P and CP-odd fluctuations and New Thermalization Scenario in Heavy Ion Collisions (based on Nucl.Phys. A (2011)

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1. Motivation.

- The main goal of this talk is to argue that two, naively unrelated, phenomena:

- 1.local P, CP violating fluctuations in QCD as observed at RHIC

- 2. universal behaviour of multihadron production in high energy e^+e^-, $\bar{p}p$, pp, NN collisions described by a universal hadronization temperature $T_H \sim 150$ MeV are in fact tightly related, as they describe different sides of the same fundamental physics.

2. Charge separation effect. CME.

- The $\theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu a}$ term is a key player in strongly interacting QCD

- $\theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu a} = \theta \partial_\mu K^\mu$ is total derivative, does not change the equation of motion. Still, it leads to the physically observable effects: dipole moment, $\eta' \to 2\pi$

- $\theta < 10^{-9}$ must be small (now) as it violates P, CP invariance in strong interactions.

- Still, a large domain with effective $\theta_{ind} \neq 0$ may be induced as a result of non-equilibrium dynamics during the QCD phase transition. It may result in local P and CP odd fluctuations (observed at RHIC).

- For the uniform magnetic field the electric field will be induced along B in the presence of θ

- the induced electric field will lead to the induced currents and to the separation of charges along B (CME):

$$L^2 E_z^{ind} = -\left(\frac{e\,\theta}{2\pi}\right) l, \quad \text{where} \quad l = \frac{e}{2\pi}\int d^2x_\perp {B_z}^{ext}$$

$$\vec{J} = (\mu_L - \mu_R)\frac{e\vec{B}}{2\pi^2}, \quad \text{where} \quad (\mu_L - \mu_R) = \dot{\theta}$$

- A similar phenomenon happens when the system is rotating (it effectively replaces the magnetic field B). Therefore: an upper hemisphere can thus have either excess of quarks over anti-quarks or vice-versa.

$$[Q(z=+L) - Q(z=-L)] \sim \left(\frac{e\,\theta}{2\pi}\right) l$$

- D. Kharzeev and A. Zhitnitsky, 2007; D. E. Kharzeev, L. D. McLerran, H. J. Warringa, 2007; K. Fukushima, D. E. Kharzeev and H. J. Warringa, 2008;

3. Universal hadronization temperature

- Hadron production studies in a variety of high energy collision experiments have shown a remarkably universal feature, indicating a universal hadronization temperature $T_H \sim (150 - 200)\ \mathrm{MeV}$

- It is very difficult to understand its nature as the statistical thermalization in e^+e^-, pp and $\bar{p}p$ could never be reached in those systems.

- <u>We adopt the conjecture</u> that this ``apparent thermalization" originates from the event horizon in an accelerating frame. It leads to the thermal character of the Unruh radiation.

- We do not attempt to compute acceleration "a" in terms of the strongly coupled QCD. Instead, we assume that such description exists, and we use "a" as a free parameter in our analysis.

- Early papers on the subject (treating the "thermalization" as the Unruh effect): A. Salam and J. Strathdee, 1977; S. Barshay and W. Troost, 1978 ; A. Hosoya, 1979 ; M. Horibe (1979).

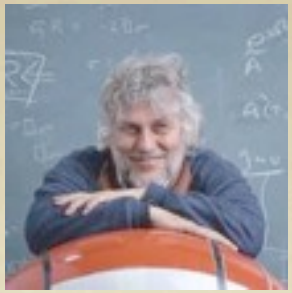
- The modern, QCD based formulation of this idea has been developed quite recently: D. Kharzeev and K. Tuchin, 2005; D. Kharzeev, E. Levin and K. Tuchin, 2007; P. Castorina, D. Kharzeev and H. Satz, 2007 + many more....

- The key ingredient of this approach is as follows: an observer moving with an acceleration "a" experiences the influence of a thermal bath with an effective temperature expressed in terms of QCD (string tension, saturation scale...)

$$T = \frac{a}{2\pi}, \quad a \simeq \sqrt{2\pi\sigma}, \quad a \sim 1 \text{ GeV}$$

- it explains a number of puzzles, e.g. the universality of the temperature, as it does not depend on the processes, nor on the energy of colliding particles.

4. Accelerating system. The Unruh effect, $T \neq 0$



- The Minkowski separation (of positive frequency modes from negative ones) is maintained throughout the whole space as a consequence of Poincare invariance.

- A transition from a complete orthonormal set of modes to different one (the so-called Bogolubov's transformations) in **accelerating system** will always mix positive frequency modes with negative frequency ones.

- As a result of this mixture, the vacuum state defined by a particular choice of the annihilation operators will be filled with particles in a different system (the Unruh Effect).

- The Rindler metric describes a constantly accelerating system when L(R)-observers do not ever have access to the entire space-time

$$ds^2 = e^{2a\xi}(d\eta^2 - d\xi^2), \quad t = \frac{e^{a\xi^R}}{a}\sinh a\eta^R, \quad x = \frac{e^{a\xi^R}}{a}\cosh a\eta^R$$

- Bogolubov's coefficients are known exactly for this case (mixing the positive and negative modes), which allows to represent the Minkowski vacuum as a nontrivial "squeezed state"

$$|0_M> = \prod_k \frac{1}{\sqrt{(1 - e^{-2\pi\omega/a})}} \exp\left[e^{-\pi\omega/a} b_k^{R\dagger} b_{-k}^{L\dagger}\right] \left|0^R\right\rangle \otimes \left|0^L\right\rangle,$$

- Number of particles in mode "k" is determined by the Bogolubov's coefficients $< 0_M|\mathrm{N}^R|0_M > = \frac{1}{(e^{2\pi\omega/a} - 1)}$,

- The Planck spectrum observed in high energy collisions is <u>interpreted as a result of preparation of the ground state</u> $|0_M>$. It explains the puzzle with rapid"thermalization" observed in all systems

5. Another θ -related connection...

- The θ dependence in QCD determines the η' mass (Witten,Veneziano, 1979)

$$L = \frac{1}{2}\partial_\mu\eta'\partial^\mu\eta' - \frac{1}{\chi}Q^2 - \left(\theta - \frac{\eta'}{f_{\eta'}}\right)Q + N_f m_q|<\bar{q}q>|\cos\left[\frac{\eta'}{f_{\eta'}}\right]$$

$$Q \equiv \frac{\alpha_s}{8\pi}G^a_{\mu\nu}\tilde{G}^{\mu\nu a}, \quad \chi = -\frac{\partial^2\epsilon_{vac}(\theta)}{\partial\theta^2} = i\int d^4x <T\{Q(x),Q(0)\}>$$

- The topological susceptibility $\chi \neq 0$ does not vanish in spite of the fact that operator Q is total derivative, the so-called Witten's contact term.

- Sign of χ is opposite to what one should expect from a physical degree of freedom -- so the term "the Veneziano Ghost" saturating the WI.

- Integrating out Q field produces η' mass with no any traces of massless (unphysical) ghosts.

- Topological susceptibility in the Veneziano model can be computed as follows

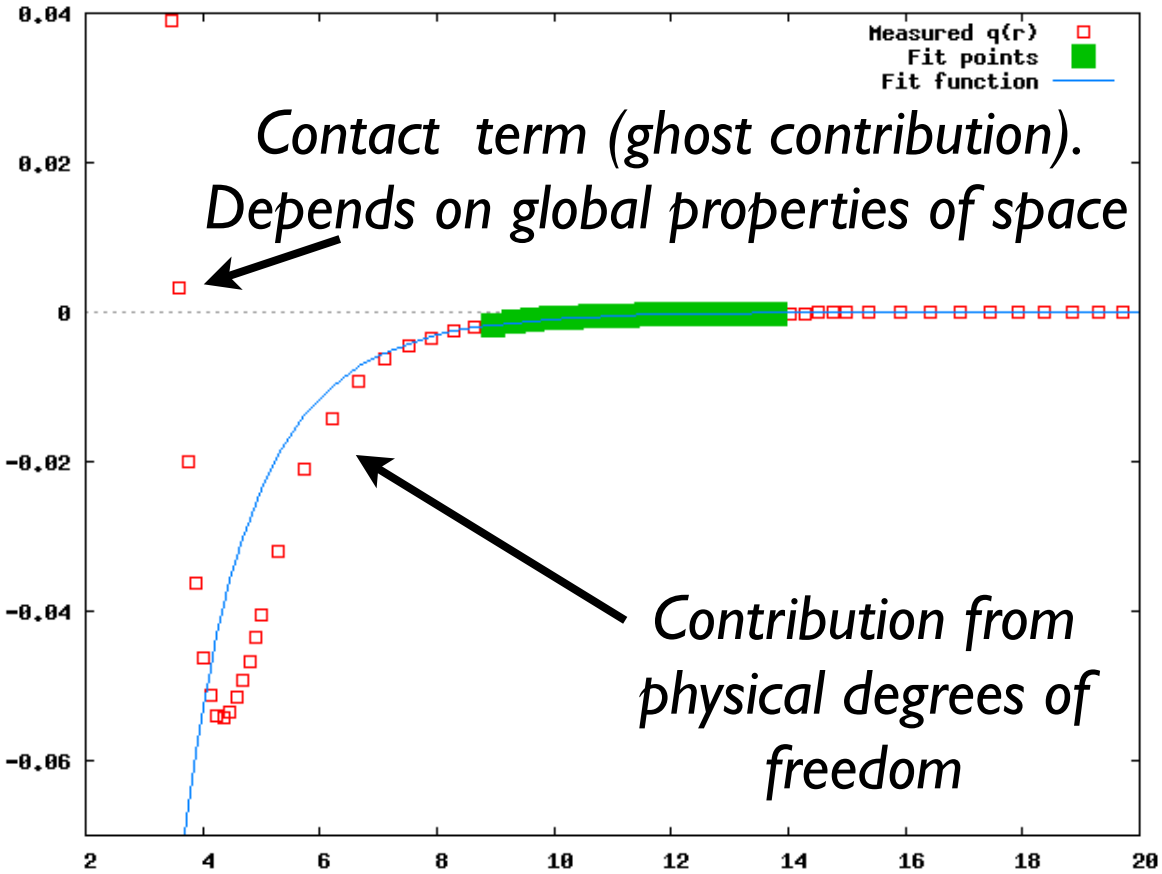
ghost (non-dispersive) contribution *Conventional physical degrees of freedom*

$$\chi_{QCD} \equiv \int d^4x < T\{Q(x), Q(0)\} >= \frac{f_{\eta'}^2 m_{\eta'}^2}{4} \cdot \int d^4x \left[\delta^4(x) - m_{\eta'}^2 D^c(m_{\eta'} x)\right],$$

- In this expression the $\delta^4(x)$ represents the contact term (ghost contribution), while $D^c(m_{\eta'} x)$ is the Green's function of massive eta' meson.

- The topological susceptibility vanishes in the chiral limit as a result of exact cancellation of two terms in complete accordance with Ward Identities $\chi_{QCD}(m = 0) = 0$.

- Physical states always contribute with sign (-) in Euclidean metric. Cancellation can not be achieved without a ``wrong sign''- term due to the ghost.



The topological susceptibility $\chi(r)$ as a function of r. Wrong sign for χ is well established phenomenon; it has been tested on the lattice (plot above is from C. Bernard et al, LATTICE 2007). This $\chi(r=0)$ contribution is not related to any physical degrees of freedom, and can be interpreted as a contact term (Witten, 79) or as the ghost contribution (Veneziano, 79). It can be argued to be related to necessity to sum over different k-topological sectors of the theory as explicit computations of χ in 2d case show.

Technical reason for ghost to emerge in the system:

- The longitudinal part of the topological density operator saturates the topological susceptibility

$$Q = \frac{g^2}{64\pi^2}\epsilon_{\mu\nu\rho\sigma}G^{a\mu\nu}G^{a\rho\sigma} = \partial_\mu K^\mu = \Box\Phi, \qquad K_\mu \equiv \partial_\mu\Phi$$

- The induced (Veneziano) term in the lagrangian is a 4 -derivative operator $Q^2 \sim (\Box\Phi)^2$. It plays a key role in the resolution of the $U(1)_A$ problem.

- The induced 4 -derivative operator signals that the ghost (Veneziano ghost) must be in the system:

$$\frac{m^2_{\eta'}}{\Box\Box + m^2_{\eta'}\Box} = \left(\frac{1}{-\Box - m^2_{\eta'}} - \frac{1}{-\Box}\right) .$$

- This is the old and well-known story when the theory is formulated in infinite Minkowski space.

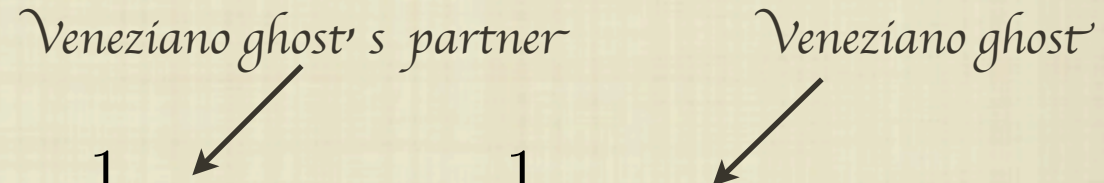
- **What happens to the contact term (represented by the Veneziano ghost) if the system is accelerating with rate "a" ?**

- The Veneziano ghost describes contact non-dispersive term. It is topologically protected and sensitive to the boundary, horizon and other global characteristics of the system, in contrast with conventional dispersive terms.

- We will see that the non-dispersive (contact) term changes (fluctuates) when the background varies. These coherent P-odd fluctuations will play a key role in analysis of P-odd correlations in accelerating background (observed at RHIC).

6. The Veneziano Ghost in 4d. T=0
Careful analysis: no integrating out.

- One can explicitly demonstrate that the low energy lagrangian for U(1)_A degrees of freedom in 4d QCD is **identical** to the 2d QED, including θ term and KS ghost (Kogut- Susskind, 1975) .



$$\mathcal{L} = \frac{1}{2}\partial_\mu\eta'\partial^\mu\eta' + \frac{1}{2}\partial_\mu\phi_2\partial^\mu\phi_2 - \frac{1}{2}\partial_\mu\phi_1\partial^\mu\phi_1$$
$$- \frac{1}{2}m^2_{\eta'}\eta'^2 + m_q|<\bar{q}q>|\cos\left[\theta + \frac{\eta' + \phi_2 - \phi_1}{f_{\eta'}}\right]$$

- The Veneziano ghost is introduced to account for the "wrong" sign in χ. It gives the same physics as the Witten's contact term and provides the η' mass.

- The negative sign in the Lagrangian does not lead to any problems (unitarity, causality...) when auxiliary (similar to Gupta-Bleuler in QED) conditions on the physical Hilbert space are imposed:

$$(Gubta - Bleuler \text{ in } QED): \quad (\partial_\mu A^\mu)^+ |\mathcal{H}_{\rm phys}>= 0;$$

$$(\phi_2 - \phi_1)^{(+)} |\mathcal{H}_{\rm phys}\rangle = 0\,. \qquad \textit{positive frequency part enters this condition!}$$

- the hamiltonian has sign minus for the ghost. However, the expectation value for any physical state vanishes as a result of GB condition,

$$\mathrm{H} = \sum_k \omega_k \left(b_k^\dagger b_k - a_k^\dagger a_k \right). \qquad < \mathcal{H}_{\rm phys}|\mathrm{H}|\mathcal{H}_{\rm phys} >= 0\,.$$

- It is similar to what happens in QED when two unphysical photon's polarizations cancel each other as a result of Gupta-Bleuler conditions.

- I use the Veneziano (rather than the Witten's) approach to study the non-dispersive term in a time-dependent/ curved background (or finite manifold).

7. Veneziano Ghost in Rindler space $T \neq 0$

- We treat acceleration "a" as a free parameter in order to separate topological fluctuations of size ~1/a from conventional QCD fluctuations ~ fm.

$$1\ \mathrm{GeV} \gg a \gg m_q$$

- in this limit the problem is reduced to the previously studied case when the Bogolubov's coefficients are exactly known.

- The cancellation between the Veneziano ghost and its partner does not hold for the accelerating Rindler observer (in contrast with Minkowski).

$$< 0|\omega_k \left(b_k^{(R,L)\dagger} b_k^{(R,L)} - a_k^{(R,L)\dagger} a_k^{(R,L)} \right) |0 >= \frac{2\omega}{(e^{2\pi\omega/a} - 1)}.$$

Technical reason for non-cancellation:

- The ground state for Minkowski observer is defined as usual

$$a_k|0>=0\,,\quad b_k|0>=0\,,\quad \forall k\,.$$

- The vacuum for R-Rindler observer is defined as

$$a_k^L|0_R>=0\,,\quad a_k^R|0_R>=0\,,\quad b_k^L|0_R>=0\,,\quad b_k^R|0_R>=0\,,\quad \forall k\,.$$

- The Bogolubov's coefficients are known to mix positive and negative frequency modes:

$$a_k^L=\frac{e^{-\pi\omega/2a}a_{-k}^{1\dagger}+e^{\pi\omega/2a}a_k^2}{\sqrt{e^{\pi\omega/a}-e^{-\pi\omega/a}}}\qquad a_k^R=\frac{e^{-\pi\omega/2a}a_{-k}^{2\dagger}+e^{\pi\omega/2a}a_k^1}{\sqrt{e^{\pi\omega/a}-e^{-\pi\omega/a}}}$$

$$b_k^L=\frac{e^{-\pi\omega/2a}b_{-k}^{1\dagger}+e^{\pi\omega/2a}b_k^2}{\sqrt{e^{\pi\omega/a}-e^{-\pi\omega/a}}}\qquad b_k^R=\frac{e^{-\pi\omega/2a}b_{-k}^{2\dagger}+e^{\pi\omega/2a}b_k^1}{\sqrt{e^{\pi\omega/a}-e^{-\pi\omega/a}}}\,.$$

8. Veneziano ghost in accelerating system. Interpretation, $T \neq 0$

- No cancellation between the Veneziano ghost and its partner could occur as a result of opposite sign (-) in commutation relations and negative sign (-) in Hamiltonian.

- The cancellation fail to hold for the accelerating Rindler observer because the properties of the operator which selects the positive frequency modes with respect to η Minkowski time t and observer's proper time are not equivalent.

- Veneziano ghost does fluctuate, but it does not propagate to infinity. It is NOT an asymptotic state, it does not contribute to any dispersive parts

- We interpret the extra contribution to the energy observed by an accelerating observer as a result of formation of the squeezed state which can be coined as the "ghost condensate" size $2\pi/a$ (will be identified with P-odd domains) rather than a presence of "free particles" at $T = a/2\pi$ prepared in a specific mixed, rather than pure quantum state,

$$|0>=\prod_k \frac{1}{\sqrt{(1-e^{-2\pi\omega/a})}} \exp\left[e^{-\pi\omega/a}\left(b_k^{R\dagger}b_{-k}^{L\dagger} - a_{-k}^{R\dagger}a_k^{L\dagger}\right)\right]|0^R>\otimes|0^L>$$

- We interpret the ghost contribution to the energy as a convenient way to account for topologically nontrivial sectors of the theory in accelerating frame.

- Number density of P -odd domains with size $\lambda \simeq \frac{2\pi}{\omega}$ is

$$dN_\omega = \frac{d^3k}{(2\pi)^3}\frac{2}{(e^{2\pi\omega/a}-1)},$$

9. Applications to P odd fluctuations observed at RHIC. Basic Picture.

- The conventional quark and gluon fluctuations with fm- scale are propagating in the environment of very slow topological fluctuations with wave lengths $2\pi/a, \;\; a \ll 1\ \mathrm{GeV}$.

- These slow topological fluctuations carry 0^{-+} quantum numbers and can be thought as large P-odd domains for conventional fast fluctuations (analogous to $\dot{\theta}_{ind} \sim a$ discussed previously).

- Fast fluctuations provide the expected Planck spectrum with temperature "T". The only new element of this work: the fast fluctuations are formed in the P- odd environment effectively described by slow fluctuating "ghost condensate" with 0^{-+} quantum numbers.

10. Direct consequences of this basic Picture. The Universality.

- 1. P and CP odd fluctuations are present in any accelerating system when the thermal aspects have been already observed (including e^+e^-, pp, $p\bar{p}$)

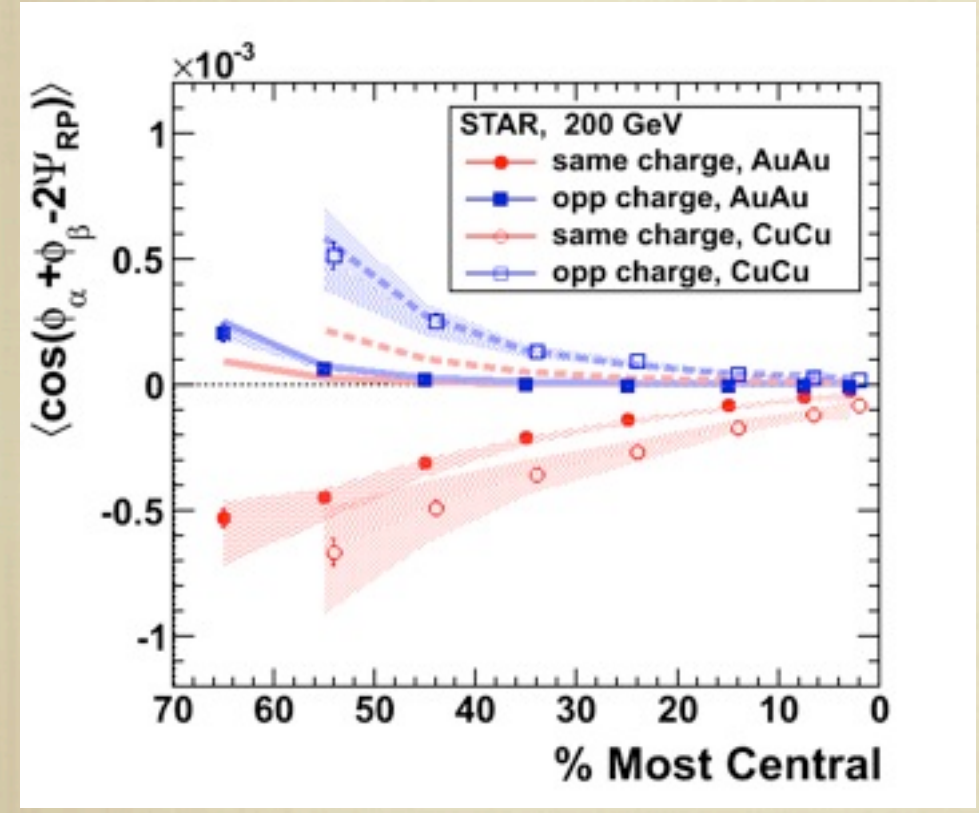
- However, "a" for point-like particles is large ~ GeV -> P-odd effects strongly fluctuate. If "a" becomes small->P-odd effects become coherent on scale $1/a$

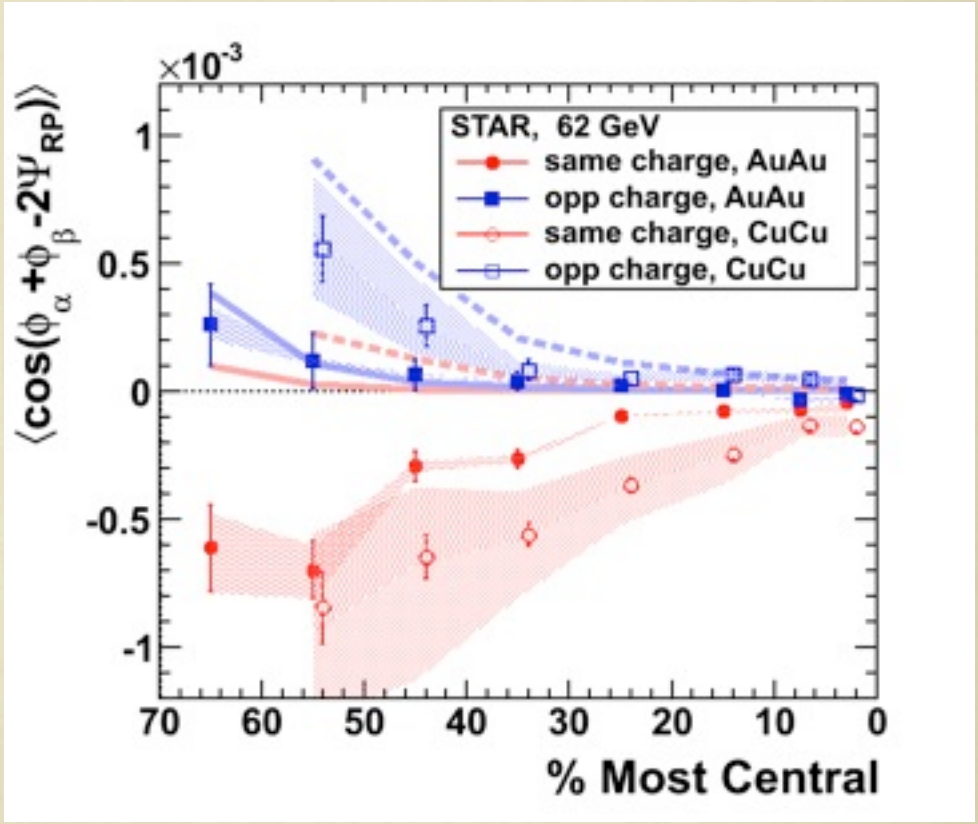
- Heavy Ion collisions are unique as "a" depends on centrality, Dima&Co, 2007. We can vary "a" !

$$a(J) \simeq a_{J=0}\left(1 - cJ^2\right), \quad c > 0,$$

- Sensitivity on "a" is exponential: slight reduction of"a" may produce drastic changes in correlations.

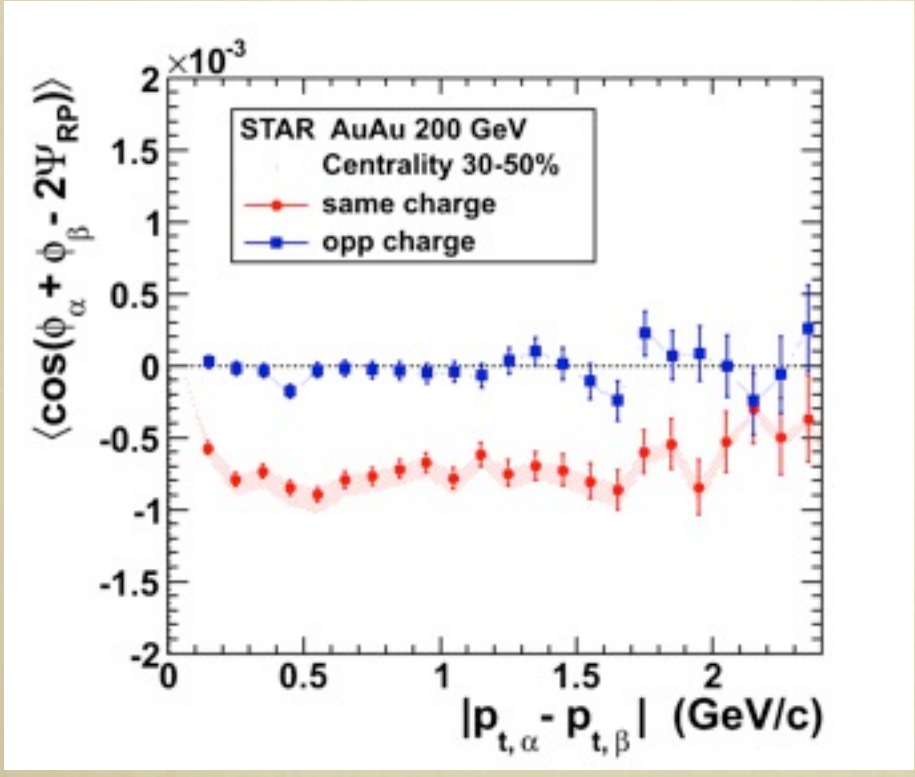
- The correlations should demonstrate the **universal behaviour** similar to the **universality observed in all high energy collisions**. In particular, the correlations should not depend on energy of colliding ions in ideal world(when $a << 1$ and the P-odd domains are very large in size).

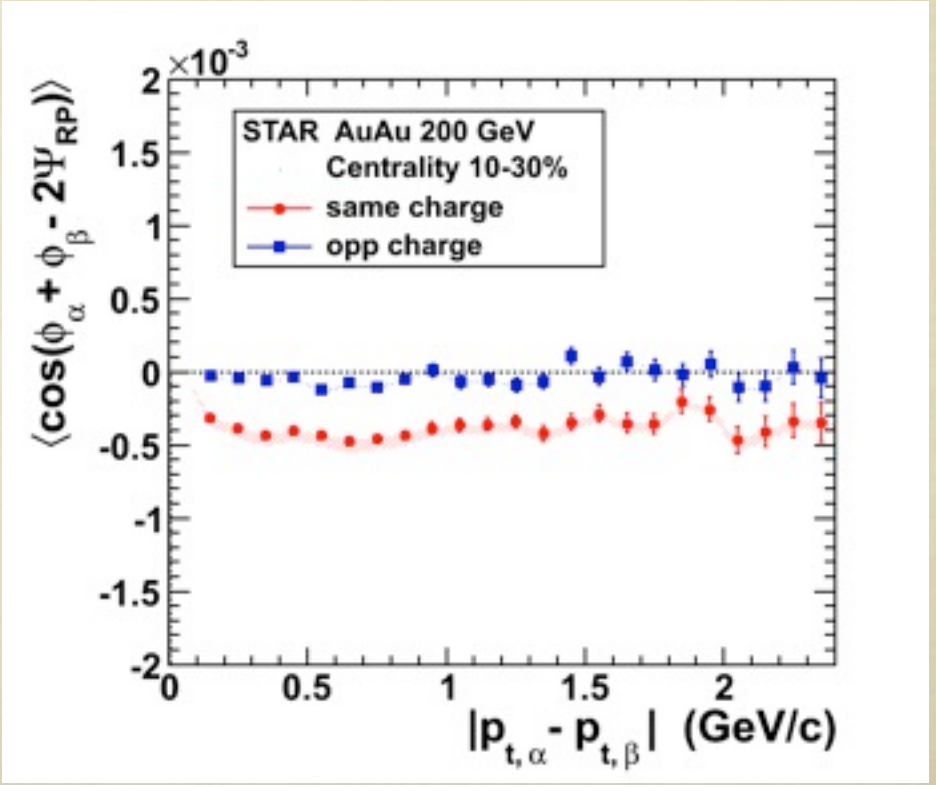




- The plots indeed demonstrate the universality in behaviour for Au+Au, Cu+Cu for 200 and 62 GeV.

- The arguments on universality of the correlation strength do not depend on transverse momenta even for large $k_\perp > 1\,\mathrm{GeV}$. This prediction of the universality should be contrasted with "naive" arguments suggesting some preferences for small $k_\perp$. This universality argument are also consistent with observations.





11. Future directions

- Connection between the acceleration "a" and measured parameters (centrality, energy, etc). It will allow us to test the universality conjecture.

- Searching for P-odd correlations in other high energy collisions, including LHC.

- testing the scaling on the lattice. Casimir like effects are predicted for 4d QCD: $1/L$ instead e^{-L}. Lattice confirmation (B. Holdom, Phys. Lett B 2011).

- Naive argument (on $\exp(-L)$ behaviour) fails because the correction $1/L$ is related to non-dispersive term, not related to absorptive physical part.

- Profound consequences for the expanding universe