Particle correlators and possible local parity violation in nuclear collisions

Parfenov Peter Okorokov Vitali

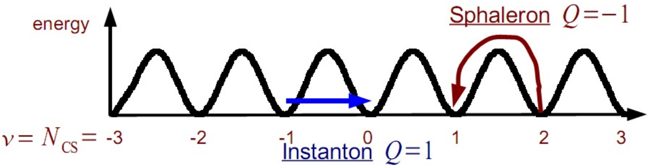
Nuclear Research National University "MEPhI"
Moscow

Dubna 2015

1. Motivation
   - *CP* symmetry in QCD
   - Heavy ion collisions
2. Results
   - Magnetic field
   - Correlators
3. Summary

Problem formulation

- The QCD Lagrangian has natural terms that are able to break the *CP* symmetry.
- There are no such experimentally known violation in QCD sector.
- The QCD vacuum topology may cause local domains with $N_L - N_R \neq 0$.



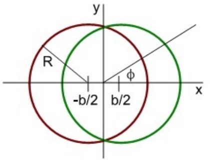
Chiral Magnetic Effect

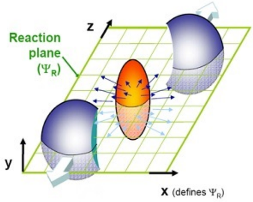
Separation of the charged particles via background magnetic field in local region is called Chiral Magnetic Effect.

- At $\sqrt{s_{NN}} \sim 10^2\ GeV$, magnetic field must be around $e\boldsymbol{B} \sim 10^2 - 10^3\ MeV^2\ (\sim 10^{15} - 10^{16} G)$.
- Charged particles separate around overlap region. Correlation between this particles could be measured experimentally.

$\Delta_\pm = N^\pm_\uparrow - N^\pm_\downarrow \longrightarrow \langle\Delta^2_\pm\rangle, \langle\Delta_+\Delta_-\rangle \longrightarrow$ Measurment of the effect.

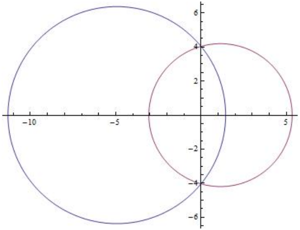
Scheme of the collisions





Symmetric type of the nuclear collisions. R – is the nucleon radius, b – impact parameter.

$$0 < b \leqslant 2R$$



Asymmetric type of the collsions. Impact parameter lies in the range:

$$|R_2 - R_1| < b \leqslant R_2 + R_1$$

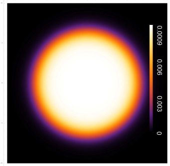
Parametrisations of the nuclear density

Rigid sphere model

$$\rho^H_{\pm}(\boldsymbol{x}'_{\perp}) = \frac{2}{\frac{4}{3}\pi R^3} y_{\pm}(\boldsymbol{x}'_{\perp})$$

Fermi based model

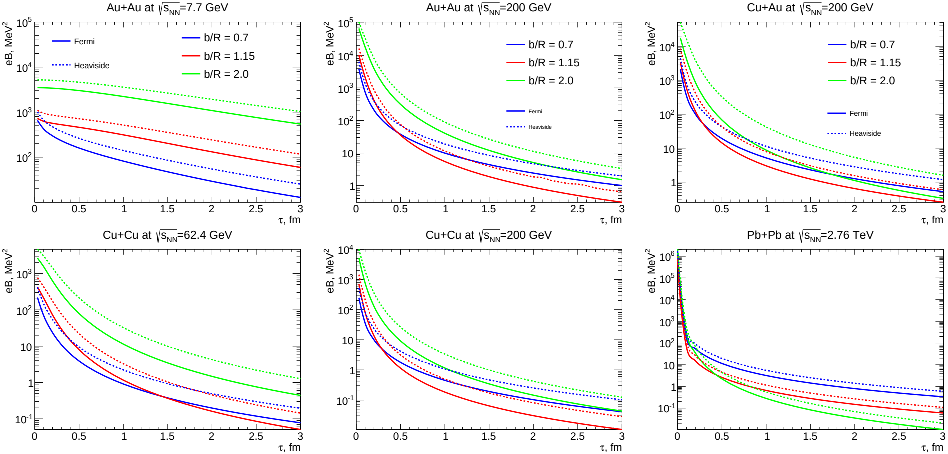
$$\rho^F_{\pm}(\boldsymbol{x}'_{\perp}) = N^F \frac{y_{\pm}(\boldsymbol{x}'_{\perp})}{1 + e^{\frac{-y_{\pm}(\boldsymbol{x}'_{\perp})}{a}}},$$



$$y_{\pm}(\boldsymbol{x}'_{\perp}) = \sqrt{R^2_{1,2} - \left(\boldsymbol{x}'_{\perp} \pm \frac{\boldsymbol{b}}{2} \mp \frac{R_2^2 - R_1^2}{2b}\mathbf{e}'_{\perp}\right)^2}$$

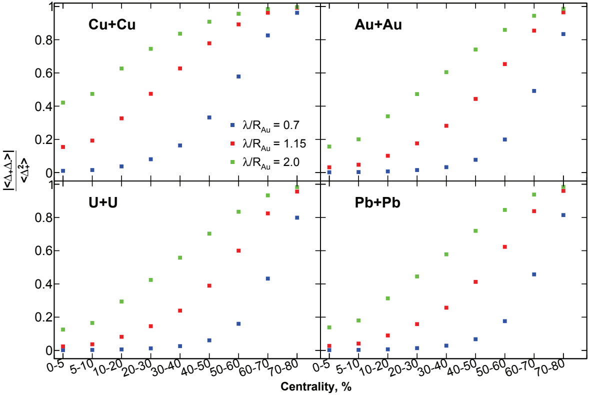
- Similar work with Wood-Saxon distribution was made by Yu-Jun Mo in Phys. Rev. C88 (2013) 2, 024901.

$eB(\tau)$ in heavy ion collisions



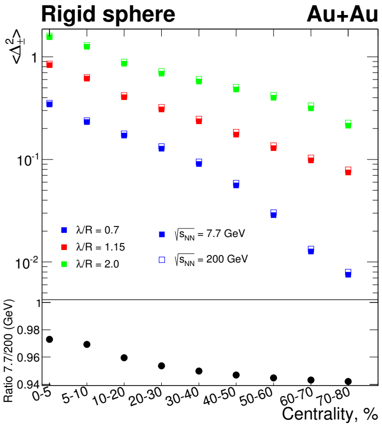
Magnetic field calculated for RHIC and LHC energies.

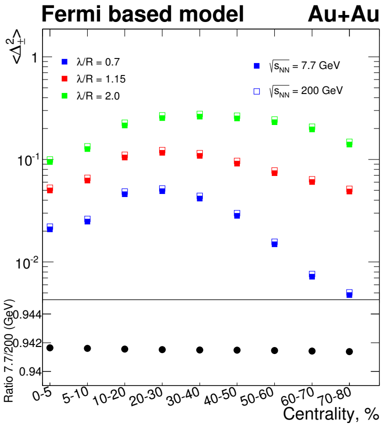
Correlator's ratio



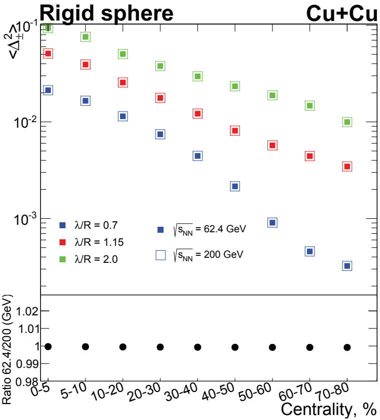
- Ratio depends on size of the systems only.
- Parameter $\frac{\lambda}{R}$ is scalable, so we fix R.

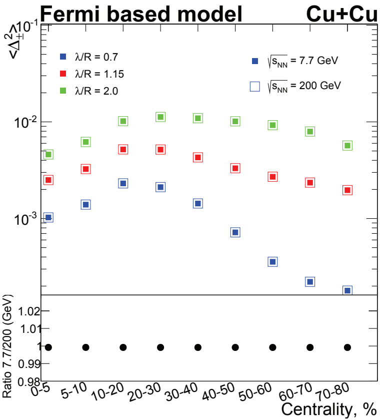
Correlators $\langle \Delta_+^2 \rangle = \langle \Delta_-^2 \rangle$



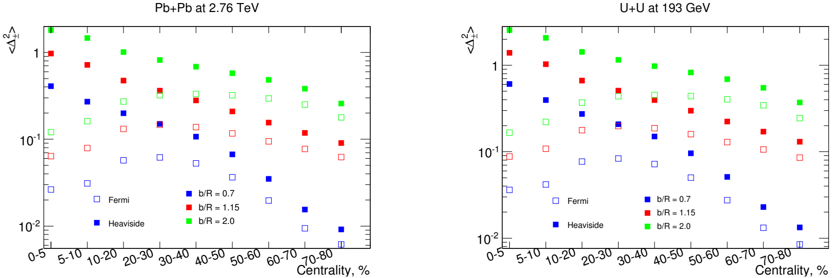


Correlators $\langle\Delta_+^2\rangle = \langle\Delta_-^2\rangle$





Correlators $\langle \Delta_+^2 \rangle = \langle \Delta_-^2 \rangle$



The energy dependance is unsignificant. The multiplicity of charged particles is the main contribution to the energy dependance which can be observed experimentally.

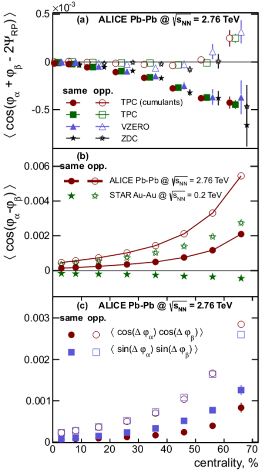
Summary

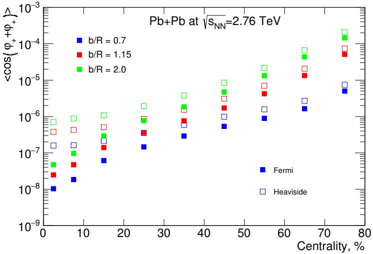
- The ***eB*** as function of time has been computed in AuAu, CuCu, CuAu and PbPb collisions. The value satisfies theoretical requirements.
- Correlator's ratio was computed and depends on the size of the system.
- Absolute values of the correlators rises unsignificantly with energy.

- Further work:
  - Need to take into account multiplicity of the charged particles.
  - Experimentally measured correlators for opposite charged particles larger than ones for same charges. This contradicts to our results.

Backup

Results of the computation with multiplicity of the charged particles





Left: Centrality dependance of the two-particle correlator (PRL 110(1) 012301 (2013))
Right: Computed centrality of the two-particle correlator

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Computation formulae 1

Correlators

$$\frac{d\langle\Delta_{\pm}^2\rangle}{d\eta} = 2\kappa\alpha_s\left[\sum_f q_f^2\right]^2 \int\limits_{V_\perp} d^2\boldsymbol{x}'_\perp \left[\xi_+^2\left(\boldsymbol{x}'_\perp\right) + \xi_-^2\left(\boldsymbol{x}'_\perp\right)\right] \int\limits_{\tau_i}^{\tau_f} d\tau\,\tau\left[e\boldsymbol{B}\left(\tau,\eta,\boldsymbol{x}'_\perp\right)\right]^2,$$

$$\frac{d\langle\Delta_+\Delta_-\rangle}{d\eta} = -4\kappa\alpha_s\left[\sum_f q_f^2\right]^2 \int\limits_{V_\perp} d^2\boldsymbol{x}'_\perp \xi_+\left(\boldsymbol{x}'_\perp\right)\xi_-\left(\boldsymbol{x}'_\perp\right) \int\limits_{\tau_i}^{\tau_f} d\tau\,\tau\left[e\boldsymbol{B}\left(\tau,\eta,\boldsymbol{x}'_\perp\right)\right]^2.$$

Normalization of Fermi based model

$$N^F = \frac{2}{4\pi a\left[R^2\ln\left(1+e^{\frac{R}{a}}\right) + 2Ra\,\mathrm{Li}_2\left(-e^{\frac{R}{a}}\right) - 2a^2\,\mathrm{Li}_3\left(-e^{\frac{R}{a}}\right) - \frac{3}{2}a^2\zeta(3)\right]}$$

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Computation formulae 2

Correlator's ratio

$$\frac{|\Delta_+ \Delta_+|}{\Delta_+^2} = \frac{2 \int\limits_{V_\perp} d^2\boldsymbol{x}'_\perp \xi_+ \left(\boldsymbol{x}'_\perp\right) \xi_- \left(\boldsymbol{x}'_\perp\right)}{\int\limits_{V_\perp} d^2\boldsymbol{x}'_\perp \left[\xi_+^2 \left(\boldsymbol{x}'_\perp\right) + \xi_-^2 \left(\boldsymbol{x}'_\perp\right)\right]}.$$

Screening function

$$\xi_\pm \left(\boldsymbol{x}'_\perp\right) = e^{\frac{-|y_\pm\left(\boldsymbol{x}'_\perp\right) - y|}{\lambda}},$$

$$y_+ \left(\boldsymbol{x}'_\perp\right) = -y_- \left(\boldsymbol{x}'_\perp\right) = \begin{cases} \sqrt{R_1^2 - \left(\boldsymbol{x}'_\perp - \frac{b}{2} + \frac{R_2^2 - R_1^2}{2b}\right)^2}, & V_\perp(left) \leqslant x \leqslant 0 \\ \sqrt{R_2^2 - \left(\boldsymbol{x}'_\perp + \frac{b}{2} - \frac{R_2^2 - R_1^2}{2b}\right)^2}, & 0 \leqslant x \leqslant V_\perp(right) \end{cases}$$

Computation formulae 3

Spectator

$$eB_s^{\pm 1,2} = \pm Z^{1,2} \alpha_{EM} \sinh(Y_0) \int d^2 x'_\perp \rho_\pm^{1,2}(x'_\perp)[1 - \theta_\mp^{1,2}(x'_\perp)] \times$$

$$\times \frac{(x'_\perp - x_\perp) \times e_z}{[(x'_\perp - x_\perp)^2 + (\tau \sinh(Y_0 \mp \eta))^2]^{\frac{3}{2}}}, \; \mathrm{x}_\perp \equiv \mathrm{x}_\perp^{1,2} = -\frac{R_{2,1}^2 - R_{1,2}^2}{2b}$$

Participants

$$eB_p^{\pm 1,2} = \pm \alpha_{EM} \int\limits_{V_\perp^{1,2}} d^2 x'_\perp \int\limits_{-Y_0}^{Y_0} dY f(Y) \sinh(Y) \times$$

$$\times \left(Z^1 \rho_\pm^1(x'_\perp) \theta_\mp^1(x'_\perp) + Z^2 \rho_\pm^2(x'_\perp) \theta_\mp^2(x'_\perp) \right) \frac{(x'_\perp - x_\perp) \times e_z}{[(x'_\perp - x_\perp)^2 + (\tau \sinh(Y \mp \eta)^2]^{\frac{3}{2}}}.$$

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Computation formulae 4

Integral boundaries

$$V_1^{min} = -\frac{R_2}{2}\left[\left(\frac{b}{R_2}+\frac{R_2^2-R_1^2}{bR_2}\right)\cos\varphi - \sqrt{4-\left(\frac{b}{R_2}+\frac{R_2^2-R_1^2}{bR_2}\right)^2\sin^2\varphi}\right]$$

$$V_1^{max} = \frac{R_1}{2}\left[\left(\frac{b}{R_1}-\frac{R_2^2-R_1^2}{bR_1}\right)\cos\varphi + \sqrt{4-\left(\frac{b}{R_1}-\frac{R_2^2-R_1^2}{bR_1}\right)^2\sin^2\varphi}\right]$$

Computation formulae 5

Approximation for the magnetic field

$$e\boldsymbol{B} = e\boldsymbol{B}_p + e\boldsymbol{B}_s \approx Z\alpha_{EM}\left[ce^{-\frac{Y_0}{2}}\frac{1}{R^{\frac{1}{2}}\tau^{\frac{3}{2}}}f\left(\frac{b}{R}\right) + 4e^{-2Y_0}\frac{b}{\tau^3}\right]$$

$$a_{++} = a_{--} = \frac{1}{N_+^2}\frac{\pi^2}{16}2Z^2\alpha_{EM}^2\kappa\alpha_s\left[\sum_f q_f^2\right]^2\int\limits_{V_\perp} d^2\boldsymbol{x}'_\perp\left[\xi_+^2\left(\boldsymbol{x}'_\perp\right) + \xi_-^2\left(\boldsymbol{x}'_\perp\right)\right]\times$$

$$\times\left(c^2e^{-Y_0}\frac{1}{R\tau_i}f^2\left(\frac{b}{R}\right) + \frac{16}{5}ce^{-\frac{5}{2}Y_0}\frac{b^2}{R^{\frac{1}{2}}\tau_i^{\frac{5}{2}}} + 4e^{-4Y_0}\frac{b^2}{\tau_i^4}\right),$$

$$f\left(\frac{b}{R}\right) = f_+\left(\frac{b}{R}\right) + f_-\left(\frac{b}{R}\right), \quad f_\pm\left(\frac{b}{R}\right) = \mp R^{\frac{1}{2}}\int\limits_{V_\perp} d^2\boldsymbol{x}'_\perp\rho_\pm\left(\boldsymbol{x}'_\perp\right)\theta_\mp\left(\boldsymbol{x}'_\perp\right)\frac{x'_\perp}{\left|\boldsymbol{x}'_\perp\right|^{\frac{3}{2}}}$$

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Computation formulae 6

$$a_{++} = a_{--} = \frac{1}{N_+^2}\frac{\pi^2}{16}2\alpha_{EM}^2\kappa\alpha_s\left[\sum_f q_f^2\right]^2 \sum_{1,2}\int_{V_\perp^{1,2}} d^2\boldsymbol{x}'_\perp\left[\xi_+^2\left(\boldsymbol{x}'_\perp\right)+\xi_-^2\left(\boldsymbol{x}'_\perp\right)\right]\times$$

$$\times\left[c^2 e^{-Y_0}\frac{1}{\tau_i}\left(\frac{Z_1}{R_1^{\frac{1}{2}}}f_1^2\left(\frac{b}{R}\right)+\frac{Z_2}{R_2^{\frac{1}{2}}}f_2^2\left(\frac{b}{R}\right)\right)^2+\frac{16}{5}ce^{-\frac{5}{2}Y_0}\frac{b}{\tau_i^{\frac{5}{2}}}\left(Z_1+Z_2\right)\times\right.$$

$$\left.\times\left(\frac{Z_1}{R_1^{\frac{1}{2}}}f_1^2\left(\frac{b}{R}\right)+\frac{Z_2}{R_2^{\frac{1}{2}}}f_2^2\left(\frac{b}{R}\right)\right)+4e^{-4Y_0}\frac{b}{\tau_i^4}\left(Z_1+Z_2\right)\right],$$

$$f_{1,2}\left(\frac{b}{R}\right)=f_+^{1,2}\left(\frac{b}{R}\right)+f_-^{1,2}\left(\frac{b}{R}\right),$$

$$f_\pm^{1,2}\left(\frac{b}{R}\right)=\int d^2\boldsymbol{x}'_\perp\left(R_1^{\frac{1}{2}}\rho_\pm^1\left(\boldsymbol{x}'_\perp\right)\theta_\mp^1\left(\boldsymbol{x}'_\perp\right)+R_2^{\frac{1}{2}}\rho_\pm^2\left(\boldsymbol{x}'_\perp\right)\theta_\mp^2\left(\boldsymbol{x}'_\perp\right)\right)\frac{x'_\perp}{|\boldsymbol{x}'_\perp|^{\frac{3}{2}}}$$

Computation formulae 7

$$a_{++} \sim \frac{1}{N_+^2}\frac{\pi^2}{16}2\kappa\alpha_s Z^2\alpha_{EM}^2\left[\sum_f q_f^2\right]^2\left[2\arccos\left(\frac{b}{2R}\right) - \frac{b}{R}\sqrt{1-\frac{b^2}{4R^2}}\right]\frac{b^2}{4R^2}$$

$$a_{++} \sim \frac{\pi^2 2\kappa\alpha_s Z^2\alpha_{EM}^2}{N_+^2 16}\left[\sum_f q_f^2\right]^2 \frac{1}{2}\left(\frac{b^2}{4R_1^4}+\frac{b^2}{4R_2^4}\right)\times$$

$$\times\left[R_1^2\arccos\left(\frac{b^2+R_1^2-R_2^2}{2bR_1}\right)+R_2^2\arccos\left(\frac{b^2+R_2^2-R_1^2}{2bR_2}\right)-\right.$$

$$\left.-\frac{1}{2}\sqrt{(-b+R_1+R_2)(b+R_1-R_2)(b-R_1+R_2)(b+R_1+R_2)}\right].$$