CERN, Summer Theory Institute, Aug.2010

The theoretical challenges

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Outlook: quite a few dreams

1. Today's QFT map
2. Gravity, pomerons, equilibration, Gravity dual for the heavy ion collisions
3. ``Higgsed" AdS/CFT
4. From fluctuations and the sounds to EOS and viscosity
5. real-time topological fluctuations: QCD sphalerons in (double diffractive) pp and AA

Map of the QFTs today

$\mathcal{N}=4$ SYM
No-Higgs
Conformal
E/M Self-dual
AdS/CFT
Integrable?

AdS/QCD

QCD
Exp.spectrum
Lattice
sQGP

$\mathcal{N}=4$
SYM
Higgsed
New
duality?

$\mathcal{N}=2$ SYM
Higgsed
SW solution
SW dualities
Confinement
Chiral
sym.breaking
Wall crossing

Adjoint QCD
T_{conf} and T_{chiral}

$\mathcal{N}=1$ SYM no scalars!
Confinement+
Chiral sym.breaking
Seiberg phase diagram

1d compactificaton
Periodic fermions =>
SUSY

It is important to make a bridge, so two communities can speak In particular, to learn what is done in SYM about weak-strong transition and E/M dualities

get lattice people serious about SUSY simulations, to understand the mechanisms of Confinement+Chiral sym.breaking through the whole chain of theories

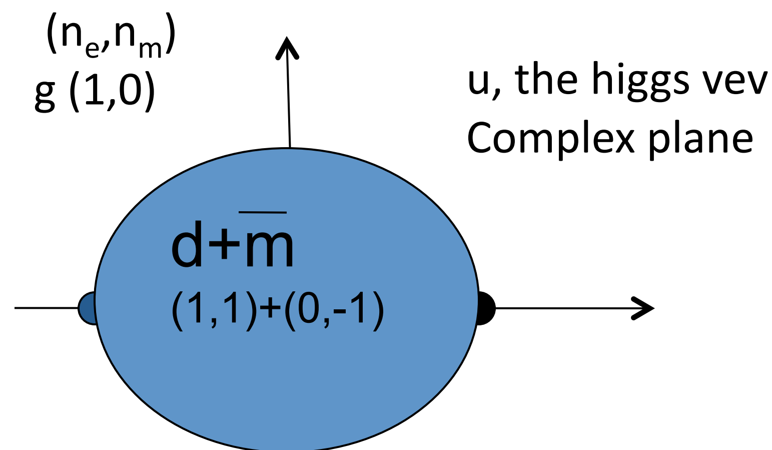
Recent development in $\mathcal{N}$=2 SYM

the wall crossing formulae

- Black dots: SW (1994) singularities in which mono and dyon gets massless
- Blue oval is the (stronger coupling) region separated by "the wall" at which decays are possible (level crossings)
- here the **spectrum changes discontinuously** but not the moduli metric or the charges:

(states disapper into the IR by becoming infinite size)

(For those who want to learn more lectures by Gregory Moore are recommended)



Dyons were promoted to dyonic black holes in N=2 supergravity and their bound states have been studied

Recently "wall crossing formula" =>

M. Kontsevich and Y. Soibelman, "Motivic Donaldson-Thomas invariants:summary of results," arXiv:0910.4315

T. Dimofte, S. Gukov and Y. Soibelman, "Quantum Wall Crossing in N=2 Gauge Theories," arXiv:0912.1346 [hep-th].

Understanding transitions from weak to strong coupling regime

- Even when there are no singularities (phase transitions), like in $\mathscr{N}$=2 SYM, there are ``walls"
- At those the spectrum/density of states **jumps discontinuously** and thus change of description is mandatory.
- (dream !) Are there such ``wall crossing phenomena" in **QCD-like theories, especially** above Tc? Heavy quarks/gluons (M=600 MeV) and light monopoles (M=200 MeV or so) near Tc are seen on the lattice: what about dyons?

M-dual to $\mathcal{N}$=1 SYM, QCD…

- Two known examples of conformal theories: => $\mathcal{N}$=4 SYM; => $\mathcal{N}$=2 with N_f=4 (fundamental) are both **E/M selfdual** **as is seen via semiclassical monopole+fermion zero mode analysis: same lagrangian,** **so the coupling need to run both up and down: thus it does not run**
- **In $\mathcal{N}$=1,0 theories magnetic multiplet is not vector; but what are those magnetic objects?**
- **a bridge between SYM and QCD is compactification with periodic fermions (Unsal)**

Equilibration in pQCD; instabilities

- (Mrowczinski….F.Gelis and others): numerically simulated **perturbative instabilities, which** lead to the equilibration (in a fixed box, scalar theory, certain time scale…)
- But the mechanism and equilibration time is not not yet well understood
- (dream !). **Understand if those mechanisms can be seen as a hologram, of the AdS gravitational instabilities leading to black hole formation?**

(dream !) ``Higgsed" AdS/CFT

AdS/CFT has been developed for conformal (un-Higgsed) N=4 SYM.

- Can one also study the Higgsed sector via multi-center 10-d black hole solutions?
- Can one tune better the AdS/QCD models to neat-Tc region?

Gravity, equilibration and pomerons

- The idea that in 1+1d T comes from the Unruh effect of longitudinal acceleration (Kharzeev, Satz, Zhitnitsky…)
- In 3+1 d it get realized in the AdS BH setting (Witten 98)
- Equilibration = creation of the black hole in AdS5 (next page)
- Pomerons: colorless objects which have a variable spin:
  weak coupling S=1+O(g^2) BFKL
  strong coupling S= 2- O(1/g sqrt(N)) Polchinski, Strassler
- (dream !) Can Pomerons effective theory be created, now in AdS5, based on **quantum** gravity, describing any intermediate coupling case?

Gravity dual for the heavy ion collisions

- Pure AdS5 space corresponds to extreme BH (mass is minimal for its charge and there is no T and no horizon (entropy))
- As collision creates falling "debris", they will form a non-extreme BH in the bulk Nastase 03
- which is falling (describing expanding/cooling fireball) => departing horizon $z_h(t)$ Sin,ES and Zahed 04, **yet its entropy is fixed**
- BH can be longitudinally stratching - rapidity independent example Janik-Peschanski 05… Yet Janik et al are refusing to have any matter or "singularities"
- The most elegant solution for equilibration problem: **flat massive membrane falling under its own weight**
  Shu Lin, ES **Phys.Rev.D78:125018,2008.**
  e-Print: arXiv:0808.0910

Toward the AdS/CFT Gravity Dual for High Energy Collisions. 3.Gravitationally Collapsing Shell and Quasiequilibrium

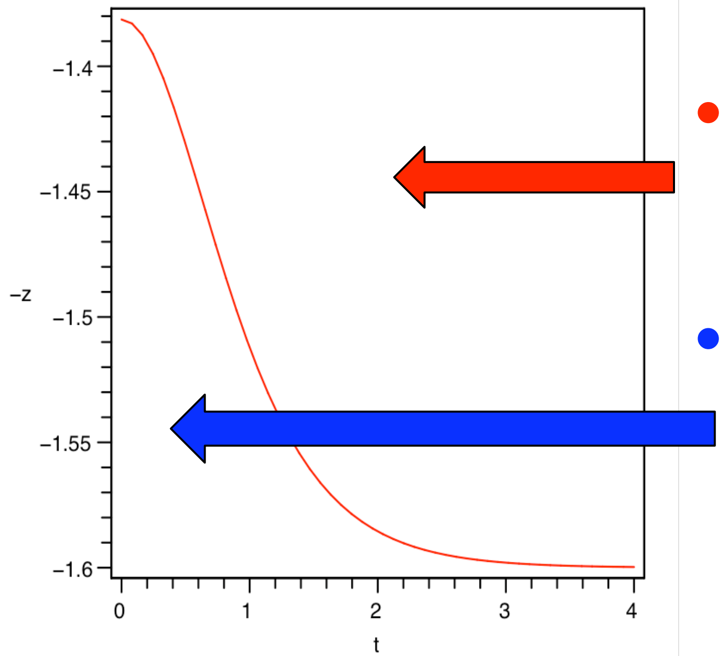
Shu Lin[1], and Edward Shuryak[2]

The main simplification of the paper is that this shell is *flat* - independent on our world 3 spatial coordinates. Therefore the overall solution of Einstein eqns reduces to two separate regions with well known *static* AdS-BH and AdS metrics. The falling of the shell is time dependent, its equation of motion is determined by the Israel junction condition, which we solve and analyzed. We also determined how final temperature (horizon position) depends on initial scale and shell tension.

- Falling is dual to equilibration UV=>IR, 2 regions, already equilibrated and untouched

This is *quasiequilibrium* in the title. More specifically it means the following. In this geometry a "single point observer" – who is only able to measure the *average density and pressure* – would be driven to the conclusion that the matter is instantaneously equilibrated at *all* times. However more sophisticated "two point observer" who is able to study correlation functions of stress tensors would be able to observe deviations from the thermal case. We computed them explicitly, calculating a number of spectral densities at various positions of the shell, corresponding (in quasi-static approximation) to different stages of equilibration.

Israel's junction condition gives EOM which is dual to the equilibration dynamics



- Thermal BH AdS above= fully equilibrated
- Pure (T=0) AdS5 below= not equilibrated

$$\frac{dz}{dt} = \frac{\dot{z}}{\dot{t}} = \frac{f\sqrt{(\frac{\kappa_5^2 p}{6})^2 + (\frac{3}{2\kappa_5^2 p})^2(1-f)^2 - \frac{1+f}{2}}}{\frac{\kappa_5^2 p}{6} + \frac{3}{2\kappa_5^2 p}(1-f)}$$

Two types of observers

- Single-point observer sees just the thermal stress tensor
- 2-point experiments (e g. the correlator of the stress tensors) send signal into the bulk and therefore finds that equilibration **below the membrane** does not yet exist

$\langle T_{mn} \rangle$ is thermal but Correlators (measured by the two-point observers) deviate from equilibrium

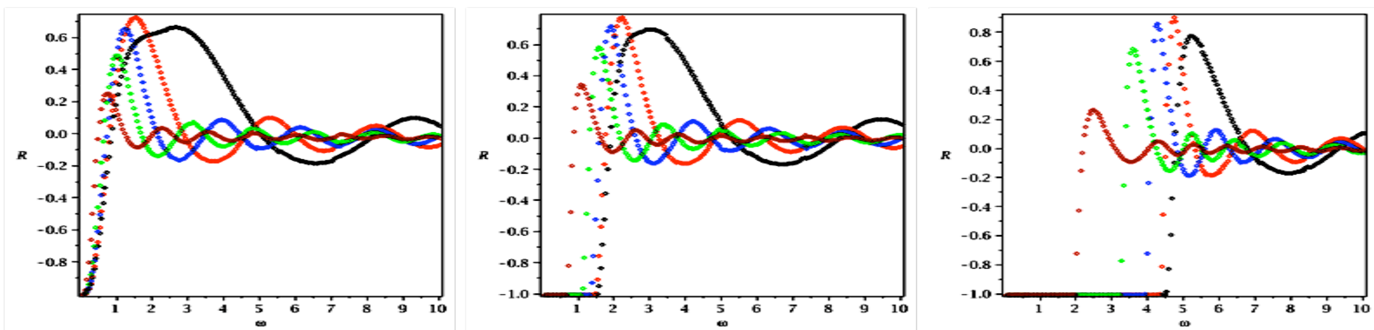


Figure 3: (color online)The relative deviation R at $q = 0$ left, $q = 1.5$ middle and $q = 4.5$ right. Different stages of thermalization are indicated by: black($u_m = 0.1$), red($u_m = 0.3$), blue($u_m = 0.5$), green($u_m = 0.7$), brown($u_m = 0.9$). As u_m approaches 1, i.e. the medium evolves to equilibrium, the oscillation decreases in amplitude and increases in frequency, thus the spectral density relaxes to thermal one

The reason for oscillations in spectral densities is in fact
the ``echo” effect, induced by a gravitons scattering from a membrane,
Confirmed numerically and semiclassically

Entropy production

estimates of area of trapped surface

A significant leap forward had been done recently by Gubser, Pufu and Yarom [123], who proposed to look at heavy ion collision as a process of head-on collision of two point-like black holes, separated from the boundary by some depth L – tuned to the nuclear size of Au to be about 4 fm, see Fig.??. By using global AdS coordinates, these authors argued that (apart of obvious axial O(2) symmetry) this case has higher – namely O(3)– symmetry with the resulting black hole at the collision moment at its center, thus in certain coordinate

$$q = \frac{\vec{x}_\perp^2 + (z-L)^2}{4zL} \tag{91}$$

the 3-d trapped surface C at the collision moment should be just a 3-sphere, at constant $q = q_c$. (Here $x_\perp$ are two coordinates transverse to the collision axes.) The picture of it is shown in Fig.29(b)

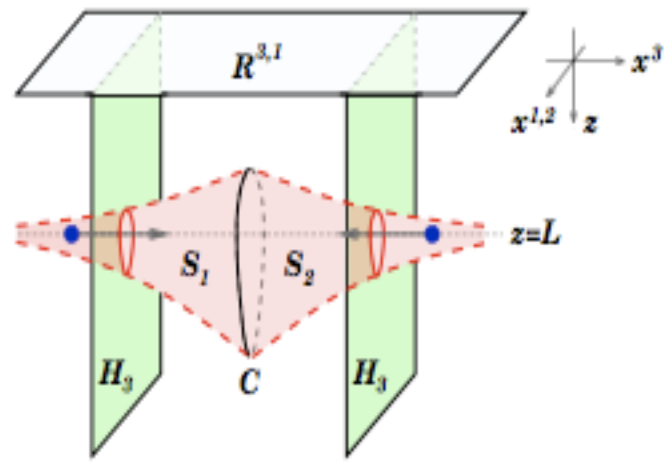
If so, one can find the radius at which it is the trapped null-surface and determine its energy and Bekenstein entropy. For large q_c these expressions are

$$E \approx \frac{4L^2 q_c^3}{G_5}, \quad S \approx \frac{4\pi L^3 q_c^2}{G_5}, \tag{92}$$

from which, eliminating q_c, the main result of the paper follows, namely that the entropy grows with the collision energy as

$$S \sim E^{2/3} \tag{93}$$

Note that this power very much depends on the 5-dimentional gravity and is different from the 1950's prediction of Fermi and Landau (??) in which this power was 1/2 and (accidentally or not) fits the data better.



- Gubser,Pufu and Yarom" Heavy ion collisions as that of two black holes

Grazing Collisions of Gravitational Shock Waves and Entropy Production in Heavy Ion Collision

Shu Lin[1], and Edward Shuryak[2]

The shock wave moving in $+x^3$ direction is given by:

$$ds^2 = L^2\frac{-dudv + (dx^1)^2 + (dx^2)^2 + dz^2}{z^2} + L\frac{\Phi(x^1, x^2, z)}{z}\delta(u)du^2$$

with $\Phi(x^1, x^2, z)$ satisfies the following equation:

$$\left(\Box - \frac{3}{L^2}\right)\Phi = 16\pi G_5 J_{uu}$$

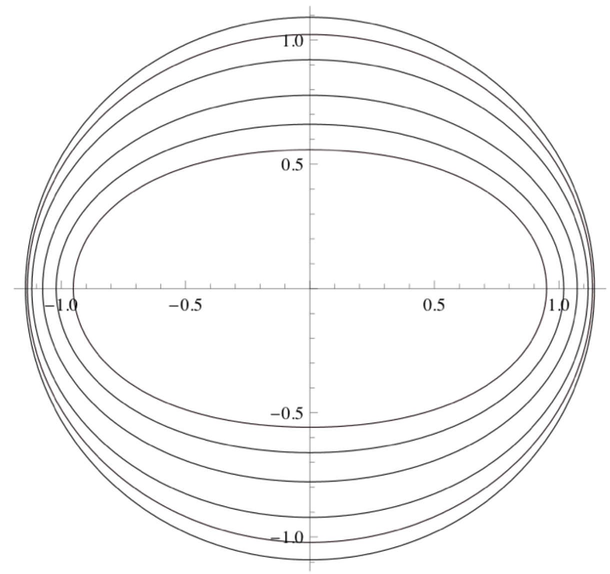
The vanishing of expansion gives the equation:

$$\left(\Box - \frac{3}{L^2}\right)(\Psi_1 - \Phi_1) = 0$$

$$\Psi_1|_{\mathcal{C}} = \Psi_2|_{\mathcal{C}} = 0$$

The boundary $\mathcal{C}$ should be chosen to satisfy the constraint:

$$\nabla\Psi_1 \cdot \nabla\Psi_2|_{\mathcal{C}} = 4$$



The trapping surface solution
Disappears suddenly at some b

Off-center collisions in AdS_5 with applications to multiplicity estimates in heavy-ion collisions

Steven S. Gubser,* Silviu S. Pufu,† and Amos Yarom‡

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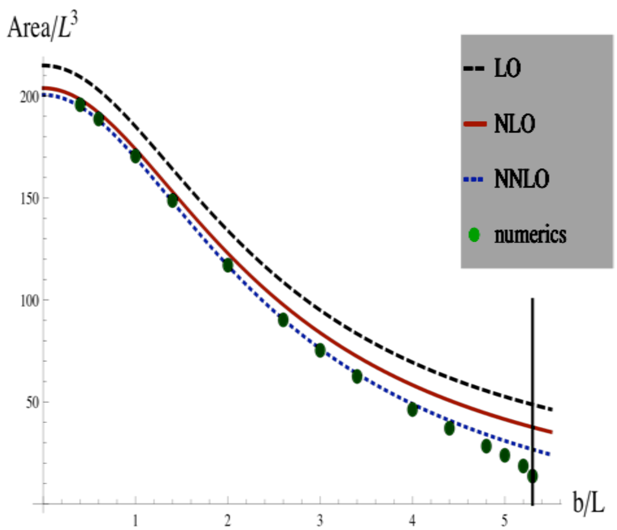
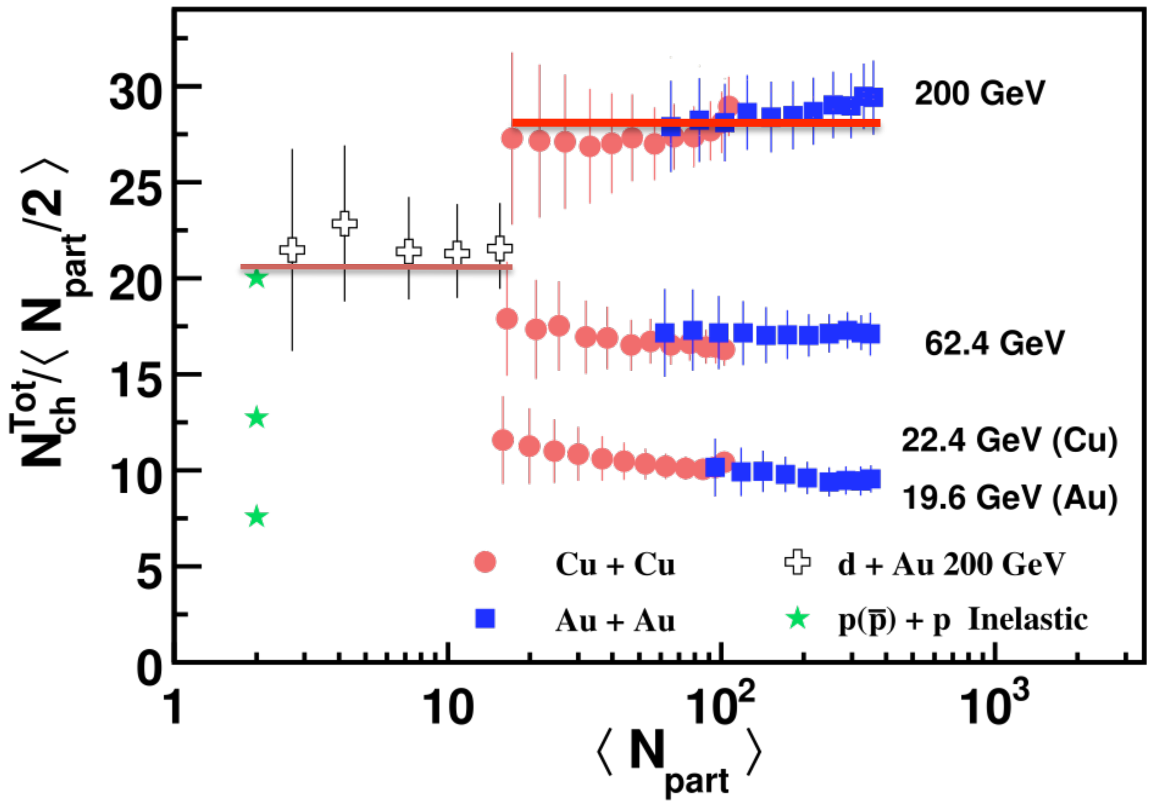


Figure 1: (Color online.) Comparisons between the numerics of [36] and the analytic formula (58). The black dashed curve represents the leading term in (58); the solid red curve corresponds to the first two terms in (58); the dotted blue curve represents the expression (58), which is correct up to a term of order $\mathcal{O}(1/\zeta^2)$; the green dots represent the numerical evaluations used in figure 3 of [36]; lastly, the vertical green line marks the place where, according to [36], the maximum impact parameter $b_{\max}/L$ occurs. We thank S. Lin and E. Shuryak for providing us with the results of their numerical evaluations.

Large-b (grazing) collisions => no black hole: it disappears with a **finite jump**!

Do we see it happening in experiment? In a way yes:



- PHOBOS data on multiplicity:
- Apparent jump between pp_like and **AA-like**
- **Should the same happen in pp, at some high enough energy?** (question by G.Farrar)

Fluctuations and sounds

Fluctuations and sounds

- The odds are **all** correlated! geometry tells us that peripheral events would be 3-peaks (dream !)

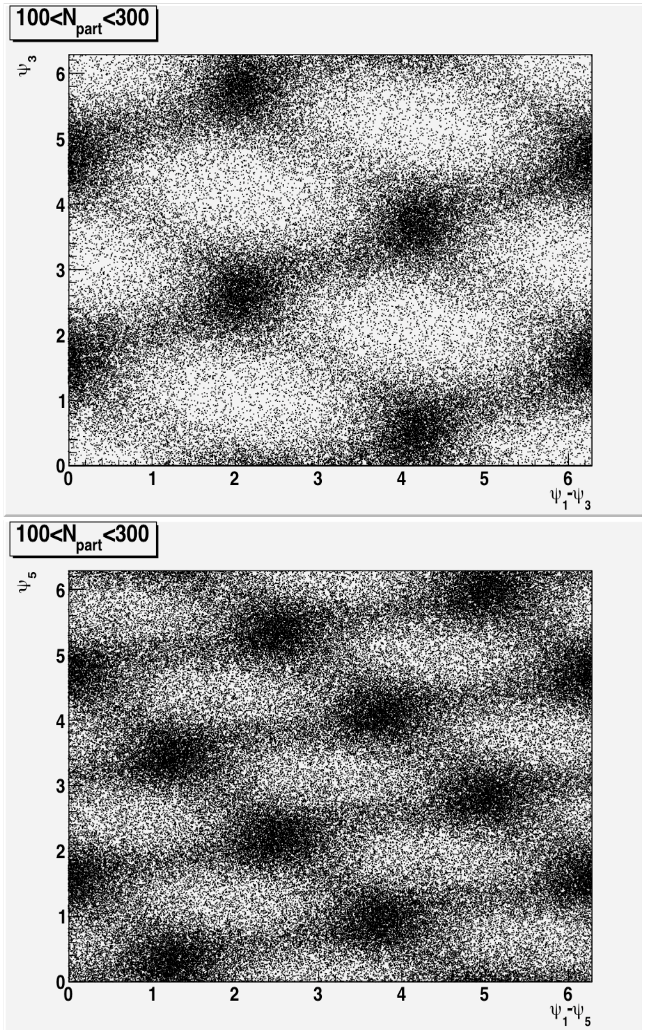


FIG. 8: Scatter plot of the ψ_3 vs $\psi_3 - \psi_1$ (above), and of the ψ_5 vs $\psi_5 - \psi_1$ (below), the same centrality

tips

waists

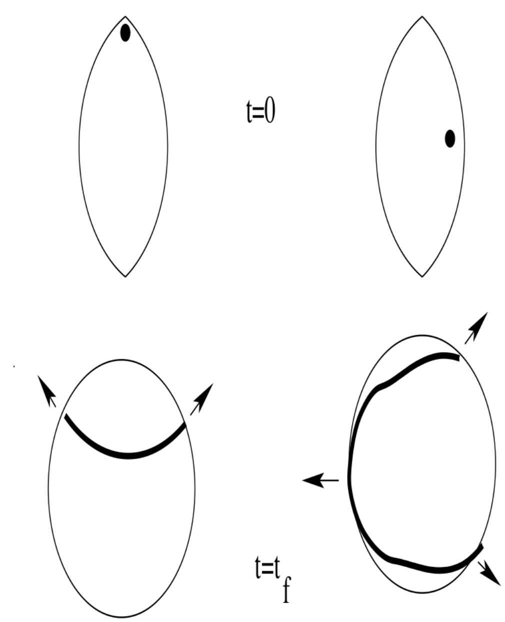


FIG. 4: Two upper picture correspond to initial time $t = 0$: the system has almond shape and contains perturbations (black spots). Two lower pictures show schematically location and diffuseness of the sound fronts at the freezeout time t_f. The arrows indicate the angular direction of the maxima in the angular distributions, 2 and 3 respectively.

Understanding all angular harmonics => deduce sound and viscous horizons

- Huge new activity after triangular flow paper
  Alver,Roland, just in few days
- **The Fate of the Initial State Fluctuations in Heavy Ion Collisions. II The Fluctuations and Sounds.**
  Pilar Staig, ES arXiv:1008.3139
- **The Sound of the Little Bangs.**
  Agnes Mocsy, Paul Sorensen, arXiv:1008.3381
- **Influence of tubular initial conditions on two-particle correlations in relativistic nuclear collisions.**
  Rone Peterson G. Andrade, Frederique Grassi, Yogiro Hama, Wei-Liang Qian, arXiv:1008.4612

Azimuthal anisotropy: transition from hydrodynamic flow to jet suppression

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(Dated: August 24, 2010)

$$\frac{v_{2k}(p_T)}{\varepsilon_{2k}} = \frac{v_{2k}^{\mathrm{h}}(p_T)}{\varepsilon_{2k}} \left[\frac{1}{1+\frac{K^*(p_T)}{K_0}}\right]^k \quad k = 1, 2, ...$$

$$K = \lambda/\bar{R}$$

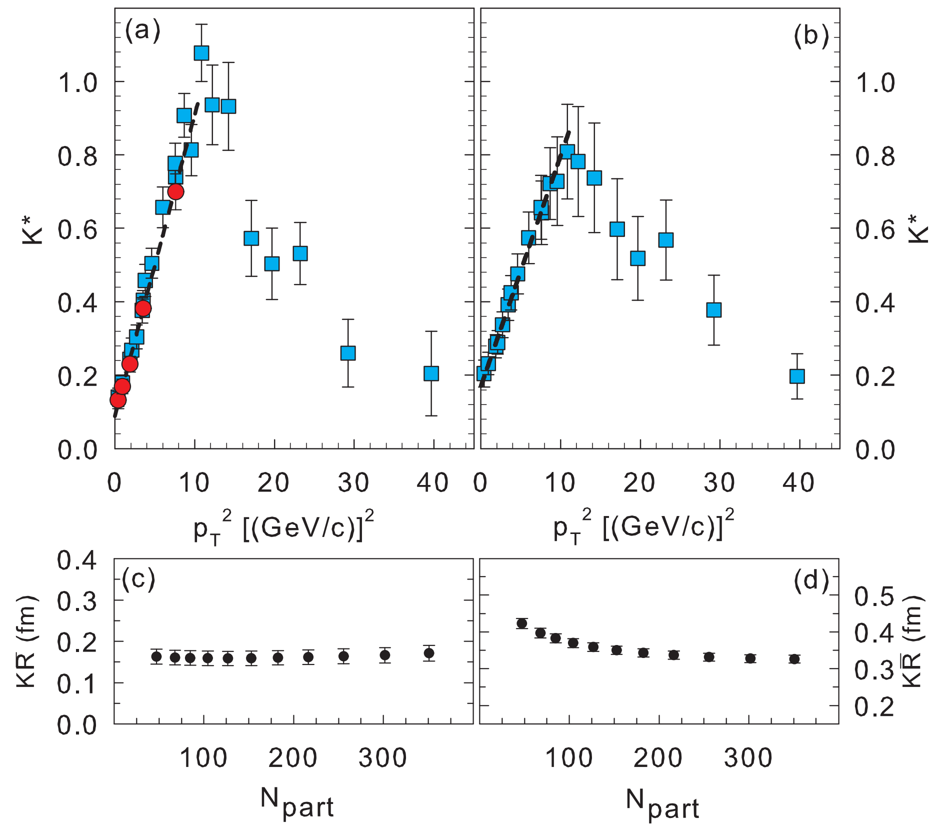


FIG. 4. (color online) K^* vs. $\langle p_T \rangle^2$ (a) and (b), and $K\bar{R}$ vs. $N_{\rm part}$ (c) and (d), extracted with MC-KLN (left panels) and MC-Glauber geometry (right panels). The filled circles in (a) indicate results from the simultaneous fits shown in Fig. 2. The dashed curves in (a) and (b) show a fit to the data for $\langle p_T \rangle^2 \lesssim 10$ [GeV/c]^2.

ation time which grows with p_T. The extracted viscous corrections also constrain the estimates $4\pi\frac{\eta}{s} \sim 1.1 \pm 0.1$ (2.1 ± 0.2) and $T_f = 162 \pm 11$ MeV $(173 \pm 11$ MeV) for MC-KLN (MC-Glauber) collision geometries for a strongly coupled plasma. The onset of a transition from

real-time QCD topology

QCD sphalerons and their explosion => diffractive clusters at RHIC

Semiclassical Theory of High Energy Collisions based on Instantons and Sphalerons

- ''pomeron from instantons'':

ES, Zahed PRD62:085014,2000 hep-ph/0005152

D. E. Kharzeev, Y. V. Kovchegov and E. Levin Nucl. Phys. A **690**, 621 (2001) [hep-ph/0007182].

M. A. Nowak, ES and Zahed, PRD 64, 034008 (2001) [hep-ph/0012232].

G.W.Carter,D.Ostrovsky and ES, Phys. Rev. D **65**, 074034 (2002) [hep-ph

- the turning states and their explosion

D.Ostrovsky, G.W.Carter and ES, hep-ph/0204224,PRD

- Landau method for cross section - rescaled YM sphalerons are produced

D. Diakonov and V. Petrov, Phys. Rev. D **50**, 266 (1994) R. A. Janik, ES and Zahed, hep-ph/0206005.

- Explicit solution of the Dirac eqn in the exploding field background: an end of ''the fermion puzzle''?

ES and Zahed, hep-ph/0206022.

- Gluonic cluster production in double-Pomeron processes (e.g. $pp->pp\eta'; ppf_0(1600), pp+$cluster) compared to data; ES and Zahed,2002
- Instanton-induced Double DIS $\gamma^*\gamma^*$)ES and Zahed,2003

Carter-Ostrovsky,ES 2001: the potential and the QCD sphalerons

- What is the minimal potential energy of static Yang-Mills field, consistent with the constraints:

(i) the given value of (corrected) Chern-Simons number.
(ii) the given value of the r.m.s. size $< r^2 >= \int d^3x r^2 \mathcal{B}^2 / \int d^3x \mathcal{B}^2$

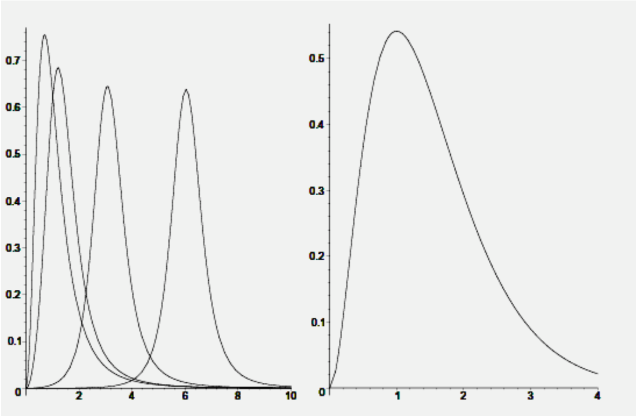
- Solution (found by D.Ostrovsky) is a ball made of three magnetic gluon fields (out of 8 in SU(3)) rotated around x,y,z axes

$B^2/2 = 24(1-\kappa^2)^2\rho^4/(r^2+\rho^2)^4$

$E_{stat} = 3\pi^2(1-\kappa^2)^2/(g^2\rho)$ $\tilde{N}_{CS} = \text{sign}(\kappa)(1-|\kappa|)^2(2+|\kappa|)/4.$

Eliminating κ one gets the topological potential energy,

$\kappa = 0$ gives the sphaleron



Explosion of the Turning States

Left: the snapshots of the r^2 energy
Right: the spectrum of the produced fermions

- Solved both numerically (G.Carter) and analytically (by D.Ostrovsky based on work by Luescher and Schehter from 1977 which can also be via conformal transformation -Zahed)
- Sphalerons at $t = 0 =>$ (at large t) into a spherical transverse wave $4\pi e(r,t) = \frac{8\pi}{g^2\rho^2}(1-\kappa^2)^2\left(\frac{\rho^2}{\rho^2+(r-t)^2}\right)^3$

- ES+Zahed: new solution to the Dirac equation in exploding backgroun obtained by inversion of the fermionic O(4) zero mode of O(4) symmetric solution.
It explicitly shows how the quark acceleration occurs, starting from zero energy at t=0 to the final spectrum
- The sphalerons produce one level crossing $N_F \bar{L}R$ quarks, and the antisphaleron-like clusters the chirality opposite.

Semiclassical Double-Pomeron Production of Glueballs, η' and clusters

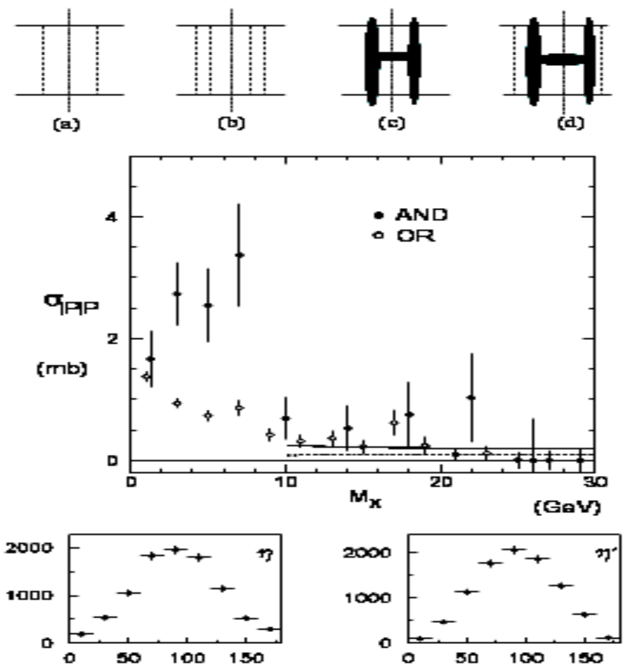
ES and I.Zahed,Phys.Rev. D68 (2003) 034001

Pomeron-Pomeron into cluster, cross section from UA8 collaboration: heavy gluonic clusters with isotropic decay. What are they?

Note: a cross section that is an order of magnitude larger than the one predicted by Pomeron factorization

WA102 collaboration at CERN, pp Double-Pomeron into identified central hadron: strong dependence of the cross section on the azimuthal angle ϕ (between two kicks to two protons), not expected from standard Pomeron phenomenology.

we get $cos^2(\phi)$ for P=+ and $sin^2(\phi)$ for P=-1.



sphalerons in pp:

- Double-diffractive cluster production in STAR+"Roman pots" => proposal pending
- Sphaleron produces 6 units of chirality!
- Expected exclusive channels which are well observed like $KK\pi$ etc (but not $\pi\pi\pi$) like it was in η_c decays (Bjorken,Schafer)
- Because pp has magnetic field => charge

asymmetry in final states (Kharzeev)

topological fluctuations in QGP

- Kharzeev**: charge separation in B field**. Yet chirality spot grows slow (diffusively) while B(t) decreases rapidly.
- If the STAR/PHENIX correlations are **the effect**, the domain seem to **be large** (CuCu vs AuAu)
- Zhitnitsky: but Veneziano ghost is massless, so maybe it grows with a speed of light
- ES 2002: about 10 (uncorrelated) domains from sphalerons per central AuAu at RHIC

Rafaelle Millo is Ph.D.student of my former student P.Faccioli who is professor at University of Trento. He visited in Dec. 09 for a week and we made (in 2 days) the following paper

Macroscopic Chirality Fluctuations in Heavy Ion Collisions should induce CP forbidden Decays

Raffaele Millo[1] and Edward V. Shuryak[2]

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[2] *Department of Physics and Astronomy, State University of New York, Stony Brook NY 11794-3800, USA*
(Dated: December 24, 2009)

If large fluctuations of quark chirality occur in heavy ion collisions, they result in macroscopic CP-odd "spots" of the so called theta-vacua, with a non-zero $\theta(x)$. We consider particular decays of mesons, CP-forbidden in the vacuum with zero θ, like $\eta \to \pi\pi$. We evaluate their rates for such decays near hadronic freezeout. These rates, as well as charge asymmetries already observed, are proportional to square of the CP-violating parameter $\langle\theta^2\rangle$ averaged over the fireball and events. With such input, we found that the forbidden decay rates are likely to be orders of magnitude larger than CP-allowed ones. We further estimated that up to about one per mill of η mesons produced in heavy ion collisions should decay in this way. We further discuss how those can be observed. We argue using STAR data on charge asymmetries for AuAu and CuCu collisions that the size of CP-odd spots at freezeout is as large as Cu nuclei: this fortunate fact (not explained so far by itself) suggests that the two-pion invariant mass is modified by only about a percent, which is comparable to experimental resolution. If so, we think experimental observation of these decays is within the reach of current dataset. If those decays are found, it would confirm that CP-odd interpretation of charge asyymetry is correct, even without complication related to geometry, impact parameter or magnetic field induced on the fireball.

arXiv:0912.4894

- We since have learned that A.R.Zhitnitsky had the same idea before us , he also calculated such decay in hep-ph/0003191
- All the parameters in the answer coinside, but he considered 2 flavors and we did 3 with eta-eta' mixing., amplitude different by factor 3
- (At that time Kharzeev, Pisarski and Tytgut proposed **metastable minima,** domains of theta vacua: this is a different Idea which did not worked out. Now we all consider just the CP-odd fluctuations which do not require any new minima)

- Decays which were forbidden are now allowed:

  $\eta \Rightarrow \pi^+\pi^-$, $\eta' \Rightarrow \eta\pi$, $\eta' \Rightarrow \pi^+\pi^-$

- in the CP-odd spot <theta> is nonzero => disbalance between instantons and anti-instantons even at freezeout in the near-vacuum state
- Calculated from the chiral Lagrangian at nonzero theta

The CP-odd part of the ChPT Lagrangian in the leading chiral order and at leading order in the $1/N_c$ expansion, is equal to[18]

$$L_{eff} = -i\frac{\chi_{top} N_f}{2N_c}\bar{\theta}\left[\mathrm{Tr}[U(x) - U^{\dagger}(x)] - 2\log\det U(x)\right] \quad (5)$$

where $\bar{\theta}$ is an *effective* θ *parameter.*

$$\bar{\theta} \simeq \frac{F_\pi^2 N_c m_\pi^2}{4N_f \chi_{top}}\theta \quad (6)$$

it is clear that any theta effect can only be visible if no quarks is massless: thus theta-bar variable.

$$\bar{\theta} \approx 0.06\theta$$

$$\Gamma_{\eta\to\pi^+\pi^-} = \frac{1}{32\pi^2}|A_{\eta\to\pi^+\pi^-}|^2 \frac{|\bar{p}_\pi|}{m_\eta^2} d\Omega$$

$$\simeq \frac{1}{24\pi}\frac{\chi_{top}^2}{F_\pi^6}\bar{\theta}^2 \frac{\sqrt{m_\eta^2 - 4m_\pi^2}}{m_\eta^2} \approx 140 MeV \bar{\theta}^2$$

So, for theta=O(1)
thetabar is few percents

$$P_{\eta\to\pi^+\pi^-} = \Gamma_{\eta\to\pi^+\pi^-}\Delta\tau_f \frac{V_{spot}}{V_f} \sim 0.1\theta^2 \frac{\Delta\tau_f}{1fm}\frac{V_{spot}}{V_f}$$

Map of the QFTs today

$\mathcal{N}$=4 SYM
No-Higgs
Conformal
E/M Self-dual
AdS/CFT
Integrable?

AdS/QCD

QCD
Exp.spectrum
Lattice
sQGP

$\mathcal{N}$=4
SYM
Higgsed
New
duality?

$\mathcal{N}$=2 SYM
Higgsed
SW solution
SW dualities
Confinement
Chiral
sym.breaking
Wall crossing

Adjoint QCD
T_{conf} and T_{chiral}

$\mathcal{N}$=1 SYM no scalars!
Confinement+
Chiral sym.breaking
Seiberg phase diagram

1d compactificaton
Periodic fermions =>
SUSY

It is important to bridge ``two peaks”, in particular learn what is done in SYM about weak-strong transition and E/M dualities

get lattice people serious about SUSY simulations, to understand the mechanisms of Confinement+Chiral sym.breaking through the whole chain of theories