# ELECTROWEAK SYMMETRY BREAKING (EWSB) after the 4th of July

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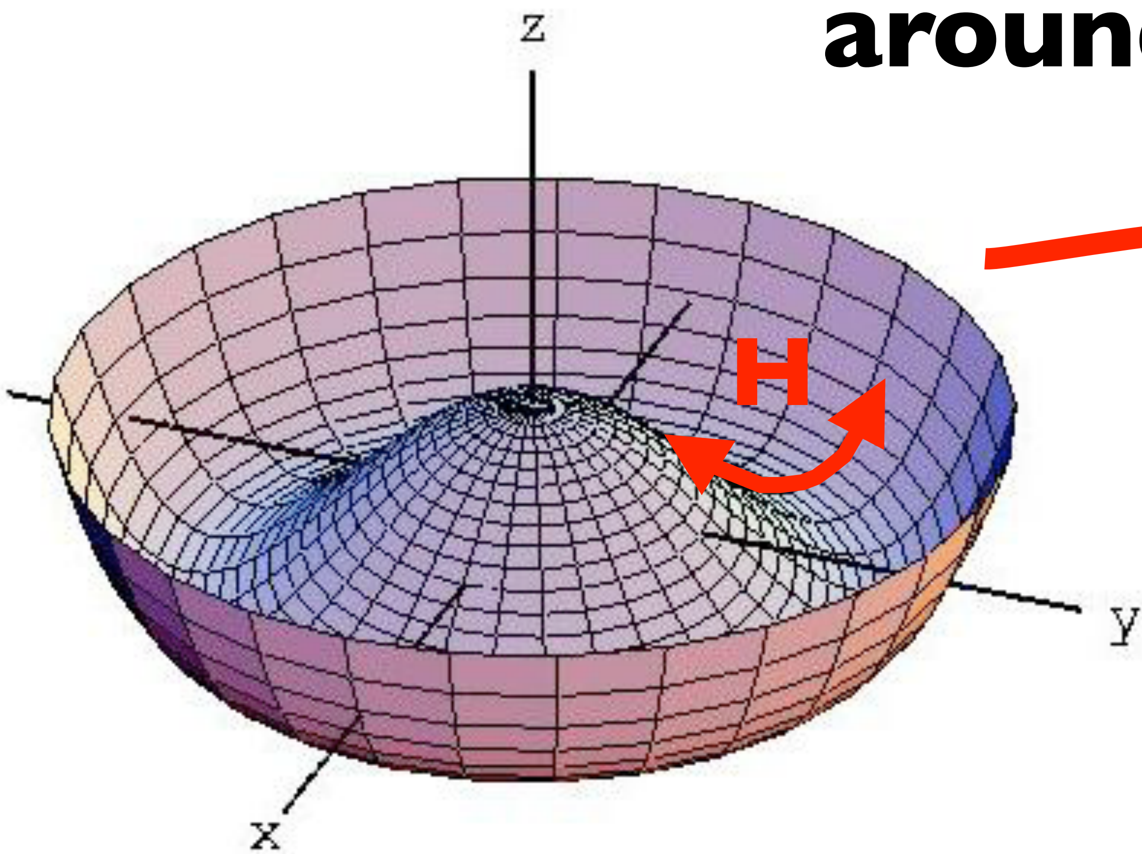
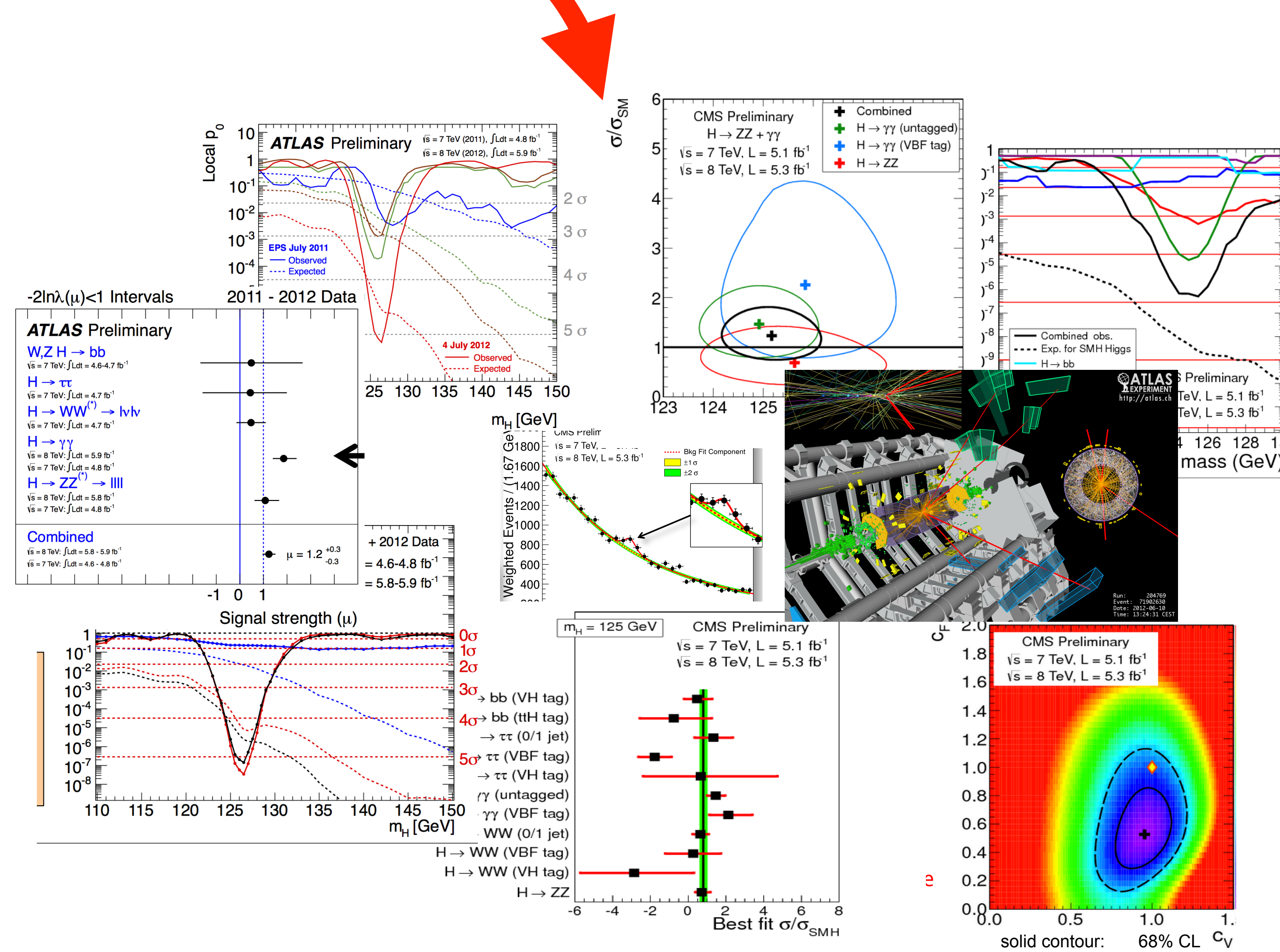
UAB (Barcelona)

# After the 4th of July 2012

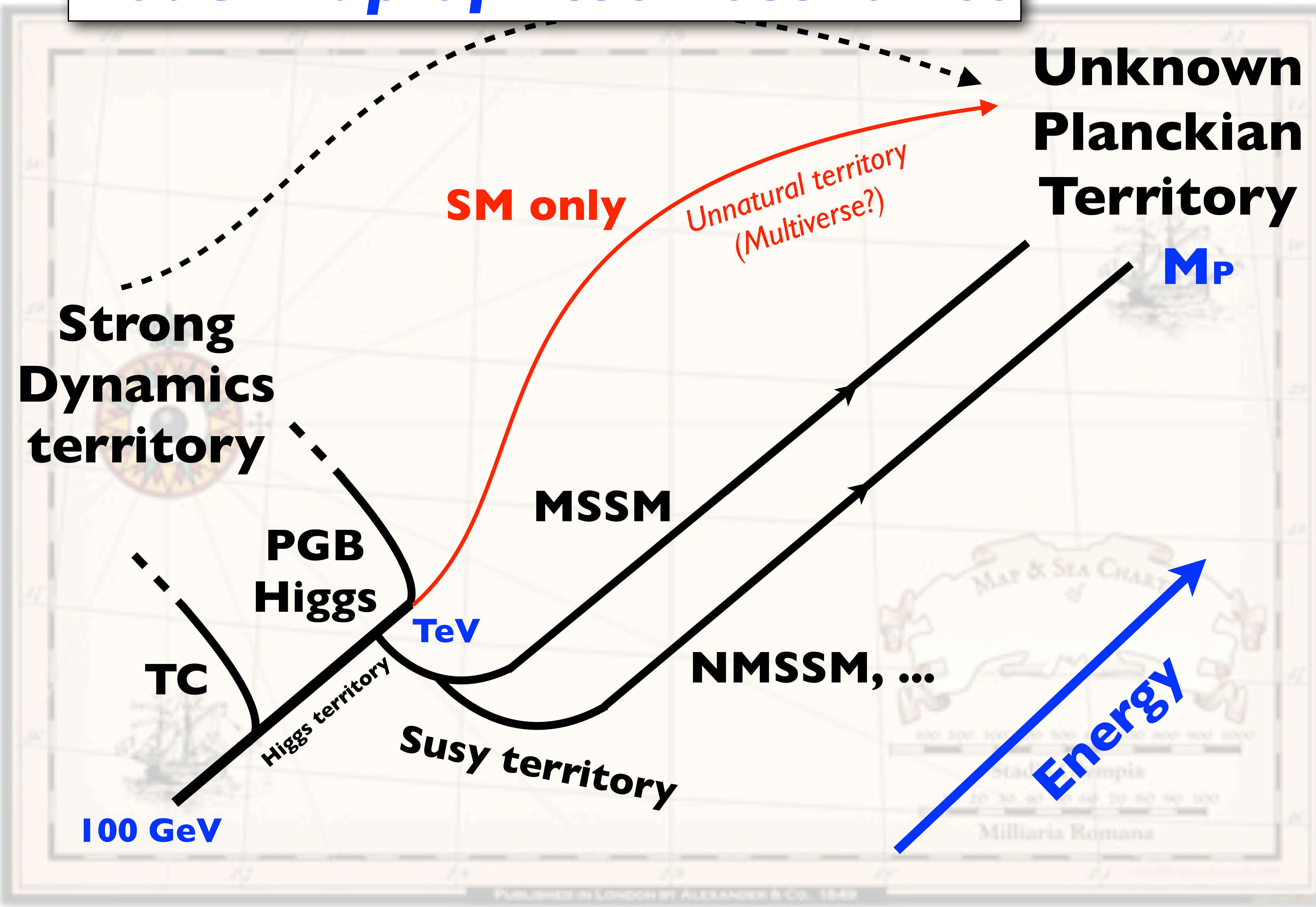
## Plenty of new data on a “radial” excitation around the EWSB vacuum:




## ➥ Implications on models for EWSB

# Road Map of EWSB scenarios



# What Data tells us?

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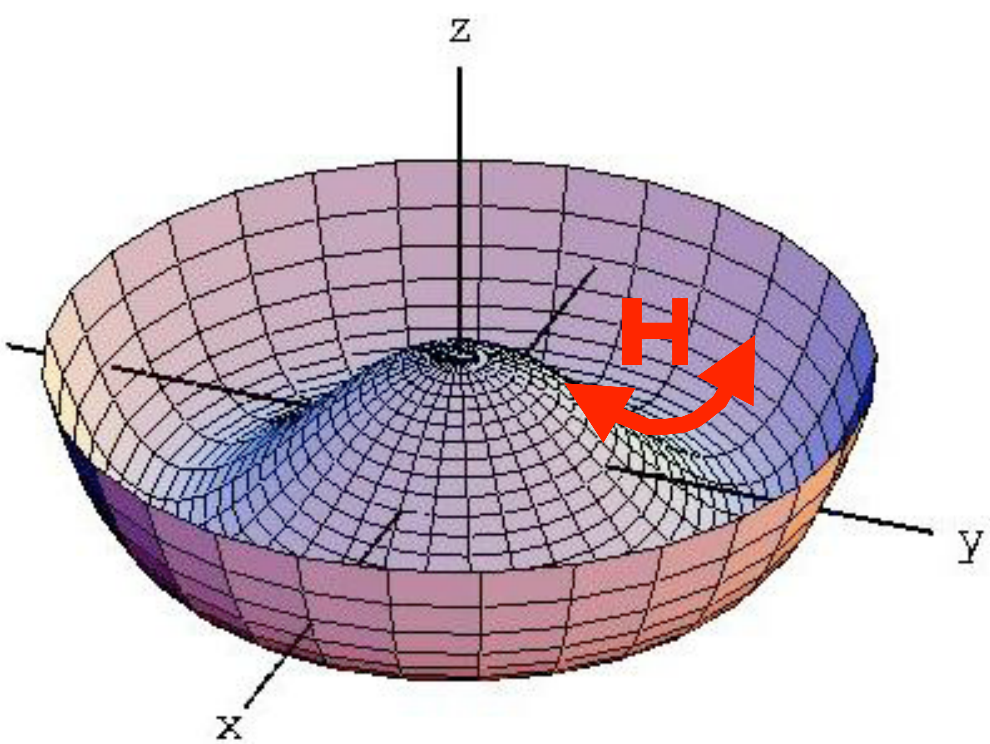
**Light state:** $\mathbf{m_H \approx 125\ GeV}$

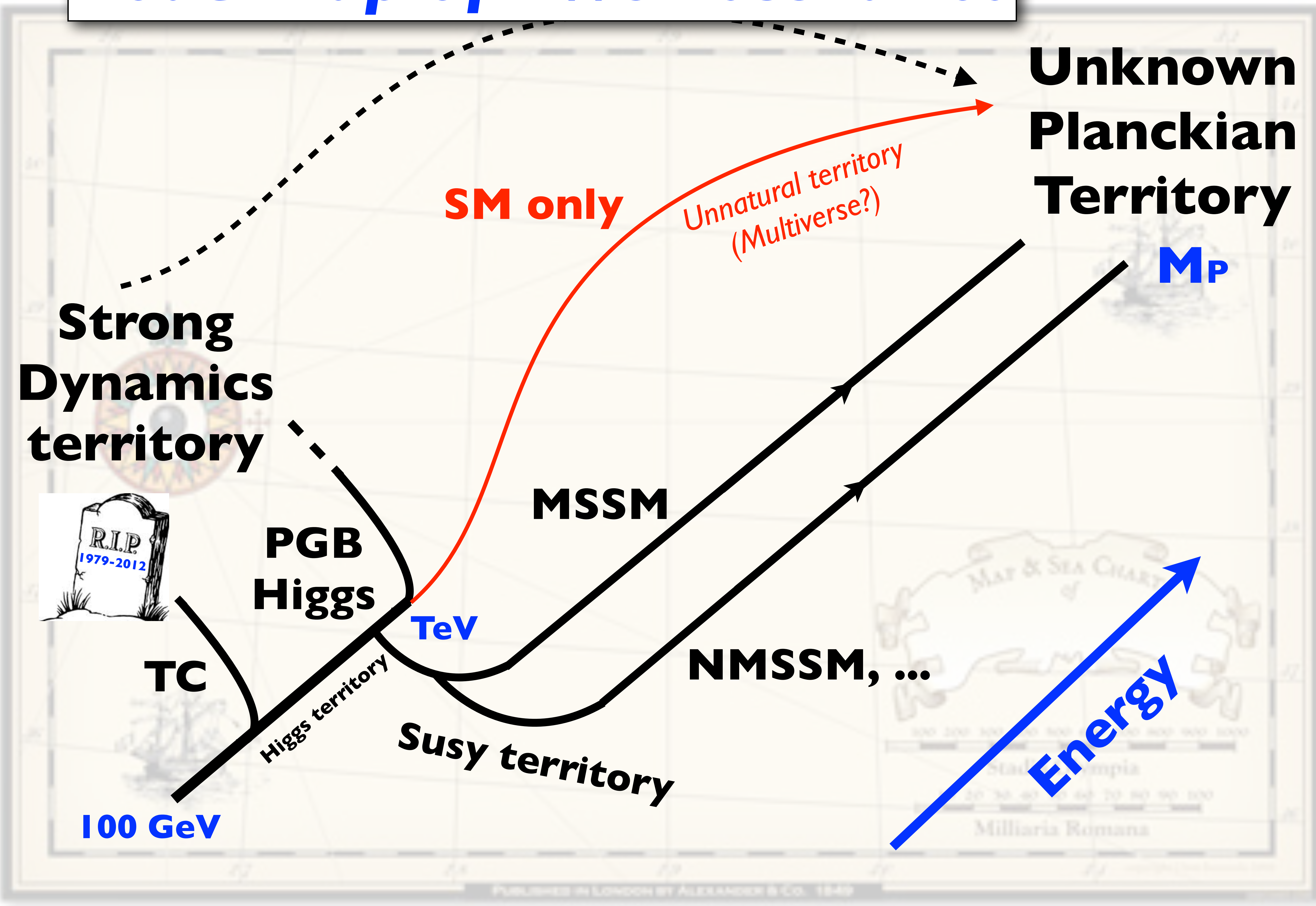



$$\mathbf{m_H^2 = \lambda v^2}$$

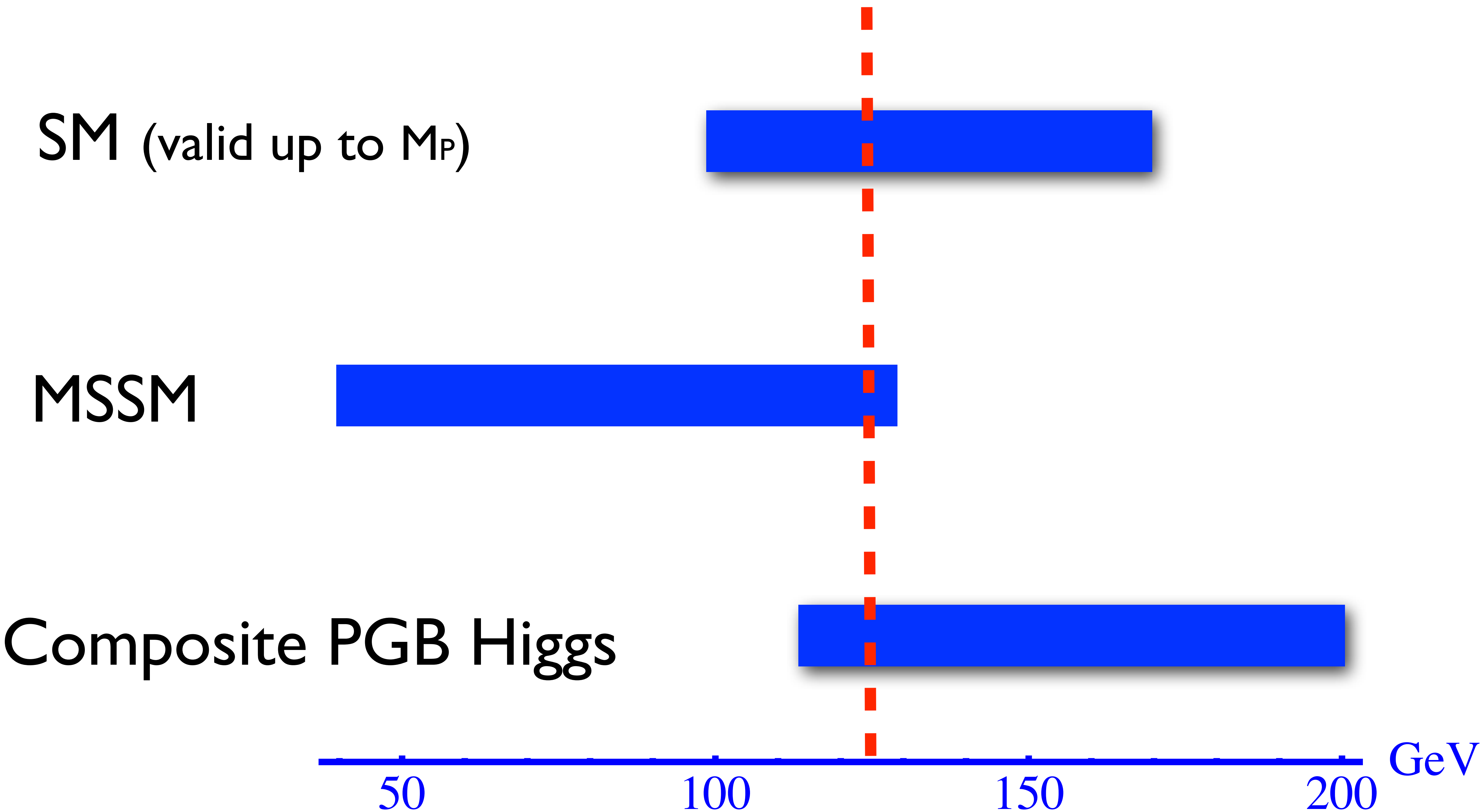
$\lambda$ ~ 0.26 (perturbative coupling)

Origin of the EWSB potential → a weakly-coupled theory

# Road Map of EWSB scenarios



**Three options left:**



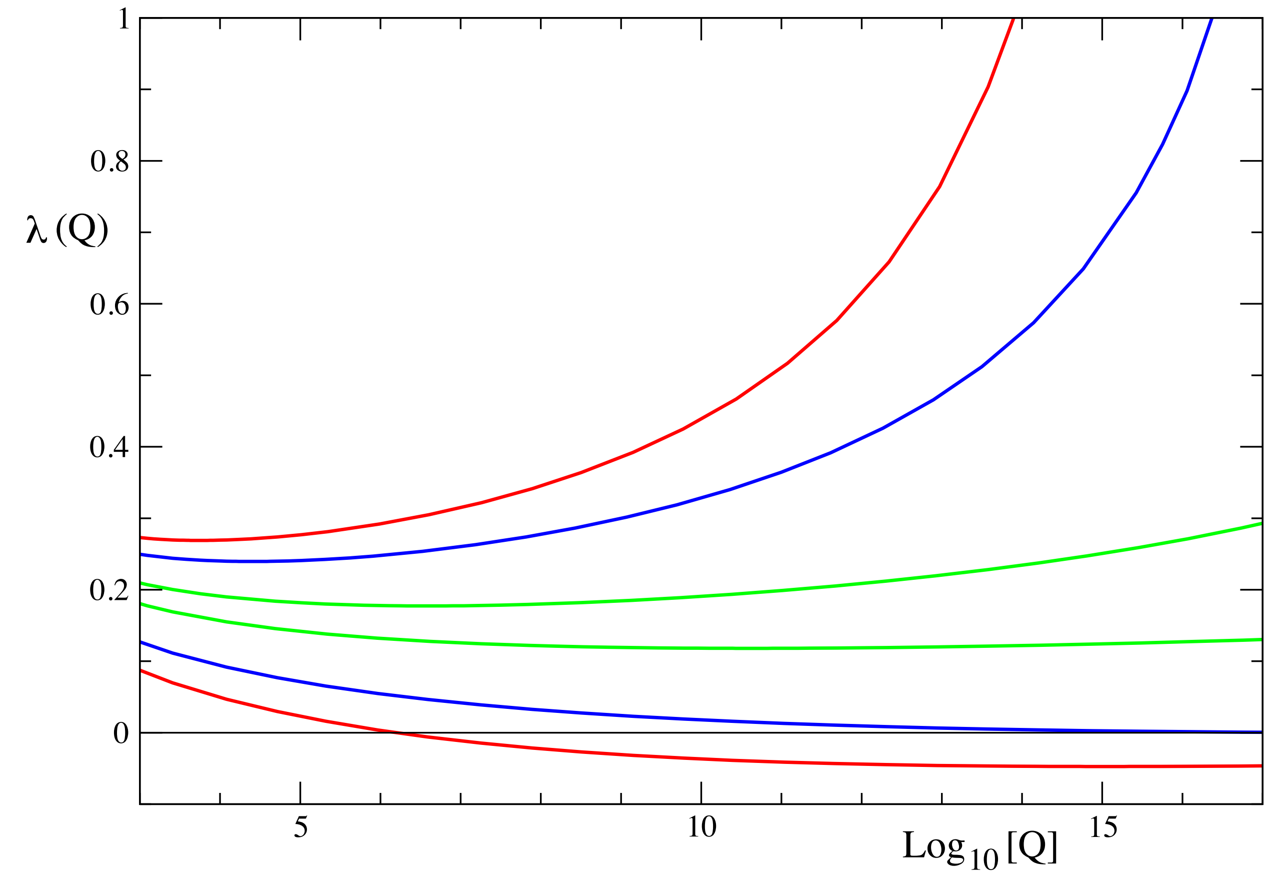

**Rough Higgs mass range**

# 125 GeV SM Higgs

# In the SM:

$$m_H^2 = \lambda v^2$$

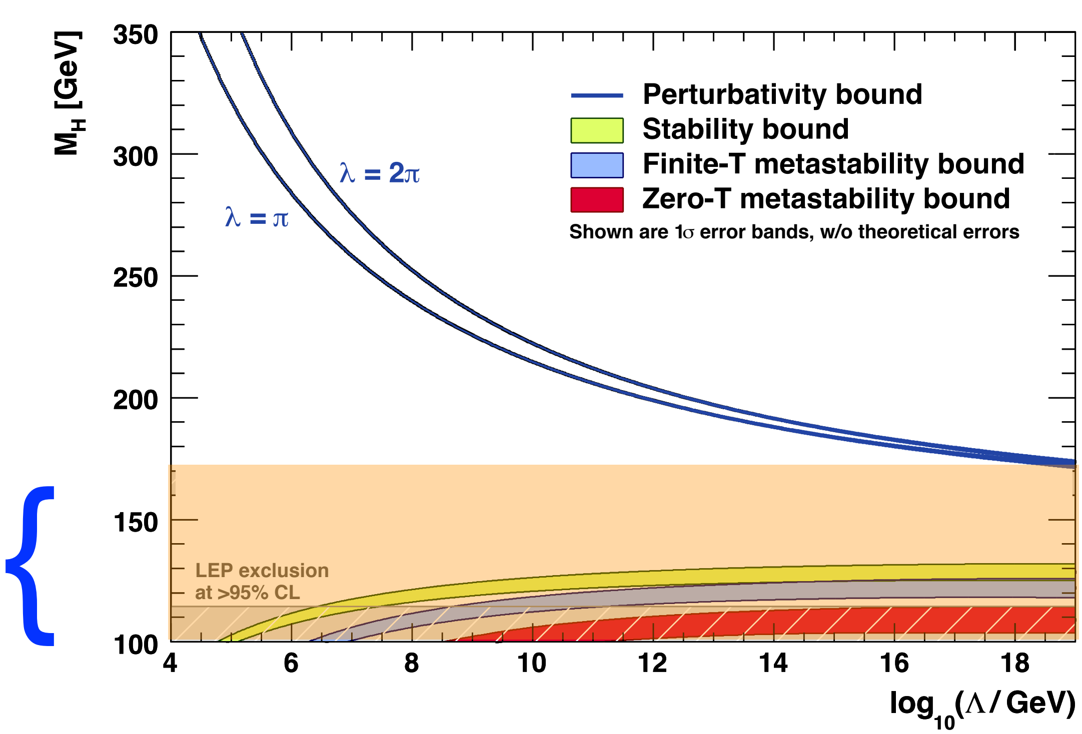
Evolves with the energy




Demanding λ not too large (keep perturbativity),
not too negative that destabilizes the Higgs potential:

from Phys.Lett. B679 (2009) 369

Only a small window
in the Higgs mass
makes the SM consistent
all the way to the Planck scale



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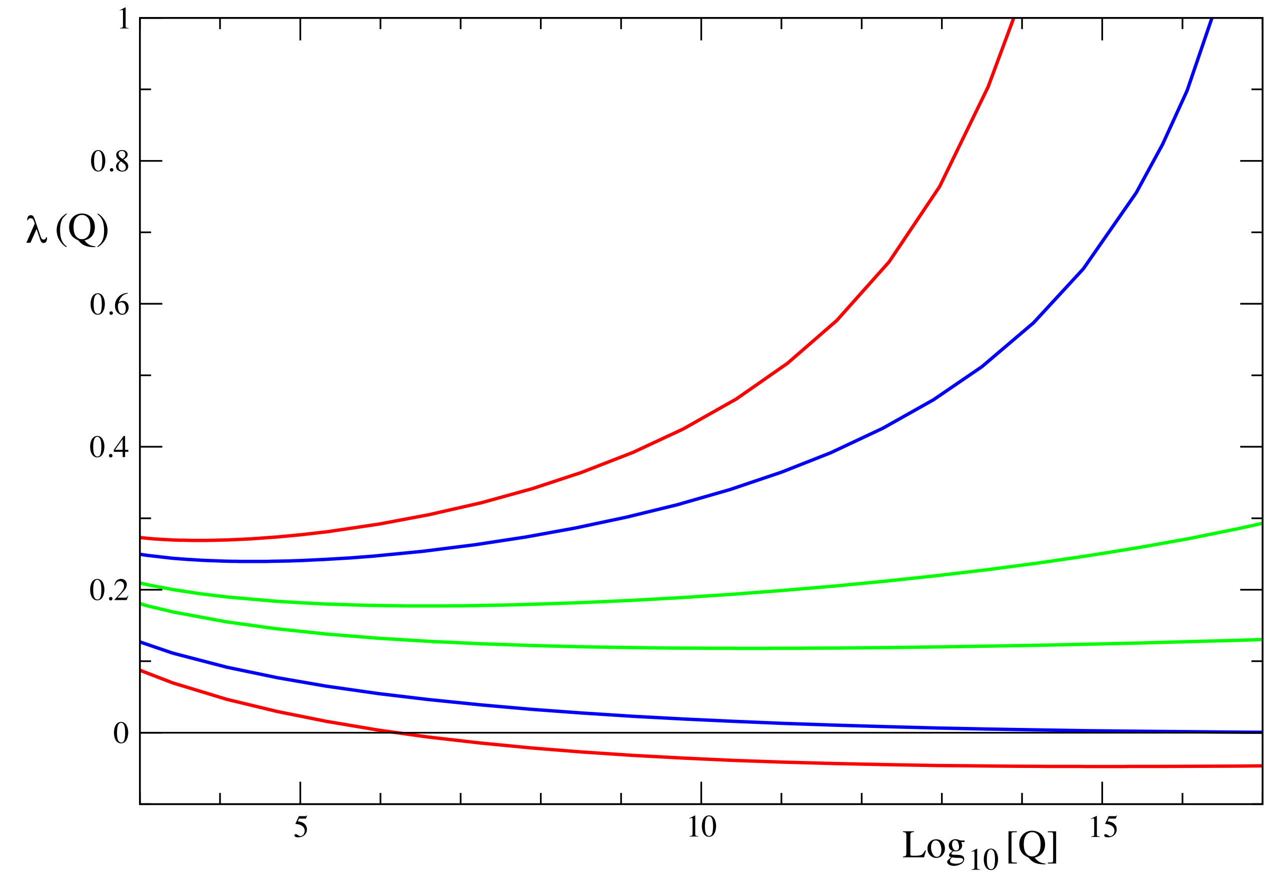


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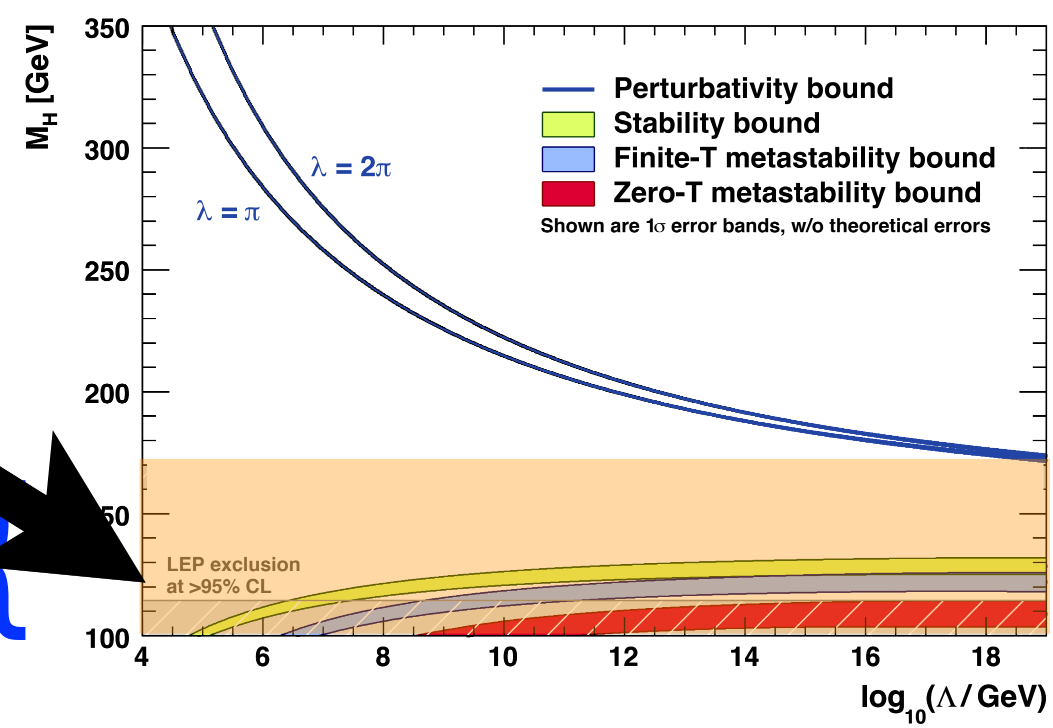
from Phys.Lett. B679 (2009) 369

A 125 GeV Higgs is in this window!

Only a small window
in the Higgs mass
makes the SM consistent
all the way to the Planck scale



# 125 GeV MSSM Higgs

# In the MSSM:

$$\mathbf{M_h^2 \leq M_Z^2 + \Delta m^2}$$

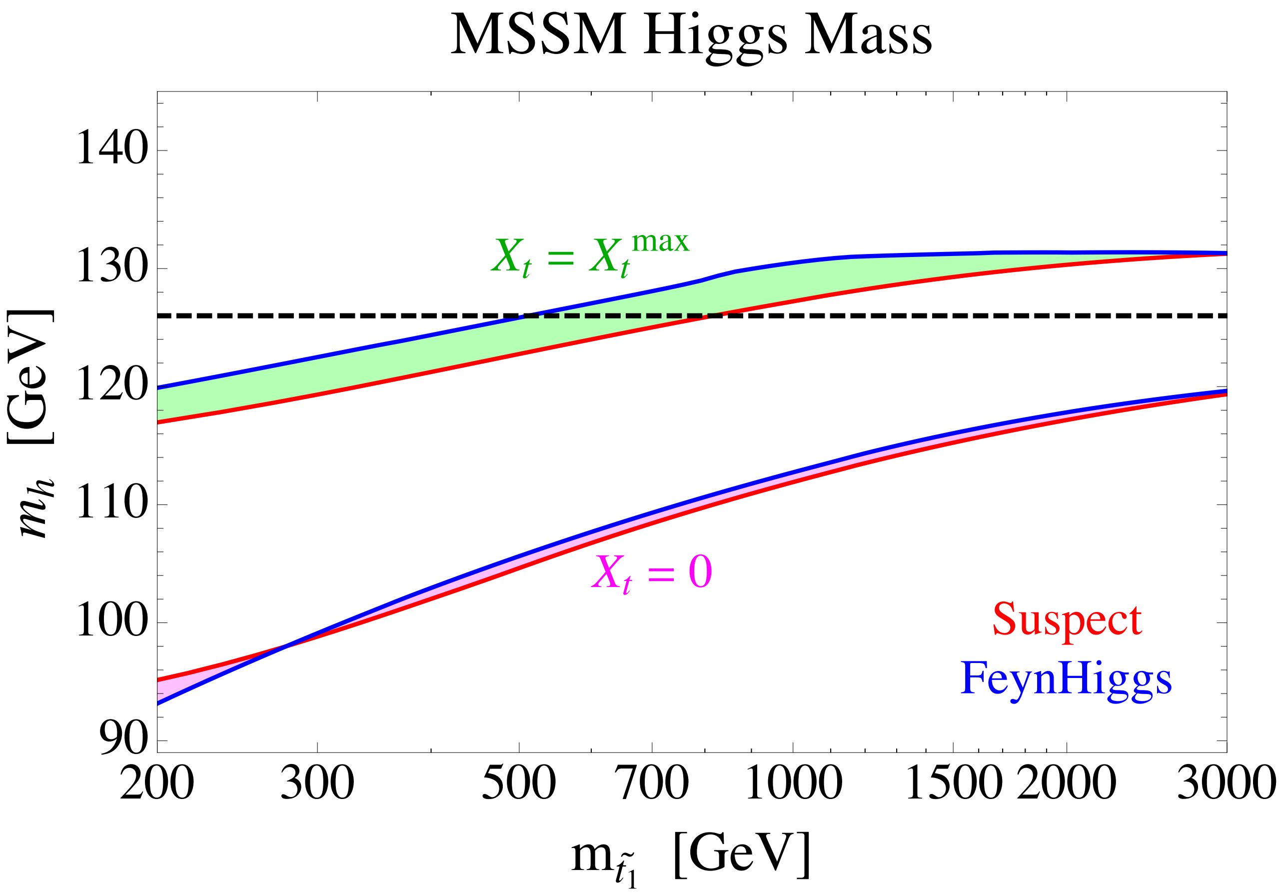
➥ susy breaking term (at one-loop)

$\mathbf{(125\ GeV)^2}$

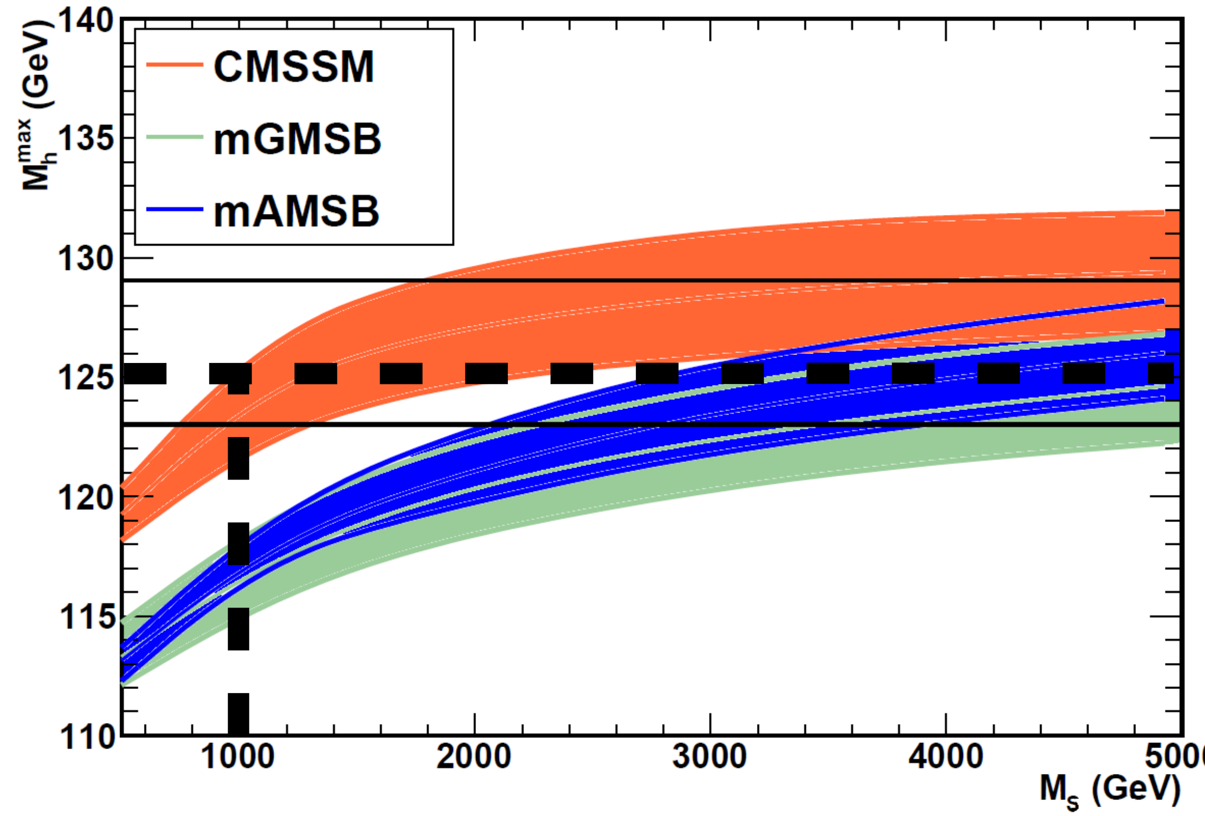
$\mathbf{(91\ GeV)^2}$ $\mathbf{(86\ GeV)^2}$

both have similar size:
Susy must be "badly" broken!

The Higgs bodyguards, the stops, are not so close to the Higgs from JHEP 1204 (2012) 131




from arXiv:1207.1348




Very heavy stops (beyond LHC reach)
or large susy-breaking trilinear terms

**➥ MSSM entering the unnatural territory**

(>99% parameter space excluded)

**Directions to go**:

**Beyond the MSSM:**

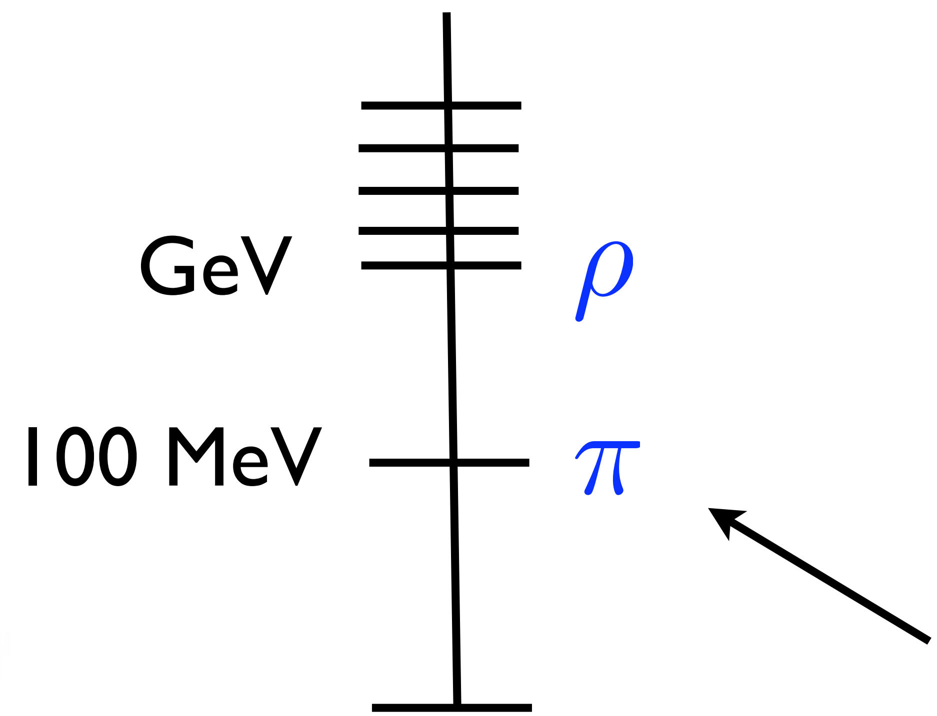
- Extra states (singlets): **NMSSM**
- New sources of Susy breaking

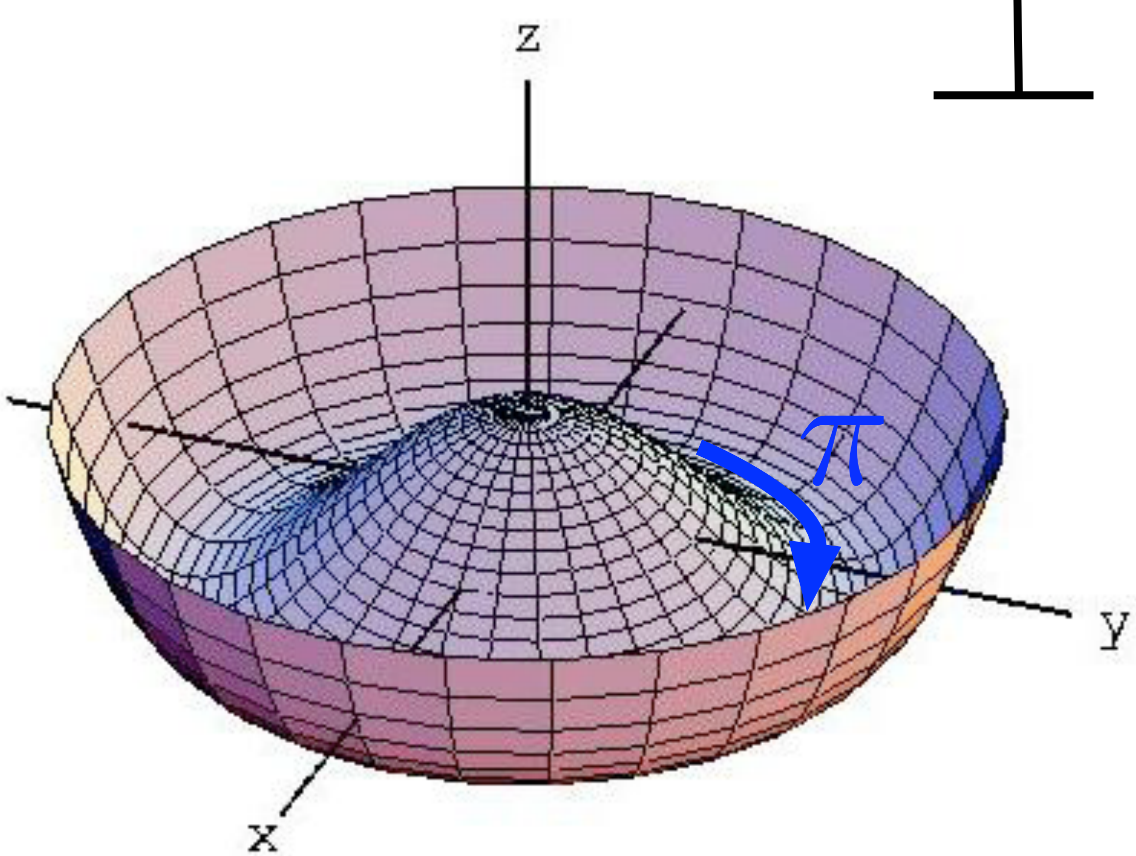
# 125 GeV Composite Pseudo-Goldstone Higgs

# Composite PGB Higgs

inspired by QCD where one observes
that the (pseudo) scalar are the lightest states

Spectrum:



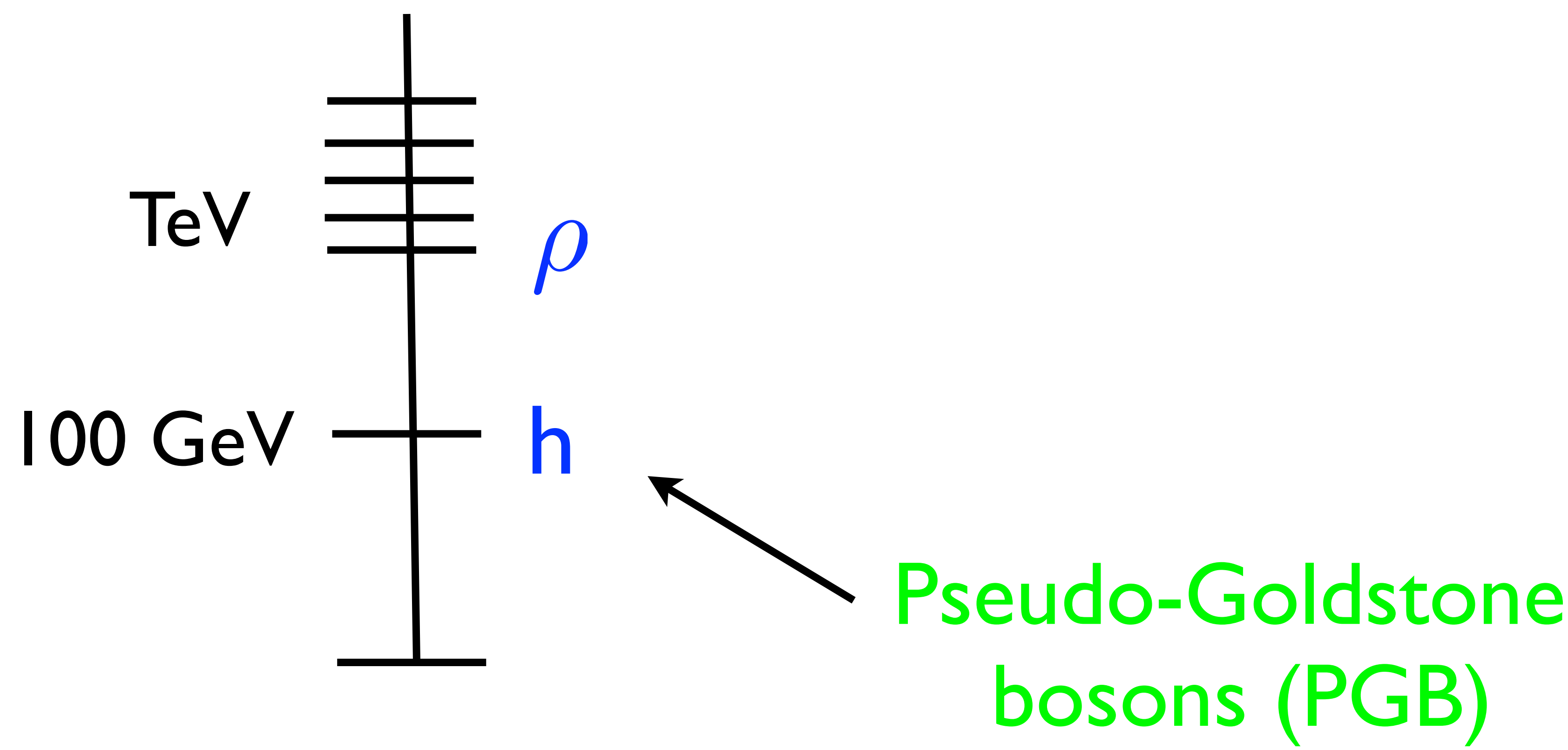

Are Pseudo-Goldstone
bosons (PGB)

Mass protected by the
global QCD symmetry!

$$\pi \to \pi + \alpha$$

## → Can the light Higgs be a kind of a pion from a new strong sector?

We'd like the spectrum of the new strong sector to be:




Minimal model: Spontaneous breaking in the strong sector:

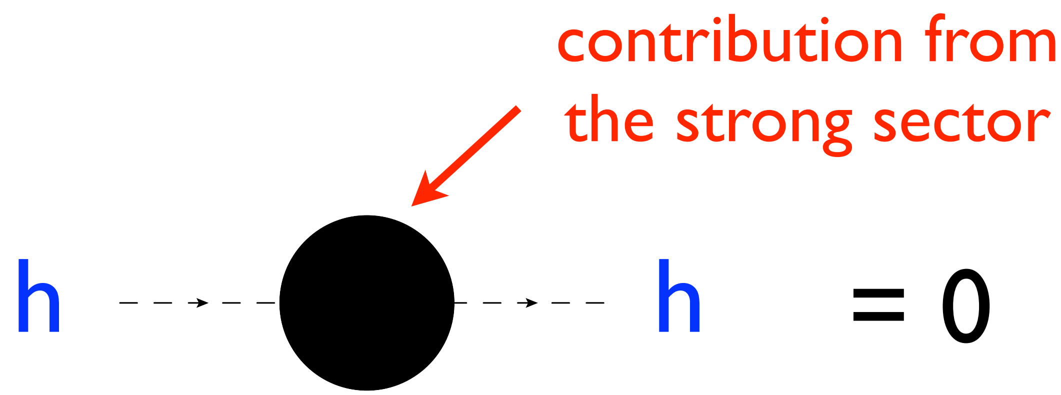
**SO(5) → SO(4)**

4 Goldstones

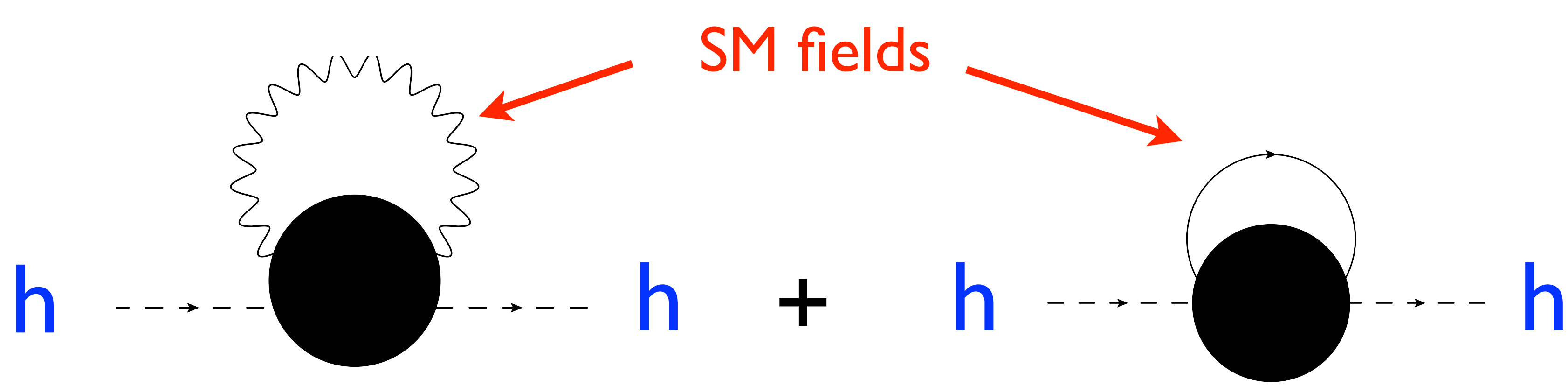
⇓

**Higgs doublet**

**Light Higgs** since its mass arises from one loop (explicit breaking of the global symmetry due to the SM couplings):



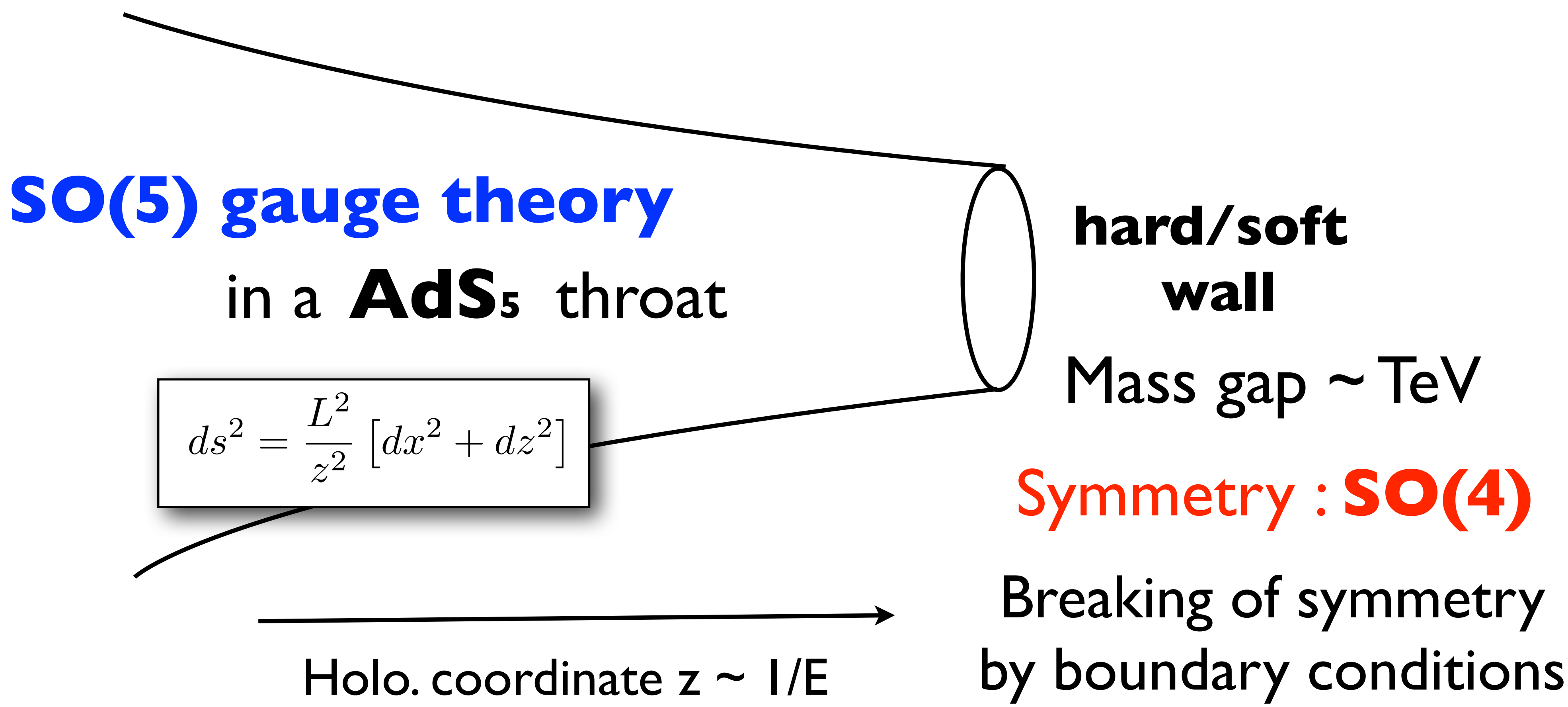

= 0 it's a Goldstone




➥ $$V(h) = \frac{g_{SM}^2 m_\rho^2}{16\pi^2} h^2 + \cdots$$

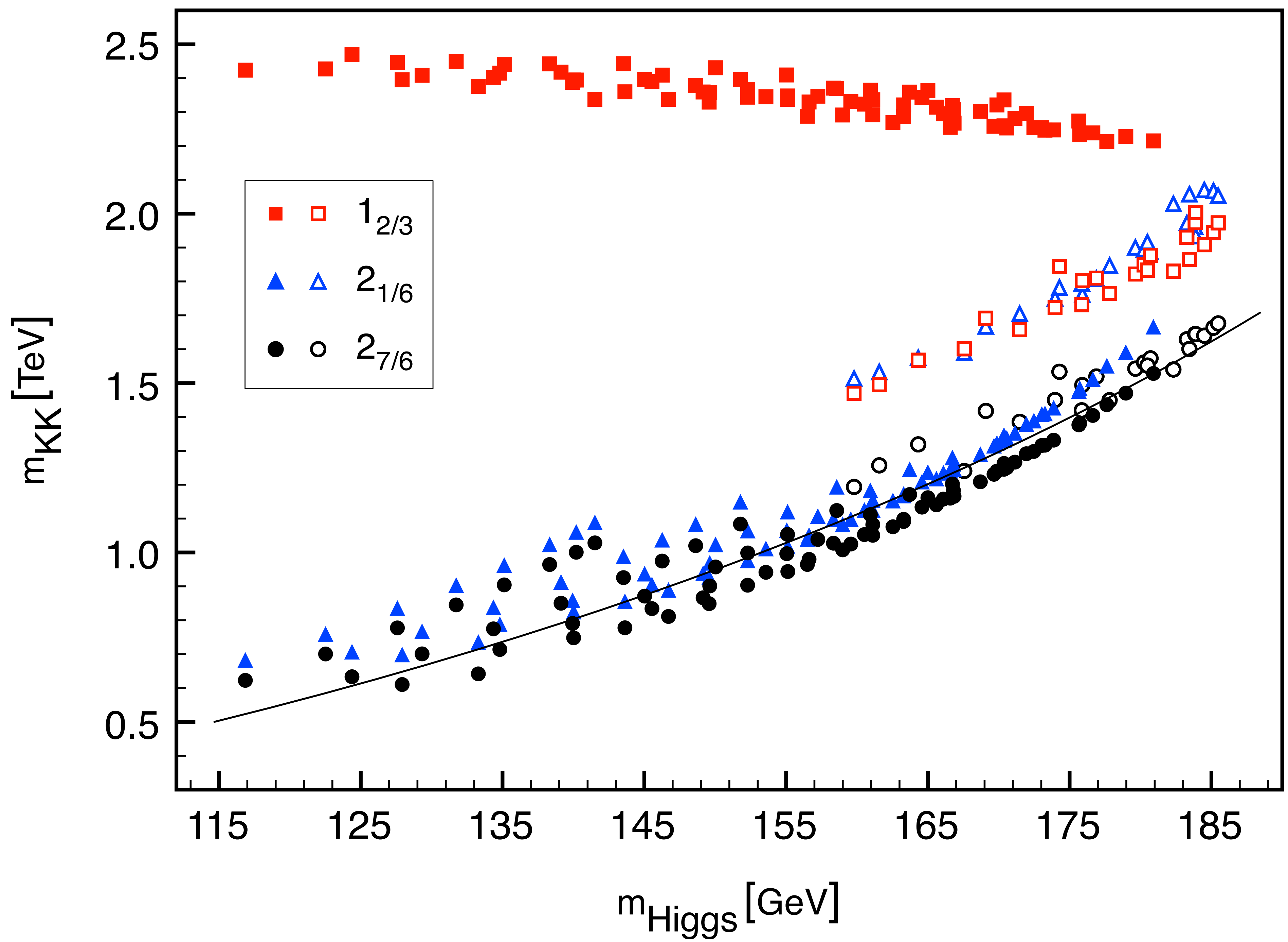
Difficult to get predictions due to the intractable **strong** dynamics**!**

Using holography (AdS/CFT) we can relate this scenario to a weakly-coupled 5D dimensional model and get predictions:



Contino,DaRold,AP 07

$m_\rho = 2.5$ TeV , $f = 500$ GeV



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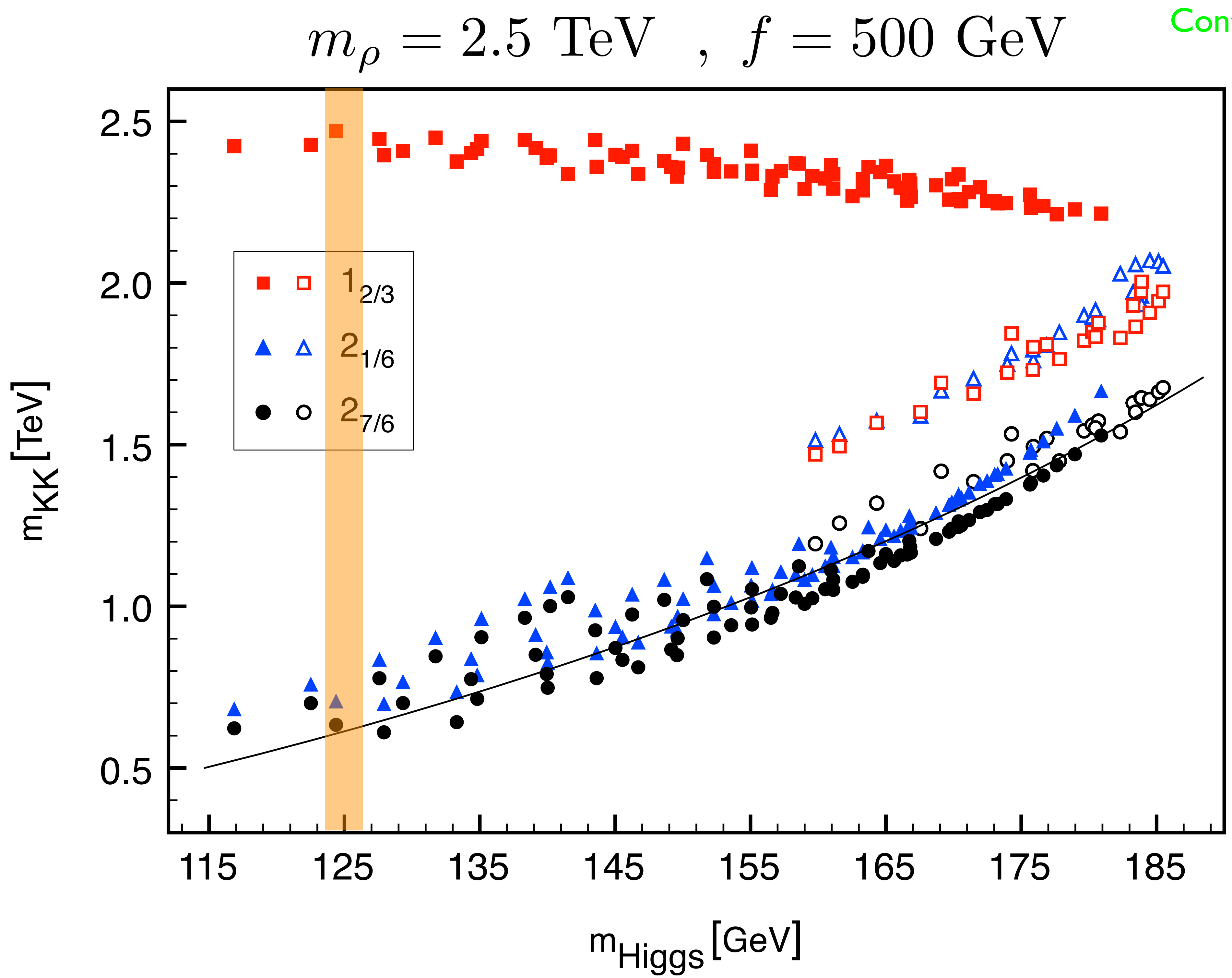


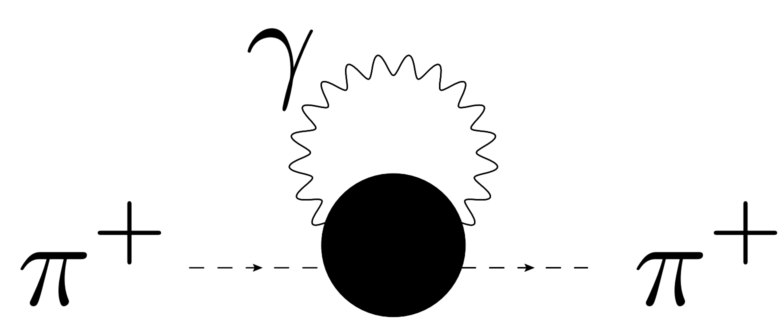

For a 125 GeV Higgs, the fermionic **resonances** of the top are light ~ 600 GeV

# Simpler derivation of the connection:
# Light Higgs - Light Resonance

- Deconstruction: Matsedonskyi,Panico,Wulzer; Redi,Tesi 12

- Weinberg Sum Rules: Marzocca,Serone,Shu; AP, Riva 12

  ➥ As Das,Guralnik,Mathur,Low,Young 67
  for the charged pion mass:



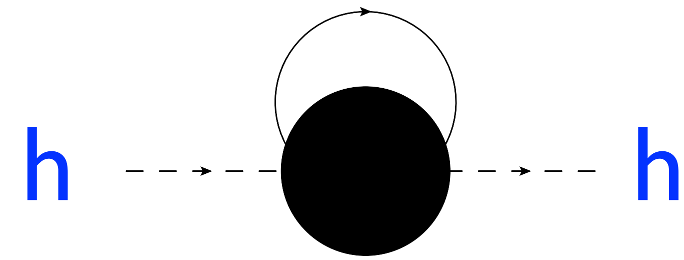

➥ Correlator dominated by the minimal number of resonances giving the right convergence at high momentum

$$m_{\pi^+}^2 - m_{\pi^0}^2 \simeq \frac{3\alpha}{2\pi} m_\rho^2 \log 2 \simeq (37\ \mathrm{MeV})^2$$

Exp. (35 MeV)²

*quite successful!*

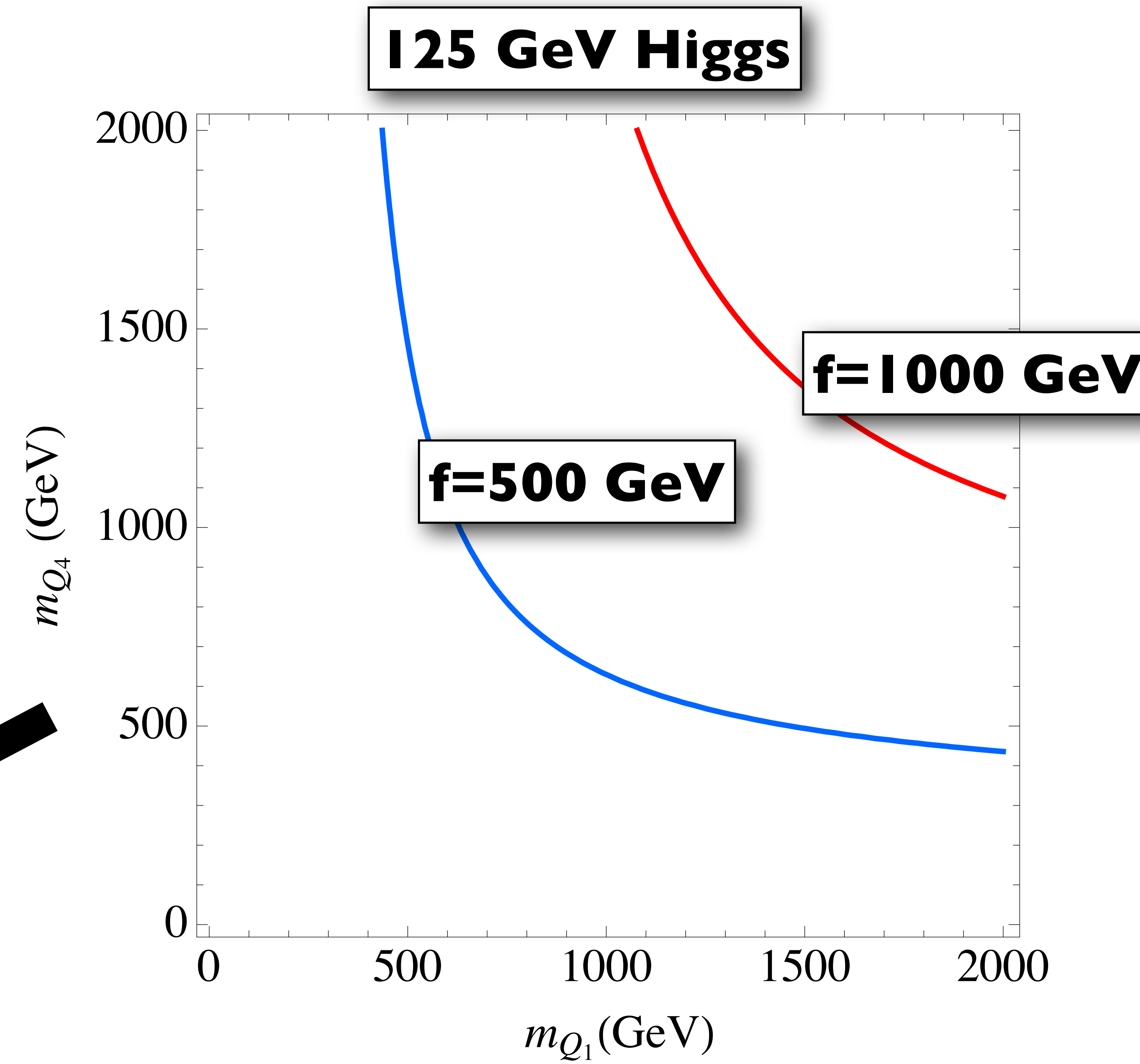
Following the same approach
for the minimal composite PGB Higgs model:




$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

$f$ = Decay-constant of the PGB Higgs

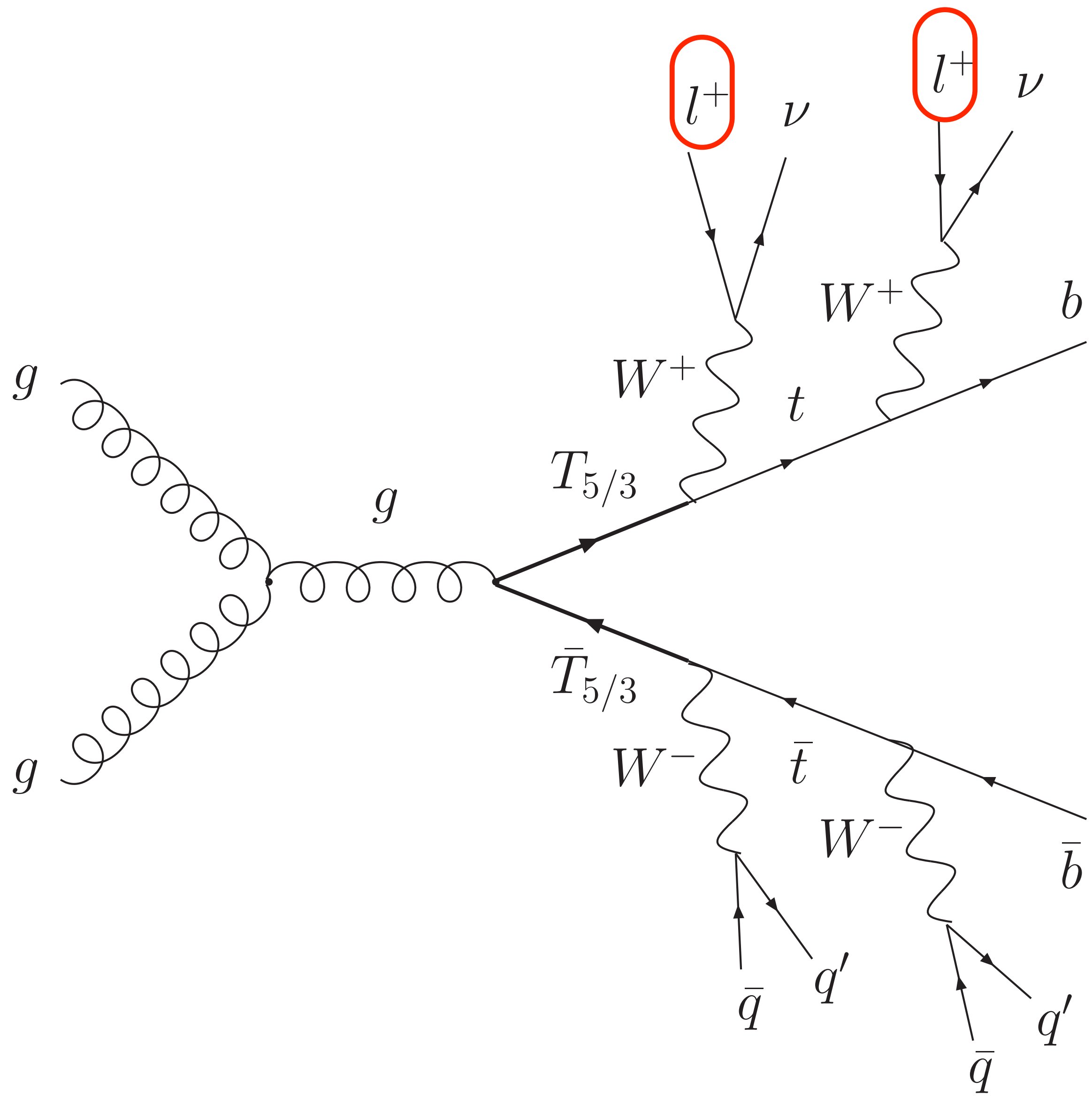
mass of color vector-like fermions
with EM charges 5/3,2/3,-1/3




Fermion resonances must
be below the TeV

# Color vector-like fermions with charge 5/3:

If this fermion is light, it can be double produced:

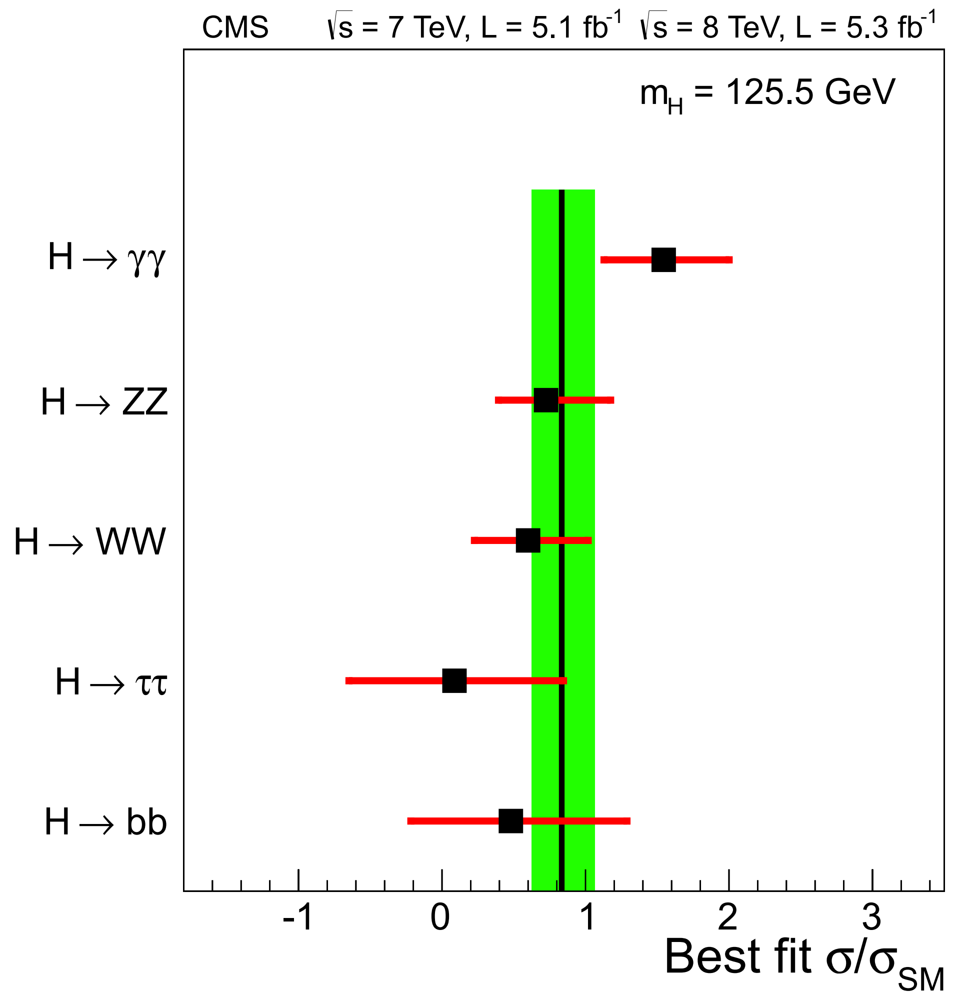


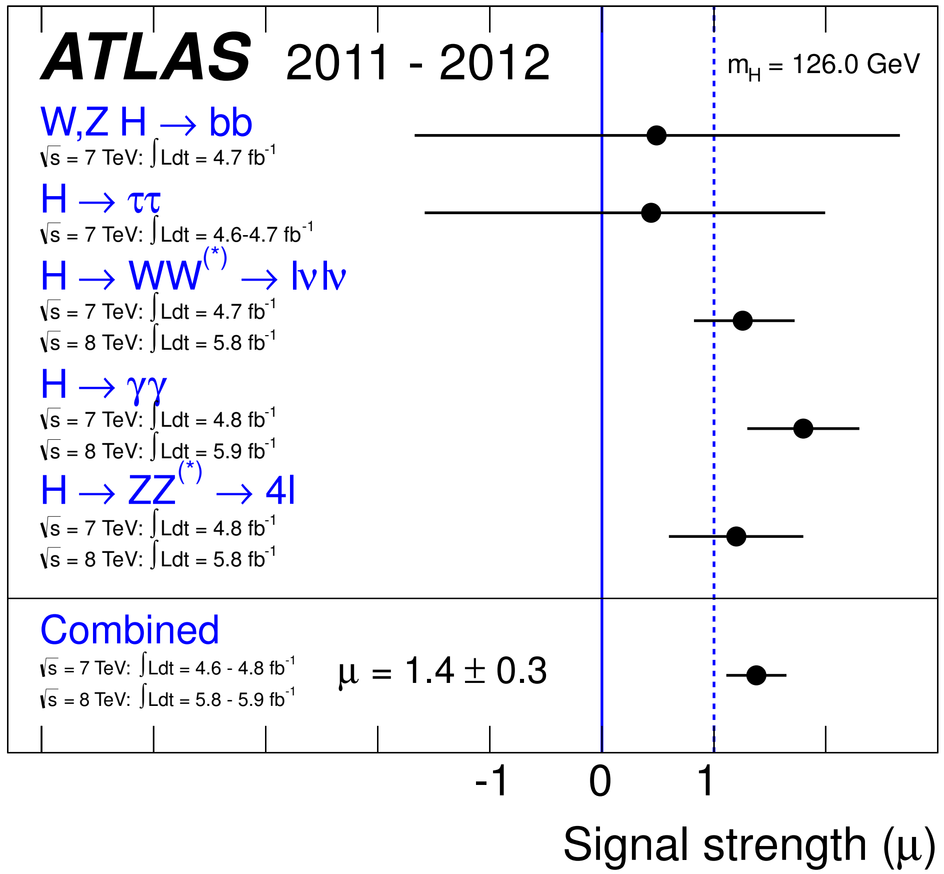

same-sign di-leptons

ATLAS-CONF-2012-130:

$$M_{T_{5/3}} \gtrsim 700\ \mathrm{GeV}$$

# What the Higgs couplings tells us?



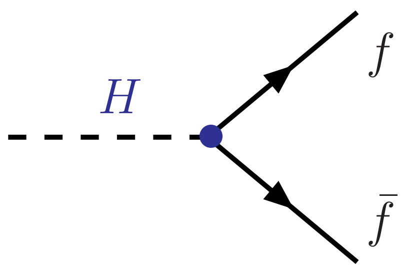




**Not significant deviations from a SM Higgs!**

(1-2 sigma level)

➥ **Improved by BSM physics?**

# Main pieces of information extracted from data:

1) 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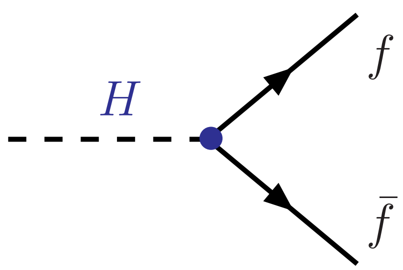
2) 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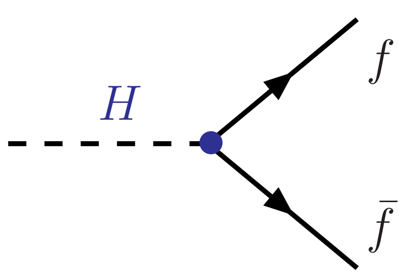
3) 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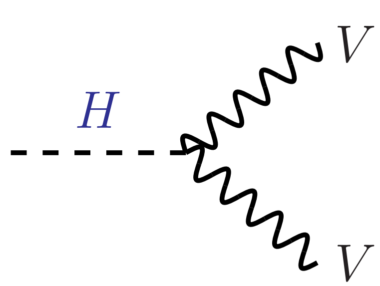
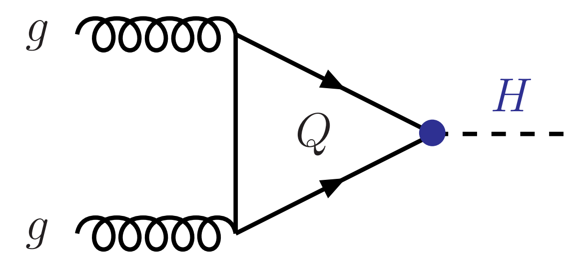
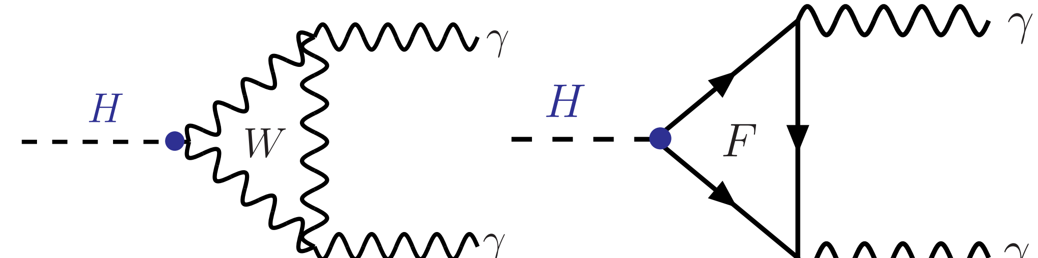
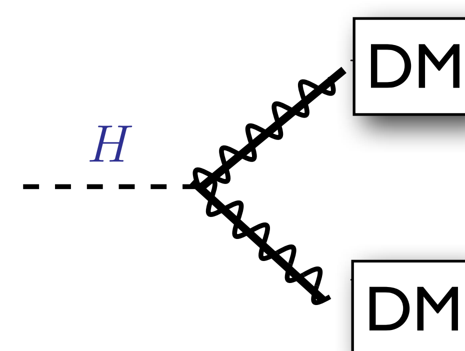
4) 


5) 


6) 


7) 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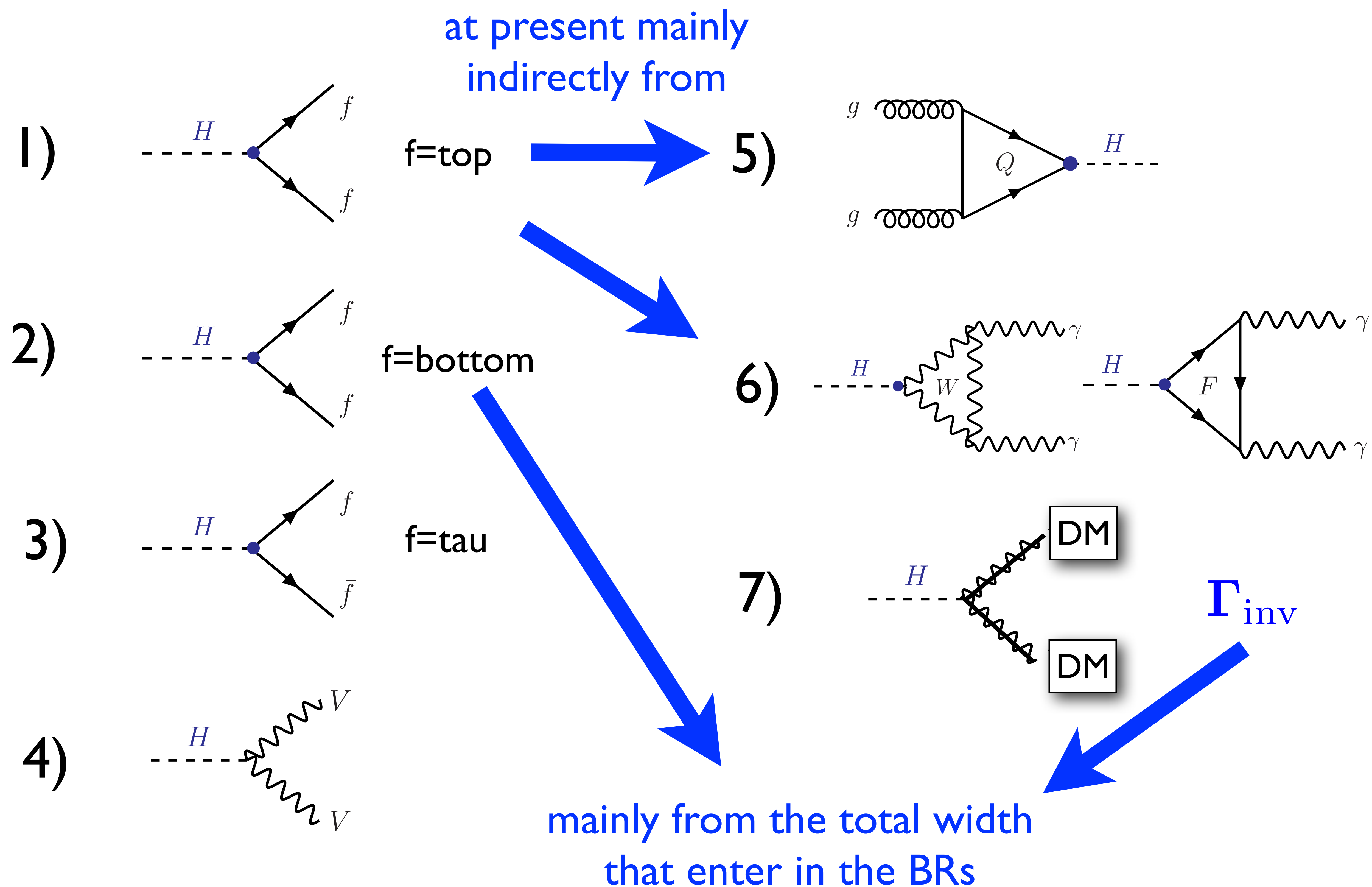

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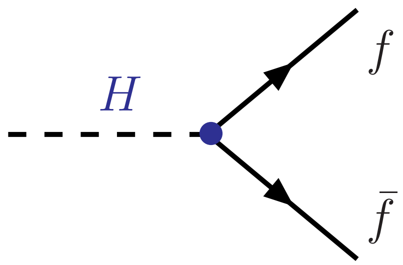
1) 

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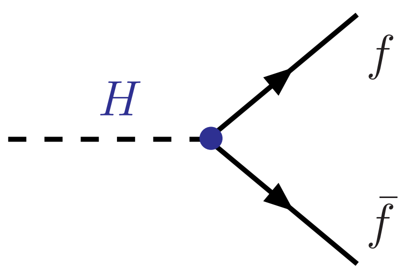
2) 

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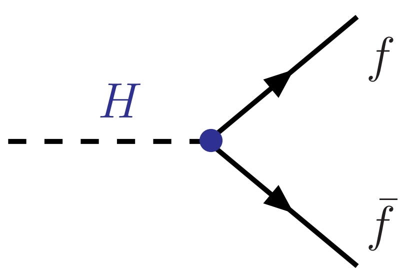
3) 

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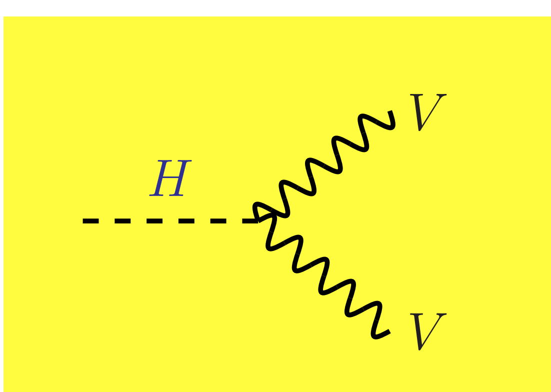
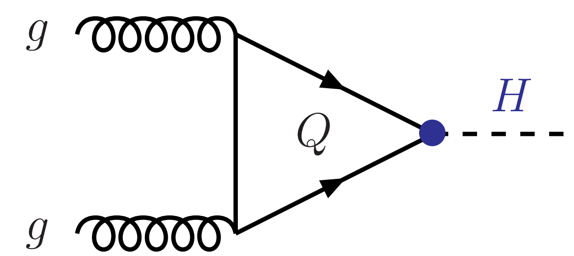
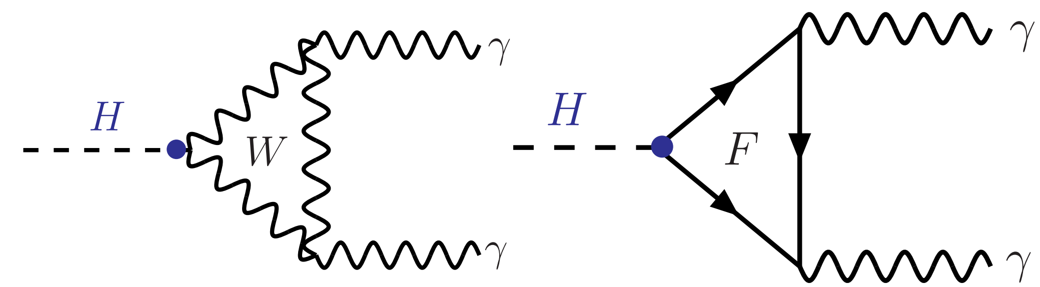
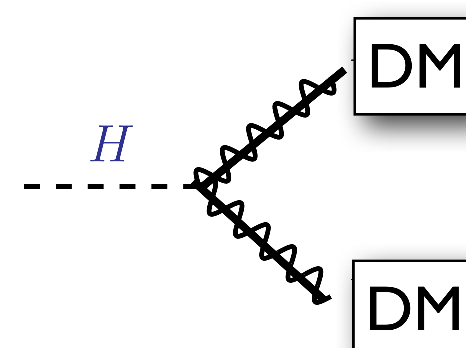
4) 


5) 


6) 


7) 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Most genuine Higgs coupling
(determines its role in EWSB)

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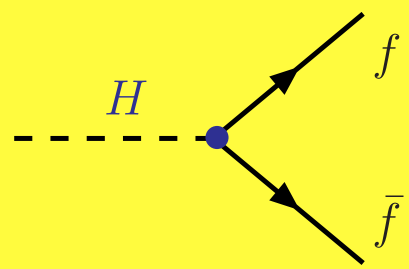


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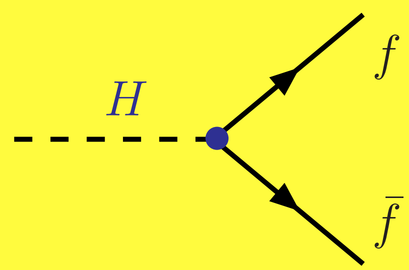


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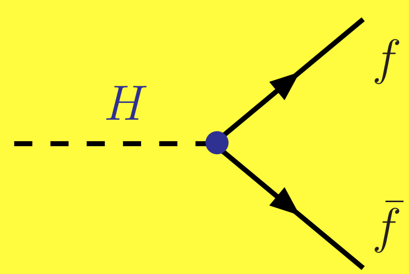


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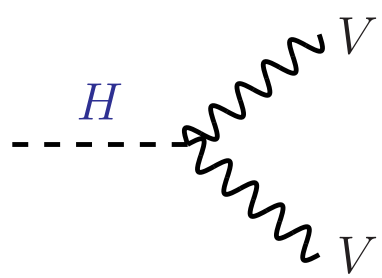


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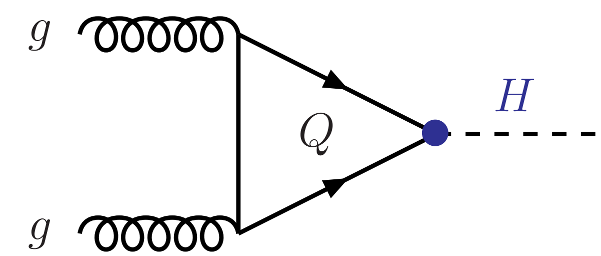


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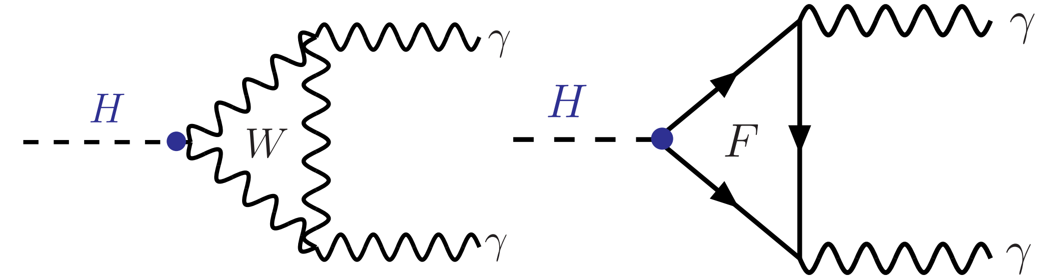


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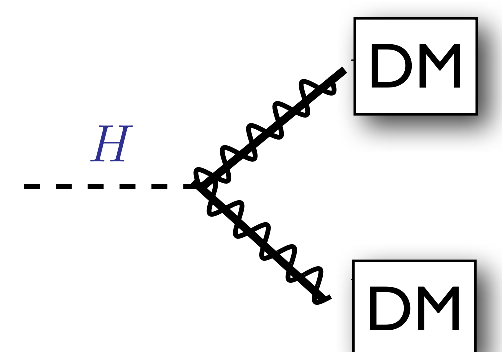


$\Gamma_{\rm inv}$

could also arise from a scalar that has nothing to do with EWSB

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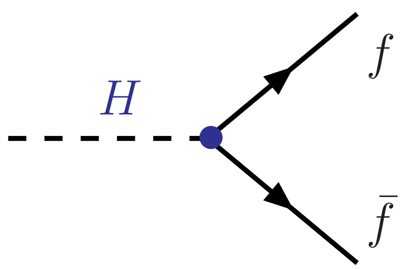
1) 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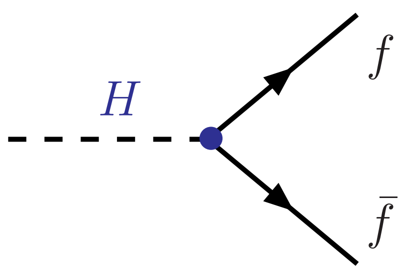
2) 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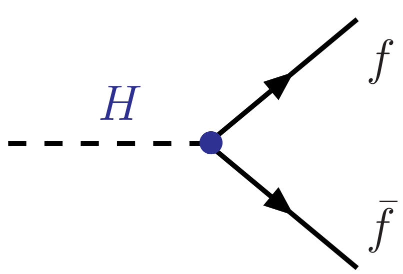
3) 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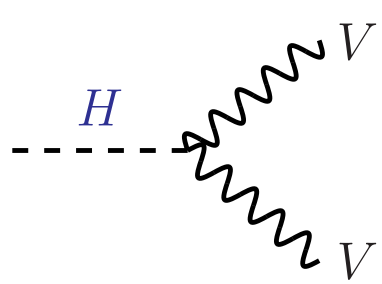
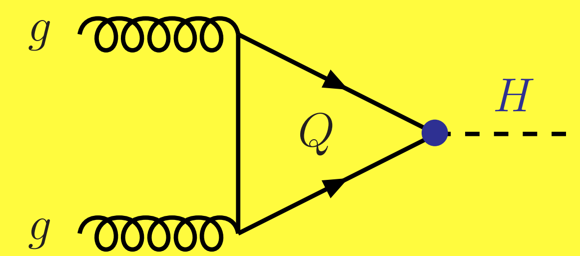
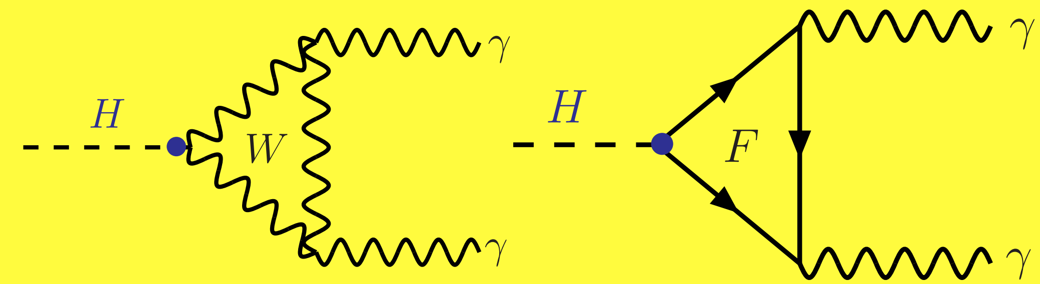
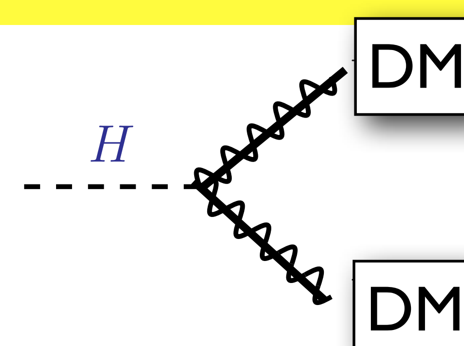
4) 


5) 


6) 


7) 


$\Gamma_{\rm inv}$

Sensitive to new states

(not necessary related with EWSB)

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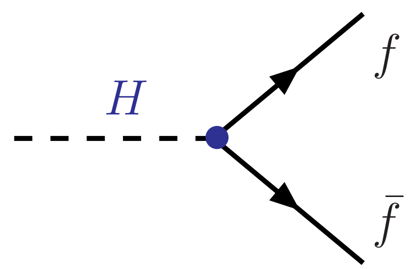


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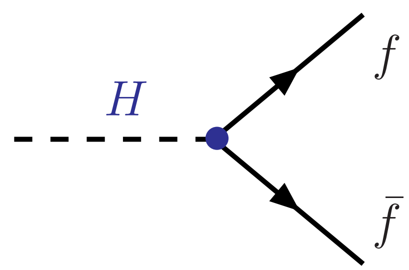


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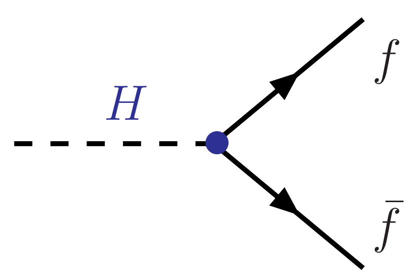


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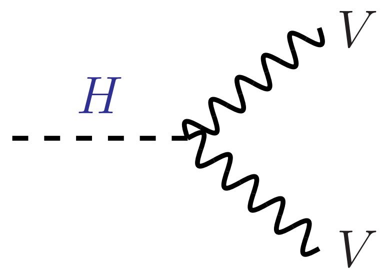


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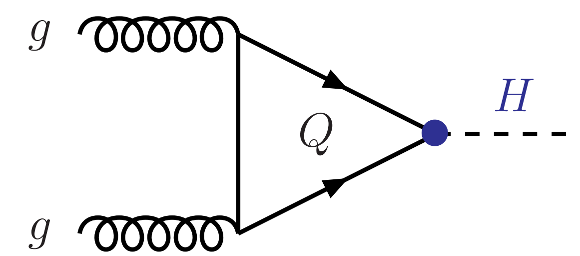


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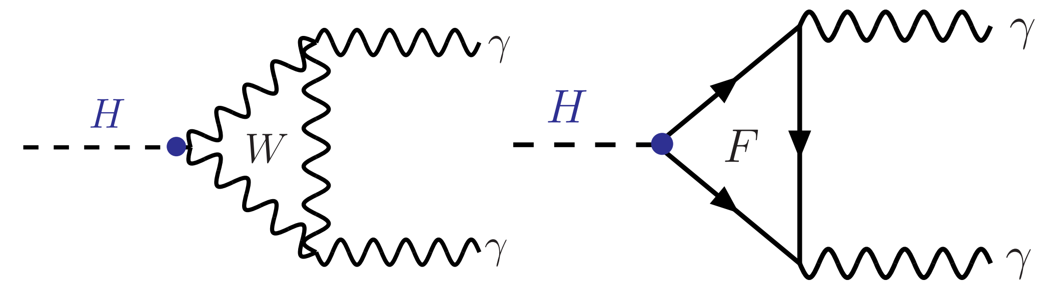
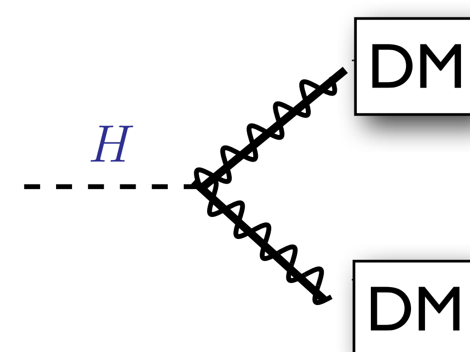



7)




$\Gamma_{\text{inv}}$

**7 parameters to be extracted from data**

Different EWSB models give different predictions for these 7 couplings

**Interestingly**, in certain well-motivated scenarios, only few couplings are predicted to deviate from the SM-couplings

**Three examples:**

a) **MSSM**

1) with light Stops
2) Heavy spectrum $M_{susy} \gg m_W$

b) **Composite PGB Higgs**

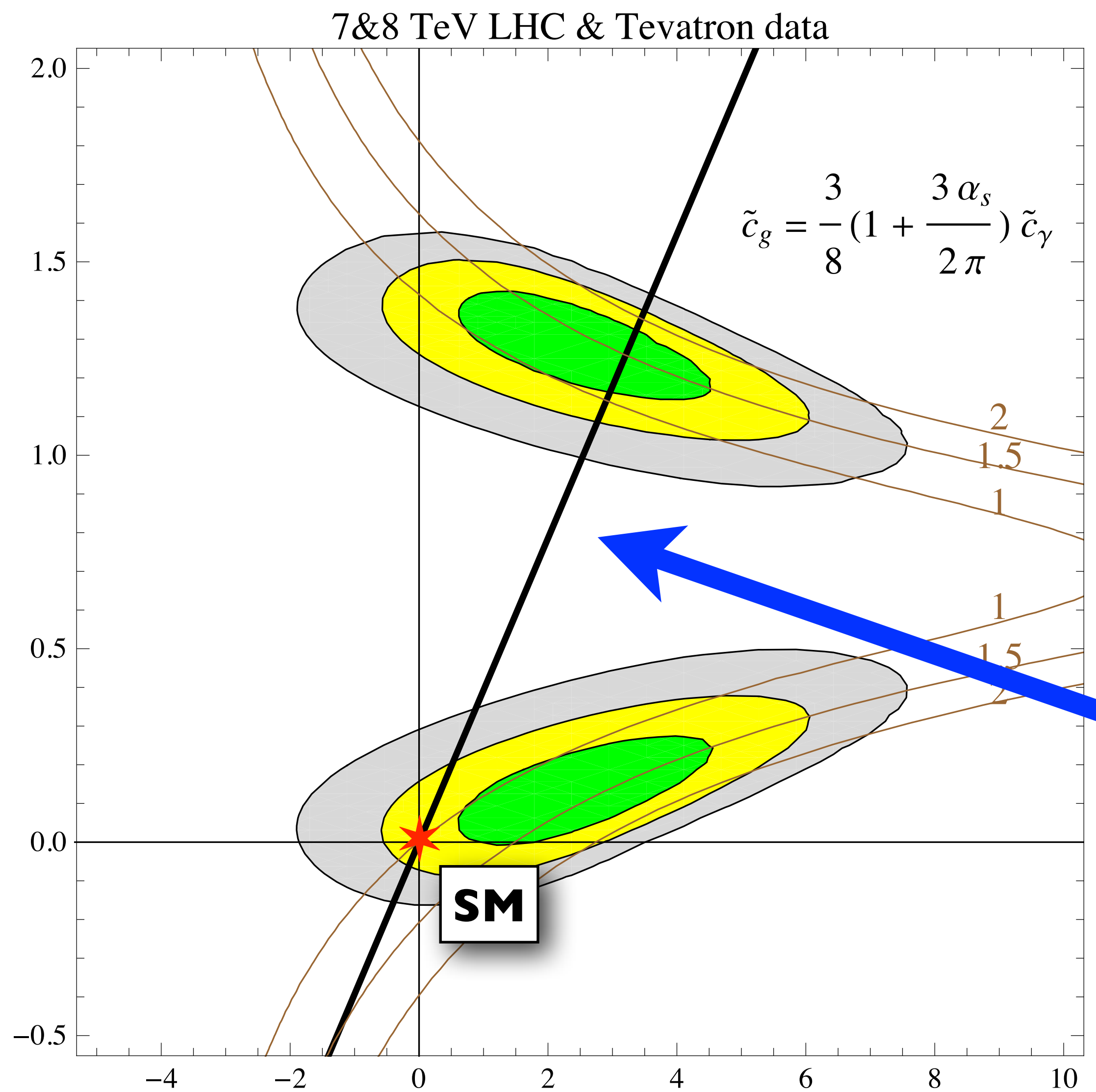
c) **Dilaton**

# 1) MSSM with light Stops (200-400 GeV)

Effects at the one-loop level to the Higgs-$\gamma\gamma$(gg) coupling. Effects correlated:

from Espinosa et al (arXiv:1207.7355)

$-\delta g_{hGG}$




Stop effects

$\delta g_{h\gamma\gamma}$

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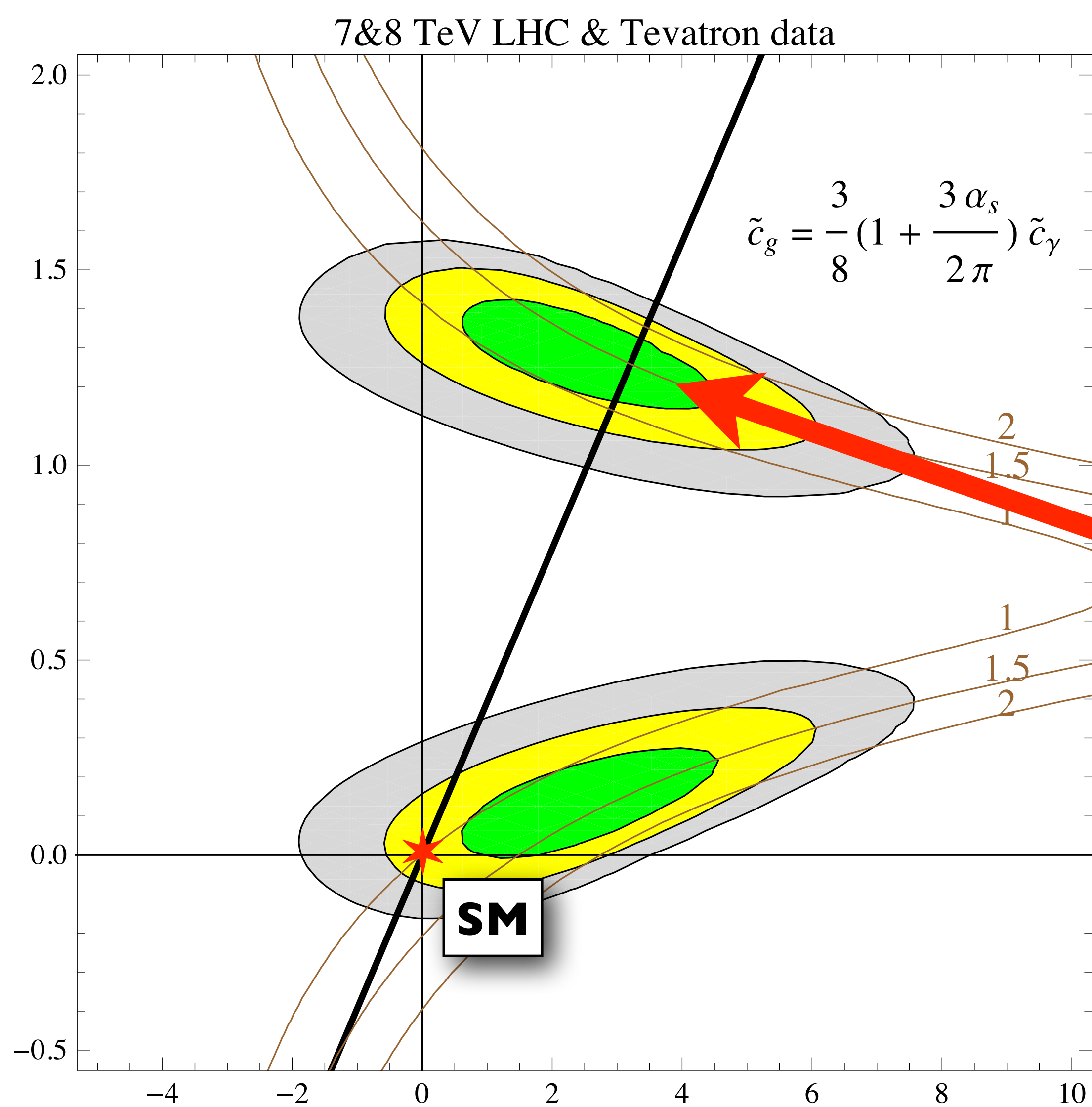



$-\delta g_{hGG}$

$\delta g_{h\gamma\gamma}$

from Espinosa et al (arXiv:1207.7355)

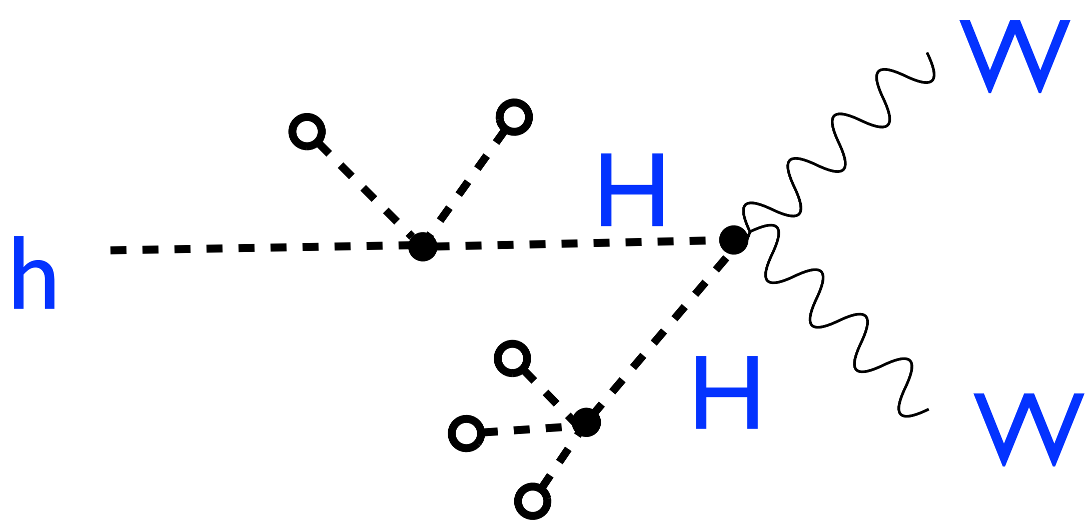
problems with color-breaking minima

(Reece arXiv:1208.1765)

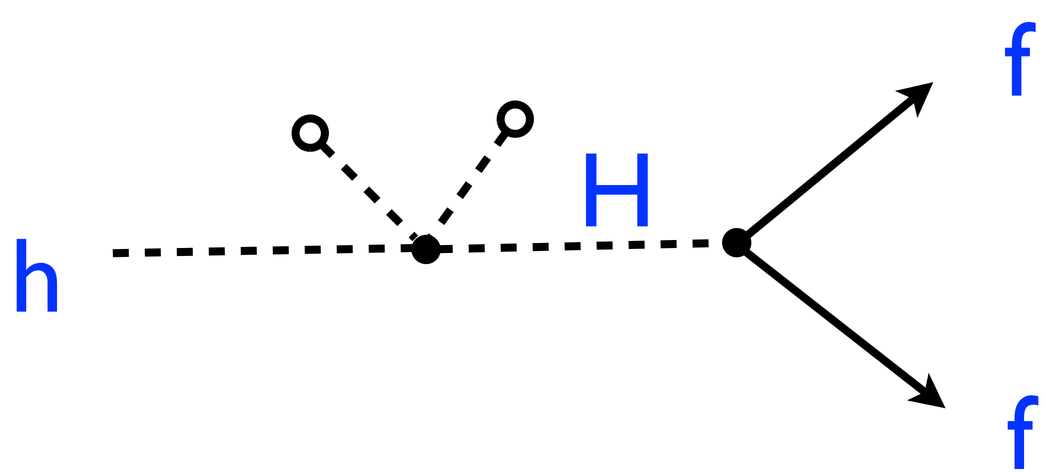
Not a fit much better than the SM!

# 1) MSSM with heavy spectrum

At $\mathcal{O}(v^2/M_{susy}^2)$ main effects from the 2nd Higgs doublet on the Higgs couplings to fermions:




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




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

**Dominant effect!**

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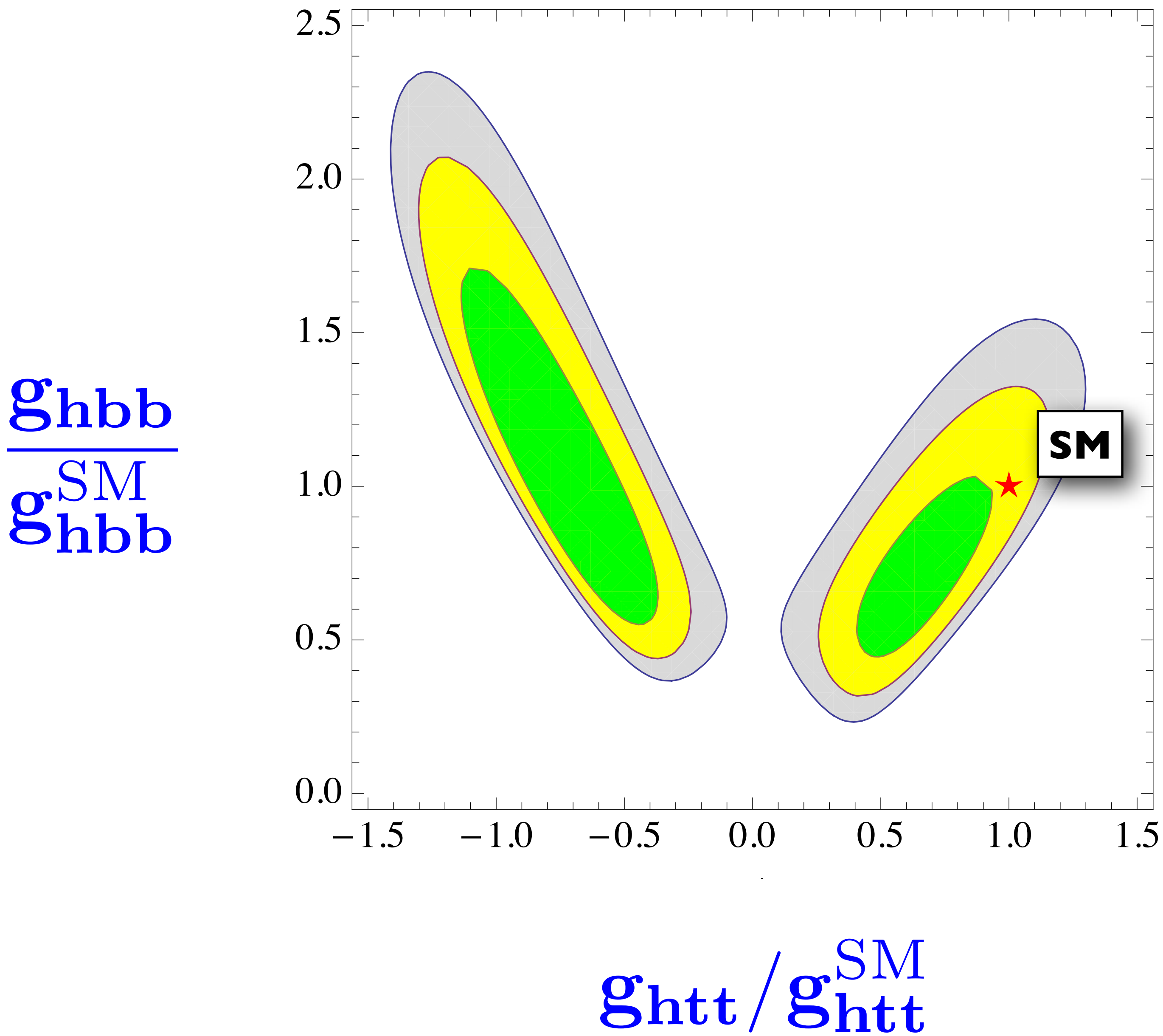
At $\mathcal{O}(v^2/M^2_{susy})$ main effects from the 2nd Higgs doublet on the Higgs couplings to fermions:




from, e.g., Montull,Riva
arXiv:1207.1716
(previous study: arXiv:1206.1058)

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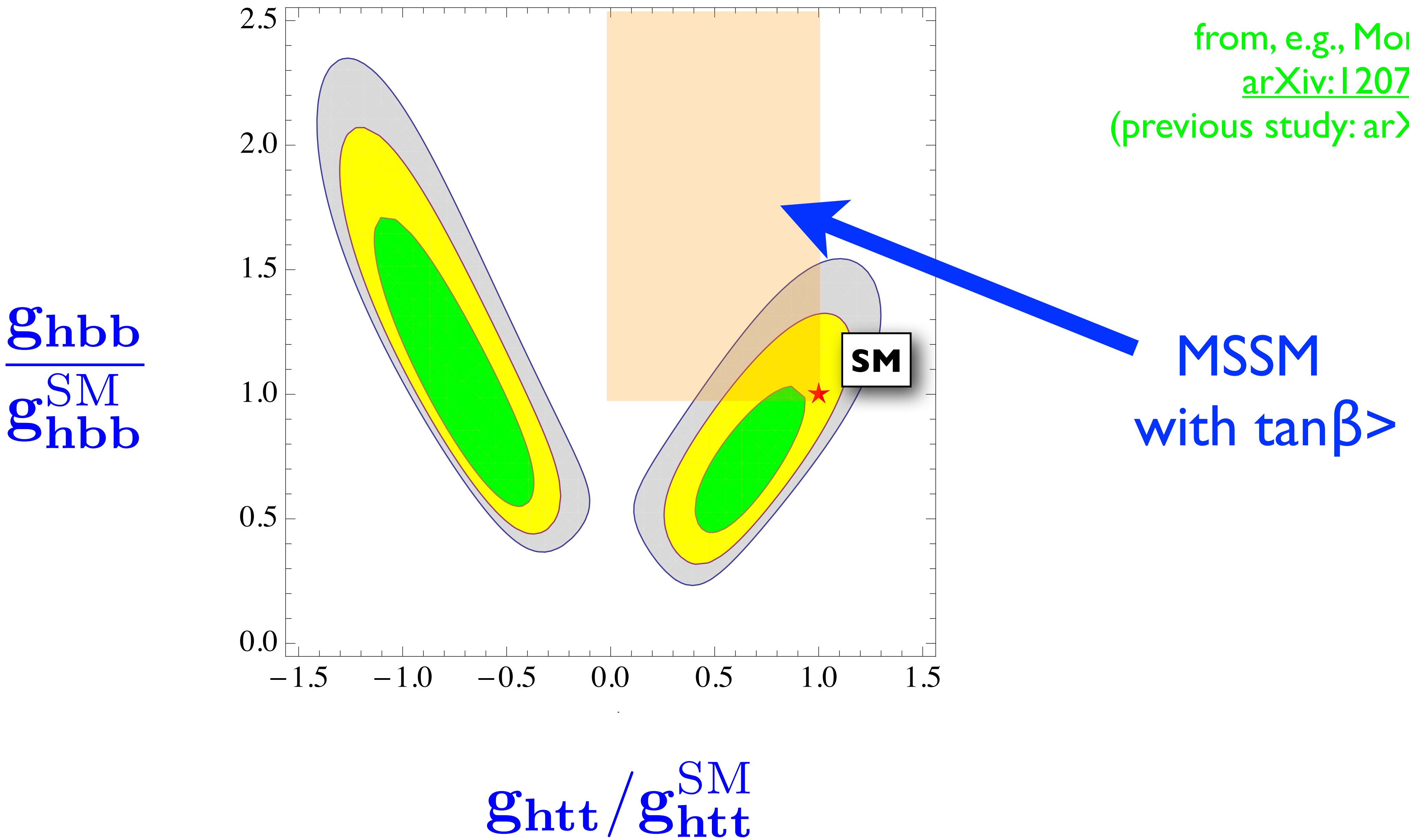


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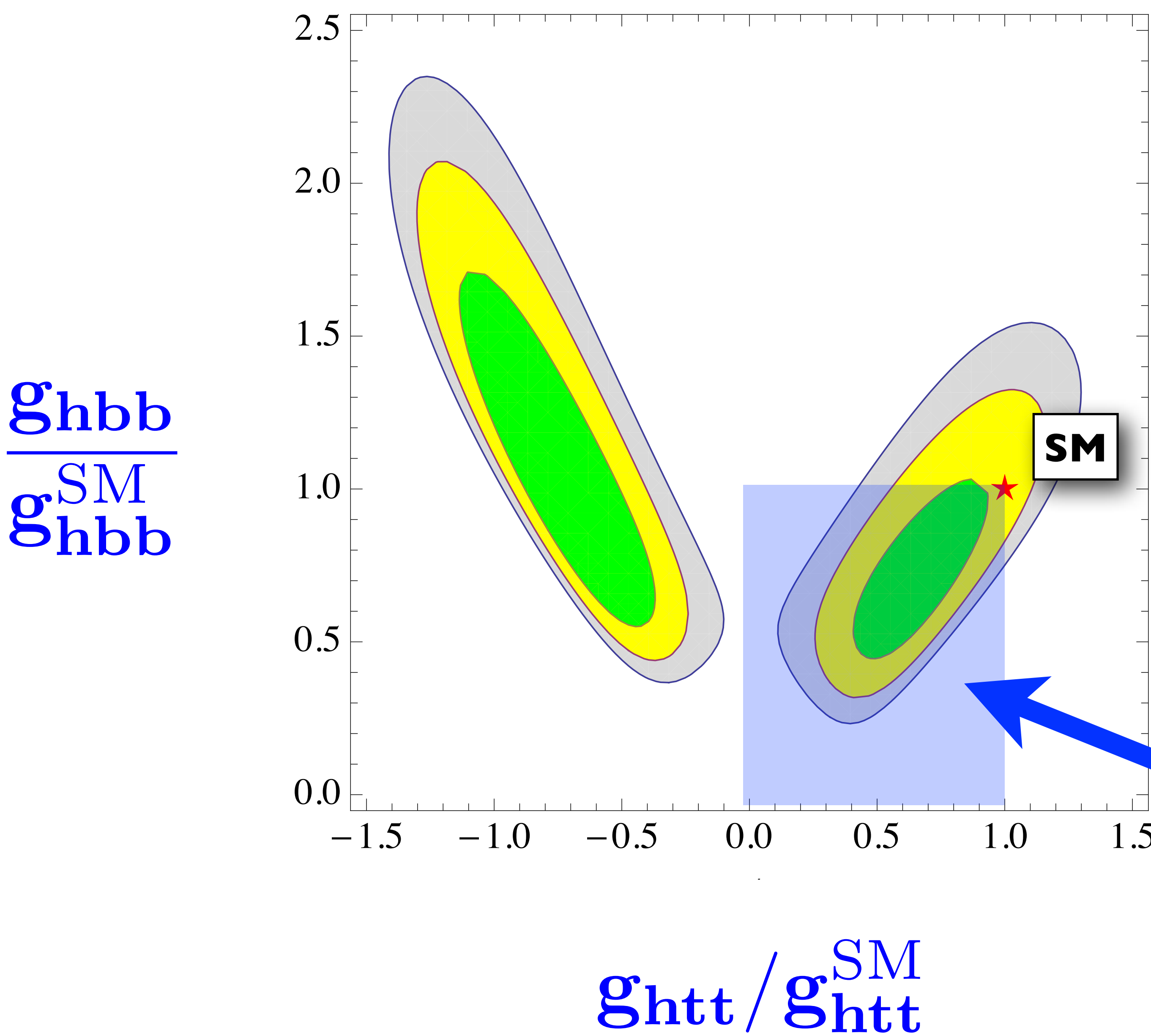



2HDM type I
give a better fit!!

# 2) Composite Higgs as a PGB

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

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

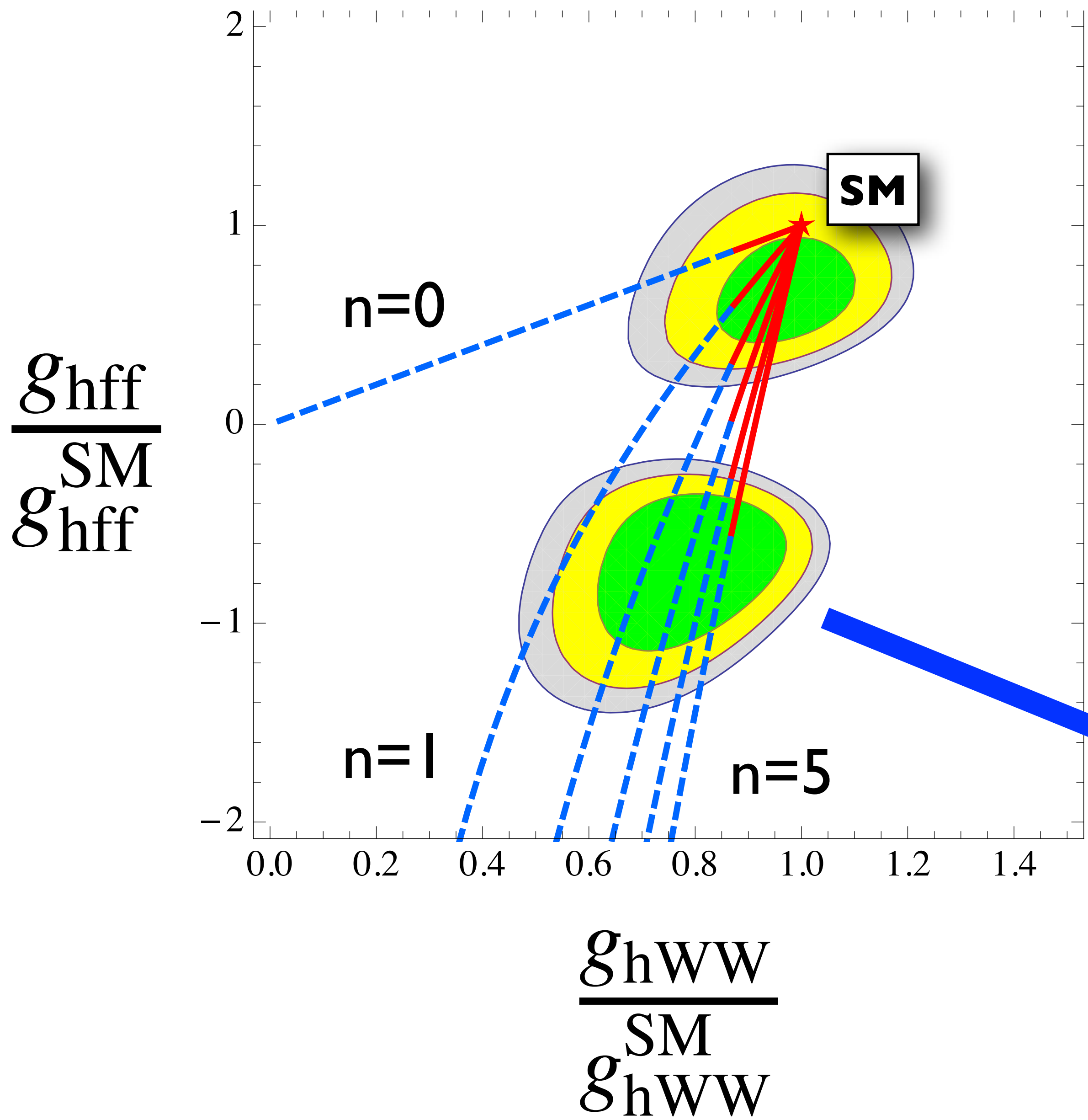
$$\frac{g_{hWW}}{g_{hWW}^{\rm SM}} = \sqrt{1-\frac{v^2}{f^2}}$$

$f$ = Decay-constant of the PGB Higgs

$$\frac{g_{hff}}{g_{hff}^{\rm SM}} = \frac{1-(1+n)\frac{v^2}{f^2}}{\sqrt{1-\frac{v^2}{f^2}}} \qquad n = 0, 1, 2, \ldots$$

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

# 2) Composite Higgs as a PGB




from, e.g., Montull,Riva
arXiv:1207.1716

Allowed area where constructive interference between top and W loops enhances the $\gamma\gamma$ channel

Fit slightly better than the SM!

# 3) Dilaton

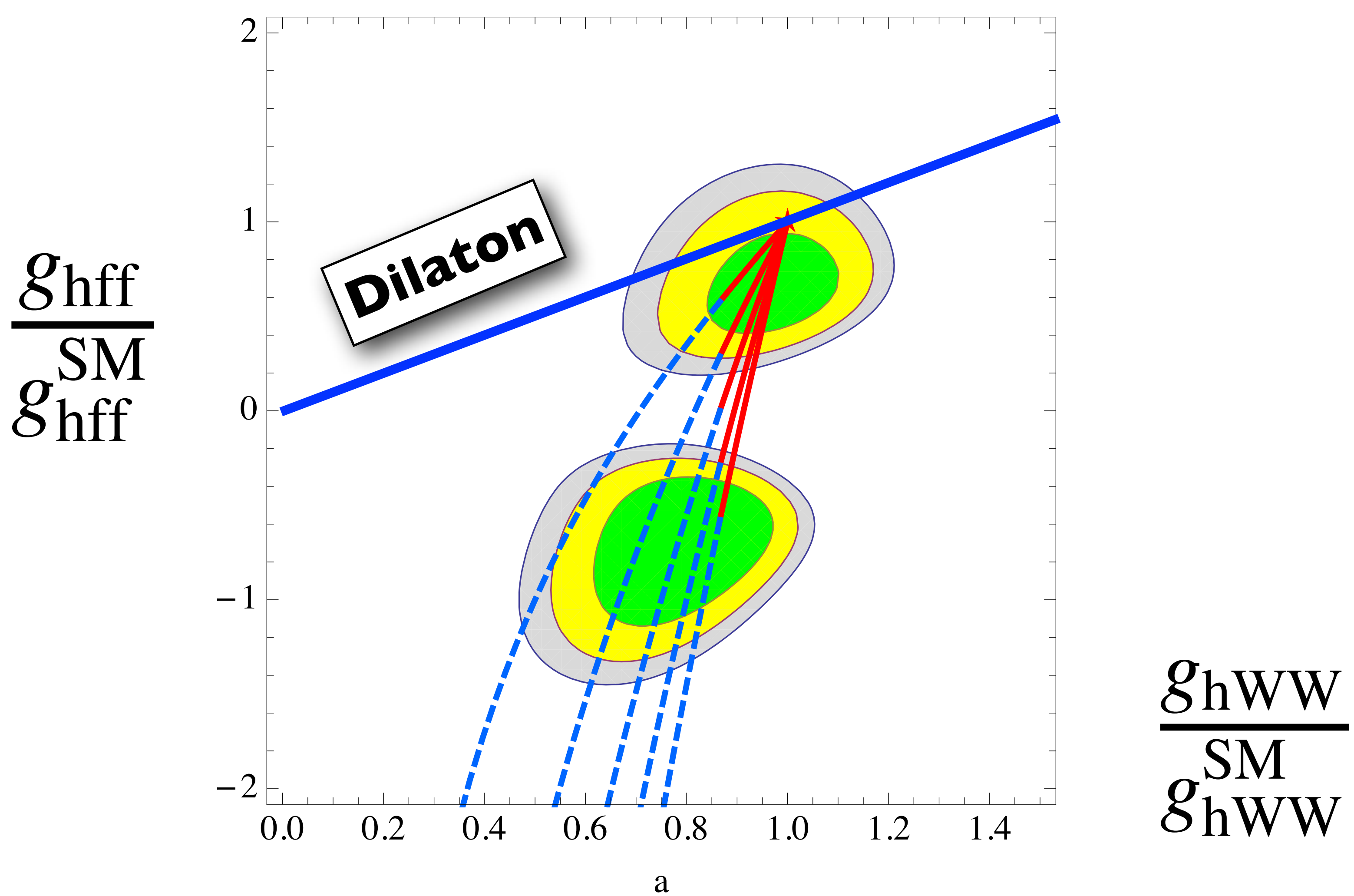
Goldstone of the spontaneous breaking of scale invariance

Last (desperate) hope for Higgsless models

(I see it as a good "punching bag")

↳ Couples as a Higgs up to an overall scale:

$$\frac{g_{hVV}}{g_{hVV}^{\rm SM}} = \frac{g_{hff}}{g_{hff}^{\rm SM}} = \frac{v}{f_D}$$



# Conclusions

- New data has brought very important information on the EWSB: **A light Higgs-like state**

  Disfavored models: TC-like, top-condensate, ...
  where no light scalar was expected

- Three options still possible:

  1) **SM only** (in quite good shape)
  2) **MSSM** (a lighter Higgs was expected)
  3) **Composite PGB Higgs**
     (light Higgs ⇒ Light fermionic resonances)

- Higgs coupling determination: Not decisive yet
  Not particular scenario is favored (neither the SM)

Let's hope at the end of the year a clearer picture will emerge!