A few concluding remarks
(theory summary)

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CERN

'The flavor of Higgs' workshop
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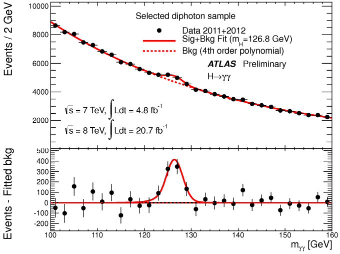
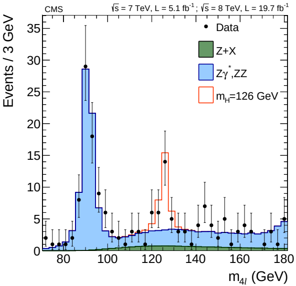
Introduction

The recent discovery of an Higgs-like state opens a **new era** in particle physics





We can **directly test**

the mechanism of **ElectroWeak symmetry breaking**

Introduction

Interpreting the data requires a dedicated theoretical framework:

- selecting **motivated** scenarios
- compare them with the experiments by developing and testing hypothetical models

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- selecting **motivated** scenarios
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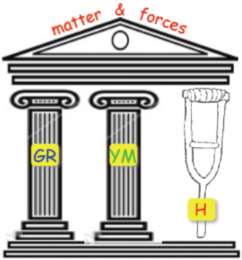
The Standard Model realization

- **minimal** implementation of EWSB
- the Higgs is an **elementary scalar**
- several **accidental symmetries**
  - compatible with EW precision data (LEP)
  - consistent with flavor measurements

Introduction

... **but** the SM Higgs is a **weird** object!



(from G. Giudice)

- ➢ all other known scalars are **emergent** (composite): eg. the pions
- ➢ its couplings are **not dictated** by a gauge symmetry
- ➢ its mass is unstable: huge amount of **tuning** (Hierarchy Problem)

Several **alternative theories** have been proposed

- Supersymmetry
- Composite Higgs
- Extra dimensions
- ...

Introduction

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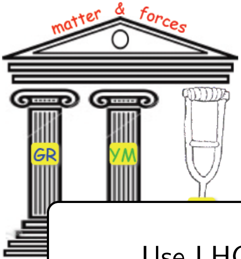

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➢ its couplings are **not dictated** by a gauge symmetry

of

Use LHC data to select the correct model!

Several **alternative theories** have been proposed

- Supersymmetry
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- …

Introduction: Determining the Higgs properties

According to its role in the SM, the Higgs is a privileged portal to explore EWSB

Primary task: extract the Higgs properties!

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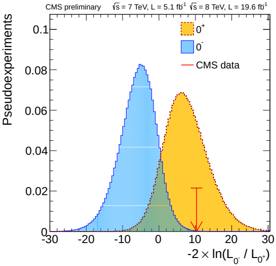
Primary task: extract the Higgs properties!

➢ quantum numbers
[talk by David]

- compatible with spin 0 and parity even hypothesis
- part of an $\mathrm{SU}(2)_L$ doublet? (difficult, clear test only with multiple Higgs interactions)



Introduction: Determining the Higgs properties

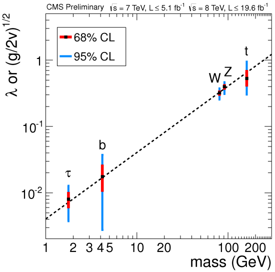
According to its role in the SM, the Higgs is a privileged portal to explore EWSB

Primary task: extract the Higgs properties!

➢ quantum numbers
[talk by David]

➢ couplings
[talks by Spira, Spannowsky, Kamenik, Falkowski, Soreq, Brod]

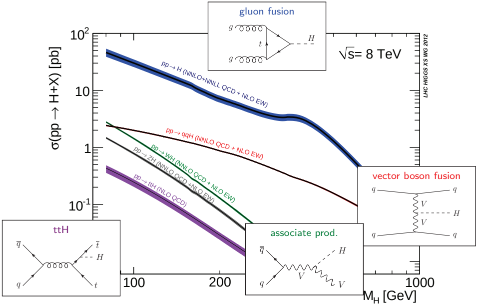
- compatible with SM expectation
  (but sizable deviations can still be there!)

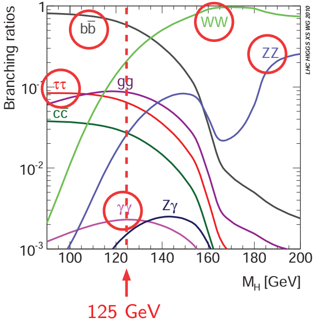


Higgs Properties

Several Higgs production and decay channels accessible

- very useful to measure different Higgs couplings
- can be used to disentangle possible deformations of the SM





Higgs couplings

Use a **model-independent** approach: **effective Higgs Lagrangian**

Some (mild) initial **assumptions**:

- Higgs is a parity-even scalar
- custodial symmetry (helps with EW precision data)
- no extra light particles

The Higgs couplings: The effective Higgs Lagrangian

We can write an **effective Lagrangian** for a **light Higgs-like scalar** [Contino, Grojean, Moretti, Piccinini, Rattazzi 2010]

$$\left.\begin{aligned}\mathcal{L}_{eff} \;=\; & \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \sum_\psi m_\psi \overline{\psi}\psi\left(1 + c_\psi \frac{h}{v} + \cdots\right) \\ & - \left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu\right)\left(1 + 2\,a\frac{h}{v} + \cdots\right)\end{aligned}\right\} \mathcal{O}(p^2)$$

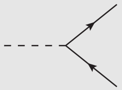
$$\left.\begin{aligned}& + \frac{g^2}{16\pi^2}\left(c_{WW} W_{\mu\nu}^+ W^{-\mu\nu} + c_{ZZ} Z_{\mu\nu}^2 + c_{Z\gamma} Z_{\mu\nu}\gamma^{\mu\nu}\right)\frac{h}{v} + \cdots \\ & + \frac{g^2}{16\pi^2}\gamma_{\mu\nu}^2\left(c_{\gamma\gamma}\frac{h}{v} + \cdots\right) + \frac{g_s^2}{16\pi^2}G_{\mu\nu}^2\left(c_{gg}\frac{h}{v} + \cdots\right)\end{aligned}\right\} \mathcal{O}(p^4)$$

In the SM: $a = c_\psi = 1$, $c_{VV} = c_{\gamma\gamma} = c_{gg} = 0$

- **New physics** can give contributions to **each** coupling

The Higgs couplings: The effective Higgs Lagrangian

Controls the $h\psi\psi$ coupling



$= c_\psi \cdot g^{SM}_{h\psi\psi}$

W **grangian** for a **light Higgs-like**
sc

[Contino, Grojean, Moretti, Piccinini, Rattazzi 2010]

$$
\begin{aligned}
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sc... [Cor... ...)]

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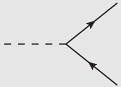
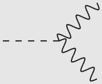


$$= c_\psi \cdot g^{SM}_{h\psi\psi}$$

Controls the hVV couplings



$$= a \cdot g^{SM}_{hVV}$$

$$\mathcal{L}_{eff} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \sum_\psi m_\psi \bar{\psi}\psi \left(1 + c_\psi \frac{h}{v} + \cdots\right)$$
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sc [Cor]

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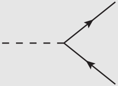

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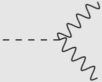
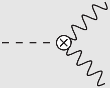


$= a \cdot g^{SM}_{hVV}$

Corrections to hVV couplings



$\propto c_{VV}$

$$\mathcal{L}_{eff} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2} m_h^2 h^2 - \sum_\psi m_\psi \bar{\psi}\psi \left(1 + c_\psi \frac{h}{v} + \cdots\right)$$

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The Higgs couplings: The effective Higgs Lagrangian

W… grangian

sc… [Co…)]

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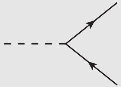

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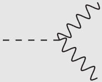

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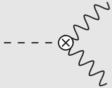
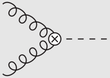


$\propto c_{VV}$

Modify gluon fusion and $\gamma\gamma$ decay



$\propto c_{\gamma\gamma}, c_{gg}$

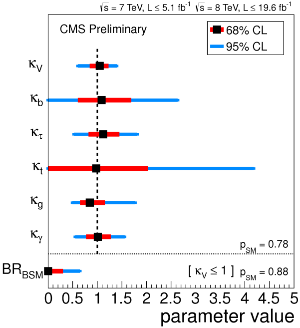
In the SM: $a = c_\psi = 1$, $c_{VV} = c_{\gamma\gamma} = c$…

- **New physics** can give contribut…

The Higgs couplings: The effective Higgs Lagrangian

The current measurements are in good agreement with the SM

The absence of light new resonances and the agreement with the EW data suggest that deviations should be small $\lesssim 10\%$



- hard to explain if Higgs is a singlet
- **natural** if the Higgs is part of an $\mathrm{SU}(2)_L$ doublet (corrections from dimension-six operators suppressed with respect to the SM couplings: **SILH** power counting)

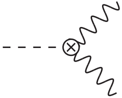
[Giudice, Grojean, Pomarol, Rattazzi; see talk by Spira]

The Higgs couplings: The effective Higgs Lagrangian

Inclusive cross sections can give us only access to specific combinations of the new physics operators

To distinguish some of them we need to use differential distributions

$$c_{VV} V_{\mu\nu} V^{\mu\nu} \frac{h}{v} \quad \Rightarrow$$



$$\propto \; i\, c_{VV} \left(\eta^{\mu\nu} \left(\frac{\hat{s}}{2} - m_V^2 \right) - p_3^\mu p_2^\nu \right)$$

Kick the Higgs with extra objects in the final state

- kicking with a jet: $H + jets$ [Harlander, Naumann; Banfi, Martin, Sanz; Azatov, Paul; Grojean et al.; Schlaffer et al.; Buschman et al.]
- kicking with jets: VBF [Eboli et al.; Plehn, Rainwater, Zeppenfeld; Zang et al.; Hamkele, Klamke, Zeppenfeld; Alloul, Fucks, Sanz]
- kicking with a gauge boson: HV [Ellis, You, Sanz; Isidori, Trott; Godbole et al.]

The Higgs couplings: The effective Higgs Lagrangian

Radiative corrections can be important (in particular QCD effects)

Tools for NLO calculation within the effective theory approach are already available

- automatic NLO generators [see talk by Maltoni]
- eDECAY for Higgs decays (including also EW corrections) [see talk by Spira]

The Higgs couplings

Two Higgs couplings have a very special role:

- Couplings to the **EW bosons**:

$$\left(2\,\kappa_{\rm W}\,W^+_\mu W^{-\mu} + \kappa_{\rm Z}\,Z_\mu Z^\mu\right)\frac{h}{v}$$

- Coupling to the **top quark**:

$$m_t\,\kappa_t\,\bar{t}t\frac{h}{v}$$

The Higgs coupling to the gauge bosons

The Higgs coupling to gauge bosons

The role of the Higgs in the SM is linked to the generation of the W and Z masses:

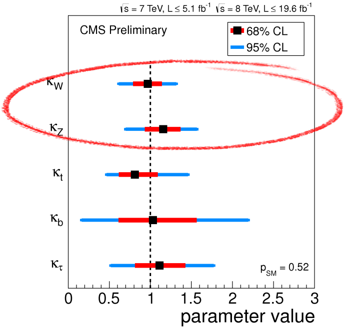
➢ a non vanishing coupling implies that the 125 GeV boson is connected to EWSB

So far determined with a 20% uncertainty

Measurement compatible with custodial symmetry: [see talk by David]

$$\kappa_{\rm W} = \kappa_{\rm Z} = \kappa_{\rm V}$$

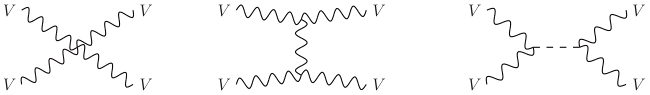
$$\lambda_{\rm WZ} = \begin{cases} 0.94^{+0.14}{}_{-0.29} & \text{ATLAS} \\ 0.86 \pm 0.13 & \text{CMS} \end{cases}$$



Vector boson scattering

In the SM the Higgs is responsible for regulating the growth of WW scattering at high energy and ensure **perturbativity** up to high energy scales:

$$\mathcal{A}(W_L W_L \to W_L W_L) \sim \frac{m_h^2}{s}$$



$+ \ cross.$

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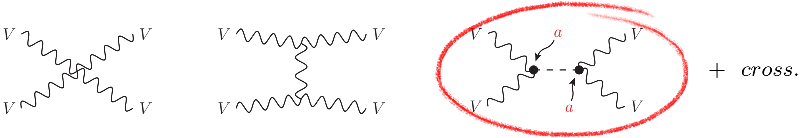


If the Higgs coupling to the gauge bosons are modified the amplitude **grows** with the energy [Contino et al. '10]

$$\mathcal{A}(W_L W_L \to W_L W_L) \sim \frac{s}{v^2}(a^2 - 1)$$

- Very had to see because of accidental suppression ($W_T W_T \to W_T W_T$ dominates)

Vector boson fusion

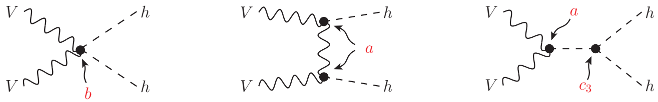
Vector boson fusion into tho Higgses has a similar behavior

[Contino et al. '10]

$$\mathcal{A}(W_L W_L \to hh) \sim \frac{s}{v^2}\left(b - a^2\right)$$

It depends on the non-linear Higgs interactions

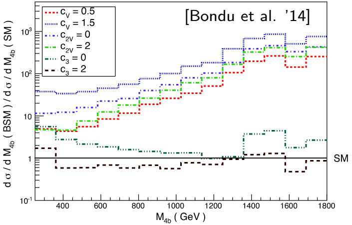
$$b\, g^{SM}_{hhVV}\, hhVV\,, \qquad c_3\, g^{SM}_{hhh}\, hhh$$



- Can be used to test if the Higgs is part of a doublet: $a^2 - 1 = b - a^2$

Vector boson fusion

- corrections to a and b give a strong enhancement of the cross section
- the trilinear Higgs coupling c_3 has a small impact

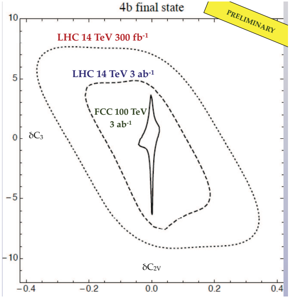


small cross section:

only for the (very) late LHC

can extract b with $\sim 20\%$ accuracy

[Bondu, Oliviera, Contino, Gouzevitch, Massironi, Rojo '14; see also Dolan, Englert, Greiner, Spannowsky '12]



[Rojo @ CERN hxswg '14]

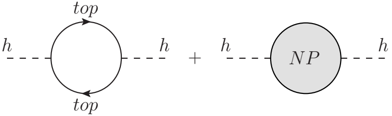
The role of the top quark

The top quark and naturalness

The Hierarchy problem has been the main motivation and guideline to go beyond the SM

Largest effects from the top quark loops

$$\delta m_h^2\big|_{1-loop} \sim$$



$$\sim -\frac{y_{top}^2}{8\pi^2}\Lambda_{NP}^2 \lesssim \text{TeV}$$

The New Physics that screens the top loop must be connected to the top dynamics

- ➢ possible deviations in the top couplings
- ➢ light new states linked to the top sector

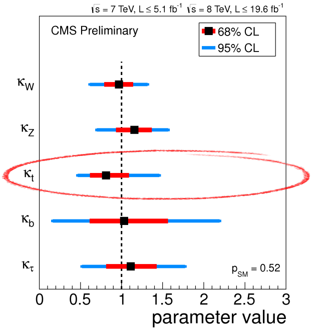
Extracting the top Yukawa

The top Yukawa can be extracted from the $\bar{t}tH$ production channel

The small cross section requires high integrated luminosity to achieve good precision

[see talks by Spannowsky and Juste]

- large backgrounds
- theory uncertainty
- use of boosted techniques can improve sensitivity

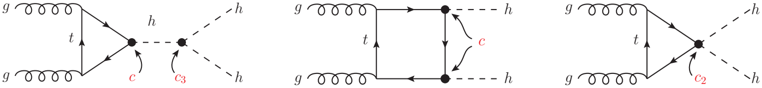


Double Higgs production in gluon fusion

The top Yukawa is also important for double Higgs production in gluon fusion [Baur, Plehn, Rainwater; Grober, Muhlleitner; Contino et al.; Dolan, Englert, Spannowsky; Baglio et al.; Barger et al.; ...]

The relevant Higgs couplings can be parametrized as

$$m_{top}\,\bar{t}t\left(c\,\frac{h}{v}+c_2\,\frac{h^2}{v^2}\right)\,,\qquad c_3\,g_{hhh}^{SM}\,h^3$$

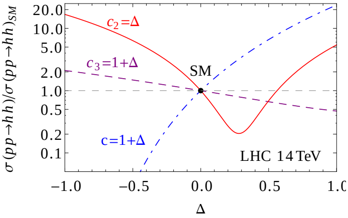


- ➢ can be used to extract the Higgs trilinear coupling c_3
- ➢ sensitive to **non-renormalizable Higgs interactions** ($\bar{t}thh$ is a distinctive sign of a composite Higgs)

Double Higgs production in gluon fusion

The cross section can be significantly **modified** even for small deviations of the Higgs couplings

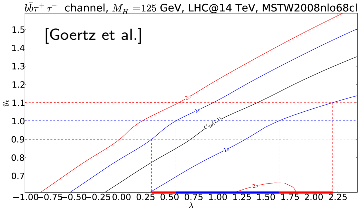
- ➢ strong dependence on c and c_2
- ➢ milder dependence on c_3



Measuring the top Yukawa with good accuracy is useful to improve the precision on the Higgs trilinear in generic scenarios

a 10% uncertainty on y_t doubles the uncertainty on c_3:

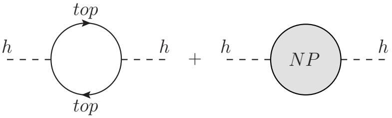
$$0.55 \lesssim c_3 \lesssim 1.6 \quad ➠ \quad 0.3 \lesssim c_3 \lesssim 2.2$$



Naturalness and New Physics

The Hierarchy problem gives us an estimate of the scale at which New Physics should appear

$$\delta m_h^2\big|_{1-loop} \sim$$



$$\sim -\frac{y_{top}^2}{8\pi^2}\Lambda_{NP}^2 \lesssim \text{TeV}$$

minimizing the amount of tuning requires **light new physics**

$$\Delta \gtrsim \left(\frac{\Lambda_{NP}}{400\ \text{GeV}}\right)^2$$

Naturalness and New Physics

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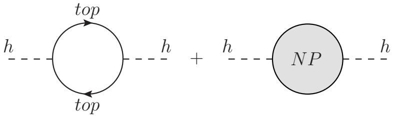

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minimizing the amount of tuning
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Natural SUSY:
light stops

$\Leftrightarrow$

Natural Composite Higgs:
light top partners

Detecting light resonances

The presence of light resonances has many phenomenological consequences

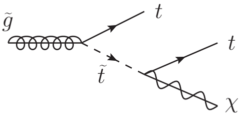
- ❖ **Indirect effects**: loops can modify Higgs physics
  - single Higgs production rates [see talk by Azatov]
  - double Higgs production rates [Grojean et al.]
- ❖ **Direct effects**: search for resonances
  - new states linked to the heavy quarks, look for final states with top quarks [see talk by Azatov]

Supersymmetric new resonances

In **Natural SUSY** the **stops** and the **gluinos** must be light

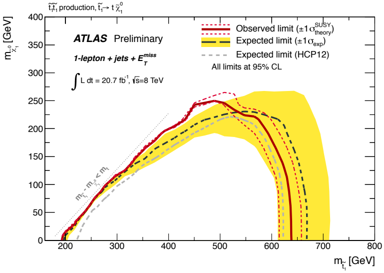
[Weiler, Papucci Ruderman; Katz, Burst, Sundrum]

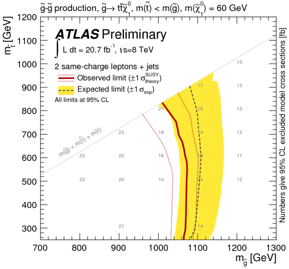
Stop searches can benefit from
multiple tops in the final states



Limits from stop and gluinos pair production:

$$pp \to \widetilde{tt} \to tt + E_T^{miss} \qquad pp \to \widetilde{g}\widetilde{g} \to \widetilde{tt}tt \to tttt + E_T^{miss}$$





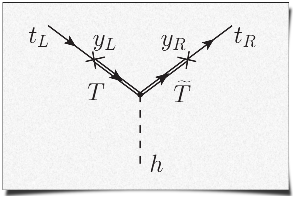
Composite new resonances

In natural **Composite Higgs** models **light top partners** are needed to generate the top mass and the Higgs potential

[Contino, Da Rold, Pomarol; Matsedonskyi, Panico, Wulzer; Marzocca et al.; Redi et al.; Pomarol et al.]

Resonances strongly mixed with the top quark

$$\mathcal{L} = y_L \overline{q}_L \Psi_R + y_R \overline{t}_R \Psi_L + h.c.$$



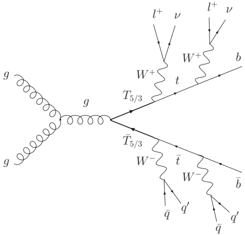
Extended multiplets and **exotic states** are likely to be present (for custodial symmetry)

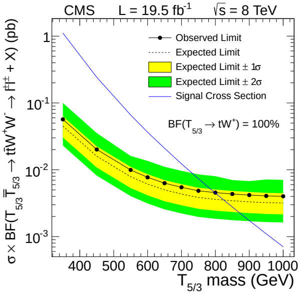
$$\psi_4 = (\mathbf{2},\mathbf{2})_{SO(4)} = \begin{pmatrix} T & X_{5/3} \\ B & X_{2/3} \end{pmatrix} \qquad \psi_1 = (\mathbf{1},\mathbf{1})_{SO(4)} = \begin{pmatrix} \widetilde{T} \end{pmatrix}$$

Exclusion on exotic resonances

The exotic state $X_{5/3}$ can be probed in final states with two same-sign leptons

$$pp \to X_{5/3}\overline{X}_{5/3} \to tW\bar{t}W$$



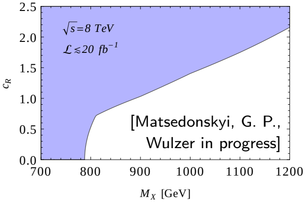


- Bound from QCD pair production

$$m_X \gtrsim 800 \text{ GeV}$$

- Including single production the bound can be significantly improved

[Azatov, Son, Salvarezza, Spannowsky; Matsedonskyi, G. P., Wulzer in progress]



Charge $2/3$ partners

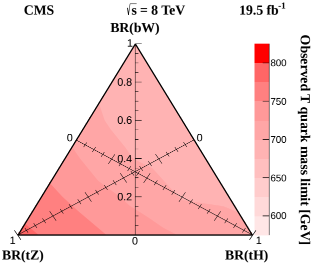
Additional bounds from charge $2/3$ partners

- Three possible decay channels

$$T \to bW\,, \quad T \to tZ\,, \quad T \to th$$

- QCD pair production bounds

$$m_T \gtrsim 600 - 800 \text{ GeV}$$



Can Higgs precision compete with direct searches?

(a composite Higgs example)

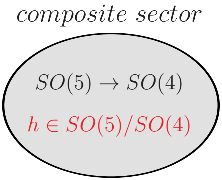
The composite Higgs construction

Higgs as a Goldstone boson coming from a composite dynamics

[Georgi, Kaplan; ...; Agashe, Contino, Pomarol; Contino, Da Rold, Pomarol; ...]

Minimal models are based on the symmetry breaking pattern

$$SO(5) \to SO(4)$$



The Higgs is described by a **non-linear σ-model**

$$\mathcal{L} = \frac{f^2}{2} \sum_i \partial_\mu U^t_{5i}\ \partial^\mu U_{i5} \qquad\qquad U = \exp\left[i\, h_i T^i\right]$$

($f \equiv$ Goldstone decay constant)

The composite Higgs construction

Higgs as a Goldstone boson coming from a composite dynamics

[Georgi, Kaplan; ...; Agashe, Contino, Pomarol; Contino, Da Rold, Pomarol; ...]

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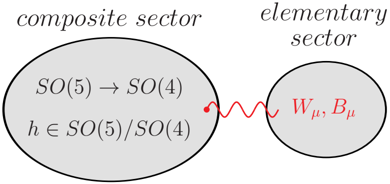

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SM gauge fields coupled by gauging $SU(2)_L \times U(1)_Y \subset SO(5)$

$$\partial_\mu U \rightsquigarrow D_\mu U = \partial_\mu U - i\, g\, A_\mu U$$

The Higgs couplings

❖ The **non-linear Higgs dynamics** induces corrections to the Higgs couplings

$$\mathcal{L} = m_W^2 W_\mu^+ W^{-\mu} \left(1 + 2\, a \frac{h}{v}\right) - \sum_\psi m_\psi \overline{\psi}\psi \left(1 + c_\psi \frac{h}{v}\right) + h.c.$$

- size of the corrections controlled by $\xi = v^2/f^2$

$$\text{MCHM}_4 \qquad a = \sqrt{1-\xi}$$

$$\text{MCHM}_5 \qquad a = \sqrt{1-\xi}\,,\ c_\psi = \frac{1-2\xi}{\sqrt{1-\xi}}$$

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$$\begin{array}{ll} \text{MCHM}_4 & a = \sqrt{1-\xi} \\ \text{MCHM}_5 & a = \sqrt{1-\xi}\,,\ c_\psi = \dfrac{1-2\xi}{\sqrt{1-\xi}} \end{array}$$

➢ The deviations of the Higgs couplings depend **only** on the Goldstone structure

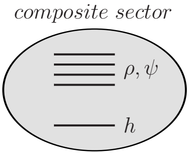
➢ At the LHC we can test $\xi \gtrsim 0.1$

The resonances

The strongly-coupled dynamics dynamics gives rise to **composite resonances**

The resonances are in general (SILH power counting) described by:

- a mass scale m_ρ
- a typical coupling g_ρ



The Goldstone structure implies a relation between the two parameters

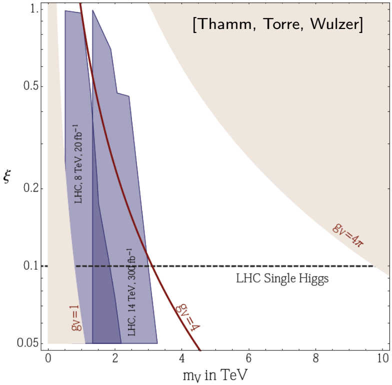
$$m_\rho \sim g_\rho f$$

Higgs couplings vs direct searches

- Direct searches can reach

$$m_\rho \lesssim 3\ \text{TeV} \quad \Leftrightarrow \quad g_\rho \lesssim 4$$

- The bounds from single-Higgs coupling measurements are competitive for sizable values of the coupling $g_\rho \gtrsim 4$



Higgs and flavor

Higgs and flavor in the SM

Higgs couplings in the SM have a very special form

Chiral structure and renormalizability imply that the Higgs couplings in the SM are **flavor-diagonal**

$$\mathcal{L}_Y = -\lambda_{ij}\overline{\psi}^i_L \psi^j_R \phi + h.c. \quad \Rightarrow \quad \mathcal{L}_Y = -m_i \left(1 + \frac{h}{v}\right) \overline{\psi}^i_L \psi^j_R + h.c.$$

Flavor changing effects are only generated by loop effects and are small

➢ Use as a **null test** for the SM!

Higgs and flavor

In BSM scenarios Higgs coupling structure can be modified

[see talks by Falkowski, Kamenik, Brod]

$$\mathcal{L}_Y = -\lambda_{ij}\overline{\psi}^i_L \psi^j_R \phi - \frac{\lambda'_{ij}}{\Lambda^2}\overline{\psi}^i_L \psi^j_R \phi(\phi^\dagger \phi) + h.c. + \cdots$$

➢ Sizable corrections, off-diagonal couplings and CP-violating effects are (in principle) possible

➢ **but** large corrections are only obtained in some specific scenarios:

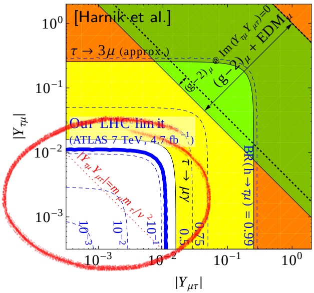
- very difficult in the leptonic sector
- more plausible in the quark sector
  (eg. 2HDM with MFV [Dery, Efrati, Hiller, Hochberg, Nir])

Higgs and flavor: Leptonic sector

Lepton flavor violating Higgs couplings are already constrained by many direct and indirect measurements [see talk by Kamenik]

- leptonic $(g-2)$
- EDMs
- Higgs data
- $l \to l'\gamma$
- ...

Some deviations in the $\mu\tau$ sector are still allowed



Higgs and flavor: Quark sector

In the quark sector corrections to the Higgs couplings can be there for each generation

- ➢ Flavor universal deformations are already highly constrained
[see talk by Falkowski]

- ➢ Enhancements of the **charm** Yukawa affects the Higgs measurements through the change of the higgs width
[see talk by Falkowski]

$$\frac{\Gamma_h}{\Gamma_{h,\mathrm{SM}}} \approx 0.57 \frac{y_b^2}{y_{b,\mathrm{SM}}^2} + 0.03 \frac{y_c^2}{y_{c,\mathrm{SM}}^2} + \cdots \quad \Rightarrow \quad y_c \lesssim 3\, y_{c,\mathrm{SM}}$$

- ➢ Enhancement of the **light quarks** Yukawa's can be constrained by looking at Higgs decays into vector mesons
[see talk by Soreq]

$$H \to \phi\gamma \quad \Rightarrow \quad y_s \lesssim 5\, y_{s,\mathrm{SM}} \quad (\text{late LHC})$$

Conclusions

Conclusions

The discovery of the $125\ \mathrm{GeV}$ boson opened a **new era** in high energy physics: direct access to the **mechanism of EWSB**

A joined experimental and theoretical effort is needed to extract information from the data:

- many ideas and scenarios to probe
- several analyses on the way and many more to come with the next run

Although no deviation from the SM has been seen so far it is too early to get depressed: still large space for **New Physics!**