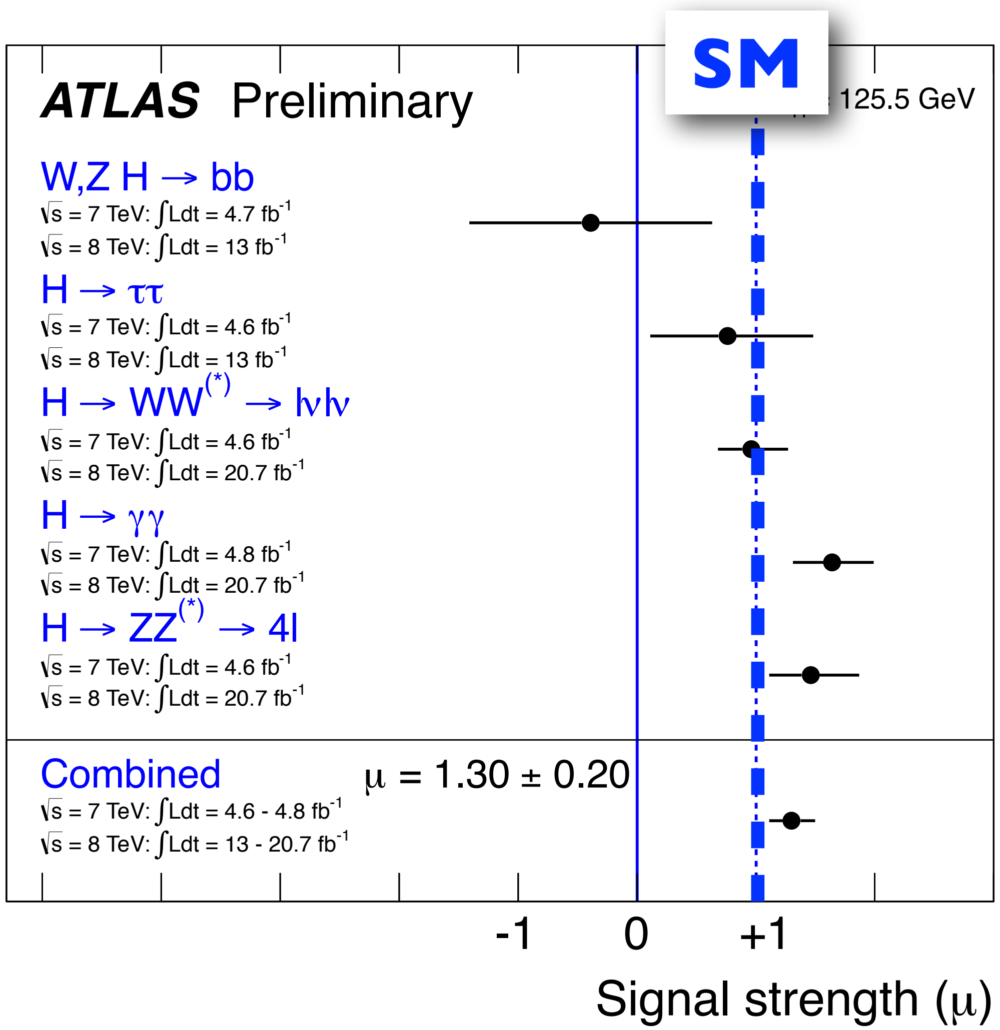
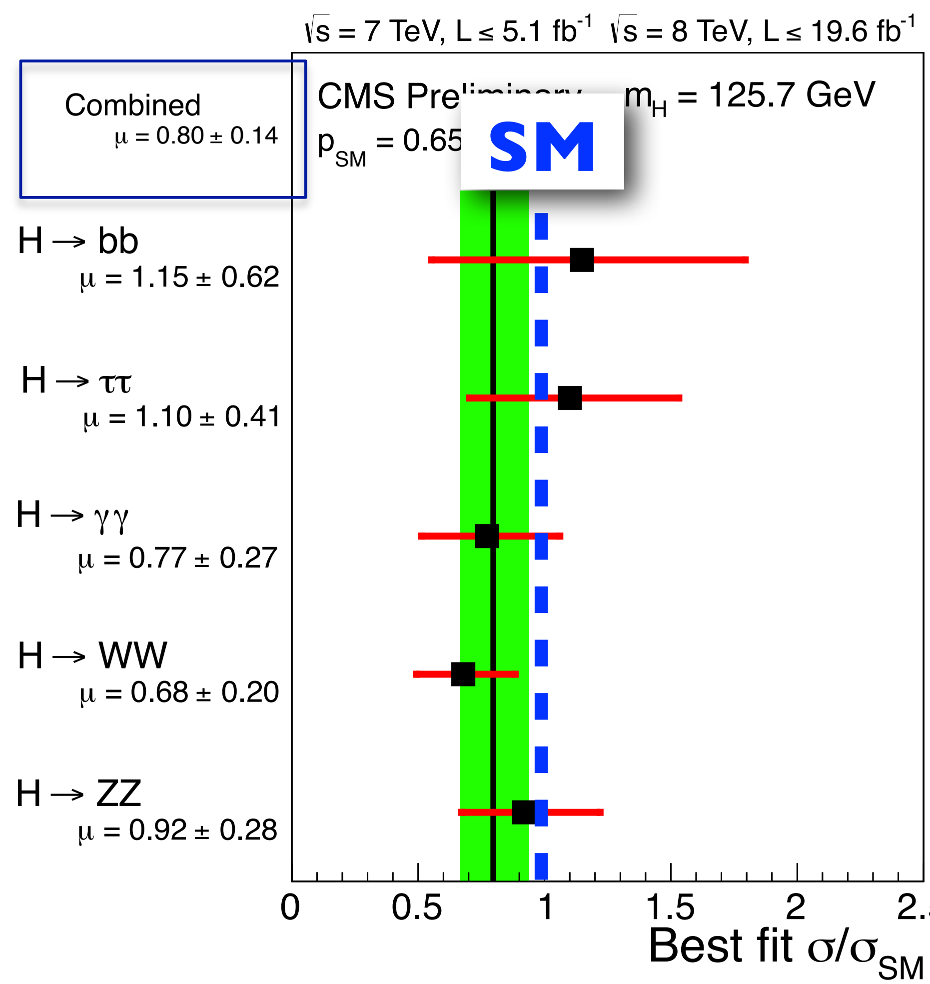
Where could BSM physics hide in the scalar sector?

Alex Pomarol, UAB (Barcelona)

The best LHC first-run legacy:

New particle discovered in accordance with the SM scalar:





ATLAS and CMS results
"dancing" around the SM values...

With a new SM particle,
a new handle to look for indirect BSM effects

So far, no sign of BSM in the h properties...

Where else should we look for?

- **$pp \to hW$?**
- **$pp \to hh$ double-Higgs production?**
- **$h \to Vff$ E,p distributions? CP-violation?**
- **$h \to Z\gamma$?**

⋮

An thorough model-independent analysis is needed

Main purpose of this talk

New-physics scale Λ seems to be heavier than M_W.

If so, we can obtain an effective Lagrangian by integrating out new-physics states and performing an expansion in derivatives and SM fields:

(assuming lepton & baryon number)

$$\mathcal{L}_{\rm eff} = \frac{\Lambda^4}{g_*^2}\mathcal{L}\left(\frac{D_\mu}{\Lambda}\,,\ \frac{g_H H}{\Lambda}\,,\ \frac{g_{f_{L,R}} f_{L,R}}{\Lambda^{3/2}}\,,\ \frac{g F_{\mu\nu}}{\Lambda^2}\right) \simeq \mathcal{L}_4 + \mathcal{L}_6 + \cdots$$

SM

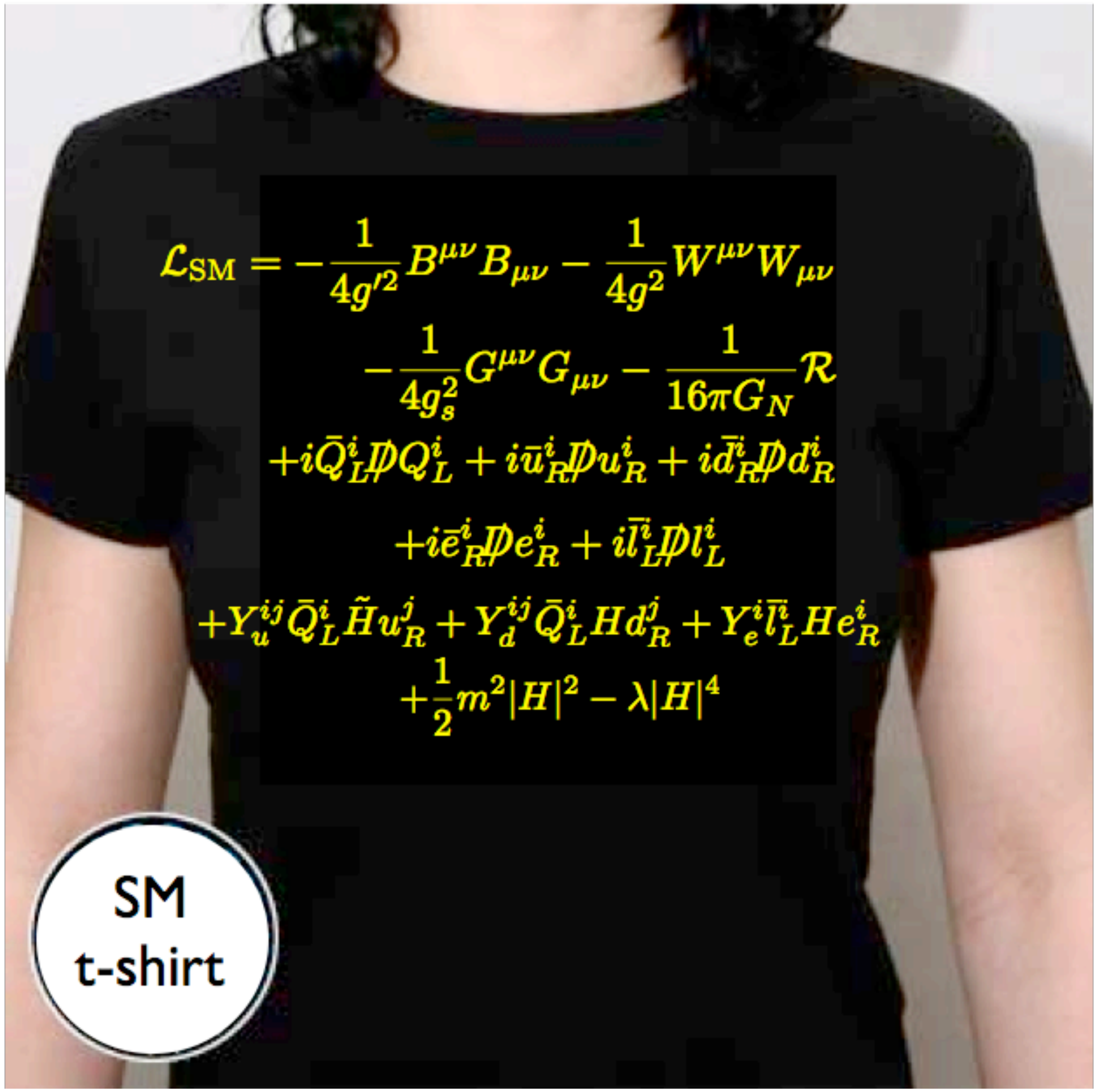
leading deviations from the SM

$\mathcal{L}_6$: made of dimension-6 operators e.g. $\frac{1}{\Lambda^2} H^\dagger D_\mu H \bar{f}\gamma^\mu f$

↳ particular subset of *deformations* of the SM

what are the predictions?

$\mathcal{L}_4$ can fit in a t-shirt:



not possible for $\mathcal{L}_6$

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

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

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

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

Too many new terms to say something?

Two important lessons can be derived for the h-scalar physics

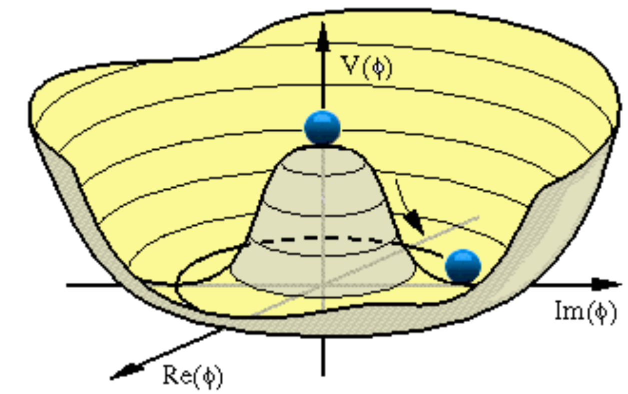
- Elias-Miro, Espinosa, A.P. & Masso: arXiv:1308.1879
- A.P. & Riva arXiv:1308.2803

I

SM Scalar is the excitation around the EWSB vacuum:

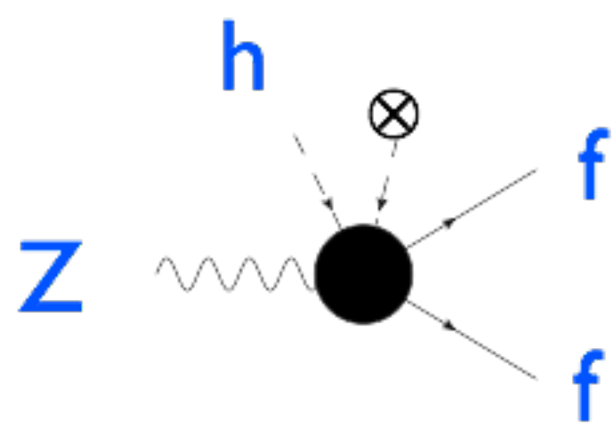
ϕ = v+h

vacuum

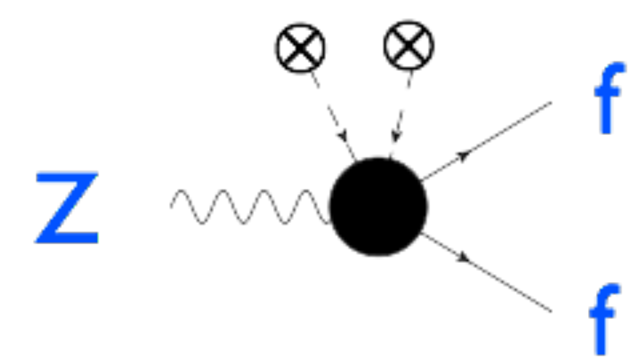


Potentially new BSM-effects in h physics
could have been already tested in the vacuum

e.g.



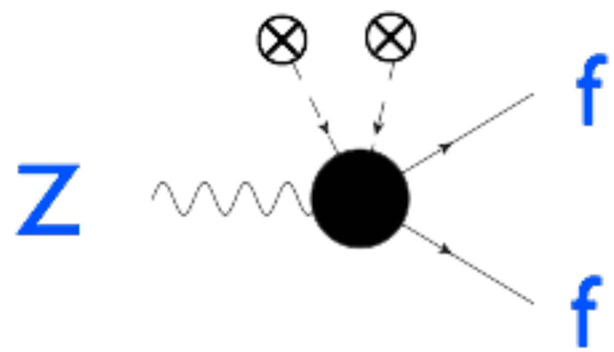
$$= \frac{1}{2v} \times$$



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

Modifications in h→Zff related to Z→ff

How many possible BSM-effects in h physics
are already constrained by electroweak precision data?



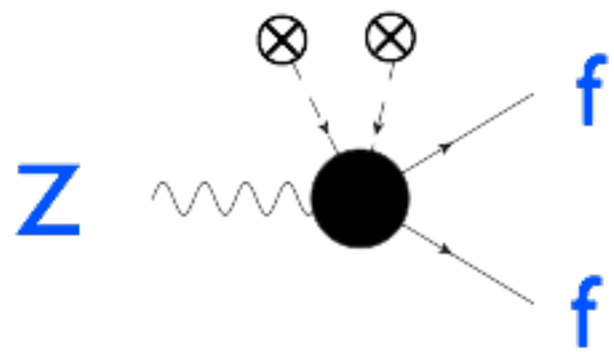
$f = e_L, e_R, \nu_L, u_R, u_L, d_R, d_L$

All constrained by LEP1 at the per-mille level:

(assuming family-universality)

$$\boxed{\Gamma(Z \to ll), A^l_{FB}, \Gamma_Z, \Gamma(Z \to hadrons), R_b, A^b_{FB}, A^c_{FB}}$$

SM input parameters:
α, M_Z, M_W



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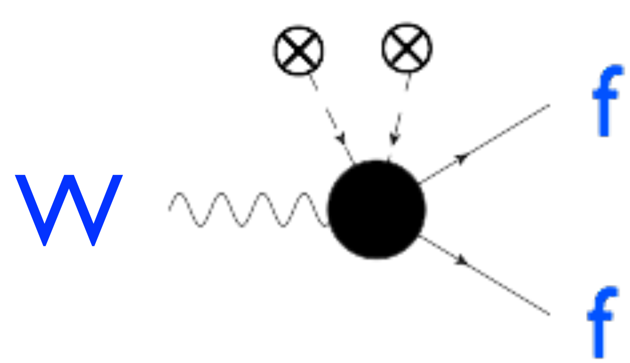
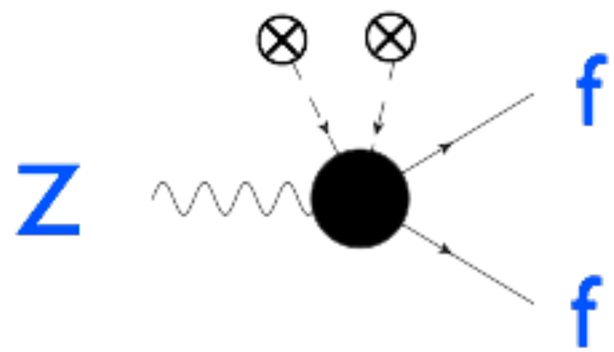


?



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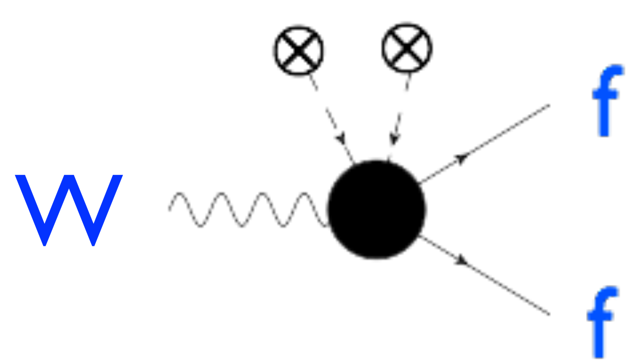
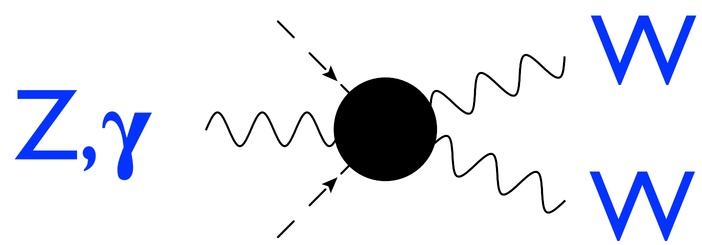


not independent contributions
from dimension-six operators
(accidental custodial-symmetry)

Lucky us!

Triple Gauge Couplings (TGC)



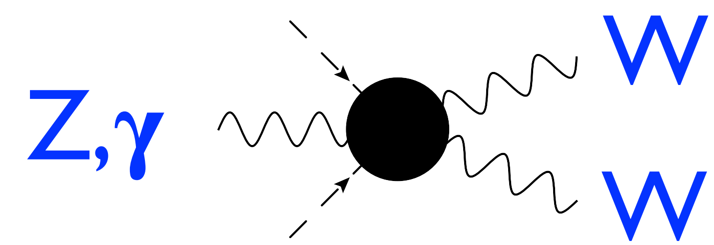
from e.g. $(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$

Deviations in the ZWW coupling
& induce dipole-moments for the W

Constrained from: $e^+e^- \to W^+W^-$ (LEP2)

... LHC becoming also competitive

Triple Gauge Couplings (TGC)



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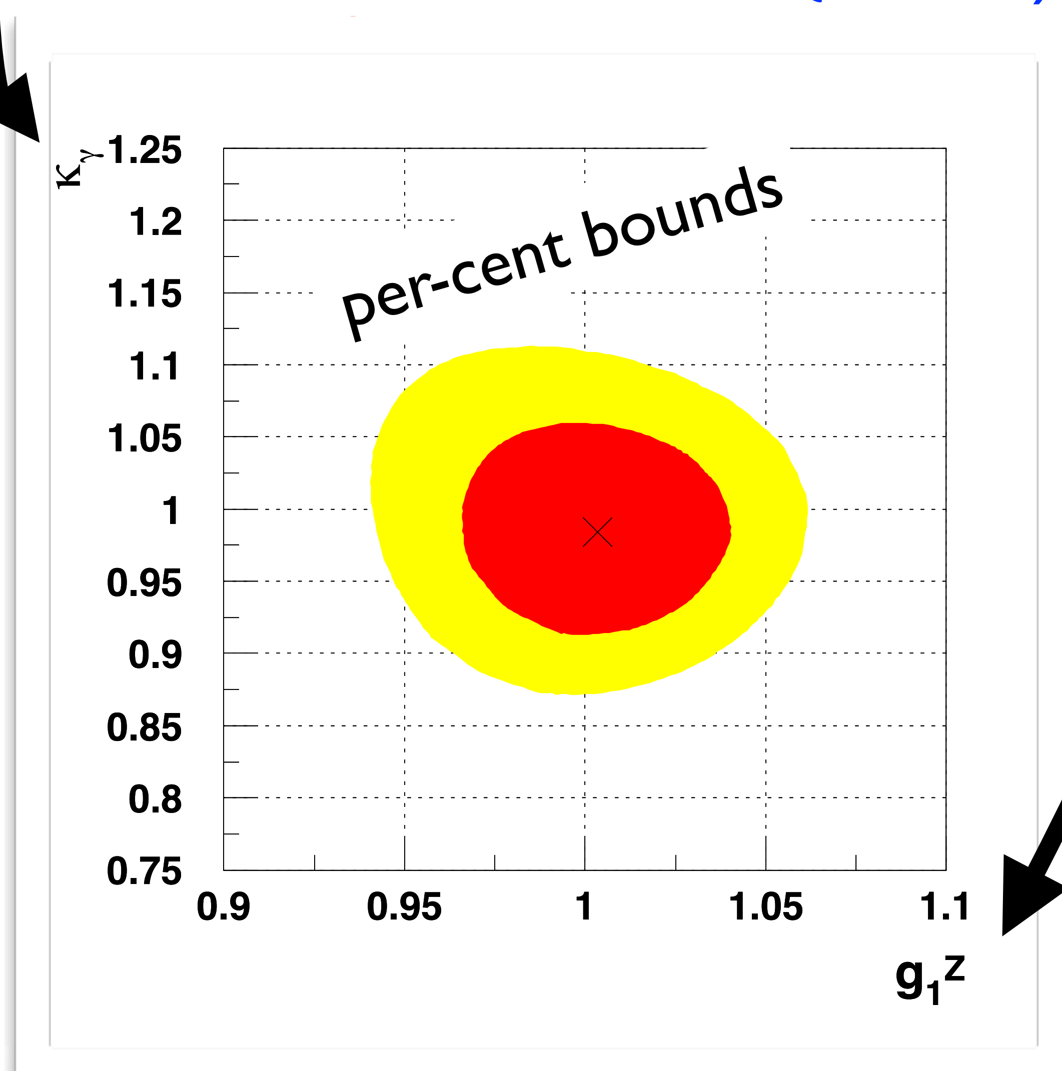

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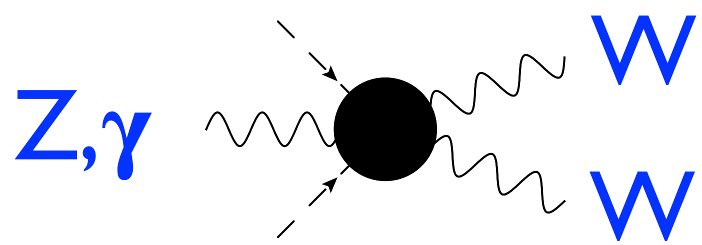

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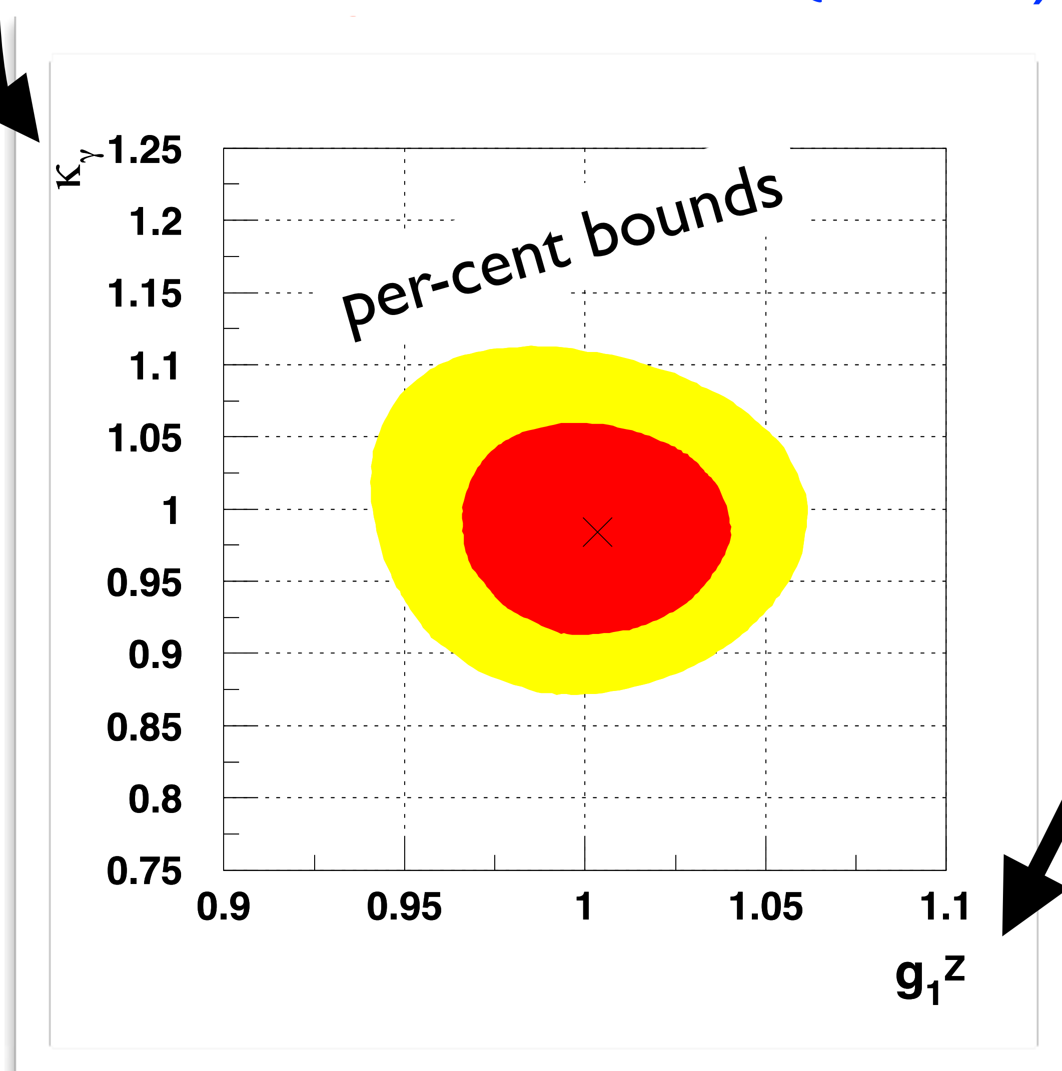


No new effects in quartic-gauge couplings!

(accidental symmetries in dim-6 operators)

First lesson:

All BSM-effects leading to EWSB
have already been tested
in EWPT (~LEP1/Tevatron) and TGC (~LEP2)!

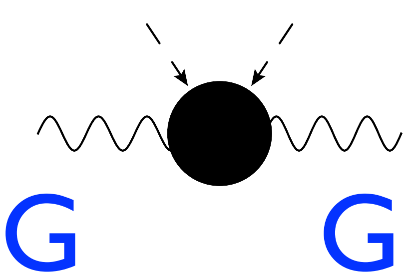
These BSM-effects are too small to be seen
in Higgs physics !

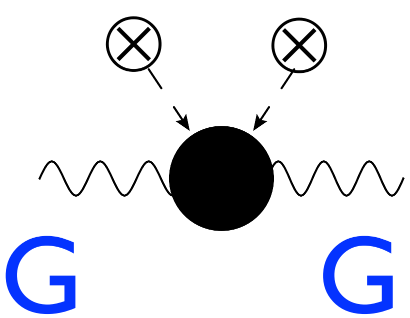
II

What BSM-effects scalar physics can be probing?

Effects that on the vacuum, $\phi = v$, give only
a redefinition of the SM couplings:

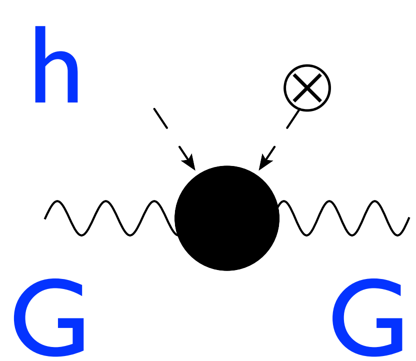
e.g. $$\frac{1}{g_s^2}G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2}G_{\mu\nu}^2 \to \left(\frac{1}{g_s^2}+\frac{v^2}{\Lambda^2}\right)G_{\mu\nu}^2$$





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**

(assuming CP-conservation)

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$\mathbf{g_s}$

$\mathbf{g}$

$\mathbf{g'}$

$\mathbf{m_W}$

$\mathbf{m_h}$

$\mathbf{m_f}$

(f=t,b,τ)

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

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(assuming CP-conservation)

g_s	$\|H\|^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\longrightarrow$ **GG→h**
g	$\|H\|^2 B_{\mu\nu} B^{\mu\nu}$	$\longrightarrow$ **h→γγ**
g'	$\|H\|^2 W^a_{\mu\nu} W^{\mu\nu\, a}$	
m_W	$\|H\|^2 \|D_\mu H\|^2$	$\longrightarrow$ **h→VV*** (custodial invariant)
m_h	$\|H\|^6$	
m_f (f=t,b,τ)	$\|H\|^2 \bar{f}_L H f_R + h.c.$	$\longrightarrow$ **h→bb,$\tau\tau$**

How many of these effects can we have?

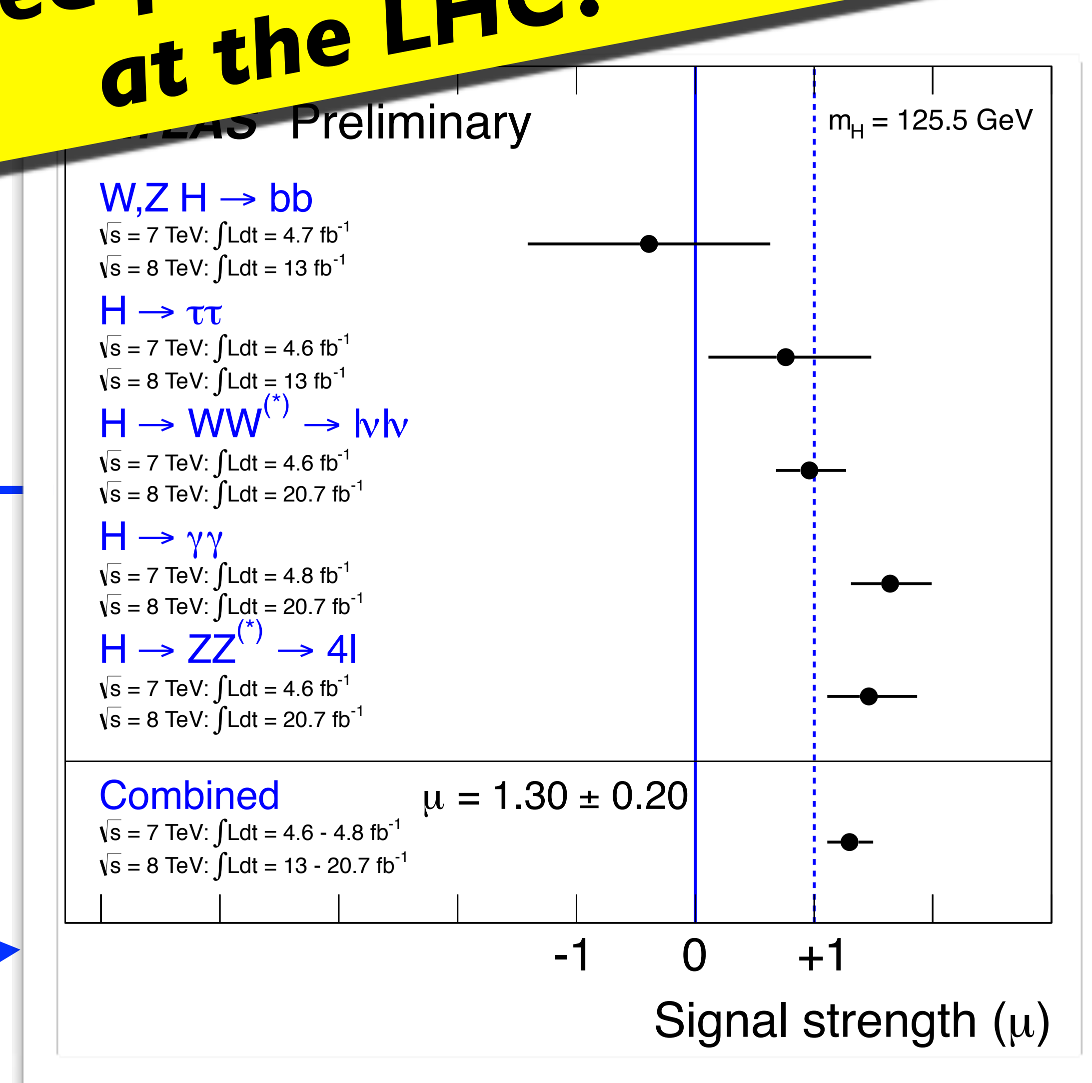
As many as parameters in the SM: **8**

(assuming CP-conservation)

g_s	$\lvert H\rvert^2 G^A_{\mu\nu}G^{A\mu\nu}$	→ **GG→h**
g	$\lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$	
g'	$\lvert H\rvert^2 W^a_{\mu\nu}W^{\mu\nu\, a}$	
m_W	$\lvert H\rvert^2 \lvert D_\mu H\rvert^2$	→ **h**
m_h	$\lvert H\rvert^6$	
m_f	$\lvert H\rvert^2 \bar{f}_L H f_R + h.c.$	→

(f=t,b,τ)

All were new BSM effects, probed for the first time at the LHC!



How many of these effects can we have?

As many as parameters in the SM: **8**

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g_s — $|H|^2 G^A_{\mu\nu} G^{A\mu\nu}$ → **GG→h**

g — $|H|^2 B_{\mu\nu} B^{\mu\nu}$ → **h→γγ**

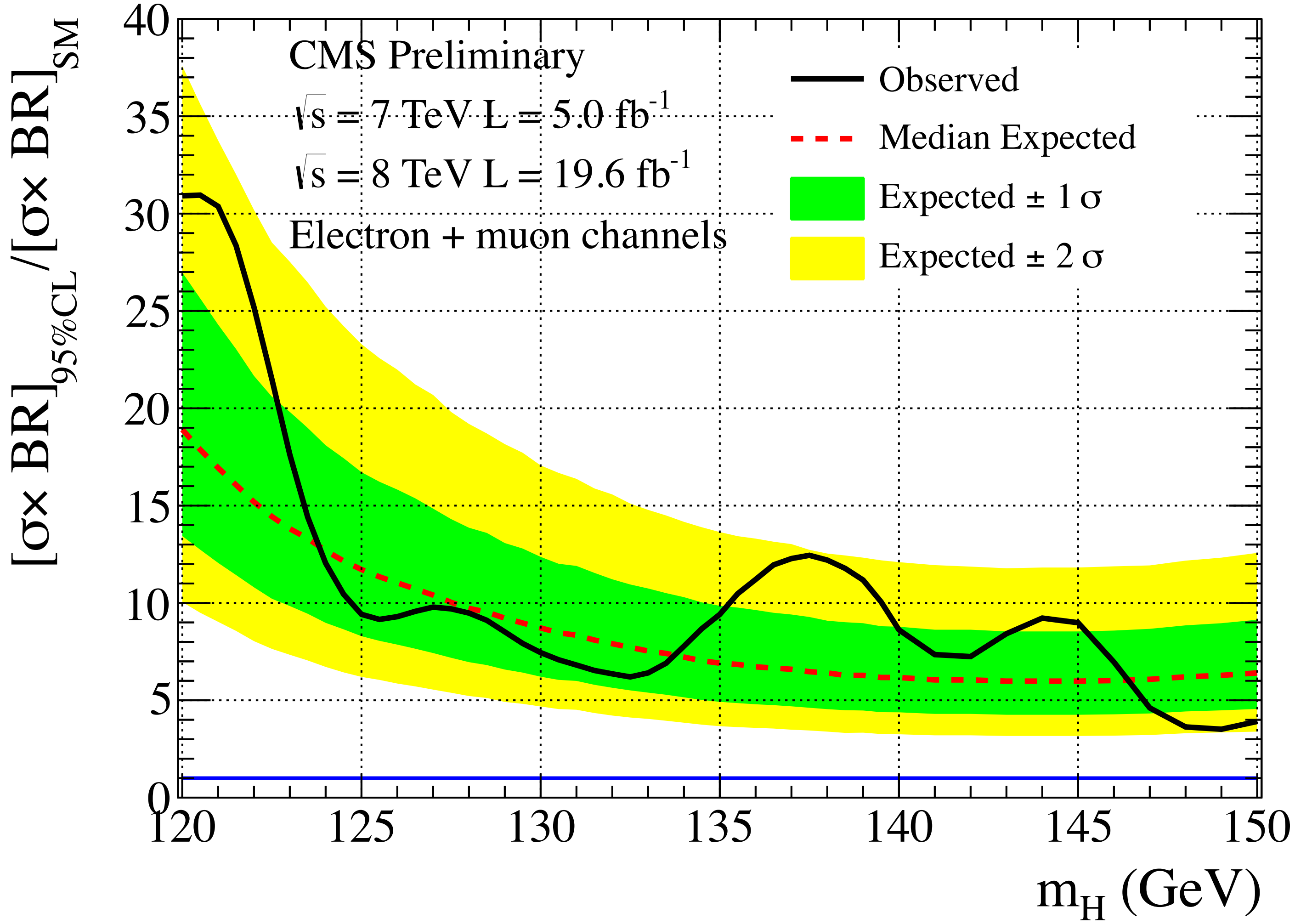
g' — $|H|^2 W^a_{\mu\nu} W^{\mu\nu\, a}$ → **h→Zγ**

m_W — $|H|^2 |D_\mu H|^2$ → **h→VV*** (custodial invariant)

m_h — $|H|^6$ → **Affects h^3: It can be measured in the far future by GG→hh**

m_f (f=t,b,τ) — $|H|^2 \bar{f}_L H f_R + h.c.$ → **h→bb,$\tau\tau$**; → **GG→tth** (htt deviation)

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



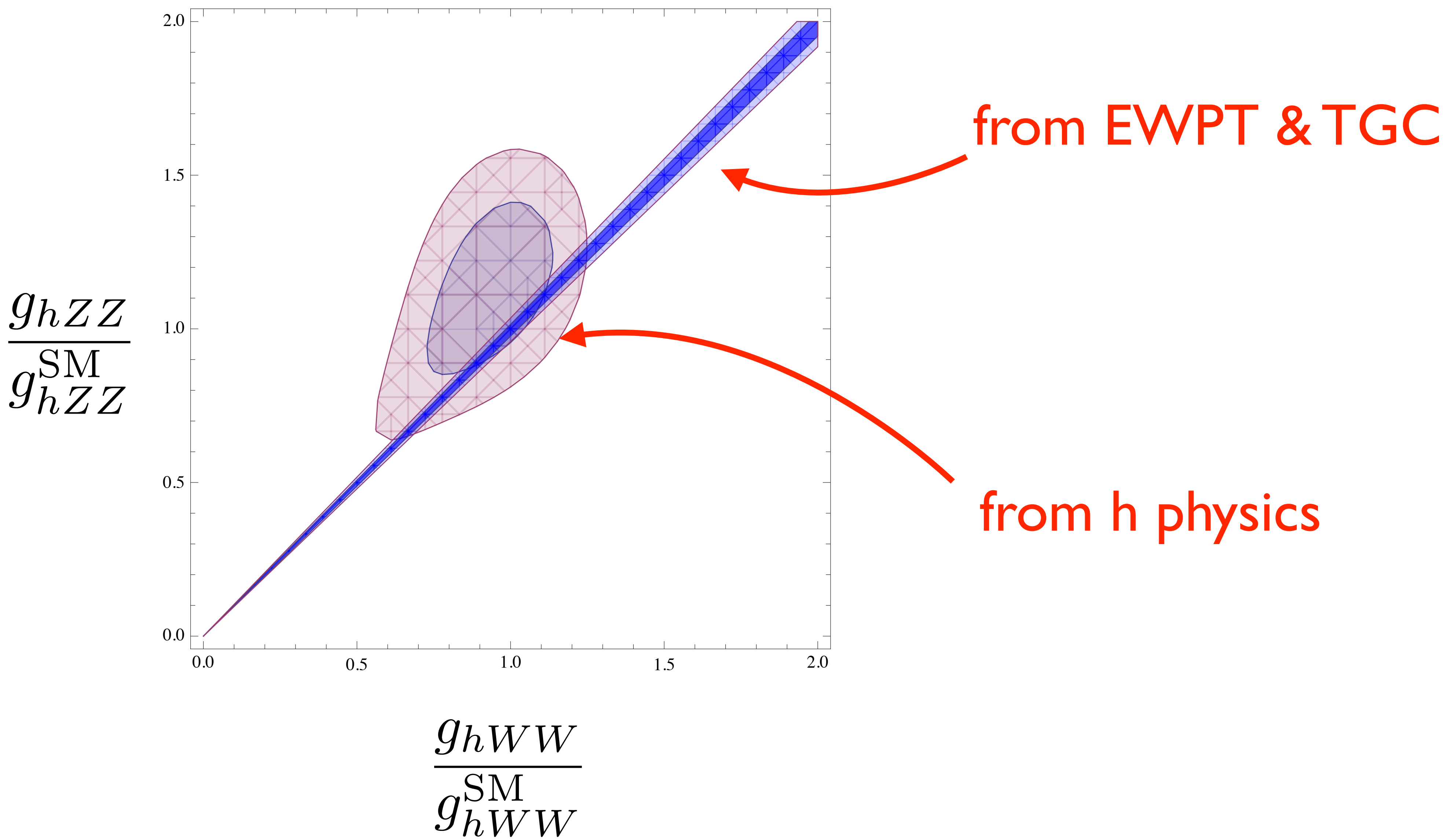
small in the SM since it comes at one-loop

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

(possibility in composite Higgs models)

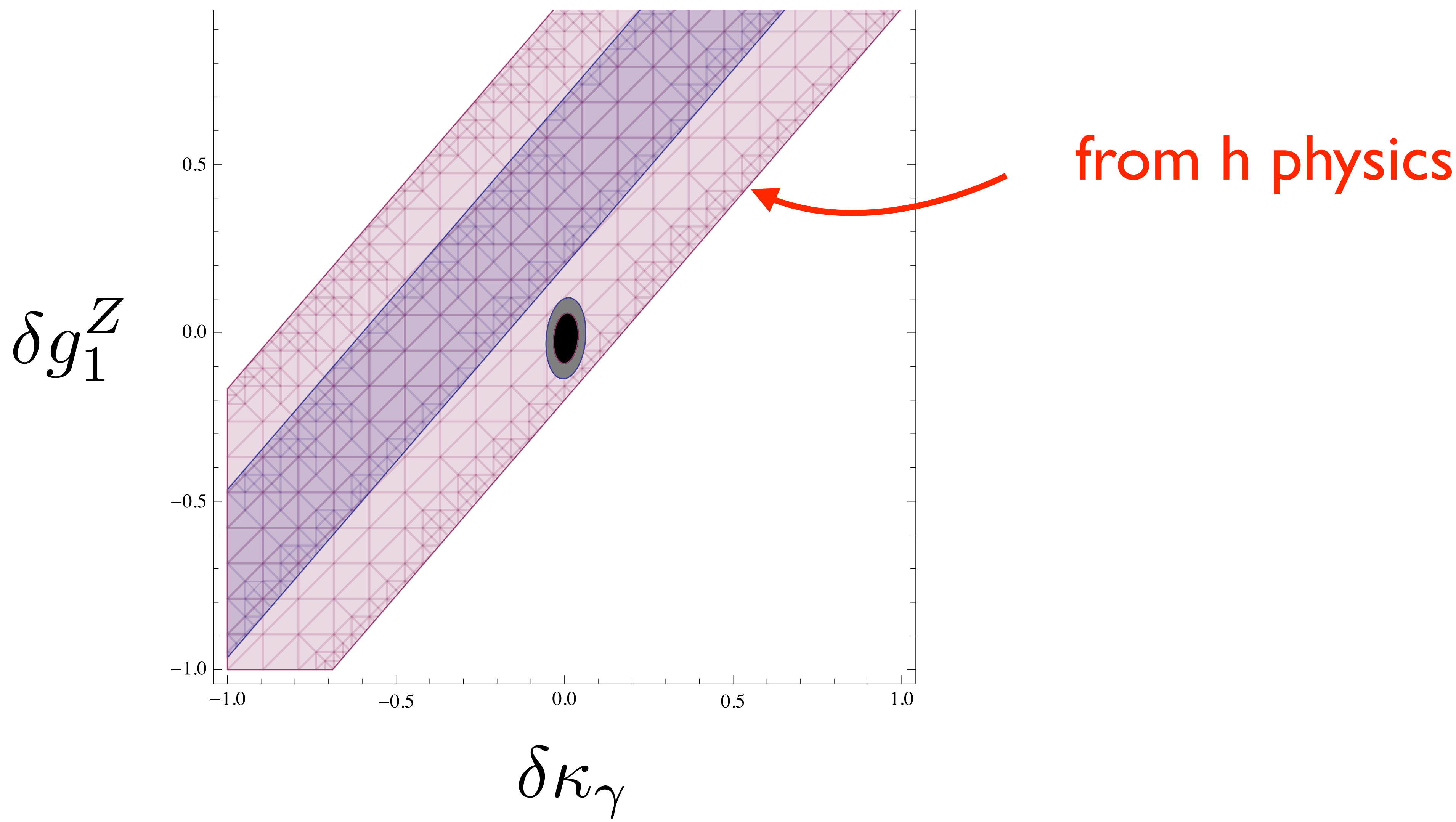
Where deviations on SM-scalar physics should not be found?

Where deviations on SM-scalar physics should not be found?

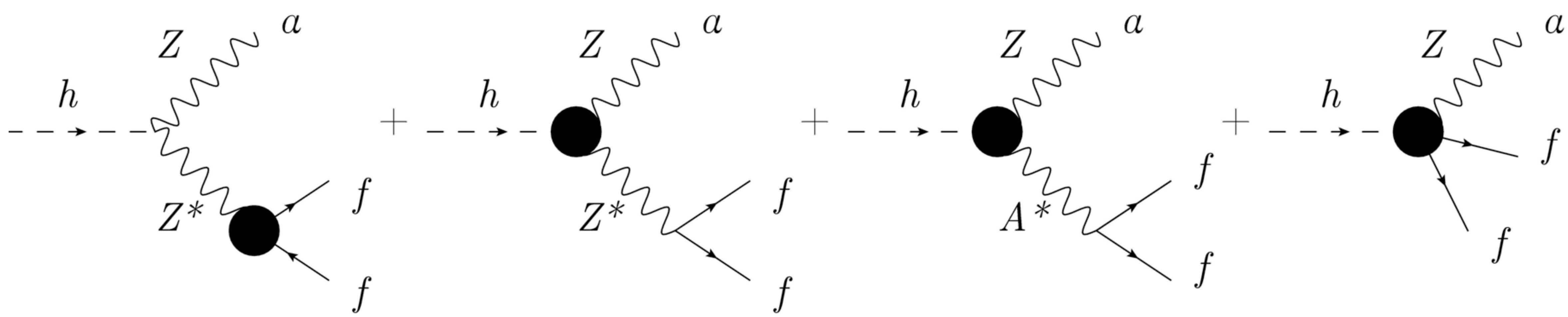


➥ **No large custodial-breaking effects allowed**

Contrary to certain literature, no relevant information from h physics to TGC



Predictions on h→Wff,Zff form-factors:



(assuming m_f=0 and CP-conservation)

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

$$A_f^V = a_f^V + \widehat{a}_f^V \frac{p^2 + M_V^2}{p^2 - M_V^2} \qquad\qquad B_f^V = b_f^V \frac{1}{p^2 - M_V^2} + \widehat{b}_f^V \frac{1}{p^2}$$

In principle, many new parameters to be measured in momentum distributions but already constrained from EWPT and TGC:

1) No large deviations from universality in $h \to Wff, Zff$ allowed

2)

using EWPT & TGC

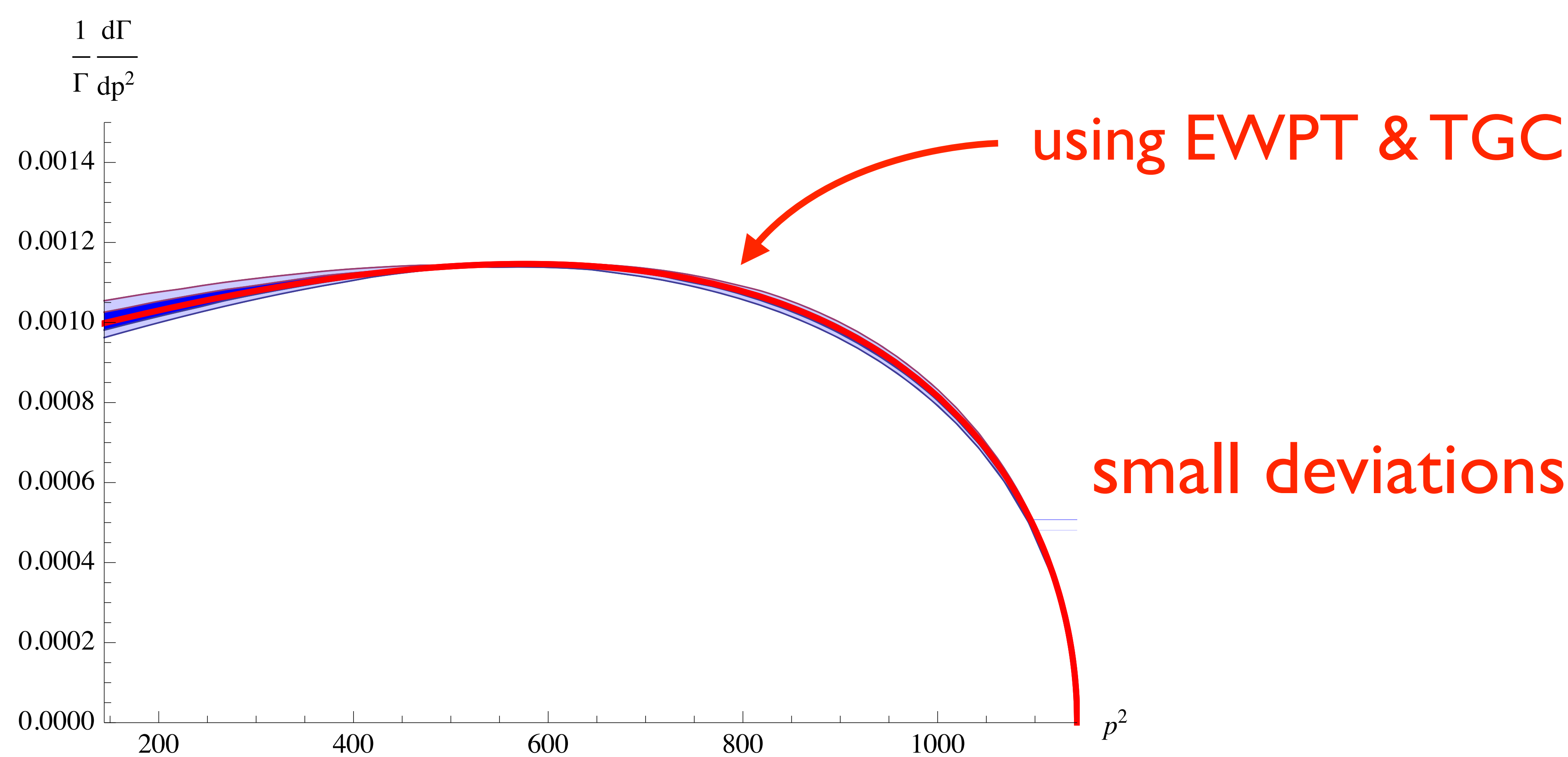
small deviations

(assuming no new-physics in $h \to \mathbf{Z}\gamma$)

but already constrained from EWPT and TGC:

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

2)



(assuming no new-physics in h→**Z**γ)

Conclusions

- Where could BSM physics hide in the SM-scalar sector?

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I wish I knew

- Model-independent analysis of new-effects on SM-scalar physics implies (assuming $\Lambda > M_W$):

<u>BSM-effects can hide in</u>

- $h \to \gamma\gamma$, $GG \to h$, $h \to ff$, $h \to VV^*$ (but already tested)
- $GG \to htt$, $h \to Z\gamma$ (to be tested at the LHC next run)

<u>No new BSM-effects expected in</u>

- $h \to Zff, Wff$ (small custodial breaking effect & small deviations in momentum distributions)

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- Model-independent analysis of new-effects on SM-scalar physics implies (assuming $\Lambda > M_W$):

<u>BSM-effects can hide in</u>

- $h \to \gamma\gamma$, $GG \to h$, $h \to ff$, $h \to VV^*$ (but already tested)
- $GG \to htt$, $h \to Z\gamma$ (to be tested at the LHC next run)

<u>No new BSM-effects expected in</u>

- $h \to Zff, Wff$ (small custodial breaking effect & small deviations in momentum distributions)

If discovered here,
we could have been missing light new-physics!

Backup

Backup

(are you really so interested that you want to see more slides?)

Not possible splitting between W-couplings and Z-couplings with dim-6 operators:

$$W_{3\,\mu} J_3^\mu \in \mathbf{3x3} = \mathbf{5} + \dots$$ of SU(2)

$\hookrightarrow$ not possible at order $h^2 \in H^\dagger \sigma^a H \in \mathbf{3}$

Remnants of SU(2) (custodial) symmetry:

➥ Deviations in W-couplings related to those in Z-couplings

BSM Scenarios:

Composite Higgs

PGB Higgs:
Invariance under
H→H+c

$$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2$$

$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$

$$\mathcal{O}_6 = \lambda |H|^6$$

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$$

$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$

$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$

$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$$

h→Zγ

$\mathcal{O}_{y_u} = y_u \|H\|^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \|H\|^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \|H\|^2 \bar{L}_L H e_R$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
		$\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$

BSM Scenarios:

MSSM Higgs

$$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2$$

$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$

$$\mathcal{O}_6 = \lambda |H|^6$$

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$$

$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$

$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$

at the loop-level

$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$$

$\mathcal{O}_{y_u} = y_u |H|^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d |H|^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e |H|^2 \bar{L}_L H e_R$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}^{(3)\,q}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
		$\mathcal{O}^{(3)\,l}_{LL} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$