Some insights into the magnetic “QCD” phase diagram from the Sakai-Sugimoto model

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Twelfth Workshop on Non-Perturbative Quantum Chromodynamics, l’Institut d’Astrophysique de Paris, June 10-13, 2013

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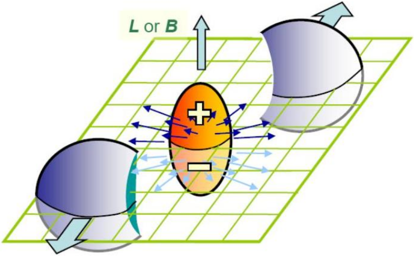
Overview

Overview

Why study strong magnetic fields?

- experimental relevance: appearance in QGP after a heavy ion collision (order $eB \sim 1 - 15 m_\pi^2$) (work of Skokov, Tuchin, Kharzeev, McLerran, Deng, Huang



- lifetime$_{\text{constant}B} \sim 10$ fm McLerran, Skokov, arXiv:1305.0774; Tuchin, arXiv:1305.5806 .
  lifetime$_{QGP} \sim 1 - 10$ fm $\rightarrow$ Incentive to take eB constant (ignoring "spatial decay" as well!))
- from a holographic viewpoint: interesting for comparison with recent lattice efforts

Why study strong magnetic fields?

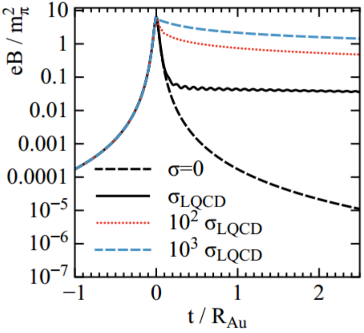


Figure : McLerran, Skokov, arXiv:1305.0774

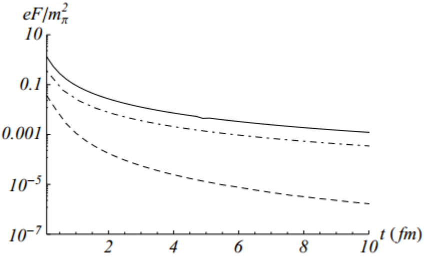
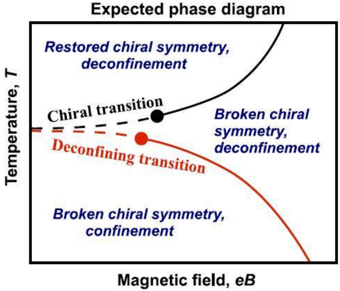


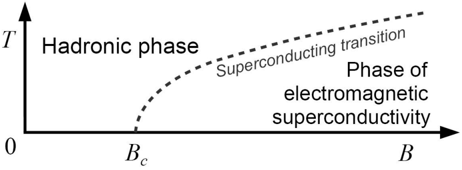
Figure : Tuchin, arXiv:1305.5806

Studied effects

- split between $T_c(eB)$ and $T_\chi(eB)$?



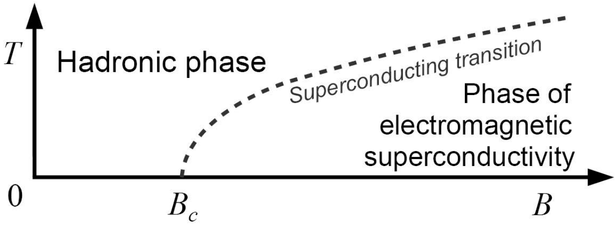
- ρ meson condensation?



ρ meson condensation

Studied effect: ρ meson condensation in vacuum ($T = 0$) (see: Chernodub, Van Doorsselaere, Verschelde; PRD85 (2012) 045002; Chernodub, PRL106 (2011) 142003, first suggestion made in Schramm, Muller, Schramm, MPLA7 (1992) 973, inspiration from Ambjorn, Olesen on *W*-condensation (80ies))

QCD vacuum instable towards forming a superconducting state of condensed charged ρ mesons at critical magnetic field eB_c



Small note: academic exercise ("hubris") since by the time ρ enters, *B* might have already (long) left...

ρ meson condensation: Landau levels

The energy levels ε of a free relativistic spin-s particle moving in a background of the external magnetic field $\vec{B} = B\vec{e}_z$ are the Landau levels

Landau levels

$$\varepsilon^2_{n,s_z}(p_z) = p_z^2 + m^2 + (2n - 2s_z + 1)|eB|.$$

Appropriate polarization combinations (spin $s_z = 1$ parallel to $\vec{B}$) can condense, since in the lowest energy state ($n = 0$, $p_z = 0$):

$$M_\rho^2(eB) = m_\rho^2 - eB,$$

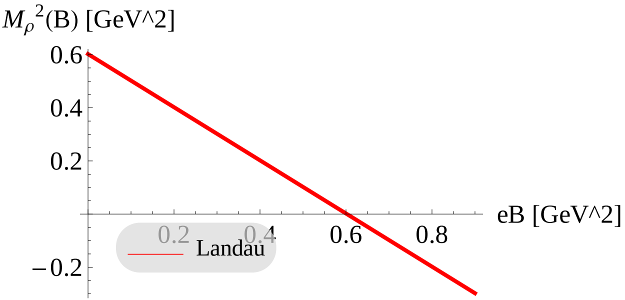
$\rightarrow$ tachyonic if the magnetic field is strong enough. Important: gyromagnetic ratio = 2!

ρ meson condensation: Landau levels

$$M_\rho^2(eB) = m_\rho^2 - eB,$$

$\Longrightarrow$ The fields ρ and $\rho^\dagger$ should condense at the critical magnetic field

$$eB_c = m_\rho^2.$$



ρ meson condensation

- phenomenological models: $eB_c = m_\rho^2 = 0.6\ \mathrm{GeV}^2$ (effective DSGS ρ-model, Chernodub, PRD82 (2010) 085011), $eB_c \approx 1\ \mathrm{GeV}^2$ (NJL) Chernodub, PRL106 (2011) 142003
- lattice simulation: $eB_c \approx 0.9\ \mathrm{GeV}^2$ Braguta et al, PLB718 (2012) 667
- $\rightsquigarrow$ holographic approach:
  - can the ρ meson condensation be modeled?
  - can this approach deliver new insights? e.g. taking into account strong magnetic effects on constituents ($\rightarrow$ ρ-substructure), effect on eB_c

Callebaut, Dudal, Verschelde, JHEP 1303 (2013) 033; work in progress

Overview

Holographic QCD

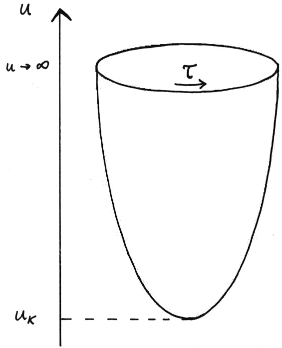
- **What is holographic QCD?**

"QCD" $\stackrel{dual}{=}$ (super)gravitation in a higher-dimensional background: $4D$ "QCD" "lives" on the boundary of a $5D$ space where the (super)gravitation theory is defined

- **Origin of the QCD/gravitation duality idea?**

AdS/CFT-correspondence (Maldacena 1997):
supergravitation in AdS_5 space $\stackrel{dual}{=}$ conformal $\mathcal{N}$=4 SYM theory

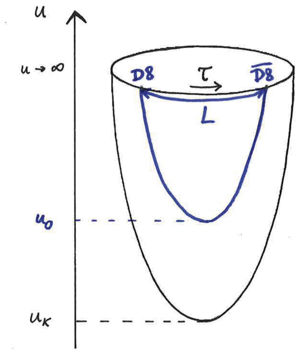
The D4-brane background



$$ds^2 = \left(\frac{u}{R}\right)^{3/2} \left(\eta_{\mu\nu} dx^\mu dx^\nu + f(u) d\tau^2\right) + \left(\frac{R}{u}\right)^{3/2} \left(\frac{du^2}{f(u)} + u^2 d\Omega_4^2\right),$$

$$e^\phi = g_s \left(\frac{u}{R}\right)^{3/4} \quad , \quad F_4 = \frac{N_c}{V_4} \varepsilon_4 \quad , \quad f(u) = 1 - \frac{u_K^3}{u^3} \; ,$$

The Sakai-Sugimoto model



$$ds^2 = \left(\frac{u}{R}\right)^{3/2}\left(\eta_{\mu\nu}dx^\mu dx^\nu + f(u)d\tau^2\right) + \left(\frac{R}{u}\right)^{3/2}\left(\frac{du^2}{f(u)} + u^2 d\Omega_4^2\right),$$

$$e^\phi = g_s\left(\frac{u}{R}\right)^{3/4}, \quad F_4 = \frac{N_c}{V_4}\varepsilon_4, \quad f(u) = 1 - \frac{u_K^3}{u^3},$$

The Sakai-Sugimoto model

- Flavour $\rightarrow N_f$ pairs of D8-$\overline{\text{D8}}$ flavour branes are added to the D4-brane background. Karch, Katz, JHEP 0206 (2002) 043
- Probe approximation $N_f \ll N_c$: backreaction of flavour branes on background is ignored $\sim$ quenched "QCD".
- Stack of N_f coinciding pairs of D8-$\overline{\text{D8}}$ flavour branes $\rightarrow$ $U(N_f)_L \times U(N_f)_R$ theory, to be interpreted as the chiral symmetry in QCD
- background geometry ($\cup$-shape) enforces "$L = R$" (joining of flavour branes): $U(N_f)_L \times U(N_f)_R \rightarrow U(N_f)_V$.

Sakai, Sugimoto, PTP113 (2005) 843; PTP114 (2005) 1083

The flavour gauge field

The $U(N_f)$ **gauge field** $A_\mu(x^\mu, u)$ that lives on the flavour branes describes **a tower of vector mesons** $v_{\mu,n}(x^\mu)$ in the dual QCD-like theory:

$U(N_f)$ gauge field

$$A_\mu(x^\mu, u) = \sum_{n\geq 1} v_{\mu,n}(x^\mu)\psi_n(u)$$

with $v_{\mu,n}(x^\mu)$ a tower of vector mesons with masses m_n, and $\{\psi_n(u)\}_{n\geq 1}$ a complete set of functions of u, satisfying the **eigenvalue equation**

$$u^{1/2}\gamma_B^{-1/2}(u)\partial_u\left[u^{5/2}\gamma_B^{-1/2}(u)\partial_u\psi_n(u)\right] = -R^3 m_n^2\psi_n(u),$$

Why use the Sakai-Sugimoto model

- the way it works:

dynamics of the flavour D8/$\overline{\text{D8}}$-branes: 5D YM theory $S_{DBI}[A_\mu] = \cdots$,
$A_\mu(x^\mu, u) = \sum_{n\geq 1} v_{\mu,n}(x^\mu)\psi_n(u)$

$\downarrow$ integrate out the extra radial dimension u

effective 4D meson theory for $v_\mu^n(x^\mu)$

- ideal holographic QCD model to study low-energy QCD
  - confinement and chiral symmetry breaking
  - effective low-energy QCD models drop out: Skyrme (π, also: baryons as skyrmions), HLS (π,ρ coupling), VMD

Approximations of the model

Duality is valid in the limit $N_c \to \infty$ and large 't Hooft coupling $\lambda = g_{YM}^2 N_c \gg 1$, and at low energies (where redundant massive d.o.f. decouple).

Approximations (inherent to the model):

- quenched approximation ($N_f \ll N_c$)
- chiral limit ($m_\pi = 0$, bare quark masses zero)

Choices of parameters:

- $N_c = 3$
- $N_f = 2$ to model charged mesons

How to turn on the magnetic field

A non-zero value of the flavour gauge field $A_m(x^\mu, z)$ on the boundary,

$$A_m(x^\mu, u \to \infty) = \overline{A}_\mu,$$

corresponds to an external gauge field in the boundary field theory that couples to the quarks

$$\overline{\psi} i \gamma_\mu D_\mu \psi \quad \text{with} \quad D_\mu = \partial_\mu + \overline{A}_\mu.$$

To apply an external electromagnetic field A_μ^{em}, put

$$A_\mu(u \to +\infty) = -iQ_{em}A_\mu^{em} = \overline{A}_\mu$$

How to turn on the magnetic field

To apply a magnetic field along the x_3-axis,

$$A_2^{em} = x_1 B,$$

in the $N_f = 2$ case,

$$Q_{em} = \begin{pmatrix} 2/3 & 0 \\ 0 & -1/3 \end{pmatrix} = \frac{1}{6}\mathbf{1}_2 + \frac{1}{2}\sigma_3,$$

we set

$$\overline{A}_\mu = -ieQ_{em}A_\mu^{em} = -ieQ_{em}x_1 B\delta_{\mu 2}$$

Overview

Plan

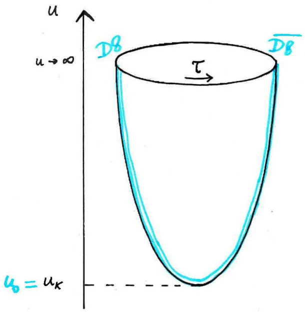
DBI action:

$$S_{DBI} = -T_8 \int d^4x \, 2\int_{u_0}^{\infty} du \int \varepsilon_4 \; e^{-\phi} \, \mathrm{STr}\sqrt{-\det\left[g_{mn}^{D8} + (2\pi\alpha')iF_{mn}\right]},$$

with

- $\mathrm{STr}(F_1 \cdots F_n) = \frac{1}{n!}\mathrm{Tr}(F_1 \cdots F_n + \text{all permutations})$ the symmetrized trace,
- $g_{mn}^{D8} = g_{mn} + g_{\tau\tau}(D_m\tau)^2$ the induced metric on the D8-branes (with covariant derivative $D_m\tau = \partial_m\tau + [A_m, \tau]$)
- $\tau =$ the brane embedding (+ fluctuations)

Simplest embedding to start: $u_0 = u_K$



1. Embedding trivial: $\partial_u \bar{\tau} = 0$ for all values of the magnetic field
2. Determine EOM for ρ_μ:
   - STr reduces to regular Tr (because of coincident branes)
   - $\tilde{A}_m$ and $\tilde{\tau}$ automatically decouple
   - $\tilde{A}_\mu = \rho_\mu(x)\psi(u)$ (retain only lowest meson of the tower, most likely to condense)

$$\mathcal{L}_{5D} = \int d^4x \int du \left\{ -\frac{1}{4} f_1 (F^a_{\mu\nu})^2 - \frac{1}{2} f_2 (F^a_{\mu u})^2 - \frac{1}{2} f_3 \sum_{\mu,\nu=1}^{2} \overline{F}^3_{\mu\nu} \varepsilon_{3ab} \tilde{A}^a_\mu \tilde{A}^b_\nu \right\}$$

EOM for ρ for $u_0 = u_K$

$$\mathcal{L}_{5D} = \int d^4x \int du \left\{ -\frac{1}{4} f_1 \underbrace{(F^a_{\mu\nu})^2}_{(\mathcal{F}^a_{\mu\nu})^2\psi^2} - \frac{1}{2} f_2 \underbrace{(F^a_{\mu u})^2}_{(\rho^a_\mu)^2(\partial_u\psi)^2} - \frac{1}{2} f_3 \sum_{\mu,\nu=1}^{2} \overline{F}^3_{\mu\nu}\varepsilon_{3ab} \underbrace{\tilde{A}^a_\mu \tilde{A}^b_\nu}_{\rho^a_\mu\rho^b_\nu\psi^2} \right\}$$

demand $\int du\, f_1\psi^2 = 1$ and $\int du\, f_2(\partial_u\psi)^2 = m^2_\rho$, then $\int du\, f_3\psi^2 = k$

$$\Rightarrow \mathcal{L}_{4D} = \int d^4x \left\{ -\frac{1}{4}(\mathcal{F}^a_{\mu\nu})^2 - \frac{1}{2} m^2_\rho (\rho^a_\mu)^2 - \frac{1}{2} k \sum_{\mu,\nu=1}^{2} \overline{F}^3_{\mu\nu}\varepsilon_{3ab}\rho^a_\mu\rho^b_\nu \right\}$$

(with $\mathcal{F}^a_{\mu\nu} = D_\mu\rho^a_\nu - D_\nu\rho^a_\mu$)

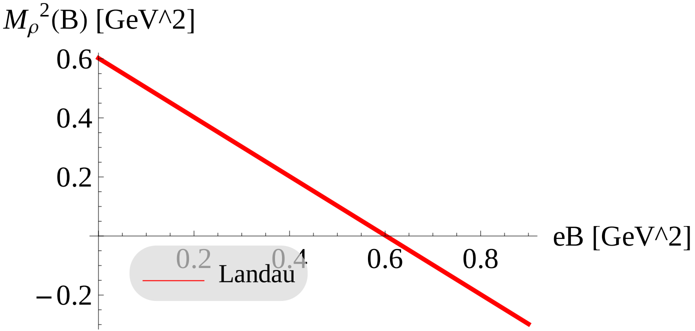
standard 4D Lagrangian for a vector field in an external EM field

Landau levels for Sakai-Sugimoto $u_0 = u_K$

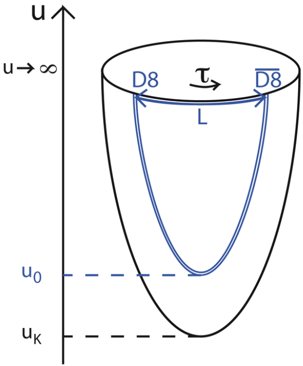
Standard 4D Lagrangian for a vector field in an external EM field with $k = 1$ ($\Leftarrow f_3 = f_1$)

$\rightsquigarrow$ Landau levels and

$$M_\rho^2(eB) = m_\rho^2 - eB$$



General embedding $u_0 > u_K$



$u_0 > u_K$ to model non-zero constituent quark mass which is related to the distance between u_0 and u_K.

Aharony, Sonnenschein, Yankielowicz, Ann.Phys.322 (2007) 1420

Numerical fixing of holographic parameters

There are three unknown free parameters (u_K, u_0 and $\kappa(\sim \lambda N_c)$).
In order to get results in physical units, we fix the free parameters by matching to

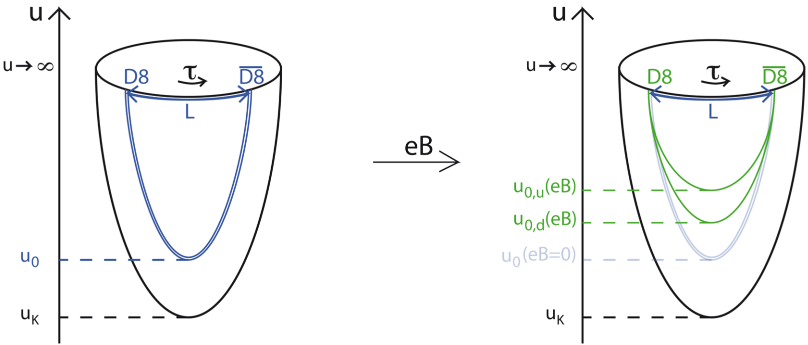
- the constituent quark mass $m_q = 0.310$ GeV,
- the pion decay constant $f_\pi = 0.093$ GeV and
- the ρ meson mass in absence of magnetic field $m_\rho = 0.776$ GeV.

Results:

$$u_K = 1.39 \text{ GeV}^{-1}, \quad u_0 = 1.92 \text{ GeV}^{-1} \text{ and } \quad \kappa = 0.00678$$

- cross-check: "QCD" string tension $\sigma \approx 0.18 \text{ GeV}^2$ (= standard lattice estimate)

eB-dependent embedding for $u_0 > u_K$



Keep L fixed: $u_0(eB)$ rises with eB. This models magnetic catalysis of chiral symmetry breaking Johnson, Kundu JHEP0812 (2008) 053; in general: Miransky et al.

Non-Abelian: $u_{0,u}(eB) > u_{0,d}(eB)$! $U(2) \to U(1)_u \times U(1)_d$

eB-dependent embedding for $u_0 > u_K$

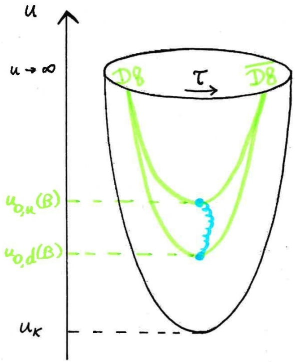
Change in embedding models:

- chiral magnetic catalysis $\Rightarrow m_u(eB)$ and $m_d(eB) \nearrow$
- eB explicitly breaks global $U(2) \to U(1)_u \times U(1)_d$

Effect on ρ mass?

- expect $m_\rho(eB) \nearrow$ as constituents get heavier
- split between branes generates other mass mechanism: 5D gauge field gains mass through holographic Higgs mechanism

eB-induced Higgs mechanism



The string associated with a charged ρ meson ($\overline{u}d$, $\overline{d}u$) stretches between the now separated up- and down brane ⇒ because a string has tension it contributes to the mass.

EOM for ρ for $u_0 > u_K$?

Non-trivial embedding

$$\bar{\tau}(u) = \begin{pmatrix} \bar{\tau}_u(u)\theta(u-u_{0,u}) & 0 \\ 0 & \bar{\tau}_d(u)\theta(u-u_{0,d}) \end{pmatrix} \not\propto \mathbf{1},$$

describing the splitting of the branes, utterly complicates the analysis (but necessary for a realistic modeling!).

$$\mathcal{L}_{5D} = \mathrm{STr}\Big\{ ..\left([\tilde{A}_m,\bar{\tau}] + D_m\tilde{\tau}\right)^2 + ..(F_{\mu\nu})^2 + ..(F_{\mu u})^2 + ..\overline{F}_{\mu\nu}[\tilde{A}_\mu,\tilde{A}_\nu] \\ + ..(\partial_u\bar{\tau})\overline{F}\left([\tilde{A},\bar{\tau}] + D\tilde{\tau}\right)F \Big\}$$

with all the .. different functions $\mathcal{H}(\partial_u\bar{\tau},\overline{F};u)$ of the background fields $\partial_u\bar{\tau}$, $\overline{F}$.

STr-prescription

Myers, JHEP 9912 (1999) 022; Denef, Sevrin, Troost, Nucl.Phys. B581 (2000) 135

- STr $=$ symmetric average over all orderings of F_{ab}, $D_a\phi^i$, $[\phi^i,\phi^j]$ and the individual non-Abelian scalars ϕ^k appearing in the non-Abelian Taylor expansions of the background fields.

$$STr\left(\mathcal{H}(\overline{F})\tilde{F}^2\right) = -\frac{1}{2}\sum_{a=1}^{2}\tilde{F}_a^2 \;\; I(\mathcal{H}) + \sum_{a=0,3}\cdots$$

with

$$I(\mathcal{H}) = \frac{\int_0^1 d\alpha\mathcal{H}(F_0+\alpha F_3) + \int_0^1 d\alpha\mathcal{H}(F_0-\alpha F_3)}{2}$$

- The integral functions $I(\mathcal{H})$ are complicated functions of eB and u, even discontinuous in u (at $u = u_{0,u}$).

STr-prescription

After many pages of computations (analytical + numerical)

EOM for ρ for $u_0 > u_K$

$$\mathcal{L}_{5D} = \int d^4x \int du \left\{ -\frac{1}{4} f_1(eB) \underbrace{(F^a_{\mu\nu})^2}_{(\mathcal{F}^a_{\mu\nu})^2\psi^2} - \frac{1}{2} f_2(eB) \underbrace{(F^a_{\mu u})^2}_{(\rho^a_\mu)^2(\partial_u\psi)^2} \right.$$

$$\left. -\frac{1}{2} f_3(eB) \sum_{\mu,\nu=1}^{2} \overline{F}^3_{\mu\nu}\varepsilon_{3ab} \underbrace{\tilde{A}^a_\mu \tilde{A}^b_\nu}_{\rho^a_\mu\rho^b_\nu\psi^2} - \frac{1}{2} f_4(eB) \underbrace{(\tilde{A}^a_\mu)^2}_{(\rho^a_\mu)^2\psi^2} (\overline{\tau}^3)^2 \right\}$$

demand $\int du\ f_1(eB)\psi^2 = 1$ and $\int du\ f_2(eB)(\partial_u\psi)^2 + f_4(eB)(\overline{\tau}^3)^2\psi^2 = m^2_\rho(eB)$, then $\int du\ f_3(eB)\psi^2 = k(eB) \neq 1 (\Leftarrow f_3(eB) \neq f_1(eB))$

$$\Rightarrow \mathcal{L}_{4D} = \int d^4x \left\{ -\frac{1}{4}(\mathcal{F}^a_{\mu\nu})^2 - \frac{1}{2} m^2_\rho(eB)(\rho^a_\mu)^2 - \frac{1}{2} k(eB) \sum_{\mu,\nu=1}^{2} \overline{F}^3_{\mu\nu}\varepsilon_{3ab}\rho^a_\mu\rho^b_\nu \right\}$$

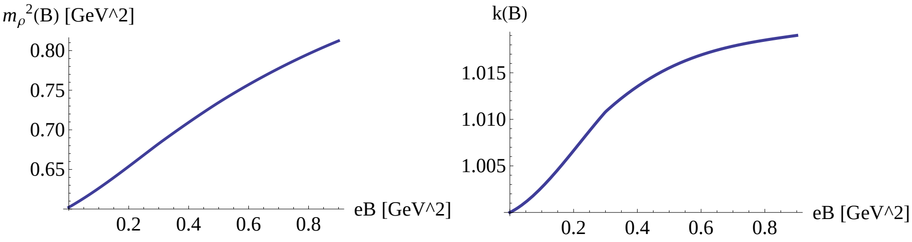
modified 4D Lagrangian for a vector field in an external EM field, with *eB*-dependent gyromagnetic coupling!

Solve the eigenvalue problem

The normalization condition and mass condition on the ψ combine to the eigenvalue equation

$$f_1^{-1}\partial_u(f_2\partial_u\psi) - f_1^{-1}f_4(\bar{\tau}_3)^2\psi = -m_\rho^2\psi$$

with b.c. $\psi(x=\pm\pi/2)=0, \psi'(x=0)=0$
which we solve with a numerical shooting method to obtain $m_\rho^2(eB)$.

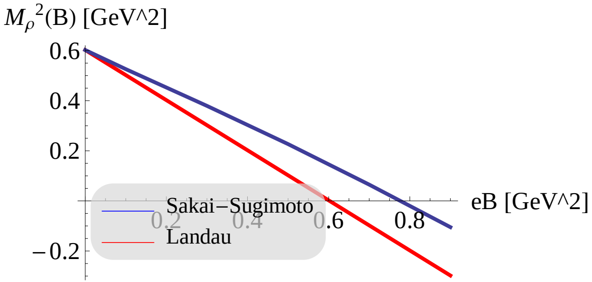


Landau vs Sakai-Sugimoto $u_0 > u_K$

Modified 4D Lagrangian for a vector field in an external EM field with $k(eB) \neq 1 (\Leftarrow f_3(eB) \neq f_1(eB))$

$\rightsquigarrow$ modified Landau levels and, with $\xi = \frac{eB}{m_\rho^2(eB)}$, Tsai, Yildiz PRD4 (1971) 3643; Obukhov et al, Theor.Math.Phys. 55 (1983) 536

$$M_\rho^2(eB) = m_\rho^2(eB) - eB + (1 - k(eB)) m_\rho^2(eB) \left(\frac{\xi^2}{2} + \xi\sqrt{1 - \xi + \frac{\xi^2}{4}} \right)$$



Summary ρ meson

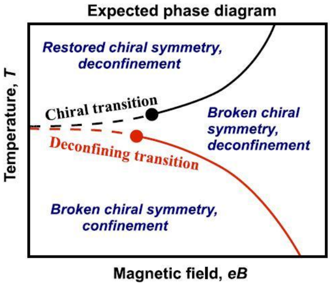
Studied effect: possibility for ρ meson condensation

- phenomenological models: $eB_c = m_\rho^2 = 0.6\ \text{GeV}^2$
- lattice simulation: slightly higher value of $eB_c \approx 0.9\ \text{GeV}^2$
- $\rightsquigarrow$ holographic approach:
  - can the ρ meson condensation be modeled? yes
  - can this approach deliver new insights? e.g. taking into account constituents, effect on eB_c
    Up and down quark constituents of the ρ meson can be modeled as separate branes, each responding to the magnetic field by changing their embedding. This is a modeling of the chiral magnetic catalysis effect. We take this into account and find also a string effect on the mass, leading to a $eB_c \approx 0.78\ \text{GeV}^2$

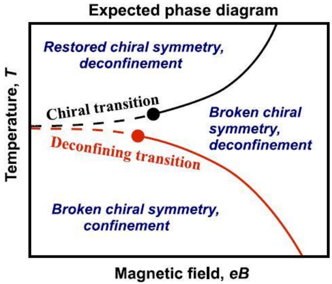
Overview

Chiral temperature

$T_\chi =$ temperature at which chiral symmetry is restored (chiral limit is understood)
Studied effect: possible split between $T_c(eB)$ and $T_\chi(eB)$



Split between T_c and T_χ

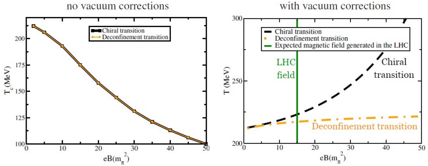


Expected behaviour (Fig from '08):

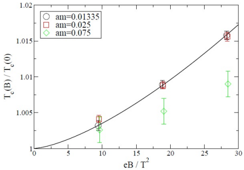
- $T_\chi(eB) \nearrow$: "chiral magnetic catalysis" seen in chirally driven models (e.g. NJL) Miransky,Shovkovy, PRD66 (2002) 045006
- $T_c(eB) \searrow$: quark gas thermodynamically favoured over pion gas (e.g. MIT bag) Agasian, Fedorov, PLB663 (2008) 445; Fraga, Palhares, PRD86 (2012) 016008; Fukushima, Hidaka, PRL110 (2013) 031601

Some results in different models

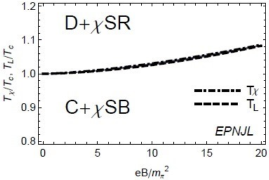
PLSM_q model Mizher, Chernodub, Fraga, PRD82 (2010) 105016

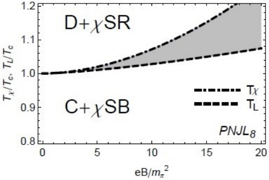


Lattice D'Elia, Mukherjee, Sanfilippo, PRD82 (2010) 051501

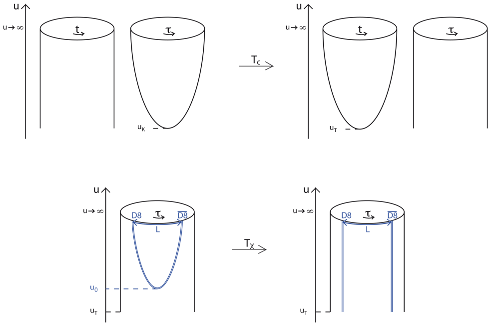


Different PNJL models Gatto, Ruggieri, PRD82 (2010) 054027; PRD83 (2011) 034016





Sakai-Sugimoto at finite temperature



"Black D4-brane background"

$$ds^2 = \left(\frac{u}{R}\right)^{3/2}\left(\hat{f}(u)dt^2 + \delta_{ij}dx^i dx^j + d\tau^2\right) + \left(\frac{R}{u}\right)^{3/2}\left(\frac{du^2}{\hat{f}(u)} + u^2 d\Omega_4^2\right)$$

$$\hat{f}(u) = 1 - \frac{u_T^3}{u^3}, \quad u_T \sim T^2$$

Numerical fixing of holographic parameters

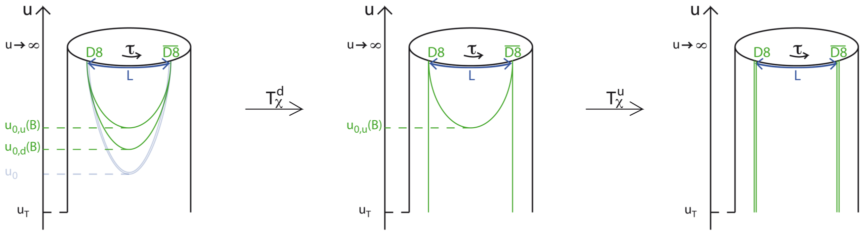
Input parameters at $eB = 0$ $f_\pi = 0.093$ GeV and $m_\rho = 0.776$ GeV fix all holographic parameters except “brane separation” L.

Choice of L a priori free, determines a kind of choice of holographic theory:

- L small $\sim$ NJL-type boundary field theory Antonyan, Harvey, Jensen, Kutasov, hep-th/0604017
- $L = \delta\tau/2$ maximal $\sim$ maximal probing of the gluon background (original antipodal Sakai-Sugimoto)

Sakai-Sugimoto at finite T and eB

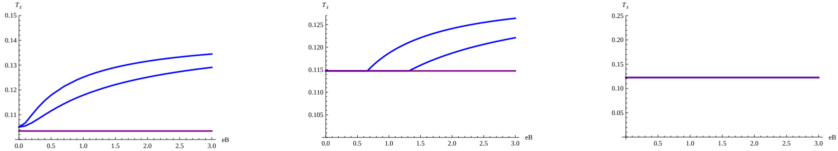
- no backreaction $\Rightarrow$ T_c independent of eB
- eB-dependent embedding of flavour branes $\Rightarrow$ $T_\chi(eB)$:



$$S_{merged} - S_{separated} = 0 \quad \Rightarrow \quad T_\chi$$

Conclusion on $T_\chi(eB)$

The appearance of a split between T_χ (GeV) (blue) and T_c (GeV) (purple) depends on the choice of L!



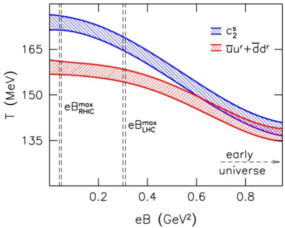
Plots for fixed L (from small to large) respectively corresponding to $m_q(eB=0)=0.357, 0.310$ and 0.272 GeV and $T_c = 0.103, 0.115$ and 0.123 GeV Callebaut, Dudal, PRD87 (2013)106002

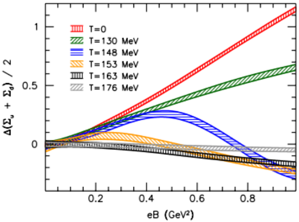
- Left: split for L small enough $\sim$ NJL results
- Middle and right: split only at large eB or no split at all for parameter values that match best to QCD $\sim SU(2), N_f = 2$ (chirally extrapolated) lattice data of Ilgenfritz et al, PRD85 (2012) 114504 (no split)

(Locally) Inverse magnetic catalysis

BIG BUT

Latest lattice data disagree with most previous results: $T_\chi(eB) \searrow$





→ quenched vs. true QCD

Bali, Bruckmann, Endrodi, Fodor, Katz, Krieg, Schafer, Szabo, JHEP 1202 (2012) 044; Phys.Rev. D86 (2012) 071502

Important task for future holographs: construct a “magnetized bulk geometry” that is sufficiently QCD-like

Fin

Merci!