Vorticity and
Polarization in Heavy-Ion Collisions

in the framework of MPD PWG3

JINR, Dubna, Russia November 19 2019

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Physics Working Groups

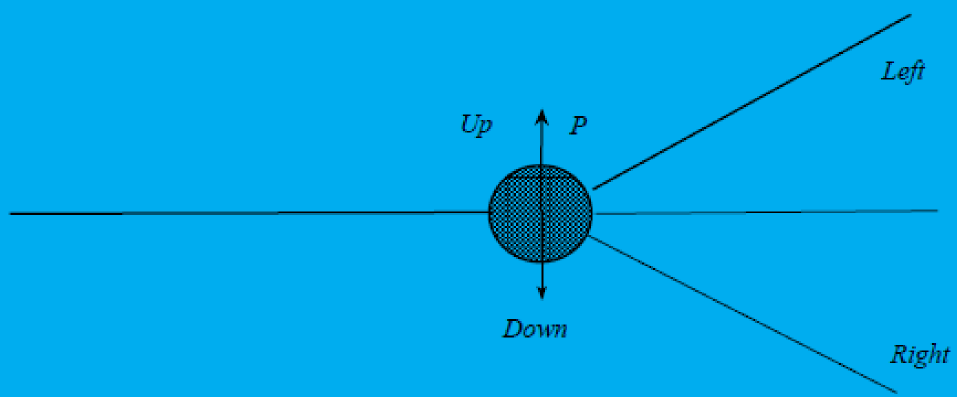
PWG1	PWG2	PWG3
Global observables	**Spectra of light flavor and hypernuclei**	**Correlations and Fluctuations**
• Total event multiplicity • Total event energy • Centrality determination • Total cross-section measurement • Vertex determination • Event plane measurement at all rapidities • Spectator measurement	• Light flavor spectra • Hyperons and hypernuclei • Total particle yields and yield ratios • Kinematic and chemical properties of the event • Mapping QCD Phase diagram	• Collective flow for hadrons • Vorticity, Λ polarization • E-by-E fluctuation of multiplicity, momentum and conserved quantities • Femtoscopy • Forward-Backward corr. • Jet-like correlations

Interest of polarization

- Very sensitive test for dynamics
- Maximally vortical fluid (Nature publication by STAR)
- Suitable for NICA energy range

Single Spin Asymmetries

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



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

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

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

Single Spin Asymmetry

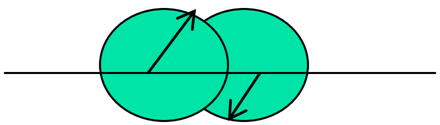
- Parity conservation – normal to scattering plane
- Interference – LS coupling: S (r x p) -> S (k x p)~ S n
- T conservation – absorptive phases

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?

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

One might compare the prediction below with the right panel figures

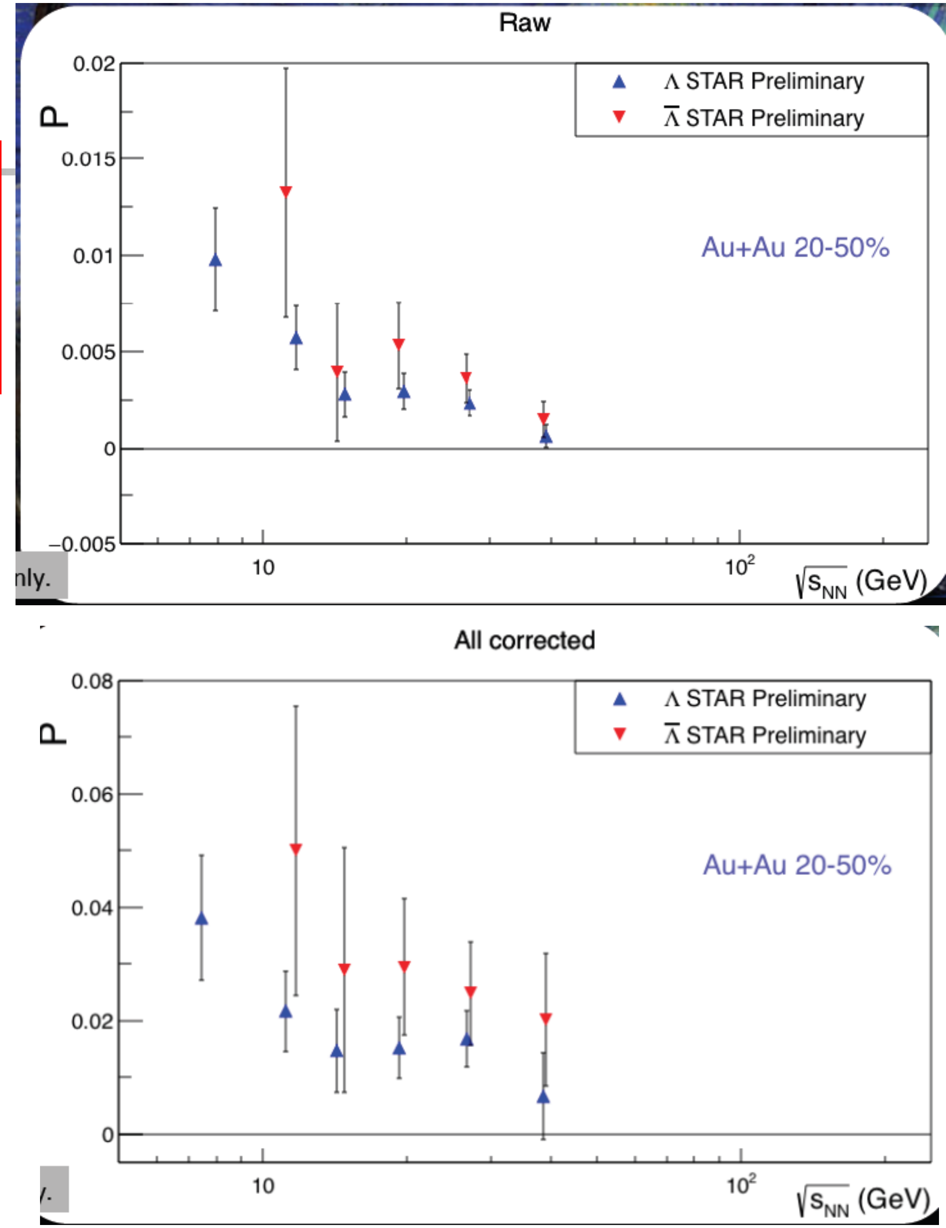
O. Rogachevsky, A. Sorin, O. Teryaev
Chiral vortaic effect and neutron asymmetries in heavy-ion collisions
PHYSICAL REVIEW C 82, 054910 (2010)

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.



Further studies:QGSM

- 1) Vorticity and polarization in baryon-rich matter
  By Mircea Baznat, Konstantin Gudima, Alexander Sorin, Oleg Teryaev.
  10.22323/1.311.0024.
  PoS CPOD2017 (2018) 024.
  2) Hyperons polarization in heavy-ion collisions
  By Mircea Baznat, Konstantin Gudima, Alexander Sorin, Oleg Teryaev.
  10.1051/epjconf/201713801008.
  EPJ Web Conf. 138 (2017) 01008.
  3) Hyperon polarization in heavy-ion collisions and holographic gravitational anomaly
  By Mircea Baznat, Konstantin Gudima, Alexander Sorin, Oleg Teryaev.
  arXiv:1701.00923 [nucl-th].
  10.1103/PhysRevC.97.041902.
  Phys.Rev. C97 (2018) no.4, 041902.
  4) Polarization in heavy-ion collisions: magnetic field and vorticity
  By M.. Baznat, K. Gudima, G. Prokhorov, A. Sorin, O. Teryaev, V. Zakharov.
  10.1088/1742-6596/938/1/012063.
  J.Phys.Conf.Ser. 938 (2017) no.1, 012063.
  5) Chaotic vortical flows and their manifestations
  By M. Baznat, K. Gudima, A. Sorin, O. Teryaev.
  10.1051/epjconf/201612602030.
  EPJ Web Conf. 126 (2016) 02030.
  6) Hydrodynamic helicity and strange hyperon polarization in heavy-ion collisions
  By M. Baznat, K. Gudima, A. Sorin, O. Teryaev.
  10.1088/1742-6596/668/1/012084.
  J.Phys.Conf.Ser. 668 (2016) no.1, 012084.
  7) Femto-vortex sheets and hyperon polarization in heavy-ion collisions
  By Mircea I. Baznat, Konstantin K. Gudima, Alexander S. Sorin, O.V. Teryaev.
  arXiv:1507.04652 [nucl-th].
  10.1103/PhysRevC.93.031902.
  Phys.Rev. C93 (2016) no.3, 031902.
  8) Helicity separation in Heavy-Ion Collisions
  By Mircea Baznat, Konstantin Gudima, Alexander Sorin, Oleg Teryaev.
  arXiv:1301.7003 [nucl-th].
  10.1103/PhysRevC.88.061901.
  Phys.Rev. C88 (2013) no.6, 061901.

Further studies: HSD/PHSD, UrQMD, 3-fluid hydro

- Vorticity and hyperon polarization at energies available at JINR Nuclotron-based Ion Collider fAcility
  By E.E. Kolomeitsev, V.D. Toneev, V. Voronyuk.
  arXiv:1801.07610 [nucl-th].
  10.1103/PhysRevC.97.064902.
  Phys.Rev. C97 (2018) no.6, 064902.
- Vorticity and hydrodynamic helicity in heavy-ion collisions in the hadron-string dynamics model
  By Oleg Teryaev, Rahim Usubov.
  10.1103/PhysRevC.92.014906.
  Phys.Rev. C92 (2015) no.1, 014906.
- Aleksei Zinchenko, A.Sorin, O. Teryaev M. Baznat, to appear in DSPIN2019 Proceedings

- Different space-time freeze-out picture - an explanation of different Λ and $\bar{\Lambda}$ polarization?
  By O. Vitiuk, L.V. Bravina, E.E. Zabrodin.
  arXiv:1910.06292 [hep-ph].

- Vorticity and Particle Polarization in Relativistic Heavy-Ion Collisions
  By Yu B. Ivanov, V.D. Toneev, A.A. Soldatov.
  arXiv:1910.01332 [nucl-th].
- 2) Estimates of hyperon polarization in heavy-ion collisions at collision energies $\sqrt{s_{NN}}=$ 4--40 GeV
  By Yu B. Ivanov, V.D. Toneev, A.A. Soldatov.
  arXiv:1903.05455 [nucl-th].
  10.1103/PhysRevC.100.014908.
  Phys.Rev. C100 (2019) no.1, 014908.
- Vortex rings in fragmentation regions in heavy-ion collisions at $\sqrt{s_{NN}}=$ 39 GeV
  By Yu B. Ivanov, A.A. Soldatov.
  arXiv:1803.01525 [nucl-th].
  10.1103/PhysRevC.97.044915.
  Phys.Rev. C97 (2018) no.4, 044915.

The main problems to be discussed at the meetings

- Calculations and comparison of vorticity and emerging polarization in various hydro and kinetic models for various nuclei, energies, centralities, kinematical domains; bringing together various groups (in particular, at JINR)
- Simulations and reconstruction of global polarization at MPD
- Simulations of (P-even) tensor polarization for vector mesons (cf K_0* at ALICE)
- P-odd momentum correlations (handedness)
- Correlation of polarization with other collective effects (in particular, flows)

Main Topics

- Polarization in QCD: from nucleons to ions
- Parity conservation: normal to some plane
- Interference: twist-3 correlators vs LS coupling
- T- reversal: phases vs dissipation

- Fast rotation and acceleration: effective gravity
- Gravitational FFs: link between hadrons and medium: pressure, shear

- Experimental tests of nuclear/hadronic complementarity

- Conclusions

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

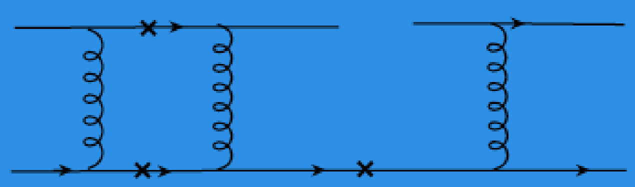
SSA - either T-violation or the phases.

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):

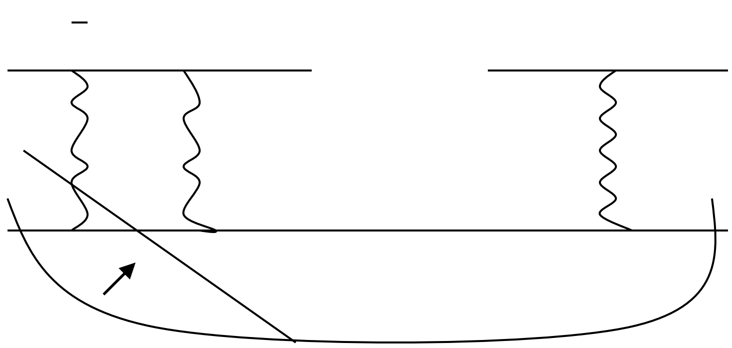


$$A \sim \frac{\alpha_S m p_T}{p_T^2 + m^2}$$

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

Short+ large overlap– twist 3

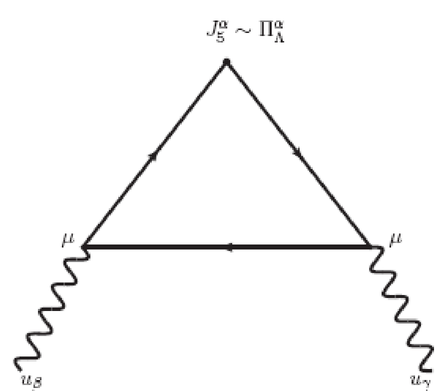
- Quarks – only from hadrons
- Various options for factorization – shift of SH separation



- 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 -> Sivers function)
- Further shift to large distances – T-odd fragmentation and (effective) distribution functions (Collins, Sivers)

Anomalous mechanism – polarization similar to CM(V)E

- 4-Velocity is also a GAUGE FIELD (V.I. Zakharov)
- No gauge invariance! $e_j A_\alpha J^\alpha \Rightarrow \mu_j V_\alpha J^\alpha$
- Triangle anomaly leads to polarization of quarks and hyperons   (Rogachevsky, Sorin, OT ’10)
- Analogous to anomalous gluon contribution to nucleon spin (Efremov,OT’88)
- Axial/trace anomaly ~ spin/mass puzzles (talk of O. Denisov)



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

$$Q_5^s = \frac{N_c}{2\pi^2} \int d^3x \, \mu_s^2(x) \gamma^2 \epsilon^{ijk} v_i \partial_j v_k$$

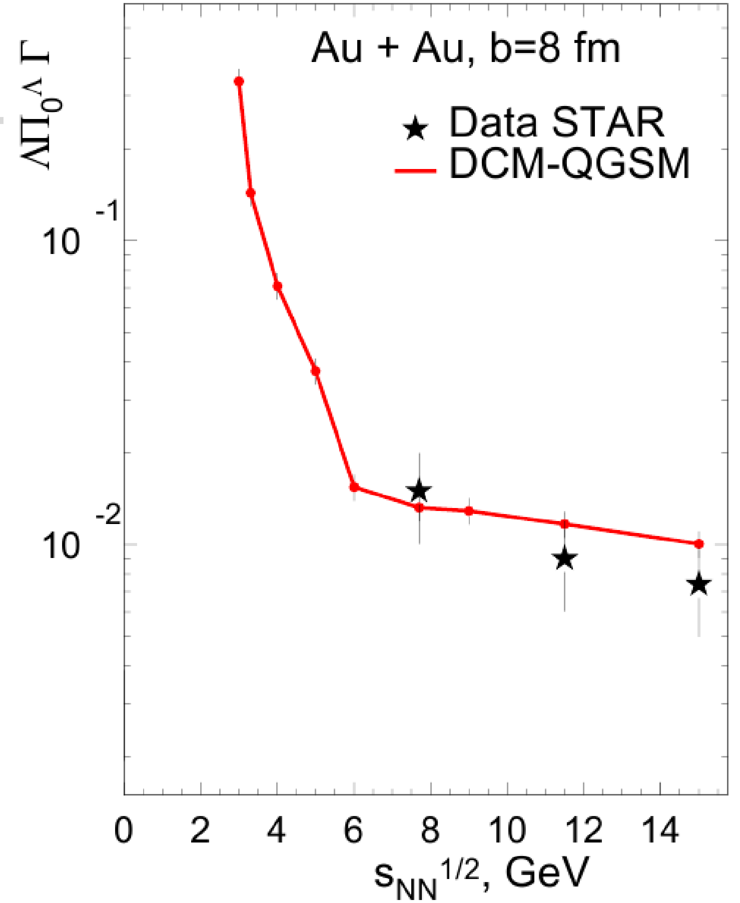
- Field -> velocity (observable: no Gauge Invariance)
- (Color) magnetic field strength -> vorticity;
- Axial charge <-> hydrodynamical helicity
- Rapid decrease with energy (cf Regge!)
- Large chemical potential: appropriate for NICA/FAIR energies

Microworld: where is the fastest possible rotation?

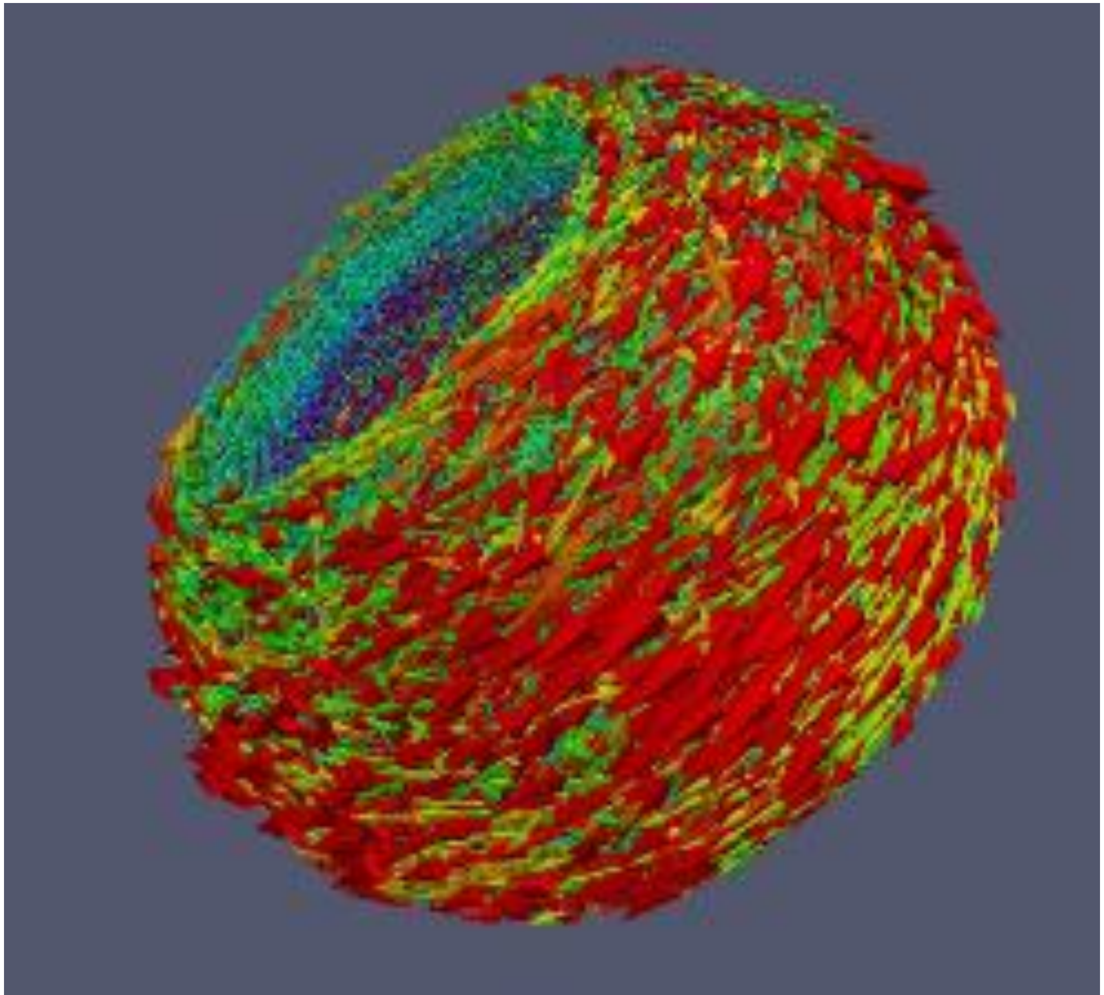
- Non-central heavy ion collisions (Angular velocity ~ c/Compton wavelength)
- ~25 orders of magnitude faster than Earth's rotation
- Differential rotation – vorticity
- P-odd :May lead to various P-odd effects (e.g. handedness – talk of A. Martynova)
- Calculation in kinetic quark - gluon string model (DCM/QGSM) – Boltzmann type eqns + phenomenological string amplitudes): Baznat,Gudima,Sorin,OT, PRC'13,16,18

Energy dependence

- Growth at low energy
- Close to STAR data



Vortex sheets (talks of Yu. Ivanov, Alexei Zinchenko)



From axial charge to polarization (and from quarks to confined hadrons) – Sorin,OT'16

- Analogy of matrix elements and classical averages

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

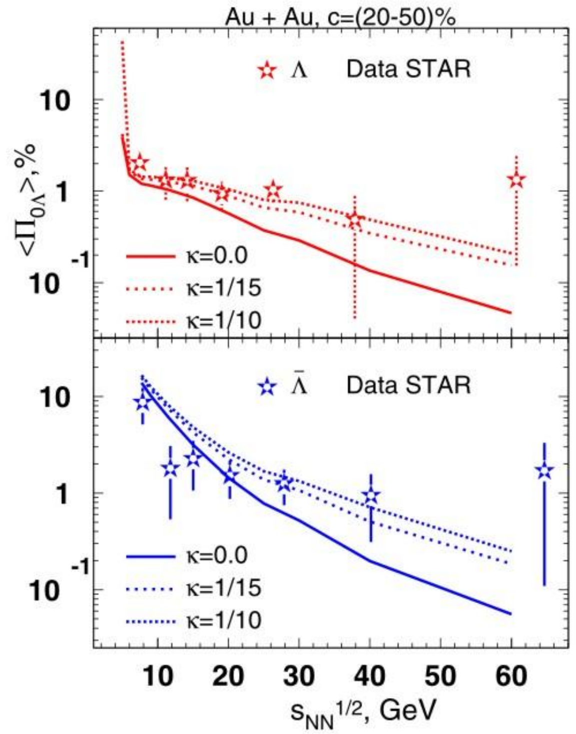
- Lorentz boost: compensated by the sign of helicity mirror structure (BGST'13; talk of Alexei Zinchhenko)

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

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

Λ vs Anti Λ

- Same (C-even) axial charge is distributed between smaller number of antihyperons
- Possible corrections due to (C-odd) strong magnetic field (talk of E. Lushevskaya)



Where is phase?! Other approach to baryons in confined phase: vortices in pionic superfluid (V.I. Zakharov, OT'17)

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

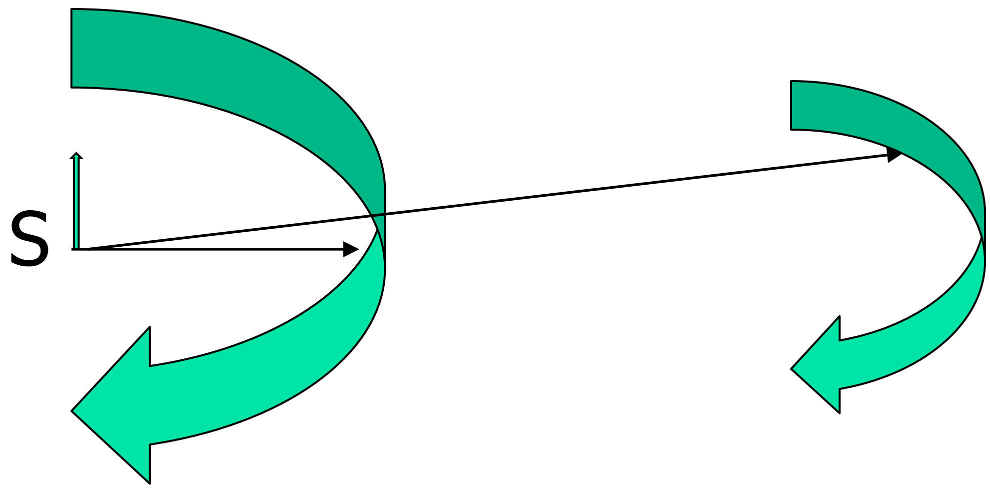
$$\frac{\pi_0}{f_\pi} = \mu \cdot t + \varphi(x_i) \qquad \partial_i \varphi = \mu v_i \qquad \oint \partial_i \varphi dx_i = 2\pi n$$

$$T_{0i} \sim \mu_5 \partial_i \tilde{\varphi}. \qquad \lim_{q_i \to 0, \omega \equiv 0} < T_{0i}, T_{0k} > \sim \mu_5^2 \frac{q_i q_k}{q_i^2}$$

$$j_5^\mu = \frac{1}{4\pi^2 f_\pi^2} \epsilon^{\mu\nu\rho\sigma} (\partial_\nu \pi^0)(\partial_\rho \partial_\sigma \pi^0)$$

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

Core of quantized vortex

- Constant circulation – velocity increases when core is approached
- 

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

Baryon spin as radiative correction

- Kinematical requirement of spin appearance – similar to "historical" arguments: v~c at Compton wavelength and v>>c at classical radius required for orbital momentum

- Baryons emerge as UV cutoff

- Transition to UV – dissipation (counterpart of absorptive phases!?)

Anomaly vs TD (talk of G. Prokhorov)

- Wigner function, Zubarev d.m. – induced axial current

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

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

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

- H+iE <-> ω + ia ("imaginary acceleration")
- Largest ever angular velocity and acceleration – effective gravity, Unruh radiation

Another manifestation of gravity in QCD: Gravitational Formfactors (talks of I. Anikin, O. Selyugin)

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

- 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 and interaction with both classical and TeV external (its weakness does not enter) gravity
- Special interest: quadrupole FF is related to pressure (talk of P. Sznajder) – another link between hadrons and QCD matter

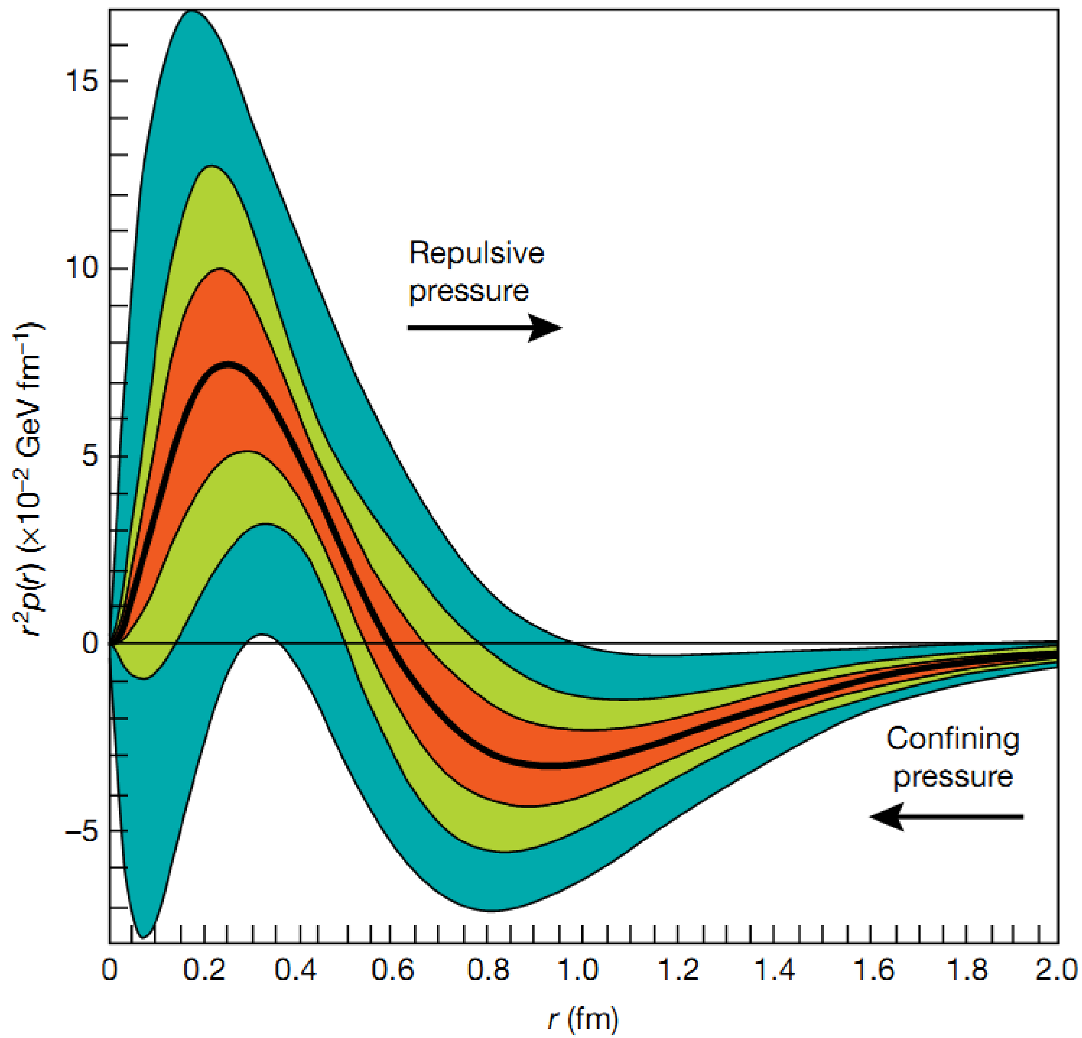
LETTER

NATURE | www.nature.com/nature

https://doi.org/10.1038/s41586-018-0060-z

The pressure distribution inside the proton

V. D. Burkert[1]*, L. Elouadrhiri[1] & F. X. Girod[1]



Counterpart of Ji's SR: Equivalence Principle (OT'99)

- Interaction – field vs metric deviation

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

$$M = \frac{1}{2}\sum_{q,G}\langle P'|T^{\mu\nu}_{q,G}|P\rangle h_{\mu\nu}(q)$$

- Static limit

$$\langle P|J^\mu_q|P\rangle = 2e_q P^\mu$$

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

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

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

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

- Mass as charge – equivalence principle

Gravitomagnetism

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

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

spin dragging twice smaller than EM

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

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

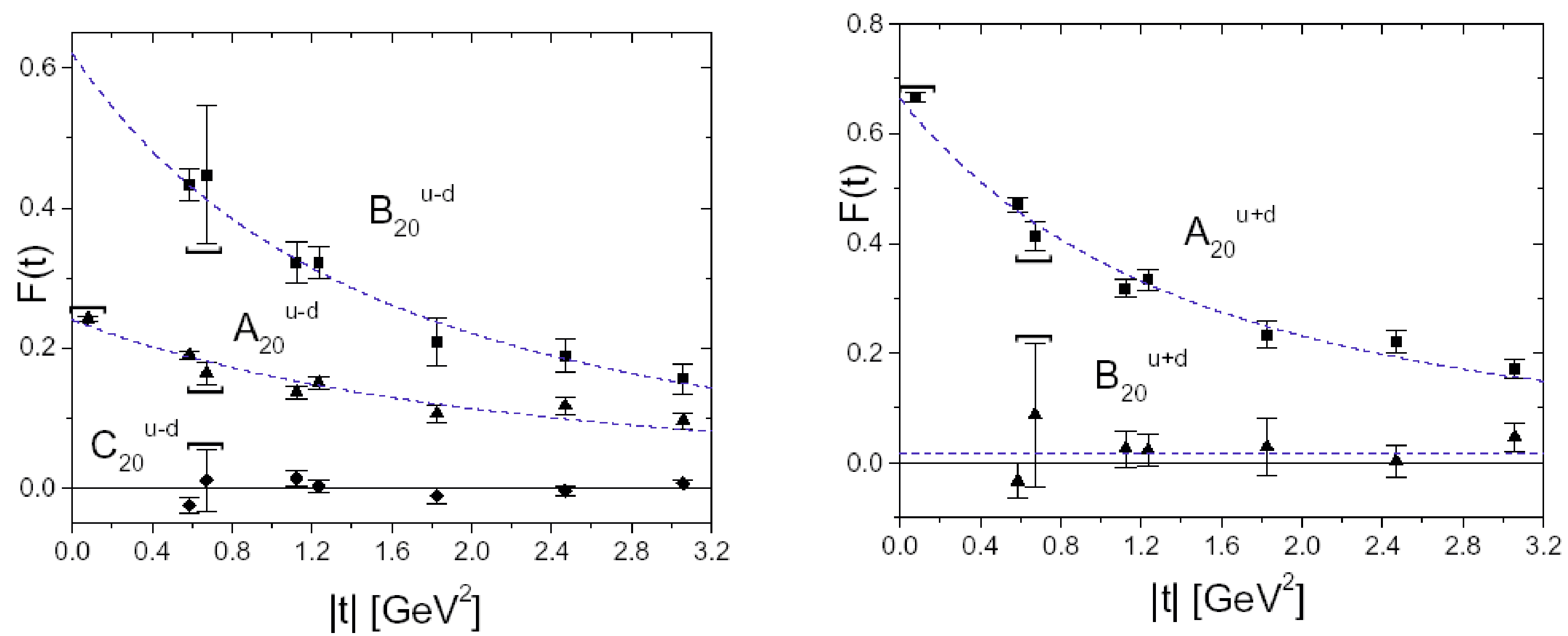
- Orbital and Spin momenta dragging – the same - Equivalence principle

Equivalence principle

- Newtonian – “Falling elevator” – well known and checked (also for elementary particles)
- Post-Newtonian – gravity action on SPIN – known since 1962 (Kobzarev and Okun’; rederived from conservarion laws - Kobzarev and V.I. Zakharov
- Anomalous gravitomagnetic (and electric-CP-odd) moment iz ZERO or
- Classical and QUANTUM rotators behave in the SAME way
- Earth rotation: practical role of quantum measurements: trivial if spin is just a vector
- Dirac equation: valid for arbitrary fields (Obukhov,Silenko,OT; talk of Yu. Obukhov)
- Gravitational analog of Ji’s SR $\int dx\, x\, (\Sigma E_q + E_G) = 0$!

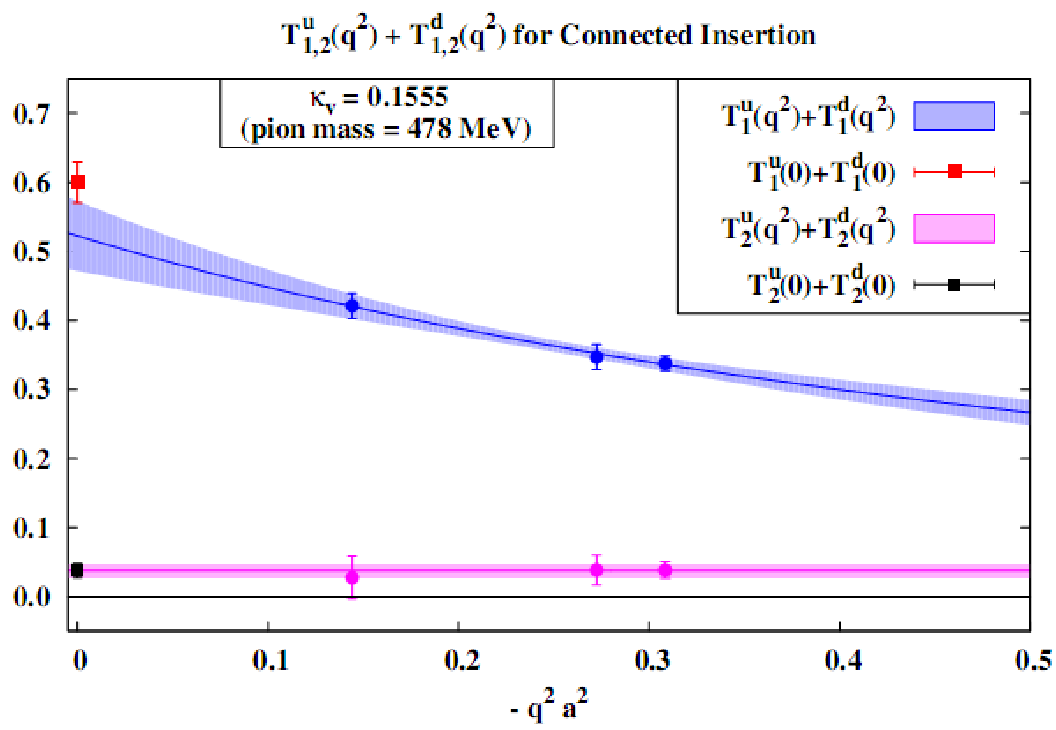
Generalization of Equivalence principle

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



Recent lattice study (M. Deka et al. Phys.Rev. D91 (2015) no.1, 014505)

- 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
- Gravityproof confinement? Nucleons are not broken even by black holes?
- Support by recent observation of smallness of ("hadronic cosmological constant") Cbar
- Actually used when pressure of quarks is extracted!

From hadrons to heavy ions via light nuclei: deuteron (Spin 1 in QC)D

- Tensor polarization in QCD: Frankfurt, Strikman (81), Efremov,OT (81)
- Spin ½: kinematically enhanced longitudinal polarization; transverse – power suppressed twist 3 (and higher: talk of A. Vladimirov)
- Spin 1: LL/TT related by tracelessness

SUM RULES

- We (A.V. Efremov,OT’81) derived zero sum rules:
- 1st moment: also in parton model by Close and Kumano (90)
- 2nd moment (forward analog of Ji’s SR)
- Average shear (traceless tensor) force (compensated between quarks and gluons)
- Gravity and (Ex)EP (zero average shear separately for quarks and gluons) – OT’09

Manifestation of post-Newtonian (Ex)EP for spin 1 hadrons

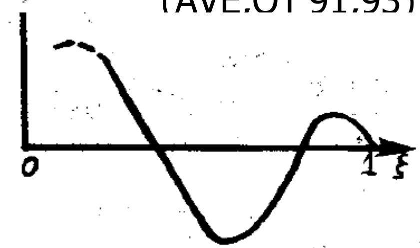
- Tensor polarization - coupling of EMT to spin in forward matrix elements - inclusive processes
- Second moments of tensor distributions should sum to zero

$$A_T = \frac{\sigma_+ + \sigma_- - 2\sigma_0}{3\bar{\sigma}}$$

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

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

(AVE,OT'91,93)



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

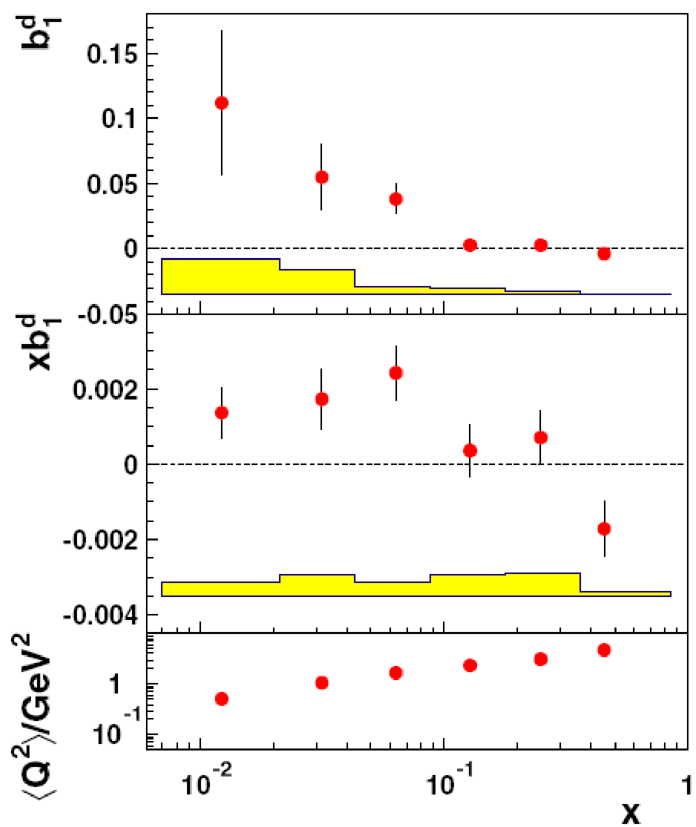
$$\langle P,S|T_g^{\mu\nu}|P,S\rangle_{\mu^2} = 2P^\mu P^\nu \delta(\mu^2) - 2M^2 S^{\mu\nu}\delta_1(\mu^2)$$

$$\sum_q \int_0^1 C_i^T(x)x dx = \delta_1(\mu^2) = 0$$ 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 (Ex)EP
- Second moments – compatible to zero better than the first one (collective glue << sea)



Where else to test?

- COMPASS/AMBER?
- EIC?
- DY@J-PARC: (Song,Kumano:1902.04712)
- However: ET'81-any hard process
- $f_{Al} \sim b_1$

$$P_{zz} = -2P_{yy} = -2P_{xx} = \frac{2\int_0^1 d\xi\, f_{Al}(\xi)\, \mathrm{Sp}[\hat{P} E(\xi, P)]}{3\int_0^1 d\xi\, f(\xi)\, \mathrm{Sp}[\hat{P} E(\xi, P)]} = \frac{2F_{Al}(x_1, x_2)}{3F(x_1, x_2)},$$

- Suggestion: hadronic tensor SSA(OT'19)

Vector vs Tensor SSA

- Vector: $A = (\sigma(+)-\sigma(-))/(\sigma(+)+\sigma(-))$

- Tensor:
  $A = (\sigma(+)+\sigma(-))/(\sigma(+)+\sigma(-)+\sigma(0))$

- Inclusive pion production: (T-odd) vector SSA may be also excluded by summing $\sigma(L)+ \sigma(R)$

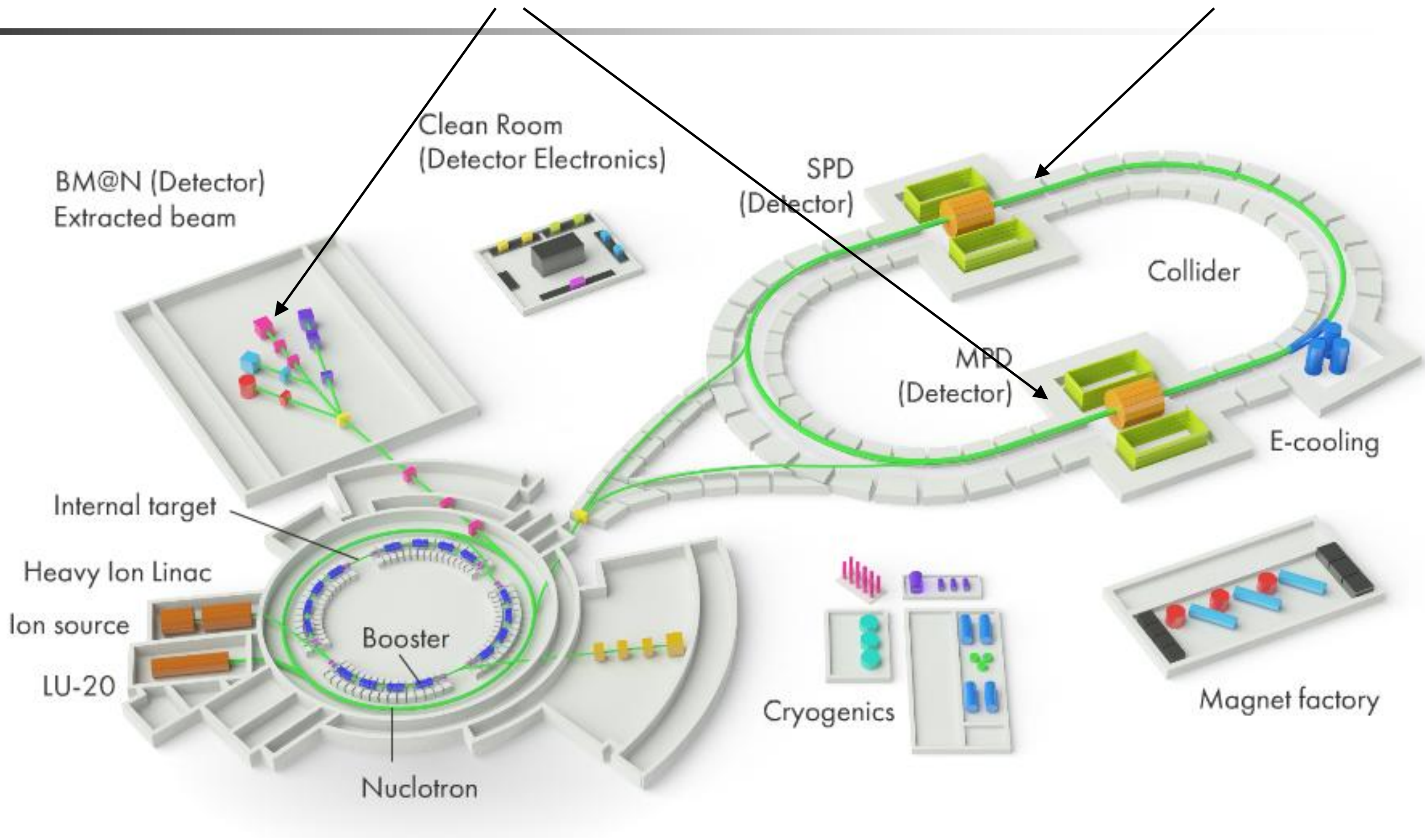
Tensor polarized beams

- Opportunity: NICA@JINR with polarized hadronic beams: SPD (and MPD?)

- Polarized deuterons is easier to accelerate: no depolarizing resonances
- Good starting point!

- DY, J/Ψ (+hadronic SSA)

NICA: heavy ions and hadrons



Conclusions/Outlook

- Same ingredients in hadrons and heavy ions – in different ways!
- Scattering plane -> Reaction plane
- Interference -> LS via anomaly
- Phases -> dissipation in core of vortices in pionic superfluid

- Strongest ever inertial effects (rotation and acceleration): role of gravity
- Gravitational Ffs of hadrons – pressure and shear
- May be studied at NICA with tensor polarized beams

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

Polarization at NICA/MPD (A. Kechechyan)

- QGSM Simulations and recovery accounting for MPD acceptance effects