

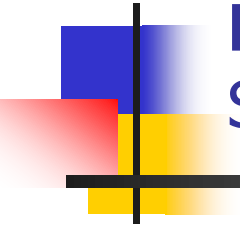
Polarisation in QCD: from hadronic to heavy-ion collisions

QCD: Old Challenges and New Opportunities

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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 properties¹. Non-central collisions have angular momentum on the order of $1000\hbar$, and the resulting fluid may have a strong vortical structure²⁻⁴ 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 vorticity¹⁵. 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 $\bar{\Lambda}$ hyperons show a positive polarization of the order of a few percent, consistent with some hydrodynamic predictions⁵. A previous measurement⁶ 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 discovery⁸ of hydrodynamic spin alignment to the subatomic realm.


arXiv:1701.06657v1 [nucl-ex] 23 Jan 2017



*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*

Outline

- 
- QCD factorization and hadronic spin
 - 2 faces of spin structure
 - Single Spin Asymmetries in QCD
 - From hadrons to heavy ions: Vorticity and hyperon polarization

QCD

Why QCD?

Major scientific problem - mass of the Universe

~ 70% - Dark Energy

~ 25% - Dark Matter

~ 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

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

Invariance -(Charge) conservation law

Local phase transformation

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

Invariance - (Minimal)interaction with photon field.

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

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

$$\Psi_{\rho}(x) \rightarrow e^{it\rho\beta^{\alpha}}\Psi_{\beta}(x) \quad (4)$$

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

Local transformation invariance - (minimal interaction with gluon field)

$$\bar{\psi}_{\alpha}\hat{A}^at_{\alpha\beta}^{\psi}\psi_{\beta}; \quad (5)$$

$N = 3$ 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 \$10⁶) that it is absolute. Explains the non existence of free coloured particles. Nuclear forces - remnant of strong colour forces like van der Waals 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.

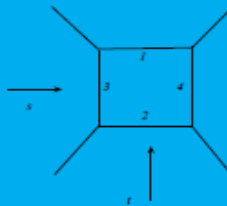
Factorization - based on the analysis of Feynman diagrams asymptotics

Useful tool α -representation

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

Large momenta - small α .

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



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

Appearance of subprocess

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

At least one of α s 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.

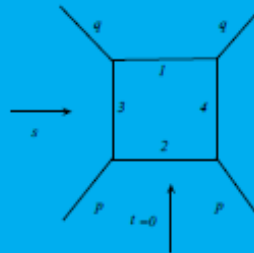
Electric circuits analogy : momentum \rightarrow current.

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 $\gamma^*(q)N(p) \rightarrow X$.

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

Simplest model - again box diagram

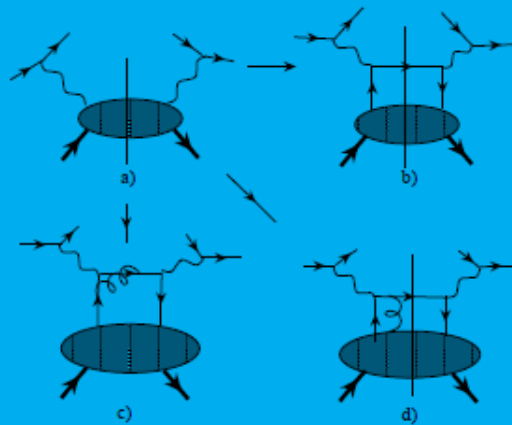


$$\sim \int_0^\infty \frac{\Pi d\alpha}{(\sum \alpha)^2} e^{i(s\alpha_1\alpha_2 + q^2\alpha_1(\alpha_3 + \alpha_4))/\sum \alpha} \quad (8)$$

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

Quarks in hadrons=hadronic matrix element of quark operator

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

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

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

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

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 .

$$\langle P | \varphi(0) \partial^{\nu_1} \dots \partial^{\nu_n} \varphi(0) | P \rangle = i^n a_n P^{\nu_1} \dots P^{\nu_n} \quad (11)$$

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

Last (but not least) step: moments

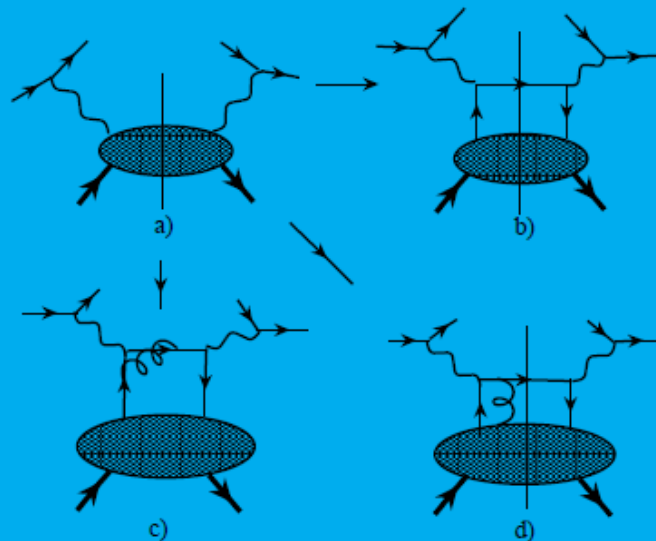
$$a_n = \int_0^1 dx f(x) x^n \quad (13)$$

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

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

Spin 1/2 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

$$\langle P | \varphi(0) \varphi(z) | P \rangle \rightarrow \langle P, S | \psi_\alpha(0) E(0, z) \bar{\psi}_\beta | P, S \rangle \quad (1)$$

$E(0, z)$ - 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 $S \rightarrow \xi p/m$, ξ is the degree of longitudinal polarization. $\rho \rightarrow \frac{1}{2}\hat{p}(1 + \xi\gamma_5)$

Consider longitudinally polarized nucleon; expansion over full set of Dirac matrices and making use of Lorentz invariance:

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

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:

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

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

Generally speaking, spin-averaged and spin-dependent distributions are unrelated, but $|\Delta q(x)| \leq q(x), |\Delta G(x)| \leq G(x)$ (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 $\int dx, \dots, \int dx$ - 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

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

for d

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

and for s (and any other)

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

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

Momentum and spin – Axial Anomaly appears

$\int dx x \dots$ - current operator with derivative - energy momentum tensor; physically - weighting with momentum fraction

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

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 β -decay. $\langle p | J_5^\mu | n \rangle$ - due to isospin invariance $\rightarrow \langle p | J_5^\mu | p \rangle = \langle n | J_5^\mu | n \rangle$ - 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



Two faces of spin structure

- Conserved Angular Momentum – non-local operators
- $x_i \rightarrow d/dp^i$ – non-forward matrix elements – Generalized Parton Distributions
- Ji's sum rules: from Generalized Parton Distributions to Energy-Momentum Tensor (Gravitational) Formfactors



Gravitational Formfactors

$$\langle p' | T_{q,g}^{\mu\nu} | p \rangle = \bar{u}(p') \left[A_{q,g}(\Delta^2) \gamma^{(\mu} p^{\nu)} + B_{q,g}(\Delta^2) P^{(\mu} i \sigma^{\nu)\alpha} \Delta_\alpha / 2M \right] u(p)$$

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

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

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

- 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!?)

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

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

$$\rho_0^{\text{Gr}}(b) = \frac{1}{2\pi} \int_0^\infty dq q J_0(qb) A(q^2)$$

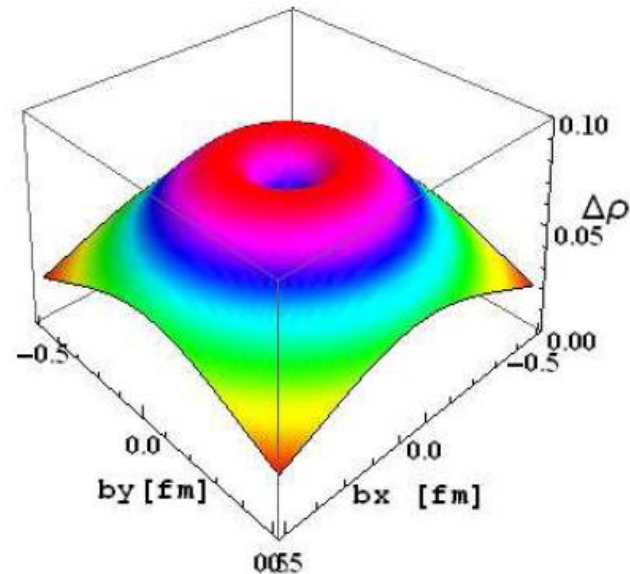


FIG. 17: Difference in the forms of charge density F_1^P and "matter" density (A)



Gravitational FFs

- $C=+$ parity: possible role in Pomeron coupling
- For pions in the time-like region may be extracted from pion pair production in collisions of real and virtual photons (Kumano, Song, OT, in progress)



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

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

spin dragging twice
smaller than EM

- Lorentz force – similar to EM case: factor $\frac{1}{2}$ cancelled with 2 from frequency same as EM

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

Larmor

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

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

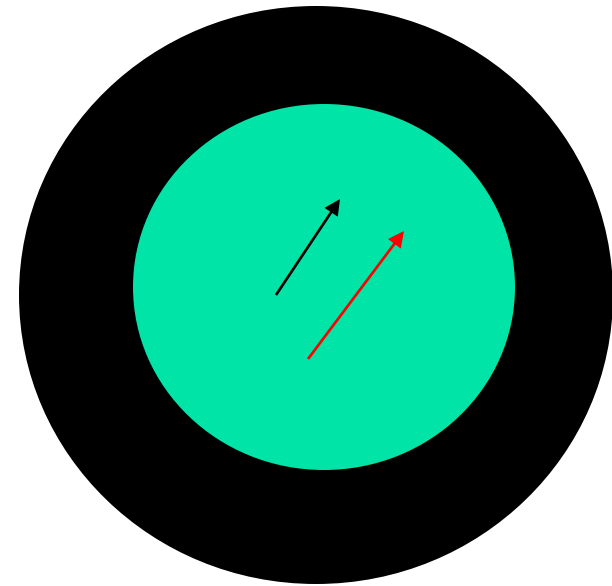


Equivalence principle

- 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 conservation laws - Kobzarev and Zakharov
- Anomalous gravitomagnetic (and electric-CP-odd) moment is 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)

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 ?!



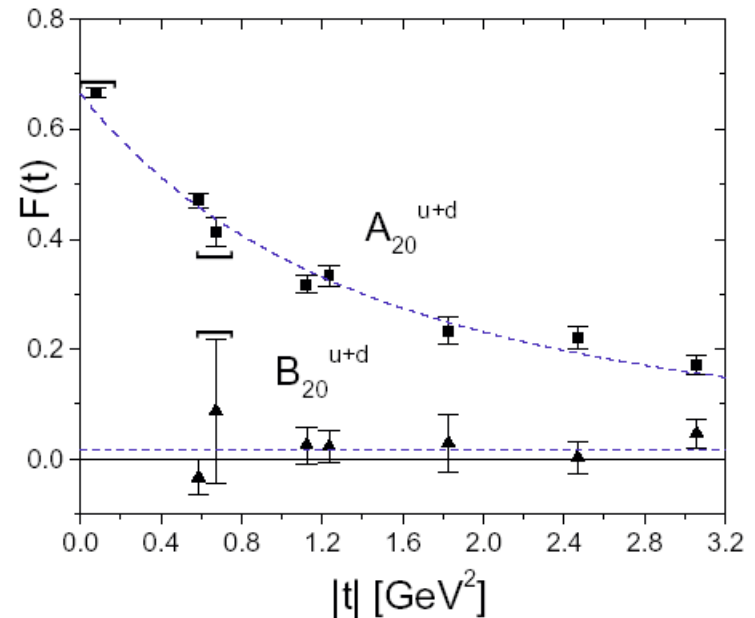
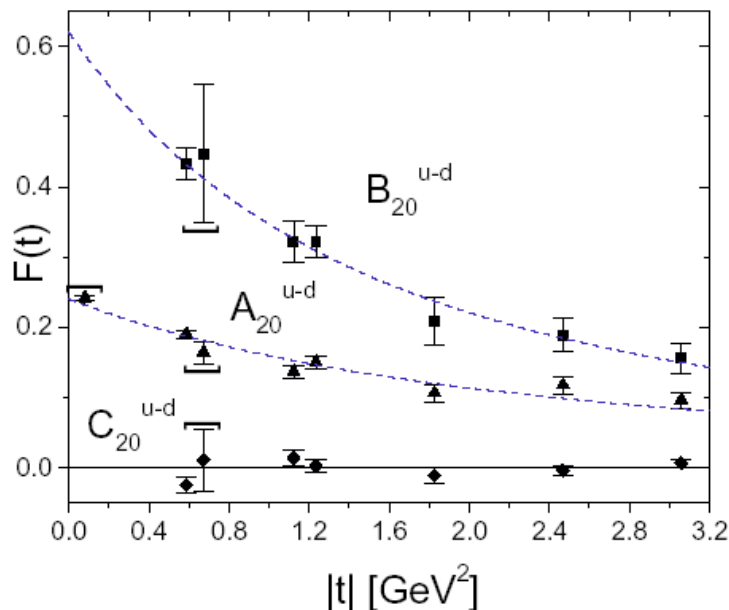


Equivalence principle for moving particles

- Compare gravity and acceleration:
gravity provides EXTRA space components of metrics $h_{zz} = h_{xx} = h_{yy} = h_{00}$
- Matrix elements DIFFER
$$\mathcal{M}_g = (\epsilon^2 + p^2)h_{00}(q), \quad \mathcal{M}_a = \epsilon^2 h_{00}(q)$$
- 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

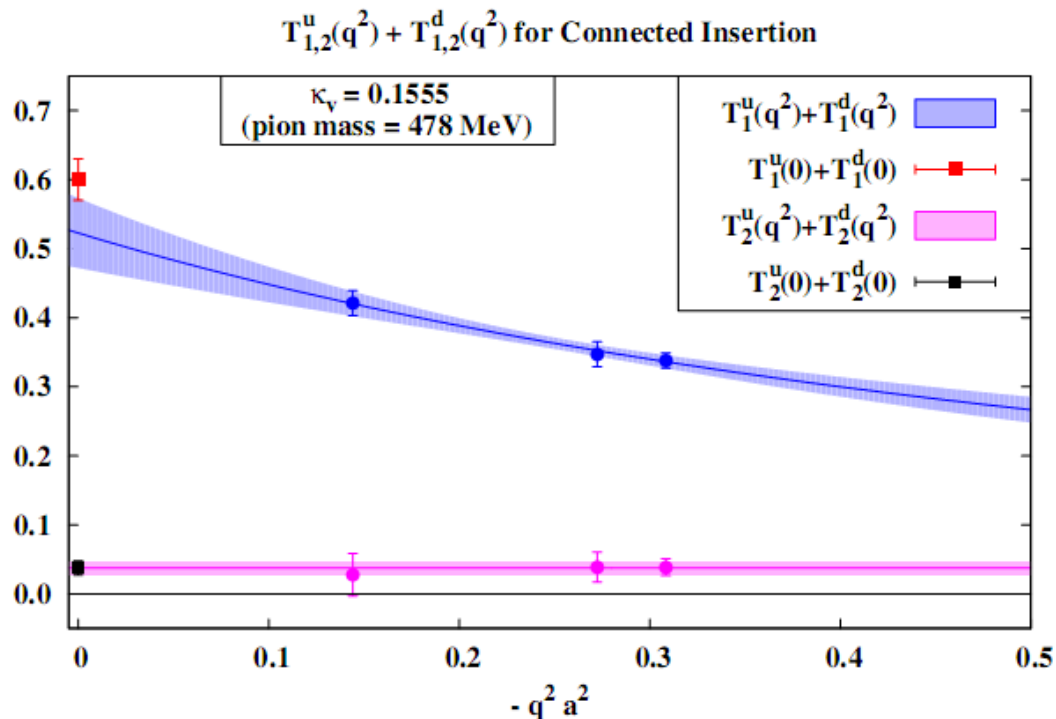
Generalization of Equivalence principle

- 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](#), PRD'14)

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



Extended Equivalence Principle

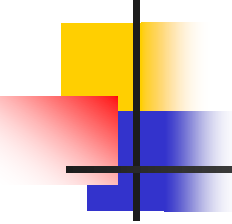


- Always $\Sigma B_i=0$; separately $B_i=0$ - equipartition of momentum and total angular momentum
- Conjectured (OT'01) prior to lattice data due to Chiral Symmetry Breaking
- Interpretation: synchronous rotation of quark and gluon contributions to nucleon spin in arbitrary strong (Black Hole!?) gravitational field : gravity-proof confinement?
- New lattice tests are of interest
- Has yet another manifestation for spin 1 particles(deuterons)



2nd face of spin structure: role of axial anomaly

- (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)

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

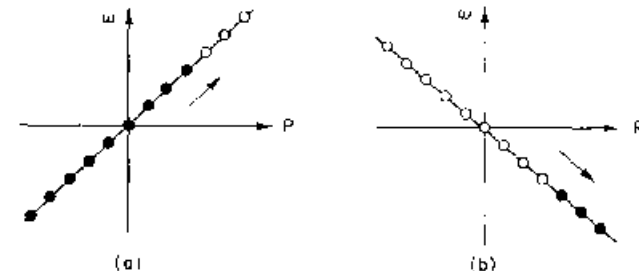
- Dilatational invariance (mass introduce dimensional scale – c.f. energy-momentum tensor of electromagnetic radiation)

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

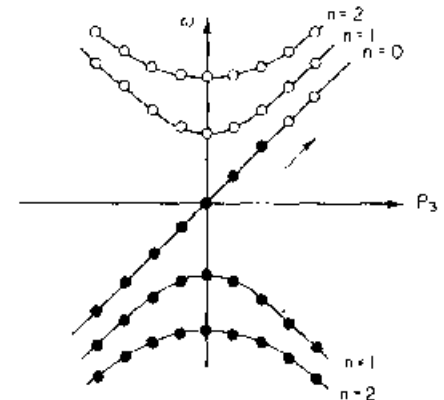
Calculation of anomalies

- Many various ways
- All lead to the same operator equation

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



- 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” $Ldp = eE \, dt \, L$
($dp = eE dt$)
- 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:
- $J \sim$ quark spin; $K \sim$ gluon spin
- GI decomposition of gluon angular momentum: Wakamatsu, Hatta....

Single and double spin asymmetries



Spin asymmetries: single vs double.

DIS structure function F_1, F_2 - averaged over spin.

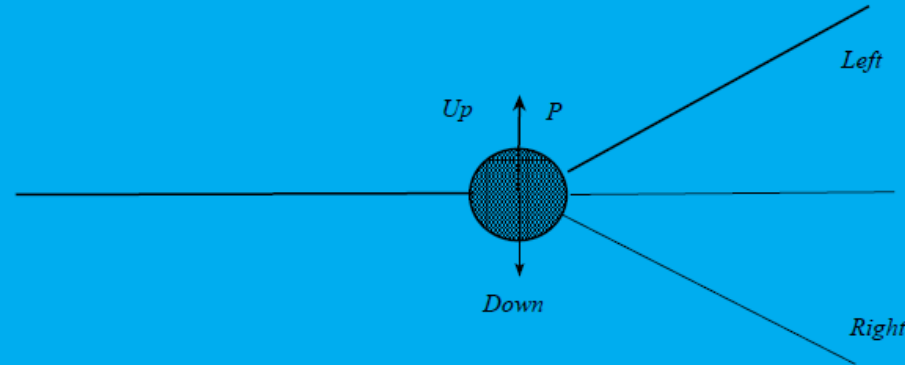
G_1, G_2 - for polarised leptons AND nucleons - double spin asymmetries

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

Simple experiment - Complicated Theory

Simple example

Simplest example - (non-relativistic) elastic pion-nucleon scattering $\pi \vec{N} \rightarrow \pi N$



$M = a + ib(\vec{\sigma}\vec{n})$ \vec{n} is the normal to the scattering plane.

Density matrix: $\rho = \frac{1}{2}(1 + \vec{\sigma}\vec{P})$,

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

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

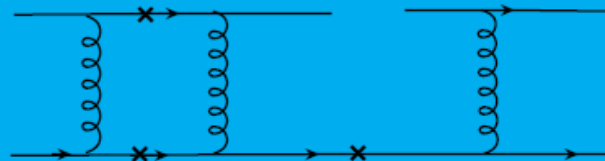
Interference of amplitudes

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):

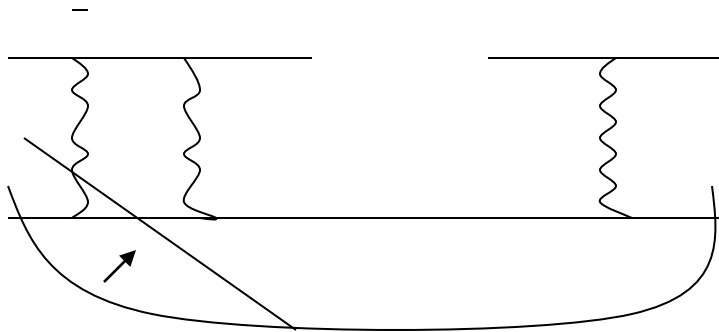


$$A \sim \frac{\alpha_S m p_T}{p_T^2 + m^2}$$

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

Short+ large overlap– twist 3

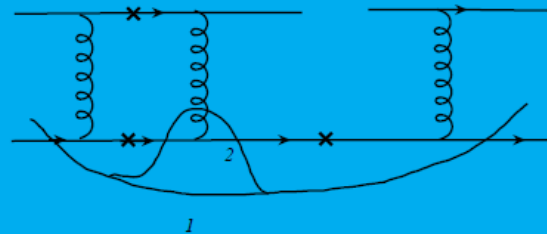
- Quarks – only from hadrons
- Various options for factorization – shift of SH separation



- 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 \rightarrow Sivers function)
- Further shift to large distances – T-odd fragmentation functions (Collins, dihadron, **handedness**)

NPQCD: twist 3 and T-odd distributions

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



At short distances - Loop \rightarrow Born diagram

At Large distances - quark distribution \rightarrow 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

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

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



Λ -polarisation

- Self-analyzing in weak decay
- Directly related to s-quarks polarization: complementary probe of strangeness
- Widely explored in hadronic processes
- Disappearance-probe of QCD matter formation (Hoyer; Jacob, Rafelsky: '87): Randomization – smearing – no direction normal to the scattering plane
- But is it complete (smoothly from hadrons to ions)? !

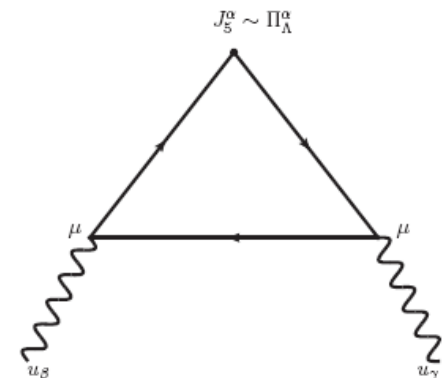


Global polarisation

- Global polarisation normal to REACTION plane
- Predictions (Z.-T.Liang et al.): large orbital angular momentum \rightarrow large polarisation
- 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 \rightarrow VORTICITY
- $\mu q \rightarrow \mu V_i J^i$ $e_j A_\alpha J^\alpha \Rightarrow \mu_j V_\alpha J^\alpha$ $\text{rot } A \rightarrow \text{rot } V$
- Triangle anomaly (Axial Vortical Effect) leads to polarisation of quarks and hyperons (Rogachevsky, Sorin, OT '10)
- Analogous to anomalous gluon contribution to nucleon spin (Efremov, OT'88)
- 4-velocity instead of gluon field!





Anomaly for polarisation

- 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

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

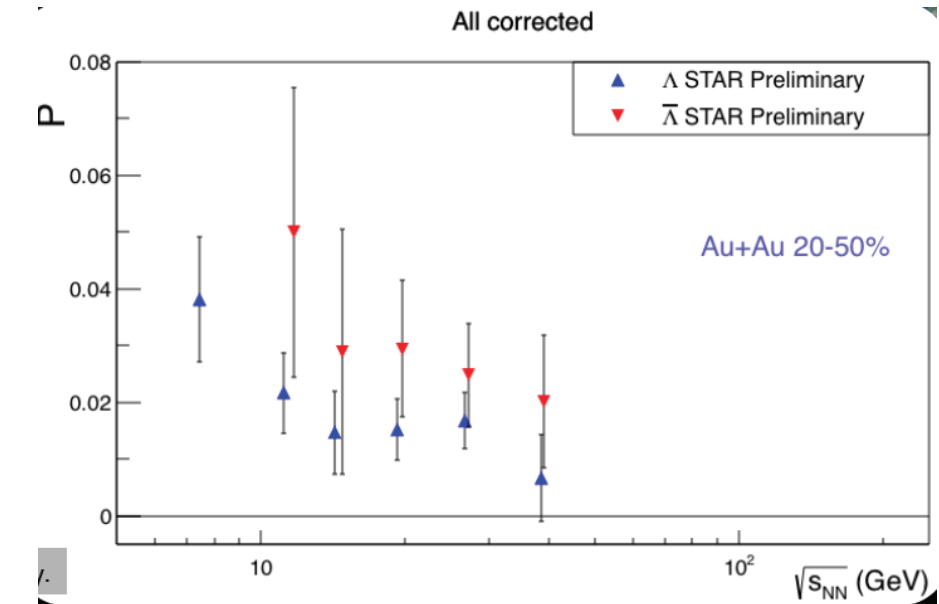
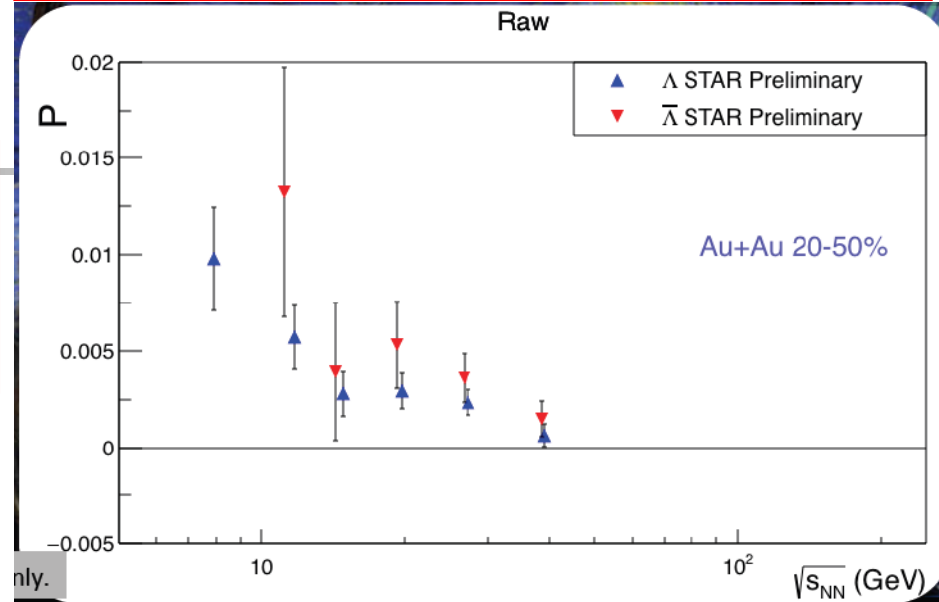
One would expect that polarization is proportional to the anomalously induced axial current [7]

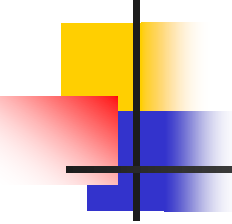
$$j_A^\mu \sim \mu^2 \left(1 - \frac{2\mu n}{3(\epsilon + P)} \right) \epsilon^{\mu\nu\lambda\rho} V_\nu \partial_\lambda V_\rho, \quad (6)$$

where n and ϵ are the corresponding charge and energy densities and P is the pressure. Therefore, the μ dependence of polarization must be stronger than that of the CVE, leading to the effect's increasing rapidly with decreasing energy.

This option may be explored in the framework of the program of polarization studies at the NICA [17] performed at collision points as well as within the low-energy scan program at the RHIC.

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





Microworld: where is the fastest possible rotation?

- Non-central heavy ion collisions (Angular velocity $\sim c/\text{Compton wavelength}$)
- ~ 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
- $L = \sum \mathbf{r} \times \mathbf{p}$
- Differential pseudovector characteristics – vorticity
- $\omega = \text{curl } \mathbf{v}$
- Pseudoscalar – helicity
- $H \sim \langle (\mathbf{v} \cdot \text{curl } \mathbf{v}) \rangle$
- Maximal helicity – Beltrami chaotic flows
 $\mathbf{v} \parallel \text{curl } \mathbf{v}$



Simulation in QGSM (Kinetics -> HD)

$50 \times 50 \times 100$ cells $dx = dy = 0.6 \text{ fm}, dz = 0.6/\gamma \text{ fm}$

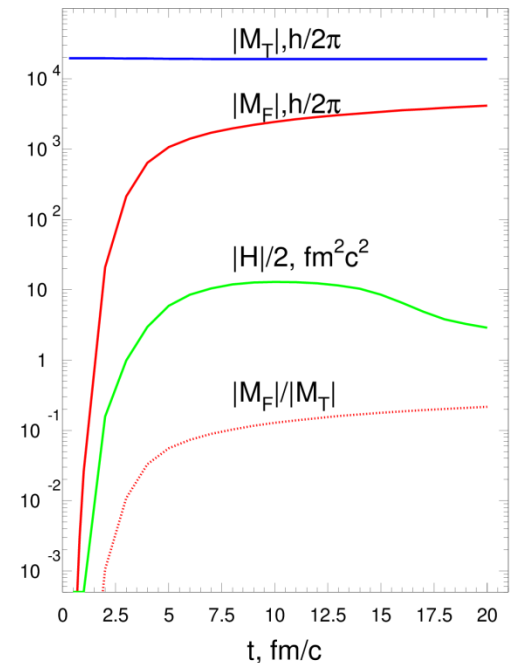
- Velocity

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

- Vorticity – from discrete partial derivatives

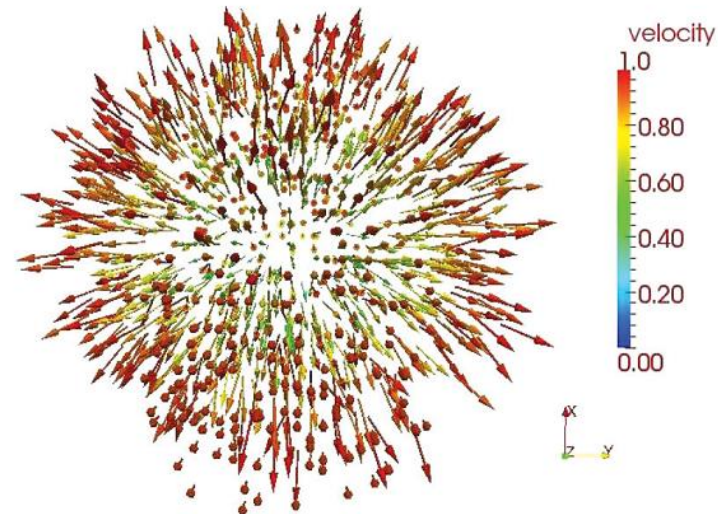
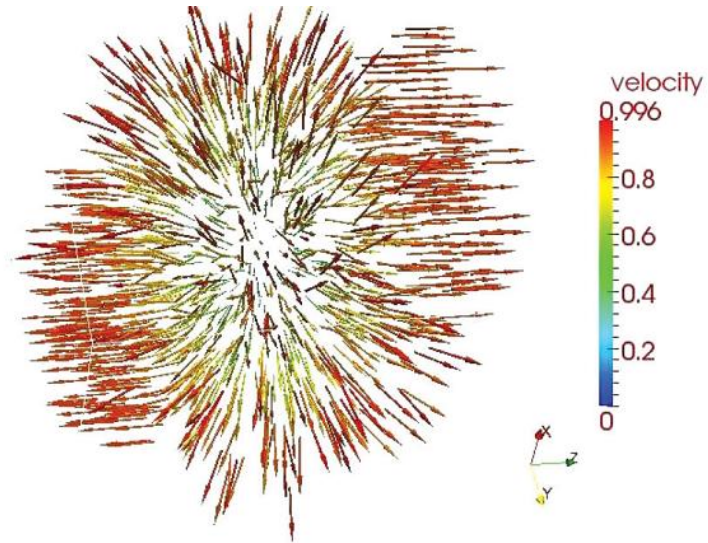
Angular momentum conservation and helicity

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



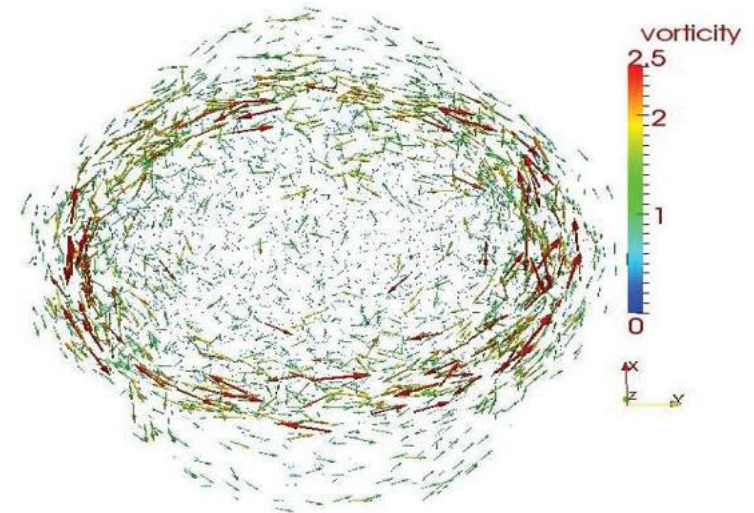
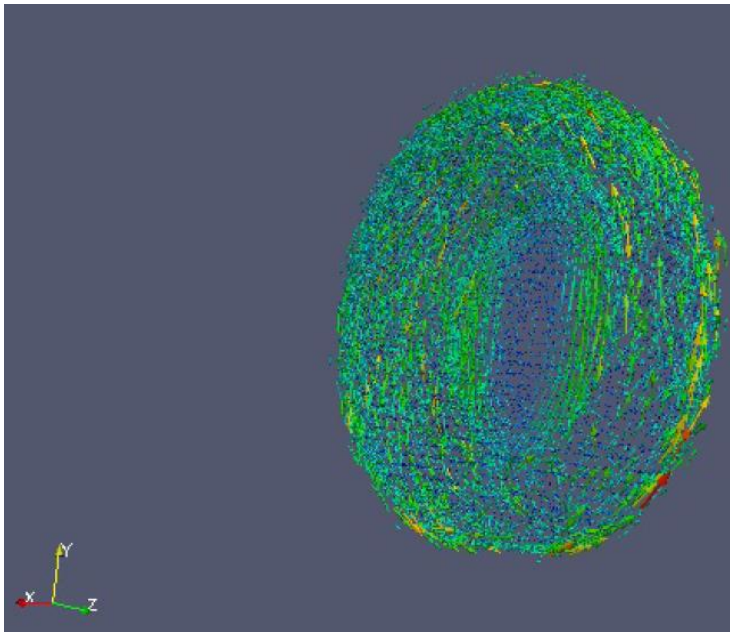
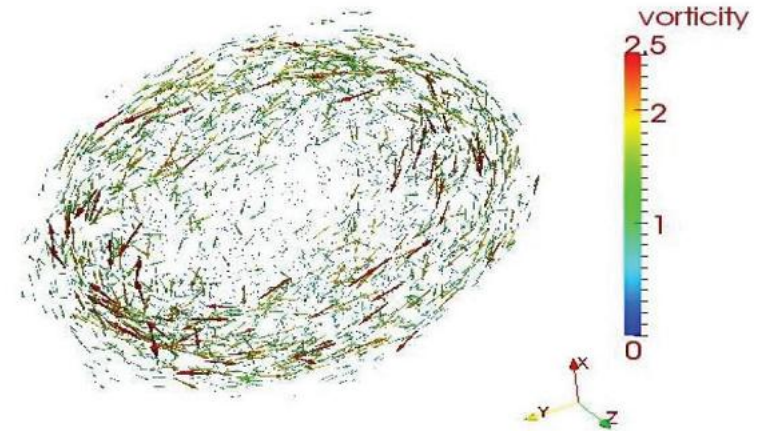
Distribution of velocity ("Little Bang")

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



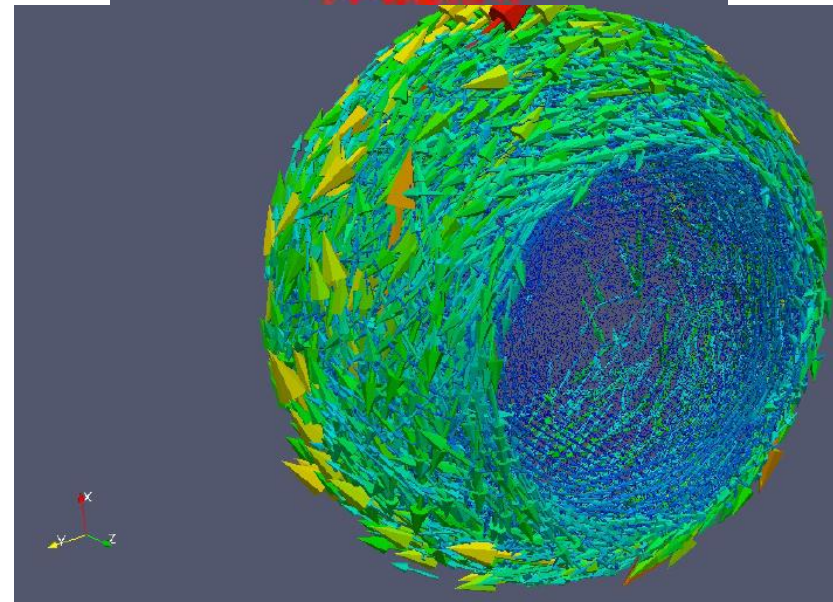
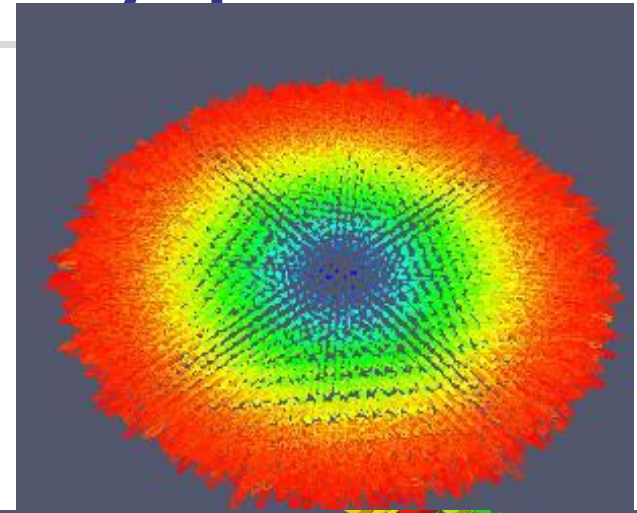
Distribution of vorticity ("Little galaxies")

- Layer (on core - corona borderline) patterns

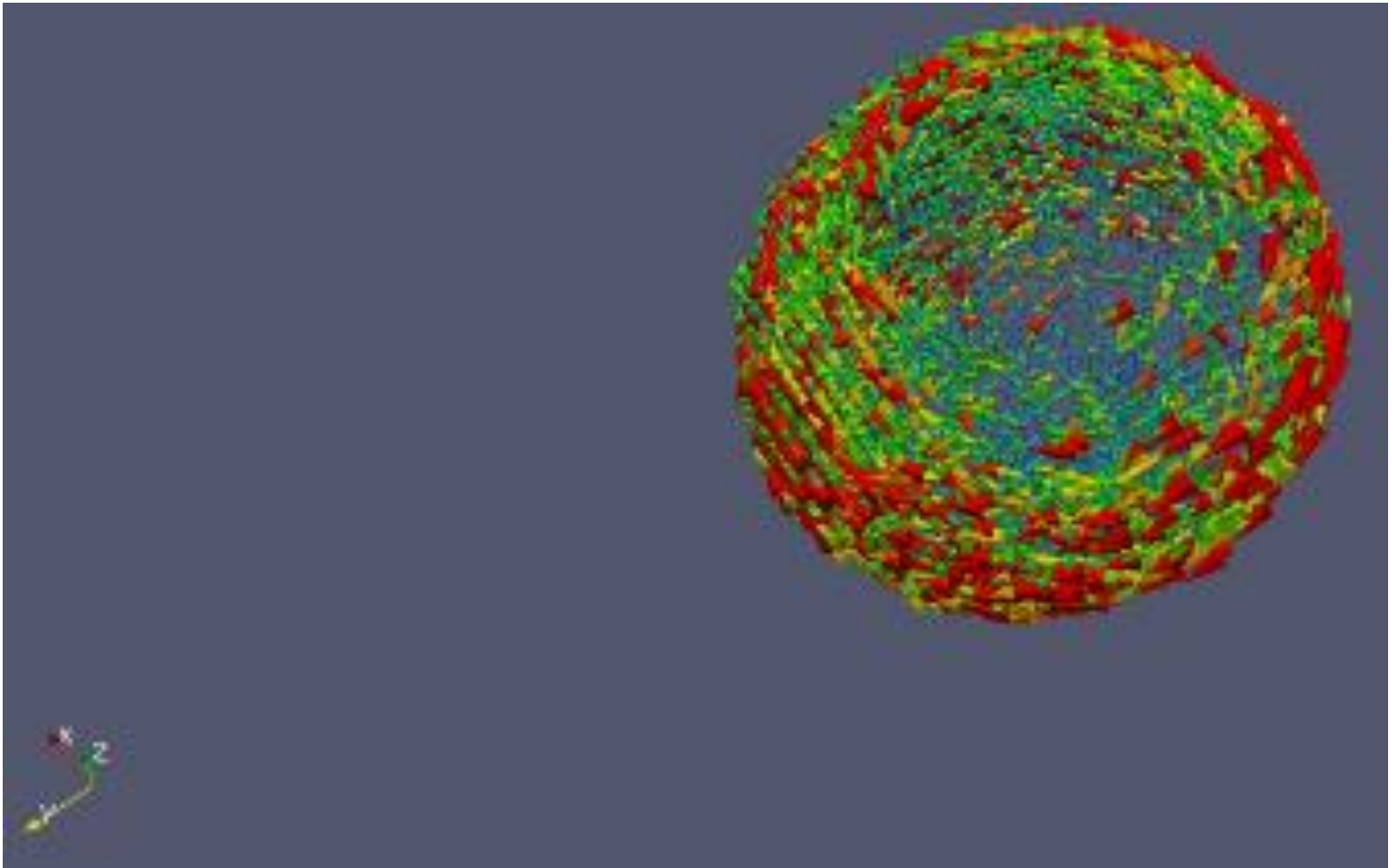


Velocity and vorticity patterns

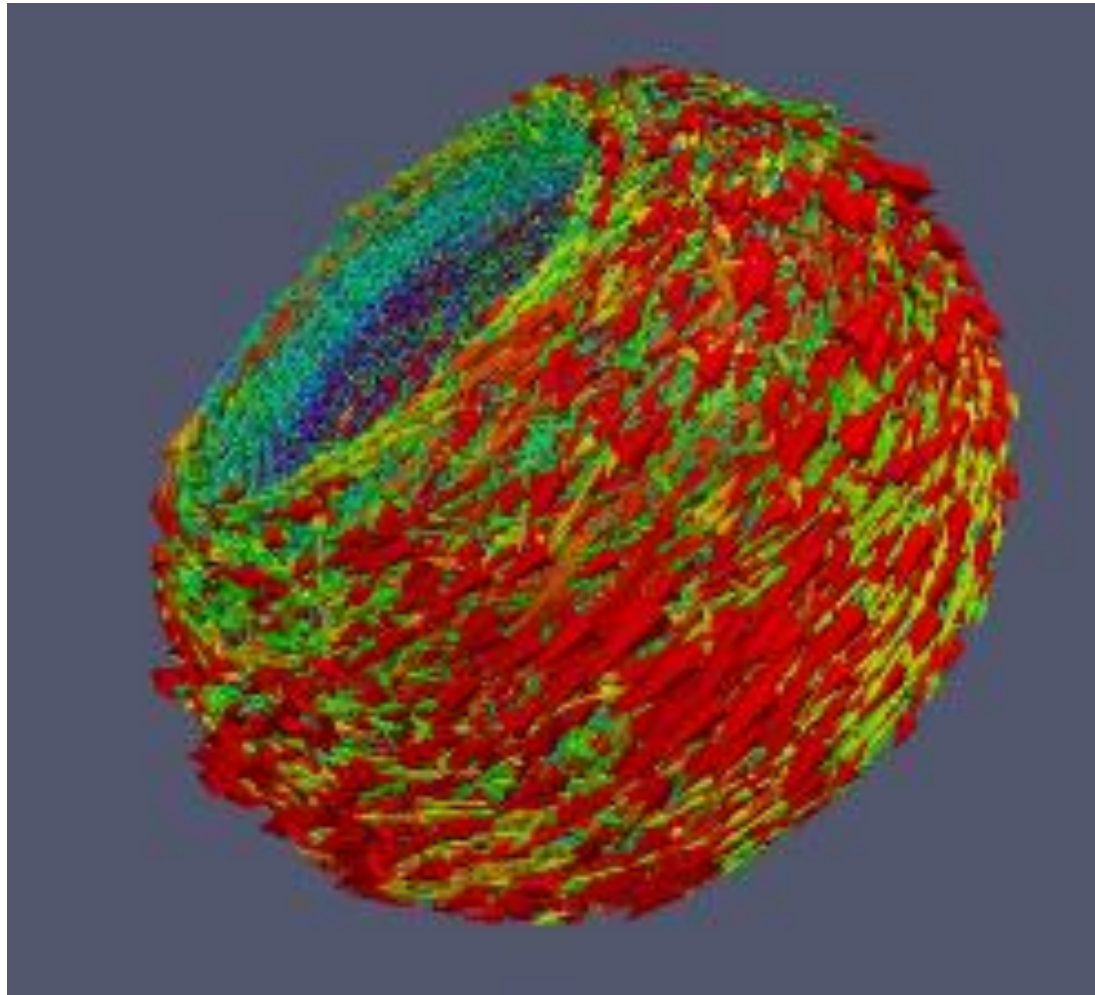
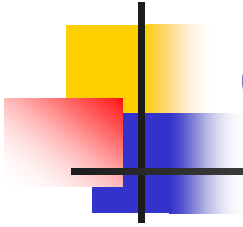
- Velocity
- Vorticity pattern –
vortex sheets -
due to L BUT
cylinder symmetry!



Vortex sheet (fixed direction of L)

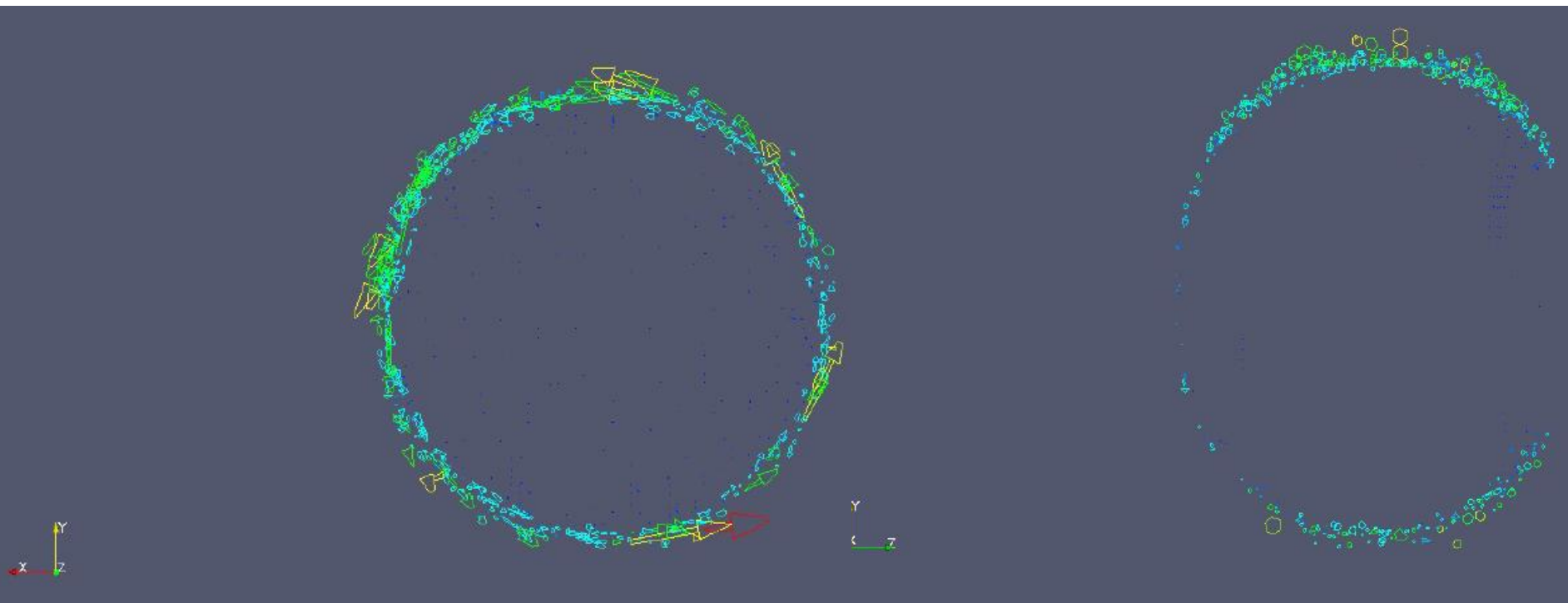


Vortex sheet (Average over L directions)



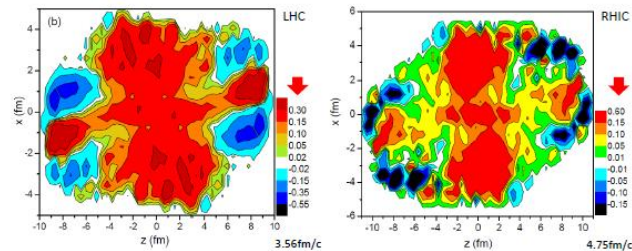
Sections of vorticity patterns

- Front and side views

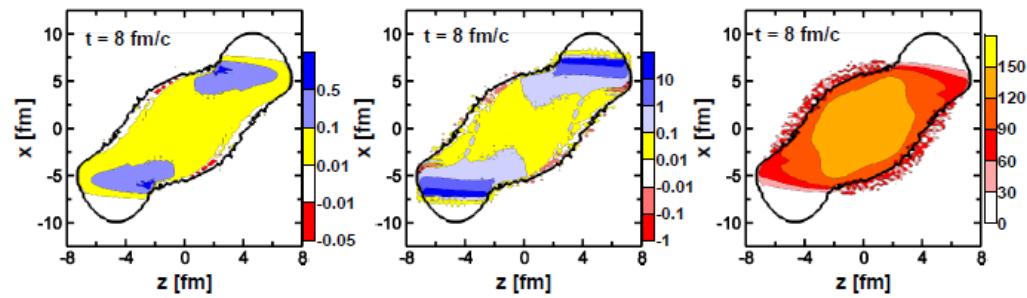


Vortex sheets

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



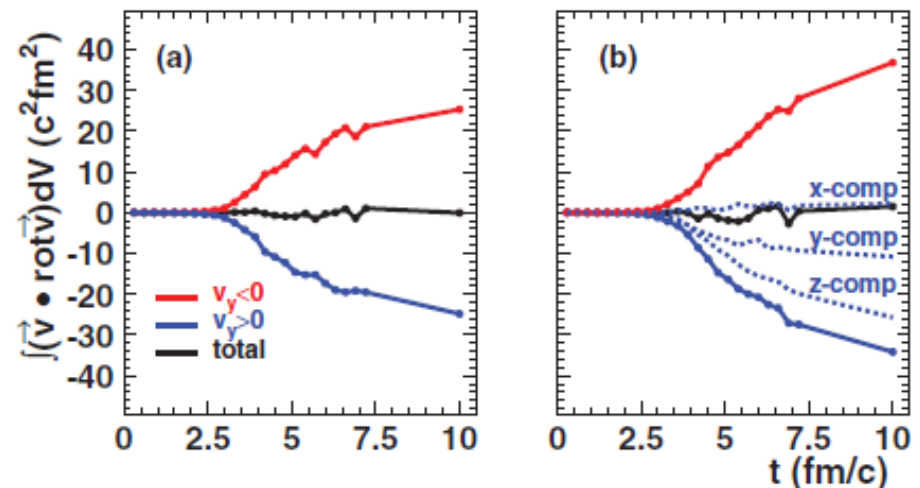
- Appears in 3 fluid dynamics model (Yu. Ivanov, A. Soldatov, [arXiv:1701.01319](https://arxiv.org/abs/1701.01319))



Helicity separation in QGSM

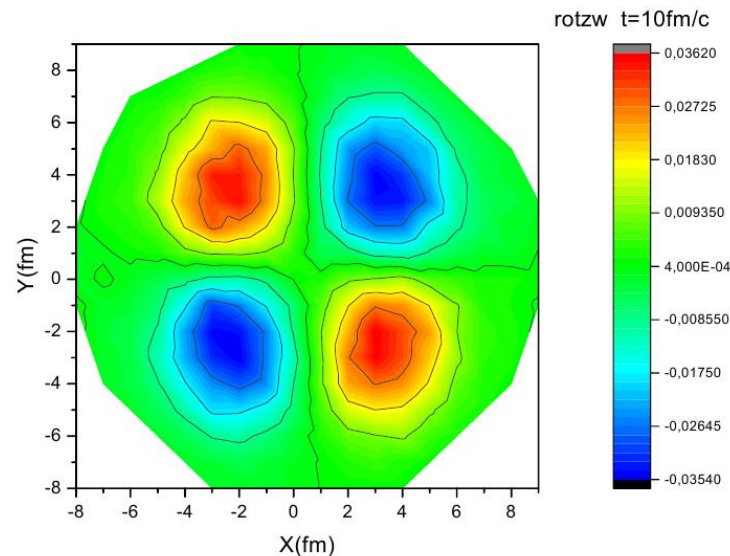
PRC88 (2013) 061901

- Total helicity integrates to zero BUT
- Mirror helicities below and above the reaction plane
- Confirmed in HSD (OT, Usubov, PRC92 (2015) 014906



Structure of vorticity

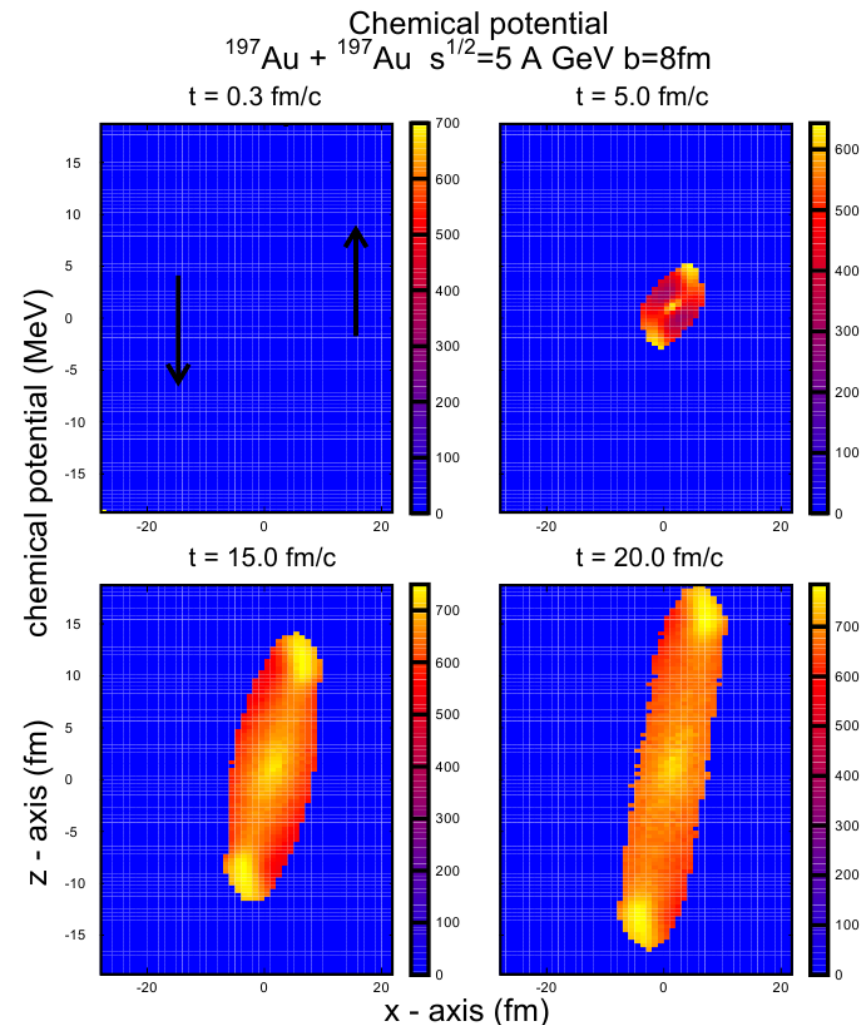
- y-component: constant vorticity, velocity changes sign
- **z-component: quadrupole structure of vorticity**



Chemical potential : Kinetics

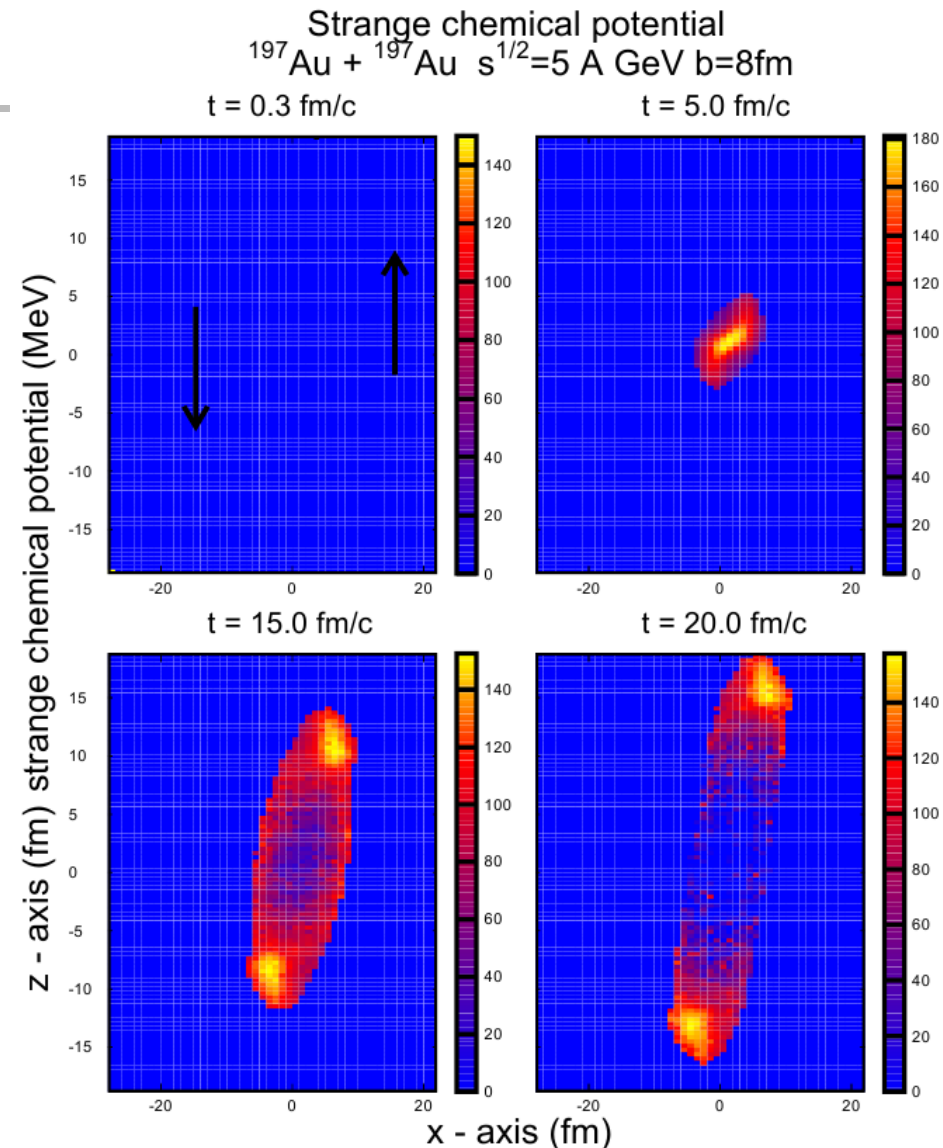
-> TD

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

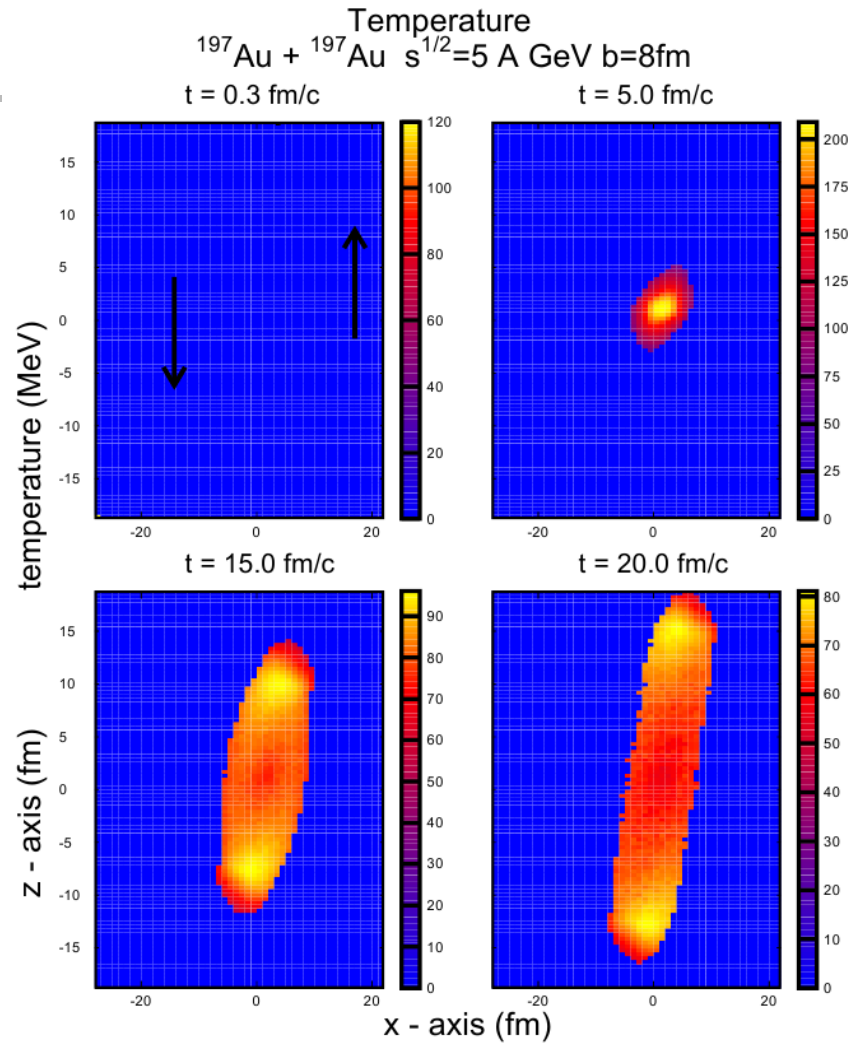


Strange chemical potential (polarisation of Lambda is carried by strange quark!)

- Non-uniform in space and time



Temperature



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

- Analogy of matrix elements and classical averages

$$\langle p_n | j^0(0) | p_n \rangle = 2p_n^0 Q_n \quad \langle Q \rangle \equiv \frac{\sum_{n=1}^N Q_n}{N} = \frac{\int d^3x j_{class}^0(x)}{N}$$

- Lorentz boost: compensate the sign of helicity

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

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

- Antihyperons (smaller N) : same sign and larger value (more pronounced at lower energy; EM difference-decrease)

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

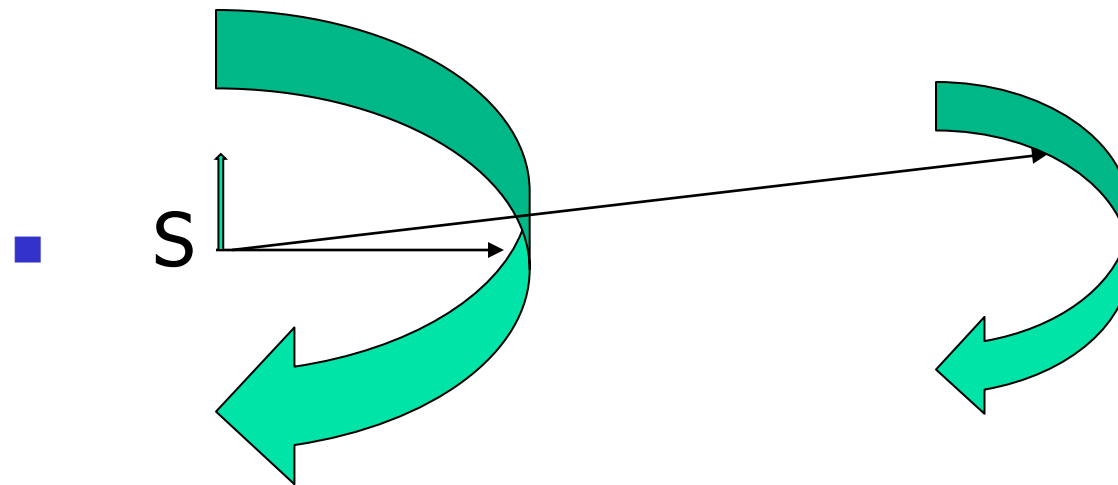
- Pions may carry the axial current due to quantized vortices in pionic superfluid (Kirilin, Sadofyev, Zakharov'12)

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

- Suggestion: core of the vortex- baryonic degrees of freedom- polarization
- (Quantum) Macro to micro at short distances
- Absorptive phases – dissipation!?

Core of quantized vortex

- Constant circulation – velocity increases when core is approached



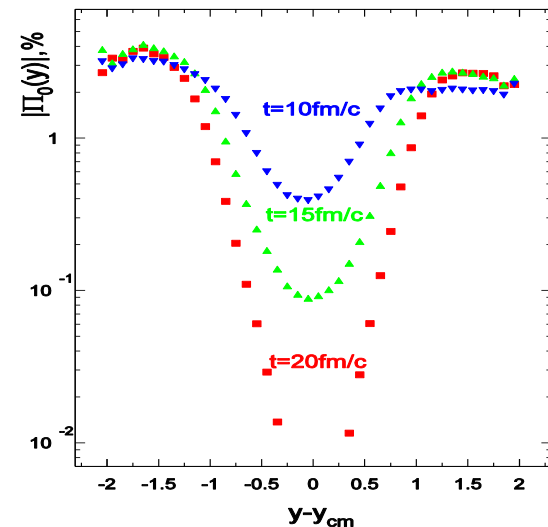
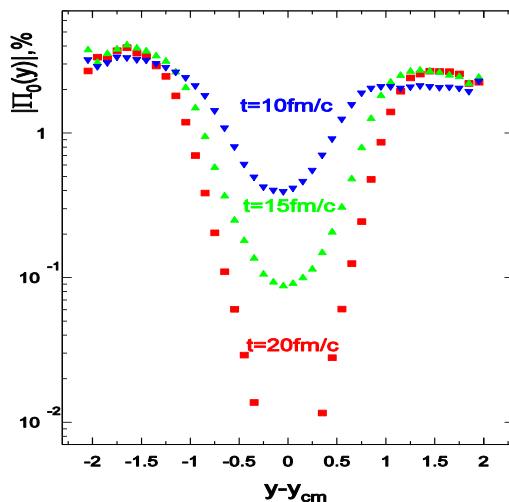
- Helium ($v < v_{\text{sound}}$) bounded by intermolecular distances
- Pions ($v < c$) \rightarrow (baryon) spin in the center

Helicity -> rest frame polarization

- Helicity \sim 0th component of polarization in lab. frame – effect of boost to Lambda rest frame – various options

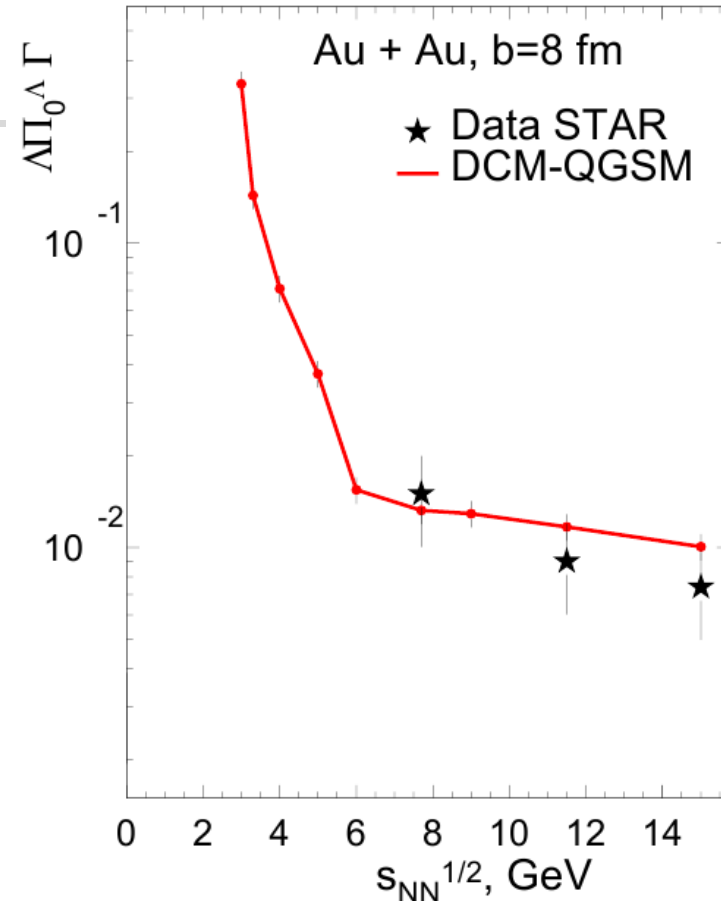
$$\Pi_0(y) = \frac{1}{(4\pi^2)} \int y^2(x) \mu_s^2(x) |\mathbf{v} \cdot \text{rot}(\mathbf{v})| n_\Lambda(y, x) w_1 d^3x / \int n_\Lambda(y, x) w_2 d^3x$$

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



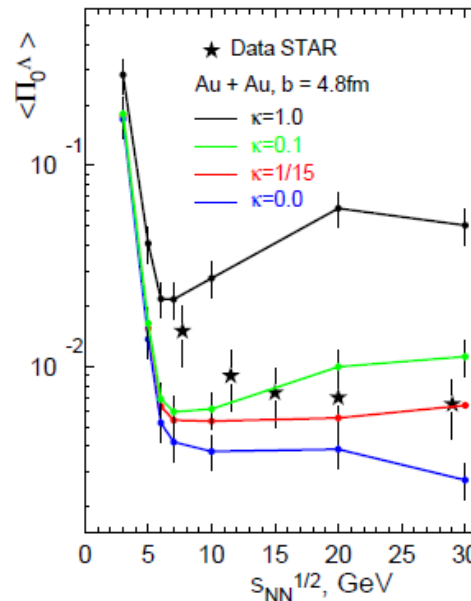
Energy dependence

- 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



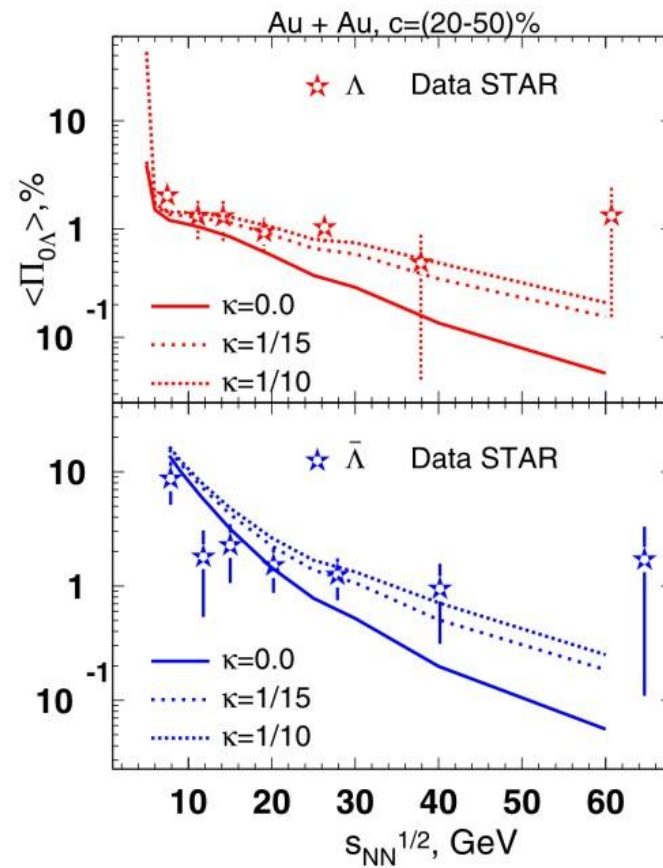
- LQCD suppression by collective effects supported



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 $(+, \text{anti } 0)$ K^* mesons with two sea quarks – small corrections
- Anti Λ – more numerous $(-, 0)$ K^* mesons with single (sea) strange antiquark
- Dominance of single spin projection of K^* - also tensor polarisation (in HIC –Bratkovskaya, Toneev, OT' 95)

Λ vs Anti Λ





Small systems

- “Collective” effects in pp (ridge)
- HIC description via Regge(Kaidalov)
- Recently: flows from Colour Glass Condensate (Maor et al), Wigner function (Hatta et al.)
- Possible solution: “duality” between statistical/hydro and dynamical description



Polarisation and small systems

- Decrease of polarisation with energy was considered natural 50 years ago!
- Pomeron dominance at high energy – no interference - no SSA
- Duality between Regge cuts and chemical potential (both are non-vacuum effects)?!



Summary

- Two faces of nucleon spin structure
- GPDs – total angular momenta
- Gravitational FFs – relation to (Extended) Equivalence Principle
- Quark and Gluon Spins – involve Axial anomaly
- Axial Anomaly in Heavy-Ion Collisions – polarisation related to vorticity
- Interplay of confinement and turbulence problems?!

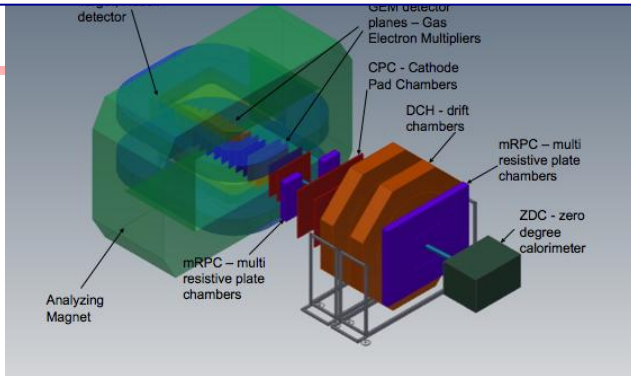


Main targets of “NICA Complex”:

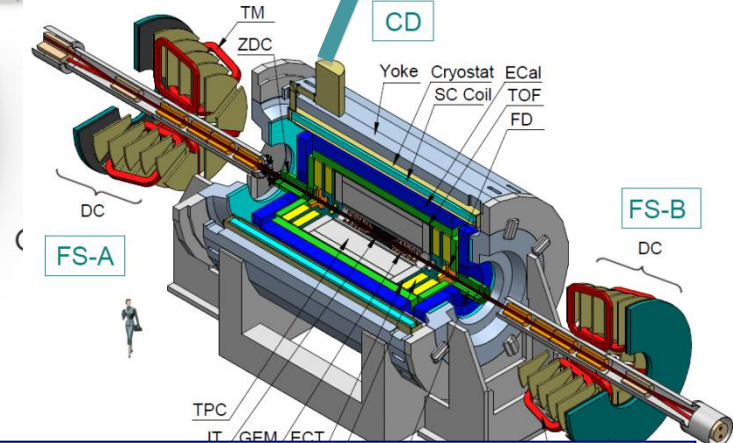
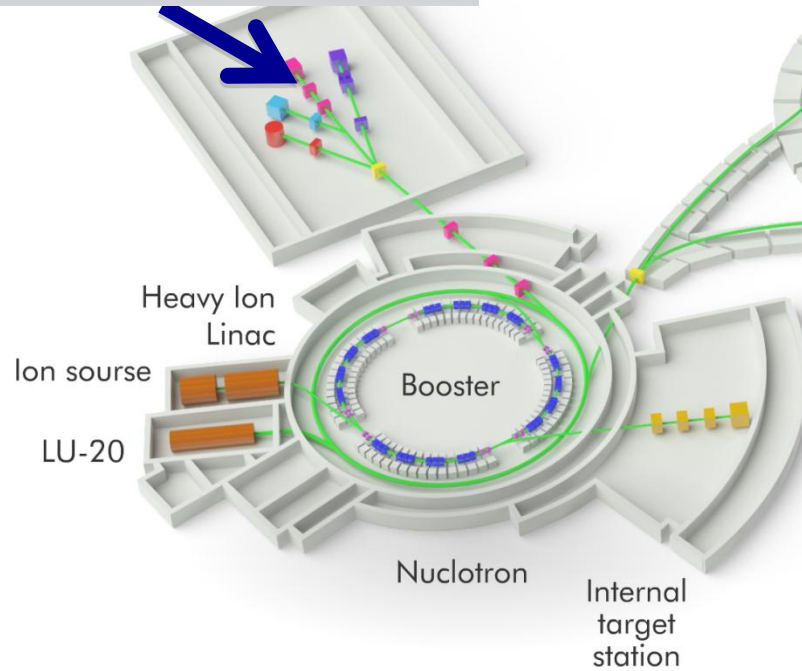
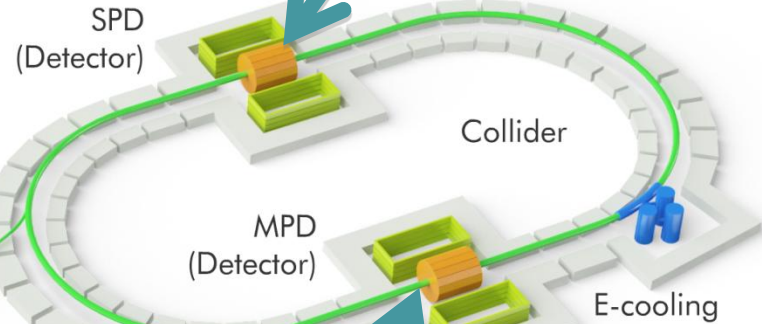
- **study of hot and dense baryonic matter**
- investigation of nucleon spin structure, polarization phenomena
- development of accelerator facility for HEP @ JINR providing intensive beams of relativistic ions from p to Au polarized protons and deuterons with energy up to $\sqrt{s} = 11 \text{ GeV}$ (Au^{79+} , $L \sim 10^{-2} \text{ cm}$)
 $\sqrt{s} = 27 \text{ GeV}$ (p , $L \sim 10^{-2} \text{ cm}$)

NICA Complex

Baryonic Matter at Nuclotron (BM@N)



SPD (Spin Physics Detector)

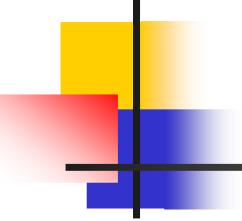


MultiPurpose Detector (MPD)



Thank you very much for
attention!

Welcome to Dubna!



- **BACKUP SLIDES**



Experimental test of PNEP

- Reinterpretation of the data on G(EDM) search

PHYSICAL REVIEW
LETTERS

VOLUME 68

13 JANUARY 1992

NUMBER 2

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

B. J. Venema, P. K. Majumder, S. K. Lamoreaux, B. R. Heckel, and E. N. Fortson

Physics Department, FM-15, University of Washington, Seattle, Washington 98195
(Received 25 September 1991)

- If (CP-odd!) $G_{EDM}=0 \rightarrow$ constraint for AGM (Silenko, OT'07) from Earth rotation – was considered as obvious (but it is just EP!) background

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

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



Manifestation of equivalence principle (cf with EM)

- Classical and quantum rotators rotate with the same frequency (EM: spin $\frac{1}{2}$ – twice faster); Dirac eq. analysis (Obukhov, Silenko, OT) – for strong fields
- 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

Torsion – acts only on spin

Dirac eq+FW transformation-Obukhov,Silenko,OT

■ Hermitian Dirac Hamiltonian

$$e_i^{\hat{0}} = V \delta_i^0, \quad e_i^{\hat{a}} = W^{\hat{a}}_b (\delta_i^b - c K^b \delta_i^0)$$

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

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

$$\mathcal{F}^b_a = V W^b_{\hat{a}}, \quad \Upsilon = V \epsilon^{\hat{a}\hat{b}\hat{c}} \Gamma_{\hat{a}\hat{b}\hat{c}}, \quad \Xi^a = \frac{V}{c} \epsilon^{\hat{a}\hat{b}\hat{c}} (\Gamma_{\hat{0}\hat{b}\hat{c}} + \Gamma_{\hat{b}\hat{c}\hat{0}} + \Gamma_{\hat{c}\hat{0}\hat{b}})$$

■ Spin-torsion coupling

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

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

■ FW – semiclassical limit - precession

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



Experimental bounds for torsion

- Magnetic field+rotation+torsion

$$H = -g_N \frac{\mu_N}{\hbar} \mathbf{B} \cdot \mathbf{s} - \boldsymbol{\omega} \cdot \mathbf{s} - \frac{c}{2} \tilde{\mathbf{T}} \cdot \mathbf{s},$$

- Same '92 EDM experiment

$$\frac{\hbar c}{4} |\tilde{\mathbf{T}}| \cdot |\cos \Theta| < 2.2 \times 10^{-21} \text{ eV}, \quad |\tilde{\mathbf{T}}| \cdot |\cos \Theta| < 4.3 \times 10^{-14} \text{ m}^{-1}$$

- New(based on Gemmel et al '10)

$$\frac{\hbar c}{2} |\tilde{\mathbf{T}}| \cdot |(1 - \mathcal{G}) \cos \Theta| < 4.1 \times 10^{-22} \text{ eV}, \quad |\tilde{\mathbf{T}}| \cdot |\cos \Theta| < 2.4 \times 10^{-15} \text{ m}^{-1},$$
$$\mathcal{G} = g_{He}/g_{Xe}$$

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!
- SR: $\sum \int dx T(x, x) = 0$ (but relation of gluon Sivers to twist 3 still not found – prediction!)

$$\sum \int \int dx_1 dx_2 \frac{T(x_1, x_2)}{x_1 - x_2 + i\varepsilon} = 0$$
- 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

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

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

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

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

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:

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

