Searching for New Phenomena
(under susy abstinence)

Interpreting *null* results… and one hope!

Alex Pomarol, CERN & UAB/IFAE (Barcelona)
Impressive number of searches for new phenomena at LHC, giving us plenty of negative results!

“What’s the opposite of Eureka?”
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But even null results allow us to make progress!

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But even null results allow us to make progress!

If experiments are well-motivated!

“What’s the opposite of Eureka?”

as Michelson-Morley experiment
Making progress from *null* results:
If we assume that the only scale is $\langle H \rangle \sim 246$ GeV (as in the SM), we have excluded experimentally any new physics!

Making progress from null results:

No extra fermions, gauge bosons, ... getting their mass from H
Making progress from *null* results:

If we assume that the only scale is $\langle H \rangle \sim 246$ GeV (as in the SM), we have excluded experimentally any new physics!

We know this thanks to the interplay between direct & indirect searches:

- **If light**: should have been seen in detectors
- **If heavy**: should have been seen indirectly

![Diagram showing fermion and force representations](image)
Making progress from null results:

We have been able to clean up the electroweak sector, being now confident in the SM.

No theory argument to have \( SU(3) \times SU(2) \times U(1) \) with 3 families (the SM), instead of something else.
Consequences:

New states should bring their own mass-scale

e.g. \( M \bar{\Psi} \Psi \)
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e.g. $M\bar{\Psi}\Psi$

But... why $M$ should be around the EW-scale?
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But… why \( M \) should be around the EW-scale?

Crucial question to **address** to know whether there are motivations to search for them at the LHC
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How could new physics scales be connected to the EW scale?
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How could new physics scales be connected to the EW scale?

Assume \( \langle H \rangle \) is not a fundamental parameter:

There is a more fundamental scale at \( \sim \) TeV from which \( m_H \) (or \( \langle H \rangle \)) arises, together with something else

\[ \langle H \rangle \]

SM masses
Consequences:

New states should bring their own mass-scale

e.g. $M \bar{\Psi} \Psi$

But… why $M$ should be around the EW-scale?

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How could new physics scales be connected to the EW scale?

Assume $\langle H \rangle$ is not a fundamental parameter:

There is a more fundamental scale at $\sim$TeV from which $m_H$ (or $\langle H \rangle$) arises, together with something else

Also needed if we want to explain why $m_H \ll M_P$!
What could be this $\Lambda \sim \text{TeV}$?
What could be this $\Lambda \sim \text{TeV}$?

- In the Susy approach:
  $\Lambda \sim \text{scale of Susy-breaking}$
  $? = \text{superpartners}$
What could be this $\Lambda \sim \text{TeV}$?

**QCD as a guidance:**

![Graph showing QCD as a guidance](image)

Explains why $\Lambda_{\text{QCD}} << M_P$ and the origin of most hadron masses.
What could be this $\Lambda \sim \text{TeV}$?

**QCD as a guidance:**

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

**New strong dynamics at TeV**

**Composite 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.

Expected spectrum of the TeV Composite Sector

![Diagram of expected spectrum of the TeV Composite Sector](image-url)

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

Good BSM prototype for many searches
Expected spectrum of the TeV Composite Sector

spin-2 resonances
spin-1 resonances

color fermionic resonances

125 GeV  Higgs

3 TeV

1 TeV

500 GeV

Good BSM prototype for many searches

By the AdS/CFT correspondence:
Physics of Composite Sector ↔ Physics of Extra dimension

Clues for cosmological conundrums

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Expected spectrum of the TeV Composite Sector

By the AdS/CFT correspondence:

Physics of Composite Sector ↔ Physics of Extra Dimension
Expected spectrum of the TeV Composite Sector

Before 13 TeV LHC bounds dominated by indirect effects
Expected spectrum of the TeV Composite Sector

Before 13 TeV LHC bounds dominated by indirect effects
Spin-1 resonance searches:

- Enhanced by large couplings from the composite sector
- Suppressed by large couplings from the composite sector
Spin-1 resonance searches:

Glimpses at the LHC?

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

Not much of a di-Boson excess... but we are now at the interesting mass scale!
Clues for cosmological conundrums

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**Expected spectrum of the TeV Composite Sector**

![Graph showing expected spectrum of the TeV Composite Sector. The spectrum includes spin-1 and spin-2 resonances at 1 TeV and 3 TeV, respectively, with a focus on 500 GeV color fermionic resonances from the 7/8 TeV LHC searches.](image-url)
Colored fermion resonances at LHC 13 TeV

\[ m(X_{5/3}) > 960 \text{ GeV} \]
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The situation starts being worrisome...
but not yet desperate
Colored fermion resonances at LHC 13 TeV

The situation starts being worrisome..
but not yet desperate

\( m(X_{5/3}) > 960 \text{ GeV} \)

(not as bad as susy)
Colored fermion resonances at LHC 13 TeV

\[ m(X_{5/3}) > 960 \text{ GeV} \]

The situation starts being worrisome.
but not yet desperate

Who is keeping the Higgs light?

\[ \hat{y}_t \, f \]

The missing top-partner problem!
“I have second thoughts. Maybe the Lord is malicious” remark to Vladimir Bargmann, quoted in Einstein in America (1985)
“Twin Higgs” Models:

\[ \Lambda \sim 5 \text{ TeV} \]

Strong sector

\begin{itemize}
  \item Perfectly preserves the global SU(4) of the Higgs sector.
  \item During the BBN, dark neutrinos, photons, electrons contribute to the radiative degrees of freedom.
  \item If \( T_{\text{dark}} = T_{\text{dark}} \), this is completely unacceptable.
  \item The hidden and visible sector maintain the equilibrium via Higgs interactions down to < 10 GeV.
  \item If we reheat above this temperature, the sector has the same number of degrees of freedom.
\end{itemize}

Reheating below the equilibrium temperature raises very serious questions about the accommodation of DM and baryogenesis into this mechanism.

“I have second thoughts. Maybe the Lord is malicious”
remark to Vladimir Bargmann, quoted in Einstein in America (1985)
“Twin Higgs” Models:

\[ \Lambda \sim 5 \, \text{TeV} \]

Strong sector

A neutral sector keeps the Higgs light!
Not possible to see these top-partners at the LHC as they are not charged under the SM

**Main LHC signature:**
Higgs decays invisibly (to the “mirror” world) that **could** decay back to us (giving displaced vertices)

Higgs portal to the “Mirror SM”
In spite of so much negative results...

"We are allowed to be slightly excited"

CERN Director-General
In spite of so much negative results...

”We are allowed to be slightly excited”

CERN Director-General

The word “slightly” not fully understood by theorists!
The di-photon ANOMALY
An unexpected newcomer?

Breaking-down the contributions

- Excess at 760 GeV comes mostly from EBEB categories.
- Driven by 3.8T category.
- Observed one event in the 0T dataset compatible with 3.8T excess.

\[
\begin{align*}
\text{Spin-0 Selection} & = 13 \text{ TeV, } 3.2 \text{ fb}^{-1} \\
\text{Data} & \quad \text{Background-only fit} \\
\text{Spin-2 Selection} & = 13 \text{ TeV, } 3.2 \text{ fb}^{-1} \\
\text{Data} & \quad \text{Fit model} \\
\end{align*}
\]

- **ATLAS Preliminary**
  - Data
  - Background-only fit

  Spin-0 Selection
  \[\sqrt{s} = 13 \text{ TeV, } 3.2 \text{ fb}^{-1}\]

- **CMS Preliminary**
  - Data
  - Fit model
  - Background-only fit

\[
\begin{align*}
\text{Data - fitted background} & \quad \text{Events / 20 GeV} \\
\end{align*}
\]

\[
\begin{align*}
\text{Spin-0} & = 750 \text{ GeV, } \Gamma_X \sim 45 \text{ GeV (6\%)} \\
\text{Local } Z & = 3.9 \sigma \\
\text{Global } Z & = 2.0 \sigma \\
\end{align*}
\]
Pointing towards...

a (pseudo)-scalar of mass 750 GeV with sizable couplings to photons & gluons (or bottoms)

![Feynman diagram](image)

a width $\Gamma/M$ of 6% slightly favored!
If large width ($\Gamma/M \sim 6\%$), we must have $\Gamma_{YY}/M \approx 10^{-4}$
What is this $S(750)$ telling us?
What is this $S(750)$ telling us?

Theorist recent entertainment:

The pleasure (and risk) of extrapolation!
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Theorist recent entertainment:

Understandable:

Little BSM experimental data, for too many theorists

4 μ(T) = 77.9 H(0.104/day T)

0 10 20 30 40 50 60
0
50
100
150
200
250
T (Days)
Cumul. num. of papers
ATLAS γγ

Above expectations: ~390 in 5 months!

Couplings needed for $S(750)$:

$$S F_{\mu\nu} F^{\mu\nu}$$
$$S G_{\mu\nu} G^{\mu\nu}$$

(or the CP-odd counterparts)
Couplings needed for $S(750)$:

\[ S F^{\mu\nu} F_{\mu\nu} \]
\[ S G^{\mu\nu} G_{\mu\nu} \]

: where have I seen this before?

(or the CP-odd counterparts)
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\[ S F^{\mu\nu} F_{\mu\nu} \]
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(where have I seen this before?)

(or the CP-odd counterparts)

- **Higgs**: $\Gamma_{\gamma\gamma}/m_H \sim 10^{-7}$ much smaller! ✗
- **Axion**: but $m_a \ll 750$ GeV! ✗
- **SGoldstino in GMSB**: but expected heavier ✗
- **Goldstone (as pions in QCD)**? ✓
- **Quarkonium**? ✓
Although variations are possible to resemble $S$:

**Couplings needed for $S(750)$:**

\[ S F^{\mu \nu} F_{\mu \nu} \]
\[ S G^{\mu \nu} G_{\mu \nu} \]

(or the CP-odd counterparts)

- **Higgs:** $\Gamma_{\gamma \gamma} / m_H \sim 10^{-7}$ much smaller!  
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- **Goldstone (as pions in QCD)?**  
  - $\checkmark$

- **Quarkonium?**  
  - $\checkmark$
Figure 4: Weakly coupled models.

Here we describe how to obtain weakly coupled (renormalizable) models realising the scenario discussed in the previous section via the Feynman diagram in fig. 4. The SM is extended by adding one (or more) scalar singlets $S$, and extra vector-like fermions $Q^f$ (written in Dirac notation) or scalars $\tilde{Q}^s$ with mass $M_i$, hypercharge $Y_i$, charge $Q_i$ and in the colour representation $r_i$, with the couplings $S\bar{Q}^f(y^f + i y^5)Q^f + S\bar{\tilde{Q}}^s\gamma^5\tilde{Q}^s$.

As before, the use of the scalar or pseudo-scalar interaction depends on the CP nature of $S$.

This kind of structure is fairly generic in models that extend the SM sector around the weak scale. One is easily convinced that our conclusions are not dramatically affected by allowing also matter with SU(2)$_L$ quantum numbers. The case in which the scalar $S$ is part of a SU(2)$_L$ multiplet will be dealt with later and the model building constraints imposed by the large width will be investigated in the next subsection.

Focusing on the CP-even couplings, we find that the fermion and scalar loops induce the following widths:

\begin{align*}
(S \rightarrow gg) &= M_s^2 \frac{2}{3} \pi^2 \sum_{\pi^f} y_f^2 + \sum_{\pi^s} y_s^2 \left( \frac{M_f}{750 \text{ GeV}} \right) \\
(S \rightarrow \gamma \gamma) &= M_s^2 \frac{16}{15} \pi^2 \sum_{\pi^f} y_f^2 + \sum_{\pi^s} y_s^2 \left( \frac{M_f}{750 \text{ GeV}} \right) \, .
\end{align*}

\[ (20) \]

In the limit of heavy extra particles ($\pi \rightarrow 1$) we have $P(\pi) \approx 1/\pi$, $S(\pi) \approx 2/3$, $F(\pi) \approx 1/3$.\[ (22) \]

S(750) as an extra Higgs

- many Higgs in supersymmetric models:
  MSSM + Singlet = NMSSM
  \[ \text{can be accommodated to be the 750} \]

BUT, extra colored & charged states needed!

Smallest width:

\[ N_{\text{fermions}} \sim 6 \times \left( \frac{1}{Q_f} \right)^2 \left( \frac{1}{y_f} \right) \left( \frac{M_f}{750 \text{ GeV}} \right) \]

Large width (6%):

\[ N_{\text{fermions}} \sim 60 \]

\[ \text{Sick theory: Couplings blow-up below M}_P \]

\[ \text{more must be added at higher energies} \]
**3 Weakly coupled models**

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As before, the use of the scalar or pseudo-scalar interaction depends on the CP nature of $S$. This kind of structure is fairly generic in models that extend the SM sector around the weak scale. One is easily convinced that our conclusions are not dramatically affected by allowing also matter with SU(2)$_L$ quantum numbers. The case in which the scalar $S$ is part of a SU(2)$_L$ multiplet will be dealt with later and the model building constraints imposed by the large width will be investigated in the next subsection.

Focusing on the CP-even couplings, we find that the fermion and scalar loops induce the following widths:

$$\sigma(S \rightarrow gg) = \frac{M_i^2}{3} \pi \, (1 + \frac{1}{2} P(\tilde{\tau}_i))$$

$$\sigma(S \rightarrow gg) = \frac{M_i^2}{16} \pi \, (1 + \frac{1}{2} P(\tilde{\tau}_i))$$

where $\tilde{\tau}_i = \frac{4}{M_i^2}$, and $I_r$ and $d_r$ are the index and dimension of the colour representation (e.g. $I_3 = 1/2$, $I_8 = 3$), and $P(\tilde{\tau}_i) = \arctan \left( \frac{1}{2 \tilde{\tau}_i} \right)$.

In the limit of heavy extra particles ($\tilde{\tau}_i \rightarrow 1$) we have $P(\tilde{\tau}_i) \approx 1/\tilde{\tau}_i$, $S(\tilde{\tau}_i) \approx 2/3 \tilde{\tau}_i$, $F(\tilde{\tau}_i) \approx 1/3 \tilde{\tau}_i$.

**S(750) as an extra Higgs**

 grote Higgs in supersymmetric models:

 MSSM + Singlet = NMSSM

 can be accommodated to be the 750

 BUT, extra colored & charged states needed!

Why so much extra matter there?
Possible, but not expected!

Smallest width:

$$N_{\text{fermions}} \sim 6$$

Large width (6%):

$$N_{\text{fermions}} \sim 60$$

Sick theory: Couplings blow-up below $M_P$
more must be added at higher energies
Lessons from QCD:

Lighter as they are Pseudo-Goldstone bosons (PGB) pseudo-scalars have sizable couplings to photons:

\[ \pi \rightarrow \gamma \rightarrow \gamma \]
2.3 Loop induced decays into $\gamma\gamma$, $\gamma Z$ and $gg$ Since gluons and photons are massless particles, they do not couple to the Higgs boson directly. Nevertheless, the $Hgg$ and $H\gamma\gamma$ vertices, as well as the $HZ\gamma$ coupling, can be generated at the quantum level with loops involving massive [and colored or charged] particles which couple to the Higgs boson. The $H\gamma\gamma$ and $HZ\gamma$ couplings are mediated by W boson and charged fermions loops, while the $Hgg$ coupling is mediated only by quark loops; Fig. 2.14.

For fermions, only the heavy top quark and, to a lesser extent, the bottom quark contribute substantially for Higgs boson masses $M_H > \sim 100$ GeV.

Lessons from QCD:

Lighter as they are Pseudo-Goldstone bosons (PGB)

- pseudo-scalars have sizable couplings to photons:

$S(750)$ as a Pseudo-Goldstone
**S(750) as a Quarkonium**

\[ Q \text{CD bound state} \]

Q: new vector-like quark
\[ m_Q = 750/2 \text{ GeV } = 375 \text{ GeV} \]
\[ |\text{EM-charge}| \geq 4/3 \]

But also possible double-production of Q:

Signal: \( pp \rightarrow jjj + jji \)

Still the question, why is \( m_Q \) around the EW scale?
For the future...
“Consistency checks” for the future

SU(2)_L invariance implies:

\[
\frac{\Gamma(S \rightarrow WW)}{\Gamma(S \rightarrow \gamma\gamma)}
\]

\[
\frac{\Gamma(S \rightarrow ZZ)}{\Gamma(S \rightarrow \gamma\gamma)}
\]

\[
\frac{\Gamma(S \rightarrow Z\gamma)}{\Gamma(S \rightarrow \gamma\gamma)}
\]

ratio of coefficients of the SU(2)_L invariant operators

(lower-bounds for CP-even S)
“Consistency checks” for the future

SU(2)_L invariance implies:

\[ \frac{\Gamma(S \to ZZ)}{\Gamma(S \to W^+W^-)} \]

\[ \frac{\Gamma(S \to Z\gamma)}{\Gamma(S \to \gamma\gamma)} \]

ratio of coefficients of the SU(2)_L invariant operators
Important things we want to know:

(similar as the Higgs scrutinization, but here different priority list)

• Is it real?
• Assure that it’s a scalar & whether has narrow or broad width
  ✝ possibly with more $\gamma\gamma$
• CP-odd or CP-even?
  ✤ look at distributions in $pp \rightarrow Sjj$ and/or in $S \rightarrow ZZ$ if found
• Surrounded by other scalars?
  (complex field? $\rightarrow$ 2 states, weak-doublet? $\rightarrow$ 4 states, …)
  ✤ look around as EWSB-effects are small: $m_W \ll M_S$!
• Its couplings: search for new decays & production mechanisms
Conclusions

- The long-awaited 13 TeV collider is finally here!
  
  Main aim: learn on the origin of the SM electroweak scale

  First rounds: Mostly Negative Results!

- Missing top-partner problem becoming more severe
  
  but we must dig more to see how serious it is!

- Some hope from an unexpected newcomer… The 750-GeV!

  Not yet clear who ordered!
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  Main aim: learn on the origin of the SM electroweak scale
  First rounds: **Mostly Negative Results**!
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  but we must *dig* more to see how serious it is!
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  If true, a lot more waiting to be discovered!