent.

"Zoology" of various non-perturbative inputs - like zoology in pre-Darwinian era.

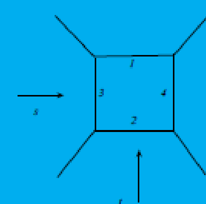
Factorization - based on the analysis of Feynman diagrams asymptotics

Useful tool $\alpha-$representation

$$\frac{1}{k^2 - m^2 + i\varepsilon} = i \int_0^\infty d\alpha e^{\alpha(i(k^2-m^2)-\varepsilon)} \tag{6}$$

Large momenta - small α.

Integral over momenta - Gaussian - easily performed. Remaining integrals over αs - determined by the diagram topology. Elastic scattering of scalar massless particles) - box diagram



$$\sim \int_0^\infty \frac{\Pi d\alpha}{(\sum \alpha)^2} e^{i(s\alpha_1\alpha_2 + t\alpha_3\alpha_4)/\sum \alpha} \tag{7}$$

Appearance of subprocess

Asymptotic $s \to \infty$ - small unless $\alpha_1\alpha_2$ is small - rapidly oscillating function.

At least one of αs whose removal splits diagram to two (connected) components in which momentum with large square enters ("kills" the dependence of process on the respective large variable) MUST be small: this is just the reason for subprocess appearance.

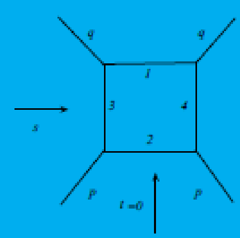
Electric circuits analogy : momentum $\to$ current.

Large current due to its conservation should flow at least at one of the (afterwards) removed conductors.

The most known hard subprocess - Deep Inelastic Scattering $\gamma^*(q)N(p) \to X$.

Optical theorem: Total cross section - imaginary part of forward scattering amplitude.

Simplest model - again box diagram

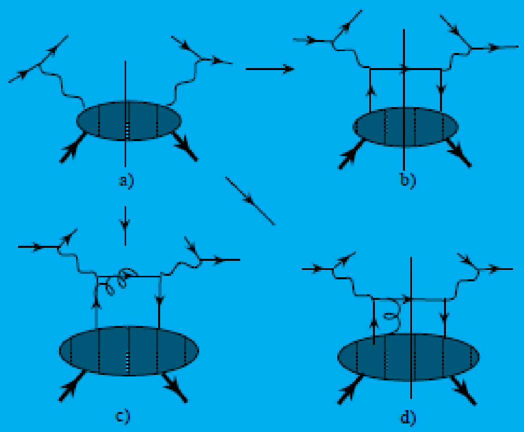


$$\sim \int_0^\infty \frac{\Pi d\alpha}{(\sum \alpha)^2} e^{i(s\alpha_1\alpha_2+q^2\alpha_1(\alpha_3+\alpha_4))/\sum\alpha} \tag{8}$$

Large variables $Q^2 = -q^2, s = (p+q)^2$ - $\alpha_1 \to 0$ - HANDBAG subprocess.

Quarks in hadrons

It appears at any order of perturbation theory.



a) Blob - hadronic matrix elements of quark fields - basic animal of our Zoo.

b) Radiative corrections

c) Higher twists

$$W \sim \int d^4z < P|\varphi(0)\varphi(z)|P > H(z) \tag{9}$$

Expand matrix element to the power series: Factorization (b) ensures that all singular in z terms appear only in H.

$$< P|\varphi(0)\varphi(z)|P >= \sum \frac{1}{n!} z^{\nu_1} ... z^{\nu_n} < P|\varphi(0)\partial^{\nu_1} ... \partial^{\nu_n}\varphi(0)|P > \tag{10}$$

For small z - only first term contribute BUT in pseudo-Euclidian space only z^2 is small, while (zP) is large.

Twist

Leading twist all indices (number = spin) are carried by large vector P. Higher twists (c+...) dimension is not compensated by spin suppressed as M.

$$< P|\varphi(0)\partial^{\nu_1}...\partial^{\nu_n}\varphi(0)|P >= i^n a_n P^{\nu_1}...P^{\nu_n} \tag{11}$$

$$W \sim \int d^4 z H(z) \Sigma \frac{1}{n!} a_n (iPz)^n \tag{12}$$

Last (but not least) step: moments

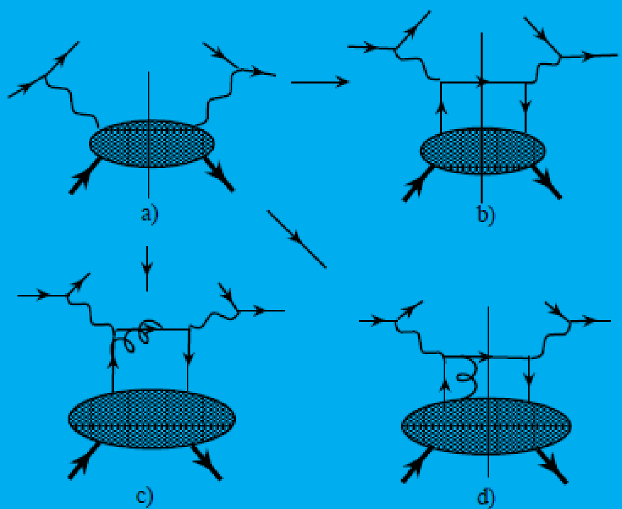
$$a_n = \int_0^1 dx f(x) x^n \tag{13}$$

$$W \sim \int_0^1 dx f(x) \int d^4 z H(z) \Sigma \frac{1}{n!} (ixPz)^n = \int_0^1 dx f(x) H(xP) \tag{14}$$

Parton "model" is derived. Radiative corrections (b) Q^2-dependence (Lecture 4).

Spin ½ quarks

Back to DIS



Factorization for toy model of scalar quarks - hadronic matrix elements of quark fields. Realistic case - both quarks and hadrons (nucleons) are spin $1/2$ particles

$$< P|\varphi(0)\varphi(z)|P > \to < P, S|psi_\alpha(0)E(0,z)\bar{\psi}_\beta|P, S > \quad (1)$$

$E(0,z)$ - gluonic string providing gauge invariance of non-local operator (sum of the longitudinal gluons at Fig. (d)).

Quark spin - "contained" in indices α, β. Nucleon spin - covariant polarization S: Scalar quarks distributions - probabilities to find quarks in nucleon. Dirac quarks - spin density matrix inside nucleon.

Density matrix of quarks inside hadrons

Recall first the free quark (or electron) density matrix
$\rho = \frac{1}{2}(\hat{p} + m)(1 + \hat{s}\gamma_5)$
At large energies mass is suppressed and longitudinal polarization is enhanced $S \to \xi p/m$, ξ is the degree of longitudinal polarization. $\rho \to \frac{1}{2}\hat{p}(1 + \xi\gamma_5)$
Consider longitudinally polarized nucleon; expansion over full set of Dirac matrices and making use of Lorentz invariance:

$$< P, \xi|\psi_\alpha(0)\hat{E}(0,z)\bar{\psi}_\beta(z)|P,\xi >= \int dx e^{i(Pz)x}[q(x)\hat{P} + \Delta q\hat{P}\gamma_5\xi] + O(M) \quad (2)$$

The density matrix of massless quarks is reproduced except spin-dependent and spin-independent terms enter with separate probabilistic weights: spin-dependent and spin independent distributions.

Flavours and gluons

Distributions may be defined for each quark (and antiquark!) flavour and also for gluons:

$$< P,\xi|A^{\mu}(0)\tilde{E}(0,z)A^{\nu}(z)|P,\xi >= \int dx e^{i(Pz)x}[G(x)g_{\perp}^{\mu\nu} + i\Delta G(x)\xi\varepsilon^{\mu\nu\rho\sigma}P_{\rho}n_{\sigma}] \quad (3)$$

Physical light-cone gauge $n^2 = (An) = 0$. $g_{\perp}$-in the plane transverse to P, n. Density natrix of circular polarized gluon.

Generally speaking, spin-averaged and spin-dependent distributions are unrelated, but $|\Delta q(x)| \le q(x), |\Delta G(x)| \le G(x)$ (otherwise. in principle, one may get negative cross sections, as $q(x) \pm \Delta q(x), G(x) \pm \Delta G(x)$ enter to the scattering on the nucleons of definite helicity) QCD corrections - Lecture 4.

What are the other constraints for the distributions?

Constraining lowest moments

Sum rules

The moments of parton distributions - local operators. Lowest moments $\int dx ...., \int dex$ - conserved operator - fixed by the respective conservation law. Physically: although details of parton distributions are defined by non-perturbative dynamics, averaged characteristics are constrained

$\int dx$ - local vector current - matrix elements are fixed by charge conservation (which can be electric, baryonic, hypercharge)

So for $u-$ quarks in the proton

$$\int_0^1 dx[u(x) - \bar{u}(x)] = 2 \tag{4}$$

for d

$$\int_0^1 dx[d(x) - \bar{d}(x)] = 1 \tag{5}$$

and for s (and any other)

$$\int_0^1 dx[s(x) - \bar{s}(x)] = 0 \tag{6}$$

Therefore $q(x) - \bar{q}(x)$ carry quantum numbers - "valence" (but not constituent) quarks $q(x) + \bar{q}(x)$ - "sea" quarks.

Single and double spin asymmetries

Spin asymmetries: single vs double.

DIS structure function F_1, F_2 - averaged over spin.

G_1, G_2 - for polarised leptons AND nucleons - double spin asymmetries

What about Single Spin Asymmetries (only one particle is polarized)?

Simple experiment - Complicated Theory

Summary of Lecture 1

- QCD factorization – "Zoo" of parton distributions (correlations)
- Hadron structure encoded in hadronic matrix elements of quark/gluon fields – natural objects of Lattice/NP QCD
- Spin – related to axial current and Anomaly (Lecture 2)
- Single Spin Asymmetries – Spin Orbital Interactions (Lecture 3)

Main Topics

> *Polarization data has often been the graveyard of fashionable theories.*
> *If theorists had their way, they might just ban such measurements altogether out of self-protection.*
> *J.D. Bjorken*
> *St. Croix, 1987*

- Spin density matrices of real and virtual photons
- Polarization in Thomson scattering
- Virtual photon/graviton polarization at LHC

- Spin-gravity interactions
- Equivalence principle with spin
- Spin Precession in Bianchi-1 and 9 Universe
- Gravity induced transitions to sterile Dirac neutrinos and dark matter

Spin density matrix: photons

- Expansion of 2(transverse)d matrix to Pauli matrices: coefficients - Stokes parameters: ξ_1 , ξ_2 , ξ_3
- (Anti)Symmetric part – (Circular)Linear polarization
- Scattering of unpolarized photons results in linear polarization perpendicular to scattering plane (used for gravity waves search)
- Scalar QED: $\xi_3 = \sin^2\theta/(1+\cos^2\theta)$
- Spinor QED Compton: $\xi_3 = \sin^2\theta/(z+1/z-\sin^2\theta)$
- Same for final photon energy fraction z -> 1

Virtual photons density matrix

- 3 component of wf ->8 parameters
- Circular-> 3 components of vector
- Linear -> 5 components of symmetric traceless tensor
- Partons collision –> tensor polarized photons -> angular distributions of final particles
- Annihilation of quarks to leptons ->
- $d\sigma \sim 1+\cos^2\theta$

Angular distributions

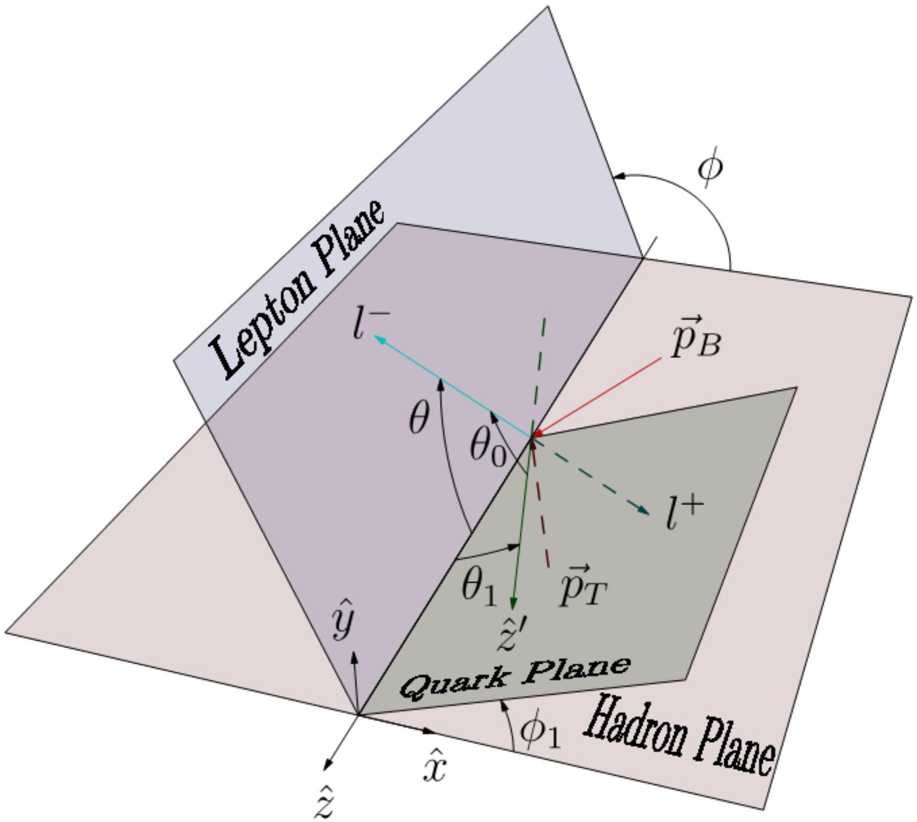
- SM gauge bosons: detailed check of production mechanisms
- Higgs – spin 0 – isotropic distributions
- Gravitons – spin 2 – 4 component density matrix – $\cos^4\theta$ enters – searched for and not found
- Any s-channel resonance – slow decrease with angle/transverse momentum

Detailed tests of SM at LHC

- Interpretation of Angular Distributions of Z-boson Production at Colliders; Jen-Chieh Peng,Wen-Chen Chang, Randall Evan McClellan, and Oleg Teryaev; 1511.09893 and PLB

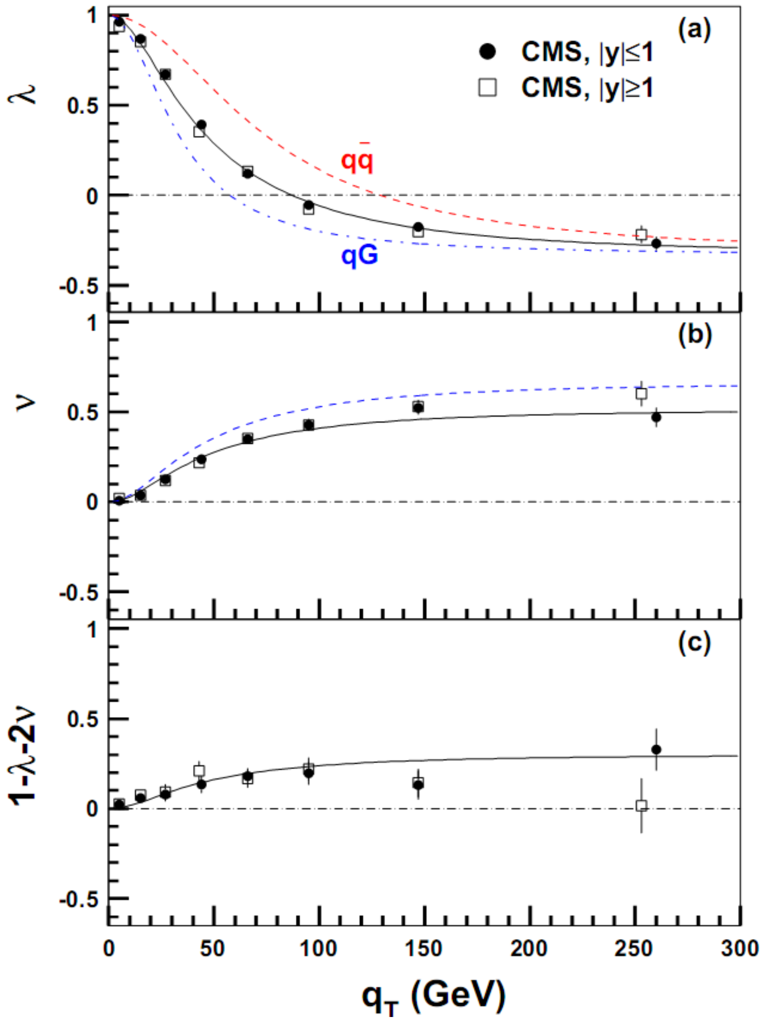
- Geometrical picture

- Non-coplanarity – disbalance of quark and hadron planes



CMS (8 TeV) data

- Necessity to account for
- qq - 41.5(1.6)%
- qG - 58.5(1.6)%
- $< \cos 2\varphi_1 >= 0.77$



Spin-gravity interactions

- 1. Dirac equation
- Gauge structure of gravity manifested; limit of classical gravity - FW transformation
- 2. Matrix elements of Energy- Momentum Tensor
- May be studied in non-gravitational experiments/theory
- Simple interpretation in comparison to EM field case

Gravitational Formfactors

$$\langle p'|T^{\mu\nu}_{q,g}|p\rangle = \bar{u}(p')\Big[A_{q,g}(\Delta^2)\gamma^{(\mu}p^{\nu)} + B_{q,g}(\Delta^2)P^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha/2M\big]u(p)$$

- Conservation laws - zero Anomalous Gravitomagnetic Moment : $\mu_G = J$ (g=2)

$$P_{q,g} = A_{q,g}(0) \qquad A_q(0) + A_g(0) = 1$$

$$J_{q,g} = \frac{1}{2}\left[A_{q,g}(0) + B_{q,g}(0)\right] \qquad A_q(0) + B_q(0) + A_g(0) + B_g(0) = 1$$

- May be extracted from high-energy experiments/NPQCD calculations
- Describe the partition of angular momentum between quarks and gluons
- Describe interaction with both classical and TeV gravity

Generalized Parton Diistributions (related to matrix elements of non local operators) – models for both EM and Gravitational Formfactors (Selyugin,OT '09)

- Smaller mass square radius (attraction vs repulsion!?)

$$\rho(b) = \sum_q e_q \int dx q(x,b) \qquad = \int d^2 q F_1(Q^2 = q^2) e^{i\vec{q}\,\vec{b}}$$

$$= \int_0^\infty \frac{qdq}{2\pi} J_0(qb) \frac{G_E(q^2) + \tau G_M(q^2)}{1+\tau}$$

$$\rho_0^{\rm Gr}(b) = \frac{1}{2\pi} \int_\infty^0 dq q J_0(qb) A(q^2)$$

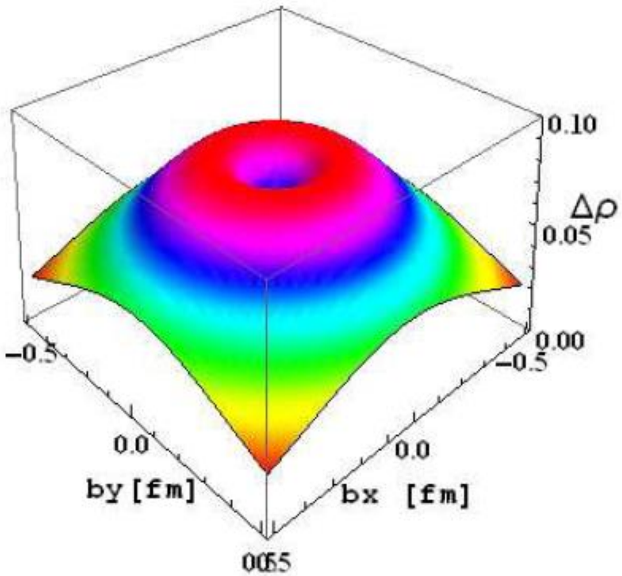


FIG. 17: Difference in the forms of charge density F_1^P and "matter" density (A)

Electromagnetism vs Gravity

- Interaction – field vs metric deviation

$$M = \langle P'|J_q^\mu|P\rangle A_\mu(q)$$

$$M = \frac{1}{2}\sum_{q,G}\langle P'|T_{q,G}^{\mu\nu}|P\rangle h_{\mu\nu}(q)$$

- Static limit

$$\langle P|J_q^\mu|P\rangle = 2e_q P^\mu$$

$$\sum_{q,G}\langle P|T_i^{\mu\nu}|P\rangle = 2P^\mu P^\nu$$

$$h_{00} = 2\phi(x)$$

$$M_0 = \langle P|J_q^\mu|P\rangle A_\mu = 2e_q M\phi(q)$$

$$M_0 = \frac{1}{2}\sum_{q,G}\langle P|T_i^{\mu\nu}|P\rangle h_{\mu\nu} = 2M\cdot M\phi(q)$$

- Mass as charge – equivalence principle

Gravitomagnetism

- Gravitomagnetic field (weak, except in gravity waves) – action on spin from $M=\frac{1}{2}\sum_{q,G}\langle P'|T^{\mu\nu}_{q,G}|P\rangle h_{\mu\nu}(q)$

$$\vec{H}_J=\frac{1}{2}rot\vec{g};\ \vec{g}_i\equiv g_{0i}$$

spin dragging twice smaller than EM

- Lorentz force – similar to EM case: factor ½ cancelled with 2 from $h_{00}=2\phi(x)$ Larmor frequency same as EM

$$\omega_J=\frac{\mu_G}{J}H_J=\frac{H_L}{2}=\omega_L\ \vec{H}_L=rot\vec{g}$$

- Orbital and Spin momenta dragging – the same - Equivalence principle

Equivalence principle

- Newtonian – "Falling elevator" – well known and checked (also for elementary particles)
- Post-Newtonian – gravity action on SPIN – known since 1962 (Kobzarev and Okun'); rederived from conservarion laws - Kobzarev and Zakharov
- Anomalous gravitomagnetic (and electric-CP-odd) moment iz ZERO or
- Classical and QUANTUM rotators behave in the SAME way
- - not checked on purpose but in fact checked in atomic spins experiments at % level (Silenko,OT'07)

Experimental test of PNEP

- Reinterpretation of the data on G(EDM) search

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Search for a Coupling of the Earth's Gravitational Field to Nuclear Spins in Atomic Mercury

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- If (CP-odd!) GEDM=0 -> constraint for AGM (Silenko, OT'07) from Earth rotation – was considered as obvious (but it is just EP!) background

$$\mathcal{H} = -g\mu_N \boldsymbol{B}\cdot\boldsymbol{S} - \zeta\hbar\boldsymbol{\omega}\cdot\boldsymbol{S}, \quad \zeta = 1+\chi$$

$$|\chi(^{201}\mathrm{Hg}) + 0.369\chi(^{199}\mathrm{Hg})| < 0.042 \quad (95\%\mathrm{C.L.})$$

Equivalence principle for moving particles

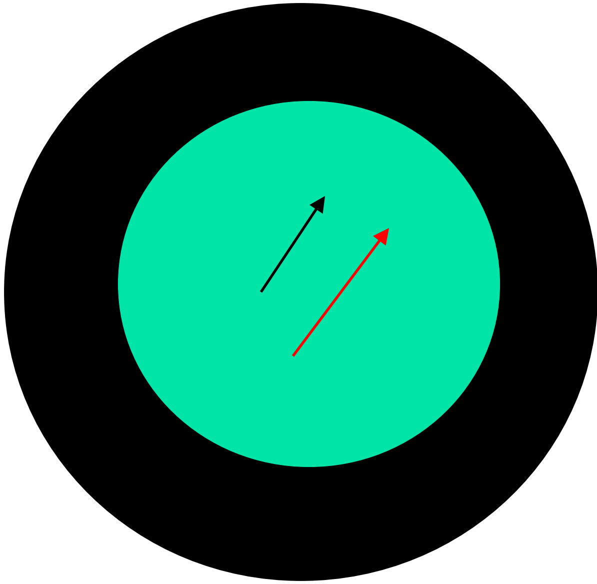
- Compare gravity and acceleration: gravity provides EXTRA space components of metrics $h_{zz} = h_{xx} = h_{yy} = h_{00}$
- Matrix elements DIFFER

$$\mathcal{M}_g = (\epsilon^2 + p^2) h_{00}(q), \qquad \mathcal{M}_a = \epsilon^2 h_{00}(q)$$

- Ratio of accelerations: $R = \frac{\epsilon^2 + p^2}{\epsilon^2}$ - confirmed by explicit solution of Dirac equation (Silenko, OT, ‘05)
- Arbitrary fields – Obukhov, Silenko, OT ’09,’11,’13

Cosmological implications of PNEP

- Necessary condition for Mach's Principle (in the spirit of Weinberg's textbook) -
- Lense-Thirring inside massive rotating empty shell (=model of Universe)
- For flat "Universe" - precession frequency equal to that of shell rotation
- Simple observation-Must be the same for classical and quantum rotators – PNEP!
- More elaborate models - Tests for cosmology ?!



Manifestation of equivalence principle (cf with EM)

- Classical and quantum rotators rotate with the same frequency (EM: spin ½ – twice faster); Dirac eq. analysis (Obukhov, Silenko, OT) – for strong fileds
- Velocity rotates twice faster than classical rotator- helicity changes
  (EM – helicity of Dirac fermion conserved – used for AMM measurement) –BUT conserved in the rotating comoving frame

Dirac Eq and Foldy - Wouthausen transformation

- Metric of the type

$$ds^2 = V^2c^2dt^2 - \delta_{\hat{a}\hat{b}}W^{\hat{a}}{}_c W^{\hat{b}}{}_d(dx^c - K^c c dt)(dx^d - K^d c dt).$$

- Tetrads in Schwinger gauge

$$e_i^{\hat{0}} = V\delta_i^0, \qquad e_i^{\hat{a}} = W^{\hat{a}}{}_b(\delta_i^b - cK^b\delta_i^0),$$

$$e_{\hat{0}}^i = \frac{1}{V}(\delta^i{}_0 + \delta^i{}_a cK^a), \qquad e_{\hat{a}}^i = \delta^i{}_b W^b{}_{\hat{a}}, \qquad a = 1, 2, 3,$$

- Dirac eq $\quad (i\hbar\gamma^\alpha D_\alpha - mc)\Psi = 0, \qquad \alpha = 0, 1, 2, 3.$

$$D_\alpha = e^i_\alpha D_i, \qquad D_i = \partial_i + \frac{iq}{\hbar}A_i + \frac{i}{4}\sigma^{\alpha\beta}\Gamma_{i\alpha\beta}.$$

Dirac hamiltonian

- Connection

$$\Gamma_{i\hat{a}\hat{0}} = \frac{c^2}{V} W^b{}_{\hat{a}} \partial_b V e_i{}^{\hat{0}} - \frac{c}{V} \mathcal{Q}_{(\hat{a}\hat{b})} e_i{}^{\hat{b}},$$

$$\Gamma_{i\hat{a}\hat{b}} = \frac{c}{V} \mathcal{Q}_{[\hat{a}\hat{b}]} e_i{}^{\hat{0}} + (\mathcal{C}_{\hat{a}\hat{b}\hat{c}} + \mathcal{C}_{\hat{a}\hat{c}\hat{b}} + \mathcal{C}_{\hat{c}\hat{b}\hat{a}}) e_i{}^{\hat{c}}.$$

$$\mathcal{Q}_{\hat{a}\hat{b}} = g_{\hat{a}\hat{c}} W^d{}_{\hat{b}} \left(\frac{1}{c} \dot{W}^{\hat{c}}{}_d + K^e \partial_e W^{\hat{c}}{}_d + W^{\hat{c}}{}_e \partial_d K^e \right),$$

$$\mathcal{C}_{\hat{a}\hat{b}}{}^{\hat{c}} = W^d{}_{\hat{a}} W^e{}_{\hat{b}} \partial_{[d} W^{\hat{c}}{}_{e]}, \qquad \mathcal{C}_{\hat{a}\hat{b}\hat{c}} = g_{\hat{c}\hat{d}} \mathcal{C}_{\hat{a}\hat{b}}{}^{\hat{d}}.$$

- Hermitian Hamiltonian

$$i\hbar \frac{\partial \psi}{\partial t} = \mathcal{H} \psi. \qquad \psi = (\sqrt{-g} e_{\hat{0}}^0)^{\frac{1}{2}} \Psi.$$

$$\mathcal{H} = \beta m c^2 V + q\Phi + \frac{c}{2}(\pi_b \mathcal{F}^b{}_a \alpha^a + \alpha^a \mathcal{F}^b{}_a \pi_b) + \frac{c}{2}(\boldsymbol{K} \cdot \boldsymbol{\pi} + \boldsymbol{\pi} \cdot \boldsymbol{K}) + \frac{\hbar c}{4}(\boldsymbol{\Xi} \cdot \boldsymbol{\Sigma} - \Upsilon \gamma_5).$$

$$\Upsilon = V \epsilon^{\hat{a}\hat{b}\hat{c}} \Gamma_{\hat{a}\hat{b}\hat{c}} = -V \epsilon^{\hat{a}\hat{b}\hat{c}} \mathcal{C}_{\hat{a}\hat{b}\hat{c}},$$

$$\Xi_{\hat{a}} = \frac{V}{c} \epsilon_{\hat{a}\hat{b}\hat{c}} \Gamma_{\hat{0}}{}^{\hat{b}\hat{c}} = \epsilon_{\hat{a}\hat{b}\hat{c}} \mathcal{Q}^{\hat{b}\hat{c}}.$$

Foldy-Wouthuysen transformation

- Even and odd parts

$$\mathcal{H} = \beta\mathcal{M} + \mathcal{E} + \mathcal{O}, \qquad \beta\mathcal{M} = \mathcal{M}\beta,$$
$$\beta\mathcal{E} = \mathcal{E}\beta, \qquad \beta\mathcal{O} = -\mathcal{O}\beta.$$

- FW transformation (Silenko '08)

$$U = \frac{\beta\epsilon + \beta\mathcal{M} - \mathcal{O}}{\sqrt{(\beta\epsilon + \beta\mathcal{M} - \mathcal{O})^2}}\beta, \qquad \psi_{\rm FW} = U\psi, \qquad \mathcal{H}_{\rm FW} = U\mathcal{H}U^{-1} - i\hbar U\partial_t U^{-1}.$$

$$U^{-1} = \beta\frac{\beta\epsilon + \beta\mathcal{M} - \mathcal{O}}{\sqrt{(\beta\epsilon + \beta\mathcal{M} - \mathcal{O})^2}}. \qquad \epsilon = \sqrt{\mathcal{M}^2 + \mathcal{O}^2}$$

$$\begin{aligned}\mathcal{H}' = \beta\epsilon + \mathcal{E} + \frac{1}{2T}\big(&[T,[T,(\beta\epsilon + Z)]] \\ &+ \beta[\mathcal{O},[\mathcal{O},\mathcal{M}]] - [\mathcal{O},[\mathcal{O},Z]] \\ &- [(\epsilon+\mathcal{M}),[(\epsilon+\mathcal{M}),Z]] - [(\epsilon+\mathcal{M}),[\mathcal{M},\mathcal{O}]] \\ &- \beta\{\mathcal{O},[(\epsilon+\mathcal{M}),Z]\} + \beta\{(\epsilon+\mathcal{M}),[\mathcal{O},Z]\}\big)\frac{1}{T},\end{aligned}$$

$$T = \sqrt{(\beta\epsilon + \beta\mathcal{M} - \mathcal{O})^2}$$

$$Z = \mathcal{E} - i\hbar\frac{\partial}{\partial t}$$

$$\mathcal{H}' = \beta\epsilon + \mathcal{E}' + \mathcal{O}', \qquad \beta\mathcal{E}' = \mathcal{E}'\beta, \qquad \beta\mathcal{O}' = -\mathcal{O}'\beta,$$

$$\mathcal{H}_{\rm FW} = \beta\epsilon + \mathcal{E}' + \frac{1}{4}\beta\left\{\mathcal{O}'^2, \frac{1}{\epsilon}\right\}.$$

FW for arbitrary gravitational field

- Result

$$\mathcal{H}_{\mathrm{FW}} = \mathcal{H}_{\mathrm{FW}}^{(1)} + \mathcal{H}_{\mathrm{FW}}^{(2)}.$$

$$\epsilon' = \sqrt{m^2c^4V^2 + \frac{c^2}{4}\delta^{ac}\{p_b, \mathcal{F}^b{}_a\}\{p_d, \mathcal{F}^d{}_c\}},$$

$$\mathcal{T} = 2\epsilon'^2 + \{\epsilon', mc^2V\}.$$

$$\mathcal{M} = mc^2V,$$

$$\mathcal{E} = q\Phi + \frac{c}{2}(\boldsymbol{K}\cdot\boldsymbol{\pi} + \boldsymbol{\pi}\cdot\boldsymbol{K}) + \frac{\hbar c}{4}\boldsymbol{\Xi}\cdot\boldsymbol{\Sigma},$$

$$\mathcal{O} = \frac{c}{2}(\pi_b\mathcal{F}^b{}_a\alpha^a + \alpha^a\mathcal{F}^b{}_a\pi_b) - \frac{\hbar c}{4}\Upsilon\gamma_5.$$

$$\mathcal{H}_{\mathrm{FW}}^{(1)} = \beta\epsilon' + \frac{\hbar c^2}{16}\left\{\frac{1}{\epsilon'}, (2\epsilon^{cae}\Pi_e\{p_b, \mathcal{F}^d{}_c\partial_d\mathcal{F}^b{}_a\}\right.$$
$$\left. + \Pi^a\{p_b, \mathcal{F}^b{}_a\Upsilon\})\right\}$$
$$+ \frac{\hbar mc^4}{4}\epsilon^{cae}\Pi_e\left\{\frac{1}{\mathcal{T}}, \{p_d, \mathcal{F}^d{}_c\mathcal{F}^b{}_a\partial_bV\}\right\},$$

$$\mathcal{H}_{\mathrm{FW}}^{(2)} = \frac{c}{2}(K^ap_a + p_aK^a) + \frac{\hbar c}{4}\Sigma_a\Xi^a$$
$$+ \frac{\hbar c^2}{16}\left\{\frac{1}{\mathcal{T}}, \left\{\Sigma_a\{p_e, \mathcal{F}^e{}_b\}, \left\{p_f, \left[\epsilon^{abc}\left(\frac{1}{c}\dot{\mathcal{F}}^f{}_c\right.\right.\right.\right.\right.$$
$$\left. - \mathcal{F}^d{}_c\partial_dK^f + K^d\partial_d\mathcal{F}^f{}_c\right)$$
$$\left.\left.\left.\left. - \frac{1}{2}\mathcal{F}^f{}_d(\delta^{db}\Xi^a - \delta^{da}\Xi^b)\right]\right\}\right\}\right\},$$

Operator EOM

- Polarization operator $\mathbf{\Pi} = \beta \mathbf{\Sigma}$

$$\frac{d\mathbf{\Pi}}{dt} = \frac{i}{\hbar}[\mathcal{H}_{\rm FW}, \mathbf{\Pi}] = \mathbf{\Omega}_{(1)} \times \mathbf{\Sigma} + \mathbf{\Omega}_{(2)} \times \mathbf{\Pi}.$$

- Angular velocities

$$\Omega^a_{(1)} = \frac{mc^4}{2}\left\{\frac{1}{\mathcal{T}}, \{p_e, \epsilon^{abc}\mathcal{F}^e{}_b\mathcal{F}^d{}_c\partial_d V\}\right\} + \frac{c^2}{8}\left\{\frac{1}{\epsilon'}, \{p_e, (2\epsilon^{abc}\mathcal{F}^d{}_b\partial_d\mathcal{F}^e{}_c + \delta^{ab}\mathcal{F}^e{}_b\Upsilon)\}\right\},$$

$$\Omega^a_{(2)} = \frac{\hbar c^2}{8}\left\{\frac{1}{\mathcal{T}}, \left\{\{p_e, \mathcal{F}^e{}_b\}, \left\{p_f, \left[\epsilon^{abc}\left(\frac{1}{c}\dot{\mathcal{F}}^f{}_c - \mathcal{F}^d{}_c\partial_d K^f + K^d\partial_d\mathcal{F}^f{}_c\right) - \frac{1}{2}\mathcal{F}^f{}_d(\delta^{db}\Xi^a - \delta^{da}\Xi^b)\right]\right\}\right\}\right\} + \frac{c}{2}\Xi^a.$$

Semi-classical limit

- Average spin

$$\frac{ds}{dt} = \mathbf{\Omega} \times s = (\mathbf{\Omega}_{(1)} + \mathbf{\Omega}_{(2)}) \times s,$$

$$\Omega^a_{(1)} = \frac{c^2}{\epsilon'} \mathcal{F}^d{}_c p_d \Big(\frac{1}{2} \Upsilon \delta^{ac} - \epsilon^{aef} V C_{ef}{}^c + \frac{\epsilon'}{\epsilon' + mc^2 V} \epsilon^{abc} W^e{}_{\hat{b}} \partial_e V \Big),$$

$$\Omega^a_{(2)} = \frac{c}{2} \Xi^a - \frac{c^3}{\epsilon'(\epsilon' + mc^2 V)} \epsilon^{abc} Q_{(bd)} \delta^{dn} \mathcal{F}^k{}_n p_k \mathcal{F}^l{}_c p_l,$$

Application to anisotropic universe (Kamenshchik,OT)

- Bianchi-1 Universe

$$ds^2 = dt^2 - a^2(t)(dx^1)^2 - b^2(t)(dx^2)^2 - c^2(t)(dx^3)^2.$$

- Particular case $W_1^{\hat{1}} = a(t),\ W_2^{\hat{2}} = b(t),\ W_3^{\hat{3}} = c(t).$

$$W_{\hat{1}}^1 = \frac{1}{a(t)},\ W_{\hat{2}}^2 = \frac{1}{b(t)},\ W_{\hat{3}}^3 = \frac{1}{c(t)}.$$

- No anholonomity $\Upsilon = 0$

$$\Omega_{(2)}^{\hat{1}} = \frac{\gamma}{\gamma+1} v_{\hat{2}} v_{\hat{3}} \left(\frac{\dot{b}}{b} - \frac{\dot{c}}{c}\right).$$

$$Q_{\hat{1}\hat{1}} = -\frac{\dot{a}}{a},\ Q_{\hat{2}\hat{2}} = -\frac{\dot{b}}{b},\ Q_{\hat{3}\hat{3}} = -\frac{\dot{c}}{c}.$$

Kasner solution

- t-dependence

$$a(t) = a_0 t^{p_1},\ b(t) = b_0 t^{p_2},\ c(t) = c_0 t^{p_3},$$

$$p_1 + p_2 + p_3 = 1,\ \ p_1^2 + p_2^2 + p_3^2 = 1.$$

- Euler-type expressions

$$\Omega^{\bar{1}}_{(2)} = \frac{\gamma}{\gamma + 1} v_{\bar{2}} v_{\bar{3}} \left(\frac{p_2 - p_3}{t} \right)$$

Heckmann-Schucking solution

- Dust admixture

$$a(t) = a_0 t^{p_1} (t_0 + t)^{\frac{2}{3} - p_1}, \; b(t) = b_0 t^{p_2} (t_0 + t)^{\frac{2}{3} - p_2},$$
$$c(t) = c_0 t^{p_3} (t_0 + t)^{\frac{2}{3} - p_3}.$$

- Modification:

$$\Omega^{\bar{1}}_{(2)} = \frac{\gamma}{\gamma + 1} v_{\bar{2}} v_{\bar{3}} \frac{(p_2 - p_3) t_0}{t(t_0 + t)}$$

$$= \frac{\gamma}{\gamma + 1} v_{\bar{2}} v_{\bar{3}} \frac{(p_2 - p_3) t_0}{t^2} \left(1 + o\left(\frac{t_0}{t}\right)\right)$$

Biancki-IX Universe

- Metric $W^{\hat{b}}{}_{a} = \begin{pmatrix} -a\sin x^3 & a\sin x^1\cos x^3 & 0 \\ b\cos x^3 & b\sin x^1\sin x^3 & 0 \\ 0 & c\cos x^1 & c \end{pmatrix}$ $W^{c}{}_{\hat{b}} = \begin{pmatrix} -\frac{1}{a}\sin x^3 & \frac{1}{b}\cos x^3 & 0 \\ \frac{1}{a}\frac{\cos x^3}{\sin x^1} & \frac{1}{b}\frac{\sin x^3}{\sin x^1} & 0 \\ -\frac{1}{a}\frac{\cos x^1\cos x^3}{\sin x^1} & -\frac{1}{b}\frac{\sin x^3\cos x^1}{\sin x^1} & \frac{1}{c} \end{pmatrix}$
- Anholonomity coefficients
- $C^{\hat{3}}_{\hat{1}\hat{2}} = \frac{c}{ab}$ + cyclic permutations
- -> non-zero $\Upsilon = 2\left(\frac{c}{ab} + \frac{b}{ac} + \frac{a}{bc}\right)$

$$\Omega^{\hat{1}}_{(1)} = v^{\hat{1}}\left(\frac{c}{ab} + \frac{b}{ac} - \frac{a}{bc}\right)$$

Approach to singularity

- Chaotic oscillations – sequence of Kasner regimes $p_1 = -\frac{u}{1+u+u^2},\ p_2 = \frac{1+u}{1+u+u^2},\ p_3 = \frac{u(1+u)}{1+u+u^2}$
- If Lifshitz-Khalatnıkov parameter u >1 – "epochs" $p'_1 = p_2(u-1),\ p'_2 = p_1(u-1),\ p'_3 = p_3(u-1)$

$$p'_1 = p_1\left(\frac{1}{u}\right),\ p'_2 = p_3\left(\frac{1}{u}\right),\ p'_3 = p_2\left(\frac{1}{u}\right)$$

- If u< 1 – "eras"
- Change of eras – chaotic mapping of [0,1]interrval

$$Tx = \left\{\frac{1}{x}\right\},\quad x_{s+1} = \left\{\frac{1}{x_s}\right\}$$

Angular velocities

- New epoch: u -> -u
- New era – changed sign

$$\Omega^{\hat{1}}_{(2)} = \frac{\gamma}{(\gamma+1)t} v_{\hat{2}} v_{\hat{3}} \cdot \frac{1-u^2}{1+u+u^2},$$
$$\Omega^{\hat{2}}_{(2)} = \frac{\gamma}{(\gamma+1)t} v_{\hat{1}} v_{\hat{3}} \cdot \frac{2u+u^2}{1+u+u^2},$$
$$\Omega^{\hat{3}}_{(2)} = -\frac{\gamma}{(\gamma+1)t} v_{\hat{1}} v_{\hat{2}} \cdot \frac{1+2u}{1+u+u^2}.$$

- Odd velocity

$$\Omega^{\hat{1}}_{(1)} \sim -v^{\hat{1}}(t)^{\left(-1-\frac{2u}{1+u+u^2}\right)},$$
$$\Omega^{\hat{b}}_{(1)} \sim v^{\hat{b}}(t)^{\left(-1-\frac{2u}{1+u+u^2}\right)}, \ b = 2, 3.$$

- New epoch
- New era - preserved

$$\Omega^{\hat{2}}_{(1)} \sim -v^{\hat{2}}(t)^{\left(-1-\frac{2u-2}{1-u+u^2}\right)},$$
$$\Omega^{\hat{a}}_{(1)} \sim v^{\hat{a}}(t)^{\left(-1-\frac{2u-2}{1-u+u^2}\right)}, \ a = 1, 3.$$

Possible applications

- Anisotropy (c.f. crystals) ~ magnetic field
- Spin precession + equivalence principle = helicity flip (~AMM effect)
- Dirac neutrino – transformed to sterile component in early (bounced) Universe
- Angular velocity ~ 1/t -> amount of decoupled ~ 1
- Possible new candidate for dark matter?!
- Other fields AFTER inflation?

CONCLUSIONS

- Polarization – extra sensitive tests
- Gravity leads to spin effects related to Kobzarev-Okun equivalence principle
- Bianchi universe – spin precession and neutrino helicity flip

- BACKUP SLIDES

Semi-classical limit

- Average spin precession

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = (\vec{\Omega}_{(1)} + \vec{\Omega}_{(2)}) \times \vec{s}.$$

- Angular velocity contributions

$$\Omega^{\hat{a}}_{(1)} = \frac{1}{\varepsilon'} W^{d}_{\hat{c}} p_d \left(\frac{1}{2} \Upsilon \delta^{\hat{a}\hat{c}} - \varepsilon^{\hat{a}\hat{e}\hat{f}} C^{\hat{c}}_{\hat{e}\hat{f}} \right),$$

$$\Omega^{\hat{a}}_{(2)} = \frac{1}{2} \Xi^{\hat{a}} - \frac{1}{\varepsilon'(\varepsilon' + m)} \varepsilon^{\hat{a}\hat{b}\hat{c}} Q_{(\hat{b}\hat{d})} \delta^{\hat{d}\hat{n}} W^{k}_{\hat{n}} p_k W^{l}_{\hat{c}} p_l.$$

Torsion – acts only on spin

Dirac eq+FW transformation-Obukhov,Silenko,OT

- Hermitian Dirac Hamiltonian

$$e_i^{\hat{0}} = V\,\delta_i^0, \qquad e_i^{\hat{a}} = W^{\hat{a}}{}_b\left(\delta_i^b - cK^b\,\delta_i^0\right)$$

$$ds^2 = V^2c^2dt^2 - \delta_{\hat{a}\hat{b}}W^{\hat{a}}{}_cW^{\hat{b}}{}_d\,(dx^c - K^c cdt)\,(dx^d - K^d cdt)$$

$$\mathcal{H} = \beta mc^2V + q\Phi + \frac{c}{2}\left(\pi_b\,\mathcal{F}^b{}_a\alpha^a + \alpha^a\mathcal{F}^b{}_a\pi_b\right) + \frac{c}{2}\left(\boldsymbol{K}\cdot\boldsymbol{\pi} + \boldsymbol{\pi}\cdot\boldsymbol{K}\right) + \frac{\hbar c}{4}\left(\boldsymbol{\Xi}\cdot\boldsymbol{\Sigma} - \Upsilon\gamma_5\right),$$

$$\mathcal{F}^b{}_a = VW^b{}_{\hat{a}}, \qquad \Upsilon = V\epsilon^{\hat{a}\hat{b}\hat{c}}\Gamma_{\hat{a}\hat{b}\hat{c}}, \qquad \Xi^a = \frac{V}{c}\epsilon^{\hat{a}\hat{b}\hat{c}}\left(\Gamma_{\hat{0}\hat{b}\hat{c}} + \Gamma_{\hat{b}\hat{c}\hat{0}} + \Gamma_{\hat{c}\hat{0}\hat{b}}\right)$$

- Spin-torsion coupling

$$-\frac{\hbar cV}{4}\left(\boldsymbol{\Sigma}\cdot\check{\boldsymbol{T}} + c\gamma_5\check{T}^{\hat{0}}\right)$$

$$\check{T}^\alpha = -\frac{1}{2}\eta^{\alpha\mu\nu\lambda}T_{\mu\nu\lambda}$$

- FW – semiclassical limit - precession

$$\boldsymbol{\Omega}^{(T)} = -\frac{c}{2}\check{\boldsymbol{T}} + \beta\frac{c^3}{8}\left\{\frac{1}{\epsilon'},\left\{\boldsymbol{p},\check{T}^{\hat{0}}\right\}\right\} + \frac{c}{8}\left\{\frac{c^2}{\epsilon'(\epsilon' + mc^2)},\left(\{\boldsymbol{p}^2,\check{\boldsymbol{T}}\} - \{\boldsymbol{p},(\boldsymbol{p}\cdot\check{\boldsymbol{T}})\}\right)\right\}$$

Experimental bounds for torsion

- Magnetic field+rotation+torsion

$$H = -g_N \frac{\mu_N}{\hbar} \boldsymbol{B} \cdot \boldsymbol{s} - \boldsymbol{\omega} \cdot \boldsymbol{s} - \frac{c}{2} \check{\boldsymbol{T}} \cdot \boldsymbol{s}.$$

- Same '92 EDM experiment

$$\frac{\hbar c}{4} |\check{T}| \cdot |\cos\Theta| < 2.2 \times 10^{-21}\,\mathrm{eV}, \qquad |\check{T}| \cdot |\cos\Theta| < 4.3 \times 10^{-14}\,\mathrm{m}^{-1}$$

- New(based on Gemmel et al '10)

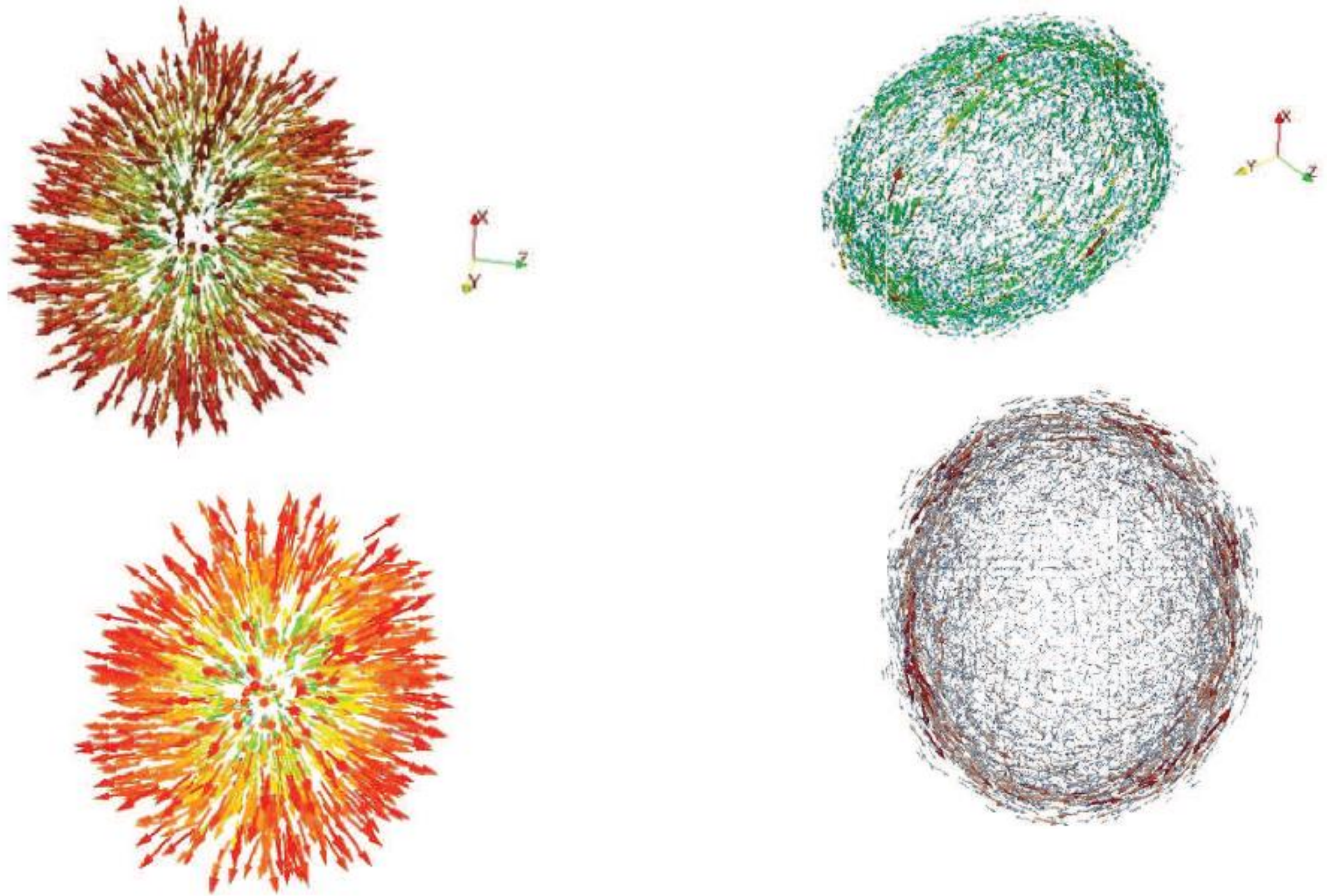
$$\frac{\hbar c}{2} |\check{T}| \cdot |(1-\mathcal{G})\cos\Theta| < 4.1 \times 10^{-22}\,\mathrm{eV}, \qquad |\check{T}| \cdot |\cos\Theta| < 2.4 \times 10^{-15}\,\mathrm{m}^{-1}.$$

$$\mathcal{G} = g_{He}/g_{Xe}$$

Microworld: where is the fastest possible rotation?

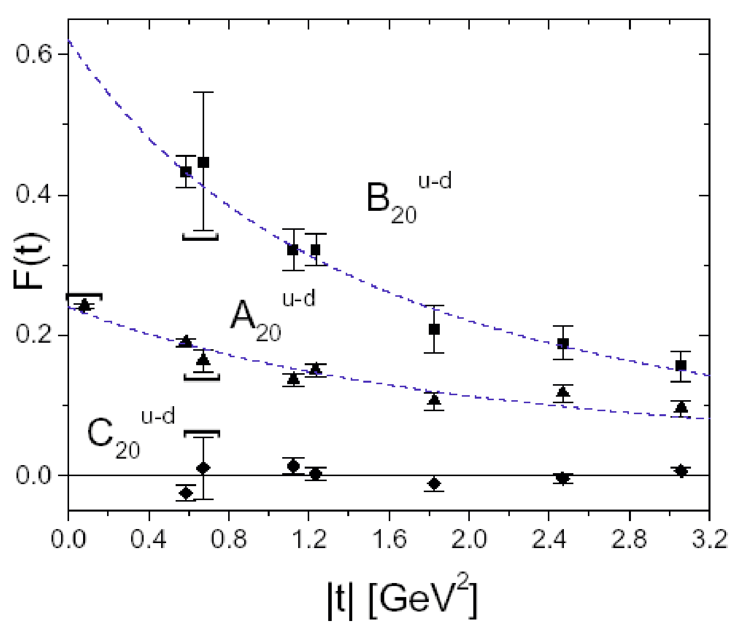
- Non-central heavy ion collisions (~c/Compton wavelength) – "small Bang"
- Differential rotation – vorticity
- Leads to hyperons polarization – should be larger at small energy – predicted in 2010 (Rogachevsky, Sorin, OT) now found by STAR@RHIC
- Calculation in quark - gluon string model (Baznat,Gudima,Sorin,OT,PRC'13)

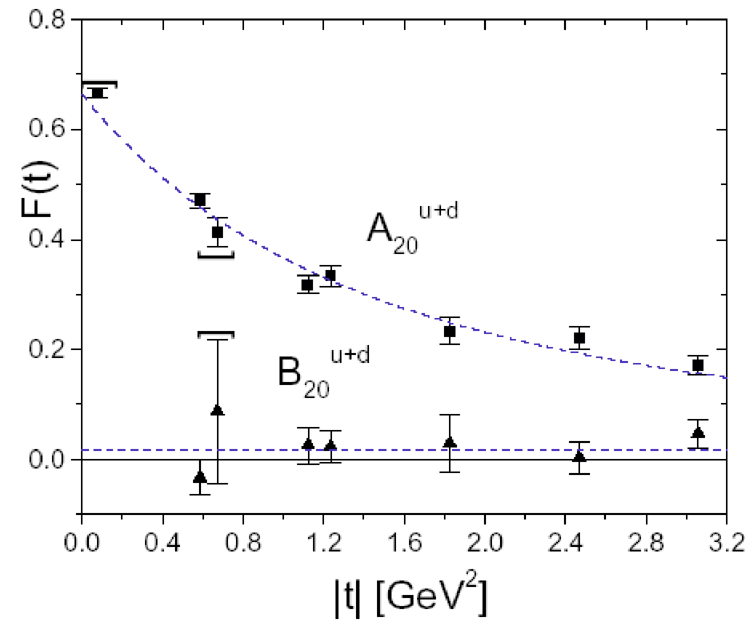
Structure of velocity and vorticity fields (NICA@JINR-5 GeV/c)



Generalization of Equivalence principle

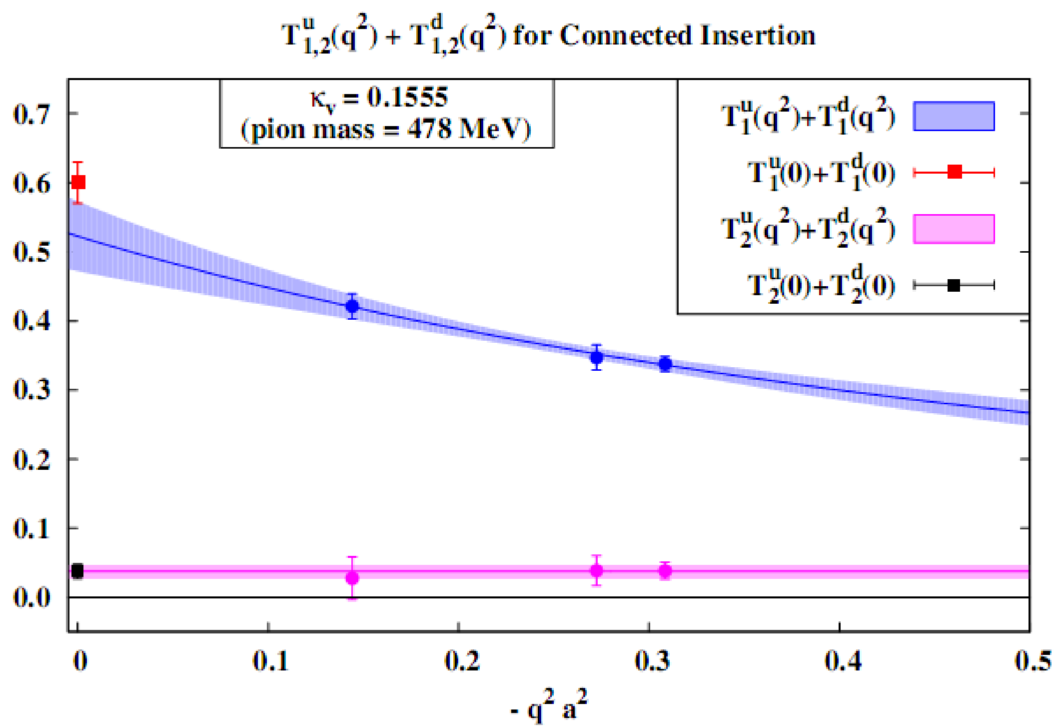
- Various arguments: AGM $\approx$ 0 separately for quarks and gluons – most clear from the lattice (LHPC/SESAM)





Recent lattice study (M. Deka et al. **arXiv:1312.4816**; **cf plenary talk of K.F. Liu**)

- Sum of u and d for Dirac (T1) and Pauli (T2) FFs



Extended Equivalence Principle=Exact EquiPartition

- In pQCD – violated
- Reason – in the case of ExEP- no smooth transition for zero fermion mass limit (Milton, 73)
- Conjecture (O.T., 2001 – prior to lattice data) – valid in NP QCD – zero quark mass limit is safe due to chiral symmetry breaking
- Supported by generic smallness of E (isoscalar AMM)

Sum rules for EMT (and OAM)

- First (seminal) example: X. Ji’s sum rule (’96). Gravity counterpart – OT’99
- Burkardt sum rule – looks similar: can it be derived from EMT?
- Yes, if provide correct prescription to gluonic pole (OT’14)

Pole prescription and Burkardt SR

- Pole prescription (dynamics!) provides ("T-odd") symmetric part!
  $$\sum \int \int dx_1 dx_2 \frac{T(x_1, x_2)}{x_1 - x_2 + i\varepsilon} = 0$$
- SR: $\sum \int dx T(x,x) = 0$ (but relation of gluon Sivers to twist 3 still not founs – prediction!)
- Can it be valid separately for each quark flavour: nodes (related to "sign problem")?
- Valid if structures forbidden for TOTAL EMT do not appear for each flavour
- Structure contains besides S gauge vector n: If GI separation of EMT – forbidden: SR valid separately!

Another manifestation of post-Newtonian (E)EP for spin 1 hadrons

- Tensor polarization - coupling of gravity to spin in forward matrix elements - inclusive processes
- Second moments of tensor distributions should sum to zero

$$\langle P,S|\bar{\psi}(0)\gamma^{\nu}D^{\nu_1}...D^{\nu_n}\psi(0)|P,S\rangle_{\mu^2} = i^{-n}M^2S^{\nu\nu_1}P^{\nu_2}...P\nu_n\int_0^1 C_q^T(x)x^n dx$$

$$\sum_q \langle P,S|T_i^{\mu\nu}|P,S\rangle_{\mu^2} = 2P^{\mu}P^{\nu}(1-\delta(\mu^2)) + 2M^2S^{\mu\nu}\delta_1(\mu^2)$$

$$\langle P,S|T_g^{\mu\nu}|P,S\rangle_{\mu^2} = 2P^{\mu}P^{\nu}\delta(\mu^2) - 2M^2S^{\mu\nu}\delta_1(\mu^2)$$

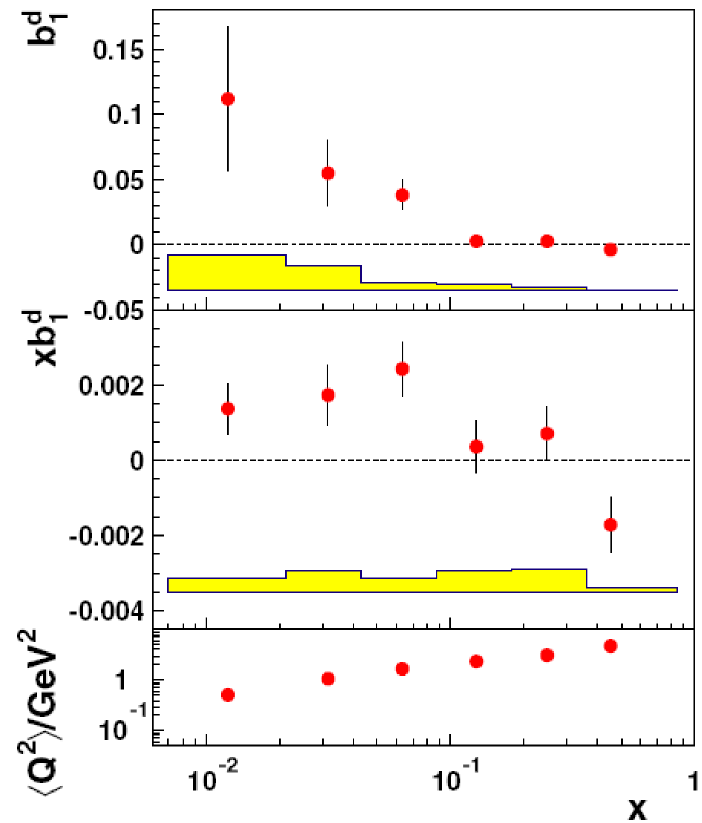
$$\sum_q \int_0^1 C_i^T(x)x dx = \delta_1(\mu^2)$$ =0 for ExEP

HERMES – data on tensor spin structure function

PRL 95, 242001 (2005)

- Isoscalar target – proportional to the sum of u and d quarks – combination required by EEP
- Second moments – compatible to zero better than the first one (collective glue << sea) – for valence:

$$\int_0^1 C_i^T(x)dx = 0$$



Are more accurate data possible?

- HERMES – unlikely
- JLab may provide information about collective sea and glue in deuteron and indirect new test of Equivalence Principle

CONCLUSIONS

- Spin-gravity interactions may be probed directly in gravitational (inertial) experiments and indirectly – studing EMT matrix element
- Torsion and EP are tested in EDM experiments
- SR's for deuteron tensor polarization-indirectly probe EP and its extension separately for quarks and gluons

EEP and AdS/QCD

- Recent development – calculation of Rho formfactors in Holographic QCD (Grigoryan, Radyushkin)
- Provides g=2 identically!
- Experimental test at time –like region possible