Higgs Physics

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Outline

1) The Higgs Boson
   • Higgs Mechanism
   • Standard Model Higgs
   • LHC data
   • Higgs-singlet extension

2) Aspects of EWSB
   • Naturalness
   • Vacuum stability
   • Custodial Symmetry
   • Unitarity

3) Two Higgs Doublets
   • FCNCs
   • Flavour alignment
   • Flavour bounds
   • LHC constraints
   • EDMs
   • Rare decays
A New Higgs-Like Boson

\[ \begin{align*}
H & \rightarrow \gamma\gamma \\
H & \rightarrow ZZ^* \rightarrow 4\ell \\
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H & \rightarrow ZZ^* \rightarrow 4\ell
\end{align*} \]

\[ M_H = (125.09 \pm 0.21 \pm 0.11) \text{ GeV} \]

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Great success of the Standard Model

BEGHHK (≡ Higgs) Mechanism

Kibble, Guralnik, Hagen, Englert, Brout

Higgs, 1964

\[ v = 246 \text{ GeV} \]

\[ M_Z \cos \theta_W = M_W = \frac{1}{2} v g \]

\[ \text{SU}(2)_L \otimes \text{U}(1)_Y \]
Beautiful Discovery

Boson, $J = 0$

Fermions = Matter ; Bosons = Forces

- **Fundamental Boson:** New interaction which is not gauge
- **Composite Boson:** New underlying dynamics
Beautiful Discovery

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If New Physics exists at \( \Lambda_{NP} \)

\[
\delta M_H^2 \sim \frac{g^2}{(4\pi)^2} \Lambda_{NP}^2 \log \left( \frac{\Lambda_{NP}^2}{M_H^2} \right)
\]

Which symmetry keeps \( M_H \) away from \( \Lambda_{NP} \)?

- Fermions: Chiral Symmetry
- Gauge Bosons: Gauge Symmetry
- Scalar Bosons: Supersymmetry, Scale/Conformal Symmetry . . . ?
Possible Scenarios of EWSB

1. **SM Higgs:** Favoured by EW precision tests

2. **Alternative perturbative EWSB:**

   Scalar Doublets and singlets

   \[
   \rho_{\text{tree}} = \frac{M_W^2}{M_Z^2 c_W^2} = \frac{\sum_i \nu_i^2 [T_i (T_i + 1) - Y_i^2]}{2 \sum_i \nu_i^2 Y_i^2}
   \]

3. **Dynamical (non-perturbative) EWSB:**

   Pseudo-Goldstone Higgs

   Scalar Resonance
Possible Scenarios of EWSB

1. SM Higgs: Favoured by EW precision tests

2. Alternative perturbative EWSB:
   - Scalar Doublets and singlets
   
   $\rho_{\text{tree}} = \frac{M_W^2}{M_Z^2 c_W^2} = \frac{\sum_i \psi_i^2 [T_i(T_i+1) - \gamma_i^2]}{2 \sum_i \psi_i^2 \gamma_i^2}$

3. Dynamical (non-perturbative) EWSB:
   - Pseudo-Goldstone Higgs
   - Scalar Resonance
Higgs Mechanism:

Gauge invariance

Massless $W^\pm, Z$ (spin 1)

$3 \times 2$ polarizations $= 6$
Higgs Mechanism: 3 additional degrees of freedom $\varphi_i(x)$

Gauge invariance

Massless $W^\pm, Z$ (spin 1)

$3 \times 2$ polarizations $= 6$

+ $3$ Goldstones $\varphi_i(x)$

SSB

Massive $W^\pm, Z$

$3 \times 3$ polarizations $= 9$
Higgs Mechanism: 3 additional degrees of freedom $\varphi_i(x)$

**Gauge invariance**

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**Spontaneous Symmetry Breaking**

$L_\Phi = (D_\mu \Phi)^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$

$\mu^2 < 0$

$$\Phi(x) = \exp \left\{ i \vec{\sigma} \cdot \vec{\varphi}(x) \right\} \frac{1}{\sqrt{2}} \begin{bmatrix} v & 0 \\ v + H(x) \end{bmatrix}$$
Higgs Mechanism: 3 additional degrees of freedom $\varphi_i(x)$

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$+$

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SSB

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$D_\mu \Phi = (\partial_\mu + \frac{i}{2} g \vec{\sigma} \cdot \vec{W}_\mu + \frac{i}{2} g' B_\mu) \Phi$ ; \quad $v^2 = -\mu^2 / \lambda$

$(D_\mu \Phi)^\dagger D^\mu \Phi \rightarrow M_W^2 W_\mu^\dagger W^\mu + \frac{M_Z^2}{2} Z_\mu Z^\mu$

$M_W = M_Z \cos \theta_W = \frac{1}{2} g v$

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$(D_\mu \Phi)^\dagger D^\mu \Phi \rightarrow M_{W}^2 W_\mu^\dagger W^\mu + \frac{M_Z^2}{2} Z_\mu Z^\mu \times (1 + \frac{H}{v})^2$

$M_{W} = M_{Z} \cos \theta_{W} = \frac{1}{2} g v$

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Higgs Physics 7
\[
\Phi(x) = \exp \left\{ \frac{i}{v} \vec{\sigma} \vec{\phi}(x) \right\} \frac{1}{\sqrt{2}} \left[ v + H(x) \right]
\]

\[
V(\Phi) + \frac{\lambda}{4} v^4 = \lambda \left( |\Phi|^2 - \frac{v^2}{2} \right)^2 = \frac{1}{2} M_H^2 H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4
\]

\[
v = \frac{2M_W}{g} = \left( \sqrt{2} G_F \right)^{-1/2} = 246 \text{ GeV}
\]

\[
M_H = (125.09 \pm 0.24) \text{ GeV}
\]

\[
\lambda = \frac{M_H^2}{2v^2} = 0.13
\]
Standard Model Yukawas

\( \Phi = \begin{pmatrix} \phi^+(1) \\ \phi^0(0) \end{pmatrix} \), \( \langle 0 | \Phi | 0 \rangle = \begin{pmatrix} 0 \\ \frac{\nu}{\sqrt{2}} \end{pmatrix} \), \( \bar{\Phi} \equiv i \tau_2 \Phi^* \)

\[ \mathcal{L}_Y = -c_1 (\bar{u}_L, \bar{d}_L) \Phi d_R - c_2 (\bar{u}_L, \bar{d}_L) \bar{\Phi} u_R - c_3 (\bar{\nu}_L, \bar{e}_L) \Phi e_R + \text{h.c.} \]

SSB

\[ \mathcal{L}_Y = - (1 + \frac{H}{\nu}) \left\{ m_d \bar{d}d + m_u \bar{u}u + m_e \bar{e}e \right\} \]

\[ m_d = c_1 \frac{\nu}{\sqrt{2}}, \quad m_u = c_2 \frac{\nu}{\sqrt{2}}, \quad m_e = c_3 \frac{\nu}{\sqrt{2}} \]

Couplings proportional to masses
Signal Strengths

\[ \mu \equiv \sigma \cdot \text{Br}/(\sigma \cdot \text{Br})_{\text{SM}} \]

**ATLAS Preliminary**

- \( m_H = 125.36 \text{ GeV} \)

| Decay Mode | ATLAS \((M_H = 125.36 \text{ GeV})\) | CMS \((M_H = 125.0 \text{ GeV})\) |
|------------|----------------------------------|----------------------------------|
| \( H \to bb \) | \( 0.63 \pm 0.39 \) | \( 0.84 \pm 0.44 \) |
| \( H \to \tau\tau \) | \( 1.44 \pm 0.42 \) | \( 0.91 \pm 0.28 \) |
| \( H \to \gamma\gamma \) | \( 1.17 \pm 0.28 \) | \( 1.12 \pm 0.24 \) |
| \( H \to WW^* \) | \( 1.18 \pm 0.24 \) | \( 0.83 \pm 0.21 \) |
| \( H \to ZZ^* \) | \( 1.46 \pm 0.40 \) | \( 1.00 \pm 0.29 \) |
| Combined | \( 1.18 \pm 0.15 \) | \( 1.00 \pm 0.14 \) |

\[ \langle \mu \rangle = 1.09 \pm 0.10 \]

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Production Channels

Gluon Fusion

Vector Boson Fusion

$V = W^{\pm}, Z$

Ass. VH Production

Ass. $t\bar{t}H$ Production

ATLAS Preliminary

$\sqrt{s} = 7$ TeV, 4.5-4.7 fb$^{-1}$

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

$H_{m}^{*}$

$WW \rightarrow H_{m}^{*}$

$ZZ \rightarrow H_{m}^{*}$

$bb \rightarrow H_{m}^{*}$

$\tau \tau \rightarrow H_{m}^{*}$

CMS

$19.7$ fb$^{-1} (8$ TeV$) + 5.1$ fb$^{-1} (7$ TeV$)$

$H \rightarrow \gamma \gamma$ tagged

$H \rightarrow ZZ$ tagged

$H \rightarrow WW$ tagged

$H \rightarrow \tau \tau$ tagged

$H \rightarrow bb$ tagged

SM Higgs

A. Pich Higgs Physics
Strong (indirect) evidence for Higgs coupling to \( t \)

Dominant Production Mechanism

\[ \Gamma \sim |1 - 0.21|^2 \]

\( \kappa_i \equiv \frac{g_i}{g_i^{\text{SM}}} \)

| \( H \to \gamma \gamma \) | Signal Strength |
|-----------------|----------------|
| ATLAS \( 7 \text{ TeV} \) | \( 1.17 \pm 0.28 \) |
| CMS \( 8 \text{ TeV} \) | \( 1.12 \pm 0.24 \) |

Direct (tree-level) sensitivity through \( t\bar{t}H \)
Strong evidence for Higgs coupling to $\tau$ and $b$

### Signal Strength

| Signal | ATLAS ($M_H = 125.36 \text{ GeV}$) | CMS ($M_H = 125.0 \text{ GeV}$) |
|--------|-------------------------------|-------------------------------|
| $H \rightarrow bb$ | $0.63^{+0.39}_{-0.37}$ | $0.84 \pm 0.44$ |
| $H \rightarrow \tau\tau$ | $1.44^{+0.42}_{-0.37}$ | $0.91 \pm 0.28$ |
**Effective Couplings**

\[ \kappa_i \equiv \frac{g_i}{g_i}^{\text{SM}} \]

\[ \sigma(i \rightarrow H) \cdot \text{Br}(H \rightarrow f) = \sigma(i \rightarrow H) \cdot \frac{\Gamma(H \rightarrow f)}{\Gamma_H} \sim \left(\frac{\kappa_i \kappa_f}{\kappa_H}\right)^2 \]
It is a Higgs Boson

\[ \lambda_f = \left( \frac{m_f}{M} \right)^{1+\epsilon} , \quad (\frac{g_V}{2v})^{1/2} = (\frac{M_V}{M})^{1+\epsilon} \]

Ellis-You, 1303.3879

SM: \( \epsilon = 0 \), \( M = v = 246 \) GeV

CMS: (95% CL) \( \epsilon \in [-0.054, 0.100] \), \( M \in [217, 279] \) GeV
QCD Exotics

\[ X \in SU(3)_C \quad \text{representation} \quad R \]

\[ g \xrightarrow{X} H \sim \sum_a^{d_A} \text{Tr} \left[ t^a_R t^a_R \right] = C_R d_R \]

Non decoupling: \[ \mathcal{L} = -\frac{M_X}{v} (\bar{X} X) H \]

Exotic fermions in higher-colour representations could only exist provided their masses are not generated by the SM Higgs

(or fine-tuned cancelations with scalar loops)
Higgs-Singlet Extension of the SM

\[ V(\Phi, S) = \lambda \left( |\Phi|^2 - \frac{v^2}{2} \right)^2 + (a_\Phi S + b_\Phi S^2) \left( |\Phi|^2 - \frac{v^2}{2} \right) + \frac{1}{2} M_S^2 S^2 + a_S S^3 + \lambda_S S^4 \]

- Real singlet and neutral field: \( S = S^\dagger \)
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- Real singlet and neutral field: \( S = S^\dagger \)
- Minima: \( \langle S \rangle = 0 \), \( \langle \phi^{(0)} \rangle = \frac{v}{\sqrt{2}} \)
  \[ \phi^{(0)} = \frac{1}{\sqrt{2}} (v + \varphi) \]

\( M_S^2 > \frac{a_\Phi}{4\lambda} > 0 \)

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Higgs Physics
Higgs-Singlet Extension of the SM

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  \[ M_S^2 > a_\Phi^2 / (4\lambda) > 0 \]
- Positive growing at large field values: \( \lambda, \lambda_S, b_\Phi > 0 \)
Higgs-Singlet Extension of the SM

\[ V(\Phi, S) = \lambda \left( |\Phi|^2 - \frac{v^2}{2} \right)^2 + \left( a_\Phi S + b_\Phi S^2 \right) \left( |\Phi|^2 - \frac{v^2}{2} \right) + \frac{1}{2} M_S^2 S^2 + a_S S^3 + \lambda_S S^4 \]

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  \[ M_S^2 > a_\Phi^2 / (4\lambda) > 0 \]
- Positive growing at large field values: \( \lambda, \lambda_S, b_\Phi > 0 \)
- Mass eigenstates (**mixing**):
\[ V(\Phi, S) = \lambda \left( |\Phi|^2 - \frac{v^2}{2} \right)^2 + (a_\Phi S + b_\Phi S^2) \left( |\Phi|^2 - \frac{v^2}{2} \right) + \frac{1}{2} M_S^2 S^2 + a_S S^3 + \lambda_S S^4 \]

- Real singlet and neutral field: \[ S = S^\dagger \]
- Minima:\[ \langle S \rangle = 0 , \quad \langle \phi^{(0)} \rangle = \frac{v}{\sqrt{2}} \quad \phi^{(0)} = \frac{1}{\sqrt{2}} (v + \varphi) \]

\[ M_S^2 > a_\Phi^2 / (4\lambda) > 0 \]

- Positive growing at large field values: \( \lambda, \lambda_S, b_\Phi > 0 \)
- Mass eigenstates (mixing): \[ (-\frac{\pi}{2} \leq \alpha \leq \frac{\pi}{2}) \]

\[
\begin{pmatrix} h \\ H \end{pmatrix} = \begin{bmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{bmatrix} \begin{pmatrix} \varphi \\ S \end{pmatrix}, \quad \tan 2\alpha = \frac{2a_\Phi v}{2v^2\lambda - M_S^2} \]

\[ M_h^2 = \frac{1}{2} (\Sigma - \Delta) < M_H^2 = \frac{1}{2} (\Sigma + \Delta) \]

\[ \Sigma = 2v^2\lambda + M_S^2 , \quad \Delta = \sqrt{(2v^2\lambda - M_S^2)^2 + 4a_\Phi^2 v^2} \]
The singlet scalar does not couple to fermions and gauge bosons

\[ \kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\text{SM}}} = \cos \alpha \quad , \quad \kappa_f \equiv \frac{y_{hff}}{y_{hff}^{\text{SM}}} = \cos \alpha \]
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\[ \text{Br}(h \rightarrow f) = \text{Br}(h \rightarrow f)^{SM} \]
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Signal Strengths:

\[ \mu_h = \cos^2 \alpha \]

\[ \text{Br}(h \rightarrow f) = \text{Br}(h \rightarrow f)_\text{SM} \]
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Signal Strengths:

\[ \text{Br}(h \rightarrow f) = \text{Br}(h \rightarrow f)^{SM} \]

\[ \mu_h = \cos^2 \alpha , \quad \mu_{H \rightarrow VV, f\bar{f}} = \sin^2 \alpha [1 - \text{Br}(H \rightarrow hh)] \]
The singlet scalar does not couple to fermions and gauge bosons

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**Signal Strengths:**

\[ \text{Br}(h \rightarrow f) = \text{Br}(h \rightarrow f)_{SM} \]

\[ \mu_h = \cos^2 \alpha \quad , \quad \mu_{H \rightarrow VV, f\bar{f}} = \sin^2 \alpha [1 - \text{Br}(H \rightarrow hh)] \]

\[ m = M_H \quad , \quad \lambda_1 = \lambda \]

\[ \tan \beta = 4v\lambda_S / a_S \]

Robens-Stefaniak, 1501.02234
\[ M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi \alpha}{\sqrt{2}} (1 + \Delta r) \]

\[ \delta(\Delta r) = \Delta r_H^H + \Delta r_h - \Delta r_{SM} \propto \sin^2 \alpha \]

\[ \sin^2 \alpha \]

\[ \cos^2 \alpha - 1 \]
Backup Slides
Higgs Width

Sensitivity to $\Gamma_H$ off-shell:

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm_{ZZ}^2} \sim \frac{g_{ggH}^2 g_{hZZ}^2}{(m_{ZZ}^2 - M_H^2)^2 + M_H^2 \Gamma_H^2}$$

$\sigma_{gg\to H\to ZZ} \sim \left\{ \begin{array}{ll}
\frac{g_{ggH}^2 g_{hZZ}^2}{M_H \Gamma_H} & \text{(on-shell)} \\
\frac{g_{ggH}^2 g_{hZZ}^2}{4M_Z^2} & \text{($m_{ZZ} > 2M_Z$)}
\end{array} \right.$

CMS, 1405.3455

$$\Gamma_H < 5.4 \frac{\Gamma_H^{SM}}{\Gamma_H^{SM}} = 22 \text{ MeV} \quad (95\% \text{ CL})$$

ATLAS-CONF-2014-042:

$$\Gamma_H < 5.7 \frac{\Gamma_H^{SM}}{\Gamma_H^{SM}}$$

Assumes constant couplings unrelated to $\Delta \Gamma_H$

Englert-Spannowsky, 1405.0285
Alternative analysis:

\[ \mathcal{L} = -c_t \frac{m_t}{v} \bar{t} t H + \frac{g_s^2}{48\pi^2 v^2} c_g G_{\mu\nu} G^{\mu\nu} H \]

\[ \sigma \sim |c_t + c_g|^2 \quad \text{(on-shell)} \]

\[ \mathcal{M}_{c_g} \sim c_g \hat{s} \quad (\hat{s} \gg m_t^2) \]
Invisible Higgs Width

$\ln L$ vs $\Delta - 2$

-2 $\Delta \ln L$ vs $Br_{BSM}$
-2 $\Delta \ln L$ vs $Br_{inv}$

Observed vs Exp. for SM H

$\kappa_{\gamma}$, $\kappa_{g}$, $Br_{BSM}$
$\kappa_{\gamma}$, $\kappa_{g}$, $Br_{inv}$
$\kappa_{\gamma} = 1$, $\kappa_{g} = 1$, $Br_{inv}$

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Higgs Physics

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