Spin and New Physics at CMS

Experimental Methods of Particle Physics (IAG-85)
JINR, August 8, 2019

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Polarization data has often been the graveyard of fashionable theories.
If theorists had their way, they might just ban such measurements altogether out of self-protection.
J.D. Bjorken
St. Croix, 1987

Main Topics

- Spin and invariants of angular distributions
- Virtual photon/graviton polarization at CMS
- Missed transverse momentum angular distributions and probes of dark matter

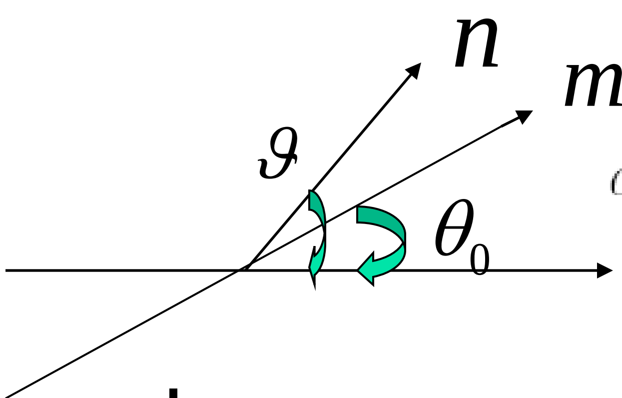
Spin and angular distributions at CMS

- 2005: Invitation of I.A. Golutvin to participate in CMS activity and to visit CERN
- Model-independent search of new physics?
- Possible role of spin and angular asymmetries (less sensitive to pdfs – to be measured from xsections)

Angular distributions

- SM gauge bosons: detailed check of production mechanisms
- Higgs – spin 0 – isotropic distributions
- Gravitons – spin 2 – 4 component density matrix – $\cos^4\theta$ enters – searched for and not found (CMS: S. Shmatov, M. Savina)
- Any s-channel resonance – slow decrease with angle/transverse momentum
- How to measure (frame)?

Kinematic azimuthal asymmetry from polar one (OT'05)



$$d\sigma \propto 1 + \lambda_0 (\vec{n}\vec{m})^2 = 1 + \lambda_0 \cos^2 \theta_{nm}^2$$

Only polar asymmetry with respect to m!

$$\cos\theta_{nm} = \cos\theta\cos\theta_0 + \sin\theta\sin\theta_0\cos\phi$$

- azimuthal angle appears with new

$$\lambda = \lambda_0 \frac{2 - 3\sin^2\theta_0}{2 + \lambda_0 \sin^2\theta_0}$$

$$\nu = \lambda_0 \frac{2 sin^2\theta_0}{2 + \lambda_0 \sin^2\theta_0}$$

- λ_0 - invariant!

Generalized Lam-Tung relation

- Relation between coefficients (high school math sufficient!)

$$\lambda_0 = \frac{\lambda + \frac{3}{2}\nu}{1 - \frac{1}{2}\nu}$$

- Reduced to standard LT relation for transverse polarization (λ_0 =1)
- LT (physical meaning originally unclear) - contains two very different inputs: kinematical asymmetry+transverse polarization
- Rederived in 10's: P. Faccioli, C. Lourenco, J. Seixas, and H. K. Wohri, The European Physical Journal C 69, 657 (2010).
- J.-C. Peng: Non-coplanarity – violation of LT

Recent activity (triggered by CMS measurement of Z decay angular distribution)

- 1) Lepton angular distributions of Drell-Yan process in pQCD and a geometric approach
  By Wen-Chen Chang, Randall Evan McClellan, Jen-Chieh Peng, Oleg Teryaev.
  arXiv:1907.11356 [hep-ph].

  2) Lepton angular distribution of Z boson production and jet discrimination
  By Jen-Chieh Peng, Wen-Chen Chang, Randall Evan McClellan, Oleg Teryaev.
  arXiv:1907.10483 [hep-ph].

  5) Rotation-invariant observables as Density Matrix invariants
  By Margarita Gavrilova, Oleg Teryaev.
  arXiv:1901.04018 [hep-ph].
  10.1103/PhysRevD.99.076013.
  Phys.Rev. D99 (2019) no.7, 076013.

  6) Lepton Angular Distributions of Fixed-target Drell-Yan Experiments in Perturbative QCD and a Geometric Approach
  By Wen-Chen Chang, Randall Evan McClellan, Jen-Chieh Peng, Oleg Teryaev.
  arXiv:1811.03256 [hep-ph].
  10.1103/PhysRevD.99.014032.
  Phys.Rev. D99 (2019) no.1, 014032.

  7) On the rotational invariance and non-invariance of lepton angular distributions in Drell–Yan and quarkonium production
  By Jen-Chieh Peng, Daniël Boer, Wen-Chen Chang, Randall Evan McClellan, Oleg Teryaev.
  arXiv:1808.04398 [hep-ph].
  10.1016/j.physletb.2018.11.061.
  Phys.Lett. B789 (2019) 356-359.

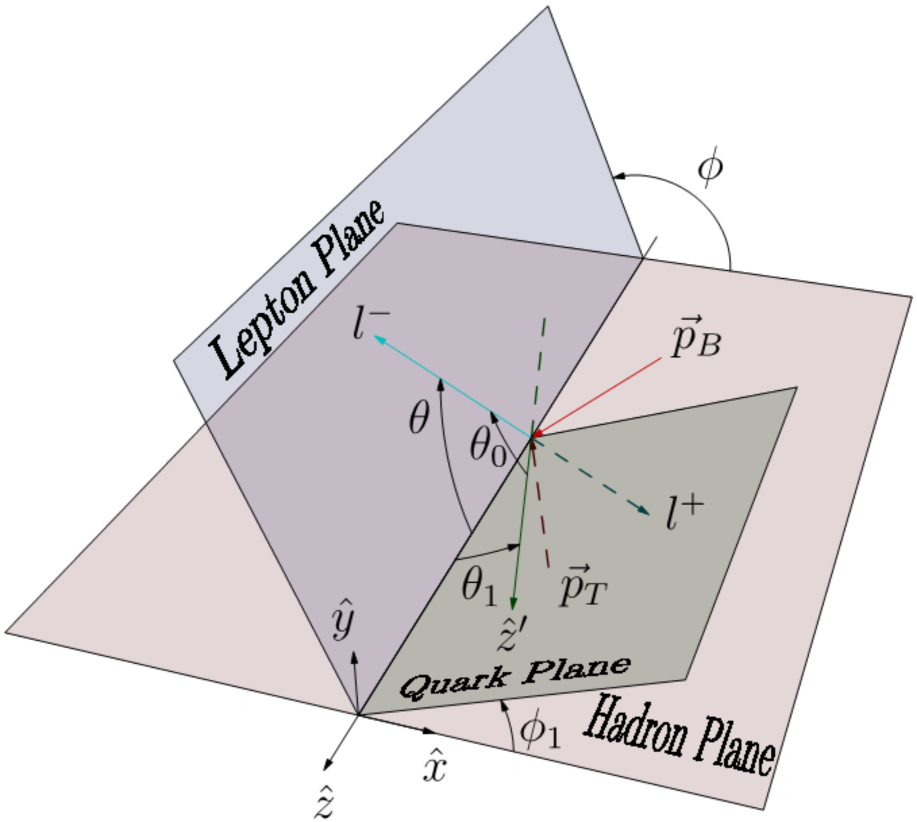
  8) Dependencies of lepton angular distribution coefficients on the transverse momentum and rapidity of Z bosons produced in pp collisions at the LHC
  By Wen-Chen Chang, Randall Evan McClellan, Jen-Chieh Peng, Oleg Teryaev.
  arXiv:1708.05807 [hep-ph].
  10.1103/PhysRevD.96.054020.
  Phys.Rev. D96 (2017) no.5, 054020.

  9) Interpretation of Angular Distributions of Z-boson Production
  By Jen-Chieh Peng, Wen-Chen Chang, Oleg Teryaev, Randall Mcclellan.
  10.22323/1.284.0044.
  PoS QCDEV2016 (2017) 044.

  10) Interpretation of Angular Distributions of Z-boson Production at Colliders
  By Jen-Chieh Peng, Wen-Chen Chang, Randall Evan McClellan, Oleg Teryaev.
  arXiv:1511.08932 [hep-ph].
  10.1016/j.physletb.2016.05.035.
  Phys.Lett. B758 (2016) 384-388.

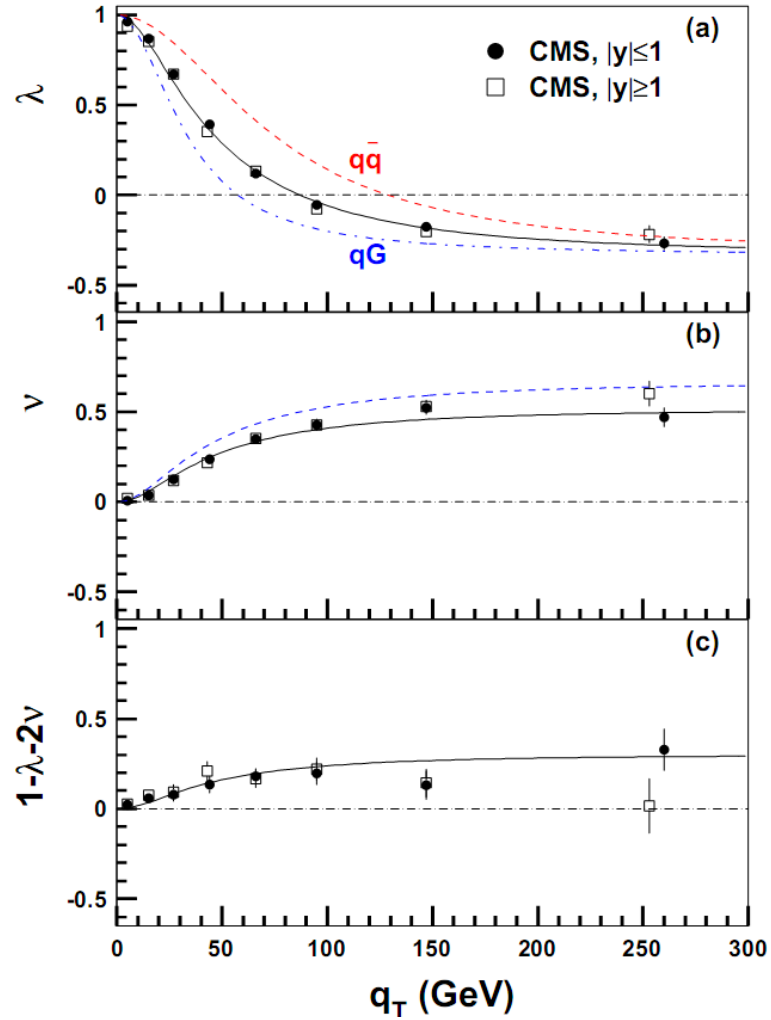
Detailed tests of SM at LHC

- Interpretation of Angular Distributions of Z-boson Production at Colliders; Jen-Chieh Peng,Wen-Chen Chang, Randall Evan McClellan, and Oleg Teryaev; PLB'15
- Geometrical picture
- Non-coplanarity – disbalance of quark and hadron planes



CMS (8 TeV) data

- Necessity to account for
- qq - 41.5(1.6)%
- qG - 58.5(1.6)%
- $< \cos 2\varphi_1 >= 0.77$



New activity at CMS initiated by I.A. Golutvin

- Ilya Gorbunov: 13 TeV data+ dilepton mass apart of Z peak + e/μ + modeling of various subprocesses + test of the absence of new ($\cos^4\Theta$…) terms…
- New option: angular distribution of missed transverse momenta (~ spin of unseen particles)

- HAPPY BIRTHDAY, dear Igor Anatol'evich!

Spin-gravity interactions

- 1. Dirac equation
- Gauge structure of gravity manifested; limit of classical gravity - FW transformation
- 2. Matrix elements of Energy- Momentum Tensor
- May be studied in non-gravitational experiments/theory
- Simple interpretation in comparison to EM field case

Gravitational Formfactors

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

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

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

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

- May be extracted from high-energy experiments/NPQCD calculations
- Describe the partition of angular momentum between quarks and gluons
- Describe interaction with both classical and TeV gravity

Generalized Parton Diistributions (related to matrix elements of non local operators) – models for both EM and Gravitational Formfactors (Selyugin,OT '09)

- Smaller mass square radius (attraction vs repulsion!?)

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

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

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

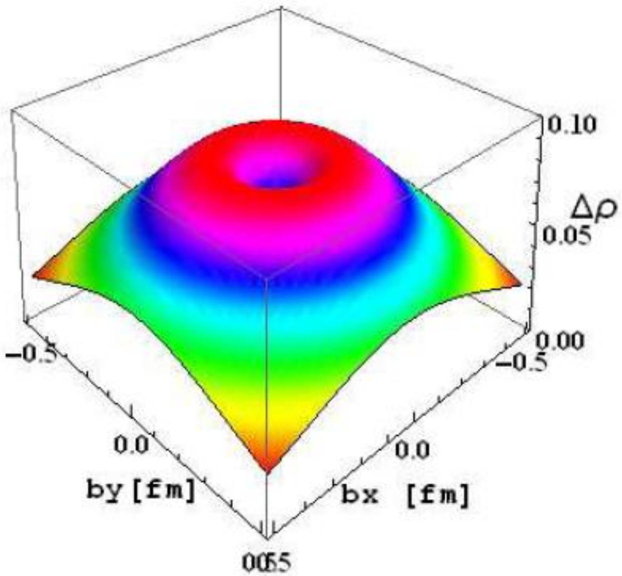


FIG. 17: Difference in the forms of charge density F_1^P and "matter" density (A)

Electromagnetism vs Gravity

- Interaction – field vs metric deviation

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

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

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

  $\vec{H}_J = \frac{1}{2} rot \vec{g};\ \vec{g}_i \equiv g_{0i}$ 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 Zakharov
- Anomalous gravitomagnetic (and electric-CP-odd) moment iz ZERO or
- Classical and QUANTUM rotators behave in the SAME way
- - not checked on purpose but in fact checked in atomic spins experiments at % level (Silenko,OT’07)

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

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

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

Equivalence principle for moving particles

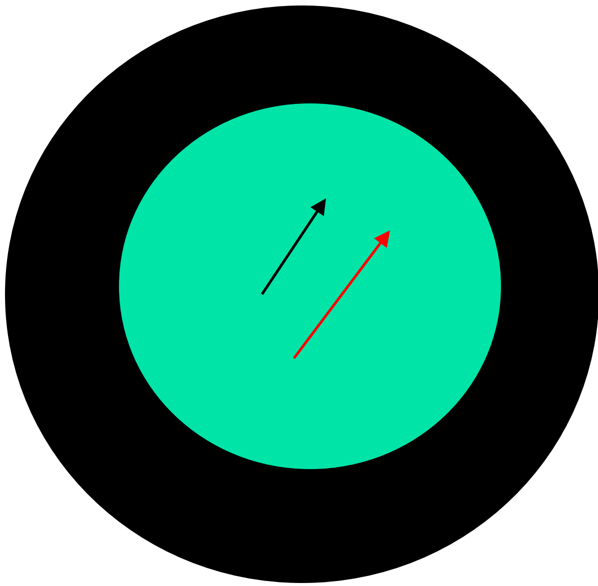
- Compare gravity and acceleration: gravity provides EXTRA space components of metrics $h_{zz} = h_{xx} = h_{yy} = h_{00}$
- Matrix elements DIFFER

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

- Ratio of accelerations: $R = \frac{\epsilon^2 + p^2}{\epsilon^2}$ - confirmed by explicit solution of Dirac equation (Silenko, OT, ‘05)
- Arbitrary fields – Obukhov, Silenko, OT ’09,’11,’13

Cosmological implications of PNEP

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



Manifestation of equivalence principle (cf with EM)

- Classical and quantum rotators rotate with the same frequency (EM: spin ½ – twice faster); Dirac eq. analysis (Obukhov, Silenko, OT) – for strong fileds
- Velocity rotates twice faster than classical rotator- helicity changes
(EM – helicity of Dirac fermion conserved – used for AMM measurement) –BUT conserved in the rotating comoving frame

Dirac Eq and Foldy - Wouthausen transformation

- Metric of the type

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

- Tetrads in Schwinger gauge

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

$$e_{\hat{0}}^i = \frac{1}{V}(\delta^i{}_0 + \delta^i{}_a cK^a), \qquad e_{\hat{a}}^i = \delta^i{}_b W^b{}_{\hat{a}}, \qquad a = 1, 2, 3,$$

- Dirac eq $\quad (i\hbar\gamma^\alpha D_\alpha - mc)\Psi = 0, \qquad \alpha = 0, 1, 2, 3.$

$$D_\alpha = e_\alpha^i D_i, \qquad D_i = \partial_i + \frac{iq}{\hbar}A_i + \frac{i}{4}\sigma^{\alpha\beta}\Gamma_{i\alpha\beta}.$$

Dirac hamiltonian

- Connection

$$\Gamma_{i\hat{a}\hat{0}} = \frac{c^2}{V} W^b{}_{\hat{a}} \partial_b V e_i{}^{\hat{0}} - \frac{c}{V} \mathcal{Q}_{(\hat{a}\hat{b})} e_i{}^{\hat{b}},$$

$$\Gamma_{i\hat{a}\hat{b}} = \frac{c}{V} \mathcal{Q}_{[\hat{a}\hat{b}]} e_i{}^{\hat{0}} + (\mathcal{C}_{\hat{a}\hat{b}\hat{c}} + \mathcal{C}_{\hat{a}\hat{c}\hat{b}} + \mathcal{C}_{\hat{c}\hat{b}\hat{a}}) e_i{}^{\hat{c}}.$$

$$\mathcal{Q}_{\hat{a}\hat{b}} = g_{\hat{a}\hat{c}} W^d{}_{\hat{b}} \left(\frac{1}{c} \dot{W}^{\hat{c}}{}_d + K^e \partial_e W^{\hat{c}}{}_d + W^{\hat{c}}{}_e \partial_d K^e \right),$$

$$\mathcal{C}_{\hat{a}\hat{b}}{}^{\hat{c}} = W^d{}_{\hat{a}} W^e{}_{\hat{b}} \partial_{[d} W^{\hat{c}}{}_{e]}, \qquad \mathcal{C}_{\hat{a}\hat{b}\hat{c}} = g_{\hat{c}\hat{d}} \mathcal{C}_{\hat{a}\hat{b}}{}^{\hat{d}}.$$

- Hermitian Hamiltonian

$$i\hbar \frac{\partial \psi}{\partial t} = \mathcal{H} \psi. \qquad \psi = (\sqrt{-g} e_{\hat{0}}^0)^{\frac{1}{2}} \Psi.$$

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

$$\Upsilon = V \epsilon^{\hat{a}\hat{b}\hat{c}} \Gamma_{\hat{a}\hat{b}\hat{c}} = -V \epsilon^{\hat{a}\hat{b}\hat{c}} \mathcal{C}_{\hat{a}\hat{b}\hat{c}},$$

$$\Xi_{\hat{a}} = \frac{V}{c} \epsilon_{\hat{a}\hat{b}\hat{c}} \Gamma_{\hat{0}}{}^{\hat{b}\hat{c}} = \epsilon_{\hat{a}\hat{b}\hat{c}} \mathcal{Q}^{\hat{b}\hat{c}}.$$

Foldy-Wouthuysen transformation

- Even and odd parts

$$\mathcal{H} = \beta\mathcal{M} + \mathcal{E} + \mathcal{O}, \qquad \beta\mathcal{M} = \mathcal{M}\beta,$$
$$\beta\mathcal{E} = \mathcal{E}\beta, \qquad \beta\mathcal{O} = -\mathcal{O}\beta.$$

- FW transformation (Silenko '08)

$$U = \frac{\beta\epsilon + \beta\mathcal{M} - \mathcal{O}}{\sqrt{(\beta\epsilon + \beta\mathcal{M} - \mathcal{O})^2}}\beta, \qquad \psi_{\mathrm{FW}} = U\psi, \qquad \mathcal{H}_{\mathrm{FW}} = U\mathcal{H}U^{-1} - i\hbar U\partial_t U^{-1}.$$

$$U^{-1} = \beta\frac{\beta\epsilon + \beta\mathcal{M} - \mathcal{O}}{\sqrt{(\beta\epsilon + \beta\mathcal{M} - \mathcal{O})^2}}. \qquad \epsilon = \sqrt{\mathcal{M}^2 + \mathcal{O}^2}$$

$$\begin{aligned}\mathcal{H}' = {} & \beta\epsilon + \mathcal{E} + \frac{1}{2T}([T,[T,(\beta\epsilon + Z)]] \\ & + \beta[\mathcal{O},[\mathcal{O},\mathcal{M}]] - [\mathcal{O},[\mathcal{O},Z]] \\ & - [(\epsilon + \mathcal{M}),[(\epsilon + \mathcal{M}),Z]] - [(\epsilon + \mathcal{M}),[\mathcal{M},\mathcal{O}]] \\ & - \beta\{\mathcal{O},[(\epsilon + \mathcal{M}),Z]\} + \beta\{(\epsilon + \mathcal{M}),[\mathcal{O},Z]\})\frac{1}{T},\end{aligned}$$

$$T = \sqrt{(\beta\epsilon + \beta\mathcal{M} - \mathcal{O})^2}$$

$$Z = \mathcal{E} - i\hbar\tfrac{\partial}{\partial t}$$

$$\mathcal{H}' = \beta\epsilon + \mathcal{E}' + \mathcal{O}', \qquad \beta\mathcal{E}' = \mathcal{E}'\beta, \qquad \beta\mathcal{O}' = -\mathcal{O}'\beta,$$

$$\mathcal{H}_{\mathrm{FW}} = \beta\epsilon + \mathcal{E}' + \frac{1}{4}\beta\left\{\mathcal{O}'^2, \frac{1}{\epsilon}\right\}.$$

FW for arbitrary gravitational field

- Result

$$\mathcal{H}_{\mathrm{FW}} = \mathcal{H}_{\mathrm{FW}}^{(1)} + \mathcal{H}_{\mathrm{FW}}^{(2)}.$$

$$\begin{aligned}\epsilon' &= \sqrt{m^2c^4V^2 + \frac{c^2}{4}\delta^{ac}\{p_b, \mathcal{F}^b{}_a\}\{p_d, \mathcal{F}^d{}_c\}},\\ \mathcal{T} &= 2\epsilon'^2 + \{\epsilon', mc^2V\}.\end{aligned}$$

$$\mathcal{M} = mc^2V,$$

$$\mathcal{E} = q\Phi + \frac{c}{2}(\boldsymbol{K}\cdot\boldsymbol{\pi} + \boldsymbol{\pi}\cdot\boldsymbol{K}) + \frac{\hbar c}{4}\boldsymbol{\Xi}\cdot\boldsymbol{\Sigma},$$

$$\mathcal{O} = \frac{c}{2}(\pi_b\mathcal{F}^b{}_a\alpha^a + \alpha^a\mathcal{F}^b{}_a\pi_b) - \frac{\hbar c}{4}\Upsilon\gamma_5.$$

$$\begin{aligned}\mathcal{H}_{\mathrm{FW}}^{(1)} = {}& \beta\epsilon' + \frac{\hbar c^2}{16}\Big\{\frac{1}{\epsilon'}, (2\epsilon^{cae}\Pi_e\{p_b, \mathcal{F}^d{}_c\partial_d\mathcal{F}^b{}_a\}\\ &+ \Pi^a\{p_b, \mathcal{F}^b{}_a\Upsilon\})\Big\}\\ &+ \frac{\hbar mc^4}{4}\epsilon^{cae}\Pi_e\Big\{\frac{1}{\mathcal{T}}, \{p_d, \mathcal{F}^d{}_c\mathcal{F}^b{}_a\partial_bV\}\Big\},\end{aligned}$$

$$\begin{aligned}\mathcal{H}_{\mathrm{FW}}^{(2)} = {}& \frac{c}{2}(K^ap_a + p_aK^a) + \frac{\hbar c}{4}\Sigma_a\Xi^a\\ &+ \frac{\hbar c^2}{16}\Big\{\frac{1}{\mathcal{T}}, \Big\{\Sigma_a\{p_e, \mathcal{F}^e{}_b\}, \Big\{p_f, \Big[\epsilon^{abc}\Big(\frac{1}{c}\dot{\mathcal{F}}^f{}_c\\ &- \mathcal{F}^d{}_c\partial_dK^f + K^d\partial_d\mathcal{F}^f{}_c\Big)\\ &- \frac{1}{2}\mathcal{F}^f{}_d(\delta^{db}\Xi^a - \delta^{da}\Xi^b)\Big]\Big\}\Big\}\Big\},\end{aligned}$$

Operator EOM

- Polarization operator $\mathbf{\Pi} = \beta\mathbf{\Sigma}$

$$\frac{d\mathbf{\Pi}}{dt} = \frac{i}{\hbar}[\mathcal{H}_{\rm FW}, \mathbf{\Pi}] = \mathbf{\Omega}_{(1)} \times \mathbf{\Sigma} + \mathbf{\Omega}_{(2)} \times \mathbf{\Pi}.$$

- Angular velocities

$$\Omega^a_{(1)} = \frac{mc^4}{2}\left\{\frac{1}{\mathcal{T}}, \{p_e, \epsilon^{abc}\mathcal{F}^e{}_b\mathcal{F}^d{}_c\partial_d V\}\right\}$$
$$+ \frac{c^2}{8}\left\{\frac{1}{\epsilon'}, \{p_e, (2\epsilon^{abc}\mathcal{F}^d{}_b\partial_d\mathcal{F}^e{}_c + \delta^{ab}\mathcal{F}^e{}_b\Upsilon)\}\right\},$$

$$\Omega^a_{(2)} = \frac{\hbar c^2}{8}\left\{\frac{1}{\mathcal{T}}, \left\{\{p_e, \mathcal{F}^e{}_b\}, \left\{p_f, \left[\epsilon^{abc}\left(\frac{1}{c}\dot{\mathcal{F}}^f{}_c - \mathcal{F}^d{}_c\partial_d K^f + K^d\partial_d\mathcal{F}^f{}_c\right) - \frac{1}{2}\mathcal{F}^f{}_d(\delta^{db}\Xi^a - \delta^{da}\Xi^b)\right]\right\}\right\}\right\} + \frac{c}{2}\Xi^a.$$

Semi-classical limit

- Average spin

$$\frac{d\mathbf{s}}{dt} = \mathbf{\Omega} \times \mathbf{s} = (\mathbf{\Omega}_{(1)} + \mathbf{\Omega}_{(2)}) \times \mathbf{s},$$

$$\Omega^a_{(1)} = \frac{c^2}{\epsilon'} \mathcal{F}^d{}_c p_d \Big(\frac{1}{2} \Upsilon \delta^{ac} - \epsilon^{aef} V C_{ef}{}^c + \frac{\epsilon'}{\epsilon' + mc^2 V} \epsilon^{abc} W^e{}_{\hat{b}} \partial_e V \Big),$$

$$\Omega^a_{(2)} = \frac{c}{2} \Xi^a - \frac{c^3}{\epsilon'(\epsilon' + mc^2 V)} \epsilon^{abc} Q_{(bd)} \delta^{dn} \mathcal{F}^k{}_n p_k \mathcal{F}^l{}_c p_l,$$

Application to anisotropic universe (Kamenshchik,OT)

- Bianchi-1 Universe

$$ds^2 = dt^2 - a^2(t)(dx^1)^2 - b^2(t)(dx^2)^2 - c^2(t)(dx^3)^2.$$

- Particular case $W_1^{\hat{1}} = a(t),\ W_2^{\hat{2}} = b(t),\ W_3^{\hat{3}} = c(t).$

$$W_{\hat{1}}^1 = \frac{1}{a(t)},\ W_{\hat{2}}^2 = \frac{1}{b(t)},\ W_{\hat{3}}^3 = \frac{1}{c(t)}.$$

- No anholonomity $\Upsilon = 0$

$$\Omega^{\hat{1}}_{(2)} = \frac{\gamma}{\gamma+1} v_{\hat{2}} v_{\hat{3}} \left(\frac{\dot{b}}{b} - \frac{\dot{c}}{c}\right).$$

$$Q_{\hat{1}\hat{1}} = -\frac{\dot{a}}{a},\ Q_{\hat{2}\hat{2}} = -\frac{\dot{b}}{b},\ Q_{\hat{3}\hat{3}} = -\frac{\dot{c}}{c}.$$

Kasner solution

- t-dependence

$$a(t) = a_0 t^{p_1},\ b(t) = b_0 t^{p_2},\ c(t) = c_0 t^{p_3},$$

$$p_1 + p_2 + p_3 = 1,\ \ p_1^2 + p_2^2 + p_3^2 = 1.$$

- Euler-type expressions

$$\Omega^{\bar{1}}_{(2)} = \frac{\gamma}{\gamma+1} v_{\bar{2}} v_{\bar{3}} \left(\frac{p_2 - p_3}{t} \right)$$

Heckmann-Schucking solution

- Dust admixture

$$a(t) = a_0 t^{p_1} (t_0 + t)^{\frac{2}{3} - p_1}, \; b(t) = b_0 t^{p_2} (t_0 + t)^{\frac{2}{3} - p_2},$$
$$c(t) = c_0 t^{p_3} (t_0 + t)^{\frac{2}{3} - p_3}.$$

- Modification:

$$\Omega^{1}_{(2)} = \frac{\gamma}{\gamma + 1} v_2 v_3 \frac{(p_2 - p_3) t_0}{t(t_0 + t)}$$

$$= \frac{\gamma}{\gamma + 1} v_2 v_3 \frac{(p_2 - p_3) t_0}{t^2} \left(1 + o\left(\frac{t_0}{t}\right)\right)$$

Biancki-IX Universe

- Metric $W^{\hat{b}}{}_{a} = \begin{pmatrix} -a\sin x^3 & a\sin x^1\cos x^3 & 0 \\ b\cos x^3 & b\sin x^1\sin x^3 & 0 \\ 0 & c\cos x^1 & c \end{pmatrix}$ $W^{c}{}_{\hat{b}} = \begin{pmatrix} -\frac{1}{a}\sin x^3 & \frac{1}{b}\cos x^3 & 0 \\ \frac{1}{a}\frac{\cos x^3}{\sin x^1} & \frac{1}{b}\frac{\sin x^3}{\sin x^1} & 0 \\ -\frac{1}{a}\frac{\cos x^1\cos x^3}{\sin x^1} & -\frac{1}{b}\frac{\sin x^3\cos x^1}{\sin x^1} & \frac{1}{c} \end{pmatrix}$
- Anholonomity coefficients
- $C^{\hat{3}}_{\hat{1}\hat{2}} = \dfrac{c}{ab}$ + cyclic permutations
- -> non-zero $\Upsilon = 2\left(\dfrac{c}{ab} + \dfrac{b}{ac} + \dfrac{a}{bc}\right)$

$$\Omega^{\hat{1}}_{(1)} = v^{\hat{1}}\left(\frac{c}{ab} + \frac{b}{ac} - \frac{a}{bc}\right)$$

Approach to singularity

- Chaotic oscillations – sequence of Kasner regimes $p_1 = -\frac{u}{1+u+u^2},\ p_2 = \frac{1+u}{1+u+u^2},\ p_3 = \frac{u(1+u)}{1+u+u^2}$
- If Lifshitz-Khalatnıkov parameter u >1 – "epochs" $p'_1 = p_2(u-1),\ p'_2 = p_1(u-1),\ p'_3 = p_3(u-1)$

$$p'_1 = p_1\left(\frac{1}{u}\right),\ p'_2 = p_3\left(\frac{1}{u}\right),\ p'_3 = p_2\left(\frac{1}{u}\right)$$

- If u< 1 – "eras"
- Change of eras – chaotic mapping of [0,1]interrval

$$Tx = \left\{\frac{1}{x}\right\},\quad x_{s+1} = \left\{\frac{1}{x_s}\right\}$$

Angular velocities

- New epoch: u -> -u
- New era – changed sign

$$\Omega^{\hat{1}}_{(2)} = \frac{\gamma}{(\gamma+1)t} v_{\hat{2}} v_{\hat{3}} \cdot \frac{1-u^2}{1+u+u^2},$$
$$\Omega^{\hat{2}}_{(2)} = \frac{\gamma}{(\gamma+1)t} v_{\hat{1}} v_{\hat{3}} \cdot \frac{2u+u^2}{1+u+u^2},$$
$$\Omega^{\hat{3}}_{(2)} = -\frac{\gamma}{(\gamma+1)t} v_{\hat{1}} v_{\hat{2}} \cdot \frac{1+2u}{1+u+u^2}.$$

- Odd velocity

$$\Omega^{\hat{1}}_{(1)} \sim -v^{\hat{1}}(t)^{\left(-1-\frac{2u}{1+u+u^2}\right)},$$
$$\Omega^{\hat{b}}_{(1)} \sim v^{\hat{b}}(t)^{\left(-1-\frac{2u}{1+u+u^2}\right)}, \ b = 2,3.$$

$$\Omega^{\hat{2}}_{(1)} \sim -v^{\hat{2}}(t)^{\left(-1-\frac{2u-2}{1-u+u^2}\right)},$$
$$\Omega^{\hat{a}}_{(1)} \sim v^{\hat{a}}(t)^{\left(-1-\frac{2u-2}{1-u+u^2}\right)}, \ a = 1,3.$$

- New epoch
- New era - preserved

Possible applications

- Anisotropy (c.f. crystals) ~ magnetic field
- Spin precession + equivalence principle = helicity flip (~AMM effect)
- Dirac neutrino – transformed to sterile component in early (bounced) Universe
- Angular velocity ~ 1/t -> amount of decoupled ~ 1
- Possible new candidate for dark matter?!
- Other fields AFTER inflation?

CONCLUSIONS

- Polarization – extra sensitive tests
- Gravity leads to spin effects related to Kobzarev-Okun equivalence principle
- Bianchi universe – spin precession and neutrino helicity flip

- BACKUP SLIDES

Semi-classical limit

- Average spin precession

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = (\vec{\Omega}_{(1)} + \vec{\Omega}_{(2)}) \times \vec{s}.$$

- Angular velocity contributions

$$\Omega^{\hat{a}}_{(1)} = \frac{1}{\varepsilon'} W^{d}_{\hat{c}} p_d \left(\frac{1}{2} \Upsilon \delta^{\hat{a}\hat{c}} - \varepsilon^{\hat{a}\hat{e}\hat{f}} C_{\hat{e}\hat{f}}^{\hat{c}} \right),$$

$$\Omega^{\hat{a}}_{(2)} = \frac{1}{2} \Xi^{\hat{a}} - \frac{1}{\varepsilon'(\varepsilon' + m)} \varepsilon^{\hat{a}\hat{b}\hat{c}} Q_{(\hat{b}\hat{d})} \delta^{\hat{d}\hat{n}} W^{k}_{\hat{n}} p_k W^{l}_{\hat{c}} p_l.$$

Torsion – acts only on spin

Dirac eq+FW transformation-Obukhov,Silenko,OT

- Hermitian Dirac Hamiltonian

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

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

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

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

- Spin-torsion coupling

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

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

- FW – semiclassical limit - precession

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

Experimental bounds for torsion

- Magnetic field+rotation+torsion

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

- Same '92 EDM experiment

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

- New(based on Gemmel et al '10)

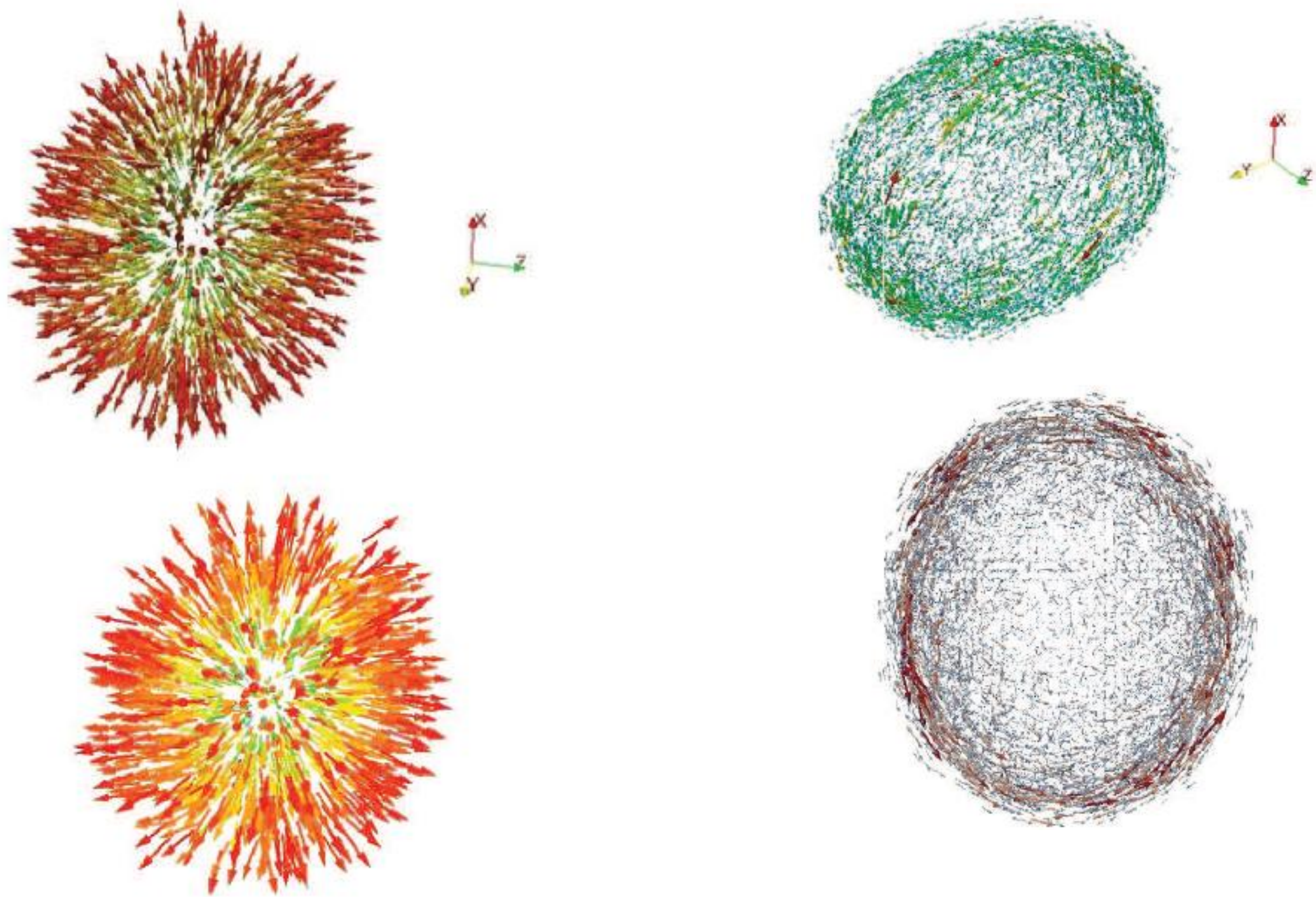
$$\frac{\hbar c}{2} |\check{\boldsymbol{T}}| \cdot |(1-\mathcal{G})\cos\Theta| < 4.1 \times 10^{-22}\,\mathrm{eV}, \qquad |\check{\boldsymbol{T}}| \cdot |\cos\Theta| < 2.4 \times 10^{-15}\,\mathrm{m}^{-1}$$

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

Microworld: where is the fastest possible rotation?

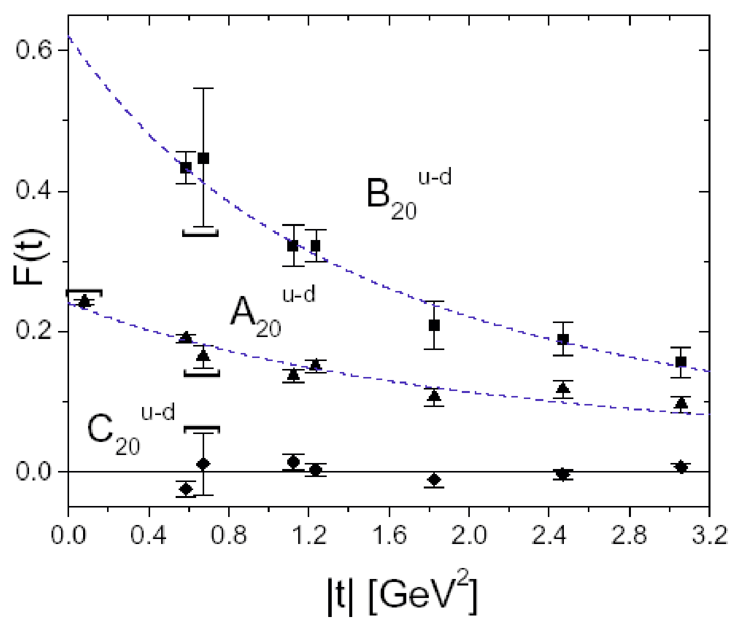
- Non-central heavy ion collisions (~c/Compton wavelength) – “small Bang”
- Differential rotation – vorticity
- Leads to hyperons polarization – should be larger at small energy – predicted in 2010 (Rogachevsky, Sorin, OT) now found by STAR@RHIC
- Calculation in quark - gluon string model (Baznat,Gudima,Sorin,OT,PRC’13)

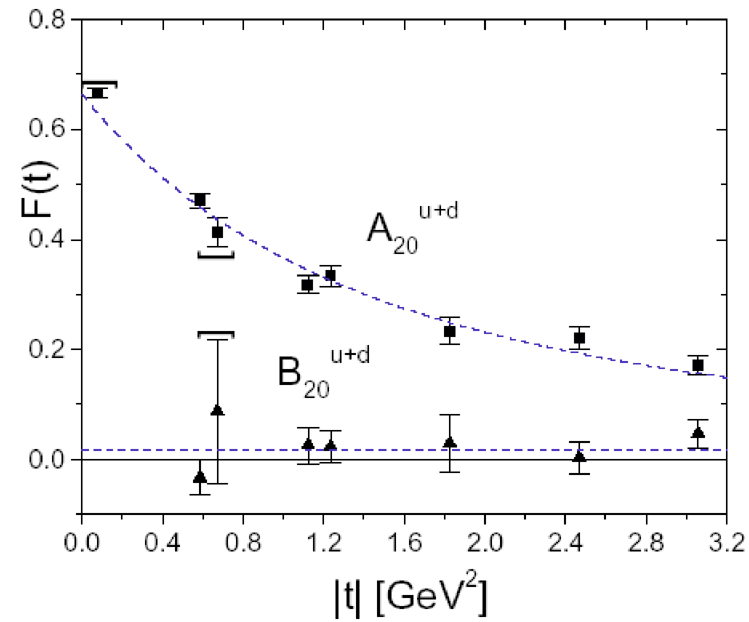
Structure of velocity and vorticity fields (NICA@JINR-5 GeV/c)



Generalization of Equivalence principle

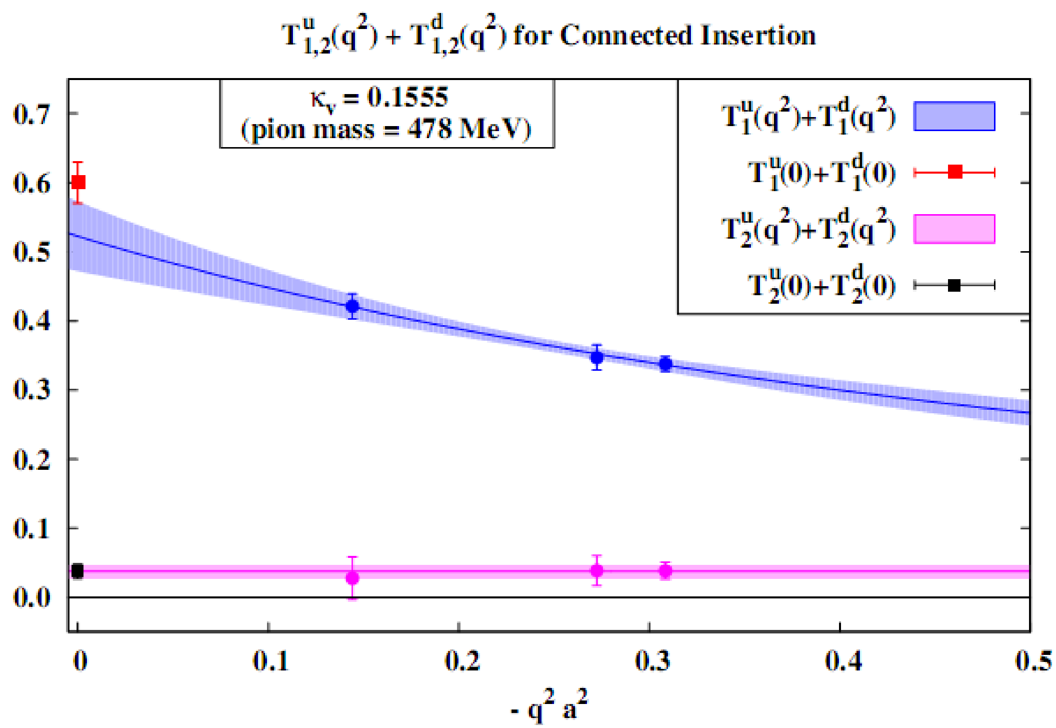
- Various arguments: AGM ≈ 0 separately for quarks and gluons – most clear from the lattice (LHPC/SESAM)





Recent lattice study (M. Deka et al. **arXiv:1312.4816; cf plenary talk of K.F. Liu**)

- 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
- Supported by generic smallness of E (isoscalar AMM)

Sum rules for EMT (and OAM)

- First (seminal) example: X. Ji's sum rule ('96). Gravity counterpart – OT'99
- Burkardt sum rule – looks similar: can it be derived from EMT?
- Yes, if provide correct prescription to gluonic pole (OT'14)

Pole prescription and Burkardt SR

- Pole prescription (dynamics!) provides ("T-odd") symmetric part!
- SR: $\sum \int dx T(x,x) = 0$ $\quad \sum \int \int dx_1 dx_2 \frac{T(x_1,x_2)}{x_1 - x_2 + i\varepsilon} = 0$ (but relation of gluon Sivers to twist 3 still not founs – prediction!)
- Can it be valid separately for each quark flavour: nodes (related to "sign problem")?
- Valid if structures forbidden for TOTAL EMT do not appear for each flavour
- Structure contains besides S gauge vector n: If GI separation of EMT – forbidden: SR valid separately!

Another manifestation of post-Newtonian (E)EP for spin 1 hadrons

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

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

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

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

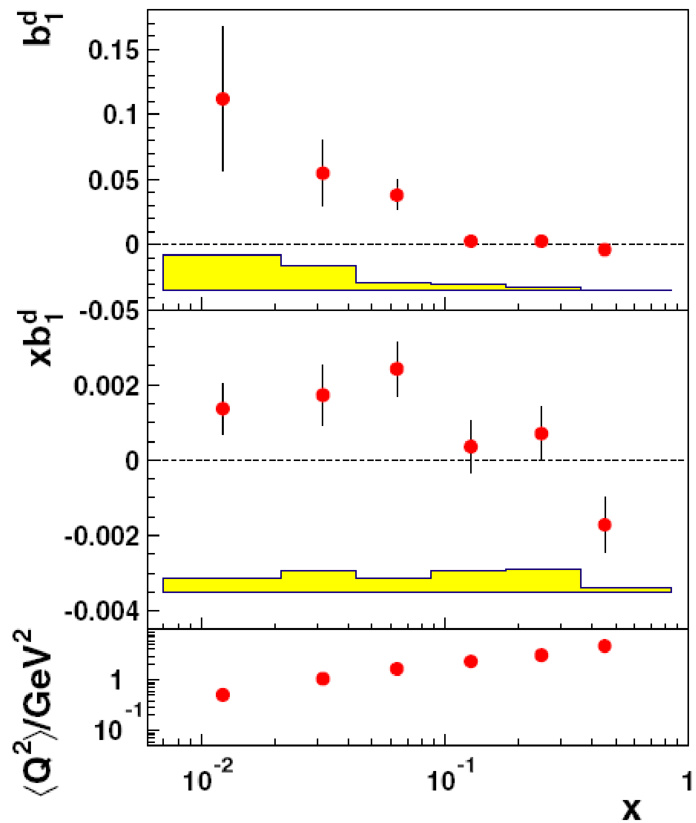
$$\sum_q \int_0^1 C_i^T(x)x dx = \delta_1(\mu^2)$$ =0 for ExEP

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 EEP
- Second moments – compatible to zero better than the first one (collective glue << sea) – for valence:

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



Are more accurate data possible?

- HERMES – unlikely

- JLab may provide information about collective sea and glue in deuteron and indirect new test of Equivalence Principle

CONCLUSIONS

- Spin-gravity interactions may be probed directly in gravitational (inertial) experiments and indirectly – studing EMT matrix element
- Torsion and EP are tested in EDM experiments
- SR’s for deuteron tensor polarization-indirectly probe EP and its extension separately for quarks and gluons

EEP and AdS/QCD

- Recent development – calculation of Rho formfactors in Holographic QCD (Grigoryan, Radyushkin)
- Provides g=2 identically!
- Experimental test at time –like region possible