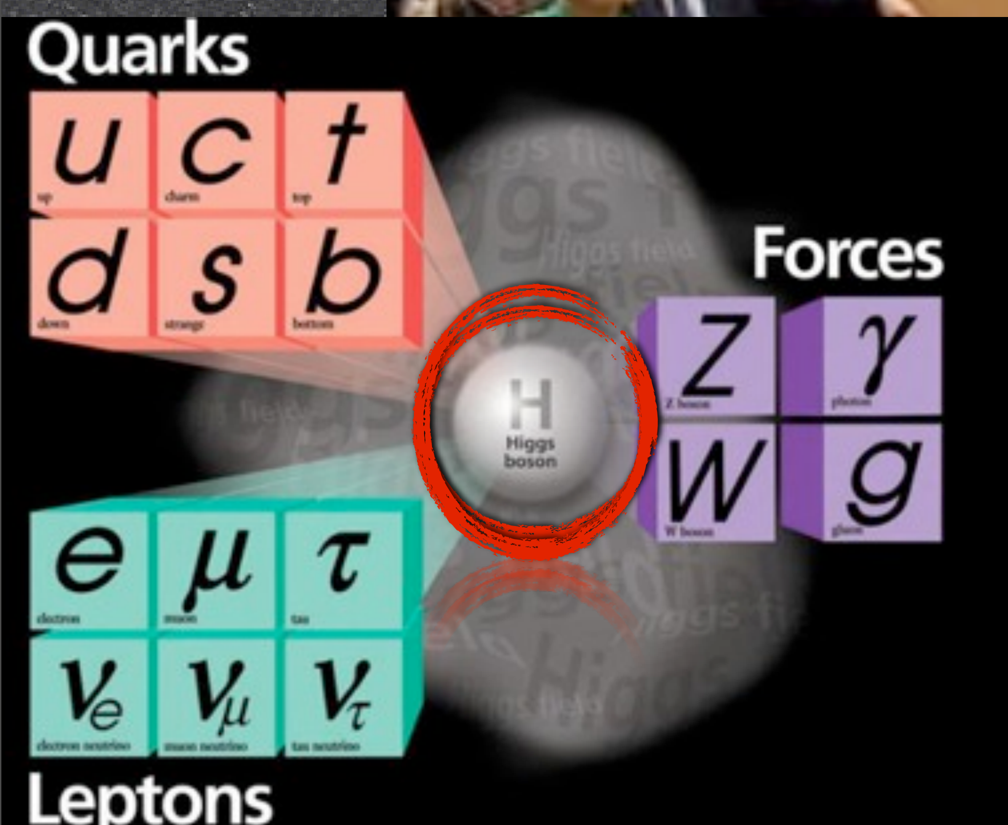
Searching For New Physics via Exotic Higgs Decays

HEFT Workshop

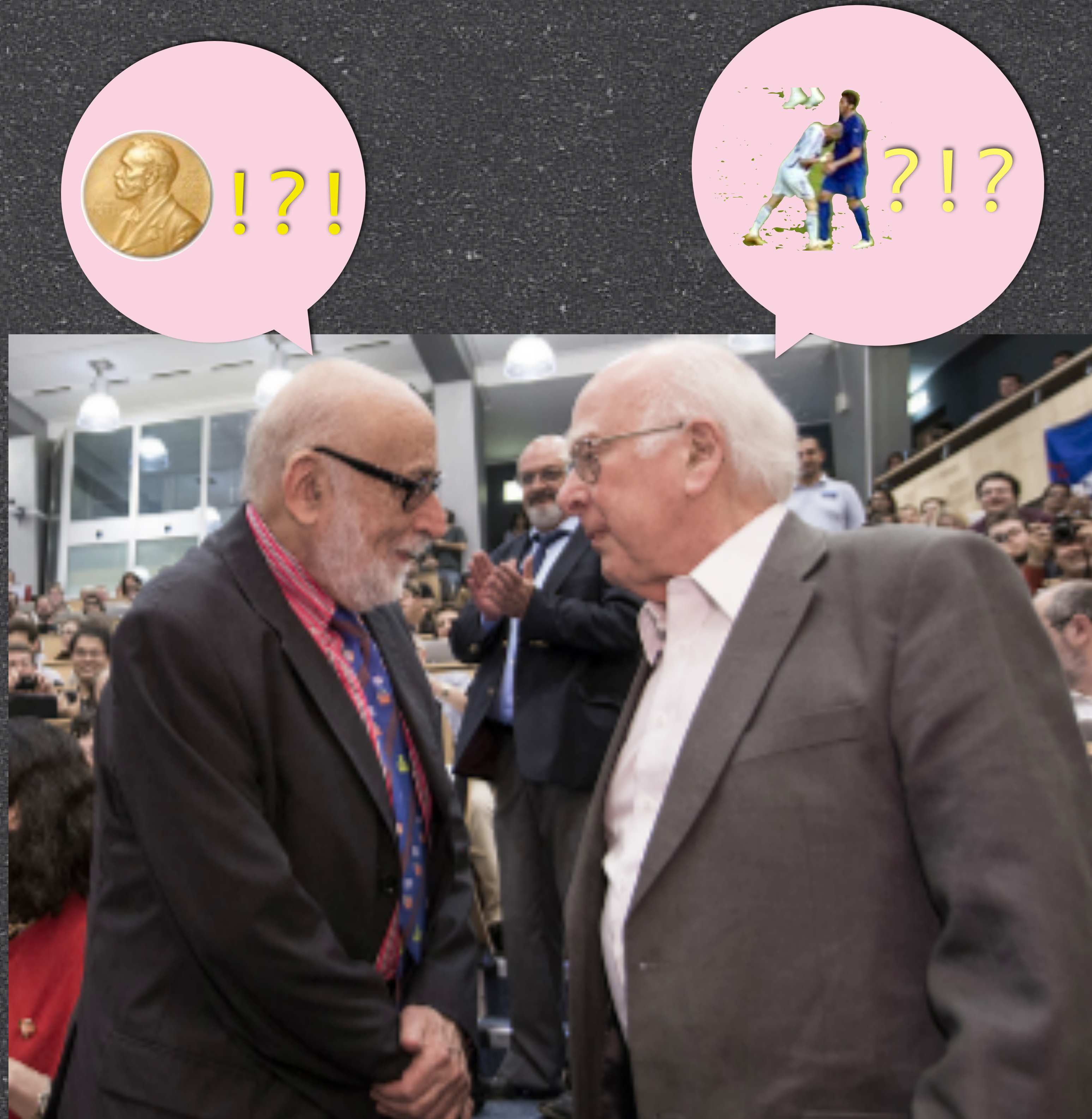
CERN, 10 October 2013

Habemus Higgsam!



4th of July 2012

Habemus Higgsam and Englertam!



4th of July 2012

Habemus Noblam!

08.10.2013

Habemus Noblam!

Time for party!

Beer borrowed from Carla Biggio

08.10.2013

Habebamus Noblam!

...so this was yesterday, now this is today

10.10.2013

Habemus Higgsam

"...this is this moment after a party when you wake up and see who are you in bed with..."

10.10.2013

7 parameter fit

Best fit and 68% CL range for 7 parameters of effective Higgs Lagrangian

$$\mathcal{L}_{h,\mathrm{sim}} = \frac{h}{v}\Big(\quad 2c_V m_W^2 W_\mu^+ W_\mu^- + c_V m_Z^2 Z_\mu Z_\mu$$
$$-c_u \sum_{q=u,c,t} m_q \bar{q} q - c_d \sum_{q=d,s,b} m_q \bar{q} q - c_l \sum_{l=e,\mu\tau} m_l \bar{l} l$$
$$+\frac{1}{4} c_{gg} G^a_{\mu\nu} G^a_{\mu\nu} - \frac{1}{4} c_{\gamma\gamma} \gamma_{\mu\nu} \gamma_{\mu\nu}$$
$$-\frac{1}{2} c_{WW} W^+_{\mu\nu} W^-_{\mu\nu} - \frac{1}{4} c_{ZZ} Z_{\mu\nu} Z_{\mu\nu} - \frac{1}{2} c_{Z\gamma} \gamma_{\mu\nu} Z_{\mu\nu} \Big)$$

$$c_V = 1.04^{+0.03}_{-0.04}$$

$$c_u \in (-1.3, 1.3)$$

$$c_d = 1.02^{+0.12}_{-0.17}$$

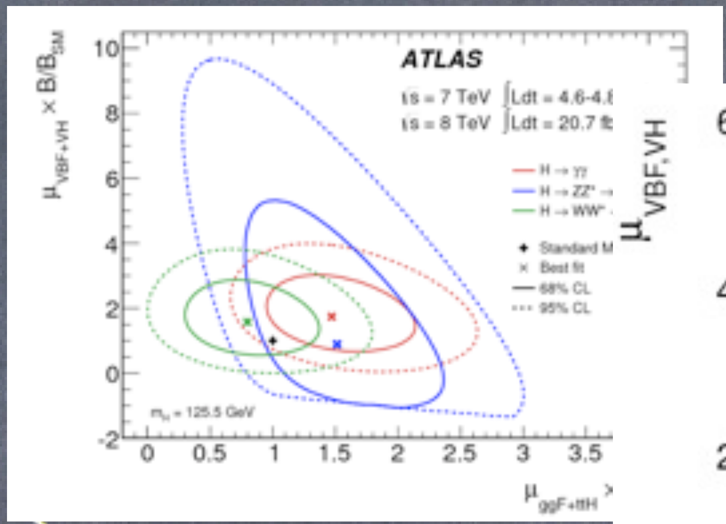
$$c_l = 0.98^{+0.21}_{-0.21}$$

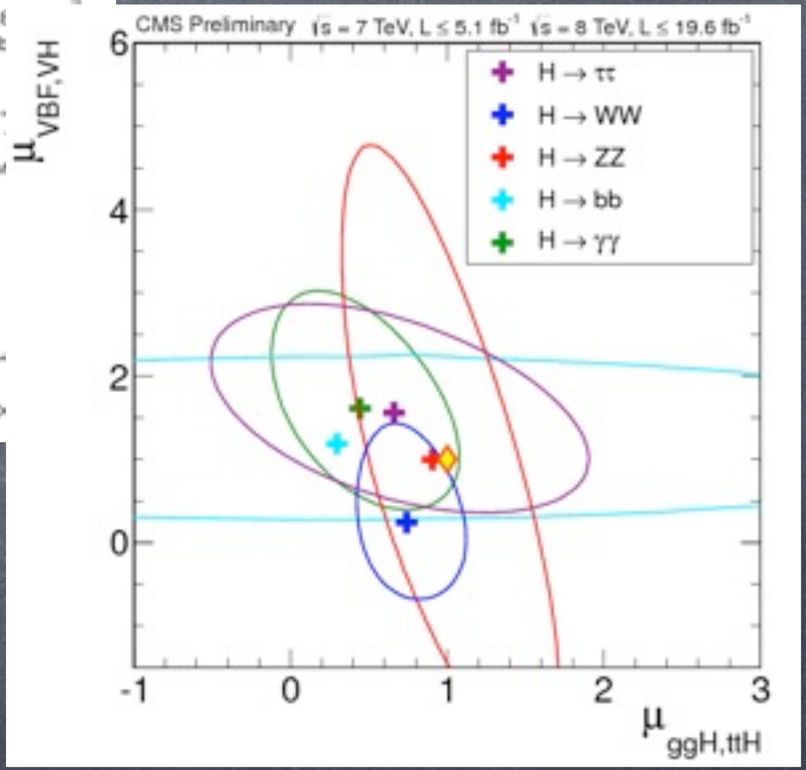
$$c_{gg} \in (-0.026, 0.026)$$

$$c_{\gamma\gamma} = 0.0001^{+0.0018}_{-0.0021}$$

$$c_{Z\gamma} = 0.006^{+0.015}_{-0.028}$$

Islands of good fit with negative cu, cd, cl ignored here



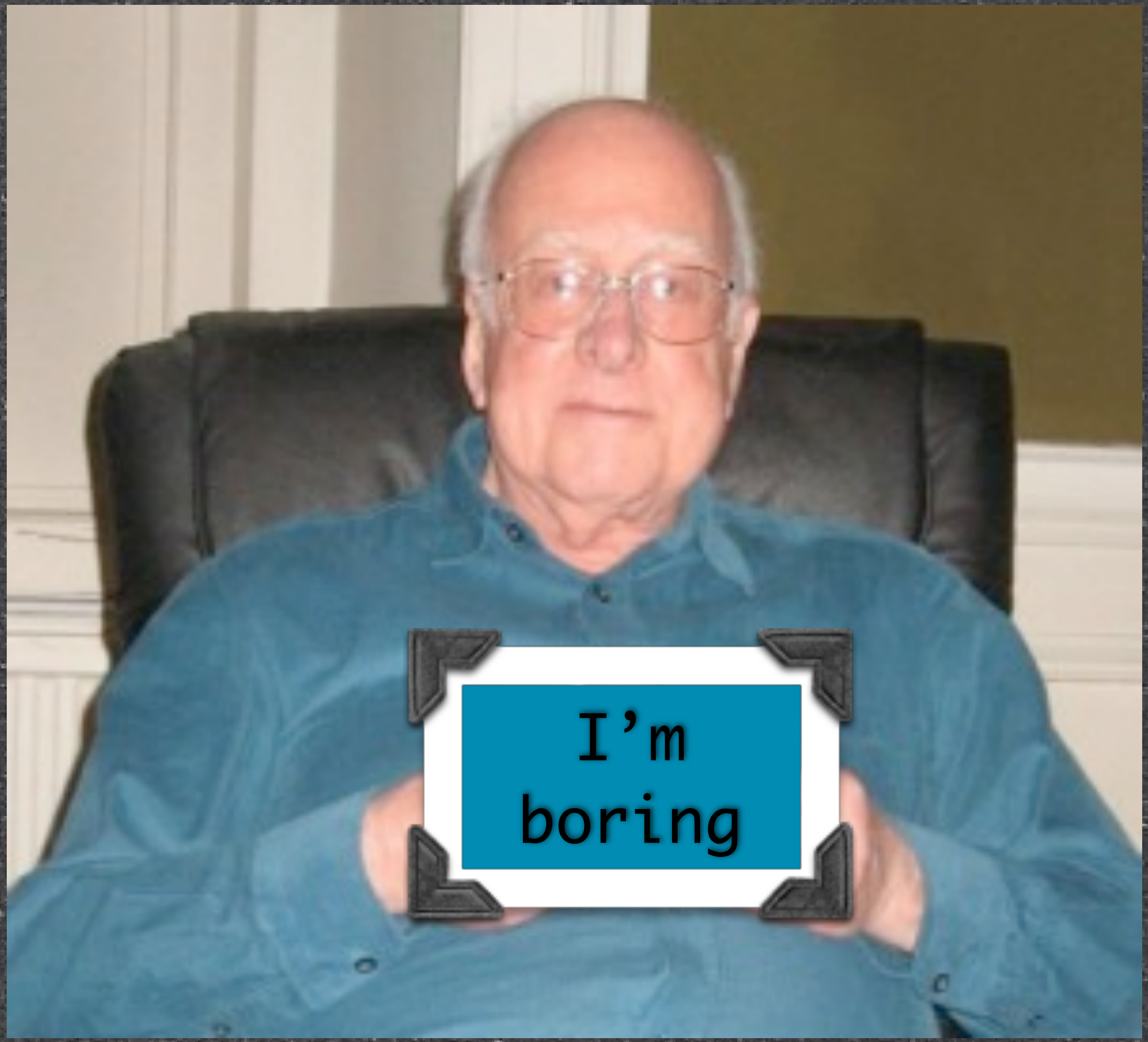


$\Delta\chi^2 = \chi^2_{SM} - \chi^2_{min} \approx 7$, with 7 d.o.f. the SM hypothesis is a perfect fit

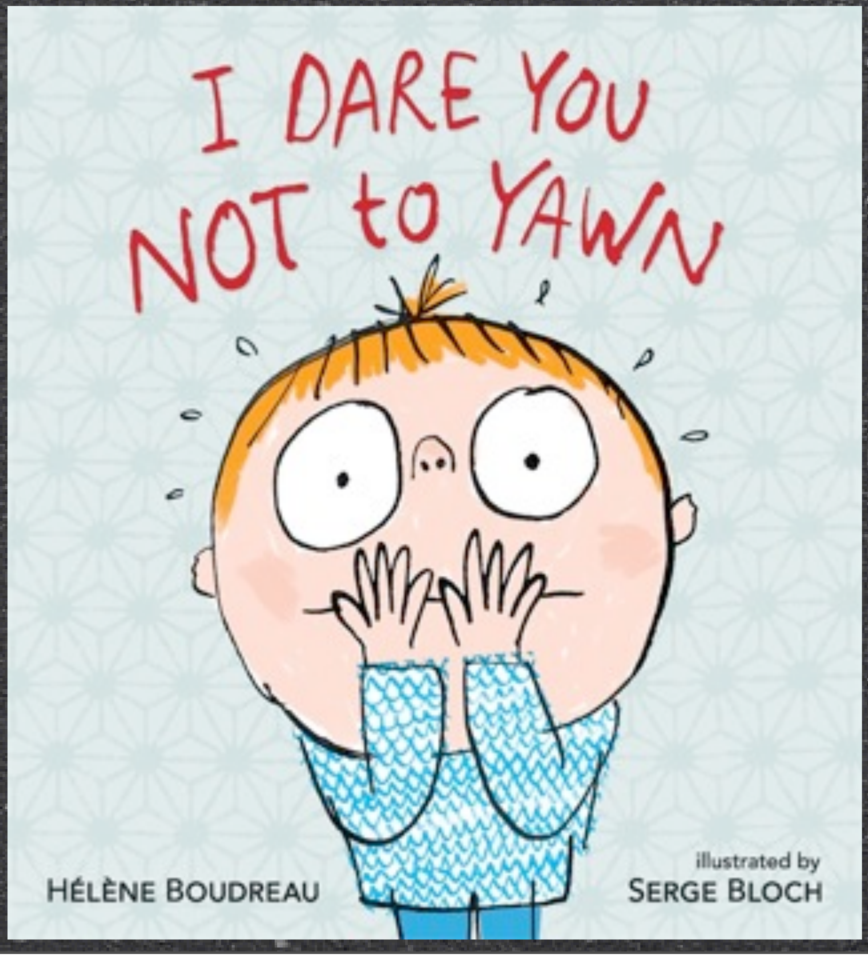
Fit as of 23/09/2013

(thanks to Hermès Belusca)

Habemus Higgsam



Are we stuck with precision Higgs physics?



Habemus Higgsam

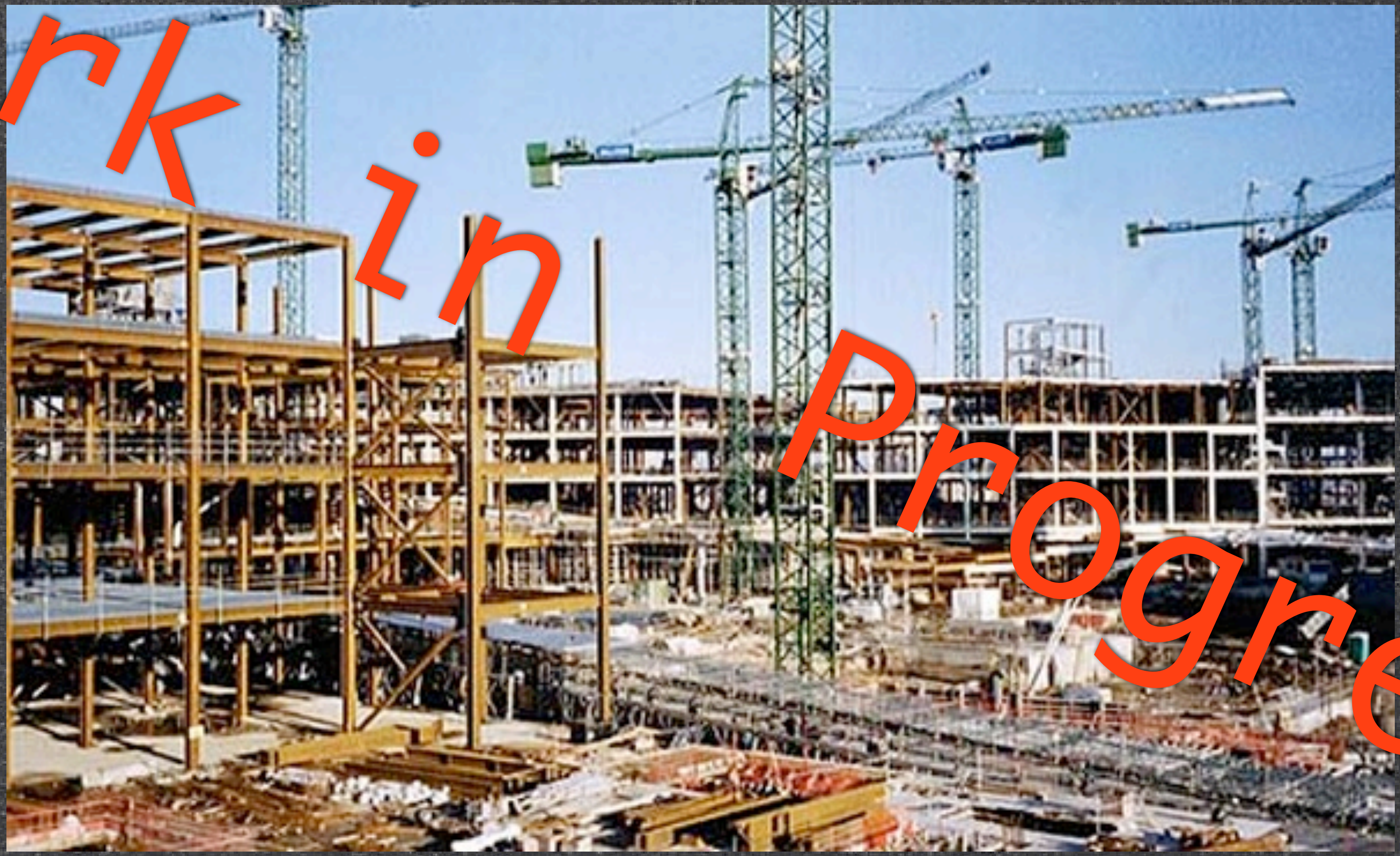
But maybe Higgs has a more interesting face?

THIS TALK: Discuss the possibility of exotic Higgs decay channels

(exotic==not predicted in the SM or predicted with a ridiculous branching fraction)

Exotic Higgs Decays

Work in Progress



All numbers very preliminary,
take them with a grain of salt
or outwardly ignore

Exotic Higgs Decays - Why?

- Indirect constraints (via visible decays) allow for up to ~25% branching fraction into exotic states (if the Higgs production rate is as in the SM), or even up to ~50% with some conspiracy (if the Higgs production rate is enhanced). That means the LHC cross section for exotic Higgs decays could easily be order picobarn
- The SM Higgs width is just 4 MeV, so even weakly coupled new physics can lead to a significant branching fraction for exotic decays. E.g., a new scalar X coupled as $c|H|^2 |X|^2$ corresponds to $BR(h\to X^*X)=10\%$ BR for $c\sim 0.01$.
- Thanks to the large Higgs cross section even tiny exotic branching fractions may possibly be probed. For spectacular enough signatures we can probe $BR\sim O(10^{-5})$ now and $BR\sim O(10^{-8})$ in the asymptotic future. [Note that the Higgs was first <u>discovered</u> in the diphoton ($BR\sim 10^{-3}$) and 4-lepton ($BR\sim 10^{-4}$) channels]

Exotic Higgs Decays - How?

New light degrees of freedom affecting Higgs decays

No new light degrees of freedom beyond those of the SM

SM+X

Multiple possibilities, large model dependence

HEFT

Leading effects expected from dimension 6 operators beyond the SM

Exotic Higgs Decays: SM+X

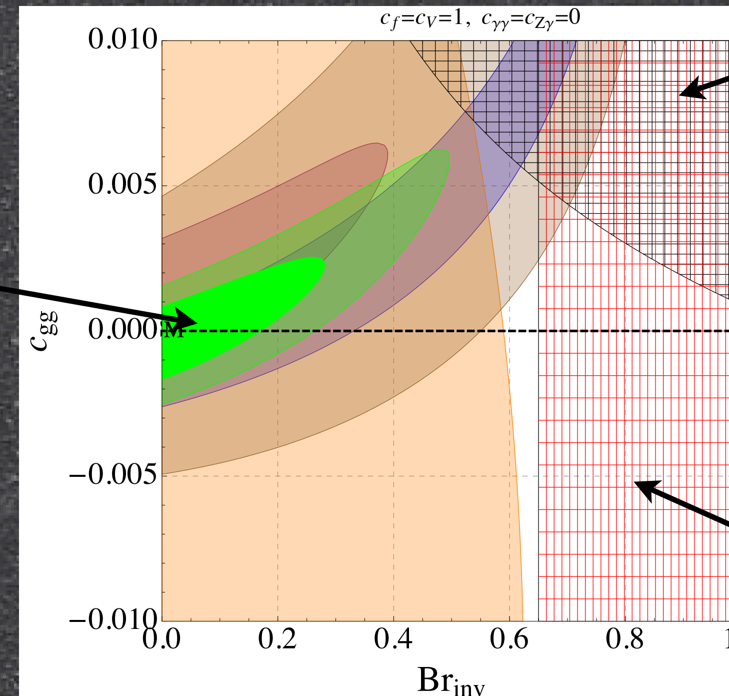
Examples:

h → invisible

h → XX, possible e.g.
Higgs portal DM models

$$X^2|H|^2$$

Searches ongoing, interesting experimental limits, but somewhat stronger indirect limits



Favored

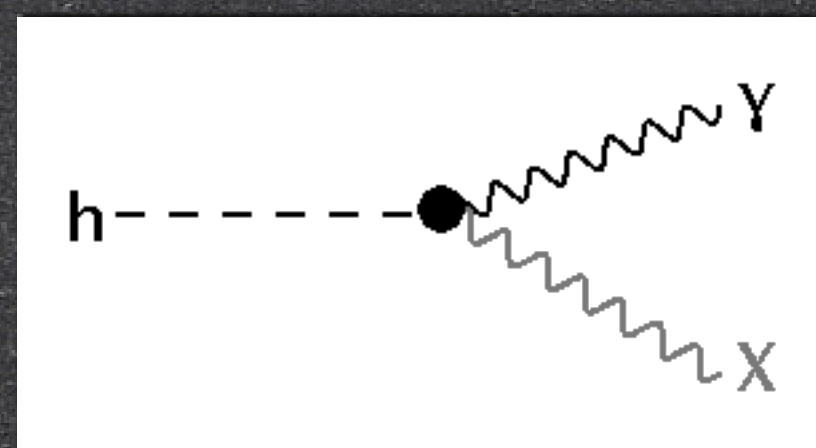
Excluded by monojets

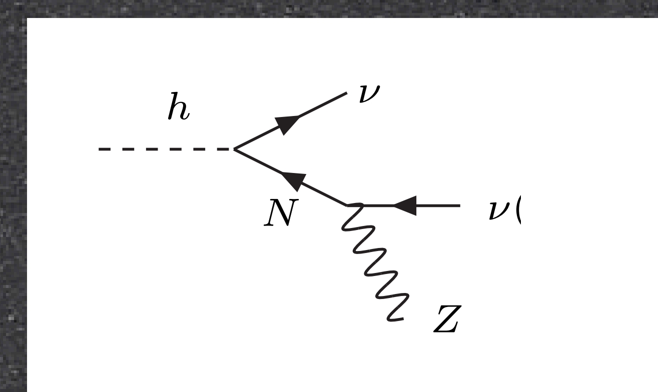
Excluded by ZH→invisible

h → monophoton/monoZ

h → XV, possible e.g. in hypercharge portal models or in inverse see-saw

$$|H|^2 X_{\mu\nu} B_{\mu\nu}$$





No experimental limits whatsoever, and I'm not aware of ongoing experimental searches....

Exotic Higgs Decays: SM+X

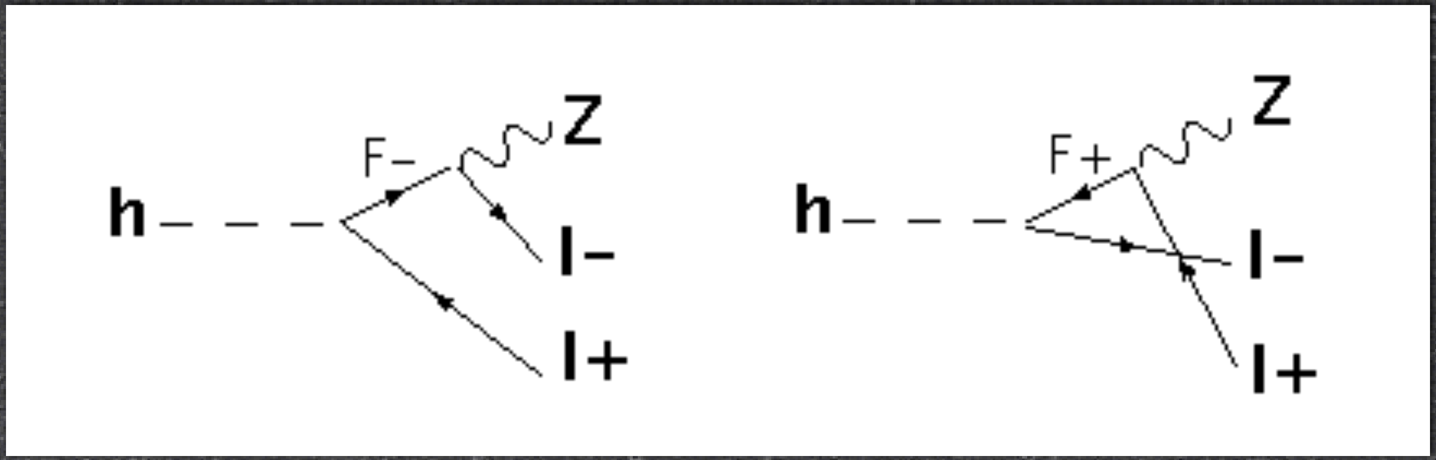
Examples:

h → Four Fermions

e.g. h → lX → Zll → 4l

$$yh\bar{X}l + \text{h.c.}$$

$$gZ_\mu \bar{X}\gamma_\mu l + \text{h.c.}$$



- can arise e.g. in models of composite leptons

- F can be lighter than 125 GeV for all we know, so Higgs can decay to on-shell F

- Yukawa coupling as small as 0.01 leads to BR(h→lX)~0.01

- Distinct kinematics from the golden channel (Z-l resonance,)

- If F couples to 2 different fermions then Z l l‘ signatures with no SM background

Not so fast: recent trilepton bounds exclude X→Ze or X→Zμ with <125 GeV, but X→Zτ is OK

AA, Straub, Vicente, in progress

work in progress with R.Vega-Morales

But, since this is a HEFT workshop...

Exotic Higgs Decays: HEFT approach

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \mathcal{L}_{d=5} + \mathcal{L}_{d=6} + \ldots$$

$$\mathcal{L}_{d=6} = \mathcal{L}_{\rm SILH} + \mathcal{L}_{\rm 2FV} + \mathcal{L}_{\rm 2FD} + \mathcal{L}_{\rm 4F} + \mathcal{L}_{\rm Gauge} + \mathcal{L}_{\rm CPB}$$

Higgs interactions with itself, SM gauge bosons and Yukawa interactions with fermions

$$\frac{\bar{c}_H}{2v^2}\partial^\mu(H^\dagger H)\partial_\mu(H^\dagger H) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\lambda}{v^2}(H^\dagger H)^3$$
$$+ \left(\left(\frac{\bar{c}_u}{v^2} y_u H^\dagger H\, \bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2} y_d H^\dagger H\, \bar{q}_L H d_R + \frac{\bar{c}_l}{v^2} y_l H^\dagger H\, \bar{L}_L H l_R\right) + h.c.\right)$$
$$+ \frac{i\bar{c}_W g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D}^\mu H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)(\partial^\nu B_{\mu\nu})$$
$$+ \frac{i\bar{c}_{HW} g}{m_W^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i\bar{c}_{HB} g'}{m_W^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$+ \frac{\bar{c}_\gamma g'^2}{m_W^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g g_S^2}{m_W^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu},$$

2-fermion vertex corrections

$$\frac{i\bar{c}_{Hq}}{v^2}(\bar{q}_L\gamma^\mu q_L)(H^\dagger \overleftrightarrow{D}_\mu H) + \frac{i\bar{c}'_{Hq}}{v^2}(\bar{q}_L\gamma^\mu\sigma^i q_L)(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H)$$
$$+ \frac{i\bar{c}_{Hu}}{v^2}(\bar{u}_R\gamma^\mu u_R)(H^\dagger \overleftrightarrow{D}_\mu H) + \frac{i\bar{c}_{Hd}}{v^2}(\bar{d}_R\gamma^\mu d_R)(H^\dagger \overleftrightarrow{D}_\mu H)$$
$$+ \left(\frac{i\bar{c}_{Hud}}{v^2}(\bar{u}_R\gamma^\mu d_R)(H^{c\dagger} \overleftrightarrow{D}_\mu H) + h.c.\right)$$
$$+ \frac{i\bar{c}_{HL}}{v^2}(\bar{L}_L\gamma^\mu L_L)(H^\dagger \overleftrightarrow{D}_\mu H) + \frac{i\bar{c}'_{HL}}{v^2}(\bar{L}_L\gamma^\mu\sigma^i L_L)(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H)$$
$$+ \frac{i\bar{c}_{Hl}}{v^2}(\bar{l}_R\gamma^\mu l_R)(H^\dagger \overleftrightarrow{D}_\mu H),$$

2-fermion dipole operators

$$\frac{\bar{c}_{uB} g'}{m_W^2} y_u \bar{q}_L H^c \sigma^{\mu\nu} u_R B_{\mu\nu} + \frac{\bar{c}_{uW} g}{m_W^2} y_u \bar{q}_L \sigma^i H^c \sigma^{\mu\nu} u_R W^i_{\mu\nu} + \frac{\bar{c}_{uG} g_S}{m_W^2} y_u \bar{q}_L H^c \sigma^{\mu\nu}\lambda^a u_R G^a_{\mu\nu}$$
$$+ \frac{\bar{c}_{dB} g'}{m_W^2} y_d \bar{q}_L H \sigma^{\mu\nu} d_R B_{\mu\nu} + \frac{\bar{c}_{dW} g}{m_W^2} y_d \bar{q}_L \sigma^i H \sigma^{\mu\nu} d_R W^i_{\mu\nu} + \frac{\bar{c}_{dG} g_S}{m_W^2} y_d \bar{q}_L H \sigma^{\mu\nu}\lambda^a d_R G^a_{\mu\nu}$$
$$+ \frac{\bar{c}_{lB} g'}{m_W^2} y_l \bar{L}_L H \sigma^{\mu\nu} l_R B_{\mu\nu} + \frac{\bar{c}_{lW} g}{m_W^2} y_l \bar{L}_L \sigma^i H \sigma^{\mu\nu} l_R W^i_{\mu\nu} + h.c.$$

4-fermion operators

Gauge boson self-interactions

CP Violating interactions

$$\frac{i\tilde{c}_{HW} g}{m_W^2}(D^\mu H)^\dagger \sigma^i (D^\nu H)\tilde{W}^i_{\mu\nu} + \frac{i\tilde{c}_{HB} g'}{m_W^2}(D^\mu H)^\dagger (D^\nu H)\tilde{B}_{\mu\nu}$$
$$+ \frac{\tilde{c}_\gamma g'^2}{m_W^2} H^\dagger H B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{\tilde{c}_g g_S^2}{m_W^2} H^\dagger H G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$
$$+ \frac{\tilde{c}_{3W} g^3}{m_W^2}\epsilon^{ijk} W^{i\nu}_\mu W^{j\rho}_\nu \tilde{W}^{k\mu}_\rho + \frac{\tilde{c}_{3G} g_S^3}{m_W^2} f^{abc} G^{a\nu}_\mu G^{b\rho}_\nu \tilde{G}^{c\mu}_\rho,$$

N>>59 ways to leave your SM lover

Some operators probed by precision Higgs physics, and some by exotic Higgs decays

Exotic Higgs Decays: HEFT approach

Questions:

work in progress with
T. Volansky and R.Vega-Morales

- What kind of exotic Higgs signature can arise within the EFT framework of SM + dimension-6 operators ?
- What are the current constraints on the couplings mediating the exotic decays?
- For each decay channel, what is the maximum branching fraction allowed by current constraints?
- In case the branching fraction is observable, what scale of the operator is being probed?

c.f. with precision Higgs physics probing $\Lambda \sim 1$ TeV, or EWPT probing $\Lambda \sim 10$ TeV, or B physics probing $\Lambda \sim 100$ TeV

In this talk, I restrict to exotic decay channels with charged leptons

HEFT: 2-body LFV decays

SM BSM

$$\mathcal{L} = -\bar{L}_L H Y l_R - \frac{|H|^2}{\Lambda^2}\bar{L}_L H \tilde{Y} l_R + \text{h.c.}$$

$$\mathcal{L} \to -y_{ij}\bar{l}^i_L l^j_R + \text{h.c.} \qquad i \neq j \qquad y \sim \tilde{Y}\frac{v^2}{\Lambda^2}$$

Harnik et al 1209.1397:

$$y_{\mu e} \lesssim 3.6 \times 10^{-6} \quad \Rightarrow \quad \text{Br}(h \to \mu e) \lesssim 10^{-8}$$

$$y_{\tau e} \lesssim 1.4 \times 10^{-2} \quad \Rightarrow \quad \text{Br}(h \to \tau e) \lesssim 20\%$$

$$y_{\tau \mu} \lesssim 1.6 \times 10^{-2} \quad \Rightarrow \quad \text{Br}(h \to \tau \mu) \lesssim 25\%$$

Probing Br of 1/0.1% translates to
probing Λ of 5/8 TeV
(!better than Higgs precision!)

HEFT: 3-body LFV decays from vertex operator

- Consider vertex operators violating lepton flavor

-Higgs couplings come at cost of LFV Z-boson couplings

$$\frac{i\bar{c}_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu q_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)+\frac{i\bar{c}'_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu\sigma^i q_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right)$$
$$+\frac{i\bar{c}_{Hu}}{v^2}\left(\bar{u}_R\gamma^\mu u_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)+\frac{i\bar{c}_{Hd}}{v^2}\left(\bar{d}_R\gamma^\mu d_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)$$
$$+\left(\frac{i\bar{c}_{Hud}}{v^2}\left(\bar{u}_R\gamma^\mu d_R\right)\left(H^{c\dagger} \overleftrightarrow{D}_\mu H\right)+h.c.\right)$$
$$+\frac{i\bar{c}_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu L_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)+\frac{i\bar{c}'_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu\sigma^i L_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right)$$
$$+\frac{i\bar{c}_{Hl}}{v^2}\left(\bar{l}_R\gamma^\mu l_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right),$$

$$(1+h/v)^2 Z_\mu\left(g_{Zll',L}\bar{l}_L\gamma^\mu l'_L+g_{Zll',R}\bar{l}_R\gamma^\mu l'_R\right)+\text{h.c.}$$

Old limits from OPAL and DELPHI

$$\text{BR}(Z\to e^\pm\mu^\mp) < 1.7\times10^{-6} \quad\Rightarrow\quad \delta g^2_{Ze\mu} < 1.8\times10^{-6}$$
$$\text{BR}(Z\to e^\pm\tau^\mp) < 9.8\times10^{-6} \quad\Rightarrow\quad \delta g^2_{Ze\tau} < 1.0\times10^{-5}$$
$$\text{BR}(Z\to \mu^\pm\tau^\mp) < 1.2\times10^{-5} \quad\Rightarrow\quad \delta g^2_{Z\mu\tau} < 1.2\times10^{-5}$$

imply stringent limits on branching fractions:

$$\text{Br}(h\to Ze\mu) < 3.3\times10^{-8}$$
$$\text{Br}(h\to Ze\tau) < 1.9\times10^{-7}$$
$$\text{Br}(h\to Z\mu\tau) < 2.4\times10^{-7}$$

so that will never be observable

HEFT: 3-body LFV decays from dipole operators

- Consider dipole operators violating lepton flavor

$$\frac{\bar{c}_{uB}\, g'}{m_W^2} y_u\, \bar{q}_L H^c \sigma^{\mu\nu} u_R\, B_{\mu\nu} + \frac{\bar{c}_{uW}\, g}{m_W^2} y_u\, \bar{q}_L \sigma^i H^c \sigma^{\mu\nu} u_R\, W^i_{\mu\nu} + \frac{\bar{c}_{uG}\, g_S}{m_W^2} y_u\, \bar{q}_L H^c \sigma^{\mu\nu} \lambda^a u_R\, G^a_{\mu\nu}$$
$$+ \frac{\bar{c}_{dB}\, g'}{m_W^2} y_d\, \bar{q}_L H \sigma^{\mu\nu} d_R\, B_{\mu\nu} + \frac{\bar{c}_{dW}\, g}{m_W^2} y_d\, \bar{q}_L \sigma^i H \sigma^{\mu\nu} d_R\, W^i_{\mu\nu} + \frac{\bar{c}_{dG}\, g_S}{m_W^2} y_d\, \bar{q}_L H \sigma^{\mu\nu} \lambda^a d_R\, G^a_{\mu\nu}$$
$$+ \frac{\bar{c}_{lB}\, g'}{m_W^2} y_l\, \bar{L}_L H \sigma^{\mu\nu} l_R\, B_{\mu\nu} + \frac{\bar{c}_{lW}\, g}{m_W^2} y_l\, \bar{L}_L \sigma^i H \sigma^{\mu\nu} l_R\, W^i_{\mu\nu} + h.c.$$

- Higgs couplings to γll’ come at price of dipole operators contributing to l’→lγ which are very strongly constrained

$$(1 + h/v)\left(\frac{d_{ll'Z}}{v}\bar{l}_L \sigma^{\mu\nu} l'_R Z_{\mu\nu} + \frac{d_{ll'\gamma}}{v}\bar{l}_l \sigma^{\mu\nu} l_R \gamma_{\mu\nu}\right) + \text{h.c.}$$

-Higgs couplings to Z come at cost of LFV Z-boson couplings

$$d^2_{e\mu Z} + d^2_{\mu e} < 3.2 \times 10^{-6} \quad \Rightarrow \quad \text{Br}(h \to Ze\mu) < 1.9 \times 10^{-8}$$
$$d^2_{e\tau Z} + d^2_{\tau e} < 1.8 \times 10^{-5} \quad \Rightarrow \quad \text{Br}(h \to Ze\tau) < 1.1 \times 10^{-7}$$
$$d^2_{\mu\tau Z} + d^2_{\tau\mu} < 2.2 \times 10^{-5} \quad \Rightarrow \quad \text{Br}(h \to Z\tau\mu) < 1.3 \times 10^{-7}$$

similar limits as for vertex mediated decays,
never unobservable

HEFT: 3-body LFC decays from dipole operators

- Consider dipole operators that conserve flavor

$$\frac{\bar{c}_{uB}\, g'}{m_W^2} y_u\, \bar{q}_L H^c \sigma^{\mu\nu} u_R\, B_{\mu\nu} + \frac{\bar{c}_{uW}\, g}{m_W^2} y_u\, \bar{q}_L \sigma^i H^c \sigma^{\mu\nu} u_R\, W^i_{\mu\nu} + \frac{\bar{c}_{uG}\, g_S}{m_W^2} y_u\, \bar{q}_L H^c \sigma^{\mu\nu} \lambda^a u_R\, G^a_{\mu\nu}$$
$$+ \frac{\bar{c}_{dB}\, g'}{m_W^2} y_d\, \bar{q}_L H \sigma^{\mu\nu} d_R\, B_{\mu\nu} + \frac{\bar{c}_{dW}\, g}{m_W^2} y_d\, \bar{q}_L \sigma^i H \sigma^{\mu\nu} d_R\, W^i_{\mu\nu} + \frac{\bar{c}_{dG}\, g_S}{m_W^2} y_d\, \bar{q}_L H \sigma^{\mu\nu} \lambda^a d_R\, G^a_{\mu\nu}$$
$$+ \frac{\bar{c}_{lB}\, g'}{m_W^2} y_l\, \bar{L}_L H \sigma^{\mu\nu} l_R\, B_{\mu\nu} + \frac{\bar{c}_{lW}\, g}{m_W^2} y_l\, \bar{L}_L \sigma^i H \sigma^{\mu\nu} l_R\, W^i_{\mu\nu} + h.c.$$

- Higgs couplings to Zll make a tiny shift to golden channel width

$$(1 + h/v)\left(\frac{d_{lZ}}{v}\bar{l}_L \sigma^{\mu\nu} l_R Z_{\mu\nu} + \frac{d_{l\gamma}}{v}\bar{l}_L \sigma^{\mu\nu} l_R \gamma_{\mu\nu}\right) + \text{h.c.}$$

- Higgs couplings to γee and γμμ come at price of anomalous magnetic moment operators and are strongly constrained

- But γττ only constrained by LEP-2 and larger Higgs coupling to γττ is allowed

$$d_{\tau\gamma} < 0.06$$

though needs some cancellation in dτZ

$$\text{Br}(h \to \gamma\tau^+\tau^-) < 6 \times 10^{-4}$$

observable?

EFT for Exotic Higgs Decays

- Complete list of operators, including quark operators too (more difficult experimentally, but weaker limits from LEP)
- Effective theory approach for SM+X, for scalar, fermionic or vector X

work in progress with
T.Volansky and R.Vega-Morales

Summary

- Exotic Higgs decays may be the portal to new physics
- Large exotic decay rates readily possible if there exists a light BSM degree of freedom coupled to Higgs
- Stringent constraints within HEFT, but a few window of opportunities remain