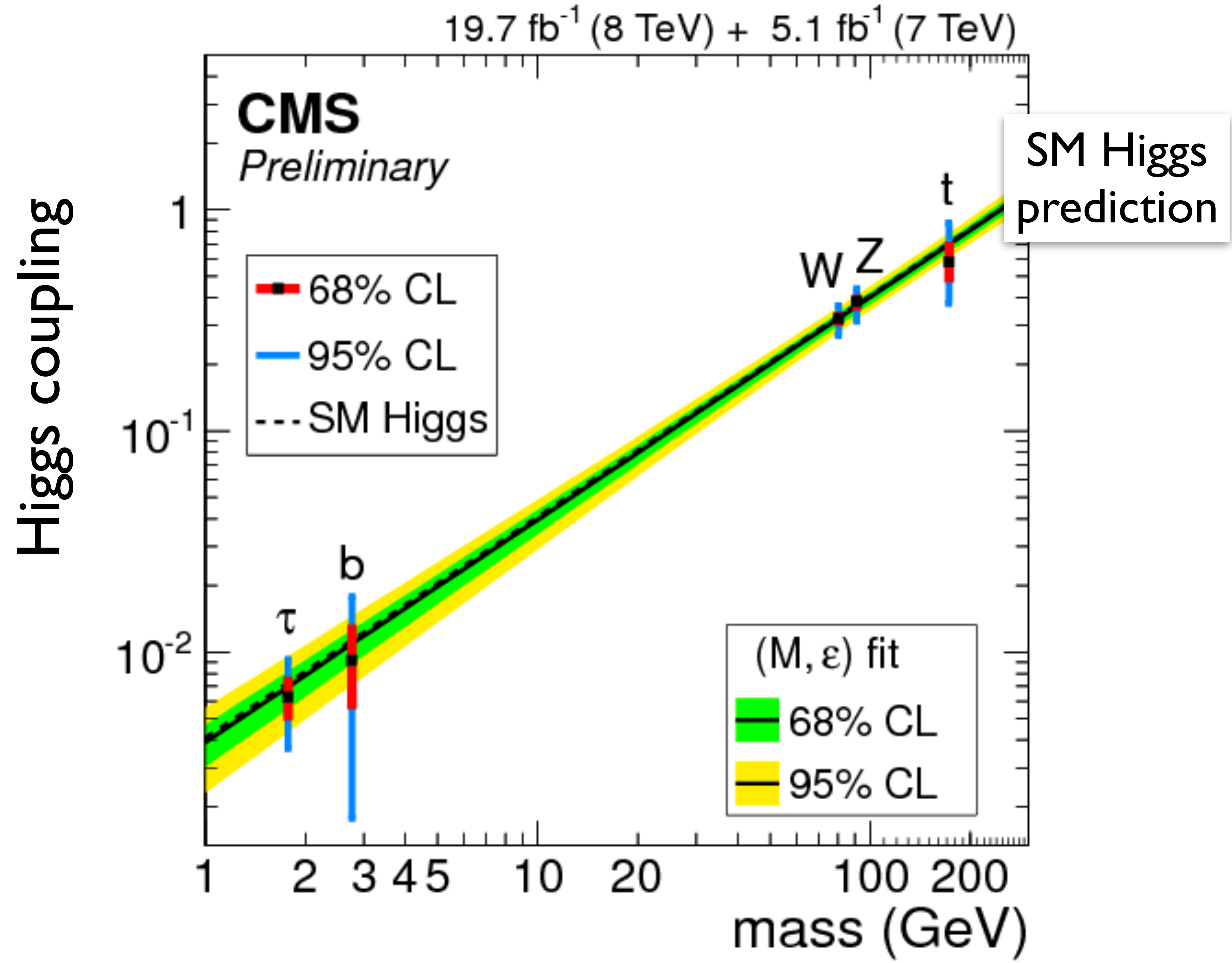
Perspectives in EWSB & Higgs Physics

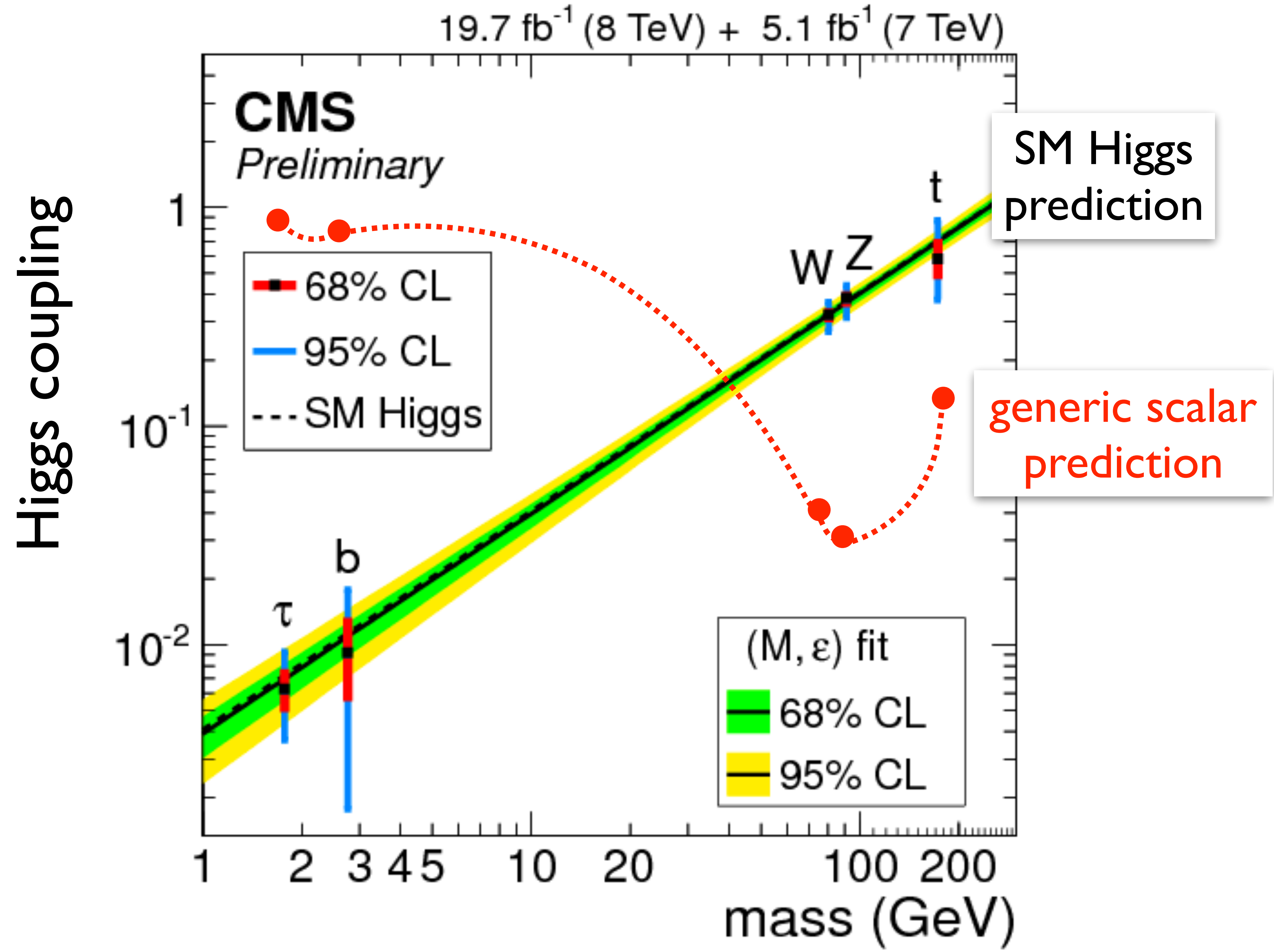
Alex Pomarol, UAB (Barcelona)

Best **LHC** Run I legacy: **The Higgs discovery**



Coupling-Mass relations as in the SM Higgs

Best **LHC** Run I legacy: The Higgs discovery



➥ **"Higgs impostors" left behind!**

The SM is established !

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Where to expect new-physics (beyond the SM)?

Where a new paradigm is needed?

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Where to expect new-physics (beyond the SM)?

Where a new paradigm is needed?

To answer this, we can follow Einstein's path:

"*Gedankenexperiment*"

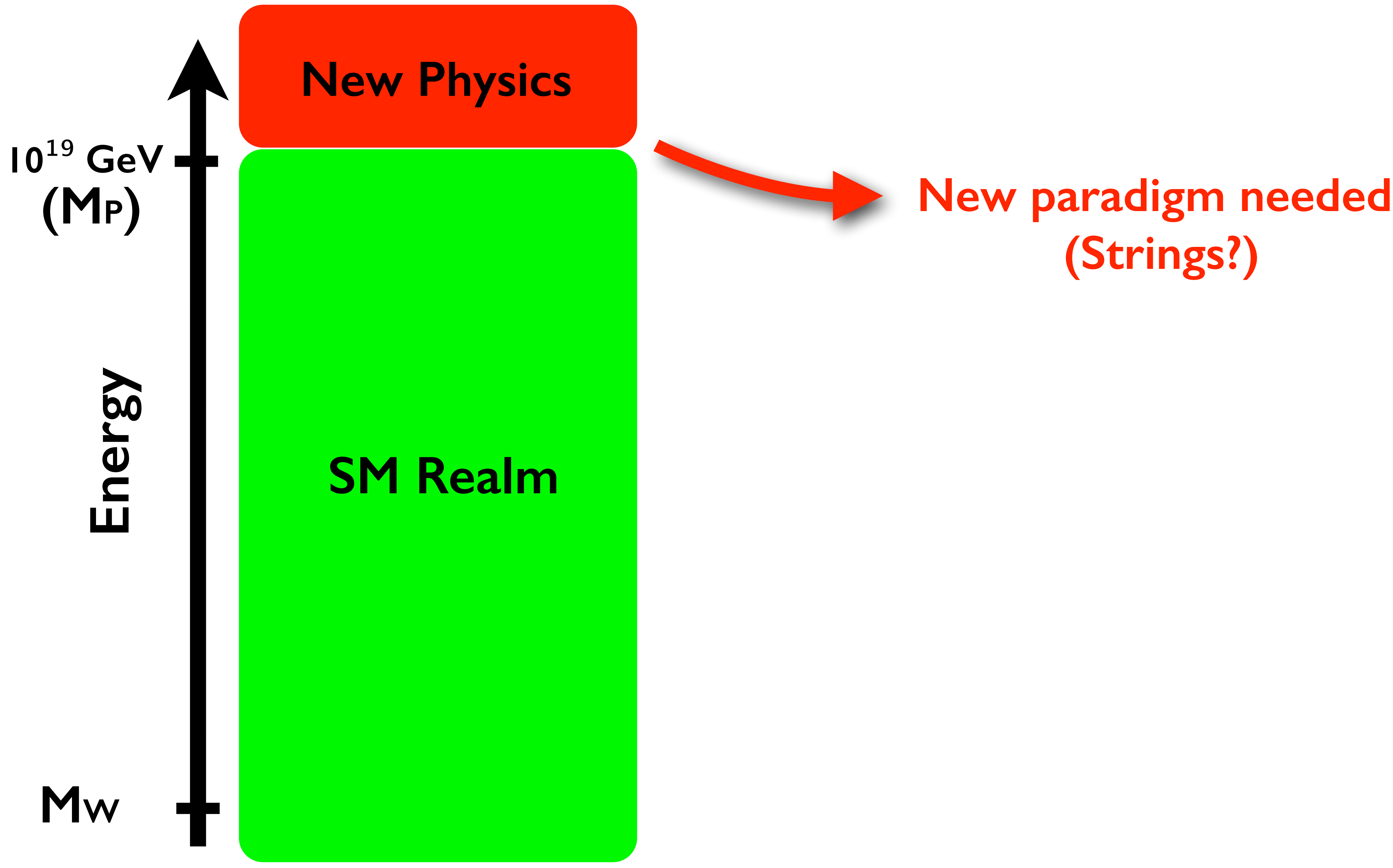
(*thought experiments*):

look at which regime the theory **fails,**
and therefore **new physics** must appear!

☛ <u>no-lose theorem</u>
for a discovery

guaranteed the discover of the positron, charm,…, top & Higgs (or something else)

With m_H~125 GeV, **the SM**, is a consistent theory all the way to M_P



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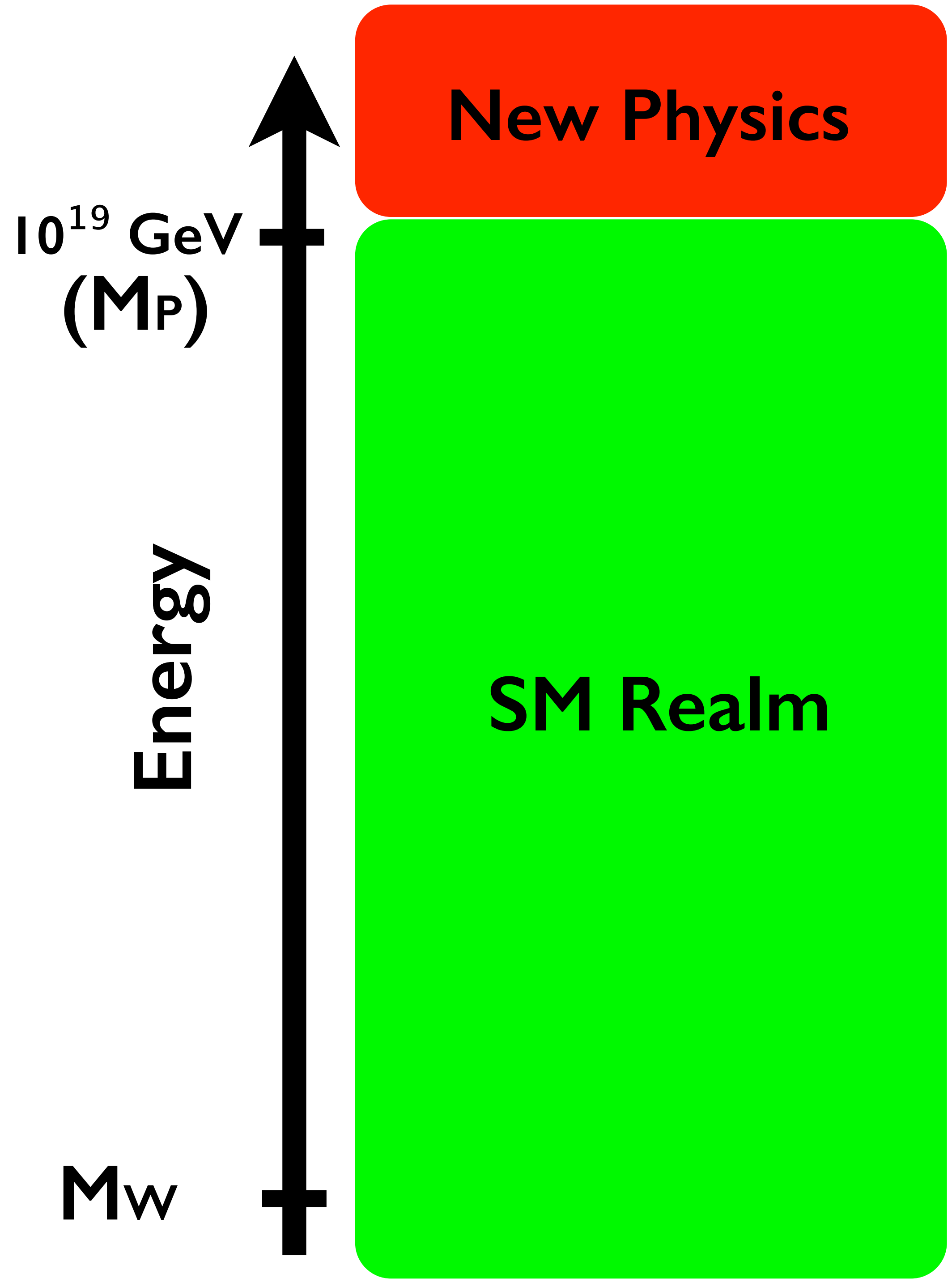

New paradigm needed
(Strings?)

First time in particle physics that **new-physics** scale is **far away** from current **experiments**

dying of success?

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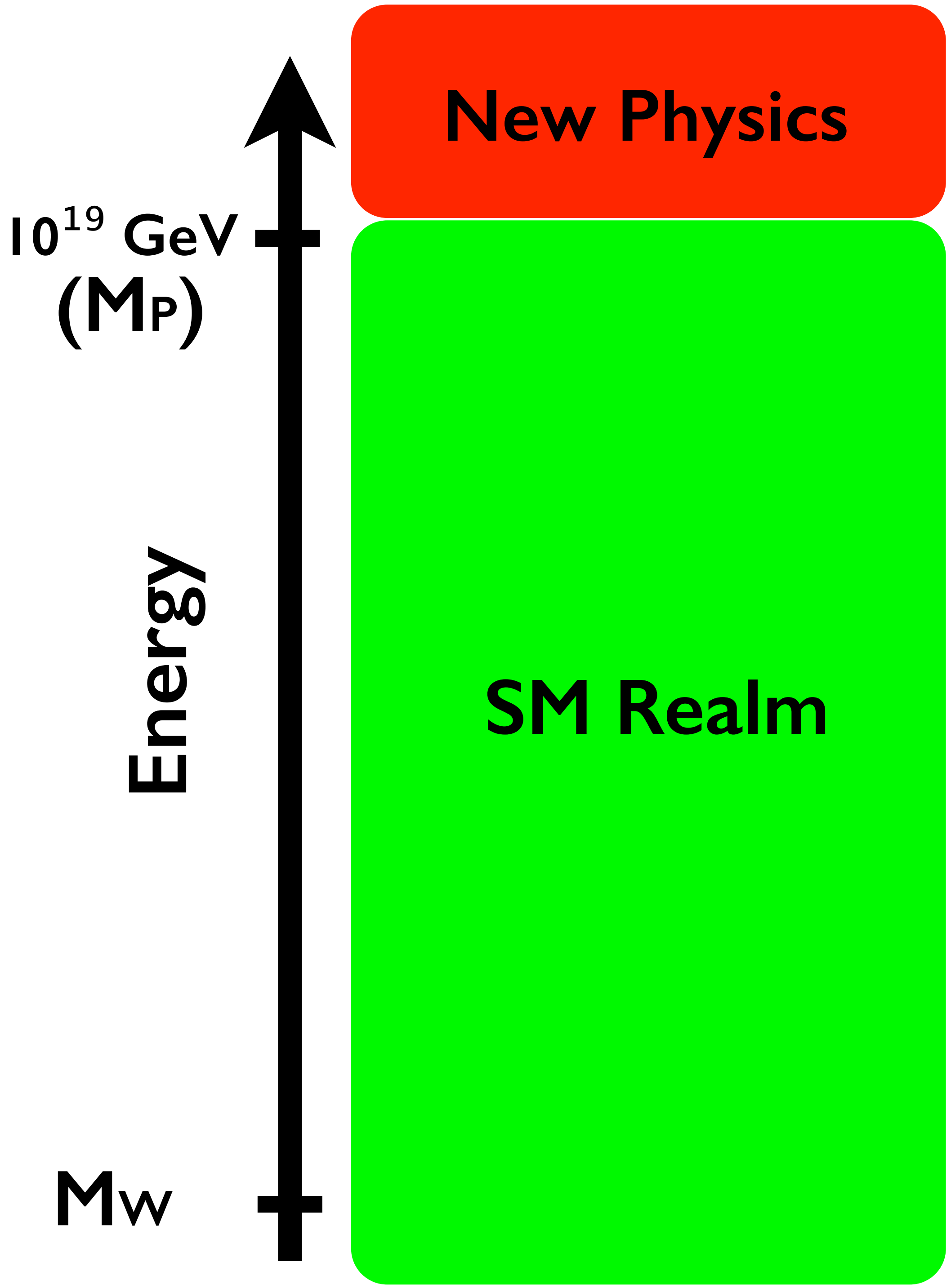
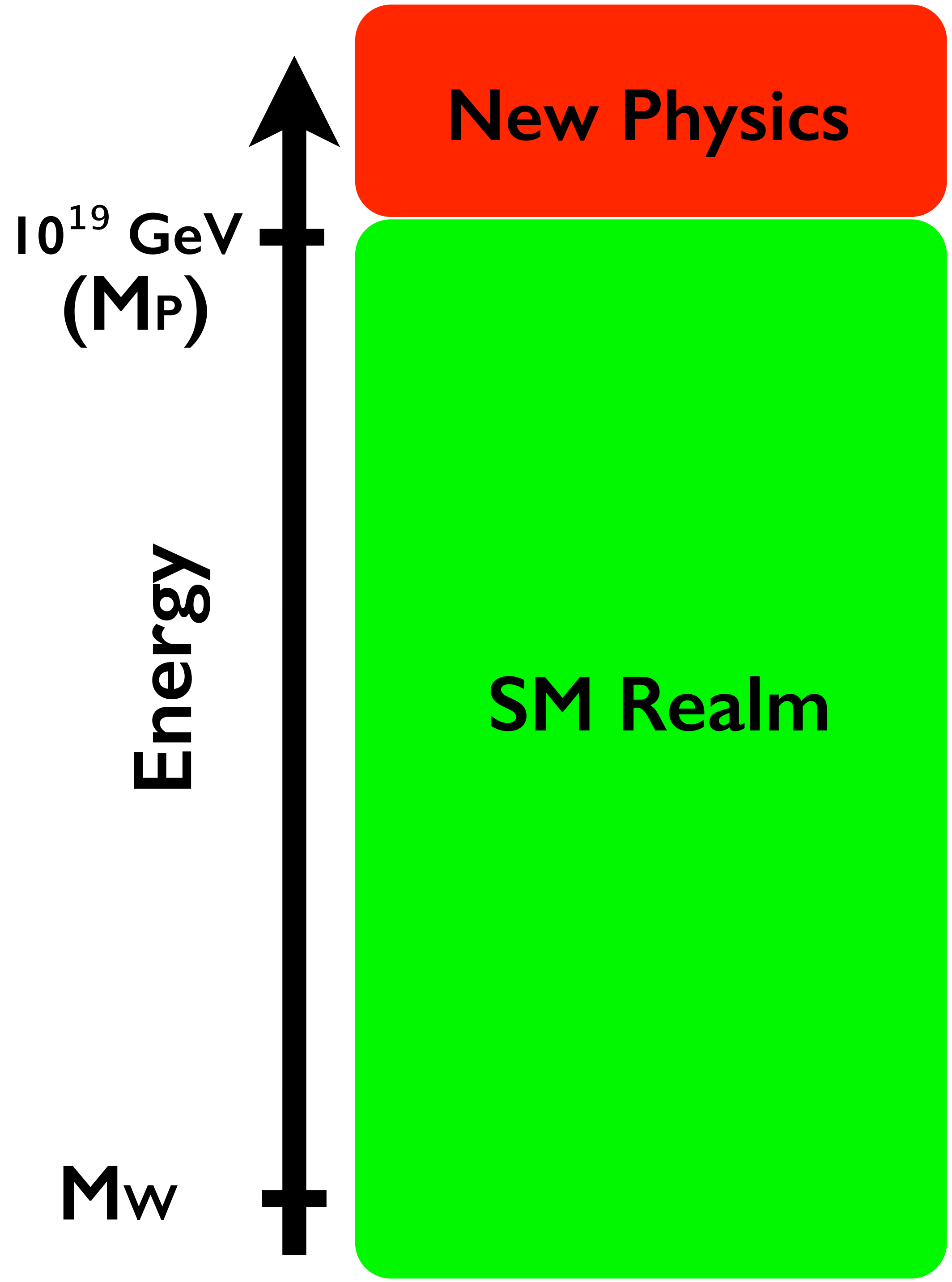


New motivation to go beyond:

Naturalness (Esthetics!)

With m_H~125 GeV, **the SM**, is a consistent theory all the way to M_P

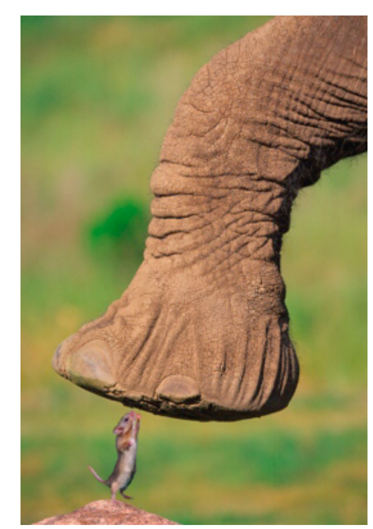


New motivation to go beyond:
Naturalness (Esthetics!)

m_H << M_P

Why so different?

Not natural/stable to expect



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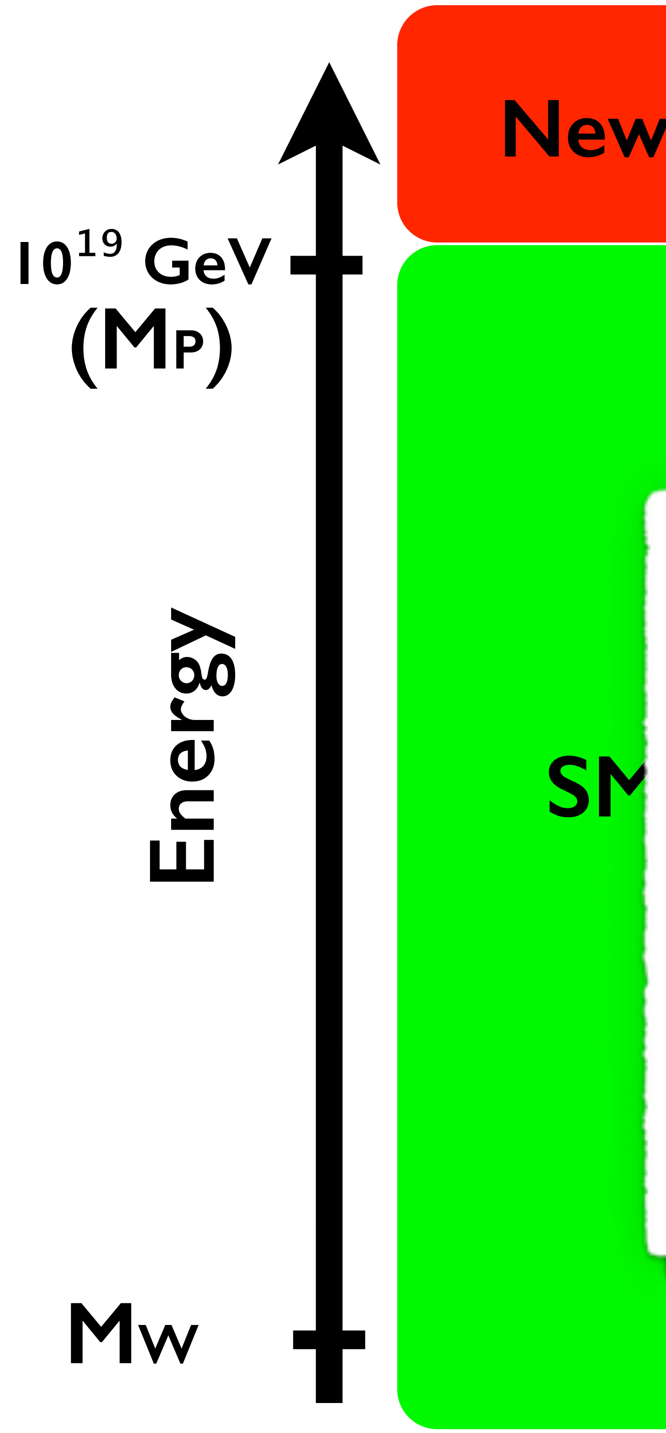
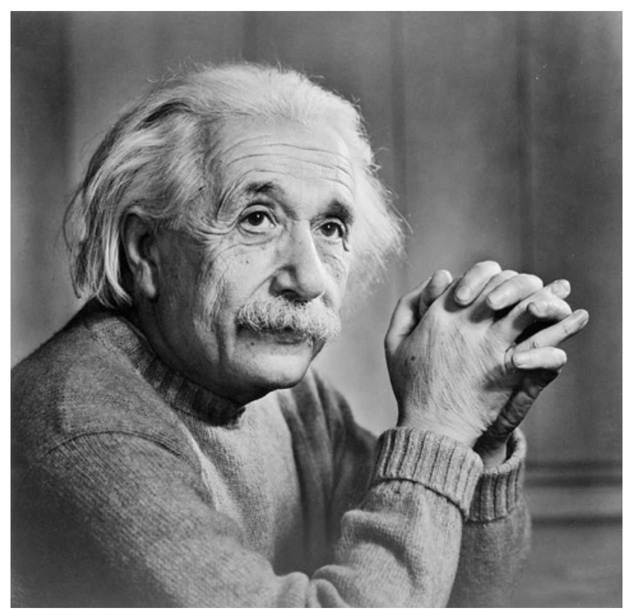


New motivation to go beyond:
Naturalness (Esthetics!)

Following a more (risky) mature Einstein's path:



"the principle of the universe will be beautiful and simple"

$m_H << M_P$?

Towards naturalness

"fermionizing" the Higgs

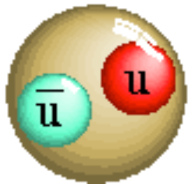
Supersymmetry

"marrying" a fermion:

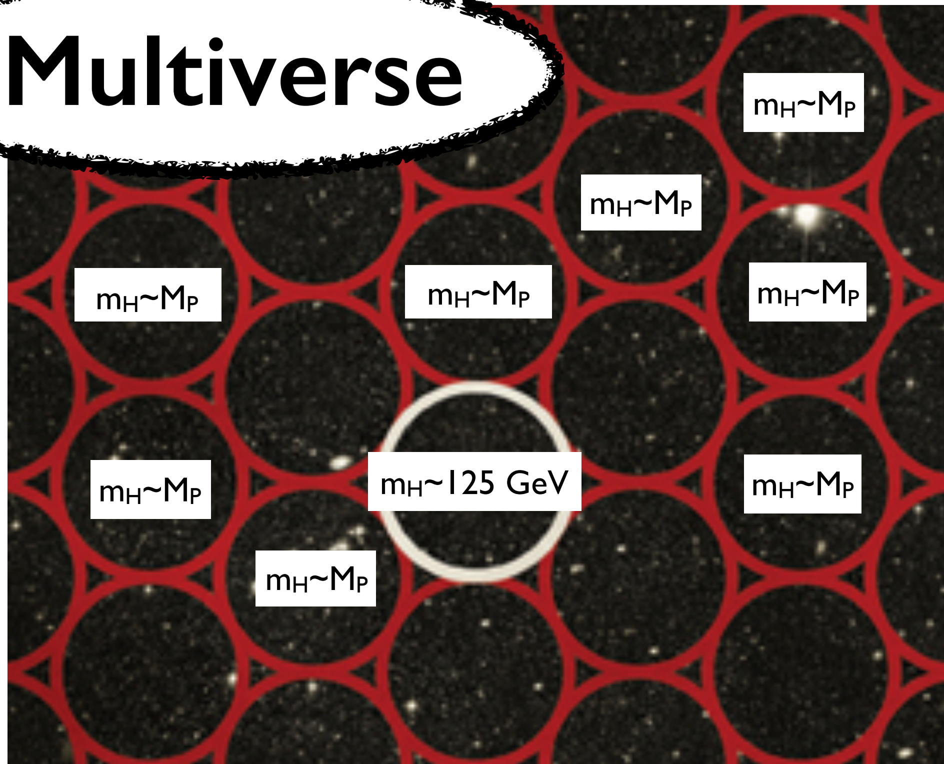
Higgs ⟷ Higgsino

Compositeness

The "transvestite" Higgs:

H = 

Multiverse



relaxation mechanism?

arXiv:1504.07551

$m_H << M_P$?

Towards naturalness

No new TeV-physics

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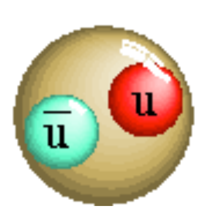
H = 

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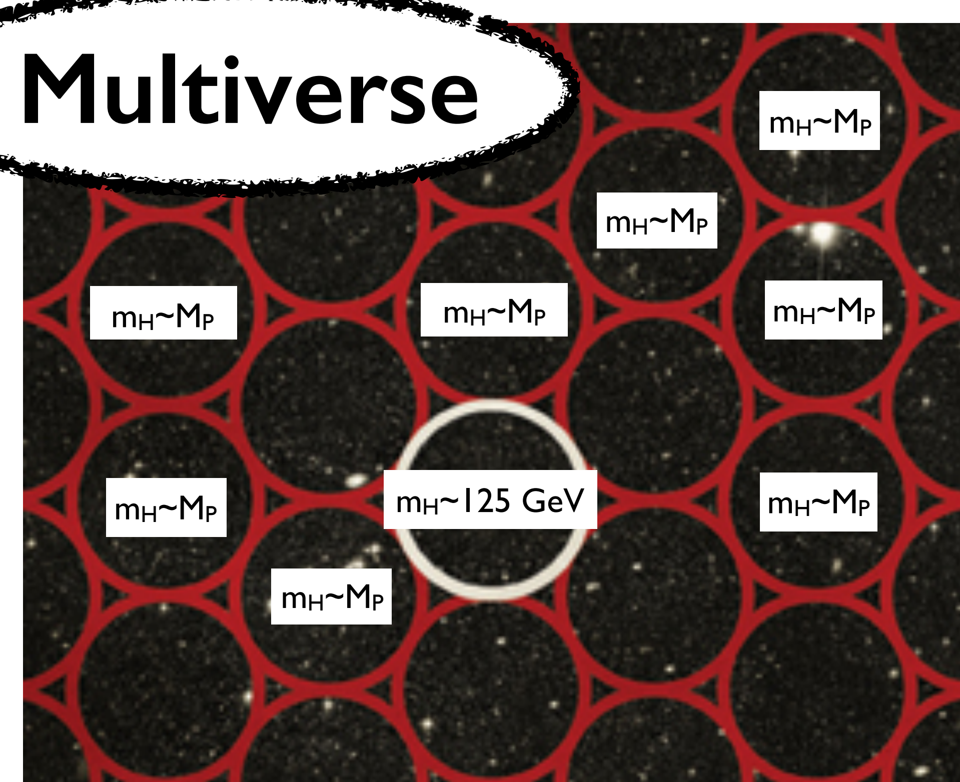

new TeV-physics

$m_H << M_P$?

Towards naturalness

Here we will discuss:

Supersymmetry

"marrying" a fermion:

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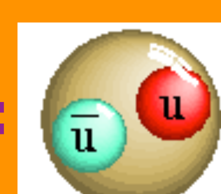
H = 

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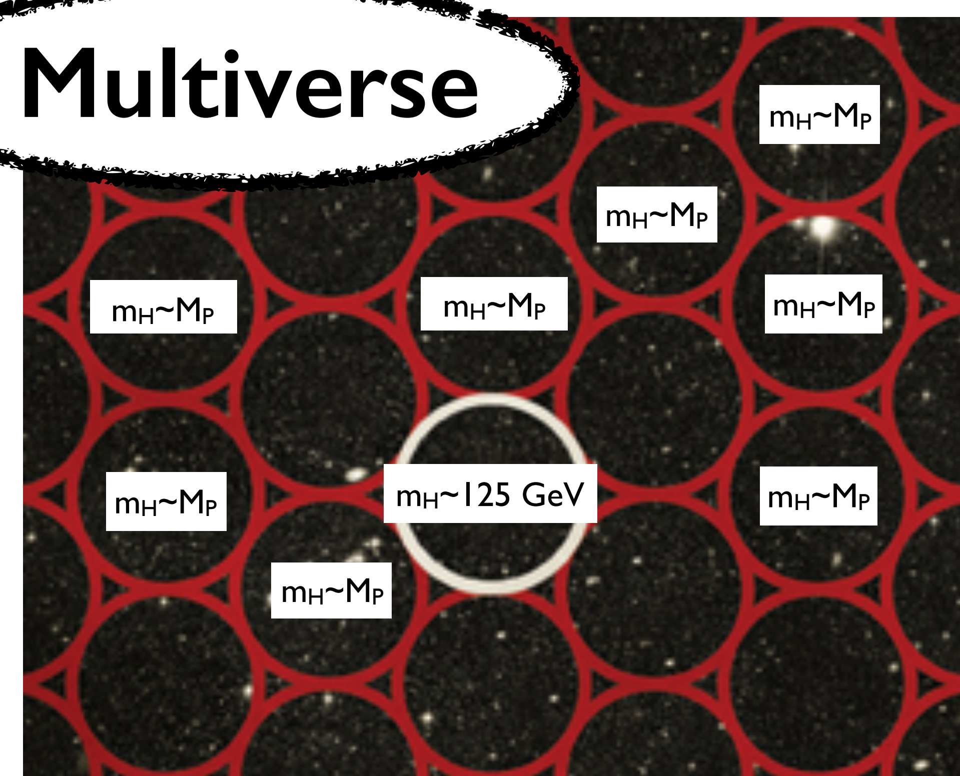

First important place for *natural* theories (BSM) to show up:

LEP

~ millions of Z produced

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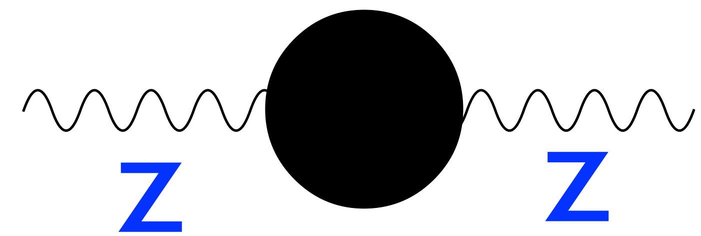
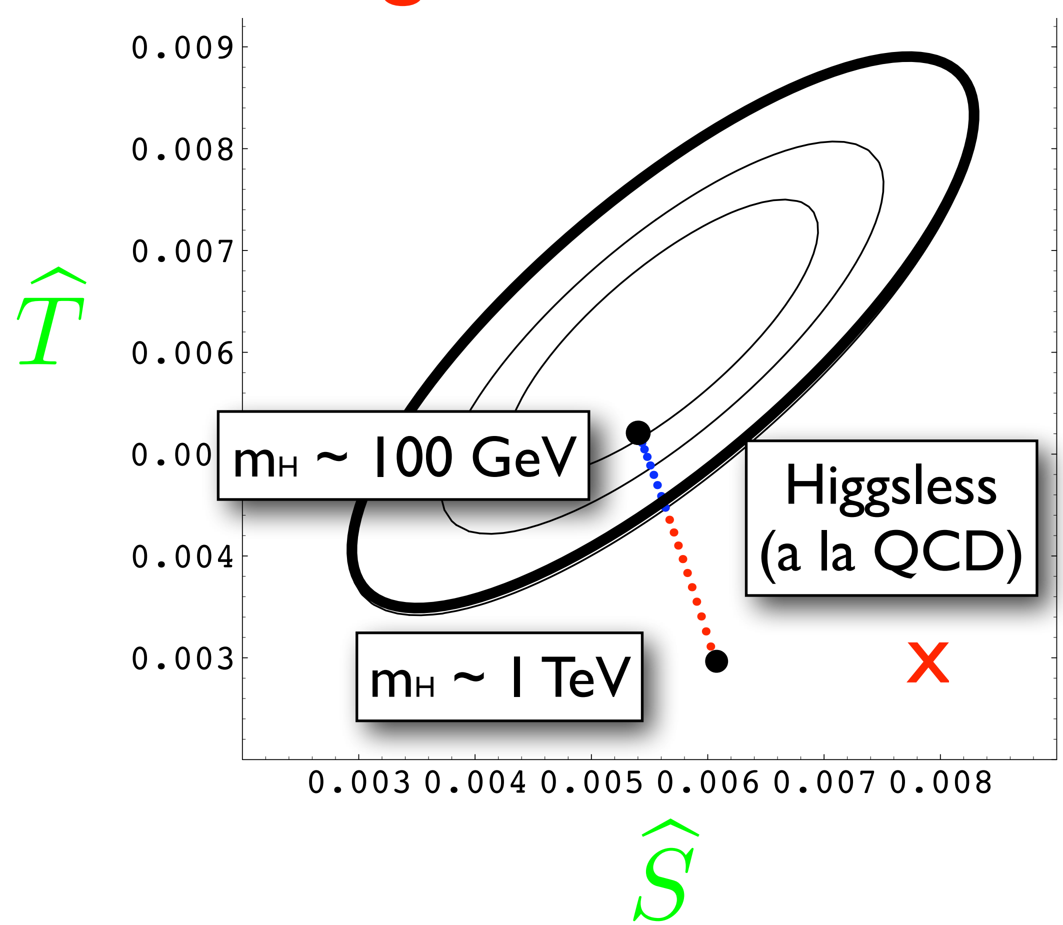


But no sign of BSM effects:



Expected from Composite Higgs:

$\hat{T}$~$O(1)$ 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”

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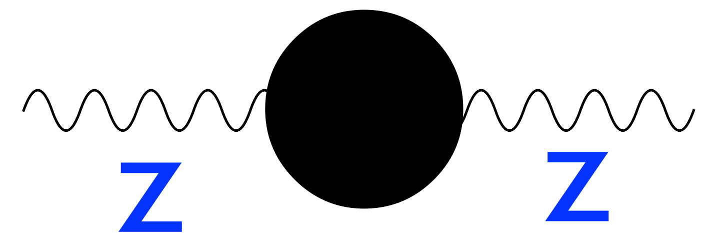

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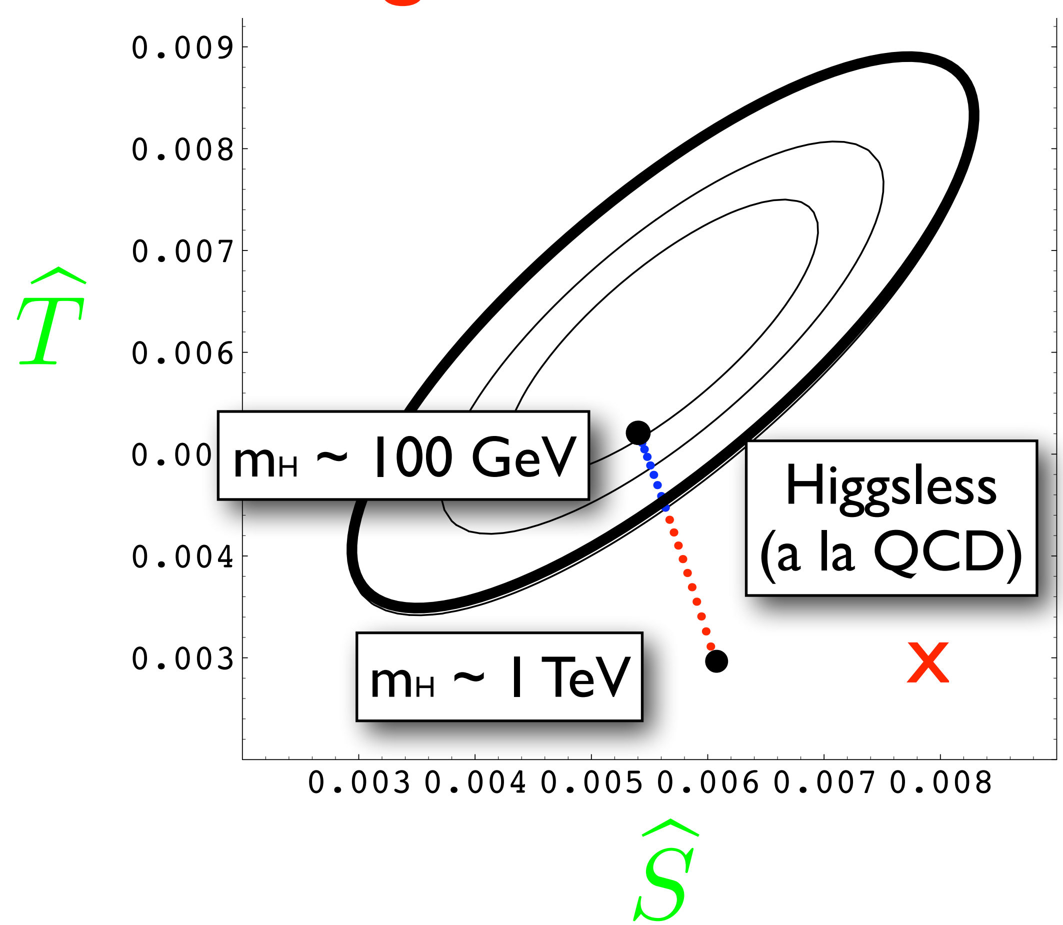
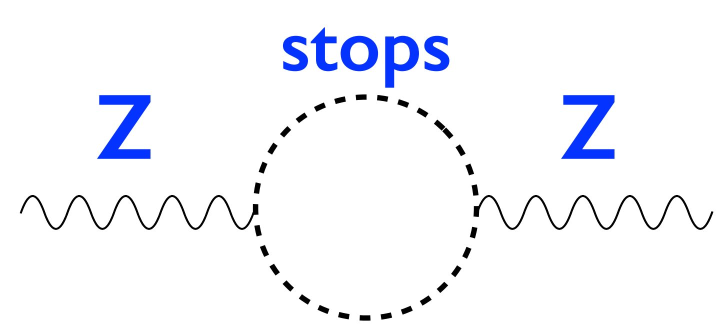


In the supersymmetric Higgs:

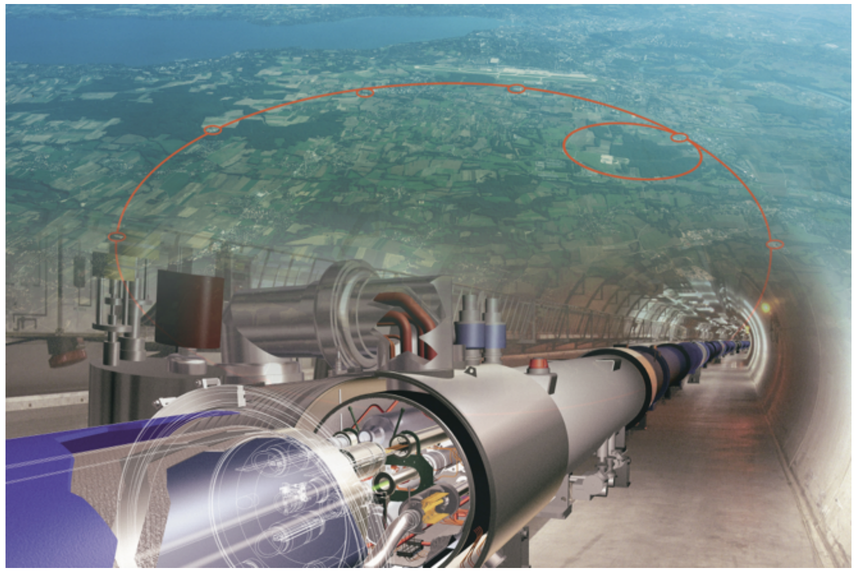


$\hat{T} \sim O(10^{-2})$

stop mass > 300 GeV

Second important place for *natural* theories (BSM) to show up:

LHC



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**

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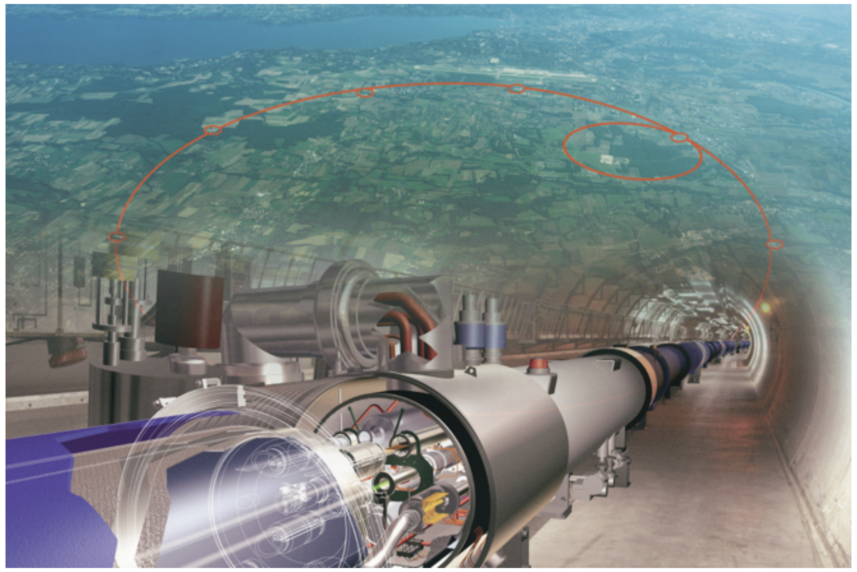


the Higgs discovery has provided a new "handle" to catch BSMs

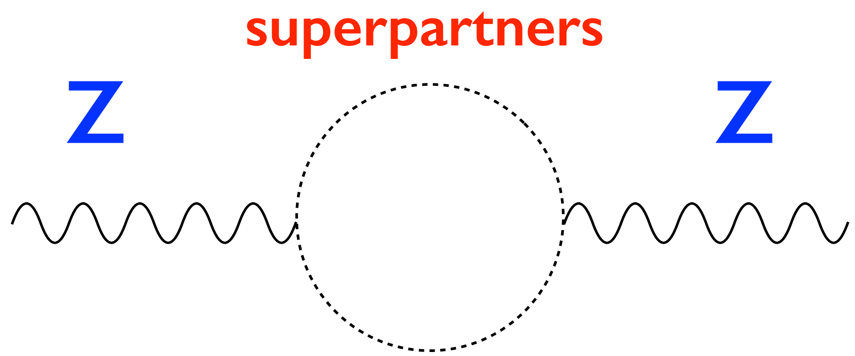
With the **Higgs**, we have had access to new relevant information by measuring its **properties**

The Higgs is the most "sensitive" SM particle to new-physics, and therefore the best place to look for *natural* BSM

Examples:

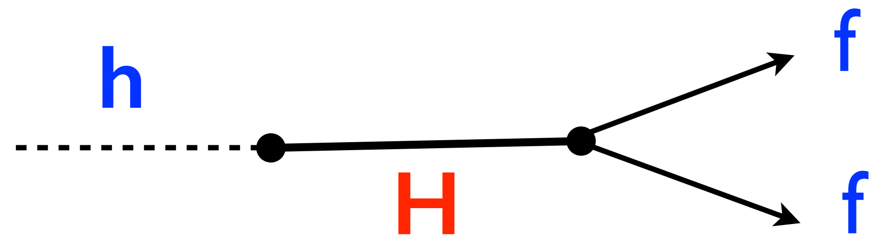
1) <u>MSSM</u>:

Gauge bosons:



~ loop effects

Higgs:



~ tree-level effects

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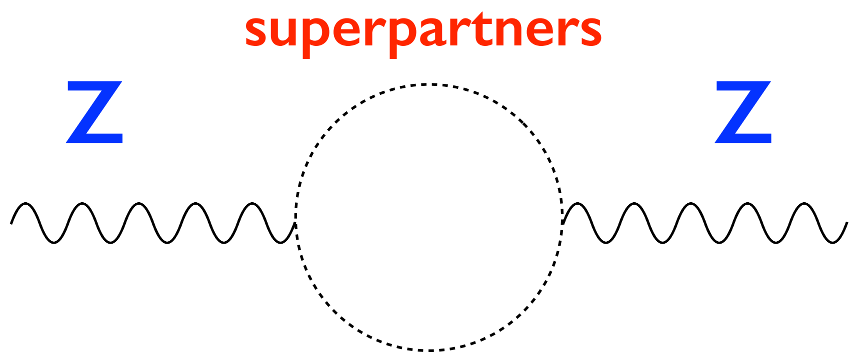

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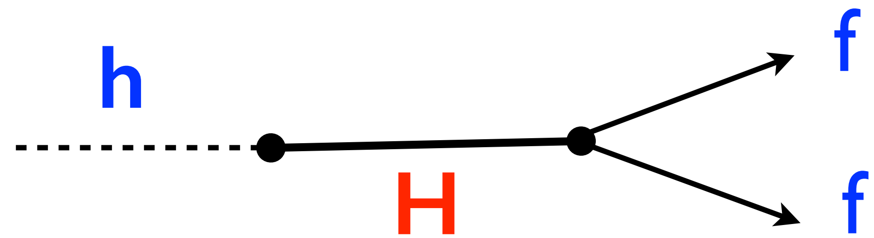

~ tree-level effects

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

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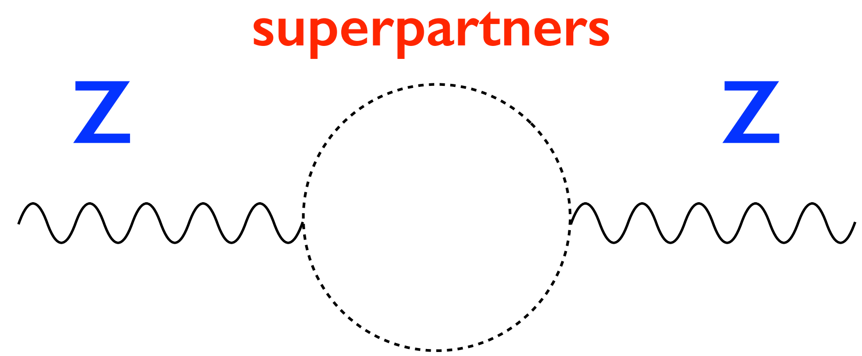
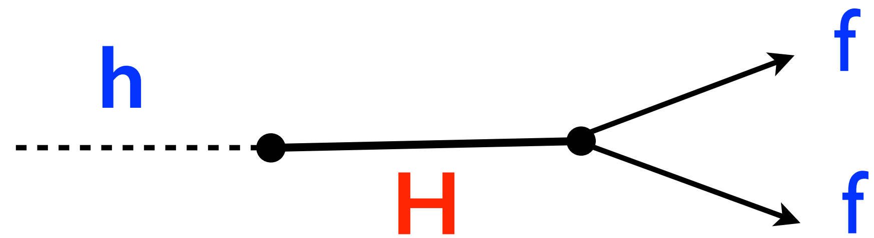


~ loop effects

Higgs:

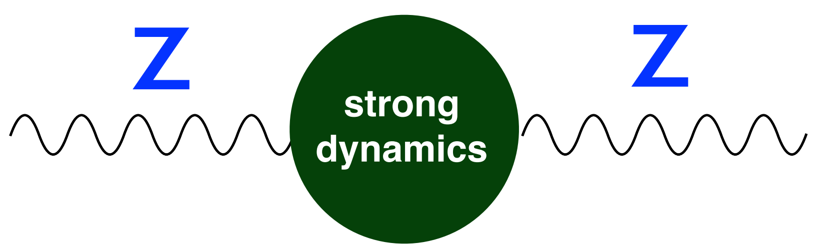


~ tree-level effects

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

2) Composite models:

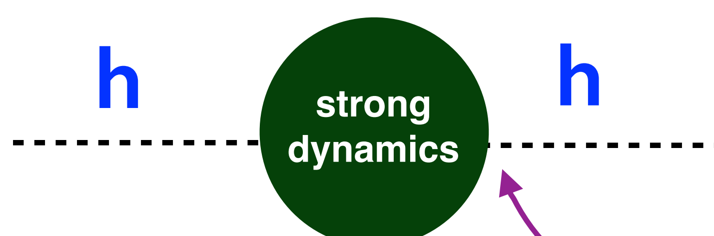
Gauge bosons:



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

(Λ=composite scale)

Higgs:



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

"strong" Higgs coupling

Consequences:

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

LEP: **ee→ Z (→ff) ~ millions of events**

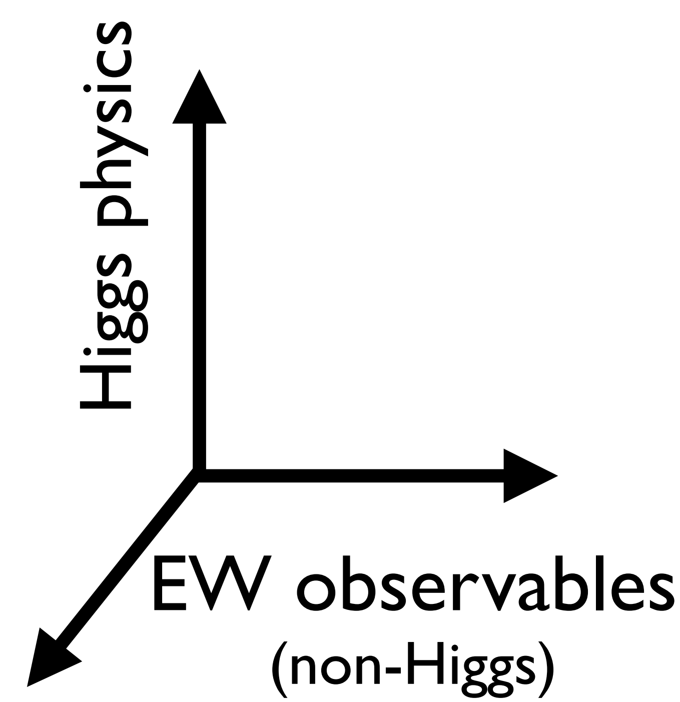
LHC: **pp→h (→γγ) ~ thousands of events**

First question to address in Higgs couplings:

Which are the most relevant Higgs couplings to measure?

probes testing
new directions in the
"parameter space" of BSMs

(tell us things that we didn't know!)



Model independent analysis

Assuming a large new-physics scale: **Λ>>m$_W$** (as LHC suggests)

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

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

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

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

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

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

$\mathcal{O}_{y_u} = y_u \vert H\vert^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \vert H\vert^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \vert H\vert^2 \bar{L}_L H e_R$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu \sigma^a Q_L)$	$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$ $\mathcal{O}_L^l = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$ $\mathcal{O}_L^{(3)\,l} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu \sigma^a L_L)$
$\mathcal{O}_{LR}^u = (\bar{Q}_L \gamma^\mu Q_L)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}_{LR}^{(8)\,u} = (\bar{Q}_L \gamma^\mu T^A Q_L)(\bar{u}_R \gamma^\mu T^A u_R)$ $\mathcal{O}_{RR}^u = (\bar{u}_R \gamma^\mu u_R)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}_{LL}^q = (\bar{Q}_L \gamma^\mu Q_L)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}_{LL}^{(8)\,q} = (\bar{Q}_L \gamma^\mu T^A Q_L)(\bar{Q}_L \gamma^\mu T^A Q_L)$	$\mathcal{O}_{LR}^d = (\bar{Q}_L \gamma^\mu Q_L)(\bar{d}_R \gamma^\mu d_R)$ $\mathcal{O}_{LR}^{(8)\,d} = (\bar{Q}_L \gamma^\mu T^A Q_L)(\bar{d}_R \gamma^\mu T^A d_R)$ $\mathcal{O}_{RR}^d = (\bar{d}_R \gamma^\mu d_R)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}_{LR}^e = (\bar{L}_L \gamma^\mu L_L)(\bar{e}_R \gamma^\mu e_R)$ $\mathcal{O}_{RR}^e = (\bar{e}_R \gamma^\mu e_R)(\bar{e}_R \gamma^\mu e_R)$ $\mathcal{O}_{LL}^l = (\bar{L}_L \gamma^\mu L_L)(\bar{L}_L \gamma^\mu L_L)$
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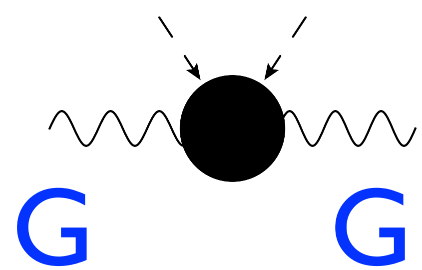
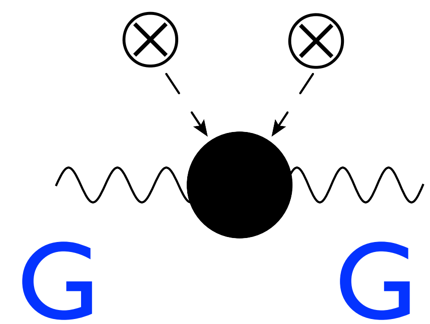
$\mathcal{O}_{DB}^u = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \widetilde{H} g' B_{\mu\nu}$ $\mathcal{O}_{DW}^u = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \sigma^a \widetilde{H} g W^a_{\mu\nu}$ $\mathcal{O}_{DG}^u = y_u \bar{Q}_L \sigma^{\mu\nu} T^A u_R \widetilde{H} g_s G^A_{\mu\nu}$	$\mathcal{O}_{DB}^d = y_d \bar{Q}_L \sigma^{\mu\nu} d_R H g' B_{\mu\nu}$ $\mathcal{O}_{DW}^d = y_d \bar{Q}_L \sigma^{\mu\nu} d_R \sigma^a H g W^a_{\mu\nu}$ $\mathcal{O}_{DG}^d = y_d \bar{Q}_L \sigma^{\mu\nu} T^A d_R H g_s G^A_{\mu\nu}$	$\mathcal{O}_{DB}^e = y_e \bar{L}_L \sigma^{\mu\nu} e_R H g' B_{\mu\nu}$ $\mathcal{O}_{DW}^e = y_e \bar{L}_L \sigma^{\mu\nu} e_R \sigma^a H g W^a_{\mu\nu}$

Too many new terms to say something?

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

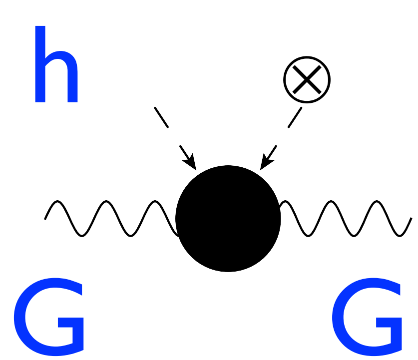
e.g. $$\frac{1}{g_s^2}G_{\mu\nu}^2+\frac{|H|^2}{\Lambda^2}G_{\mu\nu}^2\to\left(\frac{1}{g_s^2}+\frac{v^2}{\Lambda^2}\right)G_{\mu\nu}^2$$





Not physical!

But can affect **Higgs** physics:



affects GG →h!

There are 8 operators of this type

for one family

(assuming CP-conservation)

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

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

$$|H|^2 W^a_{\mu\nu} W^{\mu\nu\, a}$$

$$|H|^2 |D_\mu H|^2$$

$$|H|^6$$

$$|H|^2 \bar{f}_L H f_R + h.c.$$

(f=b, τ, t)

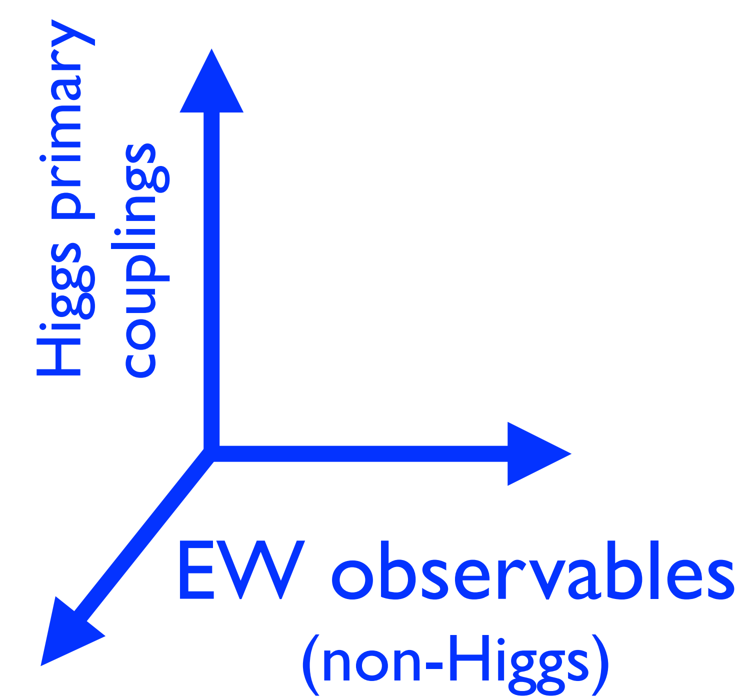
➥ Only **8 Higgs couplings** *(assuming CP-conservation and one family)*

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

8 Primary Higgs couplings:

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

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



➥ Only **8 Higgs couplings** *(assuming CP-conservation and one family)*

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

$\boxed{\text{8 Primary Higgs couplings:}}$

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

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

important:
custodial invariant!!
& zero-momentum

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

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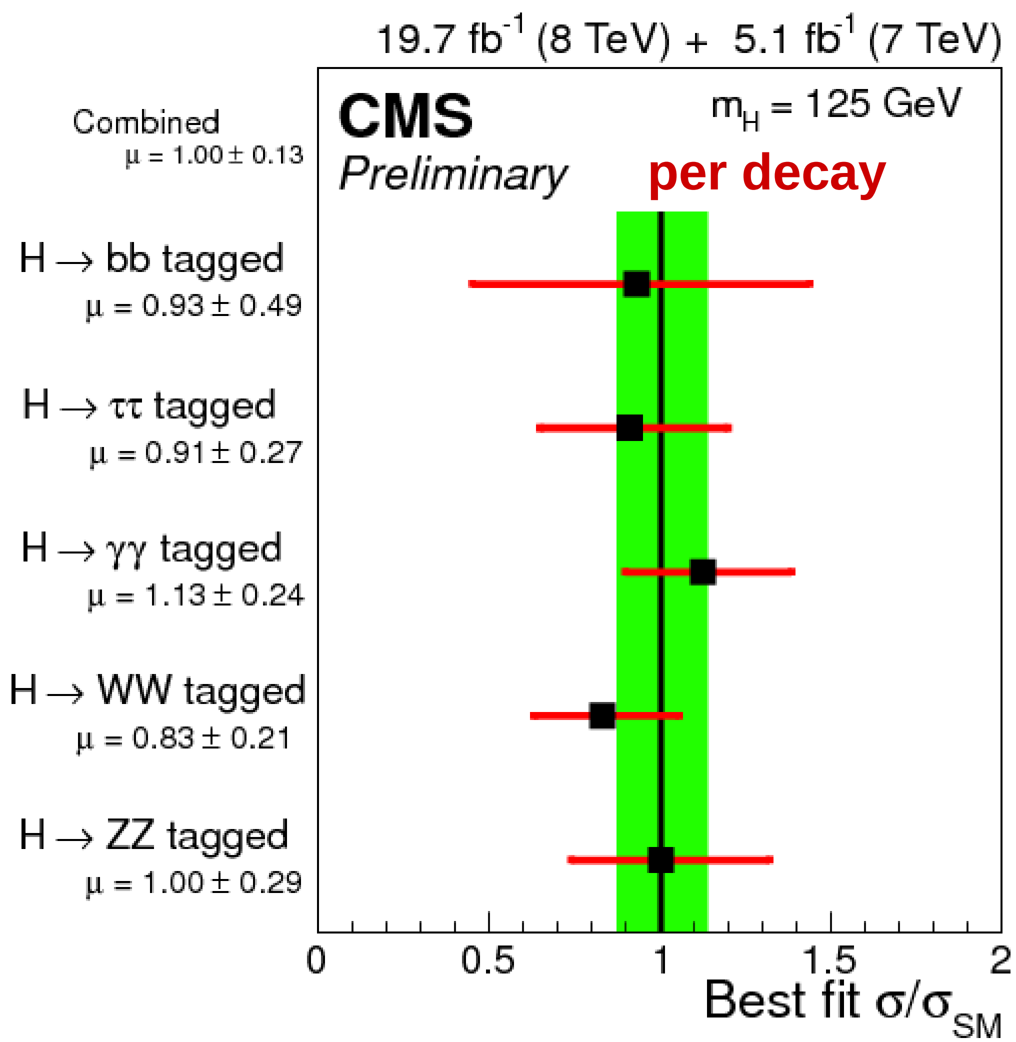
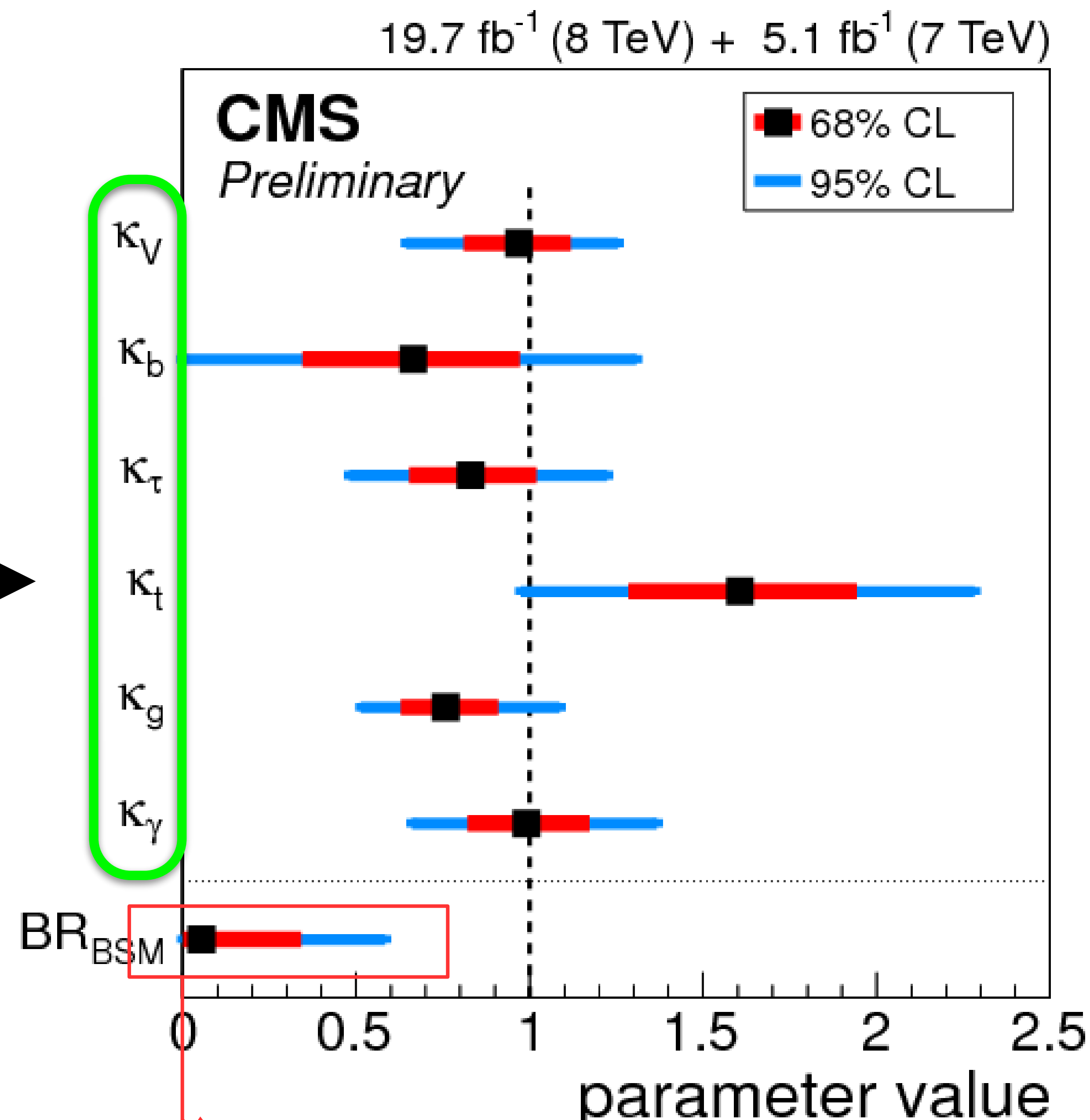
$$+\, \delta g_{3h}\, h^3$$

6 measured at the LHC
(the “kappas”)

Higgs coupling determination



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



All parameters floating and $\kappa_V \leq 1$

reasonable good agreement with the SM !

➥ Only 8 Higgs couplings *(assuming CP-conservation and one family)*

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Elias-Miro, Espinosa, Masso, AP, JHEP 1311 (2013) 066
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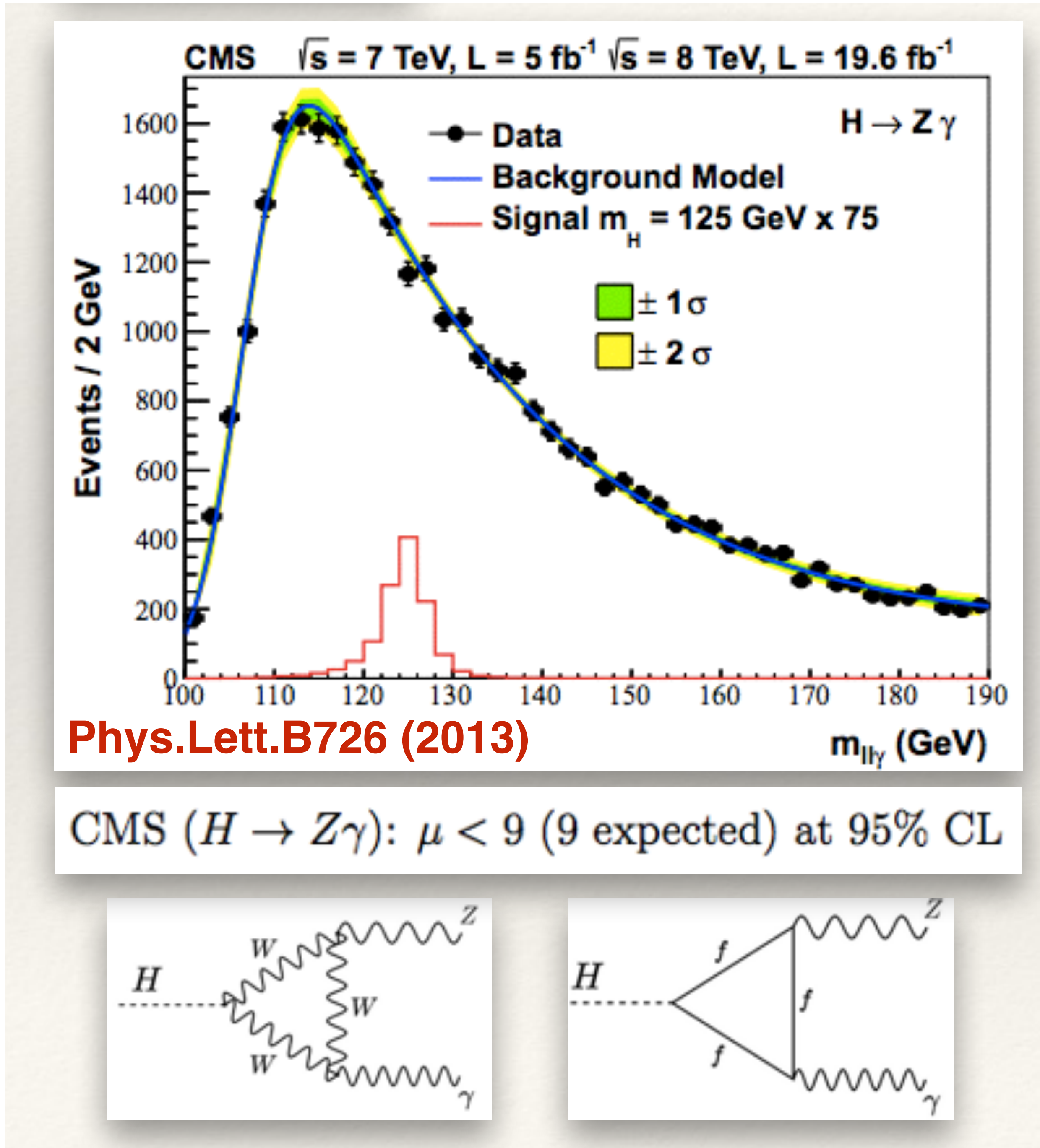
$$+\, \delta g_{3h}\, h^3$$

6 measured at the LHC (the "kappas")

$h \to Z\gamma$

It can be measured in the far future by $GG \to hh$

Experimental bound on $h \to Z\gamma$



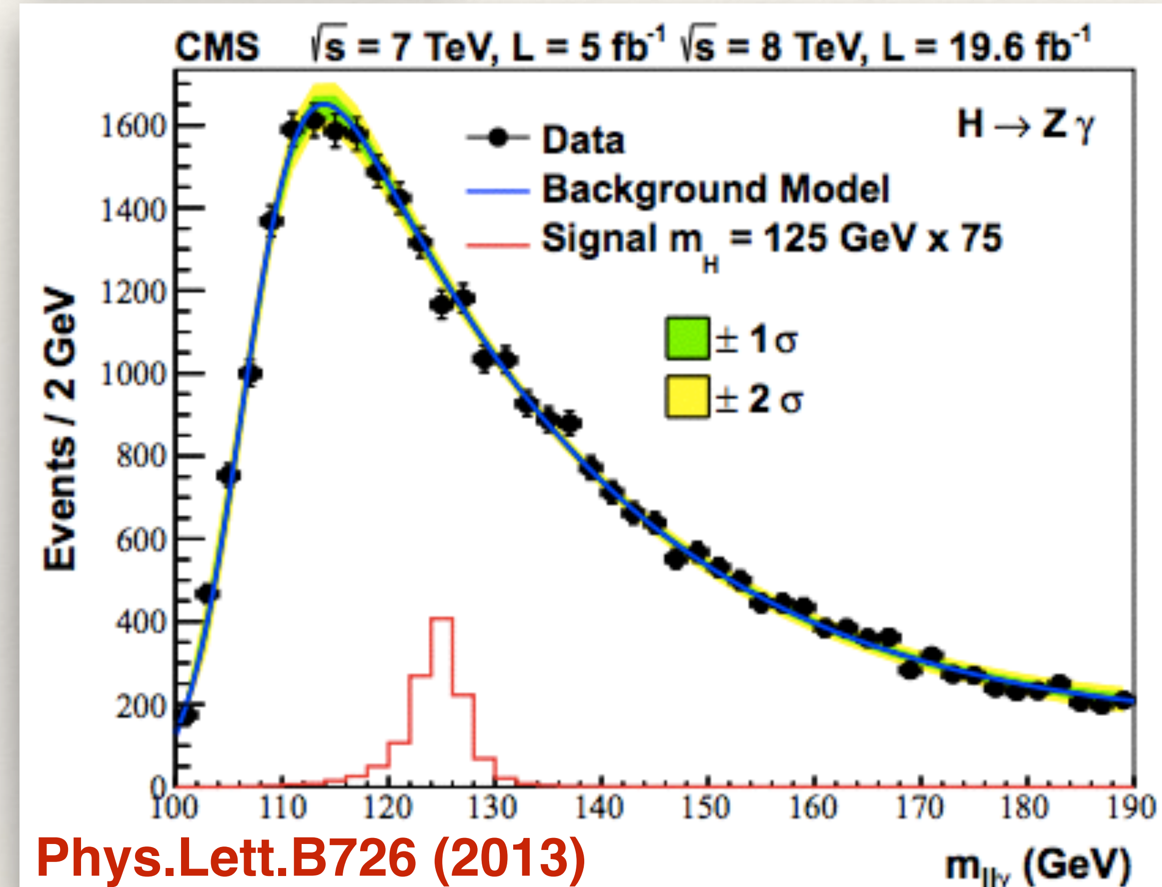
BR($h \to Z\gamma$)~0.001 small in the SM since it comes at one-loop:

still allowed to be 9 x BR_{SM}

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

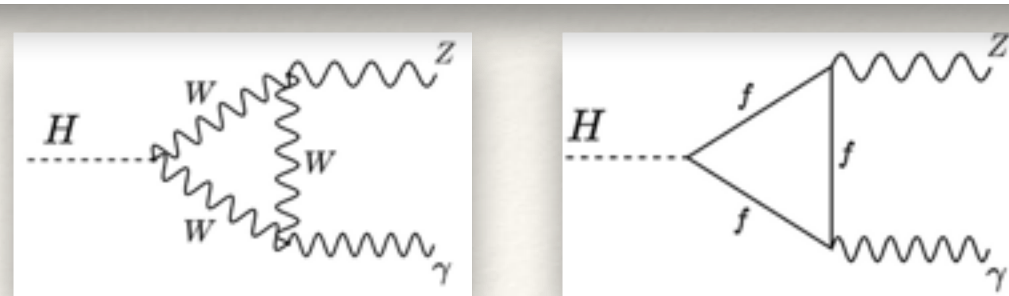
(possibility in **composite Higgs** models)

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:

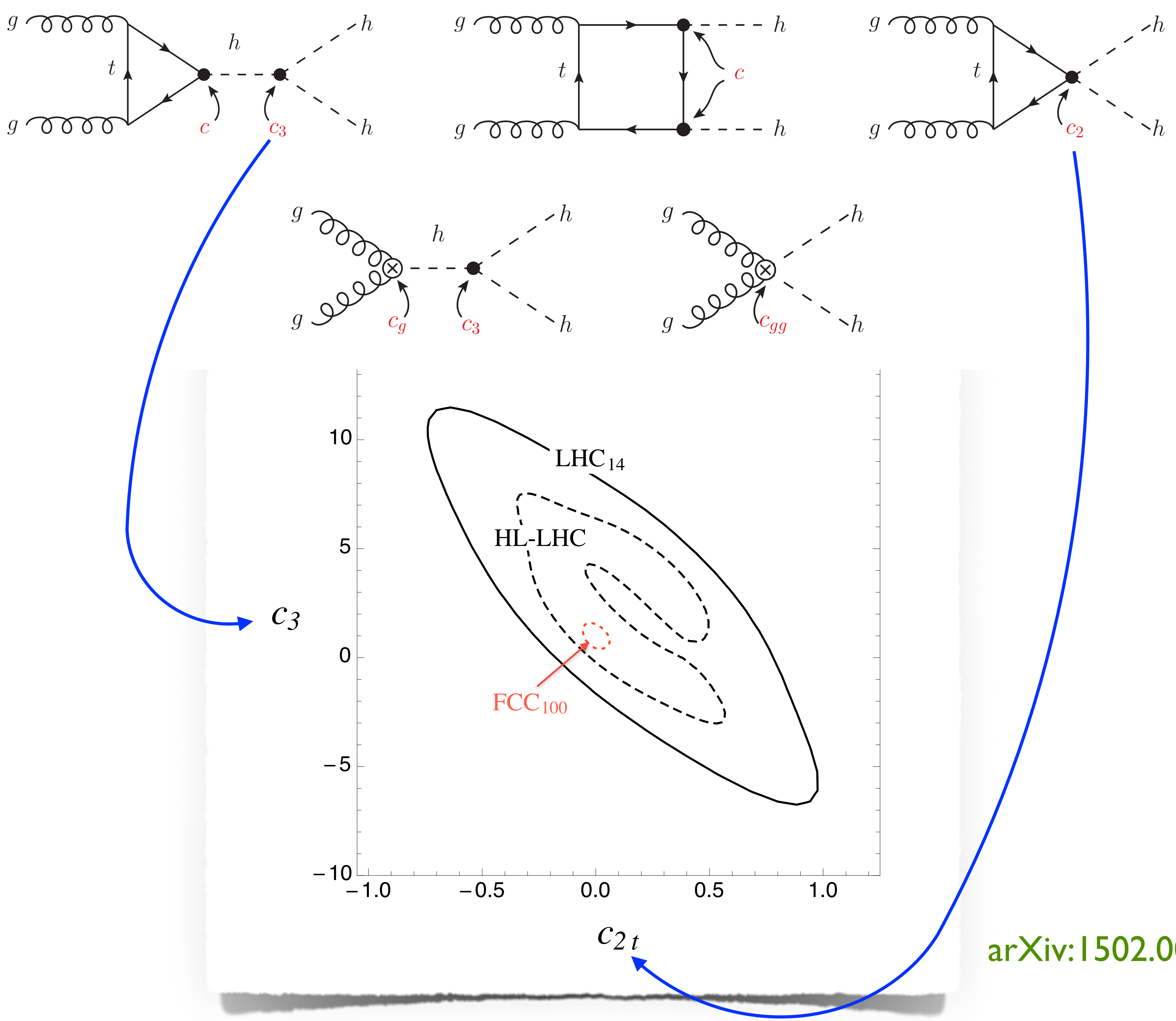


still allowed to be 9 x BR$_{SM}$

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

(possibility in **composite Higgs** models)

Prospects for 3h-coupling



arXiv:1502.00539

Natural expectations for primary Higgs couplings

<u>Expected</u> largest corrections to Higgs couplings in different BSM scenarios:

	hff	hVV	hγγ	hγZ	hGG	h^3
MSSM	√					√
NMSSM	√	√	√	√	√	√
PGB Composite	√	√		√		√
SUSY Composite	√	√				√
SUSY partly-composite			√	√	√	√
“Bosonic TC”						√
Higgs as a dilaton			√	√	√	√

We have specific patterns!

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	hff	hVV	hγγ	hγZ	hGG	h^3
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“Bosonic TC”						√
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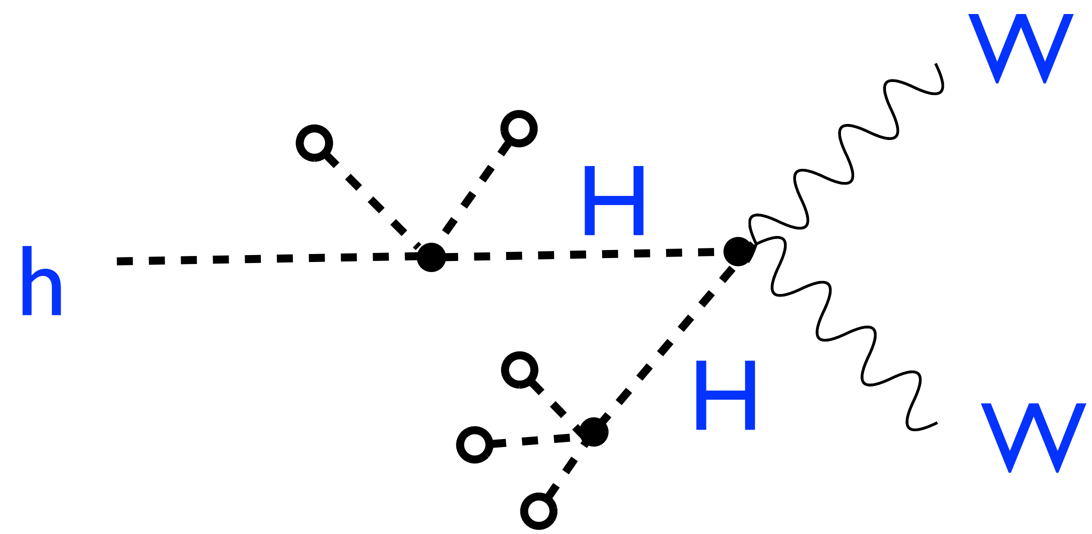
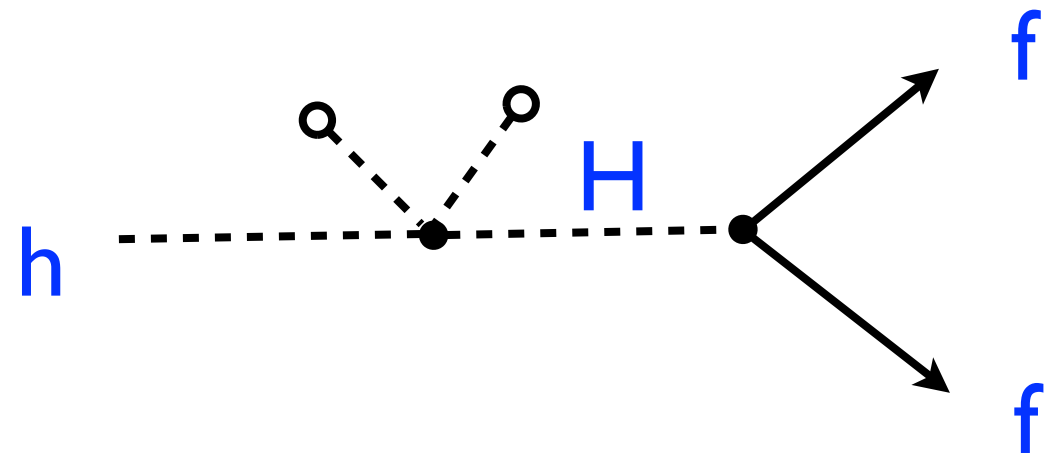
We have specific patterns!

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

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



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



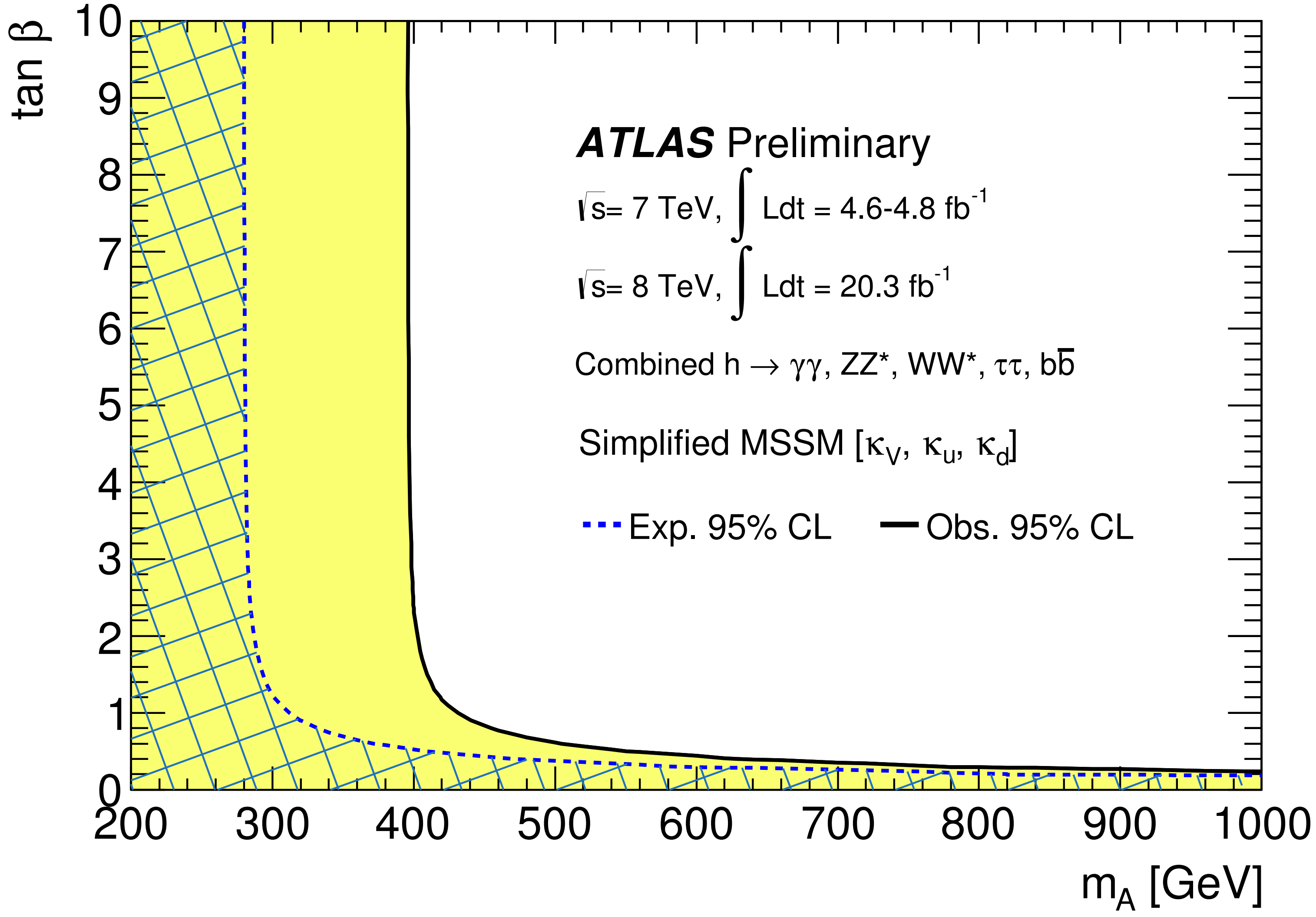
$$\sim \frac{v^2}{M_H^2}$$

Dominant effect!

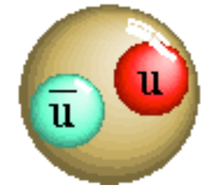
Superpartners can only modify Higgs couplings at the loop-level:
Only stops/sbottoms give some contribution to hgg/h$\gamma\gamma$ (not very large)

MSSM

Higgs coupling measurements already **rules out** susy-parameter space



Composite Higgs

H = 

(Higgs as a pion)

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

Giudice,Grojean,AP,Rattazzi 07

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

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

(model dependent but expected f ~ v)

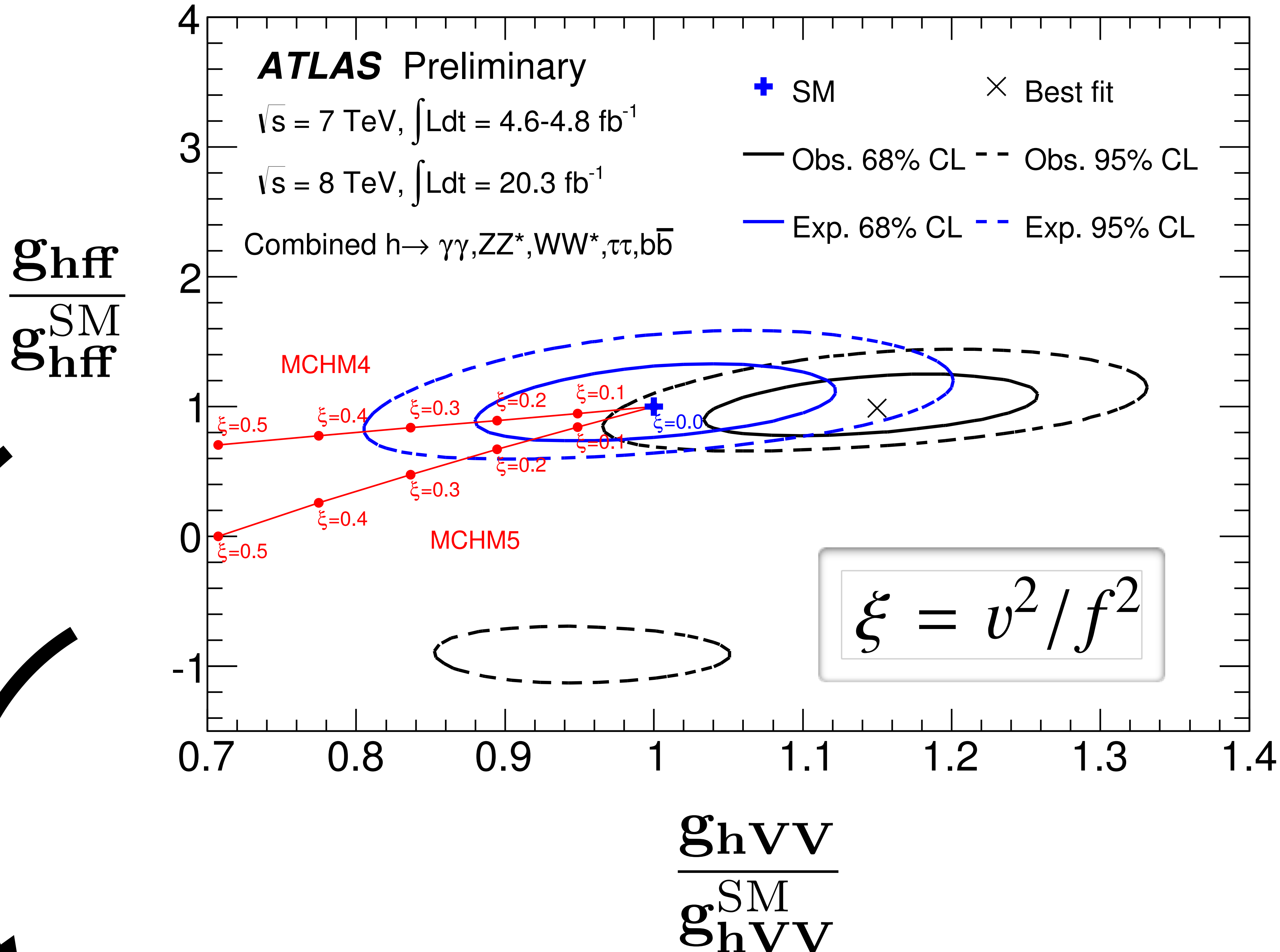
AP,Riva 12

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

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

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**

New Higgs decays also possible

The most interesting ones:

1) invisible Higgs decay:

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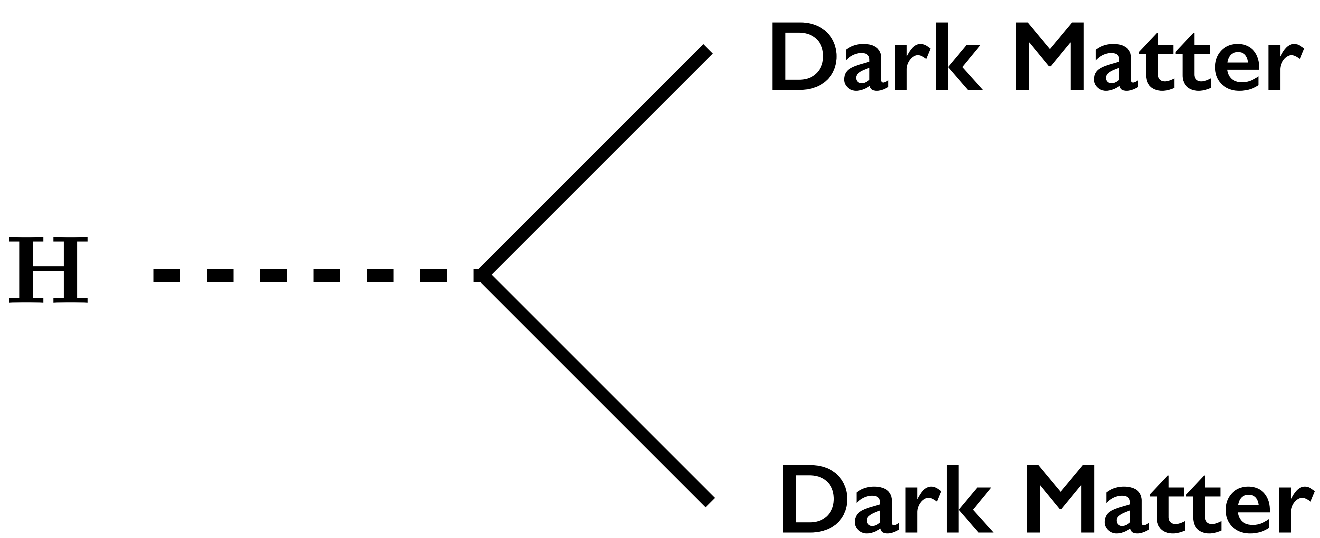

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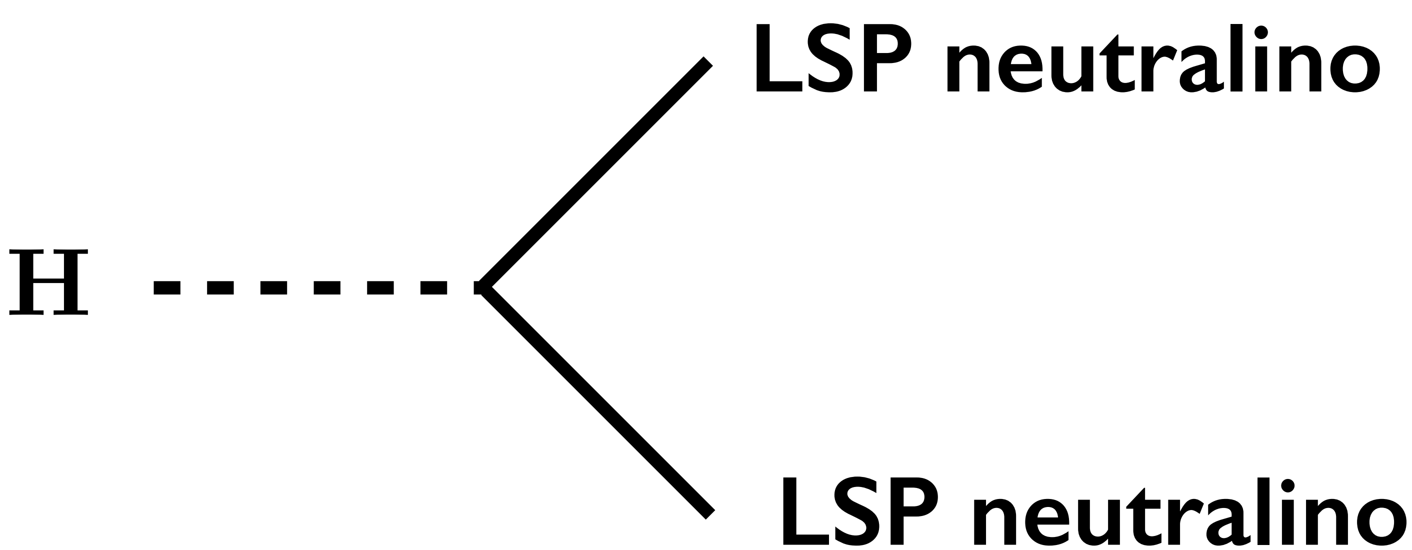

in supersymmetric models

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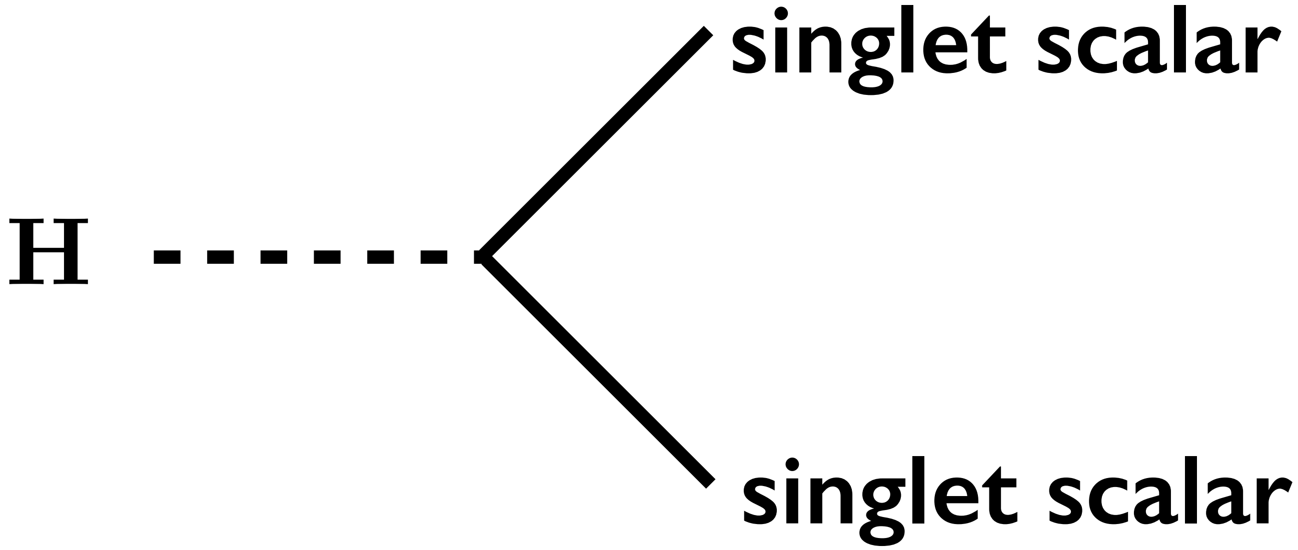

in models with more composite Higgs

New Higgs decays also possible

The most interesting ones:

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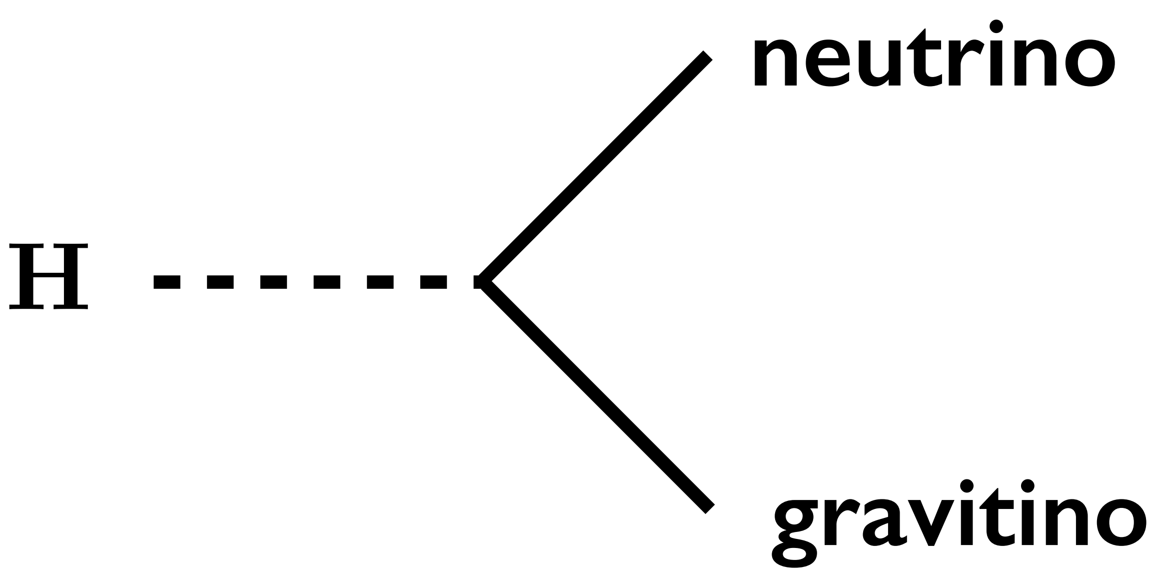
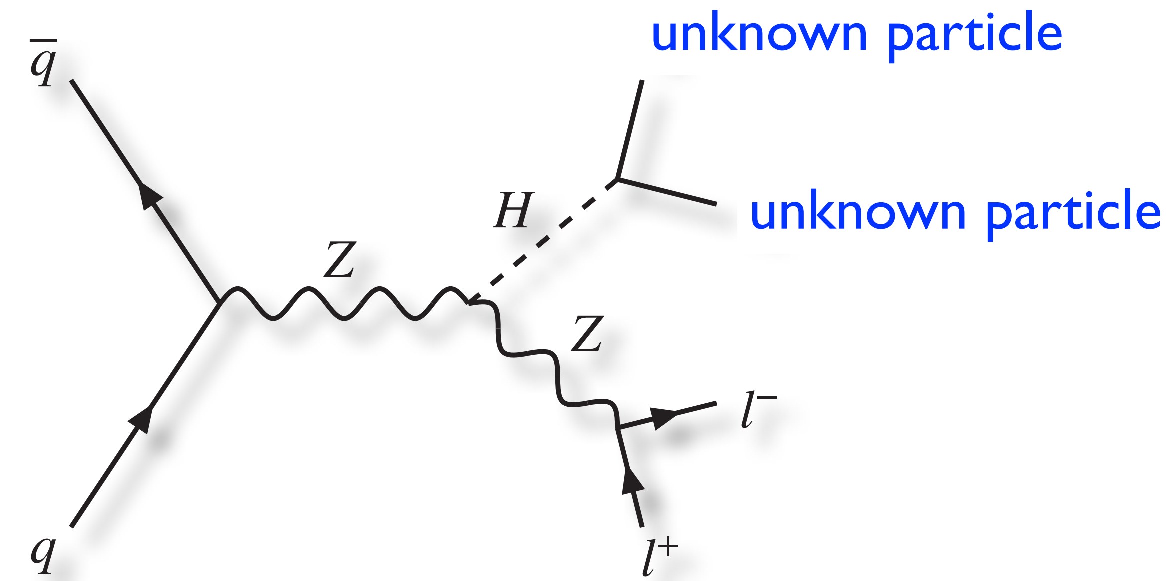


in theories where the Higgs
is the superpartner of the neutrino
Fayet,'76; AP,Riva,Biggio'12

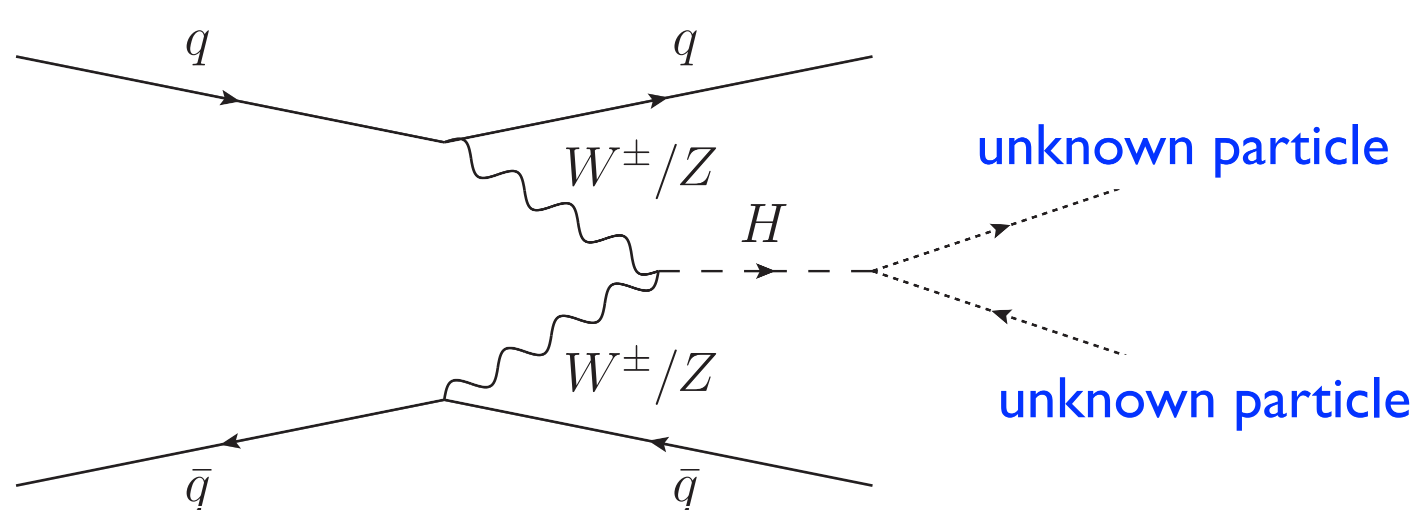
How to “see” it?

HV channel:



missing E_T + l^+l^-

VBF channel:



missing E_T + jets

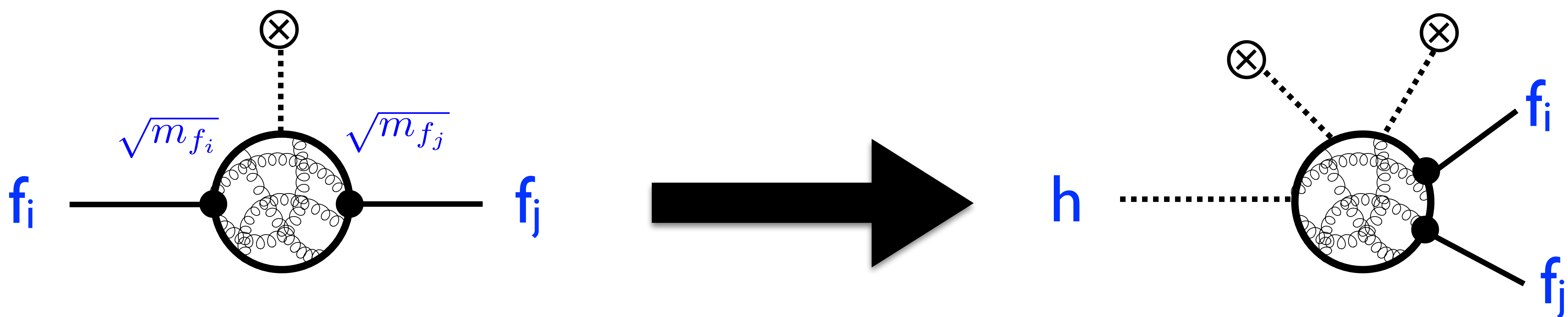
No sign of so, up to now:

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

ATLAS: BR_{inv} < 29% (35% expected)

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

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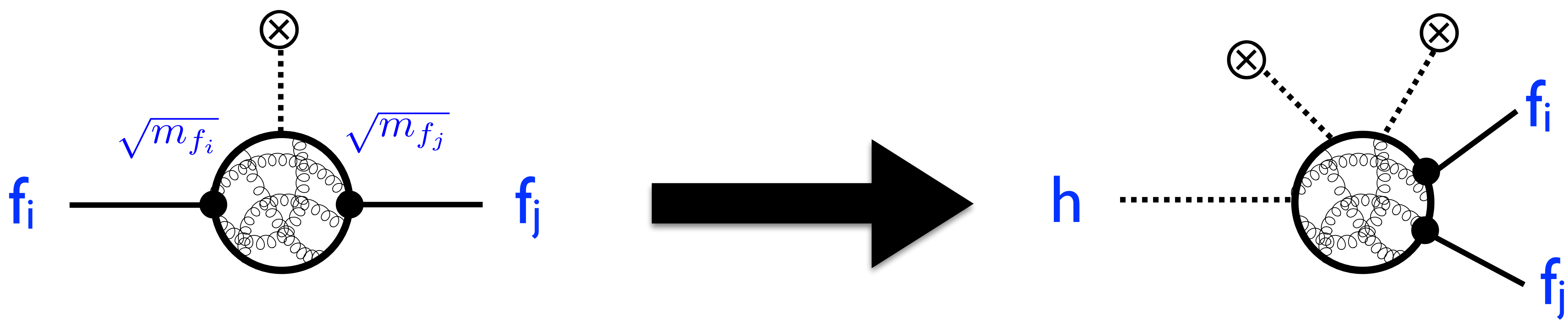

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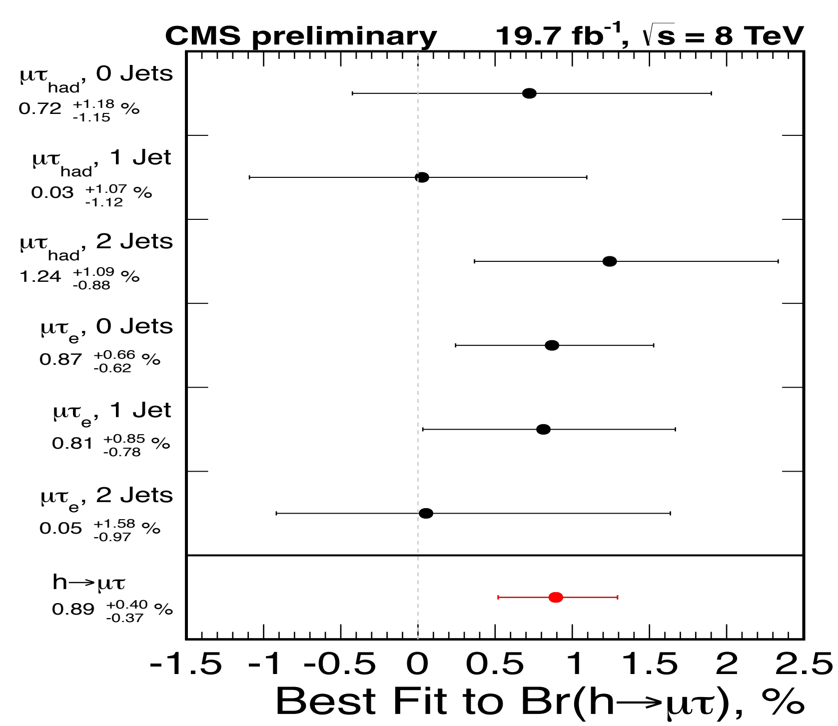
Getting there (CMS):



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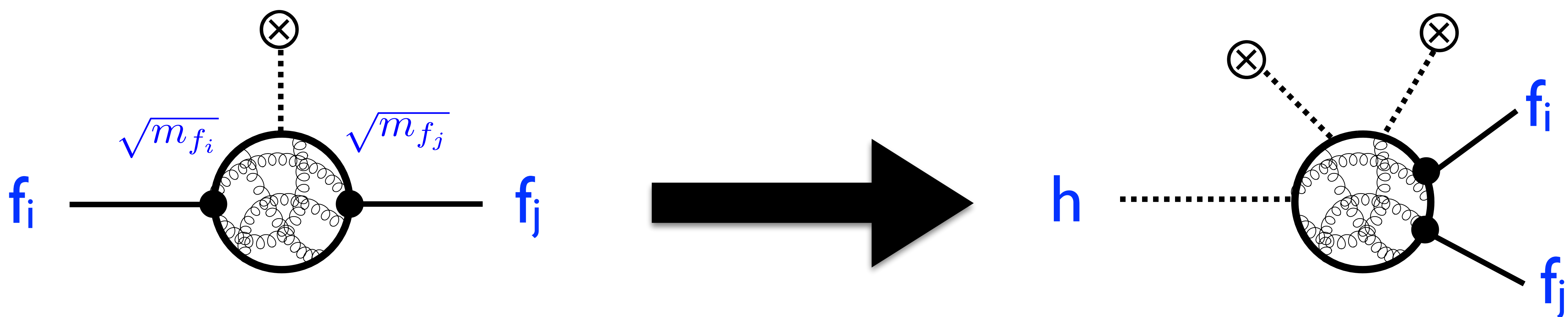

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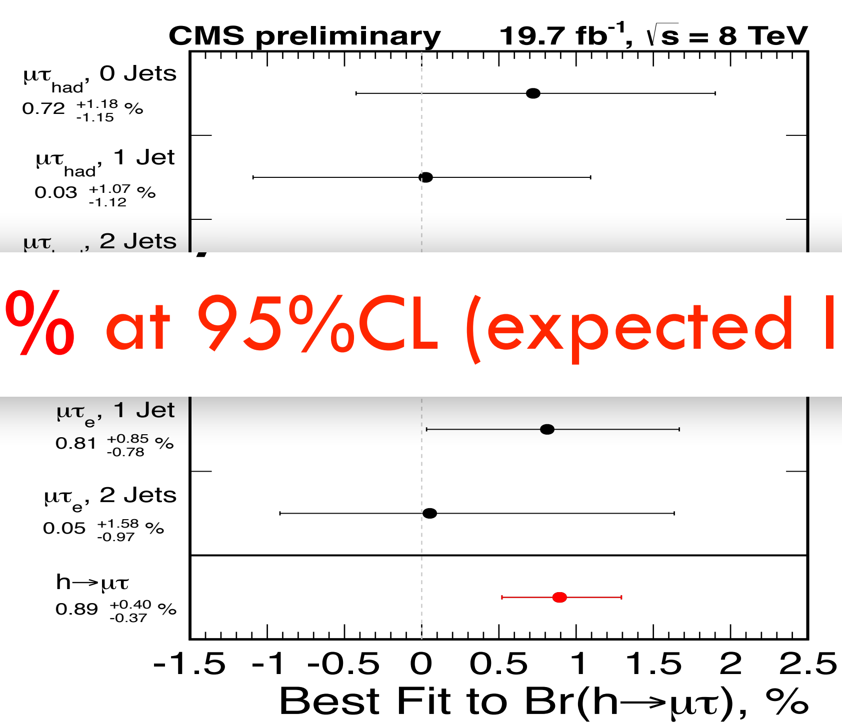


BR(H→μτ) < 1.57% at 95%CL (expected limit of 0.75%)

Beyond the primary Higgs couplings

Beyond the primary Higgs couplings

custodial breaking hVV

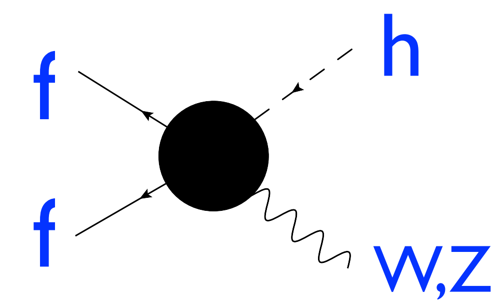
$$\Delta\mathcal{L}_h \quad = \quad \boxed{\delta g^h_{ZZ}}\, h\frac{Z^\mu Z_\mu}{2c^2_{\theta_W}}$$

Beyond the primary Higgs couplings

custodial breaking hVV

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

contact interactions



Beyond the primary Higgs couplings

custodial breaking hVV

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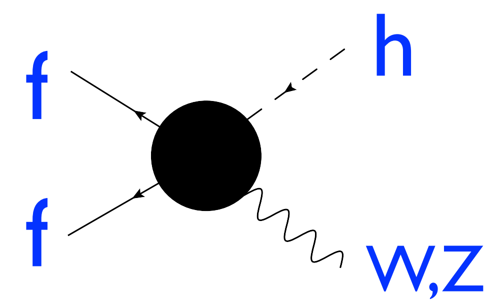
contact interactions

momentum-dependent
hVV couplings



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custodial breaking hVV

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$$+ \boxed{\kappa_{WW}}\, \frac{h}{v} W^{+\,\mu\nu} W^-_{\mu\nu} + \boxed{\kappa_{ZZ}}\, \frac{h}{2v} Z^{\mu\nu} Z_{\mu\nu}\,,$$

contact interactions

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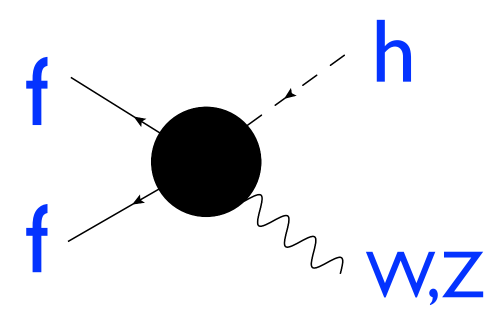

but remember BSM effects here are <u>not</u> independent from effects to other couplings!

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

$$\delta g^W_{ff'} = \frac{c_{\theta_W}}{\sqrt{2}}\left(\delta g^Z_{ff} V_{\rm CKM} - V_{\rm CKM}\delta g^Z_{f'f'}\right) \quad \text{for } f = f_L$$

$$\delta g^h_{ZZ} = 2g t^2_{\theta_W} m_W \left(c^2_{\theta_W}\boxed{\delta g_1^Z} - \boxed{\delta\kappa_\gamma}\right),$$

$$g^h_{Zff} = 2\boxed{\delta g^Z_{ff}} - 2\boxed{\delta g_1^Z}(g^Z_{ff} c_{2\theta_W} + g^\gamma_{ff} s_{2\theta_W}) + 2\boxed{\delta\kappa_\gamma} Y_f \frac{e s_{\theta_W}}{c^3_{\theta_W}},$$

$$\kappa_{ZZ} = \frac{1}{c^2_{\theta_W}}\boxed{\delta\kappa_\gamma} + 2\frac{c_{2\theta_W}}{s_{2\theta_W}}\boxed{\kappa_{Z\gamma}} + \boxed{\kappa_{\gamma\gamma}},$$

$$g^h_{Wff'} = 2\boxed{\delta g^W_{ff'}} - 2\boxed{\delta g_1^Z} g^W_{ff'} c^2_{\theta_W},$$

$$\kappa_{WW} = \boxed{\delta\kappa_\gamma} + \boxed{\kappa_{Z\gamma}} + \boxed{\kappa_{\gamma\gamma}},$$

arXiv:1405.0181
arXiv:1412.4410

Zff couplings δg^Z_{ff}

Higgs primary couplings $\kappa_{\gamma\gamma}$, $\kappa_{Z\gamma}$

TGC δg_1^Z, $\delta\kappa_\gamma$

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

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$$\delta g^h_{ZZ} = 2 g t^2_{\theta_W} m_W \left(c^2_{\theta_W} \boxed{\delta g^Z_1} - \boxed{\delta \kappa_\gamma}\right) ,$$

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

$$\kappa_{ZZ} = \frac{1}{c^2_{\theta_W}}\boxed{\delta\kappa_\gamma} + 2\frac{c_{2\theta_W}}{s_{2\theta_W}}\boxed{\kappa_{Z\gamma}} + \boxed{\kappa_{\gamma\gamma}},$$

$$g^h_{Wff'} = 2\boxed{\delta g^W_{ff'}} - 2\boxed{\delta g^Z_1} g^W_{ff'} c^2_{\theta_W} ,$$

$$\kappa_{WW} = \boxed{\delta\kappa_\gamma} + \boxed{\kappa_{Z\gamma}} + \boxed{\kappa_{\gamma\gamma}},$$

arXiv:1405.0181
arXiv:1412.4410

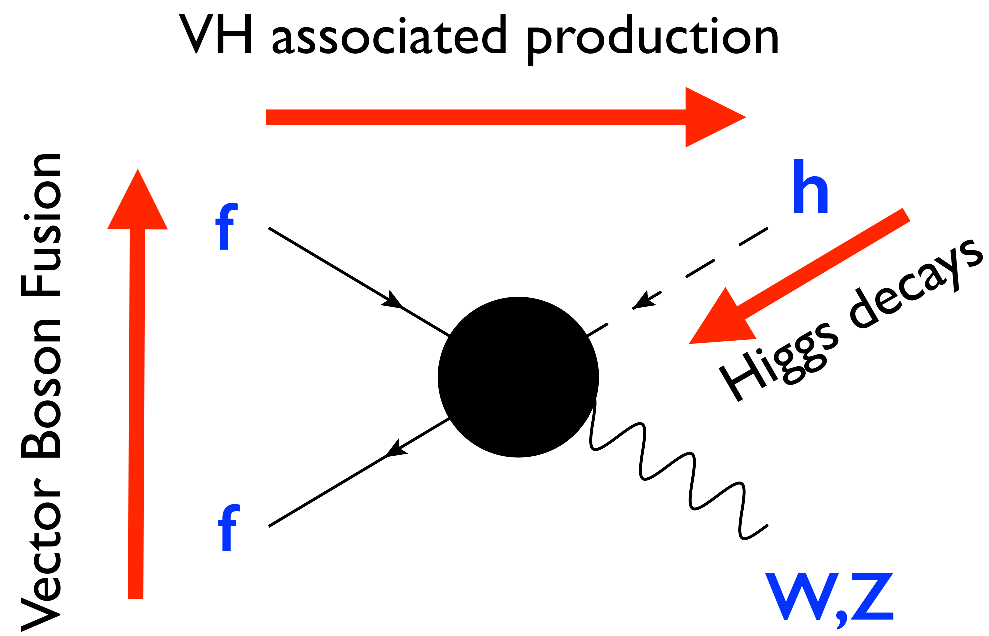
➥ no large deviations expected in these couplings

Zff couplings δg^Z_{ff}

Higgs primary couplings $\kappa_{\gamma\gamma}$, $\kappa_{Z\gamma}$

TGC δg^Z_1 , $\delta\kappa_\gamma$

Non-primary Higgs couplings can be disentangled in distributions:



$$\mathcal{M}_{hVff}(q,p) = \frac{1}{v}\epsilon^{*\mu}(q)\, J^{\nu}_{V}(p)\left[A^V\,\eta_{\mu\nu} + B^V\,(p\cdot q\,\eta_{\mu\nu} - p_\mu\, q_\nu) + C^V\epsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma\right]$$

$$A^V = a^V + \widehat{a}^V\frac{m_V^2}{p^2-m_V^2}\,, \qquad B^V = b^V\frac{1}{p^2-m_V^2} + \widehat{b}^V\frac{1}{p^2}$$

one-to-one correspondence
with Higgs couplings

$\mathbf{hV_\mu J^\mu}$ $\mathbf{hV^\mu V_\mu}$ $\mathbf{hV^{\mu\nu}V_{\mu\nu}}$ $\mathbf{hZ^{\mu\nu}A_{\mu\nu}}$

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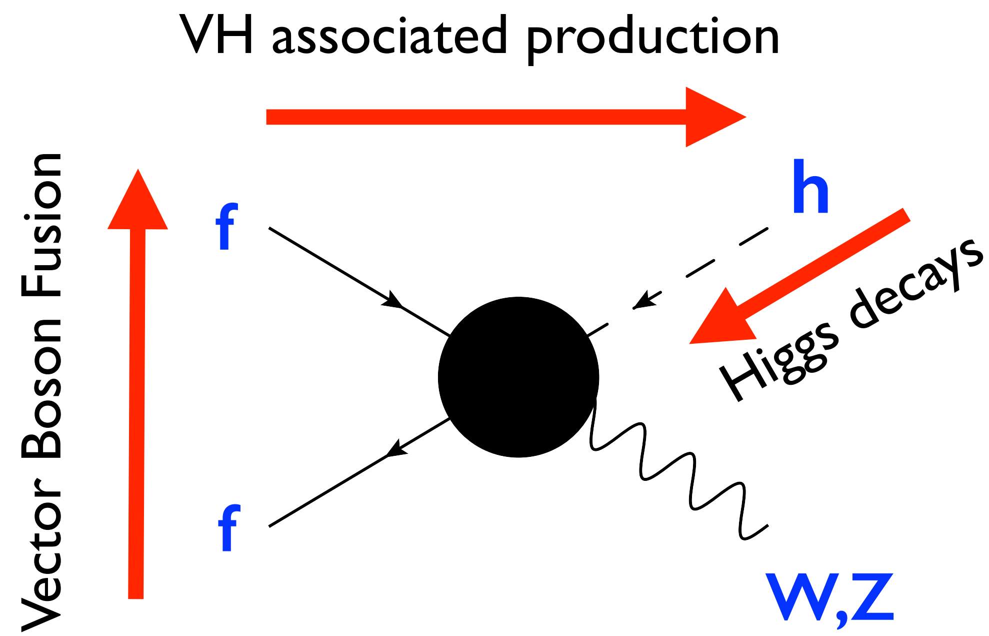


$$\mathcal{M}_{hVff}(q,p) = \frac{1}{v}\epsilon^{*\mu}(q)\, J_V^{\nu}(p)\left[A^V\,\eta_{\mu\nu} + B^V\,(p\cdot q\,\eta_{\mu\nu} - p_\mu\, q_\nu) + C^V\epsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma\right]$$

$$\boxed{A^V = a^V} + \widehat{a}^V\frac{m_V^2}{p^2-m_V^2}\,, \qquad B^V = b^V\frac{1}{p^2-m_V^2} + \widehat{b}^V\frac{1}{p^2}$$

one-to-one correspondence
with Higgs couplings

$\boxed{\mathbf{hV_\mu J^\mu}}$ $\quad \mathbf{hV^\mu V_\mu} \quad \mathbf{hV^{\mu\nu}V_{\mu\nu}} \quad \mathbf{hZ^{\mu\nu}A_{\mu\nu}}$

dominant at high-energy!

Main new contribution that the LHC run 2 will afford:

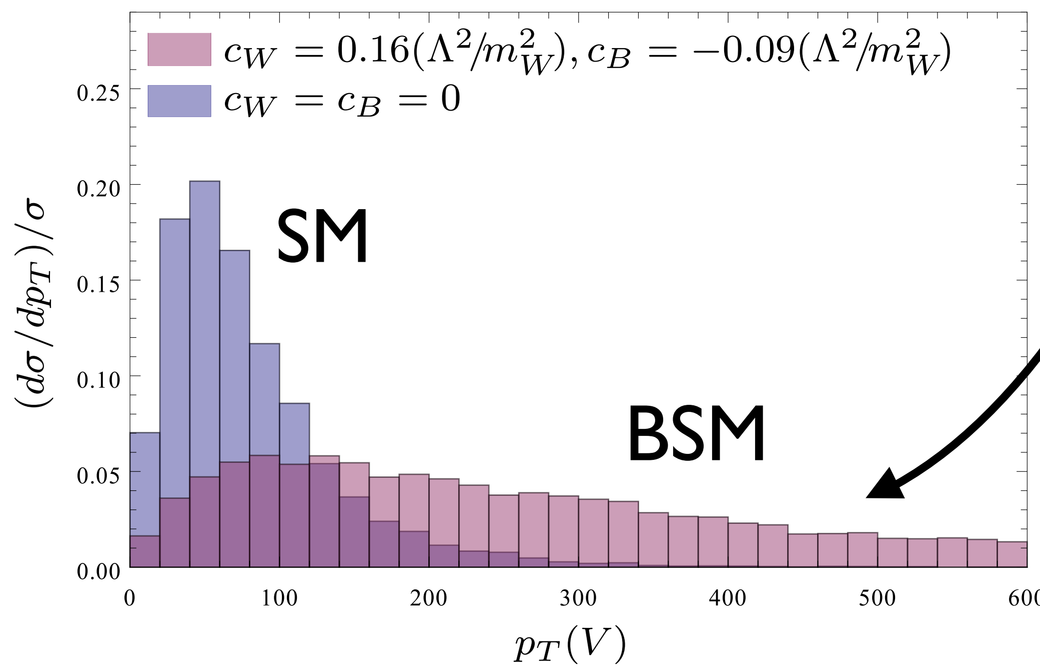
Higgs couplings at the high-energy regime

important as some Higgs-couplings grow with the energy

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

leading effects from contact interactions: $\mathbf{hV_\mu \bar{f}\gamma^\mu f}$

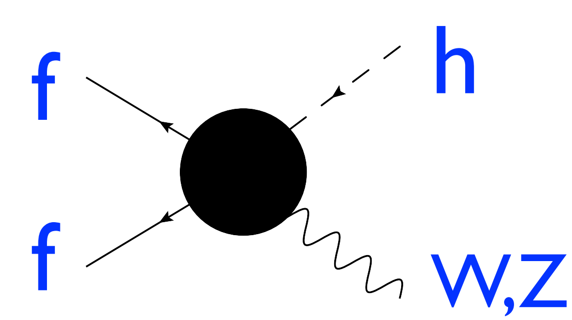
arXiv:1406.7320



BSM-effects enhanced at the *tail* of distributions

But only certain BSMs give large effects there!

strongly-coupled SM fermions and Higgs at TeV:



Conclusions

- After LHC run 1 ➠ the SM has been completed

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

End of <u>no-lose theorems</u> for discovery at the TeV

- We start a very different phase in particle physics:

BSM only motivated by the **unnaturalness** of the SM !

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, a weapon of BSM destruction**

- At the LHC run 2, who knows, it can illuminate on new-physics