Higgs couplings from a BSM perspective

Alex Pomarol, CERN & UAB (Barcelona)

Outline

- Rationale for a **Higgs-coupling** parametrization
- The most **important** Higgs couplings (*primaries*):

  the equivalent of the **S & T** parameters in EWPT
- BSM contributions to Higgs couplings
- **Beyond** *primaries*
- LHC high-energy regime

(most of this can be found in arXiv:1412.4410)

With the Higgs discovery, the SM has been established!

But still a lingering problem, the lightness of the Higgs…

	Massless	**Massive**
Vector $\mathbf{A}_\mu$	2 *dof* (+,-)	3 *dof* (+,0,-)
Fermion (charged)	2 *dof* Ψ_L	4 *dof* Ψ_L ,Ψ_R
Scalar	1 *dof*	1 *dof*

2≠3 ✔ *Massless vectors are save*

2≠4 ✔ *Massless fermions are save*

1=1 Problem!

Quantum fluctuations can give mass to scalars

…demanding new-physics!

Main importance of the Higgs discovery:

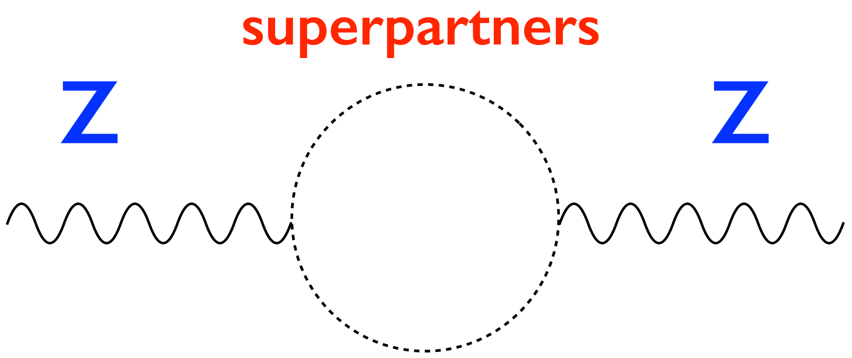
With the **Higgs**, by measuring its **properties** ,
we have access to new & relevant information about **BSMs**

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

Examples:

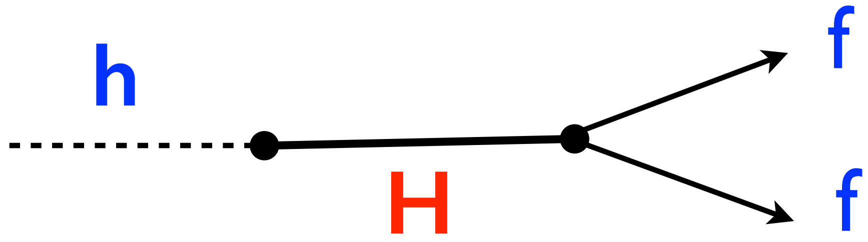
1) **MSSM**:

Gauge bosons:



~ loop effects

Higgs:



~ tree-level effects

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

Examples:

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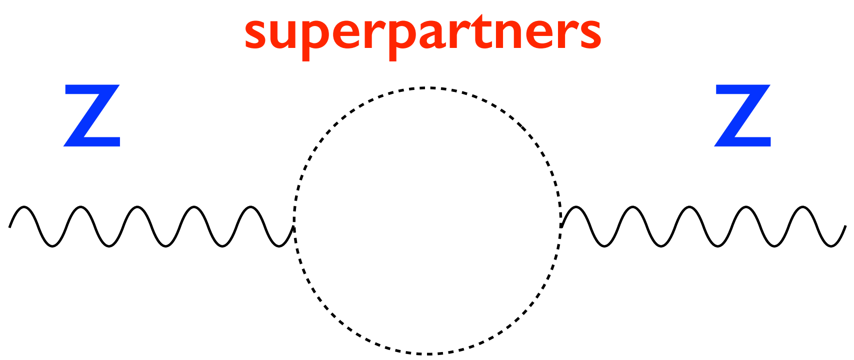

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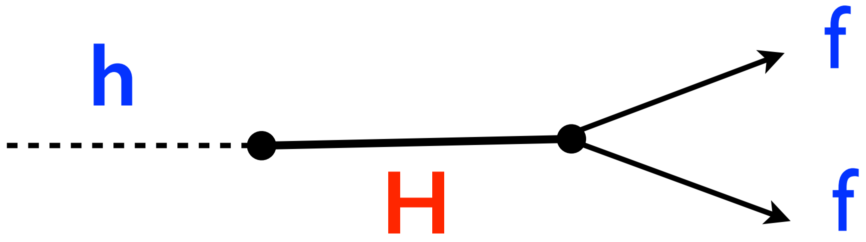
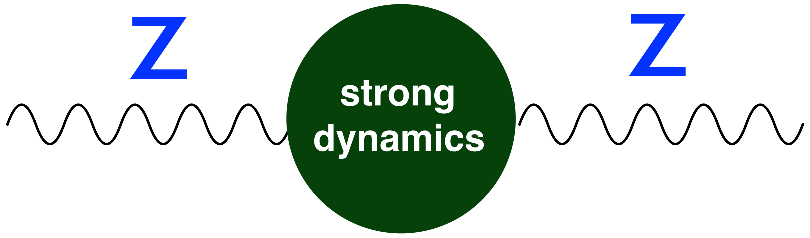


~ tree-level effects

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

2) Composite models:

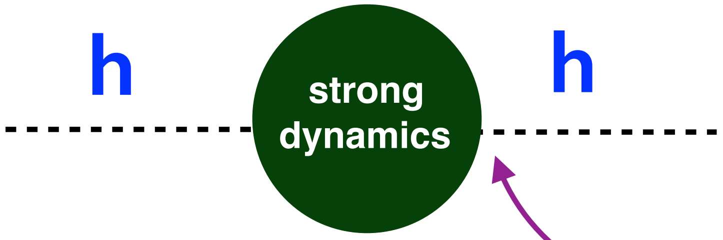
Gauge bosons:



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

(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

Examples:

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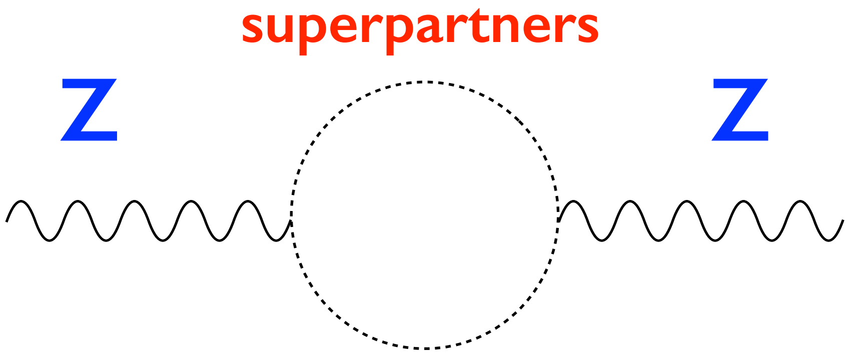
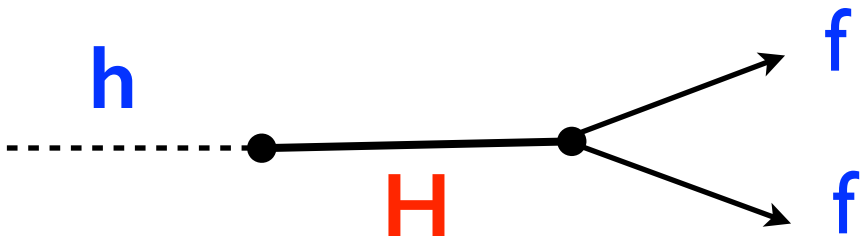


~ loop effects

Higgs:



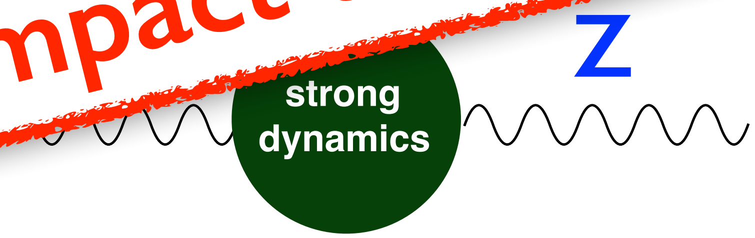
~ tree-level effect

0 larger!

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

2) Composite m

Gau



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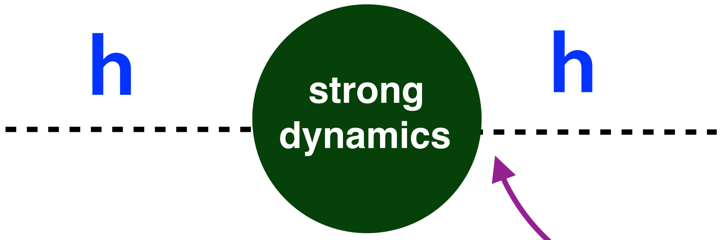

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“strong” Higgs coupling

Rationale for a Higgs-coupling parametrization

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Integrating out new-physics in a generic BSM:

$$\mathcal{L}_{\rm EFT} = \frac{\Lambda^4}{g_*^2}\mathcal{L}\left(\frac{D_\mu}{\Lambda}\,,\,\frac{g_* H}{\Lambda}\,,\,\frac{g_* f_{L,R}}{\Lambda^{3/2}}\,,\,\frac{g F_{\mu\nu}}{\Lambda^2}\right)$$

g_* = coupling that can be as large as ~4π

Λ = new-physics scale

Generic case difficult to be treated ➧ extra assumption needed!

1) Quite conservatively, we can assume **$\Lambda \gg$ E, m_h**

(extra light matter, weakly coupled to the Higgs, can also be easily incorporated)

$$\mathcal{L}_{\rm EFT} = \frac{\Lambda^4}{g_*^2}\mathcal{L}\left(\boxed{\frac{D_\mu}{\Lambda}}\,,\,\frac{g_* H}{\Lambda}\,,\,\frac{g_* f_{L,R}}{\Lambda^{3/2}}\,,\,\frac{g F_{\mu\nu}}{\Lambda^2}\right)$$

$\ll 1$

➥ we can expand in derivatives

Higgs couplings: $g_{\phi_i\phi_j\phi_k} = \frac{\delta\mathcal{L}_{\rm EFT}}{\delta\phi_i\delta\phi_j\delta\phi_k}$

All relevant couplings for *single* Higgs physics:

arXiv:1412.4410

$$\begin{aligned}\mathcal{L}_h^{\rm primary} &= g^h_{VV}\, h\left[W^{+\,\mu}W^-_\mu + \frac{1}{2c^2_{\theta_W}}Z^\mu Z_\mu\right] + \frac{1}{6}\, g_{3h}\, h^3 + g^h_{ff}\ (h\bar{f}_L f_R + h.c.)\\ &+ \kappa_{GG}\,\frac{h}{2v}G^{A\,\mu\nu}G^A_{\mu\nu} + \kappa_{\gamma\gamma}\,\frac{h}{2v}A^{\mu\nu}A_{\mu\nu} + \kappa_{Z\gamma}\frac{h}{v}A^{\mu\nu}Z_{\mu\nu}\,,\end{aligned}$$

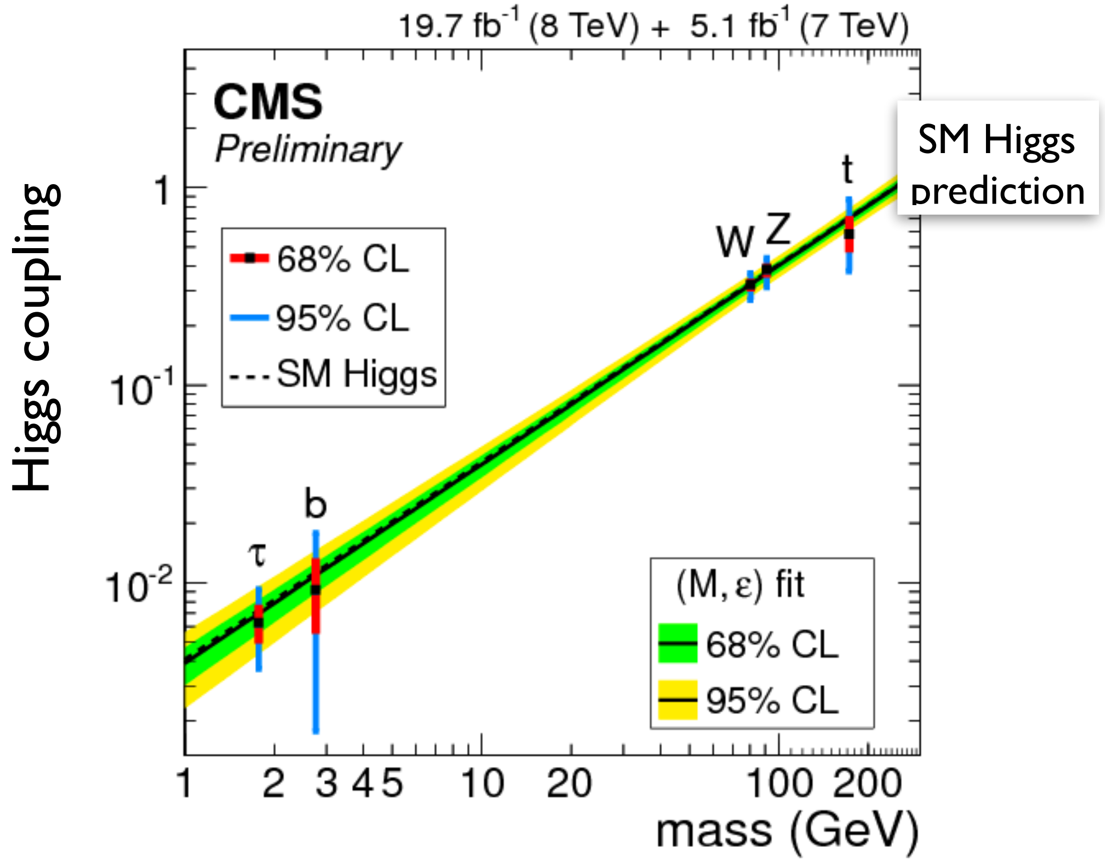
$$\begin{aligned}\Delta\mathcal{L}_h &= \delta g^h_{ZZ}\, h\frac{Z^\mu Z_\mu}{2c^2_{\theta_W}} + g^h_{Zff}\,\frac{h}{2v}\,(Z_\mu J^\mu_N + h.c.) + g^h_{Wff'}\,\frac{h}{v}\,(W^+_\mu J^\mu_C + h.c.)\\ &+ \kappa_{WW}\,\frac{h}{v}W^{+\,\mu\nu}W^-_{\mu\nu} + \kappa_{ZZ}\,\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu}\,,\end{aligned}$$

$J^\mu_{N,C}$: currents of SM fermions

up to $O(h^3)$, $O(h\partial^2V^2)$ and $O(hVf^2)$

(assuming CP-conservation)

Empirical evidence, Higgs (and Z/W) couplings follow SM predictions:



SM Higgs prediction

➡ suggests that the SM is a good approximation in nature!

We can also expand in the Higgs field (and other SM fields):

$$\mathcal{L}_{\rm EFT} = \frac{\Lambda^4}{g_*^2}\mathcal{L}\left(\underset{\ll 1}{\boxed{\frac{D_\mu}{\Lambda}}}\,,\underset{\ll 1}{\boxed{\frac{g_* H}{\Lambda}\,,\ \frac{g_* f_{L,R}}{\Lambda^{3/2}}\,,\ \frac{g F_{\mu\nu}}{\Lambda^2}}}\right) \simeq \mathcal{L}_4 + \mathcal{L}_6 + \cdots$$

SM just validated

leading deviations to **SM** from BSM

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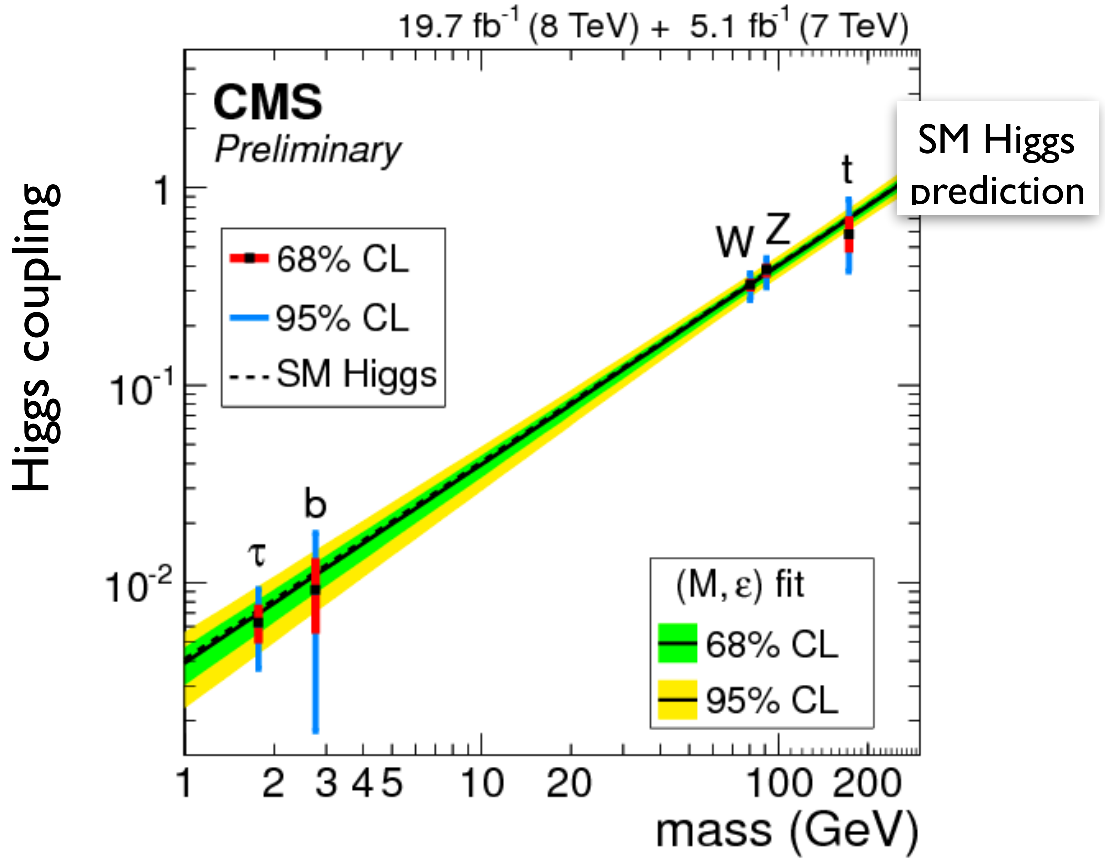

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$\ll 1$ $\ll 1$

there is a caveat to be discussed later!

SM
just validated

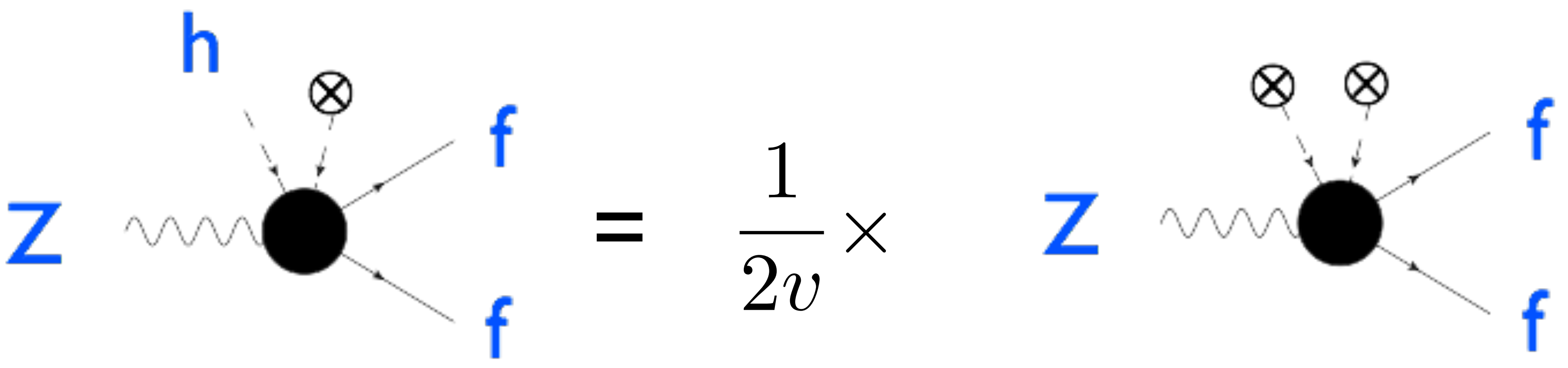
leading deviations
to **SM** from BSM

➥ **Not all type of Higgs couplings can arise from $\mathcal{L}_6$!**

There are plenty of correlations among possible deviations

☛ this is the important information to extract

For example:



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

☛ Correlation between h→Zff and Z→ff

Higgs couplings

(assuming CP-conservation)

independent from other SM couplings

$$\mathcal{L}_h^{\rm primary} = g^h_{VV}\, h \left[W^{+\,\mu} W^-_\mu + \frac{1}{2c^2_{\theta_W}} Z^\mu Z_\mu \right] + \frac{1}{6}\, g_{3h}\, h^3 + g^h_{ff}\, \left(h \bar{f}_L f_R + h.c. \right)$$

$$+ \quad \kappa_{GG}\, \frac{h}{2v} G^{A\,\mu\nu} G^A_{\mu\nu} + \kappa_{\gamma\gamma}\, \frac{h}{2v} A^{\mu\nu} A_{\mu\nu} + \kappa_{Z\gamma} \frac{h}{v} A^{\mu\nu} Z_{\mu\nu}\,,$$

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

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

$J^\mu_{N,C}$: currents of SM fermions

correlated to other SM couplings

indirectly "measured"

8 Primary Higgs couplings related to **8** dim-six operators with $|H|^2$

(on the vacuum $|H|^2 = v^2$, they give a SM operator)

for one family
(CP-conserving)

$|H|^2 G^A_{\mu\nu} G^{A\mu\nu}$ → **GGh coupling**

$|H|^2 B_{\mu\nu} B^{\mu\nu}$ → **hγγ coupling**

$|H|^2 W^a_{\mu\nu} W^{\mu\nu\, a}$ → **hZγ coupling**

$|H|^2 |D_\mu H|^2$ → **hVV** (custodial invariant)

$|H|^6$ → **h^3 coupling**

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

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

Other reason why primary Higgs couplings are the most important ones:

Receive the largest contributions from main BSM

Expected largest corrections to Higgs couplings in 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!

Higgs couplings

(assuming CP-conservation)

Almost all Higgs primaries have been measured at the LHC (the “kappas”):

$$\mathcal{L}_h^{\rm primary} = \boxed{g^h_{VV}}\, h\left[W^{+\,\mu}W^-_\mu + \frac{1}{2c^2_{\theta_W}} Z^\mu Z_\mu\right] + \frac{1}{6}\, g_{3h}\, h^3 + \boxed{g^h_{ff}}\left(h\bar{f}_L f_R + h.c.\right)$$

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(f=b, τ, t)

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

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

→ correlated to other SM couplings

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$$\bar f_L f_R + h.c.)$$

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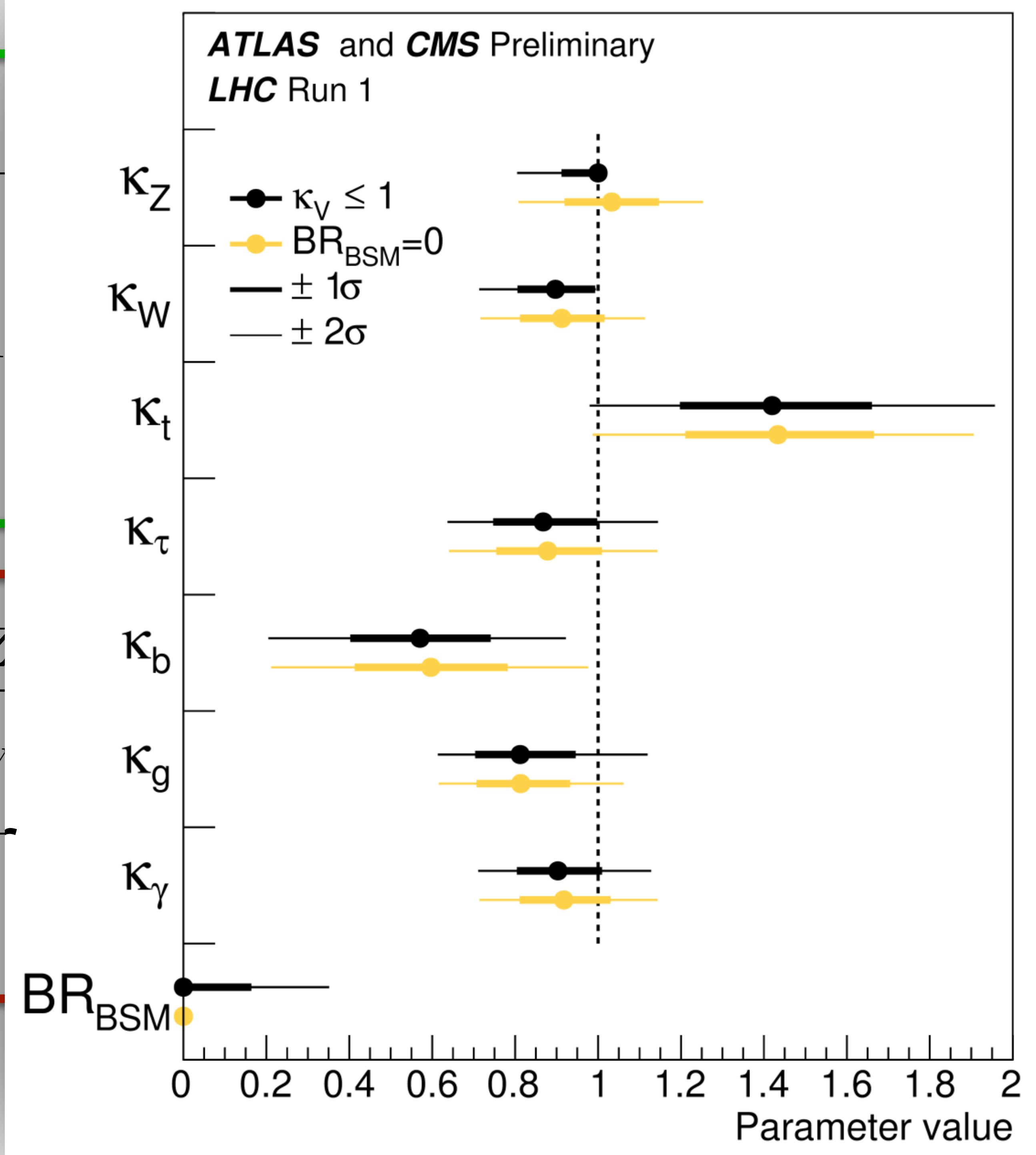
(f=b, τ, t)



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

$$J^\mu_C + h.c.)$$

$$+ \kappa_{WW} \frac{h}{v} W^+$$

1 couplings

indirectly "measured"

Higgs couplings

(assuming CP-conservation)

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$$\mathcal{L}_h^{\text{primary}} = \boxed{g^h_{VV}}\, h \Big[W \quad \cdots \quad \bar f_L f_R + h.c.)$$

(f=b, τ, t)

$$+ \boxed{\kappa_{GG}} \frac{h}{2v} G^A \quad \cdots$$

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

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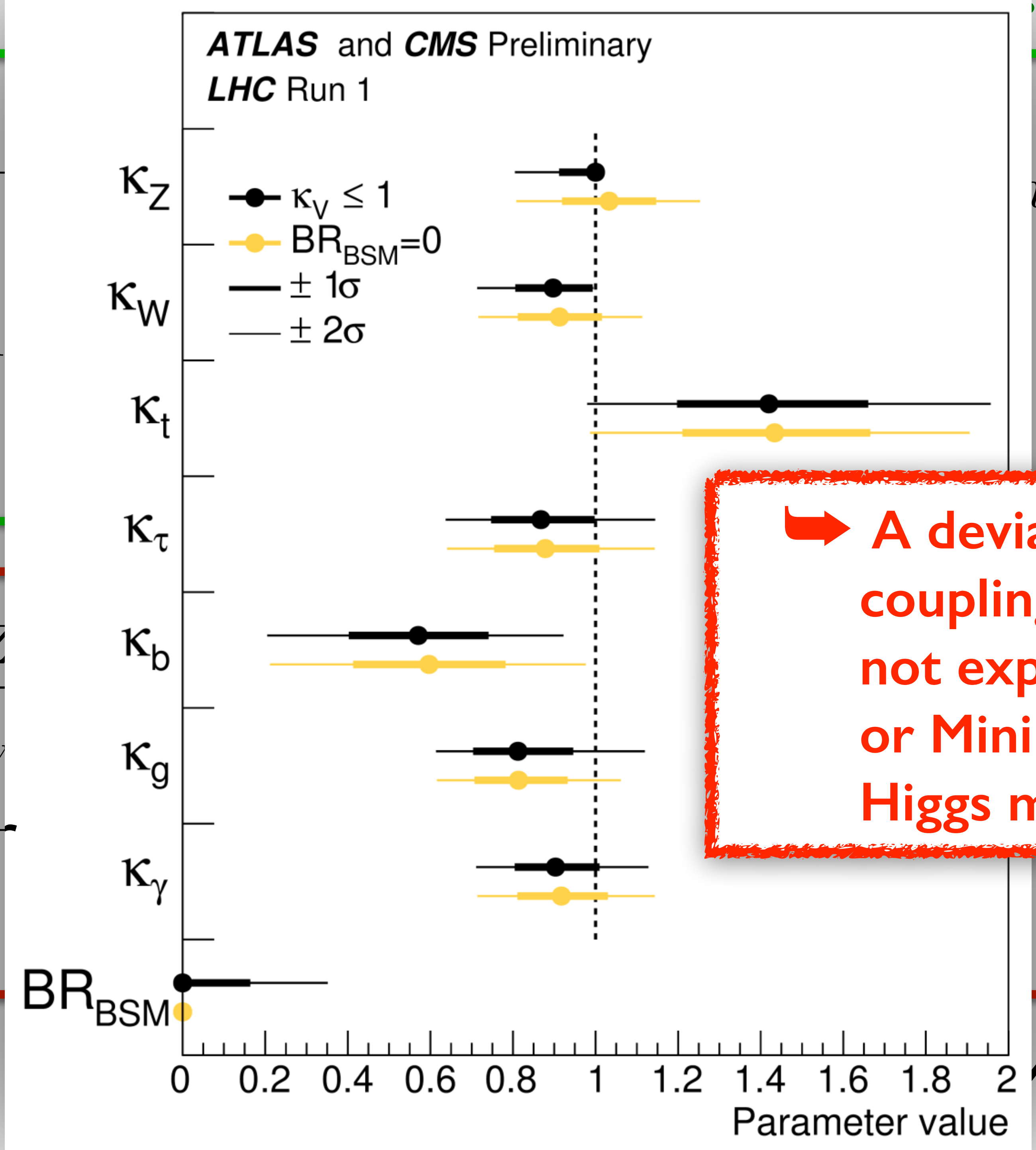

➡ A deviation only on the coupling to the top, not expected in MSSM or Minimal Composite Higgs models

1 couplings

indirectly "measured"

Higgs couplings

(assuming CP-conservation)

Only two remain to be measured:

pp→h*→hh

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(f=b, τ, t)

h→Zγ

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

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correlated to other SM couplings

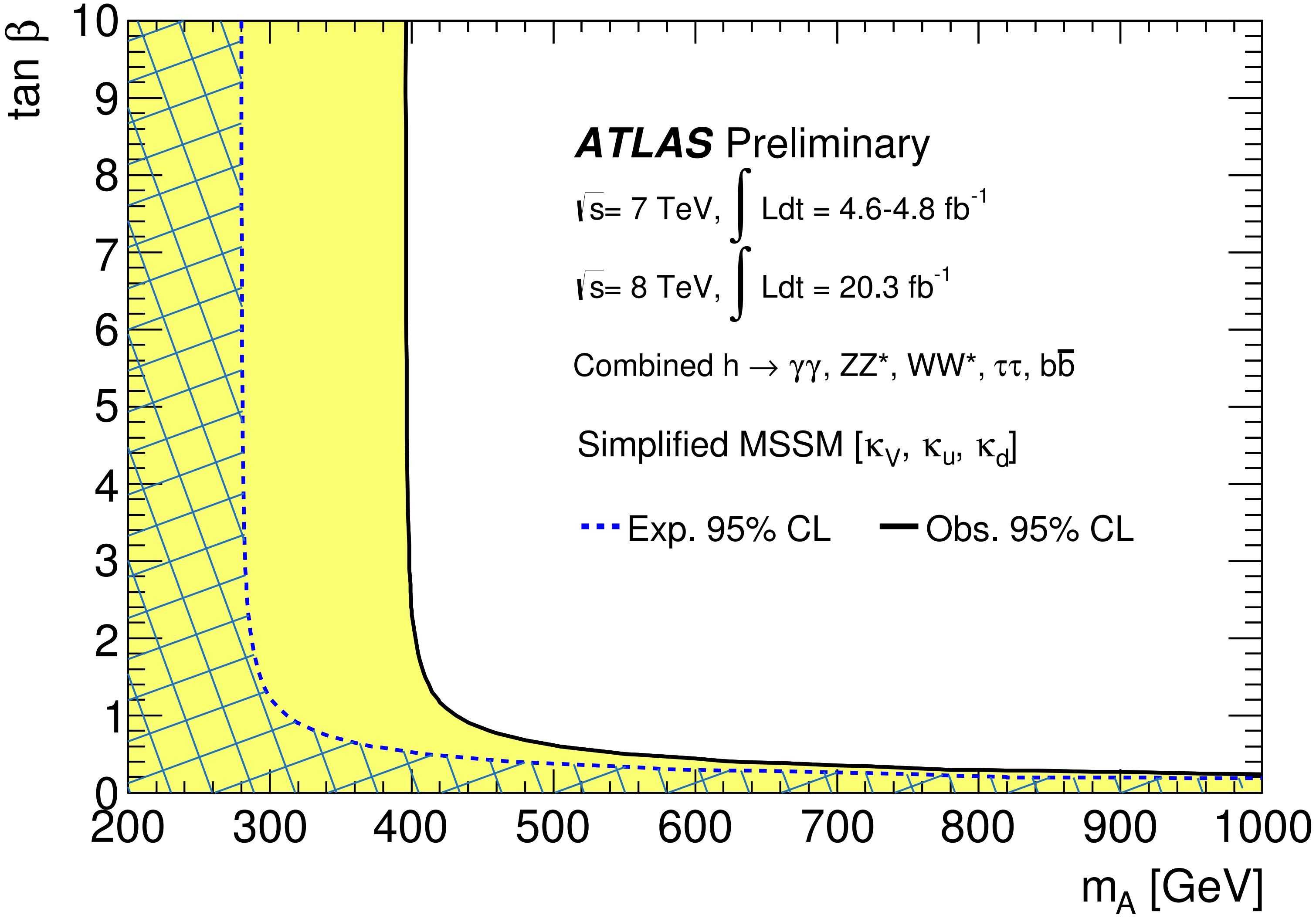
indirectly "measured"

Impact on BSM from Higgs coupling measurements

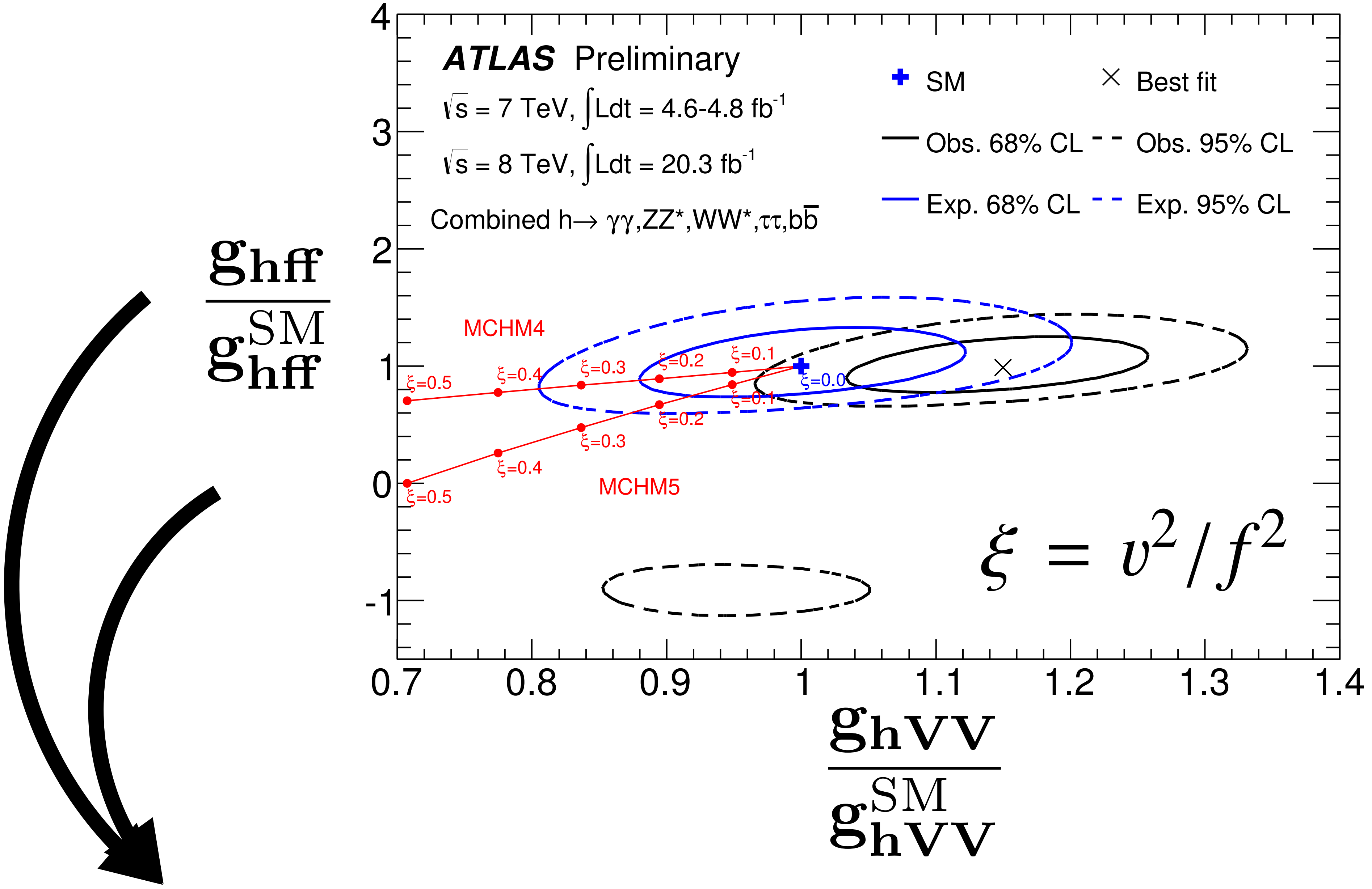
- Today, as Higgs coupling measurements agree with the SM, we only place bounds on new-physics

The Higgs is our best weapon of BSM mass-destruction

Higgs coupling measurements are already **ruling out** regions of the **MSSM** parameter space



Higgs coupling measurements are already **limiting the degree of compositeness of the Higgs**

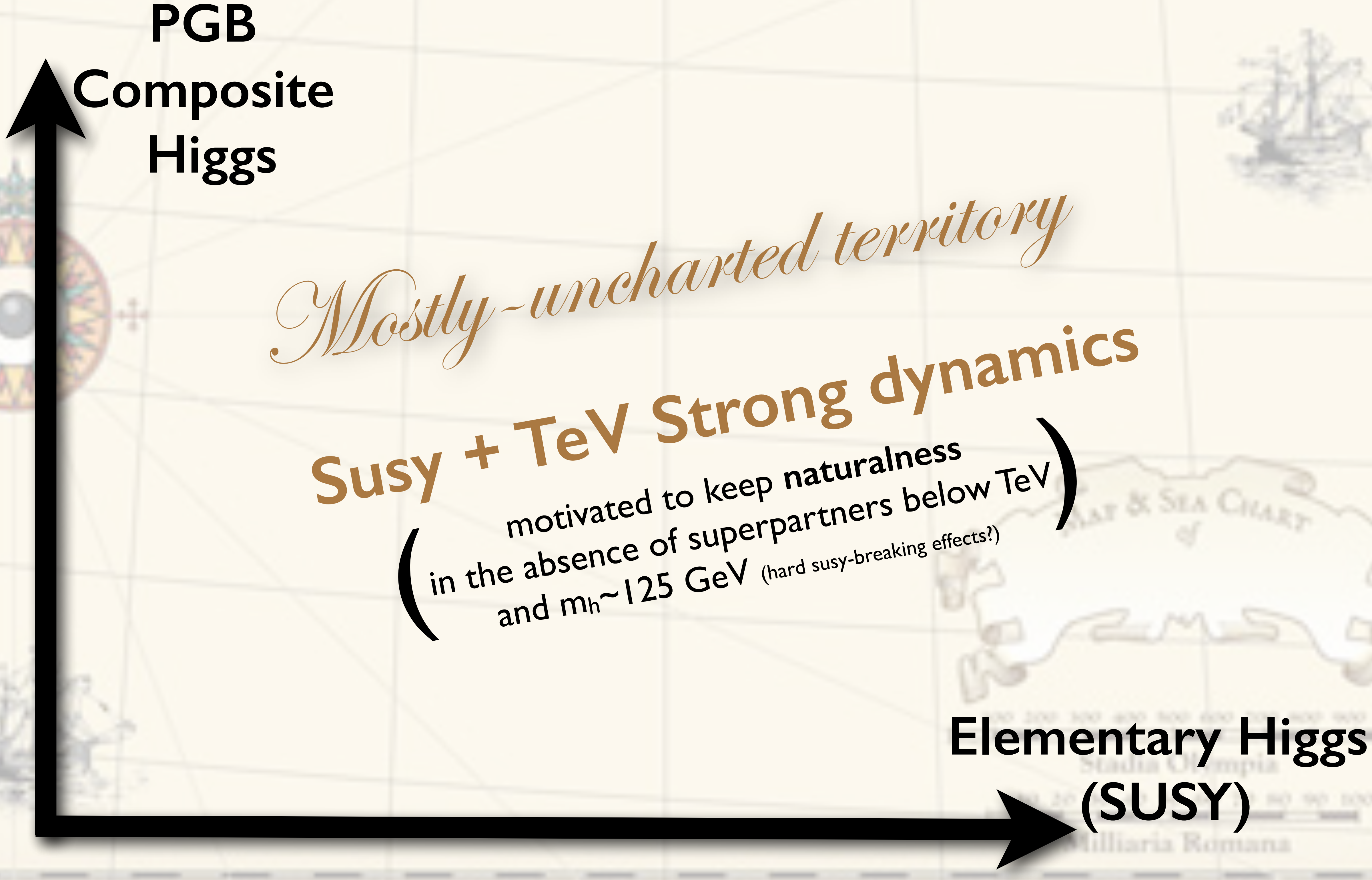


$$\xi = v^2/f^2$$

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

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

The “space” of *natural* BSMs can have a large “cartography”



Mostly-uncharted 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?))

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:

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

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

T. Gherghetta, AP 11

☛ that could also break the EW symmetry

similarity with Bosonic TC

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

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

2) Higgs coupled to a TeV strong-sector breaking also EW symmetry (Bosonic TechniColor (TC)):

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

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

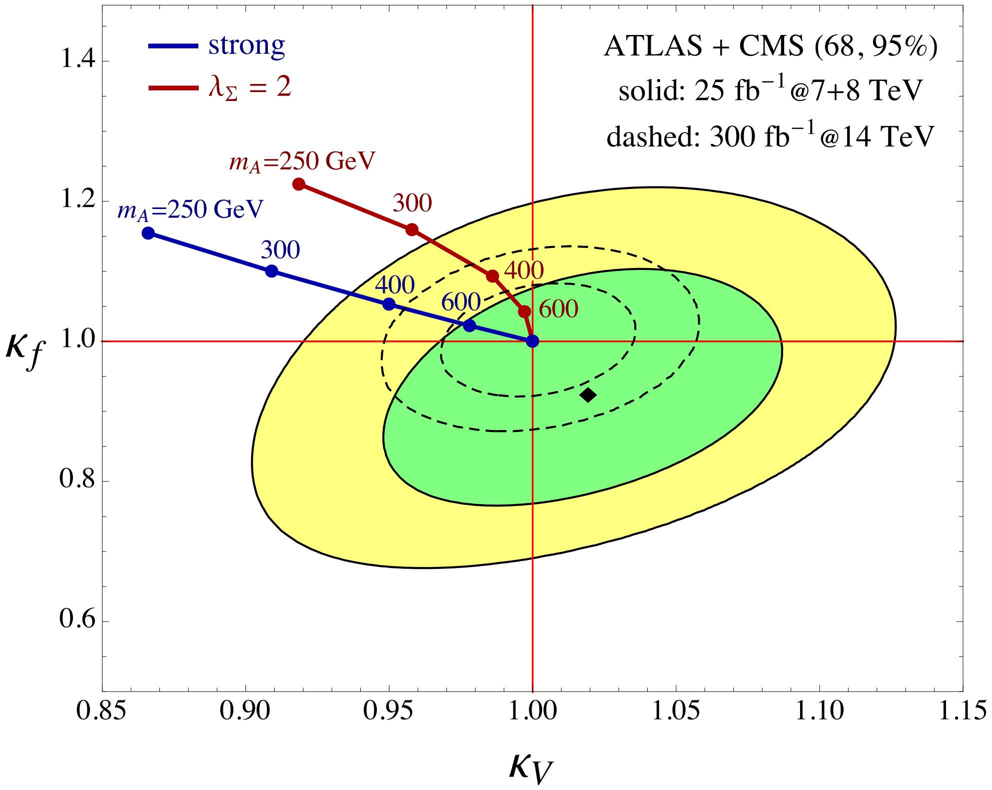
T. Gherghetta, AP 11

- **Important:** Invalidates the EFT description, since new source of EWSB other than the Higgs:

↪ the Higgs VEV is induced from a mixing to the TC sector

The BSM has heavy tachyons!
It is non-decoupling!

- Still small deformations of **hVV & hff** Higgs couplings, if the Higgs has a small mixing with the TC sector



arXiv:1411.6023

...but $\mathcal{O}(1)$ effects in the h^3-coupling!

Beyond the primary Higgs couplings

Beyond the primary Higgs couplings

custodial breaking hVV

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

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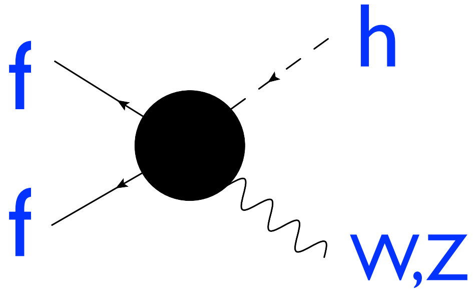
contact interactions



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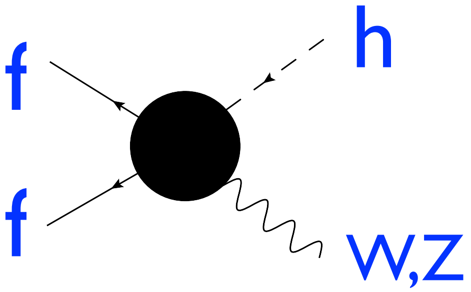
contact interactions

momentum-dependent
hVV couplings



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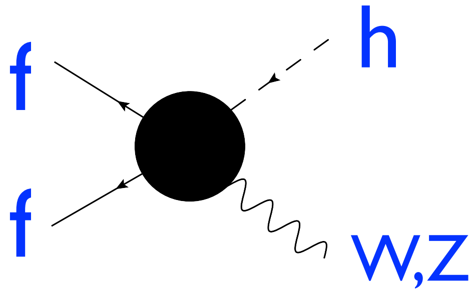


remember that BSM effects here are not independent from effects to other couplings!

arXiv:1412.4410

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

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

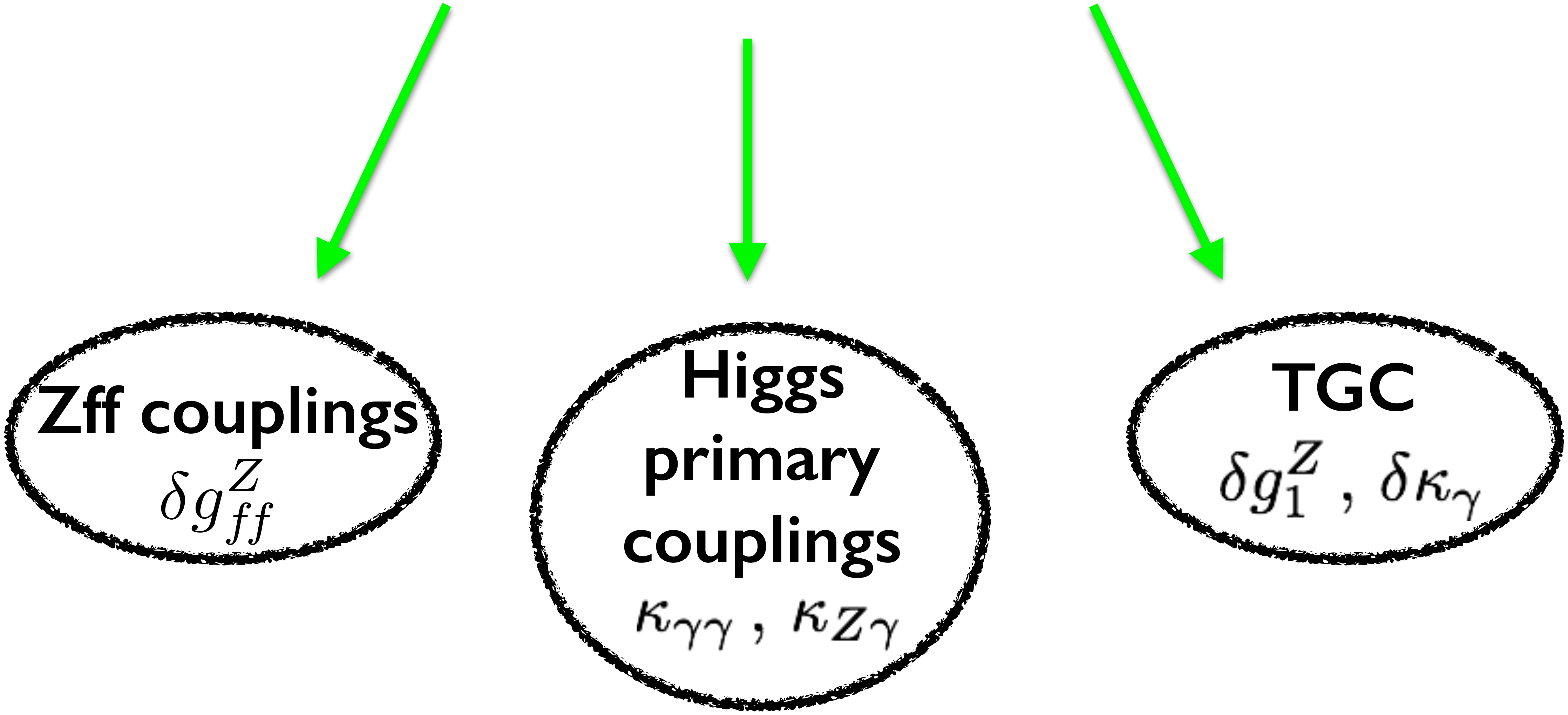
$$\delta g^W_{ff'} = \frac{c_{\theta_W}}{\sqrt{2}}\left(\delta g^Z_{ff} V_{\rm CKM} - V_{\rm CKM}\delta g^Z_{f'f'}\right) \quad \text{for } \; f = f_L$$

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

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

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

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



Zff couplings

δg^Z_{ff}

Higgs primary couplings

$\kappa_{\gamma\gamma}$, $\kappa_{Z\gamma}$

TGC

δg^Z_1 , $\delta\kappa_\gamma$

arXiv:1412.4410

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

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

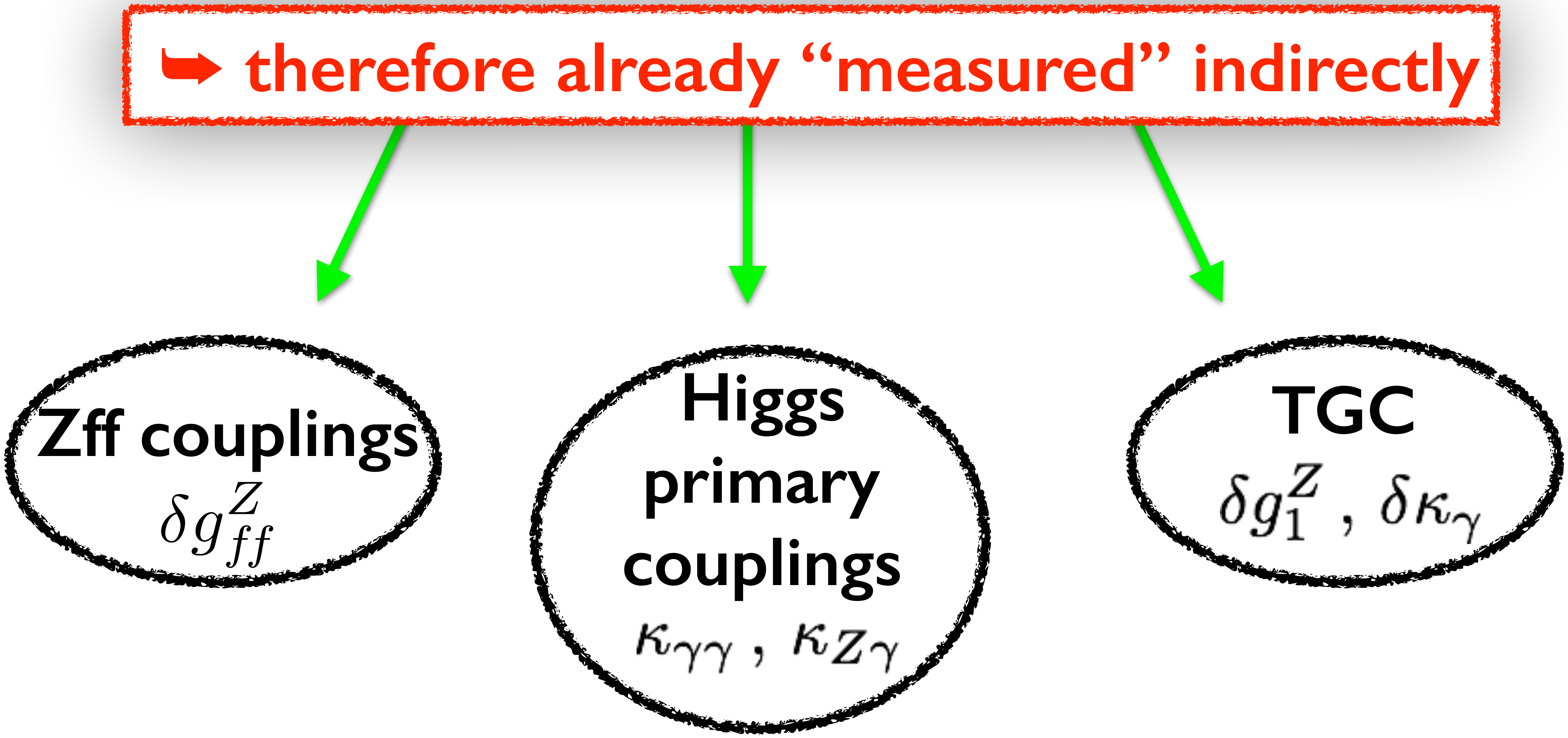
$$g^h_{Zff} = 2\boxed{\delta g^Z_{ff}} - 2\boxed{\delta g^Z_1}(g^Z_{ff} c_{2\theta_W} + g^\gamma_{ff} s_{2\theta_W}) + 2\boxed{\delta\kappa_\gamma} Y_f \frac{e s_{\theta_W}}{c^3_{\theta_W}} ,$$

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

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

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

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



➥ therefore already “measured” indirectly

Zff couplings δg^Z_{ff}

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

TGC δg^Z_1 , $\delta\kappa_\gamma$

For example:

Breaking of custodial in h→ZZ^*,WW^*:

$$\lambda_{WZ}^2 \equiv \frac{\Gamma(h \to WW^{(*)})}{\Gamma^{\rm SM}(h \to WW^{(*)})} \frac{\Gamma^{\rm SM}(h \to ZZ^{(*)})}{\Gamma(h \to ZZ^{(*)})}$$

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

$$\lambda_{WZ}^2 - 1 \approx 0.6\ \delta g_1^Z - 0.5\ \delta\kappa_\gamma - 1.6\ \kappa_{Z\gamma}$$

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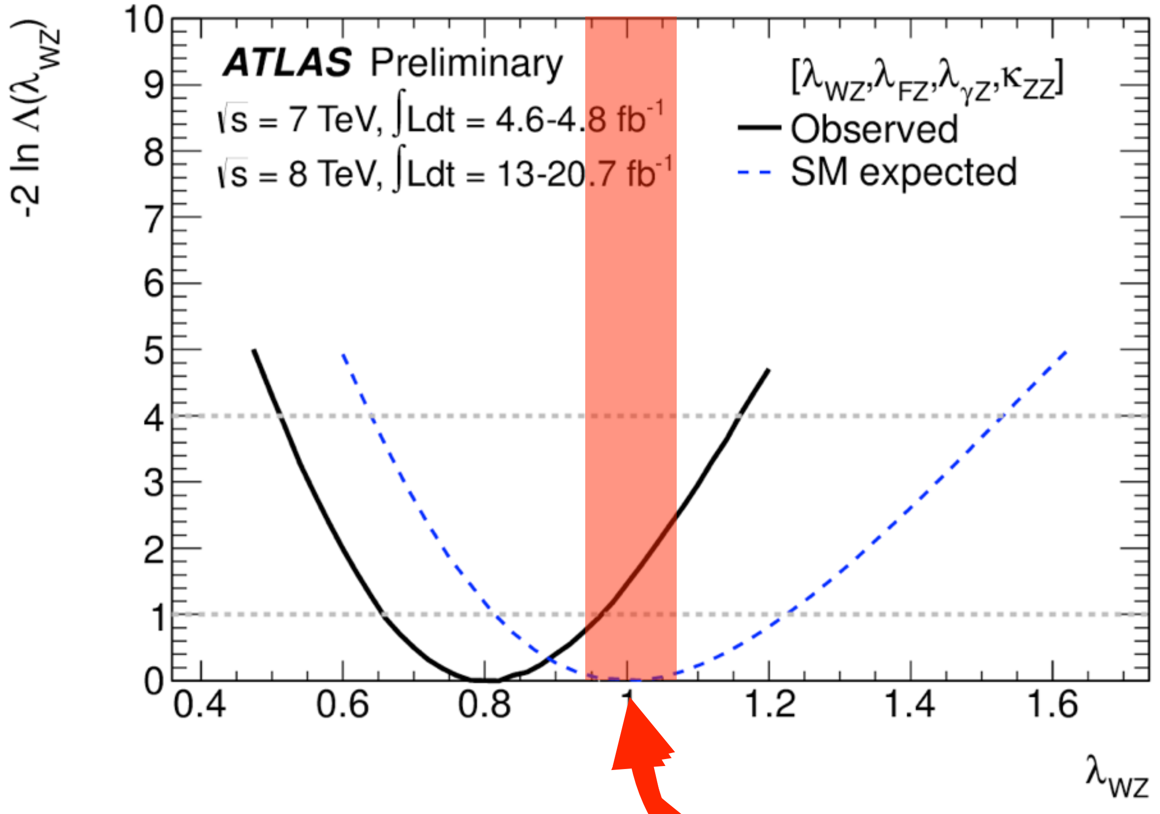
Breaking of custodial in h→ZZ*,WW*:

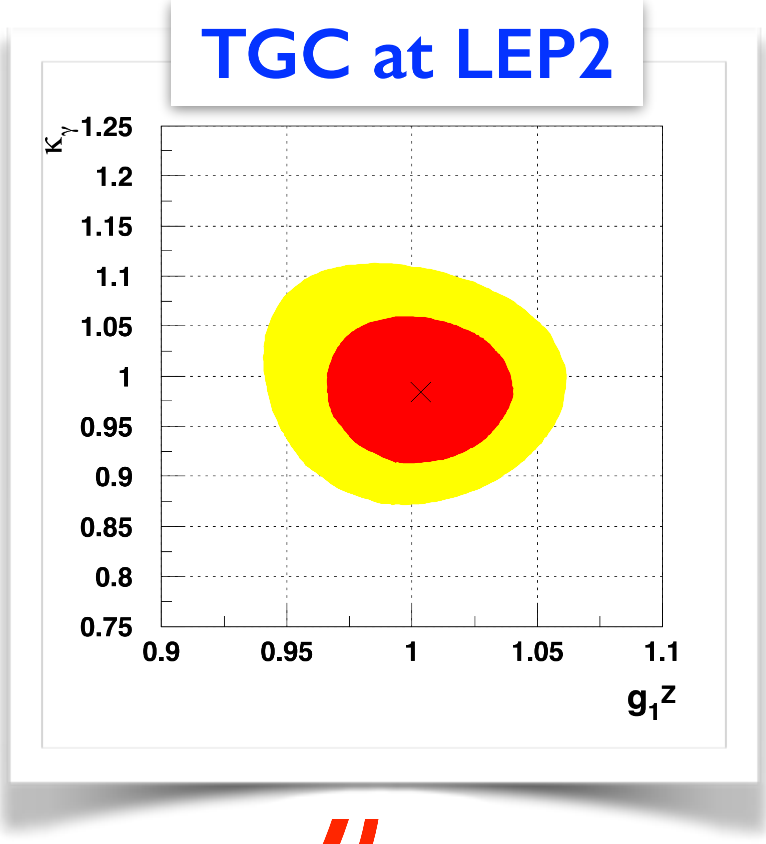
$$\lambda_{WZ}^2 \equiv \frac{\Gamma(h \to WW^{(*)})}{\Gamma^{\rm SM}(h \to WW^{(*)})}\,\frac{\Gamma^{\rm SM}(h \to ZZ^{(*)})}{\Gamma(h \to ZZ^{(*)})}$$

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

$$\lambda_{WZ}^2 - 1 \approx 0.6\,\delta g_1{}^Z - 0.5\,\delta\kappa_\gamma - 1.6\,\kappa_{Z\gamma}$$

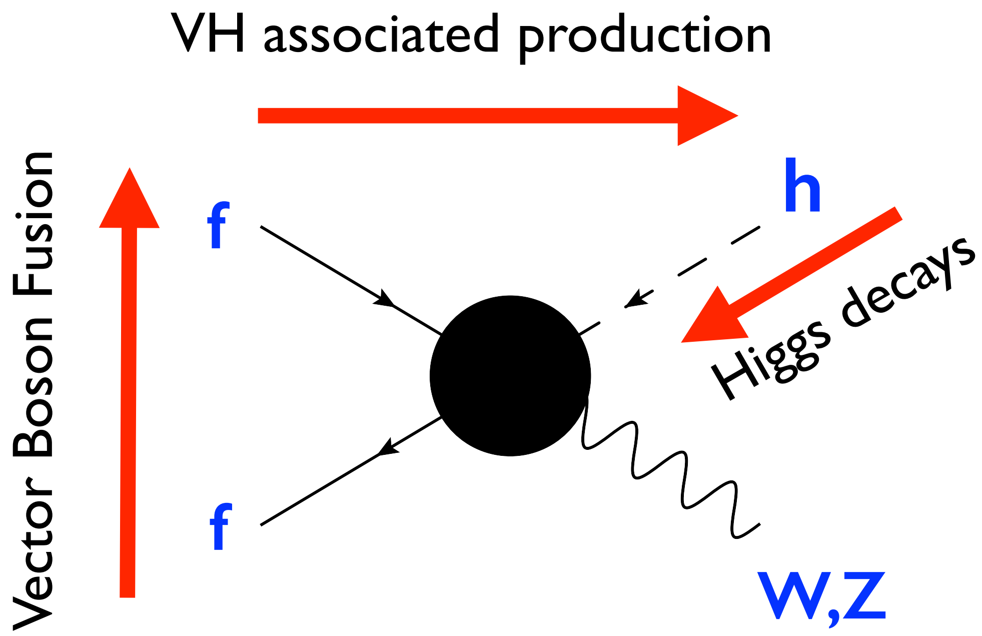


TGC at LEP2



h→Zγ bound

Non-primary Higgs couplings can be disentangled in distributions:



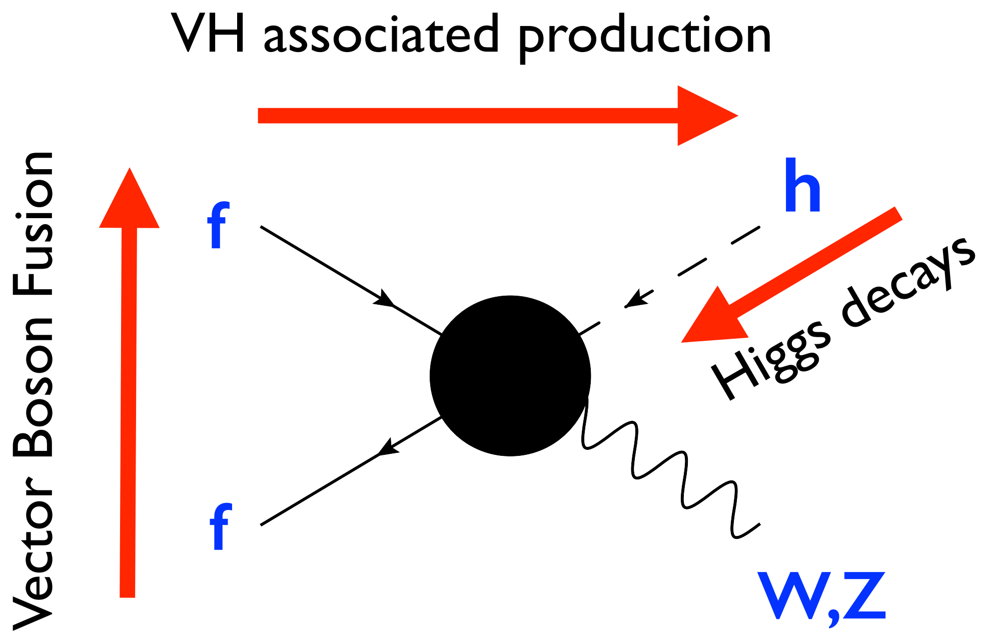
$$\mathcal{M}_{hVff}(q,p) = \frac{1}{v}\epsilon^{*\mu}(q)\, J_V^{\nu}(p)\left[\, A^V\,\eta_{\mu\nu} + B^V\,(p\cdot q\,\eta_{\mu\nu} - p_\mu\, q_\nu) + C^V\,\epsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma\right]$$

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

one-to-one correspondence
with Higgs couplings

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

Non-primary Higgs couplings can be disentangled in distributions:



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

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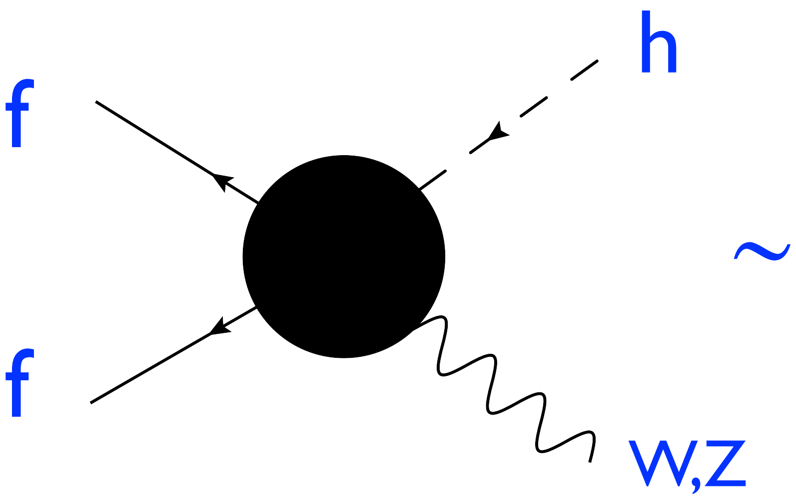
one-to-one correspondence with Higgs couplings

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

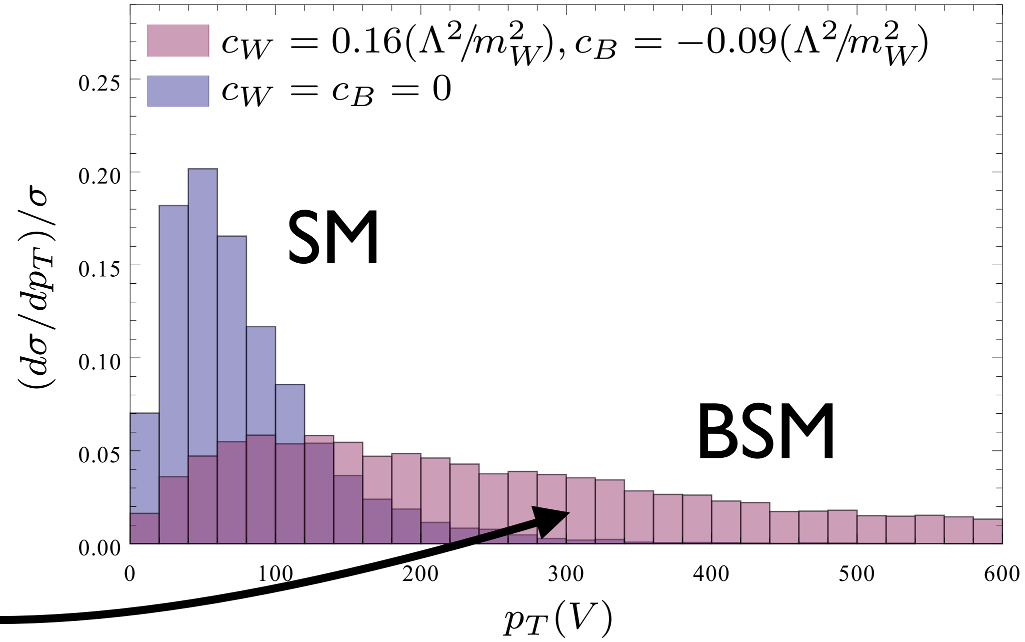
↳ enhanced at high-energies = <u>ideal for the LHC</u>!

Example: $pp \to Vh$:



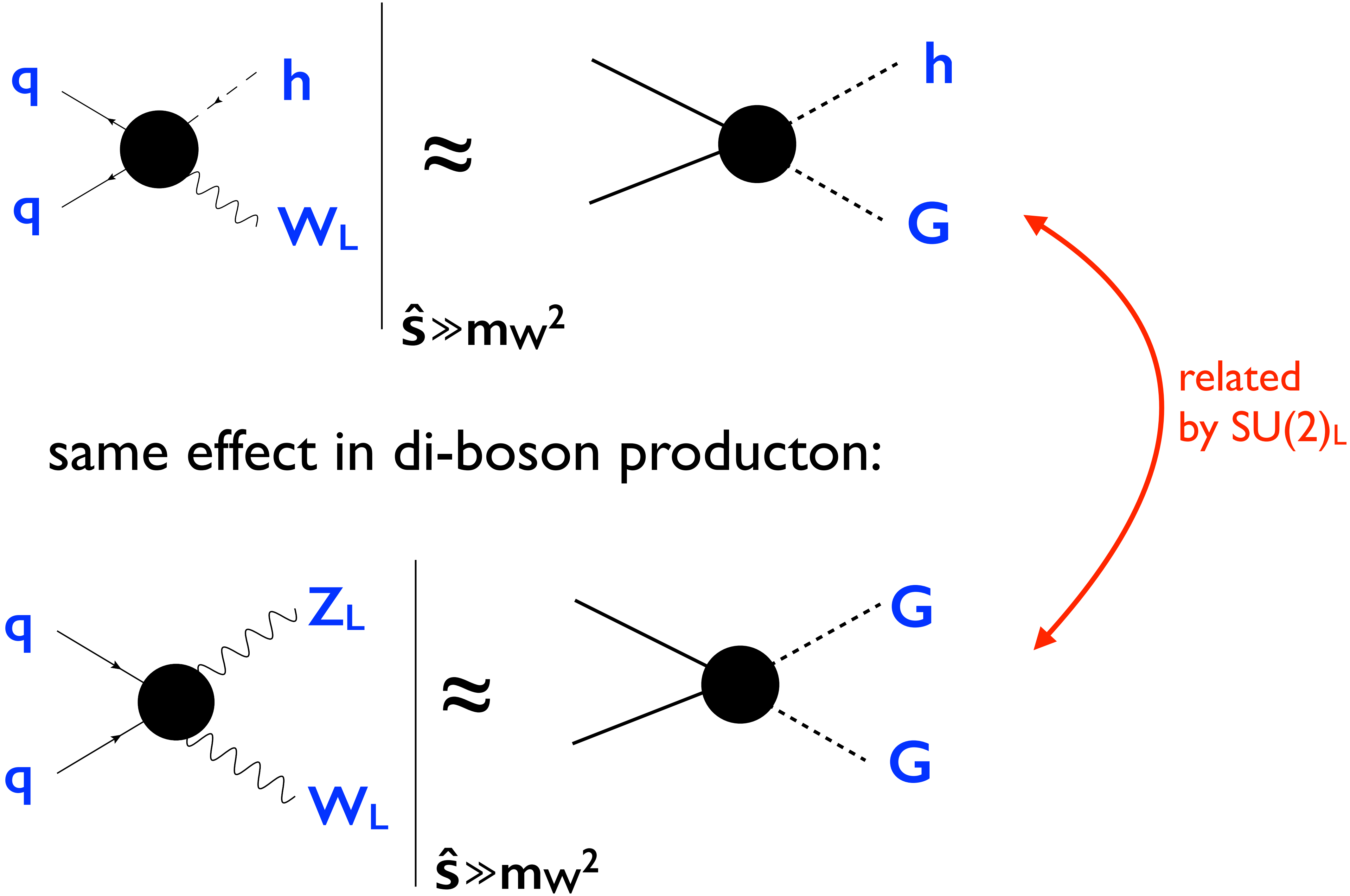
$\sim E^2/\Lambda^2$

BSM-effects enhanced
at the *tail* of distributions



arXiv:1406.7320

Can do better than *indirect* measurements (non-Higgs measurements)?

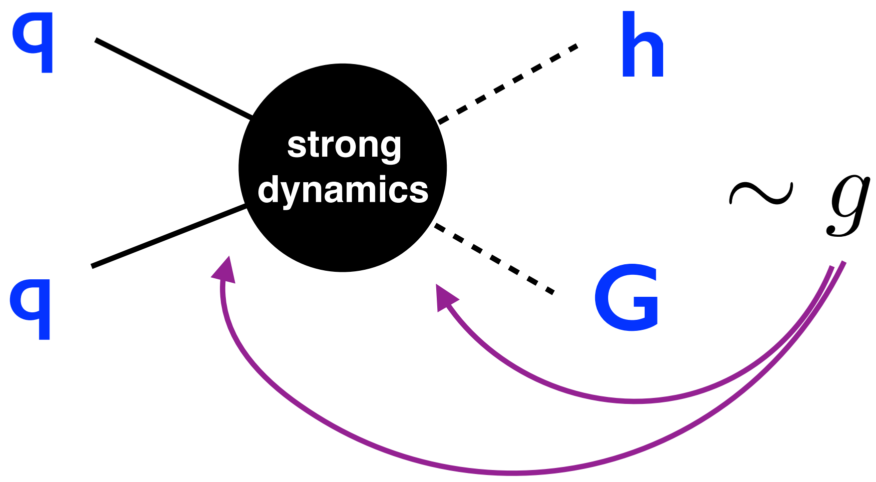


same effect in di-boson producton:

bounds must be combined!

What **BSMs** can we probe here?

BSMs where fermions and Higgs belong to a **strong sector** at ~TeV



$$\sim g_*^2 \frac{E^2}{\Lambda^2} \Bigg|_{E\to\Lambda} \to g_*^2 \lesssim 16\pi^2$$

"strong" coupling

strong-coupling at E~Λ
(as in pion-pion scattering)

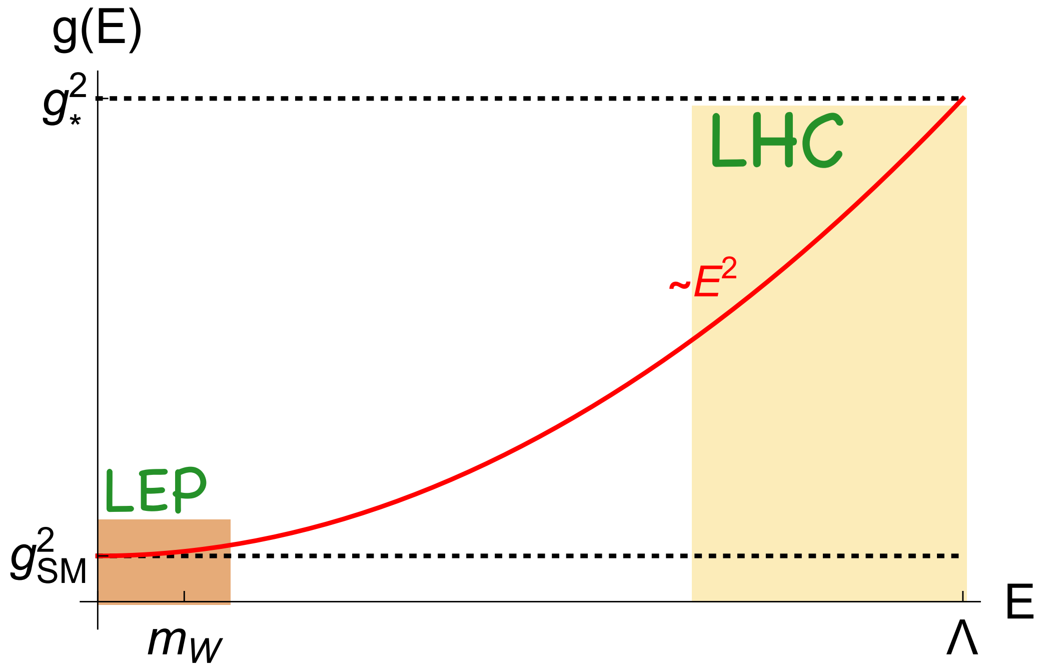
It can dominate over the SM!

Consistent picture: the **strong sector** can have *accidental* symmetries that do not allow for SM couplings, e.g., **H→H+c & flavor sym.**
➡ interactions arise from higher-dimensional operators

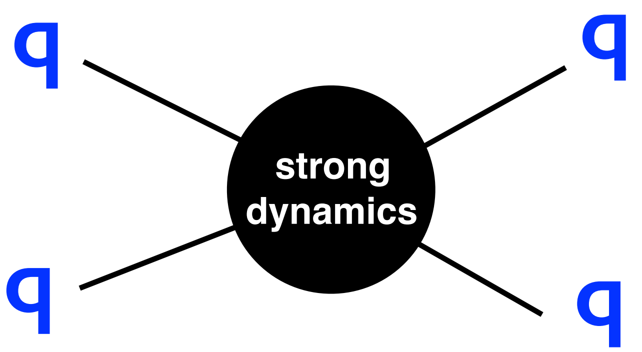
Small breaking of these symmetries could generate the SM couplings (Yukawa & Higgs potential)
➡ SM fermions and Higgs appear "accidentally" weakly-coupled at low-energies

To probe this type of scenarios we must scatter fermions and Higgs at high-energies:

2→2 scattering strength:



However, not clear that Higgs physics is the best place to look, as we also expect:



☛ dijets

Conclusions

- At the end of the **LEP era**, the precise measurements of Z couplings led to strong constraints on **BSM**

  ➧ mainly characterized by the **S & T** parameters

- At the **LHC**, Higgs couplings afford new and even more interesting probes of **BSMs**, mainly the ***primary*** **Higgs-couplings**

At present, Higgs physics plays already an important role in BSM destruction

Highest motivation to measure these couplings better and better

- Beyond them, the LHC high-energy regime affords new probes for new (more exotic) BSM in **Vh** (and **VV**) associated production