Weak-to-strong coupling transition in AdS/CFT and QCD phenomenology

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outlook

- **No jets at strong coupling!** (Stress tensor of the expanding Maldacena dipole, Lin+ES,07)
- High energy collisions and weak-strong transition. Equilibraiton= BH formation. Transition with a jump **(0bserved?)**
- Two-domain model for AdS/QCD (ES 07) Had we observed anomalous dimensions in strong couping already?

Toward the AdS/CFT Gravity Dual for High Energy Collisions: II. The Stress Tensor on the Boundary

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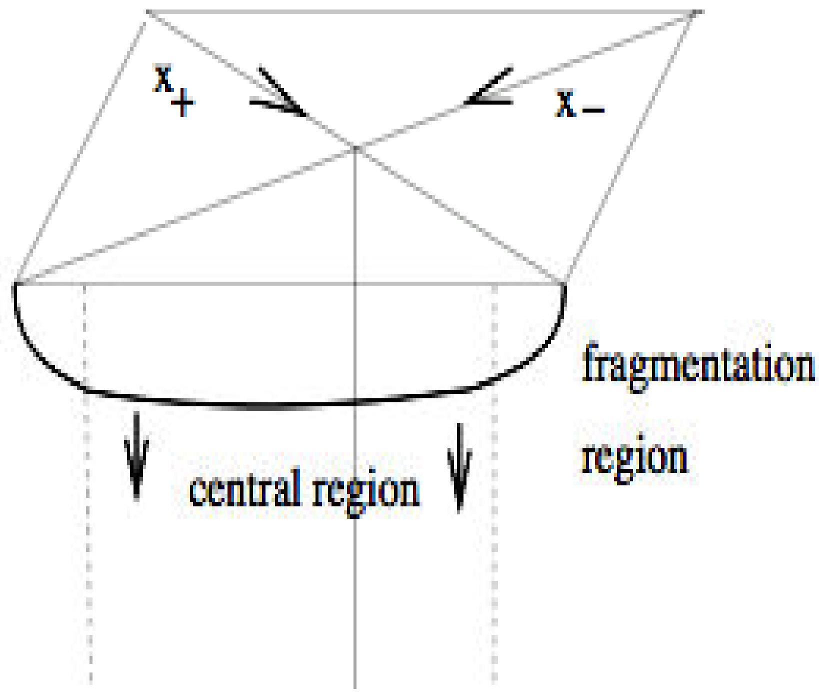
In this second paper of the series we calculate the stress tensor of excited matter, created by "debris" of high energy collisions at the boundary. We found that massive objects ("stones") falling into the AdS center produce gravitational disturbance which however has *zero* stress tensor at the boundary. The falling open strings, connected to receeding charges, do produce a nonzero stress tensor which we found analytically from time-dependent linearized Einstein equations in the bulk. It corresponds to exploding non-equilibrium matter: we discuss its behavior in some detail, including its internal energy density in a comoving frame and the "freezeout surfaces". We then discuss what happens for the ensemble of strings.

If colliding objects are made of heavy quarks moved by an "invisible hand" with +/- v

- Stretching strings are falling under the AdS gravity
- **(Instability** of simple scaling solution and numerical studies:

may be analogs of longitudinal E,B in weak coupling)

Calculation of the **hologram**



- Holographic imag
  of a falling string
- *(as far as we know the
  first time-dependent
  hologramm)*
- T_{00} , T_{oi}

- **No jets!**
- **Yet it cannot be represented by hydrodynamical**

explosion => anisotropic pressure in the ``comoving frame"

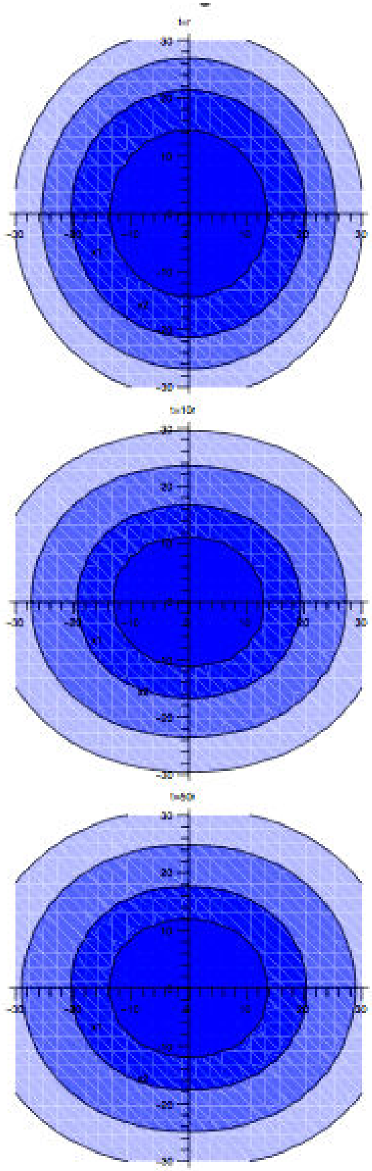


FIG. 1: (color online) The contours of energy density T^{00}, in unit of $\frac{2\sqrt{\lambda}}{f_0^3\pi^2}$, in $x_1 - x_2$ plane at different time. The three plots are made for $t = r$, $t = 10r$ and $t = 50r$ from top to bottom. The magnitude of T^{00} is represented by the color,

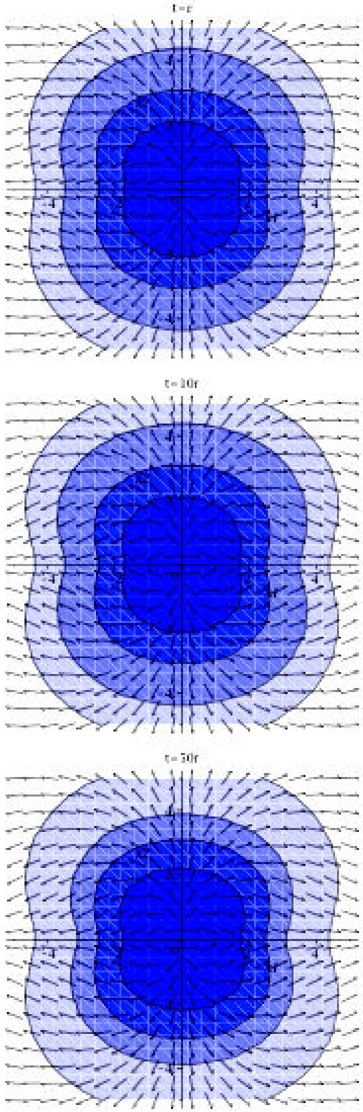


FIG. 2: (color online)The contours of momentum den sity T^{0i}, in unit of $\frac{2\sqrt{\lambda}}{f_0^3\pi^2}$, in $x_1 - x_2$ plane at differen time. The three plots are made for $t = r$, $t = 10$ and $t = 50r$ from top to bottom. The magnitude i represented by color, with darker color corresponding t greater magnitude. The corresponding contour values ar

Gravity dual for the heavy ion collisions

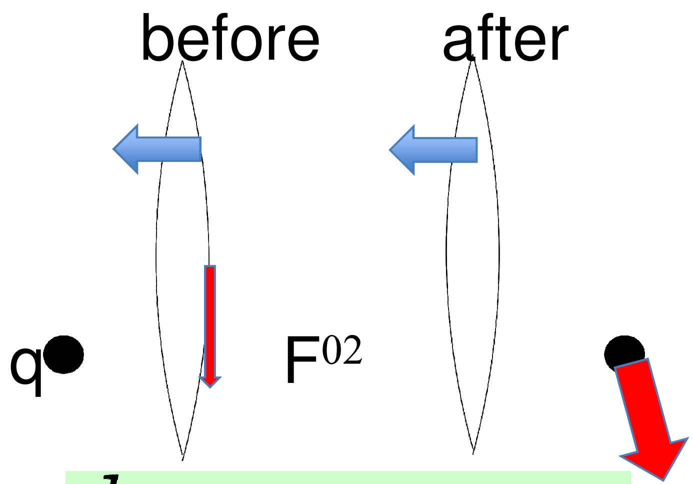
- AdS metric corresponds to extreme BH (mass is minimal for its charge and no horizon)
- As collision creates falling “debris”, they will form a non-extreme BH with a horizon Nastase 03
- Expanding/cooling fireball= departing horizon

Sin,ES and Zahed 04,

- BH is longitudinally stratching - rapidity independent example Janik-Peschanski 05…
- New meaning of dissipation: Relaxation=formation of a horizon (trapping surface) where information is lost

Interaction with ultrarelativistic charge and mass, respectively

Gauge theory

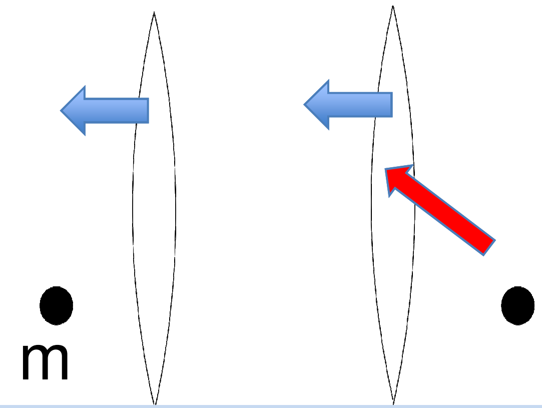


$$\frac{m}{q}\frac{du_\mu}{ds} = F^{\mu\nu} u_\nu$$

$$F^{01}_{boosted} = \left(cosh(y)^2 - sinh(y)^2\right) F^{01} = F^{01}$$

Because of
Anti symmetry

Gravity

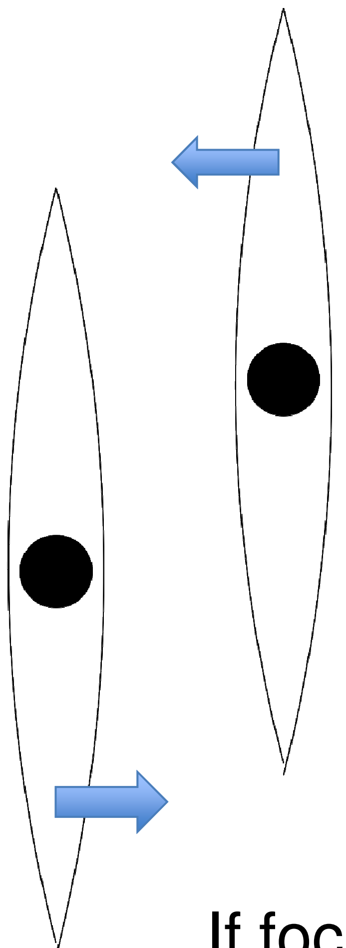


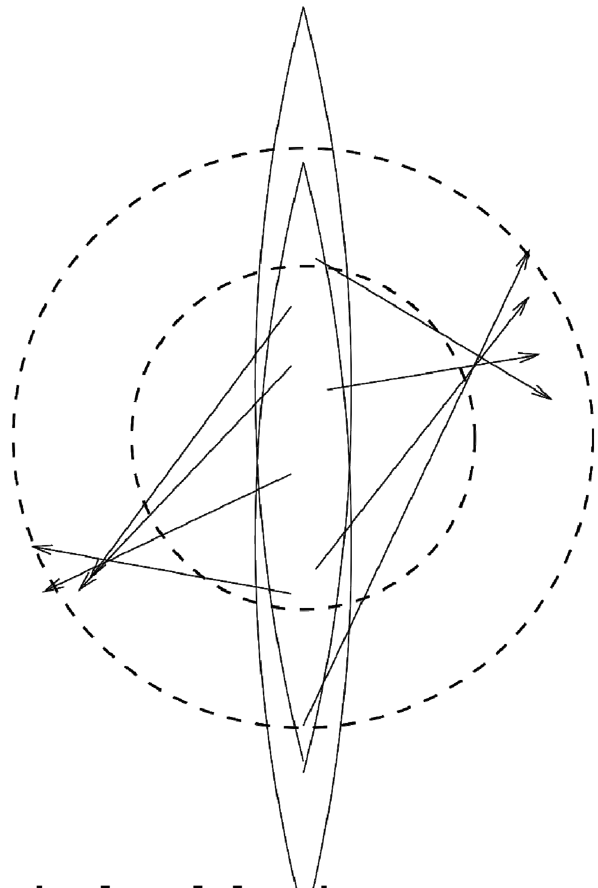
$$\frac{du^\mu}{ds} = -\Gamma^\mu_{\nu\lambda} u^\nu u^\lambda$$

No anti symmetry here,
Boosted tensor looks mostly longitudinal!

Energy is gravity's source:
so a kick is proportional not to the mass
but to the energy of the shock
even large rapidity can be transferred
to the mass

Gravitational shocks are lens





If focussed matter is **inside** the trapped surface,
Black hole is formed

Entropy production

estimates of area of trapped surface

A signifcant 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)

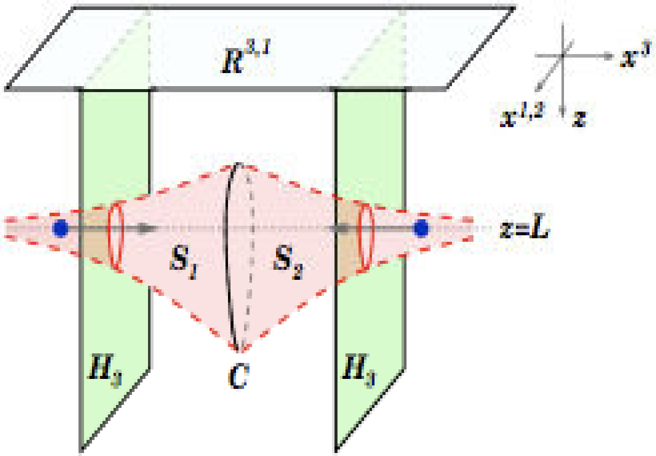
If so, one can find the radius at which it is the trapped null-surface and determine its energy and Bekenstein entropy. For large q_c these expressions are

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

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

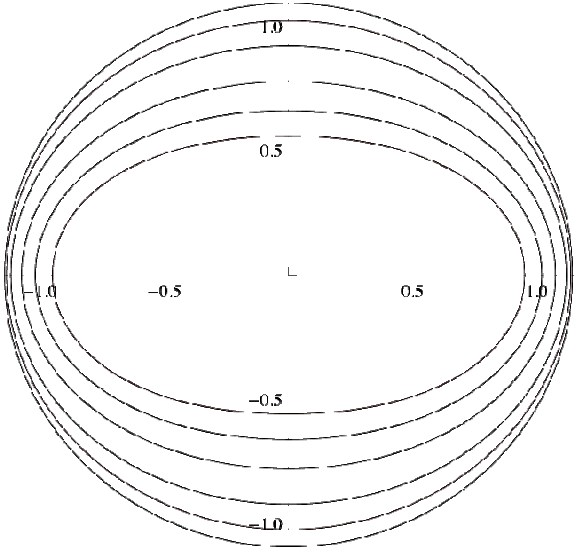
Shu Lin[1], and Edward Shuryak[2]

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:

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

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

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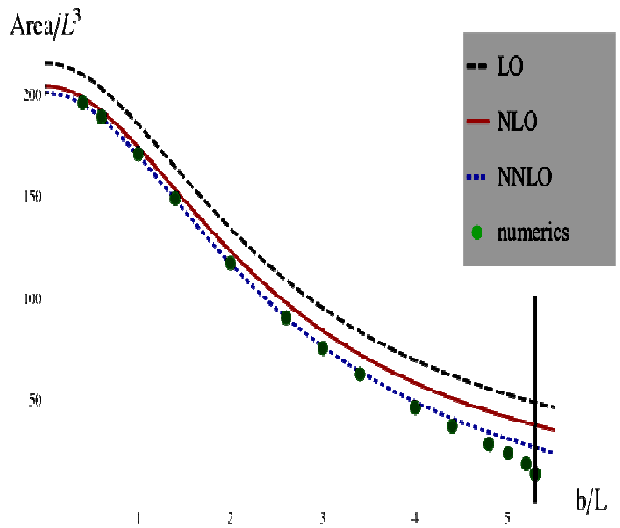
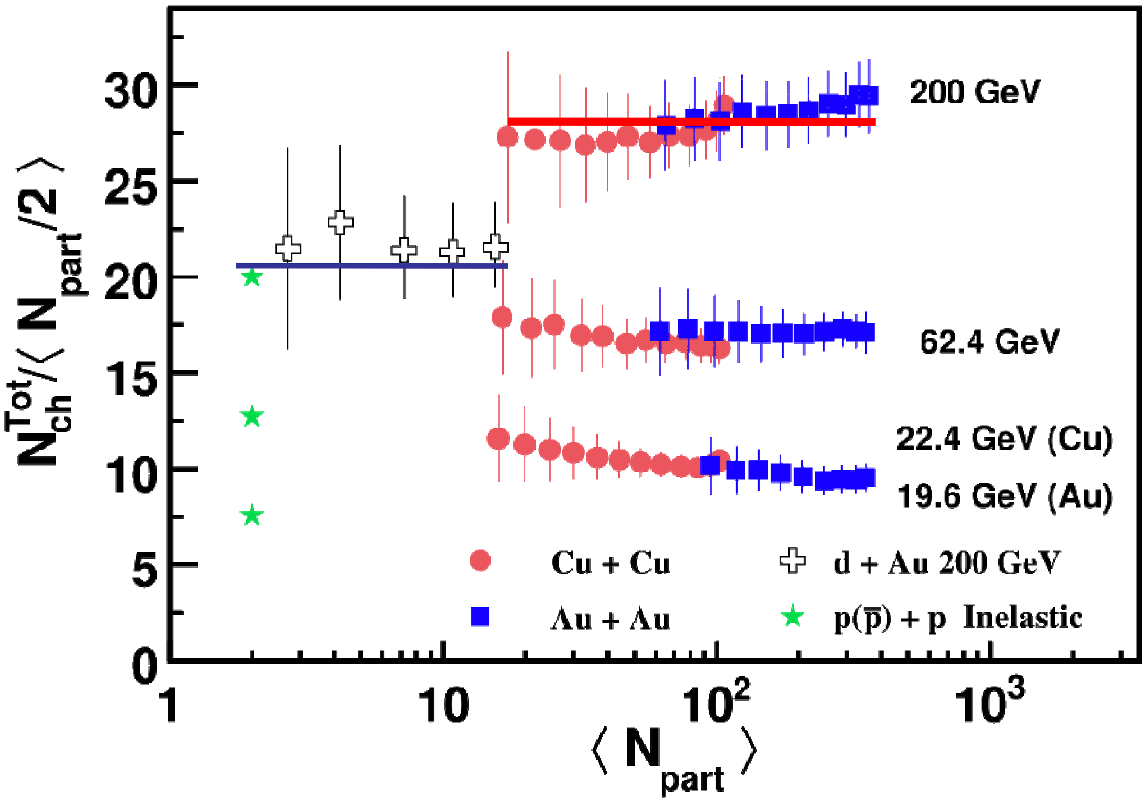


Figure 1: (Color online.) Comparisons between the numerics of [36] and the analytic formula (58). The black dashed curve represents the leading term in (58); the solid red curve corresponds to the first two terms in (58); the dotted blue curve represents the expression (58), which is correct up to a 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 something similar in experiment?



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

A "Domain Wall" Scenario for the AdS/QCD

- Strongly coupled domain with about constant coupling
- Weakly coupled is also approximately conformal
- But one continuous w.f. describing how hadrons are distributed in size

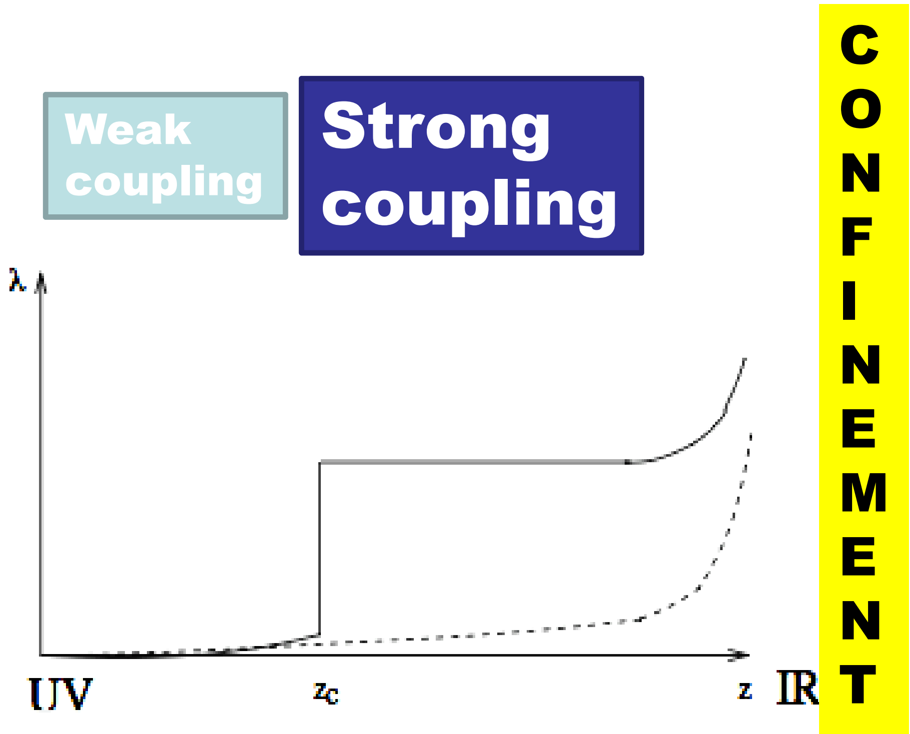


FIG. 1: Schematic dependence of the t'Hooft coupling λ on the holographic 5-th coordinate z.

From bulk to boundary spectroscopy

Bulk wave eqns for spin-S fields have a generic form

$$\partial_z e^{-B} \partial_z \phi(z) + (m_4^2 - M_5^2/z^2) e^{-B} \phi(z) = 0 \qquad (3)$$

Here

$$B = z^2 + (2S-1) ln(z) \qquad (4)$$

Standard substitution $\phi = e^{B/2}\psi$ transform this into Schreodinger-like eqn without first order derivatives

$$-\psi'' + V(z)\psi = m_4^2 \psi \qquad (5)$$

$$V(z) = z^2 + 2(S-1) + \frac{S^2 + M_5^2 - 1/4}{z^2}$$

- KKSS (Katz et al)=> $m_4^2=4(n+S)$
- Nice Regge trajectories: but outside few protected operators, **why no anomalous dimensions**?

Anomalous dimensions - M_5

are nontrivial!

Much less is done for the operators with the usual spin S. In the case of large spin S anomalous dimension grow only logarithmically

$$\Delta - S = f(\lambda) ln(S/\sqrt{\lambda}) \quad (11)$$

and $f(\lambda)$ seems to be universal function for cusps: its large coupling limit $f(\lambda) \to \sqrt{\lambda}/\pi$ correspond to folded spinning strings as shown in [33]. For orientation, the strongest QCD couling we think is possible is $\lambda \sim 80$, and thus this function can reach $f(\lambda) \sim 3$: so in fact strongly coupled QCD channels are expected to have anomalous dimensions of the size of several units or so.

Hard processes in AdS

Polchinski-Strassler => Brodsky-Teramond

$$FF(Q) \sim \int dz \psi(z) \partial_m \psi A_m(z)$$

A is the hard bulk photon
It is about exp(-Qz) =>
Only small-z tail of psi
important

Brodsky and Teramond [] obtained the following nice expression for a formfactor

$$F(Q^2) = \Gamma(\tau) \frac{\Gamma(1 + Q^2/4)}{\Gamma(\tau + Q^2/4)} \quad (16)$$

where τ is the relevant twist. $\tau = \Delta - S$. It described well the experimental data for pions and nucleons, assuming that pions have twist $\tau = 2$ and nucleons $\tau = 3$.

- Pions can be produced by the **protected** axial current but **nucleons obviously have anom.dim and twist is >3.**
- **why don't we see anomalous powers in the data?**

Hard processes in the 2-domain picture

pling and anomalous dimensions. The renormalizability of the theory implies that the equations depend on *current* coupling $\lambda(z)$ which itself changes due to first-order renormalization group equation

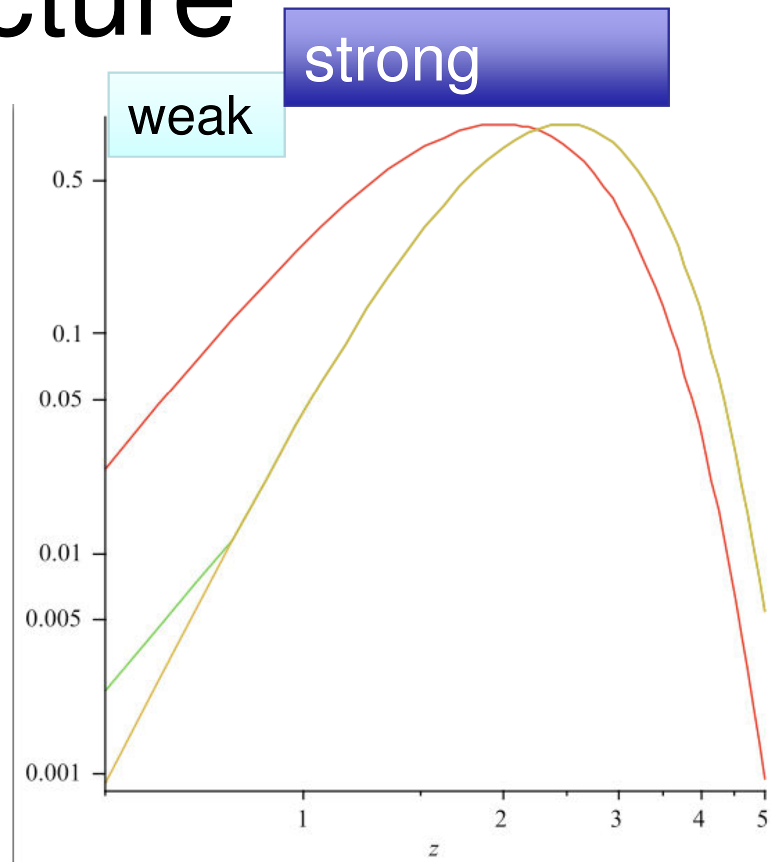
$$\frac{d\lambda}{dz} = \beta(\lambda(z)) \tag{17}$$

(Relation to second order eqn for the dilaton which follows from the Lagrangian is explained in [15].) Similar first order eqns are expected for the bulk (mixing) masses of a set of fields $\phi_A, A = 1..K$ with the same quantum numbers should be given by a similar evolution equations depending on the local coupling

$$\frac{dM^2_{AB}(z)}{dz} = \gamma_{AB}(\lambda(z)) \tag{18}$$

Since those are the first order eqns, one has to specify just their initial values, which are bare canonical dimensions at the boundary $M_{AB}(z = 0) = 0$. Combining these two eqns one gets a generic solution

$$M^2(\lambda) = M^2(0) + \int_0^\lambda d\lambda' \frac{\gamma(\lambda')}{\beta(\lambda')} \tag{19}$$



- Twists 6,8 and a wave function with **a jump in m_5**

Is the domain wall already observed?

- D.Ashery - pion => 2 jets (fermilab experiment)
- 2 clearly different regimes, wave functions upper plots
- Power jumps from 6 (pQCD) => 11 or so, if log derivative used

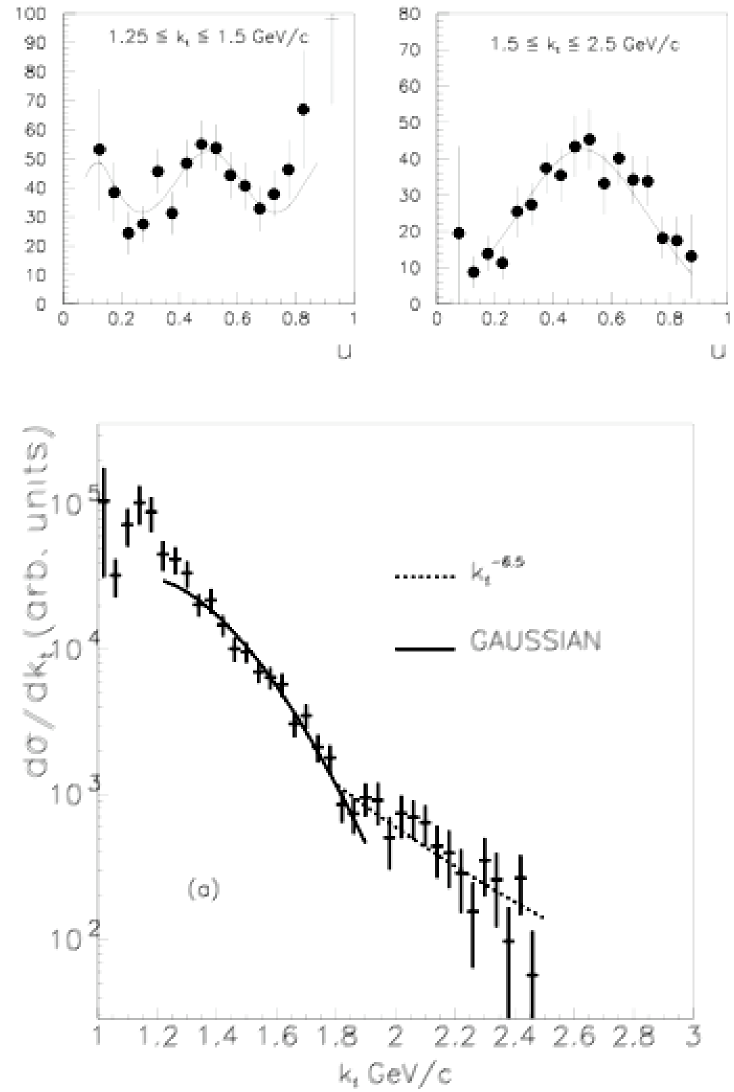


FIG. 3: (upper) The Acceptance-corrected u distributions of diffractive di-jets obtained by applying correction to the E791 results, (lower)experimental k_t distribution, again with certain fits (curves)

Normalized ff/ff(bare power) and the data for pion=> 2 jets

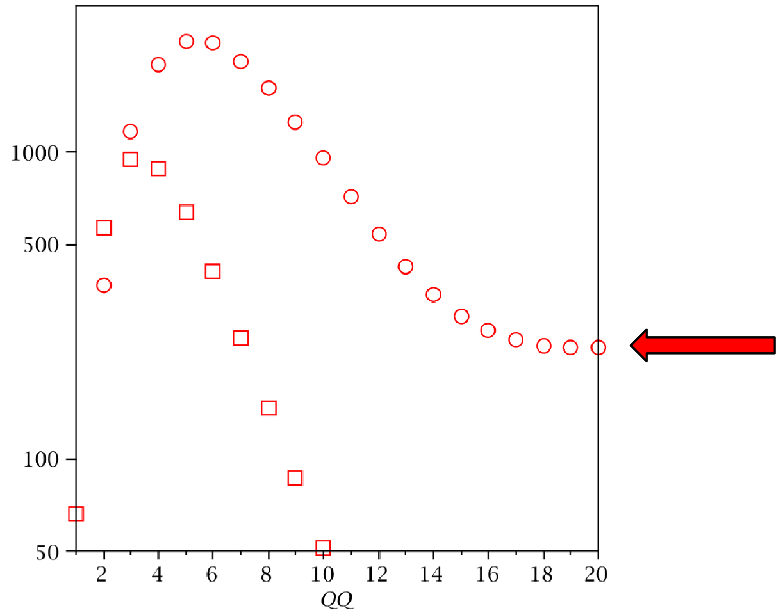


FIG. 4: (color online) The combination $Q^6 f(Q)$ where $f(Q)$ is elastic formfactor, versus Q (in units $m_\rho/2$). The decreasing curve (boxes) is for wave function with the dimension 7. The curve stabilized at large Q (circles) is for the combined wave function, which at $z < z_{dw}$ has the (original bare) dimension 3.

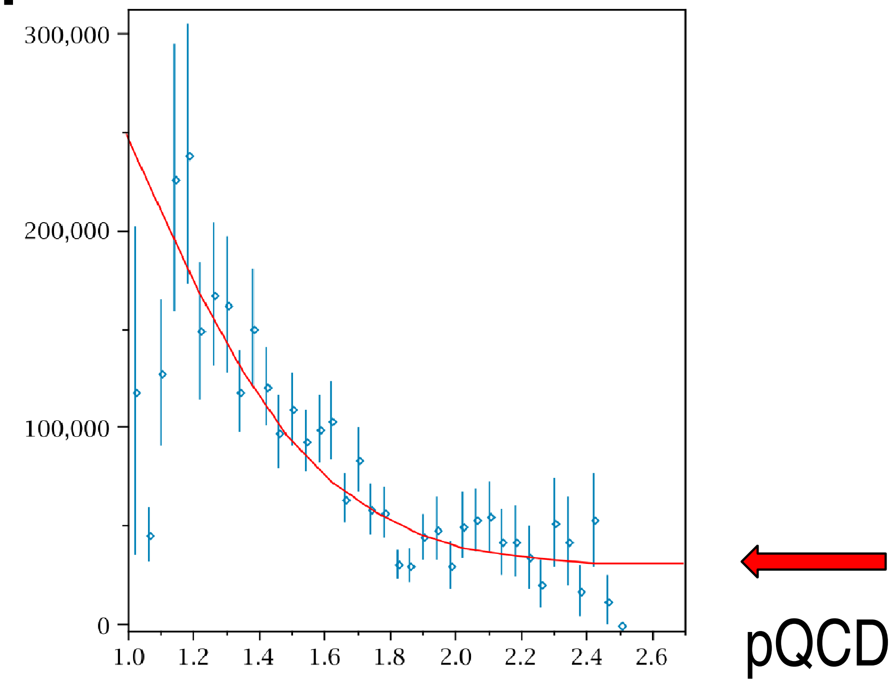


FIG. 5: (upper) The Acceptance-corrected u distributions of diffractive di-jets events from E791 [31]. (lower) The points are experimental k_t distribution, shwn as $k_t^6 d\sigma/dk_t$ (arbitrary units) vs k_t (GeV). The curve is (rescaled) formfactor shown in Fig.4 by circles: it is plotted to test the agreement of their shapes.

QCD instantons: ES 1982

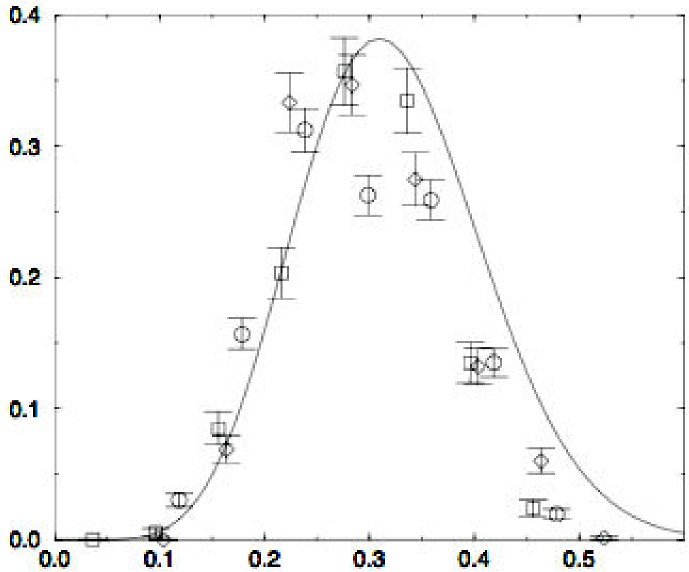
These puzzles were resolved by realization [19] that small-size instantons $\rho \sim 1/3\, fm$ are very abundant in the QCD vacuum. In spite of small coupling making the semiclassical exponent frighteningly small

$$exp(-8\pi^2/g^2(\rho)) \sim exp[-10] \tag{23}$$

large preexponent and attractive interactions increase it substantially, leading to actual instanton diluteness parameter

$$n_{I+A}\bar{\rho}^4 \sim 10^{-2} \tag{24}$$

(here $n_{I+A}, \bar{\rho}$ are the instanton (plus antiinstanton) density and mean radius, respectively.



- Confirmed by lattice about 10 years later
- As Nc=>large,

=> delta function of the size

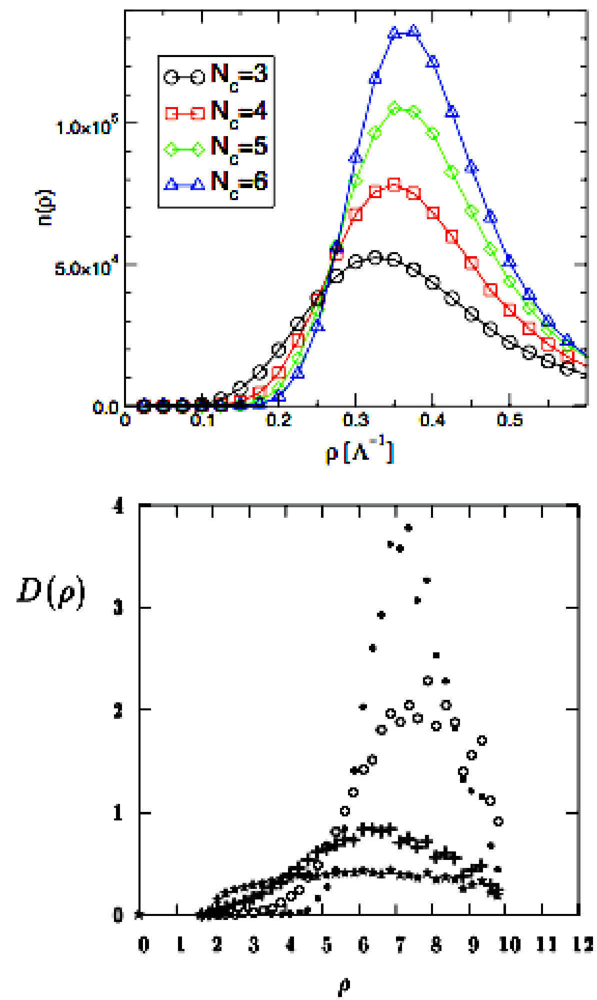


FIG. 5: The figure on the left shows the instanton size distribution obtained from numerical simulations of the instanton ensemble in pure gauge QCD for different numbers of colors [24]. The figure on the right shows lattice results reported by Teper [25]. The ⋆ + ○● symbols correspond to $N_c = 2, 3, 4, 5$.

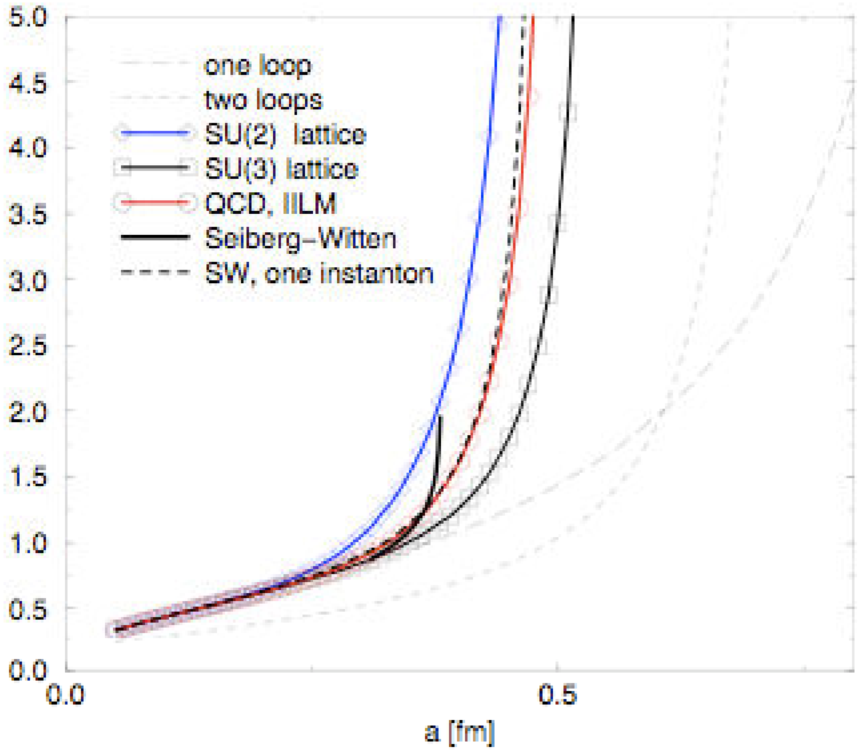


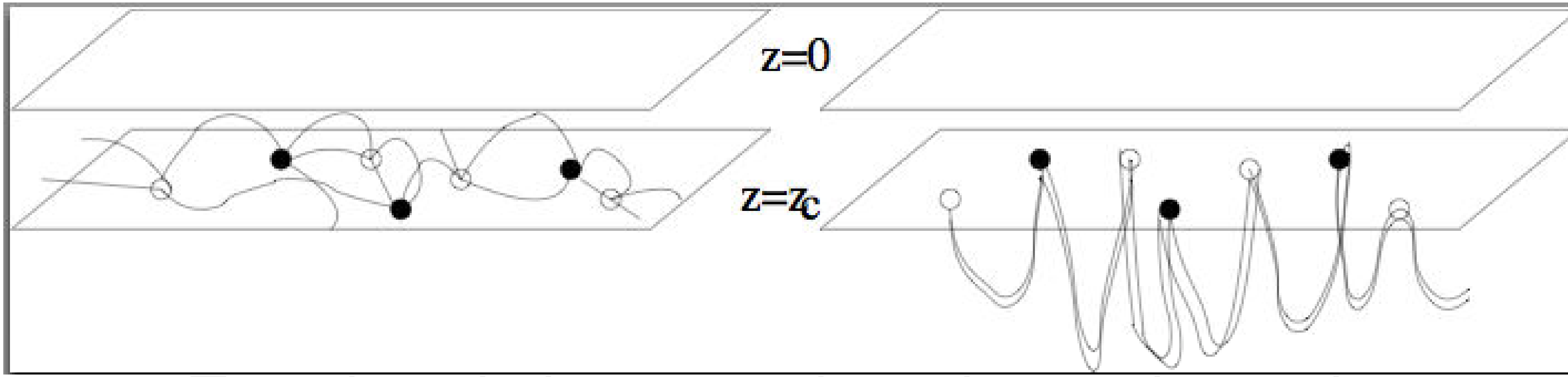
FIG. 6: The effective charge $b\,g^2_{eff}(\mu)/8\pi^2$ (b is the coefficient of the one-loop beta function) versus normalization scale μ (in units of its value at which the one-loop charge blows up). The thick solid line correspond to exact Seiberg-Witten solution for the $\mathcal{N}$ =2 SYM, the thick dashed line shows the one-instanton correction. Lines with symbols (as indicated on figure) stand for N=0 QCD-like theories, SU(2) and SU(3) pure gauge ones and QCD itself. Thin long-dashed and short-dashed lines are one and tho-loop results.

- instantons affect running of the coupling, in QCD and N=2 SYM

(from Randall, Ratazzi,ES,97)

actually for N=2 SYM the SW answer = the sum of all instantons: N.Nekrasov

The wall is made of the instanton liquid



- Two descriptions: quark exchange in weak coupling domain
- **PS mesons exchange at strongly coupled domain**
- A wall is a substitute for the ``matter brain" of the Sakai-Sugimoto model: chiral quarks live there

Summary

- AdS/QCD: include weak coupling region $z<1/3$ fm
- hard processes ignored anomalous dimensions: **we should see them in experiments!**
- The domain wall is made of instantons (large Nc)

and provides artificial “matter branes” e.g. of Sakai-Sugimoto model

- Gravitational collisions are very different from gauge theory: large longitudinal kicks possible=> no jets
- 2 regimes, with and without b.h., with a jump

As a function of b and s: will it happen with pp?□□

Old chiral scale of NJL
(where 4-fermion coupling dies)

1960's. Nambu-Iona-Lasinio model of 1961 was the first model which introduced the "chiral scale"

$$\Lambda_\chi = 4\pi f_\pi \approx 1.2\, GeV \qquad (1)$$

- In 1970’s QCD but Λ_{QCD}=1/fm=.2 GeV

That lead to a puzzle: why dont these two scales match?

Furthermore, perturbative coupling is still too small α_s ~ 1/3 to reproduce the strength of the NJL-type 4-fermion interaction needed to achieve chiral symmetry breaking. Thus, already in 1970’s it was clear that some important physics at the scale Q ~ $\Lambda\chi$ was missing

Correlators which crucially depend on the wall

The logically simplest applications are instanton contributions to gluonic pseudoscalar (scalar) correlation functions

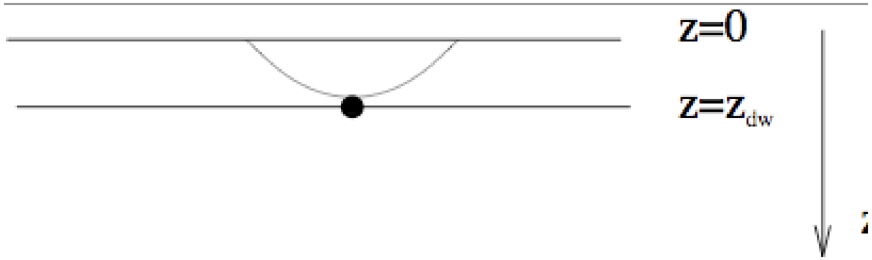
$$\Pi(x,y) =< O(x)O(y) > \quad (30)$$

where $O_{PS} = \frac{\alpha_s}{8\pi} G\tilde{G}$ and O_S has GG without dual. On the gauge side the contribution simply means the inclusion of the instanton gauge fields in the Green function. The answer is simpler for the Fourier transform of this (Euclidean) correlator

$$Pi_{S,PS}(Q) = \pm \int \frac{d\rho d(\rho)}{\rho^5} [Q^2 \rho^2 K_2(\rho Q)]^2 \quad (31)$$

where $d(\rho)$ is the instanton size distribution.

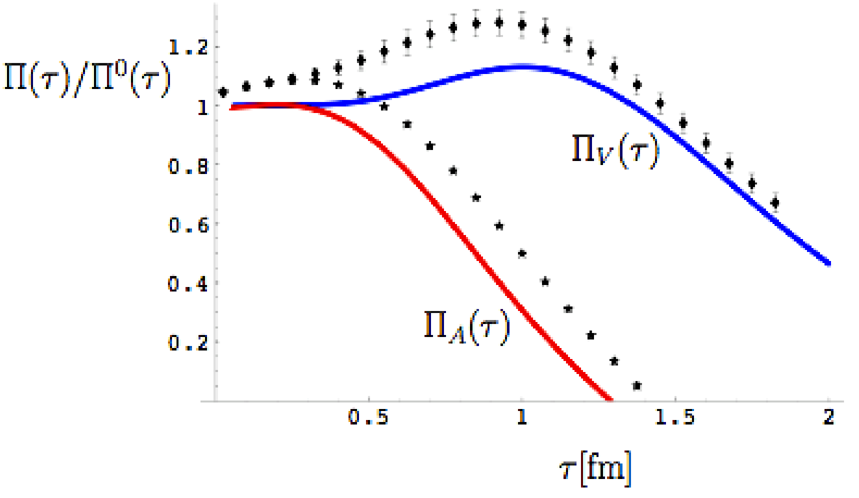
This results was recently re-discussed by Katz and Schwartz [21] in the AdS/QCD model framework. The result is the same except that instead of the instanton density $d(\rho = z)$ they have an "anomaly coupling" κ.



- Instantons are **not floating in the AdS bulk** (thus no divergence)
- But they are at the domain wall instead

Correlators which do not see the wall (protected casses)

- ES RMP 93 Euclidean correlators from experiment and instantons: radical difference for V,A vs S,PS



- T.Schafer AdS/QCD
- 0711.0236

FIG. 1: Vector and axialvector current correlation functions. We show the ratio of the correlation function to the free correlator as a function of euclidean separation τ. The solid curves show the result in the holographic model. The data points are taken from an analysis of Aleph data on hadronic tau decays [12].