Strong Dynamics at the TeV for the hierarchy problem

Alex Pomarol, UAB & IFAE (Barcelona)
Why Strong Dynamics at $\Lambda \sim \mathrm{TeV}$?

To explain why $m_H \ll M_P \sim 10^{19}$ GeV

As in QCD:

Expects why $\Lambda_{QCD} << M_P$ and the origin of most hadron masses
Why Strong Dynamics at $\Lambda \sim \text{TeV}$?

To explain why $m_H \ll M_P \sim 10^{19}$ GeV

As in QCD:

It could explain why $m_H \lesssim \Lambda_* \sim \text{TeV} \ll M_P$

New strong dynamics at TeV

Composite Higgs
Why Strong Dynamics at $\Lambda \sim \text{TeV}$?

To explain why $m_H \ll M_P \sim 10^{19}$ GeV

As in QCD:

More generically: we need a theory quasi-conformal ($\text{CFT}_4 \leftrightarrow \text{AdS}_5$)

New strong dynamics at TeV

It could explain why $m_H \lesssim \Lambda_* \sim \text{TeV} \ll M_P$

Composite Higgs
Dealing with strong dynamics....

Beyond the lamp-post:

perturbation theory

Strong dynamics
We can well-define the UV theory:
- gauge-symmetry
- + matter content

E.g. $\text{SU}(N) + N_F q_{R,L}$

Dealing with strong dynamics....
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Questions posed to strong dynamics can be addressed by an $AdS_5$
predictive theories!
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...but we do not know the predictions at the IR.

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Lattice can help here

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Dealing with strong dynamics....

We can well-define the UV theory: gauge-symmetry + matter content
e.g. SU(N) + N_F q_{R,L}

...but we do not know the predictions at the IR

.string theory can help here

Holography

Questions posed to strong dynamics can be addressed by an AdS_5 predictive theories!

Lattice can help here
plausible scenario of strong dynamics at the TeV

But not a well-defined & complete model!
(like the MSSM in the susy approach)

Nevertheless, it has provided a characterization of the expected signals (needed to be searched for)
The simplest possibility

= copy of QCD at the TeV

 règle out: light Higgs exists!

Why Nature didn’t use such a simple mechanism for EWSB?

Big mystery…Nature likes to be original?

Fermion masses? \( \mathcal{L}_{\text{bil}} \sim \bar{f}_i O_H f_j \) e.g. \( O_H \sim \bar{\psi}\psi \)

rule out: light Higgs exists!

small masses: perfect, except for the top!

Why there is a quark so heavy in Nature?
Attempt II
The Higgs, the lightest of the new strong resonances, as pions in QCD: they are Pseudo-Goldstone Bosons (PGB).
Inspiration from holography

$G$ gauge theory
in a $\text{AdS}_5$ throat

$$ds^2 = \frac{L^2}{z^2} [dx^2 + dz^2]$$

Holo. coordinate $z \sim 1/E$

hard/soft wall

Mass gap $\sim \text{TeV}$

Symmetry: $\mathcal{H}$

Breaking of symmetry by boundary conditions

Agashe, Contino, A.P.
Inspiration from holography

\[ \psi(z) \]

\[ \text{AdS}_5 \]

\[ \text{1st & 2nd family} \]

\[ \text{3rd family} \]

Mass gap \( \sim \) TeV

Symmetry: \( \mathcal{H} \)

Breaking of symmetry by boundary conditions

Simple geometric approach to fermion masses

Agashe, Contino, A.P.
Using the AdS/CFT dictionary:

linear-mixing: \[ \mathcal{L}_{\text{lin}} = \epsilon f_i \bar{f}_i \mathcal{O}_{f_i} \]

For the top, we need large mixing:
\[ \text{dim}[\mathcal{O}_{\text{top}}] \sim 5/2 \] needed!

Exist gauge theories with this property?
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Exist gauge theories with this property?

e.g. **SU(4) strong sector**

Fermions \( \{ \text{three, five} \} \)

\( \Psi_{L,R} \in 4 \) (fundamental)

\( \gamma \in 6 \) (antisym. matrix)

Global symmetry:

\[ G = SU(5) \times SU(3) \times SU(3)' \times U(1)_X \times U(1)' \]

\[ H = SO(5) \times SU(3)_{\text{color}} \times U(1)_X \]

Operator that can be coupled to the top

arXiv:1502.00390
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\[ \Psi_{L,R} \in 4 \text{ (fundamental)} \]

\( \Upsilon \in 6 \text{ (antisym. matrix)} \)

\[ \Psi \Upsilon \Psi = \mathcal{O}_{\text{top}} \]

Operator that can be coupled to the top

Dimension at weak coupling: \( 9/2 \)

Dimension needed at strong coupling: \( 5/2 \)

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e.g. \( \text{SU}(4) \) strong sector

Fermions \[ \{ \begin{array}{l}
\text{three} \\
\text{five}
\end{array} \] \( \Psi_{L,R} \in 4 \) (fundamental) \quad \[ \begin{array}{l}
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Global symmetry:
\[ G = SU(5) \times SU(3) \times SU(3) \times U(1) \]
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Operator that can be coupled to the top

dimension at weak coupling: \( 9/2 \)

dim. needed at strong coupling: \( 5/2 \)
New flavor-violating & CP-violating transitions

Lower bounds on the scale of the strong dynamics $\Lambda$

$\Lambda$ (TeV)

- $\Delta M_B$
- $\epsilon_K$
- $B_s \to \mu^+\mu^-$
- $\mu \to e\gamma$

Passes all flavor & EDM tests: Bounds of $O$(TeV)!
Clues for cosmological conundrums

Could TeV physics be behind other fundamental questions in particle physics and cosmology, such as the origin of Dark Matter (DM), the abundance of matter over anti-matter in our universe (Baryogenesis), the origin of inflation or neutrino masses? Though not necessary the case, as the mandatory new-physics at the Planck scale could be the true responsible for these phenomena, it is well possible that some of these questions are addressed by TeV physics, opening an exciting possibility of resolving these mysteries in well controlled experiments, such as TeV colliders. The most likely of the above important questions to be addressed by TeV new-physics is the DM origin. This hope arises from the so-called "WIMP miracle": A stable particle with mass of order the electroweak scale and $O(1)$ renormalizable-interactions is in the ballpark of the needed relic abundance for a DM candidate. In the MSSM, as well as in the MCHM, we find many DM candidates [52]. For instance, the lightest superpartner, if neutral, as the neutralinos (superpartners of the $Z$, photon or Higgs), can be a good candidate for DM in certain "well-tempered" region of the parameter space [53]. Similarly, DM can arise in composite Higgs models.
Clues for cosmological conundrums

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Expected spectrum in Composite Higgs Scenarios

- 500 GeV: Color fermionic resonances
- 1 TeV: Spin-1 resonances
- 3 TeV: Spin-2 resonances
- 125 GeV: Higgs
Colored fermion resonances at LHC 13 TeV

First important constraint from LHC:

$$M(X_{5/3}) \gtrsim 1.3 \text{ TeV}$$
Colored fermion resonances at LHC 13 TeV

First important constraint from LHC:

\[ M(X_{5/3}) \geq 1.3 \text{ TeV} \]

The situation starts being worrisome...

but not yet desperate
Colored fermion resonances at LHC 13 TeV

First important constraint from LHC:

$$M(X_{5/3}) \gtrsim 1.3 \text{ TeV}$$

The situation starts being worrisome..

but not yet desperate...

(not as bad as susy)
New inside from Lattice…
Conformal window in SU(3) with large number of fermions ($N_F$)

QCD-like $\rightarrow$ Conformal $\rightarrow$ Free theory

8-9 $\beta=0$ 16.5

Banks-Zacks fixed point
Conformal window in SU(3) with large number of fermions ($N_F$)

QCD-like $\rightarrow$ Conformal $\rightarrow$ Free theory $\rightarrow N_F$

$N_F=8$ $\rightarrow$ Conformal $\rightarrow$ Free theory

Lattice results:

$N_F=12$ (LatKMI)

The scalar, the lightest (apart from the pion)
Conformal window in SU(3) with large number of fermions ($N_F$)

QCD-like  \[ \text{Conformal} \]  Free theory

$N_F=8$  \[ 8-9 \]  $\beta=0$  \[ 16.5 \]

Banks-Zaks fixed point

Lattice results:

$a m_h = 0.100$

$a m_q$

$N_F=12$ (LatKMI)

The scalar, the lightest (apart from the pion)

a light dilaton?

a Higgs-like particle? Resurrecting Technicolor?
What could we say from holography?

in collaboration with G.Panico, O.Pujolas & L.Salas
Conformal breaking as $N_F$ decreases

QCD-like $\beta=0$ Free theory $N_F$

1 2 3 $\text{Dim}[q\bar{q}]$

Decreasing $N_F$

Imaginary

Lee, Son, Stephanov, Kaplan
arXiv:0905.4752

using a truncation of the Schwinger-Dyson eqs.
Conformal breaking as $N_F$ decreases

QCD-like $\beta=0$ Free theory

$N_F$

decreasing $N_F$

QCD-like $\beta=0$ Free theory

$N_F$

Dim[$q\bar{q}$] = $2 + \sqrt{4 + M^2_{\Phi} L^2}$

AdS/CFT

$\Phi$ scalar in AdS$_5$

$M^2_{\Phi}(z)$

AdS$_5$ tachyon!

Lee, Son, Stephanov, Kaplan
arXiv:0905.4752

using a truncation of the Schwinger-Dyson eqs.
Conformal breaking in AdS$_5$ due to mass running below the BF bound

$$M^2_\Phi(z)$$
Conformal breaking in AdS$_5$ due to mass running below the BF bound

$$M^2_{\Phi}(z)$$
Conformal breaking in AdS$_5$ due to mass running below the BF bound

- The metric back-reacts where the tachyon blows up
- For simplification, we can regularize the IR with a brane (it will characterize the back-reaction)
- Position of the brane where tachyon becomes order one

\[ M_{\Phi}^2(z) \]

\[ z^2 \sin[(\sqrt{\Delta M_{\Phi}^2 \ln \frac{z}{z_0}})] \]

\[ \Phi|_{\text{IR}} = \Phi_* \]
Light dilaton?

In AdS\(_5\): Light **dilaton** expected if the IR brane is almost free to move (almost flat potential for the (radion) brane position)

Not the case for the AdS tachyon:

\[ z^2 \sin\left(\sqrt{\Delta M_F^2} \ln \frac{z}{z_0}\right) \]

AdS tachyon grows as \( \sim z^2 \) ➔ sizable cost of energy to move the brane

**No light dilaton expected!**
Nevertheless...
as $N_F$ decreases, $q\bar{q}$ approaches the free scalar limit
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as $N_F$ decreases, $q\bar{q}$ approaches the free scalar limit

Unitarity bound

$1$

free scalar field

massless scalar!

QCD-like $\to \beta=0 \to$ Free theory $\to N_F$

$\text{Dim}[q\bar{q}]$

Imaginary

decreasing $N_F$

Lee,Son,Stephanov,Kaplan

arXiv:0905.4752

using a truncation of the Schwinger-Dyson eqs.
Nevertheless…
as $N_F$ decreases, $q\bar{q}$ approaches the free scalar limit

Limit, of course, not reached!

But… how 2 is close to 1?
Nevertheless... as $N_F$ decreases, $q\bar{q}$ approaches the free scalar limit

Unitarity bound $1$

free scalar field

massless scalar!

$\dim[q\bar{q}] = 2 + \sqrt{4 + M^2_\Phi L^2}$

AdS/CFT

$\Phi$ scalar in AdS$_5$

$M^2_\Phi(z)$

AdS$_5$ tachyon!

Lee, Son, Stephanov, Kaplan
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using a truncation of the Schwinger-Dyson eqs.
AdS predictions

excitations around the AdS-tachyon vacuum

the scalar becomes a factor $\sim 1/2$ lighter at $\text{dim}[q\bar{q}]=2$
$SU(2) \times SU(2) \rightarrow SU(2)$

QCD-like theories approaching the conformal transition

The scalars become the lightest resonance!

Also the mass splitting $\rho - a_1$ reduces
Implications for the LHC

(in strong dynamics to solve the hierarchy problem)
Nice scenarios to solve the hierarchy problem:

Tachyon in AdS puts you out from a CFT

Hierarchy controlled by the “slow-rolling” of $M_\Phi$

(stable under radiative corrections)
Nice scenarios to solve the hierarchy problem:

Tachyon in AdS puts you out from a CFT

\( M^2_{\Phi}(z) \)

Hierarchy controlled by the “slow-rolling” of \( M_{\Phi} \)

(stable under radiative corrections)

\( \Phi|_{\text{IR}} \sim \mathcal{O}(1) \)

\( \Delta M^2_{\phi} \equiv -4 - M^2_{\phi} \)

\[ \Lambda_{\text{IR}} \sim \Lambda_{\text{UV}} \ e^{-\pi/\sqrt{\Delta M^2_{\phi}}} \]

BKT transition
Excitations around the AdS-tachyon expected to be lighter
Could this scalar be the Higgs? Resurrecting Technicolor?
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Could this scalar be the Higgs? Resurrecting Technicolor?

**Mass?** Not light enough

For $M_{TC\cdot\rho} \sim 2\text{-}3\text{ TeV}$ we have $M_H \sim M_{TC\cdot\rho}/2 \sim \text{TeV}$
Could this scalar be the Higgs? Resurrecting Technicolor?

**Mass?** Not light enough

For $M_{TC-\rho} \sim 2-3$ TeV we have $M_H \sim M_{TC-\rho}/2 \sim$ TeV

**Higgs-like coupling?** Approaching free scalar limit = SM Higgs

![Graphs showing $g_{hWW}/g_{SM}$ and $g_{hff}/g_{SM}$ ratio versus dim[$q\bar{q}$].]
We can allow the Oi ggs boson to have $^{+}\text{ff}$ decay to weakly interacting stable particles and $^{−}\text{ff}$ decay to channels not searched for $^{3}\text{ff}$ cascade decay with unexpected topology $^{4}\text{ff}$.

Kit performed constraining $|k| V B = \kappa_i = \frac{g_{H_{\text{eff}}}}{g_{H_{\text{SM}}}}$ is hardly compatible with present measurements.

Hardly compatible with present measurements

$|\kappa_V| \leq 1$

$B_{\text{BSM}} \geq 0$
Composite PGB Higgs

Goldstone from a $G \rightarrow H$ breaking in the strong sector

Expected spectrum

- 125 GeV: Higgs (lighter as it’s a PGB!)
- 1 TeV: fermionic resonances
- 3 TeV: spin-1 resonances, spin-2 resonances

Comments:
- $125 \text{ GeV}$ is lighter as it’s a PGB!
Composite PGB Higgs

Expected spectrum

3 TeV
- spin-2 resonances
- spin-1 resonances

1 TeV
- fermionic resonances
  - scalar resonances
  - radial components

125 GeV
- Higgs
  (lighter as it’s a PGB!)

Goldstone from a $G \rightarrow H$ breaking in the strong sector

If due to an AdS tachyon

angular components
Composite PGB Higgs

Expected spectrum

- 3 TeV
  - spin-2 resonances
  - spin-1 resonances
  - fermionic resonances
  - scalar resonances

- 1 TeV

Goldstone from a $G \rightarrow H$ breaking in the strong sector

If due to an AdS tachyon

Changes the searches for top partners:

$T \rightarrow S t \rightarrow \tilde{t} \tilde{t} \tilde{t}$

(work in progress!)
Concluding…

★ Strong dynamics at the TeV is still one of the best ways to tackle the hierarchy problem

**Present situation:** We can “visualize” plausible realistic scenarios, and provide signals to future experiments (LHC)…

**Challenges**

- Exp ➡ No evidences so far!
- Th ➡ large top mass (needed fermion oper. with large $\gamma$)

**In the future:**

- **Lattice** could shed light on conformal theories ($\gamma$ of fermionic operators)
  - Present simulations close to the QCD conformal transition ➡ lighter scalars!
  - **Holographically:** $qq$-operator towards the decoupling limit ($\text{dim}[qq] \rightarrow 1$)

★ The *dream situation* would be to have (as in the 60’) experimental data (e.g. LHC), leading the field in the future