New Strong Dynamics at the TeV scale

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After the Higgs discovery...

... we’ve moved to a different situation in particle physics:

We have the theory, but now we’d like to understand why it is like it is

In particular, we’d like to understand:

Why \( m_H \ll M_P \sim 10^{19} \text{ GeV} \)?

provides a (unique?) solid argument for TeV new-physics
Among the few possibilities to solve the hierarchy problem:

**Compositeness:** \( H = \) \( u \) \( \bar{u} \)

*“dead dogs don't bite”:*

If no elementary Higgs, \( m_H \) is not anymore a fundamental parameter
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\[
\begin{align*}
\Lambda_{\text{QCD}} & \quad \alpha_s \\
M_P & \quad E
\end{align*}
\]

as in QCD:

Explain why \( \Lambda_{\text{QCD}} \ll M_P \)
Among the few possibilities to solve the hierarchy problem:

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“dead dogs don't bite”:

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![Graph showing new strong dynamics at TeV]

It could explain why \( m_H \lesssim \Lambda_* \sim \text{TeV} \ll M_P \)
The Higgs, the lightest of the new strong resonances, as pions in QCD: they are Pseudo-Goldstone Bosons (PGB)
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\[
\begin{align*}
\text{QCD} & \quad \text{Composite Higgs} \\
\text{GeV} & \quad \text{TeV} \\
130 \text{ MeV} & \quad 125 \text{ GeV} \\
\pi & \quad h \\
\frac{\text{SU}(2)_L \times \text{SU}(2)_R}{\text{SU}(2)_V} & \quad \frac{\text{SO}(5)}{\text{SO}(4)}
\end{align*}
\]

Minimality should not the guiding principle!

Let’s not repeat Sakurai's mistake:

... and since any successful theory must be simple... Sakurai

The rho-meson was not a gauge boson! (even though was the simplest theory to built)
Even though no possibility to calculate...

it’s possible provide a characterization of the expected signals

(as in the 60’, experiments will be driving the field)
Expected spectrum in Composite Higgs Scenarios

- 3 TeV: spin-2 resonances, spin-1 resonances
- 1 TeV: color fermionic resonances
- 500 GeV: color fermionic resonances
- 125 GeV: Higgs

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. 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. Similarly, DM can arise in composite Higgs models.
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Best way to unravel new dynamics:

Discovering new resonances!
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Best way to unravel new dynamics: Discovering new resonances!

- m($X_{5/3}$) > 960 GeV

Right-handed

Combined

 CMS Preliminary, 2.2 fb$^{-1}$ (13 TeV)
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Glimpses at the LHC?

$M_{W'}$ expected at 2-3 TeV

At 8 TeV, some **excess** in $ZW$ decays (in jets) mostly in ATLAS:
At the LHC 13...

Not much of di-Boson excess...

M. Pierini’s talk at Moriond 16:

Still, not enough lumi to exclude the Run I excess or to confirm it
Di-photon excess:

- $m_X \sim 750 \text{ GeV}, \Gamma_X \sim 45 \text{ GeV}$ (6%)
- Local $Z = 3.9 \sigma$
- Global $Z = 2.0 \sigma$

Pointing towards...

- a (pseudo)-scalar of mass 750 GeV
- with a sizable BR to photons & gluons
- a width $\Gamma/M$ of 6% slightly favored!
Was this resonance expected/predicted?

Strong dynamics at TeV?
Was this resonance expected/predicted? Not really… but…

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Lessons from QCD:

Lighter as they are Pseudo-Goldstone bosons (PGB) pseudo-scalars with sizable couplings to photons:
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Lessons from QCD:

Comosite Higgs:

Lighter as they are Pseudo-Goldstone bosons (PGB)

pseudo-scalars with sizable couplings to photons:
If these excesses are not confirmed... and the new-strong sector turns out to be too heavy...

10 TeV

New Resonances

125 GeV

$h$
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Even if we cannot get the resonance, we could get its tail

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Effects of the resonance “tails”

Encoded in Higher-dimensional operators, e.g. \((D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}\), \(W^a_\mu \nu W^b_\nu \rho W^c_\rho \mu\), … generated after integrating out new-physics

Goal: Recognize the relevant effects
e.g. those that make the 2\rightarrow 2 amplitudes grow with E
Effects of the resonance “tails”

Encoded in Higher-dimensional operators, e.g. \((D^\mu H)^\dagger (D^\nu H)B_{\mu\nu}\), \(W^a_\mu \nu W^b_\nu \rho W^c_\rho \mu\), … generated after integrating out new-physics

Goal: Recognize the relevant effects

Plenty of LHC data: \(qq\to VV/h, \ qq\to qq, \ VV\to VV\)

Plenty of higher-dim operators:

How to extract the relevant information?
Restrict to dimension-6 operators?

This can either be…

**Redundant:** Missing correlations

**Incomplete:** Dimension-8 operator also relevant in certain BSMs
The energy expansion parameter:

\[
\frac{E^2}{\Lambda^2} \ll 1
\]

can be overcomed by strong couplings: \( g_* = \text{coupling of the BSM} \)

\[
1 \ll \frac{g_*^2}{g^2} \lesssim 16\pi^2 \sim 160!
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\]
Example:

Dim-4:

\[ A_{SM} \sim g^2 \]

Dim-6:

\[ \frac{\delta A}{A_{SM}} \sim \frac{g_* E^2}{g \Lambda^2} \]

Dim-8:

\[ \frac{\delta A}{A_{SM}} \sim \left( \frac{g_* E^2}{g \Lambda^2} \right)^2 \]

At the LHC only models with large deviations \( g_* E^2 / g \Lambda^2 \gg 1 \) can be probed, therefore dim-8 can dominate!
We need a different rational!

Crucial first to recognize the different BSM scenarios classified at least by either symmetries or dynamical structure

Useful to characterize the possible patterns of Strong coupling for LHC searches:

D. Liu, A.P., R. Rattazzi, F.Riva  arXiv:1603.03064
In the simplest Composite Higgs Models

Apart from Higgs physics, only $WW$-scattering is expected to grow sizably with the energy:

$$
\sim \frac{g^2 E^2}{m_\ast^2} \left( 1 + \frac{E^2}{m_\ast^2} + \ldots \right)
$$

But small cross-sections at the LHC!
What else?

New possibilities if other SM states arise from the new strong TeV-dynamics:

\[ 10 \text{ TeV} \quad \text{New Resonances} \]

\[ 125 \text{ GeV} \quad h \quad \text{SM Vectors?} \]

What to expect?
Composite SM Vectors?

Really? Their (gauge) coupling $g$ is small \((g/4\pi \ll 1)\) & corrections to their propagators small (from LEP)

But remember pions (PGB) have two different type of couplings:

**Large** derivative-couplings: \((\pi \partial_\mu \pi)^2\) (preserve $\pi \rightarrow \pi + c$)

**Small** couplings: \((\pi \partial_\mu \pi) A^\mu\) (break $\pi \rightarrow \pi + c$)

**Possibility:** Composite SM vector only with sizable field-strength interactions $F_{\mu \nu}$
Effective Theory of Strong Dipole Interactions

$A^\mu \sim \begin{array}{c} + \qquad + \qquad + \qquad + \qquad + \end{array}$

$dipole \gg 1/\Lambda$

$Q=1$

Example: QED at $E<m_e = Euler-Heisenberg\ EFT$
Effective Theory of Strong Dipole Interactions

We cannot provide a real model...
but a consistent (stable!) low-energy description
as charge is not renormalized:

\[ \mathcal{L} = \frac{M^4}{g^2} \mathcal{L} \left( \partial_\mu + \frac{igA_\mu}{M}, \frac{g^*}{M^2}, \Phi \right) \]

We named these scenarios *Remedios*

*Remedios the Beauty was not a creature of this world* - Gabriel Garcia Marquez.
In the non-abelian case, e.g. $SU(2)_L$:

Strong sector symmetry

$$[U(1)_{\text{local}}]^3 \rtimes SU(2)_{\text{global}}$$

Smoothly deformed by $g$

$$SU(2)_{\text{local}}$$

$$\mathcal{L} = \frac{M^4}{g^2_*} L \left( \frac{\partial_\mu}{M}, g_* \frac{\hat{F}_{\mu\nu}^a}{M^2}, \Phi \right)$$

$$\mathcal{L} = \frac{M^4}{g^2_*} L \left( \frac{\partial_\mu + igA_\mu^a}{M}, g_* \frac{F_{\mu\nu}^a}{M^2}, \Phi \right)$$
In the non-abelian case, e.g. $SU(2)_L$:

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The inverse of a Inonu-Wigner contraction:

Galilei Group

$U(1) \times U(1) \times U(1)$

Poincare Group

$SU(2)$

$1/c \to 0$

$g \to 0$
Effects: \( F_{\mu\nu} \) \( g_\ast \) \( \frac{g_\ast}{\Lambda^2} \text{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_\rho] \)
Effects:\n\[ F_{\mu\nu} \]

\[ g_* \]

\[ \frac{g_*}{\Lambda^2} \text{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^\mu] \]

\[ \lambda_\gamma \left[ \frac{(q_1 - q_2)^\mu}{m_W^2} \left( \frac{s}{2} g^{\alpha\beta} - p^\alpha p^\beta \right) + p^\alpha g_{\mu\beta} - p^\beta g^{\mu\alpha} \right] \]
95% CL intervals. Results are compared to the world average values, as explained in the text.

The component is simulated with the CMS system and is sensitive to the systematics.

The signal efficiency in each bin is computed. The total systematic uncertainty in each bin is the sum of the various backgrounds described in Section 5.

The analysis is performed using the method described in Section 7.

Better than LEP!

LHC8: $\Lambda \approx 8.5 \text{ TeV}$ (for $g_* \sim 4\pi$)

Remember: Only valid for this type of strongly-coupled models!
Remedios + Composite PGB Higgs

For concreteness: $H \rightarrow H + c$ preserving $SO(4)$ custodial
Remedios + Composite PGB Higgs

For concreteness: $H \rightarrow H + c$ preserving SO(4) custodial

Effects: $F_{\mu \nu}$ $g^*_\mu$ $g^*_\nu$ $D_\mu H$ $\frac{g^*_\mu}{\Lambda^2} i(D^\mu H)^\dagger \sigma^a(D^\nu H) W^a_{\mu \nu}$
**Remedios + Composite PGB Higgs**

**For concreteness:** $H \rightarrow H + c$ preserving SO(4) custodial

**Effects:**

\[ F_{\mu\nu} \quad g^* \Rightarrow \quad D_{\mu}H \quad \rightarrow \quad \frac{g^*}{\Lambda^2} i(D_{\mu}H)^{\dagger} \sigma^a(D^\nu H) W^a_{\mu\nu} \]

\[ qq \rightarrow VV \]
Remedios + Composite PGB Higgs

For concreteness: \( H \rightarrow H + c \) preserving SO(4) custodial

Effects:

\[ F_{\mu \nu} \quad g^* \quad g^* \quad D_\mu H \]

\[ \frac{g_*}{\Lambda^2} i (D^\mu H)\dagger \sigma^a (D^\nu H) W^a_{\mu \nu} \]

\[ \text{qq} \rightarrow VV \quad \text{h} \rightarrow \gamma Z \]

correlated:

\[ \delta g^Z_1 = \frac{\delta \kappa_{\gamma}}{\cos^2 \theta_W} = \frac{\delta g_{hZ\gamma}}{\sin \theta_W \cos \theta_W} \]
What else?

New Resonances

10 TeV

125 GeV

SM Vectors? SM fermions?

Effects:

$F_{\mu\nu}$

$D_{\mu}H$

$g^*$

$\psi$
A model-independent analysis must include dim-8 operators.
What else?

New Resonances

10 TeV

125 GeV

h

SM Vectors? SM fermions ~ Goldstini?

Strong sector invariant under supersymmetry:

\[
\delta \psi = \xi + \frac{i}{2F^2} \partial_\mu \psi (\bar{\psi} \gamma^\mu \xi - \bar{\xi} \gamma^\mu \psi)
\]

Effects:

\[
D_\mu \psi, \quad F_{\mu \nu}, \quad g^*_* g^*_* D_\mu H
\]

work in progress!
Conclusions

- **New Strong dynamics at the TeV** is still one of the best options for TeV-BSM: Glimpses already (750 GeV)?

  Don’t be afraid to pursue it, even without full knowledge of the theory

  Nature does not care about our limitations!

- These BSMs can also be probed (possibly, the only ones!) in $2\to2$ scatterings at the LHC at the high-energy regime!

  A different parametrization of the effects was proposed to optimize these searches, based on a proper power-counting of the different strongly-coupled scenarios

  Crucial to understand in the absence (presence) of new-physics which BSM are disfavored (favored)!