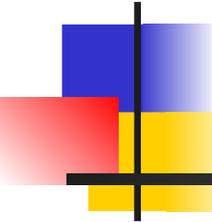


Comparing single spin asymmetries in hadronic and heavy-ion collisions

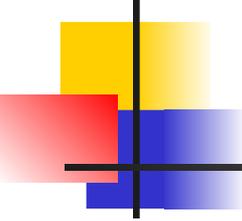
Correlations in Partonic and Hadronic Interactions
(CPHI-2020)

The CERN logo graphic consists of a vertical black line intersecting a horizontal black line. To the left of the vertical line, there are three overlapping squares: a blue one at the top, a red one in the middle, and a yellow one at the bottom. The word "CERN" is written in blue text to the right of the vertical line.

CERN

February 6 2020

Oleg Teryaev (JINR)



Main Topics

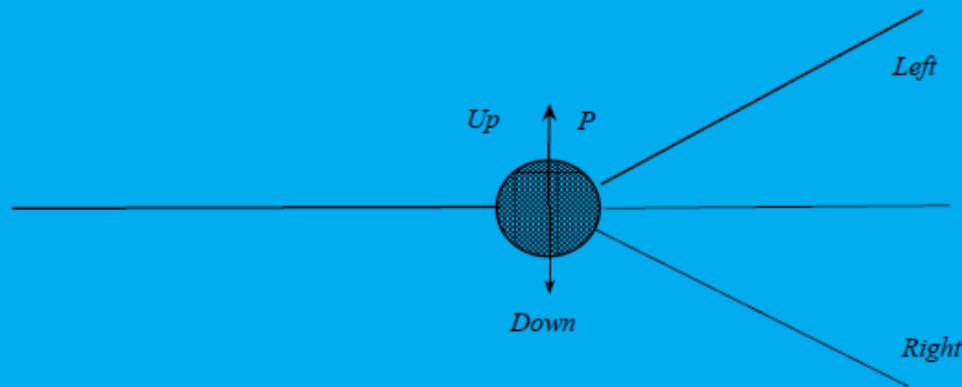
- Properties of SSA:
 - Parity conservation: normal to **some** plane
 - LS-coupling: anomaly in fluid
 - T- reversal: phases vs **dissipation**

- Other link between hadrons and medium: **shear viscosity?**

- Conclusions

Single Spin Asymmetries

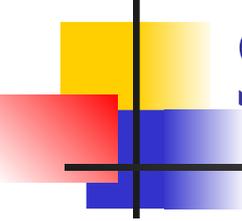
Simplest example - (non-relativistic) elastic pion-nucleon scattering $\pi \vec{N} \rightarrow \pi N$



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

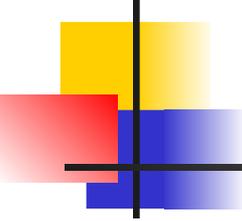
Density matrix: $\rho = \frac{1}{2}(1 + \vec{\sigma}\vec{P})$,

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



SSA

- Parity conservation – normal to scattering plane
- Interference – **LS** coupling: $S(\mathbf{r} \times \mathbf{p}) \rightarrow S(\mathbf{k} \times \mathbf{p}) \sim S_n$
- T conservation – absorptive phases



Phases and T-oddness

Clearly seen in relativistic approach:

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

Then: $d\sigma \sim \text{Tr}[\gamma_5 \dots] \sim im\epsilon_{sp_1p_2p_3\dots}$

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

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

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

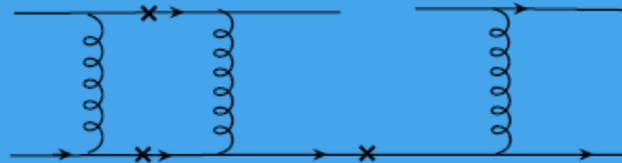
SSA - either T -violation or the phases.

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):

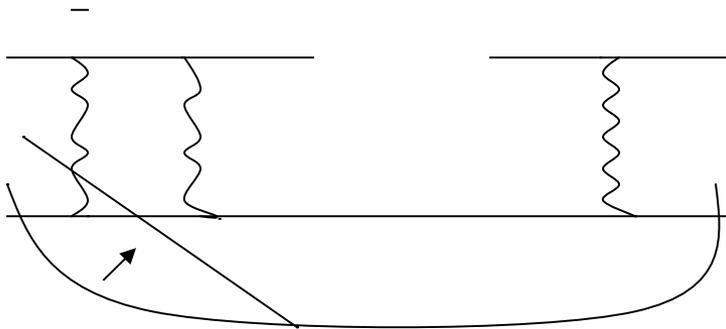


$$A \sim \frac{\alpha_S^{m_{PT}}}{p_T^2 + m^2}$$

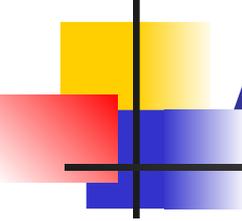
Large SSA "...contradict QCD or its applicability"

Short+ large overlap– twist 3

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

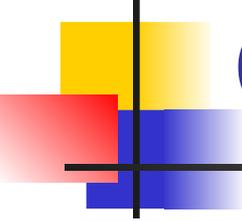


- New option for SSA: Instead of 1-loop twist 2 – Born twist 3 (quark-gluon correlator): Efremov, OT (85, Fermionic poles); Qiu, Sterman (91, **GLUONIC** poles -> **disappearance** of M/Q suppression (Brodsky, Hwang, Schmidt) - > **Sivers** function: large distances + gauge link)



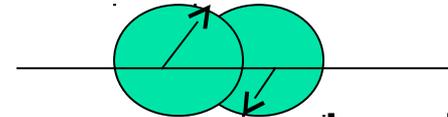
From hadrons to heavy ions; Λ -polarisation

- 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 (collective) **REACTION** plane
- Cf to other more involved P-even constructions from quark/hadron momenta (**Kotzinian-Mulders asymmetry**)
- Search by STAR (Selyuzhenkov et al.'07) : polarization NOT found at % level!
- BUT found by STAR at **lower** energy



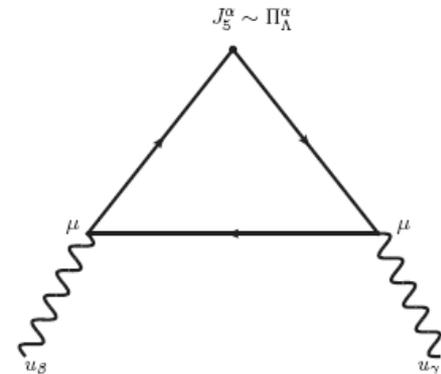
Global $\Lambda\Lambda$ hyperon polarization in nuclear collisions: evidence for the most vortical fluid
STAR Collaboration (L. Adamczyk (AGH-UST, Cracow) *et al.*). Jan 23, 2017. 21 pp.
Published in **Nature 548 (2017) 62-65**

Anomalous mechanism of polarization

- Covariant way to incorporate chemical potential: 4-Velocity is also a **GAUGE FIELD (V.I. Zakharov) but no GI (Wilson lines??!)**

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

- Triangle anomaly leads to polarization of quarks and hyperons (Rogachevsky, Sorin, OT '10)
- Analogous to anomalous gluon contribution to nucleon spin (Efremov, OT'88) **BUT** velocity instead of gluon
- **Chemical potential – decreases with energy!**



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

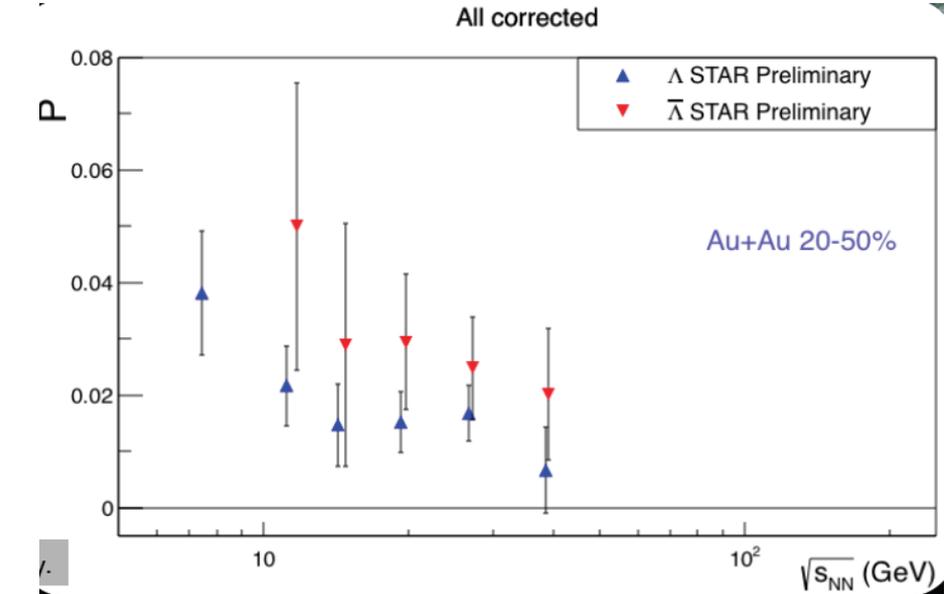
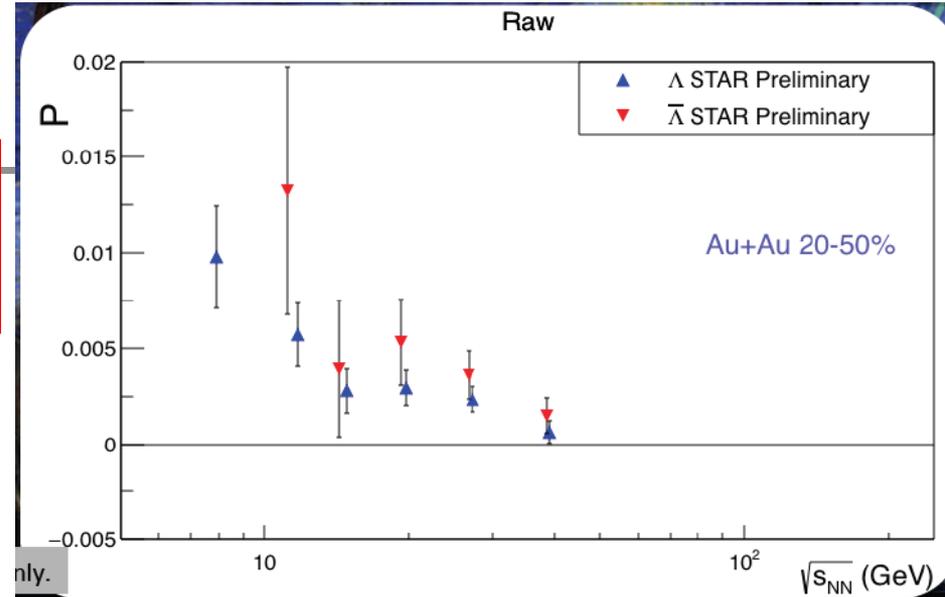
PHYSICAL REVIEW C 82, 054910 (2010)

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

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

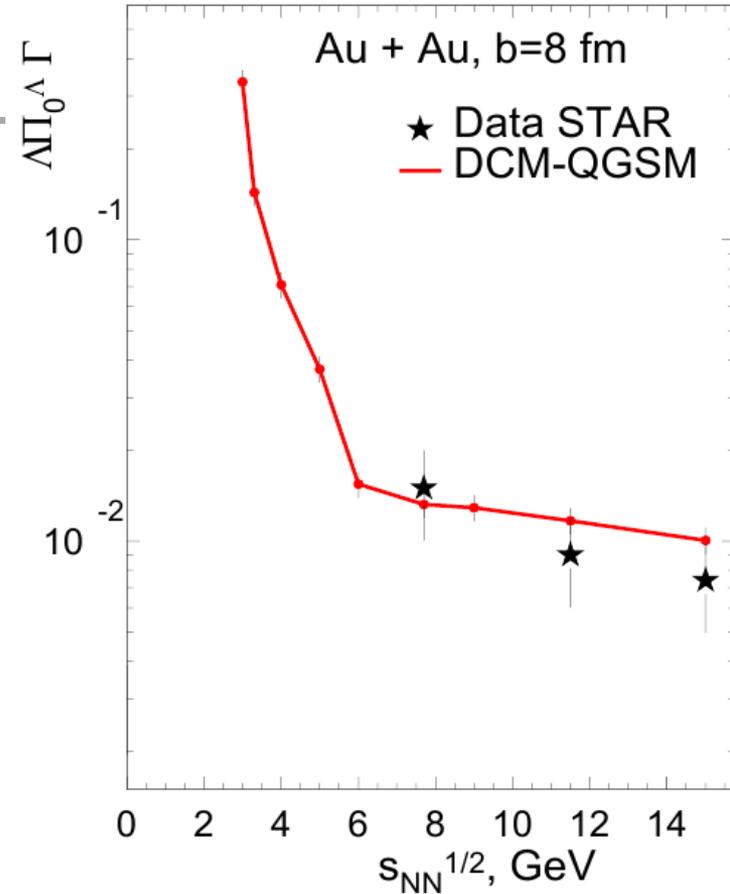
where n and ϵ are the corresponding charge and energy densities and P is the pressure. Therefore, the μ dependence of polarization must be stronger than that of the CVE, leading to the effect's increasing rapidly with decreasing energy.

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.



Energy dependence

- Growth at low energy
- Close to STAR data



Where is phase?! 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)

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

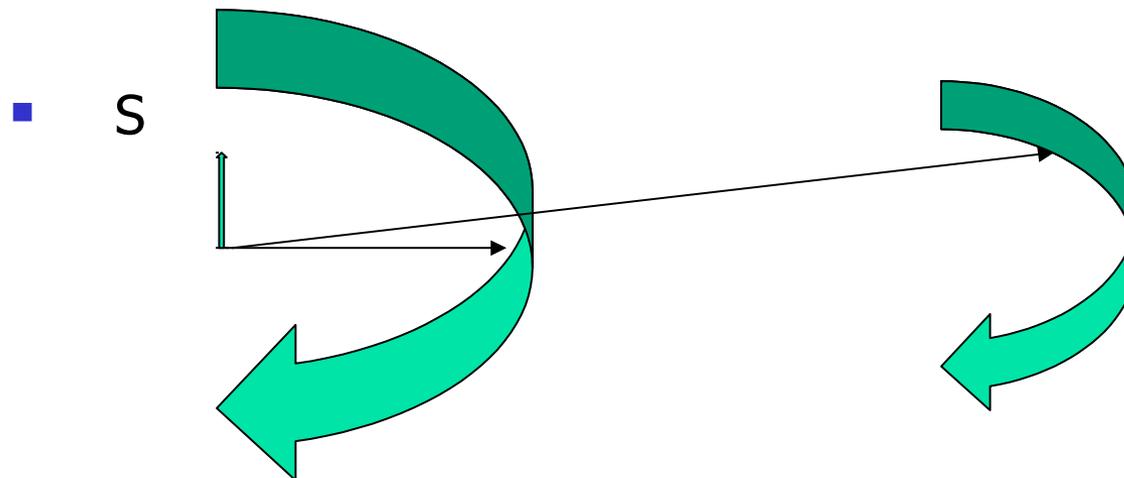
$$T_{0i} \sim \mu_5 \partial_i \tilde{\varphi}, \quad \lim_{q_i \rightarrow 0, \omega \equiv 0} \langle T_{0i}, T_{0k} \rangle \sim \mu_5^2 \frac{q_i q_k}{q_i^2}$$

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

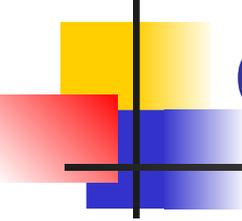
- Suggestion: core of the vortex- baryonic degrees of freedom- polarization

Core of quantized vortex

- Constant circulation – velocity increases when core is approached



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

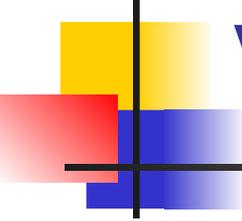


Baryon spin as radiative correction

- Kinematical requirement of spin appearance – similar to “historical” arguments: $v \sim c$ at Compton wavelength and $v \gg c$ at classical radius required for orbital momentum
- Baryons emerge as UV cutoff
- Transition to UV – **dissipation (counterpart of absorptive phases!?)**

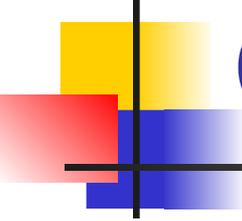
Other relation between hadrons and heavy ions (and dissipation): Shear viscosity (OT'19)?!

- From spherically symmetric object to fluid (EoS!)
- $T_{\mu\lambda} = (e+p) v_{\mu} v_{\lambda} - p g_{\mu\lambda}$
- $V_{\mu} = P_{\mu}/M$: correct normalization but no coordinate dependence
- Another suggestion:
- $V_{\mu} = (P_{\mu} + a(t) k_{T\mu}) / (M^2 + a^2(t) k_T^2)^{1/2}$
- Viscosity: $\sim \eta p^{[\mu} \Delta^{\lambda]}$
Naïve T-oddness: phases



Viscosity in crossed channel

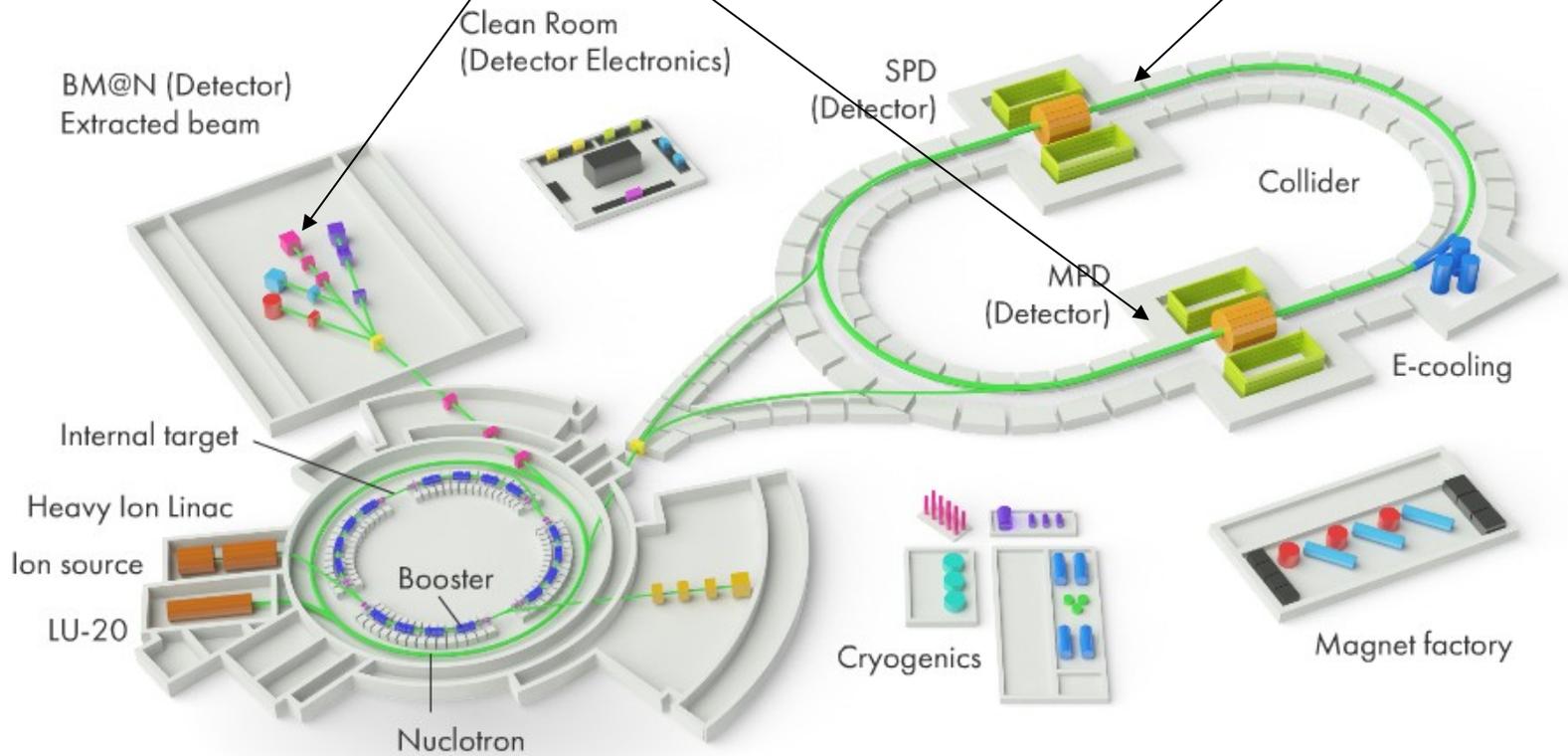
- Possibility to study gravitational FFs in time-like region by meson pair production in real and virtual photons collisions (Kumano, Song, OT'18; talk of M. Polyakov)
- **Viscosity (new!): will correspond to**
- **Exotic $J^{PC}=1^{-+}$** meson (already studied earlier: Anikin, Pire, Szymanowski, OT, Wallon'06)
- $\pi\eta$ pairs observation instead of $\pi\pi$ required
- Smallness of viscosity in HIC: related to smallness of T-odd GPDs and exotic GDAs ?!

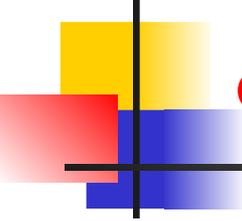


Conclusions/Outlook

- Hadrons -> heavy ions: new (sometimes unexpected) counterparts of SSA theory
- Way to viscosity? **Holographic** (cf M. Polyakov talk) bound? AdS/QCD (Brodsky, De Teramond et al.?)
- Heavy ions – **highest ever** rotation frequency and acceleration (\sim **gravity** due to (also **generalized - separately for q/g**) equivalence principle): Hawking-Unruh radiation (Prokhorov, V.I. Zakharov, OT, PRD'17-19 and work in progress) etc...
- HIC – new gravity lab??

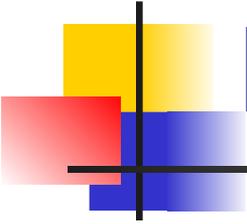
NICA: heavy ions and hadrons



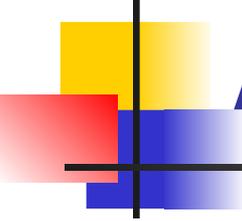


HAPPY BIRTHDAY to STAN and ARAM!

- Many thanks to **Harut and Bakur** and everybody for attention!



BACKUP

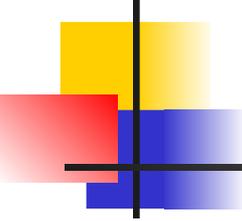


Anomaly for polarization

- 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

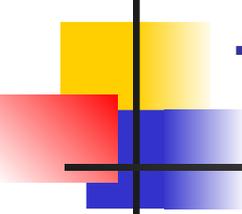


Energy dependence

- 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

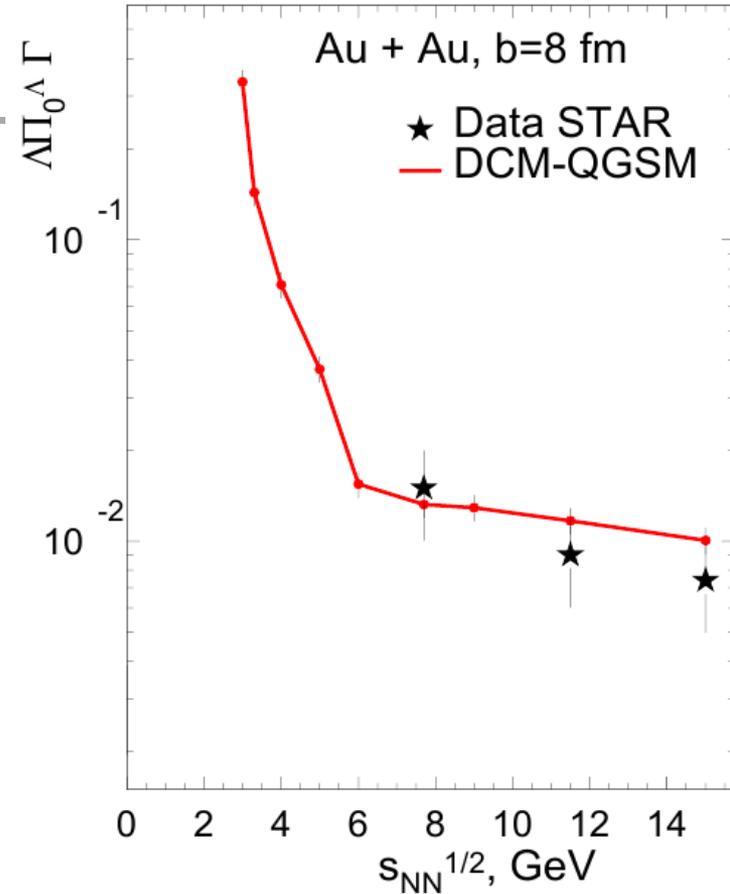


Microworld: where is the fastest possible rotation?

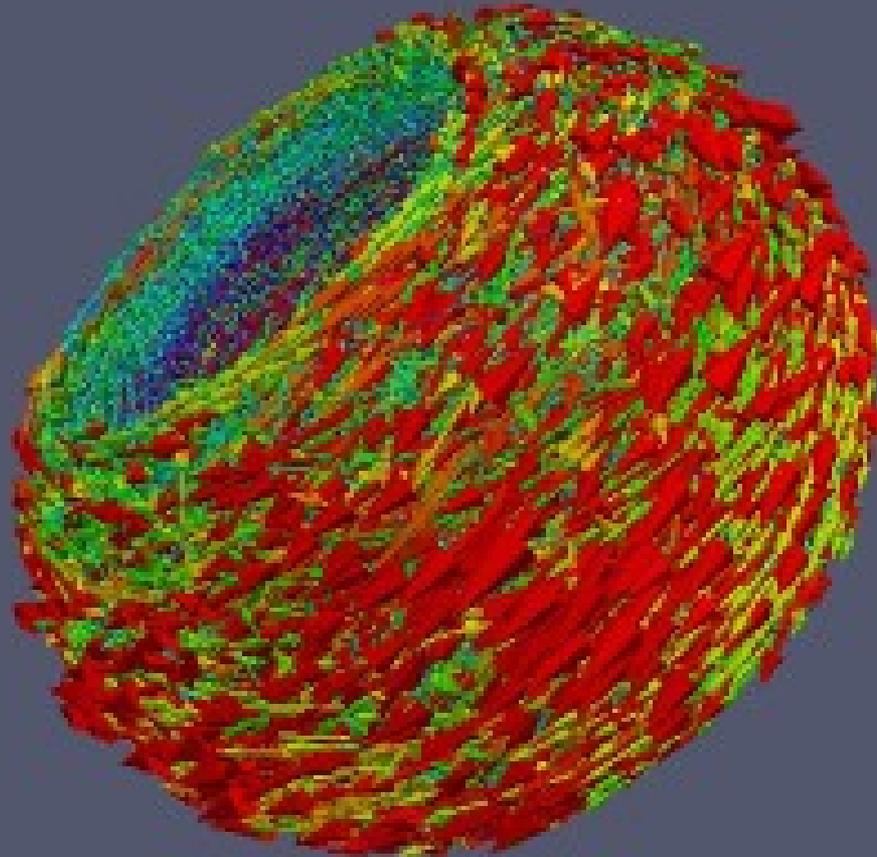
- Non-central heavy ion collisions (Angular velocity $\sim c/\text{Compton wavelength}$)
- ~ 25 orders of magnitude faster than Earth's rotation
- Differential rotation – vorticity
- P-odd :May lead to various P-odd effects (e.g. handedness – talk of A. Martynova)
- Calculation in kinetic quark - gluon 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

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

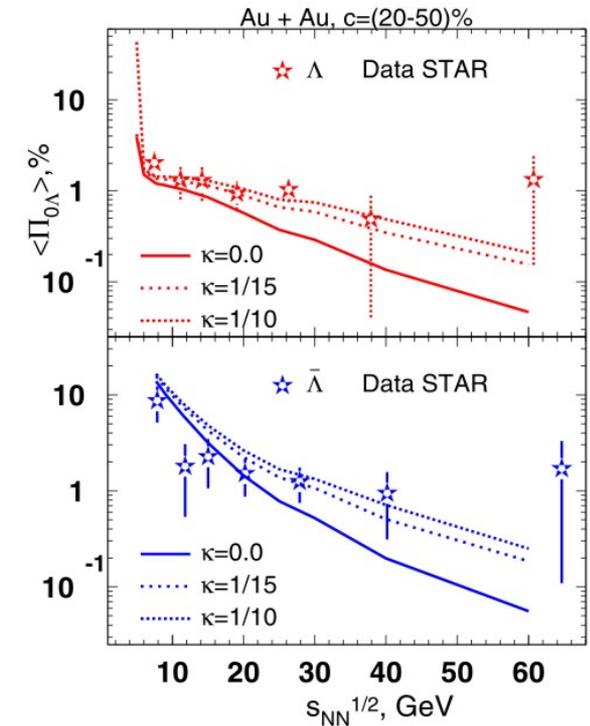
- Lorentz boost: compensated by the sign of helicity mirror structure (BGST'13; talk of Alexei Zinchhenko)

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

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

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)



Anomaly vs TD (talk of G. Prokhorov)

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

$$\langle : j_\mu^5 : \rangle = \left(\frac{1}{6} \left[T^2 + \frac{a^2 - \omega^2}{4\pi^2} \right] + \frac{\mu^2}{2\pi^2} \right) \omega_\mu + \frac{1}{12\pi^2} (\omega \cdot a) a_\mu \quad \alpha_\mu = \frac{1}{T} u^\nu \partial_\nu u_\mu = \frac{a_\mu}{T}, \quad w_\mu = \frac{1}{2T} \epsilon_{\mu\nu\alpha\beta} u^\nu \partial^\alpha u^\beta = \frac{\omega_\mu}{T}$$

$$\langle : j_\mu^5 : \rangle = 2\pi \operatorname{Im} \left[\left(\frac{1}{6} (T^2 + \varphi^2) + \frac{\mu^2}{2\pi^2} \right) \varphi_\mu \right] \quad \varphi_\mu = \frac{a_\mu}{2\pi} + \frac{i\omega_\mu}{2\pi}$$

- $H+iE \leftrightarrow \omega + ia$ (“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)

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

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

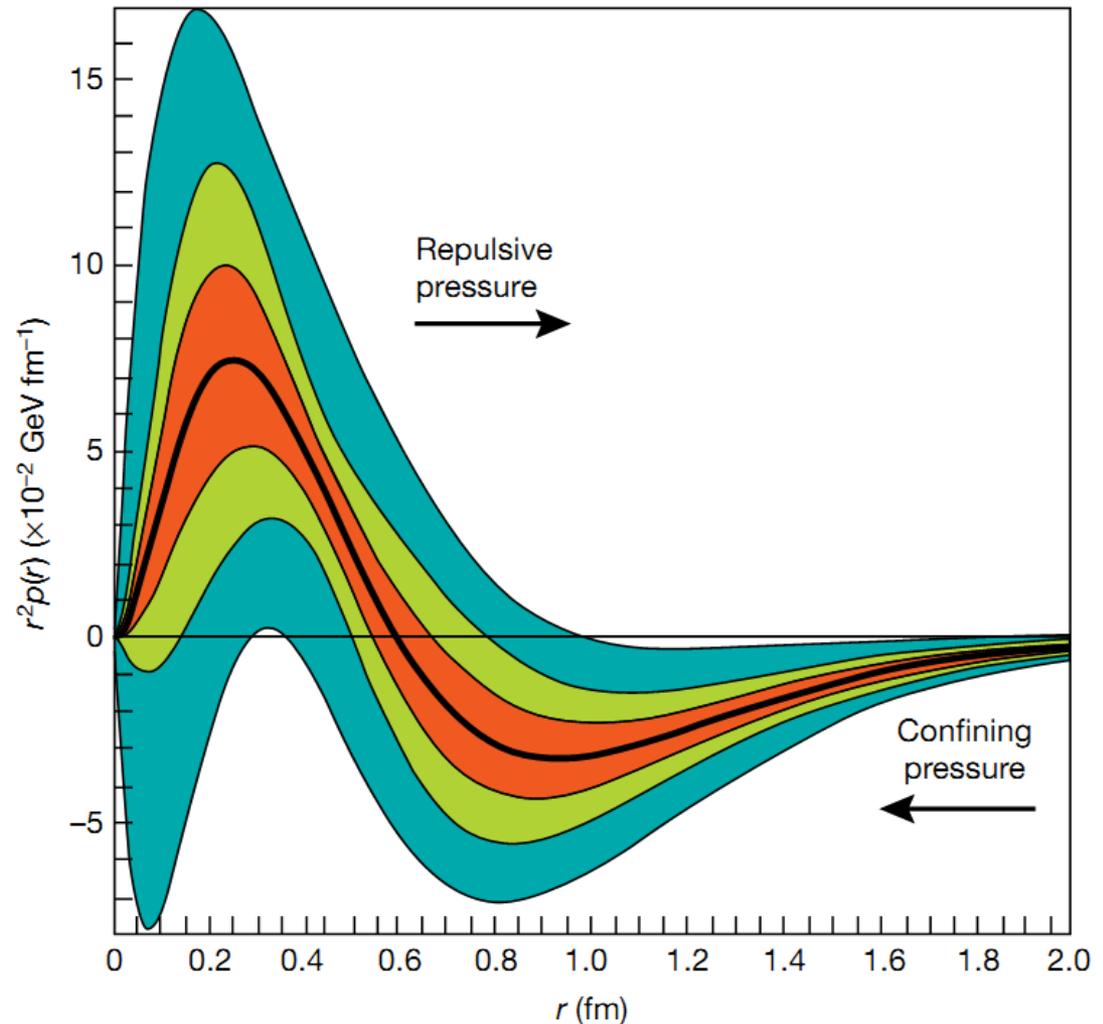
$$P_{q,g} = A_{q,g}(0) \quad A_q(0) + A_g(0) = 1$$

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

- May be extracted from high-energy experiments/NPQCD calculations
- Describe the partition of angular momentum between quarks and gluons **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

The pressure distribution inside the proton

V. D. Burkert^{1*}, L. Elouadrhiri¹ & F. X. Girod¹



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

- 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

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

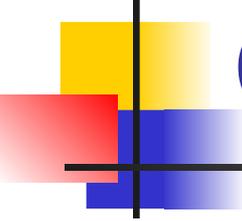
$$\sum_{q,G} \langle P | T_i^{\mu\nu} | P \rangle = 2P^\mu P^\nu$$

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

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

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

- Mass as charge – equivalence principle



Gravitomagnetism

- Gravitomagnetic field (weak, except in gravity waves)
 - action on spin from

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

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

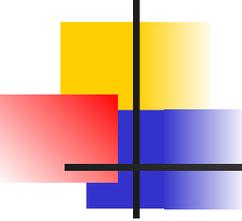
spin dragging twice
smaller than EM

- Lorentz force – similar to EM case: factor 1/2 cancelled with 2 from as EM

$$h_{00} = 2\phi(x) \quad \text{armor frequency same}$$

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

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

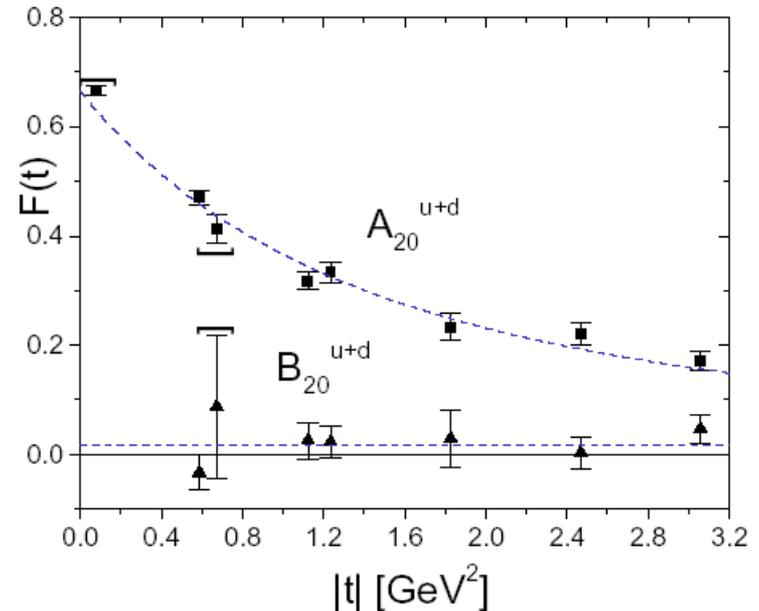
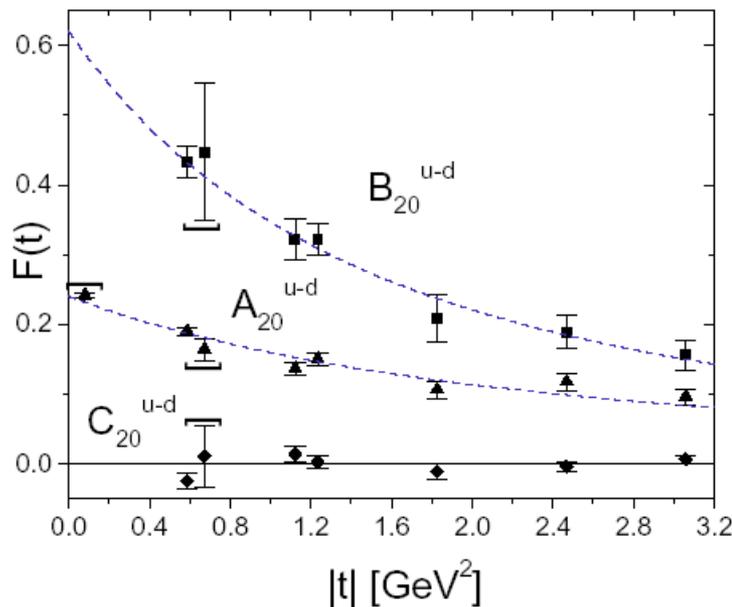


Equivalence principle

- 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 V.I. Zakharov)
- Anomalous gravitomagnetic (and electric-CP-odd) moment is 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 $\int dx \times (\Sigma E_q + E_G) = 0!$

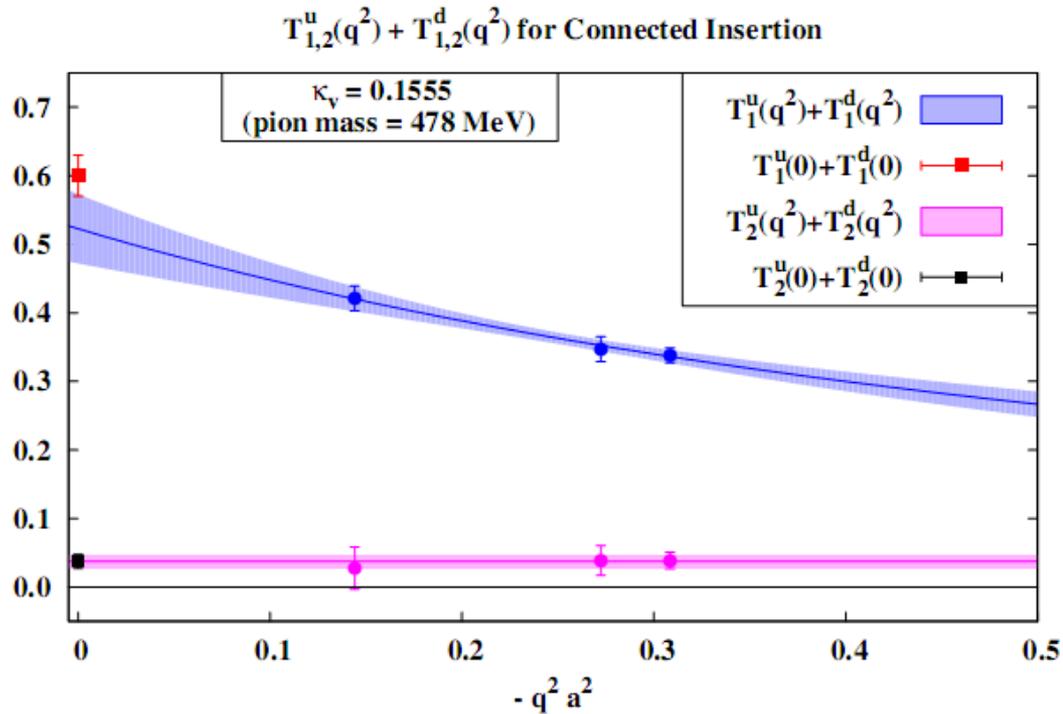
Generalization of Equivalence principle

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



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

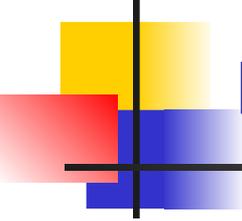
- Sum of u and d for Dirac (T1) and Pauli (T2) FFs



Extended Equivalence

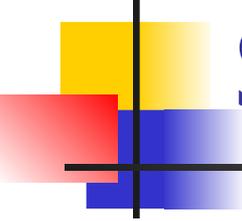
Principle=Exact EquiPartition

- 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”) C_{bar}
- 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 $1/2$: 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

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

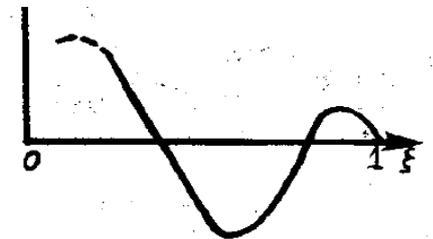
$$\langle P, S | \bar{\psi}(0) \gamma^\nu D^{\nu_1} \dots D^{\nu_n} \psi(0) | P, S \rangle_{\mu^2} = i^{-n} M^2 S^{\nu\nu_1} P^{\nu_2} \dots P^{\nu_n} \int_0^1 C_q^T(x) x^n dx$$

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

AVE, OT'91,93)

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

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



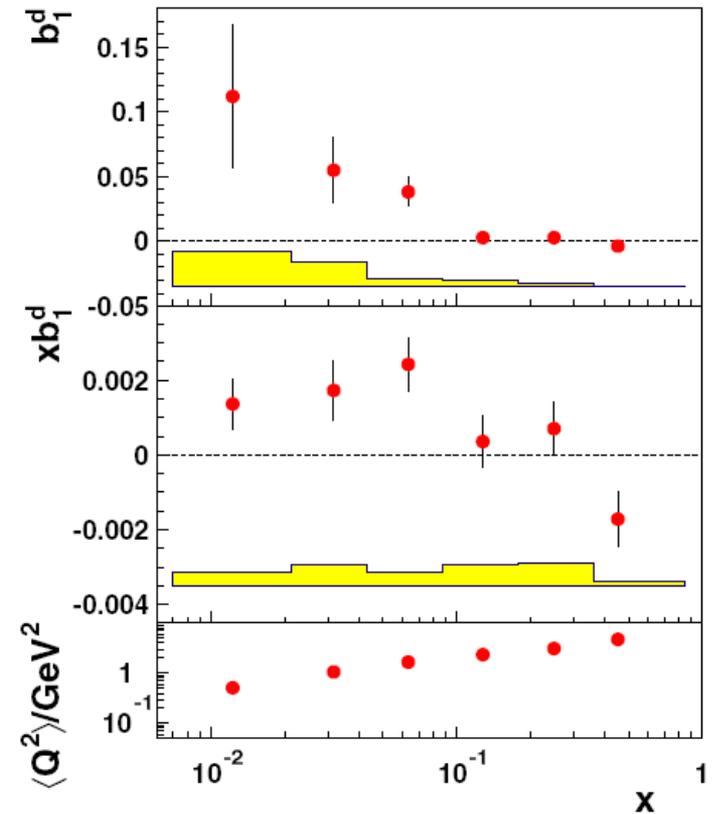
- =0 for ExEP

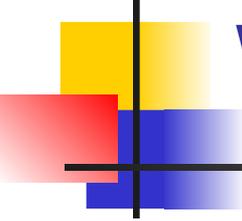
$$\sum_q \int_0^1 C_i^T(x) x dx = \delta_1(\mu^2)$$

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 \ll sea)



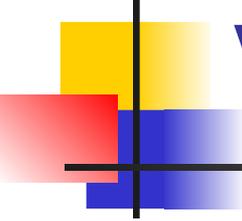


Where else to test?

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

- Suggestion: **hadronic** tensor SSA(OT'19)

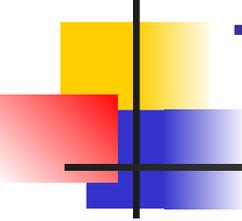
$$\frac{P_{xx} - 2P_{yy} - 2P_{zz}}{3} = \frac{2 \int_0^1 d\xi f_{Al}(\xi) \text{Sp}[\hat{P}E(\xi, P)]^2}{3 \int_0^1 d\xi f(\xi) \text{Sp}[\hat{P}E(\xi, P)]} = \frac{2F_{Al}(x_1, x_2)}{3F(x_1, x_2)}$$



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 $\sigma(L)+\sigma(R)$

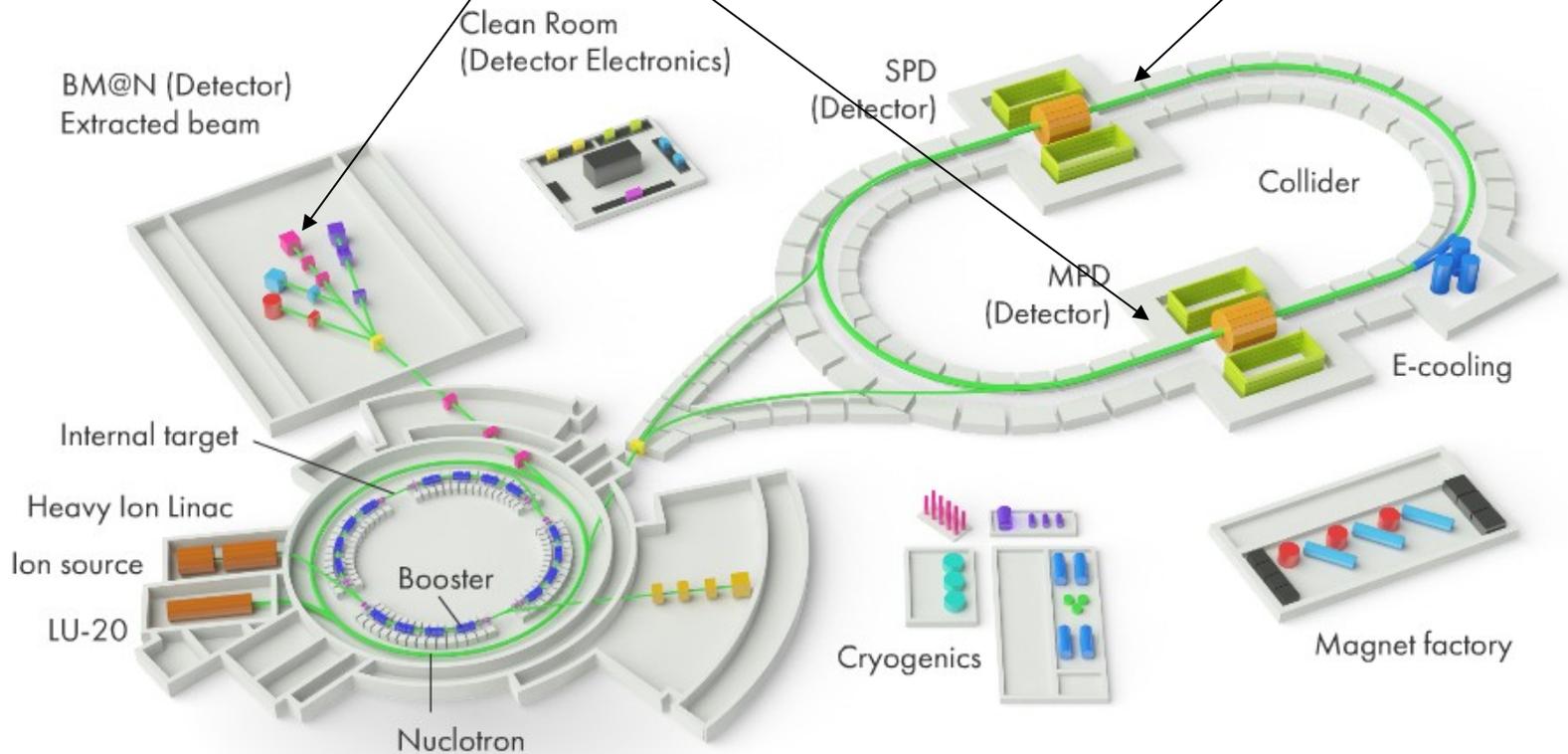
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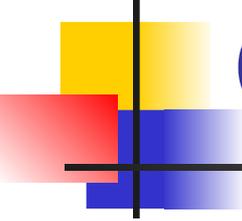


Tensor polarized beams

- 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

Polarization at NICA/MPD (A. Kechechyan)

- QGSM Simulations and **recovery**
accounting for MPD acceptance effects

