The Higgs is here, and now what?

Veronica Sanz
Sussex
November, 2013
Congratulations!

Extraordinary, global effort
Status of Higgs searches
Quantum Numbers

$JPC = 0-, 1+, 1- \text{ and } 2+$
excluded at

$97.8, 99.97, 99.7 \text{ and } 99.9\%$

(ATLAS 1307.1432)

but the Higgs could have a CP-violating component,
limits coming up
Higgs mass

\[ \mu = \frac{\sigma_{obs}}{\sigma_{SM}} \]
Couplings

CMS Preliminary  \( m_H = 125.7 \text{ GeV} \)
\( p_{\text{SM}} = 0.65 \)

- \( H \to bb \)
  \( \mu = 1.15 \pm 0.62 \)

- \( H \to \tau\tau \)
  \( \mu = 1.10 \pm 0.41 \)

- \( H \to \gamma\gamma \)
  \( \mu = 0.77 \pm 0.27 \)

- \( H \to WW \)
  \( \mu = 0.68 \pm 0.20 \)

- \( H \to ZZ \)
  \( \mu = 0.92 \pm 0.28 \)

Best fit \( \frac{\sigma}{\sigma_{\text{SM}}} \)

Preliminary

- \( \mu = 1.30 \pm 0.20 \)

Combined

- \( \mu = 1.00 \pm 0.20 \)

\( \sqrt{s} = 7 \text{ TeV}, \ L = 5.1 \text{ fb}^{-1} \quad \sqrt{s} = 8 \text{ TeV}, \ L = 19.6 \text{ fb}^{-1} \)
Probing production mechanisms

\[ m_H = 125.5 \text{ GeV} \]

\[ \mu_{VBF+VH} \times B/B_{SM} \]

\[ \mu_{ggF+ttH} \times B/B_{SM} \]

**ATLAS** Preliminary

\( \sqrt{s} = 7 \text{ TeV}: \int L dt = 4.6-4.8 \text{ fb}^{-1} \)

\( \sqrt{s} = 8 \text{ TeV}: \int L dt = 13-20.7 \text{ fb}^{-1} \)

- Red: \( H \rightarrow \gamma\gamma \)
- Blue: \( H \rightarrow ZZ^{(*)} \rightarrow 4l \)
- Green: \( H \rightarrow WW^{(*)} \rightarrow l\nu l\nu \)
- Orange: \( H \rightarrow \tau\tau \)

- Standard Model
- Best fit
- 68% CL
- 95% CL
Tevatron Run II, $L_{\text{int}} \leq 10$ fb$^{-1}$
SM Higgs Combination

- $\sigma_H \times 1.0$ (m$_H$ = 125 GeV/c$^2$)
- $\sigma_H \times 1.5$ (m$_H$ = 125 GeV/c$^2$)

Background p-value

$m_H$ (GeV/c$^2$)

Tevatron Run II, $L_{\text{int}} \leq 10$ fb$^{-1}$

$m_H$ = 125 GeV/c$^2$

- Combined (68% C.L.)
- Single channel

H = $\gamma\gamma$
H = $WW$
H = $\tau^+\tau^-$
VH = V$\bar{b}$

Best Fit ($\sigma \times Br$/SM)

$\kappa_V$

$\lambda_{WZ} = 1$
Each channel isn’t that well measured

BUT

powerful information

assume a scenario and fit
Looking for New Physics
\[ \kappa^2_g = \frac{\sigma_{prod}(gg \to h)}{\sigma_{prod}(gg \to h)_{SM}} \]
\[ \kappa^2_\gamma = \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{SM}} \]

Looking for particles in the loops
Deviations from custodial symmetry, up/down and lepton/quark structure

\[
\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z}
\]

ATLAS Preliminary

\[\lambda_{WZ} = 0.80 \pm 0.15\]
\[\lambda_{\gamma Z} = 1.10 \pm 0.18\]
\[\lambda_{FZ} = 0.74^{+0.21}_{-0.17}\]
From data to ideas
Light SM-like Higgs is a reality

stabilization of the electroweak scale

use of symmetries

SUSY and Goldstone (shift)

examples of weak and strong coupling

Higgs data

and its stabilization mechanism
Supersymmetry
SUSY Higgs

chiral multiplet with a fermion, Higgsino

$$\Phi = (H, \tilde{H})$$

chiral symmetry inherited by the Higgs

$$m_h^2 = m_Z^2 \cos^2(2\beta) + (\text{loop})m_{\tilde{t}}^2 \log(m_{\tilde{t}_2}/m_{\tilde{t}_1})$$

e.g. Giudice, Rattazzi 97
SUSY Higgs and the third generation
Light stops couple to the Higgs and affect its production and decay modes
SUSY Higgs and the third generation

Light stops couple to the Higgs and affect its production and decay modes

SM contributions

\[ F_{\gamma}^{SM}(m_t, W, m_b \cdots) = F_1(\tau_W) + \sum_{i=t,b} N_c Q_i^2 F_{1/2}(\tau_i) \left(1 - \frac{\alpha_s}{\pi}\right) \approx 1/(0.155 - 0.002 i) \]
Fit to Higgs properties in BSM
Espinosa, Grojean, VS, Trott, 2012

<table>
<thead>
<tr>
<th>All Data (48 channels)</th>
<th>Tevatron</th>
<th>ATLAS 7 TeV</th>
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Tevatron, ATLAS and CMS

effect on gg production

7&8 TeV LHC & Tevatron data

$\gamma = \frac{3}{8} \cdot \left(1 + \frac{3\alpha_s}{2\pi}\right) \gamma$

$\gamma$-effect on diphoton production

green, yellow, gray = 1, 2, and 3 sigma
+ mW + btosgamma $\rightarrow$ Stops
Higgs mass 125 $\pm$ 2 GeV calls for NMSSM or similar

$\theta_i = \frac{\pi}{4}$, $\mu = 100$, $\text{Tan}[\beta] = 10$

mass separation with the next stop

lightest stop $m_{\tilde{t}_1}$
Indirect stop $\rightarrow$ Direct searches

\[ \tilde{t}_1 \tilde{t}_1 \text{ production: } \tilde{t}_1 \rightarrow b + \tilde{\chi}_1^0, \tilde{t}_1 \rightarrow W^+ \tilde{\chi}_1^0 (\text{BR}=1, m_{\tilde{t}_1} < 200 \text{ GeV}); \tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0 (\text{BR}=1, m_{\tilde{t}_1} > 200 \text{ GeV}) \]

\[ \int L dt = 4.7 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV} \]

**ATLAS Preliminary**

- Observed limits (-1σ_{SUSY\text{ theory}})
- Observed limits (nominal)
- Expected limits (nominal)

All limits at 95% CLs

- $\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^0, \tilde{t}_1 \rightarrow W^+ \tilde{\chi}_1^0 (m_{\tilde{t}_1} < 200 \text{ GeV})$
- $\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^0, \tilde{t}_1 \rightarrow W^+ \tilde{\chi}_1^0 (m_{\tilde{t}_1} > 200 \text{ GeV})$
- $\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0 (m_{\tilde{t}_1} > 200 \text{ GeV})$

- 2-lepton ($m_{\tilde{\chi}_1} = 106 \text{ GeV}$)
- 1/2-leptons + b-jets ($m_{\tilde{\chi}_1} = 106 \text{ GeV}$)
- 1/2-leptons + b-jets ($m_{\tilde{\chi}_1} = 2 \times m_{\tilde{\chi}_1}$)
- 0-lepton
- 1-lepton
- 2-lepton
leptonic $t\bar{t} + \text{MET}$

looks a lot like leptonic $t\bar{t}$

maybe asymmetries

Reece et al, 12
95% CL exclusion

\[ \theta_{\tilde{t}} = \frac{\pi}{4} \]

\[ \tilde{t}_1 \rightarrow b W^\pm \tilde{\chi}_1^0 \]

\[ \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0 \]

1-lepton
2-leptons
0-leptons

Higgs Data

ATLAS Preliminary

- Best fit
- 68% CL
- 95% CL

\[ \sqrt{s} = 7 \text{ TeV}, \int \mathcal{L} dt = 4.6-4.8 \text{ fb}^{-1} \]

\[ \sqrt{s} = 8 \text{ TeV}, \int \mathcal{L} dt = 13-20.7 \text{ fb}^{-1} \]

L_{dt} = 13-20.7 \text{ fb}^{-1}

L_{dt} = 4.6-4.8 \text{ fb}^{-1}

s = 8 \text{ TeV}

s = 7 \text{ TeV}

68% CL

95% CL
Another option
Higgs as a pseudo-Goldstone boson

Composite Higgs

scalar doublet, CP even
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Higgs as a pseudo-Goldstone boson

Composite Higgs
scalar doublet, CP even

\[ \xi = \frac{v^2}{f^2} \]

rho, a_1, f_2...
scale symmetry
breaking: f

EW scale: v
pions
Another option

Higgs as a pseudo-Goldstone boson

Composite Higgs

scalar doublet, CP even

\[ \xi = \frac{v^2}{f^2} \]

rho, a1, f2...

scale symmetry

breaking: f

screening UV,
stabilization EW scale

EW scale: v

pions

buys you time until
hitting the resonance scale
The composite Higgs doesn’t have the same couplings as the SM higgs.

Higgs data
no unnaturalness

\[ f \gtrsim 500 \text{ GeV} \]

Strumia et al. 2013
This is (was) not **mainstream**, why?

*original idea* Georgi et al, 82

**strong** coupling

**but**

the main hurdle is generating a potential (mass, quartic...)
This is (was) not mainstream, why?

Georgi et al., 82

original idea

strong coupling

but

the main hurdle is generating a potential

(mass, quartic...)

$$m^2 \propto \lambda v^2$$

protected

same suppression

expect

$$\nu \sim f$$
But this is a symmetry argument in explicit models one can search for mechanisms

explicit models dealing strong coupling?

Holographic pseudoGB (extra-dimensions)

and partial compositeness

Pomarol et al. 04
Contino et al. 07

A lot of model building after that...
Higgs mass
top-partner contribution

\[ m_h^2 \sim \frac{N_c y_t^2 v^2}{16\pi^2 f^2} m_T^2 \]

One could still push

\[ f \sim \text{TeV} \]

but

\[ m_T \lesssim \text{TeV} \]
$m_T \lesssim \text{TeV}$
Higgs Effective Lagrangian
The LEP mentality
Now, let’s be agnostic

how can we use Higgs data to constrain NP in a “model-independent” way?

Assume NP is heavy
Higgs anomalous couplings
Effective theory approach: operators involving the HVV vertices

\[ \mathcal{L}_{\text{eff}} = \sum_i \frac{f_i}{\Lambda^2} O_i \]

\[ \epsilon_i = f_i \frac{\nu^2}{\Lambda^2} \]

\[ O_W = (D_\mu \Phi) \dagger \widehat{W}^{\mu\nu} (D_\nu \Phi) \]

\[ O_B = (D_\mu \Phi) \dagger (D_\nu \Phi) \hat{B}^{\mu\nu} \]

\[ O_{WW} = \Phi \dagger \widehat{W}^{\mu\nu} \widehat{W}_{\mu\nu} \Phi \]

\[ O_{BB} = (\Phi \dagger \Phi) \hat{B}^{\mu\nu} \hat{B}_{\mu\nu} \]

and operators contributing to tree S,T we set them to zero, but controversy

Grojean et al. 2013
Pomarol et al. 2013
eWW and eBB uses mostly h→aa

LHC data surpasses PEWT
Bounds on rare decays like $h \rightarrow \gamma Z$

$|g_{HYZ}^{(2)}| < 9.2 \times 10^{-4}$ GeV$^{-1}$ @ 95% CL

and constrain models like SUSY and X DIMS
But when it comes to $eW$ and $eB$, data $h \to WW, ZZ$

More ideas? differential information?
From total rates to differential information
New Physics

different Lorentz structure

boosted topologies & COM dependence
New Physics
different Lorentz structure
boosted topologies & COM dependence

Invariant mass in associated production w/ HEFT
not enough data yet for this, but instead

Alloul, Fuks, VS. 1310.5150
Energy dependence in associated production

$pp \rightarrow V^* \rightarrow V \ h$

double ratio

$$R_{data} \equiv \left( \frac{\sigma_{data}^{CMS \ LHC \ 8}}{\sigma_{data}^{TeVatron}} \right) / \left( \frac{\sigma_{LHC \ 8}^{0+}}{\sigma_{TeVatron}^{0+}} \right) = \frac{\sigma_{TeVatron}^{0+}}{\sigma_{data}^{TeVatron}} \frac{\sigma_{CMS \ LHC \ 8}}{\sigma_{LHC \ 8}^{0+}} = \frac{\mu_{LHC \ 8}}{\mu_{TeVatron}} = 0.47 \pm 0.58 .$$

(16)

This ‘differential’ information is more stringent than a global fit to LHC8 data.
With more data
one can start asking more questions
With more data one can start asking more questions

*Composite Higgs and Little Higgs top-partners affect the loops*

BUT

*low-energy cancellation*

No information on top-partners from Higgs couplings
Higher order corrections evade the cancellation

Banfi, Martin, VS. 2013
Higher order corrections evade the cancellation

Banfi, Martin, VS. 2013

\[ g \rightarrow t + T \rightarrow g \]

\[ h \]

\[ \sqrt{s} = 8 \text{ TeV} \]

\[ \mu_F = \mu_R = m_H \]

\[ \text{MSTW2008NNLO} \]

\[ \text{MCFM, Herwig} \]
Higher order corrections evade the cancellation

Banfi, Martin, VS. 2013

limited by lack of NLO computations
Higher order corrections evade the cancellation

Banfi, Martin, VS. 2013

limited by lack of NLO computations
Into the future
Higgs factories

1. The LHC at HL
2. A linear collider
   ILC up to 500 GeV
   CLIC up to 3 TeV
4. A circular e+e- collider: LEP3, TLEP
   A photon-photon collider: SAPPHiRE
4. A muon collider
Conclusions

Higgs, scalar particle and quite SM-like
this is just the beginning
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most powerful constraints by
fit rates and
differential distributions $\rightarrow$ precision
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SUSY, composite and little Higgs and Eff L
direct/indirect (Higgs)

Higgs data at the level of PEWT for some variables
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SUSY, composite and little Higgs and Eff L
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What now?

a lot of the theory space cleared out
data -> new ideas in model building
Example

\[ r_s \frac{2m_s^2}{\nu} S^2 h \]

Strumia et al. 2013