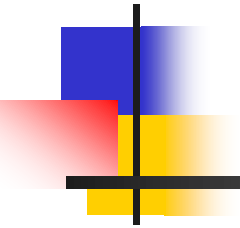
QCD and Gravity



India-JINR scientific meeting

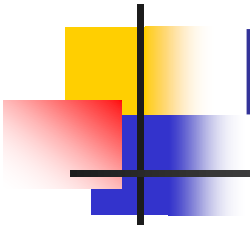
Oleg Teryaev
JINR

October 16, 2023

How strongest (QCD) and weakest (gravity) interactions are related?

- Hadronic matrix elements of energy-momentum tensor operator describe the interaction with classical gravity, and QCD hard exclusive processes

- The medium emergng in heavy-ion collisions manifests the highest ever acceleration and vorticity corresponding according to the Equivalence Principle to the superstrong Effective Gravity



Main Topics

- Equivalence Principle: way to merge strongest and weakest interactions
- Gravitational Formfactors: EP for spin and its Extension
  - D-term, pressure and inflation
  - Spin-1 and average shear
- Heavy ion collisions : highest vorticity and acceleration
  - Anomalous current and polarization (EFT/TD/Gravity)
  - Unruh radiation

Electromagnetism vs Gravity (OT'99)

- Interaction – field vs metric deviation

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

- Static limit

$$\langle P|J^{\mu}_{q}|P\rangle = 2e_{q}P^{\mu} \qquad \sum_{q,G}\langle P|T^{\mu\nu}_{i}|P\rangle = 2P^{\mu}P^{\nu}$$

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

$$M_0 = \langle P|J^{\mu}_{q}|P\rangle A_{\mu} = 2e_{q}M\,\phi(q) \qquad M_0 = \frac{1}{2}\sum_{q,G}\langle P|T^{\mu\nu}_{i}|P\rangle h_{\mu\nu} = 2M\cdot M\phi(q)$$

- Mass as charge – equivalence principle

EP and hadron structure

- "Microscopic" EP (coupling of gravity to EMT)
- +
- Conservation law
  (Momentum SR to get local from LC pdf's):
  $\int dx\, x\, (\Sigma\, q(x) + G(x)) = 1)$
- =
- "Macroscopic" EP (universal falling) :
- Tested VERY precisely

Gravitational Formfactors (Pagels'66, Ji'97,…
A. Mukherjee, D. Chakrabarti, H. Dahiya)

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

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

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

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

- No M_{Pl}! May be extracted from high-energy experiments/NPQCD calculations
- Describe the partition of angular momentum between quarks and gluons Ji's SRs
- Describe interaction with both classical and TeV gravity

Ji's and 1st moment "mass" SRs: Generalized Parton Distributions imply models for both EM and Gravitational Formfactors (Selyugin,OT '09)

- Smaller mass square radius (attraction vs repulsion ☺): follows from Regge behaviour of GPDs ~ $x^{a(t)}$ (cf AdS QCD)

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

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

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

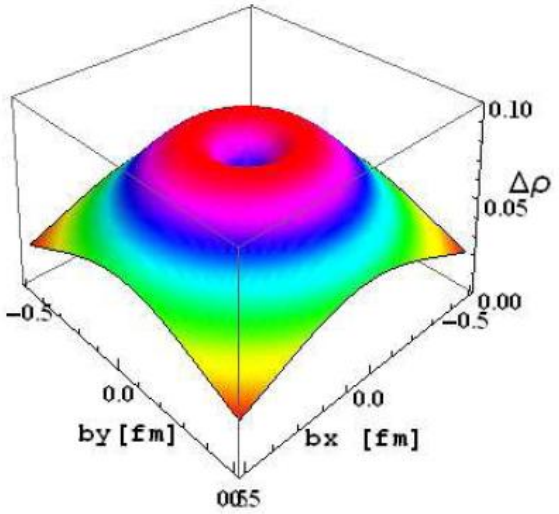
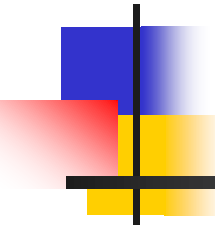


FIG. 17: Difference in the forms of charge density F_1^P and "matter" density (A)

The XIXth Workshop
on High Energy Spin Physics
dedicated to 90th anniversary of A.V. Efremov birth

September 4 - 8, 2023
Dubna, JINR, Russia



GPDs and gravitational form factors of nucleons (quark and gluon contributions)

O.V. Selyugin, O.V. Teryaev
BLTPh, JINR

Summary

- *The quarks gravitational form factor A_q is represented by dipole form*
- *With $L^2 = 1.6\ GeV^2$*

- *Using various parameterization of gluons GPDs we obtain the gravitational form factor A_g*
- *It can be represented by multipole form with n=3 and L^2 around 0.9*

- *The gluons gravitational radius is approximately equal to the electromagnetic one*

COMMENTS:
Different behaviour of gluonic GrFF may be related to extra dimension of quark-gluon LCWF (Interesting to check in the models)

Similarity of quark and gluon radii ("quark-gluon duality"): relation to extension of Equivalence Principle?

TMD/GPD relations (Chakrabarti, Maji,Mondal, OT'15)-radii from kt dpendence of TMDs?

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 (quantum!) 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 V.I. Zakharov
- Anomalous gravitomagnetic (and electric-CP-odd) moment iz ZERO or
- Classical and QUANTUM rotators behave in the SAME way

Experimental test of PNEP

- Reinterpretation of the data on G(EDM) search

PHYSICAL REVIEW
LETTERS

VOLUME 68 | 13 JANUARY 1992 | NUMBER 2

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

B. J. Venema, P. K. Majumder, S. K. Lamoreaux, B. R. Heckel, and E. N. Fortson
Physics Department, FM-15, University of Washington, Seattle, Washington 98195
(Received 25 September 1991)

- If (CP-odd!) GEDM=0 -> constraint for AGM (Silenko, OT'07) from Earth rotation – was considered as obvious (but it is just EP!) background
- New high precision EDM experiments: gravity is essential (NN Nikolaev,Vergeles,Silenko,...)

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

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

EP and quantum measurement

- If spin is just a geometric vector, EP for Earth's rotation is "trivial": spin rotates with Earth's angular velocity like Foucault pendulum
- Non-trivial if quantum measurement (quite practical here) is performed in the rotating frame

Equivalence principle for moving particles EPII vs EPI

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

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

- 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,'13,16,17: also the same dynamocs for classical and quantum rotators ("EP for strong fields")

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 ($\sim \mathbf{P}^2$) 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) and
- Flip by "gravitoelectric" field: relic neutrino (Anisotropic Universe: Kamenshchik,OT'15)? Black hole?

$$\frac{d\sigma_{+-}}{d\sigma_{++}} = \frac{tg^2(\frac{\phi}{2})}{(2\gamma - \gamma^{-1})^2}$$

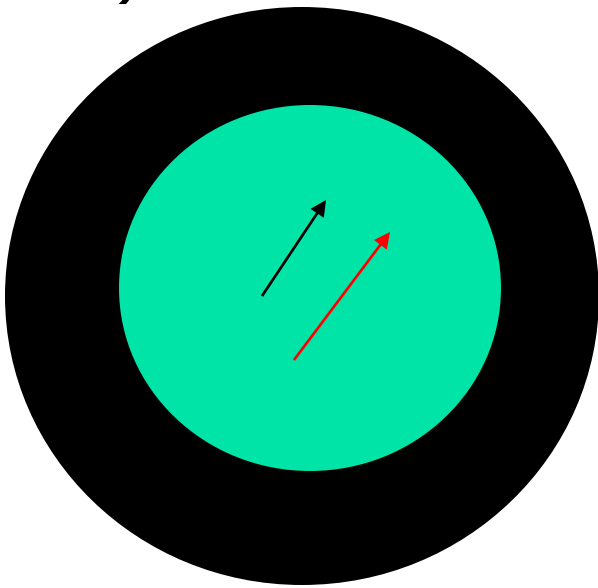
Gyromagnetic and Gravigyromagnetic ratios

- Free particles – coincide
- $\langle P+q|T^{mn}|P-q\rangle = P^{\{m}\langle P+q|J^{n\}}|P-q\rangle/e$ up to the terms linear in q
- Gravitomagnetic g=2 for any spin
- 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?!

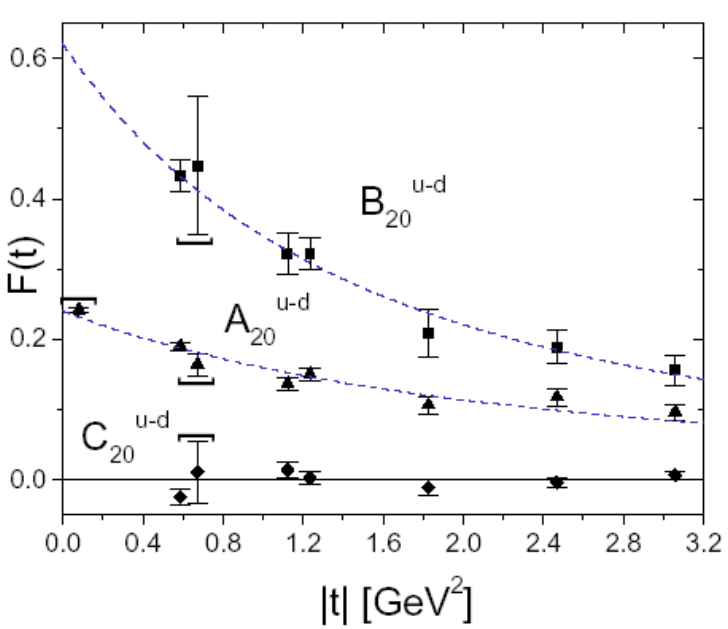
Cosmological implications of PNEP

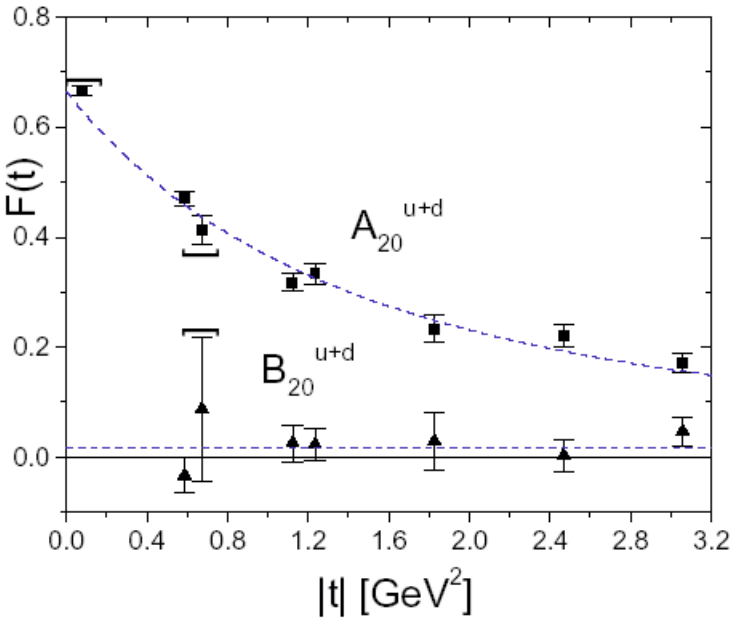
- Necessary condition for Mach's Principle (in the spirit of **S.Weinberg's** textbook-Section 9.7)
- Lense-Thirring inside massive rotating empty shell (=model of Universe)
- For flat "Universe" - precession frequency equal to that of shell rotation
- Simple observation-Must be the same for classical and quantum rotators – PNEP!
- More elaborate models - Tests for cosmology ?!



Extension of Equivalence principle

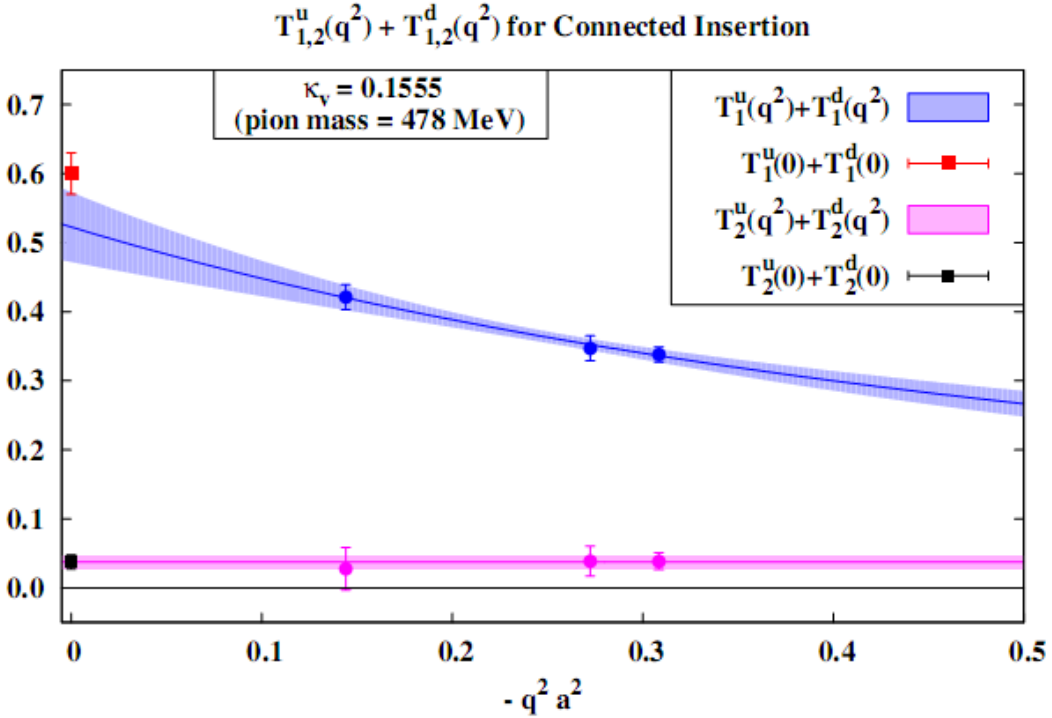
- Various arguments: AGM ≈ 0 separately for quarks and gluons – most clear from the lattice (LHPC/SESAM)





More recent lattice study (M. Deka,…K.-F. Liu 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 NLO pQCD – violated (LF:S.Brodsky et al.)
- Reason – in the case of ExEP- no smooth transition for zero fermion mass limit (Milton, 71)
- 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 do not break even by black holes?! Match BH complementarity?! "GeV Gravity"?
- Support by recent observation of smallness of EP-forbidden "Cosmological Constant"

Exact Equipartition and Pivot

- Important notion introduced by C. Lorce to relate transverse spin SR's of Ji&Yuan and Leader et al.
- Naïve interpretation of ExEP: common (approximately, averagely) pivot for quarks and gluons:
- $\langle J_{T(q,G)} \rangle = \langle x_0 \rangle \langle P_{L(q,G)} \rangle$
- Can this be satisfied for some of pivot choices?

Quadrupole formfactor: Inflation and annihilation

- Quadrupole gravitational FF

$$\langle P+q/2|T^{\mu\nu}|P-q/2\rangle = C(q^2)(g^{\mu\nu}q^2 - q^\mu q^\nu) + \ldots$$

- Vacuum – Cosmological Constant

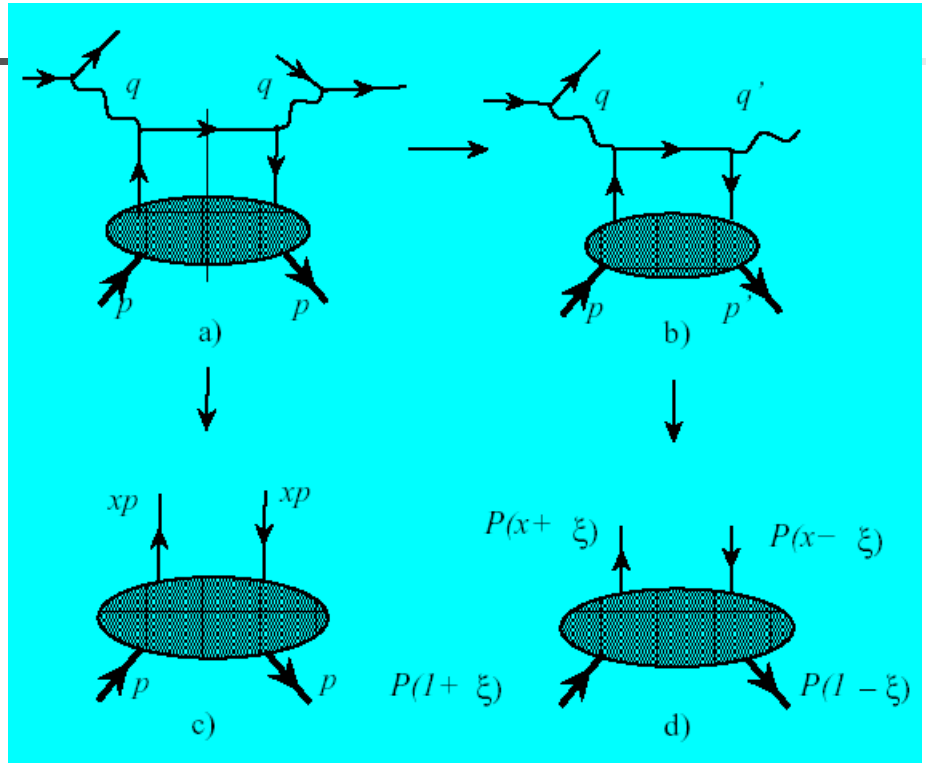
$$\langle 0|T^{\mu\nu}|0\rangle = \Lambda g^{\mu\nu}$$

- 2D effective CC – negative in scattering, positive in annihilation

$$\Lambda = C(q^2)q^2$$

- Similarity of inflation and Schwinger pair production – Starobisnky, Zel'dovich
- Was OUR Big Bang resulting from one graviton annihilation at extra dimensions??! Version of "ekpyrotic" ("pyrotechnic") universe
- Traceless+Trace =
- M_I: (3/4+1/4) X.Ji'96
- M_{Gr}: (3/2-1/2) OT'99 ("Antigravity": seen in trace part of Einstein Eqs)
- Access: D-term in GPDs

Way to D-term: cf QCD Factorization for DIS and DVCS (AND VM production)



- Manifestly spectral

$$\mathcal{H}(x_B) = \int_{-1}^{1} dx \frac{H(x)}{x - x_B + i\epsilon}$$

- Extra dependence on ξ

$$\mathcal{H}(\xi) = \int_{-1}^{1} dx \frac{H(x,\xi)}{x - \xi + i\epsilon},$$

Unphysical regions

- DIS : Analytical function – polynomial in $1/x_B$ if $1 \leq |X_B|$

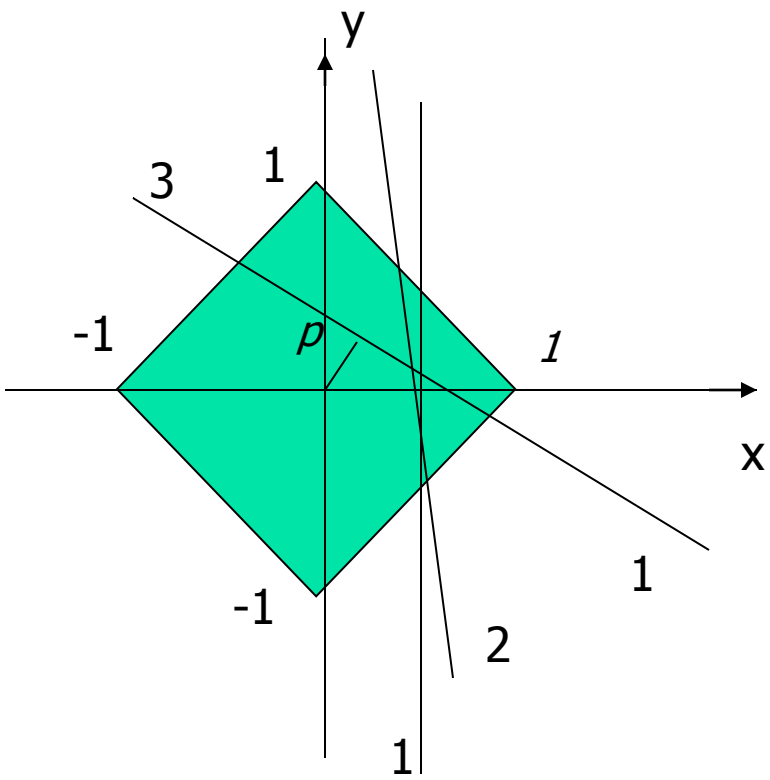
$$H(x_B) = -\int_{-1}^{1} dx \sum_{n=0}^{\infty} H(x) \frac{x^n}{x_B^{n+1}}$$

- DVCS – additional problem of analytical continuation of $H(x,\xi)$
- Solved by using of Double Distributions Radon transform

$$H(z,\xi) = \int_{-1}^{1} dx \int_{|x|-1}^{1-|x|} dy (F(x,y) + \xi G(x,y)) \delta(z - x - \xi y)$$

Double distributions and their integration

- Slope of the integration line- skewness
- Kinematics of DIS: $\xi = 0$ ("forward") - vertical line (1)
- Kinematics of DVCS: $\xi < 1$ - line 2
- Line 3: $\xi > 1$ unphysical region - required to restore DD by inverse Radon transform: tomography

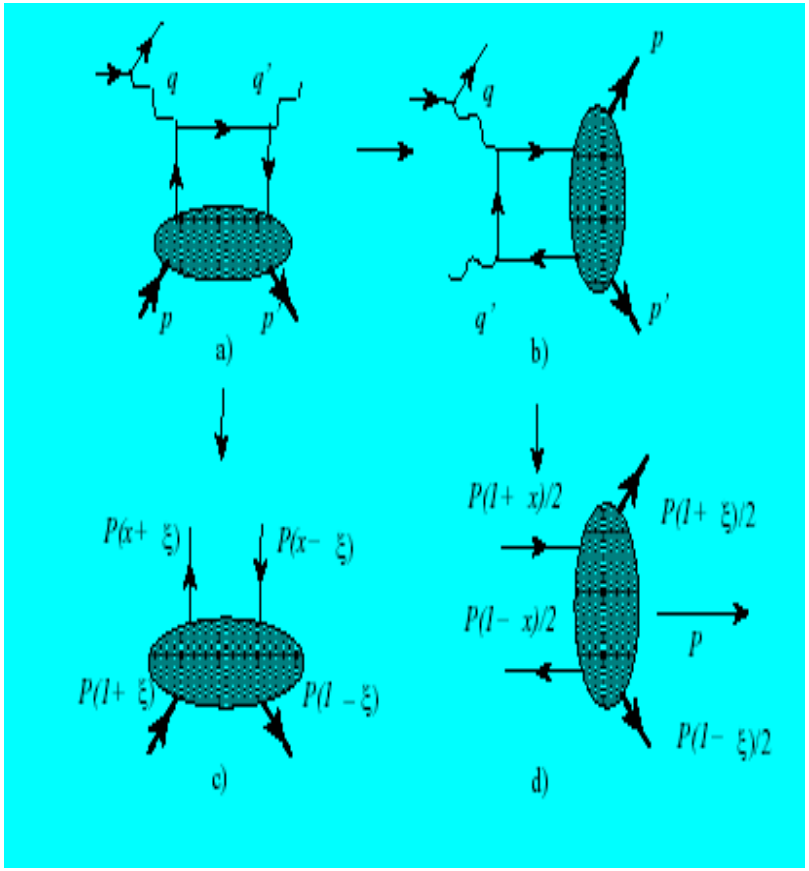


$$f(x,y) = -\frac{1}{2\pi^2}\int_0^\infty \frac{dp}{p^2}\int_0^{2\pi} d\phi |cos\phi| (H(p/cos\phi + x + ytg\phi, tg\phi) - H(x + ytg\phi, tg\phi)) =$$

$$= -\frac{1}{2\pi^2}\int_{-\infty}^\infty \frac{dz}{z^2}\int_{-\infty}^\infty d\xi (H(z + x + y\xi, \xi) - H(x + y\xi, \xi))$$

Crossing for DVCS and GPD

- DVCS -> hadron pair production in the collisions of real and virtual photons
- GPD -> Generalized Distribution Amplitudes
- Duality between s and t channels (Polyakov,Shuvaev, Guzey, Vanderhaeghen)



GDA -> back to unphysical regions for DIS and DVCS

- Recall DIS

$$H(x_B) = -\int_{-1}^{1} dx \sum_{n=0}^{\infty} H(x) \frac{x^n}{x_B^{n+1}}$$

- Non-positive powers of x_B

- DVCS

$$H(\xi) = -\int_{-1}^{1} dx \sum_{n=0}^{\infty} H(x,\xi) \frac{x^n}{\xi^{n+1}}$$

- Polynomiality (general property of Radon transforms): moments - integrals in x weighted with x^n - are polynomials in 1/ ξ of power $n+1$
- As a result, analyticity is preserved: only non-positive powers of ξ appear

Holographic property (OT'05)

- Factorization Formula ->

$$\mathcal{H}(\xi) = \int_{-1}^{1} dx \frac{H(x,\xi)}{x - \xi + i\epsilon}$$

- Analyticity -> Imaginary part -> Dispersion relation:

$$\mathcal{H}(\xi) = \int_{-1}^{1} dx \frac{H(x,x)}{x - \xi + i\epsilon}$$

$$\Delta\mathcal{H}(\xi) \equiv \int_{-1}^{1} dx \frac{H(x,x) - H(x,\xi)}{x - \xi + i\epsilon}$$

- "Holographic" equation (DVCS AND VM)

$$= \sum_{n=1}^{\infty} \frac{1}{n!} \frac{\partial^n}{\partial \xi^n} \int_{-1}^{1} H(x,\xi) dx (x - \xi)^{n-1} = const$$

Holographic property - II

- Directly follows from double distributions

$$H(z,\xi) = \int_{-1}^{1} dx \int_{|x|-1}^{1-|x|} dy (F(x,y) + \xi G(x,y)) \delta(z - x - \xi y)$$

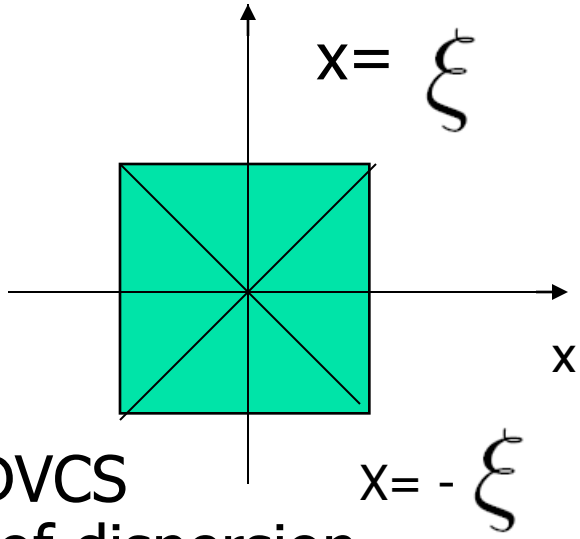
- Constant is the SUBTRACTION one - due to the (generalized) Polyakov-Weiss term G(x,y)

$$\Delta\mathcal{H}(\xi) = \int_{-1}^{1} dx \int_{|x|-1}^{1-|x|} dy \frac{G(x,y)}{1-y}$$

=-($\int_{-\xi}^{\xi} dx \frac{D(x/\xi)}{x - \xi + i\epsilon} = \int_{-1}^{1} dz \frac{D(z)}{z-1} = const$)

Holographic property - III

- 2-dimensional space -> 1-dimensional section!
- Momentum space: any relation to holography in coordinate space ?!



- Strategy (now adopted) of GPD's studies: start at diagonals (through SSA due to imaginary part of DVCS amplitude) and restore by making use of dispersion relations + subtraction constants

Analyticity of Compton amplitudes in energy plane (Anikin,OT'07)

- Finite subtraction implied

$$\mathrm{Re}\,\mathcal{A}(\nu, Q^2) = \frac{\nu^2}{\pi}\,\mathcal{P}\int_{\nu_0}^{\infty} \frac{d\nu'^2}{\nu'^2}\,\frac{\mathrm{Im}\,\mathcal{A}(\nu', Q^2)}{(\nu'^2 - \nu^2)} + \Delta \qquad \Delta = 2\int_{-1}^{1} d\beta\,\frac{D(\beta)}{\beta - 1}$$

$$\Delta^p_{\mathrm{CQM}}(2) = \Delta^n_{\mathrm{CQM}}(2) \approx 4.4, \qquad \Delta^p_{\mathrm{latt}} \approx \Delta^n_{\mathrm{latt}} \approx 1.1$$

- Numerically close to Thomson term for real proton (but NOT neutron) Compton Scattering!

- Duality (sum of squares vs square of sum; proton: 4/9+4/9+1/9=1)?!

From D-term to pressure

- *Inverse -> 1st moment (model)*
- *Kinematical factor: weighted pressure C~<p r⁴> (<p r²> =0)* *M.Polyakov'03*

$$T^Q_{\mu\nu}(\vec{r},\vec{s}) = \frac{1}{2E}\int \frac{d^3\Delta}{(2\pi)^3}\, e^{i\vec{r}\cdot\vec{\Delta}}\, \langle p', S'|\hat{T}^Q_{\mu\nu}(0)|p, S\rangle$$

$$T_{ij}(\vec{r}) = s(r)\left(\frac{r_i r_j}{r^2} - \frac{1}{3}\,\delta_{ij}\right) + p(r)\delta_{ij}$$

- *Justification: (Fourier inversed) consistency principle for Born gravitational scatterring? 2D<->3D?*

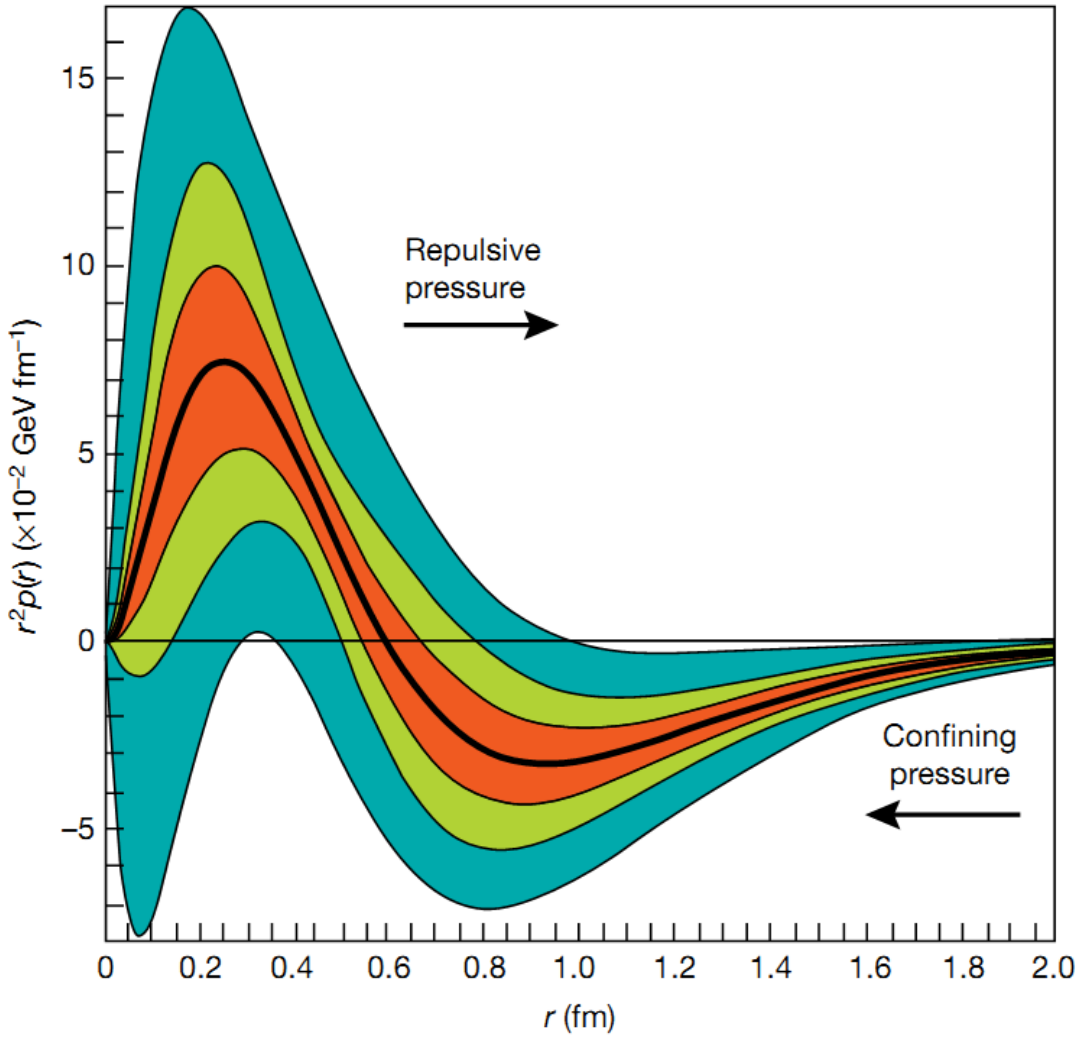
LETTER

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]



Gravitational formfactors and pressure in hadron pairs production

- Back to GDA region
- -> moments of H(x,x) - define the coefficients of powers of cosine!– $1/\xi$
- Higher powers of cosine in t-channel – threshold in s -channel
- Larger for pion than for nucleon pairs because of less fast decrease at x ->1
- Stability defines the sign of GDA

$$\mathscr{H}(\xi) = -\int_{-1/\xi}^{1/\xi} dx \sum_{n=0}^{\infty} H(x,\xi)\frac{x^n}{\xi^{n+1}}$$

$$= -\int_{-1/\xi}^{1/\xi} dx \sum_{n=0}^{\infty} H(x,x)\frac{x^n}{\xi^{n+1}} + \Delta\mathscr{H}.$$

Gravitational FFs from Belle data on GDAs

S. Kumano, Qin-Tao Song and O. Teryaev, PRD **97** (2018) 014020.

- Gravitational FFs are related to twist-2 GDAs

$$A_{\lambda_1\lambda_2} = T_{\mu\nu}\varepsilon^{\mu}(\lambda_1)\varepsilon^{\nu}(\lambda_2)/e^2$$

$$A_{++} = \sum_q \frac{e_q^2}{2}\int_0^1 dz \frac{2z-1}{z(1-z)}\Phi^q\left(z,\xi,W^2\right)$$

$$\int dz(2z-1)\Phi_q^+\left(z,\xi,W^2\right) = \frac{2}{(P^+)^2}\left\langle \pi^+(p_1)\pi^-(p_2)\left|T_q^{++}(0)\right|0\right\rangle$$

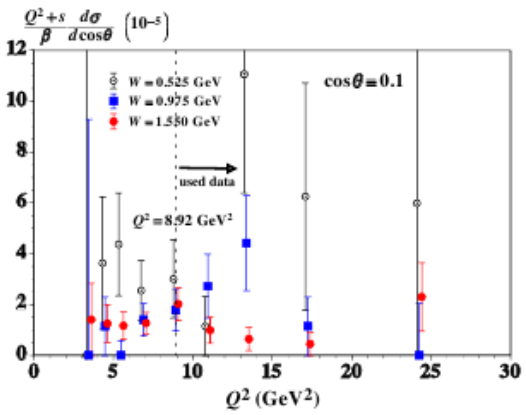
$$\left\langle \pi^0(p_1)\pi^0(p_2)\left|T^{\mu\nu}(0)\right|0\right\rangle = \frac{1}{2}\left[\left(sg^{\mu\nu}-P^{\mu}P^{\nu}\right)\Theta_1 + \Delta^{\mu}\Delta^{\nu}\Theta_2\right]$$

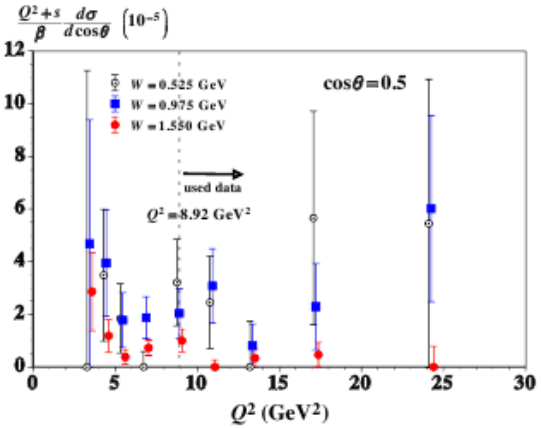
$$P = p_1 + p_2\,,\ \Delta = p_1 - p_2$$

M. Masuda et al. [Belle Collaboration], PRD 93 (2016), 032003

- Belle data and scaling : W=0.525,0.975, 1.55 GeV

$$\frac{(Q^2+s)d\sigma}{\beta d|\cos\theta|} \propto \left|\Phi^{\pi^0\pi^0}(z,\cos\theta,W,Q)\right|^2$$





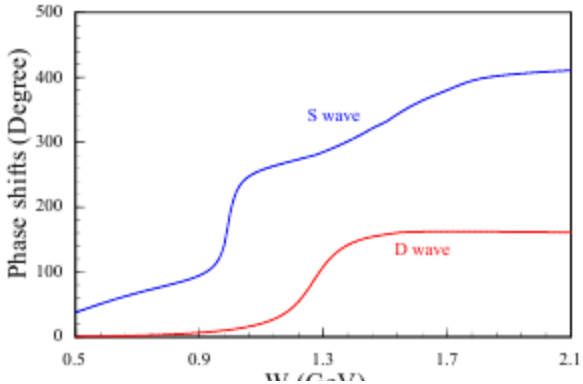
Phase shifts and resonances

- Leading harmonics

$$\sum_q \Phi_q^+\left(z,\xi,W^2\right) = 18n_f z(1-z)(2z-1)[B_{10}(W)+B_{12}(W)P_2(2\xi-1)]$$

$$= 18n_f z(1-z)(2z-1)[\tilde{B}_{10}(W)+\tilde{B}_{12}(W)P_2(\cos\theta)]$$

$$\tilde{B}_{10}(W) = \bar{B}_{10}(W)e^{i\delta_0}, \tilde{B}_{12}(W) = \bar{B}_{12}(W)e^{i\delta_2}$$



- S/D shifts

- $f_0(500)$, $f_2(1270)$ contributions

$$\bar{B}_{12}(W) = \beta^2 \frac{10 g_{f_2\pi\pi} f_{f_2} M_{f_2}^2}{9\sqrt{2}\sqrt{(M_{f_2}^2 - W^2)^2 - \Gamma_{f_2}^2 M_{f_2}^2}}$$

$$\bar{B}_{10}(W) = \frac{5 g_{f_0\pi\pi} f_{f_0}}{3\sqrt{2}\sqrt{(M_{f_0}^2 - W^2)^2 - \Gamma_{f_0}^2 M_{f_0}^2}}$$

Fits and results

- Collection

$$\Phi_q^+(z,\xi,W^2) = N_h z^\alpha (1-z)^\alpha (2z-1)[\tilde{B}_{10}(W) + \tilde{B}_{12}(W) P_2(\cos\theta)]$$

$$\tilde{B}_{10}(W) = [\frac{-3+\beta^2}{2}\frac{5R_\pi}{9}F_h(W^2) + \frac{5 g_{f_0\pi\pi} f_{f_0}}{3\sqrt{2}\sqrt{(M_{f_0}^2 - W^2)^2 - \Gamma_{f_0}^2 M_{f_0}^2}}]e^{i\delta_0}$$

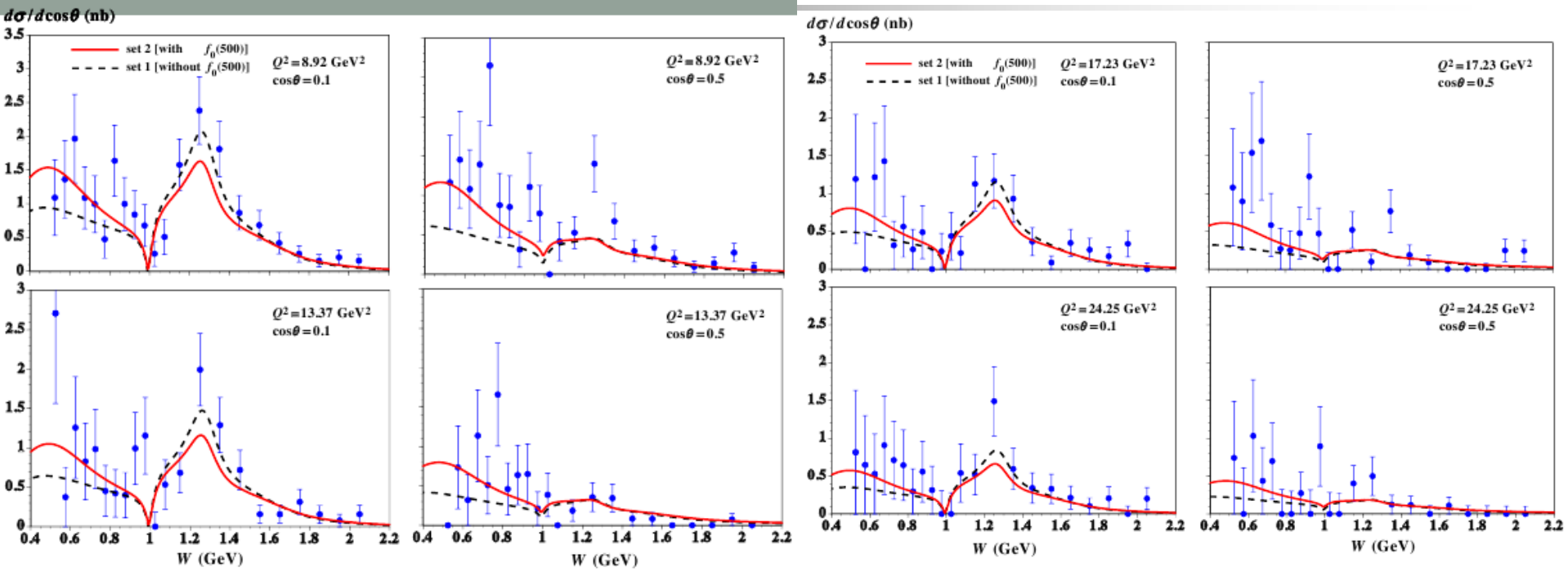
$$\tilde{B}_{12}(W) = [\beta^2\frac{5R_\pi}{9}F_h(W^2) + \beta^2\frac{10 g_{f_2\pi\pi} f_{f_2} M_{f_2}^2}{9\sqrt{2}\sqrt{(M_{f_2}^2 - W^2)^2 - \Gamma_{f_2}^2 M_{f_2}^2}}]e^{i\delta_2}$$

$$F_h(W^2) = \frac{1}{\left[1 + \frac{W^2 - 4m_\pi^2}{\Lambda^2}\right]^{n-1}}$$

- Best fit with (2) and without (1) f_0

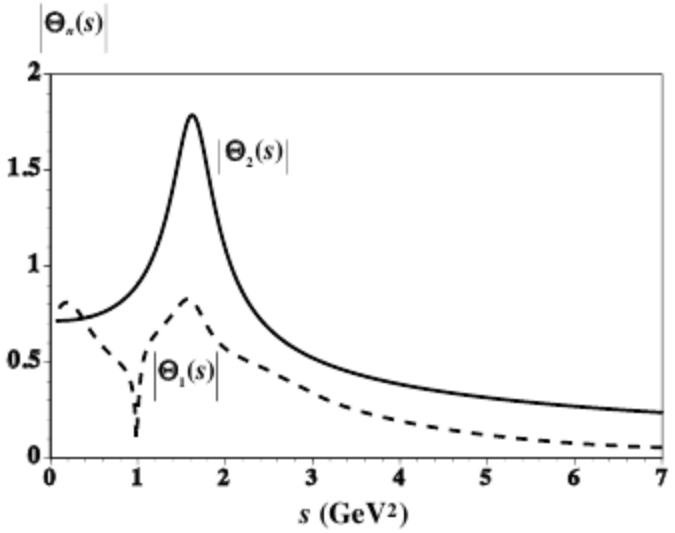
	Set 1	Set 2
α	0.801±0.042	1.157± 0.132
Λ	1.602±0.109	1.928±0.213
a	3.878± 0.165	3.800± 0.170
b	0.382± 0.040	0.407± 0.041
f_{f0}	------	0.0184± 0.034
	$\frac{\chi^2}{NOF} = 1.22$	$\frac{\chi^2}{NOF} = 1.09$

Description of data



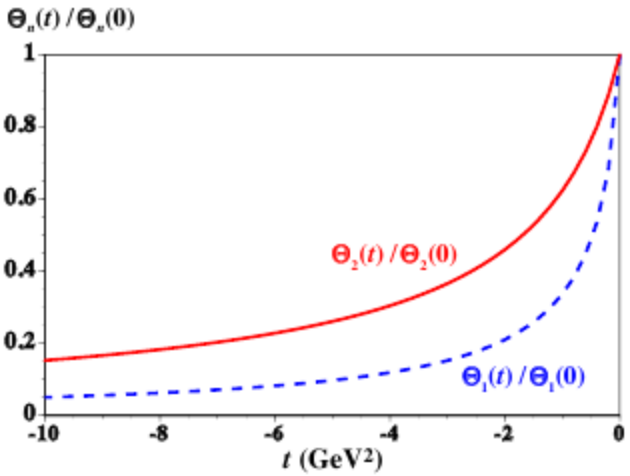
Formfactors

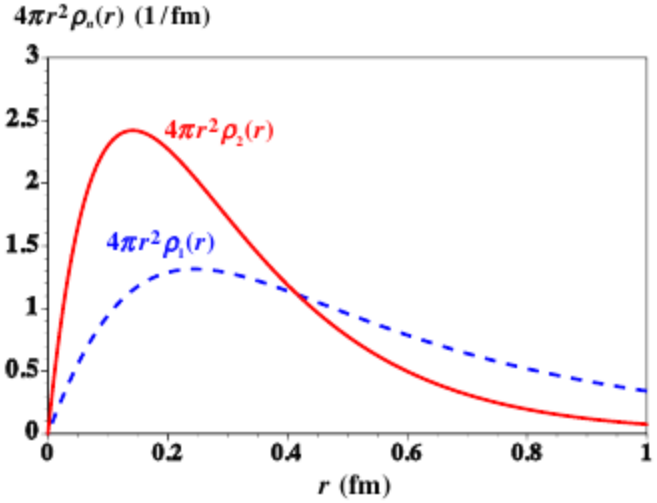
- Resonance structure in pressure – related Θ_1



Time-like -> space-like

- Dispersion relation and Fourier transform





- Mass radius

$$< r^2 >= 6 \int_{4m^2}^{\infty} \frac{\mathrm{Im}(F(s))}{s^2}$$

$$\sqrt{\langle r^2 \rangle} = 0.69 \text{ fm for } \Theta_2$$

Shear – natural counterpart of pressure

PHYSICAL REVIEW D **104,** 014008 (2021)

Forces inside the nucleon on the light front from 3D Breit frame force distributions: Abel tomography case

Julia Yu. Panteleeva[1] and Maxim V. Polyakov[1,2]

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(Received 4 March 2021; accepted 15 June 2021; published 9 July 2021)

- 3D <->2D relations

Shear viscosity

- 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 (OT'19):
- $V^{\mu} = (P^{\mu} + a(t)\, k_T^{\mu}) / (M^2 + a^2(t)\, k_T^2)^{1/2}$
- Viscosity: $\eta\, dv^{\mu}/d\, x_T^{\lambda} \sim E_{\eta}\, p^{[\mu}\, \Delta^{\lambda]}$
- Naïve T-oddness: phases
- NO such term in total EMT (but can be for quarks separately)
- Phases <-> dissipation: polarization in pionic superfluidity model (V. I. Zakharov, OT' 17)

Viscosity in GDA channel

- Viscosity:will correspond to Exotic $J^{PC}=1^{-+}$ meson (already studied : Anikin, Pire, Szymanowski,OT, Wallon'06)
- Spin: related to structure of matrix element: One index of EMT (0^{th} in rest frame) is carried by momentum and other by polarization vector - just what we need for viscosity
- NO for conserved EM: zero coupling for (G)DA!
- $\pi\eta$ pairs observation instead of $\pi\,\pi$ required
- Smallness of viscosity: related to smallness of exotic GDAs and ExEP violation?!

Exotic hybrid meson production

- **On exotic hybrid meson production in $\gamma^*\gamma$ collisions**

I.V. Anikin[1], B. Pire[2,a], L. Szymanowski[3,4,5], O.V. Teryaev[1], S. Wallon[5]

Eur. Phys. J. C 47, 71–79 (2006)
Digital Object Identifier (DOI) 10.1140/epjc/s2006-02533-7

- Possible candidate Π_1 (1400)

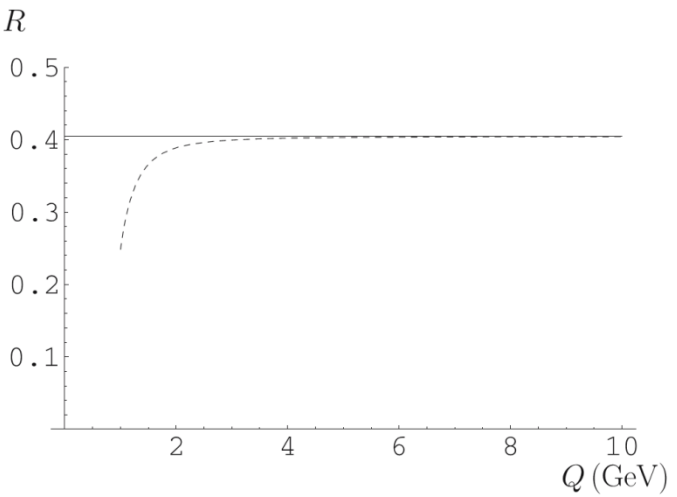


Fig. 2. The ratio $R(Q^2)$ of the squared amplitudes for H and π^0 production in $\gamma^*\gamma$ collisions at leading twist and zero-th order in α_s (*solid line*) and including twist three contributions in the numerator (*dashed line*)

Estimate of viscosity

- Terms in EMT:
- $(e+p)\, v^{\mu} v^{\lambda} \sim A\, P^{\mu} P^{\lambda}$
- $\eta\, dv^{\mu}/d\, x_T^{\lambda} \sim E_{\eta}\, p^{[\mu}\, \Delta^{\lambda]}$
- TD: e+p -> Ts
- $\eta/s\ (> 1/(4\pi)) \sim E_{\eta} T/AM$
- Correct dependence on Planck constant recovered via $\Delta^{\lambda} \rightarrow -i\hbar\, d/d\, x_T^{\lambda}$
- (cf K. Trachenko et al.)

Spin 1 EMT and inclusive processes

- Forward matrix element -> density matrix
- Contains P-even term: tensor polarization $S^{\alpha\beta}$
- Symmetric and traceless: correspond to (average) shear forces
- For spin ½: P-odd vector polarization requires another vector (q) to form vector product

SUM RULEs

- Efremov,OT'81 : zero sum rules:
- Current conservation: 1st moment: also in parton model by Close and Kumano (90)
- EMT conservation: 2nd moment (forward analog of Ji's SR: AGM $=\langle A_T \rangle = 0$)
- Average shear 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

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

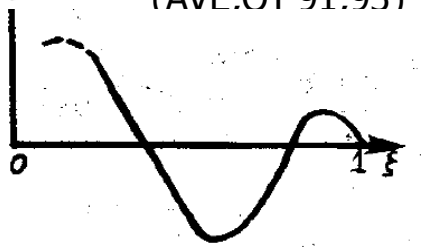
$$\int_0^1 C_i^T(x)dx = 0$$

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

(AVE.OT'91,93)

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

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

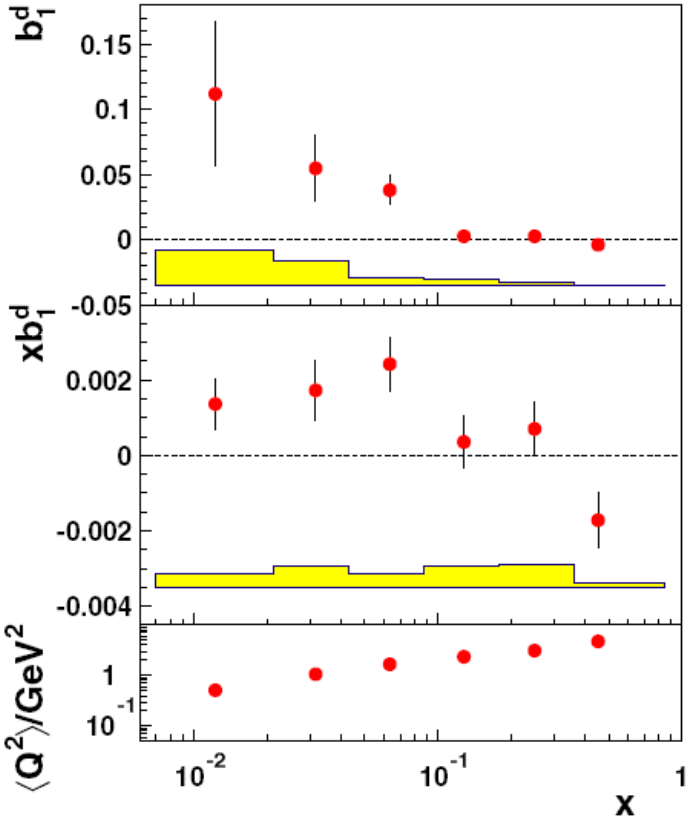


$$\sum_q \int_0^1 C_i^T(x)xdx = \delta_1(\mu^2) = 0$$ for ExEP

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 tensor polarized glue << sea)

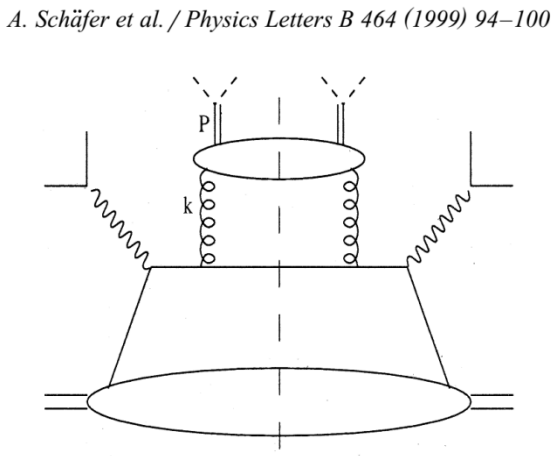


Where else to test?

- EIC
- DY@J-PARC
- ET'81-any hard process ("multi-messenger")
- Possibility: hadronic tensor SSA@NICA

Fragmentation functions

- Tensor polarized fragmentation functions: (Szymanowski, Schaefer, OT'99)



- Suggestion'21: zero SRs (analogous to momentum SR) may probe the (Ex)EP for hadrons inside partons (EIC: gluons)

More on vector mesons and ExEP

- J=1/2 -> J=1. QCD SR/model/lattice calculation of Rho's AMM gives g close to 2 (g=2 exactly in AdS QCD).
- Why?
- Maybe because of similarity of moments and ExEP
- $g-2=\langle E_u(x)\rangle$; $B=\langle xE_u(x)\rangle$
- Directly for charged Rho (combinations like p+n for nucleons unnecessary!). Not reduced to non-extended EP: Gluons momentum fraction sizable

EP: Where is the fastest possible rotation and acceleration? (cf talk of V. Braguta)

- Non-central heavy ion collisions (Anqular velocity ~ c/Compton wavelength) $\Omega \sim \frac{c}{\lambda\!\!\!^{-}_p} = \frac{m_p c^2}{\hbar}$
- ~25 orders of magnitude faster than Earth's rotation $\eta_{\rm rot} = \frac{\Omega}{\omega_\oplus} = \frac{c}{R_A} \cdot \frac{T_\oplus}{2\pi} = \frac{1}{2\pi} \cdot \frac{cT_\oplus}{R_A} \approx 10^{27}$
- Differential rotation – vorticity
- P-odd :May lead to various P-odd effects (Chiral magnetic/vortical effects)
- Acceleration: even larger ratio with the gravity of Earth

$$\eta_{\rm acc} = \frac{c}{R_A} \cdot \frac{c}{g_\oplus} = \eta_{\rm rot} \frac{2\pi c}{T_\oplus g_\oplus} \approx 10^{30} \qquad \eta_{\rm acc} = \frac{c}{R_A} \cdot \frac{c}{g_\oplus} = \frac{c^2}{v_\oplus^2} \cdot \frac{R_\oplus}{R_A}$$

Strong interactions and gravity in HIC

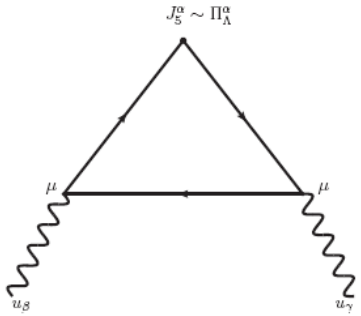
- $E_{EM}/E_G \sim e^2/(m/M_{Pl})^2$ $M_{Pl} \sim 10^{18}$ GeV
- For 2 particles with M_{Pl} mass at Compton wavelength distance $(1/M_{Pl})$: $E_G \sim (G = 1/M_{Pl}^2)\ M_{Pl}^2 / (1/M_{Pl}) = M_{Pl}$ $g \sim (G = 1/M_{Pl}^2)\ M_{Pl} / (1/M_{Pl})^2 = M_{Pl}$
- Gravitational interaction is strongly suppressed $\sim (\Lambda/M_{Pl})^2$
- Equivalence Principle
- I: Acceleration <-> Gravity
- HIC: $a \sim \Lambda$, $a/g \sim \frac{c^2}{v_\oplus^2} \cdot \frac{R_\oplus}{R_A} \sim 10^{30}$
- M_{Pl} -> Λ ("GeV Gravity")

Effective field theory: Anomalies

- 4-Velocity is also a GAUGE FIELD (V.I. Zakharov et al)

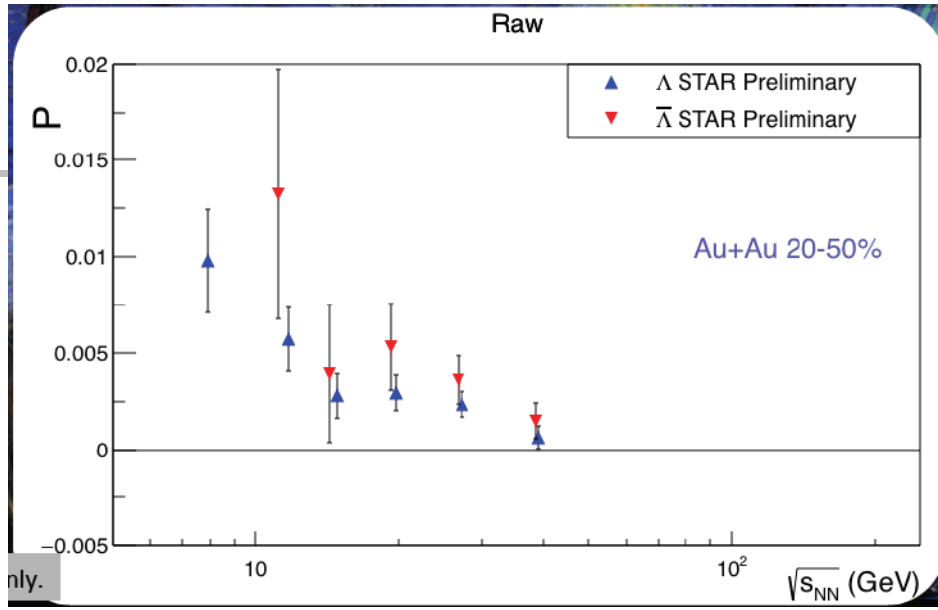
$$e_j A_\alpha J^\alpha \Rightarrow \mu_j V_\alpha J^\alpha$$

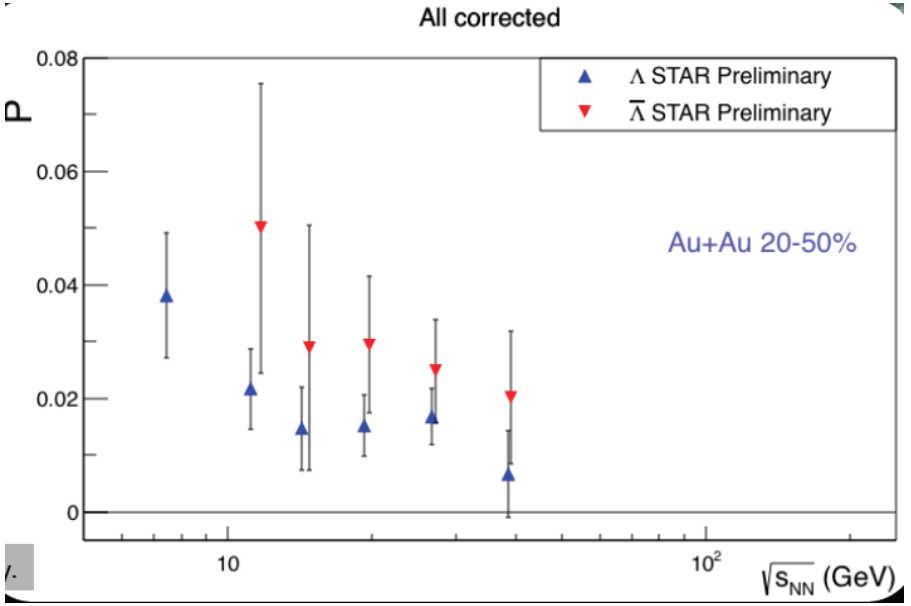
- Triangle anomaly leads to polarization of quarks and hyperons (Rogachevsky, Sorin, OT '10)
- Analogous to anomalous gluon contribution to nucleon spin (Efremov,OT'88)
- 4-velocity instead of gluon field potential and vorticity ------//------- (chromo)magnetic field strength!



Observable for AVE: polarization

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.

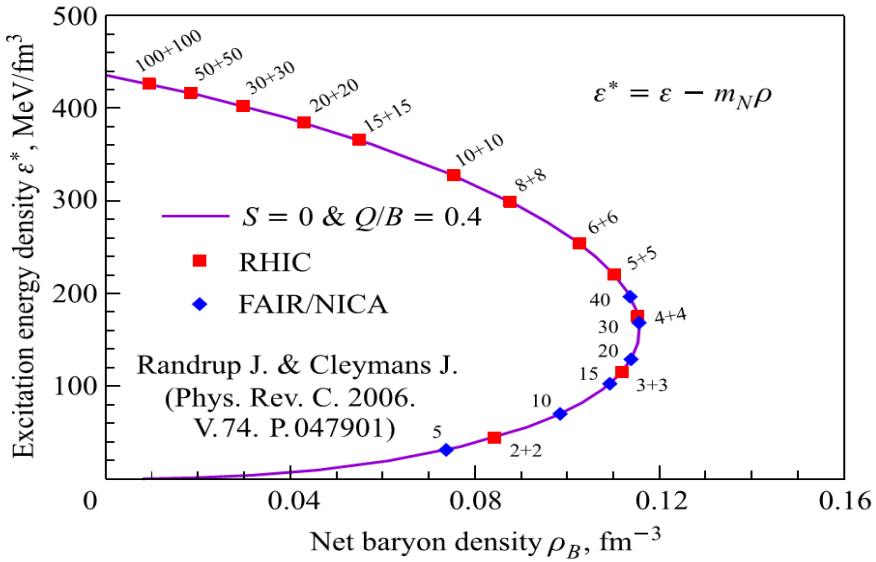
This option may be explored in the framework of the program of polarization studies at the NICA [17] performed at collision points as well as within the low-energy scan program at the RHIC.

NICA (Nuclotron based Ion Colider fAcility)

– the flagship project in HEP of Joint Institute for Nuclear Research (JINR)

Main targets of "NICA Complex":

- ***study of hot and dense baryonic matter***
- *investigation of hadronic spin structure through various polarization phenomena*
- *development of accelerator facility for HEP @ JINR providing intensive beams of relativistic ions from p to Au*

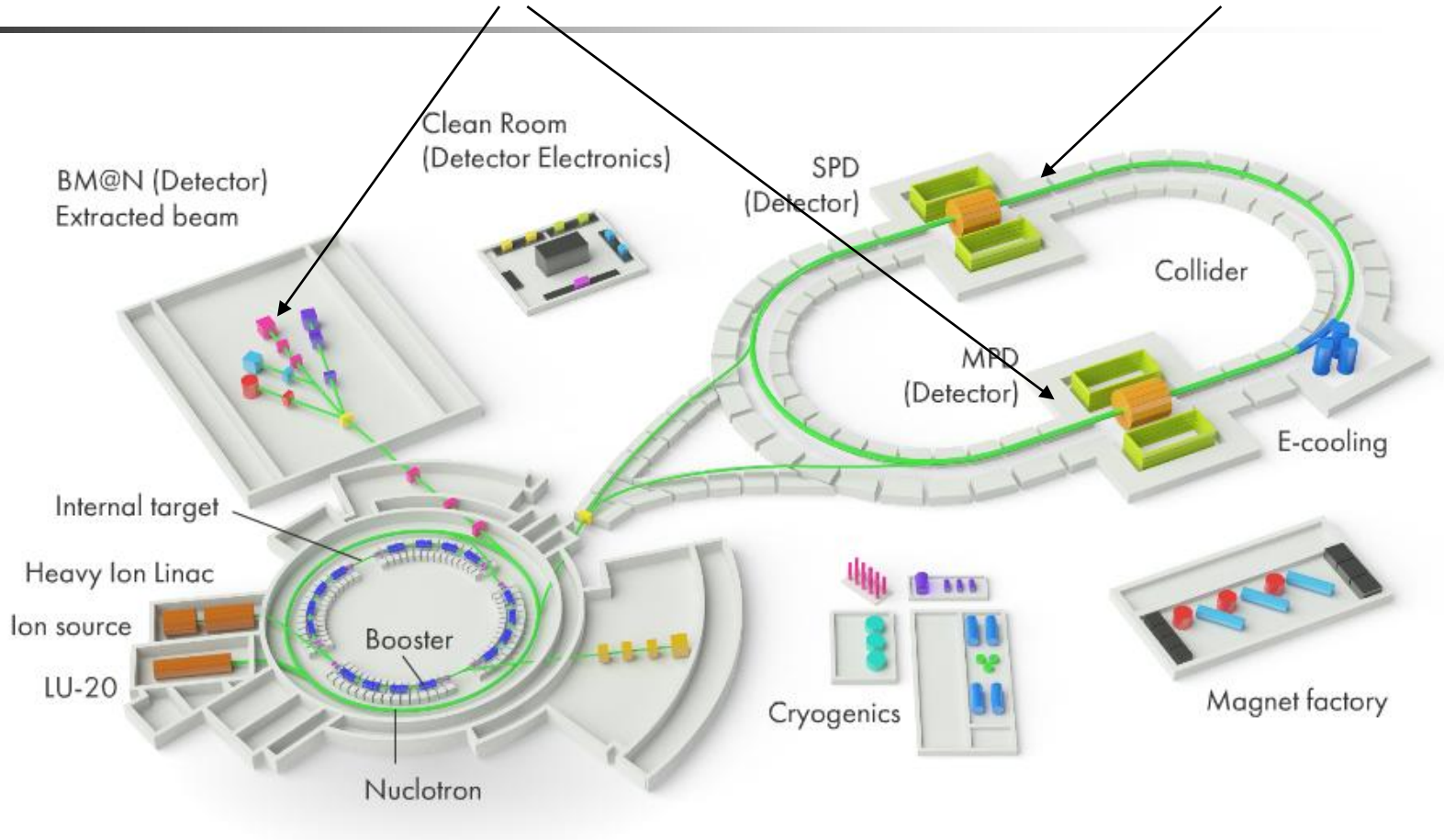


polarized protons and deuterons with energy up to

$\sqrt{s_{NN}}$ = *11 GeV (Au^{79+} , **L ~ 10^{32}** cm^{-2} c^{-1})*

$\sqrt{s}$ =*27 GeV (p, L ~ **10^{32}** cm^{-2} c^{-1})*

NICA: heavy ions and hadrons

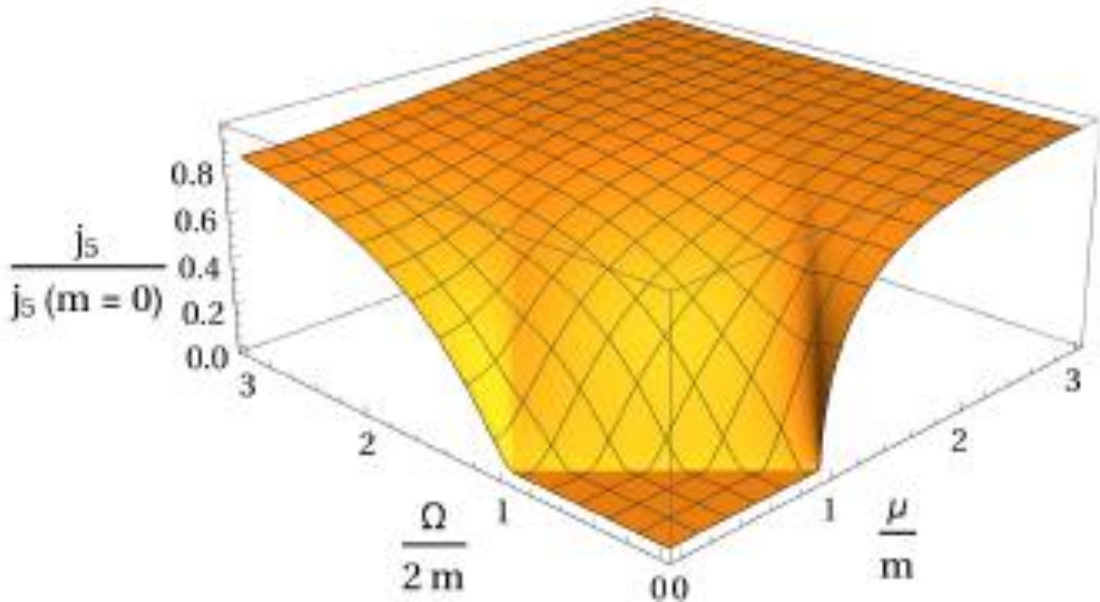


Why EP and rotating frame?

- Statistical approach (F. Becattini et al.; "Standard Model" for polarization): spin equilibrium in rotating frame
- Decrease with energy: explained by decrease of (relevant) hydrodynamic vorticity (Betz, Torrieri, Csernai, Becattini, Karpenko, Lisa,…)
- Interesting to compare with quantum measurement essential for EP: Landau&Lifshitz v. 5, Section 8 ("Law of entropy increasing"): possible relation of inequivalence of time directions due to quantum measurements
- EP/quantum measurement/statistics interplay (recall history of Kobzarev&Okun publication)?!
- Cf.: EP violation (modification?) due to thermal effects (non-zero AGM: Buzzegoli, Kharzeev'21)

Comparison of approaches: Axial ("anomalous" without anomaly) current in TD approach: Vilenkin'82,..

- Prokhorov, Zakharov, OT'18:Threshold effects in chemical potential and angular velocity
- From equilibrated spin of massive hadrons to EFT for spin of massless quarks



Rotated and accelerated frame: Wigner function and Zubarev density operator

- G. Prokhorov, V. Zakharov,OT ’19:
- Imaginary chemical potential due to acceleration appears!

$$\langle j^5_\mu \rangle = \frac{\omega_\mu + i\mathrm{sgn}(\omega a)a_\mu}{2(g_\omega - ig_a)} \int \frac{d^3p}{(2\pi)^3} \times \{n_F(E_p - \mu - g_\omega/2 + ig_a/2) - n_F(E_p - \mu + g_\omega/2ig_a/2) + n_F(E_p + \mu - g_\omega/2 + ig_\omega/2) - n_F(E_p + \mu + g_\omega/2 - ig_a/2)\} + \text{c.c.},$$

$$\rho = \frac{7\pi^2T^4}{60} + \frac{T^2a^2}{24} - \frac{17a^4}{960\pi^2} = 2\int \frac{d^3p}{(2\pi)^3}\left(\frac{|\mathbf{p}| + ia}{1 + e^{\frac{|\mathbf{p}|}{T} + \frac{ia}{2T}}} + \frac{|\mathbf{p}| - ia}{1 + e^{\frac{|\mathbf{p}|}{T} - \frac{ia}{2T}}}\right)$$

$$+4\int \frac{d^3p}{(2\pi)^3} \frac{|\mathbf{p}|}{e^{\frac{2\pi|\mathbf{p}|}{a}} - 1} \qquad (T > T_U)$$

in red: *modifications* compared to the *Wigner function*

- In the first integral, the **acceleration** enters as an **imaginary chemical potential** $\pm\frac{ia}{2}$ [G.P., O. Teryaev, V. Zakharov, Phys. Rev. D 98, no. 7, 071901 (2018)].

Statistics vs geometry: Unruh effect (Becattini'18; Prokhorov, OT, Zakharov'19)

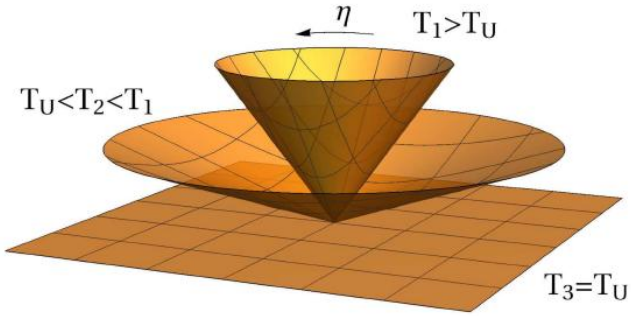
- Results for energy density of thermal system in Minkowski space coincide with the early known for the space with conical singularity (e.g. cosmic strings)

$$\rho_{s=0} = \frac{\pi^2 T^4}{30} + \frac{T^2|a|^2}{12} - \frac{11|a|^4}{480\pi^2},$$
$$\rho_{s=1/2} = \frac{7\pi^2 T^4}{60} + \frac{T^2|a|^2}{24} - \frac{17|a|^4}{960\pi^2}$$

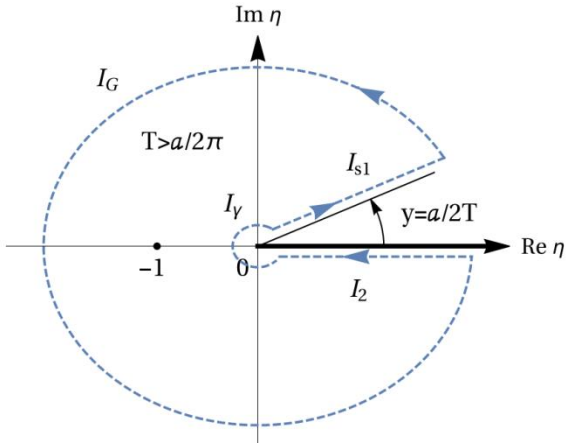
$$c_V = \frac{\mu_s^2 + \mu_A^2}{2\pi^2} + \frac{T^2}{6}, \quad Q_5^s = N_c \int d^3x\, c_V \gamma^2 \epsilon^{ijk} v_i \partial_j v_k$$

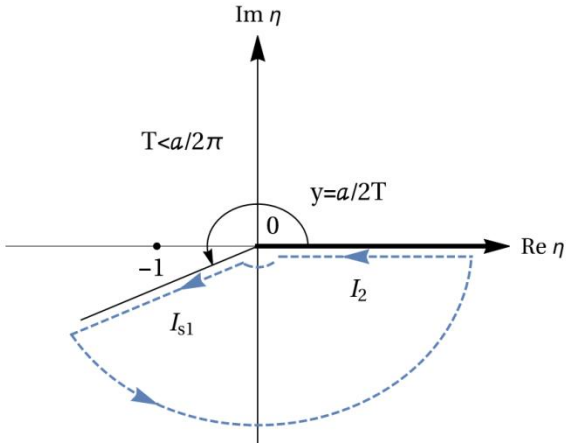
- Energy density turns to zero for $T=T_U=a/(2\pi)$ (~"physical conditions of renormalization". also simple explanation of coefficient)

Instability for high accelerations



- Normally $T>T_U$
- Fast accelration without thermalization: instability (cf rotational instability: V. Braguta)





- EP ~ fall to BH?
- Censorship: Origin for fast thermalization?

QCD and Gravity in HIC

- There are quantum effects in the thermalized quark-gluon medium (Unruh: quantum measurement in the accelerated frame) corresponding to emergent conical singularity (Relation of gravitational and thermal information loss?)
- Gravitational chiral anomaly leads to the transport (kinematical vortical) effects present also after its disappearance;Prokhorov, VI Zakharov, OT *Phys.Rev.Lett.* 129 (2022) 15, 151601, 2207.04449
-  

CONCLUSIONS

- Interplay of QCD and gravity in hadronic and heavy-ion collisions
- Special role of Equivalence Principle and Quantum Measurement
- HIC/GPDs/TMDs relations to be studied
- Modern accelerators (LHC, RHIC, CEBAF EIC,FAIR,NICA… also “effective gravity” labs