Lecture 3

Higgs couplings: present status and future strategies
Effective Lagrangian for a light Higgs-like boson

**RULES:**

- Do not assume $SU(2)_L \times U(1)_Y$ is linearly realized at high energy
- Do not assume $h(x)$ forms a doublet of $SU(2)_L$ with longitudinal $W,Z$
- Each extra derivative costs a factor $1/\Lambda$
- Each extra power of $h(x)$ costs a factor $g_*/\Lambda$
Effective Lagrangian for a light Higgs-like boson

**Rules:**

- Do not assume $\text{SU}(2)_L \times \text{U}(1)_Y$ is linearly realized at high energy

- Do not assume $h(x)$ forms a doublet of $\text{SU}(2)_L$ with longitudinal $W,Z$

- Each extra derivative costs a factor $1/\Lambda$

- Each extra power of $h(x)$ costs a factor $g_*/\Lambda$

leading operators in the case of a strongly-interacting Higgs

Giudice, Grojean, Pomarol, Rattazzi, JHEP 0706 (2007) 045
Effective Lagrangian for a light Higgs-like boson

RULES:

- Do not assume SU(2)_L x U(1)_Y is linearly realized at high energy
- Do not assume h(x) forms a doublet of SU(2)_L with longitudinal W,Z
- Each extra derivative costs a factor 1/Λ
- Each extra power of h(x) costs a factor g*/Λ

VALIDITY:

- Must be used as an effective Lagrangian: some quantities are calculable, some others are not
- No problem to use it at loop-level

Giudice, Grojean, Pomarol, Rattazzi, JHEP 0706 (2007) 045
Effective Lagrangian for a light Higgs-like boson

\[ \mathcal{L} = \frac{1}{2} (\partial_\mu h)^2 - \frac{1}{2} m_h^2 h^2 - \frac{d_3}{6} \left( \frac{3m_h^2}{v} \right) h^3 - \frac{d_4}{24} \left( \frac{3m_h^2}{v^2} \right) h^4 \ldots \]

\[ - \left( m_W^2 W_\mu W_\mu + \frac{1}{2} m_Z^2 Z_\mu Z_\mu \right) \left( 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + \ldots \right) \]

\[ - \sum_{\psi = u, d, l} m_{\psi(i)} \bar{\psi}^{(i)}(i) \psi^{(i)} \left( 1 + c_\psi \frac{h}{v} + c_{2\psi} \frac{h^2}{v^2} + \ldots \right) \]

\[ + \frac{g^2}{16\pi^2} \left( c_{WW} W^+_{\mu\nu} W^-_{\mu\nu} + c_{ZZ} Z^2_{\mu\nu} + c_{Z\gamma} Z_{\mu\nu} \gamma_{\mu\nu} \right) \frac{h}{v} + \ldots \]

\[ + \frac{g^2}{16\pi^2} \left[ \gamma^2_{\mu\nu} \left( c_{\gamma\gamma} \frac{h}{v} + \ldots \right) + G^2_{\mu\nu} \left( c_{gg} \frac{h}{v} + c_{2gg} \frac{h^2}{v^2} + \ldots \right) \right] \]

\[ + \frac{g^2}{16\pi^2} \left[ \frac{c_{hhgg}}{\Lambda^2} G^2_{\mu\nu} \frac{(\partial_\rho h)^2}{v^2} + \frac{c'_{hhgg}}{\Lambda^2} G_\mu G_\nu \frac{\partial_\mu h \partial_\nu h}{v^2} + \ldots \right] \]

\[ + \ldots \]
Effective Lagrangian for a light Higgs-like boson

\[ \mathcal{L} = \frac{1}{2} (\partial_\mu h)^2 - \frac{1}{2} m_h^2 h^2 - \frac{d_3}{6} \left( \frac{3 m_h^2}{v} \right) h^3 - \frac{d_4}{24} \left( \frac{3 m_h^2}{v^2} \right) h^4 + \ldots \]

\[- \left( m_W^2 W_\mu W_\mu + \frac{1}{2} m_Z^2 Z_\mu Z_\mu \right) \left( 1 + \frac{2a h}{v} + b \frac{h^2}{v^2} + \ldots \right) \]

\[- \sum_{\psi = u,d,l} m_\psi \bar{\psi}^{(i)} \psi^{(i)} \left( 1 + c_\psi \frac{h}{v} + c_2^\psi \frac{h^2}{v^2} + \ldots \right) \]

\[+ \frac{g^2}{16\pi^2} \left( c_{WW} W_\mu^+ W_\mu^- + c_{ZZ} Z_\mu^+ Z_\mu^- + c_\gamma Z_\mu^+ \gamma_{\mu\nu} \right) \frac{h}{v} + \ldots \]

\[+ \frac{g^2}{16\pi^2} \left[ \gamma_{\mu\nu} \left( c_\gamma \frac{h}{v} + \ldots \right) + G_{\mu\nu}^2 \left( c_{gg} \frac{h}{v} + c_{2gg} \frac{h^2}{v^2} + \ldots \right) \right] \]

\[+ \frac{g^2}{16\pi^2} \left[ \frac{c_{hhgg}}{\Lambda^2} G_{\mu\nu}^2 \frac{(\partial_\rho h)^2}{v^2} + \frac{c'_{hhgg}}{\Lambda^2} G_{\mu\rho} G_{\nu\rho} \frac{\partial_\mu h \partial_\nu h}{v^2} + \ldots \right] \]

\[+ \ldots \]

Controls the $hWW, hZZ$ couplings

\[ = a \cdot g_{hWW}^{SM} \]

RC, Grojean, Moretti, Piccinini, Rattazzi, JHEP 1005 (2010) 089
Effective Lagrangian for a light Higgs-like boson

\[ \mathcal{L} = \frac{1}{2} h^2 \left( \partial_{\mu} h \right)^2 - \frac{1}{2} m_h^2 h^2 - \frac{d_3}{6} (\frac{3m_h^2}{v}) h^3 - \frac{d_4}{24} (\frac{3m_h^2}{v^2}) h^4 \ldots \]

Controls the \( h\psi\psi \) coupling

\[- \left( m_W^2 W_{\mu} W_{\mu} + \frac{1}{2} m_Z^2 Z_{\mu} Z_{\mu} \right) \left( 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + \ldots \right) \]

\[- \sum_{\psi=u,d,l} m_{\psi(i)} \bar{\psi}^{(i)} \psi^{(i)} \left( 1 - c_{\psi} \frac{h}{v} + c_{2\psi} \frac{h^2}{v^2} + \ldots \right) \]

\[ + \frac{g^2}{16\pi^2} \left( c_{WW} W_{\mu\nu} W_{\mu\nu} + c_{ZZ} Z_{\mu\nu}^2 + c_{Z\gamma} Z_{\mu\nu} \gamma_{\mu\nu} \right) \frac{h}{v} + \ldots \]

\[ + \frac{g^2}{16\pi^2} \left[ \gamma_{\mu\nu}^{2} \left( c_{\gamma\gamma} \frac{h}{v} + \ldots \right) + G_{\mu\nu}^{2} \left( c_{gg} \frac{h}{v} + c_{2gg} \frac{h^2}{v^2} + \ldots \right) \right] \]

\[ + \frac{g^2}{16\pi^2} \left[ \frac{c_{hgg}}{\Lambda^2} G_{\mu\nu}^{2} \frac{(\partial_{\rho} h)^2}{v^2} + \frac{c'_{hgg}}{\Lambda^2} G_{\mu\rho} G_{\rho\nu} \frac{\partial_{\mu} h \partial_{\nu} h}{v^2} + \ldots \right] \]

\[ + \ldots \]
Effective Lagrangian for a light Higgs-like boson

\[ \mathcal{L} = \frac{1}{2} (\partial_\mu h)^2 - \frac{1}{2} m_h^2 h^2 - \frac{d_4}{24} \left( \frac{3m_h^4}{v^2} \right) h^4 \ldots \]

**Controls the** \( h\bar{\psi}\psi \) **coupling**

\[ \mathcal{L} = c_\psi \cdot g_{h\bar{\psi}\psi}^{SM} \left( \frac{3m_h^2}{v} \right) h^3 - \frac{d_4}{24} \left( \frac{3m_h^4}{v^2} \right) h^4 \ldots \]

**E^2 correction to** \( hVV \) **couplings**

\[ c_{ij} \sim \left( \frac{g_s v}{\Lambda} \right) \]

**Controls the** \( hWW, hZZ \) **couplings**

\[ \mathcal{L} = a \cdot g_{hWW}^{SM} \]
Effective Lagrangian for a light Higgs-like boson

\[
\mathcal{L} = \frac{1}{2} h^2 - \frac{1}{2} m_h^2 h^2 - d_3 \frac{3 m_h^2}{v^2} h^4 - d_4 \frac{3 m_h^2}{v^2} h^6 - \cdots
\]

Controls the \( h \psi \psi \) coupling

\[
\mathcal{L} = c_\psi \cdot g_{h \psi \psi}^{SM} \left( \frac{3 m_h^2}{v} \right) h^3 - \frac{d_4}{24} \left( \frac{3 m_h^2}{v^2} \right) h^4 - \cdots
\]

\( E^2 \) correction to \( hVV \) couplings

\[
E^2 \sim c_{ij} \sim \left( \frac{g_s v}{\Lambda} \right)^2
\]

doublet

\[
+ \frac{g^2}{16 \pi^2} \left( c_{WW} W_{\mu \nu}^+ W_{\mu \nu}^- + c_{ZZ} Z_{\mu \nu}^2 - c_{Z \gamma} Z_{\mu \nu} \gamma_{\mu \nu} \right) \frac{h}{v} + \cdots
\]

\[
+ \frac{g^2}{16 \pi^2} \left[ \gamma_{\mu \nu}^2 \left( c_{\gamma \gamma} \frac{h}{v} + \cdots \right) + G_{\mu \nu}^2 \left( c_{gg} \frac{h}{v} + 2 c_{gg} \frac{h^2}{v^2} + \cdots \right) \right]
\]

\[
+ \frac{g^2}{16 \pi^2} \left[ \frac{c_{hhgg}}{\Lambda^2} \frac{G_{\mu \nu}^2}{v^2} + \frac{c_{hhgg}'}{\Lambda^2} G_{\mu \rho} G_{\rho \nu} \frac{\partial_\mu h \partial_\nu h}{v^2} + \cdots \right]
\]

Controls the \( hWW, hZZ \) couplings
Effective Lagrangian for a light Higgs-like boson

\[ \mathcal{L} = \sum_{i} m_{\psi(i)} \bar{\psi}^{(i)} \psi^{(i)} \left( 1 - \frac{c_{\psi} h}{v} + \frac{c_{2\psi} h^2}{v^2} + \ldots \right) \]

- \( \left( m_W^2 W_\mu W_\mu + \frac{1}{2} m_Z^2 Z_\mu Z_\mu \right) \left( 1 - \frac{h}{v} + \frac{h^2}{v^2} + \ldots \right) \)

\[ \left( \frac{3m_h^2}{v} \right) h^3 - \frac{d_4}{24} \left( \frac{3m_h^2}{v^2} \right) h^4 \ldots \]

\[ \frac{g^2}{16\pi^2} \left( c_{WW} W^+_\mu W^-_\mu + c_{ZZ} Z^2_{\mu\nu} - c_{Z\gamma} Z_{\mu\nu} \gamma_{\mu\nu} \right) \frac{h}{v} + \ldots \]

\[ \frac{g^2}{16\pi^2} \left[ \gamma^2_{\mu\nu} \left( c_{\gamma\gamma} \frac{h}{v} + \ldots \right) + G^2_{\mu\nu} \left( c_{gg} \frac{h}{v} + c_{2gg} \frac{h^2}{v^2} + \ldots \right) \right] \]

\[ \frac{g^2}{16\pi^2} \left[ \frac{c_{hhgg}}{\Lambda^2} G^2_{\mu\nu} \frac{\left( \partial_{\mu} h \right)^2}{v^2} \right] \]

Modify \( gg \) single production and \( \gamma\gamma \) decay

\[ c_{ij} \sim \left( \frac{g_s v}{\Lambda} \right)^2 \]

Control the \( h\psi\psi \) coupling

\[ = c_{\psi} \cdot g^{SM}_{h\psi\psi} \left( \frac{3m_h^2}{v} \right) \frac{h^3}{v^3} - \frac{d_4}{24} \left( \frac{3m_h^2}{v^2} \right) h^4 \ldots \]

E\(^2\) correction to \( hVV \) couplings

\[ c_{ij} \sim \left( \frac{g_s v}{\Lambda} \right) \]

Controls the \( hWW, hZZ \) couplings
Effective Lagrangian for a light Higgs-like boson

\[ \mathcal{L} = \frac{1}{2} (\partial_\mu h)^2 - \frac{1}{2} m_h^2 h^2 - \frac{d_4}{24} \left( \frac{3 m_h^2}{v^2} \right) h^4 \ldots \]

**Controls the** \( h\psi\psi \) **coupling**

\[ = c_\psi \cdot g^{SM}_{h\psi\psi} \left( \frac{3 m_h^2}{v} \right) h^3 - \frac{d_4}{24} \left( \frac{3 m_h^2}{v^2} \right) h^4 \ldots \]

\[ = c_\psi \cdot g^{SM}_{h\psi\psi} \left( \frac{3 m_h^2}{v} \right) h^3 - \frac{d_4}{24} \left( \frac{3 m_h^2}{v^2} \right) h^4 \ldots \]

\[ = a \cdot g^{SM}_{hWW} \]

**E^2 correction to** \( hVV \) **couplings**

\[ c_{ij} \sim \left( \frac{g_s v}{\Lambda} \right)^2 \]

**Modify** \( gg \) **single production and** \( \gamma\gamma \) **decay**

\[ c_{ij} \sim \left( \frac{g_s v}{\Lambda} \right)^2 \]
Effective Lagrangian for a light Higgs-like boson

\[ \mathcal{L} = \frac{1}{2} (\partial_{\mu} h)^2 - \frac{1}{2} m_h^2 h^2 - \frac{d_4}{24} \left( \frac{3 m_h^2}{v^2} \right) h^4 \ldots \]

- \left( m_W^2 W_\mu W_\mu + \frac{1}{2} m_Z^2 Z_\mu Z_\mu \right) \left( 1 + 2 \frac{h}{v} + \ldots \right)

\[ - \sum_{\psi = u, d, l} m_{\psi(i)} \bar{\psi}^{(i)}(i) \psi^{(i)} \left( 1 + c_{\psi} \frac{h}{v} + c_{2\psi} \frac{h^2}{v^2} + \ldots \right) \]

\[ + \frac{g^2}{16 \pi^2} \left( c_{WW} \left( W_+ W^- \right)^2 + c_{ZZ} \left( Z_\mu Z_\nu \gamma_{\mu\nu} \right)^2 \right) \frac{h}{v} + \ldots \]

\[ + \frac{g^2}{16 \pi^2} \left[ \left( \frac{1}{2} \gamma_{\mu\nu} \right)^2 \gamma_{\mu\nu} + \ldots \right] + G_{\mu\nu}^2 \left( \frac{c_{gg} h}{v} + c_{2gg} \frac{h^2}{v^2} + \ldots \right) \]

\[ + \frac{g^2}{16 \pi^2} \left[ \frac{c_{hgg}}{\Lambda^2} \frac{G_{\mu\nu}^2}{\Lambda^2} \left( \frac{\partial_{\rho} h}{v^2} \right)^2 \right] \]

\[ + \ldots \]

- \left( \frac{3 m_h^2}{v^2} \right) \left( \frac{\lambda^2}{g_*^2} \right) \frac{1}{\Lambda^2} \left( \frac{\lambda^2}{g_*^2} \right) \]

\[ E^2 \text{ correction to } hVV \text{ couplings} \]

\[ c_{ij} \sim \left( \frac{g_* v}{\Lambda} \right)^2 \]

\[ \text{doublet} \]

\[ \text{extra suppression for a pNG Higgs} \]

Effective Lagrangian for a light Higgs-like boson

\[ \mathcal{L} = \frac{1}{2} (\partial_\mu h)^2 - \frac{1}{2} m_h^2 h^2 - \frac{d_3}{6} \left( \frac{3m_h^2}{v} \right) h^3 - \frac{d_4}{24} \left( \frac{3m_h^2}{v^2} \right) h^4 \ldots \]

\[ - \left( m_W^2 W_\mu W_\mu + \frac{1}{2} m_Z^2 Z_\mu Z_\mu \right) \left( 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + \ldots \right) \]

\[ - \sum_{\psi = u, d, l} m_{\psi(i)} \bar{\psi}^{(i)} \psi^{(i)} \left( 1 + c_\psi \frac{h}{v} + c_{2\psi} \frac{h^2}{v^2} + \ldots \right) \]

\[ + \frac{g^2}{16\pi^2} \left( c_{WW} W_{\mu\nu}^+ W_{\mu\nu}^- + c_{ZZ} Z_{\mu\nu}^2 + c_{Z\gamma} Z_{\mu\nu} \gamma_{\mu\nu} \right) \frac{h}{v} + \ldots \]

\[ + \frac{g^2}{16\pi^2} \left[ \gamma_{\mu\nu}^2 \left( c_{\gamma\gamma} \frac{h}{v} + \ldots \right) + G_{\mu\nu}^2 \left( c_{gg} \frac{h}{v} + c_{2gg} \frac{h^2}{v^2} + \ldots \right) \right] \]

\[ + \frac{g^2}{16\pi^2} \left[ \frac{c_{hgg}}{\Lambda^2} G_{\mu\nu} \frac{(\partial_\rho h)^2}{v^2} + \frac{c'_{hgg}}{\Lambda^2} G_{\mu\rho} G_{\nu\rho} \frac{\partial_\mu h \partial_\nu h}{v^2} + \ldots \right] \]

\[ + \ldots \]
Effective Lagrangian for a light Higgs

\[ \mathcal{L} = \frac{1}{2} (\partial_{\mu} h)^2 - \frac{1}{2} m_h^2 h^2 - \frac{d_3}{6} \left( \frac{3m_h^2}{v} \right) h^3 - \frac{d_4}{24} \left( \frac{3m_h^2}{v^2} \right) h^4 \]

\[ - \left( m_W^2 W_{\mu} W_{\mu} + \frac{1}{2} m_Z^2 Z_{\mu} Z_{\mu} \right) \left( 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + \ldots \right) \]

\[ - \sum_{\psi = u, d, l} m_{\psi(i)} \bar{\psi}^{(i)} \psi^{(i)} \left( 1 + c_{\psi} \frac{h}{v} + c_{2\psi} \frac{h^2}{v^2} + \ldots \right) \]

\[ + \frac{g^2}{16\pi^2} \left( c_{WW} W_{\mu \nu}^+ W_{\mu \nu}^- + c_{ZZ} Z_{\mu \nu}^2 + c_{2Z} Z_{\mu \nu} Z_{\mu \nu} \right) \frac{h}{v} + \ldots \]

\[ + \frac{g^2}{16\pi^2} \left[ \gamma^2_{\mu \nu} \left( c_{\gamma \gamma} \frac{h}{v} + \ldots \right) + G_{\mu \nu}^2 \left( c_{gg} \frac{h}{v} + c_{2gg} \frac{h^2}{v^2} + \ldots \right) \right] \]

\[ + \frac{g^2}{16\pi^2} \left[ \frac{c_{hgg}}{\Lambda^2} \frac{\left( \partial_{\rho} h \right)^2}{v^2} + \frac{c'_{hgg}}{\Lambda^2} G_{\mu \rho} G_{\rho \nu} \frac{\partial_{\mu} h \partial_{\nu} h}{v^2} + \ldots \right] \]

\[ + \ldots \]
Effective Lagrangian for a light Higgs-like boson

\[ L = -\frac{1}{4}m_h^2 h^2 - \frac{3}{2} \left( \frac{3m_h^2}{v} \right) h^3 - \frac{d_4}{24} \left( \frac{3m_h^2}{v^2} \right) h^4 + \ldots \]

\[ g \bigl\{ \frac{m_W^2 W_\mu W_\mu + \frac{1}{2} m_Z^2 Z_\mu Z_\mu}{2} \bigr\} \left( 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + \ldots \right) \]

\[ - \sum_{\psi=u,d,l} m_\psi \bar{\psi}(i) \psi(i) \left( 1 + c_\psi \frac{h}{v} + c_{2\psi} \frac{h^2}{v^2} + \ldots \right) \]

\[ + \frac{g^2}{16\pi^2} \left( c_{WW} W^+_{\mu\nu} W^-_{\mu\nu} + c_{ZZ} Z^2_{\mu\nu} + c_{Z\gamma} Z_{\mu\nu} \gamma_{\mu\nu} \right) \frac{h}{v} + \ldots \]

\[ + \frac{g^2}{16\pi^2} \left[ \gamma^2_{\mu\nu} \left( c_{\gamma\gamma} \frac{h}{v} + \ldots \right) + G^2_{\mu\nu} \left( c_{gg} \frac{h}{v} + c_{2gg} \frac{h^2}{v^2} + \ldots \right) \right] \]

\[ + \frac{g^2}{16\pi^2} \left[ \frac{c_{hhgg}}{\Lambda^2} G^2_{\mu\nu} \frac{(\partial_{\rho} h)^2}{v^2} + \frac{c'_{hhgg}}{\Lambda^2} G_{\mu\rho} G_{\rho\nu} \frac{\partial_{\mu} h \partial_{\nu} h}{v^2} + \ldots \right] \]

\[ + \ldots \]
Effective Lagrangian for a light Higgs-like boson

\[ L = \sum_{\psi=u,d,l} m_\psi \psi(i) \bar{\psi}(i) \left( 1 + c_\psi \frac{h}{v} + c_{2\psi} \frac{h^2}{v^2} + \ldots \right) \]

\[ - \left( m_W^2 W_\mu W_\mu + \frac{1}{2} m_Z^2 Z_\mu Z_\mu \right) \left( 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + \ldots \right) \]

\[ + \frac{g^2}{16\pi^2} \left( c_{WW} W_\mu^+ W_\mu^- + c_{ZZ} Z_\mu^2 + c_{Z\gamma} Z_\mu \gamma_\mu \right) \]

\[ + \frac{g^2}{16\pi^2} \left( \gamma^2_{\mu\nu} \left( c_{\gamma\gamma} \frac{h}{v} + \ldots \right) + G^2_{\mu\nu} \left( c_{gg} \frac{h}{v} + c_{2gg} \frac{h^2}{v^2} + \ldots \right) \right) \]

\[ + \frac{g^2}{16\pi^2} \left[ \frac{c_{hhgg}}{\Lambda^2} G^2_{\mu\nu} \frac{(\partial_\rho h)^2}{v^2} + \frac{c'_{hhgg}}{\Lambda^2} G_{\mu\rho} G_{\rho\nu} \frac{\partial_\mu h \partial_\nu h}{v^2} + \ldots \right] \]

\[ + \ldots \]
Effective Lagrangian for a light Higgs-like boson

\[ \mathcal{L} = \frac{1}{2} \partial_{\mu} h \partial^{\mu} h - \frac{1}{2} m_{h}^{2} h^{2} - \frac{g_{3}}{6} \left( \frac{3m_{h}^{2}}{v} \right) h^{3} - \frac{d_{4}}{24} \left( \frac{3m_{h}^{2}}{v^{2}} \right) h^{4} \ldots \]

- \left( m_{W}^{2} W_{\mu} W_{\mu} + \frac{1}{2} m_{Z}^{2} Z_{\mu} Z_{\mu} \right) \left( 1 + 2a \frac{h}{v} + b \frac{h^{2}}{v^{2}} + \ldots \right)

Contributes to \( gg \to hh \)

Contributes to \( WW \to hh \)

\[ E^{2} \text{ contribution to } gg \to hh \]

\[ c_{2gg} \sim \left( \frac{g^{2} v^{2}}{\Lambda^{2}} \right)^{2} \left( \frac{\lambda^{2}}{g_{*}^{2}} \right) \]

\[ c_{hhgg} \sim \left( \frac{g^{2} v^{2}}{\Lambda^{2}} \right) \]

\[ \sum_{i=0}^{\infty} m_{\phi(i)}^{2} (\psi^{(i)} \psi^{(i)}) \left( 1 + c_{\psi} \frac{h}{v} + c_{2\psi} \frac{h^{2}}{v^{2}} + \ldots \right) \]

E\(^{4}\) contribution to \( gg \to hh \)

\[ \frac{g^{2}}{16\pi^{2}} \hspace{1cm} \left[ \frac{c_{hhgg}}{\Lambda^{2}} G_{\mu\nu} \frac{(\partial_{\mu} h)^{2}}{v^{2}} + \frac{c_{2gg}}{\Lambda^{2}} G_{\mu\rho} G_{\nu\sigma} \frac{\partial_{\mu} h \partial_{\sigma} h}{v^{2}} + \ldots \right] \]

\[ + \ldots \]
Possibly large shifts to tree-level couplings $a, c$ due to Higgs non-linearities

**Benchmark scenario: composite Higgs**

- Example using MCHM5:
  - $a = \sqrt{1 - \xi}$ for $\xi = 0.25$ gives $a = 0.87$
  - $c = \frac{1 - 2\xi}{\sqrt{1 - \xi}}$ gives $c = 0.58$
Possibly large shifts to tree-level couplings $a, c$ due to Higgs non-linearities

Ex: \[ a = \sqrt{1 - \xi} \quad \text{for} \quad \xi = 0.25 \quad \Rightarrow \quad a = 0.87 \]
\[ c = \frac{1 - 2\xi}{\sqrt{1 - \xi}} \quad \Rightarrow \quad c = 0.58 \]

Analyticity and crossing symmetry imply a sum rule on $a$

\[ 1 - a^2 = \frac{v^2}{6\pi} \int_0^\infty \frac{ds}{s} \left( 2\sigma_{I=0}^{\text{tot}}(s) + 3\sigma_{I=1}^{\text{tot}}(s) - 5\sigma_{I=2}^{\text{tot}}(s) \right) \]

$a > 1$ only if $I=2$ channel dominates.

Ex: doubly charged scalar resonance

Falkowski, Rychkov, Urbano, JHEP 1204 (2012) 073
Low, Rattazzi, Vichi, JHEP 1004 (2010) 126
Benchmark scenario: composite Higgs

- Leading local contributions to $ggh$ and $\gamma \gamma h$ suppressed due to the Higgs shift symmetry

\[ g = e^{i\alpha T^a} \in SO(5) \quad h(x) \rightarrow h(x) + \alpha f \quad [\text{NG bosons couple derivatively}] \]
Benchmark scenario: composite Higgs

- Leading local contributions to $ggh$ and $\gamma\gamma h$ suppressed due to the Higgs shift symmetry

$$g = e^{i\alpha T^4} \in SO(5) \quad h(x) \rightarrow h(x) + \alpha f$$

[ NG bosons couple derivatively ]

Shift symmetry not broken by $SU(3)_c \times U(1)_Q$: two powers of weak couplings needed to generate $G_{\mu\nu}^2 H^\dagger H$, $\gamma_{\mu\nu}^2 H^\dagger H$

Giudice, Grojean, Pomarol, Rattazzi, JHEP 0706 (2007) 045

$$G_{\mu\nu}^2 H^\dagger H \frac{\alpha_s}{4\pi} \frac{Y^2_*}{m^2_*} \times \frac{\lambda^2}{g^2_*}$$
Benchmark scenario: composite Higgs

- Leading local contributions to $ggh$ and $\gamma\gamma h$ suppressed due to the Higgs shift symmetry

$$g = e^{i\alpha T^4} \in SO(5) \quad h(x) \rightarrow h(x) + \alpha f$$

[ NG bosons couple derivatively ]

Shift symmetry not broken by SU(3)$_c \times$U(1)$_Q$: two powers of weak couplings needed to generate $G_{\mu\nu}^2 H^\dagger H$, $\gamma_{\mu\nu}^2 H^\dagger H$

Giudice, Grojean, Pomarol, Rattazzi, JHEP 0706 (2007) 045
Benchmark scenario: composite Higgs

- Low energy theorems for $ggh$ and $\gamma\gamma h$:
  
  Ellis, Gaillard, Nanopoulos, NPB 106 (1976) 292
  Shifman et al., Sov. J. Nucl. Phys. 30 (1979) 711
  
  ... Kniehl, Spira Z. Phys. C69 (1995) 77
  Gillioz et al. arXiv:1206.7120

In the limit of soft Higgs emissions

(soft Higgs = vanishing Higgs mass and momentum)

$$A(gg \rightarrow h^n) \propto \left( \frac{\partial^n}{\partial h^n} \log \det [M^\dagger(h)M(h)] \right)_{h=v}$$
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In the limit of soft Higgs emissions

(soft Higgs = vanishing Higgs mass and momentum)

$$A(gg \to h^n) \propto \left( \frac{\partial^n}{\partial h^n} \log \det [M^\dagger(h)M(h)] \right)_{h=v}$$

In minimal composite Higgs models with partial compositeness

$$\det [M^\dagger(h)M(h)] \propto \lambda_L(h)\lambda_R(h) \quad \Rightarrow \quad A(gg \to h^n) = A(gg \to h^n)_{SM} \times F(\xi)$$

Falkowski, PRD 77 (2008) 055018  
Rattazzi, Vichi, JHEP 1004 (2010) 126  
Azatov, Galloway, PRD 85 (2012) 055013

No dependence upon masses of heavy fermions
Benchmark scenario: composite Higgs

\[ c_t \frac{m_H^2}{v} \frac{g_s^2}{16\pi^2} F \left( \frac{m_H^2}{m_t^2} \right) \]

\[ c_gg \frac{m_H^2}{v} \frac{g_s^2}{16\pi^2} \]
Benchmark scenario: composite Higgs

\[ c_t \frac{m_h^2}{v} \frac{g_s^2}{16\pi^2} F \left( \frac{m_h^2}{m_t^2} \right) \]

\[ c_t = 1 + O(\xi) + O \left[ \left( \frac{g_s^2 v^2}{M^2} \right) \left( \frac{\lambda^2}{g_s^2} \right) \right] \]
Benchmark scenario: composite Higgs

\[
c_t = 1 + O(\xi) + O\left[\left(\frac{g_s^2 v^2}{M^2}\right)\left(\frac{\lambda^2}{g_s^2}\right)\right]
\]

from Higgs non-linearities
Benchmark scenario: composite Higgs

\[ c_t \frac{m_h^2}{v} \frac{g^2}{16\pi^2} F \left( \frac{m_h^2}{m_t^2} \right) \]

\[ c_t = 1 + O(\xi) + O \left[ \left( \frac{g_s^2 v^2}{M^2} \right) \left( \frac{\lambda^2}{g_s^2} \right) \right] \]

\[ c_{gg} \frac{m_h^2}{v} \frac{g_s^2}{16\pi^2} \]
Benchmark scenario: composite Higgs

$c_t = 1 + O(\xi) + O\left[\left(\frac{g_*^2 v^2}{M^2}\right)\left(\frac{\lambda^2}{g_*^2}\right)\right]$ from Higgs non-linearities

$c_t \frac{m_h^2}{v} \frac{g_s^2}{16\pi^2} F\left(\frac{m_h^2}{m_t^2}\right)$ from corrections to wave-function

$c_{gg} \frac{m_h^2}{v} \frac{g_s^2}{16\pi^2}$

$c_{gg} \sim \left(\frac{g_*^2 v^2}{M^2}\right)\left(\frac{\lambda^2}{g_*^2}\right)$
Benchmark scenario: composite Higgs

$c_t = 1 + O(\xi) + O\left[\left(\frac{g_*^2 v^2}{M^2}\right)\left(\frac{\lambda^2}{g_*^2}\right)\right]$ for corrections to wave-function

$c_{gg} \sim \left(\frac{g_*^2 v^2}{M^2}\right)\left(\frac{\lambda^2}{g_*^2}\right)$

with partial compositeness: loops of heavy fermions exactly cancel the wave function correction
In the case of $gg \rightarrow h$ and $h \rightarrow \gamma \gamma$ the soft limit is a good approximation ($m_h \ll 2m_t, m_*$)

\[
A(gg \rightarrow h) = A(gg \rightarrow h)_{SM} \times c_t(\xi)
\]

\[
A(h \rightarrow \gamma \gamma) = A(h \rightarrow \gamma \gamma)^{(t)}_{SM} \times c_t(\xi) + A(h \rightarrow \gamma \gamma)^{(W)}_{SM} \times a(\xi)
\]

shifts in $gg \rightarrow h$ and $h \rightarrow \gamma \gamma$ controlled by tree-level couplings
Benchmark scenario: MSSM (Type II 2HDMs)

- Shifts to tree-level couplings due to mixing with heavier Higgs

\[
a = \sin(\beta - \alpha) \quad c_t = \frac{\cos \alpha}{\sin \beta} \quad c_b = -\frac{\sin \alpha}{\cos \beta}
\]

\[
\begin{pmatrix}
h^0 \\
H^0
\end{pmatrix} =
\begin{pmatrix}
\cos \alpha & -\sin \alpha \\
\sin \alpha & \cos \alpha
\end{pmatrix}
\begin{pmatrix}
\text{Re } H_u^0 \\
\text{Re } H_d^0
\end{pmatrix}
\]

\[
\tan \beta = \frac{v_u}{v_d}
\]
Benchmark scenario: MSSM (Type II 2HDMs)

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\begin{align*}
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    c_t &= \frac{\cos \alpha}{\sin \beta} \\
    c_b &= -\frac{\sin \alpha}{\cos \beta}
\end{align*}
\]

\[
\begin{pmatrix}
    h^0 \\
    H^0
\end{pmatrix}
= \begin{pmatrix}
    \cos \alpha & -\sin \alpha \\
    \sin \alpha & \cos \alpha
\end{pmatrix}
\begin{pmatrix}
    \text{Re } H_u^0 \\
    \text{Re } H_d^0
\end{pmatrix}
\]

\[
\tan \beta = \frac{v_u}{v_d}
\]
Benchmark scenario: MSSM (Type II 2HDMs)

- Shifts to tree-level couplings due to mixing with heavier Higgs

\[ a = \sin(\beta - \alpha) \quad c_t = \frac{\cos \alpha}{\sin \beta} \quad c_b = -\frac{\sin \alpha}{\cos \beta} \]

\[ \begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \text{Re} H_u^0 \\ \text{Re} H_d^0 \end{pmatrix} \]

\[ \tan \beta = \frac{v_u}{v_d} \]

- \( a \) always reduced
- if \( c_t > 1 \) then \( c_b < 1 \) and vice versa
Benchmark scenario: MSSM (Type II 2HDMs)

- Shifts to tree-level couplings due to mixing with heavier Higgs

\[ a = \sin(\beta - \alpha) \quad c_t = \frac{\cos \alpha}{\sin \beta} \quad c_b = -\frac{\sin \alpha}{\cos \beta} \]

\[ \left( \begin{array}{c} h^0 \\ H^0 \end{array} \right) = \left( \begin{array}{cc} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{array} \right) \left( \begin{array}{c} \text{Re } H_u^0 \\ \text{Re } H_d^0 \end{array} \right) \]

\[ \tan \beta = \frac{v_u}{v_d} \]

Only two regions in the \((c_t, c_b)\) plane accessible

Down-Suppressed region mostly inaccessible at large \(\tan \beta\)

Decoupling limit: \(\alpha \rightarrow \beta - \pi/2\) \((a, c_t, b \rightarrow 1)\)

see: Azatov, Chang, Craig, Galloway arXiv:1206.1058
Benchmark scenario: MSSM (Type II 2HDMs)

- Contributions to $ggh$ ($c_{gg}$) and $\gamma\gamma h$ ($c_{\gamma\gamma}$) from loops of stops

By virtue of the low energy theorem ($m_t \gg m_h/2$)

$$A(gg \rightarrow h), A(h \rightarrow \gamma\gamma) \propto \left( \frac{\partial}{\partial h} \log \det \mathcal{M}^2(h) \right)_{h=v}$$

$$\mathcal{M}^2 = \begin{bmatrix}
\tilde{m}_L^2 + y_t^2 |H_u^0|^2 & y_t (H_u^0 A_t - \mu H_d^0) \\
y_t (H_u^{0\dagger} A_t - \mu H_d^{0\dagger}) & \tilde{m}_R^2 + y_t^2 |H_u^0|^2
\end{bmatrix}$$

$$c_{gg} = \frac{9}{2} c_{\gamma\gamma} = \frac{1}{4} \left( \frac{m_t^2}{m_{t_1}^2} + \frac{m_t^2}{m_{t_2}^2} - \frac{m_t^2 X_t^2}{m_{t_1}^2 m_{t_2}^2} \right)$$

$$X_t = |A_t - \mu \cot \beta|$$
Contributions to $ggh$ ($c_{gg}$) and $\gamma\gamma h$ ($c_{\gamma\gamma}$) from loops of stops

By virtue of the low energy theorem ($m_i \gg m_h/2$)

$A(gg \to h), A(h \to \gamma\gamma) \propto \left( \frac{\partial}{\partial h} \log \det \mathcal{M}^2(h) \right)_{h=v}$

$$\mathcal{M}^2 = \begin{bmatrix} \tilde{m}_L^2 + y_t^2 |H_u^0|^2 & y_t (H_u^0 A_t - \mu H_d^0) \\ y_t (H_u^0 A_t - \mu H_d^0) & \tilde{m}_R^2 + y_t^2 |H_u^0|^2 \end{bmatrix}$$

$c_{gg} = \frac{9}{2} c_{\gamma\gamma} = \frac{1}{4} \left( \frac{m_t^2}{m_{t_1}^2} + \frac{m_t^2}{m_{t_2}^2} + \frac{m_t^2 X_t^2}{m_{t_1}^2 m_{t_2}^2} \right)$

$X_t = |A_t - \mu \cot \beta|$

if mixing is small: $c_{gg} = \frac{9}{2} c_{\gamma\gamma} > 0 \quad \Rightarrow \quad \Gamma(gg \to h)$ enhanced
\hspace{1cm} $\Gamma(h \to \gamma\gamma)$ suppressed

large mixing can flip the sign $\quad \Rightarrow \quad \Gamma(gg \to h)$ suppressed
\hspace{1cm} $\Gamma(h \to \gamma\gamma)$ enhanced
Naive expectation:

- Composite Higgs models:
  \[(a - 1), (c - 1) \sim O(\xi)\]
  \[c_{gg}, c_{\gamma\gamma} \approx 0\]

- Natural SUSY:
  \[a, c \approx 1\]
  \[c_{gg}, c_{\gamma\gamma} \neq 0\]
Higgs couplings: present status

- After the discovery, the main goal now is to understand the properties of the new particle

- Several theoretical studies have discussed what can be the best ways to determine the Higgs properties and understand its role in EWSB

Ideas put forward include:

- Use of effective Lagrangians for a model-independent determination of the Higgs couplings

- Use of exclusive analyses as a way to increase the sensitivity on individual couplings

- Study of systematic uncertainties

- Operative definition of quantities of interest

Zeppenfeld et al. PRD 62 (2000) 013009
Duhrssen et al. PRD 70 (2004) 113009
Giudice, Grojean, Pomarol, Rattazzi, JHEP 0706 (2007) 045
Lafaye et al. JHEP 0908 (2009) 009
R.C. et al. JHEP 1005 (2010) 089
Bock et al. PLB 649 (2010) 44
Englert, Plehn, Rauch, Zerwas, Zerwas, PLB 707 (2012) 512
Carmi, Falkowski, Kuflik, Volansky, JHEP 1207 (2012) 136
Azatov, R.C., Galloway JHEP 1204 (2012) 127
Espinosa, Grojean, Muhlleitner, Trott, JHEP 1205 (2012) 097
Giardino, Kannike, Raidal, Strumia JHEP 1206 (2012) 117
Ellis, You JHEP 1206 (2012) 140
Azatov et al. JHEP 1206 (1021) 134
Klute et al. arXiv:1205.2699
Azatov, Chang, Craig, Galloway, arXiv:1206.1058
Corbett, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, arXiv:1207.1344
Low, Lykken, Shaughnessy, arXiv:1207.1093
Giardino, Kannike, Raidal, Strumia arXiv:1207.1347
Baglio, Djouadi, Godbole, PLB 716 (2012) 203
Ellis, You, arXiv:1207.1693
Espinosa, Grojean, Muhlleitner, Trott, arXiv:1207.1717
Espinosa, Grojean, Sanz, Trott, arXiv:1207.7355
Djouadi, arXiv:1208.3436

.....
The experimental situation in a nutshell

**Figure 10:** Values of $\hat{\mu} = \sigma / \sigma_{SM}$ for the combination (solid vertical line) and for contributing channels (points) for the 7 and 8 TeV datasets separately (left) and for their combination (right). The vertical band shows the overall $\hat{\mu}$ value $0.80 \pm 0.22$. The horizontal bars indicate the $\pm 1 \sigma$ uncertainties on the $\hat{\mu}$ values for individual channels; they include both statistical and systematic uncertainties.

**Figure 11:** Values of $\hat{\mu} = \sigma / \sigma_{SM}$ for the combination (solid vertical line) and for sub-combinations (points) grouped by decay mode (left) and by a signature enhancing a specific production mechanism (right). The vertical band shows the overall $\hat{\mu}$ value $0.80 \pm 0.22$. The horizontal bars indicate the $\pm 1 \sigma$ uncertainties on the $\hat{\mu}$ values for individual channels; they include both statistical and systematic uncertainties.
The experimental situation in a nutshell

- Is there a pattern? ... not quite apparently, just values scattered around 1?

Only ‘feature’: mild excess in $\gamma\gamma$ channel. Too early to say if interesting
The experimental situation in a nutshell

- Is there a pattern? ... not quite a pattern
  - Only 'feature': mild excess in

- Warning: much more elaborate and complex analyses behind these plots
Testing Composite Higgs models

Red points at $\xi = 0.2, 0.5, 0.8$

CMS Preliminary
\[ \sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV}, L = 5.3 \text{ fb}^{-1} \]

ATLAS Preliminary
\[ \sqrt{s} = 7 \text{ TeV}, \int L dt = 4.8 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV}, \int L dt = 5.8-5.9 \text{ fb}^{-1} \]

CMS

prefers $c < 1, a \simeq 1$

deeper minimum at $c < 0$ (not shown)

ATLAS

prefers $a > 1, c \simeq 1$
Testing Composite Higgs models: channel breakdown

Best fit location is determined by several channels

J. Galloway et al. work in progress
Testing Type II 2HDMs (incl. MSSM)

\[ -2 \ln (\Lambda(\lambda_{du})) \]

\[ \frac{a}{c_t}, \frac{c_t^2}{c_{tot}}, \lambda_{du} \equiv c_b/c_t \]

ATLAS made a 3-parameter fit:
Testing Type II 2HDMs (incl. MSSM)

ATLAS made a 3-parameter fit:

\[ \frac{a}{c_t}, \frac{c_t^2}{c_{tot}}, \lambda_{du} \equiv \frac{c_b}{c_t} \]

Likelihood for \( \lambda_{du} \) rather shallow between -1 and +1: limited sensitivity on \( c_b = c_T \)
Testing Type II 2HDMs (incl. MSSM)

ATLAS made a 3-parameter fit:

\[ a/c_t, \frac{c_t^2}{c_{tot}}, \lambda_{du} \equiv \frac{c_b}{c_t} \]

Likelihood for \( \lambda_{du} \) rather shallow between -1 and +1: limited sensitivity on \( c_b = c_T \)

\( \lambda_{du} \) alone does not test Type II 2HDMs

Use \( (c_b, c_t) \) plane to test Type II 2HDMs

Fixing the total width to the SM value can help to increase the sensitivity on

Marginalizing over \( 0 < a < 1 \)

Azatov, Chang, Craig, Galloway, arXiv:1206.1058v3
Figure 7: Fits for benchmark models probing for contributions from non-SM particles: (a) Probing only the $gg \to H$ and $H \to \gamma\gamma$ loops, assuming no sizable extra contribution to the total width; (b) Probing in addition to (a) for a possible invisible or undetectable branching ratio $\text{BR}^{\text{inv, undet.}}$.

6.3.1 Assuming only SM particles contributing to the total width

A fit is shown in Figure 7(a) which assumes that there are no sizeable extra contributions to the total width caused by the non-SM particles. The free parameters are $\kappa_g$ and $\kappa_\gamma$.

The best fit values and uncertainties when profiling over the other parameter are $\kappa_g = 1.1^{+0.2}_{-0.3}$ (48) and $\kappa_\gamma = 1.2^{+0.3}_{-0.2}$ (49) at 68% CL. When removing the theoretical systematic uncertainties on the measurements of $\kappa_g$ and $\kappa_\gamma$, the uncertainty is reduced by $\sim 15\%$. It is further reduced by $\sim 5\%$ when removing the experimental systematic uncertainties. The compatibility of the SM hypothesis (2D) with the best fit point is 18%.

6.3.2 No assumption on the total width

By constraining some of the factors to be equal to their SM values, it is possible to probe for new non-SM decay modes that might appear as invisible or undetectable final states. The free parameters are $\kappa_g$, $\kappa_\gamma$ and $\text{BR}^{\text{inv, undet.}}$.

In this model the modification to the total width is parametrized as follows:

$$
\Gamma_H = \kappa_g^2 H \left( \kappa_i \right) \left( 1 - \text{BR}^{\text{inv, undet.}} \right)
\Gamma_{\text{SM}} H
$$

Figure 7(b) shows the likelihood as a function of $\text{BR}^{\text{inv, undet.}}$ when $\kappa_g$ and $\kappa_\gamma$ are profiled. The best fit values and uncertainties, and confidence level interval at 68% CL when profiling over the other parameters are $\kappa_g = 1.1^{+1.4}_{-0.2}$ (51) and $\kappa_\gamma = 1.2^{+0.3}_{-0.2}$ (52).

$\text{BR}^{\text{inv, undet.}} < 0.68$ (53)

The 95% confidence level interval on the invisible or undetectable branching fraction is $\text{BR}^{\text{inv, undet.}} < 0.84$. The 68% CL interval for the invisible or undetectable branching fraction without theory systematic uncertainties is

$$
k_g^2 = \frac{\Gamma(h \to gg)}{\Gamma(h \to gg)|_{\text{SM}}} \quad k_\gamma^2 = \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)|_{\text{SM}}}
$$

Yellow = MSSM trajectory $c_{\gamma\gamma} = 2/9c_{gg}$
The free parameters are best fit values and uncertainties, and confidence level interval at 68% when profiling over the other parameter are

6.3.1 Assuming only SM particles contributing to the total width uncertainties when profiling over the other parameter are

6.3.2 No assumption on the total width

The 68% CL interval for the invisible or undetectable branching fraction is 

\[ \text{BR} \text{ inv.,undet.} \equiv \frac{\Gamma(h \to \gamma\gamma)\text{SM}}{\Gamma(h \to \gamma\gamma)} \]

Yellow = MSSM trajectory \( c_{\gamma\gamma} = \frac{4}{9} c_{gg} \)

P1: \( m_{\tilde{t}_1} = 100 \text{ GeV}, \ m_{\tilde{t}_2} = 300 \text{ GeV}, \ \theta_t = 0 \)

P2: \( m_{\tilde{t}_1} = 200 \text{ GeV}, \ m_{\tilde{t}_2} = 500 \text{ GeV}, \ \theta_t = 0 \)

P3: \( m_{\tilde{t}_1} = 400 \text{ GeV}, \ m_{\tilde{t}_2} = 1000 \text{ GeV}, \ \theta_t = \pi/4 \)
Testing New Light Physics in Loops (incl. SUSY)

\[ k_g^2 = \frac{\Gamma(h \rightarrow gg)}{\Gamma(h \rightarrow gg)|_{SM}} \quad k_{\gamma}^2 = \frac{\Gamma(h \rightarrow \gamma\gamma)}{\Gamma(h \rightarrow \gamma\gamma)|_{SM}} \]

Yellow = MSSM trajectory \( c_{\gamma\gamma} = 2/9 c_{gg} \)

P1: \( m_{\tilde{t}_1} = 100 \text{ GeV}, \ m_{\tilde{t}_2} = 300 \text{ GeV}, \ \theta_t = 0 \)

P2: \( m_{\tilde{t}_1} = 200 \text{ GeV}, \ m_{\tilde{t}_2} = 500 \text{ GeV}, \ \theta_t = 0 \)

P3: \( m_{\tilde{t}_1} = 400 \text{ GeV}, \ m_{\tilde{t}_2} = 1000 \text{ GeV}, \ \theta_t = \pi/4 \)

Espinosa, Grojean, Sanz, Trott, arXiv:1207.7355
Limits on the Invisible Width

\[ \text{BR}_{\text{inv., undet.}} < 0.68 \ (0.84) \ \text{at 68\% (95\%) CL} \]
Effect of the theoretical uncertainty

Strong effect in $\mu_i$, much smaller in the $(a, c)$ plane

Azatov, R.C., DelRe, Galloway, work in progress
Effect of the theoretical uncertainty

Strong effect in $\mu_i$, much smaller in the $(a, c)$ plane

Azatov, R.C., DelRe, Galloway, work in progress
Expected precision on Higgs couplings

CMS Projection

Expected uncertainties on Higgs boson couplings

- $C_{\gamma}$
- $C_v$
- $C_g$
- $C_q$
- $C_l$

13 fb$^{-1}$ at $\sqrt{s} = 7$ and 8 TeV
330 fb$^{-1}$ at $\sqrt{s} = 14$ TeV
330 fb$^{-1}$ at $\sqrt{s} = 14$ TeV w/o theory unc.
Expected precision on Higgs couplings

CMS Projection

Expected uncertainties on Higgs boson couplings

- $C_\gamma$
- $C_\nu$
- $C_g$
- $C_q$
- $C_l$

O(10%) seems possible on all couplings
Expected precision on Higgs couplings

CMS Projection

Expected uncertainties on Higgs boson couplings

\[
\begin{align*}
C_\gamma &
\[\text{(uncertainty bars)}\] \\
C_v &
\[\text{(uncertainty bars)}\] \\
C_g &
\[\text{(uncertainty bars)}\] \\
C_q &
\[\text{(uncertainty bars)}\] \\
C_l &
\[\text{(uncertainty bars)}\]
\end{align*}
\]

\(O(10\%)\) seems possible on all couplings
Additional interesting processes

- Double Higgs Production via gluon fusion

- Double Higgs production via Vector Boson Fusion
Double Higgs Production via gluon fusion
in Composite Higgs models

\[ G^2_{\mu \nu} \frac{H^\dagger H}{m_*^2} \]

\[ G^2_{\mu \nu} \frac{(\partial \rho H)^\dagger (\partial \rho H)}{m_*^4} \]
Double Higgs Production via gluon fusion

in Composite Higgs models

\[ G_{\mu\nu} \frac{H^\dagger H}{m_*^2} \]

\[ G_{\mu\nu}^2 \frac{(\partial_\rho H)^\dagger (\partial_\rho H)}{m_*^4} \]
Double Higgs Production via gluon fusion

in Composite Higgs models

$G_{\mu\nu}^2 \frac{H^\dagger H}{m_*^2}$

Leading operator
suppressed
by spurion factor
$\left( \frac{\lambda}{g_*} \right)^2$

$G_{\mu\nu}^2 \frac{(\partial_\rho H)^\dagger (\partial_\rho H)}{m_*^4}$
Double Higgs Production via gluon fusion
in Composite Higgs models

\[ G^{\mu\nu} \frac{H^\dagger H}{m^2} \]  
Leading operator suppressed by spurion factor \[ \left( \frac{\lambda}{g^*} \right)^2 \]

\[ G^{\mu\nu} \frac{(\partial_\rho H)^\dagger (\partial_\rho H)}{m^4} \]  
next-to-leading operator can be important \[ \frac{m(hh)^2}{m^2} \]}
Double Higgs Production via gluon fusion

- $\sigma(gg\rightarrow hh)$ much more sensitive on new tthh couplings $c_2$ than on trilinear $d_3$

[ First noticed by:
  Dib, Rosenfeld, Zerwekh, JHEP 0605 (2006) 074
  Grober and Muhlleitner, JHEP 1106 (2011) 020 ]

results from:
R.C., Ghezzi, Moretti, Panico, Piccinini, Wulzer
JHEP 1208 (2012) 154
Double Higgs Production via gluon fusion

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  [ First noticed by:
  Dib, Rosenfeld, Zerwekh, JHEP 0605 (2006) 074
  Grober and Muhlleitner, JHEP 1106 (2011) 020 ]

- $c_2 = \Delta$
  $d_3 = 1 + \Delta$

- If $\text{BR}(h) = \text{BR}(h)_{\text{SM}}$ best channel is $hh \to bb\gamma\gamma$
  

- $\xi = 0.15 \Rightarrow \sigma(gg\to hh)\times\text{BR} \sim 3[\sigma(gg\to hh)\times\text{BR}]_{\text{SM}}$

results from:
R.C., Ghezzi, Moretti, Panico, Piccinini, Wulzer
JHEP 1208 (2012) 154
Double Higgs Production via gluon fusion

Precision on couplings (curves at 68% prob.)

Ex: Injected $\xi=0.3$ (c=d$_3$=0.48  c$_2$=-0.6)

$\Delta c_2/c_2 = 15\%-20\%$
Double Higgs Production via gluon fusion

Precision on couplings (curves at 68% prob.)

Injected MCHM5 Signal, $\xi=0.3$: LHC @ 14 TeV [ $m_h=120$ GeV ]

Ex: Injected $\xi=0.3$ (c=d$_3=0.48$ c$_2=-0.6$)

$\Delta c_2/c_2 = 15\text{--}20\%$

Contribution from heavy fermions can be numerically important

Gillioz, Grober, Grojean, Muhlleitner, Salvioni
arXiv:1206.7120
Double Higgs Production via VBF

\[ \sigma(pp \rightarrow hhjj) \text{ [fb]} \]

<table>
<thead>
<tr>
<th>( \xi )</th>
<th>MCHM4</th>
<th>MCHM5</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>9.3</td>
<td>14.0</td>
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<tr>
<td>0.8</td>
<td>6.3</td>
<td>9.5</td>
</tr>
<tr>
<td>0.5</td>
<td>2.9</td>
<td>4.2</td>
</tr>
<tr>
<td>0 (SM)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

dilaton \( v/f_D = 1.5 \)

\[ m_h = 180 \text{ GeV} \]

\[ V(h) = \frac{1}{2} m_h^2 h^2 + d_3 \frac{1}{6} \left( \frac{3m_h^2}{v} \right) h^3 + d_4 \frac{1}{24} \left( \frac{3m_h^2}{v^2} \right) h^4 + \ldots \]

<table>
<thead>
<tr>
<th>Coupling</th>
<th>MCHM4</th>
<th>MCHM5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a = g_{hWW}/g_{hWW}^{SM} )</td>
<td>( \sqrt{1-\xi} )</td>
<td>( \sqrt{1-\xi} )</td>
</tr>
<tr>
<td>( b = g_{hhWW}/g_{hhWW}^{SM} )</td>
<td>( 1 - 2\xi )</td>
<td>( 1 - 2\xi )</td>
</tr>
<tr>
<td>( c = g_{hff}/g_{hff}^{SM} )</td>
<td>( \sqrt{1-\xi} )</td>
<td>( \frac{1 - 2\xi}{\sqrt{1-\xi}} )</td>
</tr>
<tr>
<td>( d_3 = g_{hhh}/g_{hhh}^{SM} )</td>
<td>( \sqrt{1-\xi} )</td>
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</tr>
</tbody>
</table>
Double Higgs Production via VBF

\[ m_h = 180 \text{ GeV} \]

- No Coulomb singularity enhancement of transverse scattering
- Longitudinal scattering always dominating: cleaner than \( WW \rightarrow WW \)

\[
\frac{d\sigma_{LL \rightarrow hh}}{dt} \sim \frac{1}{8} \frac{(b - a^2)^2}{a^4 + (b - a^2)^2} \frac{s^2}{M_W^4}
\]
Double Higgs Production via VBF

![Graph showing model dependency]

$m_h = 180$ GeV

R.C., Grojean, Moretti, Piccinini, Rattazzi, JHEP 1005 (2010) 089

\[
\frac{d\sigma_{LL\rightarrow hh}/dt}{d\sigma_{TT\rightarrow hh}/dt} \sim \frac{1}{8} \frac{(b-a^2)^2}{a^4 + (b-a^2)^2} \frac{s^2}{M_W^4}
\]

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testing the Higgs strong interaction

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

More central Higgses
(larger HT)

Signal pure s-wave
Double Higgs Production via VBF

- Only available MonteCarlo study is for $hh \rightarrow 4W$ at $m_h = 180$ GeV

R.C., Grojean, Moretti, Piccinini, Rattazzi, JHEP 1005 (2010) 089
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- Naive inspection suggests $hh \to \bar{b}bWW$

Ex: $BR(hh \to \bar{b}bWW \to l\nu jj\bar{b}b)|_{125\text{GeV}} \simeq 0.08$

  for $\xi = 0.2$

$BR(hh \to 4W \to l^{\pm}l^{\pm}l^{\pm}\nu4j)|_{180\text{GeV}} \simeq 0.04$

  for $\xi \lesssim 0.8$

Black: $hh \to \bar{b}bWW \to l\nu jj\bar{b}b$

Blue: $hh \to 4W \to l^{\pm}l^{\pm}\nu4j$

Red: $hh \to \bar{b}b\gamma\gamma$
Conclusions

- Perhaps Nature will repeat herself and the dynamics that breaks the EW symmetry is strong, as for the chiral symmetry in QCD
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In all these scenarios, the physics behind the mechanism of EWSB will play a crucial role

Keep on searching!