Higgs and alternatives

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Alex Pomarol (Univ. Autonoma Barcelona)

Part of the enormous success of particle physics in the last 50 years has grounded in gauge theories

Impressive calculability

e.g. **QED**: g_e-2=0.0023193043



Gauge theories have allowed to explain the properties of the particle zoo

at 2010:



interactions dictated by a **gauge theory** based on the SU(3)×SU(2)×U(1) symmetry....

Gauge theories have allowed to explain the properties of the particle zoo

at 2010:



interactions dictated by a **gauge theory** based on the SU(3)xSU(2)xU(1) symmetry.... Up to mass terms!

Don't respect the SU(2)×U(1) symmetries

Gauge theories have allowed to explain the properties of the particle zoo:

at 2010:



interactions dictated by a **gauge theory** based on the SU(3)xSU(2)xU(1) symmetry....

Massive W and Z have 3 polarizations: New physical states: WL, ZL These new states W_L , Z_L (that must be present even if the masses were tiny) **spoil** the nice properties of gauge theories







Unitarity is lost at high-energies



Loops are not finite!

Do not allow for precision calculations as in QED

There is a missing ingredient in the **observed** particle content



To find this missing piece (or pieces) in the particle zoo is the main mission of the LHC !



What this missing piece(s) could be?

Blame it on the vacuum

Blame it on the vacuum

Not invariant under the EW symmetry







Gauge symmetry restoration possible if an extra scalar is present Quarks





Gauge symmetry restoration possible if an extra scalar is present = the Higgs boson Completes the SM:





Gauge symmetry restoration possible if an extra scalar is

present = the Higgs boson

Completes the SM:

or, more fair, the Hagen-Englert-Guralnik-Higgs-Brout-Kibble boson

according to Wikipedia and Sakurai-Prize committee



The Higgs is a very special scalar:

Likes to couple to heavy particles:



At tree-level the couplings must be **exactly** this ones to make the SM a **consistent** theory Otherwise is **NOT** the Higgs = "Impostor"

With the Higgs calculability is recovered:

Back to the prediction era!

Only one unknown parameter: The Higgs mass

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a) Theoretical bounds:

If we want the SM to be a theory valid up to the Planck scale:

Higgs hunting at the LHC

A precise theory, gives a precise prediction for Higgs physics at the LHC

Small uncertainties in present calculations: < 5%

Fig. 1: Total cross sections for Higgs production at the LHC. The gluon fusion result is NNLO QCD with soft gluon resummation effects included at NNLL and uses MRST2002 PDFs with renormalization/factorization scales equal to m_h . The vector boson fusion curve is shown at NLO QCD with CTEQ6M PDFs and renormalization/factorization scales equal to m_h . The Vh results (V = W, Z) include NNLO QCD corrections and NLO EW corrections and use MRST2002 PDFs with the renormalization /factorization scales equal to the $m_h - M_V$ invariant mass. The $b\bar{b} \rightarrow h$ result is NNLO QCD, with MRST2002 PDFs, renormalization scale equal to m_h and factorization scale equal to $m_h/4$. The results for $t\bar{t}h$ production are NLO QCD, use CTEQ6M PDFs and set the renormalization/factorization scale to $m_t + m_h/2$ [100].

The Vhnormal-

renormalization

results (V

boson fus

Uncertainties < 15% from strong corrections

2 PDFs.

CD, use

CTEQ6M PDFs and set the renormalization/factorization scale to $m_t + m_h/2$ [100].

Best scenario:

Production from color particles + Decay to colorless states:

ATLAS (talk at Planck10) for \sqrt{s} =7 TeV and 1/fb: "Higgs: 3 σ evidence in the mass range 145-180GeV"

... but full coverage in the long run

Is the Higgs a "hunting piece" worthy enough the LHC cost?

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Theoretical viewpoint:

There must be more than a single Higgs

Although the SM is <u>consistent</u>, it is not "<u>natural</u>"

In QFT is difficult to keep scalar masses small as compared to other large scales ($M_h << M_P$)

Is the Higgs a "hunting piece" worthy enough the LHC cost?

Theoretical viewpoint:

There must be more than a single Higgs

Although the SM is consistent, it is not "natural"

In QFT is difficult to keep scalar masses small as compared to other large scales ($M_h \ll M_P$)

Hierarchy problem!

Example of fine-tuning

Analogy with Superconductivity EWSB \Leftrightarrow Breaking of U(1) Higgs Model \Leftrightarrow Landau Model $\langle h \rangle = \langle e^- e^- \rangle$ $V(h) = m^2 |h|^2 + \lambda |h|^4$ B N phase $\langle h \rangle = 0$ Bc SC phase $\langle h \rangle \neq 0$ Tc

Analogy with Superconductivity

EWSB \Leftrightarrow Breaking of U(I)_{EM} Higgs Model \Leftrightarrow Landau Model $\langle h \rangle = \langle e^- e^- \rangle$

Give Landau Model a good description of superconductors?

Analogy with Superconductivity

EWSB \Leftrightarrow Breaking of U(I)_{EM} Higgs Model \Leftrightarrow Landau Model $\langle h \rangle = \langle e^- e^- \rangle$

$$V(h) = m^2 |h|^2 + \lambda |h|^4 + \cdots$$

Possibilities that theorists envisage to tackle the Hierarchy Problem:

 Supersymmetry: Stabilize the Higgs potential
 The Higgs is not elementary: Composite Higgs As in superconductivity: h ~ ee or QCD: pions ~ qq

Both implies changes in the Higgs sector

Brings Predictions:

I) **Extra** doublet needed: $h + H, A, H^+$

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2) One Higgs , h, always **light**: $M_h \lesssim 130 \text{ GeV}$

Good: Since EWPT favors a light Higgs

Bad: Since LEP Higgs bounds rule out a big chunk of the MSSM parameter space (~ 90% or more)

MSSM Higgs hunting at the LHC

Bad news: h too light to decay to WW/ZZ

A, H^+ have very small couplings to VV

H small regions with sizable couplings to WW/ZZ

Good news: Regions where the decays of H, A, H⁺ to leptons are enhanced (Large Tanβ region)

ral MSSM Higgs

Near future:

In the long run....

Composite Higgs

Composite Higgs

Two attitudes:

Positive: We already have examples like this in nature: QCD: $m_{\pi} << M_P$

Negative: Not again strong dynamics! calculations are difficult

Composite Higgs

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Picture from G.F. de Teramond

"Sexier" approach to composite Higgs: *Higgs as an "hologram"* Contino,Nomura,AP 03

> The 4D compositeness properties of the Higgs are due to its 5D nature (AdS/CFT correspondence) Maldacena 98

Composite Higgs scenario is inspired by QCD where one observes that the (pseudo) scalar are the lightest states

Kaplan, Georgi '80

Spectrum of the new QCD-like sector:

Arkani-Hamed, Cohen, Georgi

Parametrization of deviations from SM Higgs couplings

Contino et al 10

$$\mathcal{L} = \frac{M_V^2}{2} V_\mu^2 \left(1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} \right) - m_f \bar{\psi}_L \psi_R \left(1 + c \frac{h}{v} \right) + \cdots$$

SM Higgs: a = b = c = 1

Composite Higgs:

Giudice, Grojean, AP, Rattazzi 07

$$a = \sqrt{1 - \frac{v^2}{f_{\star}^2}} \qquad b = 1 - \frac{2v^2}{f^2} \qquad c = \sqrt{1 - \frac{v^2}{f^2}}$$

Scale related to the composite-scale

Since its couplings are different, it's **NOT** a true Higgs

1

Extra states needed to fully unitarize (for consistency)!

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(or Kaluza-Klein states of the W) $M_{\rm KK} \lesssim \frac{2 {
m TeV}}{\sqrt{1-c^2}}$

Extra states needed to fully unitarize (for consistency)!

Extra resonances (or Kaluza-Klein states of the W)

In the limit a=0 (~ **Higgsless**) KK do all the job! $M_{\rm KK} \lesssim rac{2 {
m TeV}}{\sqrt{1-a^2}}$

Maximal degree of compositeness not allowed by EWPT

 \Rightarrow a > 0.86 Put a bound on the scale of compositeness: f>500 GeV

Higgsless (a=0) disfavored

Of course, extra contributions can make a~0 case consistent with EWPT

EXAMPLE: Extra state **Dilaton**

Goldberger, Grinstein, Skiba 07

(present in certain theories with spontaneous breaking of scale invariance)

Higgs-like state with:

 $a = \sqrt{b} = c = \frac{v}{f_D} \sim \mathcal{O}(1)$ Helps for EWPT

Acts like a Higgs but has nothing to do with EWSB

The most serious Higgs **impostor**!

If the Higgs is **composite**, how it will change LHC predictions?

Bad news: Reduction of rates!

see also, Grojean, Espinosa, Muhlleitner 10

Higgs coupling measurements ~ 20-40%

recent studies Lafaye, Plehn, Rauch, Zerwas, Duhrssen 09

ILC would be a perfect machine to test these scenarios: effects could be measured up to a few % Genuine properties of the **composite** nature of the Higgs

- 1) WLWL -scattering grows at high energy
- 2) Double-Higgs production grows at high energy

Contino et al 10

In the best cases " 3σ signal significance with 300/fb collected at a 14 TeV LHC"

Genuine properties of the **composite** nature of the Higgs

- 1) WLWL -scattering grows at high energy
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Contino et al 10

In the best cases " 3σ signal significance with 300/fb collected at a 14 TeV LHC"

Distinguishing a SM Higgs, a composite Higgs and a dilaton

Contino et al 10

 $H_T = \sum_{i=1,2} |p_{TH_i}|$

The composite Higgs can have PGB companions

Gripaios, AP, Riva, Serra

In certain models: One Higgs doublet (h) + Singlet (ŋ)

Possibility for a new Higgs decay:

 $h \to \eta \eta \to b \overline{b} b \overline{b}$ or $\tau \overline{\tau} \tau \overline{\tau}$ (depending on the η -mass)

Similar signatures in non-minimal Susy Higgs models
Dermisek, Gunion

LHC **must** (and will) find the missing piece(s) of the SM

When a **Higgs-like** state is found, it will crucial to determine its role in EWSB

e.g. where it **sits** in this plane!

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e.g. where it **sits** in this plane!

A rough perspective of different theoretical scenarios:

