AdS\strongly coupled theories - Lines of developments and Current Status

(for pedestrians, ½ hour, absolutely impossible task, but I,ll try)

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Outline

- Idea of holographic duality (few words)
- Nonperturbative classification of defects in QCD
- New developments for QCD phase diagram
- New phenomena in magnetic and electric fields
- QGP via holography and transport phenomena
- «Perturbative» calculations (N=4 SYM)
- Baryons
- Light-Cone Holography
- QCD versus Condensed matter via holography

Holographic duality - the great synthesis. Result of 30 years of developments

- String theory and D- branes

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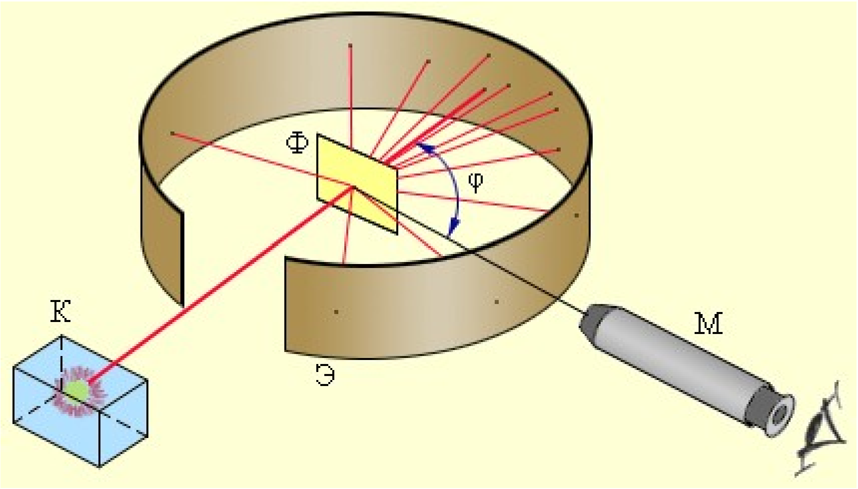
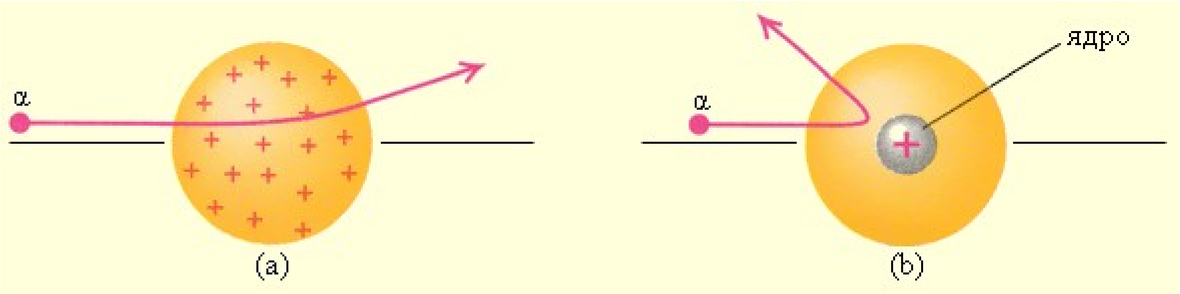
- Black Hole Holography- Area versus Entropy
- Brane World paradygm and Higher dimensions
- RG scale as 5-th coordinate
- Zoo of Dualities, stringy and field theoretic ones
- Brane democracy- different observers
- Quantum mathematics — proper language

- The idea of holography - to use a probe to understand the structure of a complicated object.

- Rutherford experiment



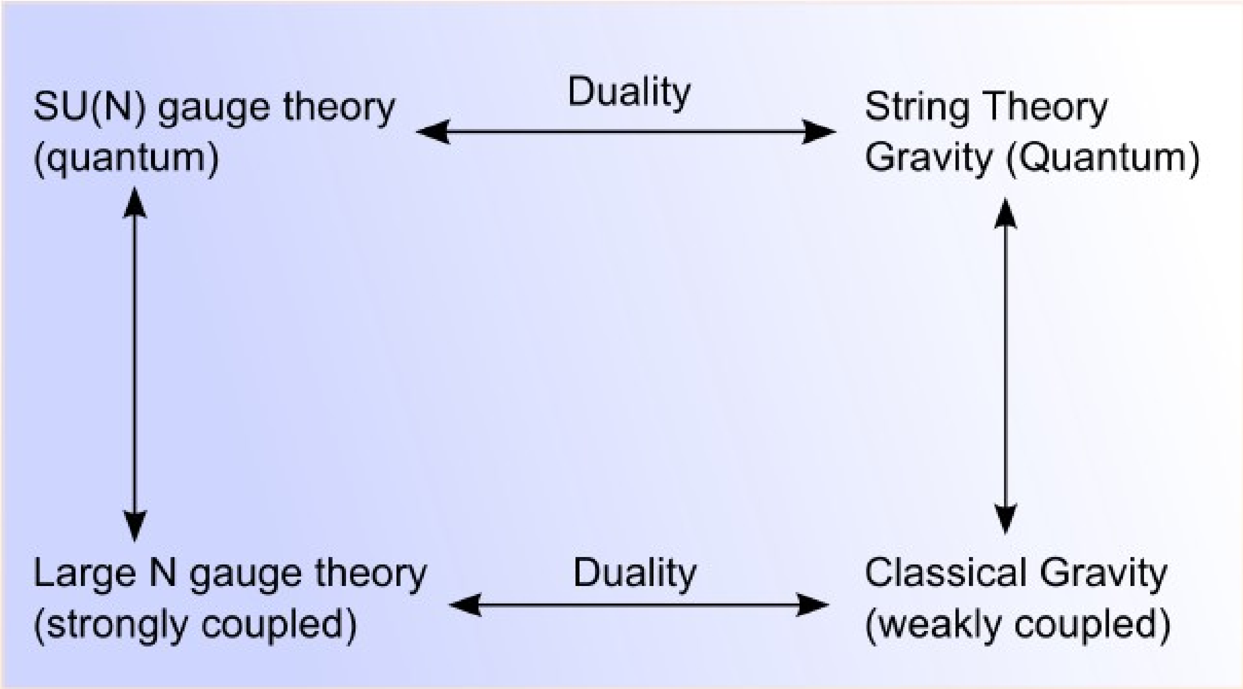
Two models are distinguished by the scattering of the probe - Rutherrford



Holography; our 4d Universe as atom and closed string as alpha- particle. Problem to be solved - select the correct model of our world, looking at the closed string dynamics

Starting point: AdS/CFT correspondence

Maldacena 1997



$N \to \infty \Leftrightarrow g_s \to 0$

't Hooft coupling λ large $\Leftrightarrow \alpha' \to 0$, energies kept fixed

N = 4 SYM	**String theory in AdS$^5 \times$ S^5**
Yang-Mills coupling: g_{YM} Number of colors: N	String coupling: g_s String tension: T
Level 1: Exact equivalence	
$g_s = g_{YM}^2/4\pi, \quad T = \sqrt{g_{YM}^2 N}/2\pi$	
Level 2: Equivalence in the 't Hooft limit	
$N \to \infty, \quad \lambda = g_{YM}^2 N$-fixed (planar limit)	$g_s \to 0, \quad T$-fixed (non-interacting strings)
Level 3: Equivalence at strong coupling	
$N \to \infty, \quad \lambda \gg 1$	$g_s \to 0, \quad T \gg 1$ (classical supergravity)

Brane democracy.

The fundamental string as a probe
is not unique possibility. Just one selected probe.

There are different types of Dp branes in the 10dim space-time with p+1 worldwolumes.

Typically the brane configururation describing the particular gauge theory involves branes of several types, say, D4,D6 and D8 branes. If we live at D4 brane our physics has to be equally described by the theories on D6 and D8 branes.

There is highly nontrivial mapping between theories in different dimensions = theories at the worldvolumes of different branes

Examples

- QCD is the theory on worldvolume of N_c «color» D4 branes while the Chiral Lagrangian (derived!) is the theory on N_f «flavor» D8 branes. The theories in the different dimensions are equivalent at low energies
- 2d\4d duality. Discovered in SUSYQCD (Tong,Shifman,Yung..). Consider the magnetic string (D2 brane). All physics in 4d gauge theory is recognized in the theory in 2d theory on the worldsheet.

Frontline in the holography in N=4 SYM

- All-loops in the scattering amplitudes. Reggeization of the amplitude (Basso,Sever,Vierra, Kazakov,Lipatov....)
- Different aspects of the entanglement entropy.Counting of degrees of freedom.a-theorem (Maldacena et.al,Komargodsky et.al..)
- Evaluation of the correlators from the string theory(.....)
- Attempt to formulate the exact RG equations
- To reduce SUSY in a controllable way

Top-down versus bottom -up

Top-down. Start with 10 -dimensional space-time and attempt to break SUSY in controllable way. Consider the theory on the Worlsvolume of the probe branes in the fixed geometry (Witten,Sakai-Sugimoto)

Bottom-up. Consider the simplest 5d model which fits With the QCD physics (Son-Stephanov,Karch........)

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Similar approach to to the condensed matter. Consider The 4d models with the probe bulk fields (Hartnoll, Herzog .McGreevy.........)

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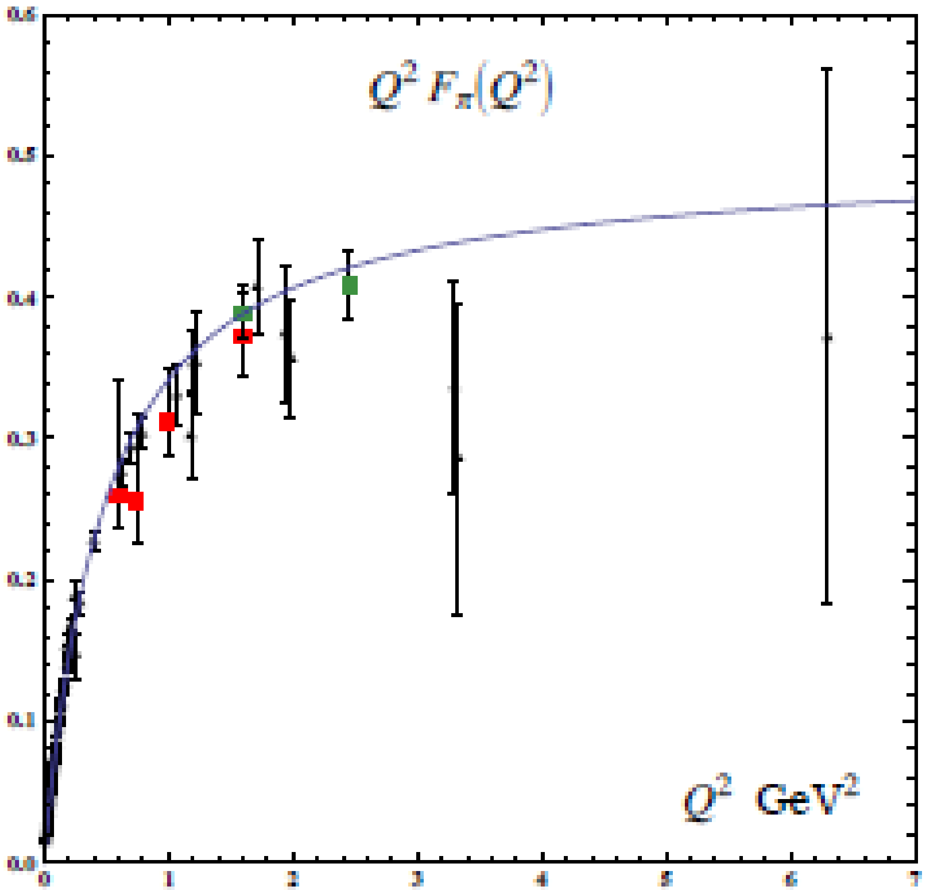
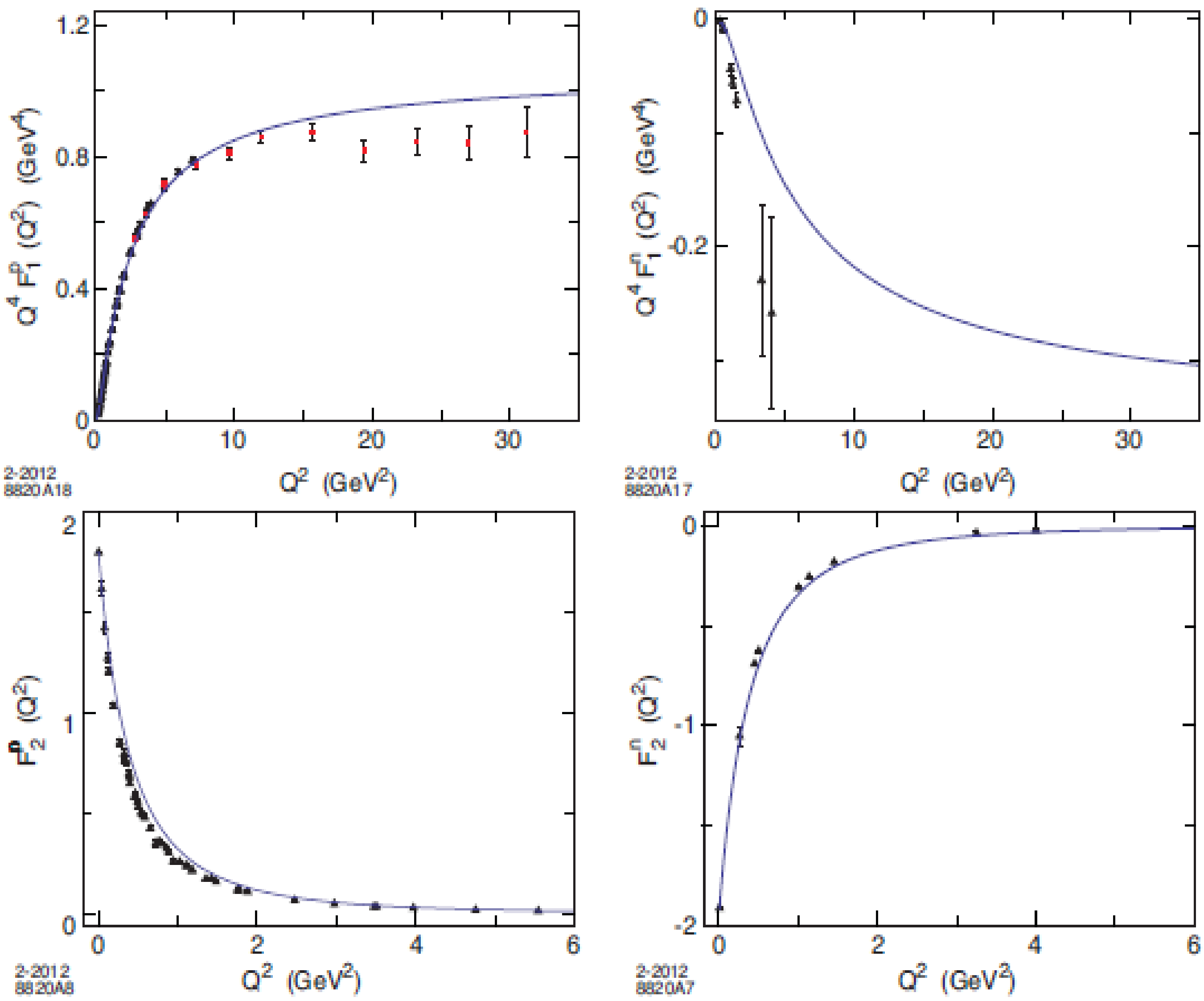
Light -cone holography -version of bottom-up model useful in phenomenologyl(Brodsky-Teramond}

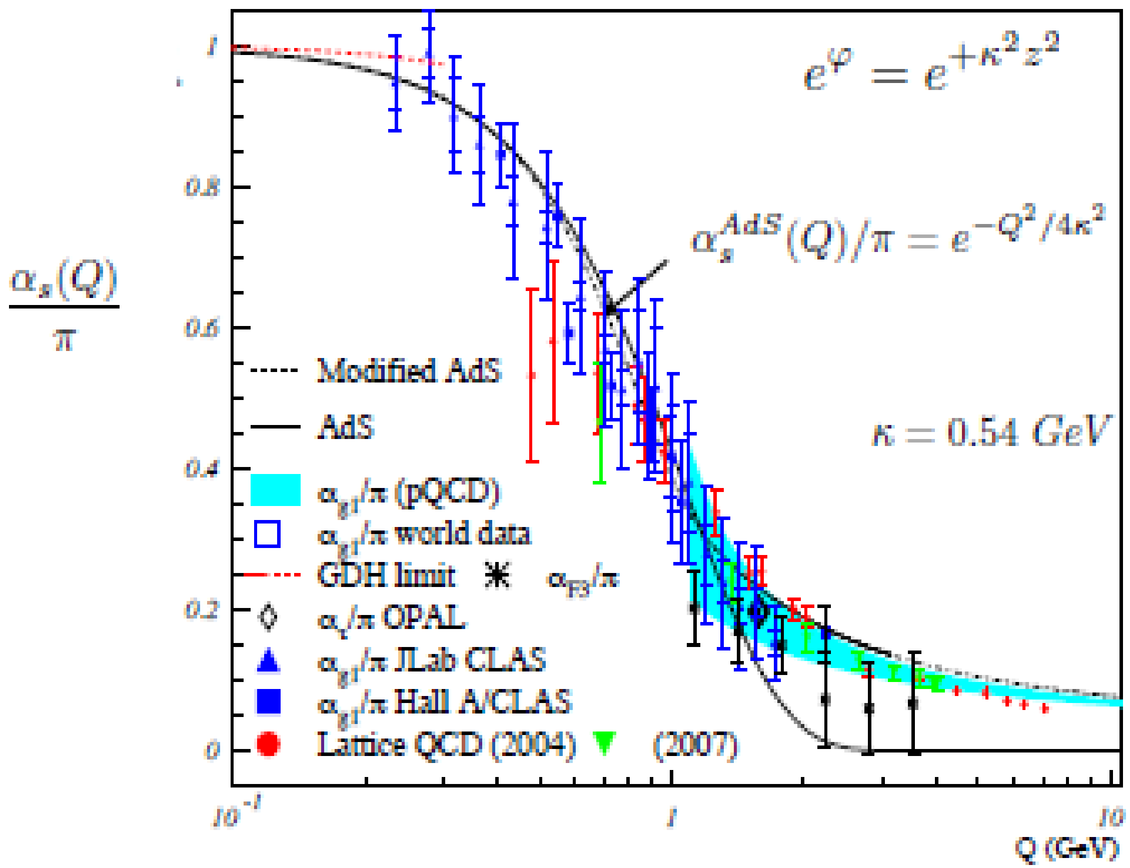


Pion formfactor in LC holography

Oversimplified model but works

Proton formactor in LC holography



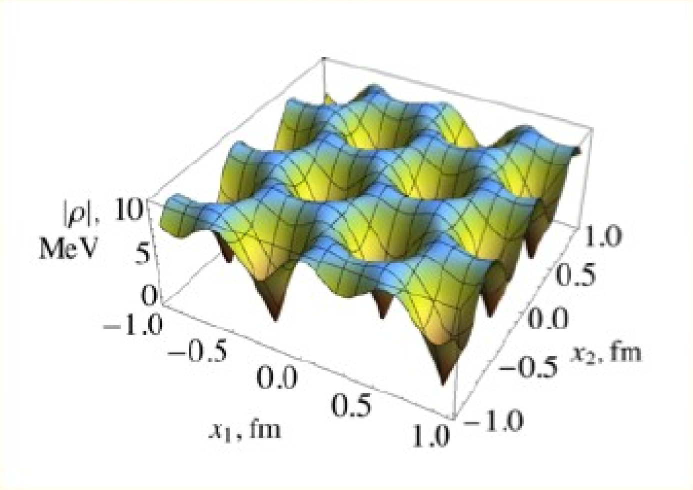


αs(Q)/π
e^φ = e^{+κ²z²}
α_s^{AdS}(Q)/π = e^{-Q²/4κ²}
κ = 0.54 GeV
Modified AdS
AdS
α_g1/π (pQCD)
α_g1/π world data
GDH limit
α_F3/π
α_τ/π OPAL
α_g1/π JLab CLAS
α_g1/π Hall A/CLAS
Lattice QCD (2004)
(2007)
1
0.8
0.6
0.4
0.2
0
10^-1
1
10
Q (GeV)

External magnetic field in QCD. Condensation of the vector mesons ? (Chernodub). Positive answer in holography(Erdmenger et al.)

Effective field theory:

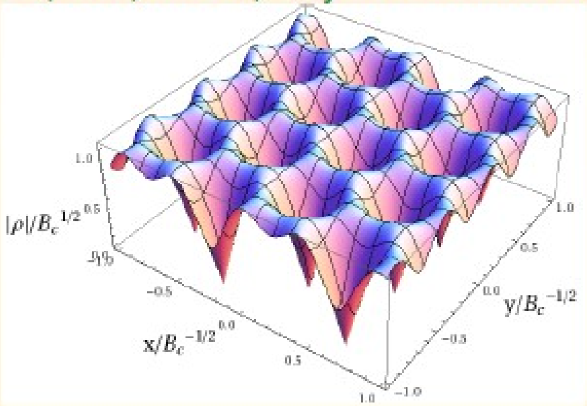
Chernodub 1101.0117



Gauge/gravity duality

magnetic field in black hole supergravity background

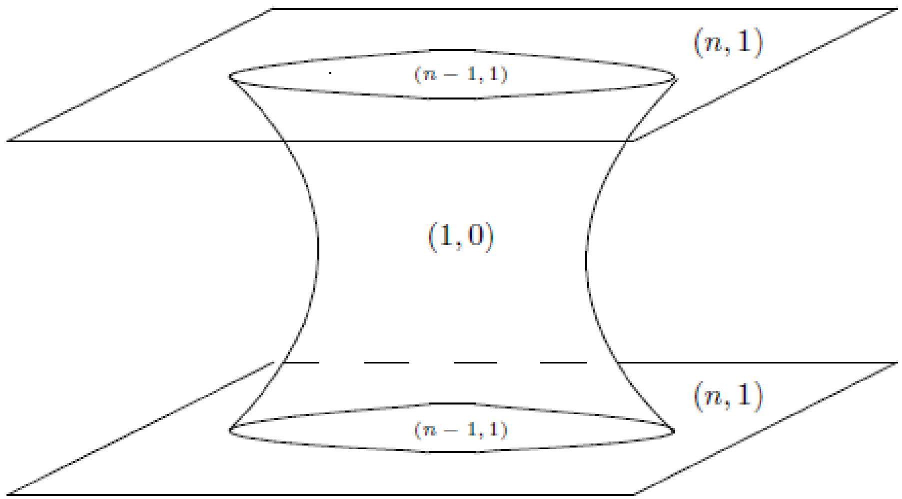
Bu, J.E., Shock, Strydom 1210.6669



Black hole geometry is important!

Schwinger effect in Holography

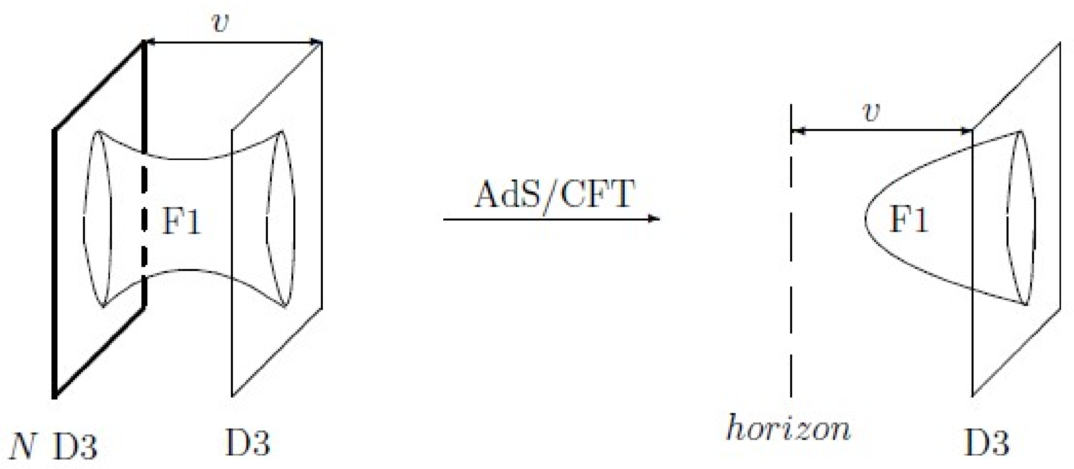
- Pair creation (or string creation in the external electric field. How it goes at strong coupling?



Geometry of the Schwinger effect at weak coupling

Geometry of the Schwinger process at strong coupling

(Saraikin,Selivanov A.G. 2001, Semenoff Zarembo 2011)



There is critical electric field at stong coupling above which there is no exponential suppression of particle production

Baryons

- Oblate instantons , no SO(4) symmetry (Rozali,Stang,van Raamsdonk)
- Dyonic Instantons , chiral symmetry breaking is taking into account (Krikun,A.G)
- The role of the «flat soliton» , new scale which logariphmically depends on coupling (Bolognesi,Satcliffe)
- New results on the baryon formactor in holography (Colangelo et.al)
- Holographic nuclear matter (Kaplunovsky,Sonnenshain, Choroku et al, Lee et al)

Comparison to lattice gauge theory

Mass of ρ meson as function of π meson mass^2 (for $N \to \infty$)

Gauge/gravity duality:

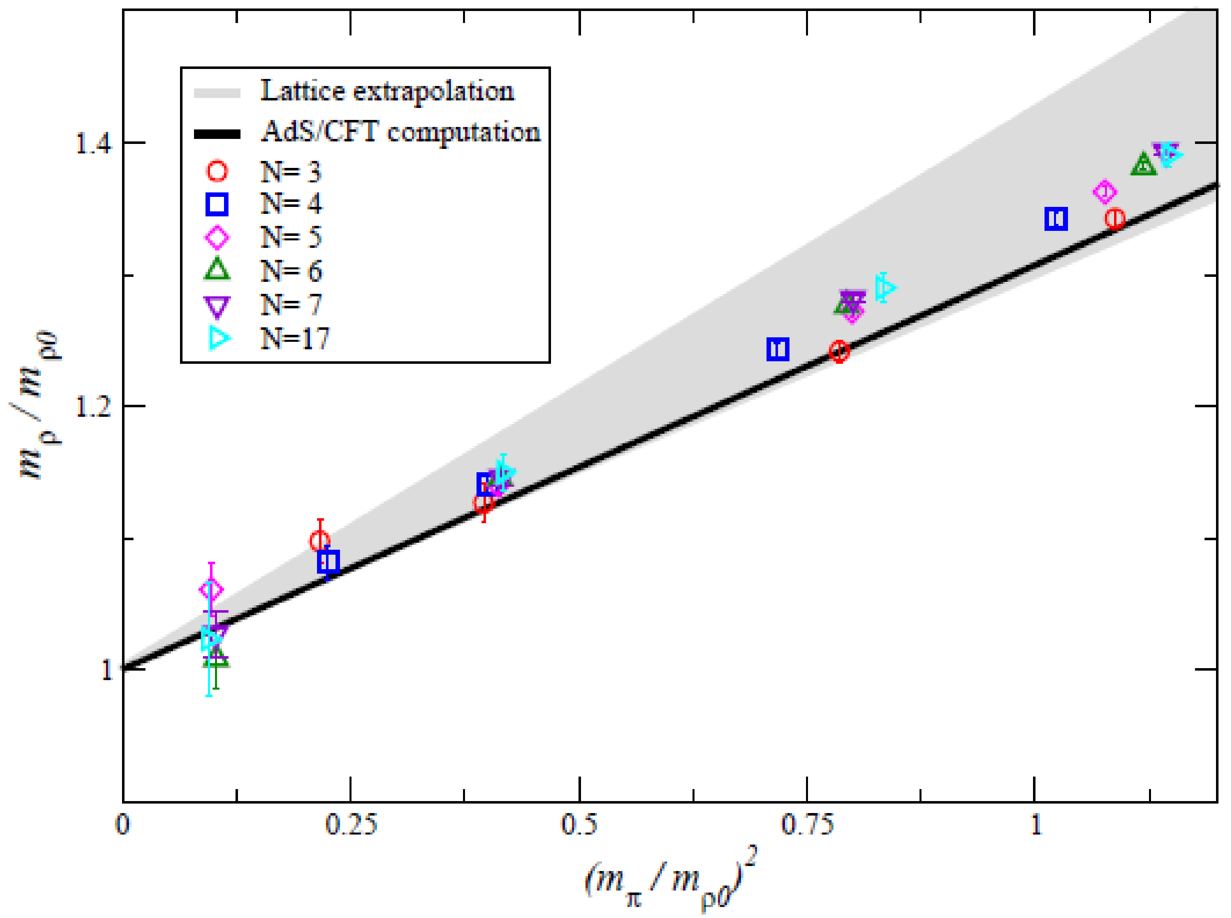
π meson mass from fluctuations of D7-brane embedding coordinate

Bare quark mass determined by embedding boundary condition

ρ meson mass from D7-brane gauge field fluctuations

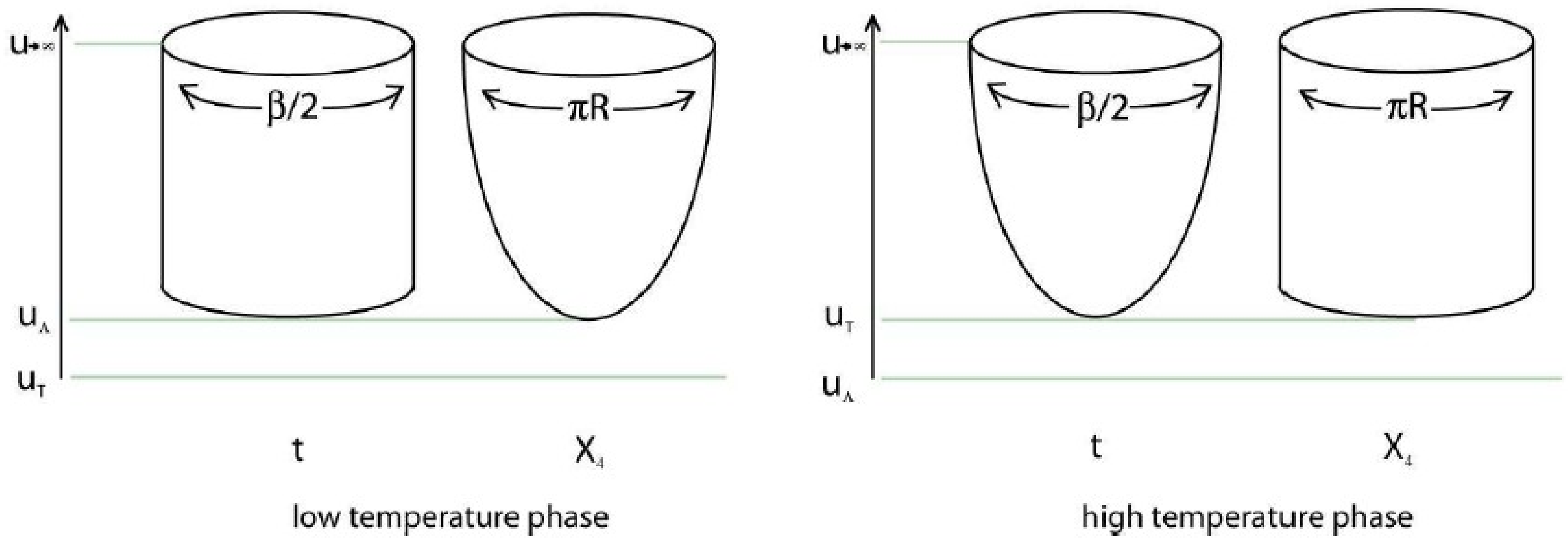
J.E., Evans, Kirsch, Threlfall 0711.4467

Lattice: Bali, Bursa, Castagnini, Collins, Del Debbio, Lucini, Panero 1304.4437



Lattice extrapolation
AdS/CFT computation
N= 3
N= 4
N= 5
N= 6
N= 7
N=17
1.4
1.2
1
0
0.25
0.5
0.75
1
$m_\rho / m_{\rho 0}$
$(m_\pi / m_{\rho 0})^2$

The are many defects predicted by the brane framework. Dp branes wrapped or non-wrapped around compact coordinates. Classification of defects is possible (Zakharov, AG 07). Some of them are seen in the lattice simulations.



Magnetic defects. Some of them becomes low tension object above phase transition. Condensation?

New anomalous transport phenomena in QGP

- Anomalous hydrodynamics (Son,Surowka...)
- Chiral magnetic wave (Kharzeev,Yee) — anomalous mixing of axial and vector currents. Holography provides the way to handle with it
- Zero sound at strong coupling via holography(Karch,Son,Starinets.....)
- Anomalous zero sound - interpolation between CMW and zero sound (Zayakin,A.G)

Chiral vortex effect for gravitational axial anomaly

Similar analysis for gravitational axial anomaly

$$\partial^\mu J^5_\mu = a(T)\, \varepsilon_{\mu\nu\rho\sigma} R^{\mu\nu}{}_{\alpha\beta} R^{\rho\sigma\alpha\beta}$$

Both holographic and field-theoretical analysis reveal $a(T) \propto T^2$

Landsteiner, Megias, Melgar, Pena-Beñitez 1107.0368
Landsteiner, Megias, Pena-Beñitez 1103.5006 (QFT)
Chapman, Neiman, Oz 1202.2469
Jensen, Loganayagam, Yarom 1207.5824

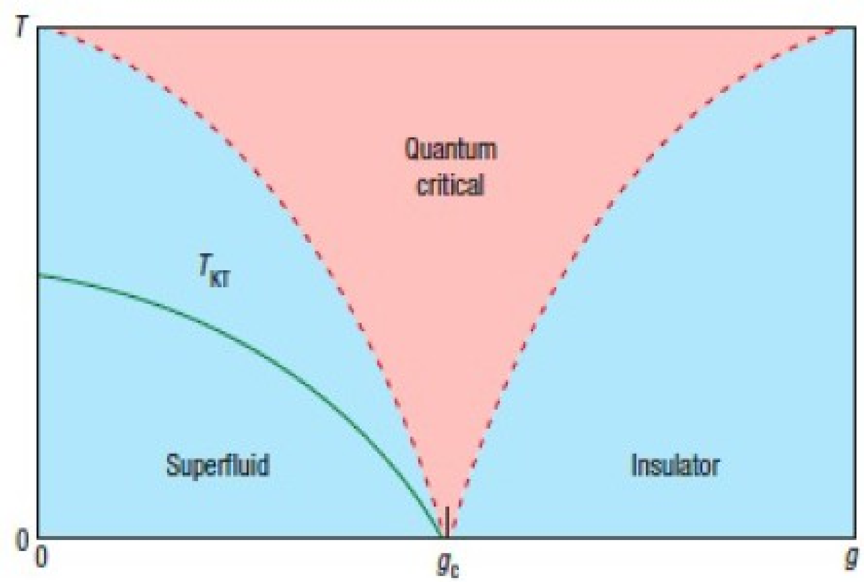
Entanglement entropy versus confinement

- EE as the measure of confinement , Klebanov,Kutasov,Muradyan -97
- Phase transition in QCD = Phase transition in EE, Sonnenshain et al, 2014
- The approach of Ryu-Takayanagi in nonconformal theories. Fine structure of the multiregion correlators
- EE and black hole horizon. Application to thermal QCD

Holographic Condensed Matter

- Kondo problem
- Holographic superconductivity
- Quantum phase transitions
- New phases of the matter
- Holographic formation of the Fermi surface
- Special point on the Fermi surface via holography (Weyl semimetals)

Typical phase dyagram in the (g,T) plane. It can be obtained via holography in AdS_4 + gauge field background



Temperature ----- black hole in the bulk
Chemical potential – asymptotics of the bulk gaige field

Spontaneously generated inhomogeneous ground states

With magnetic field:

Bolognesi, Tong; Donos, Gauntlett, Pantelidou; Jokela, Lifschytz, Lippert; Cremonini, Sinkovics; Almuhairi, Polchinski.

With Chern-Simons term at finite momentum:

Domokos, Harvey;

Helical phases: Nakamura, Ooguri, Park; Donos, Gauntlett

Charge density waves: Donos, Gauntlett; Withers;
Rozali, Smyth, Sorkin, Stang.

p-wave holographic superconductor

Einstein-Yang-Mills-Theory with $SU(2)$ gauge group

$$S = \int \mathrm{d}^5x \sqrt{-g} \left[\frac{1}{2\kappa^2} (R - 2\Lambda) - \frac{1}{4\hat{g}^2} F^a_{\mu\nu} F^{a\mu\nu} \right]$$

$$\alpha = \frac{\kappa_5}{\hat{g}}$$

Gauge field ansatz

$$A = \phi(r)\tau^3 \mathrm{d}t + w(r)\tau^1 \mathrm{d}x$$

$$\phi(r) \sim \mu + \dots \qquad w(r) \sim d/r^2$$

μ isospin chemical potential, explicit breaking $SU(2) \to U(1)_3$

condensate $d \propto \langle J^1_x \rangle$, spontaneous symmetry breaking

Anisotropic shear viscosity

$\eta_{yz}/s = 1/4\pi$; η_{xy}/s dependent on T and on α

Non-universal behaviour at leading order in λ and N

Viscosity bound preserved $\leftrightarrow$
Energy-momentum tensor remains spatially isotropic,
$T^{xx} = T^{yy} = T^{zz}$

Donos, Gauntlett 1306.4937

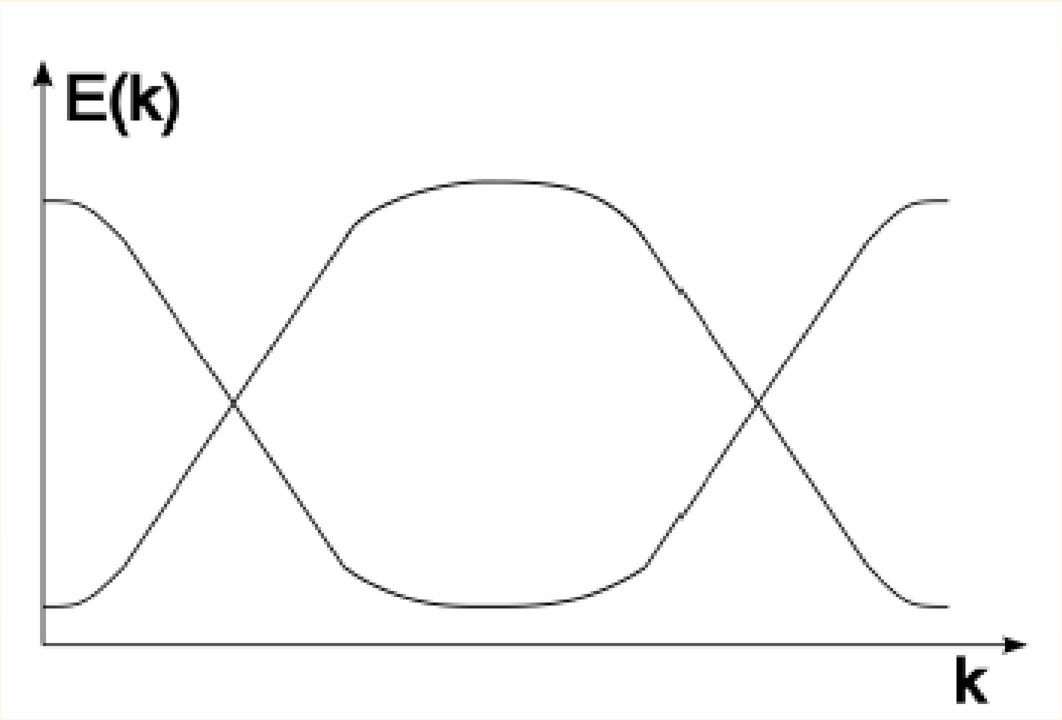
Violation of viscosity bound for

anisotropic energy-momentum tensor

Rebhan, Steineder 1110.6825

Further recent anisotropic holographic superfluids:

Jain, Kundu, Sen, Sinha, Trivedi 1406.4874;   Critelli, Finazzo, Zaniboni, Noronha 1406.6019



Band structure of Weyl semimetal

Holographic models for undoped Weyl semimetals
Umut Gursoy, Vivian Jacobs, Erik Plauschinn, Henk Stoof, Stefan Vandoren

Conclusion

- AdS\QCD — useful tool, like QCD sum rules
- Predict many nontrivial defects to be found in the lattice simulations
- To look for more complicated matching conditions for the theories on the different defects
- To say more on the hidden symmetries of the low energy sector in QCD
- A lot of applications to the condensed matter physics. New phases at strong coupling.