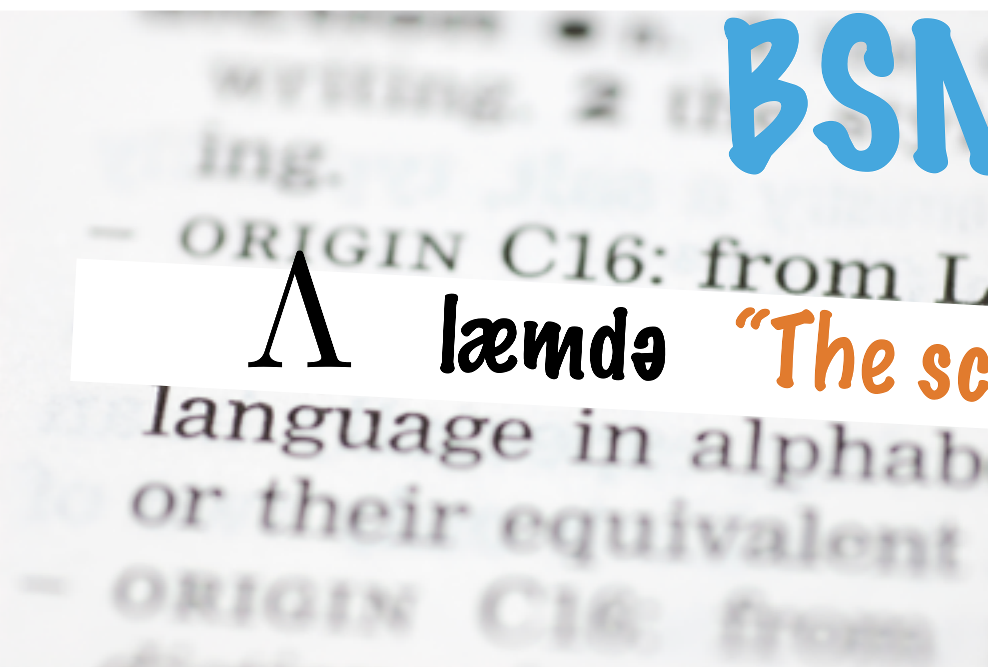
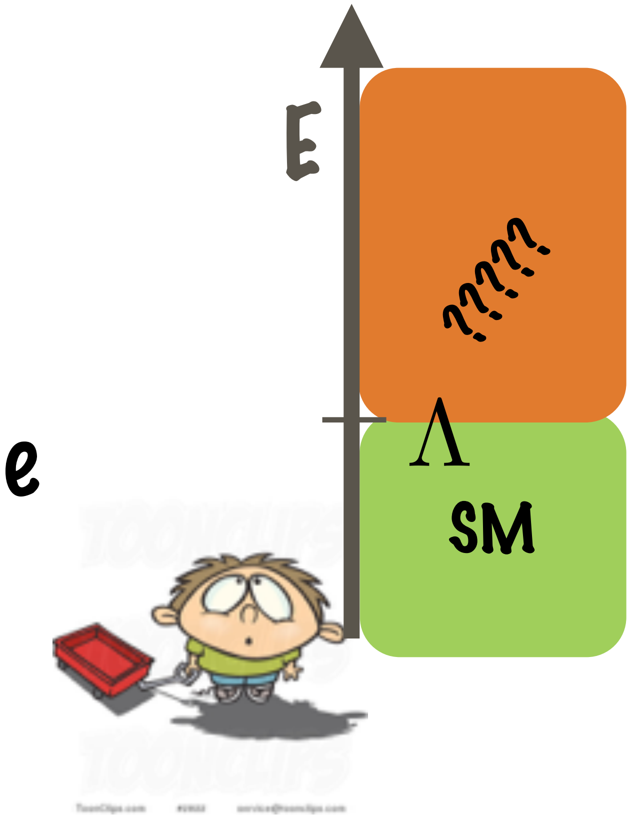
Part III

Beyond the Standard Model (BSM)

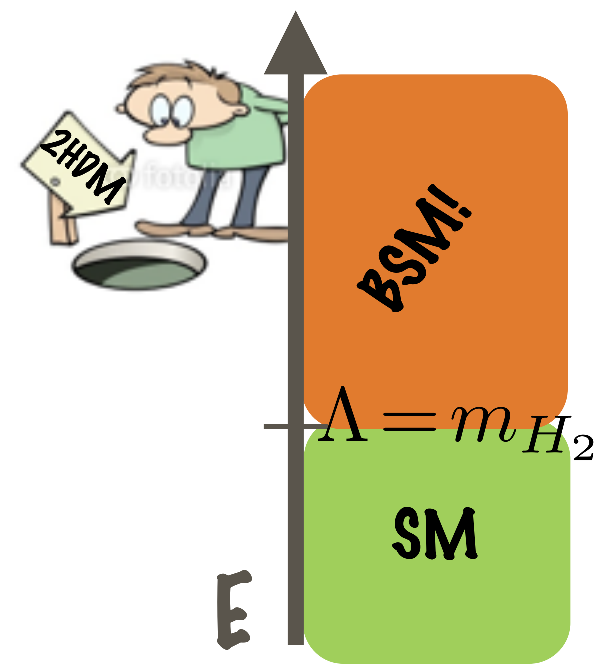
BSM dictionary



Λ læmdə *"The scale of new physics"*



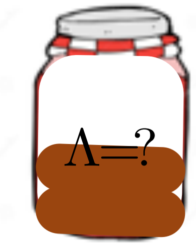
- From a **bottom-up** perspective it represent the scale up to which **only SM fields** propagate
- It parametrizes our ignorance of physics above Λ



- From a **top-down** perspective (where we assume a given BSM) it represents a typical mass scale (e.g. m_{H2} in 2 Higgs doublets models)
- Some models have more scales...

Synonyms: UV scale, Cutoff, Microscopic scale,...

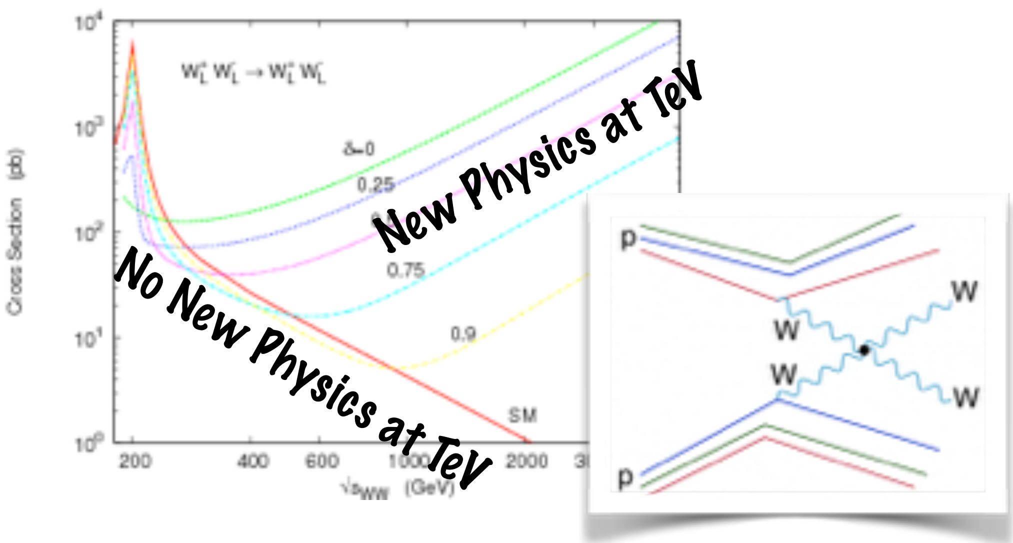
a BSM Higgs?



What did we learn from the Higgs Discovery/Mass about the Microcosm?

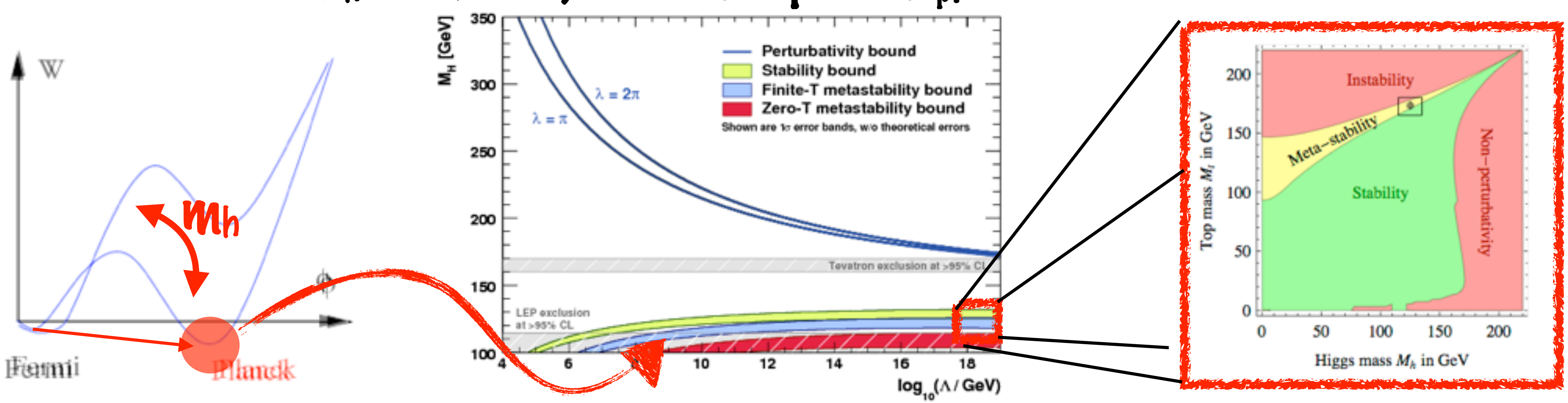
Mass m_h=125 GeV (Later: what can be learned from couplings?)

* Because of m_h=125 GeV, no more (WW) unitarity argument for new TeV physics

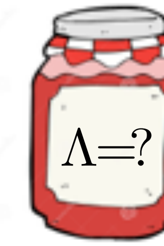


Now: $\Lambda = ?$

* Because of m_h=125 GeV, the SM up to M_{pl} is (meta) stable



a BSM Higgs?

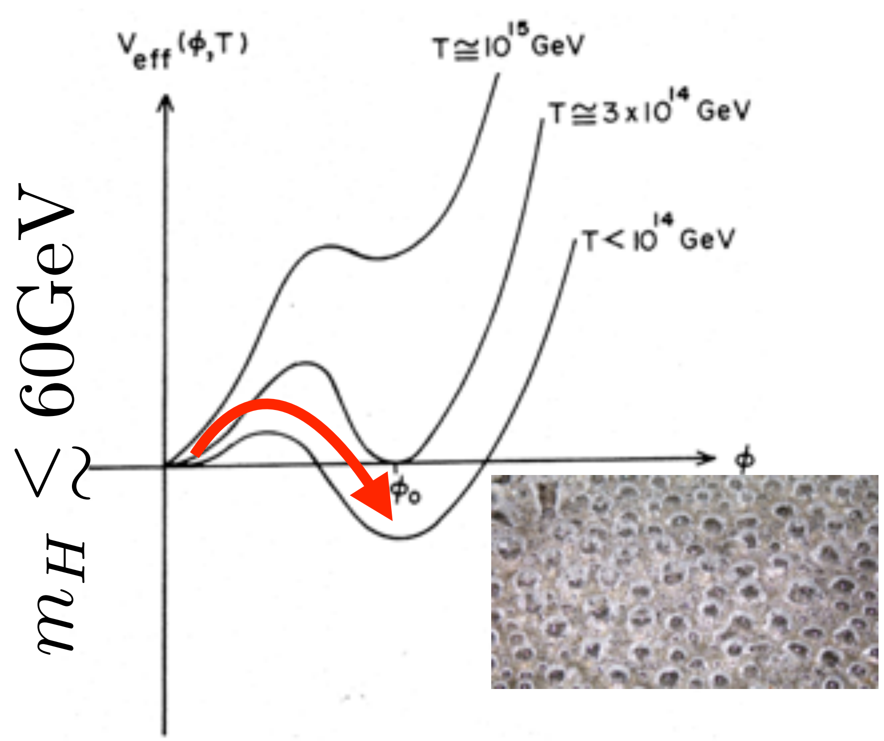


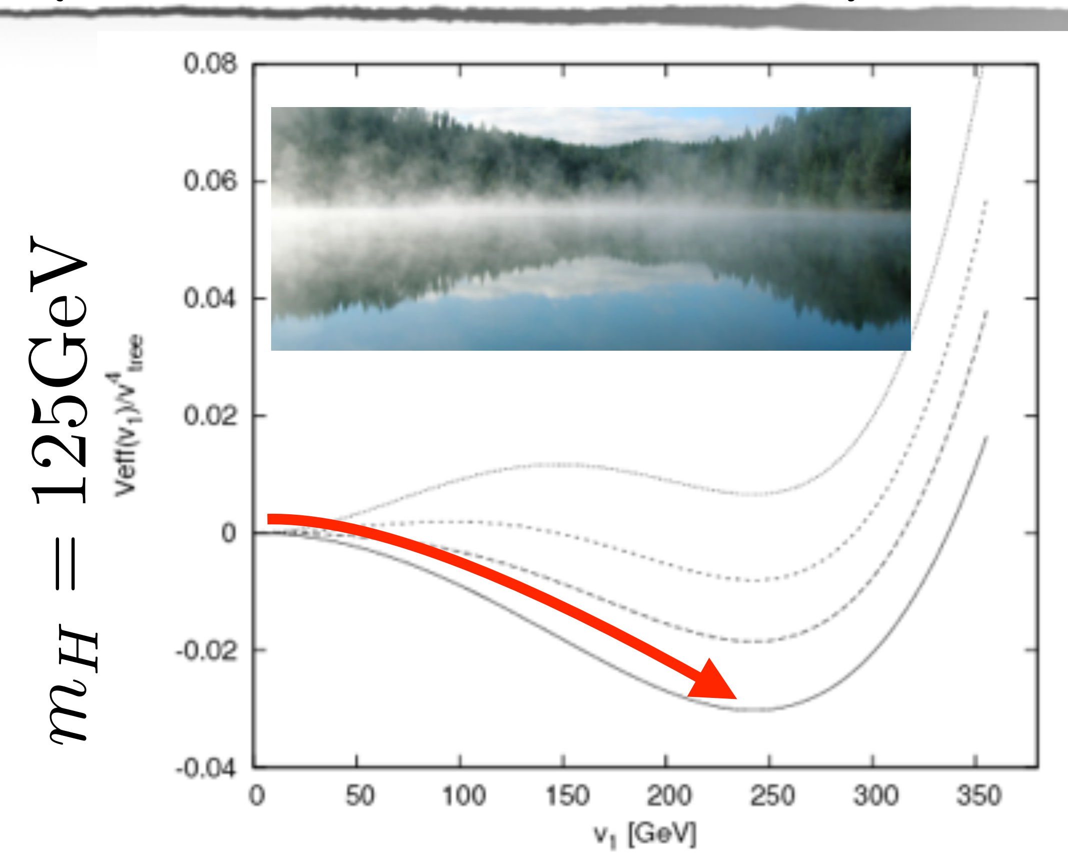
What did we learn from the Higgs Discovery/Mass about the Microcosm?

Mass m_h=125 GeV (Later: what can be learned from couplings?)

* **Because of m_h=125 GeV, the EW phase transition in the early universe is not first order**

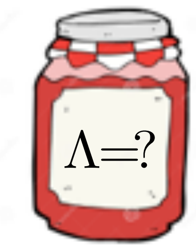
(Sakharov (1967): to produce the baryon asymmetry we need an out-of-equilibrium situations, like in a 1st order phase transition.)





→ **Need BSM!**
...but there are models with $\Lambda = 10^{15}\mathrm{GeV}$ that can produce the baryon asymmetry (leptogenesis) Λ=?

a BSM Higgs?



The hierarchy problem (brief):

see Wulzer

* Number of degrees of freedom...

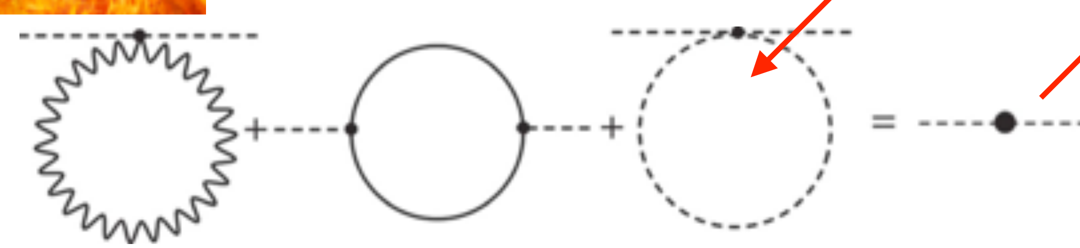
	$m=0$		$m\neq0$
Fermions:	ψ_L	2 → 4	ψ_L, ψ_R
Vectors:	$\epsilon^{\pm}$	2 → 3	$\epsilon^{\pm}$ ϵ^{0}
Scalars:	ϕ	1 → 1	ϕ

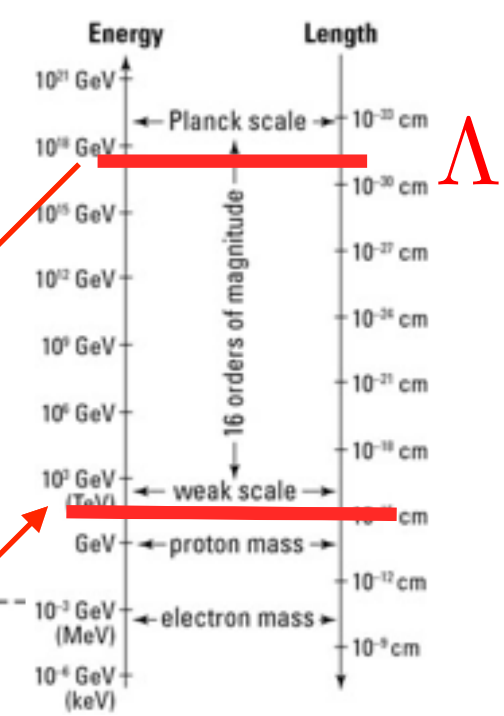
Discontinuity → quantum corrections cannot generate a mass...

Scalars have no discontinuity → generated mass of order cutoff Λ

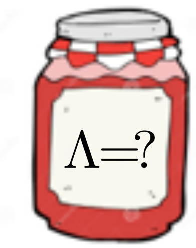
Rattazzi/Giudice

(the same computation would be used to calculate the temperature for a snowball in hell: you expect it to melt!)





a BSM Higgs?



see Wulzer

The hierarchy problem (brief):

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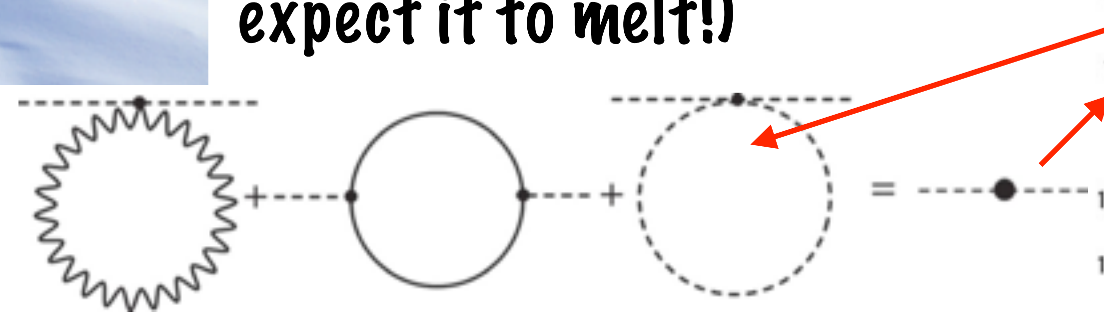
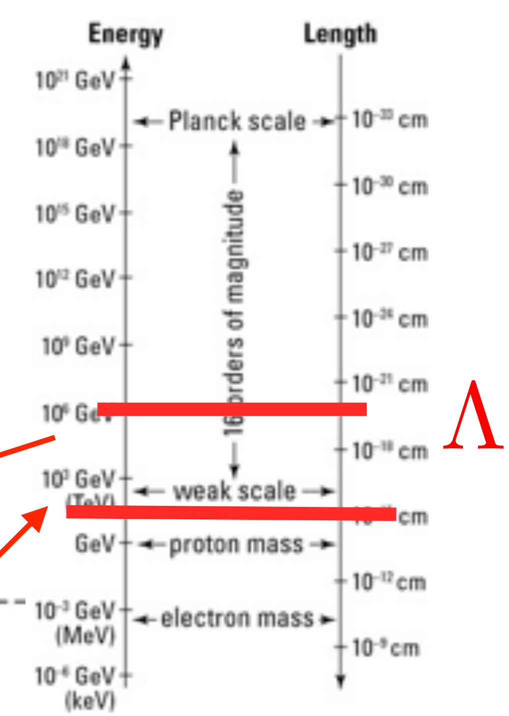
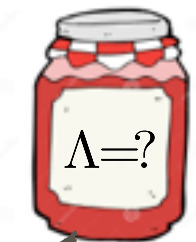


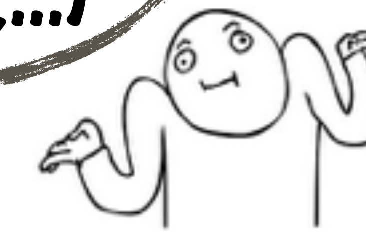


Simplest known solution: **Naturalness** $\Lambda \simeq \text{TeV}$

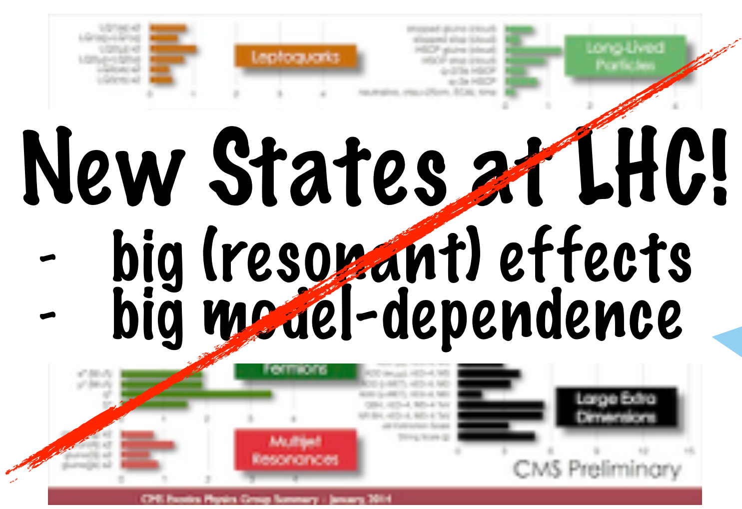
a BSM Higgs?



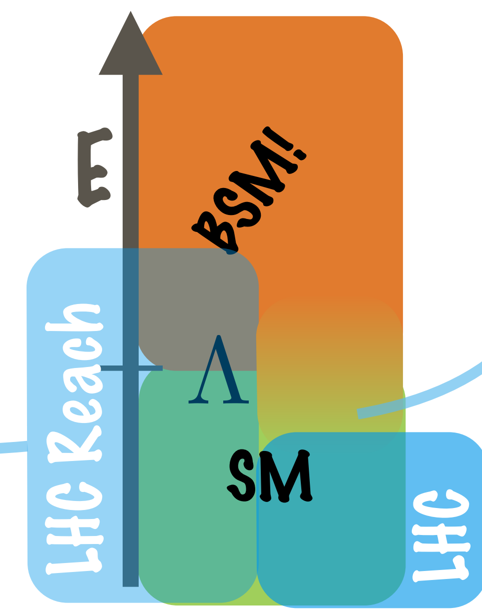
Summary so far: Physics BSM exists (DM,baryon asymmetry,...)
...but we do not now its scale (and the Higgs didn't add much)



→ Only physical hypothesis that LHC is guaranteed to test: **naturalness**
→(New states lurking around $\Lambda \approx$ TeV)



~~New States at LHC!~~
- ~~big (resonant) effects~~
- ~~big model-dependence~~



No new States at LHC!
- small effects
- model-independent parametrization possible

see Part II

→ Most general Lagrangian with SM gauge group and field content:

Effective Field Theory: $\mathcal{L} = \Lambda^4 + _{loop}\Lambda^2 |H|^2 + \mathcal{L}_4 + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \cdots$

m_h=125GeV → $\Lambda \approx$1 TeV

Might be observable!

Effective Field Theory

Write the most general Lagrangian with only light (SM) fields: it will automatically include all effects that can be generated at Λ and how they modify SM physics!

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{d\leq 4} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \cdots$$

$\mathcal{L}_n$ includes all field operators with dimension=n, e.g for dim-6: $|H^\dagger H| B_{\mu\nu} B^{\mu\nu}$

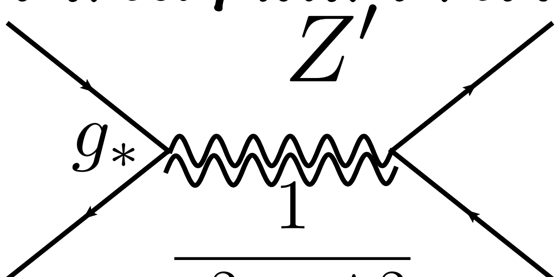
But this is non-renormalizable!

"Non-renormalizable theories are as renormalizable as renormalizable ones" - S. Weinberg
(meaning that infinities are still unobservable and the theory remains predictive - to a given $O(E/\Lambda)$)

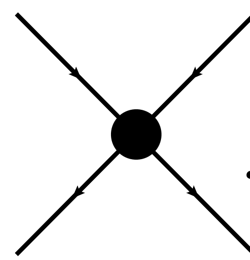
Where does it come from? (top-down perspective)

E.g. a theory with a heavy resonance of mass $m_{Z'} = \Lambda$, would look at low energy exactly like this:

(e.g. Fermi theory)



$p^2 \ll \Lambda^2$



$$g_*^2 \frac{\bar\psi\gamma^\mu\psi\bar\psi\gamma_\mu\psi}{\Lambda^2} \quad + O\left(\frac{p^2}{\Lambda^2}\right)$$

What does it do? (bottom-up perspective)

It deforms the relations implied by the SM $\mathcal{L}_{SM} \equiv \mathcal{L}_{d\leq 4}$
Exemple, the relation between Higgs couplings and particle masses:

$$\mathcal{L}_{SM} + c_f \frac{|H|^2}{\Lambda^2} \bar\psi_L H \psi_R \quad \longrightarrow$$

$$-i\frac{m_f}{v}\left(1 + c_f \frac{v^2}{\Lambda^2}\right)$$

Effective Field Theory

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{d\leq 4} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \cdots$$

EFT for the Higgs, why?

- Practically: EFT is a systematic parametrization of deviations from the SM and carries a physical meaning → precision tests comparable with direct searche
- Theoretically: If EWSB sector strongly coupled, bigger effects here

Ok, but how many new parameters are we talking about?

~~$\mathcal{L}_5$~~ Too small for LHC!

How many? Only one*... $\frac{(\bar{L}\tilde{H}^*)(L\tilde{H}^\dagger)}{\Lambda}$ $\tilde{H} = i\sigma_2 H$

What BSM generates it? Heavy RH neutrinos with m= Λ

What does it do to the SM? Gives mass to neutrinos $m_\nu \propto \frac{v^2}{\Lambda}$

$\mathcal{L}_6$ Next slides...

(*= for simplicity I'll consider a universal flavor structure and no CPV - See Gori's Lecture)

EFT for Higgs Physics

What do they do to the SM?

Are they already constrained?

Can we see them at LHC?

$\mathcal{L}_6$ Has many terms, but only* 17 affect Higgs physics (modifying the SM predictions)

$\mathcal{O}_r = \|H\|^2 (D_\mu H)^\dagger (D^\mu H)$	$\mathcal{O}_{WB} = \frac{gg'}{4}(H^\dagger \sigma^a H) W^a_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{y_d} = y_d \|H\|^2 \bar{Q}_L H d_R$	$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$
$\mathcal{O}_{y_e} = y_e \|H\|^2 \bar{L}_L H e_R$	$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$
$\mathcal{O}_{y_u} = y_u \|H\|^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$
$\mathcal{O}_{GG} = \frac{g_s^2}{4} \|H\|^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}_{BB} = \frac{g'^2}{4} \|H\|^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$
$\mathcal{O}_{WW} = \frac{g^2}{4} \|H\|^2 W^a_{\mu\nu} W^{a\mu\nu}$	$\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$
$\mathcal{O}_6 = \lambda \|H\|^6$	

$\mathcal{O}_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$
$\mathcal{O}_L^{(3)} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \sigma^a \gamma^\mu L_L)$

Actually a small number:
if #terms < #observables → relations

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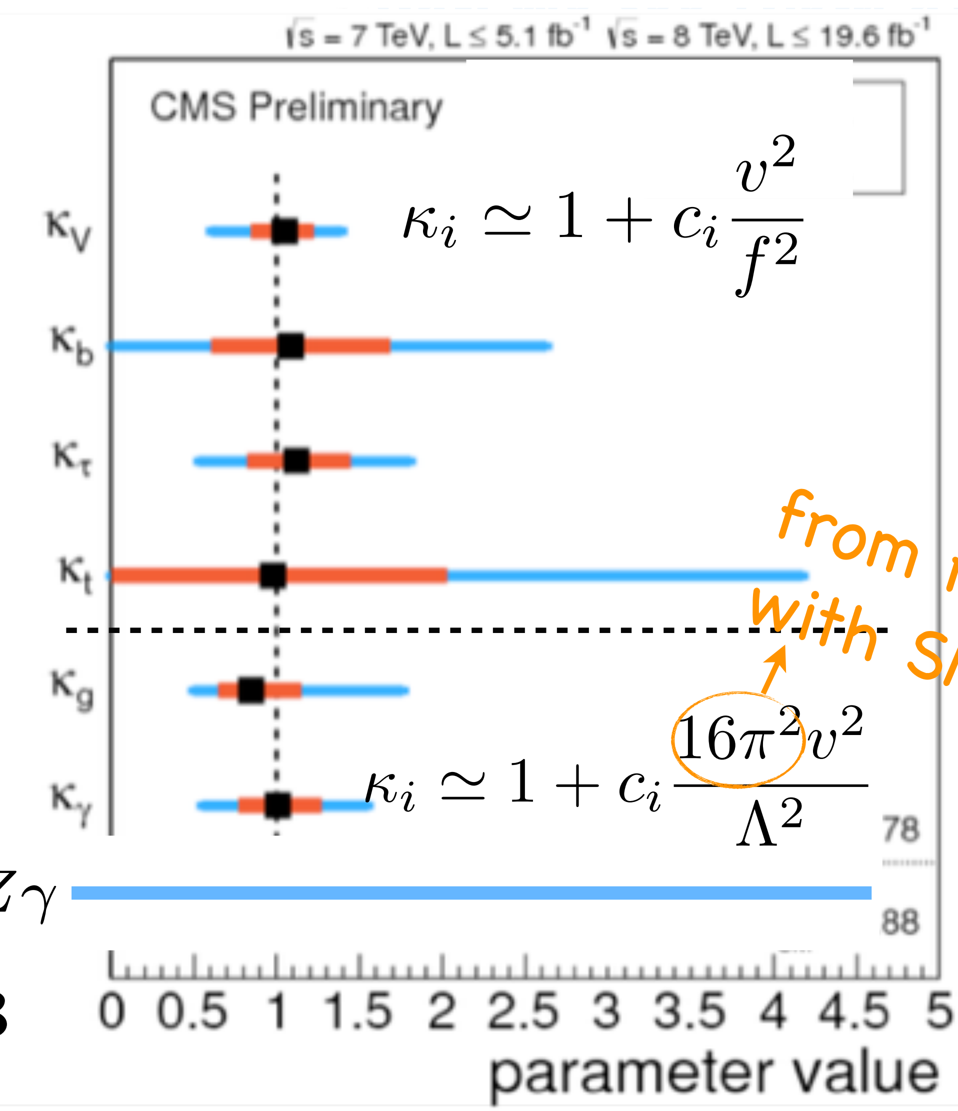
Higgs Physics Only

$\langle h \rangle = v$

v	←	$\mathcal{O}_r = \lvert H\rvert^2 (D_\mu H)^\dagger (D^\mu H)$	→	κ_V
m_d	←	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$	→	κ_b
m_e	←	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R$	→	κ_τ
m_u	←	$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \widetilde{H} u_R$	→	κ_t
g_s	←	$\mathcal{O}_{GG} = \frac{g_s^2}{4} \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	→	κ_g
g'	←	$\mathcal{O}_{BB} = \frac{g'^2}{4} \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	→	κ_γ
g	←	$\mathcal{O}_{WW} = \frac{g^2}{4} \lvert H\rvert^2 W^a_{\mu\nu} W^{a\mu\nu}$	→	$\kappa_{Z\gamma}$
m_h	←	$\mathcal{O}_6 = \lambda \lvert H\rvert^6$	→	h^3



$\kappa_i \simeq 1 + c_i \frac{v^2}{f^2}$

$\kappa_i \simeq 1 + c_i \frac{16\pi^2 v^2}{\Lambda^2}$

from ratio with SM loop

In the vacuum <h>=v, operators $\lvert H\rvert^2 \times \mathcal{L}_{SM}$ only redefine SM parameters! ▶ Observable only in Higgs physics!

$$\frac{1}{g_s^2} G_{\mu\nu} G^{\mu\nu} + \frac{\lvert H\rvert^2}{\Lambda^2} G_{\mu\nu} G^{\mu\nu} = \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2} \right) G_{\mu\nu} G^{\mu\nu} + h \frac{2v}{\Lambda^2} G_{\mu\nu} G^{\mu\nu} + \ldots$$

EFT for Higgs Physics

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Higgs Physics Only

$\langle h \rangle = v$		Operator		
v	$\longleftarrow$	$\mathcal{O}_r = \lvert H\rvert^2 (D_\mu H)^\dagger (D^\mu H)$	$\longrightarrow$	κ_V
m_d	$\longleftarrow$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$	$\longrightarrow$	κ_b
m_e	$\longleftarrow$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R$	$\longrightarrow$	κ_τ
m_u	$\longleftarrow$	$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \widetilde{H} u_R$	$\longrightarrow$	κ_t
g_s	$\longleftarrow$	$\mathcal{O}_{GG} = \frac{g_s^2}{4} \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\longrightarrow$	κ_g
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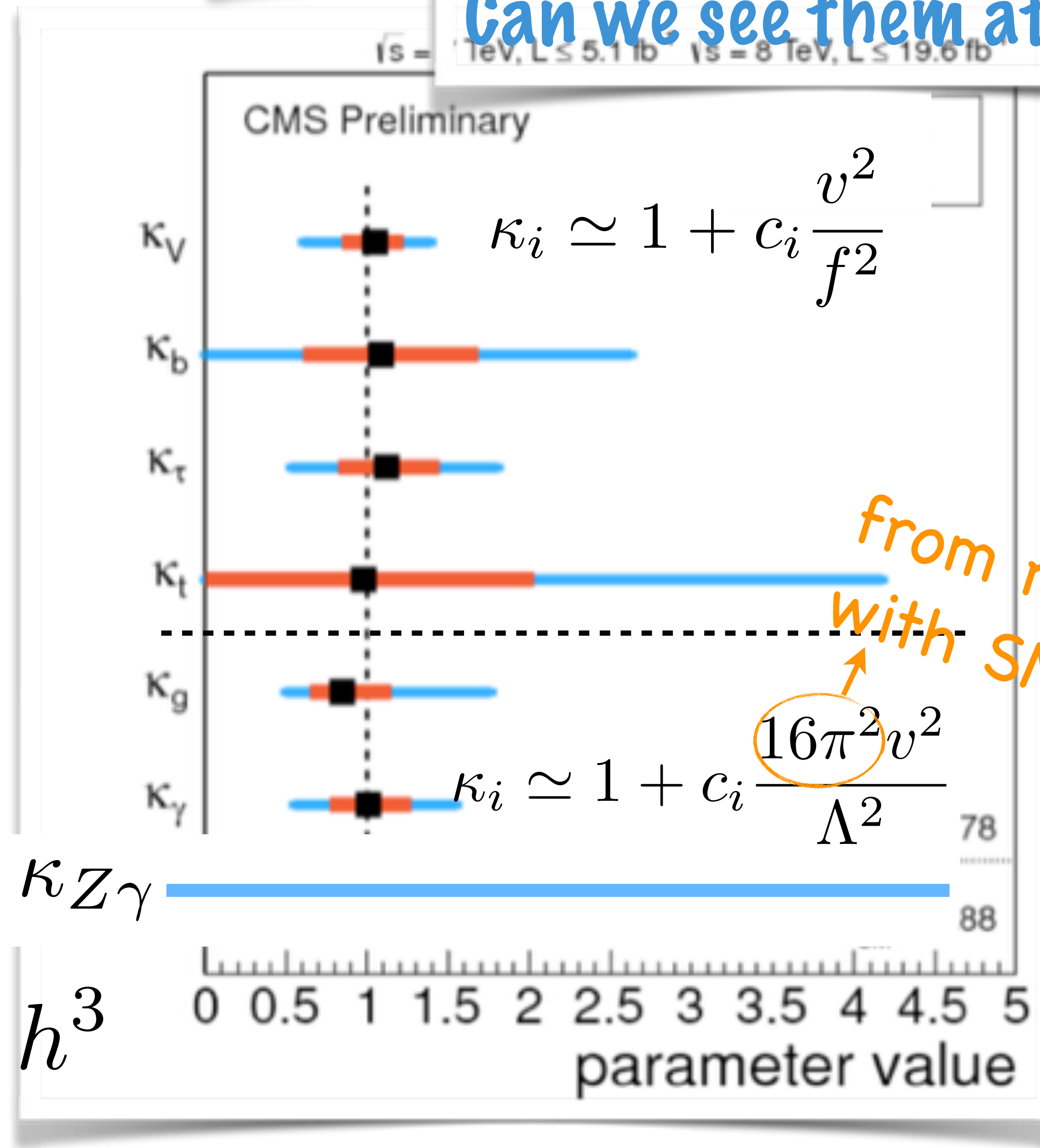
g	$\longleftarrow$	$\mathcal{O}_{WW} = \frac{g^2}{4} \lvert H\rvert^2 W^a_{\mu\nu} W^{a\mu\nu}$	$\longrightarrow$	$\kappa_{Z\gamma}$
m_h	$\longleftarrow$	$\mathcal{O}_6 = \lambda \lvert H\rvert^6$	$\longrightarrow$	h^3



$\kappa_i \simeq 1 + c_i \dfrac{v^2}{f^2}$

from ratio with SM loop

$\kappa_i \simeq 1 + c_i \dfrac{16\pi^2 v^2}{\Lambda^2}$

- **Measurements couplings are motivated by this framework**
- κ **parameters are actually testing the SM** $\kappa = 1$ **versus the EFT** $\kappa \neq 1$

EFT for Higgs Physics

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Higgs Physics Only

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Higgs and EW

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EFT for Higgs Physics

What do they do to the SM?

Are they already constrained?

Higgs and EW

In the vacuum $\langle h \rangle = v$, these operators can be measured!

7 of these operators modify:

$Z\bar{\nu}\nu \quad Z\bar{e}_L e_L \quad Z\bar{e}_R e_R$

$Z\bar{u}_L u_L \quad Z\bar{u}_R u_R \quad Z\bar{d}_L d_L \quad Z\bar{d}_R d_R$

$\mathcal{O}_{WB} = \frac{gg'}{4}(H^\dagger\sigma^a H)W^a_{\mu\nu}B^{\mu\nu}$
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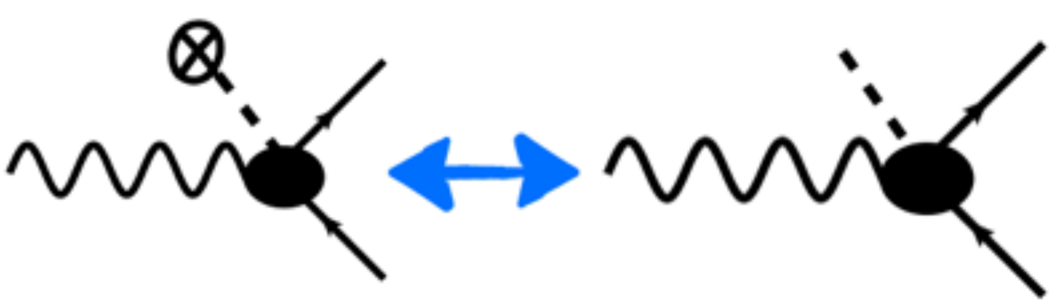
$\mathcal{O}^{(3)}_L = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L\sigma^a\gamma^\mu L_L)$

All tightly constrained by LEP <0.001



(Gupta),Pomarol,FR'13-14; Falkowski,FR'14

EFT for Higgs Physics

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Higgs and EW

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$Z\bar\nu\nu \quad Z\bar e_L e \ldots$

$Z\bar u_L u_L \quad Z \ldots d_L \quad Z\bar d_R d_R$

All tightly c... 001

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

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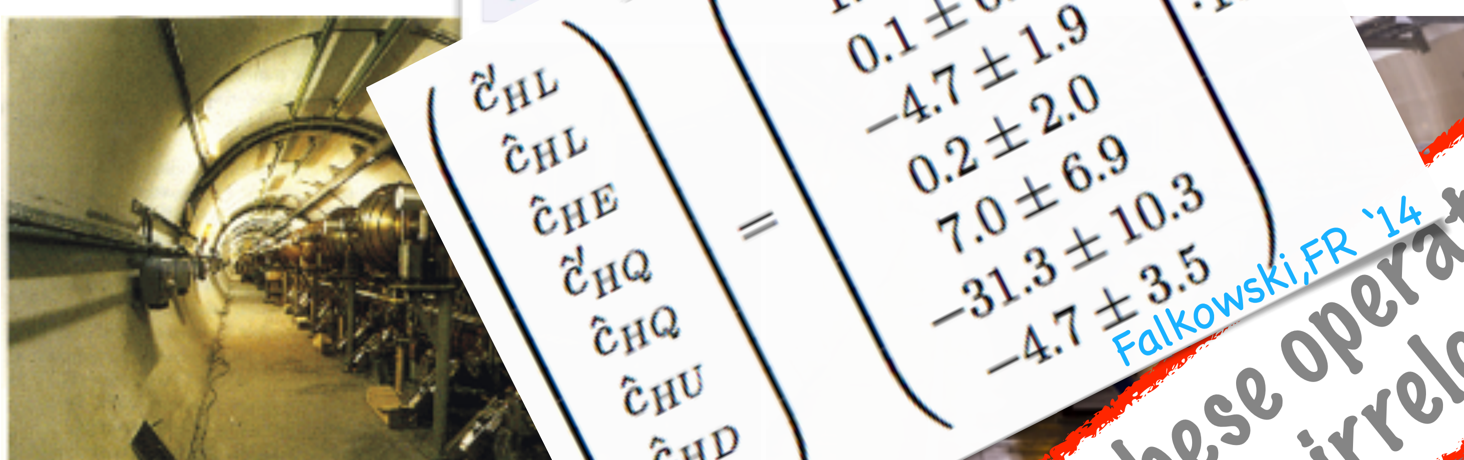
$$\mathcal{O}_L^{(3)\,q} = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar Q_L\sigma^a\gamma^\mu Q_L)$$

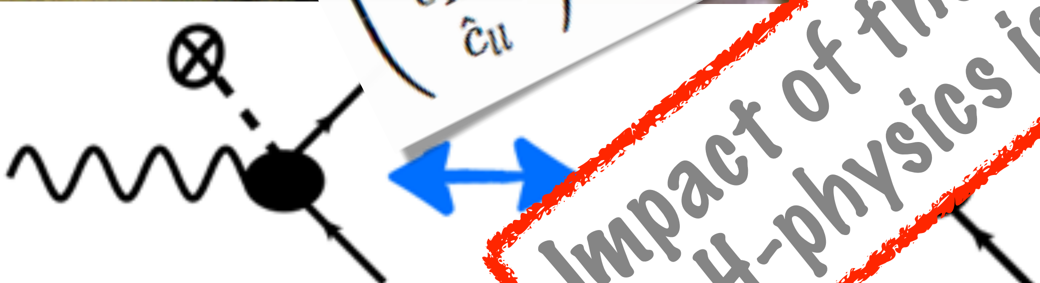
$$\ldots = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar L_L\gamma^\mu L_L)$$

$$\ldots_L = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar L_L\sigma^a\gamma^\mu L_L)$$

$$\begin{pmatrix} \delta\hat c_{HL} \\ \hat c_{HL} \\ \hat c_{HE} \\ \delta\hat c_{HQ} \\ \hat c_{HQ} \\ \hat c_{HU} \\ \hat c_{HD} \\ \hat c_{ll} \end{pmatrix} = \begin{pmatrix} -1.9\pm1.1 \\ 1.1\pm0.7 \\ 0.1\pm0.6 \\ -4.7\pm1.9 \\ 0.2\pm2.0 \\ 7.0\pm6.9 \\ -31.3\pm10.3 \\ -4.7\pm3.5 \end{pmatrix}\cdot 10^{-3}$$

Falkowski,FR `14





Impact of these operators in H-physics is irrelevant

EFT for Higgs Physics

What do they do to the SM?

Are they already constrained?

Higgs and EW

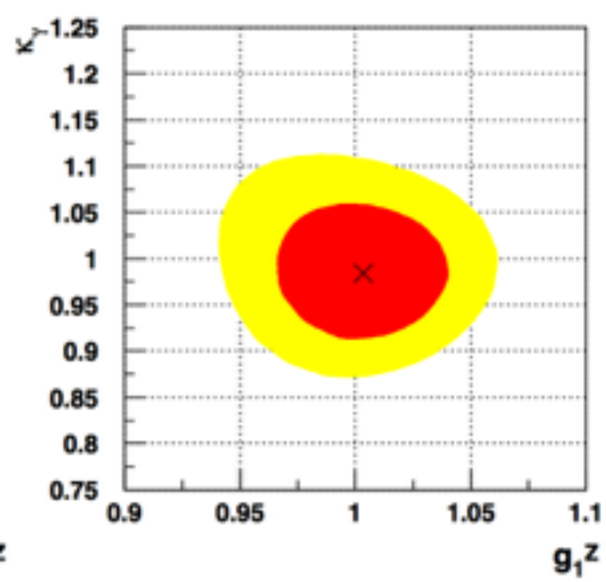
In the vacuum <h>=v, these operators can be measured!

2 of these operators modify (wrt SM):

δg_1^Z

κ_γ

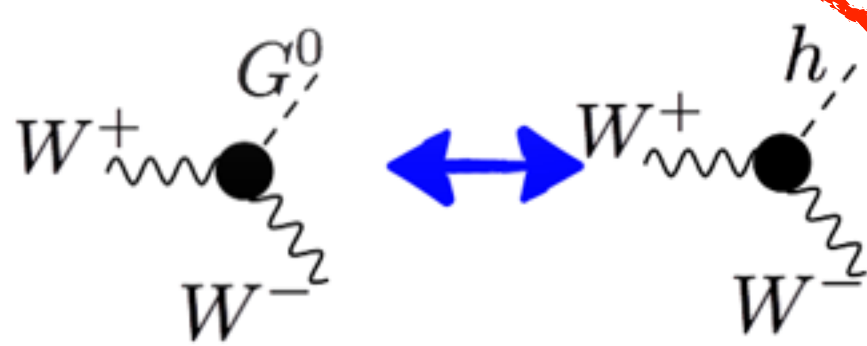
$\mathcal{O}_{WB} = \frac{gg'}{4}(H^\dagger\sigma^a H)W^a_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$
$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$
$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$
$\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$
$\mathcal{O}_L^{(3)\,q} = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\sigma^a\gamma^\mu Q_L)$
$\mathcal{O}_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu L_L)$
$\mathcal{O}_L^{(3)} = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L\sigma^a\gamma^\mu L_L)$



Again, LEP:

$$\delta g_1^Z\,,\kappa_\gamma \lesssim 0.05$$

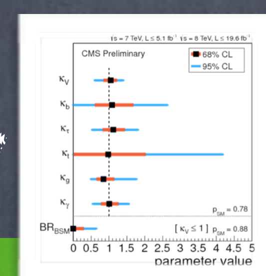
Impact of these operators in H-physics is small

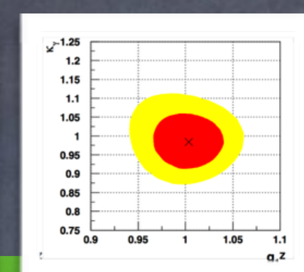


Small Summary: What do they do to the SM?

$$\mathcal{O}_r = |H|^2 (D_\mu H)^\dagger (D^\mu H)$$
$$\mathcal{O}_{y_d} = y_d |H|^2 \bar{Q}_L H d_R$$
$$\mathcal{O}_{y_e} = y_e |H|^2 \bar{L}_L H e_R$$
$$\mathcal{O}_{y_u} = y_u |H|^2 \bar{Q}_L \widetilde{H} u_R$$
$$\mathcal{O}_{GG} = \frac{g_s^2}{4} |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$
$$\mathcal{O}_{BB} = \frac{g'^2}{4} |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{WW} = \frac{g^2}{4} |H|^2 W^a_{\mu\nu} W^{a\mu\nu}$$
$$\mathcal{O}_6 = \lambda |H|^6$$

$$\mathcal{O}_{WB} = \frac{gg'}{4} (H^\dagger \sigma^a H) W^a_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_T = \frac{1}{2} \left(H^\dagger \overleftrightarrow{D}_\mu H \right)^2$$
$$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$$
$$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$$
$$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$$
$$\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$$
$$\mathcal{O}^{(3)\,q}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$$
$$\mathcal{O}_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$$
$$\mathcal{O}^{(3)}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \sigma^a \gamma^\mu L_L)$$





$$\kappa_V, \kappa_b, \kappa_\tau, \kappa_t, \kappa_G, \kappa_{\gamma\gamma}, \kappa_{Z\gamma}, \kappa_{h^3}$$

$$g_Z^1, \kappa_\gamma$$

$$\delta g_{ZeL}, \delta g_{ZeR}, \delta g_{Z\nu}, \delta g_{ZuL}, \delta g_{ZdL}, \delta g_{ZuR}, \delta g_{ZdR}$$

Are they already constrained?

Might as well use these as parameters, to keep relations between observables manifest!

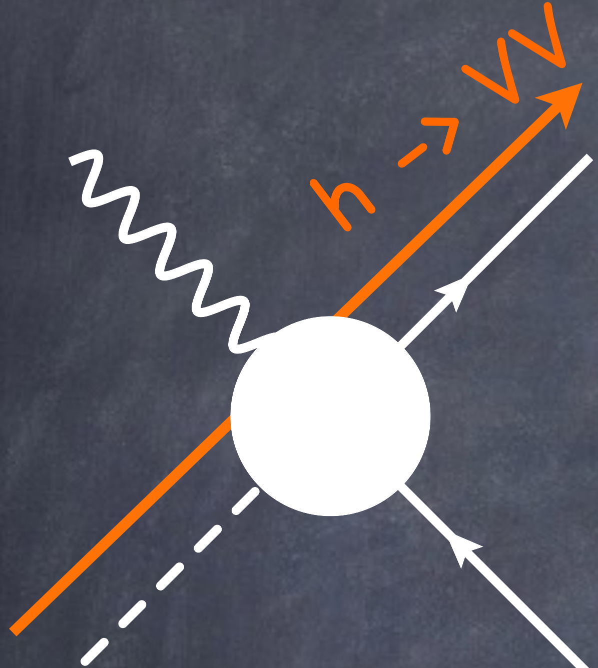
- "BSM Primaries"

Gupta,Pomarol,FR'14

1

Can we see them at LHC?

Deviations in different. distr. of $h \to Z\bar{f}f$ or $h \to W\bar{f}f$



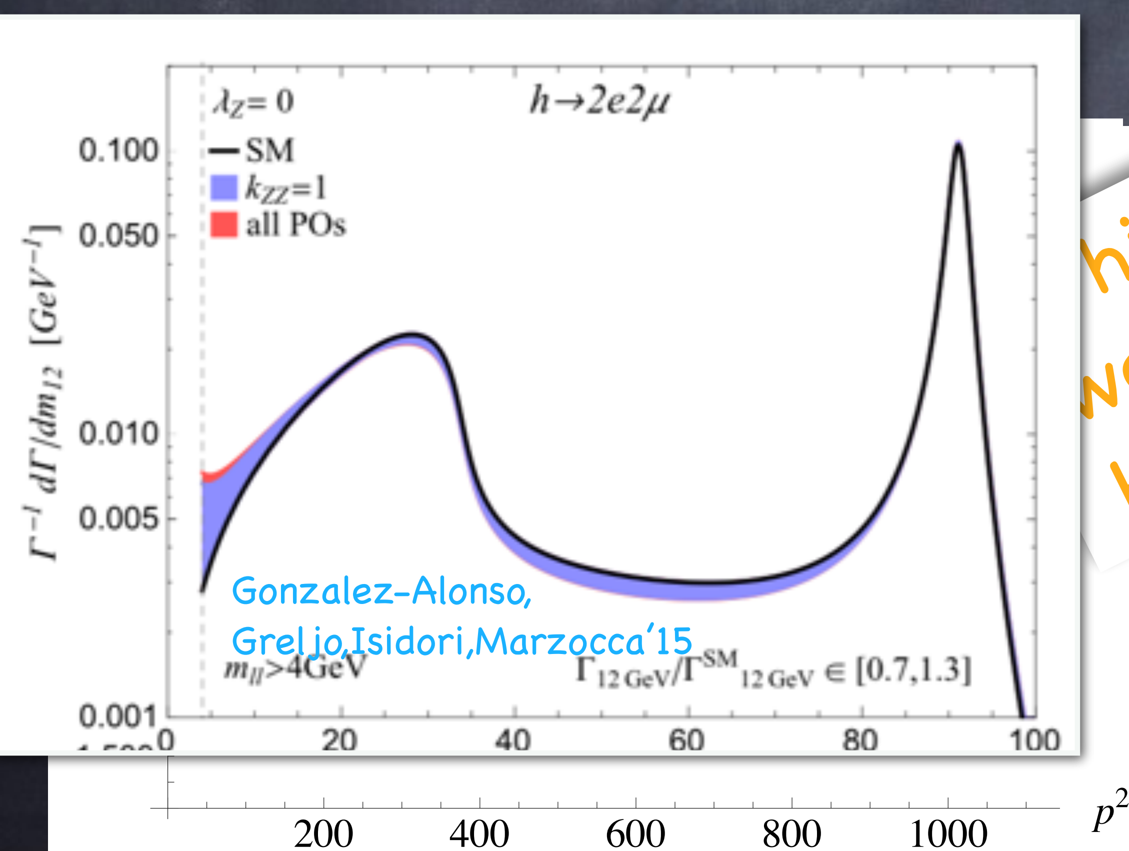
LEP 1

~~Related with Zff couplings~~

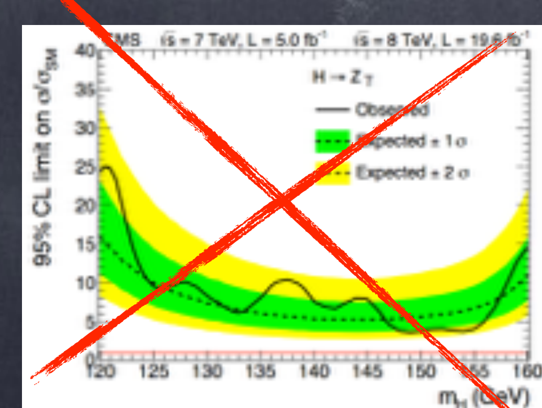
Related with Triple Gauge Coupling

Related with $h \to Z\gamma, \gamma\gamma$

his is the sensitivity
we are aiming to make
H-physics competitive!



Gonzalez-Alonso,
Greljo,Isidori,Marzocca'15



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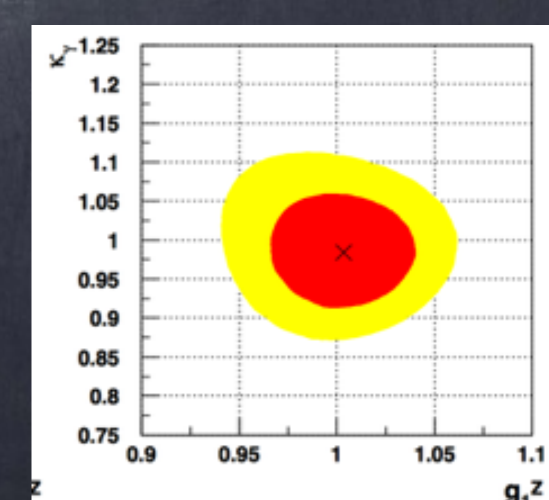


p^2>5 GeV

Pomarol,FR'13; See also: Beneke,Boito,Wang'14

Can we see them at LHC?

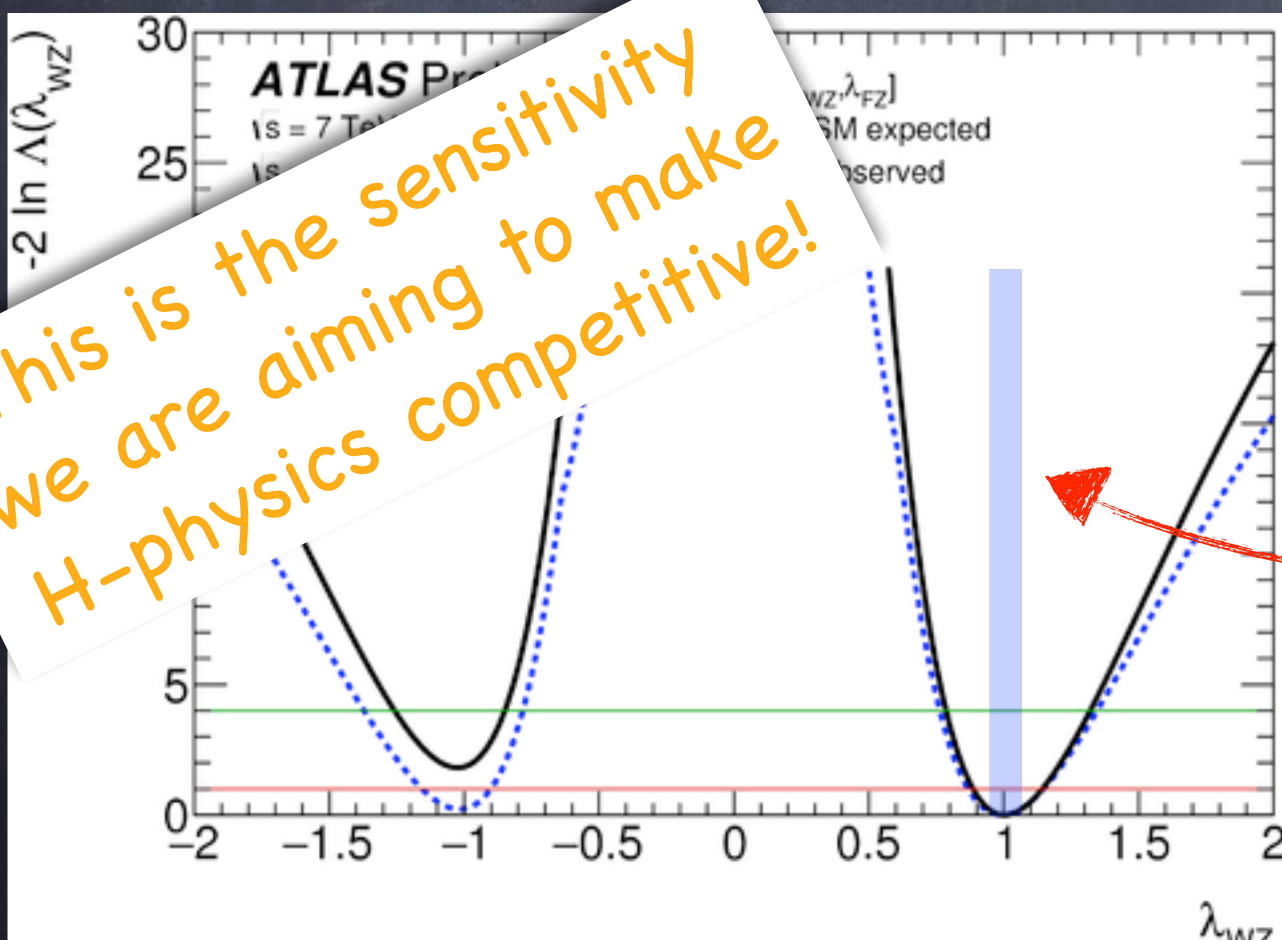
2

Custodial Symmetry in h decays h->VV* λ_{WZ}

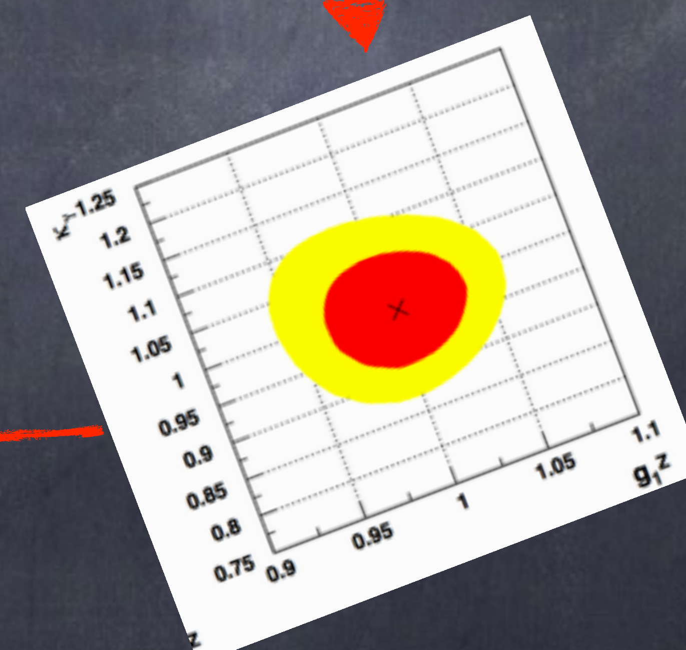
- Off-Shell V
- $m_Z \neq m_W$

▸ Integrated Decay Width already sensitive to p-dependence of hVV coupling!

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



This is the sensitivity we are aiming to make H-physics competitive!



Pomarol,FR'13

Summary of Part 3 - BSM

* EFT: systematic and self-consistent framework that motivates precision tests of the SM in terms of a physical quantity Λ

  Naturalness is the only principle suggesting this is small, and its effects visible at LHC...

* Leading expected BSM effects, parametrized by dim-6 Lagrangian:

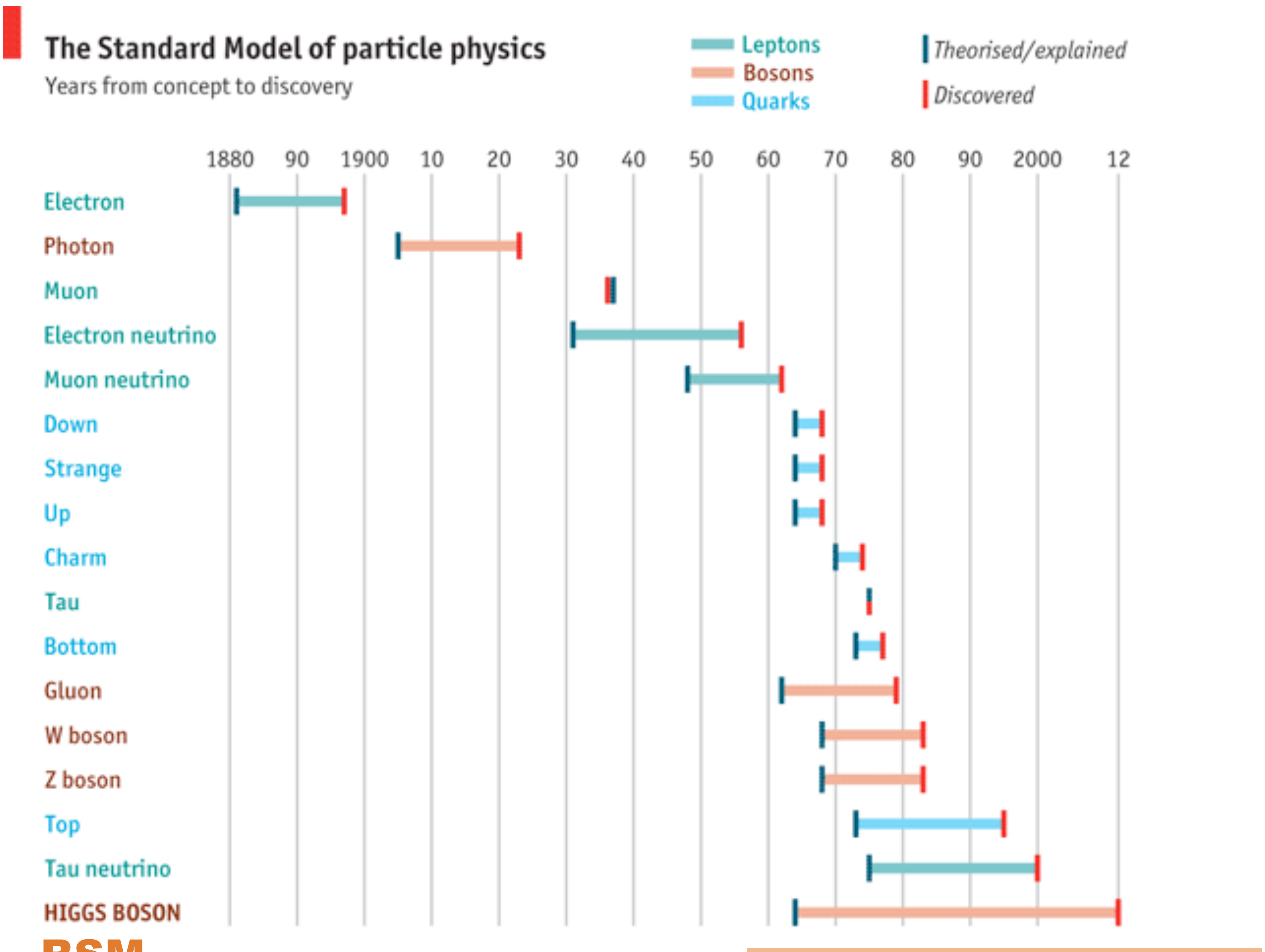
  17 New interactions that modify the predictions of the SM

* Given constraints from LEP: LHC is genuinely probing only the 8 "Higgs-Only" operators with $|H|^2$

  → Measurements of h^3 and $h \to Z\gamma$ can still hide O(1) deviations from SM

  → Deviations in distributions expected much smaller

Years from Th. Proposal to Exp. Discovery



BSM