17-ое Рабочее совещание по спиновой физике при высоких энергиях (DSPIN-17) 11-15.09.2017

О.В. Теряев


XVII Workshop on High Energy Spin Physics
DSPIN - 17
Dubna, Russia, September 11 - 15, 2017
XVII WORKSHOP ON HIGH ENERGY SPIN PHYSICS
DUBNA
2017
Hosted by
Joint Institute for Nuclear Research,
Bogoliubov Laboratory
of Theoretical Physics,
http://theor.jinr.ru/~spin/2017/
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Deadline for registration
and abstract is July 1, 2017
Topics and scope
Recent experimental data on spin physics
The nucleon spin structure and GPD's
Spin physics and QCD
Spin physics in Standard Model and beyond
T-odd spin effects
Polarization and heavy ion physics
Spin in gravity and astrophysics
The future spin physics facilities
Spin physics at NICA
Polarimeters for high energy polarized beams
Acceleration and storage of polarized beams
The new polarization technology
Related subjects
Spintronics of nanostructures
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M. Finger (co-chair) Prague
A. Sandacz (co-chair) Warsaw
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SPIN at High Energies: Workshops in Dubna

First – 1981 under the Chair of Lev Iosifovich Lapidus (1927-1986), prominent scientist who laid down the fundamentals of high energy spin physics

Biannual workshops (in odd years, between Spin Symposia) in Protvino and (1997, 2001, 2003,2005,2007,2009,2011,2013,2015,2017) Dubna

Участники

- 108 человек из стран, которые они представляли: Россия-22, США-3, Белоруссия-3, Польша-2, Германия-4, Чехия-4, Италия-4, Словакия-2, Армения, Болгария, Эстония, Великобритания, Нидерланды - по одному человеку. Как всегда, участвовало много (50) физиков из ОИЯИ.

- recent experimental data on spin physics
- the nucleon spin structure and GPD's
- spin physics and QCD
- spin physics in the Standard Model and beyond
- T-odd spin effects
- polarization and heavy ion physics
- spin in gravity and astrophysics
- the future spin physics facilities
- spin physics at NICA
- polarimeters for high energy polarized beams
- acceleration and storage of polarized beams
- the new polarization technology
- related subjects
- spintronics of nanostructures

Тематика

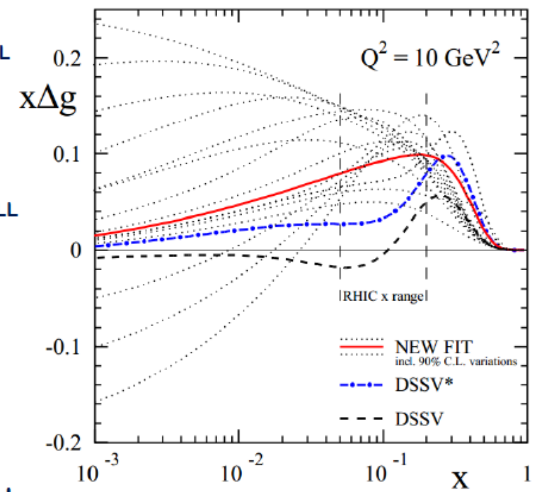
- Доклады коллабораций: STAR (Токарев), PHENIX(Barish), JLab(biselli, Punjabi), HERMES (Marukyan), LHCb Артамонов), CMS (Горбунов), COMPASS
- Теория: КХД+модели, СМ, расширения, Гравитация + астрофизика, тяжелые ионы
- Специальная сессия по проекту SPD

Поляризация глюонов

Impact on $\Delta g(x)$

- Published Include in Global fittings
  - 2006 200GeV and 62.4GeV π^0 A_{LL}
  - 2009 200GeV π^0 A_{LL}
- Published, Not yet include in Global fittings
  - 2012, 2013 510GeV Central π^0 A_{LL}
  - 2013 510GeV Central $\pi^\pm$ A_{LL}
  - 2013 510GeV Forward J/ψ A_{LL}
- Ongoing
  - 2013 510GeV Central direct photon A_{LL}
  - 2013 Jet A_{LL} at central rapidity
  - 2009, 2011 di-π^0 A_{LL}
  - 2011, 2013 500, 510GeV Forward π^0 A_{LL}

DSSV14: 10.1103/PhysRevLett.113.012001

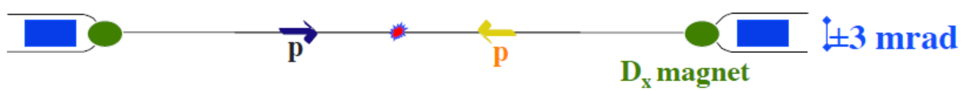


PHENIX K. Barish

Fracture??!

Very forward A_N (p_T<0.1GeV/c)

Very forward neutron production in pp collision



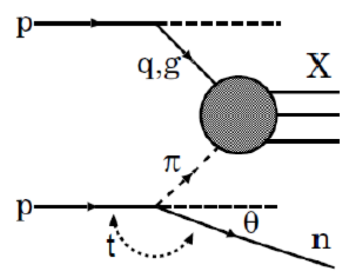
pQCD not applicable (p_T < 0.1 GeV/c)

Mechanism, Regge theory?

- » Pion exchange?
- » Pomeron exchange & decay?
- » Other reggeons?

Asymmetries

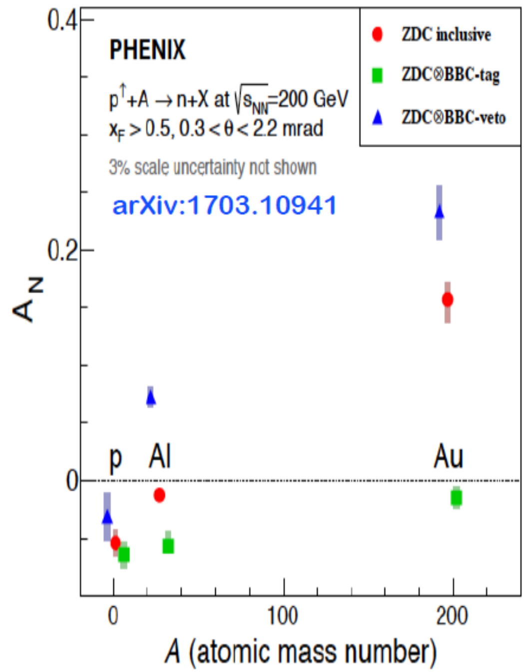
- » Initial surprise, used for polarimetry at RHIC
- » Can arise from interference between a spin flip and non-flip with different phases, e.g. π-a_1
- » A dependence?



PHENIX K. Barish

А-зависимость асимметрии нейтронов

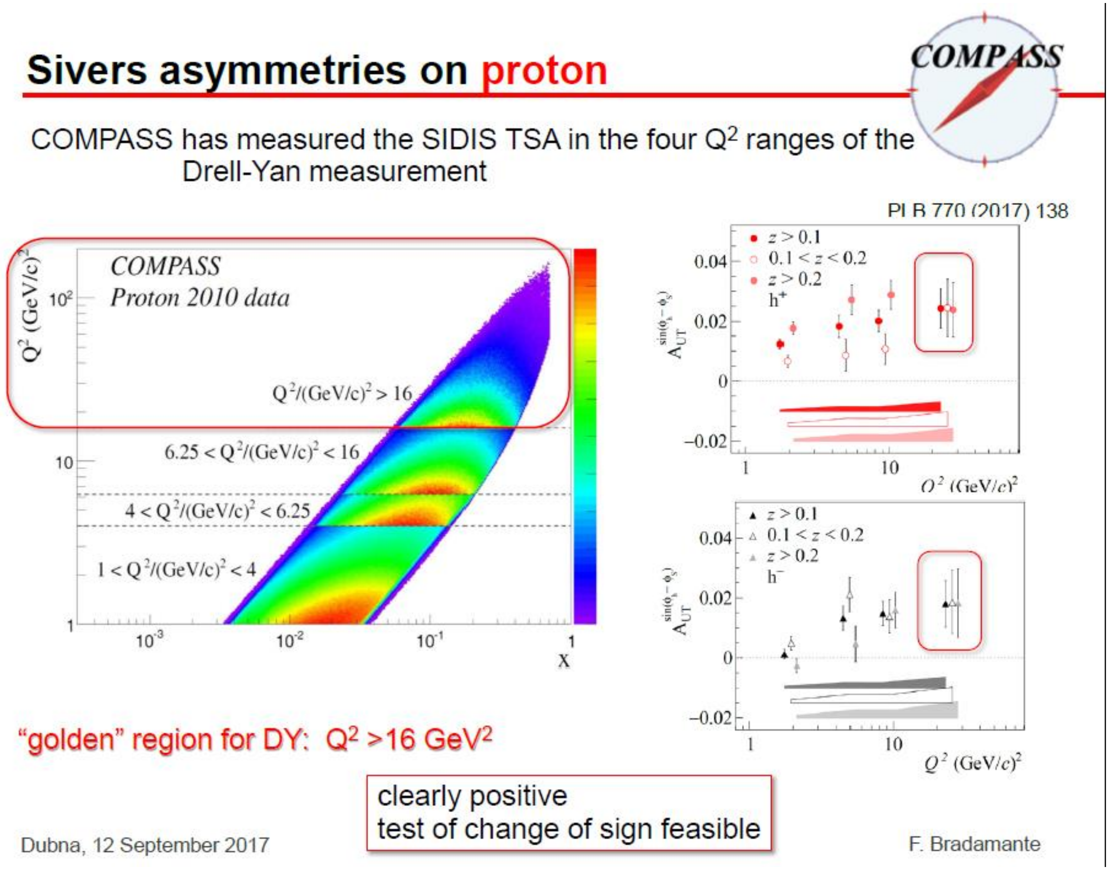
Very Forward Neutron Production pp



- Unexpectedly large A dependence in neutron asymmetries
- Sign change seen
- Possibility of ultra-peripheral collisions(UPC) effect, enhanced by Z^2 for nucleii
- (anti-)Correlations with main Collision detector system enhance/reduce UPC contribution

PHENIX K. Barish

Первые указания на смену знака функции Сиверса



Связь с твистом 3 (Аникин)

Main results

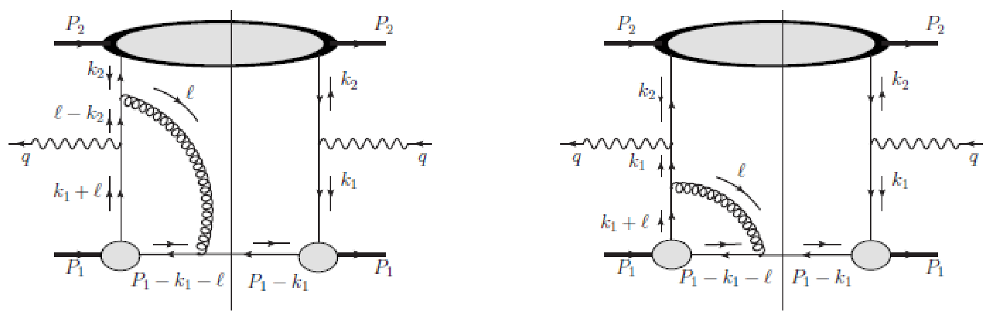
- Based on the use of Contour Gauge and Collinear Factorization, we propose a new set of SSA which can be measured in Polarized DY process by SPD@NICA.
- All of discussed SSA exists owing to the Gluon Poles manifesting in the $twist-3$ or $(twist-2 \otimes twist-3)$ parton distributions related to the transverse-polarized DY process.

- I.V.A. and O.V. Teryaev
  PLB690, 519 (2010); EPJC75, 184 (2015); PLB751, 495 (2015)
- I.V.A., L. Szymanowski, O.V. Teryaev and N. Volchanskiy
  PRD95, 111501 (2017)
- I.V.A., I.O. Cherednikov and O.V. Teryaev
  Phys.Rev. D95, 034032 (2017)

SSA under our consideration is given by

$$\mathcal{A} = \frac{d\sigma^{(\uparrow)} - d\sigma^{(\downarrow)}}{d\sigma^{(\uparrow)} + d\sigma^{(\downarrow)}}, \qquad \frac{d\sigma^{(\uparrow\downarrow)}}{d^4 q d\Omega} = \frac{\alpha_{em}^2}{2jq^4} \mathcal{L}_{\mu\nu} H_{\mu\nu} \, ,$$

where $\mathcal{L}_{\mu\nu}$ is a lepton tensor, and $H_{\mu\nu}$ – the QED gauge invariant hadron tensor (direct channel minus mirror channel; $x_F \to 1$).



- The "standard" diagram (*a*) and the "non-standard" diagram (b) differ by the hard parts. (Factorization links: IVA, O.V.Teryaev '09.)

UNIVERSITÀ
DEGLI STUDI DI TRIESTE

INFN
Istituto Nazionale di Fisica Nucleare

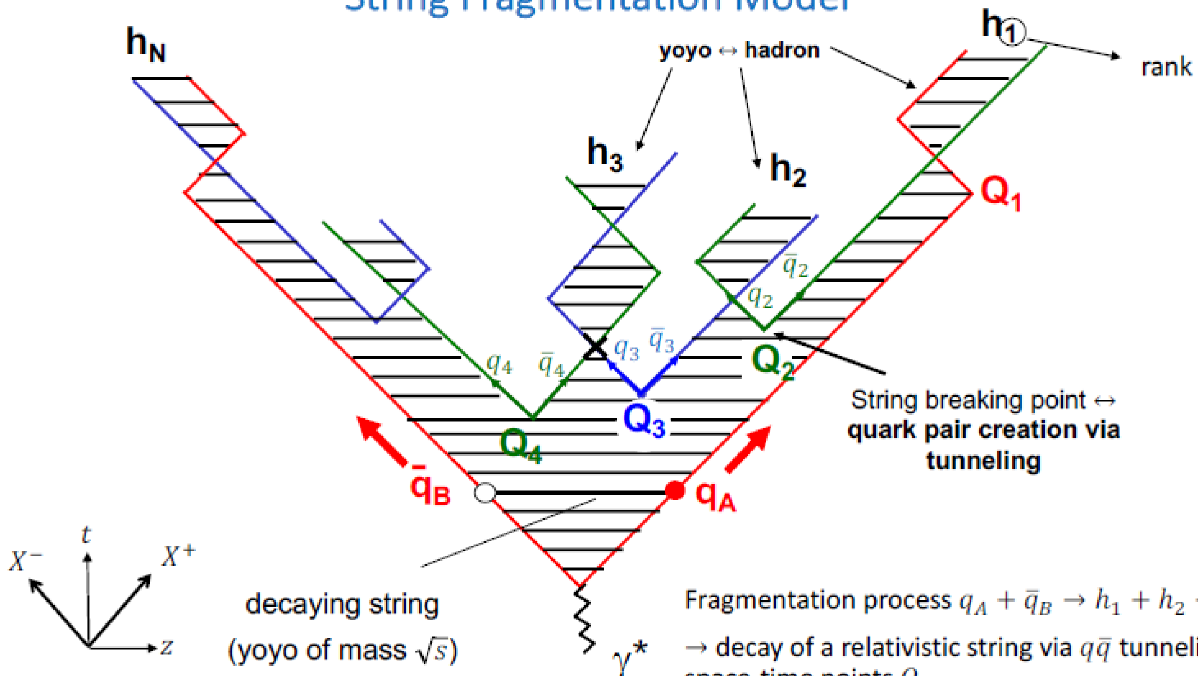
A Monte Carlo code for the fragmentation of polarized quarks

Albi Kerbizi

PhD @ University of Trieste, Trieste INFN Section

X. Artru, Z. Belghobsi, F. Bradamante, A. Martin

String Fragmentation Model



Fragmentation process $q_A + \bar{q}_B \to h_1 + h_2 + \cdots + h_N$

→ decay of a relativistic string via $q\bar{q}$ tunneling at the space-time points Q_i

→ confinement built in

Final expression for the polarized splitting distribution (pseudoscalar h)

Black → Symmetric Lund Model
~ Pythia

Blue → quark spin terms

String axis

$$F_{q',h,q}dZd^2\mathbf{k'}_T \propto \frac{dZ}{Z}d^2\mathbf{k'}_T(1-Z)^a e^{-b_L\frac{m_h^2}{Z}}\ e^{\frac{\mathbf{k}_T^2}{\frac{1}{b_T}+\frac{Z}{b_L}}}\ e^{-\left(\frac{b_L}{Z}+b_T\right)\left[\mathbf{k}'_T-\frac{b_L\mathbf{k}_T}{b_L+Zb_T}\right]^2}\ [|\mu|^2+\mathbf{k'}_T^2-2Im(\mu)\mathbf{S}_{int}\cdot\hat{\mathbf{z}}\times\mathbf{k}'_T]$$

New!

$-2Im(\mu)S_{int}k'_T\sin[\phi(S_{int})-\phi(k'_T)]$
~ "Collins effect" for trans. pol.

$$\mathbf{S}_{int}=Tr[\boldsymbol{\sigma}\hat{\rho}_{int}]$$

$$\hat{\rho}_{int}(q)\propto\hat{u}^{-\frac{1}{2}}(\mathbf{k}_T)\rho(q)\hat{u}^{\dagger-\frac{1}{2}}(\mathbf{k}_T)$$

The free parameters of the model are:

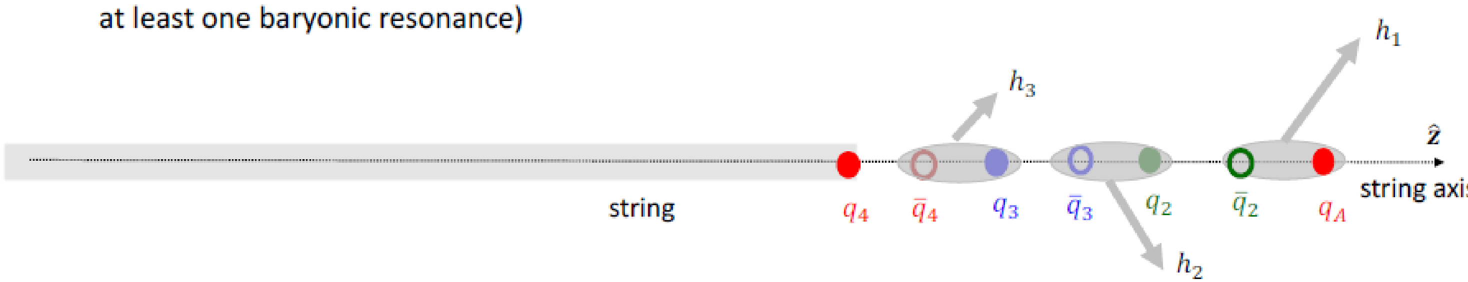
1. b_L: linked to the probability of having a string cutting point
2. b_T: order of magnitude of the $q\bar{q}$ transverse momenta in tunneling
3. a: suppression of large Z
4. μ: complex mass responsible for the Collins effect

The simulation procedure

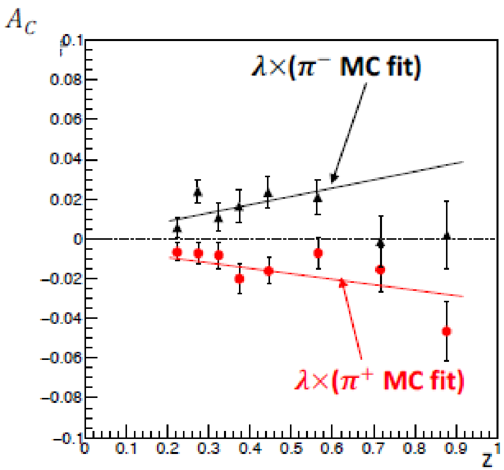
- For each event define initial quark $q_A \equiv q_1$: flavour $q_A = u, d, s$, energy, spin density matrix $\rho(q_A)$

1. Generate a $q_2\bar{q}_2$ pair and form the hadron $h_1(q_A\bar{q}_2)$
2. Construct the four-momentum of h_1 by drawing first Z_1 and then $\boldsymbol{p}_{1T}$ using $F_{q_1 h_1 q_A}$
3. Calculate the spin density matrix of q_2

- Iterate points 1-3 until the exit condition is reached (enough renamining c.m. energy to produce at least one baryonic resonance)



Comparison with COMPASS Collins asymmetry as function of z



Points -> Compass (proton)

- λ is a scale parameter estimated from COMPASS asymmetries
- $\lambda \sim \langle h_1^u / f_1^u \rangle = 0.055 \pm 0.010$
- The MC overestimates the π^- analysing power for large z
- At large z contributions from primary d quarks and ρ^0 decay should be important

Cut:

- $p_T > 0.1\ GeV$

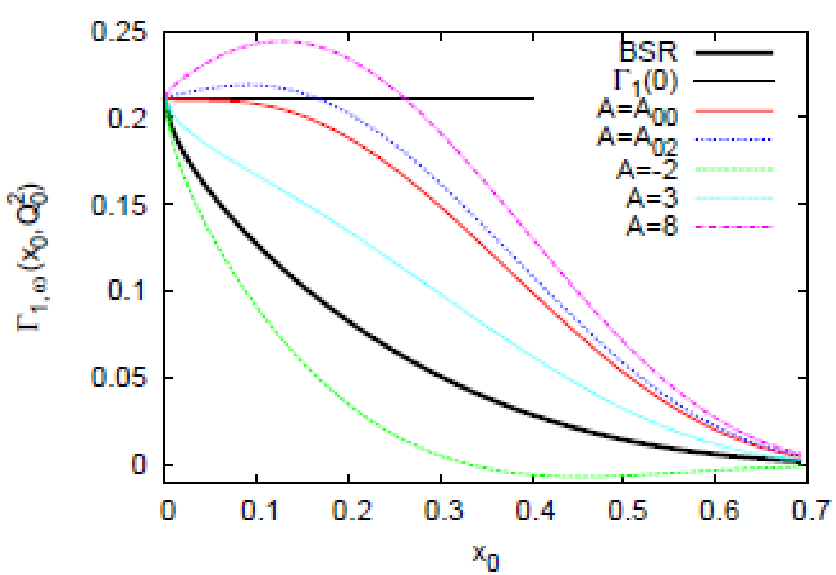
$\boldsymbol{\lambda = 0.055 \pm 0.010}$

gBSR - Introduction

We propose generalized Bjorken sum rule

$$g_1 \rightarrow g_{1,\omega} = (\omega * g_1)(x)$$

$$\int_0^1 g_{1,\omega}(x, Q^2)\, dx = \int_0^1 g_1(x, Q^2)\, dx \equiv \Gamma_1(0)$$



Truncated generalized BSR
$\Gamma_{1,\omega}(x_0, Q^2) = \int_{x_0}^1 g_{1,\omega}(x, Q^2)\, dx$

way to approach the total BSR limit $\Gamma_1(0)$ more quickly

Q^2 evolution is maintained

(Phys. Rev. D 96, 016015, 2017)

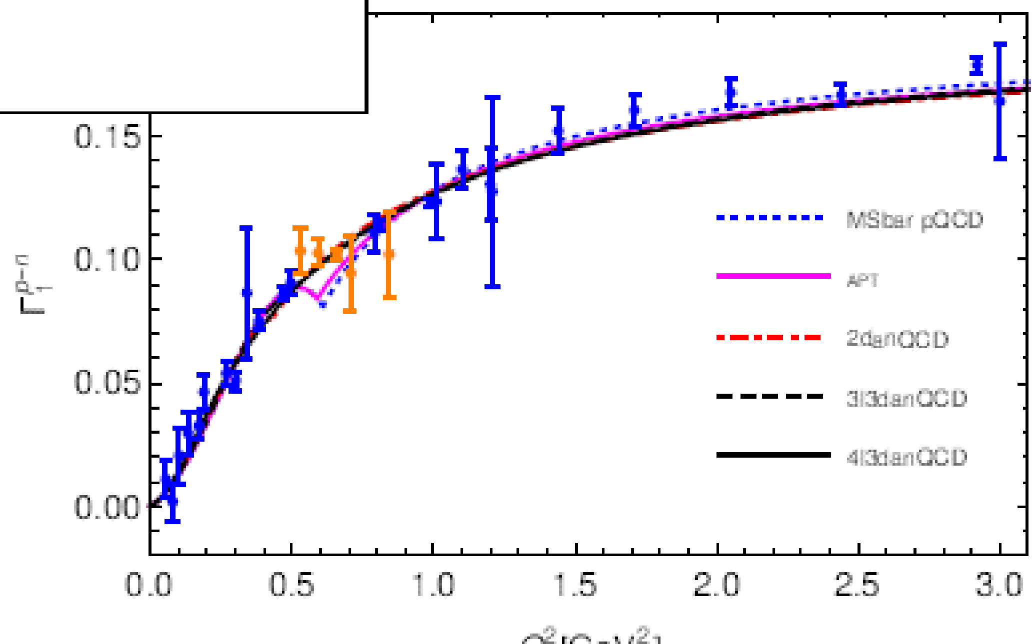
Cesar Ayala, Gorazd Cvetic, A.V. Kotikov and B.G. Shaikhatdenov

25th International Symposium on SPIN PHYSICS (SPIN2017), September 16, Dubna, 2016

Bjorken sum rule in QCD with analytic coupling

OUTLINE

1. Introduction
2. Results: Evaluation of the Bjorken sum rule in QCD with usual and analytic coupling constants.
   Based on the recent paper
   (C.Ayala, G. Cvetic, A.V. Kotikov, B.G. Shaikhatdenov, arXiv:1708.06284).
3. Conclusions



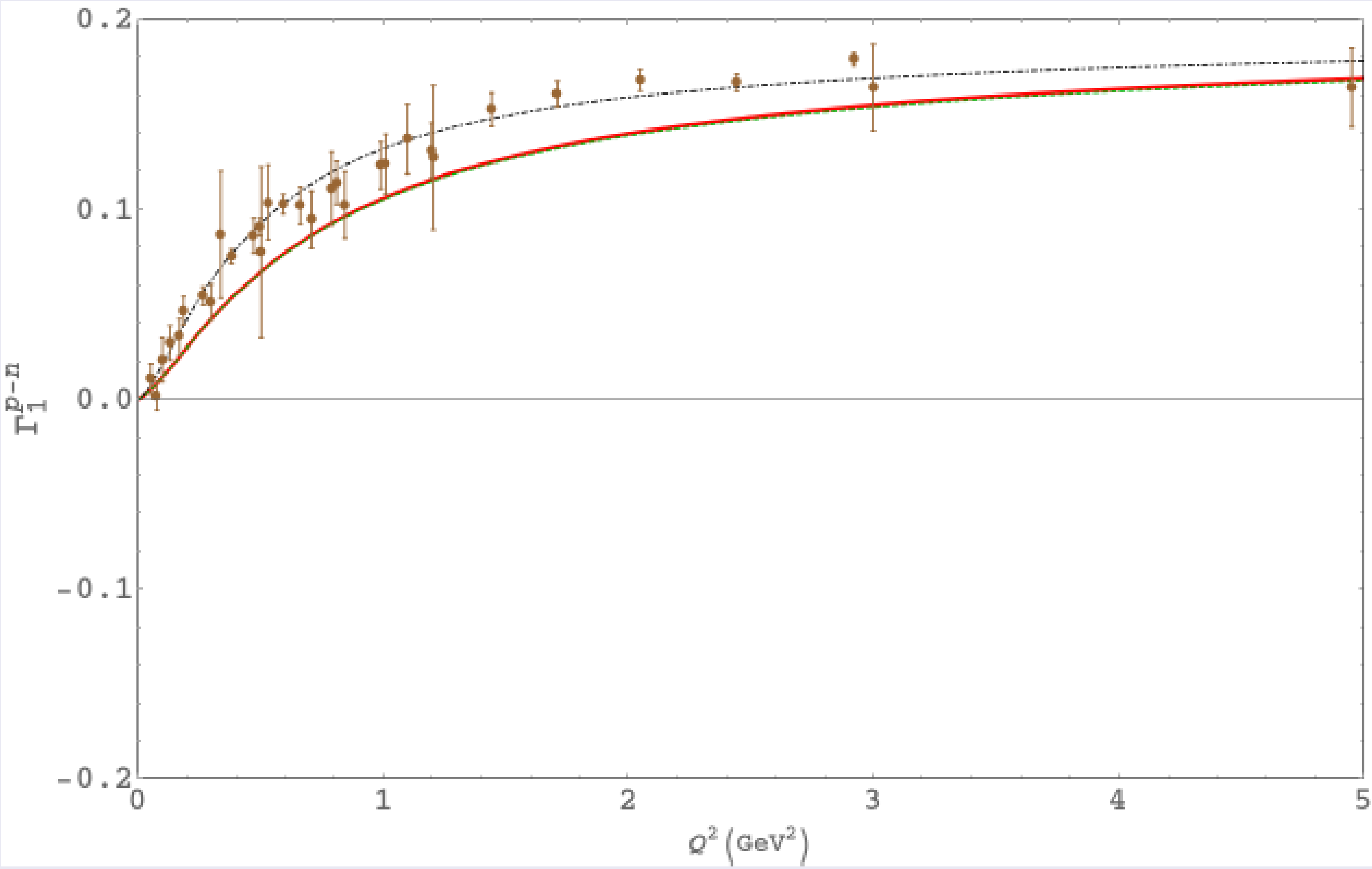


Figure: Fixed $\sigma = \rho_\Gamma$ fit. Solid red - LO, dashed green - NLO, large dashed blue - N^{2}LO, dotdashed black - N^{3}LO

Spin dynamics of fermion particles in gravitational and electromagnetic fields

Yuri N. Obukhov

Theoretical Physics Laboratory, IBRAE, Russian Academy of Sciences

Talk at "XVII Workshop on High Energy Spin Physics", DSPIN17, 11-15 September 2017

Based on joint results with O. Teryaev and A. Silenko (JINR)

Experimental bounds on torsion

- To probe spacetime geometry: dynamics of spin

$$\frac{d\mathbf{\Pi}}{dt} = \frac{i}{\hbar}[\mathcal{H}_{FW}, \mathbf{\Pi}] = \mathbf{\Omega} \times \mathbf{\Pi}$$

- *Theory*: spin precession to probe torsion: Adamowicz (1975), Rumpf (1980), Audretsch (1981), Lämmerzahl (1997); review W.T.Ni, Rep.Prog.Phys. 73 (2010) 056901
- *Experiment*: effect of Earth's gravity on nuclear spins Hg
- Spin Hamiltonian (torsion $\check{T}^\alpha = \frac{1}{2}\eta^{\mu\nu\lambda\alpha}T_{\mu\nu\lambda}$, $\check{\boldsymbol{T}} = \{\check{T}^a\}$)

$$\mathcal{H}_{FW} = -g_N\mu_N \boldsymbol{B}\cdot\mathbf{\Pi} - \frac{\hbar}{2}\boldsymbol{\omega}\cdot\mathbf{\Sigma} - \frac{\hbar c}{4}\check{\boldsymbol{T}}\cdot\mathbf{\Sigma}.$$

- B.J. Venema et al, Phys. Rev. Lett. **68** (1992) 135

Limits on torsion from Zeeman energy levels measurements

- $$|\check{\boldsymbol{T}}| < 4.3 \times 10^{-14}\mathrm{m}^{-1}$$

- Recent: C. Gemmel et al, Phys. Rev. **D82** (2010) 111901

NEUTRINO SPIN OSCILLATIONS IN CURVED SPACE TIME UNDER THE INFLUENCE OF EXTERNAL FIELDS

Maxim Dvornikov
IZMIRAN, Russia
Tomsk State University, Russia

Radial propagation of UHE neutrinos

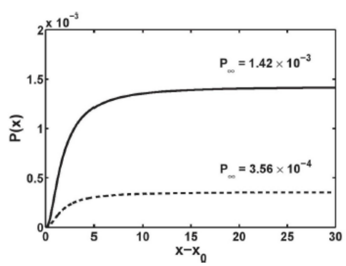
- Because of the symmetry reasons a purely radial motion in Kerr metric is possible only along the rotation axis of BH.
- If $U^0 >> 1$ (UHE neutrinos), the approximate treatment of spin oscillations is possible.
- We shall study the motion in the equatorial plane. A neutrino moves along the first axis in the vierbein frame.

$$i\frac{d\nu}{dx} = -\frac{x}{x-1} r_g (\boldsymbol{\sigma}\cdot\boldsymbol{\Omega})\nu, \quad \nu_{R,L} = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\ \pm 1\end{pmatrix},$$

$$\Omega_1 = \frac{G_F n_{eff}}{\sqrt{2}}\left[U_f^0\left(1-\frac{1}{x}\right) + r_g U_f^\phi \frac{\alpha}{x}\right],$$

$$\Omega_2 = -\mu B_0\left(1-\frac{1}{x}\right) + \frac{\alpha}{4r_g}\frac{2x-3}{x^{7/2}\sqrt{x-1}},$$

$$\Omega_3 = -\frac{G_F n_{eff}}{\sqrt{2}}\frac{\alpha}{x^2}\sqrt{1-\frac{1}{x}}\,U_f^0,$$



Gravity does not produce a sizable effect on neutrino spin oscillations

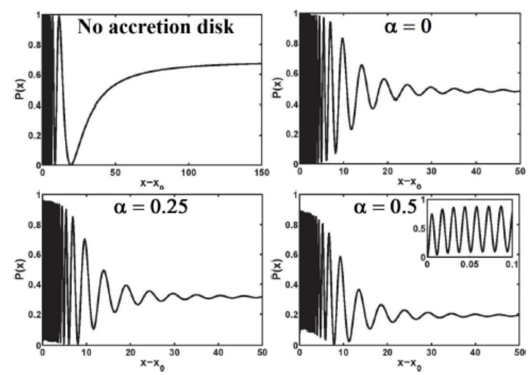
Interaction of UHE neutrinos with a relativistic accretion disk

Motivation

- Deficit of UHE ν-s was reported by IceCube (2012). In 2013 some UHE ν_e-s were observed by IceCube. Still there is a lack of signal for UHE $\nu_{\mu,\tau}$-s.
- Barranco et al. (2012) : neutrino spin oscillations in strong magnetic field ➔ the neutrino flux is reduced

Input data

- UHE ν-s emitted in GRB
- Dipole magnetic field: $B_0 = 10^{12}$ **G** / x^3
- Magnetic moment: $\mu = 10^{-12}\,\mu_B$ (Kuznetsov et al. 2009)
- Accretion disk density: $\rho = 10^2$ **g/cm³** (MacFadyen & Woosley 1999)



Result: Spin oscillations cannot explain the deficit of UHE ν-s. The neutrino interaction the a realistic relativistic accretion disk will suppress the transition probability even if magnetic field is strong.

Statistical analysis of 2D patterns and its application to astrometry and heavy-ion data

***P.Zavada* and K.Píška**
Institute of Physics, Prague

For a finite set $\{\varphi_1 ... \varphi_M\}; \qquad -\pi < \varphi_i < \pi$

we replace $\langle f(\varphi)\rangle \equiv \frac{1}{2\pi}\int_{-\pi}^{\pi} P(\varphi) f(\varphi)\, d\varphi$

by $\langle f(\varphi)\rangle_M \equiv \frac{1}{M}\sum_{k=1}^{M} f(\varphi_k)$

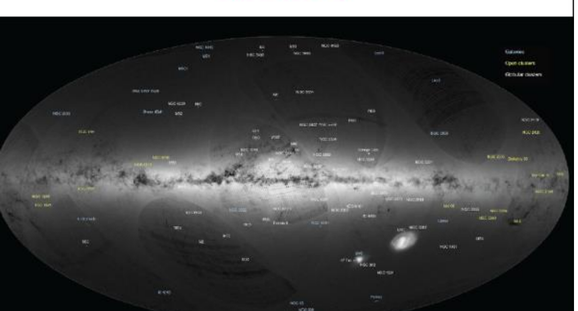
Then:

$$v_n(M) = \langle \cos[n(\varphi - \Psi_n)]\rangle_M ,$$
$$\tan(n\Psi_n^M) = \frac{\langle \sin(n\varphi)\rangle_M}{\langle \cos(n\varphi)\rangle_M}.$$

For $M \to \infty \quad \langle f(\varphi)\rangle_M \to \langle f(\varphi)\rangle, \qquad v_n(M) \to v_n, \qquad \Psi_n^M \to \Psi_n.$

The functions $\langle v_n^2(M)\rangle$ involve important information about patterns.

Gaia survey



I. Fourier analysis

Any angular distribution in 2D is defined by the set $\{v_n, \Psi_n\}$:

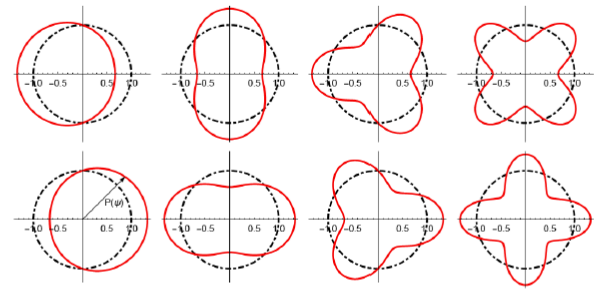
$$P(\varphi) = \frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right)$$

where

$$\langle f(\varphi)\rangle \equiv \frac{1}{2\pi}\int_{-\pi}^{\pi} P(\varphi) f(\varphi)\, d\varphi$$

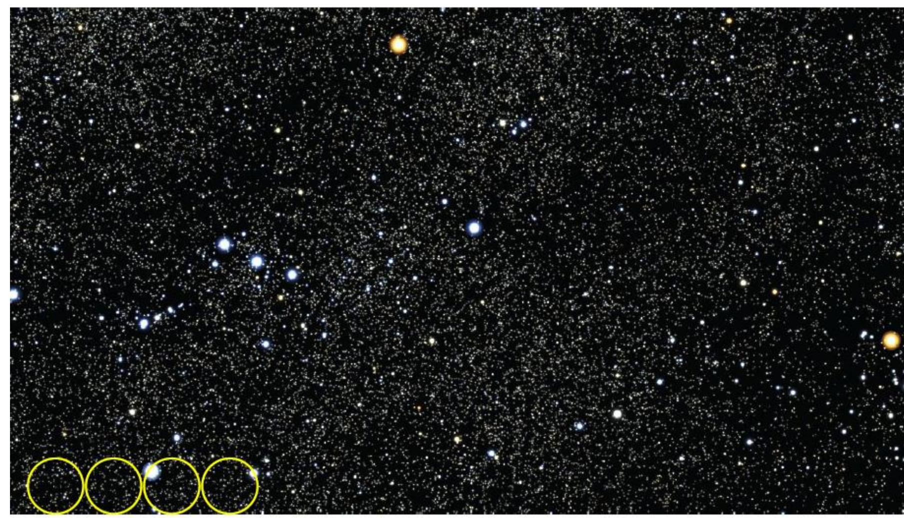
$$v_n = \langle \cos[n(\varphi - \Psi_n)]\rangle$$
$$\tan(n\Psi_n) = \frac{\langle \sin(n\varphi)\rangle}{\langle \cos(n\varphi)\rangle}.$$

We make decomposition:



$P(\psi) = 1 + 2v_n \cos(n\psi), \qquad \psi = \varphi - \Psi_n, \qquad n = 1, 2, 3, 4 \qquad v_n = \mp 1/3$

... in more detail



"events"

2D angular distances

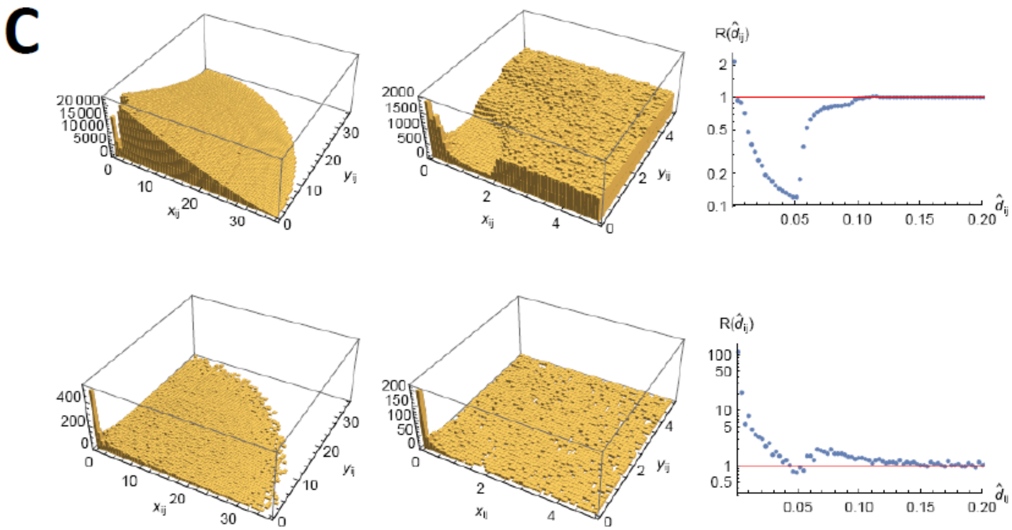


FIG. 10: Distributions of angular distances in the region C for $G \leq 15$ mag (lower panels) and for all G (upper panels). The left and central panels are 3D distributions, where the unit of x, y represent 1″. The right panels are the ratios of measured distribution of relative distances $\hat{d}_{ij}$ to the corresponding interpolation of random Monte-Carlo data.

Gaia DR1 – Catalogue validation

Gaia Collaboration, F. Arenou et al. Gaia Data Release 1. Catalogue validation. A\&A 599 (2017), pp. A50.

Gaia expert: ….*The scale you give is equivalent to 2 arcsec, below which level in the current Gaia catalogue we start to see increasingly incompleteness in the survey. This is due to the on-board detection and verification mechanism for Gaia. This is an issue we hope to be able to resolve at least partially down to about 0.1 arcsec from the examination of the accumulated data…*

1arcsec = 1as = 1″ = 4.848x10^{-6} rad

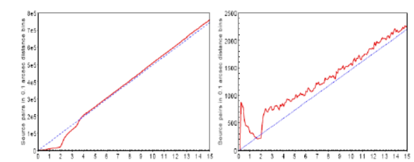


Fig. 17. Distribution of source-to-source distances in *Gaia* DR1 for a dense (l = 330°, b = −4°, ρ = 2°, *left*) and sparse (l = 260°, b = −60°, ρ = 15°, *right*) star field. The dashed lines show the relation corresponding to a random distribution of the sources.

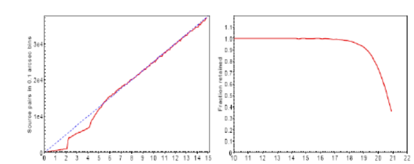


Fig. 18. Simulation of the distribution of source-to-source distances in a dense, random field (*left*) after applying selection criteria similar to *Gaia* DR1. The fraction retained is shown in the *right panel*. The field has a true source density of 500 000 stars per square degree, but only 322 000 remain after applying the selection criteria.

Polarization in heavy-ion collisions: Magnetic field and vorticity

DSPIN2017

September 13, 2017

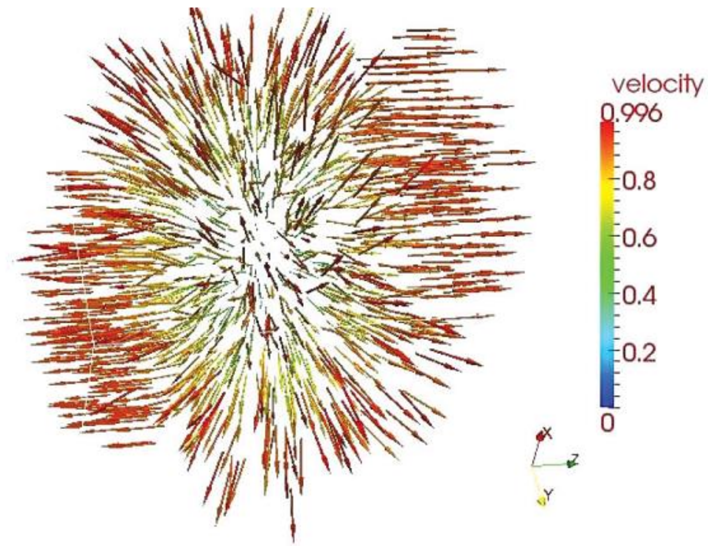
JINR

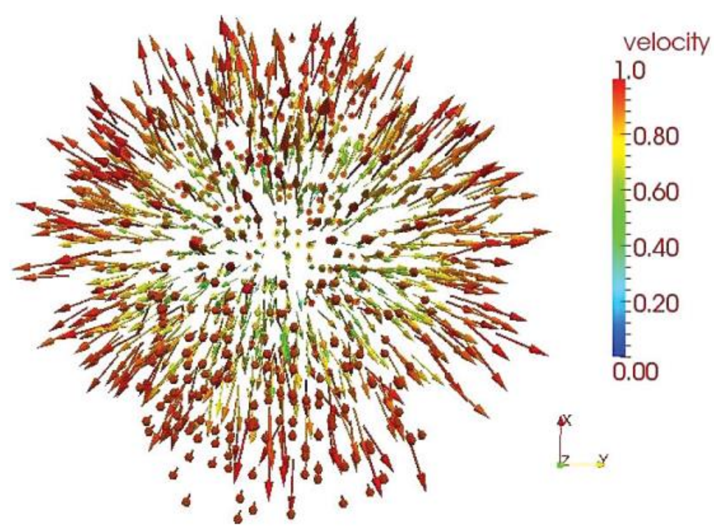
Phys.Rev. C88 (2013) 061901, C93 (2016) 031902,
C95 (2017) 011902 , ArXiv 1701.00923, 1705.0165 and work in progress

Oleg Teryaev(JINR)
in collaboration with
Mircea Baznat, Konstantin Gudima (IAP, Chisinau)
George Prokhorov, Alexander Sorin (JINR)
Valentin Zakharov (ITEP)

Distribution of velocity ("Small Bang")

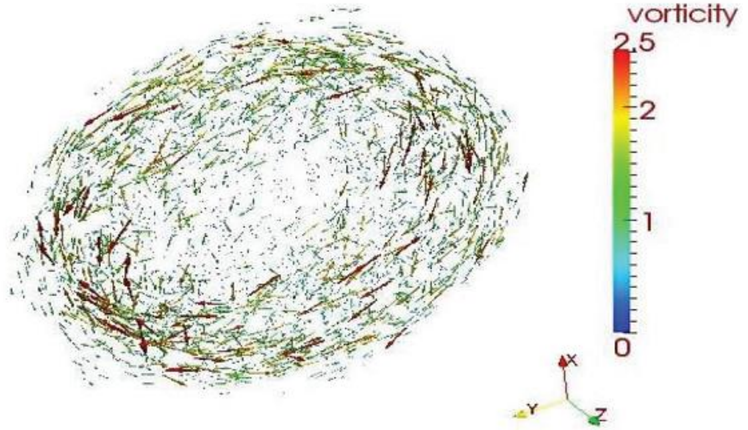
- 3D/2D projection
- z-beams direction
- x-impact paramater

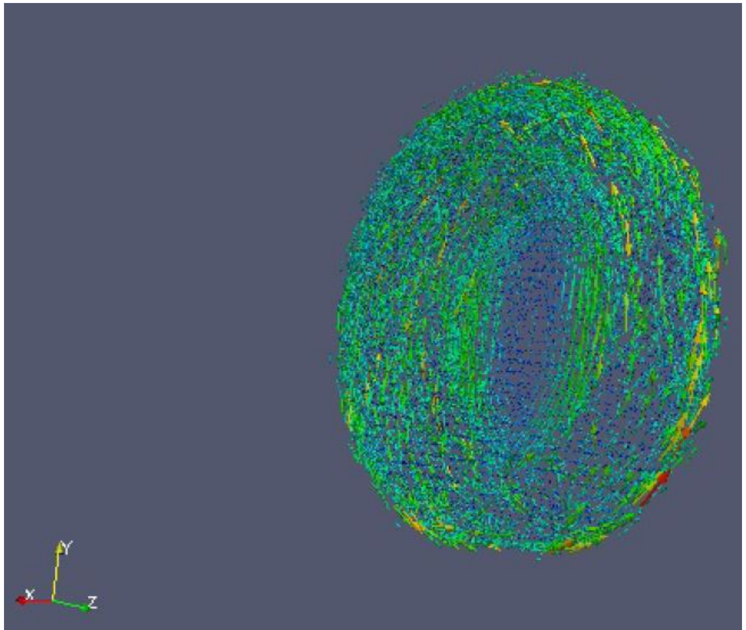


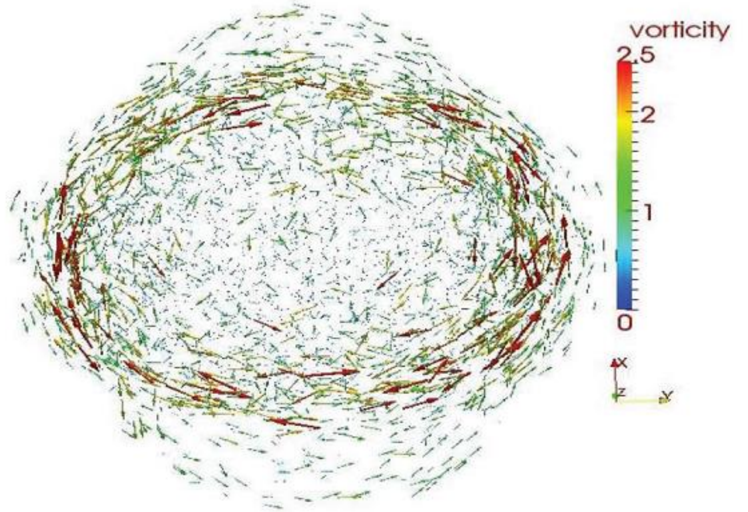


Distribution of vorticity ("small galaxies")

- Layer (on core - corona borderline) patterns





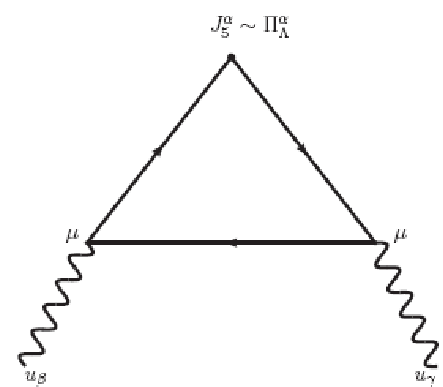


Anomalous mechanism – polarization similar to CM(V)E

- 4-Velocity is also a GAUGE FIELD (V.I. Zakharov et al): $\mu Q = \mu J_0 V^0$ -> $\mu J_\gamma V^\gamma$

$$e_j A_\alpha J^\alpha \Rightarrow \mu_j V_\alpha J^\alpha$$

- Triangle anomaly 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!



One might compare the prediction below with the right panel figures

STAR, **Nature 548 (2017) 62-65**

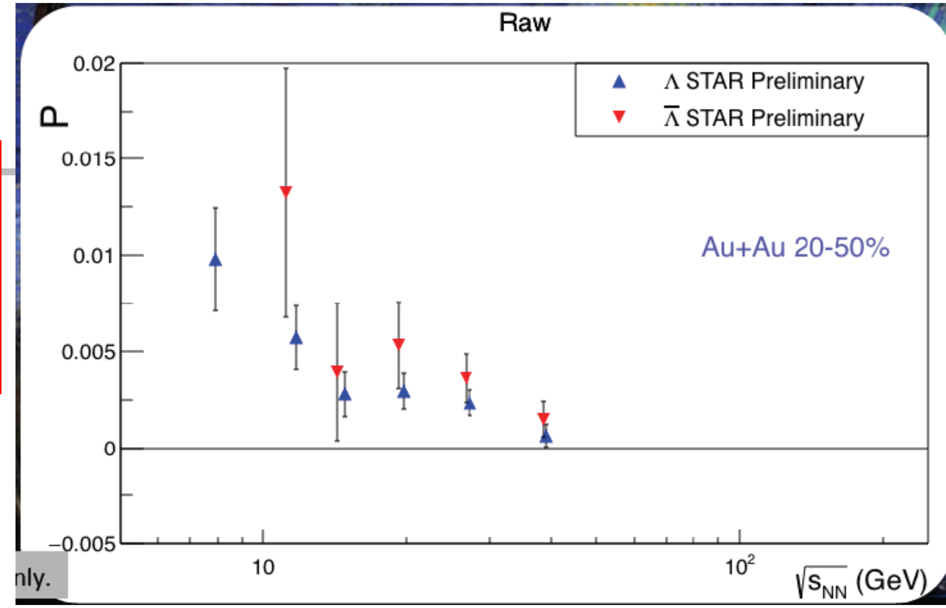
O. Rogachevsky, A. Sorin, O. Teryaev
Chiral vortaic effect and neutron asymmetries in heavy-ion collisions
PHYSICAL REVIEW C 82, 054910 (2010)

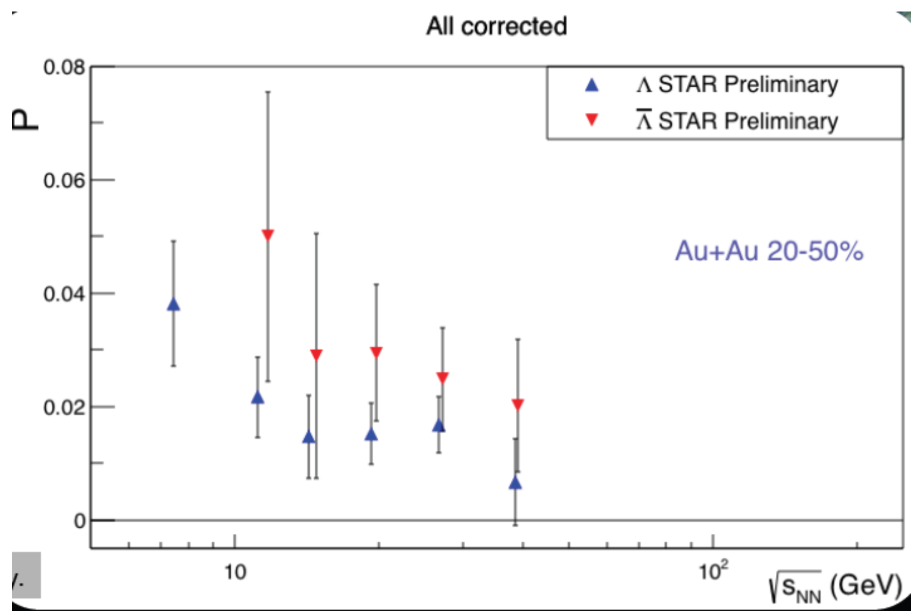
One would expect that polarization is proportional to the anomalously induced axial current [7]

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

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.

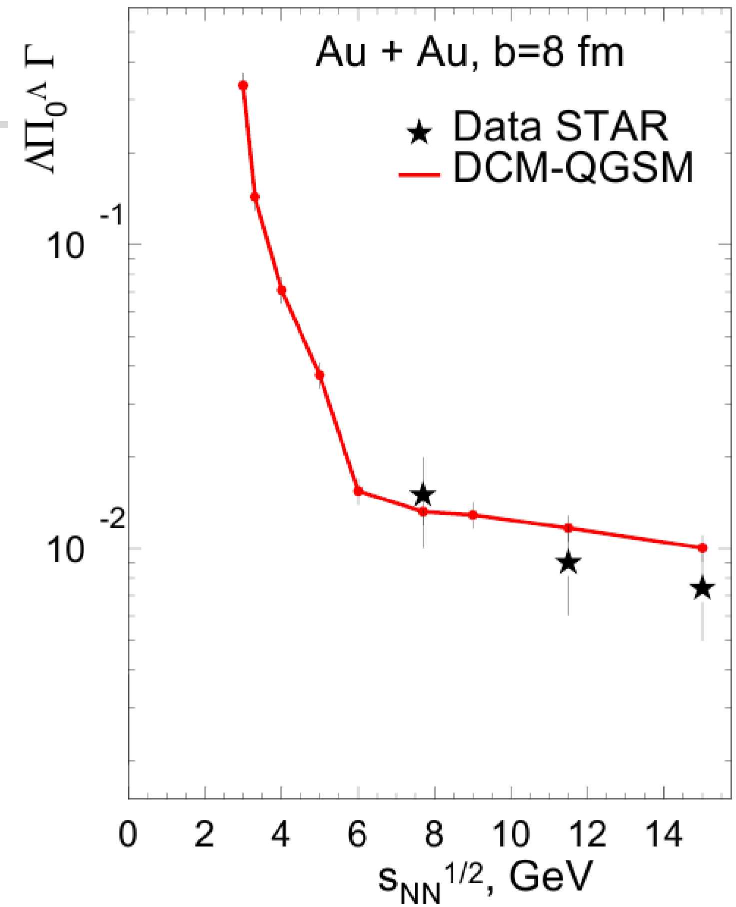
This option may be explored in the framework of the program of polarization studies at the NICA [17] performed at collision points as well as within the low-energy scan program at the RHIC.





Energy dependence

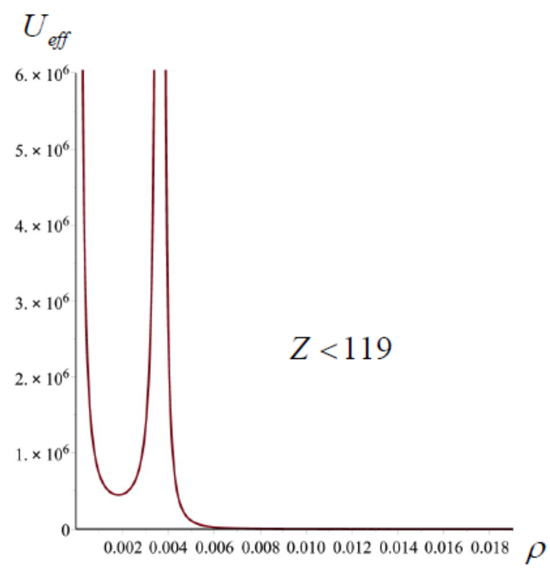
- Growth at low energy



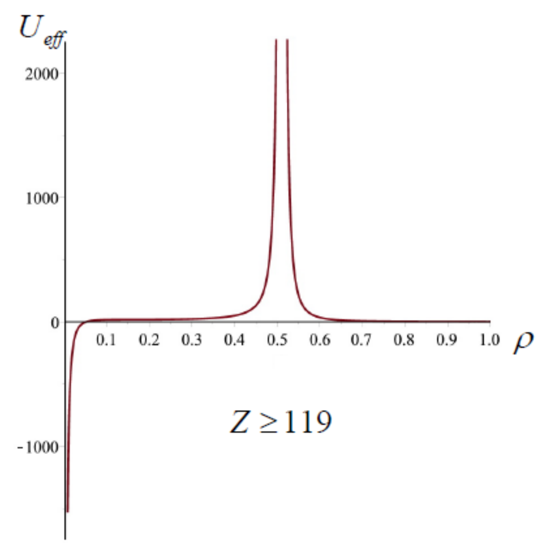
- Surprisingly close to STAR data!
- Structure – may be due to fluctuation for low particles number

Impenetrable barriers for positrons in neighbourhood of superheavy nuclei with Z>118

V.P.Neznamov



$Z < Z_{cr}$ $\left(Z = 1, \kappa = -1, \varepsilon = 1, \rho_{cl} = 0{,}00365\right)$



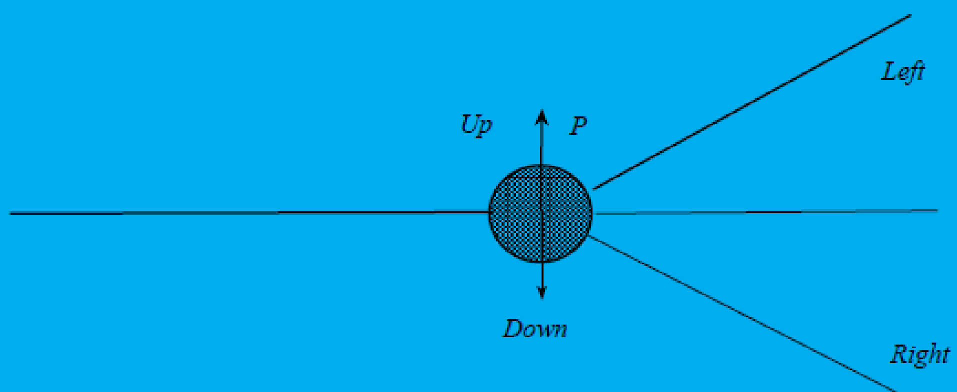
$Z > Z_{cr}$ $\left(Z = 140, \kappa = -1, \varepsilon = 1, \rho_{cl} = 0{,}51\right)$

Main Topics

- Polarization: from nucleons to ions
- Anomalous mechanism: 4-velocity as gauge field
- Chemical potential and Energy dependence
- Rotation in heavy-ion collisions: Vortical structures
- Polarization of hyperons
- Conslusions

Single Spin Asymmetries (vector polarization)

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

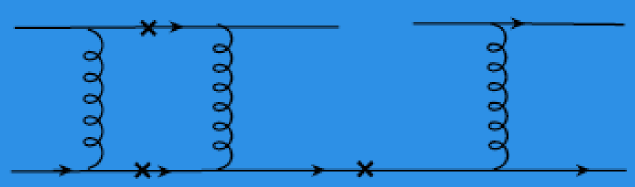
SSA

- Parity conservation – normal to scattering plane
- Interference – LS coupling
- T conservation – absorptive phases
- What is the counterpart for heavy ions? Suggestion: dissipation (cf. Montenegro, Tinti, Torrieri'17)
- QCD for hadrons – quark-gluon correlations (twist 3)~ T-odd TMD

Perturbative PHASES IN QCD

QCD factorization: where to borrow imaginary parts?

Simplest way: from short distances - loops in partonic subprocess. Quarks elastic scattering (like $q - e$ scattering in DIS):

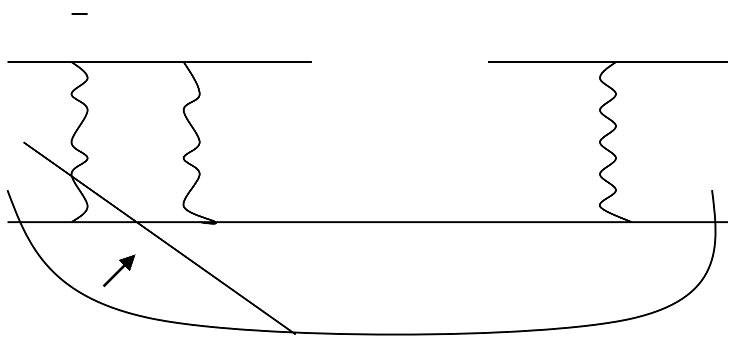


$$A \sim \frac{\alpha_S m p_T}{p_T^2 + m^2}$$

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

Short+ large overlap– twist 3

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



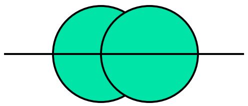
- New option for SSA: Instead of 1-loop twist 2 – Born twist 3 (quark-gluon correlator): Efremov, OT (85, Fermionic poles); Qiu, Sterman (91, GLUONIC poles (talk of I. Anikin) -> T-odd Sivers function)
- Further shift to large distances – T-odd fragmentation functions

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?

Magnetic field?

- Heavy-ion collisions – fast charged particles - largest ever magnetic field ($\sim m_\pi^2$)
- Magnetic moment -> polarization
- Field is typically increasing for large energies but polarization is observed by STAR at lower energies!

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: 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

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
- $\varpi = \mathrm{curl}\ v$
- 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

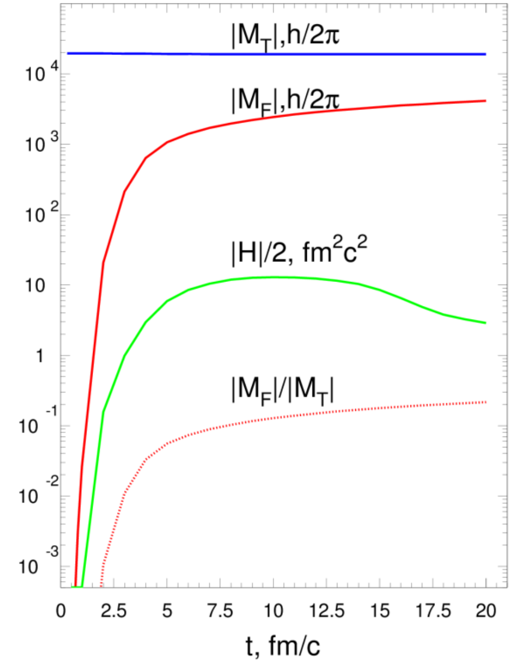
- Velocity

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

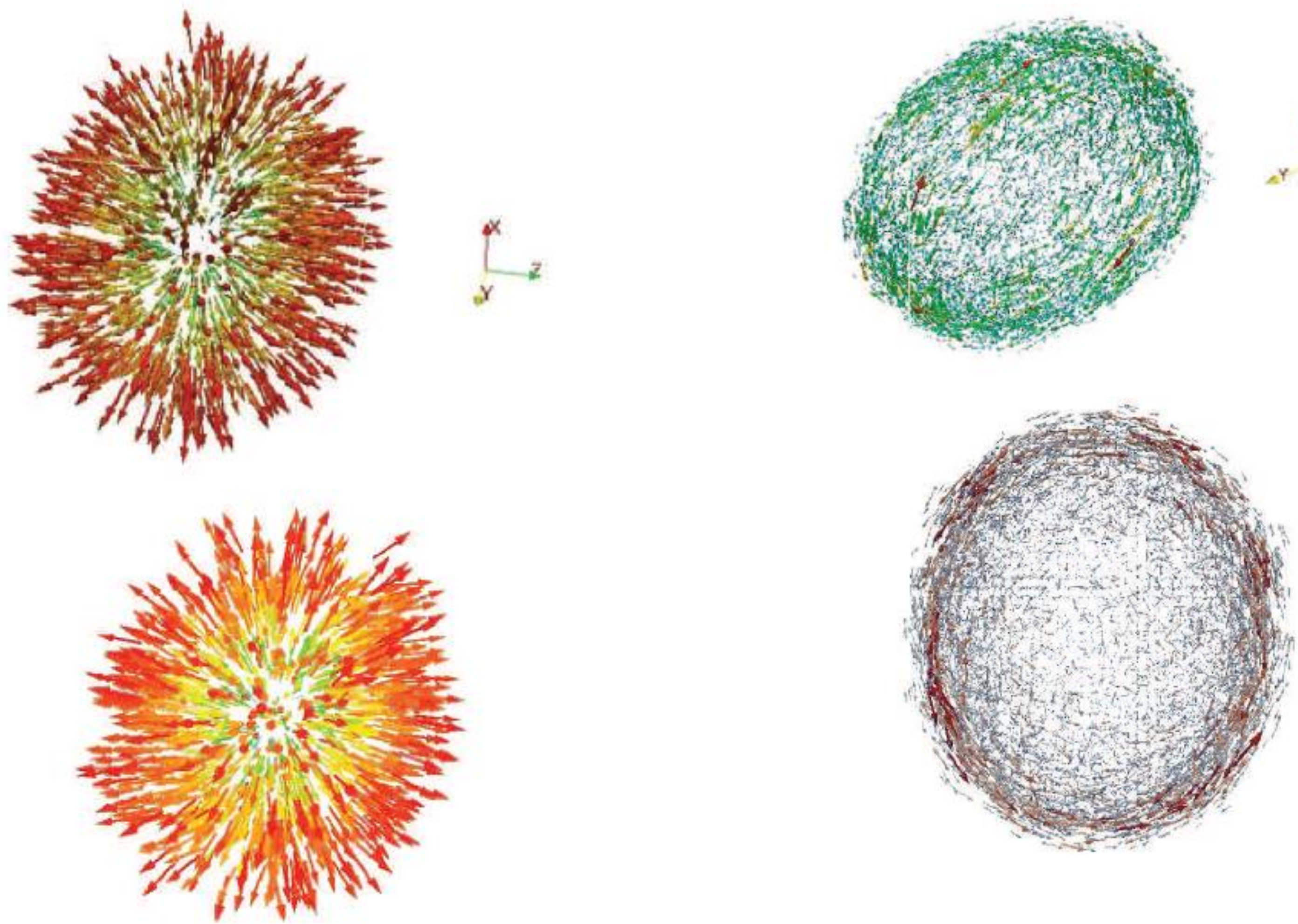
- Vorticity – from discrete partial derivatives

Angular momentum conservation and helicity

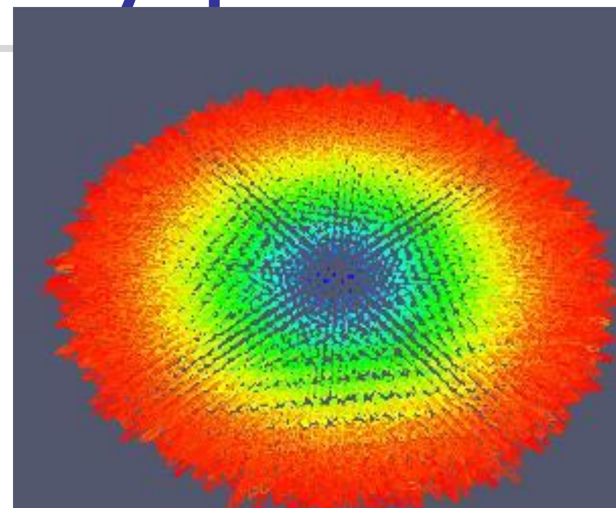
- Helicity vs orbital angular momentum (OAM) of fireball
- (~10% of total)
- Conservation of OAM with a good accuracy!



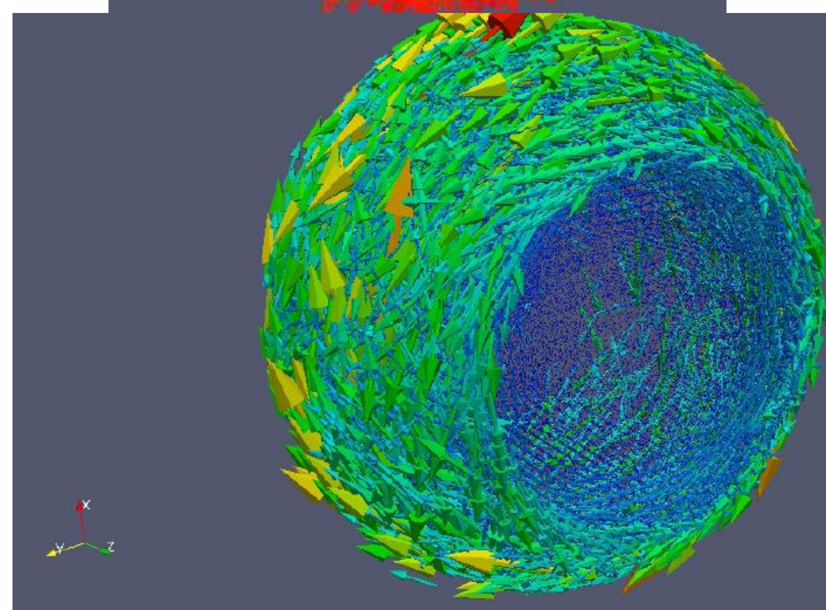
Structure of velocity and vorticity fields (NICA@JINR-5 GeV/c)



Velocity and vorticity patterns

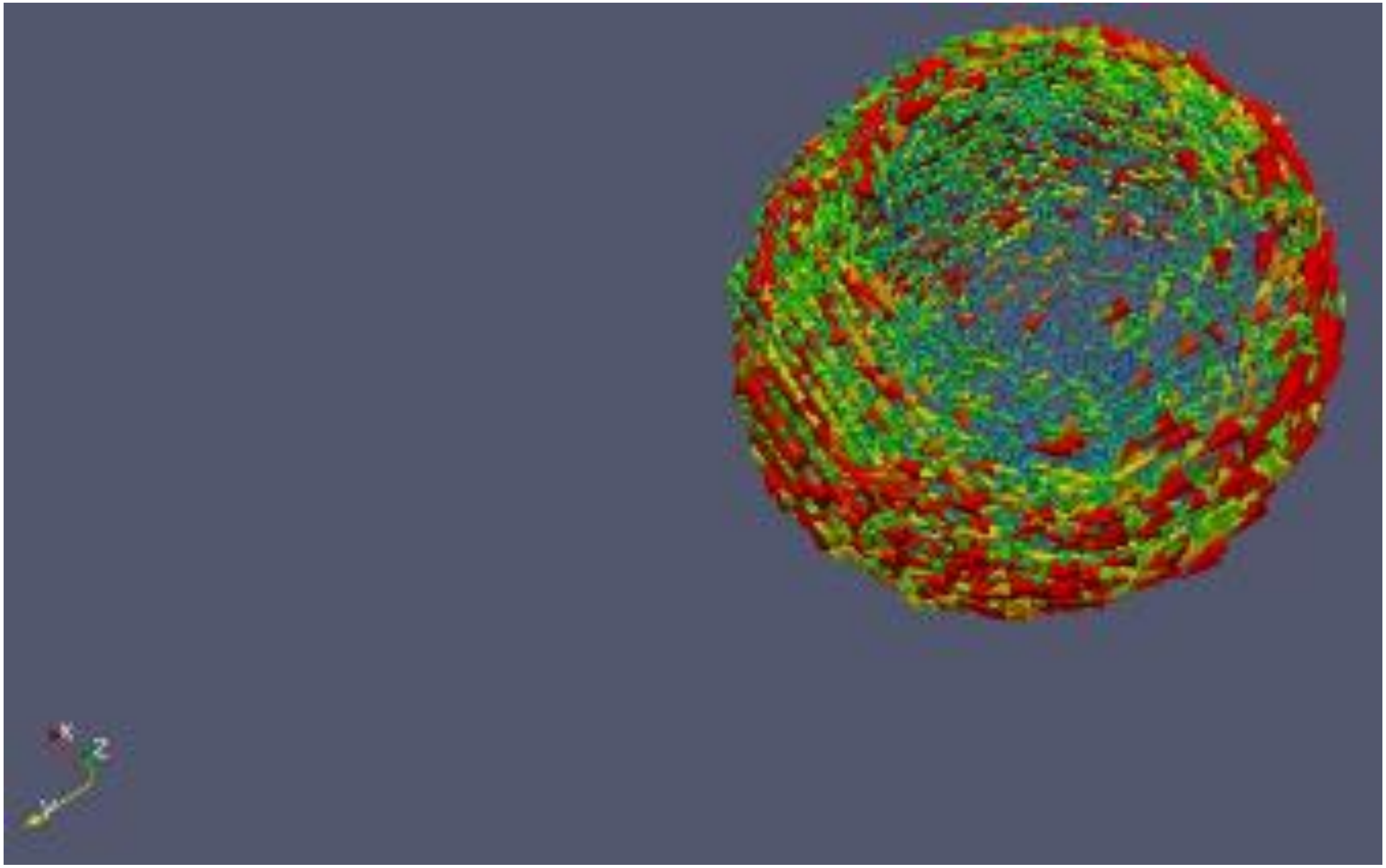


- Velocity

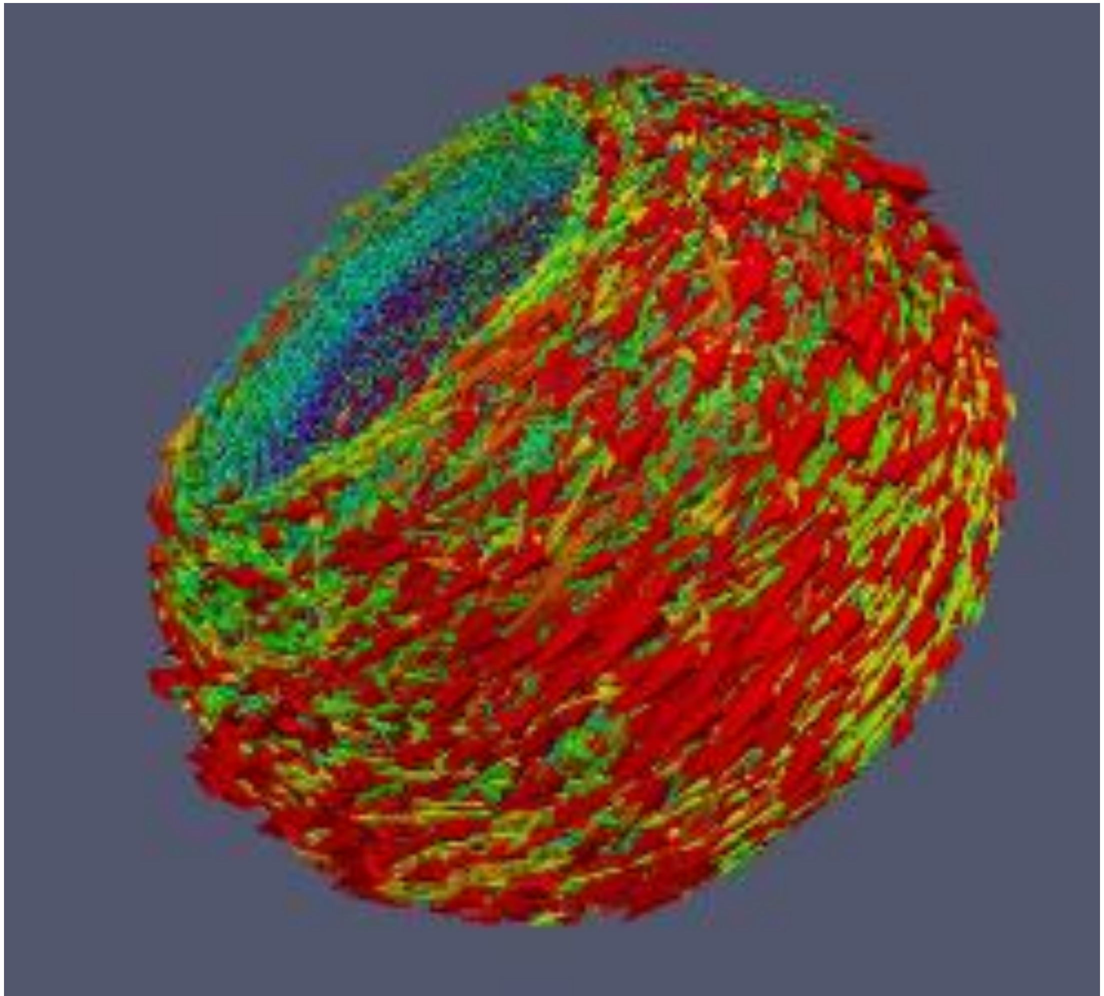


- Vorticity pattern – vortex sheets - due to L BUT cylinder symmetry!

Vortex sheet (fixed direction of L)

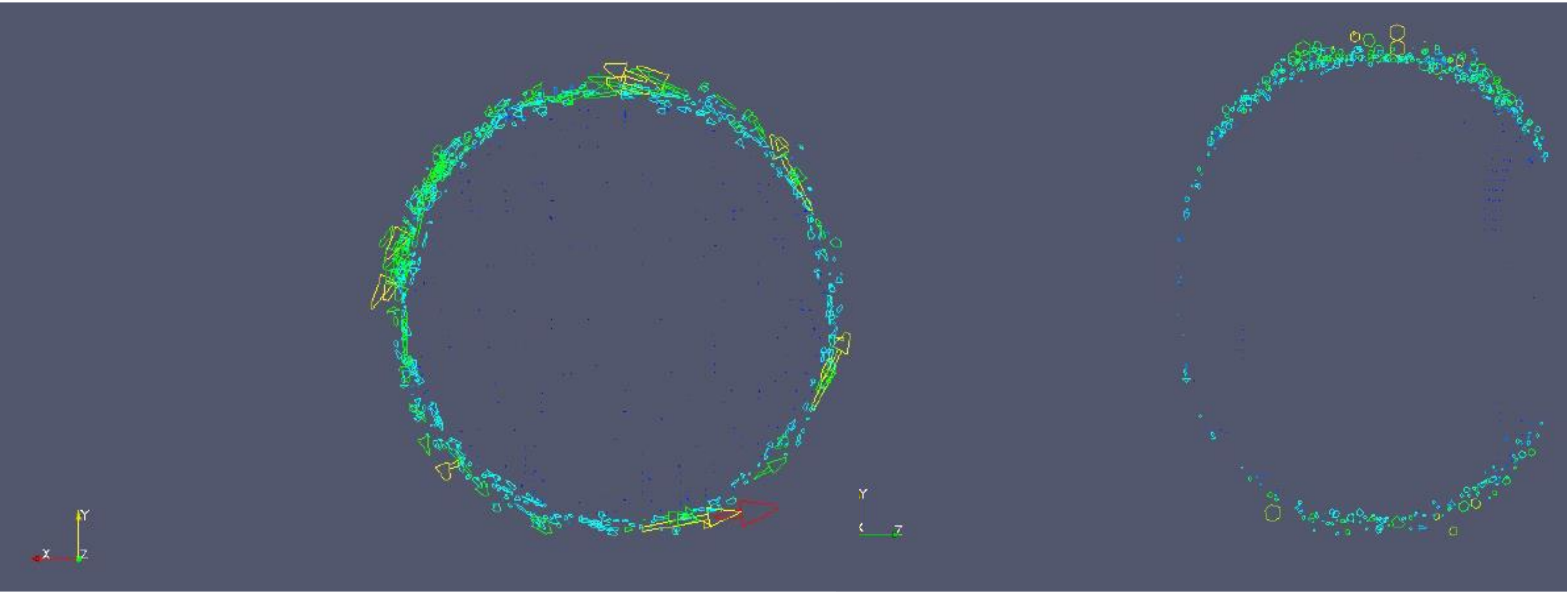


Vortex sheet （Average over L directions）



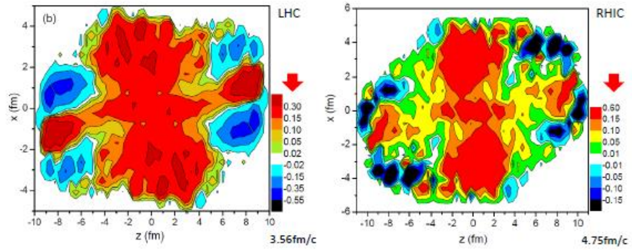
Sections of vorticity patterns

- Front and side views

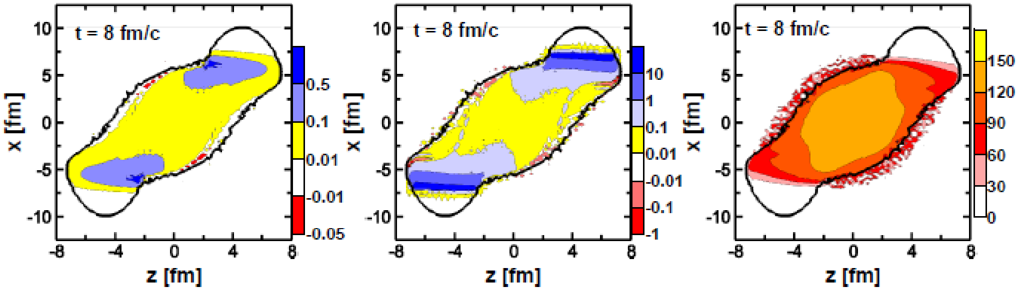


Vortex sheets

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

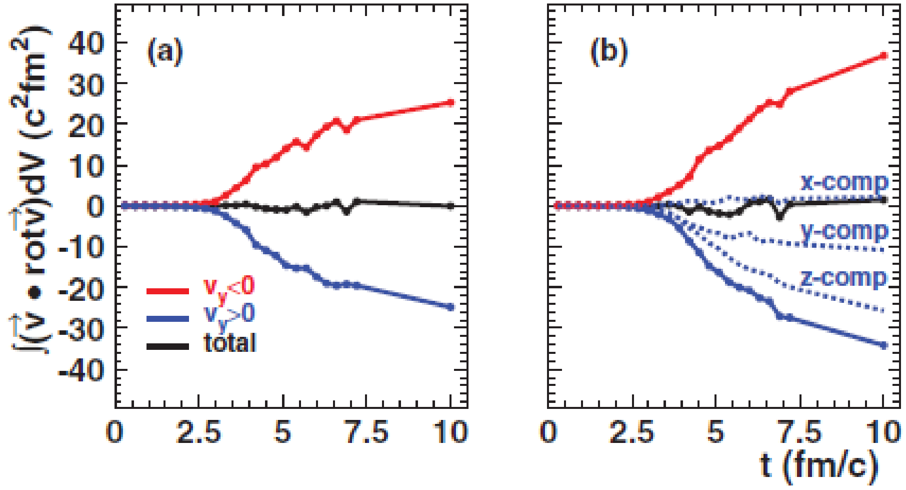


- Appears in 3 fluid dynamics model (Yu. Ivanov, A. Soldatov, **arXiv:1701.01319**)



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

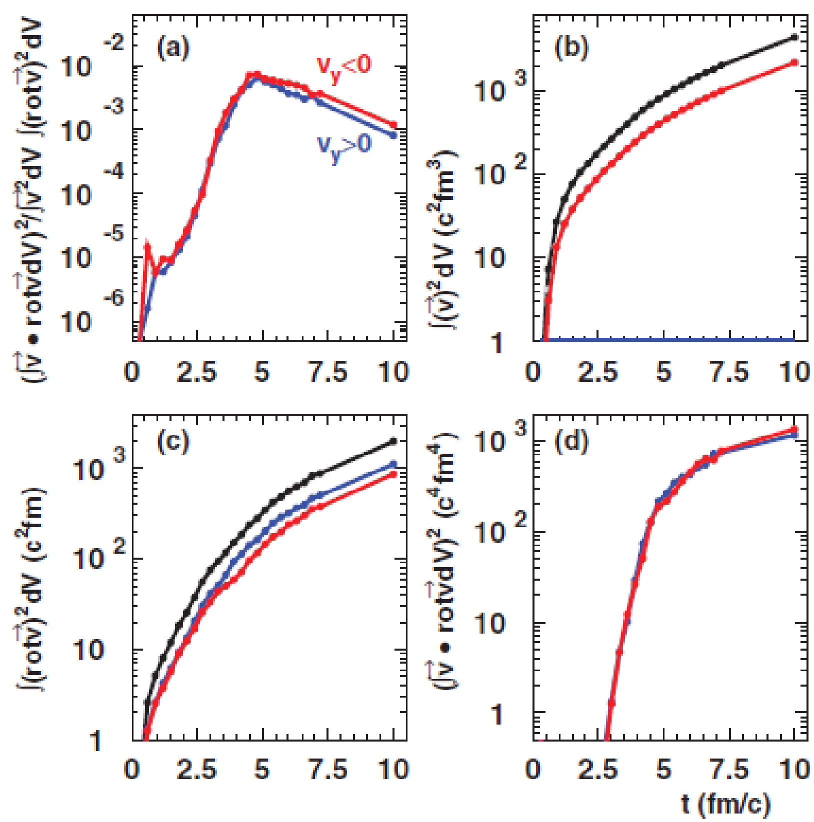
- Total helicity integrates to zero BUT
- Mirror helicities below and above the reaction plane
- Confirmed in HSD (OT, Usubov, PR**C92 (2015) 014906**



What is the relative orientation of velocity and vorticity?

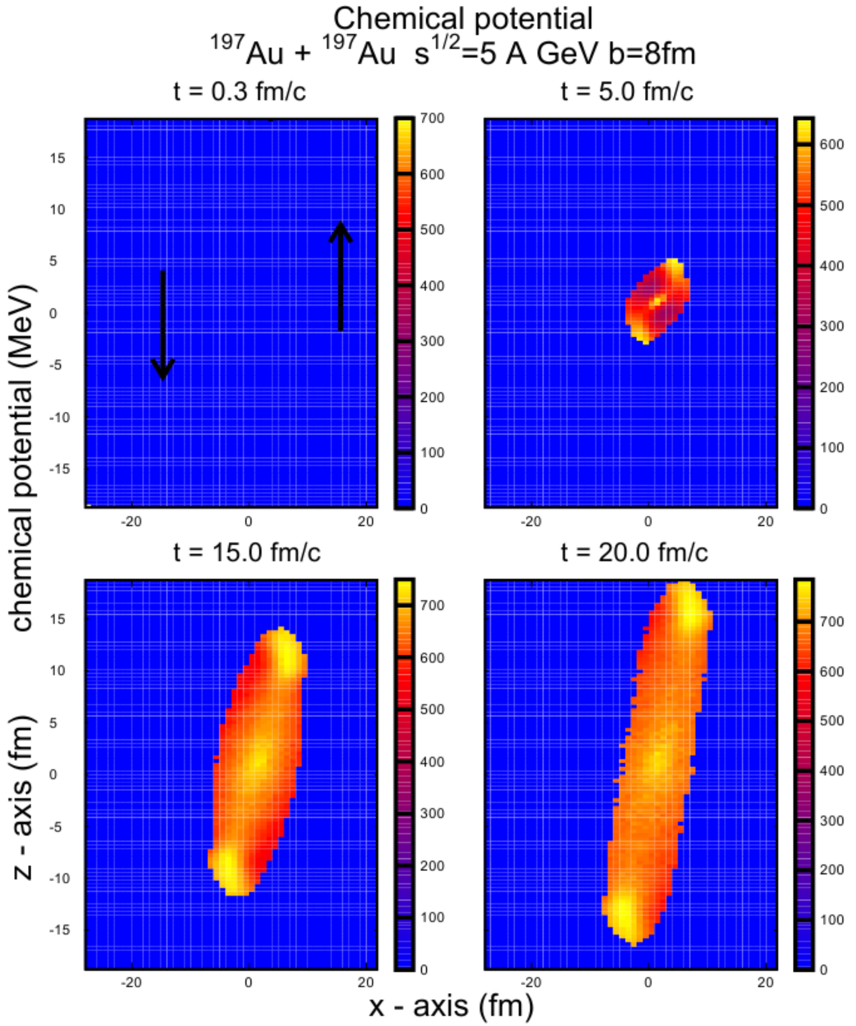
- Measure – Cauchy-Schwarz inequality
- Small but non-negligible correlation
- Maximal correlation - Beltrami flows

PHYSICAL REVIEW C 88, 061901(R) (2013)



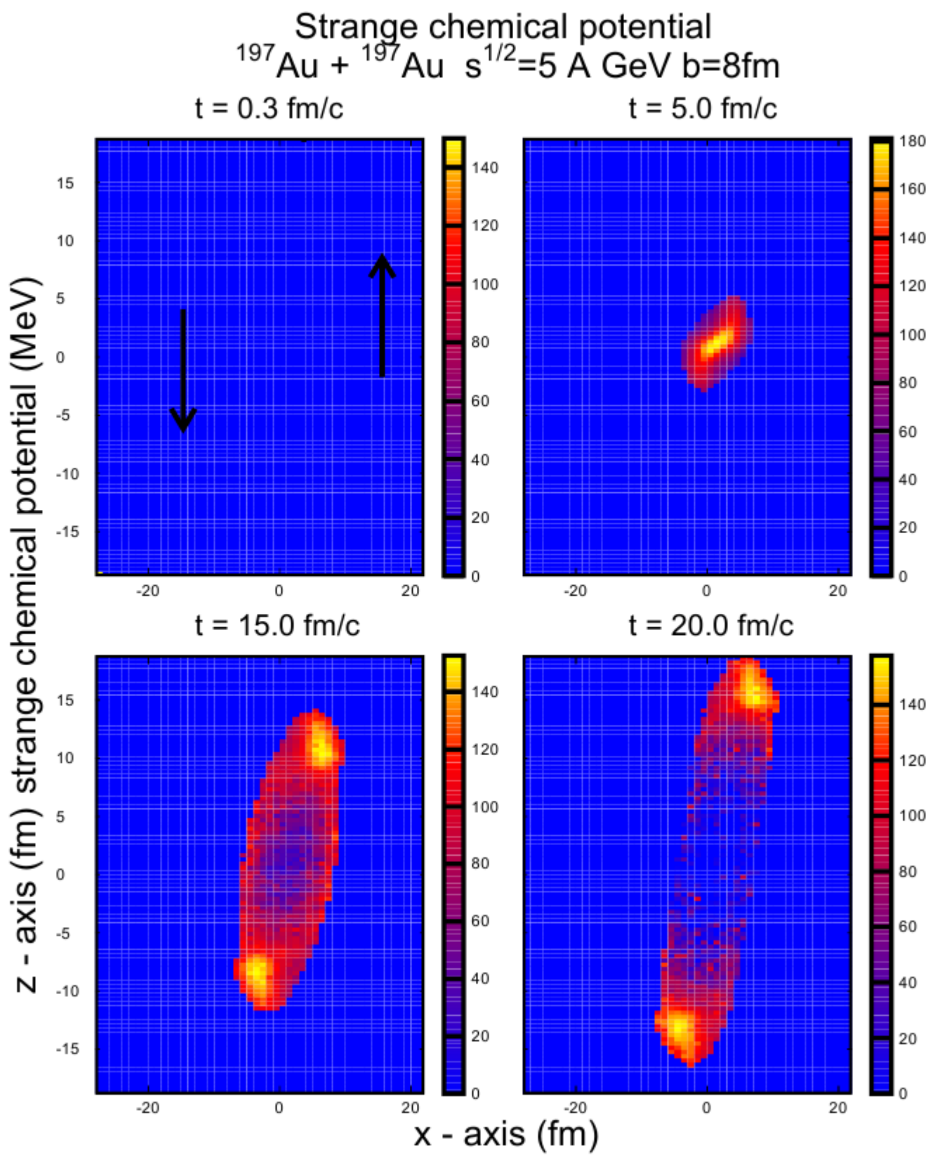
Chemical potential : Kinetics -> TD

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

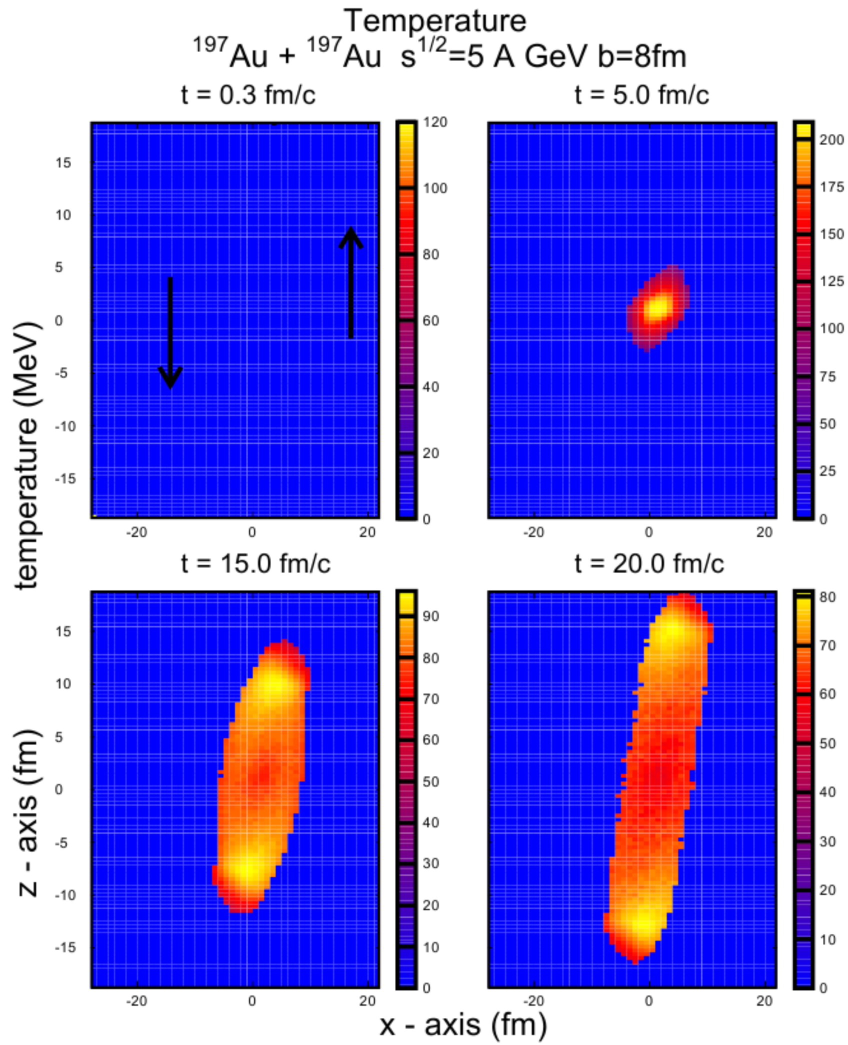


Strange chemical potential (polarization of Lambda is carried by strange quark!)

- 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 (confirmed by STAR)

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

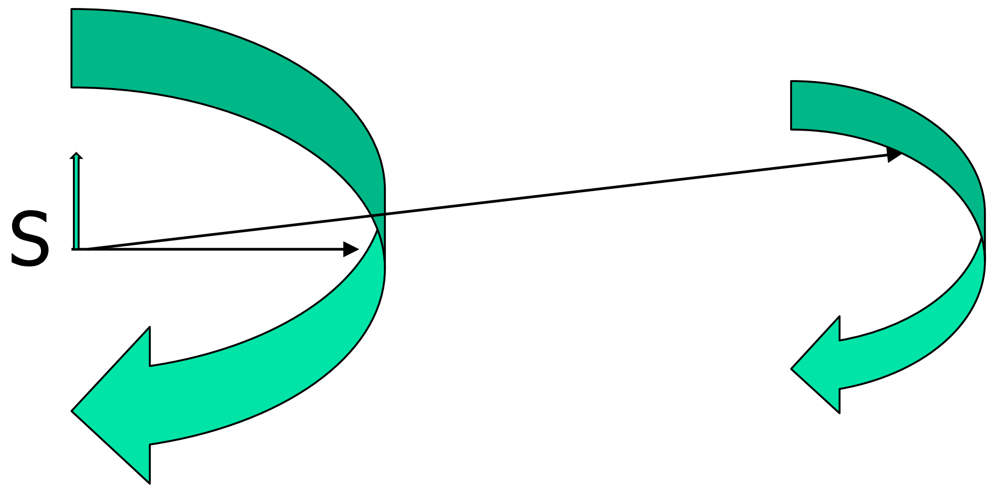
- Pions may carry the axial current due to quantized vortices in pionic superfluid (Kirilin,Sadofyev,Zakharov'12)

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

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

- Suggestion: core of the vortex- baryonic degrees of freedom- polarization
- (Quantum) Macro to micro at short distances

Core of quantized vortex

- Constant circulation – velocity increases when core is approached
- 

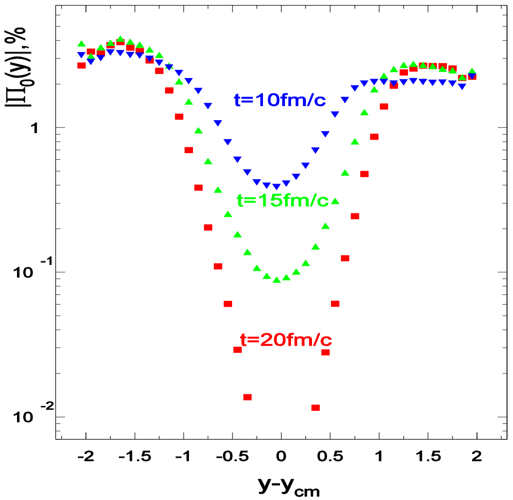
- Helium ($v < v_{sound}$) bounded by intermolecular distances
- Pions ($v<c$) –> (baryon) spin in the center

Helicity -> rest frame polarization

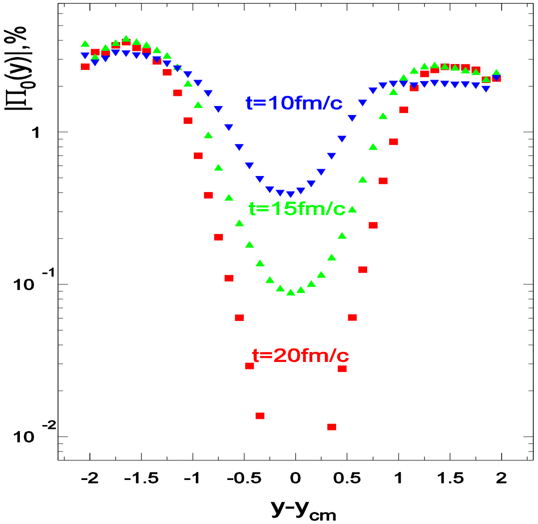
- Helicity ~ 0th component of polarization in lab. frame – effect of boost to Lambda rest frame – various options

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

$w_1=1$, $w2= 1$

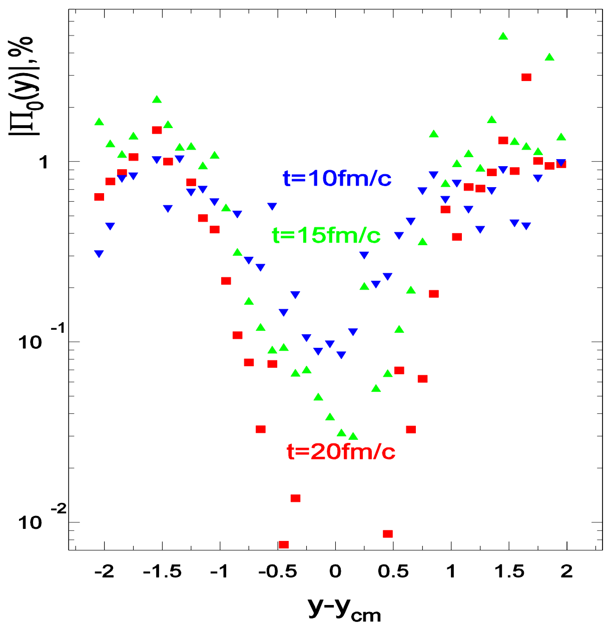


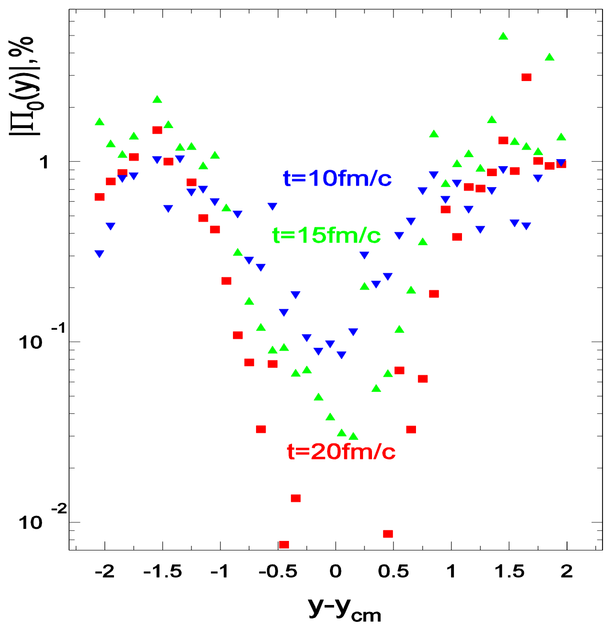
$w_1=1$, $w_2=p_y/m$



Various methods of boost implementation

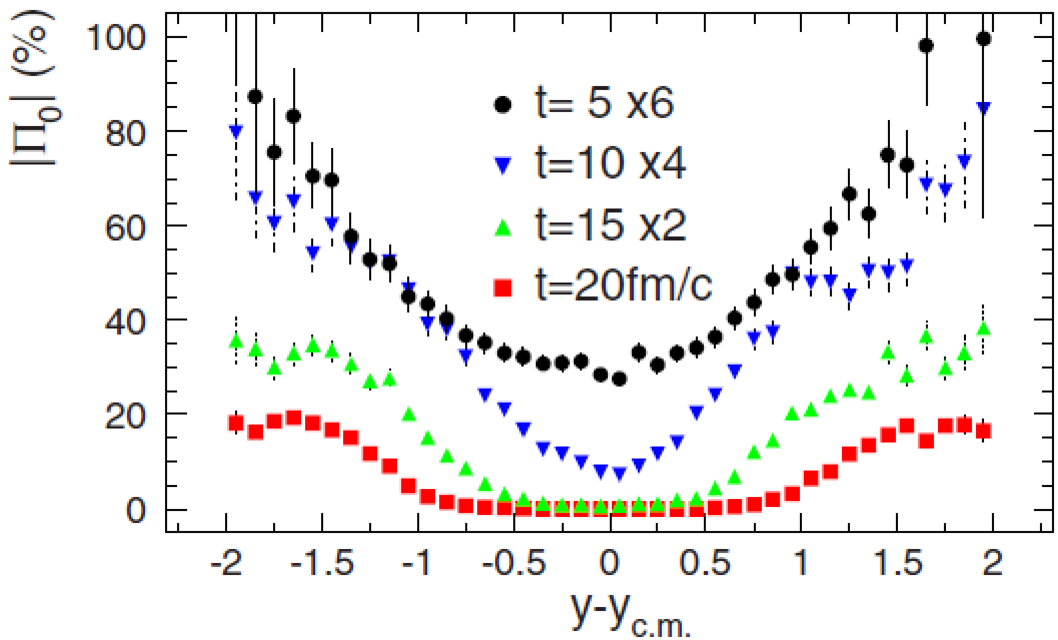
- $w_1=m/p_y$, $w_2=1$ $w_1=m/p_y$, $w_2=p_y/m$





Combining QGSM (thermal)vorticity with TD mechanism (talks of F. Becattini, S. Voloshin)

- Temperature – calculated analogously to chemical potential



- Similar polarization pattern

Comparison of methods

- Wigner function – induced axial current (triangle diagram– V.I. Zakharov) – Prokhorov, OT

$$\alpha_\mu = \frac{1}{T} u^\nu \partial_\nu u_\mu = \frac{a_\mu}{T}, \quad w_\mu = \frac{1}{2T} \epsilon_{\mu\nu\alpha\beta} u^\nu \partial^\alpha u^\beta = \frac{\omega_\mu}{T}$$

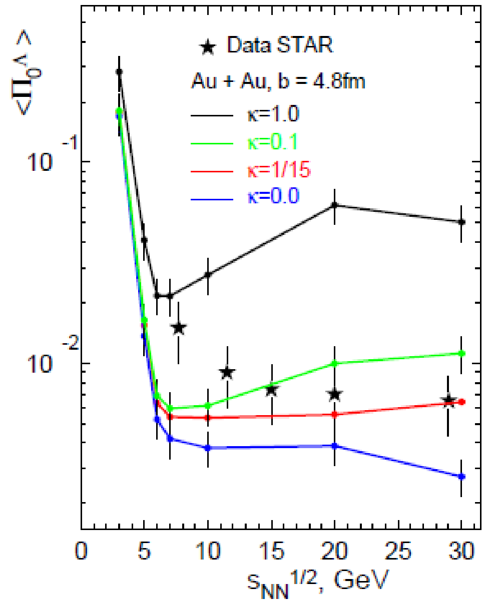
$$\langle : j^5_\mu : \rangle = \Big(\frac{1}{6} [T^2 + \frac{a^2 - \omega^2}{4\pi^2}] + \frac{\mu^2}{2\pi^2} \Big) \omega_\mu + \frac{1}{12\pi^2} (\omega \cdot a)\, a_\mu$$

$$\langle : j^5_\mu : \rangle = 2\pi \, \mathrm{Im} \Big[\big(\frac{1}{6} (T^2 + \varphi^2) + \frac{\mu^2}{2\pi^2} \big) \varphi_\mu \Big] \qquad \varphi_\mu = \frac{a_\mu}{2\pi} + \frac{i\omega_\mu}{2\pi}$$

- New terms of higher order in vorticity
- T-independent: Hawking/Unruh?

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

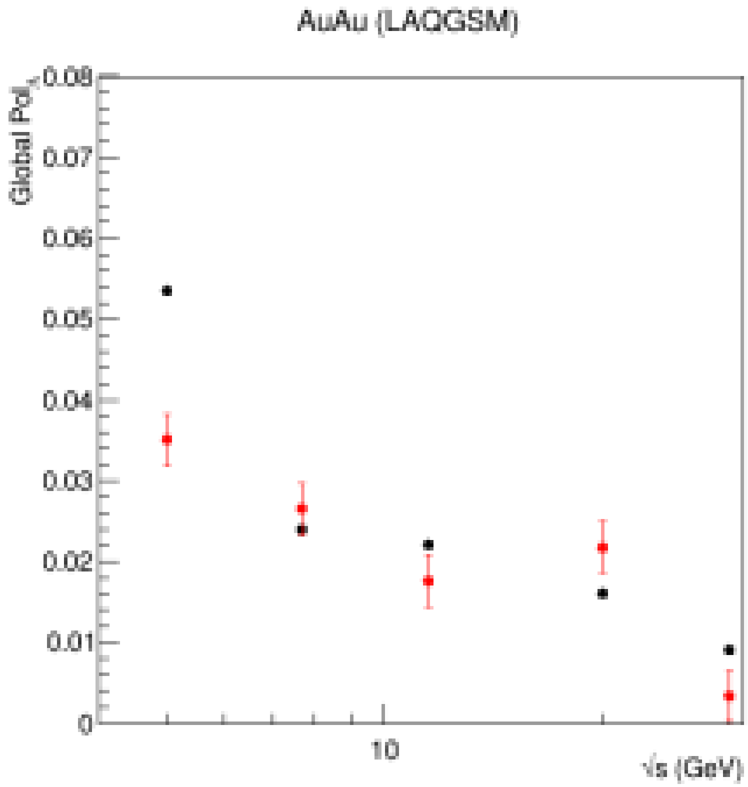
- Different values of coefficient probed



- LQCD suppression by collective effects supported

Polarization at NICA/MPD (A. Kechechyan)

- QGSM Simulations and recovery accounting for MPD acceptance effects

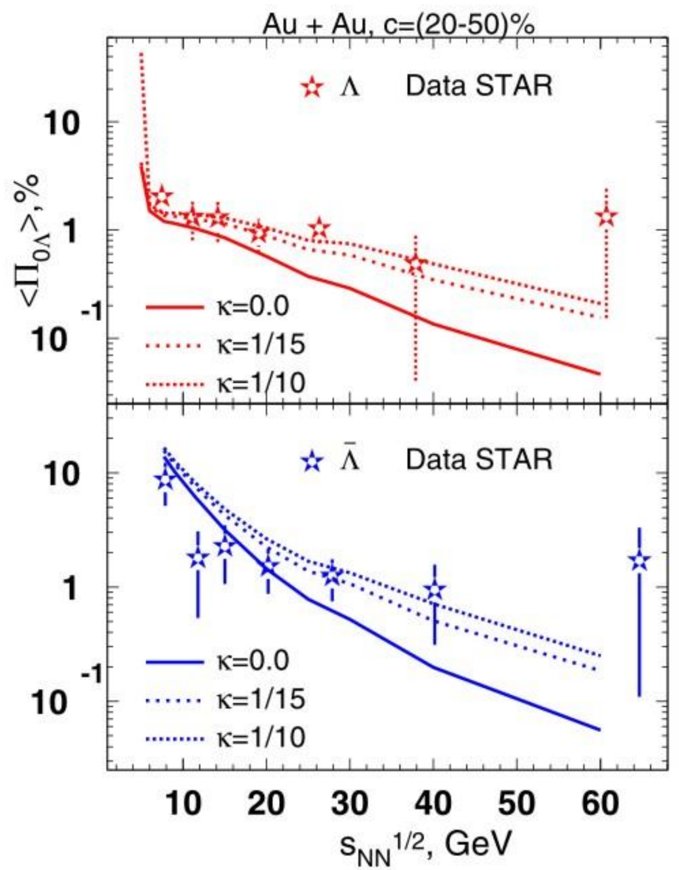


Role of vector mesons

- Strange axial charge may be also carried by K* mesons
- Λ - accompanied by (+,anti 0) K* mesons with two sea quarks – small corrections
- Anti Λ – more numerous (-,0) K* mesons with single (sea) strange antiquark

- Vector polarization implies also tensor polarization – anisotropy measurable in dilepton angular distributions

Λ vs Anti Λ (Baznat, Gudima, Sorin, OT , 1701.00923)



Conclusions/Outlook

- Polarization – new probe of anomaly (analogous to gluon polarization in nucleon) in quark-gluon matter: to be studied at NICA
- Generated by femto-vortex sheets
- Energy dependence predicted and confirmed
- Same sign and larger magnitude of antihyperon polarization
- Polarization - from core of vortices in pionic superfluid

- Inertial effect in rotating frame (Hawking/Unruh effects)?

BACKUP

Properties of SSA

The same for the case of initial or final state polarization.

Various possibilities to measure the effects: change sign of $\vec{n}$ or $\vec{P}$: left-right or up-down asymmetry.

Qualitative features of the asymmetry

Transverse momentum required (to have $\vec{n}$)

Transverse polarization (to maximize $(\vec{P}\vec{n})$)

Interference of amplitudes

IMAGINARY phase between amplitudes - absent in Born approximation

Phases and T-oddness

Clearly seen in relativistic approach:

$\rho = \frac{1}{2}(\hat{p} + m)(1 + \hat{s}\gamma_5)$

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

Imaginary parts (loop amplitudes) are required to produce real observable.

$\varepsilon_{abcd} \equiv \varepsilon^{\alpha\beta\gamma\delta} a_\alpha b_\beta c_\gamma d_\delta$ each index appears once: $P-$ (compensate S) and $T-$ odd.

However: no real $T-$violation: interchange $|i> \leftrightarrow |f>$ is the nontrivial operation in the case of nonzero phases of $<f|S|i>^* = <i|S|f>$.

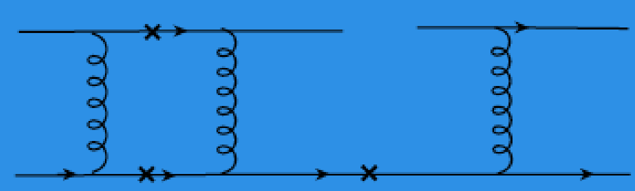
SSA - either T-violation or the phases.

DIS - no phases ($Q^2 < 0$)- real T-violation.

Perturbative PHASES IN QCD

QCD factorization: where to borrow imaginary parts?

Simplest way: from short distances - loops in partonic subprocess. Quarks elastic scattering (like $q - e$ scattering in DIS):

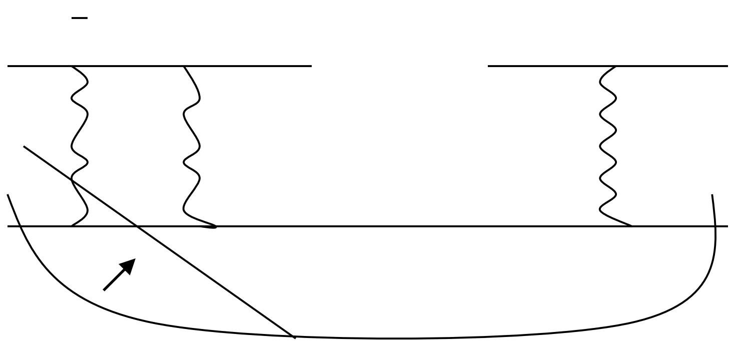


$$A \sim \frac{\alpha_S m p_T}{p_T^2 + m^2}$$

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

Short+ large overlap– twist 3

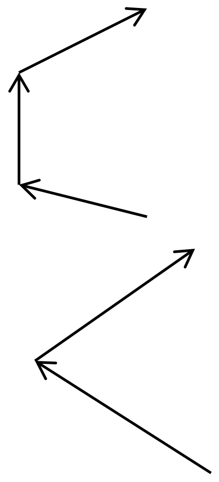
- Quarks – only from hadrons
- Various options for factorization – shift of SH separation



- New option for SSA: Instead of 1-loop twist 2 – Born twist 3 (quark-gluon correlator): Efremov, OT (85, Fermionic poles); Qiu, Sterman (91, GLUONIC poles)
- Further shift to large distances – T-odd fragmentation functions (Collins, dihadron, handedness)

Correlations of jets handedness

- LEP – quarks are polarized due to weak interaction
- BUT – how to ditinguish quark/antiquark jets?
- 2 jets - correlation of helicities – correlation of handedness
- Hadronic collisions – for jets from the same quark-antiquark pair



CONCLUSIONS (fast rotation)

- HIC: Lambda polarization of % order predominantly in forward/backward regions
- Correlation of quark jet handedness – sensitive to production mechanisms
- Correlation of handedness in HIC – measure of angular momentum?

Spin-gravity/rotation (~ 25 orders of magnitude slower!) interactions

- How to describe hadron spin/gravity(inertia) couplings?
- 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!?)

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

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

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

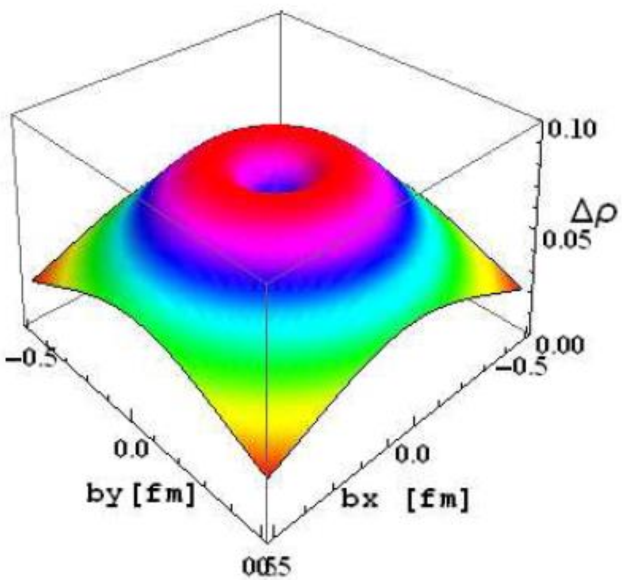


FIG. 17: Difference in the forms of charge density F_1^P and "matter" density (A)

Electromagnetism vs Gravity

- Interaction – field vs metric deviation

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

- Static limit

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

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

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

- Mass as charge – equivalence principle (Einstein ’10-11, Praha)

Equivalence principle

- Newtonian – “Falling elevator” – well known and checked with high accuracy (also for elementary particles)
- Post-Newtonian – gravity action on SPIN – known since 1962 (Kobzarev and Okun’ ZhETF paper contains acknowledgment to Landau: probably his last contribution to theoretical physics before car accident); 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

- For GEDM –checked with sometimes controversial results
- For AGM not checked on purpose but in fact checked in the same atomic spins experiments at % level (Silenko,OT’07)

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

Experimental test of PNEP

- Reinterpretation of the data on G(EDM) search

PHYSICAL REVIEW LETTERS

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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

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(Received 25 September 1991)

- 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

Gravity vs accelerated frame for spin and helicity

- Spin precession – well known factor 3 (Probe B; spin at satellite – probe of PNEP!) – smallness of relativistic correction (~$\mathbf{P}^2$) is compensated by 1/ $\mathbf{P}^2$ in the momentum direction precession frequency
- Helicity flip – the same!
- No helicity flip in gravitomagnetic field – another formulation of PNEP (OT'99)

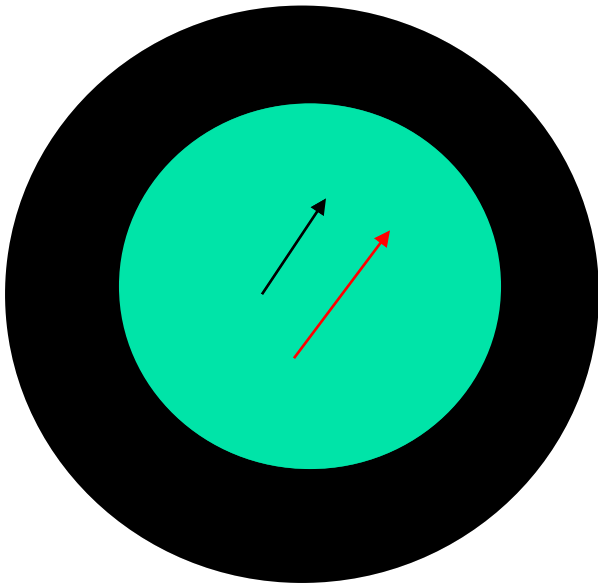
Gyromagnetic and Gravigyromagnetic ratios

- Free particles – coincide
- $<P+q|T^{mn}|P-q> = P^{\{m}<P+q|J^{n\}}|P-q>/e$ up to the terms linear in q
- Special role of g=2 for any spin (asymptotic freedom for vector bosons)

- Should Einstein know about PNEP, the outcome of his and de Haas experiment would not be so surprising
- Recall also g=2 for Black Holes. Indication of "quantum" nature?!

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 ?!



Torsion – acts only on spin (violates EP)

Dirac eq+FW transformation-Obukhov,Silenko,OT, **arXiv:1410.6197**

- Hermitian Dirac Hamiltonian

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

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

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

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

- Spin-torsion coupling

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

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

- FW – semiclassical limit - precession

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

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

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

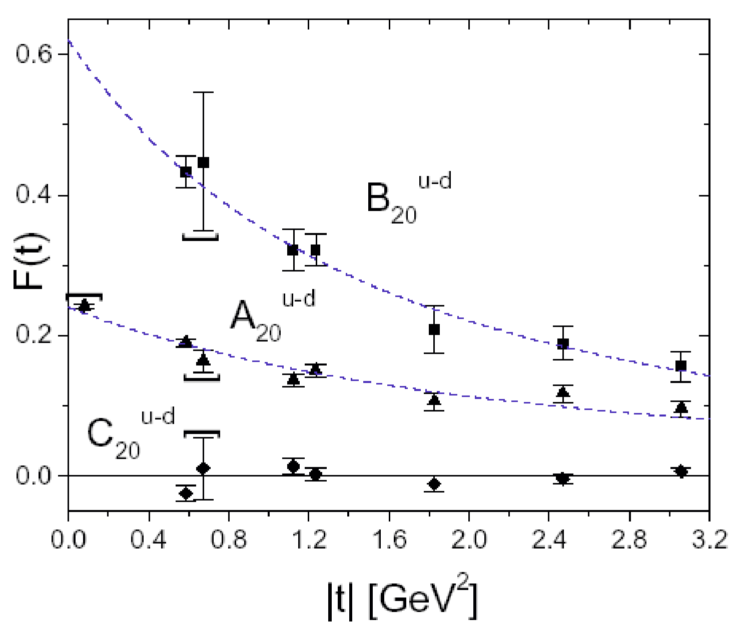
- New(based on Gemmel et al '10)

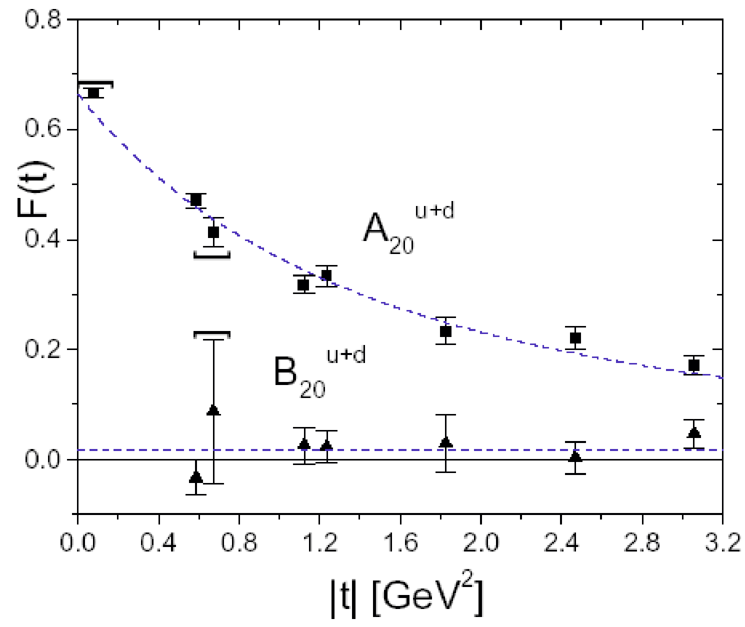
$$\frac{\hbar c}{2} |\check{\boldsymbol{T}}| \cdot |(1-\mathcal{G})\cos\Theta| < 4.1 \times 10^{-22}\,\mathrm{eV}, \qquad |\check{\boldsymbol{T}}| \cdot |\cos\Theta| < 2.4 \times 10^{-15}\,\mathrm{m}^{-1}.$$

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

Generalization of Equivalence principle

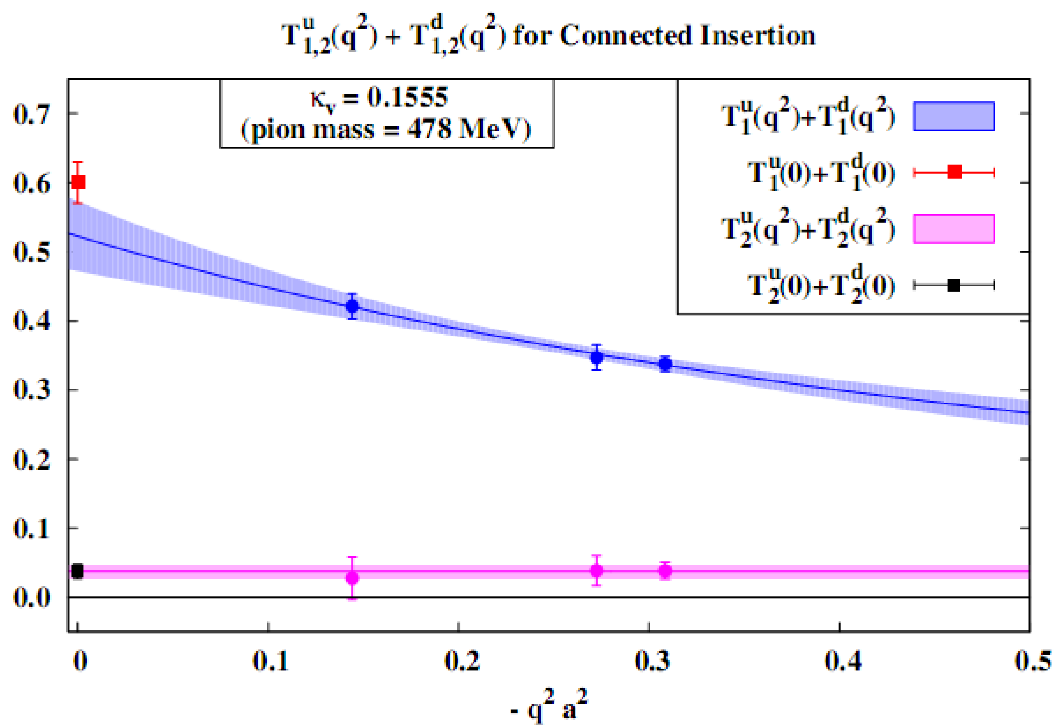
- Various arguments: AGM ≈ 0 separately for quarks and gluons – most clear from the lattice (LHPC/SESAM)





Recent lattice study (M. Deka et al. **arXiv:1312.4816**)

- 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
- Gravity-proof confinement (should the hadrons survive enetering Black Hole?)?!

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

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

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

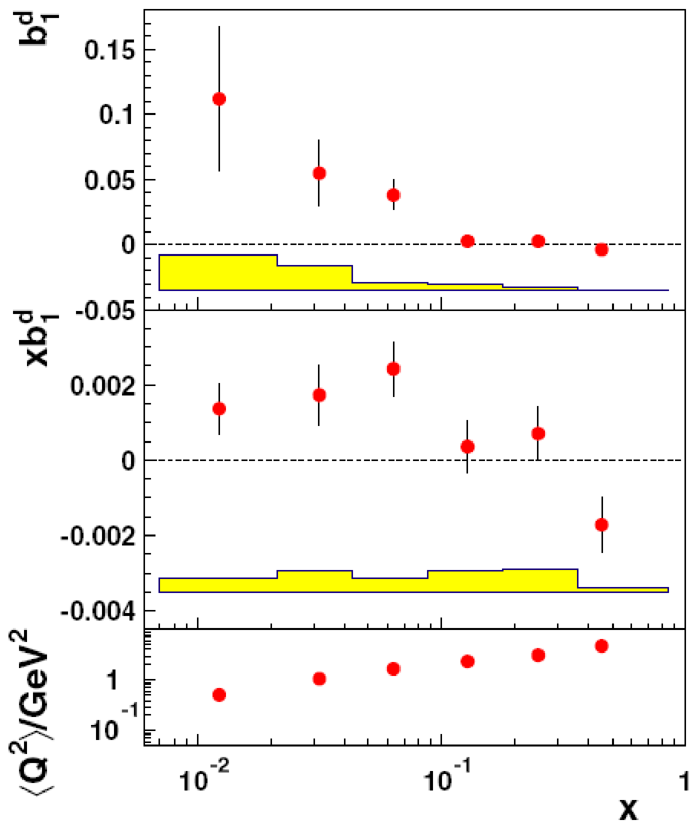
$$\langle P,S|T_g^{\mu\nu}|P,S\rangle_{\mu^2} = 2P^{\mu}P^{\nu}\delta(\mu^2) - 2M^2S^{\mu\nu}\delta_1(\mu^2)$$

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



Conclusions (slow rotation)

- Probe of equivalence principle for spin
- May be tested in EDM search experiments
- Extension of EP –validity separately for quarks and gluons

- BACKUP SLIDES

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!

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