Future prospects in Higgs Physics

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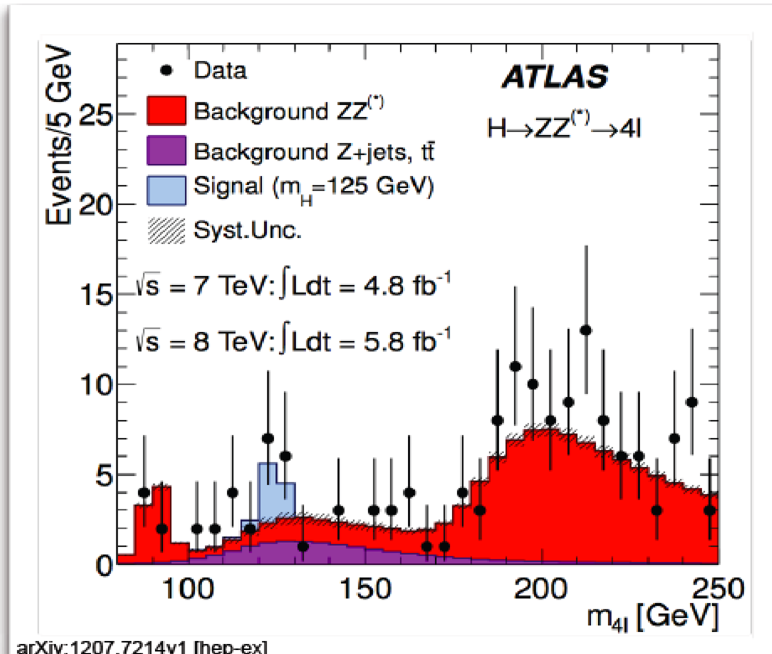
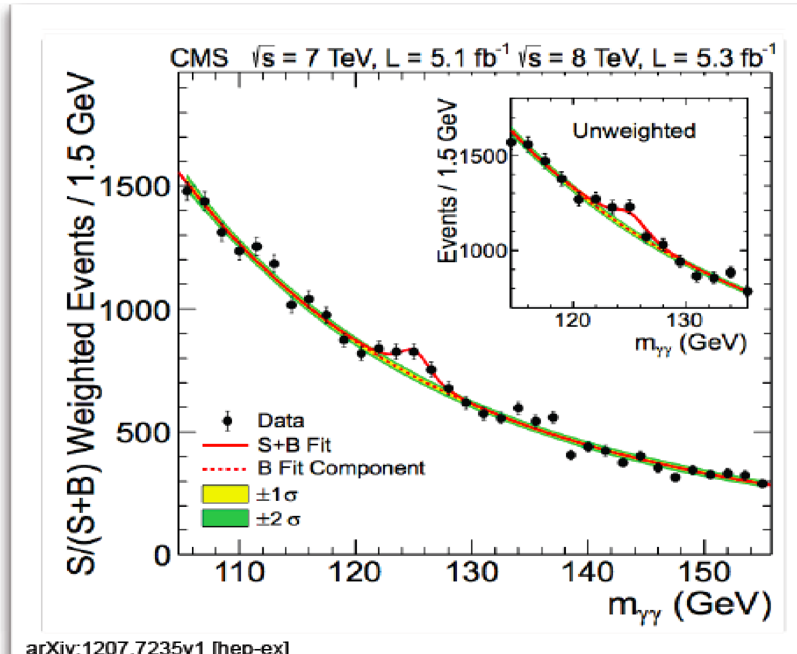
[*INFN, Frascati*]

- Introduction: what we learned so far
- The leading effective couplings
- Kinematical studies
- Rare modes within & beyond the SM
- Conclusions

Introduction [*what we learned so far*]





Introduction: what we learned so far

The discovery of the Higgs boson, and its first studies at run-I, represent a turning point in our understanding of fundamental interactions:

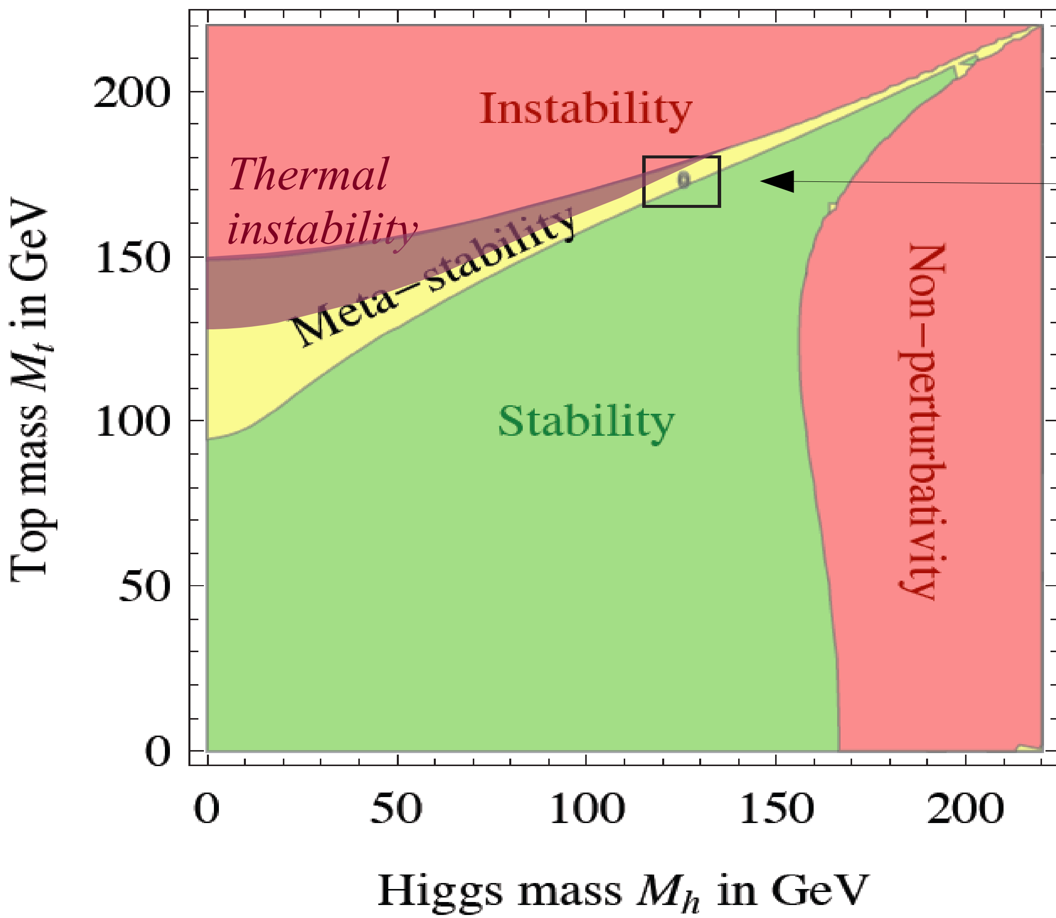
- All degrees of freedom predicted by the SM have been experimentally confirmed.

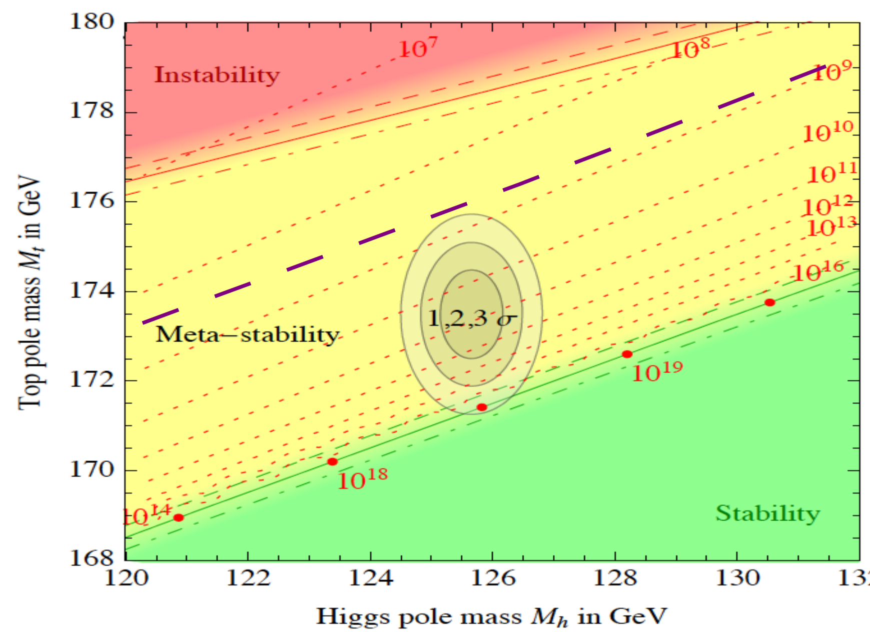
- Assuming h(125) is the the excitation of the Higgs field, then
  - m_h is compatible with the indirect constraints from e.w. precision observables ($\rightarrow$ *no clear clue for NP around the TeV scale*)
  - the leading Higgs couplings are compatible with SM expectations ($\rightarrow$ *no clear clue for extra light Higgses and/or NP around few 100 GeV*)
  - the Higgs field has a small self-interaction ($\lambda \approx \frac{1}{2} m_h^2/v^2 \approx 0.13$) and the SM potential is unstable but sufficiently metastable up to the Planck scale ($\rightarrow$ *no need for NP below the Planck scale*)

Introduction: what we learned so far [the Higgs mass]

Before the Higgs discovery there were strong hopes that knowing the *Higgs mass* (*the only mass scale in the theory*) we would have gained a clear clue about NP.

These hopes were justified, and indeed m_h *could have* given us clear clues about NP. However, we have not been so lucky...





...and the situation will not change significantly with more precise measurements of m_h

Introduction: what we learned so far

Still... the SM suffers of a series of theoretical & cosmological problems:

- Fine-tuning/UV sensitivity of the Higgs-mass term ["*hierarchy problem*"]
- Unexplained hierarchical structure of the Yukawa couplings ["*flavor puzzle*"]
- No explanation for the quantization of the U(1) charges [*hint of unification*?]
- No natural inclusion of neutrino masses [*hint of unification*?]
- Non coherent inclusion of gravity at the quantum level
- No good candidate for dark matter & no explanation of dark energy

↓

Common view: the SM (and in particular the Higgs sector) is an *effective theory*, or the low-energy limit of a more fundamental theory, with new degrees of freedom at high energies.

Introduction: what we learned so far

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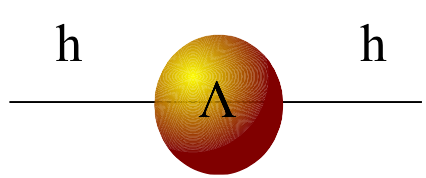
→ The only (qualitative) indication of NP not far from 1 TeV:



$$\Delta m_h^2 \sim \Lambda^2$$

Introduction: what we learned so far

The evidence of the new boson, compatible with the properties of the massive excitation of the Higgs field, indicates that the symmetry breaking sector of the effective theory has a *minimal* and *weakly coupled* structure...

$$\mathscr{L}_{\text{Symm. Break.}}(\phi, A_a, \psi_i) = D\phi^+ D\phi - V(\phi) + \ldots$$

$$V(\phi) = -\mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2 + Y^{ij} \psi_L^{\,i} \psi_R^{\,j} \phi$$

...but we are far from having established that there is nothing else beside the SM (*or that the cut-off of SM viewed as an effective theory is very high*)

↓

On general grounds, it is natural to expect possible deviations from the SM in the Higgs sector

↓

High-precision Higgs physics

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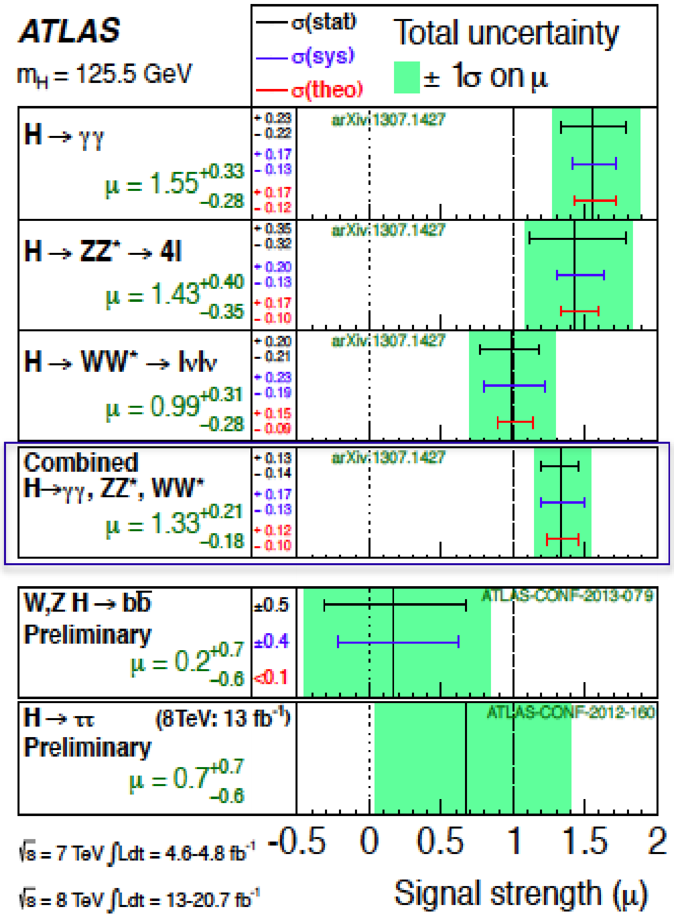
↓

High-precision Higgs physics

I. precise measurements of SM allowed processes (production & decay)

II. search for rare/exotic h decay modes

The leading effective couplings

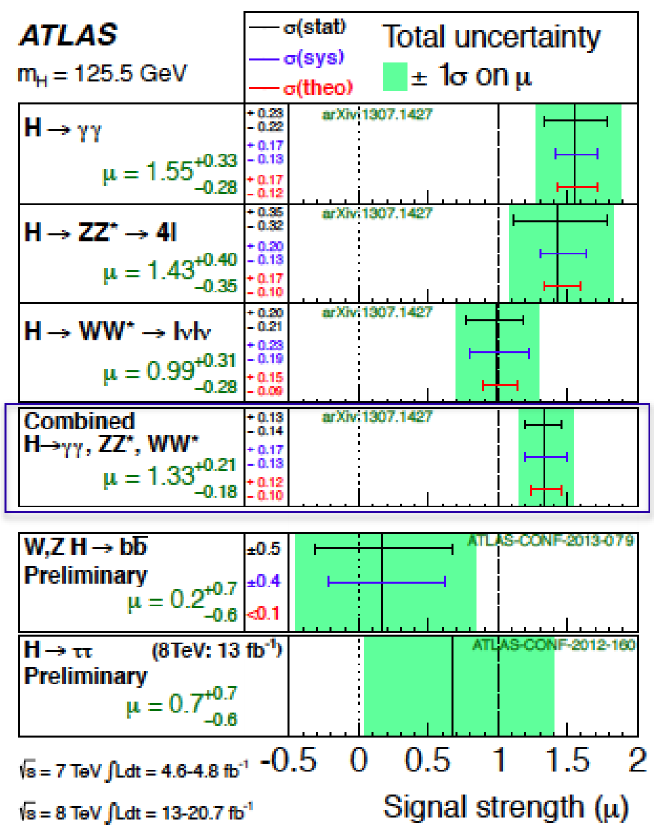


Phys. Lett. B 726 (2013), 88-119

The leading effective couplings

The first step in High-precision physics is the determination of the leading effective 3-point couplings to SM fields [h-$f_{SM}f_{SM}$]

The peculiar value $m_h \sim 125$ GeV offers the possibility to precisely measure several of these couplings.



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+ h-gg from $\sigma(gg \to h)$

h-$t\underline{t}$ from $\sigma(gg \to t\underline{t}+h)$

The leading effective couplings

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As discussed by many authors, such coupling could deviate from the SM reference values in extensions of the SM...

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

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

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

Contino *et al*. '10, '13

The leading effective couplings

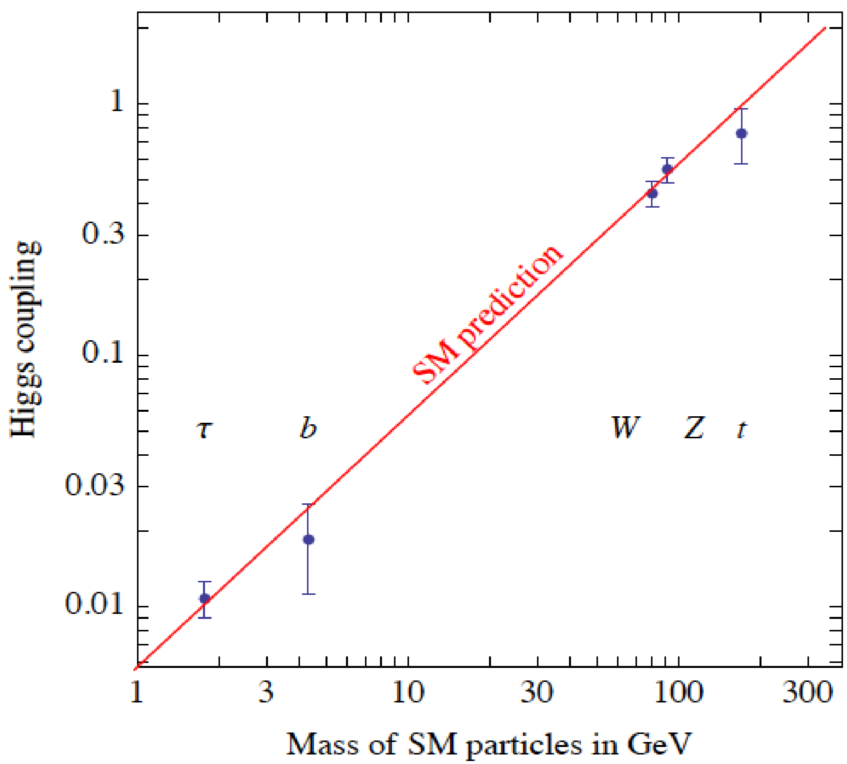
Key property within the SM:

$$c_f^{(tree)} = 2^{1/2} \frac{m_f}{v} \qquad c_V^{(tree)} = 2 \frac{m_V^2}{v^2}$$

Unitary gauge:

$$\phi = \frac{1}{2^{1/2}} \begin{bmatrix} 0 \\ v + h \end{bmatrix}$$

Fit to Higgs couplings



Giardino *et al.* '13
[similar results by many other groups]

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This prediction can change if...

- ϕ is not the only field responsible for e.w. symmetry breaking (*multi Higgs*)
- we add higher-dimensional operators (*generic heavy NP*)

$$y\, \psi_L \psi_R\, \phi + \frac{c}{\Lambda^2}\, \psi_L \psi_R\, (\phi^+\phi)\, \phi^3 + \ldots$$

Naïve estimate in generic EFT beyond SM:

$$\frac{\Delta c}{c_{SM}} \sim \frac{v^2}{\Lambda^2}$$

→ 20% Λ=0.6 TeV

→ 1% Λ=2.5 TeV

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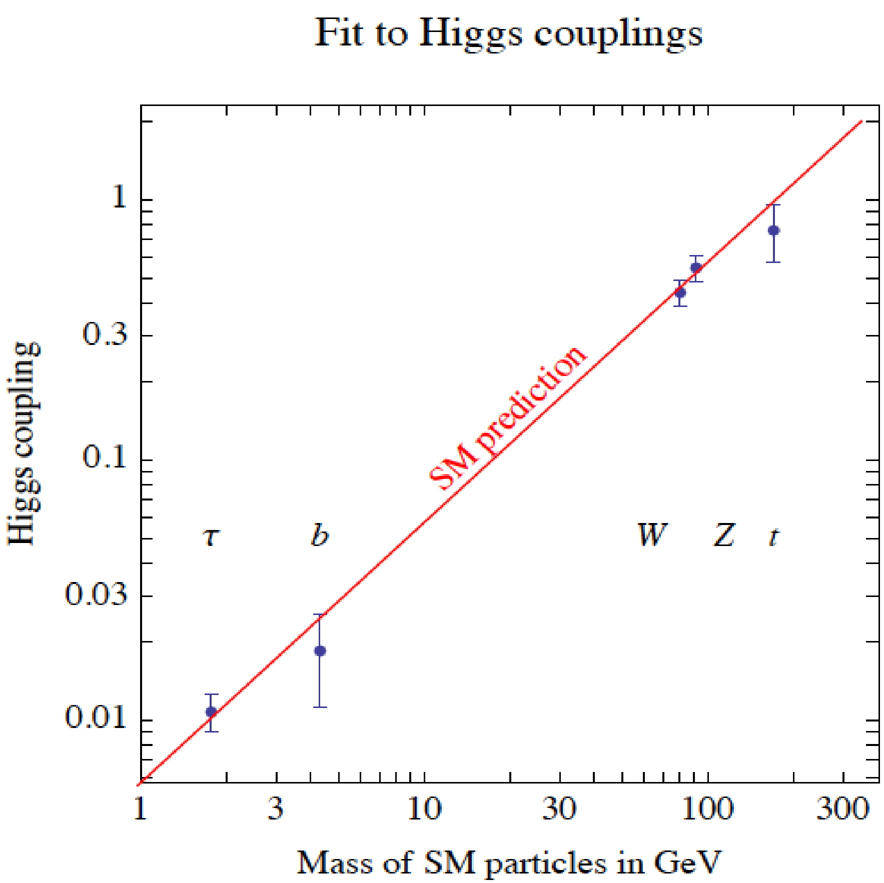
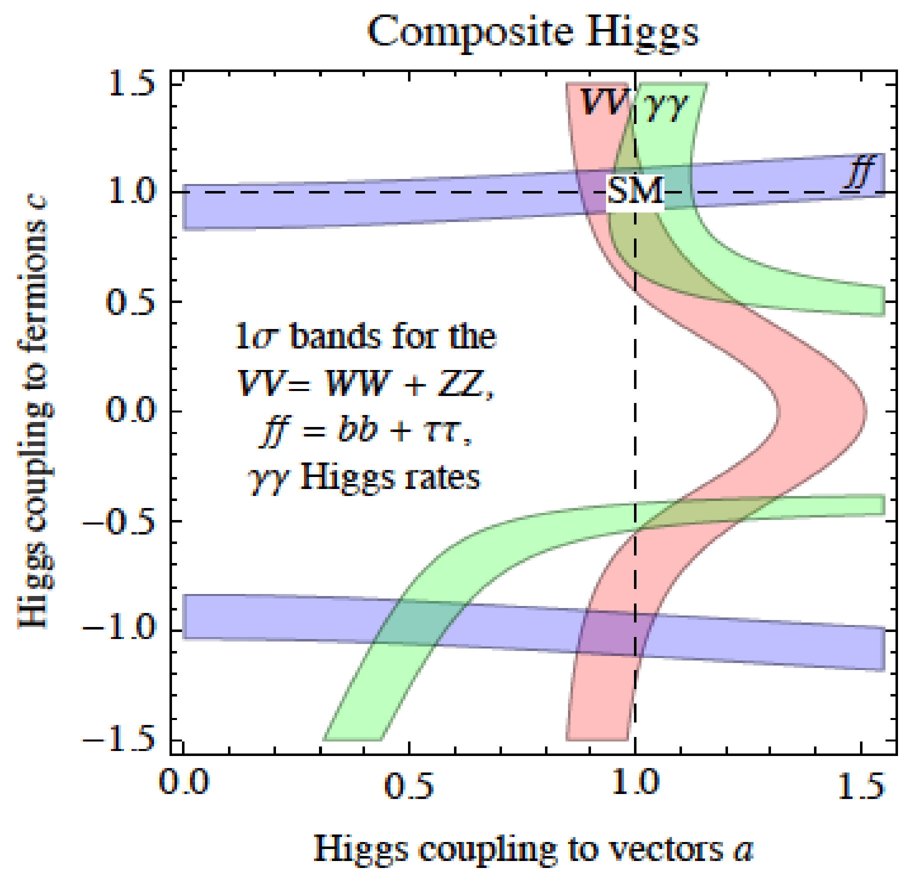
Specific models predicts specific correlations among the deviations in the various effective couplings (*reduced n. of free parameters*):

- Naïve composite/partial composite models: universal c_f & c_V
- (heavy) SUSY: 3-parameter fit c_b, c_t, c_V
- ...

▶ The leading effective couplings

A few tests of this type have already been performed:





In first approximation we have seen the SM Higgs...

Composite-Higgs models are not favored...

Giardino *et al*. '13 [similar results by many other groups]

The leading effective couplings

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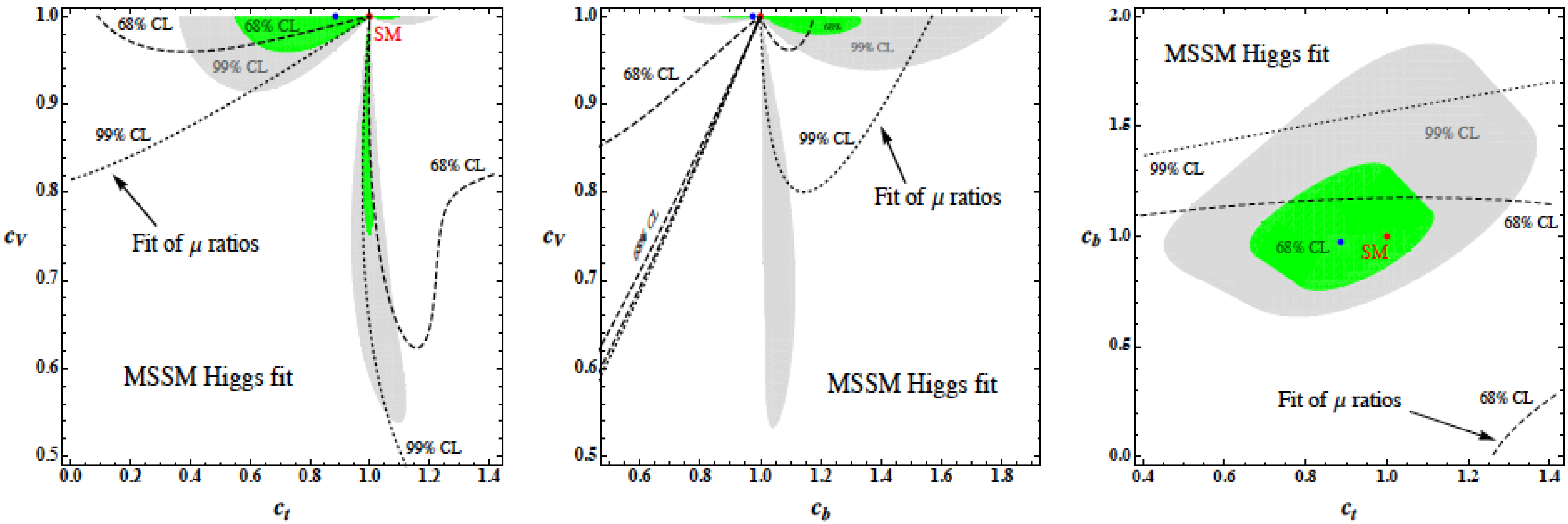


The MSSM remains in relatively good shape,
but it is hard to test it looking only at the (light) Higgs couplings...

Djouadi *et al.* '13

▶ *The leading effective couplings*

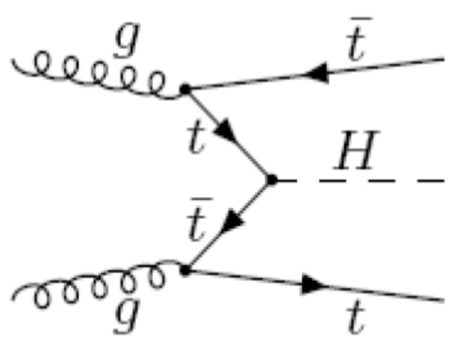
General relation to estimate the potential of future searches:

$$\frac{\Delta c}{c_{SM}} \sim \frac{v^2}{m_{NP}^2}$$

- 20% $\quad m_{NP} > m_0$
- ↓
- 2% $\quad m_{NP} > 3\times m_0$

But the deviations can be larger in specific channels (within specific NP models).

Particularly interesting case: H-$t\bar{t}$ coupling, in models where the top is a (partial-)composite state:



O(1) *deviations from the SM not impossible...*

The leading effective couplings

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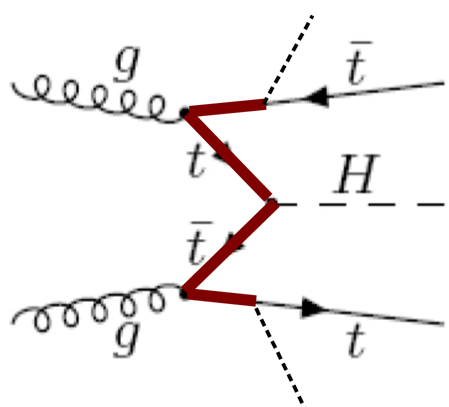


O(1) *deviations from the SM not impossible...*

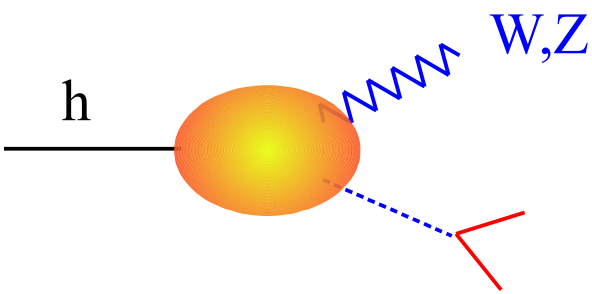
...especially if also other prod. mechanisms contribute

The leading effective couplings

But the peculiar value $m_h \sim 125$ GeV offers many more interesting tests:

Three (almost) unexplored directions:

Kinematical studies in $h \to 4l$ & in V+h associated production



$A(h \to Vff) \neq A(h \to VV^*)$

Rare SM modes [including *exclusive semi-hadronic* decays]

E.g.:

$h \to Z\gamma$ [$BR_{SM} \sim 1.5 \times 10^{-3}$]

$h \to \mu\mu$ [$BR_{SM} \sim 2.2 \times 10^{-4}$]

$h \to Z\Upsilon$ [$BR_{SM} \sim 1.6 \times 10^{-5}$]

Exotic/forbidden decay modes [e.g. *LFV* modes, *h → invisible*, *h → new light states*, ...]

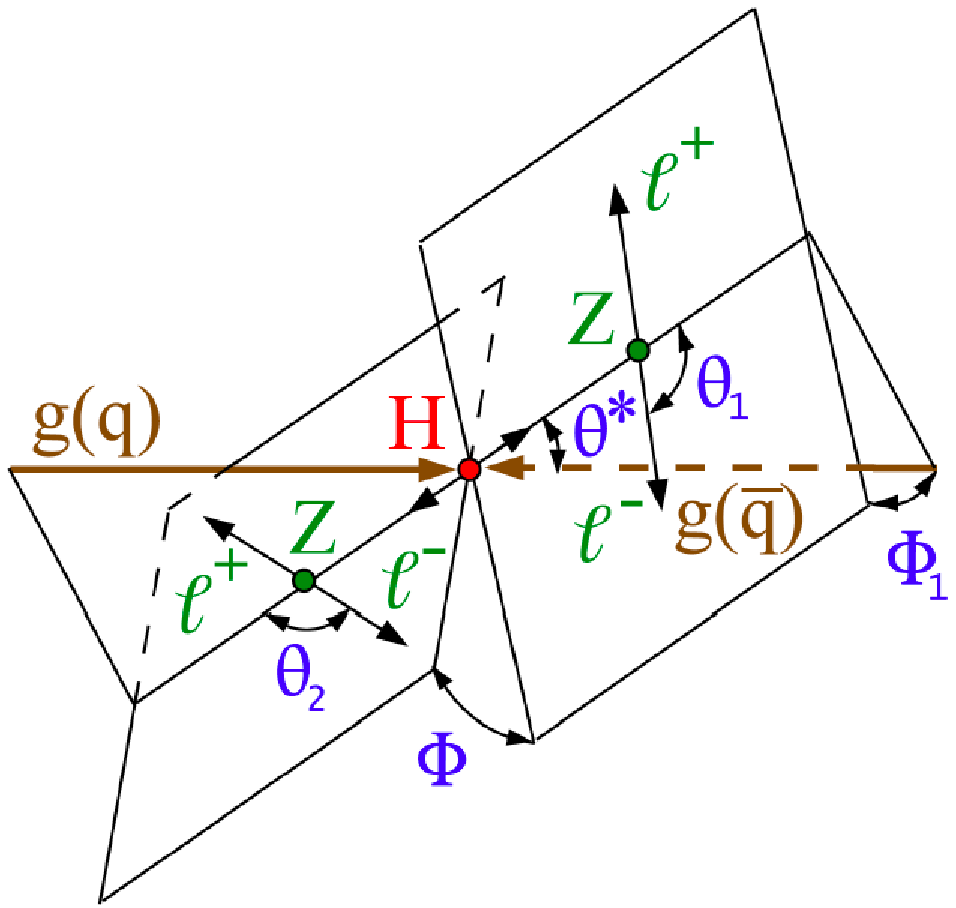
E.g.:

$h \to \mu\tau$

$h \to Z+A$

...

Kinematical studies



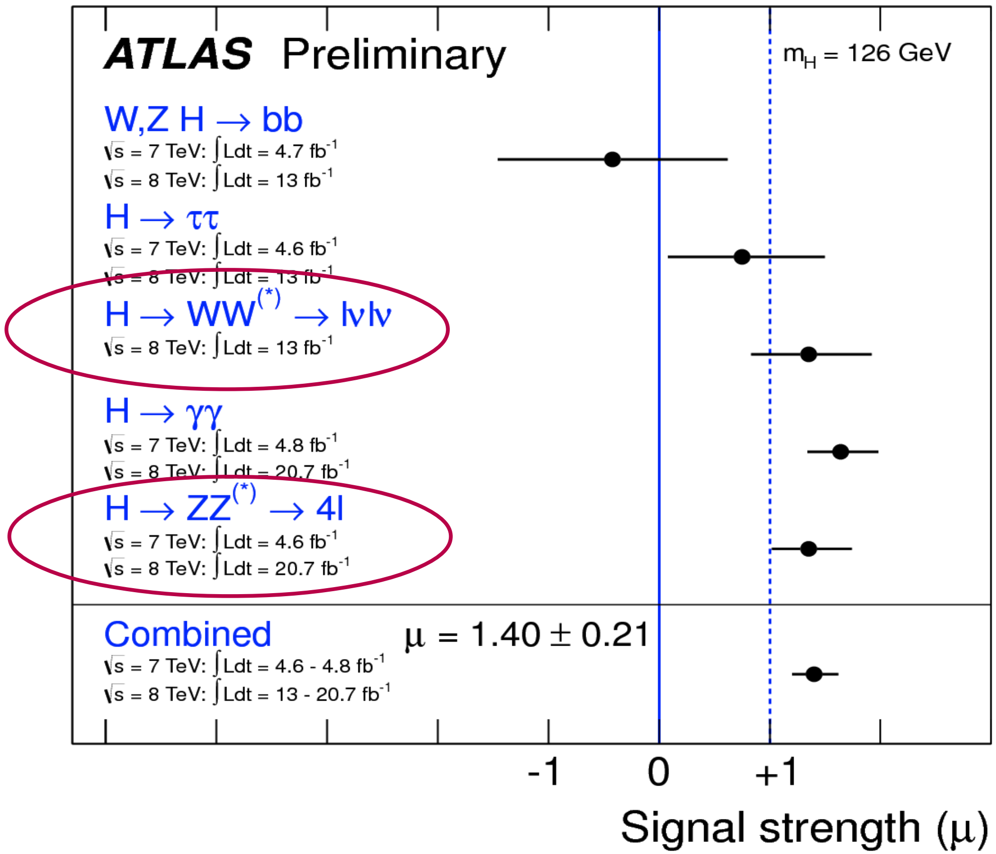
Kinematical studies [mainly $h \to 4l$]

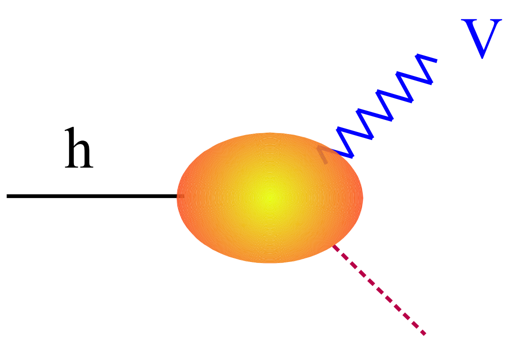
ATLAS and CMS have reported results about the $h \to WW^*$ & $h \to ZZ^*$ couplings

However, what is really measured are 4-lepton modes.

With suitable cuts what can be probed in experiments is the $h \to Vff$ amplitude (V=W, Z) and, in general,

$$A(h \to Vff) \neq A(h \to VV^*)$$





$$J_\mu^f = \bar{f}\,\gamma_\mu (v^f + a^f \gamma_5) f$$

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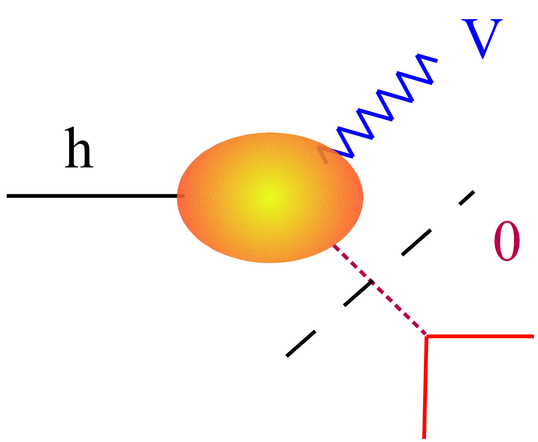
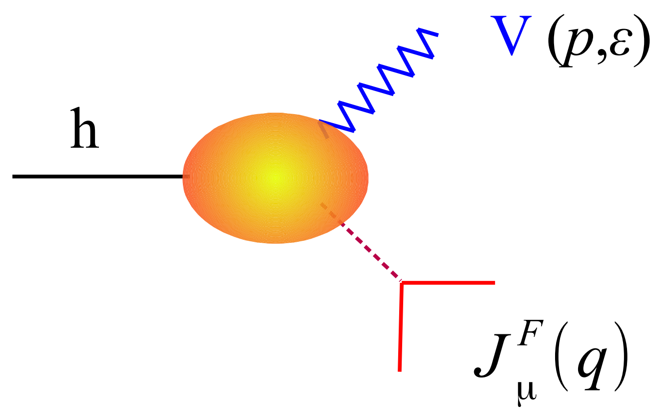


The "offshellness" of the second lepton pair allows to probe a richer dynamical structure:

- We are far enough from the pole of the amplitude at $q^2 = m_V^2$ (*the only pole within the SM*)
- Measuring the q^2 dependence we could possibly reveal new "distant poles" (↔ *contact interactions*) or even new "light poles" (↔ *new light states coupled to Higgs & fermions*)

Kinematical studies [mainly h → 4*l*]

Assuming J(h)= 0 → general decomposition of the amplitude in terms of *4 independent form factors*:

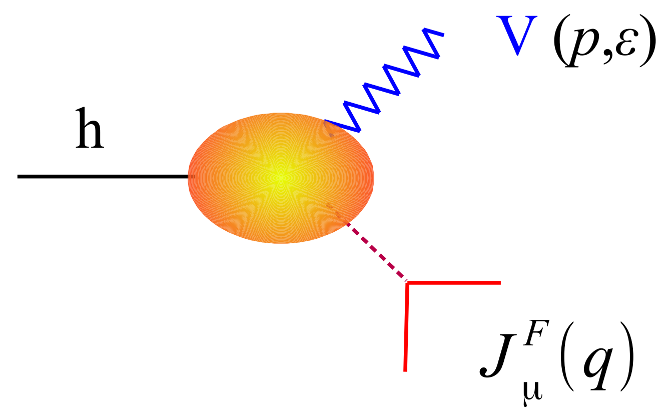


$$\mathcal{A}_V^{\mathcal{F}} = C_V g_V^2 m_V \frac{\varepsilon_\mu J_\nu^{\mathcal{F}}}{(q^2 - m_V^2)} \left[f_1^V(q^2) g^{\mu\nu} + f_2^V(q^2) q^\mu q^\nu + f_3^V(q^2)(p\cdot q\, g^{\mu\nu} - q^\mu p^\nu) + f_4^V(q^2)\epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma \right]$$

GI, Manohar, Trott, '13

- SM limit: $f_1 = 1$, $f_2 = -1/m_V^2$, $f_{3,4} = 0$
- f_2 do not contribute to conserved currents (→ irrelevant for *l*=e,μ)
- f_3 do not contribute if $J_\mu \sim q_\mu$
- Re(f_4) is CP odd in h → ZZ* if CP(h)=+
- Im(f_4) is CP even, but it is allowed only for a hW*lv* local interaction

▶ *Kinematical studies* [mainly $h \to 4l$]



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$$\mathcal{A}_V^{\mathcal{F}} = C_V g_V^2 m_V \frac{\varepsilon_\mu J_\nu^{\mathcal{F}}}{(q^2 - m_V^2)} \left[f_1^V(q^2) g^{\mu\nu} + f_2^V(q^2) q^\mu q^\nu + f_3^V(q^2)(p\cdot q\; g^{\mu\nu} - q^\mu p^\nu) + f_4^V(q^2) \epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma \right]$$

N.B.: This structure is more general than what presently used to analyze data:

$$\mathcal{A}_{VV*} = \frac{\kappa}{(q^2 - m_V^2)} \left[a_1\; g^{\mu\nu} + a_2\; q^\mu p^\nu + a_3\; \epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma \right]$$

KEY POINT:

$a_i \to a_i(q^2)$

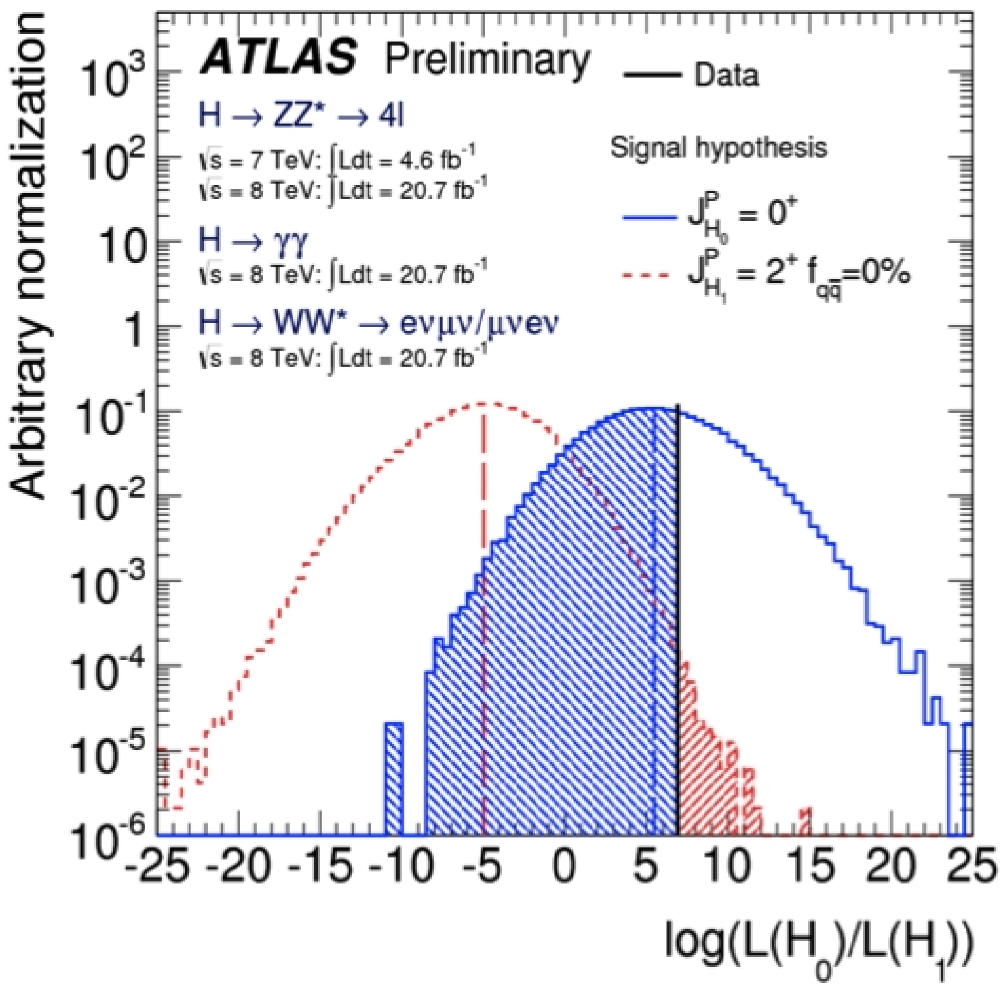
…but is trivial to relate the two parameterizations for $h \to Z+ll$

$a_1(t) = f_1(t) + f_3(t)\times(m_h^2 - m_V^2 - t)/2$ $a_3(t) = -f_3(t)$ $a_4(t) = f_4(t)$

Kinematical studies [mainly h → 4*l*]

So far the h → 4*l* analysis were focused on determining

- The signal strength (= total rate)
- The J^{CP} properties of h →

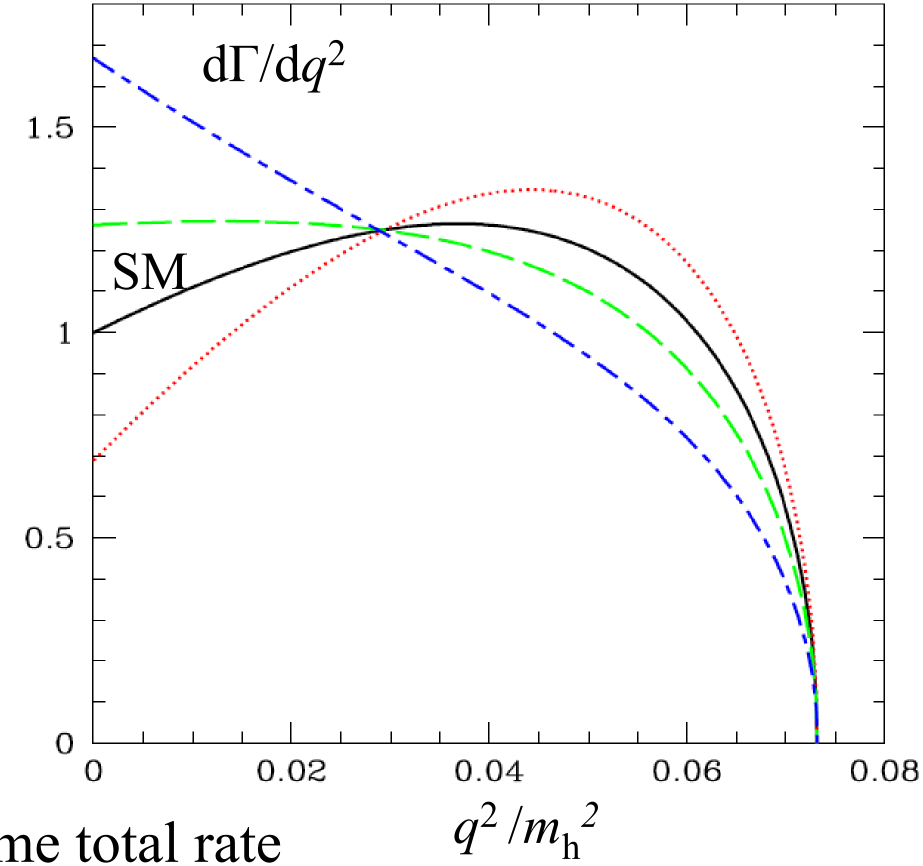


Kinematical studies [mainly h → 4l]

So far the h → 4l analysis were focused on determining

- The signal strength (= total rate)
- The J^{CP} properties of h

However, we know very little yet about possible modification of the $q^2=m_{ll}^2$ spectrum, that can easily occur even if h is a 0^+ state



Possible modifications of the spectrum,
With generic NP ~ 1 TeV, leading to the same total rate

→ significant constraints from EPWO [Pomarol & Riva, '13]

However...
- significant deviations in the Zll spectrum still possible
- testing if such constraints are verified is a powerful tool to test if h is indeed part of an SU(2) doublet

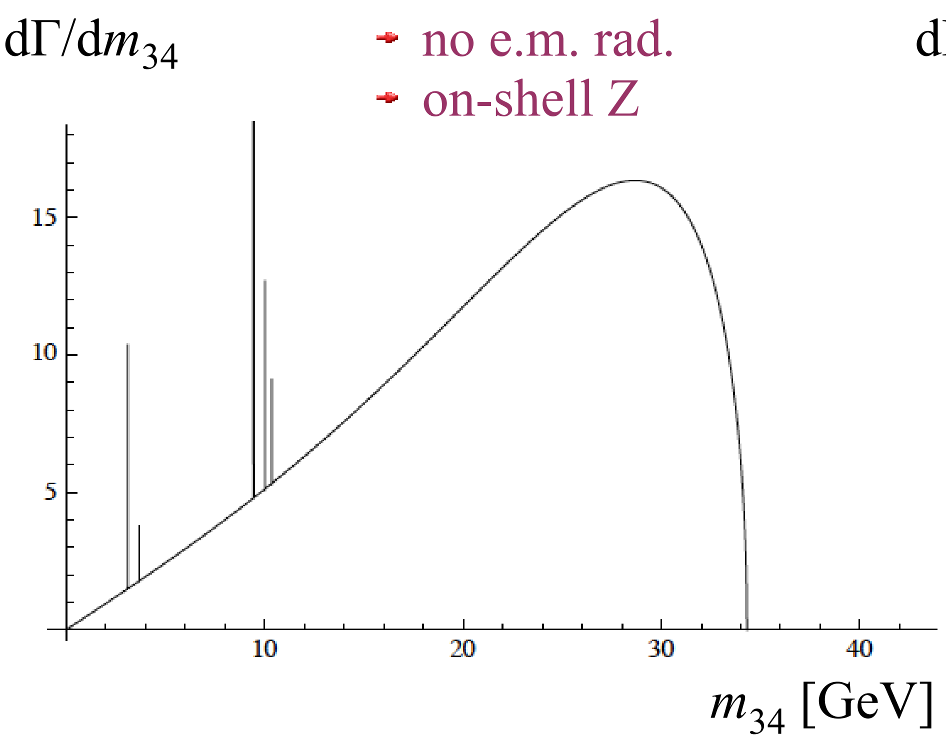
GI, Trott, '13

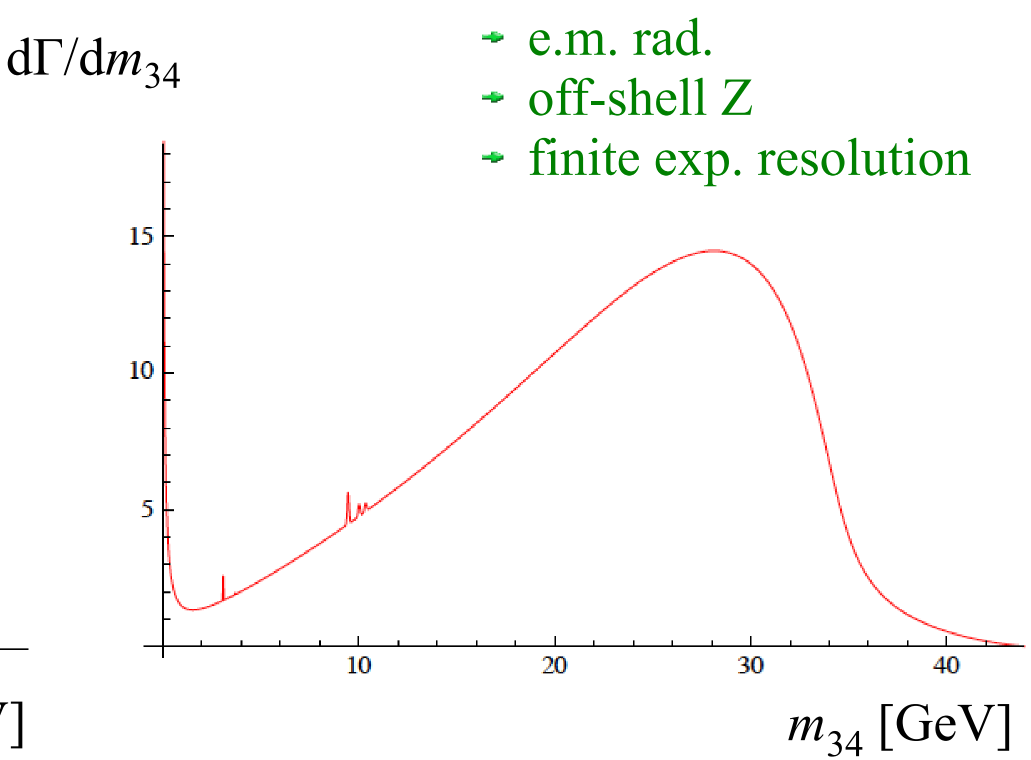
Kinematical studies [mainly $h \to 4l$]

The (spin-averaged) double differential distribution is the most efficient way to perform a model-indep. analysis aimed to extract the CP-conserving $f_i\,(q^2)$

$$\frac{d^2\Gamma}{d\,m_{34}\,d\cos\theta}$$

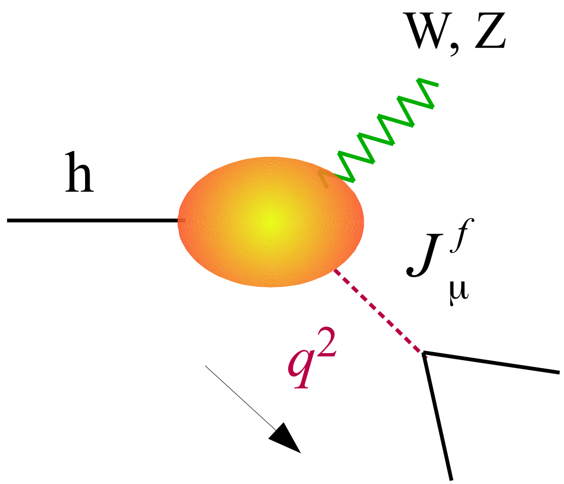
Possible to derive a very precise SM distribution, even at low m_{34}, including charmonium states [GI & Gonzales-Alonso, work in prog.]:



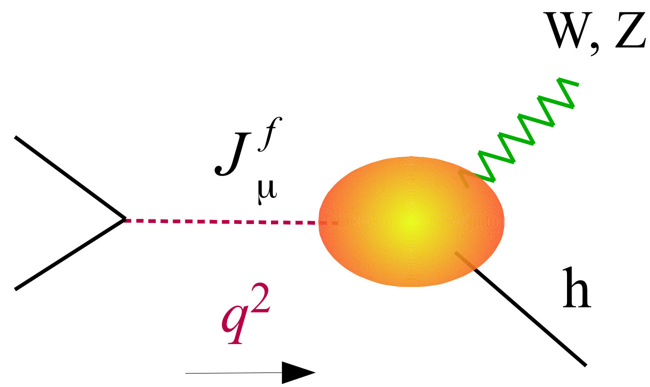


Kinematical studies [mainly $h \to 4l$]

The *hVff* form *f*actors are accessible also inV+h associated production in a different kinematical regime

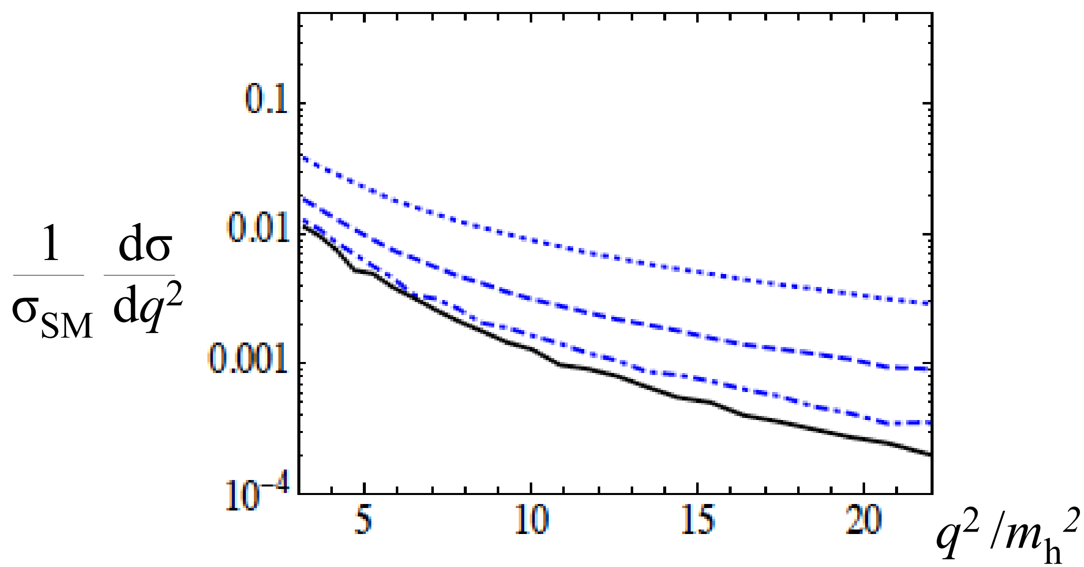


$0 < q^2 < (m_h - m_V)^2$



$q^2 > (m_h+m_V)^2$

KEY variable:
h+Z(W) invariant mass



Rare modes within & beyond the SM

Rare modes within & beyond the SM

On general grounds, rare/exotic Higgs decays offer a very interesting window to NP

On the TH side:

- Unique window on models where (light) NP couples directly (*effective tree-level coupling*) only to the Higgs field (*Higgs portal*, …)
- Large deviations from the SM less constrained by other observables (e.g. EWPO)

On the EXP side:

- Hopefully more room for improvement with increasing statistics vs. the (slow) improvement in measurements where we have already seen the SM signal...

Rare modes within & beyond the SM

I. $h \to Z\gamma$

This mode is semi-rare [$BR_{SM} \sim 1.5\times10^{-3}$] and its knowledge would complete the picture of the $h\text{-}SM_{gauge}\text{-}SM_{gauge}$ effective couplings

- Loop generated within the SM (similar to $h \to \gamma\gamma$)
- Key observation: No direct constraint within a generic EFT approach by EPWO + $h \to \gamma\gamma$ => O(1) deviations from the SM possible on general grounds (*naturally expected in composite-Higgs models*)

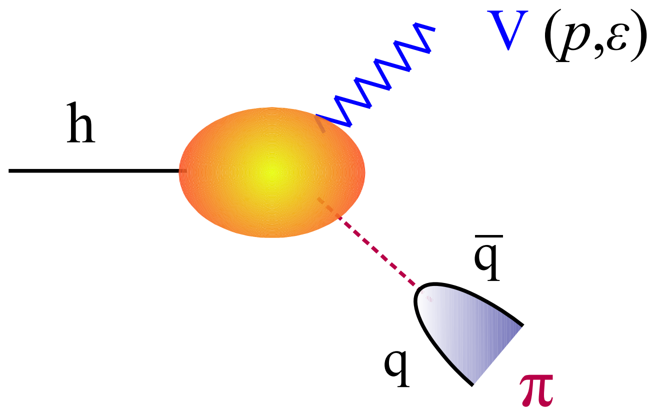
Azatov, Contino, Di Iura, Galloway, '13
Pomarol & Riva, '13

- Strong phenomenological interest if some deviation seen in $h \to \gamma\gamma$

Rare modes within & beyond the SM

II. Exclusive hadronic/semi-hadronic decays

Rare $h \to VP$ decays, where P is a single hadron state (*pseudo-scalar* or *vector-meson*) are a very interesting probe of the vacuum-structure of the theory



$$A^{\mathrm{SM}} \propto \frac{f_P}{v}$$

ratio of the two order parameters controlling the $SU(2)_L$ *breaking*

GI, Manohar, Trott, '13

Radiative modes of the type $h \to \gamma Y$ where Y is a quarkonium state have similar properties: more sensitivity to hqq couplings, but still dominated by $h \to \gamma Z^* \to \gamma Y$ within the SM

Bodwin, Petriello, Sonyev, Velasco, '13

Rare modes within & beyond the SM

II. Exclusive hadronic/semi-hadronic decays

The SM rates are suppressed but not outrageously small (*thanks to* m_h ~125 GeV), and some channels may have a (*relatively*...) clean signature

VP mode	$\mathcal{B}^{SM}$	VP^* mode	$\mathcal{B}^{SM}$
$W^-\pi^+$	0.6×10^{-5}	$W^-\rho^+$	0.8×10^{-5}
W^-K^+	0.4×10^{-6}	$Z^0\phi$	2.2×10^{-6}
$Z^0\pi^0$	0.3×10^{-5}	$Z^0\rho^0$	1.2×10^{-6}
$W^-D_s^+$	2.1×10^{-5}	$W^-D_s^{*+}$	3.5×10^{-5}
W^-D^+	0.7×10^{-6}	W^-D^{*+}	1.2×10^{-6}
$Z^0\eta_c$	1.4×10^{-5}	$Z^0 J/\psi$	1.7×10^{-6}
$h \to \gamma J/\psi$	2.5×10^{-6}	$h \to Z\Upsilon$	1.6×10^{-5}

Sizable modifications possible in various BSM frameworks

GI, Manohar, Trott, '13

Bodwin *et al.* '13
GI, Gonzales-Alonso '14

Rare modes within & beyond the SM

II. Exclusive hadronic/semi-hadronic decays

The SM rates are suppressed but not outrageously small (*thanks to* m_h ~125 GeV), and some channels may have a (*relatively*...) clean signature

VP mode	$\mathcal{B}^{SM}$	VP^* mode	$\mathcal{B}^{SM}$
$W^-\pi^+$	0.6×10^{-5}	$W^-\rho^+$	0.8×10^{-5}
W^-K^+	0.4×10^{-6}	$Z^0\phi$	2.2×10^{-6}
$Z^0\pi^0$	0.3×10^{-5}	$Z^0\rho^0$	1.2×10^{-6}
$W^-D_s^+$	2.1×10^{-5}	$W^-D_s^{*+}$	3.5×10^{-5}
W^-D^+	0.7×10^{-6}	W^-D^{*+}	1.2×10^{-6}
$Z^0\eta_c$	1.4×10^{-5}	Z^0J/ψ	1.7×10^{-6}
$h\to\gamma J/\psi$	2.5×10^{-6}	$h\to Z\Upsilon$	1.6×10^{-5}

Sizable modifications possible in various BSM frameworks

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$\to$ $BR[\,h\to W^\pm D_s^\mp(\gamma)\,]\approx10^{-4}$

They definitely deserve a dedicated experimental search !

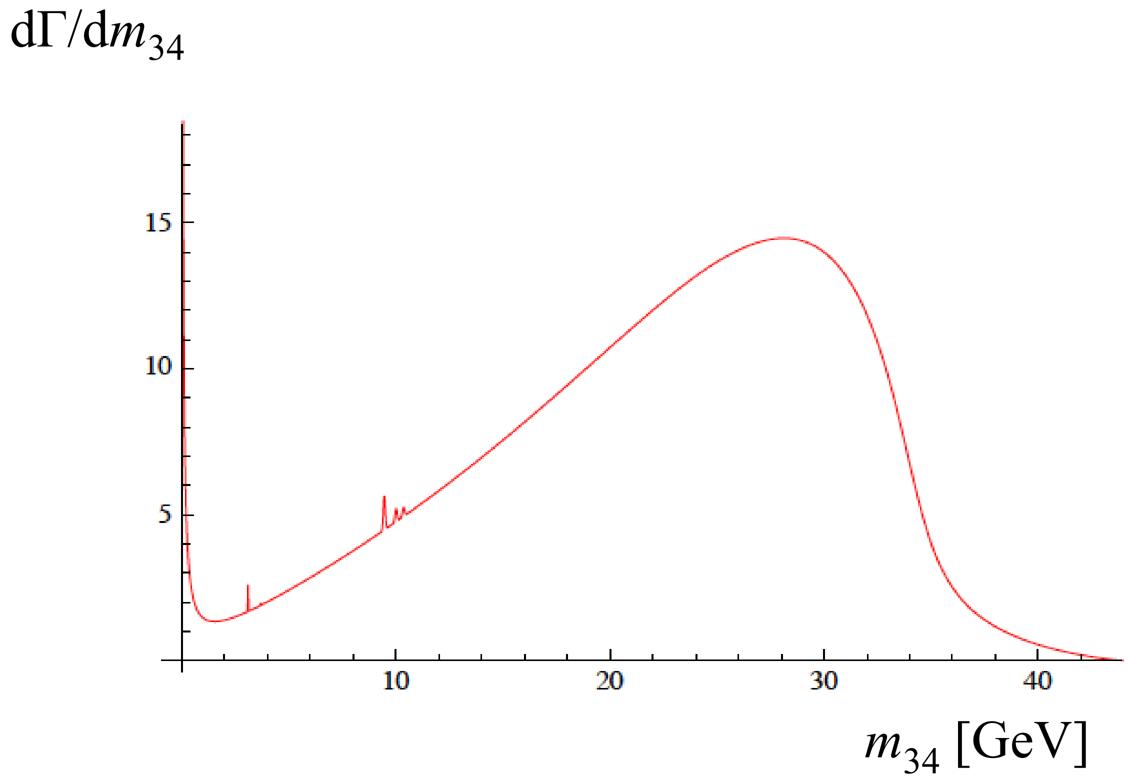
Rare modes within & beyond the SM

II. Exclusive hadronic/semi-hadronic decays

The quarkonium modes cannot be seen as peaks in the h → 4l distribution with the run-II statistics (maybe only in the HL phase).

Still, it is very interesting to search for possible larger exotic peaks in such distribution (due to h → Z + A → 4l)

Curtin *et al.* '13



Rare modes within & beyond the SM

III. LFV h decays

Higgs-mediated FCNCs are unavoidable in models with more Higgs doublets and, more generally, can be viewed as the effect of higher-dimensional operators (in the EFT approach):

$$Y^{ij}\, \psi_L^{\,i} \psi_R^{\,j}\, \phi + \varepsilon^{ij}\, \psi_L^{\,i} \psi_R^{\,j}\, \phi^3 + \ldots$$

$$\varepsilon^{ij} = \frac{c^{ij}}{\Lambda^2}$$

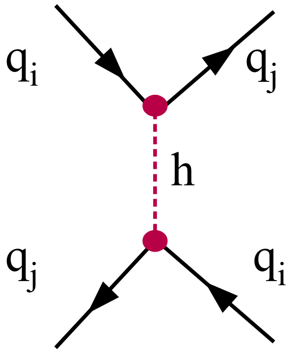
⬇

$$\underbrace{(vY^{ij} + v^3\, \varepsilon^{ij})}_{vY_{\rm eff}}\, \psi_L^{\,i} \psi_R^{\,j} + (Y^{ij} + 3v^2\, \varepsilon^{ij})\, \psi_L^{\,i} \psi_R^{\,j}\, h + \ldots$$

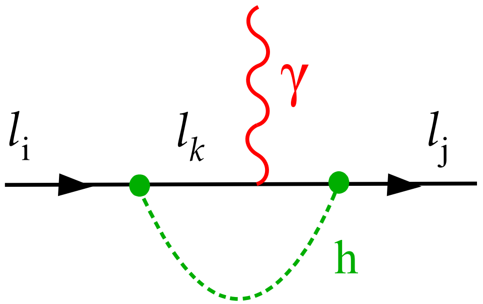
h FCNC couplings if $Y^{ij} \neq c\, \varepsilon^{ij}$

Rare modes within & beyond the SM

$$\mathcal{L}_{\rm eff} = \sum_{i,j=d,s,b\ (i\neq j)} c_{ij}\ \bar{d}^i_L d^j_R h + \sum_{i,j=u,c,t\ (i\neq j)} c_{ij}\ \bar{u}^i_L u^j_R h + \sum_{i,j=e,\mu,\tau\ (i\neq j)} c_{ij}\ \bar{\ell}^i_L \ell^j_R h + \text{H.c.}$$



Strongly bounded by ΔF=2 (except for terms involving the top)



Not very severe bounds for the τμ and τe effective couplings

↓

Flavor-changing decays into lepton pairs -with one tau- are not strongly constrained: BR(h → τμ, τe) $\lesssim$ 10% → worth a direct search !!

Blankenburg, Ellis, G.I. '12

ATLAS & CMS already have the sensitivity to set bounds on BR(h → τμ) $\lesssim$ 1%

Harnik, Kopp, Zupan, '12
Davidson, Verdier, '12

Conclusions

- A SM-like Higgs with m_h =125-126 GeV does not allow us to derive model-independent conclusions about the scale of New Physics:
  the SM Higgs potential is unstable but sufficiently long-lived

- However, *leaving aside theoretical prejudices*... there is still a lot to learn from Higgs physics: precise measurements of signal strengths, differential distributions and rare decays are almost unexplored windows that is worth to investigate in more detail.