Higgs-like scalars from non-perturbative Yang-Mills dynamics

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Motivation

Conference is focused on Higgs fields, for obvious reasons

Also very appropriate in view of the role of Sakata
in solving mysteries of the first-ever (pseudo)scalar
and his search for further scalars

Dynamical Higgs, associated with new strong interactions
is an alternative to the SM

Usually QCD lessons on $\bar{q}q$ states
are used in this connection

We will consider confinement-related scalars, in pure YM.
Much less studied. Might be closer to the Higgs dynamics
and interesting also on their own

Reservations on Higgs-implications

- No immediate suggestions for an SM Higgs
  Consider only dynamics in a broad context
- the Yang-Mills dynamics in the scalar sector
  is highly non-trivial, might be potentially important
  But rather exotic to apply straightforwardly
- Roughly speaking, the Higgs condensates are there but massless phases are not

Why Yang-Mills scalars at all?

Dual-superconductor model of confinement
For monopoles placed into a superconductor

$$\lim_{r \to \infty} V_{M\bar{M}}(r) \sim < \phi_{G-L} >^2 r$$

There is an explicit solution, Abrikosov string

By analogy,

$$\lim_{r \to \infty} V_{Q\bar{Q}}(r) = \sigma \cdot r$$

$$\sigma \sim < \Phi_M >^2$$

where Φ_M is magnetically charged 4d scalar

Dual-superconductor idea is most popular way of thinking about confinement for about 30 years

Explicit $U(1)$ examples known since long and boosted greatly by the Seiberg-Witten papers

However, it is not clear at all, what are the magnetic degrees of freedom
to be condensed in the non-Abelian
case we are interested in.

Very rich lattice phenomenology but mostly in specific lattice language
We will use the data interpreted in continuum terms, without explaining

Low-viscosity Quark-gluon plasma

Probably, at $T > T_c$ confinement problem becomes "low-viscosity-plasma"problem.
$\Delta E \cdot \Delta t \sim 1$+holography $\rightarrow$ Kovtun-Son-Starinets bound:

$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

where η is viscosity, s is entropy density

The actual plasma is only factor-of-order-unit away:

$$\left(\frac{\eta}{s}\right)_{QGP} \approx \frac{1}{4\pi}$$

Superfluid-component scenario is therefore encouraged
(not granted of course)

Relativistic superfluidity and scalars

Non-relativistically, there is identical-particles wave function:

$$\Psi_{superfluid} \sim \sqrt{N} \exp \; i\phi(x,t)$$

$$\partial_t \phi(x,t) = \mu, \quad (\partial_i)^2 \phi(x,t) = 0$$

(μ is the chemical potential)

Relativistically, no wave function. Instead, postulate, an extra 4d conserved current and

$$< \phi_{3d} > \neq 0 \; , \quad \phi^*_{3d} \neq \phi_{3d}$$

Spontaneous breaking implies 3d Nambu-Goldstone particle needed for superfluidity

Thermal scalar (1986)

Scalar particles do arise within stringy models of QCD. First example discovered is the thermal scalar

For strings, number of states grows fast with mass and at temperature $T_H \sim \Lambda_{QCD}$ the sum over states diverges, Hagedorn phase transition.
If $T \to T_H$, $T < T_H$ the whole partition function reduces to that of a static scalar with mass:

$$m_\beta^2 = \frac{(\beta - \beta_H)\beta_H}{(2\pi^2)(\alpha')^2}$$

$\beta = 1/T$, $\beta_H = 1/T_H$. Hits the Higgs region at $T = T_H$. This Higgs-like instability is equivalent to Hagedorn instability due to heavy stringy states

Another language for the massless scalar

In Euclidean picture, time τ is periodic,

$$\tau \sim \tau + 1/T$$

The thermal scalar then is once-wrapped mode. Time dependence is fixed by periodicity – lives in spatial dims

Most important: wrapping number is a new, topological stringy quantum number. Condensation of the thermal scalar at $T > T_c$ would spontaneously break a 3d U(1) symmetry, as needed for superfluidity.

Possible condensation of the thermal scalar at $T > T_c$ has been discussed in many papers, with varied conclusions

Conclusions to introductory remarks

- Spontaneously broken, non-pert U(1) symmetries,
  both 4d and 3d are welcome,
  to explain confinement and low viscosity $(*)$, resp.
- The only example relevant seems to be thermal scalar,
  or stringy topological quantum numbers
  Will try to exploit stringy models through the talk

$(*)$*Not a common viewpoint*

Confinement-related geometry (W-S-S model)

Deforming the N=4 SUSY YM one gets theory
in the same universality class in infrared
as ordinary, large N_c, YM

Geometry: begin with ordinary 4d
+ 5th dimension with (common in holography) properties:

1. conjugated to inverse momentum.
2. The 4d world is the UV limit, ($u \to \infty$)
3. there is horizon, $u > u_h$, confinement-related

Extra compact dimension

Central point: there is extra compact, x_4 dim

$$ds^2 = \left(\frac{u}{R}\right)^{3/2}\left(f(u)dx_4^2 - dt^2 + \delta_{ij}dx^i dx^j\right) +$$
$$+\left(\frac{u}{R}\right)^{-3/2}\left(\frac{du^2}{f(u)} + u^2 d\Omega_4^2\right)$$

$$f(u) = (1 - u_h^3/u^3) \quad , x_4 \sim x_4 + \beta_4, \qquad \beta_4 = 4\pi/3(R^3/u_h^3)$$

x_4 coordinate survives in the ultraviolet, does not fit reality, limits the applicability of the model to distances d

$$d \gg \beta_4$$

Finally, the 4-sphere, $d\Omega_5^2$,
is relevant to baryons and does not concern us here

Cigar-shape geometries, phase transition

At $T < T_c$ cigar-shape in the (u, x_4) coordinates:

$$R_4(u = u_h) \ = 0$$

For compact $(T \neq 0)$ Euclidean time, τ cylinder-like geometry

$$R_\tau(u) = const$$

At phase transition the geometries are interchanged:

$$R_\tau(u = u_h) \ = 0 \qquad\qquad R_4(u) = const$$

Cigar-shape geometry in (u, τ) coordinates

Defects

In YM field theory, in practice

(*nonperturbative physics*) $\approx$ (*physics of instantons*)

In the stringy formulation, there are various D-branes, stable topologically if wrapped on compact dimensions

nonperturbative physics is physics of lower dim.defects

much richer than in field theoretic formulation

In particular, instantons are D0 branes wrapped on x_4 circle. That, is

wrapping around x_4 responsible for the θ-dependence

Geometry and vanishing actions

Signs of cigar-shape is similar to thermal scalar:
vanishing $R_4(R_\tau) \to$ defect's mass/tension vanishes

$T < T_c$:
all $x_4 -$ *wrapped branes are tensionless in this approx.*

$T > T_c$:
all $\tau -$ *wrapped branes are tensionless in this approx.*
Similar to the thermal scalar (static)

Some defects percolate to infinity, or condense
D2 branes, wrapped on x_4 are identified as magnetic strings which can be open on the 't Hooft line

D2 condensation implies no confinement for the external monopoles

Life at distances $d \gg \Lambda_{QCD}^{-1}$

We have restriction, $d \ \gg \ \beta_4 \ \sim \ \Lambda_{QCD}^{-1}$

No hadron-spectrum physics survives at such distances, but confinement and plasma are there. Also massless particles, if exist.

Also, the defects survive. Worth emphasizing that usually defects action exponentially suppressed at large N_c. We assume action of order $N_c \cdot 0$ to still vanish. The geometry is borrowed from large N_c.

From Euclidean 4d to 3d

According to the theory considered,
Non-perturbative physics becomes 3d at $T = T_c$
since defects are becoming wrapped on τ

The phenomenon is well known in the limit of high temperature, $T \to \infty$ as dimensional reduction. Here, the dimensional reduction is predicted to happen sharply at $T = T_c$ (Gorsky et al) For not large N_c the transition is smoother.

In particular, magnetic strings are expected to look in τ-direction and geometrically reduce to their 3d projection, 1d defects, or particles

Conclusions to holographic models

- suggest condensation of topologically charged magnetic strings below T_c as confinement mechanism
- thus, physics of confinement is rather physics of strings, not field theory
- Euclidean-time oriented defects above T_c
- suggest condensation of scalars above T_c.
  (probably) back to field theory

Condensation of strings. Hints from the lattice

In the absence of theory, the only source is lattice.
Remarkable results (pure numerical, though):

Condensation of strings has been observed on the lattice

Turns equivalent to a single scalar living on a string:

$$(condensation\ of\ strings)\ \equiv <|\phi_M|^2> \sim\ \Lambda^2_{QCD}$$

$$<\phi_M>^2 \sim\ \Lambda^3_{QCD}\cdot a,\ <\phi_M>_{continuum} = 0$$

and vanishes, although at any finite lattice spacing a suffices to produce confinement (!)

Condensation of magnetic strings, cn'd

In field theory one would have instead

$$< \phi^2 > \sim \ a^{-2} \qquad < \phi >^2 \sim \ \Lambda^2_{QCD}$$

That is, strings are 'milder' by two dimensions

Vanishing of $< \phi_M >$, $< \phi_M > \sim \ (a\Lambda_{QCD})^{1/2}$
opens the possibility

$$\frac{< \phi_M >}{\Lambda_{QCD}} \ll \ 1$$

upon inclusion of (say, e-m) corrections.

At $T > T_c$ strings become time-oriented and condensation of strings becomes condensation of a 3d scalar (observed)

Effective 3d scalars at $T > T_c$

At $T > T_c$ we expect to deal with a field theory, which is easier for theory than strings

Begin with Euclidean time and assume condensation of thermal scalar
Then static correlator of components of energy-mometum tensor has a singularity:

$$< T_{0i}, T_{0k} >_{\mathbf{q}\to 0,\omega\equiv 0} \sim \frac{q_i q_k}{q^2} < \phi_{3d} >^2$$

Such a behaviour is the standard symptom of superfluidity (continuation to Minkowski is trivial for a static correlator)

Action of 3d defects

Another input is the action for 3d defects in Euclidean:

$$S_E = -T \int d\tau d^3x \sqrt{1 + (\partial_i \phi)^2}$$

where the minus sign is due to condensation (similar to supercritical phase in percolation theory). The meaning of ϕ is the extra fluctuating coordinate (τ).

Now we are set to continue to the Minkowski space (where plasma lives)

An exotic liquid

Luckily enough, liquid holographic dual to the Rindler space was found recently (Compere et al 1103.3022). It was shown that in in the dissipation-less approx. the liquid properties are reproduced by the action

$$S_M = (const) \int d^4x \sqrt{-\gamma}\sqrt{-(\partial_\mu \phi)^2}$$

where metric $\gamma_{ab} dx^a dx^b \equiv -r_c dt^2 + dx_i^2$ (r_c is a parameter) with the ground-state solution

$$\phi_{equilibrium} = t$$

One can readily check that this action can be considered as the Minkowskian counterpart to our Euclidean construction

Exotic liquid (cn'd)

Equilibrium energy-momentum tensor looks as

$$\left(T_{ab}\right)_{equilibrium} = (0, p, p, p)$$

($p = 1/\sqrt{r_c}$) and we note that it is the same as for the liquid living on the stretched horizon (r_c is then small)

Moreover, the "Einstein-Navier duality"allows also to find

$$\left(\frac{\eta}{s}\right) = \frac{1}{4\pi}$$

Thus, our non-perturbative component of plasma appears to be close in properties to black-hole liquid

Partial check on the lattice

The only relevant measurement on the lattice

$$(\epsilon - 3p)_{non-pert} \; < \; 0$$

and large,

$$|(\epsilon - 3p)_{non-pert}| \; \approx \; 4 \cdot (\epsilon - 3p)_{total}$$

although occupies a tiny fraction of the whole volume

That is, rather in agreement with theory

Conclusions on condensates properties

- Both 4d and 3d condensates seem to exist and relevant to the confinement and low viscosity of YM plasma
- theoretical guesses tend to agree with the lattice measurements. Especially, in the much better studied case of $T = 0$

Absence of massless excitations

A generic manifestation of extra dimensions is massless excitations living on the brane (the Luscher term is a well known example)

More specifically, found massless 3d scalar at $T > T_c$ manifested in the correlator of the momentum components and present in the action derived from duality

Similarly, at $T = 0$ could expect massless 4d scalar coupled to topological K_μ current

None is there

Nonperturbative component and unitarity

At closer look, the 3d scalar turns superluminal
with respect to the perturbative vacuum
and is not carried on to the full theory

The 4d scalar would be ghost-like
(Since non-pert effects lower the energy of the vacuum)

In other words, the non-pert component is non-unitary by itself and is incomplete in this sense even in the infrared.

Wrong-sing correlators

Some correlators have wrong sign non-perturbatively
Still, the wrong-sign contribution survives as a local term
In full theory

$$< G\tilde{G}(x), G\tilde{G}(0) >_{full\ \ theory} < \ 0, \quad x_{Euclidean} \neq 0$$
$$< G\tilde{G}(x), G\tilde{G}(0) >_{non-pert} < \ 0, \quad x_{Euclidean}$$

As a result, the non-pert term squeezed to $\delta^4(x)$ but still controls the integral over d^4x (topological susceptibility)
The story seems to be repeated in case of
$< T_{0i}(x), T_{0k}(0) >$ correlator

Overall conclusions

- Stringy holography fits well lattice phenomenology
- Condensates associated with nonperturbative scalars, 4d and 3d, seem to exist and exhibit exciting properties
- Associated with the condensation massless excitations are not observed. Non-perturbative physics cannot be treated as an independent component in this respect
- Wrong-sign nonperturbative contributions to correlator seem to squeeze to local terms and continue to control integrals