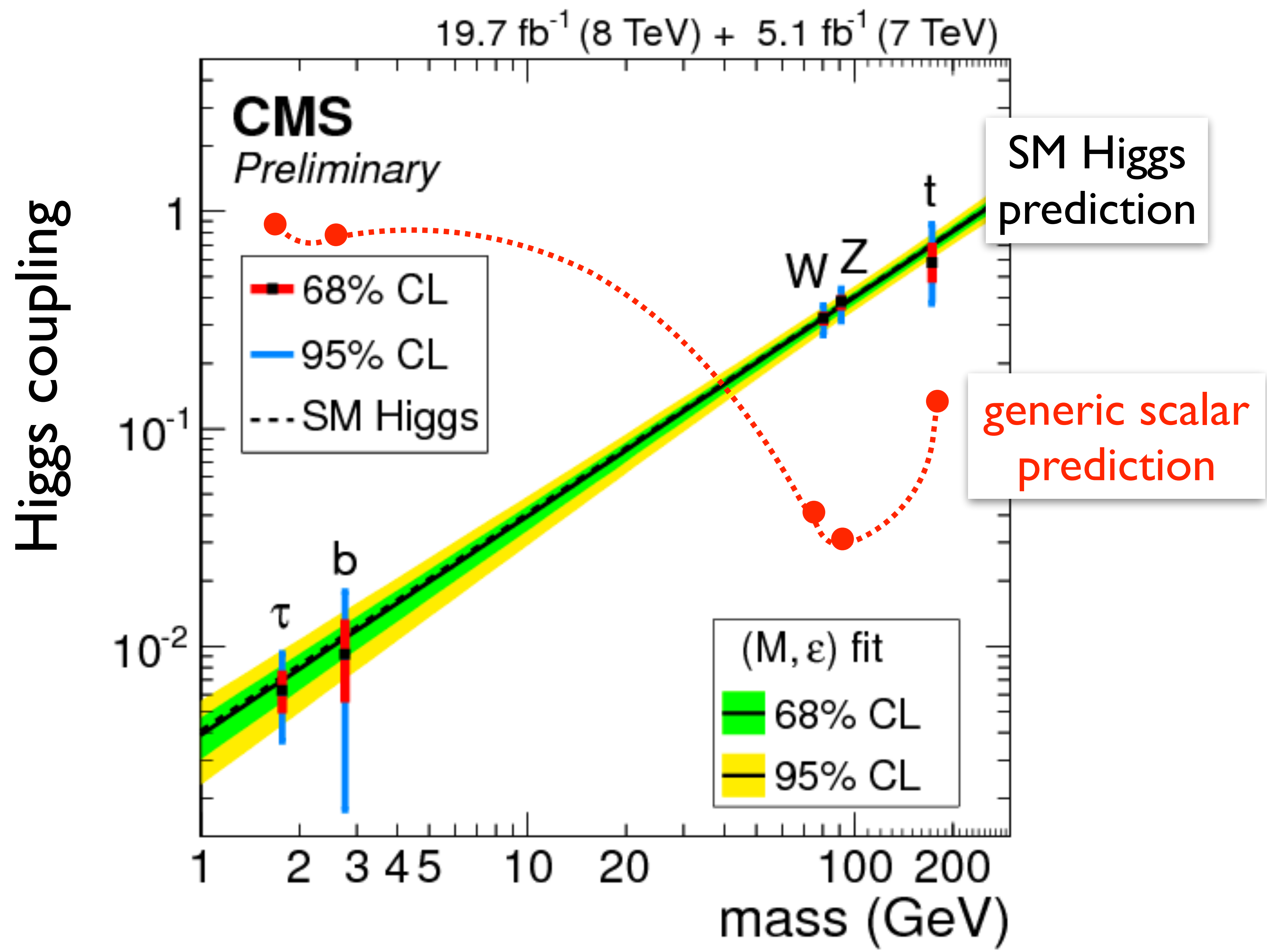
Natural expectations for Higgs physics

Alex Pomarol, UAB (Barcelona)

The most important achievement at the LHC: **The Higgs**



➥**Don't panic!** It's not a ***Tecni-Higgs***,

It looks a lot the **SM Higgs** (at least in a first approximation)

The SM is established !

But the hierarchy problem still lingering…

demanding TeV new-physics that doesn't show up!

TeV BSM had many chances to show up (indirectly):

TeV BSM had many chances to show up (indirectly):

Not necessary should follow the "**accidents**" of the SM

B violations: Proton decay

➥ $\Lambda \gtrsim 10^{15}$ GeV

L violation: Larger neutrino masses

➥ $\Lambda \gtrsim 10^{15}$ GeV

Flavor violations

➥ $\Lambda \gtrsim 10^{5}$ TeV

CP violation: EDMs

➥ $\Lambda \gtrsim 10$ TeV

TeV BSM had many chances to show up (indirectly):

Not necessary should follow the "**accidents**" of the SM

B violations: Proton decay

➥ $\Lambda \gtrsim 10^{15}$ GeV

L violation: Larger neutrino masses

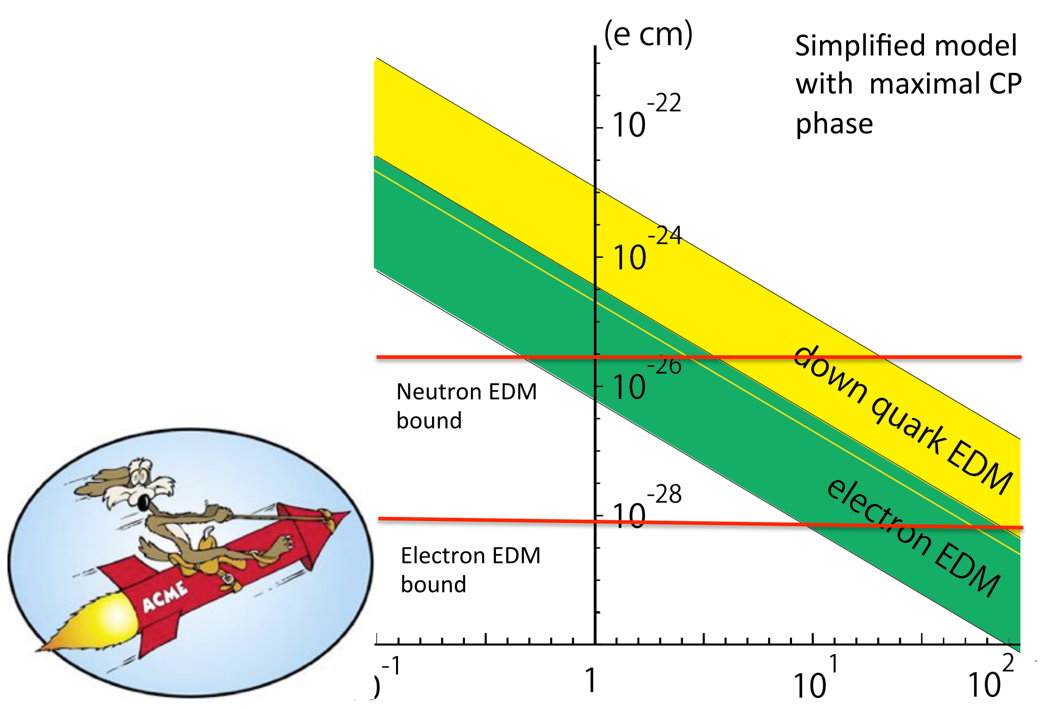
➥ $\Lambda \gtrsim 10^{15}$ GeV

Flavor violations

➥ $\Lambda \gtrsim 10^{5}$ TeV

EDMs

➥ $\Lambda \gtrsim 10$ TeV



(J. Hisano Moriond 14)

TeV BSM had many chances to show up (indirectly):

Not necessary should follow the "**accidents**" of the SM

we are **forced** to demand these symmetries to *natural* **BSM**

B violations: Proton decay

➥ $\Lambda \gtrsim 10^{15}$ GeV

L violation: Larger neutrino masses

➥ $\Lambda \gtrsim 10^{15}$ GeV

Flavor violations

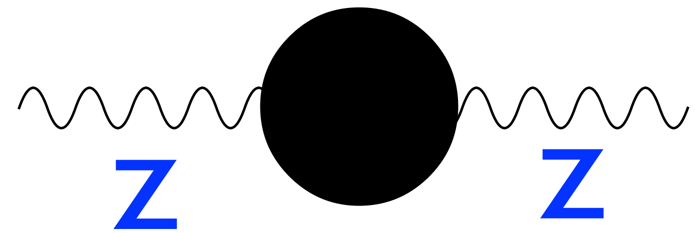
➥ $\Lambda \gtrsim 10^{5}$ TeV

CP violation: EDMs

➥ $\Lambda \gtrsim 10$ TeV

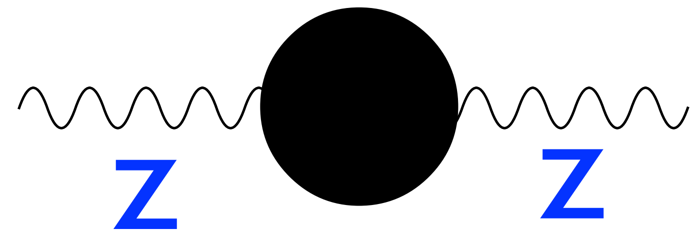
LEP: First important place for *natural* theories to show up

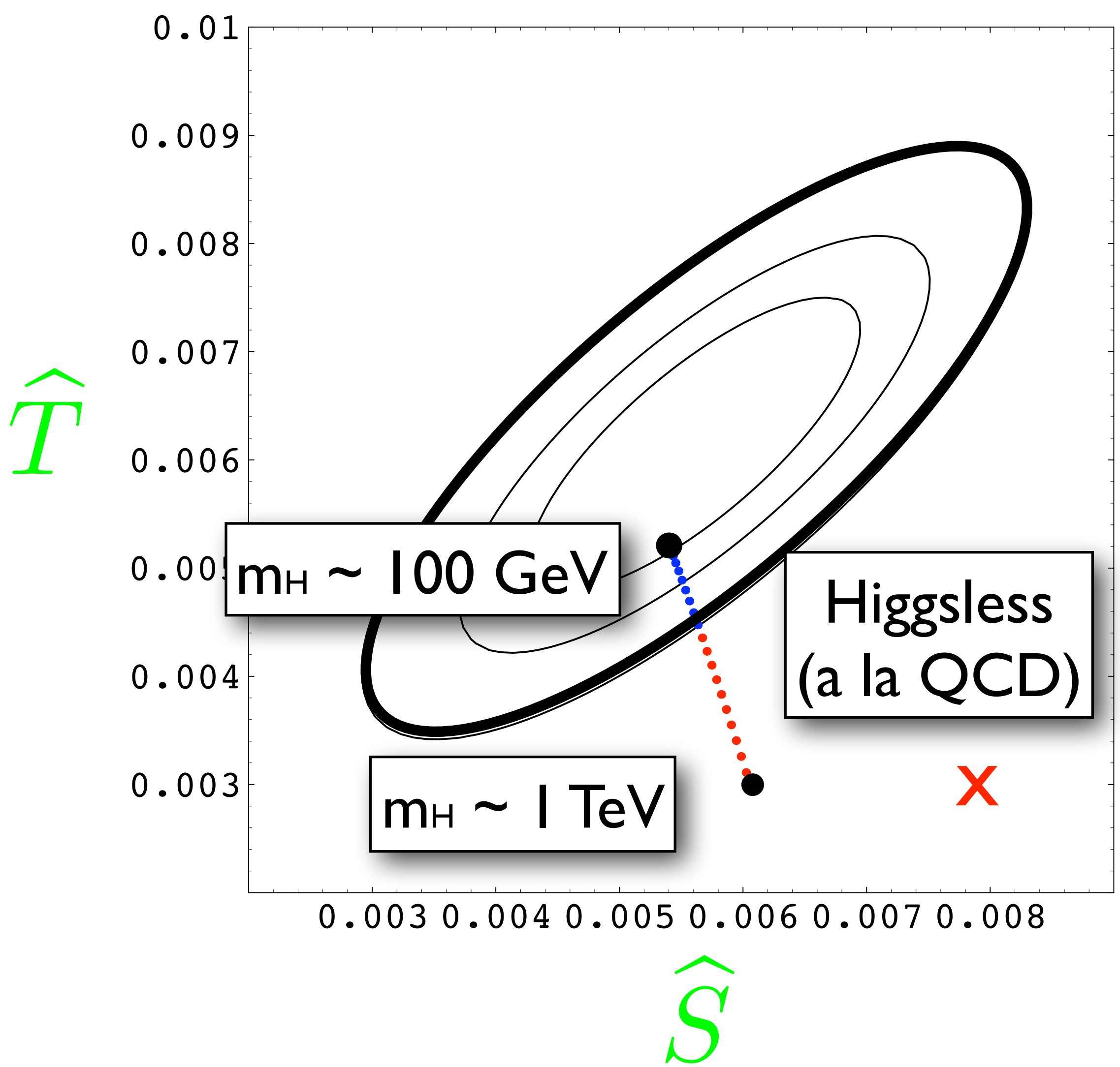
But no sign of BSM effects in ~ millions of Z:



LEP: First important place for *natural* theories to show up

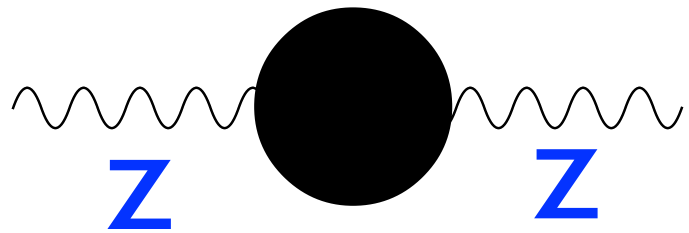
But no sign of BSM effects in ~ millions of Z:

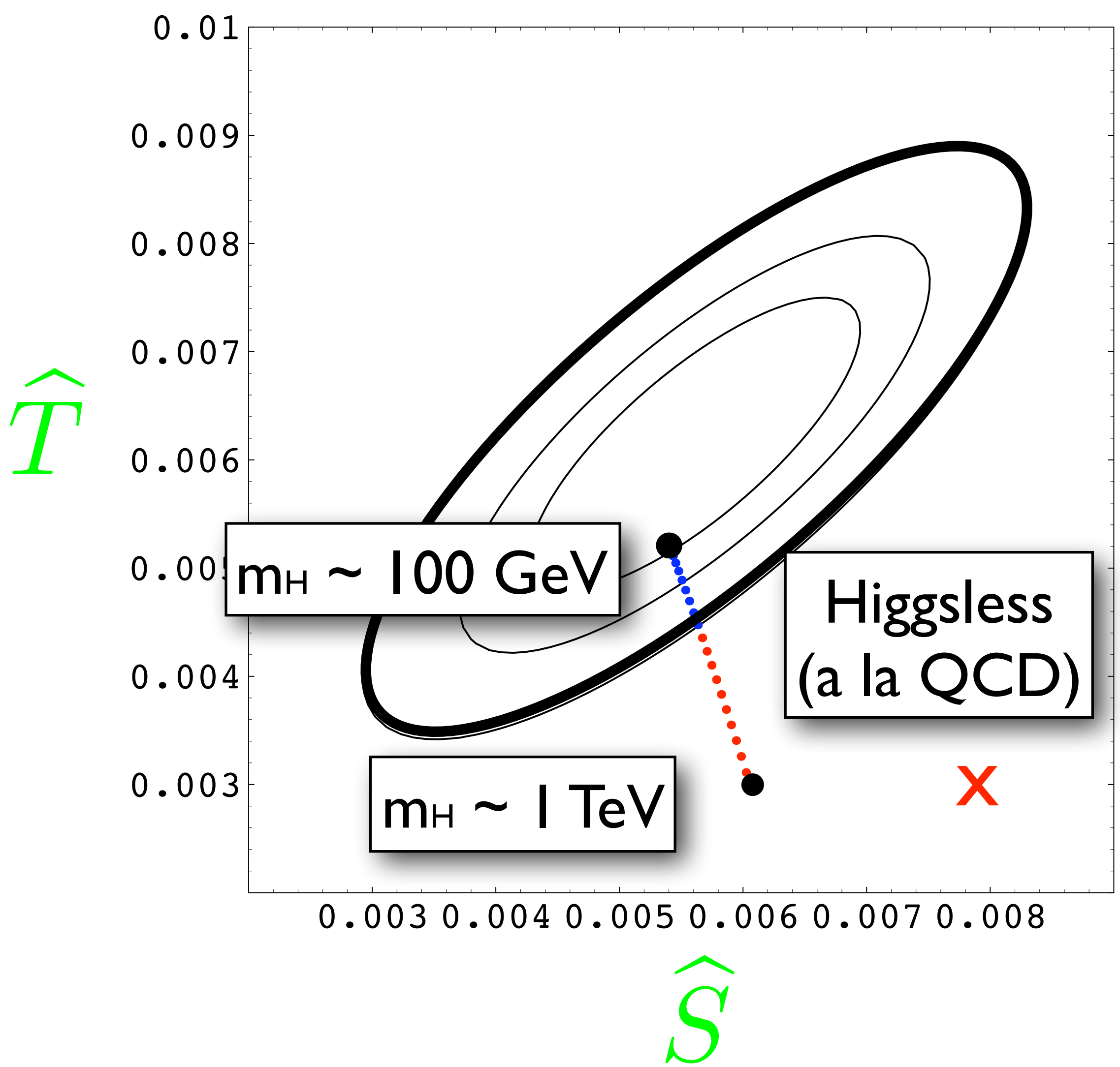




LEP: First important place for *natural* theories to show up

But no sign of BSM effects in ~ millions of Z:





Expected from strongly-coupled BSM:

$\hat{T} \sim O(1)$ effects

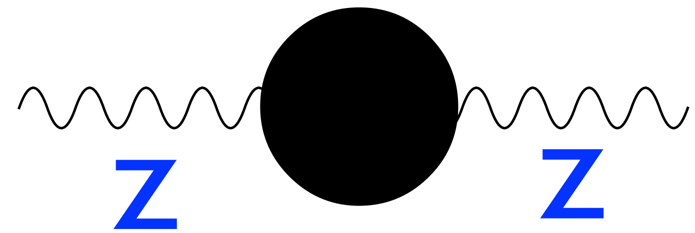
$\hat{S} \sim (m_W/\Lambda)^2 \sim 0.01$

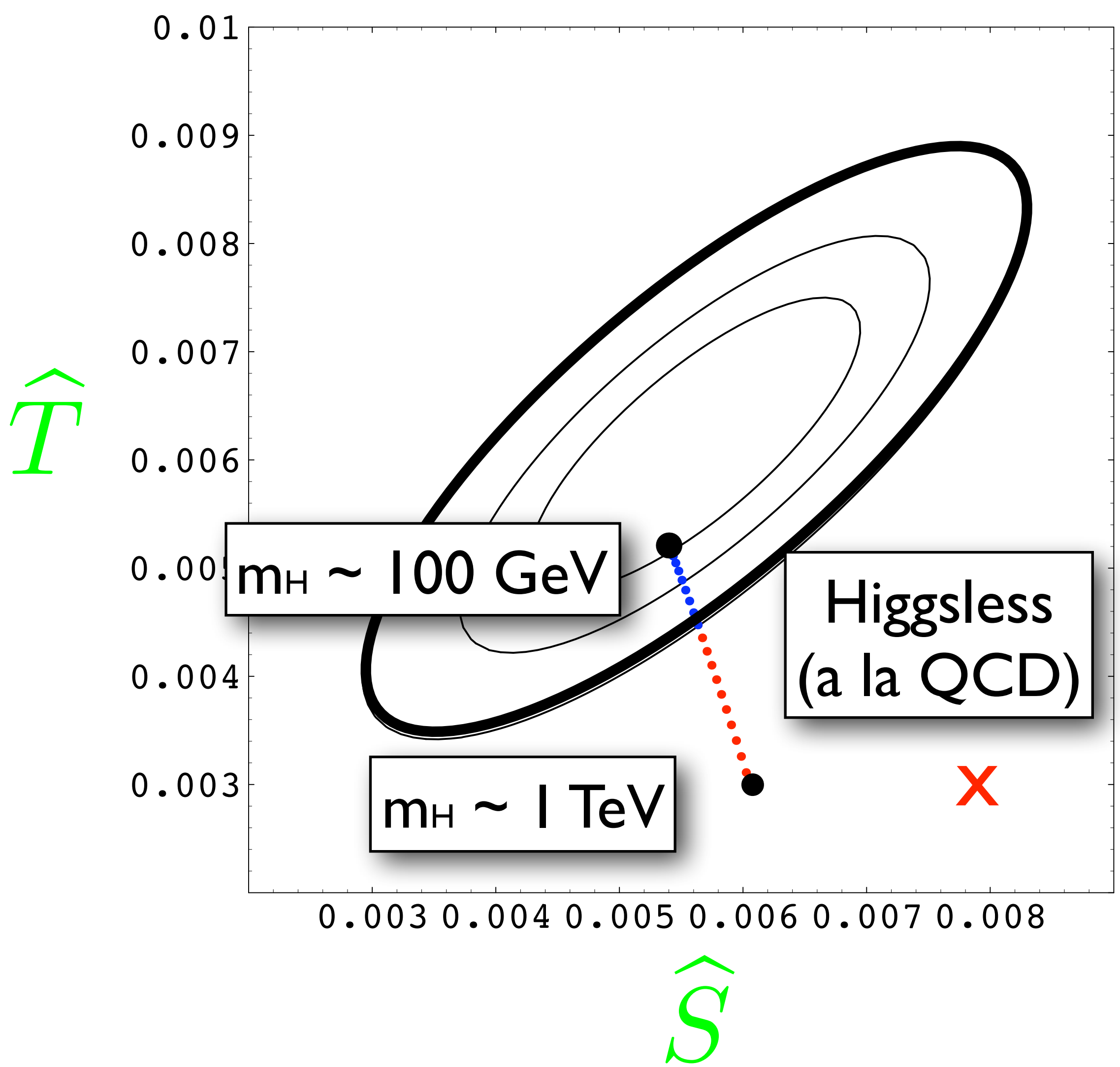
T could be made small by symmetries (custodial) but no S

☛ touching the "BSM's bones"

LEP: First important place for *natural* theories to show up

But no sign of BSM effects in ~ millions of Z:





Expected from strongly-coupled BSM:

$\hat{T}$~*O*(1) effects

$\hat{S}$ ~ $(m_W/\Lambda)^2$ ~0.01

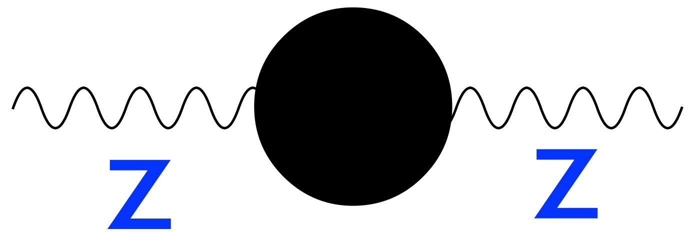
T could be made small by symmetries (custodial) but no S

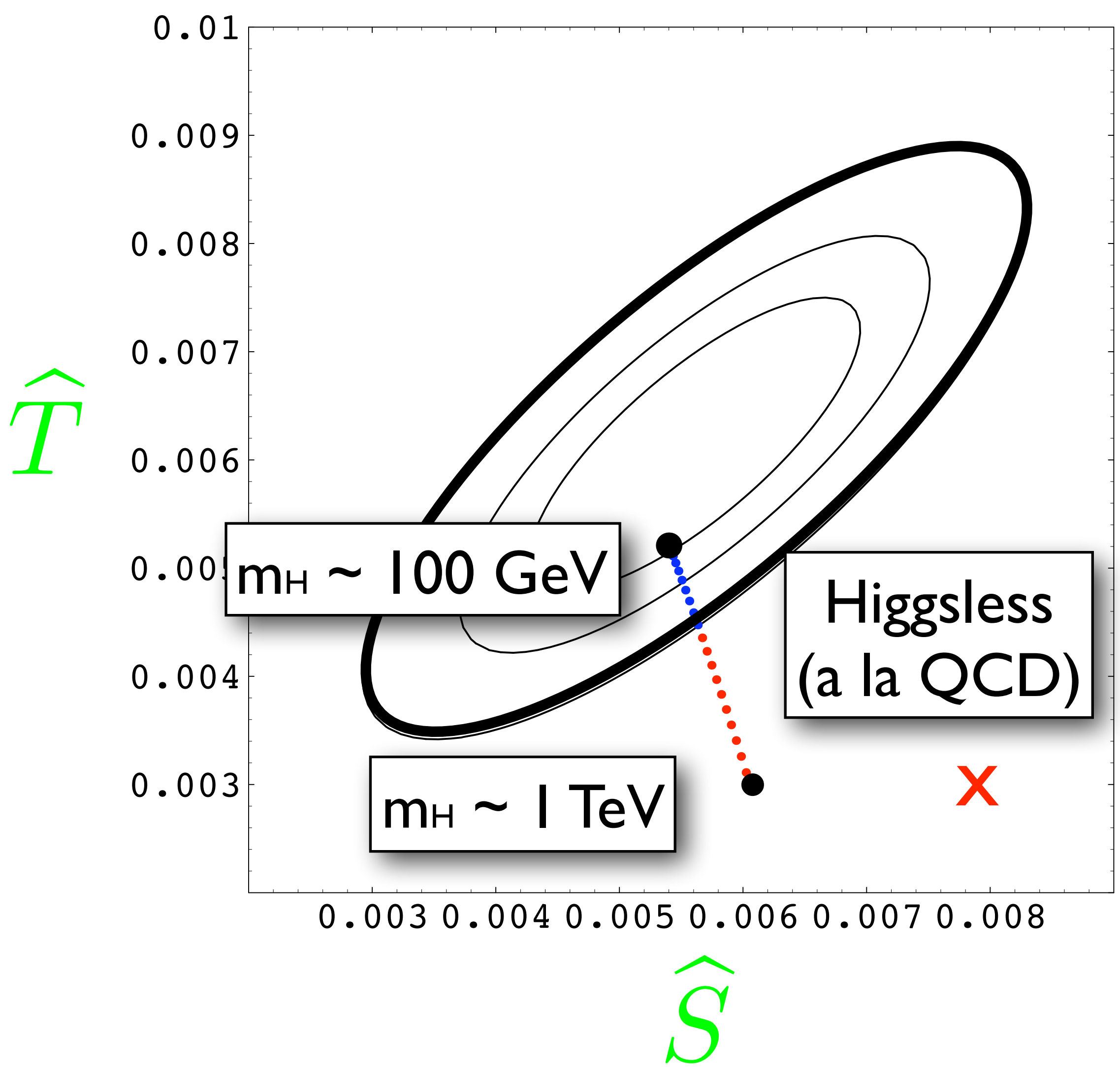
☛ touching the "BSM's bones"

But "*one swallow doesn't make a spring*"

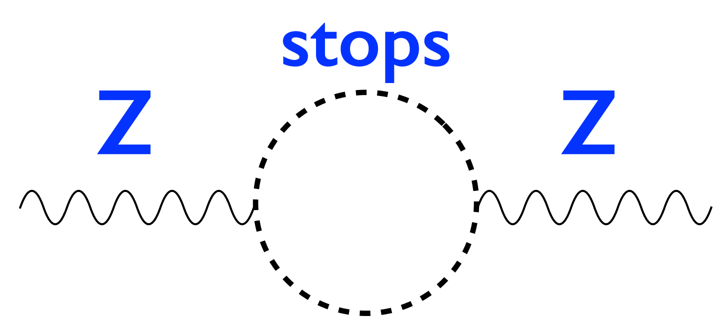
LEP: First important place for *natural* theories to show up

But no sign of BSM effects in ~ millions of Z:





In the supersymmetric SM:

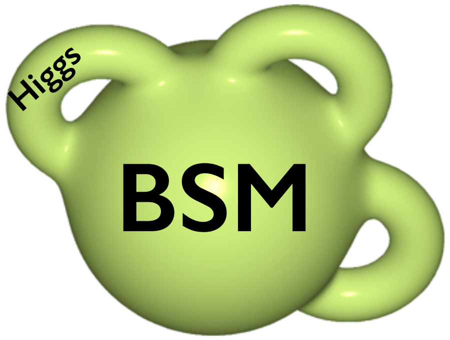


$\hat{T} \sim O(10^{-2})$

stop mass > 300 GeV

LHC: Second important place for natural theories to show up

➥ the Higgs discovery has provided a new "handle" to catch BSMs



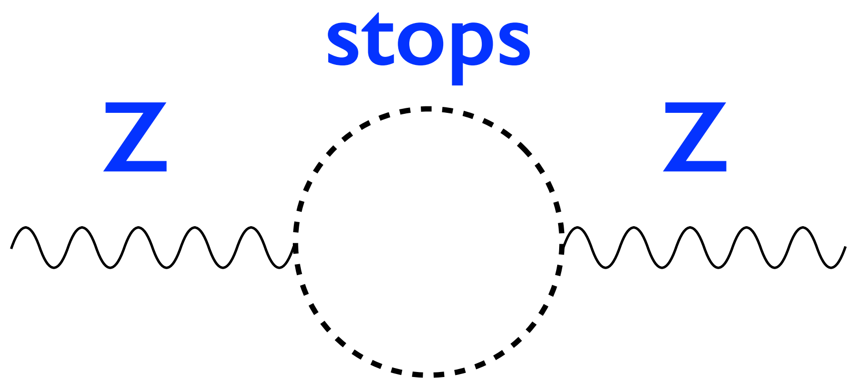
With the **Higgs**, we have had access to new relevant information by measuring its **properties**

The Higgs is usually the most "sensitive" SM particle to new-physics

Examples:

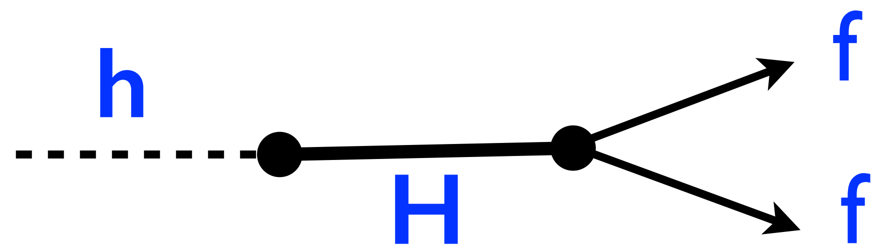
1) <u>MSSM</u>:

Gauge bosons:



~ loop effects

Higgs:



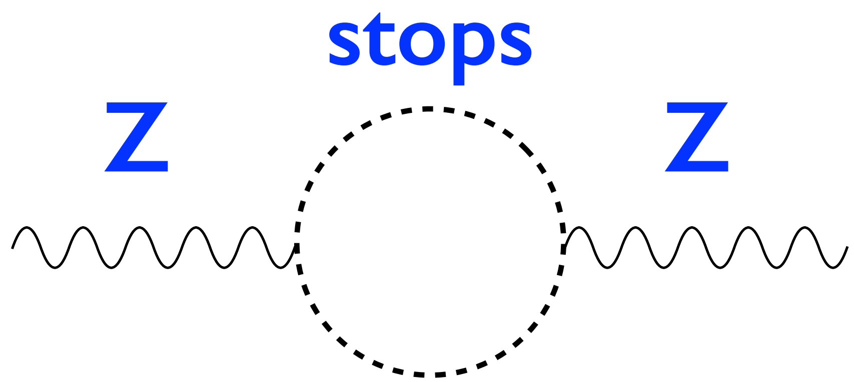
~ tree-level effects

$$\boxed{\text{Effects in Higgs physics can be a factor } 16\pi^2 \sim 100 \text{ larger!}}$$

Examples:

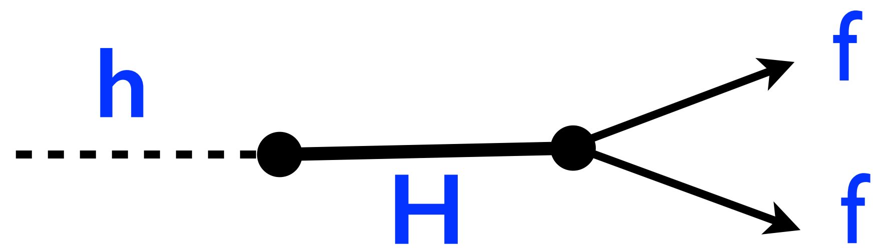
1) MSSM:

Gauge bosons:



~ loop effects

Higgs:

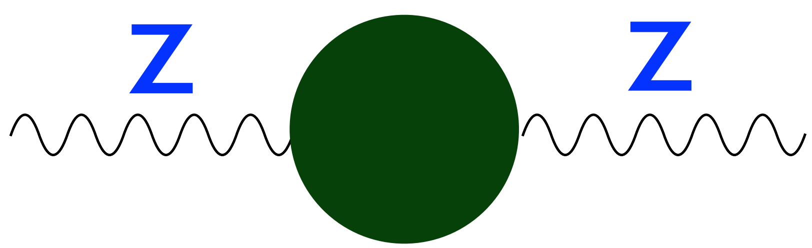


~ tree-level effects

Effects in Higgs physics
can be a factor $16\pi^2 \sim 100$ larger!

2) Composite models:

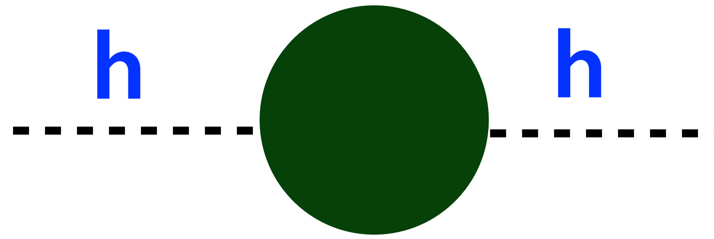
Gauge bosons:



$$\sim \frac{g^2 v^2}{\Lambda^2}$$

"strong" Higgs coupling

Higgs:



$$\sim \frac{g_H^2 v^2}{\Lambda^2} \sim \frac{16\pi^2 v^2}{\Lambda^2}$$

strong dynamics (Λ=composite scale)

Consequences:

➥ Even with less statistics at the **LHC**, similar impact today in new-physics as **LEP**

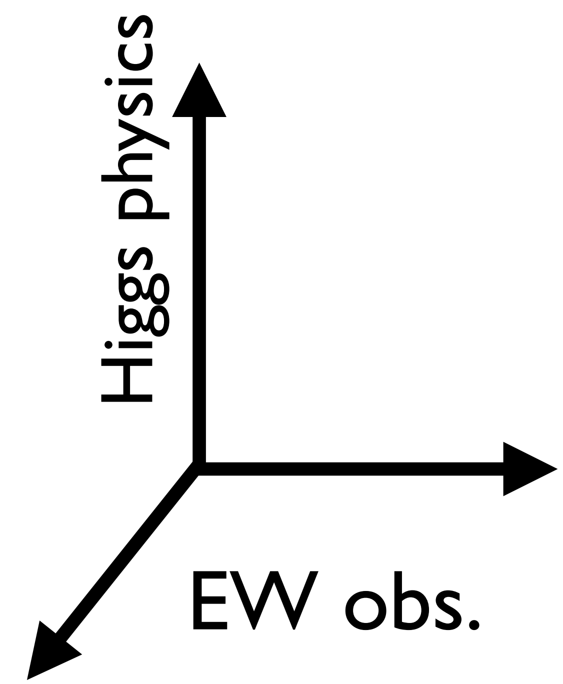
LEP: $ee \to Z\ (\to ff) \sim 10^6$ event

LHC: $pp \to h\ \ (\to \gamma\gamma) \sim 10^3$ events

First question to answer:

What are the most relevant Higgs couplings to measure?

probes testing
<u>new directions</u> in the
"parameter space" of BSMs



Model independent analysis

Assuming a large new-physics scale: **$\Lambda >> m_W$** (as LHC suggests)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

SM

just validated

NP scale

dim=6

➥ e.g. $|H|^2 G^A_{\mu\nu} G^{A\mu\nu}$

give the leading deviations
to SM Higgs physics from BSM

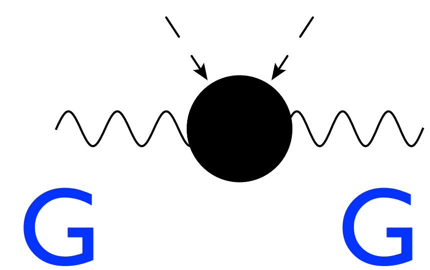
➥ <u>Only **8 Higgs couplings**</u> *(assuming CP-conservation and family universality)*

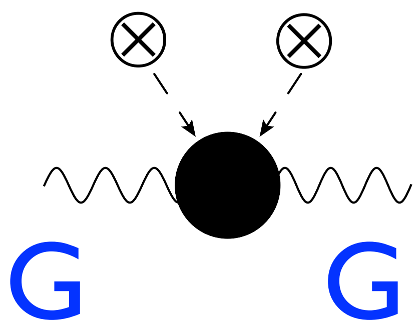
can be modified by new-physics, **not** affecting anything else

Elias-Miro, Espinosa, Masso, AP, JHEP 1311 (2013) 066
AP, Riva, JHEP 1401 (2014) 151

Coming from dimension-6 operators whose effects on the vacuum, **H = v**, give only a redefinition of the SM couplings:

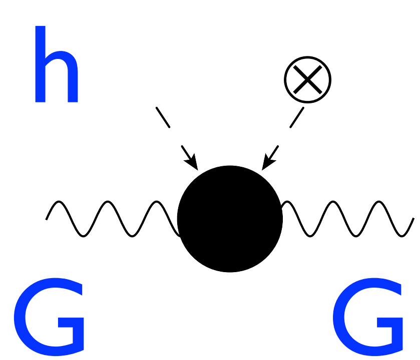
e.g. $$\frac{1}{g_s^2}G_{\mu\nu}^2+\frac{|H|^2}{\Lambda^2}G_{\mu\nu}^2 \to \left(\frac{1}{g_s^2}+\frac{v^2}{\Lambda^2}\right)G_{\mu\nu}^2$$





Not physical!

But can affect **Higgs** physics:



affects GG →h!

There are 8 operators of this type

for one family

(assuming CP-conservation)

$$|H|^2 G^A_{\mu\nu} G^{A\mu\nu} \longrightarrow \text{GGh coupling}$$

$$|H|^2 B_{\mu\nu} B^{\mu\nu} \longrightarrow \text{h}\gamma\gamma\ \text{coupling}$$

$$|H|^2 W^a_{\mu\nu} W^{\mu\nu\, a} \longrightarrow \text{hZ}\gamma\ \text{coupling}$$

$$|H|^2 |D_\mu H|^2 \longrightarrow \text{hVV (custodial invariant)}$$

$$|H|^6 \longrightarrow \text{h}^3\ \text{coupling}$$

$$|H|^2 \bar{f}_L H f_R + h.c. \longrightarrow \text{htt, hbb, h}\tau\tau$$

8 Primary Higgs couplings

(assuming CP-conservation)

$$\Delta\mathcal{L}_{\rm BSM} = \delta g_{hff}\, h \bar{f}_L f_R + h.c. \qquad \text{(f=b, } \tau \text{, t)}$$
$$+\, g_{hVV}\, h \left[W^{+\,\mu} W^-_\mu + \frac{1}{2\cos^2\theta_W} Z^\mu Z_\mu \right]$$
$$+\, \kappa_{GG} \frac{h}{v} G^{\mu\nu} G_{\mu\nu}$$
$$+\, \kappa_{\gamma\gamma} \frac{h}{v} F^{\gamma\,\mu\nu} F^\gamma_{\mu\nu}$$
$$+\, \kappa_{\gamma Z} \frac{h}{v} F^{\gamma\,\mu\nu} F^Z_{\mu\nu}$$
$$+\, \delta g_{3h}\, h^3$$

Elias-Miro, Espinosa, Masso, AP, JHEP 1311 (2013) 066
AP, Riva, JHEP 1401 (2014) 151

8 Primary Higgs couplings

(assuming CP-conservation)

$$\Delta\mathcal{L}_{\rm BSM} = \delta g_{hff}\, h\bar{f}_L f_R + h.c. \qquad \text{(f=b, } \tau\text{, t)}$$
$$+\, g_{hVV}\, h\left[W^{+\,\mu}W^-_\mu + \frac{1}{2\cos^2\theta_W}Z^\mu Z_\mu\right]$$
$$+\, \kappa_{GG}\frac{h}{v}G^{\mu\nu}G_{\mu\nu}$$
$$+\, \kappa_{\gamma\gamma}\frac{h}{v}F^{\gamma\,\mu\nu}F^\gamma_{\mu\nu}$$
$$+\, \kappa_{\gamma Z}\frac{h}{v}F^{\gamma\,\mu\nu}F^Z_{\mu\nu}$$
$$+\, \delta g_{3h}\, h^3$$

important:
custodial invariant!!

Elias-Miro, Espinosa, Masso, AP, JHEP 1311 (2013) 066
AP, Riva, JHEP 1401 (2014) 151

8 Primary Higgs couplings

(assuming CP-conservation)

$$\Delta\mathcal{L}_{\rm BSM} = \boxed{\delta g_{hff}}\, h\bar{f}_L f_R + h.c. \qquad \text{(f=b, } \tau\text{, t)}$$

6 measured at the LHC

$$+ \boxed{g_{hVV}}\, h\left[W^{+\,\mu}W^{-}_{\mu} + \frac{1}{2\cos^2\theta_W}Z^{\mu}Z_{\mu}\right]$$

$$+ \boxed{\kappa_{GG}}\,\frac{h}{v}G^{\mu\nu}G_{\mu\nu}$$

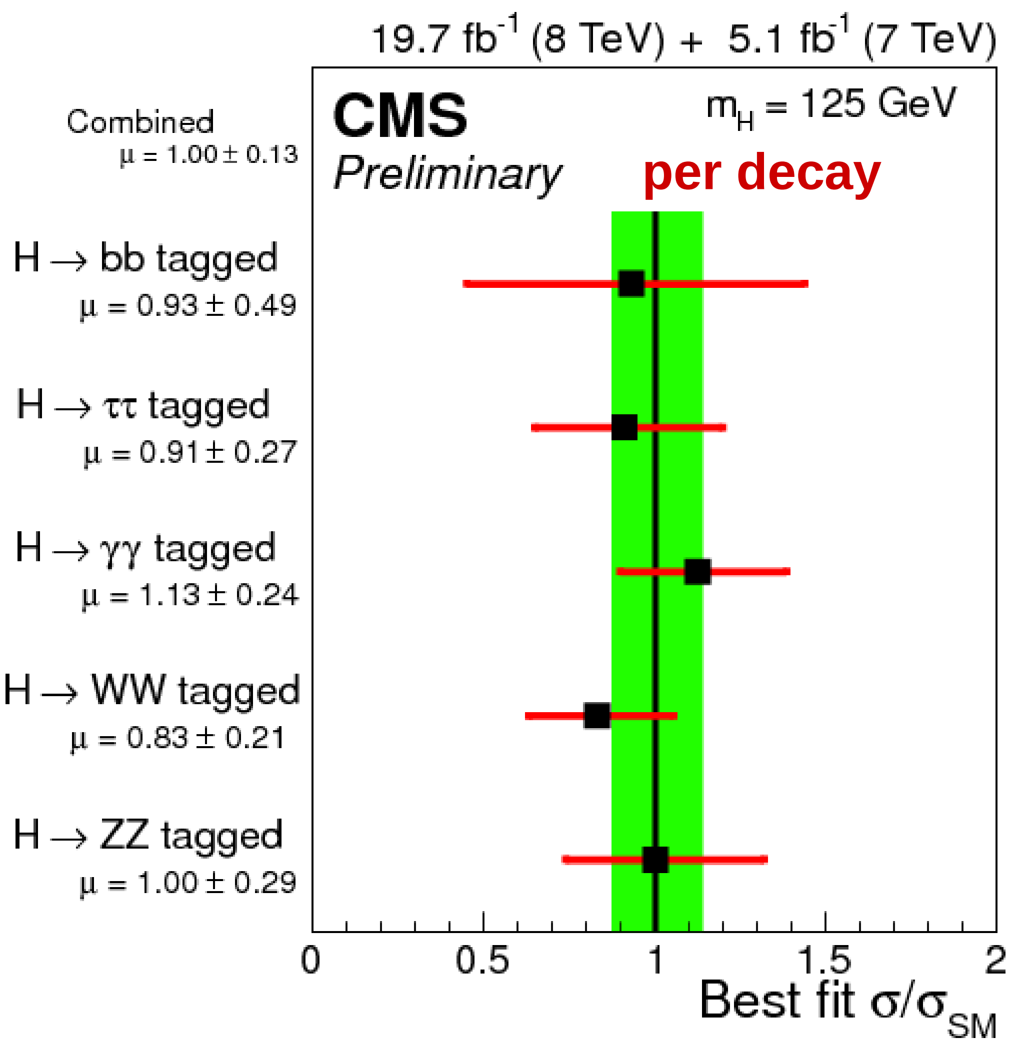
$$+ \boxed{\kappa_{\gamma\gamma}}\,\frac{h}{v}F^{\gamma\,\mu\nu}F^{\gamma}_{\mu\nu}$$

$$+ \boxed{\kappa_{\gamma Z}}\,\frac{h}{v}F^{\gamma\,\mu\nu}F^{Z}_{\mu\nu}$$

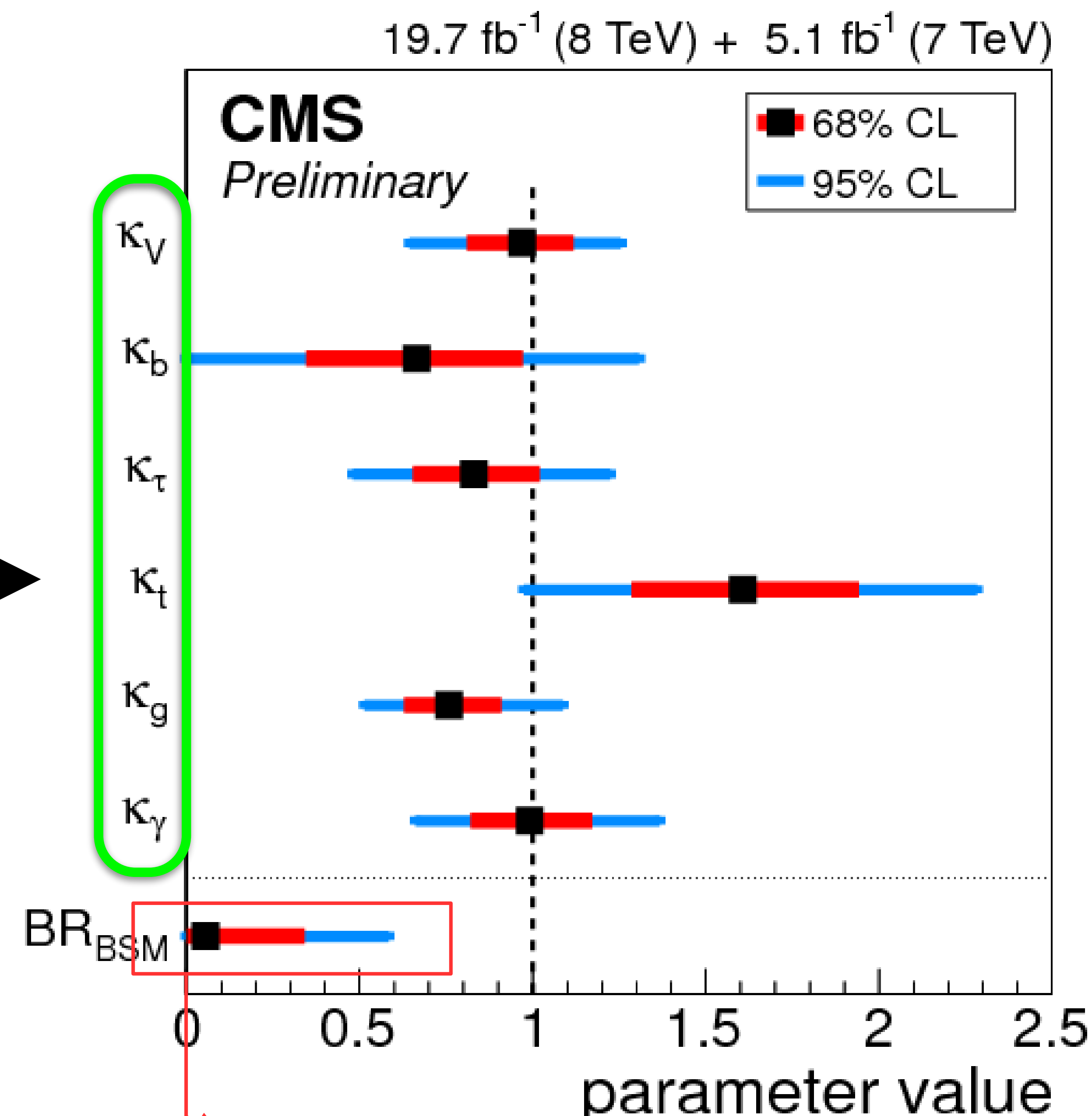
$$+ \boxed{\delta g_{3h}}\, h^3$$

Elias-Miro, Espinosa, Masso, AP, JHEP 1311 (2013) 066
AP, Riva, JHEP 1401 (2014) 151

Higgs coupling determination



$$\kappa_i = \frac{g_{hii}}{g_{hii}^{\mathrm{SM}}}$$



All parameters floating and $\kappa_V \leq 1$

8 Primary Higgs couplings

(assuming CP-conservation)

$$\Delta\mathcal{L}_{\rm BSM} = \delta g_{hff}\, h\bar{f}_L f_R + h.c. \qquad (f=b, \tau, t)$$

$$+\, g_{hVV}\, h\left[W^{+\,\mu}W^-_\mu + \frac{1}{2\cos^2\theta_W} Z^\mu Z_\mu\right]$$

$$+\, \kappa_{GG}\frac{h}{v}G^{\mu\nu}G_{\mu\nu}$$

$$+\, \kappa_{\gamma\gamma}\frac{h}{v}F^{\gamma\,\mu\nu}F^\gamma_{\mu\nu}$$

$$+\, \kappa_{\gamma Z}\frac{h}{v}F^{\gamma\,\mu\nu}F^Z_{\mu\nu}$$

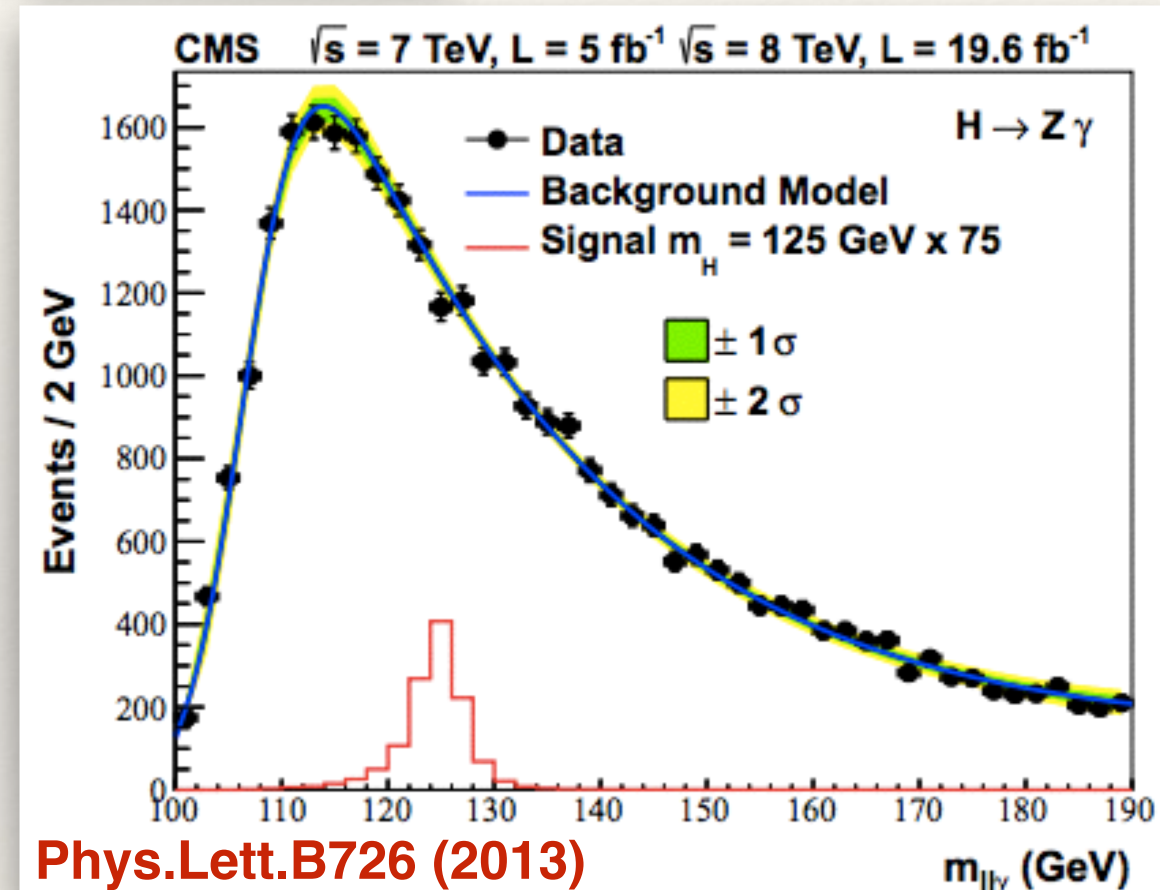
$$+\, \delta g_{3h}\, h^3$$

6 measured at the LHC

$h\rightarrow Z\gamma$

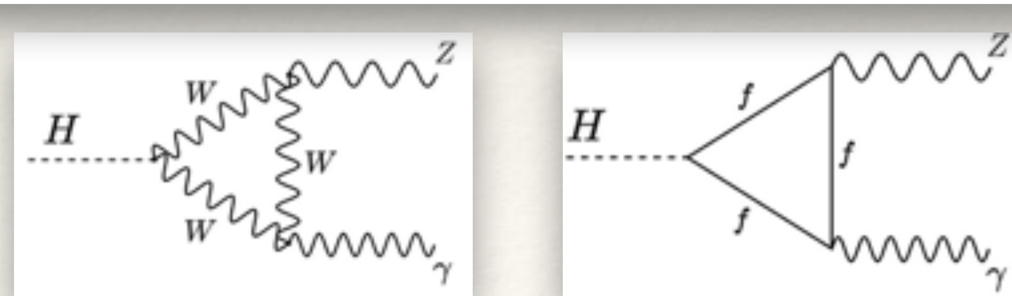
Affects h^3:
It can be measured in the far future by $GG\rightarrow hh$

Experimental bound on h→Zγ



CMS ($H \to Z\gamma$): $\mu < 9$ (9 expected) at 95% CL

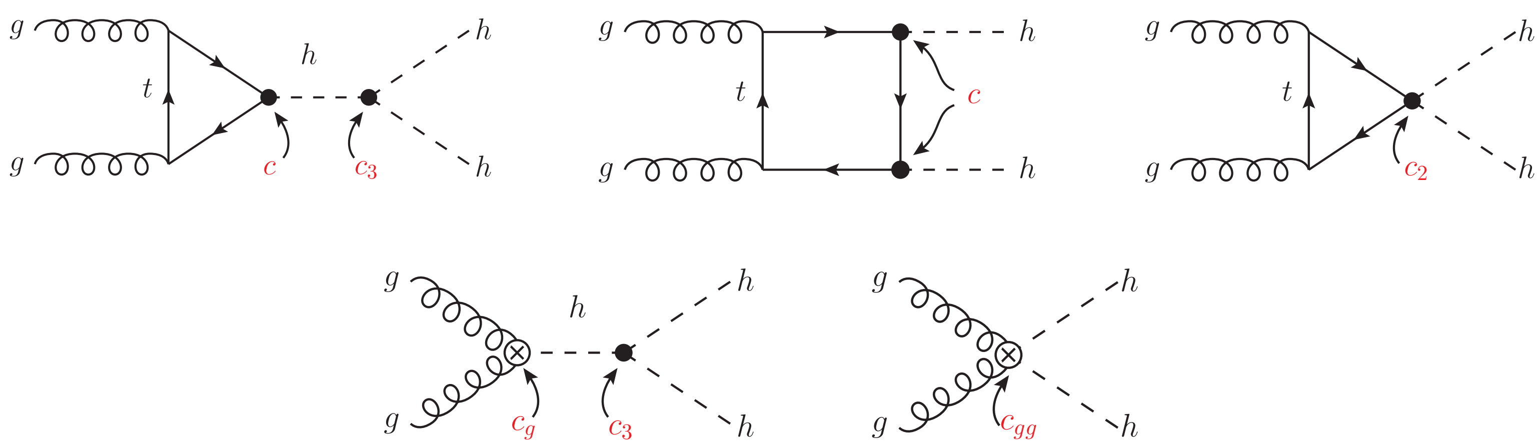
BR(h→Zγ)~0.001
small in the SM
since it comes
at one-loop:

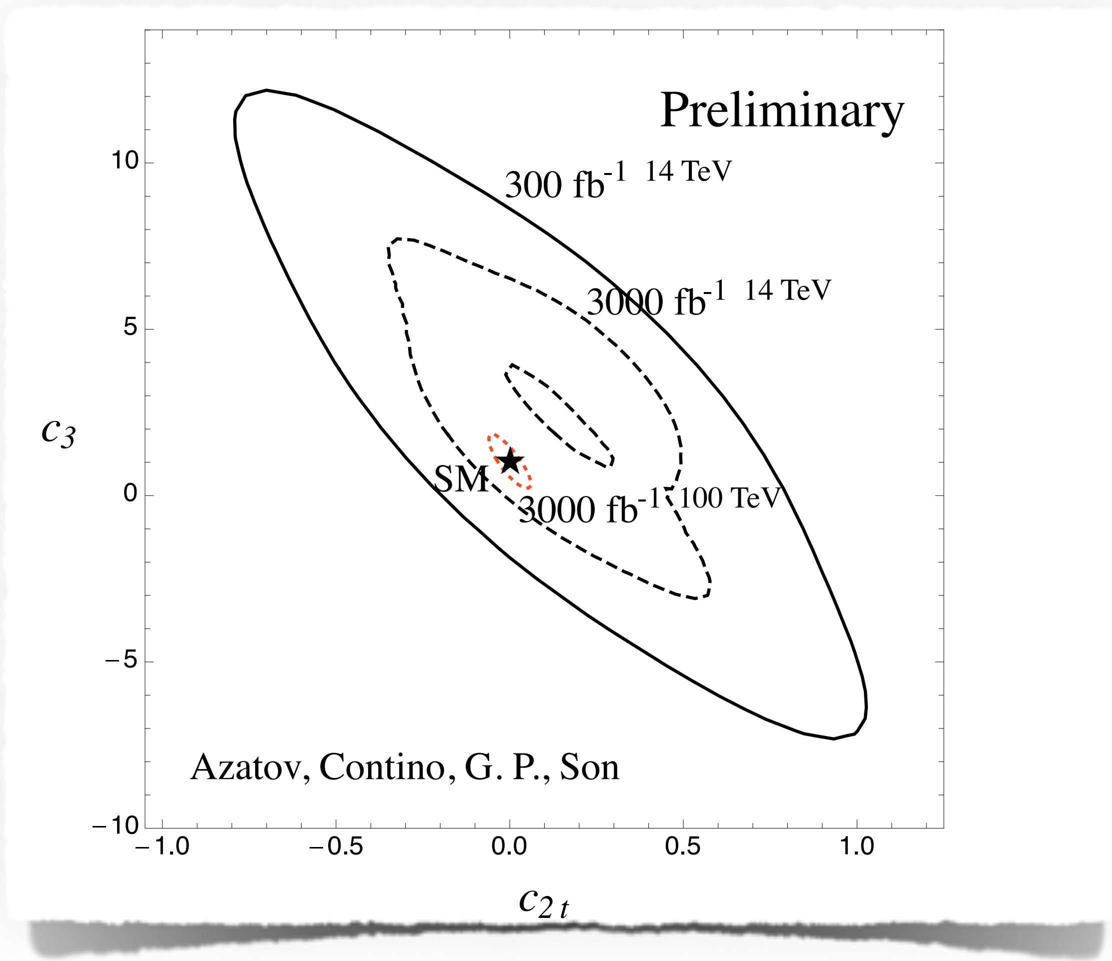


still allowed to be
9 x BR_{SM}

... last hope for finding O(1) deviations?

Prospects for 3h-coupling





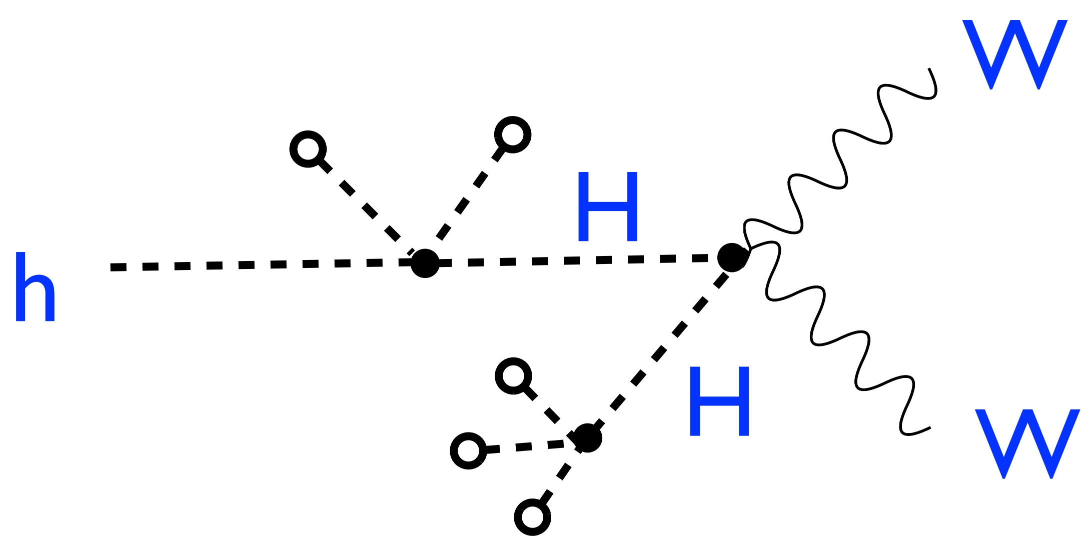
from G.Panico's talk at
"BSM Higgs Workshop@LPC"

Natural expectations for primary Higgs couplings

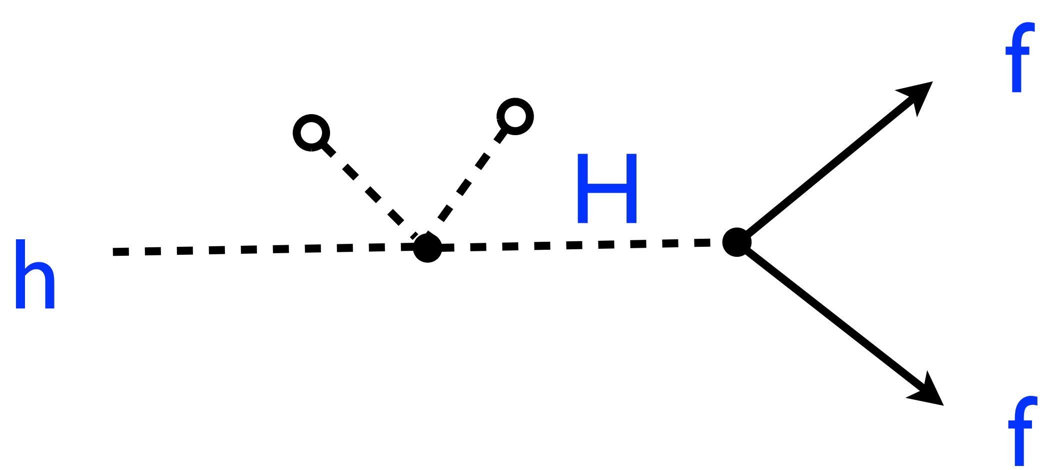
MSSM Higgs

MSSM with heavy spectrum ($\gg$100 GeV)

Main effects from the **2nd Higgs doublet:**



$$\sim \frac{v^4}{M_H^4}\, v^2$$

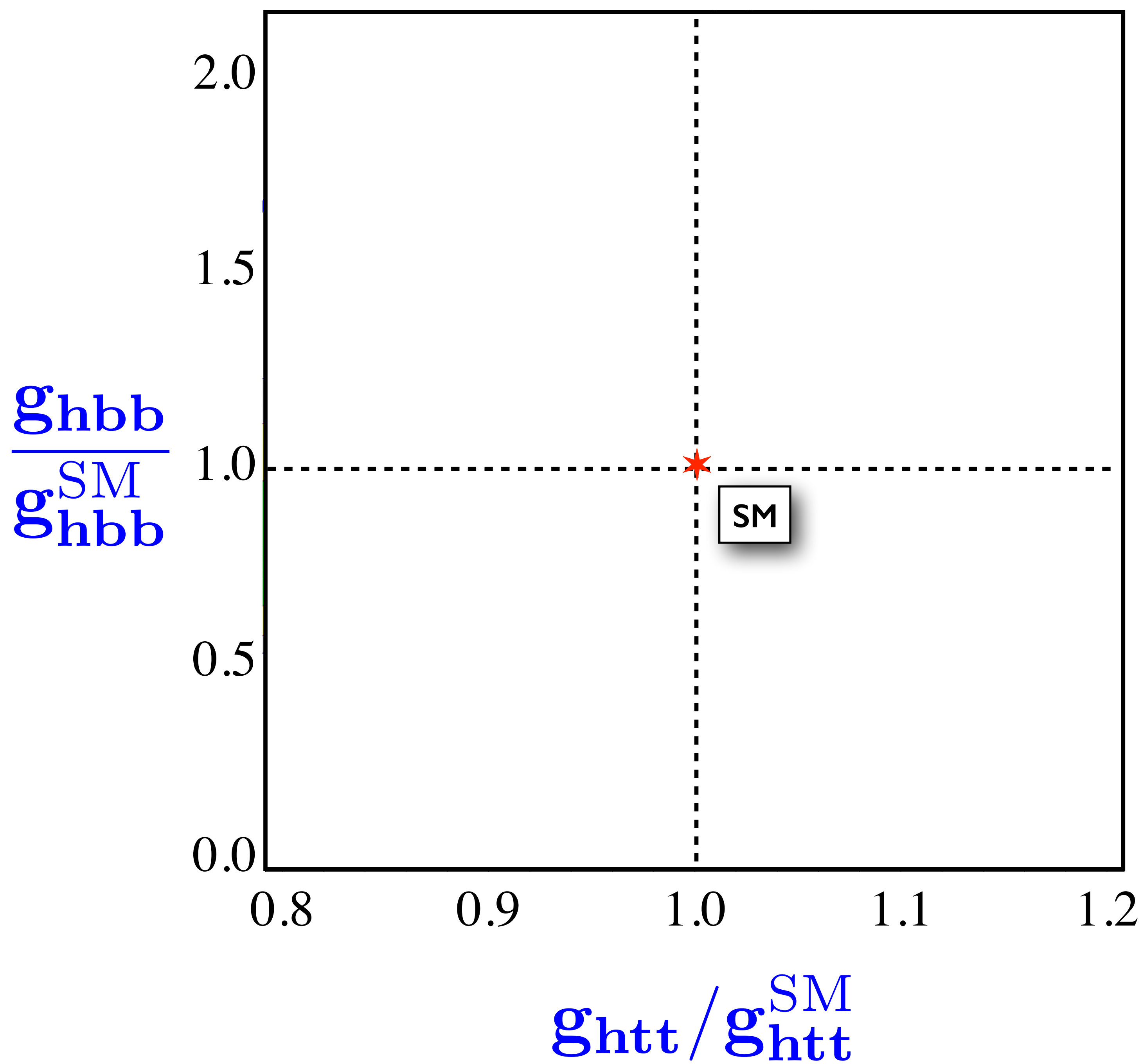


$$\sim \frac{v^2}{M_H^2}$$

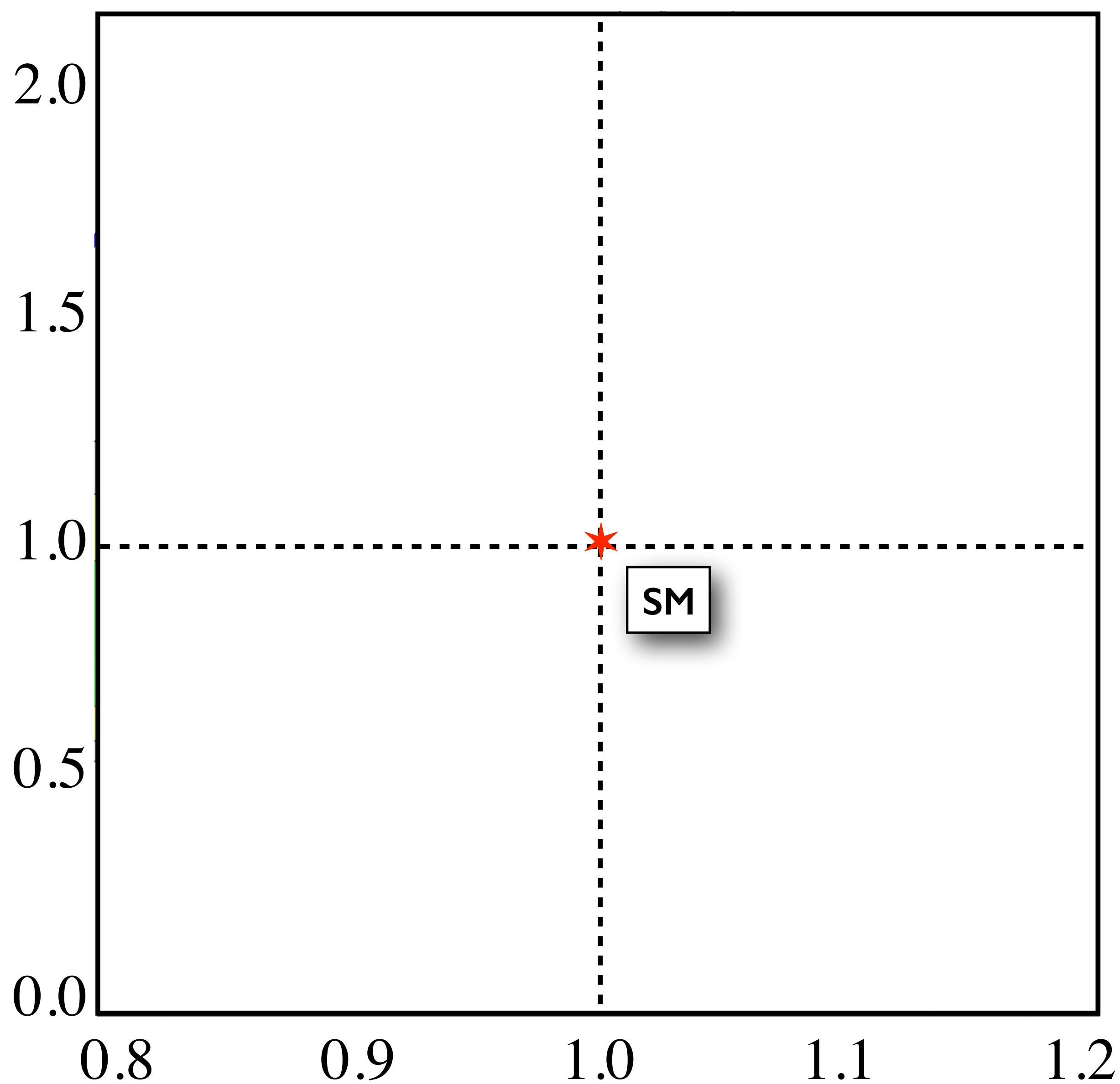
Dominant effect!

Superpartners can only modify Higgs couplings at the loop-level:
Only stops/sbottoms give some contribution to hgg/hγγ (not very large)

Relevant plane for susy Higgs couplings:



Relevant plane for susy Higgs couplings:



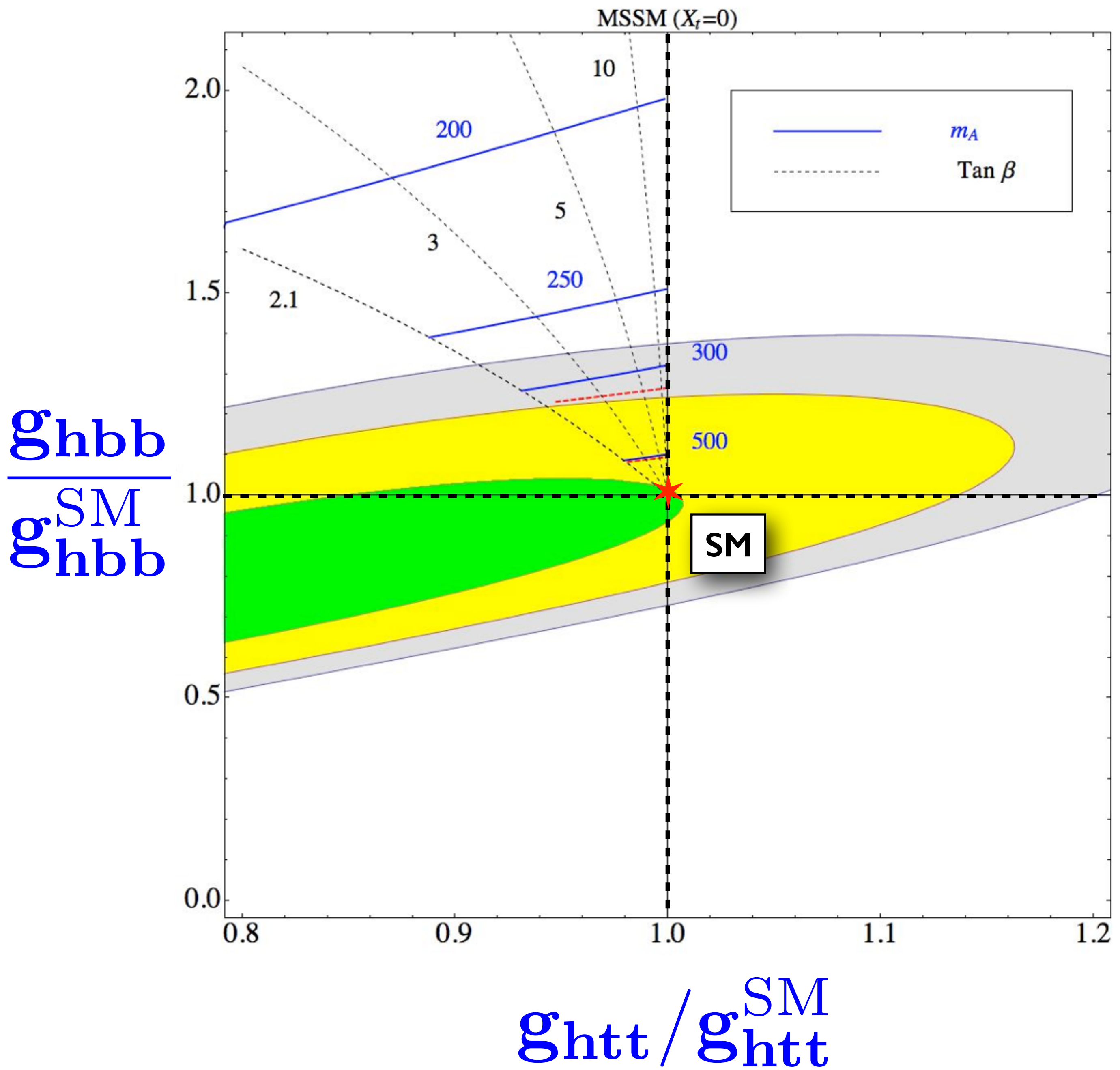
$\frac{g_{hbb}}{g_{hbb}^{SM}}$

enters in
Γ(h→bb),
impact in all BRs

g_{htt}/g_{htt}^{SM}

enters, at the loop-level, in
σ(GG→h) & BR(h→γγ)

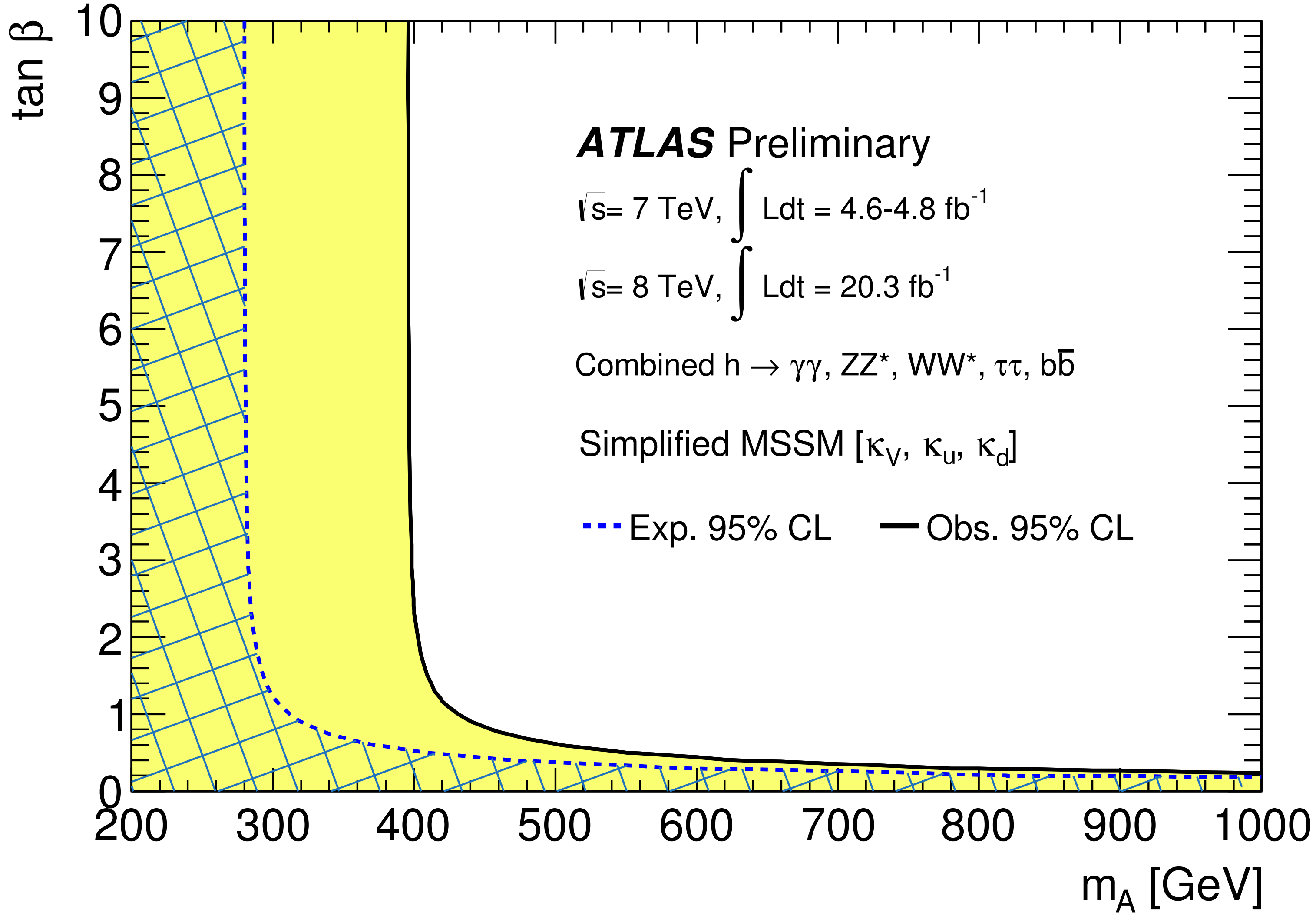
Relevant plane for susy Higgs couplings:



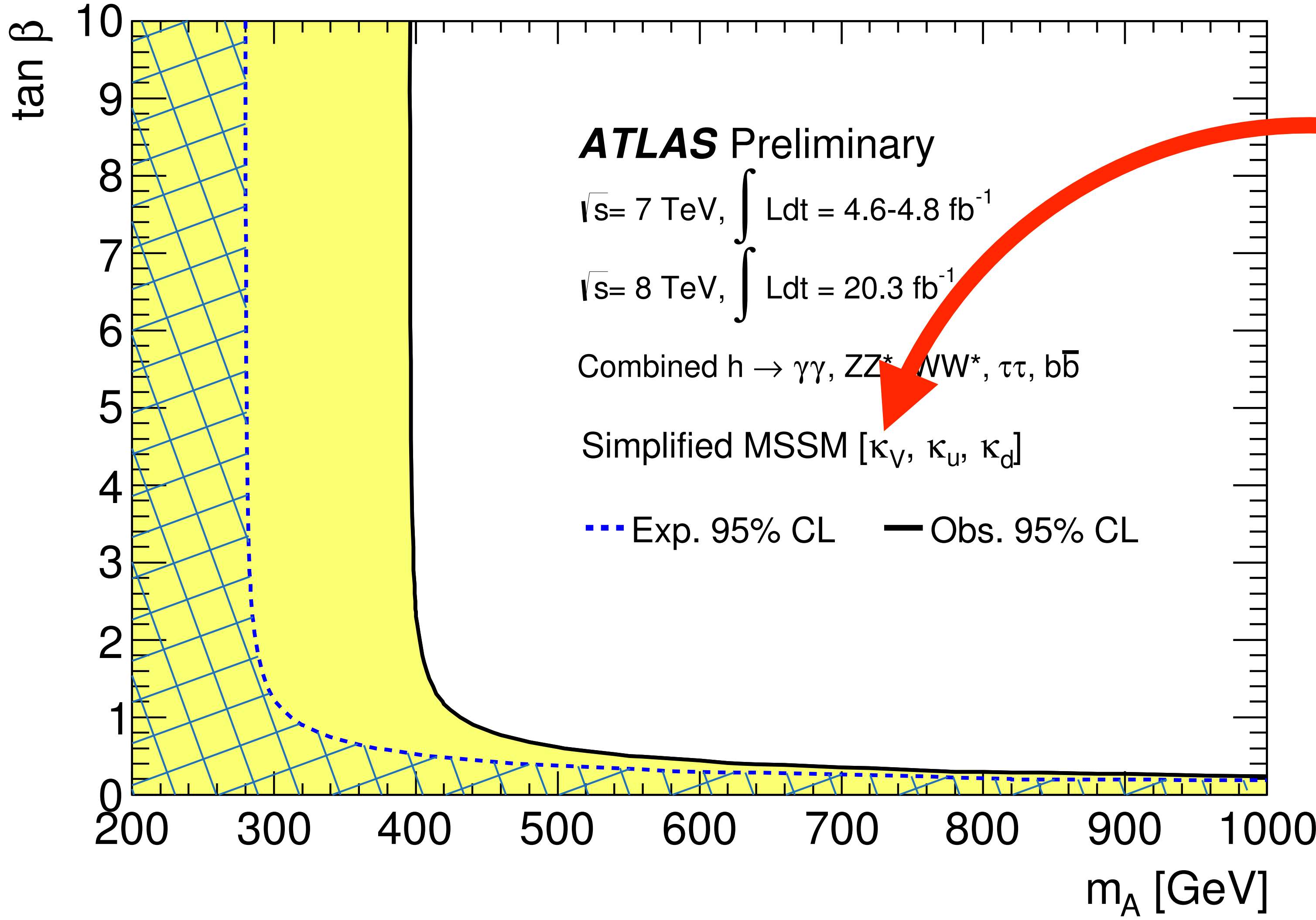
from arXiv:1212.524

(data before Moriond 13)

Higgs coupling measurements are already **ruling out** susy-parameter space



Higgs coupling measurements are already **ruling out** susy-parameter space



$\kappa_V \ll \kappa_u, \kappa_d$

(not needed in the fit)

Composite Higgs

Composite PGB Higgs couplings

Couplings dictated by symmetries (as in the QCD chiral Lagrangian)

Giudice,Grojean,AP,Rattazzi 07

$$\frac{g_{hWW}}{g_{hWW}^{\mathrm{SM}}} = \sqrt{1 - \frac{v^2}{f^2}}$$

f = Decay-constant of the PGB Higgs related to the compositeness scale

(model dependent but expected f ~ v)

Composite PGB Higgs couplings

Couplings dictated by symmetries (as in the QCD chiral Lagrangian)

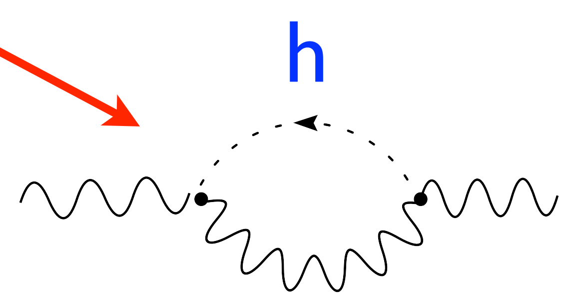
Giudice,Grojean,AP,Rattazzi 07

$$\frac{g_{hWW}}{g_{hWW}^{\mathrm{SM}}} = \sqrt{1-\frac{v^2}{f^2}}$$

f = Decay-constant of the PGB Higgs related to the compositeness scale

(model dependent but expected f ~ v)

Also affects the Z propagator, whose properties were well-measured at LEP



☛ $\xi = (v/f)^2 \lesssim 0.1$

or, equivalently:

$$\frac{\delta g_{hWW}}{g_{hWW}} \lesssim 5\%$$

Composite PGB Higgs couplings

Couplings dictated by symmetries (as in the QCD chiral Lagrangian)

Giudice,Grojean,AP,Rattazzi 07

AP,Riva 12

$$\frac{g_{hWW}}{g_{hWW}^{\rm SM}} = \sqrt{1-\frac{v^2}{f^2}}$$

f = Decay-constant of the PGB Higgs related to the compositeness scale

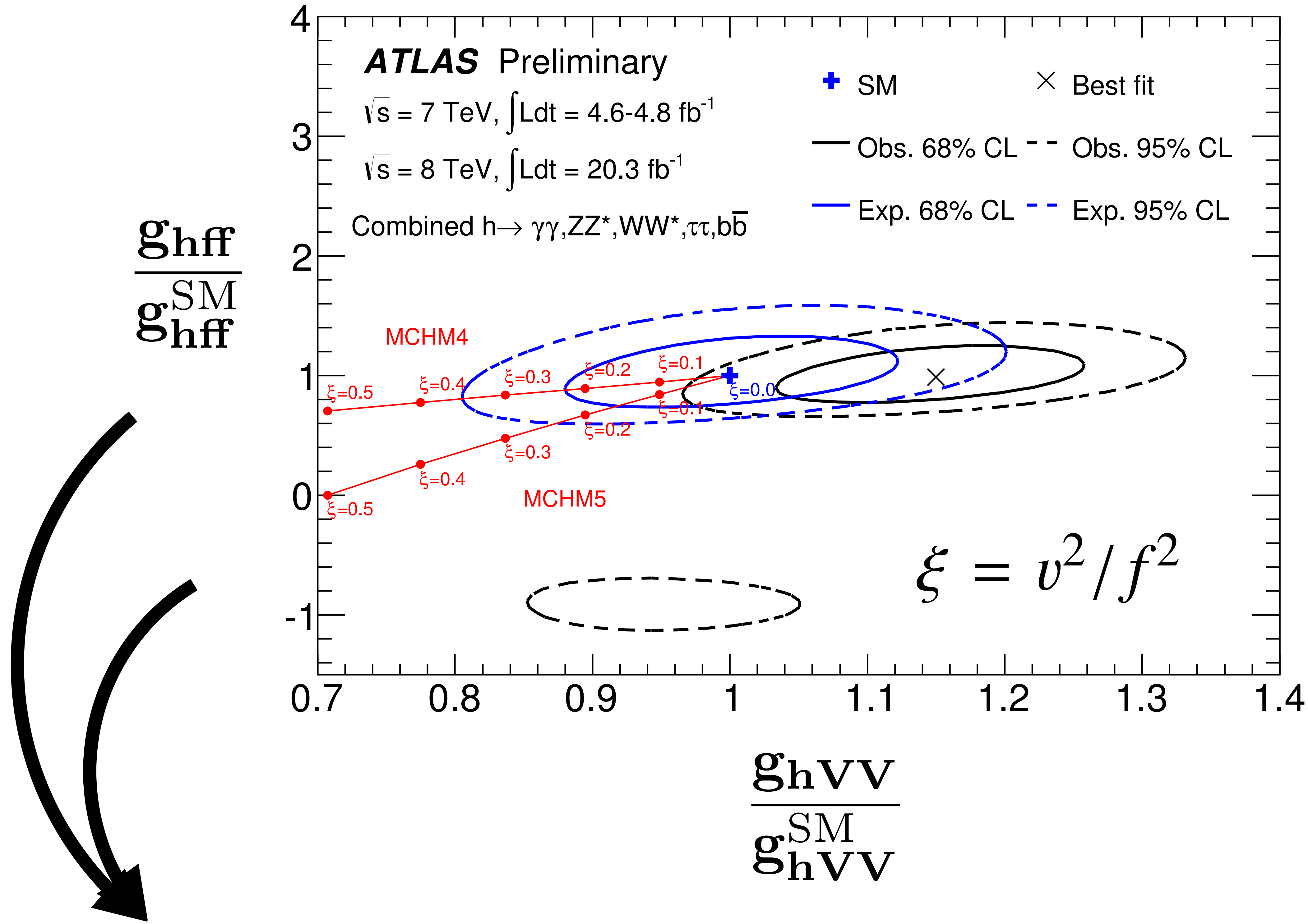
(model dependent but expected f ~ v)

$$\frac{g_{hff}}{g_{hff}^{\rm SM}} = \frac{1-(1+n)\frac{v^2}{f^2}}{\sqrt{1-\frac{v^2}{f^2}}}$$

$$n = 0, 1, 2, \ldots$$

MCHM4 MCHM5

small deviations on the h$\gamma\gamma$(gg)-coupling due to the Goldstone nature of the Higgs



observed (expected) 95% CL upper limit of $\xi < 0.12$ (0.29) **MCHM4**

$\xi < 0.15$ (0.20) **MCHM5**

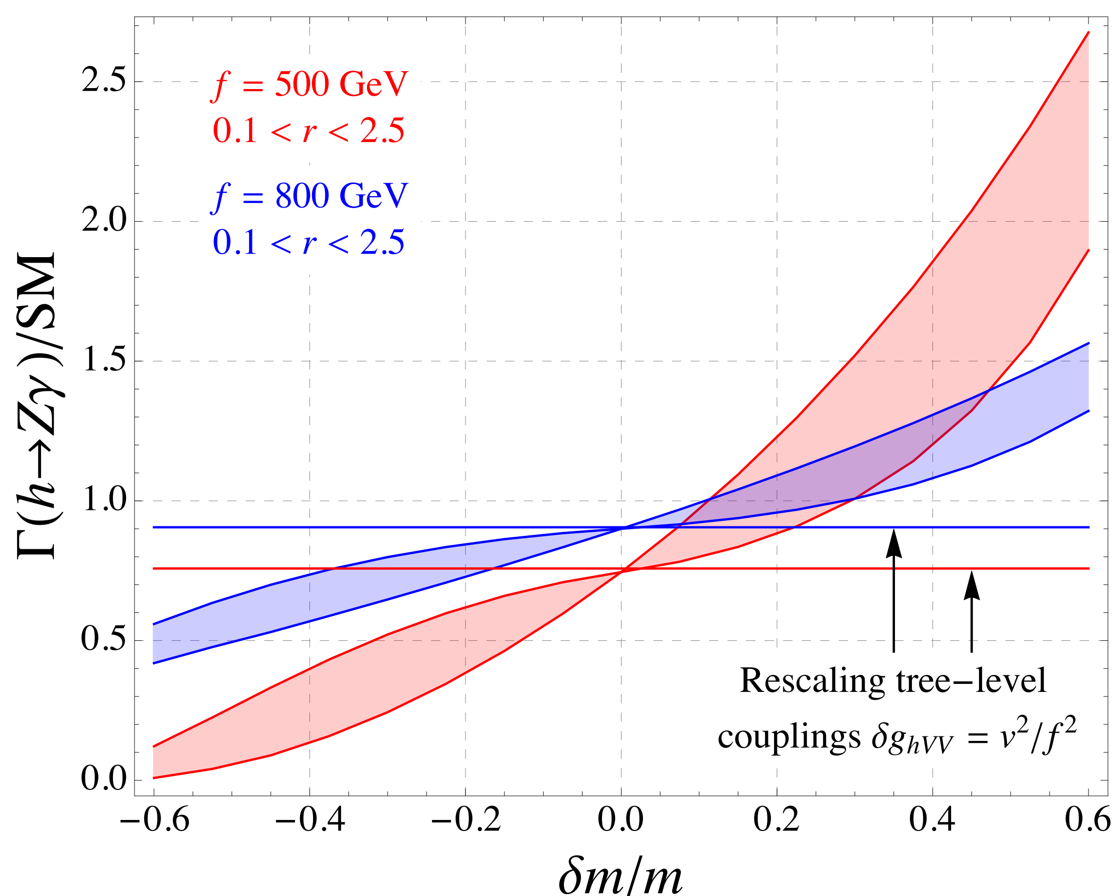
Corrections to h$\gamma\gamma$(gg)-coupling protected by the PGB symmetry

$$|H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$

"mass term"

Corrections to hZγ-coupling <u>not</u> protected by the PGB symmetry

$$D_\mu H^\dagger D_\nu H B^{\mu\nu}$$



A.Azatov, R.Contino, A.DiIura, J.Galloway 13

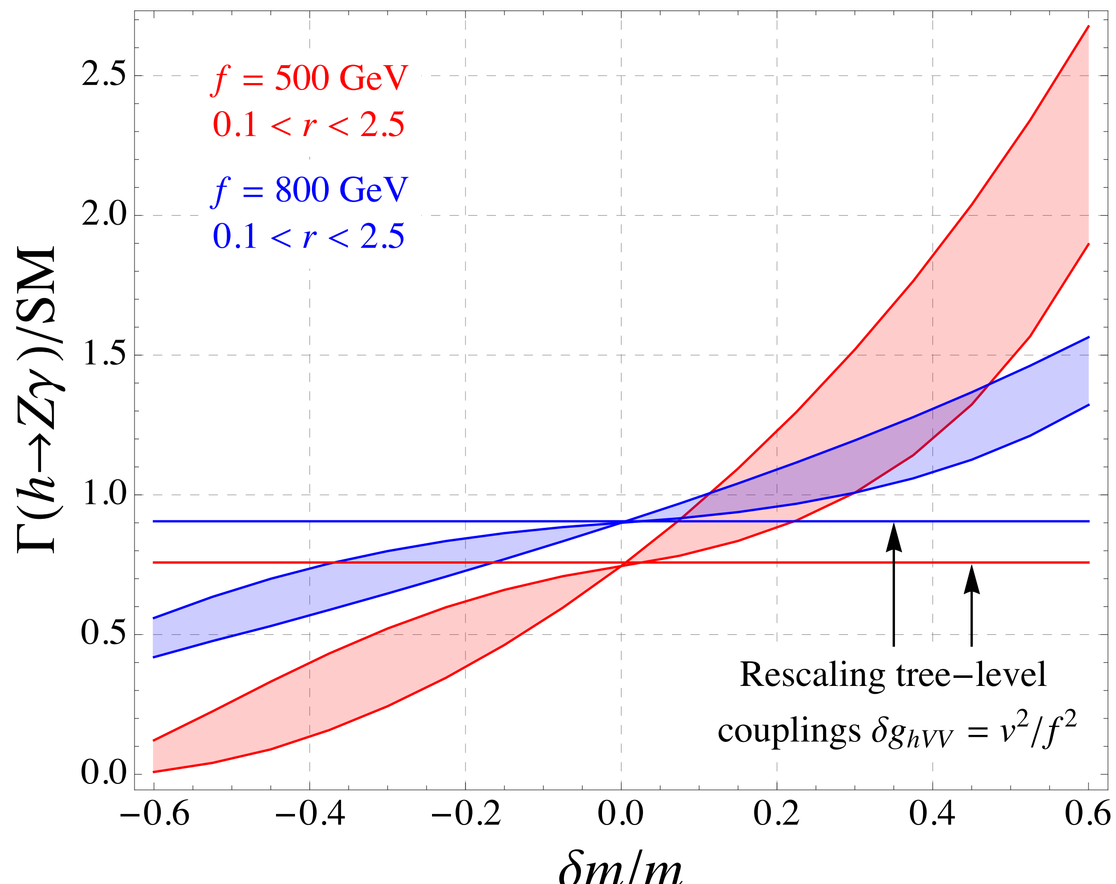
Corrections to h$\gamma\gamma$(gg)-coupling protected by the PGB symmetry

$$|H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$

“mass term”

Corrections to hZγ-coupling <u>not</u> protected by the PGB symmetry

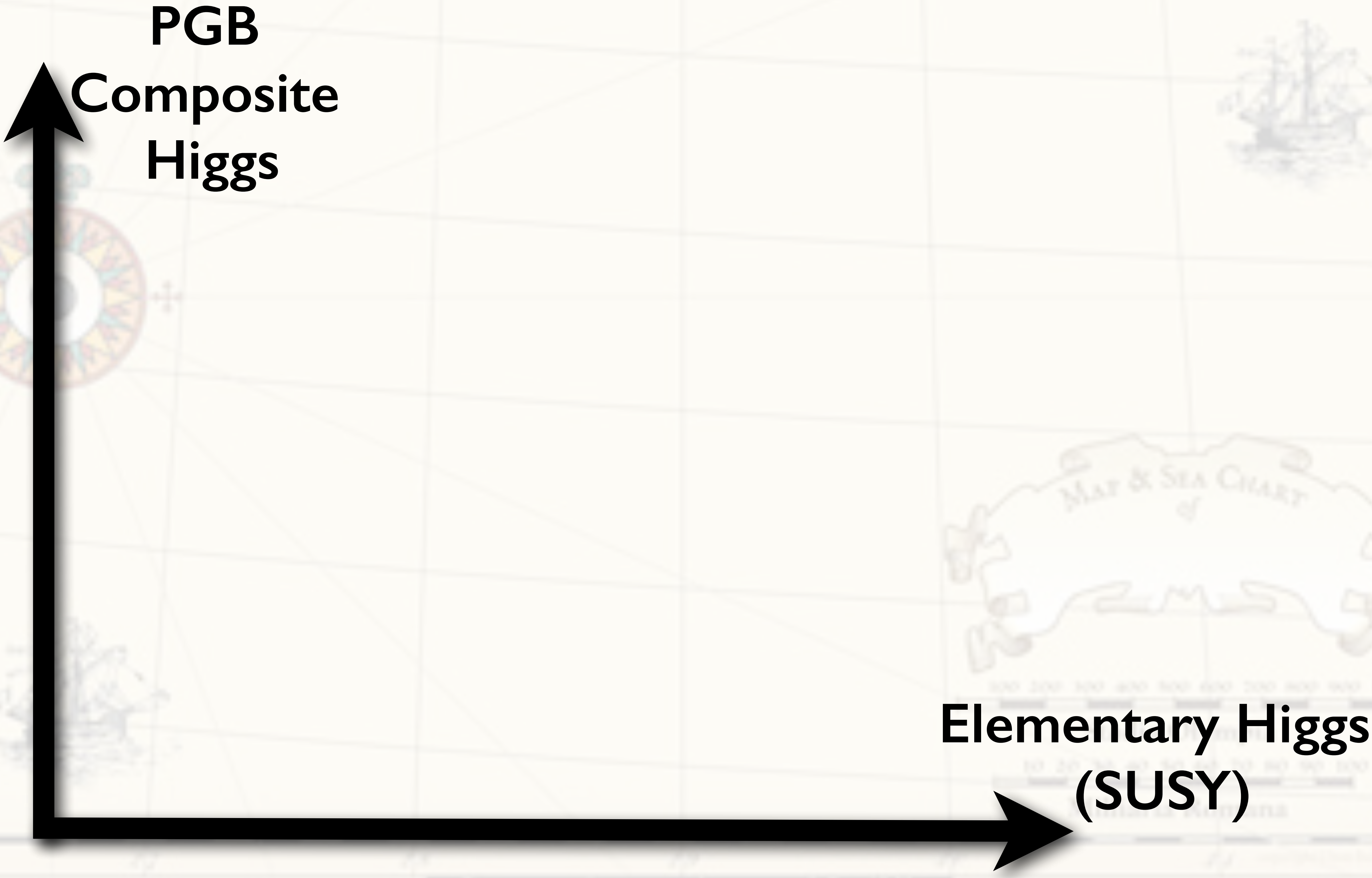
$$D_\mu H^\dagger D_\nu H B^{\mu\nu}$$



A.Azatov, R.Contino, A.DiIura, J.Galloway 13

Going beyond
the MSSM and MCHM

Towards a more extended "cartography" of *natural* BSMs



Towards a more extended "cartography" of *natural* BSMs

PGB
Composite
Higgs

Mostly unexplored territory

Susy + TeV Strong dynamics

(motivated to keep **naturalness** in the absence of superpartners below TeV and m_h~125 GeV (hard susy-breaking effects?))

Elementary Higgs
(SUSY)

Possibilities:

1) Strong-sector with accidental ("emergent") supersymmetry delivering a composite-susy light Higgs ($m_h \ll \Lambda \sim$ TeV)

T.Gherghetta, AP 03, R. Sundrum 04, M.Redi, B.Gripaios 10

2) MSSM Higgs coupled to a TeV strong-sector breaking susy (SBS):

$$g_i \int d^2\theta \; H_i \mathcal{O}_i$$

A. Azatov, J.Galloway and M.A. Luty 12

T. Gherghetta, AP 11

☛ SBS could also break EWSB

similarity with Bosonic TC

M.Dine, A.Kagan, S. Samuel 90

3) Higgs as a dilaton: $v = f_{dilat}$ (associated to the breaking of scale invariance)

1) Strong-sector with "Emergent supersymmetry" delivering a composite-susy light Higgs ($m_h \ll \Lambda$)

➥ Modifications of Higgs couplings as in MCHM but also in $h\gamma\gamma$, hGG $\sim \xi$ $= (v/f)^2$

(since **no** shift-symmetry protecting)

8 of 8

1) Strong-sector with “Emergent supersymmetry"
delivering a composite-susy light Higgs ($m_h \ll \Lambda$)

➥ Modifications of Higgs couplings
as in MCHM but also in $h\gamma\gamma$,hGG $\sim \xi$ $= (v/f)^2$

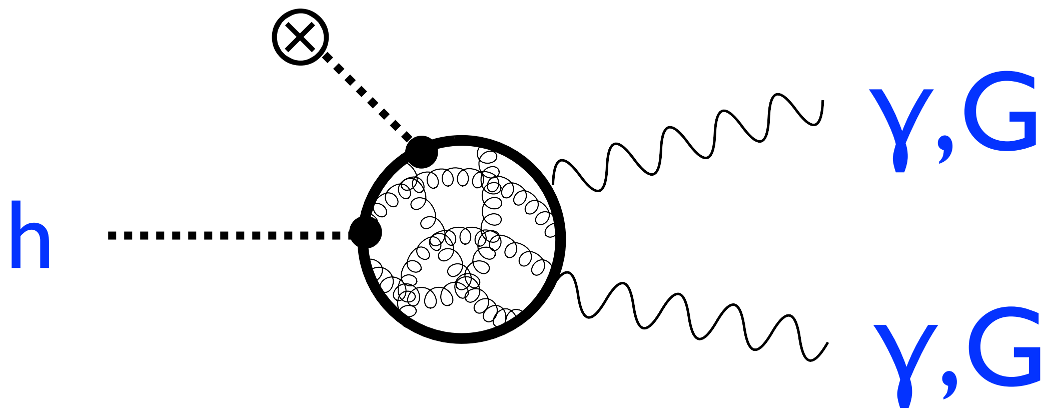
(since **no** shift-symmetry protecting)

but $\hat{T} <$ O(10^{-3})
forces f > few TeV

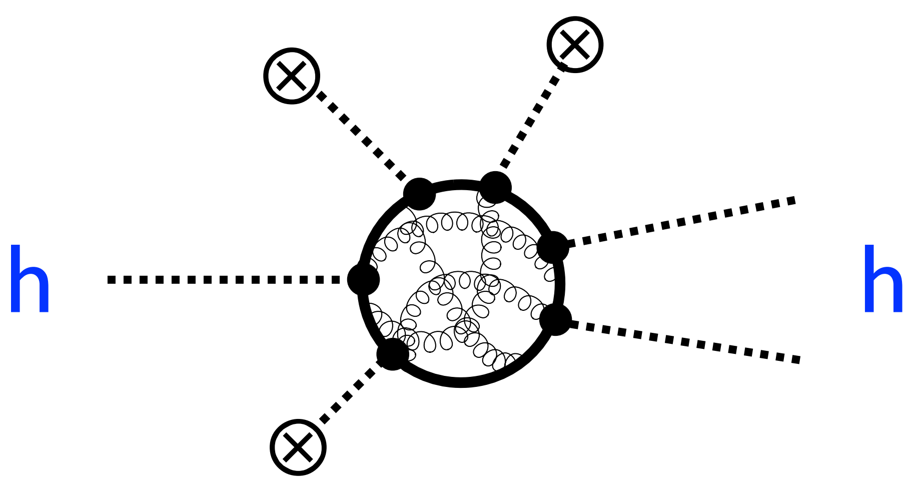
2) MSSM Higgs coupled to a strong-sector breaking susy (SBS):

Higgs mixing to the SBS: ϵ_H

Correction with respect to the SM:

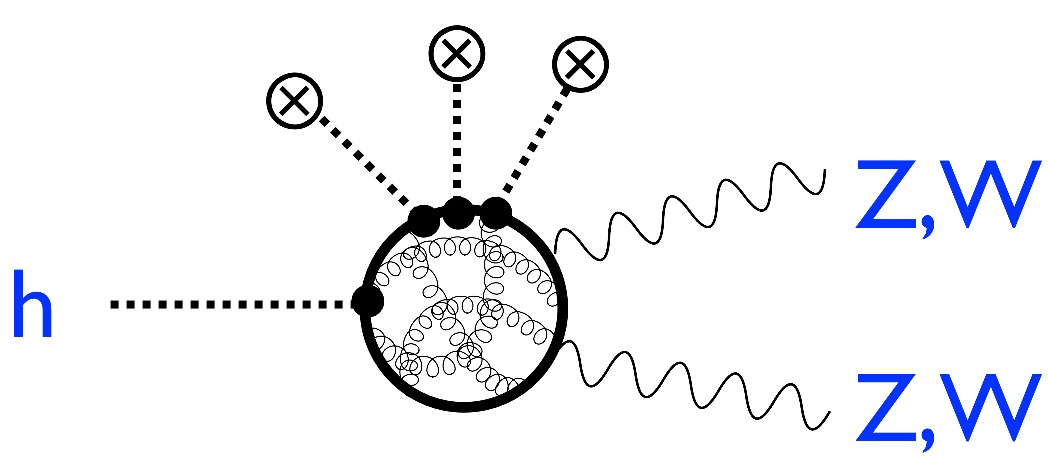


$$\frac{\delta g_{h\gamma\gamma}}{g^{\rm SM}_{h\gamma\gamma}} \sim \epsilon_H^2 \xi$$



$$\frac{\delta g_{3h}}{g^{\rm SM}_{3h}} \sim g_*^2 \epsilon_H^6 \xi \sim \epsilon_H^2 \xi$$

$$(g_*^2 \epsilon_H^4 \sim \lambda_{\rm SM} \sim 1)$$



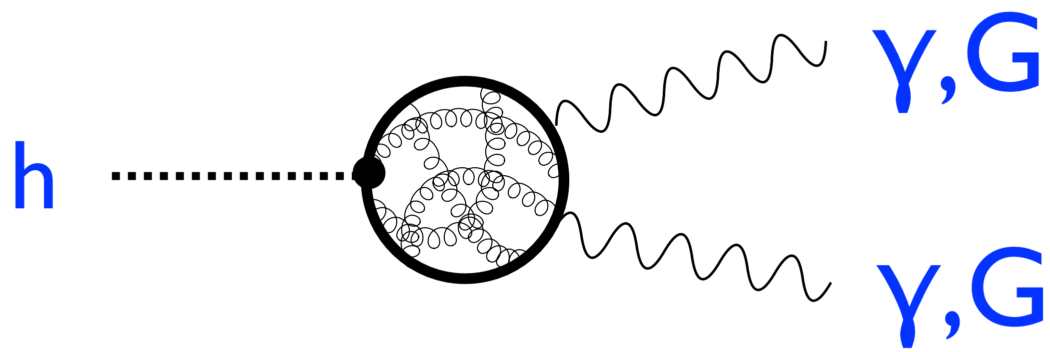
$$\frac{\delta g_{hVV}}{g^{\rm SM}_{hVV}} \sim \epsilon_H^4 \xi$$

4) Higgs as a dilaton:

excitation along the EWSB condensate = scale-breaking condensate

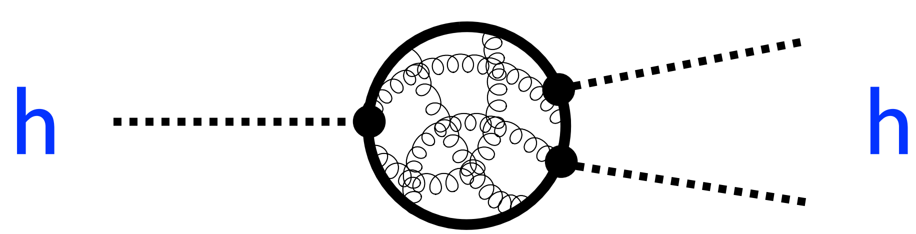
$m_h \ll \Lambda \sim$ TeV since it is a dilaton

B.Bellazzini,C.Csaki,J.Hubisz,J.Serra, J.Terning 14
F.Coradeschi, P.Lodone, D.Pappadopulo, R.Rattazzi,L.Vitale 14
E.Megias,O.Pujolas 14



$$\frac{\delta g_{h\gamma\gamma}}{g^{\rm SM}_{h\gamma\gamma}} \sim O(1)$$

extra contributions
from the scale anomaly



$$\frac{\delta g_{3h}}{g^{\rm SM}_{3h}} = \frac{5}{3}$$

Expected largest corrections to Higgs couplings:

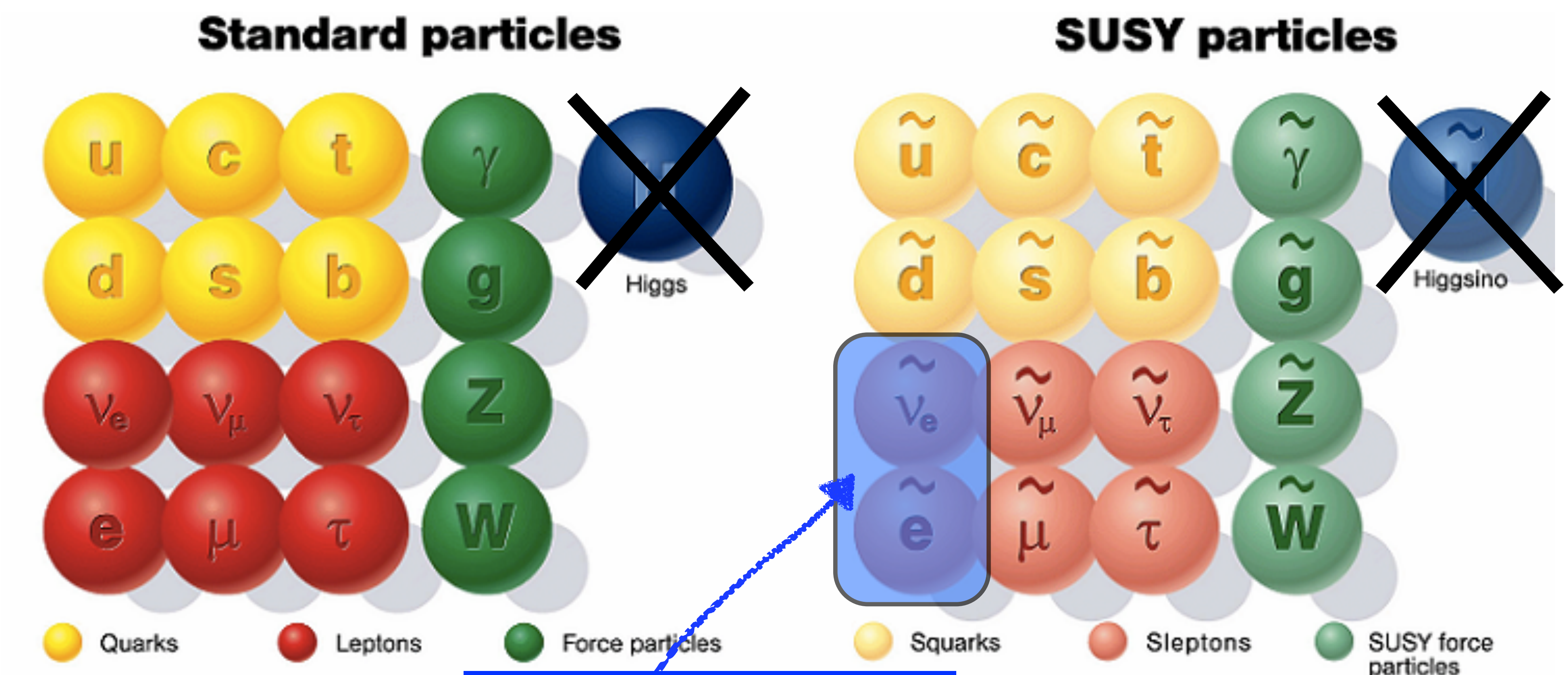
	hff	hVV	hγγ	hγZ	hGG	h
MSSM	√		√	√	√	
NMSSM	√	√	√	√	√	
PGB Composite	√	√		√		√
SUSY Composite	√	√	√	√	√	√
SUSY partly-composite			√	√	√	√
“Bosonic TC”						√
Higgs as a dilaton			√	√	√	√

New Higgs decays also possible

TeV susy-breaking allows

Higgs as the superpartner of the neutrino

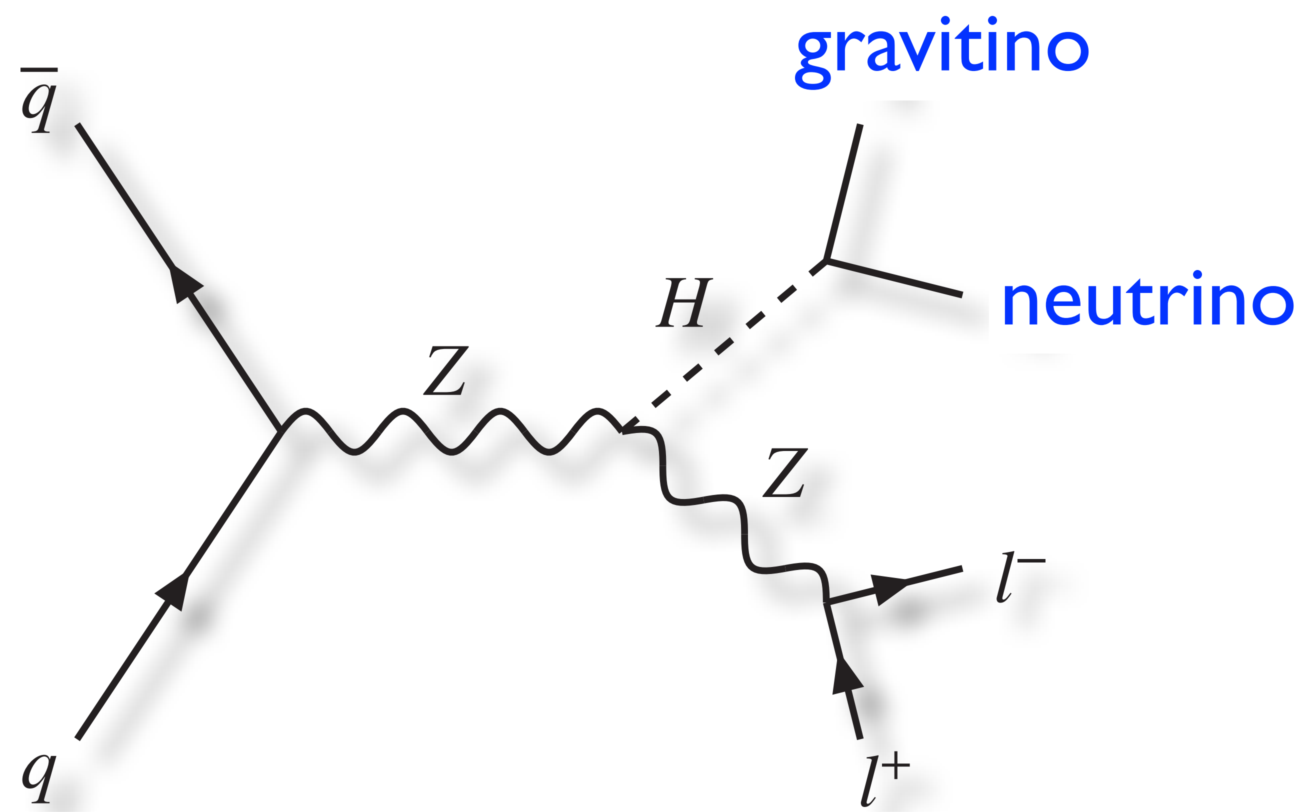
Fayet,'76; AP, Riva, Biggio'12



Higgs doublet

Is the Higgs the first SUSY particle discovered?

The Higgs could decay invisibly



missing E_T + l^+l^-

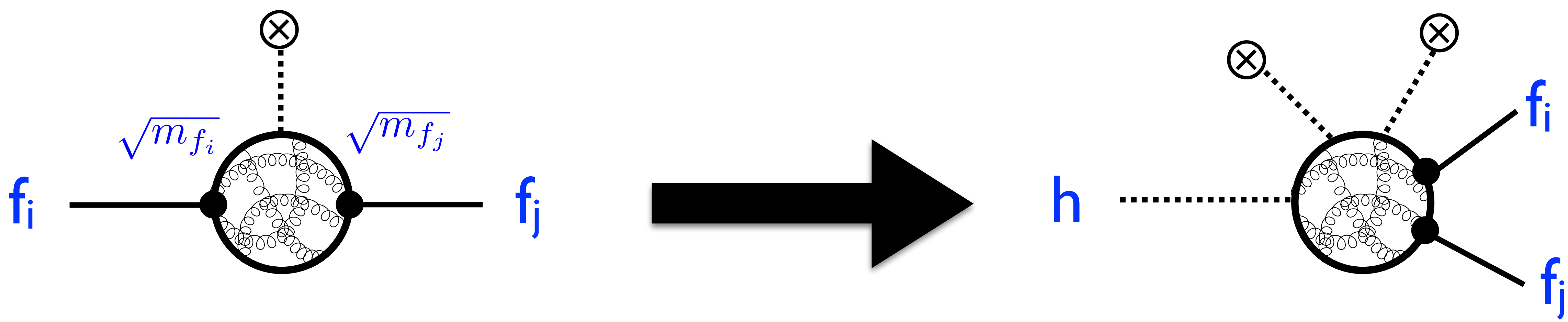
No sign of so, up to now:

CMS: BR_{inv} < 58% (44% expected)
ATLAS: BR_{inv} < 75% (62% expected)

Relaxing the MFV condition:

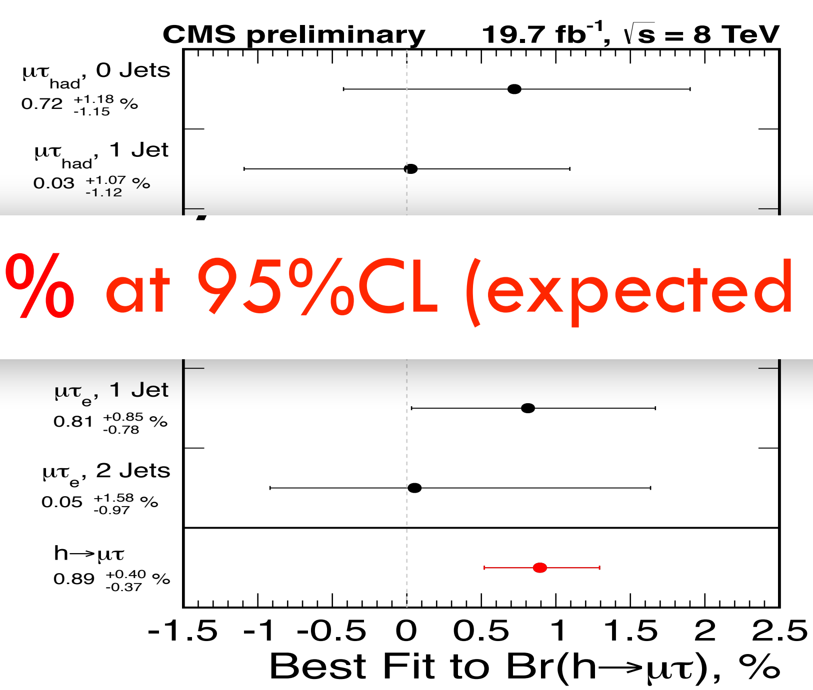
Flavor violation in Higgs decays $h \to f_1 f_2$

Interesting in models where the origin of fermion masses comes from mixing with a new sector



Prediction: $\mathbf{BR(h \to \tau\mu) \sim \frac{m_\mu}{m_\tau} BR(h \to \tau\tau) \sim 0.4\%}$

Getting there (CMS):



BR(H→μτ) < 1.57% at 95%CL (expected limit of 0.75%)

Beyond the primary Higgs couplings

Beyond the primary Higgs couplings

custodial breaking hVV

$$\begin{aligned}\Delta\mathcal{L}_h &= \delta g^h_{ZZ}\, h\frac{Z^\mu Z_\mu}{2c^2_{\theta_W}} + g^h_{Zff}\,\frac{h}{2v}\left(Z_\mu J^\mu_N + h.c.\right) + g^h_{Wff'}\,\frac{h}{v}\left(W^+_\mu J^\mu_C + h.c.\right)\\ &+ \kappa_{WW}\,\frac{h}{v}W^{+\,\mu\nu}W^-_{\mu\nu} + \kappa_{ZZ}\,\frac{h}{v}Z^{\mu\nu}Z_{\mu\nu}\,,\end{aligned}$$

contact interactions

momentum-dependent
hVV couplings

Beyond the primary Higgs couplings

custodial breaking hVV

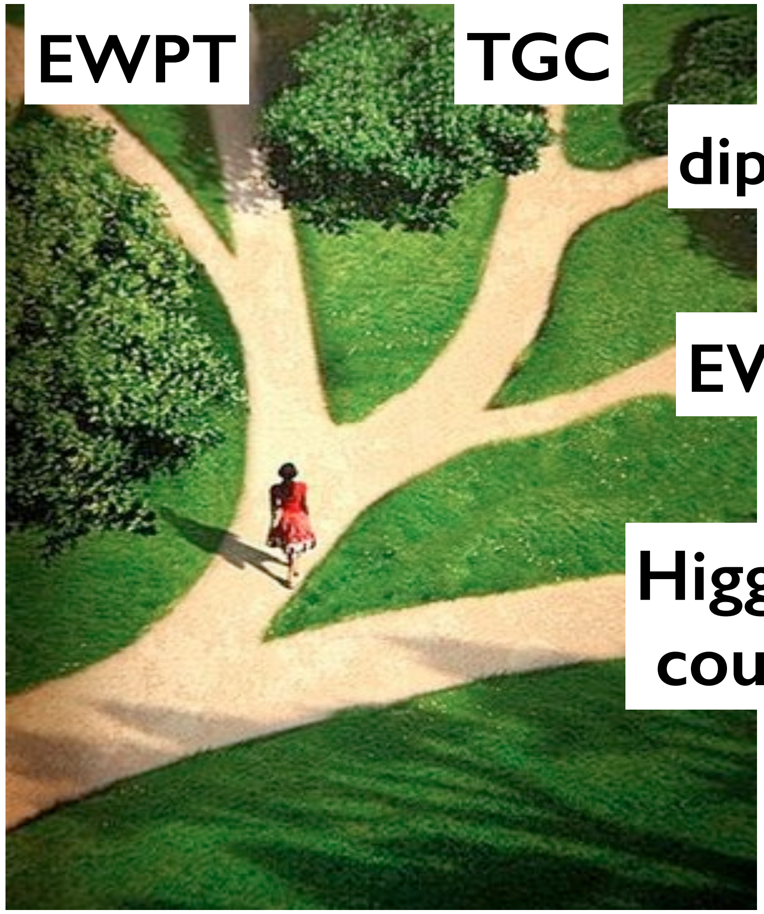
$$\Delta\mathcal{L}_h = \delta g^h_{ZZ}\, h \frac{Z^\mu Z_\mu}{2c^2_{\theta_W}} + g^h_{Zff}\, \frac{h}{2v}\left(Z_\mu J^\mu_N + h.c.\right) + g^h_{Wff'}\, \frac{h}{v}\left(W^+_\mu J^\mu_C + h.c.\right)$$

$$+ \kappa_{WW} \frac{h}{v} W^{+\,\mu\nu} W^-_{\mu\nu} + \kappa_{ZZ} \frac{h}{v} Z^{\mu\nu} Z_{\mu\nu}\,,$$

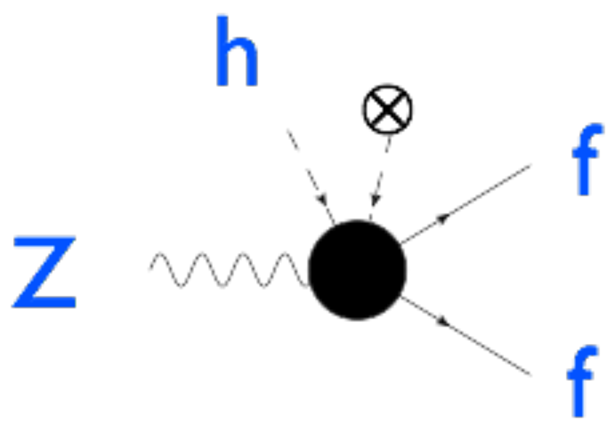
contact interactions

momentum-dependent
hVV couplings

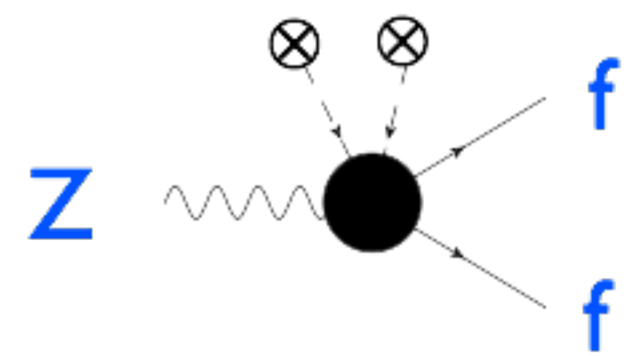
but beaten paths…
(not independent from other
couplings already tested)



Example:



$$= \frac{1}{2v} \times$$



$$H^\dagger D_\mu H \bar{f} \gamma^\mu f$$

Some modifications in h→Zff related to Z→ff

Constrained by LEP1
at the per-mille level!

custodial breaking hVV

$$\Delta\mathcal{L}_h = \delta g^h_{ZZ}\, h \frac{Z^\mu Z_\mu}{2c^2_{\theta_W}} + g^h_{Zff}\, \frac{h}{2v}\left(Z_\mu J^\mu_N + h.c.\right) + g^h_{Wff'}\, \frac{h}{v}\left(W^+_\mu J^\mu_C + h.c.\right)$$

$$+\ \kappa_{WW}\, \frac{h}{v} W^{+\,\mu\nu} W^-_{\mu\nu} + \kappa_{ZZ}\, \frac{h}{v} Z^{\mu\nu} Z_{\mu\nu}\,,$$

contact interactions

momentum-dependent
hVV couplings

All effects can be written as a function of contributions to other couplings:

$$\delta g^h_{ZZ} = 2 g m_W s^2_{\theta_W}\left(\delta g^Z_1 - \frac{\delta\kappa_\gamma}{c^2_{\theta_W}}\right)\,, \qquad \delta g^W_{ff'} = \frac{c_{\theta_W}}{\sqrt{2}}\left(\delta g^Z_{ff} V_{\rm CKM} - V_{\rm CKM}\delta g^Z_{f'f'}\right) \quad \text{for } f = f_L$$

$$g^h_{Zff} = 2\delta g^Z_{ff} - 2\delta g^Z_1 (g^Z_{ff} c_{2\theta_W} + g^\gamma_{ff} s_{2\theta_W}) + 2\delta\kappa_\gamma Y_f \frac{e s_{\theta_W}}{c^3_{\theta_W}}\,, \qquad g^h_{Wff'} = 2\delta g^W_{ff'} - 2\delta g^Z_1 g^W_{ff'} c^2_{\theta_W}$$

$$\kappa_{ZZ} = \frac{1}{2c^2_{\theta_W}}\left(\delta\kappa_\gamma + \kappa_{Z\gamma} c_{2\theta_W} + 2\kappa_{\gamma\gamma} c^2_{\theta_W}\right)\,, \qquad \kappa_{WW} = \delta\kappa_\gamma + \kappa_{Z\gamma} + 2\kappa_{\gamma\gamma}\,,$$

- **δg_1^Z, $\delta\kappa_\gamma$** : Corrections to TGC
- **δg_f^Z** : Corrections to Zff
- **δg^h_{VV}** : Corrections to hVV
- **$\kappa_{Z\gamma}$, $\kappa_{\gamma\gamma}$** : Corrections to hZγ & hγγ

custodial breaking hVV

$$\Delta\mathcal{L}_h = \delta g^h_{ZZ}\, h \frac{Z^\mu Z_\mu}{2c^2_{\theta_W}} + g^h_{Zff}\frac{h}{2v}\left(Z_\mu J^\mu_N + h.c.\right) + \underbrace{g^h_{Wff'}}_{\text{contact interactions}}\frac{h}{v}\left(W^+_\mu J^\mu_C + h.c.\right)$$

$$+ \underbrace{\kappa_{WW}}_{\substack{\text{momentum-dependent}\\ \text{hVV couplings}}}\frac{h}{v}W^{+\,\mu\nu}W^-_{\mu\nu} + \kappa_{ZZ}\frac{h}{v}Z^{\mu\nu}Z_{\mu\nu}\,,$$

All effects can be v ... er couplings:

➥ no large deviations expected in these couplings

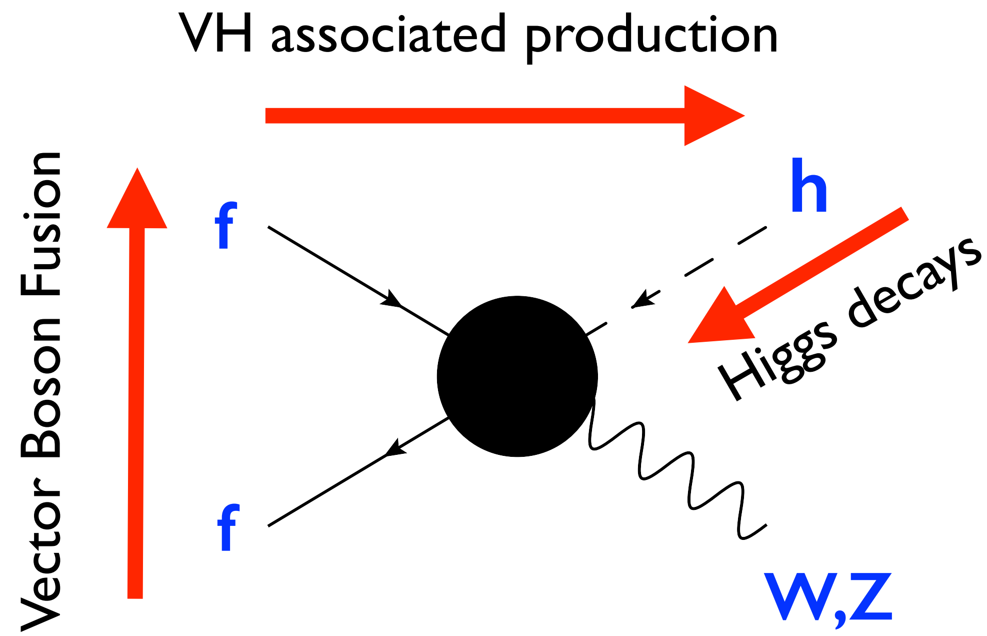
$$\delta g^h_{ZZ} = 2g m_W s^2_{\theta} \ldots \Big(\ldots \frac{\ldots}{c^2_{\theta_W}}\Big) \quad \ldots V_{\rm CKM}\delta g^Z_{f'f'}) \quad \text{for } f = f_L$$

$$g^h_{Zff} = 2\delta g^Z_{ff} - 2\delta g^Z_1 (g^Z_{ff}c_{2\theta_W} + g^\gamma_{ff}s_{2\theta_W}) + 2\delta\kappa_\gamma Y_f \frac{e s_{\theta_W}}{c^3_{\theta_W}}\,, \qquad g^h_{Wff'} = 2\delta g^W_{ff'} - 2\delta g^Z_1 g^W_{ff'}c^2_{\theta_W}$$

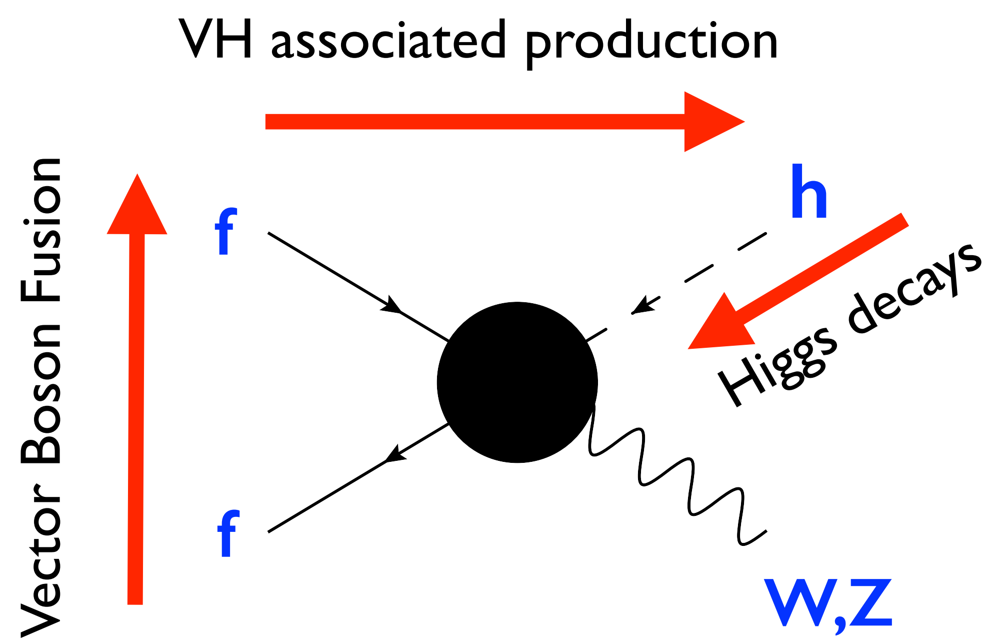
$$\kappa_{ZZ} = \frac{1}{2c^2_{\theta_W}}\left(\delta\kappa_\gamma + \kappa_{Z\gamma}c_{2\theta_W} + 2\kappa_{\gamma\gamma}c^2_{\theta_W}\right), \qquad \kappa_{WW} = \delta\kappa_\gamma + \kappa_{Z\gamma} + 2\kappa_{\gamma\gamma},$$

- **$\delta g_1^Z, \delta\kappa_\gamma$** : Corrections to TGC
- **δg_f^Z** : Corrections to Zff
- **δg^h_{VV}** : Corrections to hVV
- **$\kappa_{Z\gamma}, \kappa_{\gamma\gamma}$** : Corrections to hZγ & hγγ

BUT worth to explore. Some interesting physical effects in:



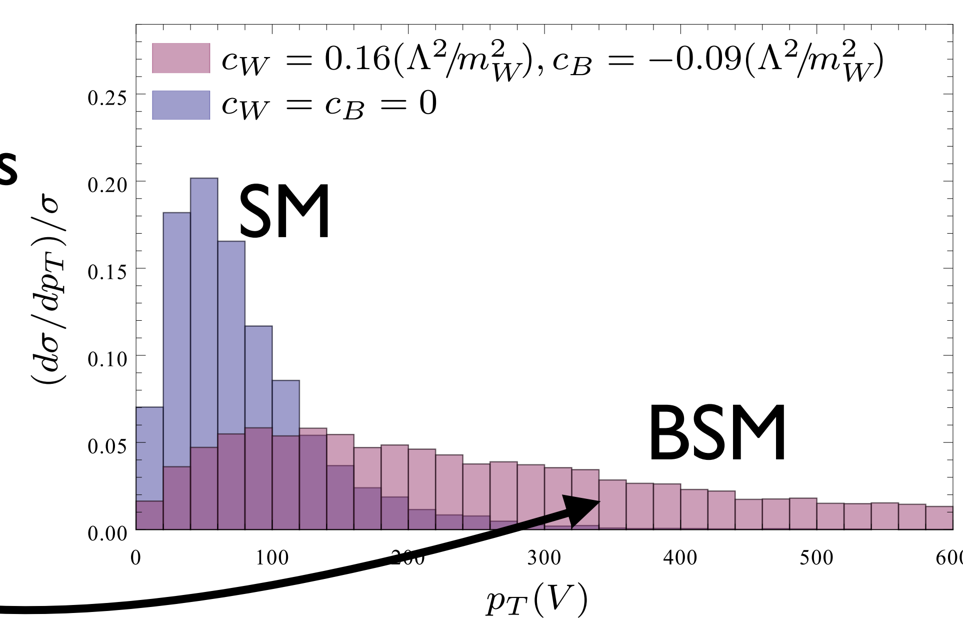
BUT worth to explore. Some interesting physical effects in:



Example: pp→V*→Vh: $\mathcal{M} \sim \mathcal{M}_{SM} + c_{BSM}\, E^2/\Lambda^2$

leading effects
from
contact interactions

BSM-effects enhanced
at the *tail* of distributions



$c_{BSM} \lesssim$ few %

arXiv:1406.7320

Conclusions

With the Higgs ➠ the SM is completed

➥ No need for anything else
(at least) up to around the Planck scale

… but very unnatural theory !

Natural models demand departures from SM **Higgs couplings:**

- Today, as Higgs coupling measurements agree with the SM, we only place bounds on new-physics

The Higgs is another weapon of BSM destruction

- Tomorrow, who knows, it can illuminate on new-physics