Higgs and physics Beyond the SM

1.- Higgs

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8th IDPASC School

IFIC, 21–28/05/2018

The Stardard Model

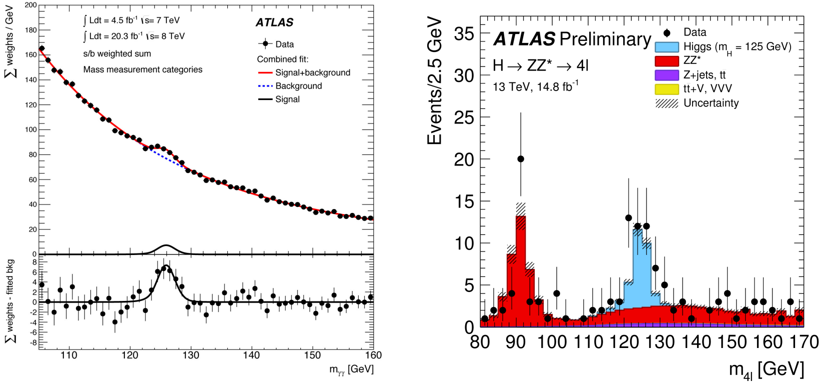
Gauge symmetry: $SU(3) \otimes SU(2)_L \otimes U(1)_Y$

Particle content:

Repr.	Q_L	u_R^c	d_R^c	H
Q. numb.	$(3, 2, \frac{1}{6})$	$(\bar{3}, 1, -\frac{2}{3})$	$(\bar{3}, 1, \frac{1}{3})$	$(1, 2, -\frac{1}{2})$
Spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	0
Repr.	L_L	e_R^c	ν_R^c	
Q. numb.	$(1, 2, -\frac{1}{2})$	$(1, 1, 1)$	$(1, 1, 0)$	
Spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	

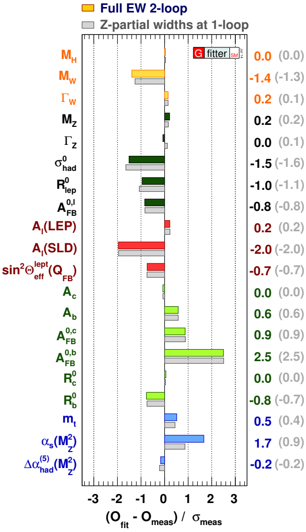
Plus scalar potential, $V_H = \mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2$, and Yukawa couplings...

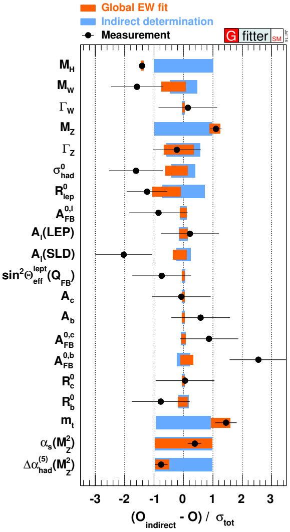
4th July 2012



"Higgs" discovered. But, is it the SM Higgs??

EW Global Fit





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Have we finished with fundamental physics??
or can we expect Physics Beyond the SM???

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We DO need Physics Beyond the SM !!

2 Higgs Doublet Models (2HDM)

Why a single scalar-doublet representation in SM??

Minimal possible extension of the SM:
addition of a second scalar doublet,
Φ_1, Φ_2, with the same hypercharge.

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$$\mathcal{L}_Y = Y_{ij}^{(1)} Q_i d_j^c \Phi_1 + Y_{ij}^{(2)} Q_i d_j^c \Phi_2$$

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Theory and phenomenology of two-Higgs-doublet models G.C. Branco, *et al.*, Phys.Rept. 516 (2012) 1-102

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- Type I 2HDM

Only Φ_1 charged under Z_2

$$\Phi_1 \to -\Phi_1, \quad \Phi_2 \to \Phi_2, \quad \Psi_i \to \Psi_i$$

$$\mathcal{L}_Y = Y^d_{ij} Q_i d^c_j \Phi_2 + Y^u_{ij} Q_i u^c_j \tilde{\Phi}_2 \qquad \tilde{\Phi}_i = i\tau_2 \Phi^*_i$$

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- Type II 2HDM

Φ_1 and d^c_R charged under Z_2

$$\Phi_1 \to -\Phi_1, \quad \Phi_2 \to \Phi_2, \quad d^c_R \to -d^c_R, \quad \Psi_i \to \Psi_i$$

$$\mathcal{L}_Y = Y^d_{ij} Q_i d^c_j \Phi_1 + Y^u_{ij} Q_i u^c_j \tilde{\Phi}_2$$

2HDM Scalar potential

General scalar potential (real, Z_2 softly broken) with two doublets:

$$
\begin{aligned}
V_H &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 \right) + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 \\
&+ \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 + \lambda_3 \, \Phi_1^\dagger \Phi_1 \, \Phi_2^\dagger \Phi_2 + \lambda_4 \, \Phi_1^\dagger \Phi_2 \, \Phi_2^\dagger \Phi_1 \\
&+ \frac{\lambda_5}{2} \left[\left(\Phi_1^\dagger \Phi_2 \right)^2 + \left(\Phi_1^\dagger \Phi_2 \right)^2 \right]
\end{aligned}
$$

Minimization of the potential preserving electric charge:

$$
\begin{aligned}
\Phi_1 &= \begin{pmatrix} \phi_1^+ \\ (v_1 + \rho_1 + i\eta_1)/\sqrt{2} \end{pmatrix} \longrightarrow \langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix} \\
\Phi_2 &= \begin{pmatrix} \phi_2^+ \\ (v_2 + \rho_2 + i\eta_2)/\sqrt{2} \end{pmatrix} \longrightarrow \langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}
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$$\lambda_1 \geq 0, \quad \lambda_2 \geq 0, \quad \lambda_3 \geq -\sqrt{\lambda_1 \lambda_2},$$
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On the other hand, quadratic terms can be negative for some values of the fields $\rightarrow$ spontaneous symmetry breaking.

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This must be checked after loop corrections and for all scales (μ)...

$$V(\phi_i) = V_{\mathrm{tree}}(\phi_i) + \frac{1}{64\pi^2} \sum_{\alpha} m_\alpha^4(\phi_i) \left[\log \left(\frac{m_\alpha^2(\phi_i)}{\mu^2} \right) - \frac{3}{2} \right]$$

S. Coleman & E. Weinberg.

In the minimum EW symmetry is broken: $v^2 = v_1^2 + v_2^2$ and $\tan\beta = \frac{v_1}{v_2}$, with v_1 and v_2 functions of the parametrers of the potential, m_{ij}^2 and λ_i.

$\Rightarrow$ Five physical scalars: $H^{\pm}$, H, h, A.

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$\Rightarrow$ **Five physical scalars: $H^\pm$, H, h, A.**

Charged scalars

$$\mathcal{L}_{m^\pm} = \frac{m_+^2}{v^2} \begin{pmatrix} \phi_1^- & \phi_2^- \end{pmatrix} \begin{pmatrix} v_2^2 & -v_1 v_2 \\ -v_1 v_2 & v_1^2 \end{pmatrix} \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix},$$

with, $m_+^2 = \left[m_{12}^2/(v_1 v_2) - \lambda_4 - \lambda_5\right]\left(v_1^2 + v_2^2\right)$ the mass of the charged Higgs $H^\pm = -\phi_1^\pm \sin\beta + \phi_2^\pm \cos\beta$, and a zero eigenvalue (Goldstone boson, $G^\pm$) eaten by $W^\pm$.

Pseudoscalar

$$\mathcal{L}_A = \frac{m_A^2}{v^2} \begin{pmatrix} \eta_1 & \eta_2 \end{pmatrix} \begin{pmatrix} v_2^2 & -v_1 v_2 \\ -v_1 v_2 & v_1^2 \end{pmatrix} \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix},$$

with, $m_A^2 = \left[m_{12}^2/(v_1 v_2) - 2\lambda_5\right]\left(v_1^2 + v_2^2\right)$ the mass of the pseudoscalar, and a Goldstone boson, G^0 eaten by Z^0.

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Neutral scalars

$$\mathcal{L}_H = -\begin{pmatrix} \rho_1 & \rho_2 \end{pmatrix} \begin{pmatrix} m_{12}^2 \frac{v_2}{v_1} + \lambda_1 v_1^2 & -m_{12}^2 + \lambda_{345} v_1 v_2 \\ -m_{12}^2 + \lambda_{345} v_1 v_2 & m_{12}^2 \frac{v_1}{v_2} + \lambda_2 v_2^2 \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} ,$$

with, $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$. Two physical neutral scalars:

light Higgs, $h = \rho_1 \sin\alpha - \rho_2 \cos\alpha$ and

heavy Higgs, $H = -\rho_1 \cos\alpha - \rho_2 \sin\alpha$

Type-III 2HDM

Tree-level FCNCs can still be present if suficiently small...

$$\mathcal{L}_Y = \eta^d_{ij} Q_i d^c_j \Phi_1 + \eta^u_{ij} Q_i u^c_j \tilde{\Phi}_1 + \xi^d_{ij} Q_i d^c_j \Phi_2 + \xi^u_{ij} Q_i u^c_j \tilde{\Phi}_2$$

- Cheng-Sher ansatz: $\xi_{ij} = \lambda_{ij} \sqrt{m_i m_j}\, \frac{\sqrt{2}}{v}$, with $\lambda_{ij} \sim \mathcal{O}(1)$.
- Minimal Flavour Violation (MFV) ($\sim$ Branco-Grimus-Lavoura):
  $\Longrightarrow$ All FC proportional to CKM matrix.
- Alignment models (Pich-Tuzon): Proportionality of η and ξ Yukawa matrices: $\xi^d_{ij} = \eta^d_{ij}$, $\xi^u_{ij} = \eta^u_{ij}$.

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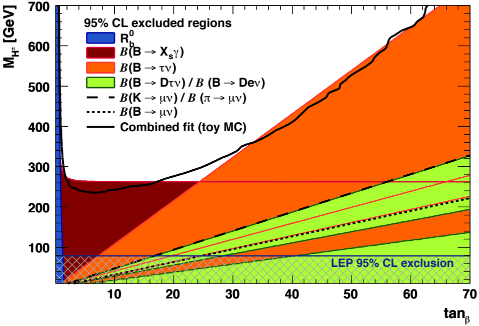
Somewhat *ad hoc* models, but can be motivated with flavour symmetries ...

2HDM phenomenology

B-physics constraints

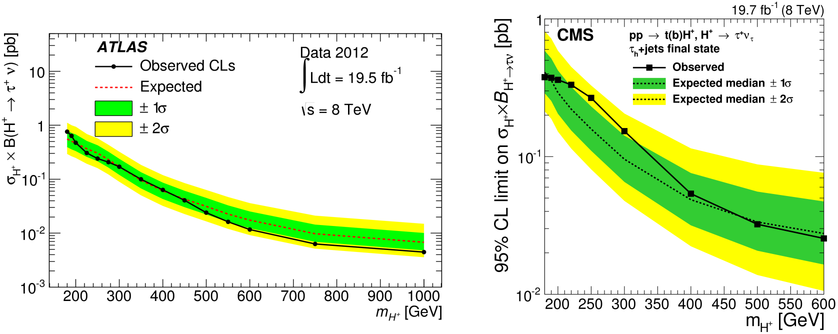
From low-energy observables: $B \to \tau\nu_\tau$, $B \to D\tau\nu_\tau$, $D_s \to \tau\nu_\tau$, $B \to X_s\gamma$, $B_0 - \bar{B}_0$ mixing.



Additional Higgs scalars ($m^2_{H^+} \simeq m^2_H \simeq m^2_A$) above 300 GeV for low $\tan\beta$ and even 600 GeV for $\tan\beta = 50$.

LHC bounds

Searches in $pp \to tH^+ \to t\tau^+\nu$ and $pp \to tH^+ \to t\ t\bar{b}$.



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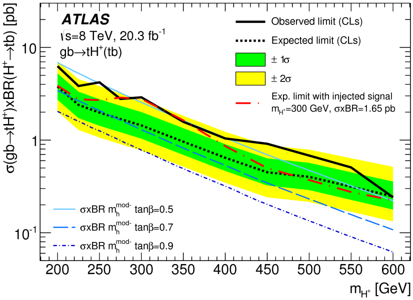

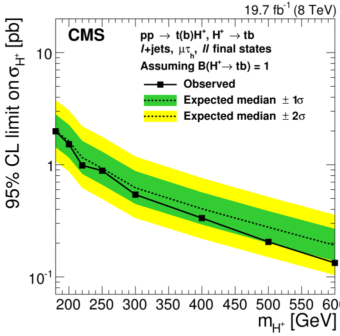

Model independent bounds on Higgs production at LHC. No sign found so far. . .

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We DO need Physics Beyond the SM !!

- Only possible extension of symmetry beyond Lie Symmetries (Coleman–Mandula Theorem).
- Correct Unification of Gauge couplings at M_{GUT}, GUT assignment of Quantum numbers (anomaly cancellation).
- Solution of the Hierarchy Problem, strong motivation for low-energy SUSY.
- "Natural" Mechanism of Electroweak Symmetry Breaking , Radiative Symmetry Breaking.
- SUSY is a necessary ingredient in String Theory. Local Supersymmetry $\Leftrightarrow$ Supergravity.

Coleman–Mandula Theorem

In the 60's attempts to combine internal and Lorentz symmetries ...

> The only conserved quantities that transform as tensors under Lorentz transformations in a theory with non-zero scattering amplitudes in 4D are the generators of the Poincare group and Lorentz invariant quantum numbers (scalar charges).

2×2 spinless particle scattering, bosonic conserved charge, $\Sigma_{\mu\nu}$,

$$\langle 1|\Sigma_{\mu\nu}|1\rangle = \alpha p^1_\mu p^1_\nu + \beta g_{\mu\nu}$$

So, in the scattering process,

$$p^1_\mu p^1_\nu + p^2_\mu p^2_\nu = p^3_\mu p^3_\nu + p^4_\mu p^4_\nu \quad \& \quad p^1_\mu + p^2_\mu = p^3_\mu + p^4_\mu$$

Not possible in a theory with non-zero scattering.

However: Coleman–Mandula theorem does not forbid conserved spinor charges, Q_α (transforming like fermions under Lorentz)

$$Q_\alpha|\text{Boson}\rangle = |\text{Fermion}\rangle \qquad Q_\alpha|\text{Fermion}\rangle = |\text{Boson}\rangle$$

$$[Q_\alpha, H] = 0 \qquad [\{Q_\alpha, \bar{Q}_{\dot\beta}\}, H] = 0$$

Supersymmetry Algebra

$$\{Q_\alpha, \bar{Q}_{\dot\beta}\} = 2\sigma^\mu_{\alpha\dot\beta} P_\mu \qquad \{Q_\alpha, Q_\beta\} = 0 \qquad \{\bar{Q}_{\dot\alpha}, \bar{Q}_{\dot\beta}\} = 0$$

Supersymmetry relates particles of different spin with equal quantum numbers and identical masses.

$$\left(\begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix}\right) \sim \left(\begin{pmatrix} q \ (\text{quark}) \\ \tilde{q} \ (\text{squark}) \end{pmatrix}\right) \qquad \left(\begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix}\right) \sim \left(\begin{pmatrix} g \ (\text{gluon}) \\ \tilde{g} \ (\text{gluino}) \end{pmatrix}\right)$$

Chiral supermultiplet Gauge supermultiplet