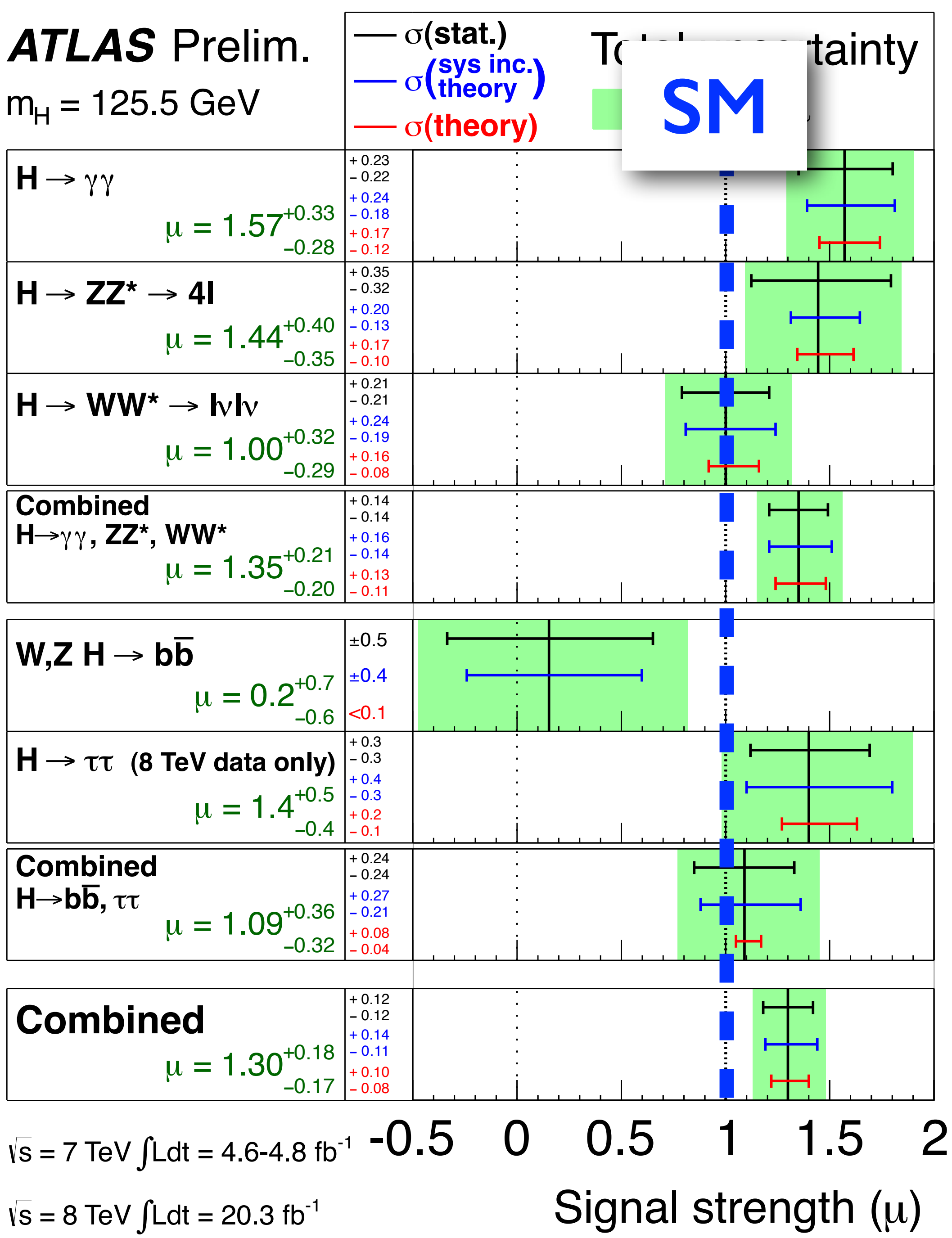
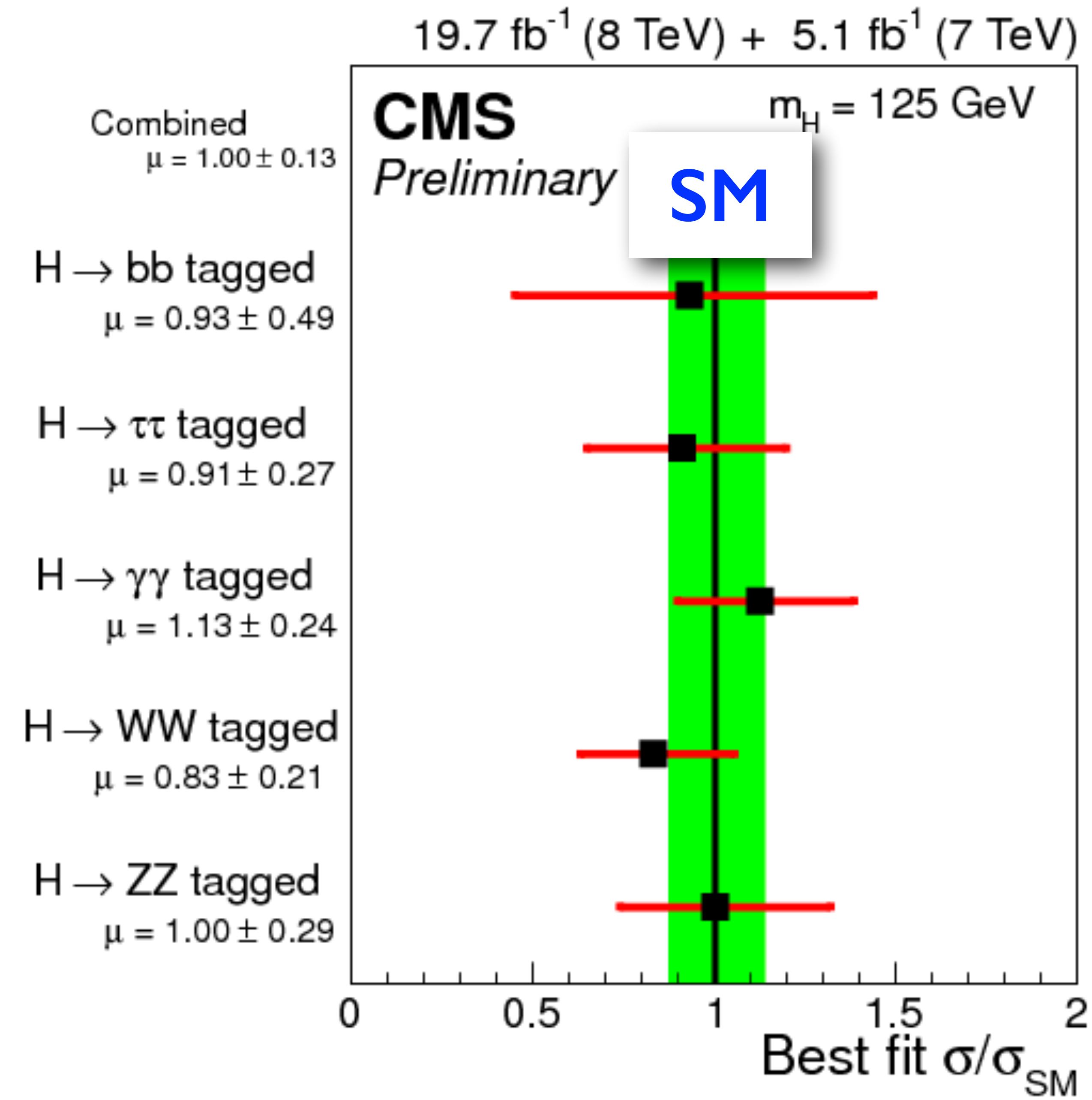
Higgs Couplings

(the best indirect BSM discriminators)

Alex Pomarol, UAB (Barcelona)

The LHC first-run legacy:

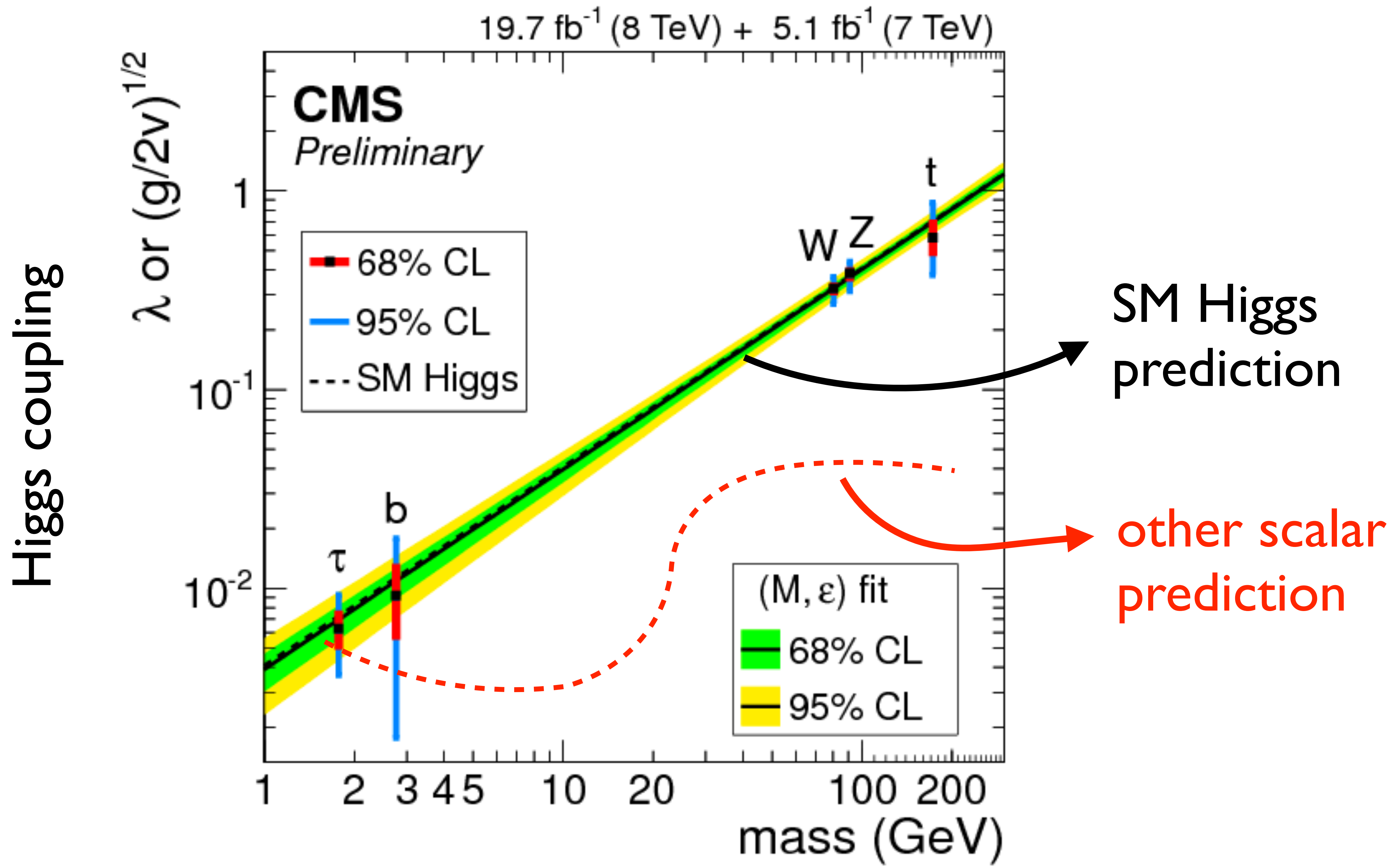




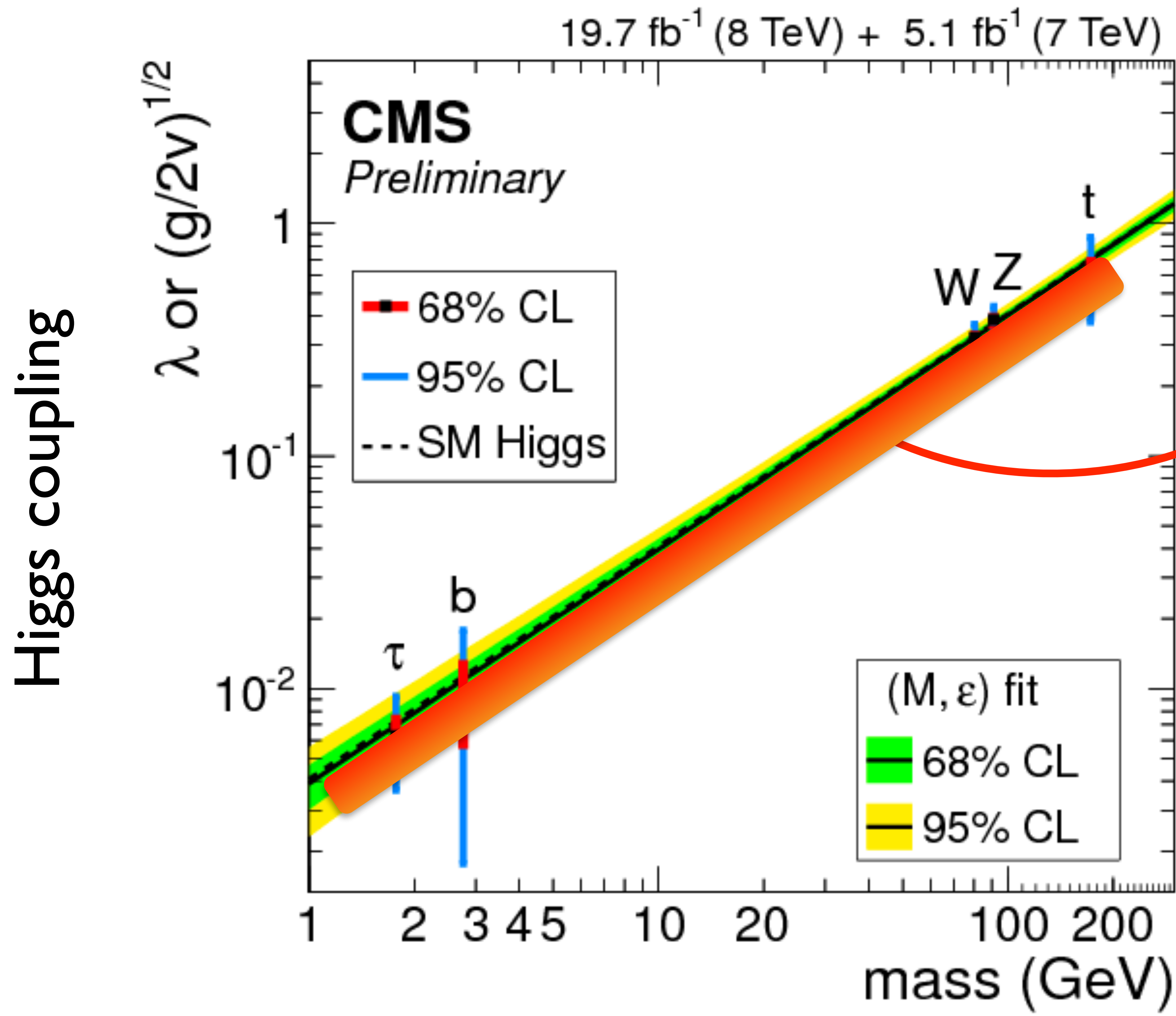
<u>Many channels available!</u>

➥ **all quite compatible with the SM Higgs !**

A better perspective to understand how close to a SM Higgs:



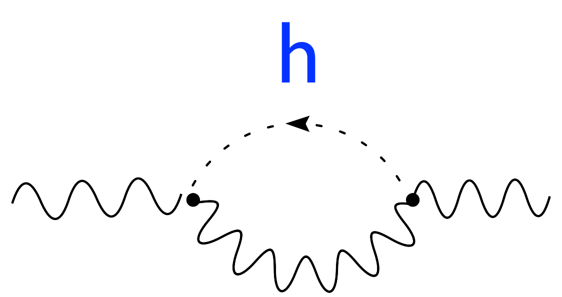
A better perspective to understand how close to a SM Higgs:



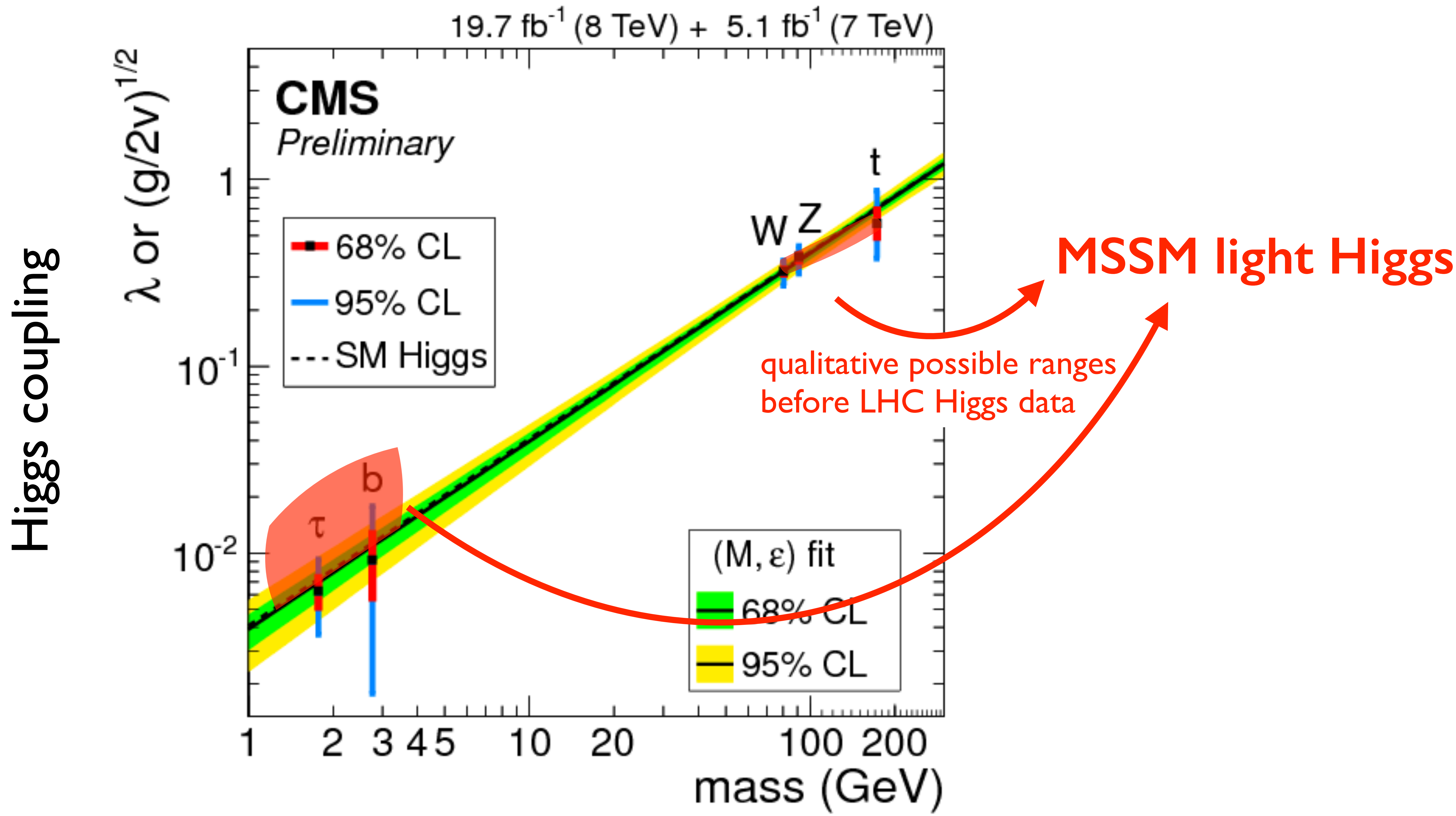
Composite Higgs

(reduction of couplings)

small effects already expected, as EWPT (LEP1) put strong limits to the coupling hVV since it affects the Z propagator:



A better perspective to understand how close to a SM Higgs:

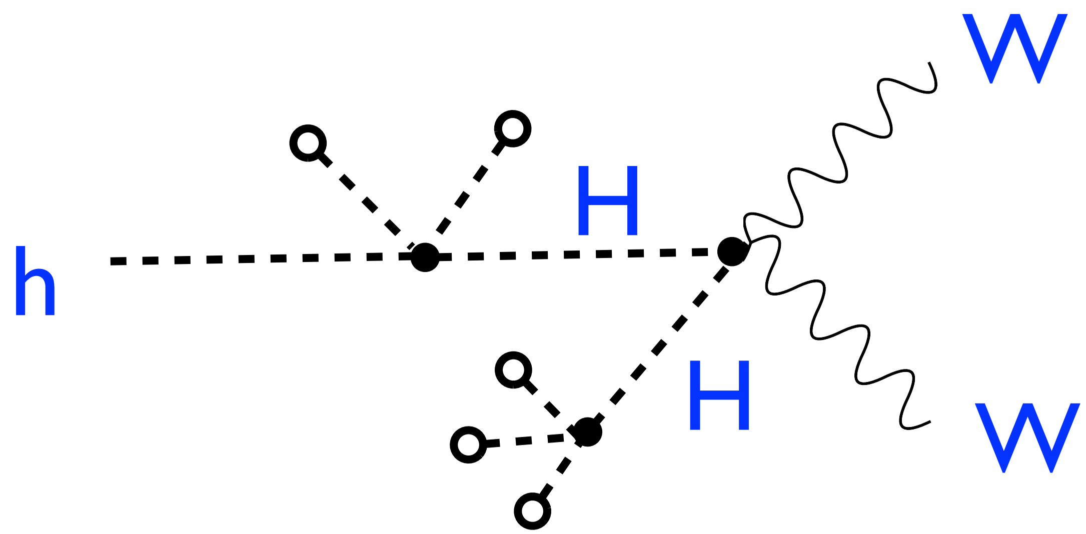


Higgs coupling measurements can place bounds on BSM !

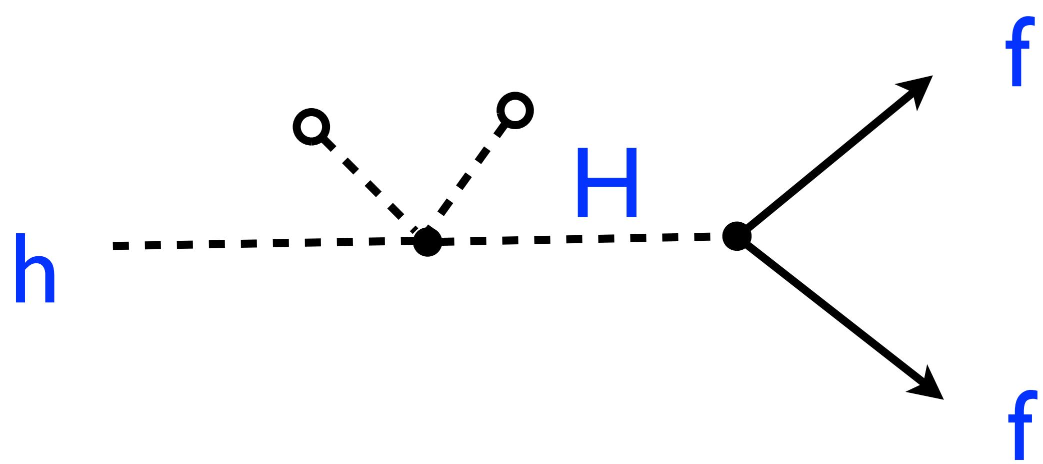
(in natural theories, the Higgs couplings must be different from those of the SM)

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

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



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

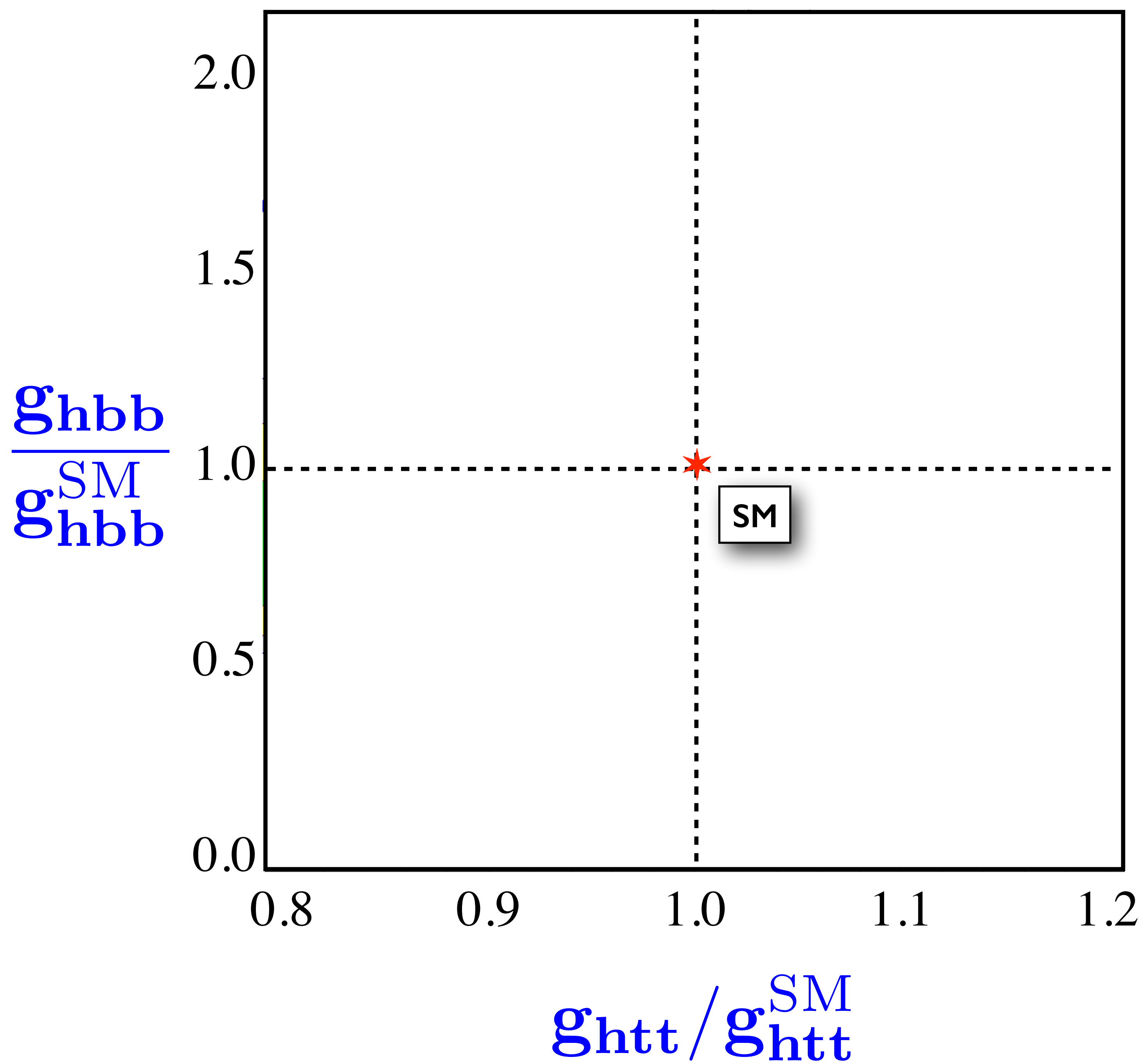


$$\sim \frac{v^2}{M_H^2}$$

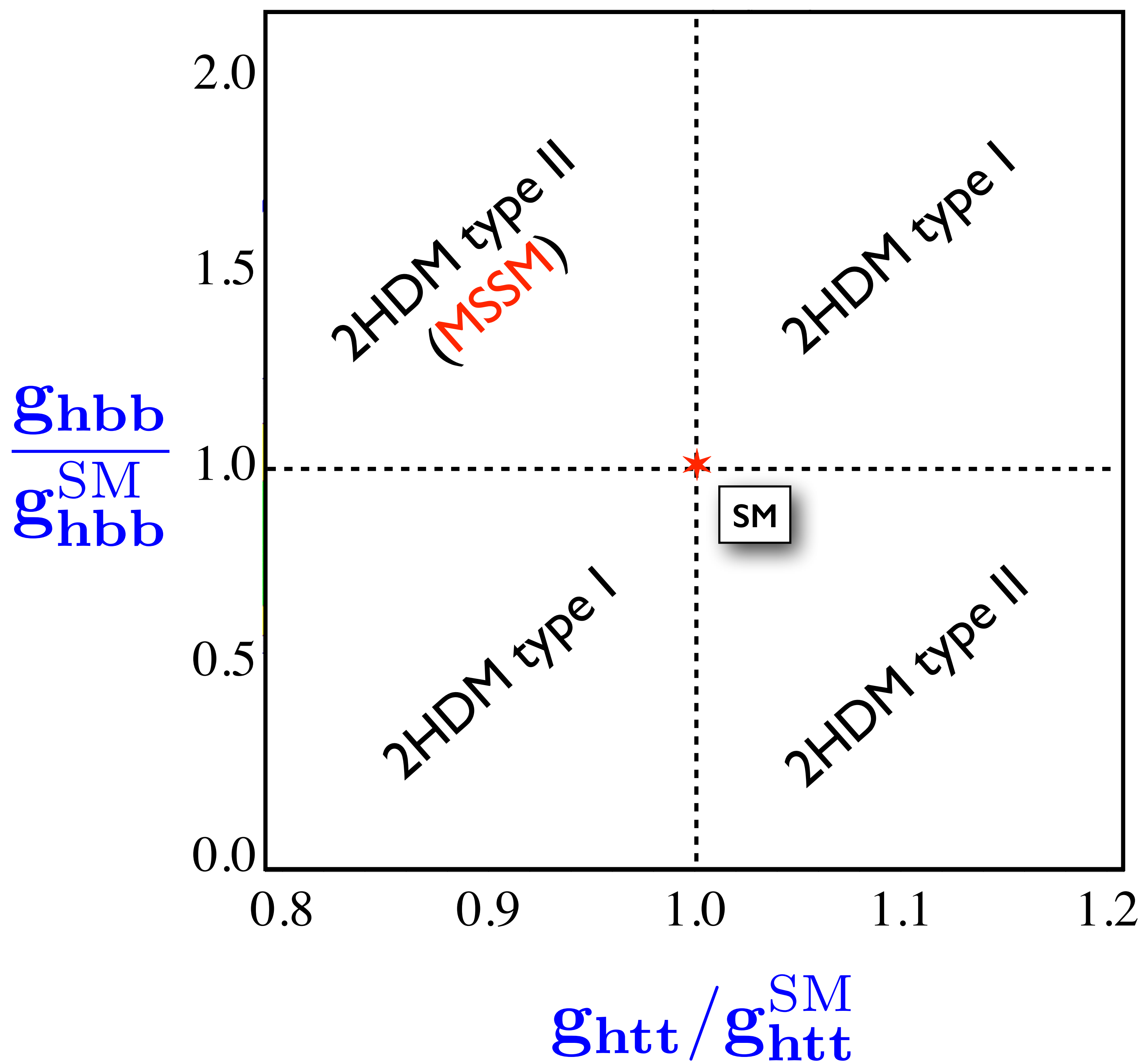
Dominant effect!

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

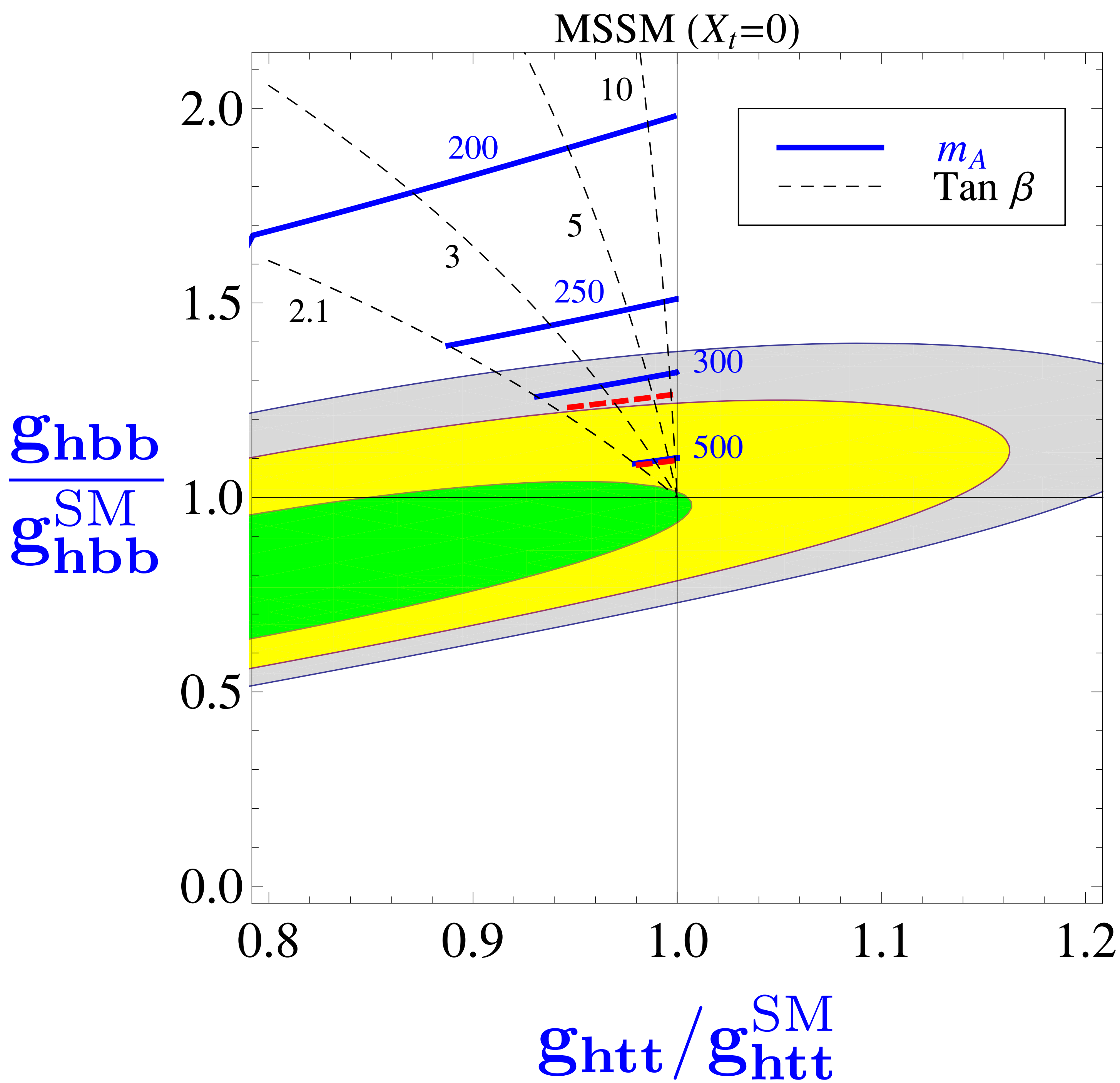
Relevant plane for susy Higgs couplings:



Relevant plane for susy Higgs couplings:



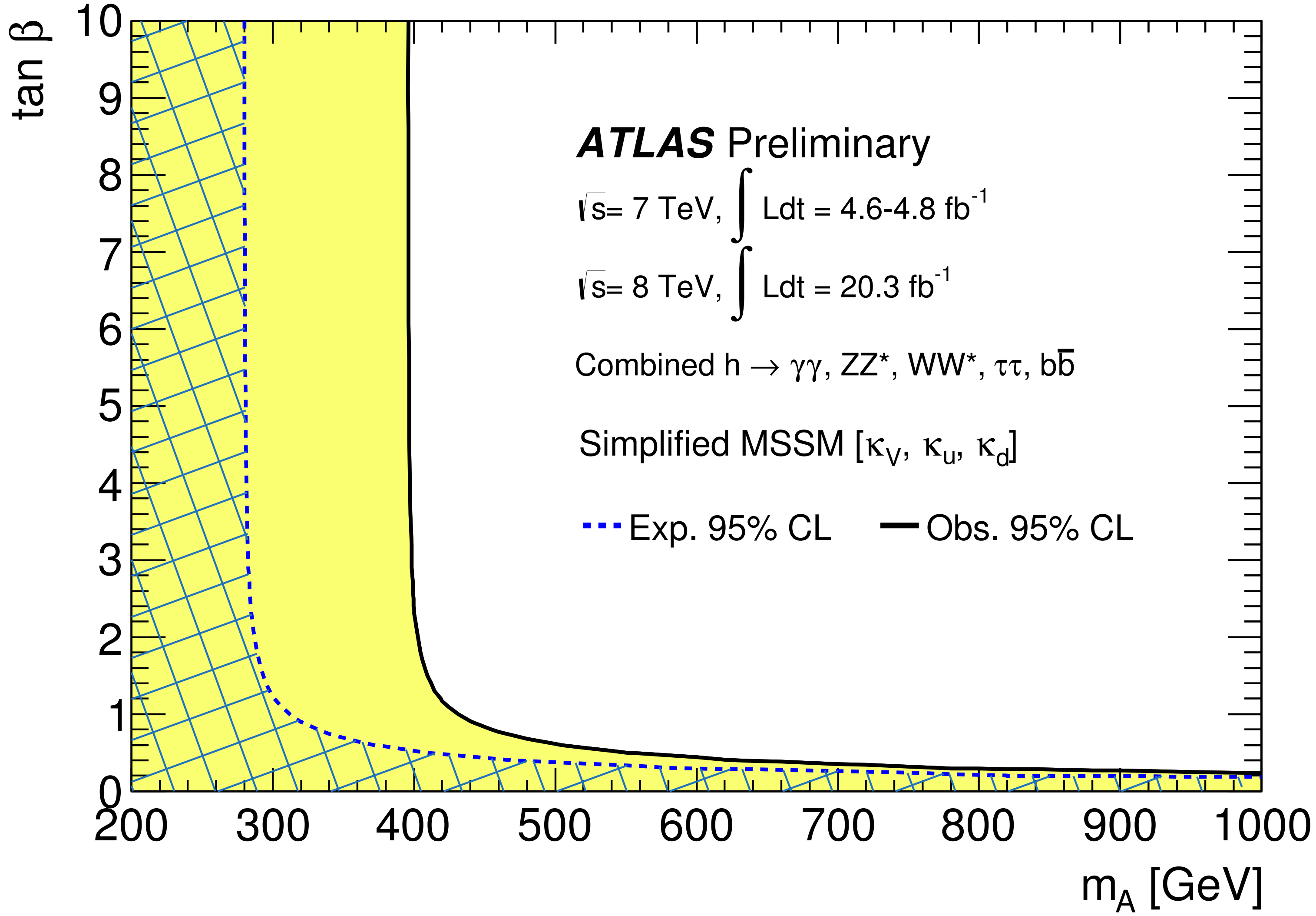
Relevant plane for susy Higgs couplings:



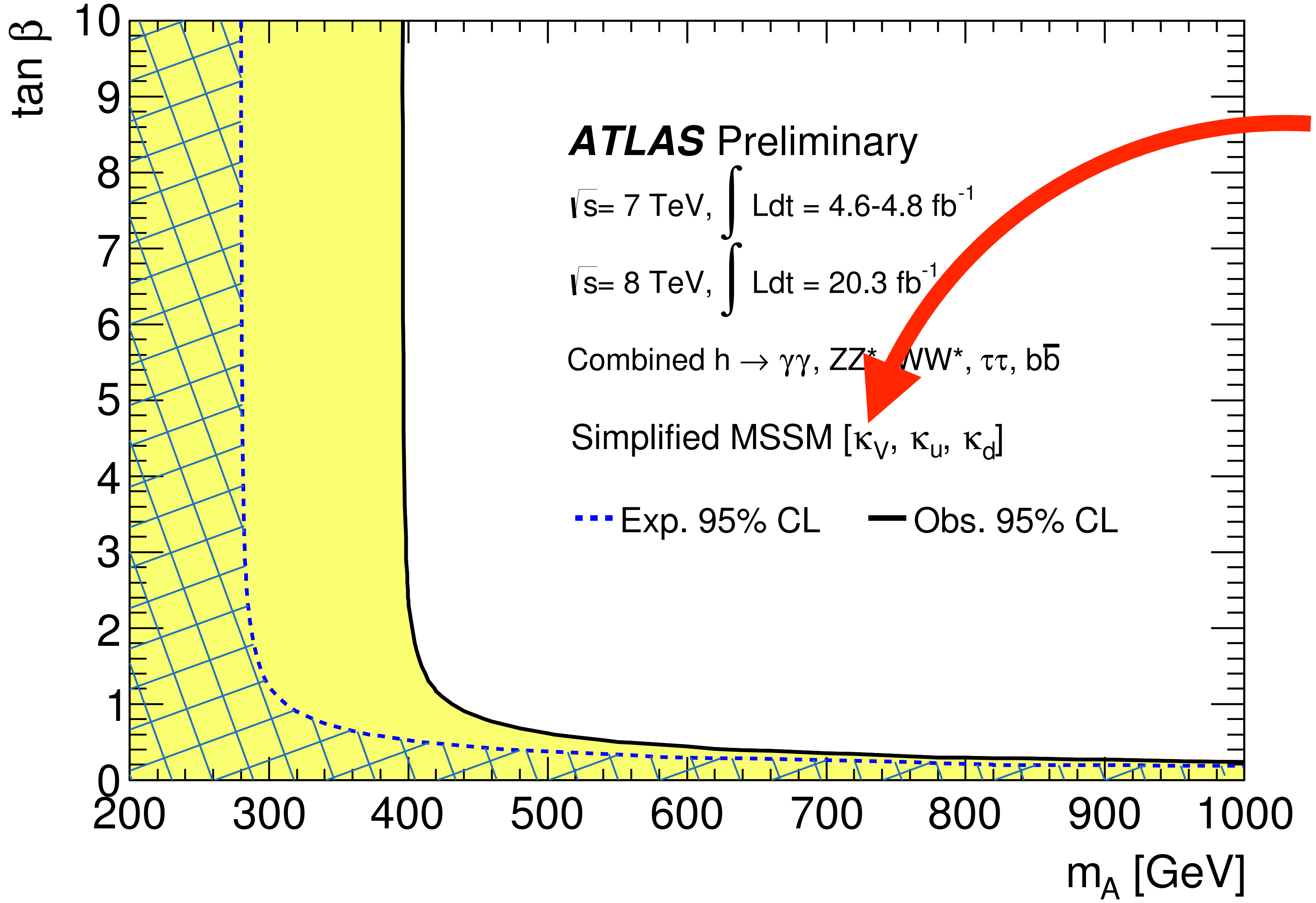
from arXiv:1212.524

(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 scenarios

Composite PGB Higgs couplings

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

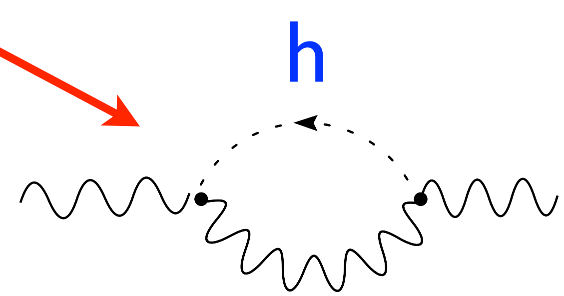
Giudice,Grojean,AP,Rattazzi 07
AP,Riva 12

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

f = Decay-constant of the PGB Higgs

(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

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

f = Decay-constant of the PGB Higgs

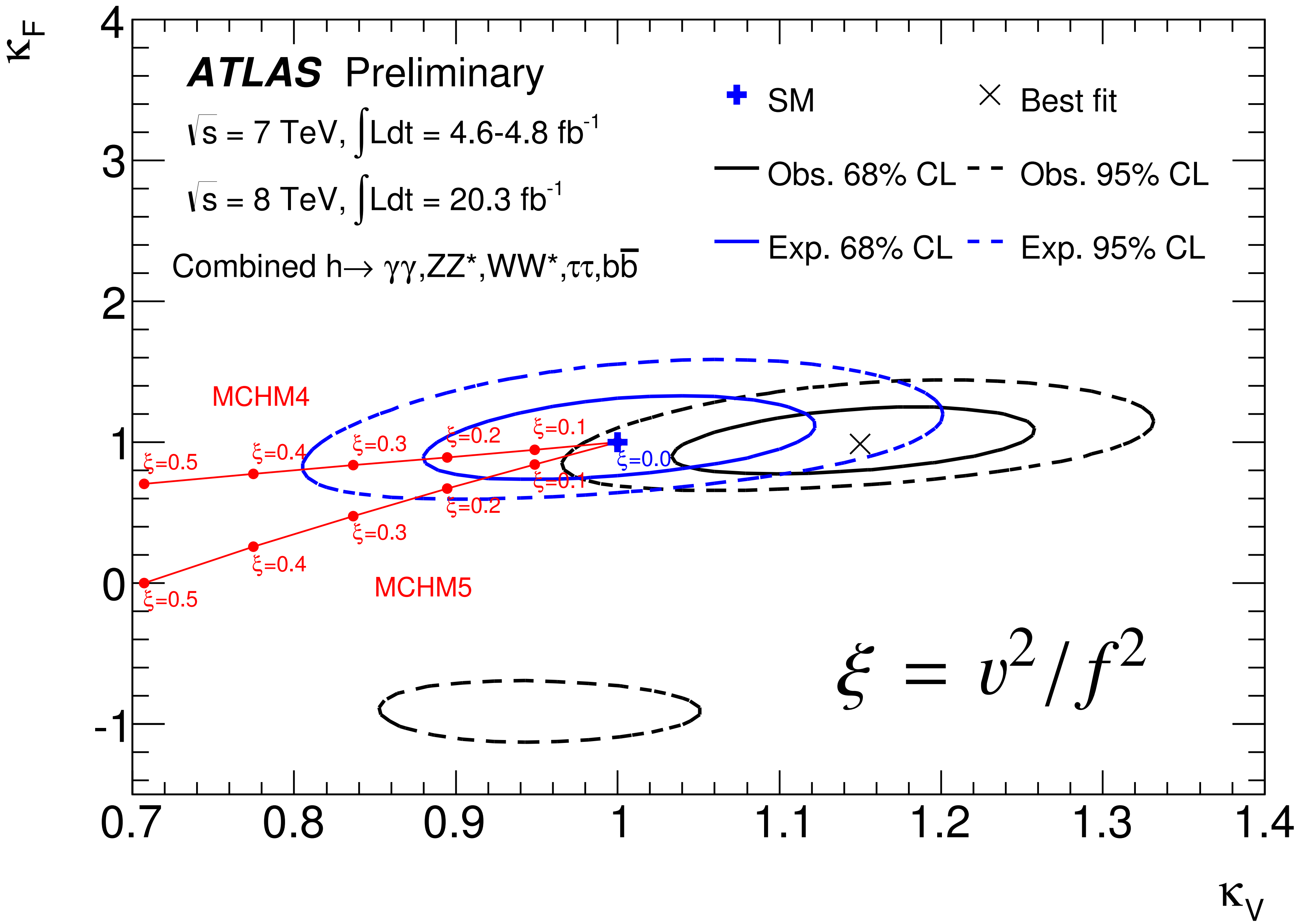
(model dependent but expected f ~ v)

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

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

MCHM4 MCHM5

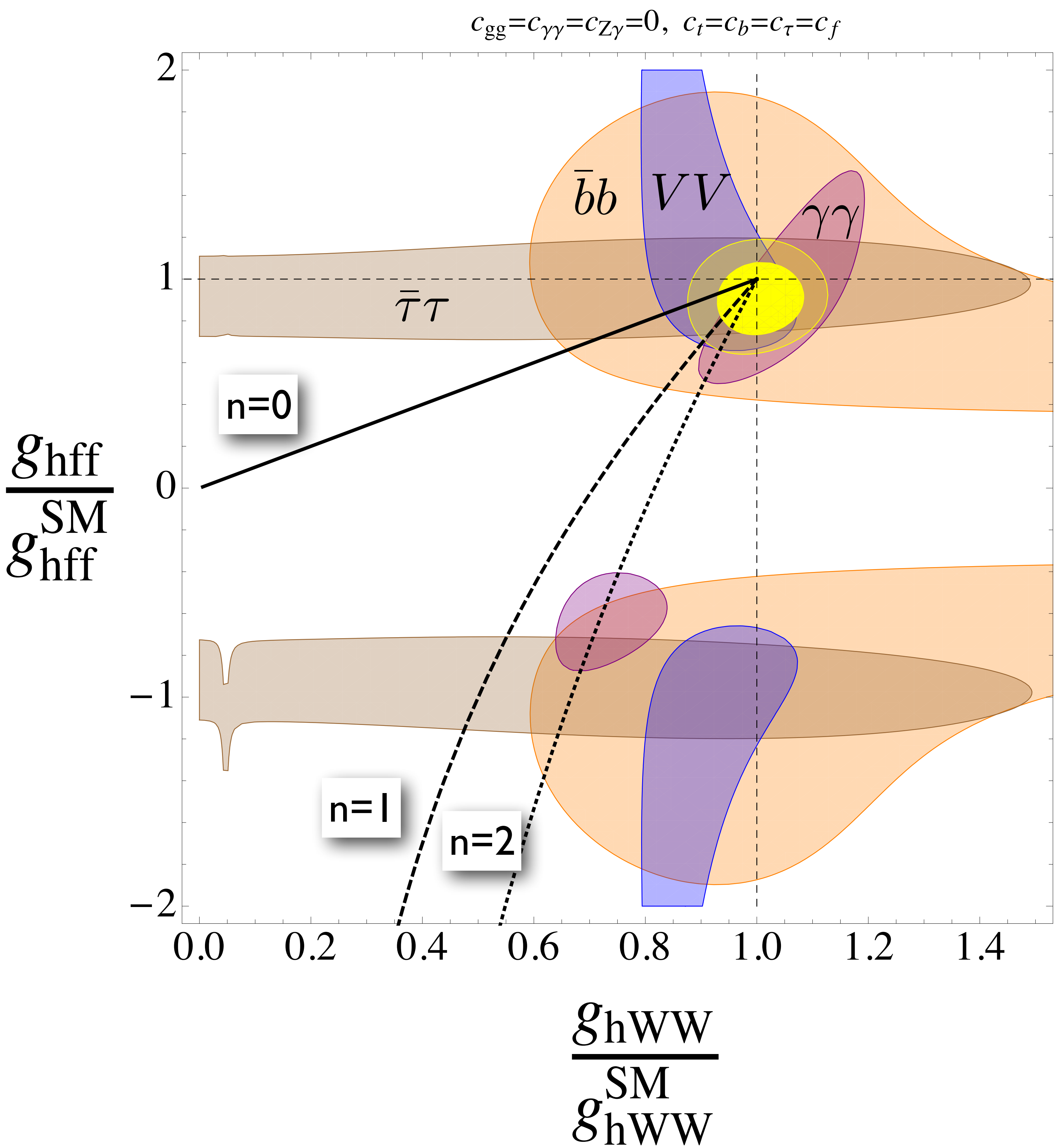
small deviations on the h$\gamma\gamma$(gg)-coupling due to the Goldstone nature of the Higgs



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

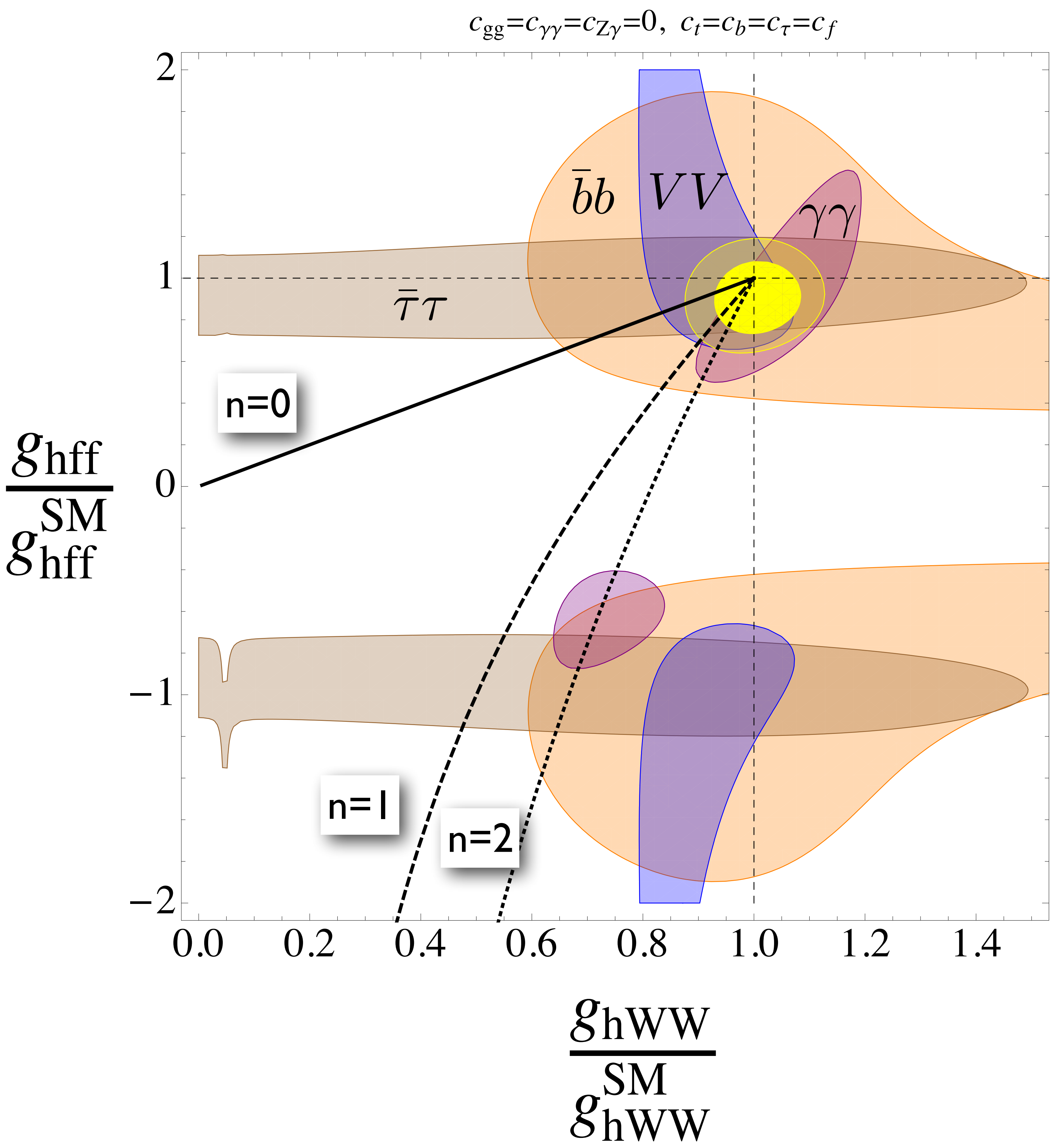
$\xi < 0.15$ (0.20) **MCHM5**

ATLAS+CMS:



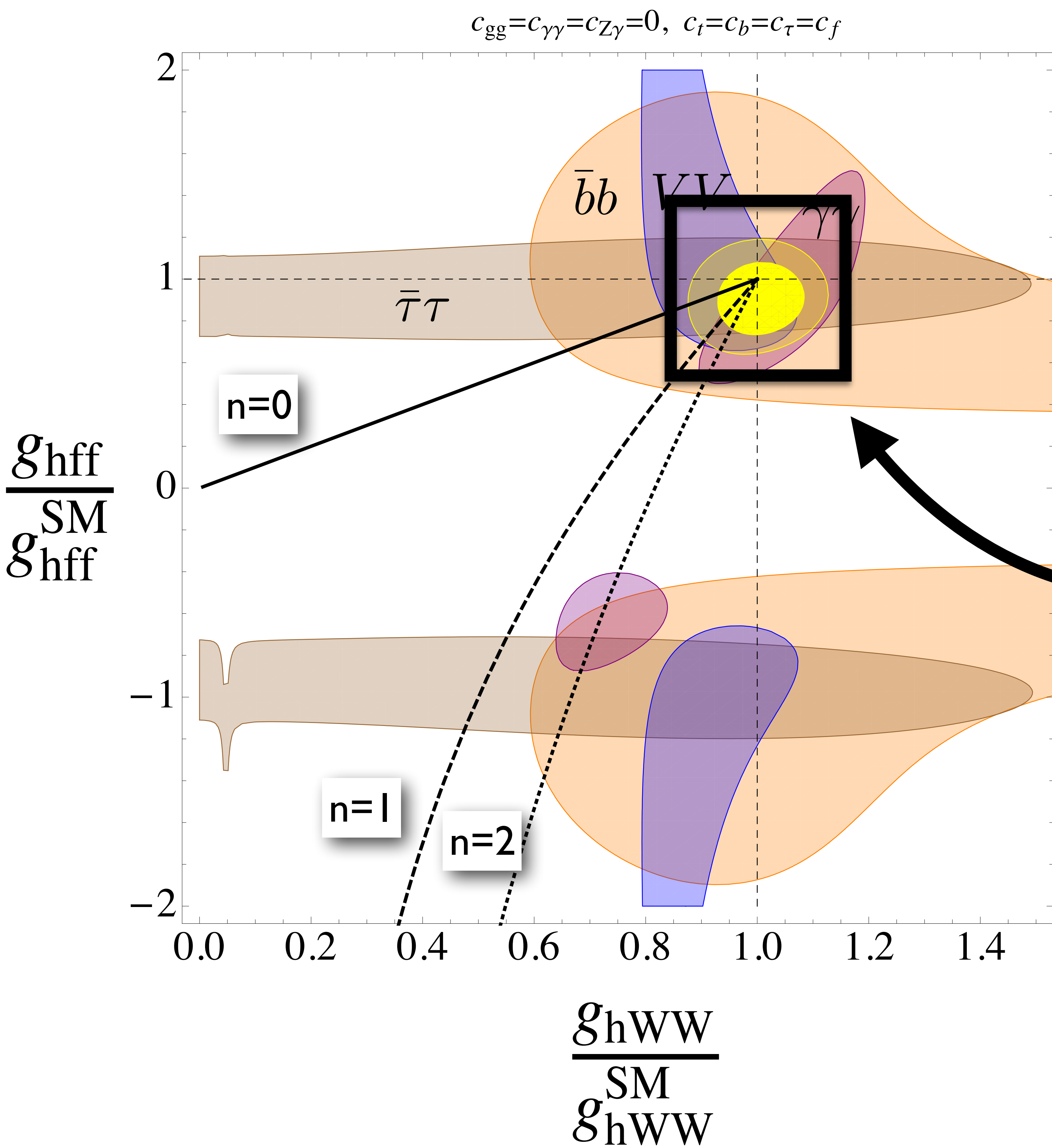
arXiv:1303.1812

ATLAS+CMS:



arXiv:1303.1812

ATLAS+CMS:



arXiv:1303.1812

getting into the interesting region

Model independent analysis

An organizing principle of possible SM deviations is needed
to know what we know and what we should know (measure!)

Parametrization of BSM effects in Higgs physics

Assuming a large new-physics scale, $\Lambda >> m_W$:

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

NP scale

dim=6

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

give the deviations
to SM Higgs physics from BSM

➥ effective theory for Higgs physics

➥ approach valid for all BSM with heavy particles !

$$\mathcal{L}_6$$ = dimension-six operators

$$\mathcal{O}_H = \tfrac{1}{2}(\partial^\mu |H|^2)^2$$
$$\mathcal{O}_T = \tfrac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
$$\mathcal{O}_6 = \lambda |H|^6$$

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$
$$\mathcal{O}_{2W} = -\tfrac{1}{2}(D^\mu W^a_{\mu\nu})^2$$
$$\mathcal{O}_{2B} = -\tfrac{1}{2}(\partial^\mu B_{\mu\nu})^2$$
$$\mathcal{O}_{2G} = -\tfrac{1}{2}(D^\mu G^A_{\mu\nu})^2$$

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu}G^{A\mu\nu}$$
$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$\mathcal{O}_{3W} = \tfrac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$$
$$\mathcal{O}_{3G} = \tfrac{1}{3!} g_s f_{ABC} G^{A\,\nu}_\mu G^B_{\nu\rho} G^{C\,\rho\mu}$$

$\mathcal{O}_{y_u} = y_u |H|^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d |H|^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e |H|^2 \bar{L}_L H e_R$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$ $\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$ $\mathcal{O}^{(3)\,q}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu \sigma^a Q_L)$	$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$ $\mathcal{O}^l_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu L_L)$ $\mathcal{O}^{(3)\,l}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu \sigma^a L_L)$
$\mathcal{O}^u_{LR} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{u}_R\gamma^\mu u_R)$ $\mathcal{O}^{(8)\,u}_{LR} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{u}_R\gamma^\mu T^A u_R)$ $\mathcal{O}^u_{RR} = (\bar{u}_R\gamma^\mu u_R)(\bar{u}_R\gamma^\mu u_R)$ $\mathcal{O}^q_{LL} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{Q}_L\gamma^\mu Q_L)$ $\mathcal{O}^{(8)\,q}_{LL} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{Q}_L\gamma^\mu T^A Q_L)$	$\mathcal{O}^d_{LR} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{d}_R\gamma^\mu d_R)$ $\mathcal{O}^{(8)\,d}_{LR} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{d}_R\gamma^\mu T^A d_R)$ $\mathcal{O}^d_{RR} = (\bar{d}_R\gamma^\mu d_R)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}^e_{LR} = (\bar{L}_L\gamma^\mu L_L)(\bar{e}_R\gamma^\mu e_R)$ $\mathcal{O}^e_{RR} = (\bar{e}_R\gamma^\mu e_R)(\bar{e}_R\gamma^\mu e_R)$ $\mathcal{O}^l_{LL} = (\bar{L}_L\gamma^\mu L_L)(\bar{L}_L\gamma^\mu L_L)$
$\mathcal{O}^{ql}_{LL} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{L}_L\gamma^\mu L_L)$ $\mathcal{O}^{(3)\,ql}_{LL} = (\bar{Q}_L\gamma^\mu \sigma^a Q_L)(\bar{L}_L\gamma^\mu \sigma^a L_L)$ $\mathcal{O}^{qe}_{LR} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{e}_R\gamma^\mu e_R)$ $\mathcal{O}^{lu}_{LR} = (\bar{L}_L\gamma^\mu L_L)(\bar{u}_R\gamma^\mu u_R)$ $\mathcal{O}^{ud}_{RR} = (\bar{u}_R\gamma^\mu u_R)(\bar{d}_R\gamma^\mu d_R)$ $\mathcal{O}^{(8)\,ud}_{RR} = (\bar{u}_R\gamma^\mu T^A u_R)(\bar{d}_R\gamma^\mu T^A d_R)$ $\mathcal{O}^{ue}_{RR} = (\bar{u}_R\gamma^\mu u_R)(\bar{e}_R\gamma^\mu e_R)$	$\mathcal{O}^{ld}_{LR} = (\bar{L}_L\gamma^\mu L_L)(\bar{d}_R\gamma^\mu d_R)$ $\mathcal{O}^{de}_{RR} = (\bar{d}_R\gamma^\mu d_R)(\bar{e}_R\gamma^\mu e_R)$	
$\mathcal{O}^{ud}_R = y_u^\dagger y_d (i\widetilde{H}^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu d_R)$		
$\mathcal{O}_{y_u y_d} = y_u y_d (\bar{Q}^r_L u_R)\epsilon_{rs}(\bar{Q}^s_L d_R)$ $\mathcal{O}^{(8)}_{y_u y_d} = y_u y_d (\bar{Q}^r_L T^A u_R)\epsilon_{rs}(\bar{Q}^s_L T^A d_R)$ $\mathcal{O}_{y_u y_e} = y_u y_e (\bar{Q}^r_L u_R)\epsilon_{rs}(\bar{L}^s_L e_R)$ $\mathcal{O}'_{y_u y_e} = y_u y_e (\bar{Q}^{r\,\alpha}_L e_R)\epsilon_{rs}(\bar{L}^s_L u^\alpha_R)$ $\mathcal{O}_{y_e y_d} = y_e y_d^\dagger (\bar{L}_L e_R)(\bar{d}_R Q_L)$		
$\mathcal{O}^u_{DB} = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \widetilde{H} g' B_{\mu\nu}$ $\mathcal{O}^u_{DW} = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \sigma^a \widetilde{H} g W^a_{\mu\nu}$ $\mathcal{O}^u_{DG} = y_u \bar{Q}_L \sigma^{\mu\nu} T^A u_R \widetilde{H} g_s G^A_{\mu\nu}$	$\mathcal{O}^d_{DB} = y_d \bar{Q}_L \sigma^{\mu\nu} d_R H g' B_{\mu\nu}$ $\mathcal{O}^d_{DW} = y_d \bar{Q}_L \sigma^{\mu\nu} d_R \sigma^a H g W^a_{\mu\nu}$ $\mathcal{O}^d_{DG} = y_d \bar{Q}_L \sigma^{\mu\nu} T^A d_R H g_s G^A_{\mu\nu}$	$\mathcal{O}^e_{DB} = y_e \bar{L}_L \sigma^{\mu\nu} e_R H g' B_{\mu\nu}$ $\mathcal{O}^e_{DW} = y_e \bar{L}_L \sigma^{\mu\nu} e_R \sigma^a H g W^a_{\mu\nu}$

Too many new terms to say something?

arXiv:1308.2803
arXiv:1405.0181

BSM primary <u>physical</u> Higgs effects !

+ correlations between observables

assuming flavor-symmetries

(see also arXiv:1406.6376)

➡ Not <u>all type</u> of deviations from SM can arise from $\mathcal{L}_6$!

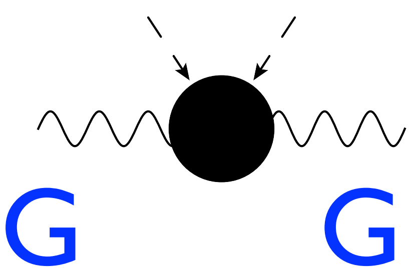
☛ There are plenty of correlations among possible observables

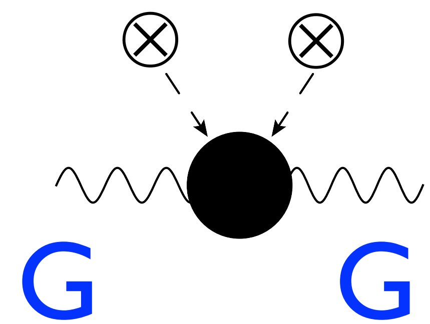
I. Primary Higgs couplings

Higgs couplings affected by BSM but **not** affecting (at tree-level) other SM observables

Effects that on the vacuum, **H = v**, give only a redefinition of the SM couplings:

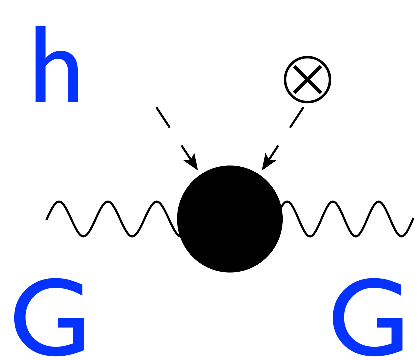
e.g.
$$\frac{1}{g_s^2}G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2}G_{\mu\nu}^2 \to \left(\frac{1}{g_s^2}+\frac{v^2}{\Lambda^2}\right)G_{\mu\nu}^2$$





Not physical!

But can affect h physics:



affects GG →h!

How many of these effects can we have?

As many as parameters in the SM: **8** for one family

(assuming CP-conservation)

How many of these effects can we have?

As many as parameters in the SM: **8** for one family

(assuming CP-conservation)

$\mathbf{g_s}$

$\mathbf{g}$

$\mathbf{g'}$

$\mathbf{m_W}$

$\mathbf{m_h}$

$\mathbf{m_f}$

(f=t,b,τ)

How many of these effects can we have?

As many as parameters in the SM: 8

for one family

(assuming CP-conservation)

$\mathbf{g_s}$	$\lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$
$\mathbf{g}$	$\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$
$\mathbf{g'}$	$\lvert H\rvert^2 W^a_{\mu\nu} W^{\mu\nu\, a}$
$\mathbf{m_W}$	$\lvert H\rvert^2 \lvert D_\mu H\rvert^2$
$\mathbf{m_h}$	$\lvert H\rvert^6$
$\mathbf{m_f}$ (f=t,b,τ)	$\lvert H\rvert^2 \bar{f}_L H f_R + h.c.$

How many of these effects can we have?

As many as parameters in the SM: 8

for one family

(assuming CP-conservation)

g_s	$\|H\|^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\longrightarrow$	GGh coupling
g	$\|H\|^2 B_{\mu\nu} B^{\mu\nu}$	$\longrightarrow$	hγγ coupling
g'	$\|H\|^2 W^a_{\mu\nu} W^{\mu\nu\, a}$	$\longrightarrow$	hZγ coupling
m_W	$\|H\|^2 \|D_\mu H\|^2$	$\longrightarrow$	hVV* (custodial invariant)
m_h	$\|H\|^6$	$\longrightarrow$	h^3 coupling
m_f (f=t,b,τ)	$\|H\|^2 \bar{f}_L H f_R + h.c.$	$\longrightarrow$	htt, hbb, h$\tau\tau$

8 BSM primary effects in Higgs physics

(assuming CP-conservation)

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

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

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

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

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

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

JHEP 1311 (2013) 066

8 BSM primary effects in Higgs physics

(assuming CP-conservation)

$$
\begin{aligned}
\Delta\mathcal{L}_{\rm BSM} = \quad & \boxed{\delta g_{hff}}\, h\bar{f}_L f_R + h.c. \\
&+ \boxed{g_{hVV}}\, h\left[W^{+\,\mu}W^-_\mu + \frac{1}{2\cos^2\theta_W} Z^\mu Z_\mu\right] \\
&+ \boxed{\kappa_{GG}}\, \frac{h}{v} G^{\mu\nu}G_{\mu\nu} \\
&+ \boxed{\kappa_{\gamma\gamma}}\, \frac{h}{v} F^{\gamma\,\mu\nu}F^{\gamma}_{\mu\nu} \\
&+ \boxed{\kappa_{\gamma Z}}\, \frac{h}{v} F^{\gamma\,\mu\nu}F^{Z}_{\mu\nu} \\
&+ \boxed{\delta g_{3h}}\, h^3
\end{aligned}
$$

(f=b, τ, t)

important:
custodial invariant!!

JHEP 1311 (2013) 066

8 BSM primary effects in Higgs physics

(assuming CP-conservation)

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

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

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

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

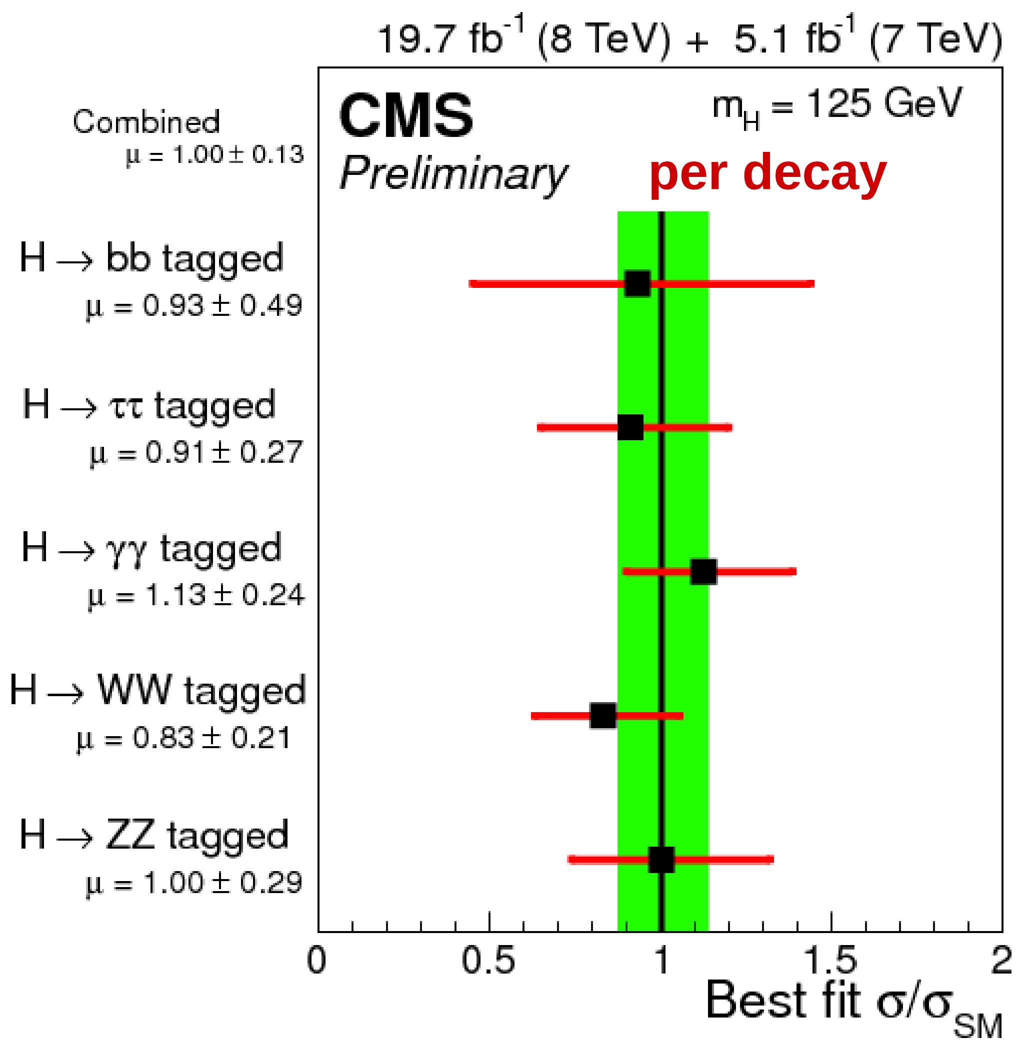
$$+\, \kappa_{\gamma Z}\frac{h}{v}F^{\gamma\,\mu\nu}F^Z_{\mu\nu}$$

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

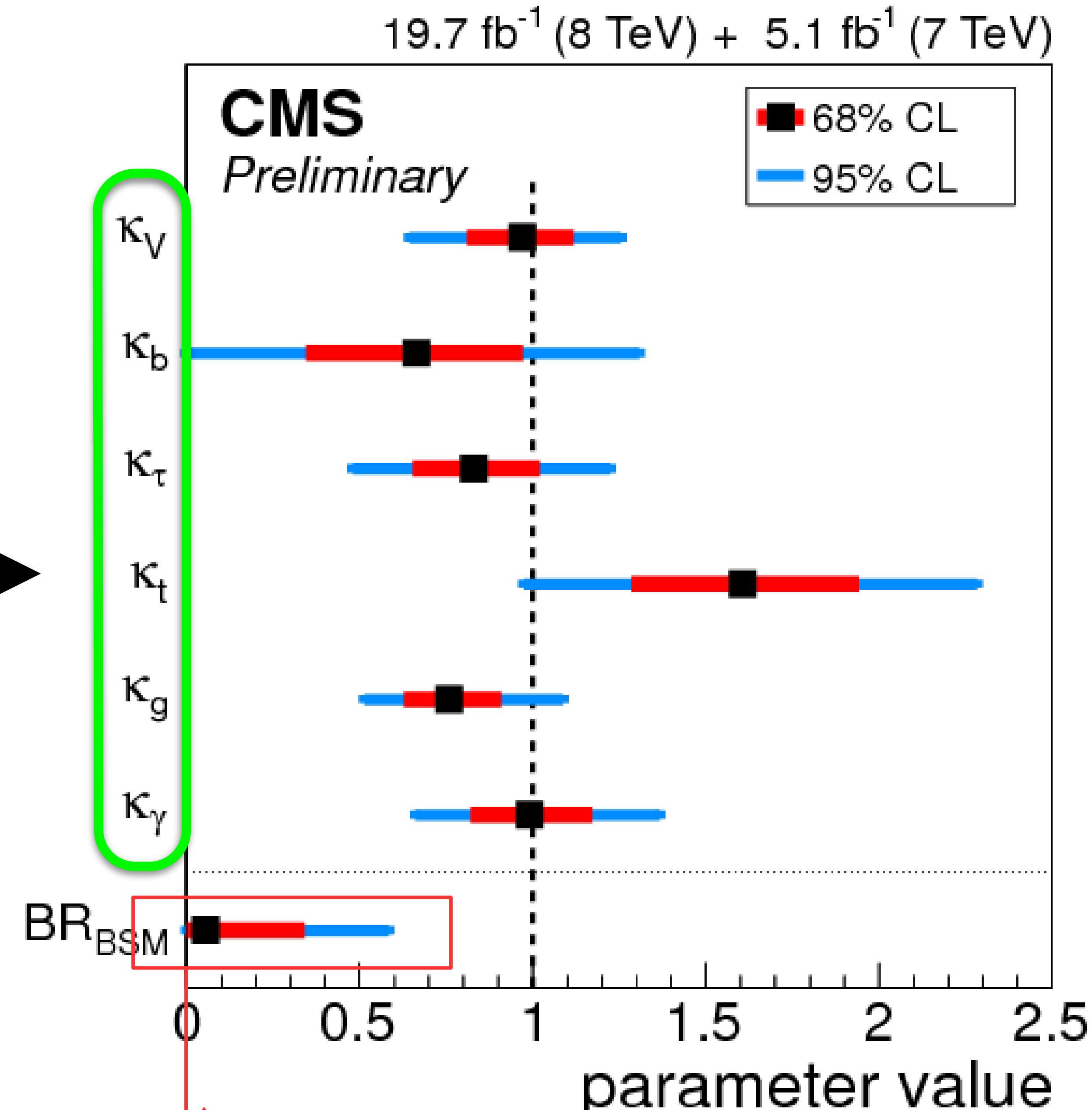
6 measured at the LHC

JHEP 1311 (2013) 066

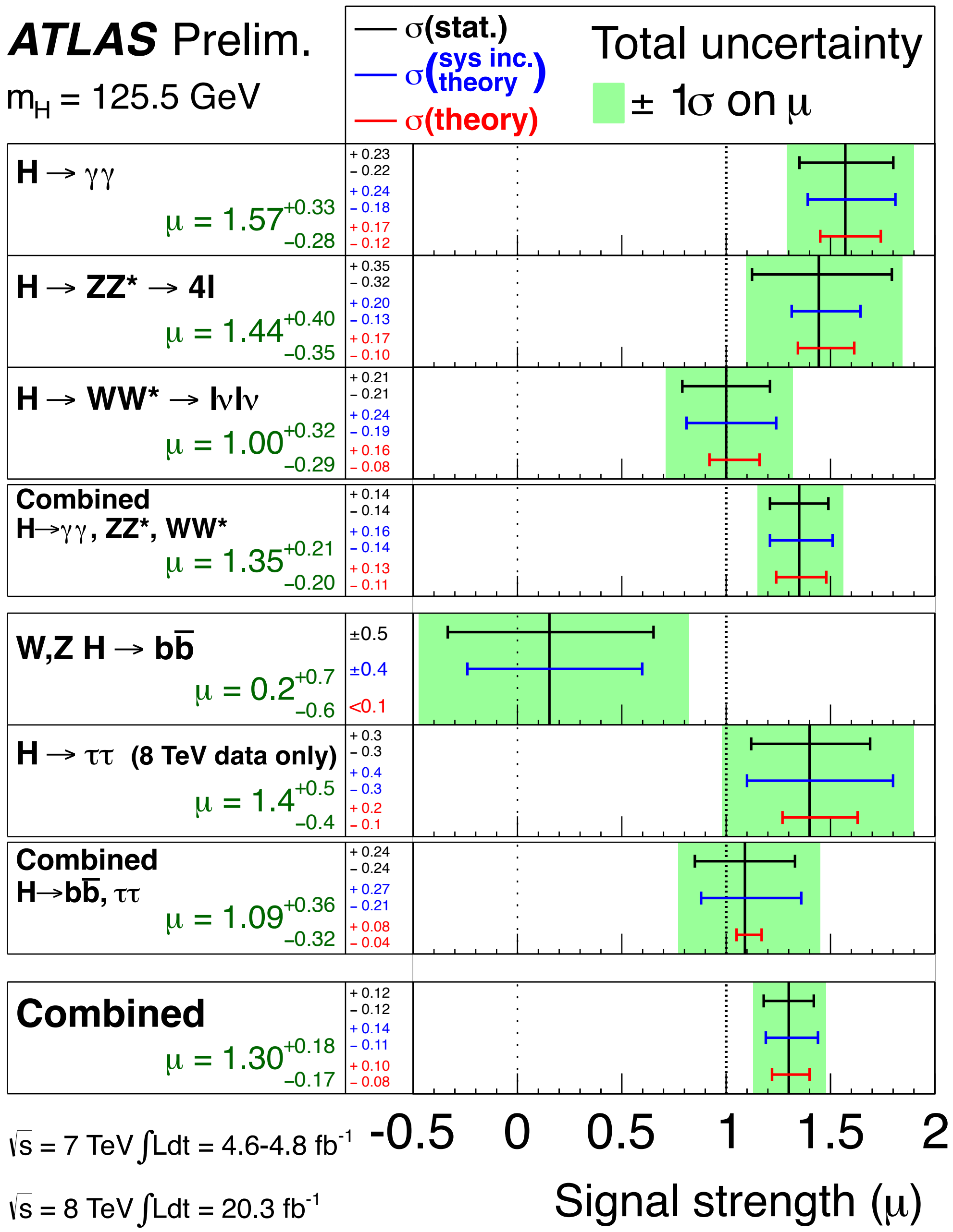
Higgs coupling determination



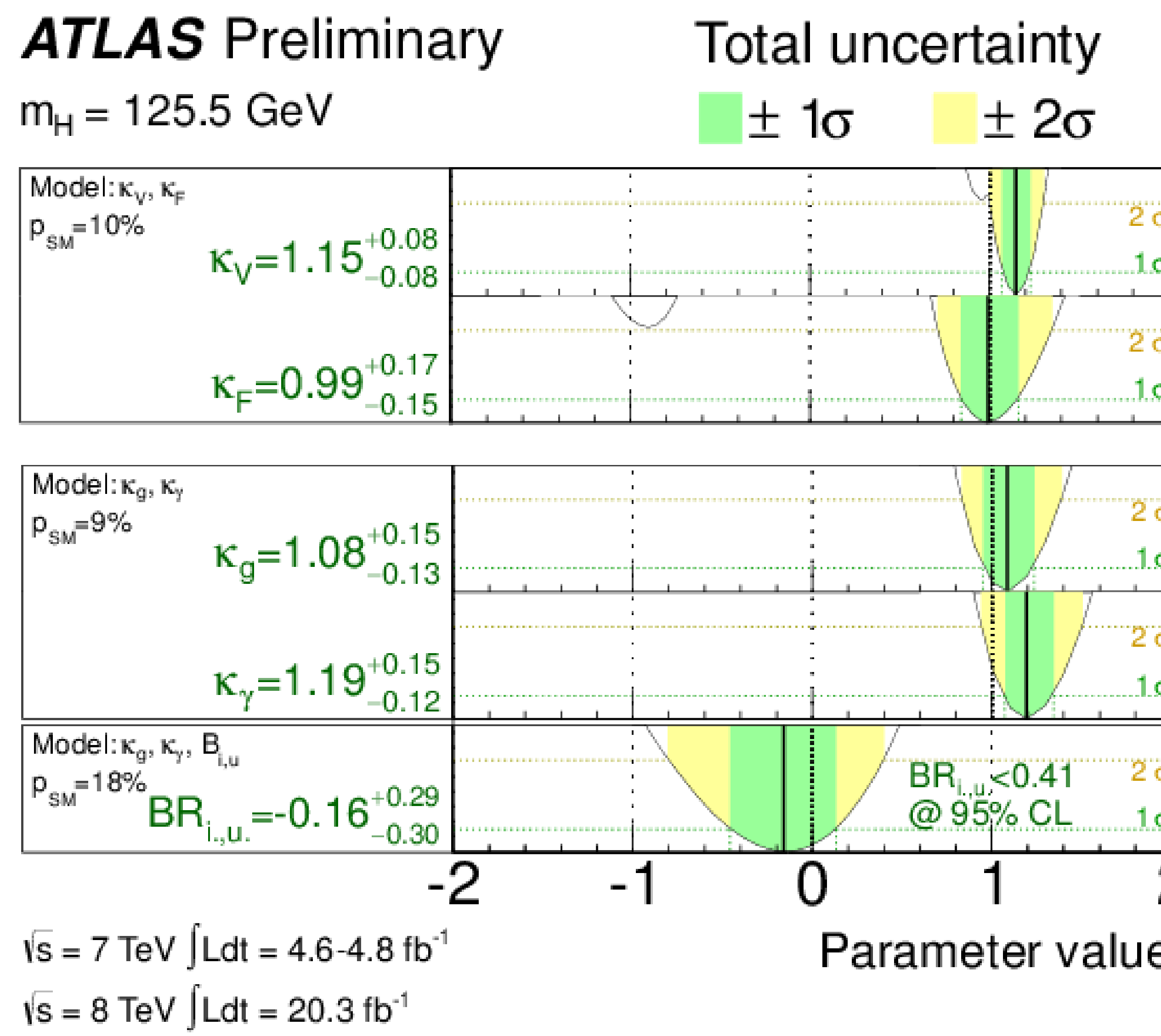
$$\kappa_i = \frac{g_{hii}}{g_{hii}^{\mathrm{SM}}}$$



All parameters floating and $\kappa_V \leq 1$



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



6-parameter fit not found!

8 BSM primary effects in Higgs physics

(assuming CP-conservation)

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

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

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

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

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

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

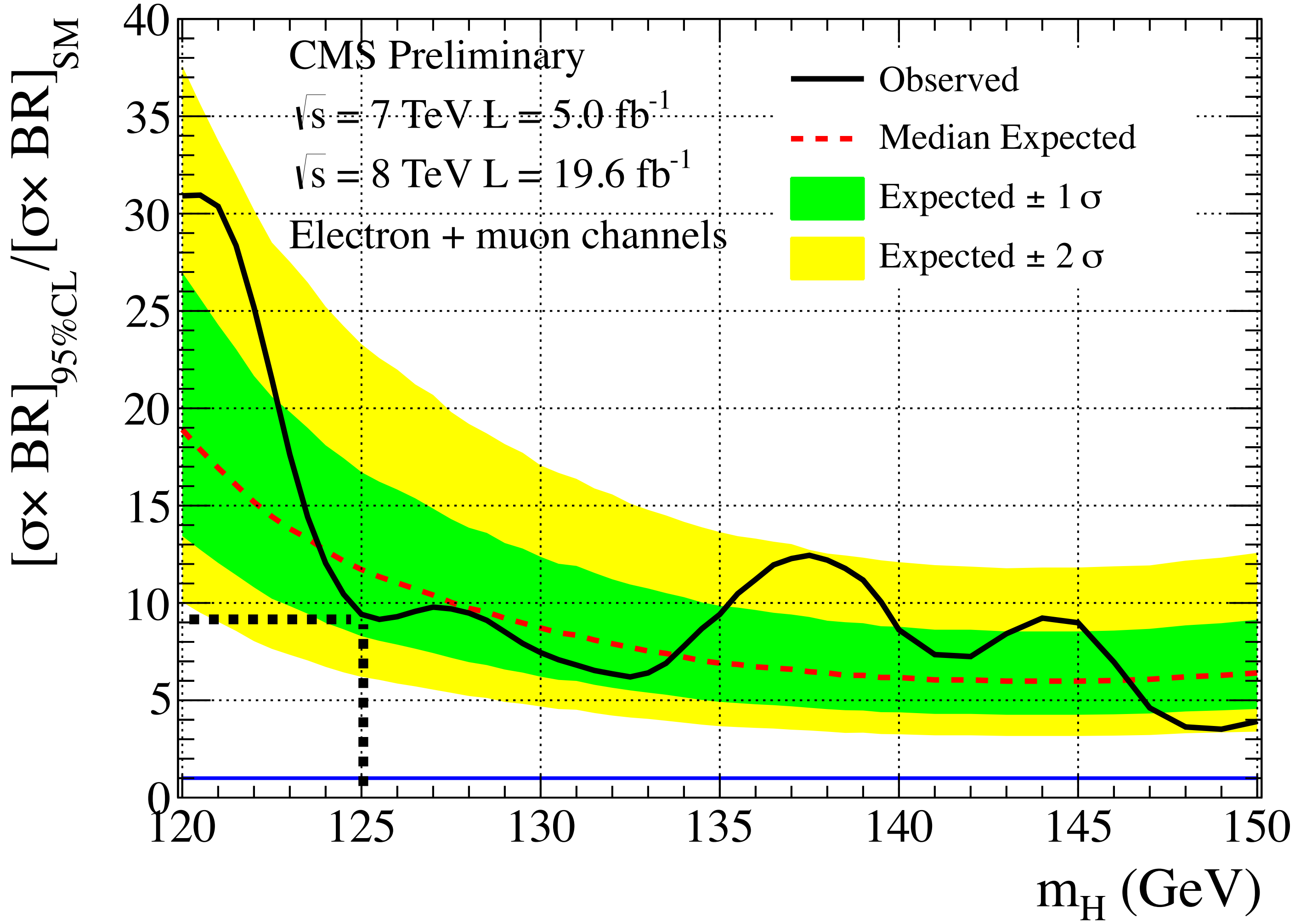
6 measured at the LHC

$h \to Z\gamma$

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

JHEP 1311 (2013) 066

Experimental bound on h→Zγ (10 x the SM)



small in the SM since it comes at one-loop

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

(possibility in composite Higgs models)

Message:

Even today, it would be very good to provide the full **<u>8-parameter</u>** fit using all data!

well motivated theoretically,

as cover all BSM (with heavy spectrum)

CP-violating Higgs couplings

6 BSM primary effects:

$$
\begin{aligned}
\Delta\mathcal{L}_{\rm BSM} = \ & \boxed{i\delta\tilde{g}_{hff}}\, h\bar{f}_L f_R + h.c. \\
& + \boxed{\tilde{\kappa}_{GG}}\frac{h}{v} G^{\mu\nu}\tilde{G}_{\mu\nu} \\
& + \boxed{\tilde{\kappa}_{\gamma\gamma}}\frac{h}{v} F^{\gamma\,\mu\nu}\tilde{F}^{\gamma}_{\mu\nu} \\
& + \boxed{\tilde{\kappa}_{\gamma Z}}\frac{h}{v} F^{\gamma\,\mu\nu}\tilde{F}^{Z}_{\mu\nu}
\end{aligned}
$$

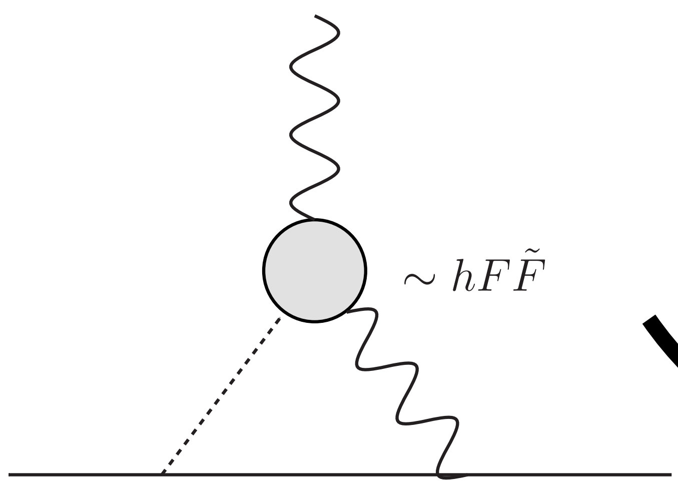
(f=b, τ, t)

($\tilde{F}_{\mu\nu} \equiv \epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$)

CP-violating Higgs couplings

Constrained indirectly: one-loop impact on Electric Dipole Moments (EDM): e.g. $\mathbf{d_e < 8.7\ 10^{-29}}$ ***e cm*** (ACME 13)

too strong to compete!



McKeen,Pospelov,Ritz 12

$\tilde{\kappa}_{\gamma\gamma} \lesssim 10^{-5}$

and similarly for $\tilde{\kappa}_{\gamma Z}$ (using also $d_{u,d}$)

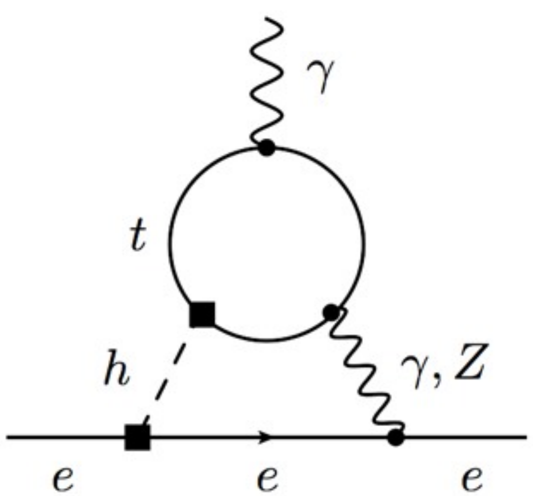
CP-violating Higgs couplings

Constrained indirectly: one-loop impact on Electric Dipole Moments (EDM):

e.g. $\mathbf{d_e < 8.7\ 10^{-29}}$ ***e cm*** (ACME 13)

too strong to compete!

$\delta\tilde{g}_{htt} \lesssim 0.01$



Brod,Haisch,Zupan 13

CP-violating Higgs couplings

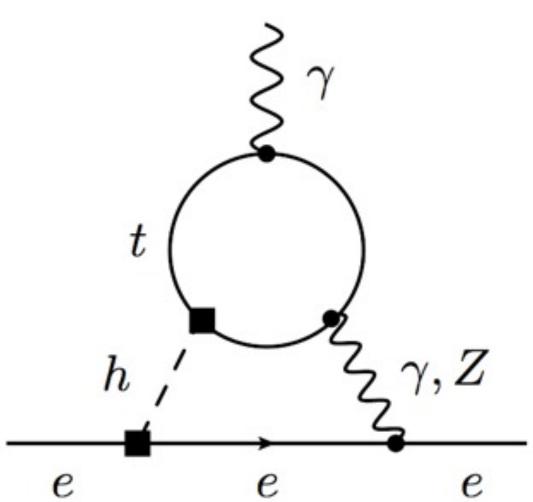
Constrained indirectly: one-loop impact on Electric Dipole Moments (EDM):

e.g. $\mathbf{d_e < 8.7\ 10^{-29}}$ $\boldsymbol{e\,cm}$ (ACME 13)

too strong to compete!

$\delta\tilde{g}_{htt} \lesssim 0.01$

☛ Small effect expected in Higgs physics (HL-LHC needed)



Brod,Haisch,Zupan 13

But weak bounds on CP-violating $h\tau\tau$ couplings:

Can we measure CPV in $h \rightarrow \tau\tau$?

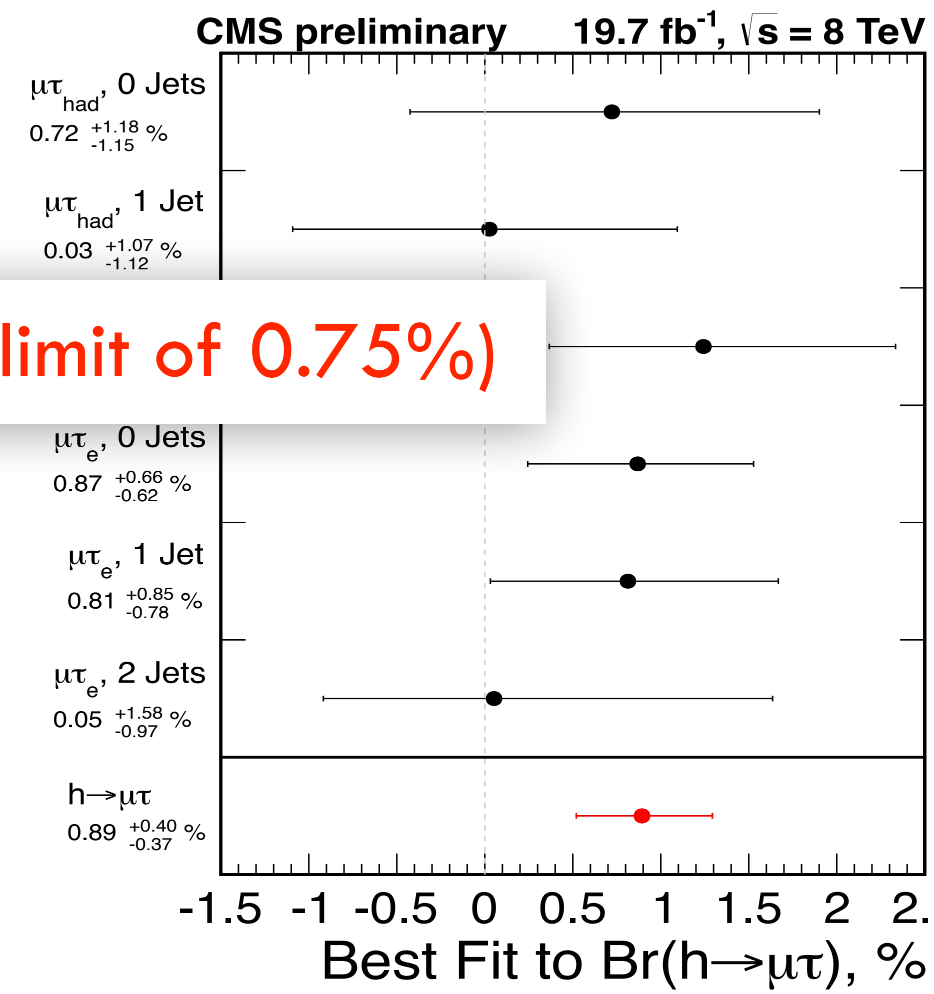
Flavor violating Higgs couplings: $h \to f_1 f_2$

Interesting region for $h \to \tau\mu$:

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

getting there (CMS):

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



2. Beyond the primary Higgs couplings

2. Beyond the primary Higgs couplings

$$h Z^{\mu} Z_{\mu}\,,\ \ \underbrace{h Z^{\mu\nu} Z_{\mu\nu}\,,\ h W^{\mu\nu} W_{\mu\nu}}_{\text{momentum-dependent hVV couplings}}\,,\ \ \underbrace{h Z^{\mu} f \gamma_{\mu} f\,,\ \ h W^{\mu} f \gamma_{\mu} f}_{\text{contact interactions}}\ ,\ldots$$

custodial breaking hVV

2. Beyond the primary Higgs couplings

$$hZ^{\mu}Z_{\mu}\,,\;\; hZ^{\mu\nu}Z_{\mu\nu}\,,\; hW^{\mu\nu}W_{\mu\nu}\,,\;\; hZ^{\mu} f\gamma_{\mu}f\,,\;\; hW^{\mu} f\gamma_{\mu}f\;,\dots$$

custodial breaking hVV

momentum-dependent
hVV couplings

contact interactions

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

2. Beyond the primary Higgs couplings

$$hZ^{\mu}Z_{\mu}\,,\;\; hZ^{\mu\nu}Z_{\mu\nu}\,,\; hW^{\mu\nu}W_{\mu\nu}\,,\;\; hZ^{\mu}f\gamma_{\mu}f\,,\;\; hW^{\mu}f\gamma_{\mu}f\;,\ldots$$

custodial breaking hVV

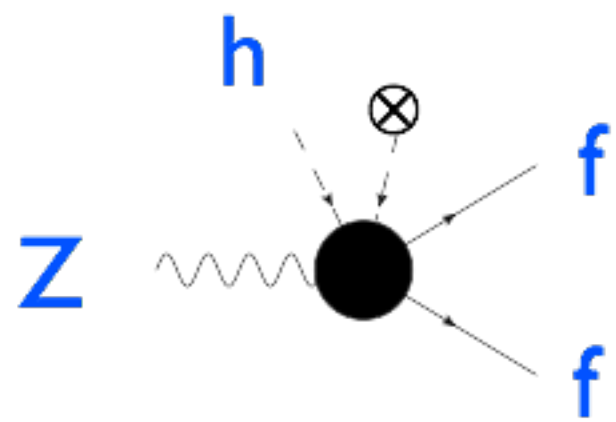
momentum-dependent
hVV couplings

contact interactions

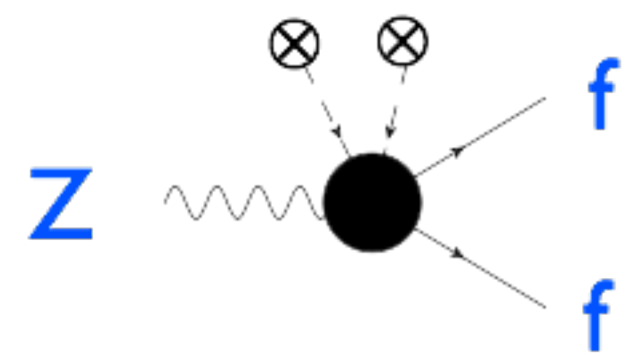
but beaten paths…
(not independent from other couplings already tested)

Deviations in these couplings are related to deviations in other SM couplings (not seen at present)

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!

Explicit correlations between hZff and Zff:

arXiv:1405.0181
arXiv:1406.6376

$$\Delta\mathcal{L}_{qq}^{V} = \boldsymbol{\delta g^{Z}_{uR}}\frac{\hat{h}^2}{v^2}Z^\mu \bar{u}_R\gamma_\mu u_R + \boldsymbol{\delta g^{Z}_{dR}}\frac{\hat{h}^2}{v^2}Z^\mu \bar{d}_R\gamma_\mu d_R$$

$$+ \boldsymbol{\delta g^{Z}_{dL}}\frac{\hat{h}^2}{v^2}\left[Z^\mu \bar{d}_L\gamma_\mu d_L - \frac{c_{\theta_W}}{\sqrt{2}}(W^{+\mu}\bar{u}_L\gamma_\mu d_L + \text{h.c.})\right]$$

$$+ \boldsymbol{\delta g^{Z}_{uL}}\frac{\hat{h}^2}{v^2}\left[Z^\mu \bar{u}_L\gamma_\mu u_L + \frac{c_{\theta_W}}{\sqrt{2}}(W^{+\mu}\bar{u_L}\gamma_\mu d_L + \text{h.c.})\right]$$

$$\hat{h} \equiv v + h$$

appear combined in the same operators

$$\Delta\mathcal{L}_{ee}^{V} = \boldsymbol{\delta g^{Z}_{eR}}\frac{\hat{h}^2}{v^2}Z^\mu \bar{e}_R\gamma_\mu e_R$$

$$+ \boldsymbol{\delta g^{Z}_{eL}}\frac{\hat{h}^2}{v^2}\left[Z^\mu \bar{e}_L\gamma_\mu e_L - \frac{c_{\theta_W}}{\sqrt{2}}(W^{+\mu}\bar{\nu_L}\gamma_\mu e_L + \text{h.c.})\right]$$

$$+ \boldsymbol{\delta g^{Z}_{\nu L}}\frac{\hat{h}^2}{v^2}\left[Z^\mu \bar{\nu}_L\gamma_\mu \nu_L + \frac{c_{\theta_W}}{\sqrt{2}}(W^{+\mu}\bar{\nu_L}\gamma_\mu e_L + \text{h.c.})\right]$$

Correlations with the primary Higgs couplings:

arXiv:1405.0181
arXiv:1406.6376

hVV form-factor correlated with hγγ

$$\Delta\mathcal{L}^h_{\gamma\gamma} = \boxed{\kappa_{\gamma\gamma}}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)\left[A_{\mu\nu}A^{\mu\nu}+Z_{\mu\nu}Z^{\mu\nu}+2W^+_{\mu\nu}W^{-\mu\nu}\right]$$

$$\Delta\mathcal{L}^h_{Z\gamma} = \boxed{\kappa_{Z\gamma}}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)\left[t_{\theta_W}A_{\mu\nu}Z^{\mu\nu}+\frac{c_{2\theta_W}}{2c^2_{\theta_W}}Z_{\mu\nu}Z^{\mu\nu}+W^+_{\mu\nu}W^{-\mu\nu}\right]$$

$$\Delta\mathcal{L}^h_{GG} = \boxed{\kappa_{GG}}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)G^A_{\mu\nu}G^{A\,\mu\nu}$$

hVV form-factor correlated with hγZ

$$\Delta\mathcal{L}^h_{ff} = \boxed{\delta g^h_{ff}}\left(h\bar{f}_Lf_R+\text{h.c.}\right)\left(1+\frac{3h}{2v}+\frac{h^2}{2v^2}\right)$$

$$\Delta\mathcal{L}_{3h} = \boxed{\delta g_{3h}}h^3\left(1+\frac{3h}{2v}+\frac{3h^2}{4v^2}+\frac{h^3}{8v^3}\right)$$

$$\Delta\mathcal{L}^h_{VV} = \boxed{\delta g^h_{VV}}\left[h\left(W^{+\mu}W^-_\mu+\frac{Z^\mu Z_\mu}{2c^2_{\theta_W}}\right)+\Delta\right]$$

$$\begin{aligned}\Delta &= \left(W^{+\mu}W^-_\mu+\frac{Z^\mu Z_\mu}{2c^2_{\theta_W}}\right)\left(\frac{2h^2}{v}+\frac{4h^3}{3v^2}+\frac{h^4}{3v^3}\right)+\frac{m_h^2}{12m_W^2}\left(\frac{h^4}{v}+\frac{3h^5}{4v^2}+\frac{h^6}{8v^3}\right)\\ &+\frac{m_f}{4m_W^2}\left(\frac{h^2}{v}+\frac{h^3}{3v^2}\right)\left(\bar{f}_Lf_R+\text{h.c.}\right),\end{aligned}$$

Correlations with triple gauge couplings (TGC):

arXiv:1405.0181
arXiv:1406.6376

$$\Delta\mathcal{L}_{\kappa_\gamma} = \frac{\boldsymbol{\delta\kappa_\gamma}}{v^2}\Big[ie\hat{h}^2\boxed{(A_{\mu\nu} - t_{\theta_W} Z_{\mu\nu})W^{+\mu}W^{-\nu}} + Z_\nu\partial_\mu\hat{h}^2(t_{\theta_W}A^{\mu\nu} - t^2_{\theta_W}Z^{\mu\nu})$$
$$+ \boxed{\frac{(\hat{h}^2 - v^2)}{2}}\Big(t_{\theta_W}Z_{\mu\nu}A^{\mu\nu} + \frac{c_{2\theta_W}}{2c^2_{\theta_W}}Z_{\mu\nu}Z^{\mu\nu} + \boxed{W^+_{\mu\nu}W^{-\mu\nu}}\Big)\Big],$$

$$\hat{h} \equiv v + h$$

hVV form-factor correlated with ZWW

$$\Delta\mathcal{L}_{g_1^Z} = \boldsymbol{\delta g_1^Z}\Big[igc_{\theta_W}\Big(Z^\mu(W^{+\nu}W^-_{\mu\nu} - \text{h.c.}) + Z^{\mu\nu}W^+_\mu W^-_\nu\Big) + \frac{e^2 v}{2c^2_{\theta_W}}hZ_\mu Z^\mu$$
$$- 2c^2_{\theta_W}\frac{h}{v}\left(g(W^-_\mu J^\mu_- + \text{h.c.}) + \frac{gc_{2\theta_W}}{c^3_{\theta_W}}Z_\mu J^\mu_Z + 2et_{\theta_W}Z_\mu J^\mu_{em}\right)\left(1 + \frac{h}{2v}\right)$$
$$- g^2c^2_{\theta_W}\left(W^+_\mu W^{-\mu} + \frac{c_{2\theta_W}}{2c^4_{\theta_W}}Z_\mu Z^\mu\right)\left(\frac{5}{2}h^2 + 2\frac{h^3}{v} + \frac{h^4}{2v^2}\right) + g^2c^2_{\theta_W}v\Delta\Big].$$

Correlations with triple gauge coupling (TGC):

arXiv:1405.0181
arXiv:1406.6376

$$\begin{aligned}\Delta\mathcal{L}_{\kappa_\gamma} &= \frac{\boldsymbol{\delta\kappa_\gamma}}{v^2}\Big[ie\hat{h}^2(A_{\mu\nu}-t_{\theta_W}Z_{\mu\nu})W^{+\mu}W^{-\nu}+Z_\nu\partial_\mu\hat{h}^2(t_{\theta_W}A^{\mu\nu}-t^2_{\theta_W}Z^{\mu\nu})\\ &+\frac{(\hat{h}^2-v^2)}{2}\left(t_{\theta_W}Z_{\mu\nu}A^{\mu\nu}+\frac{c_{2\theta_W}}{2c^2_{\theta_W}}Z_{\mu\nu}Z^{\mu\nu}+W^+_{\mu\nu}W^{-\mu\nu}\right)\Big],\end{aligned}$$

$$\hat{h}\equiv v+h$$

custodial breaking hVV-coupling
correlated with ZWW

$$\begin{aligned}\Delta\mathcal{L}_{g_1^Z} &= \boldsymbol{\delta g_1^Z}\Bigg[igc_{\theta_W}\left(Z^\mu(W^{+\nu}W^-_{\mu\nu}-\text{h.c.})+Z^{\mu\nu}W^+_\mu W^-_\nu\right)+\frac{e^2v}{2c^2_{\theta_W}}hZ_\mu Z^\mu\\ &-2c^2_{\theta_W}\frac{h}{v}\left(g(W^-_\mu J^\mu_- +\text{h.c.})+\frac{gc_{2\theta_W}}{c^3_{\theta_W}}Z_\mu J^\mu_Z+2et_{\theta_W}Z_\mu J^\mu_{em}\right)\left(1+\frac{h}{2v}\right)\\ &-g^2c^2_{\theta_W}\left(W^+_\mu W^{-\mu}+\frac{c_{2\theta_W}}{2c^4_{\theta_W}}Z_\mu Z^\mu\right)\left(\frac{5}{2}h^2+2\frac{h^3}{v}+\frac{h^4}{2v^2}\right)+g^2c^2_{\theta_W}v\Delta\Bigg].\end{aligned}$$

2. Beyond the primary Higgs couplings

$$h Z^{\mu} Z_{\mu}\,,\;\; h Z^{\mu\nu} Z_{\mu\nu}\,,\; h W^{\mu\nu} W_{\mu\nu}\,,\;\; h Z^{\mu} f \gamma_{\mu} f\,,\;\; h W^{\mu} f \gamma_{\mu} f\;\; , \ldots$$

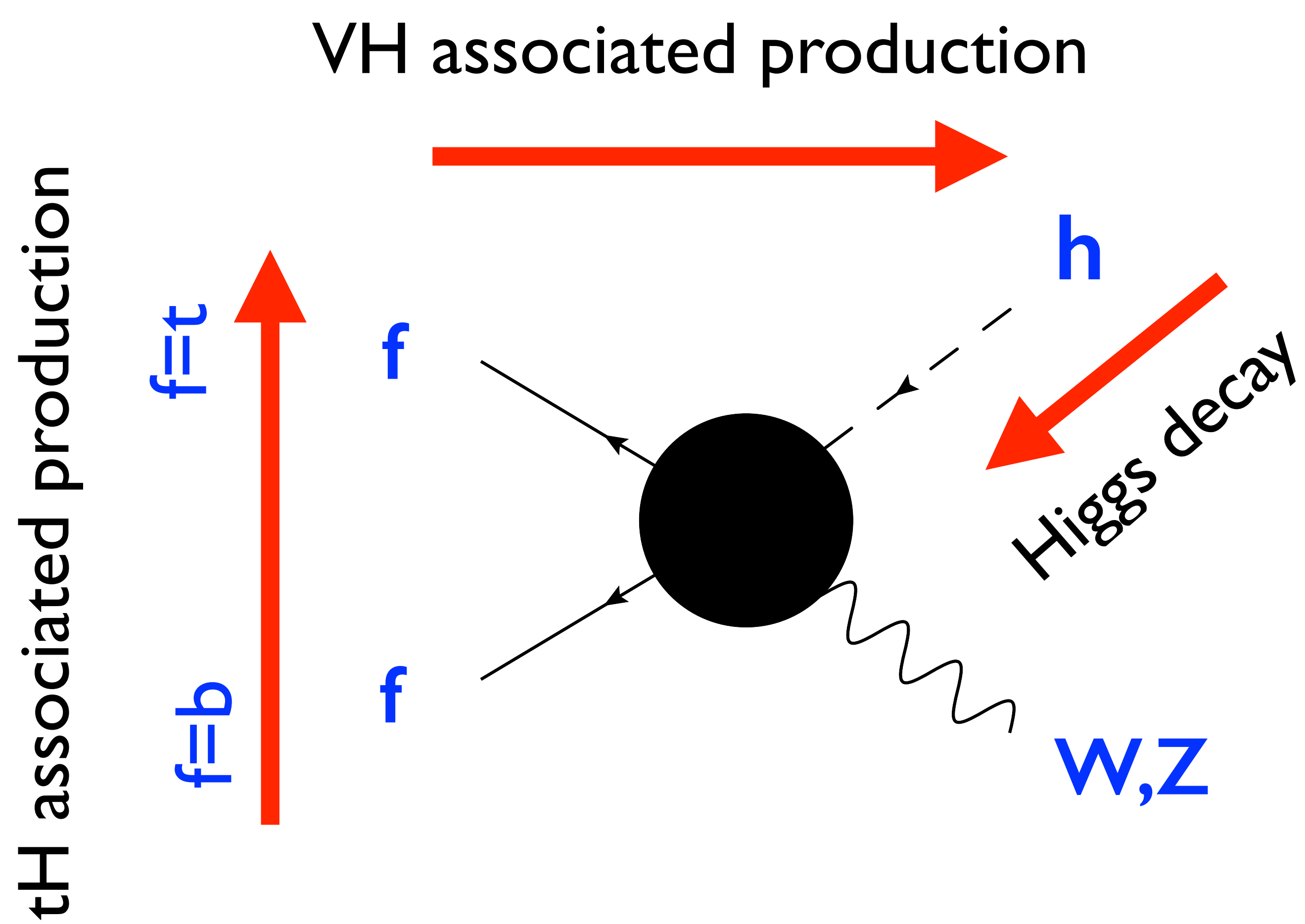
➥ <u>no large deviations</u> expected in these couplings

2. Beyond the primary Higgs couplings

$$h Z^\mu Z_\mu\,,\;\; h Z^{\mu\nu} Z_{\mu\nu}\,,\;\; h W^{\mu\nu} W_{\mu\nu}\,,\;\; h Z^\mu \bar{f}\gamma_\mu f\,,\;\; h W^\mu \bar{f}\gamma_\mu f\;,\ldots$$

➥ no large deviations expected in these couplings

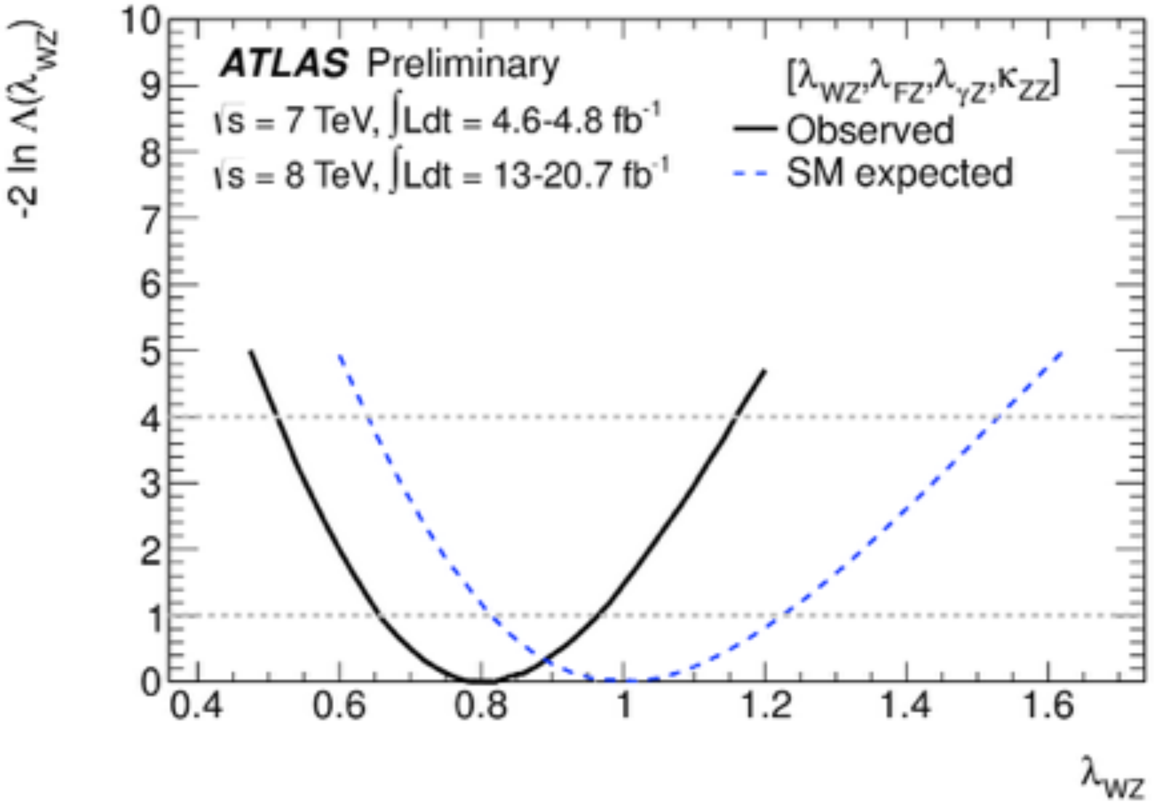
BUT worth to explore. Some interesting physical effects in:



Higgs decays:

1. breaking of custodial in $h \to ZZ^*, WW^*$:

   parametrized by λ_{WZ}

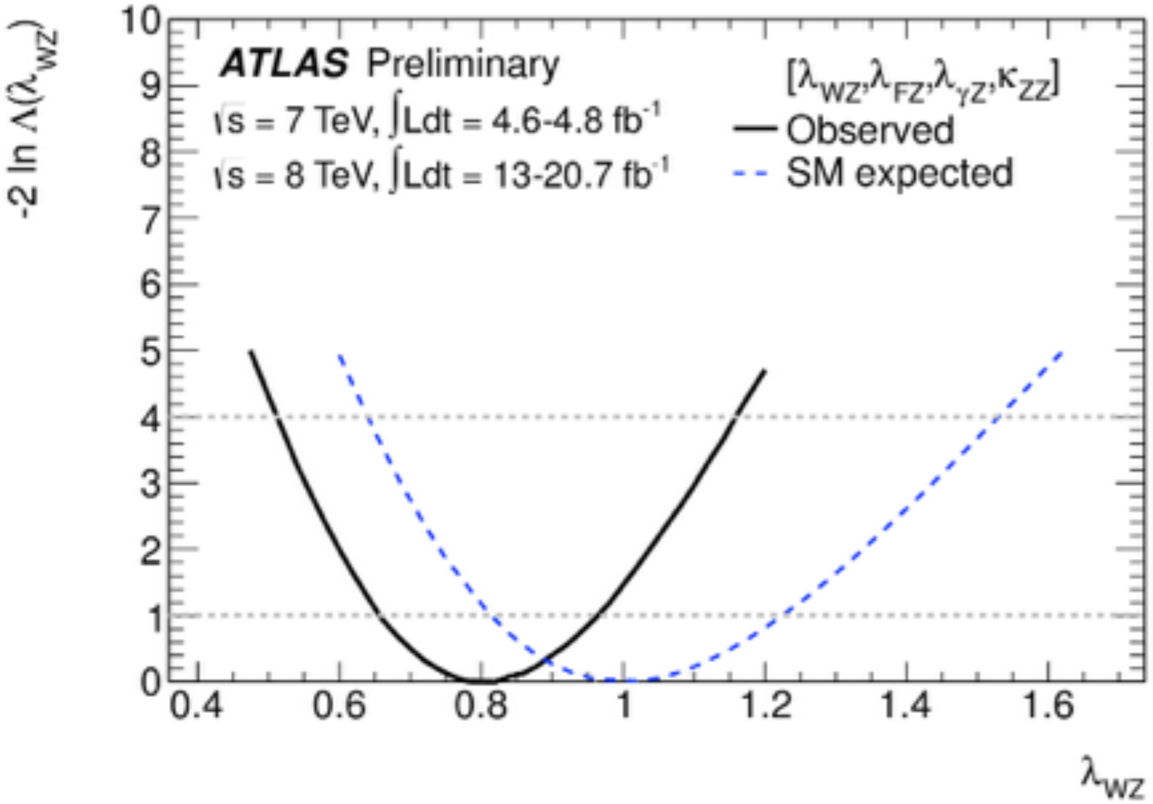


Higgs decays:

1. breaking of custodial in $h \to ZZ^*, WW^*$:

prediction from $\mathcal{L}_6$: arXiv:1308.2803

$$\lambda_{WZ} \approx 0.6\, \delta g_1^Z - 0.5\, \delta\kappa_\gamma - 1.6\, \kappa_{Z\gamma}$$

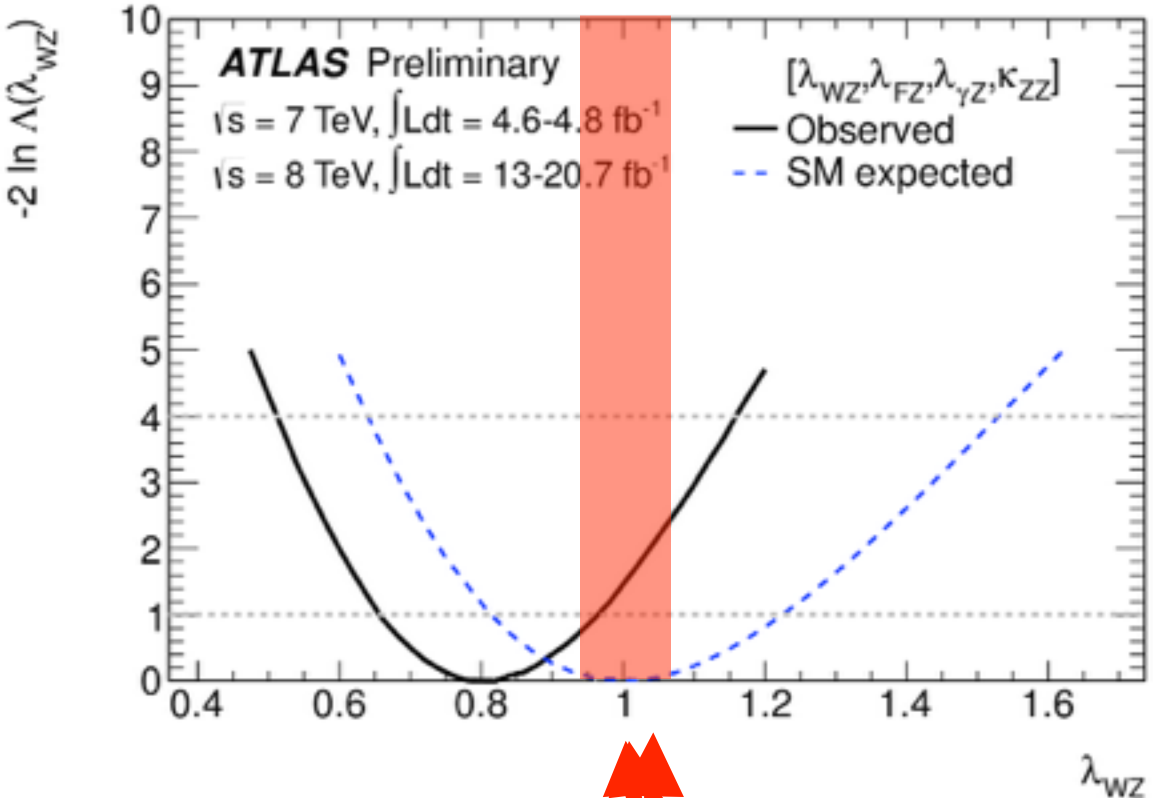


Higgs decays:

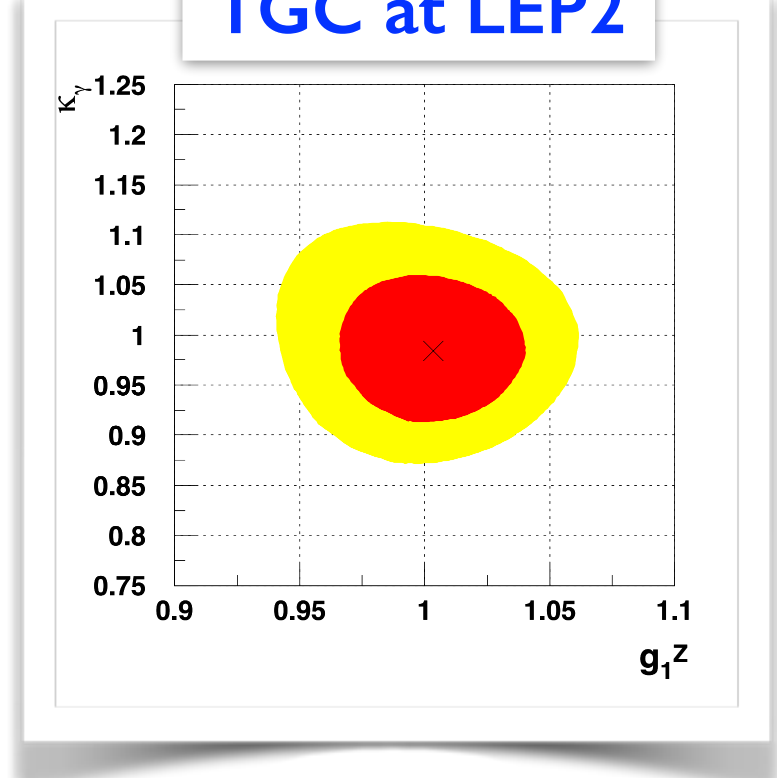
1. breaking of custodial in $h \rightarrow ZZ^*, WW^*$:

prediction from $\mathcal{L}_6$: arXiv:1308.2803

$$\lambda_{WZ} \approx 0.6\,\delta g_1{}^Z - 0.5\,\delta\kappa_\gamma - 1.6\,\kappa_{Z\gamma}$$

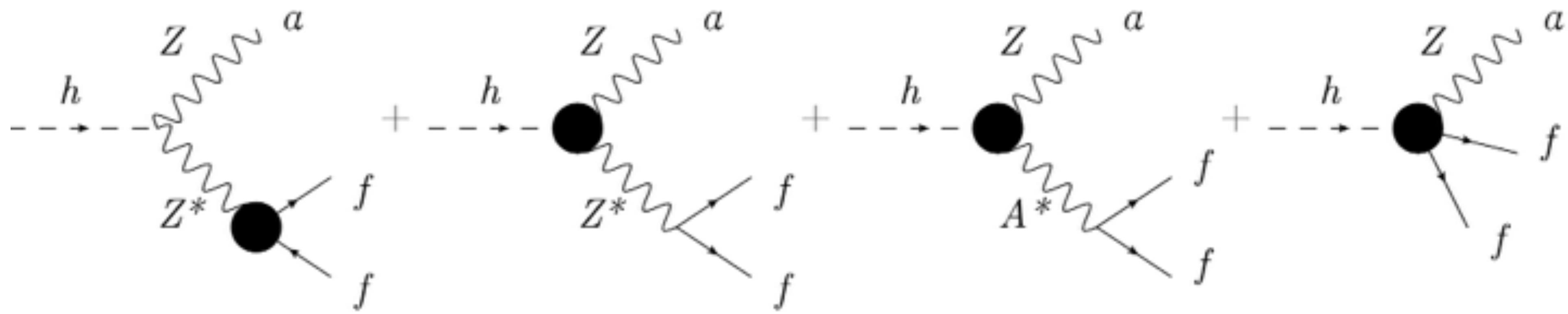


TGC at LEP2



$h \rightarrow Z\gamma$ bound

and similarly for h→Wff, Zff form-factors:



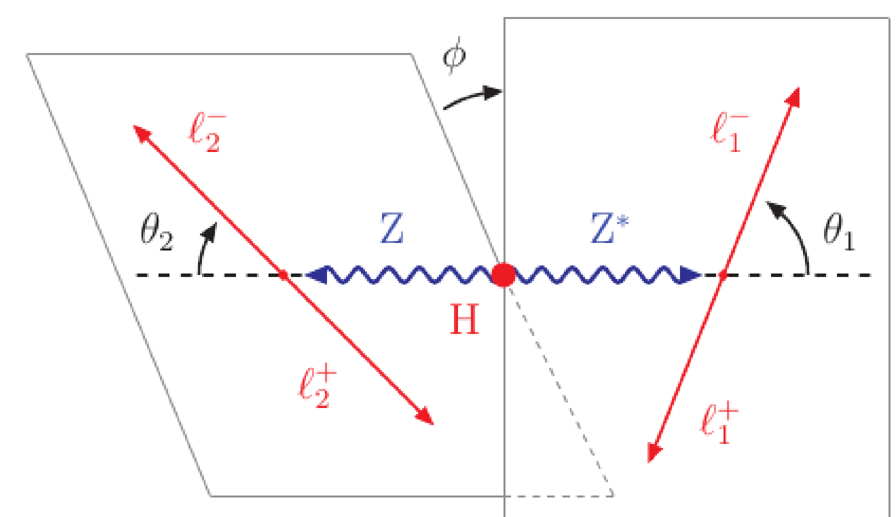
(assuming m_f=0 and CP-conservation)

$$\mathcal{M}(h \to V J_f) = (\sqrt{2} G_F)^{1/2} \epsilon^{*\mu}(q)\, J_f^{V\,\nu}(p) \left[A_f^V \eta_{\mu\nu} + B_f^V \left(p \cdot q\, \eta_{\mu\nu} - p_\mu q_\nu \right) \right]$$

$$A_f^V = a_f^V + \widehat{a}_f^V \frac{m_V^2}{p^2 - m_V^2}, \qquad B_f^V = b_f^V \frac{1}{p^2 - m_V^2} + \widehat{b}_f^V \frac{1}{p^2} \qquad (\widehat{b}_f^V = 0 \text{ for } V = W)$$

➡ 3 parameters (apart from a total rescaling; 2 for V=W) to be measured in momentum/angle distributions

(order one bounds from SM values expected after the end of LHC run2)



Predictions from $\mathcal{L}_6$:

arXiv:1308.2803

$$a_f^Z = 2\delta g_f^Z - 2\delta g_1^Z (g_f^Z c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta\kappa_\gamma g' Y \frac{s_{\theta_W}}{c_{\theta_W}^2}\,,$$

$$\widehat{a}_f^Z = 2g_f^Z + \frac{g_f^Z v}{m_Z^2 c_{\theta_W}^2}\left(\delta g_{VV}^h + \delta g_1^Z e^2 v - \delta\kappa_\gamma g'^2 v\right)\,,$$

$$b_f^Z = 2\frac{g_f^Z}{c_{\theta_W}^2}(-\delta\kappa_\gamma - \kappa_{Z\gamma} c_{2\theta_W} - 2\kappa_{\gamma\gamma} c_{\theta_W}^2)\,,$$

$$\widehat{b}_f^Z = -2eQ_f t_{\theta_W} \kappa_{Z\gamma}\,,$$

$$a_f^W = \sqrt{2} c_{\theta_W} \delta g_f^Z - 2\delta g_1^Z g_f^W c_{\theta_W}^2\,,$$

$$\widehat{a}_f^W = 2g_f^W + \frac{\delta g_{VV}^h g_f^W v}{m_W^2}\,,$$

$$b_f^W = 2g_f^W(-\delta\kappa_\gamma - \kappa_{Z\gamma} - 2\kappa_{\gamma\gamma})\,,$$

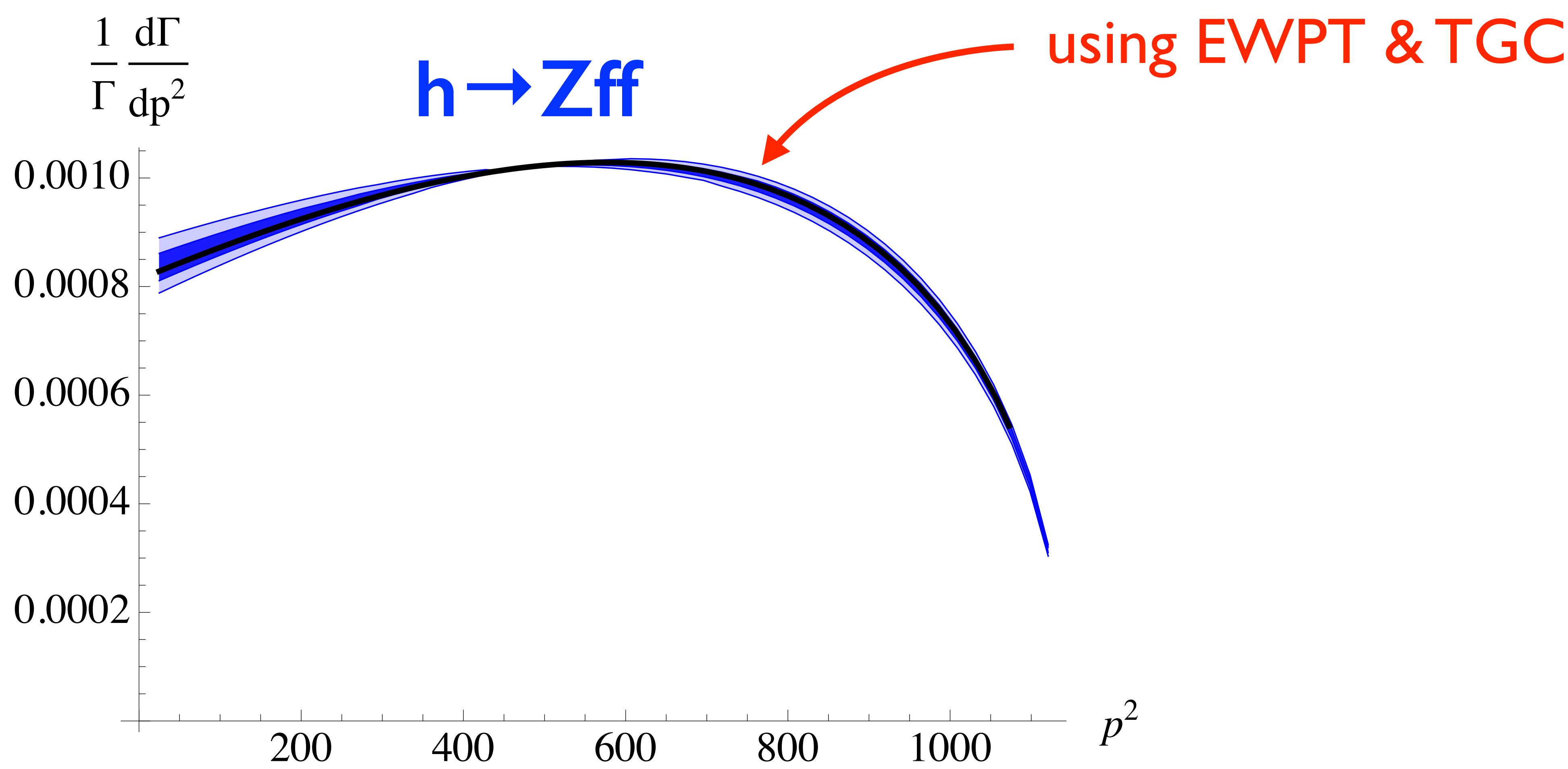
all BSM effects can be written as a functions of contributions to other couplings:

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

that tell us that already constrained from EWPT and TGC:

1) No large deviations from universality in h→Wff,Zff allowed

2) Small deviations in the distributions

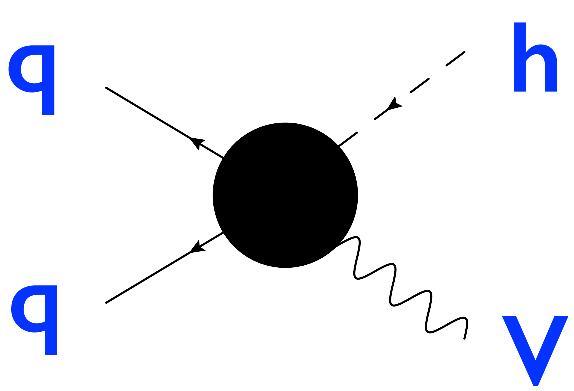


(assuming no new-physics in h→Zγ)

Towards the high-energy regime

GOOD: some BSM effects are enhanced at high-energy **E**:

Example: **$pp \to V^* \to Vh$** (same parametrization of the amplitude as in $h \to Vff$)



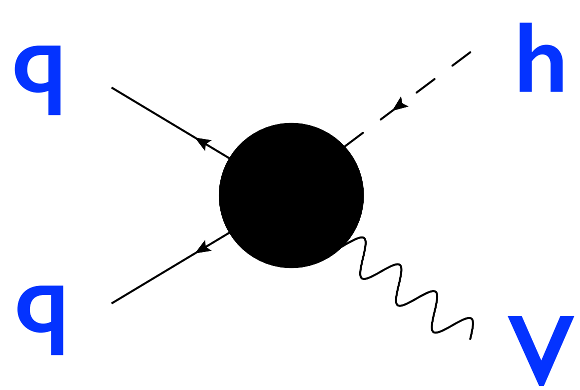
$$\mathcal{M} \sim \mathcal{M}_{SM} + c_{BSM}\, E^2/\Lambda^2$$

leading effects from contact interactions:
$h V^\mu\, q \gamma_\mu q$

Towards the high-energy regime

GOOD: some BSM effects are enhanced at high-energy **E**:

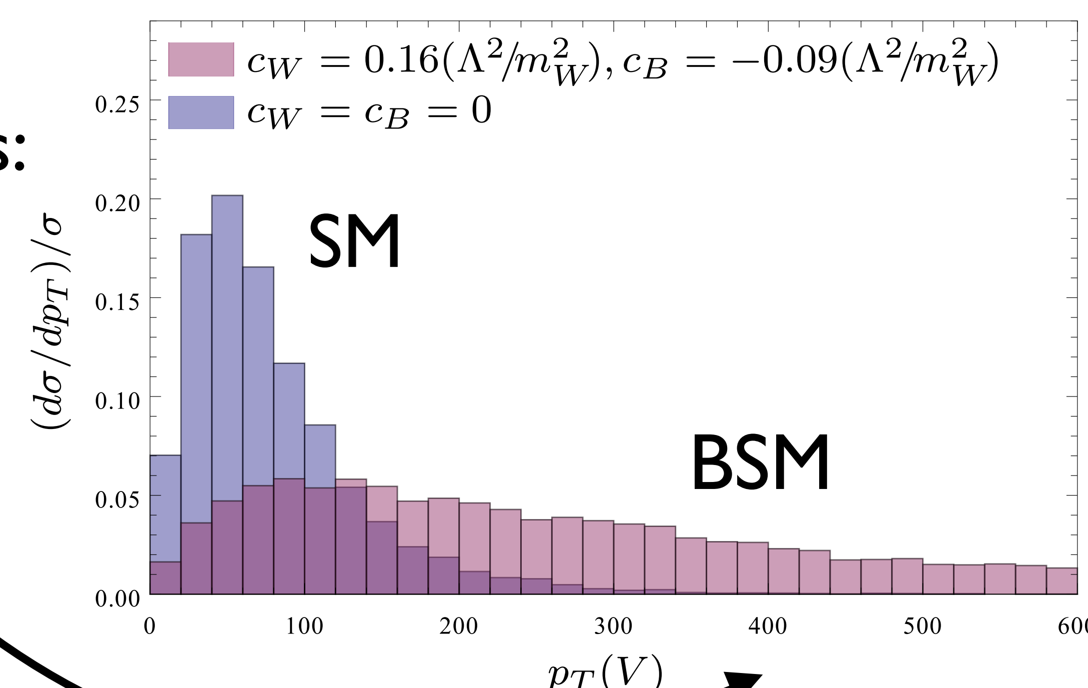
Example: $pp \to V^* \to Vh$ (same parametrization of the amplitude as in $h \to Vff$)



$$\mathcal{M} \sim \mathcal{M}_{SM} + c_{BSM}\, E^2/\Lambda^2$$

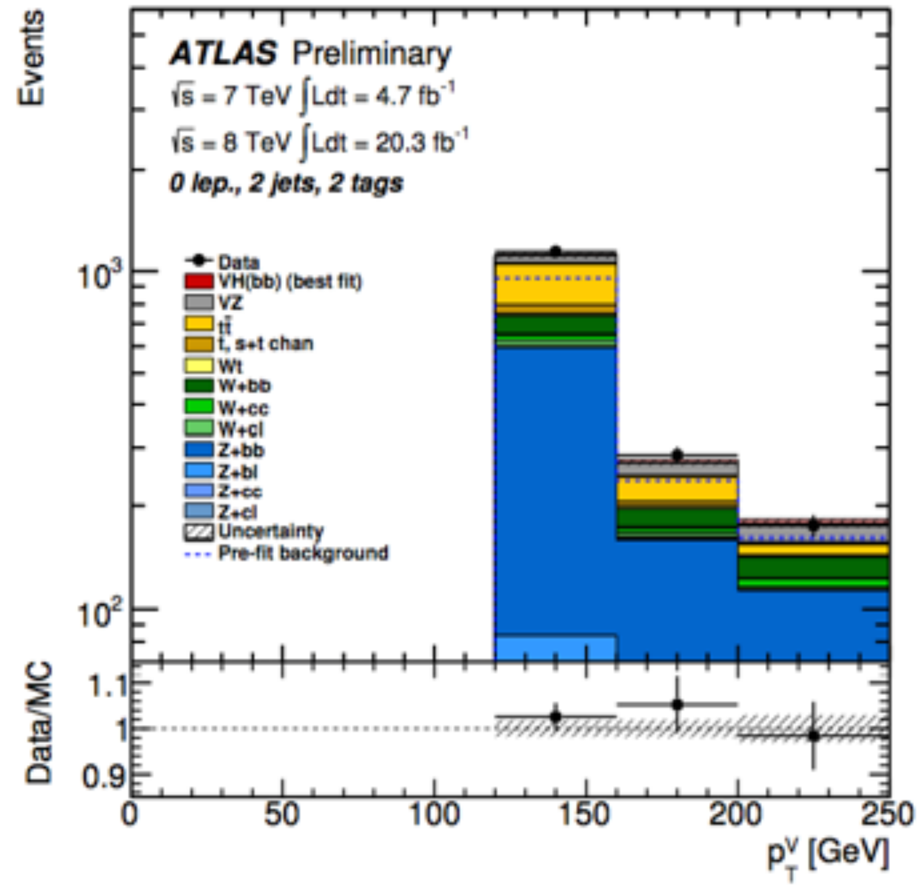
leading effects from contact interactions:
$h V^\mu q \gamma_\mu q$

BSM-effects enhanced at the *tail* of distributions:



arXiv:1406.7320

Data is coming…



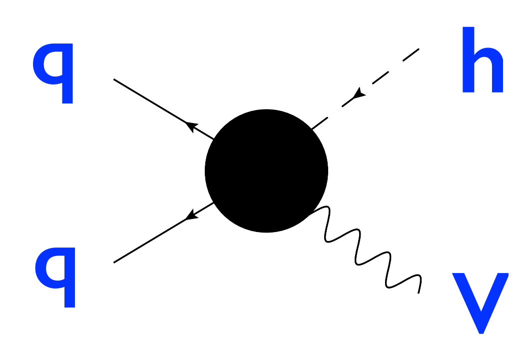
BUT: Not being yet well measured (bounds of order one $\Delta\mathcal{M}_{BSM}/\mathcal{M} < O(1)$), one has to be sure is not out of the EFT validity:

- Validity of EFT: $\epsilon \equiv E^2/\Lambda^2 \ll 1$ (expansion parameter)
- Experimental bound: $c_{BSM}\, E^2/\Lambda^2 < O(1)$

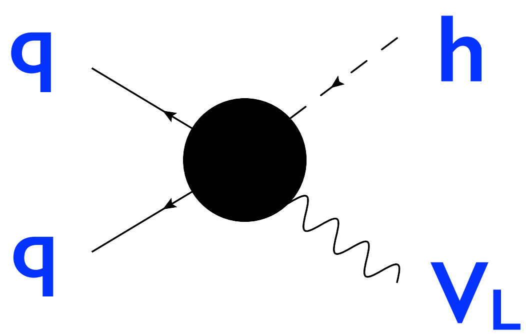
$\Big\}$ $c_{BSM} < O(1)/\epsilon$

at present we can only bound theories with large c_{BSM}

☛ strongly-coupled BSM where $c_{BSM} \sim 16\pi^2$



In this (and only this) case, hV-production put important constraints:



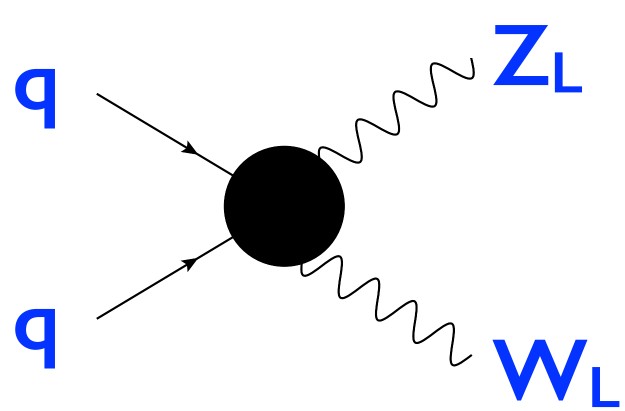
arXiv:1406.7320

$-0.06 < \delta g_1^Z < 0.02$ at 95%CL

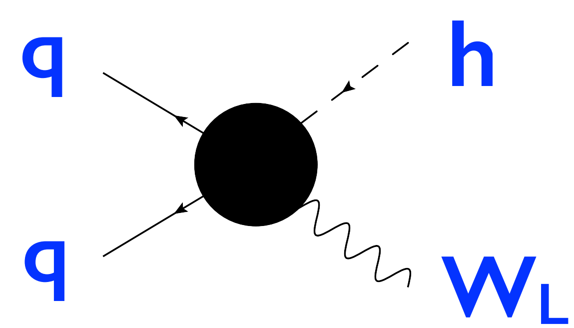
only one combination of contact-interaction
not so well-measured at LEP1

in competition with TGC (similar high-energy behaviour!):

e.g.



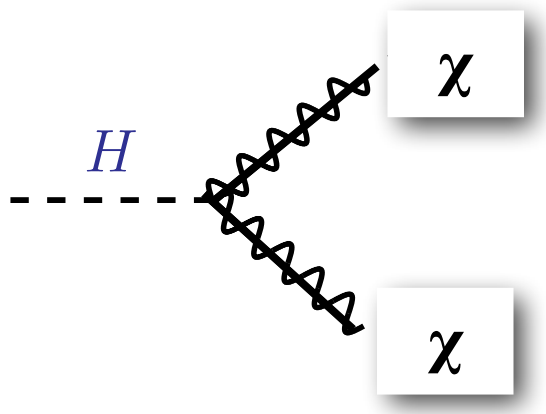
$\Big|_{\hat{s} \gg m_W^2}$ $\approx$



$\Big|_{\hat{s} \gg m_W^2}$

Invisible Higgs decay

Possible in certain models:



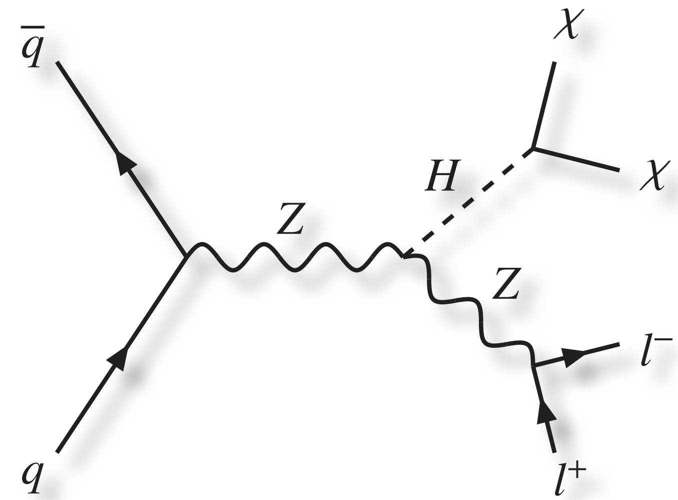
for example:

χ = Dark Matter = extra scalar, neutralinos, …

(or χ χ = gravitino + neutrino, as in models in which the Higgs is the susypartner of the neutrino)

arXiv:1211.4526

Bounds on invisible Higgs decay



stable particle

missing E_T + l^+l^-

ATLAS (4.7+13.0 fb^{-1}):

- **Br(H→χχ) < 65%** (84% exp.) @ 95% CL, m_H = 125 GeV

CMS (5+20 fb^{-1}):

- **Br(H→χχ) < 75%** (91% exp.) @ 95% CL, m_H = 125 GeV

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 !

Expected "deformations" from SM properties in natural theories
To see them, we must test the **Higgs couplings** very well

If deviations are not found… ☛ Fine-tuned SM (Multiverse?)
If we find them in $h\to ff$ only ☛ probably MSSM
We find smaller couplings ☛ probably Composite Higgs

Model-independent analysis ☛ 8 primary couplings! (one-family & CP-even)

$h\to Z\gamma$ offers best (last?) chance for large deviations

Other Higgs couplings related to other observables = **Predictions!**

Near future measurements: Probe of contact-interaction **qqhV** in $pp\to Vh$ at high-energies (in competition with $pp\to VV$)