# ELECTROWEAK SYMMETRY BREAKING (EWSB) STATUS/DIRECTIONS

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UAB (Barcelona)

# 4th of July 2012

## A very stirring day for the EWSB practitioners

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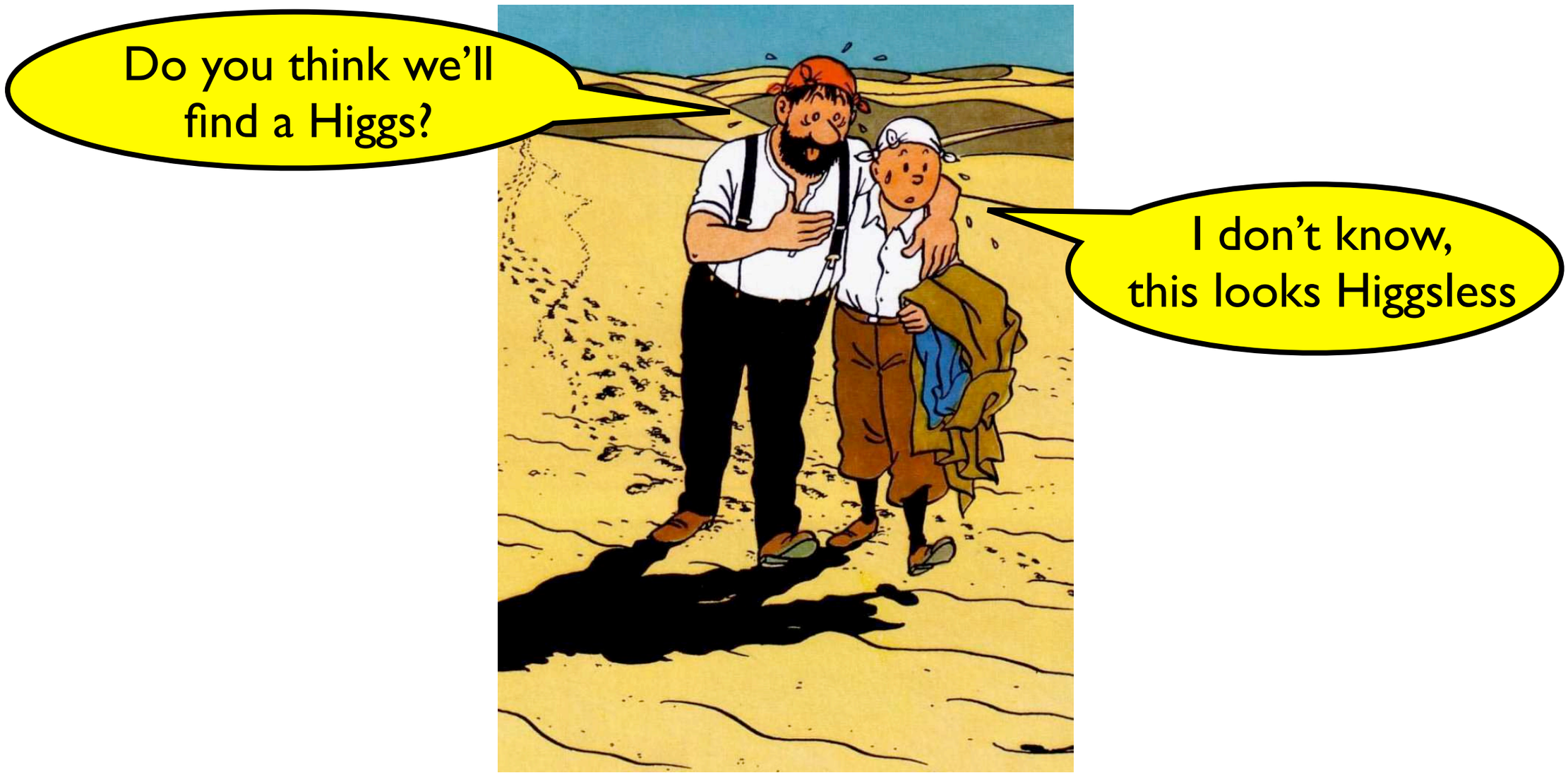
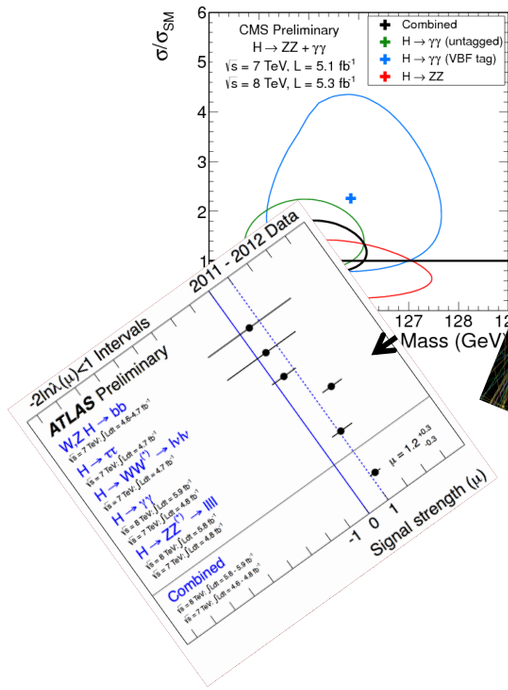
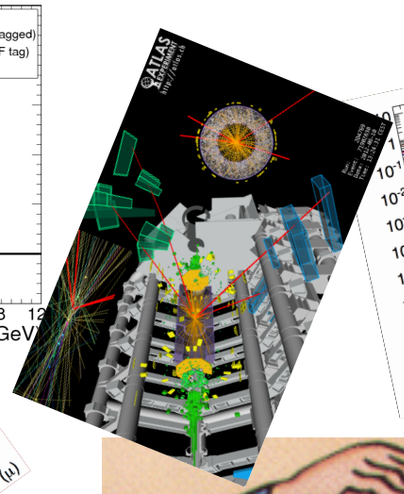
## A very stirring day for the EWSB practitioners

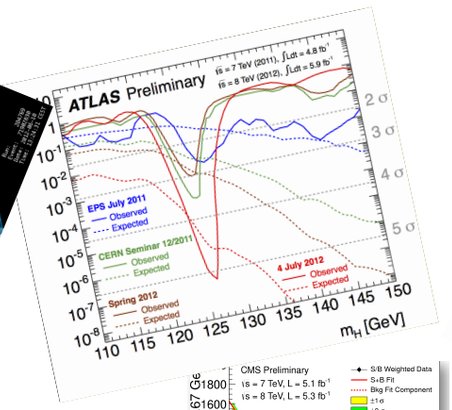
## We've been more than 40 years of mainly wandering in the desert...

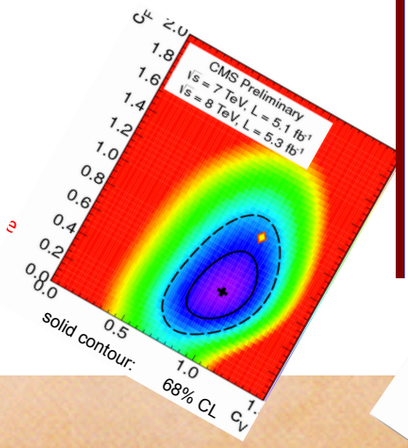


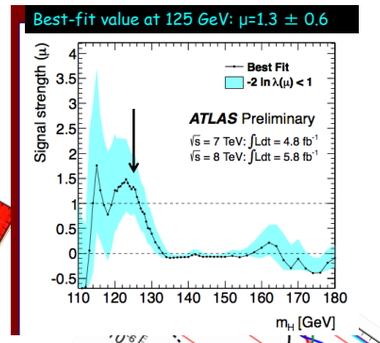
# … and finally plenty of new relevant data has begun to fall over us!



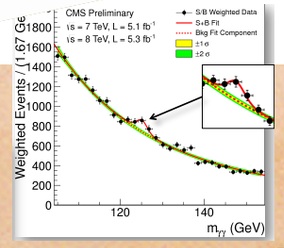



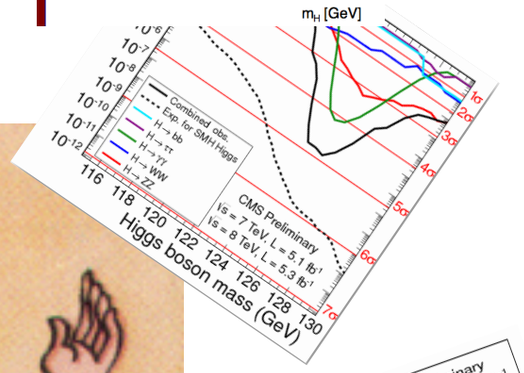



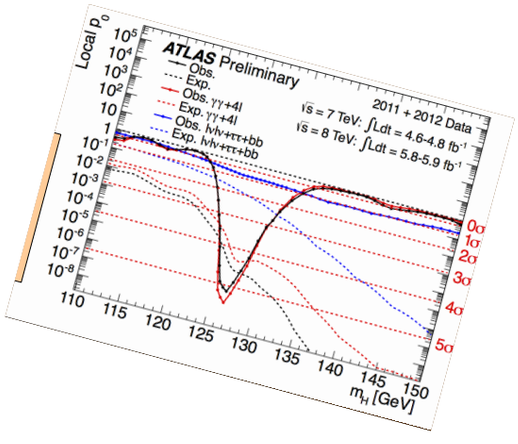



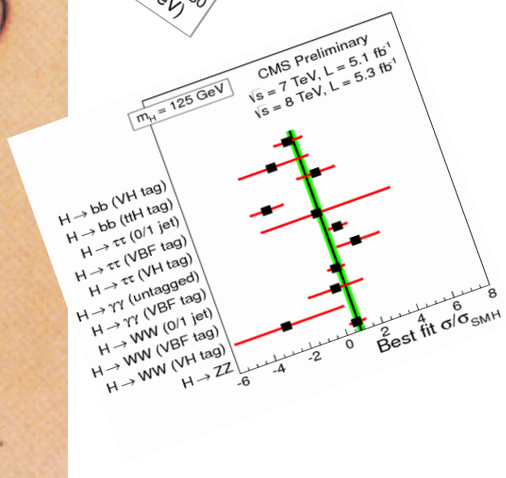






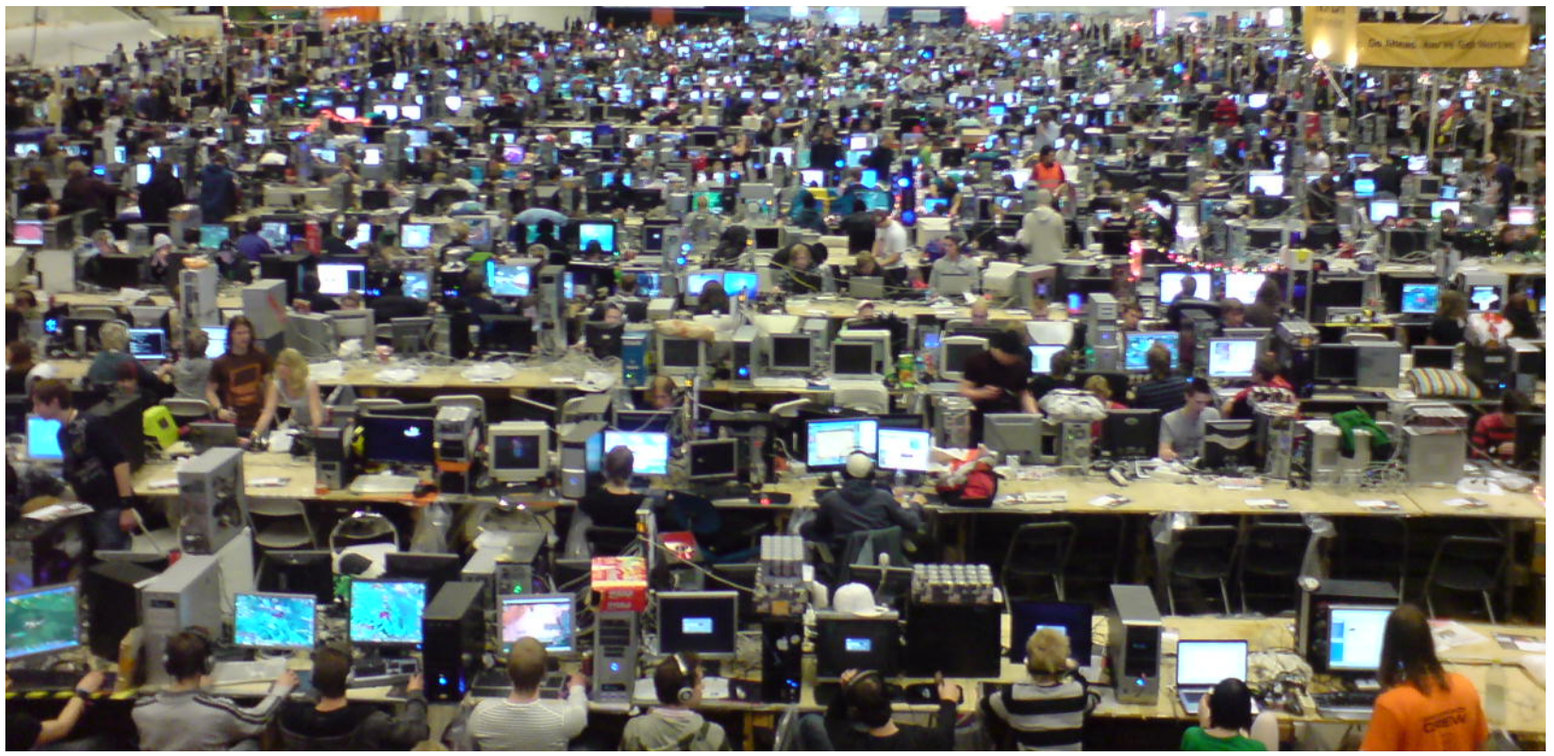



**Disclaimer: We have gotten more data on EWSB in one single day than in more than 40 years**

**↪ Not enough time to digest it!**

# many of my theory colleagues are at this moment working hard...



# ... be prepared for an outburst of papers on the 125 GeV Higgs in the next months

# What is the SM Higgs about?

# What makes the SM Higgs exceptional?

(As kangaroos are to Australia)

# What makes the Higgs special?

**<u>Not just about</u> finding the the condensate responsible for giving masses**

➥ **Also a condensate exists in Higgsless theories**

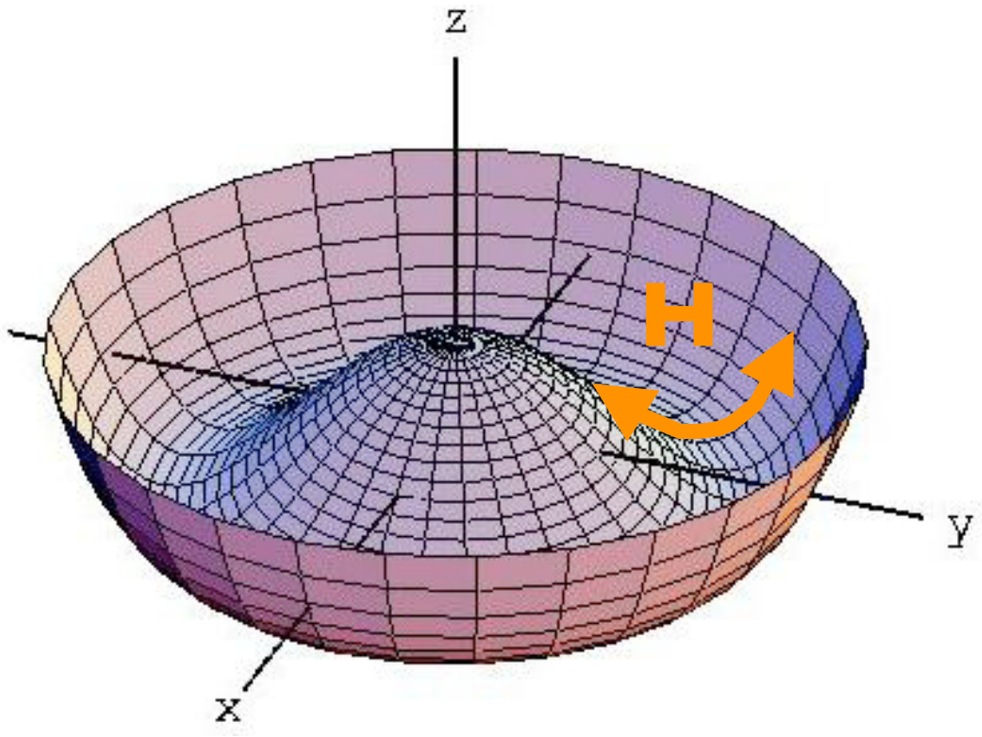
**Examples:**

- **QCD: Quark condensation <$q\bar{q}$> breaks chiral symmetry**
- **Superconductors: Cooper pair <ee> breaks EM**

➥ **none of them have a Higgs excitation**

# What makes the Higgs special?

**Not just about**
**the radial excitation**
**around the vacuum**

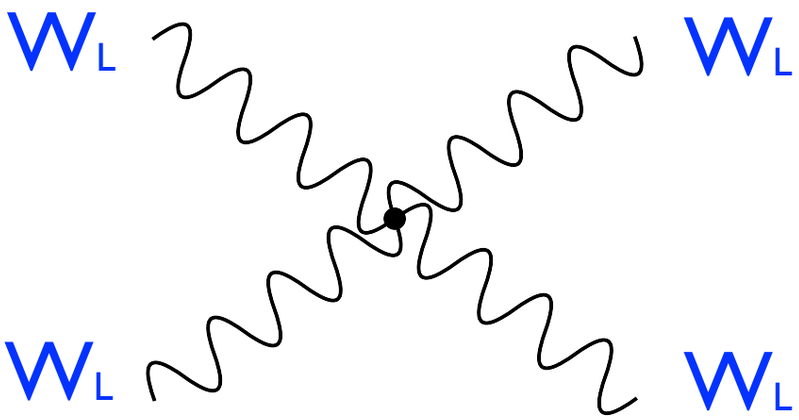



**Higgsless models have also excitations around the vacuum (as found in QCD)**

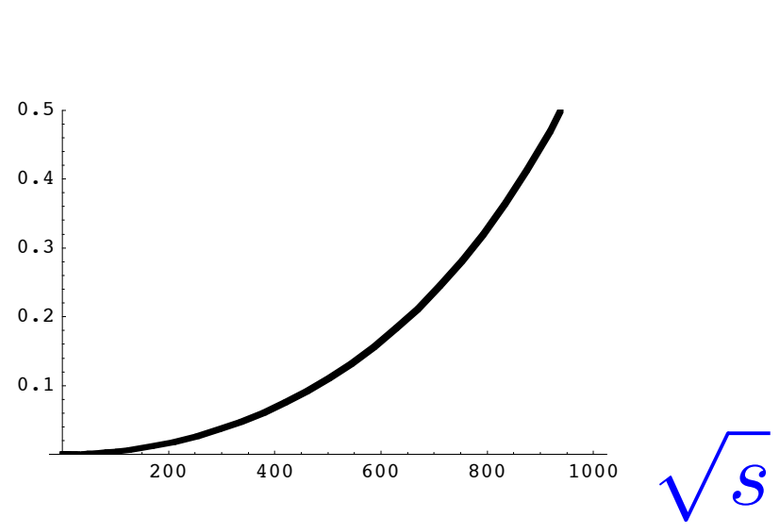
# What makes the Higgs special...

**Without a Higgs**, the states $W_L$, $Z_L$ **spoil** the nice calculability power of gauge theories

**a)**

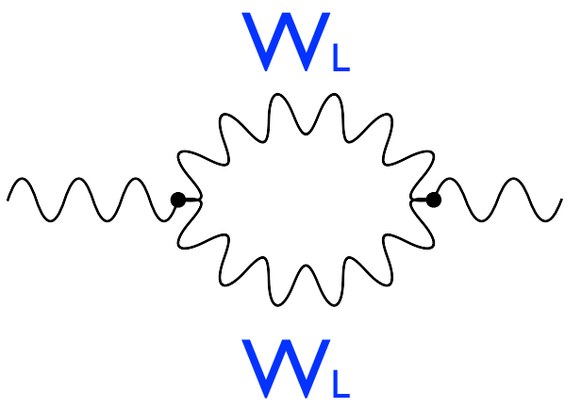



$$\propto \frac{s}{v^2}$$




Unitarity is lost at high-energies

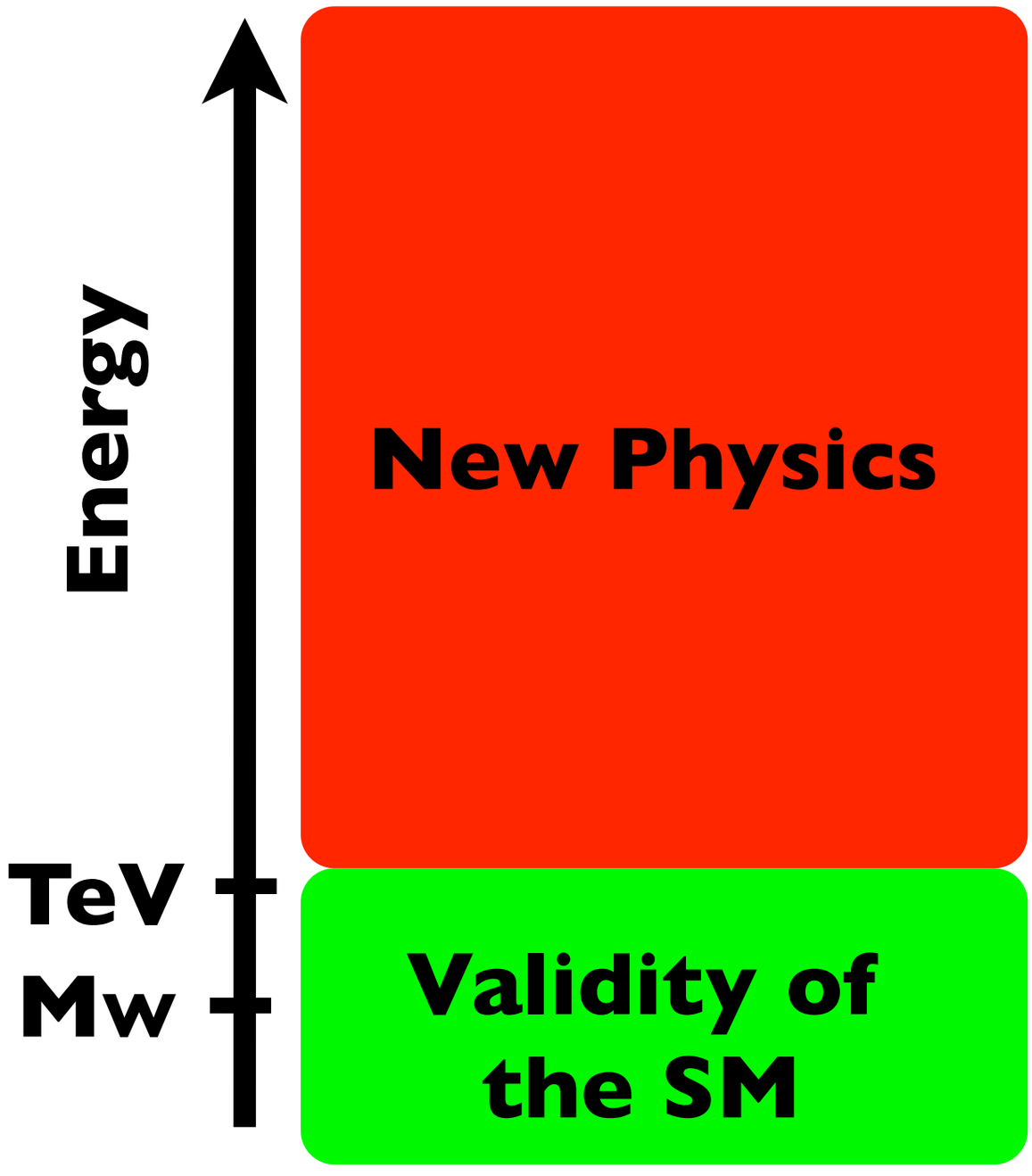
**b)**



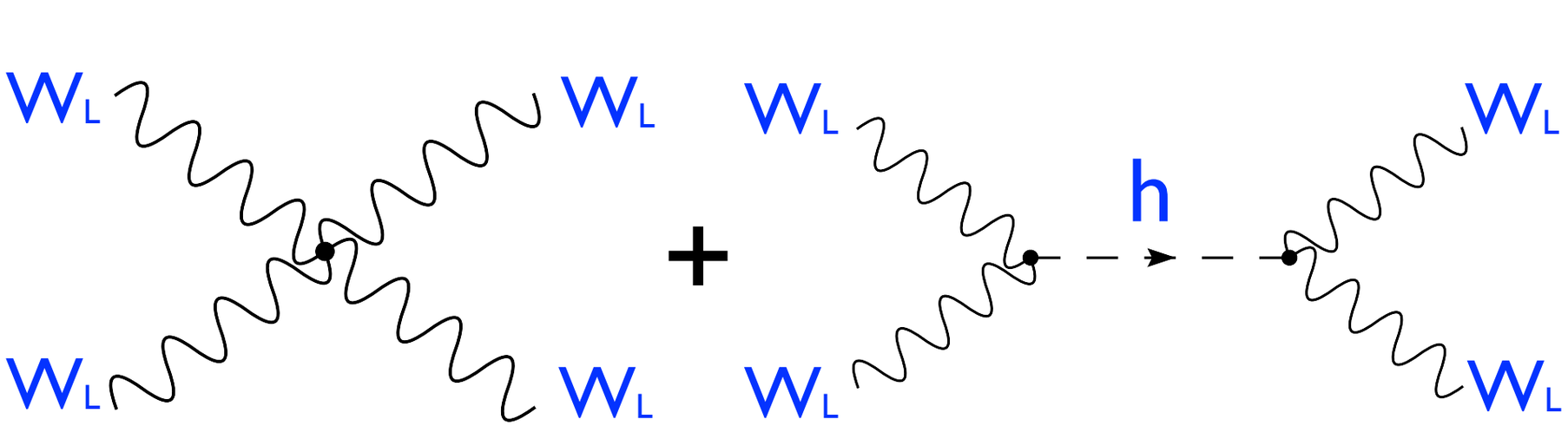

Loops are not finite!

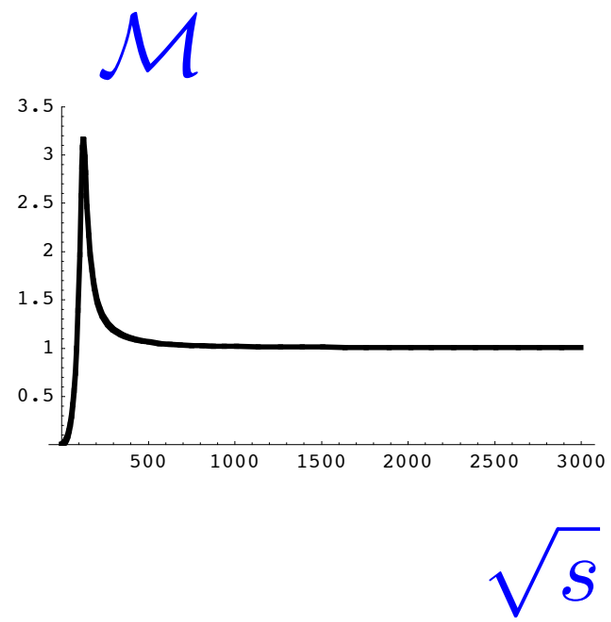
**Do not allow for precision calculations**

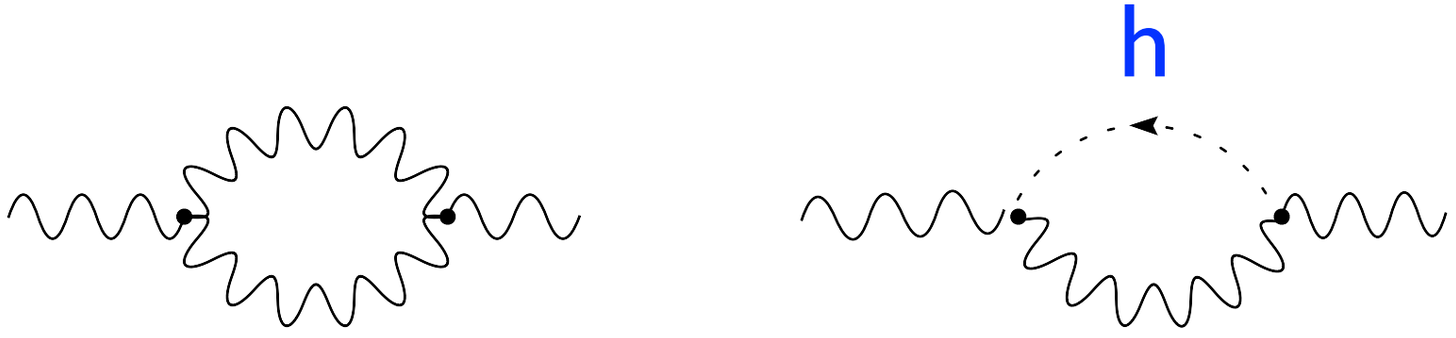
# Without a Higgs...



# With the Higgs **calculability** is recovered:



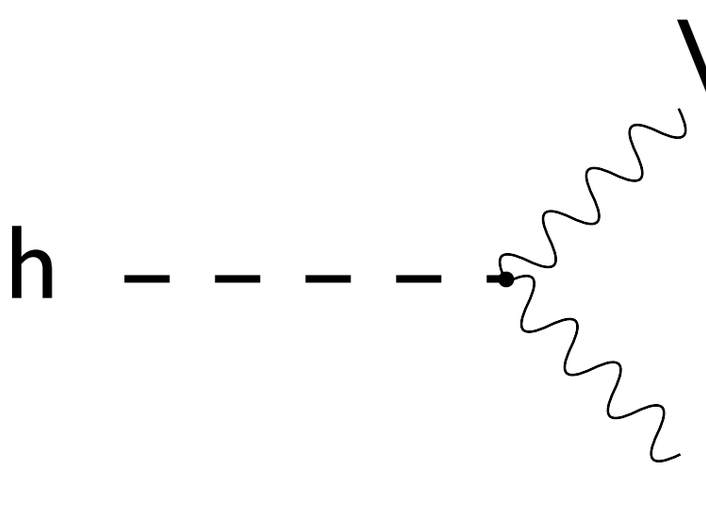



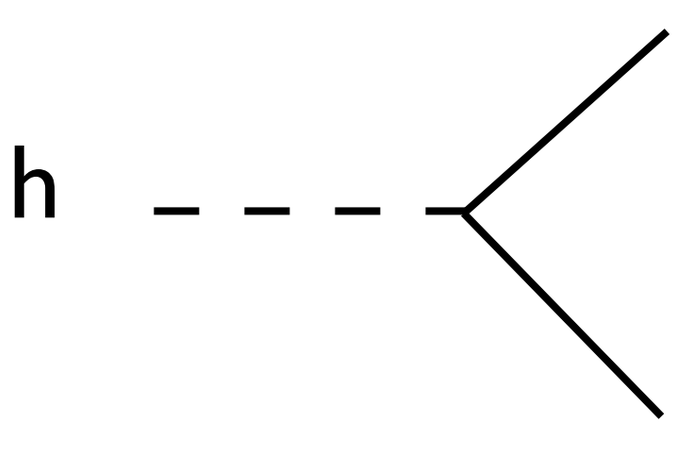

Finite results!

**Back to the prediction era!**

# To do this job, the Higgs couplings must take a particular value:




$$= \quad gM_W \quad , \quad \frac{gM_Z}{\cos\theta_W}$$

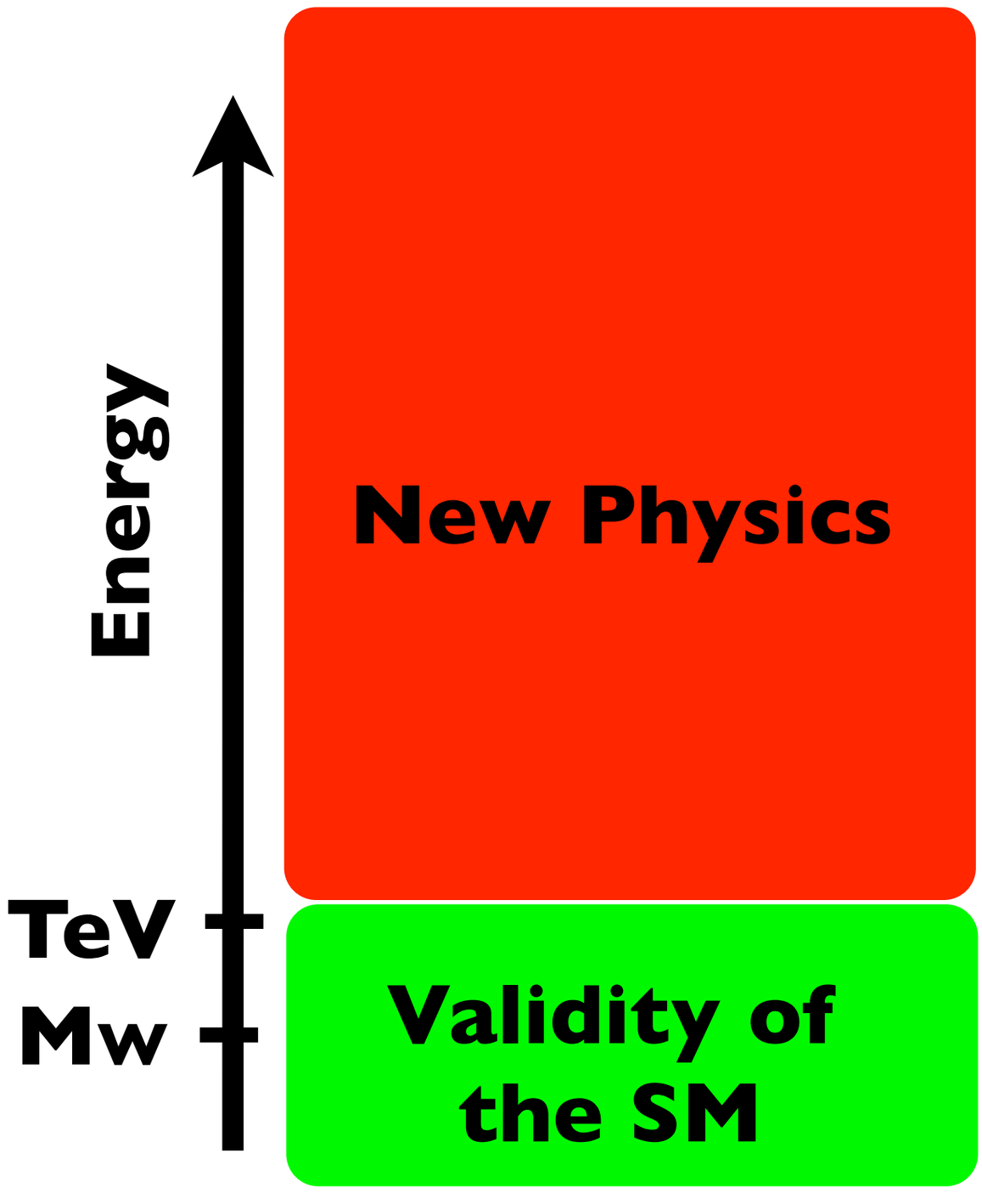



$$= \quad \frac{gM_f}{2M_W}$$

The couplings must be **exactly** these ones
(at tree-level) to make the SM a **consistent** theory

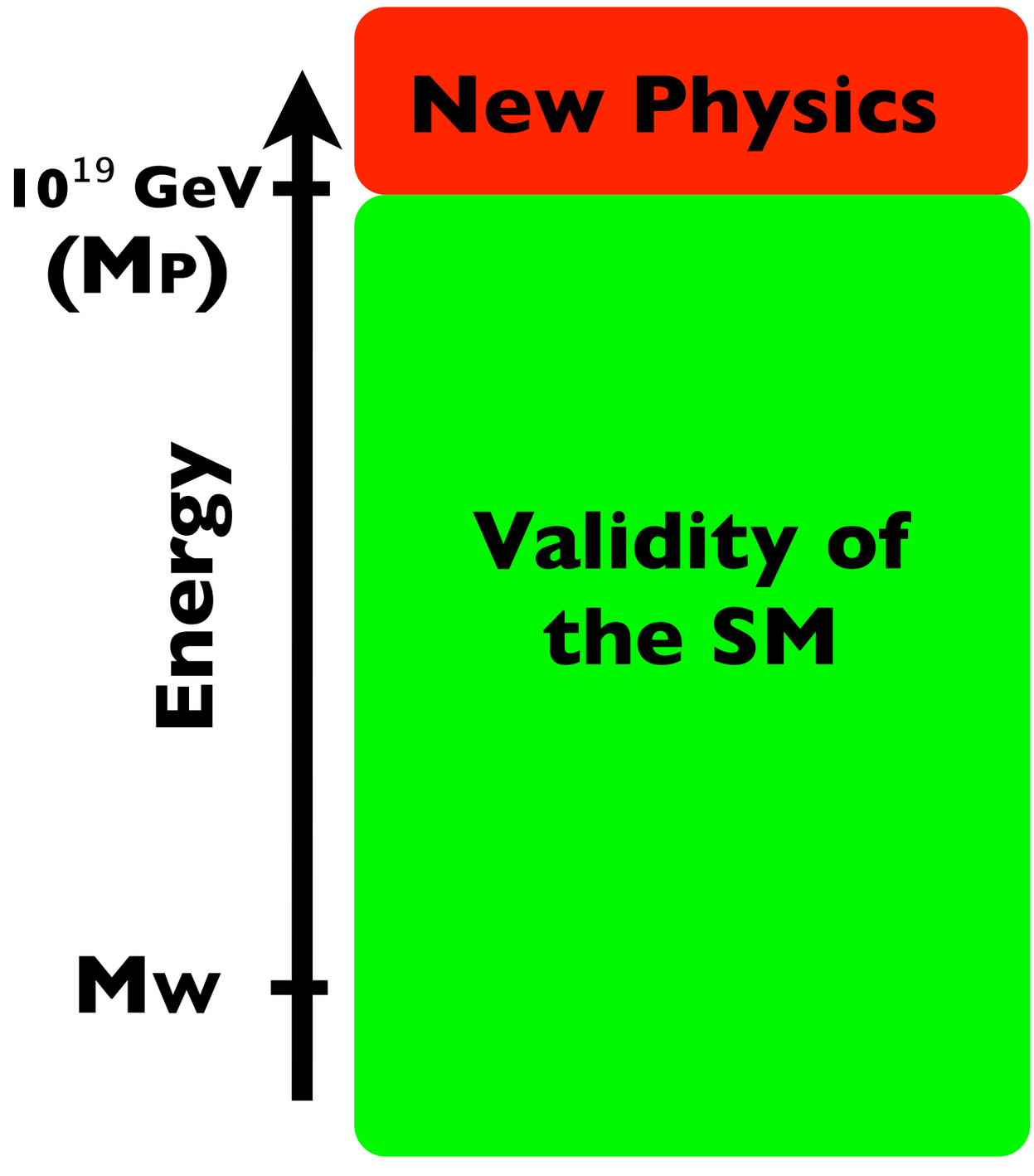
Otherwise this is **NOT** a Higgs = **"Impostor"**

# Without a Higgs




# With a Higgs

(100 GeV <mh<170 GeV)



# Although consistent, we think (and hope) the SM is not the full story

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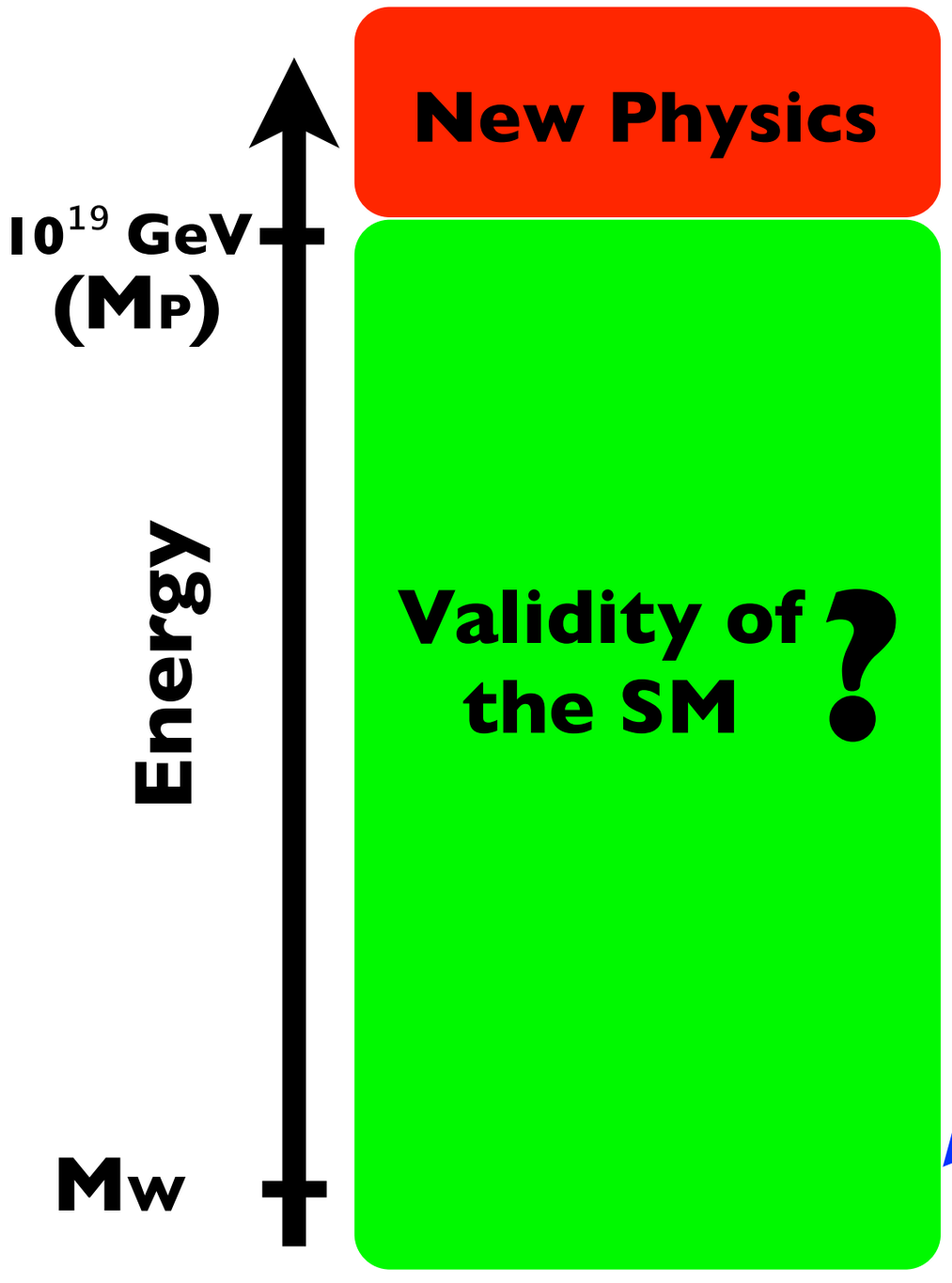
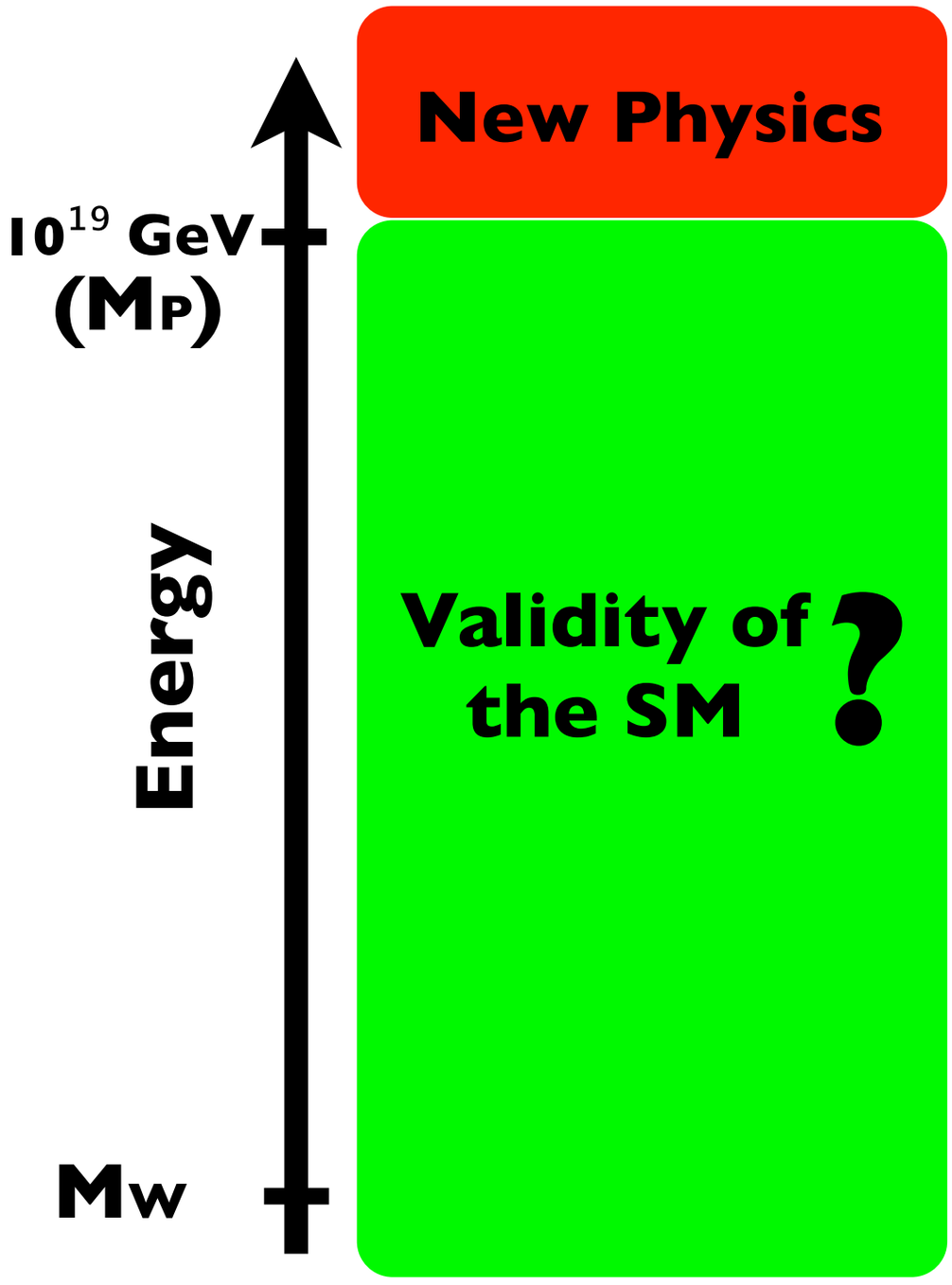



**Not understandable the origin of such a small EW scale as compared to the Planck scale**

# Although consistent, we think (and hope) the SM is not the full story




**At the quantum level "slim" scalars cannot survive in the presence of "fat" states**

**Heavy states**
**Strings/GUT**


**Higgs = Scalar**

# Possibilities that theorists envisage to tackle this problem:

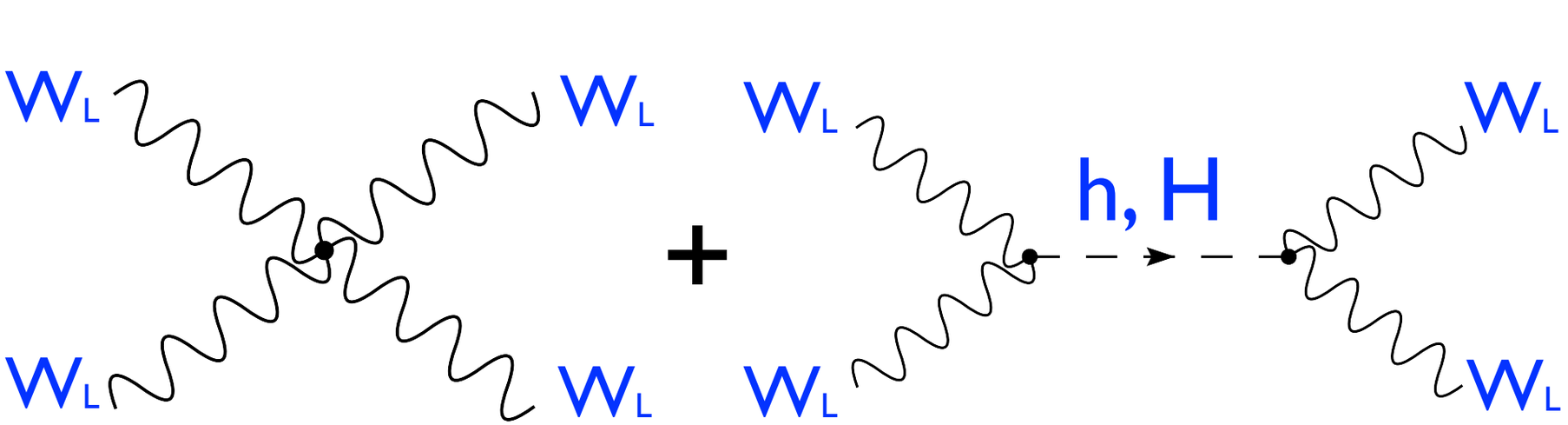
1) Keep the Higgs elementary, but protect it by symmetries: **Supersymmetry**

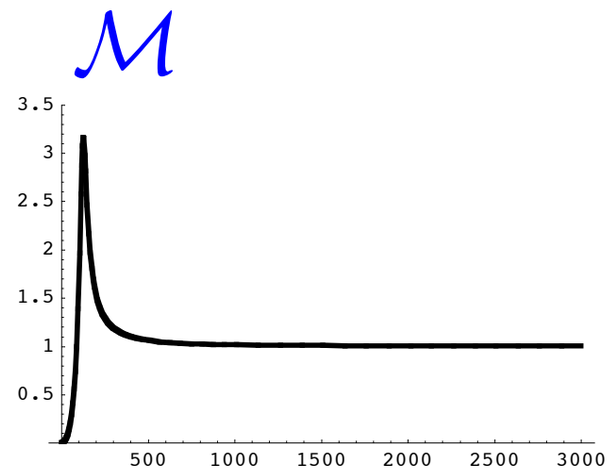
2) The Higgs is not elementary: **Composite Higgs**

➥ Both imply **changes** in the Higgs sector

# Supersymmetry = MSSM

For consistency, an **extra Higgs** (doublet) is needed, sharing the "duties" of the SM Higgs



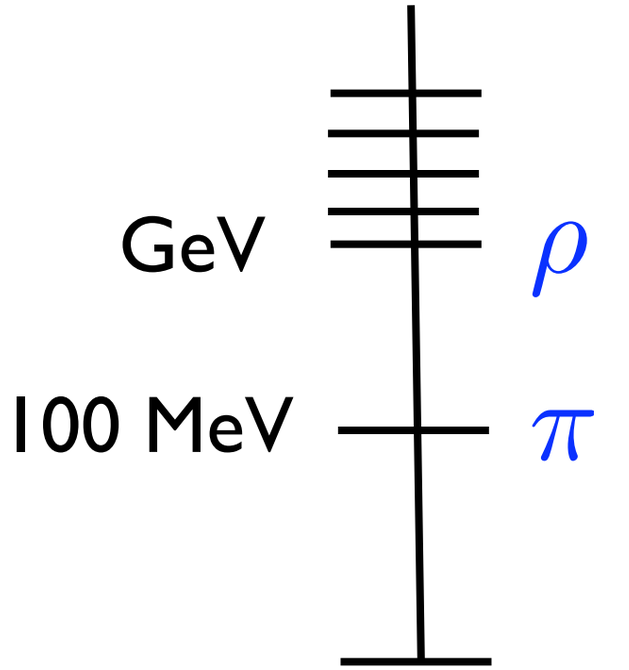



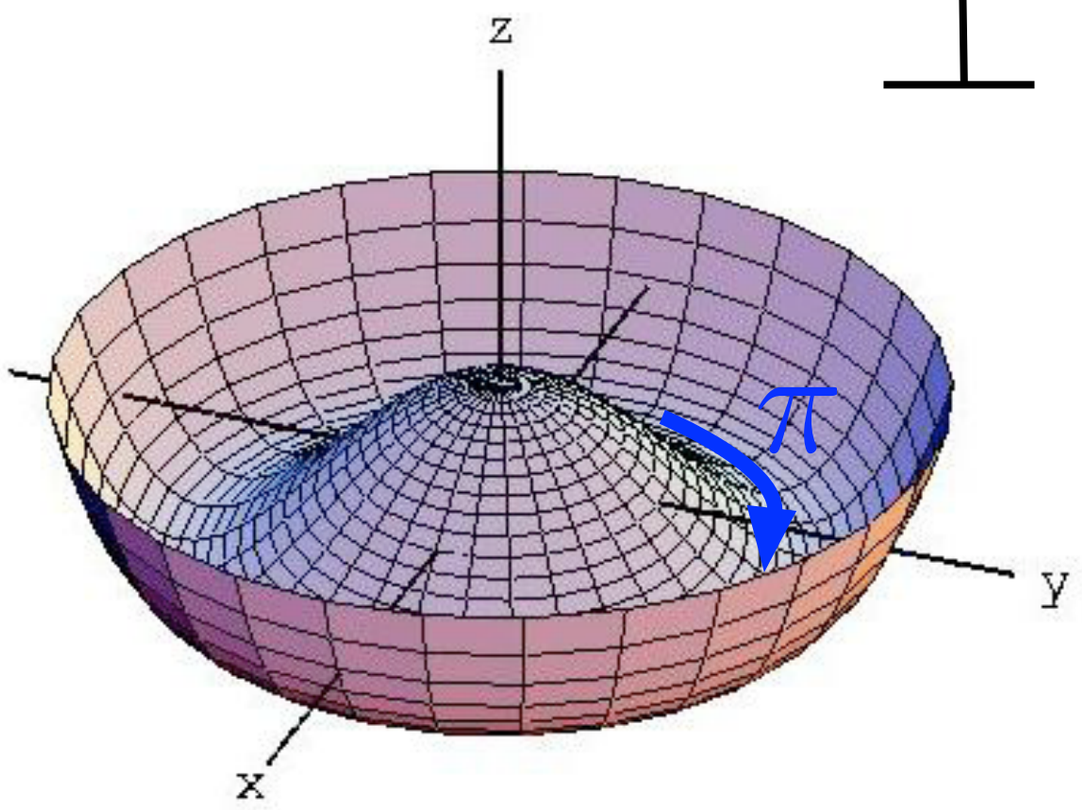

$$\mathbf{g^2_{hWW} + g^2_{HWW} = g^{SM\ 2}_{hWW}} \quad \Rightarrow \quad \boxed{\mathbf{g_{hWW}, g_{HWW} < g^{SM}_{hWW}}}$$

# Composite PGB Higgs

Inspired by QCD where one observes
that the (pseudo) scalars are the lightest states

Spectrum:



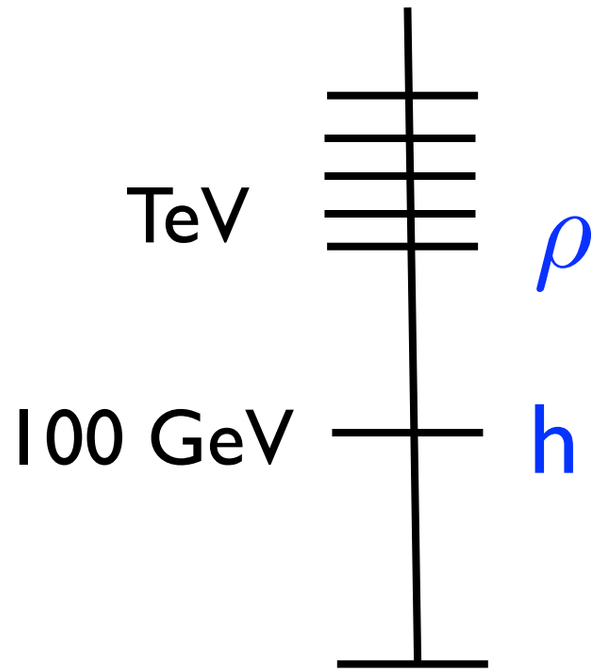

Are Pseudo-Goldstone bosons (PGB)

Mass protected by the global QCD symmetry!

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

# The light Higgs can be a kind of pion from a new strong sector

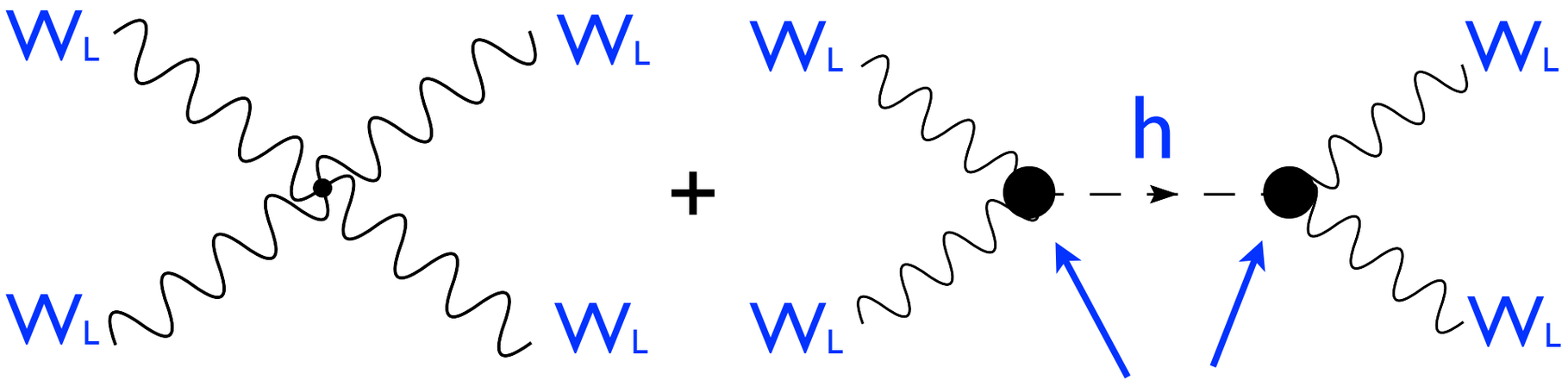
The spectrum of the new strong sector could be:



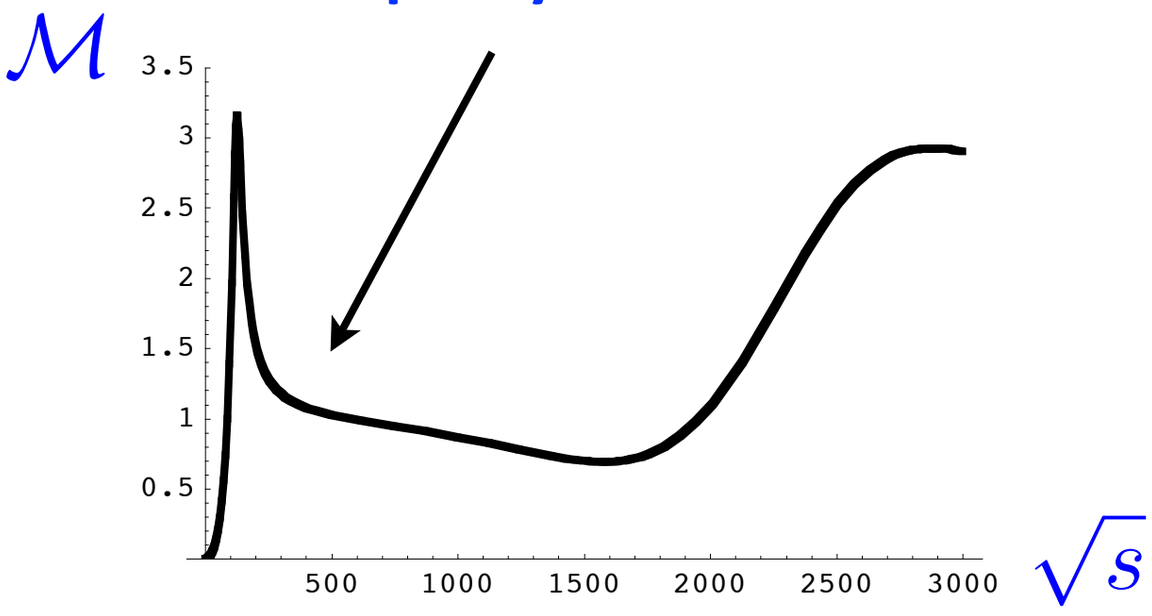

Pseudo-Goldstone bosons (PGB)

Mass protected by the global symmetries!

Being **Composite,** the Higgs couplings are different from the SM values




**partly unitarize!**




different
from the SM Higgs

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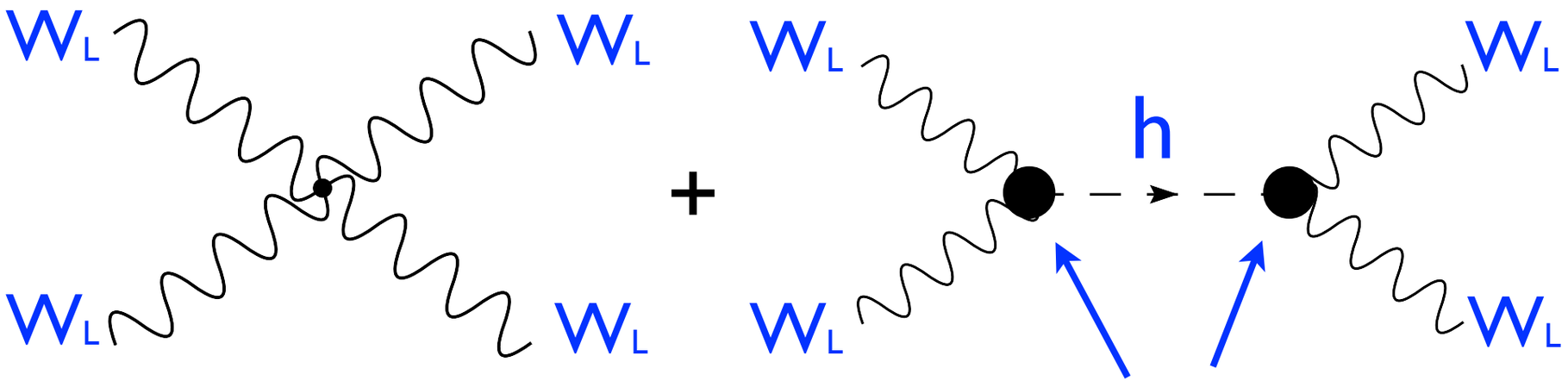
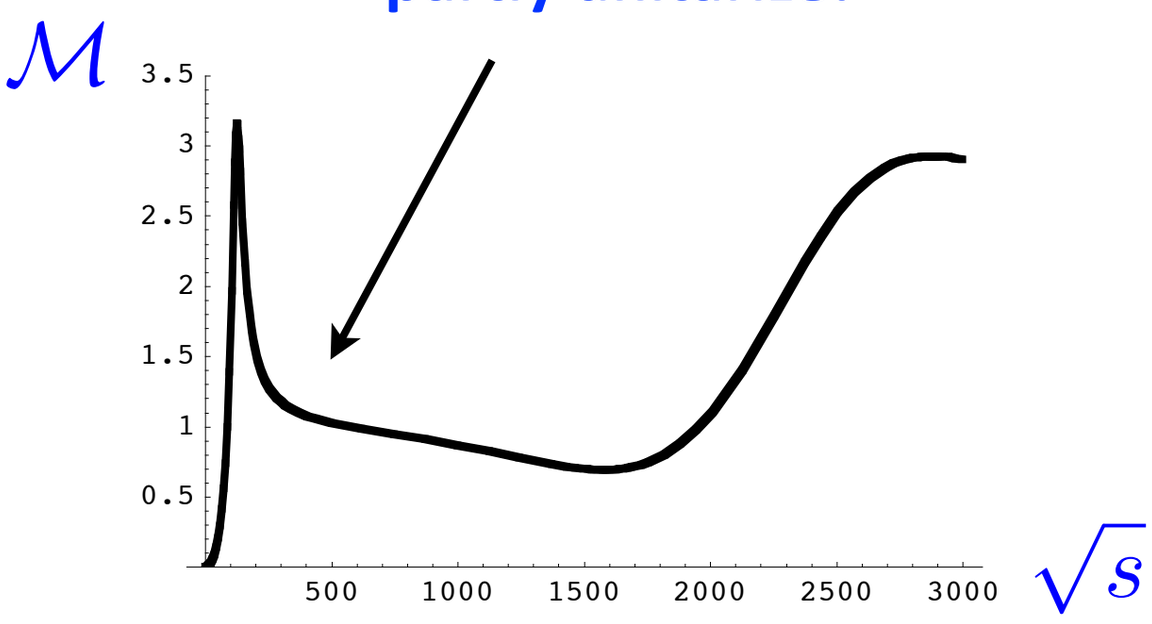



**partly unitarize!**

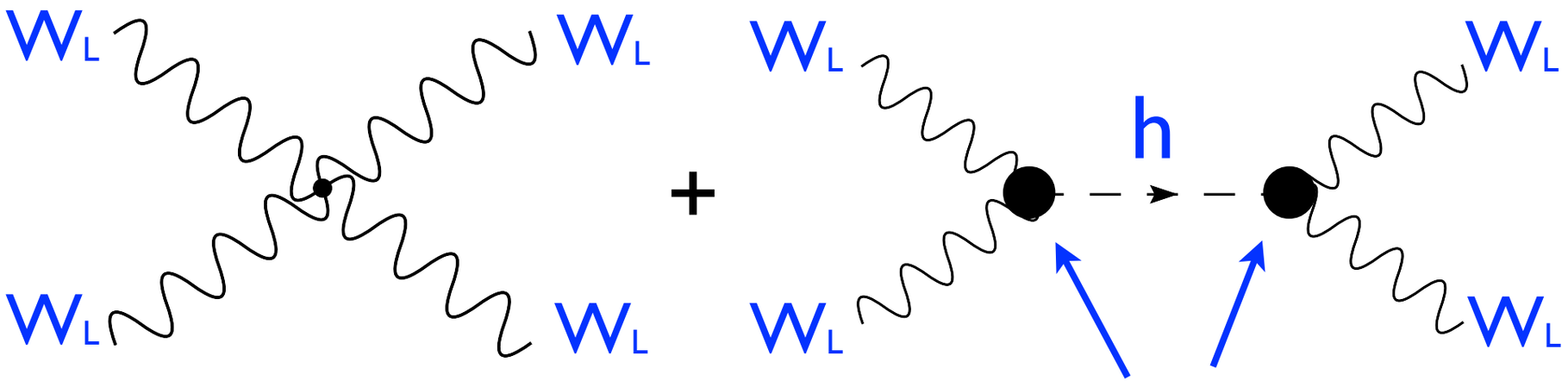



different
from the SM Higgs

A **Composite Higgs**
only partly
does the job of a **true** Higgs

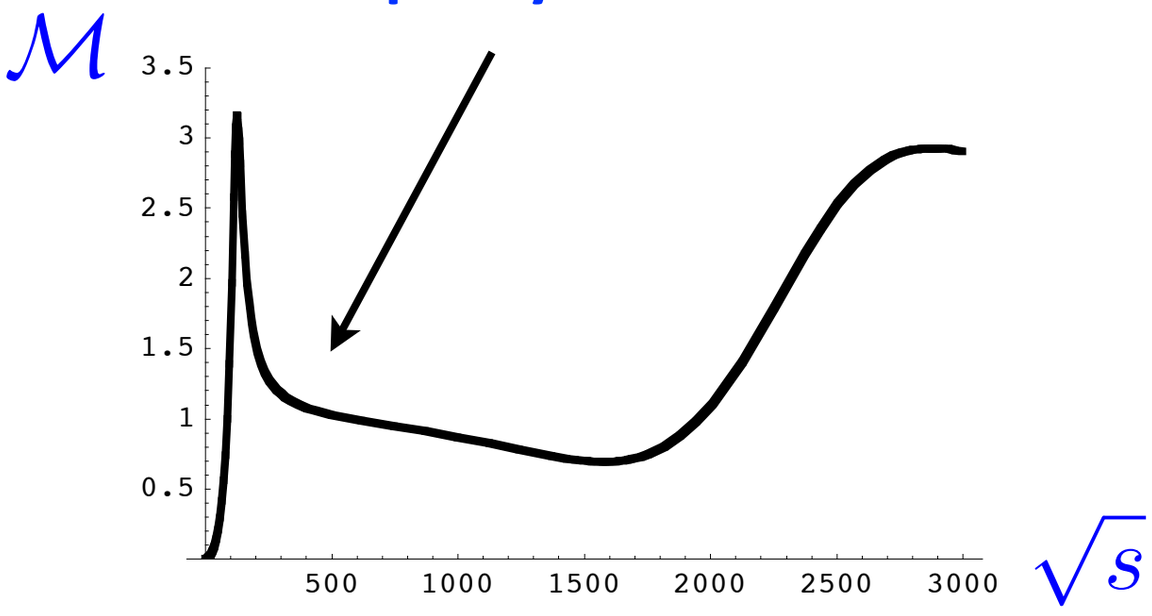
➥ **A kind of (mild) impostor**

Being **Composite,** the Higgs couplings are different from the SM values

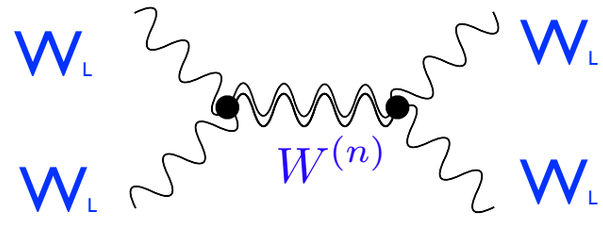



different
from the SM Higgs

**partly unitarize!**




The rest of the **strong sector** (states of spin=0,1,2,3,...) takes care of the **fully** unitarization:



# What Data tells us?

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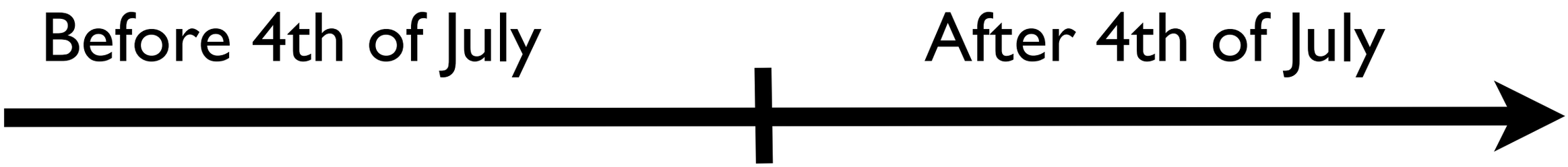
In the new calendar for EWSB practitioners:

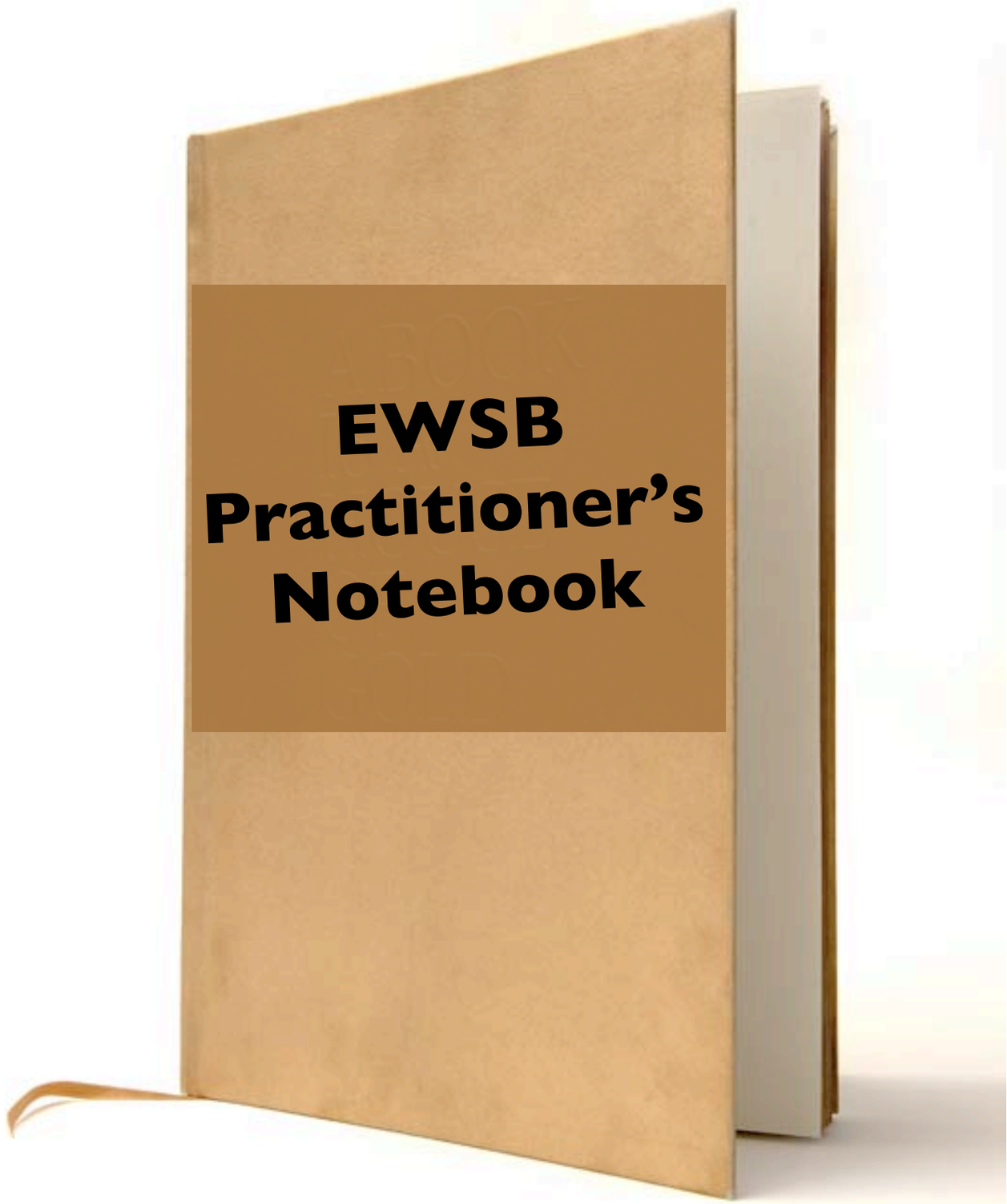



**4th of July**

Higgs-like state

“is born”

# Before the 4th of July 2012



# T-parameter

A measure of deviations on $M_W^2 - M_Z^2 \cos^2\theta_W$

Exp (LEP+Tevatron):

< 0.3 %

A custodial symmetry is needed:

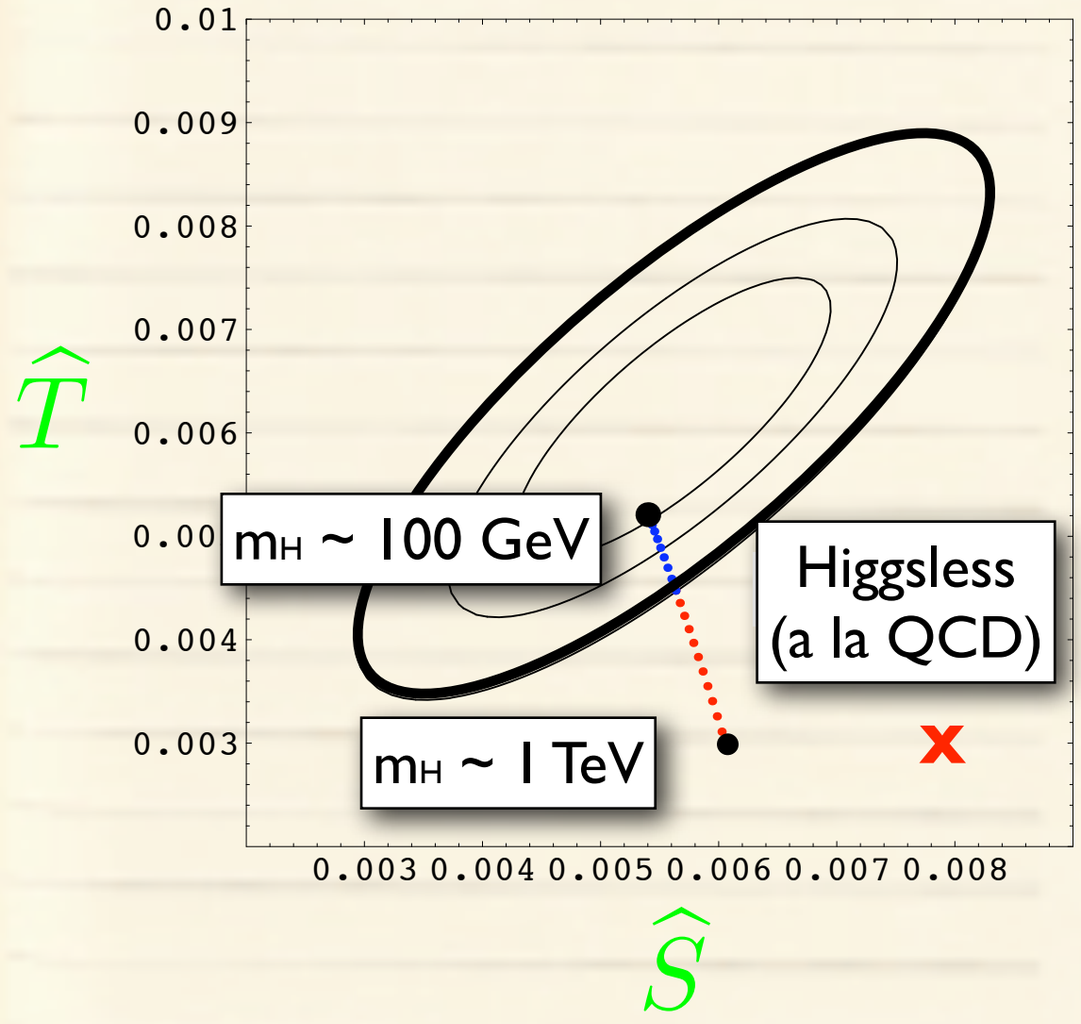
Higgs doublet, Yes

Higgs triplet, No

...

# S-parameter

A measure of the Zγ-kinetic mixing

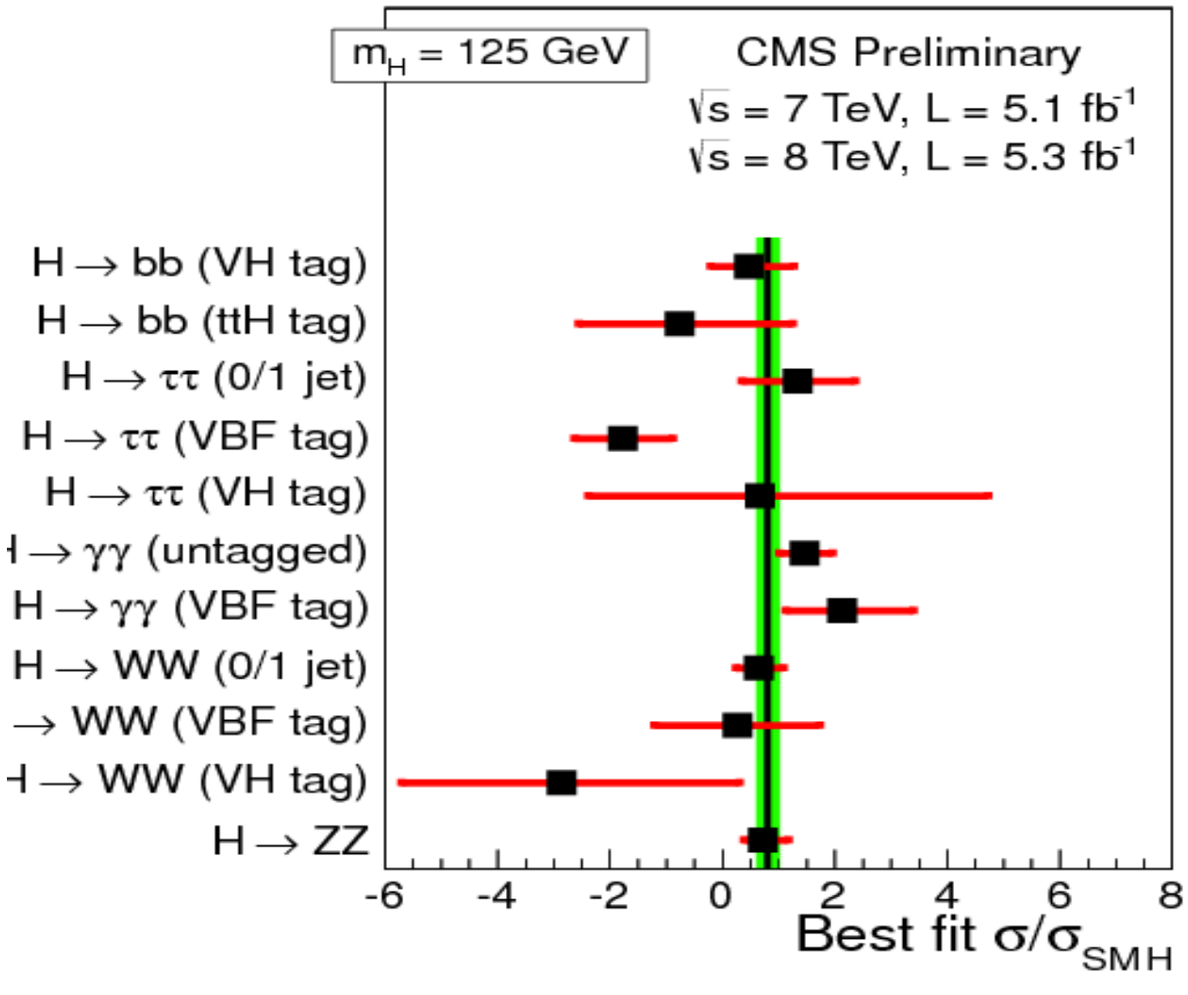


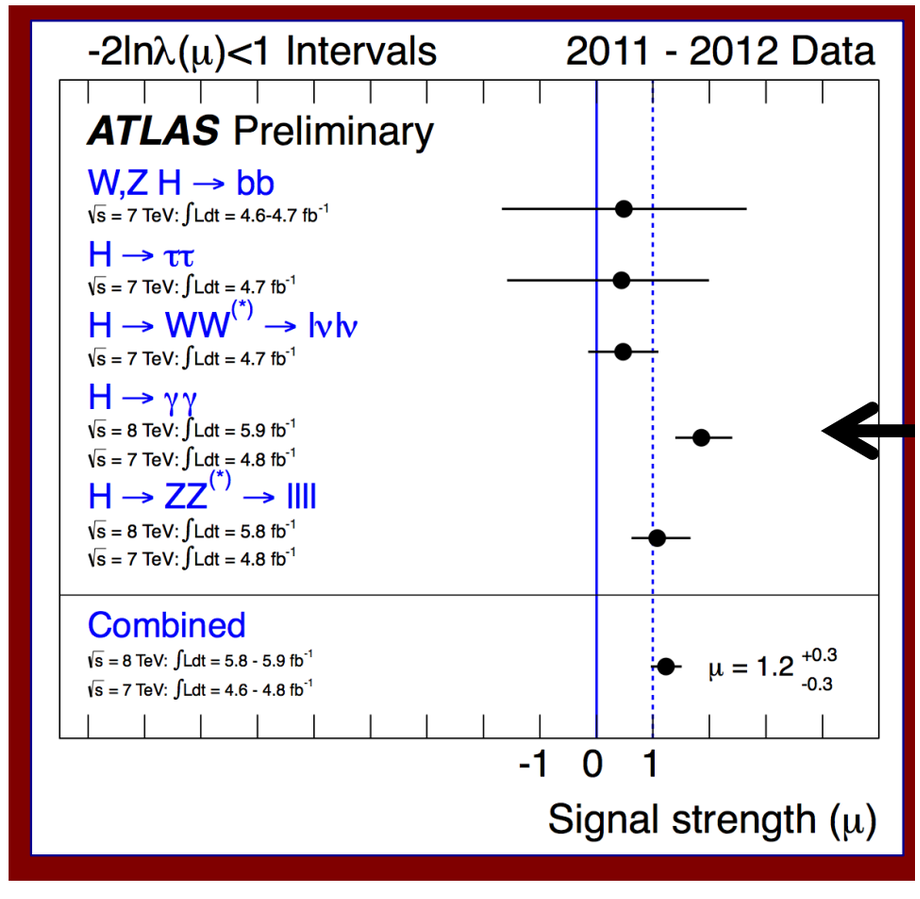

☛Light Higgs preferred

# After the 4th of July 2012

# After the 4th of July 2012

We have a Higgs-like state:



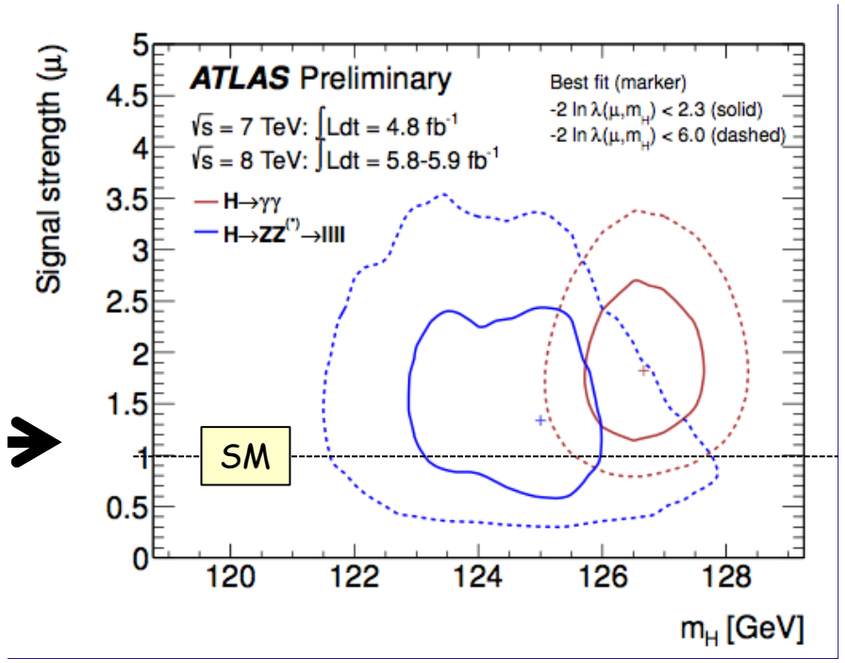




$\mathbf{m_H = 126.5\ GeV}$

# What the Higgs mass

$$m_H \approx 125\ \mathrm{GeV}$$

# tells us?



# What the Higgs mass

$$\mathbf{m_H \approx 125\ GeV}$$

# tells us?

( Light state: $\mathbf{m_H^2 = \lambda v^2}$

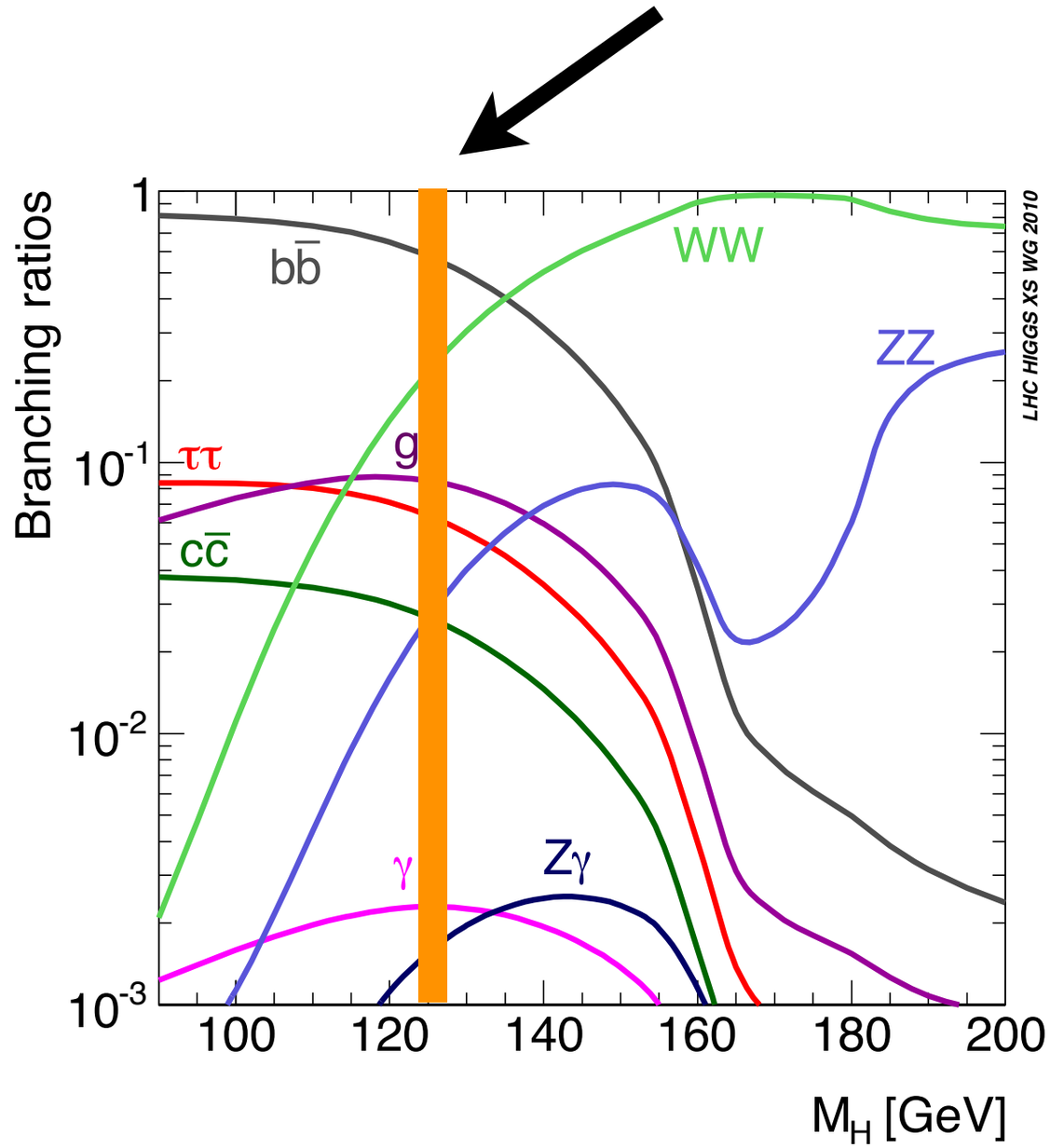
$\sim$ 0.26 (perturbative coupling)

Origin of the self-interaction → weakly-coupled theory )

# Excellent for experimentalists:

Fabiola Gianotti: "***Nature has been kind to us...***"

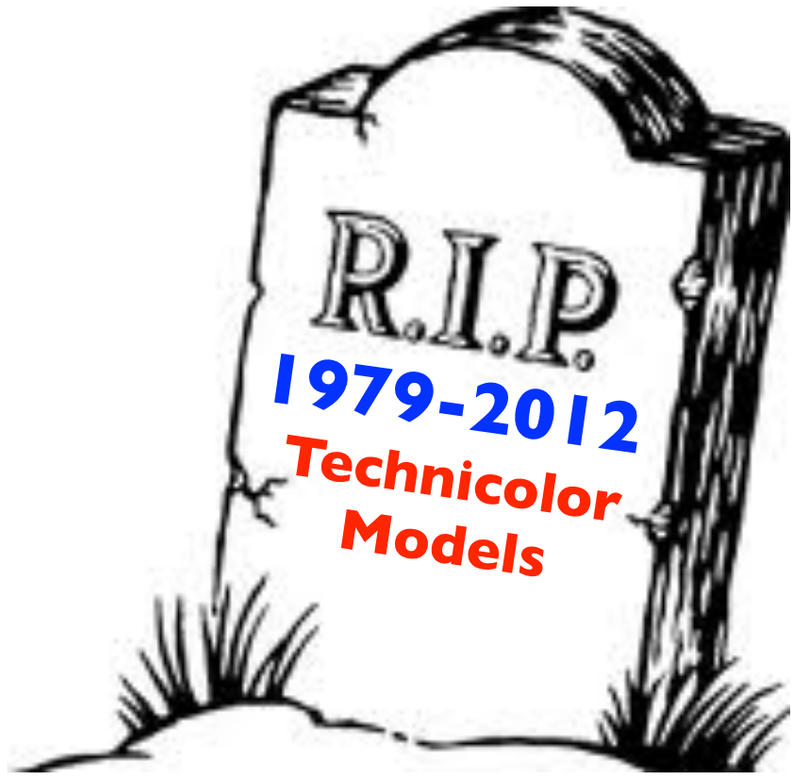
Most of decay modes visible: $\mathbf{m_H \approx 125\ GeV}$



# But not so excellent for all theorists:

## But not so excellent for all theorists:

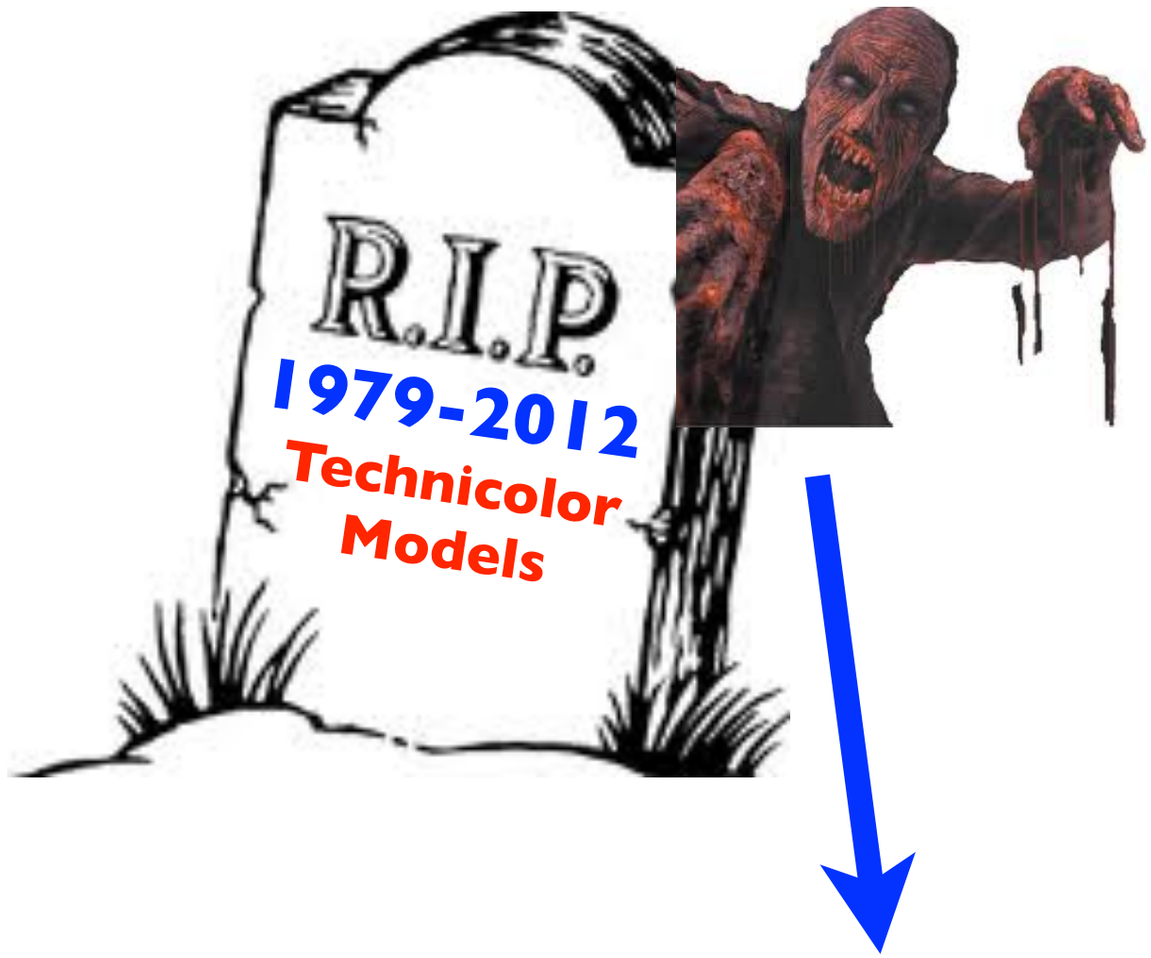
Specially for fans of **Higgsless models:**



# but be careful about resurrections...

## but be careful about resurrections...

It is *not unconceivable* that a light dilaton appears in Higgsless theories




**Dilaton**

(Goldstone of the spontaneous breaking of scale invariance)

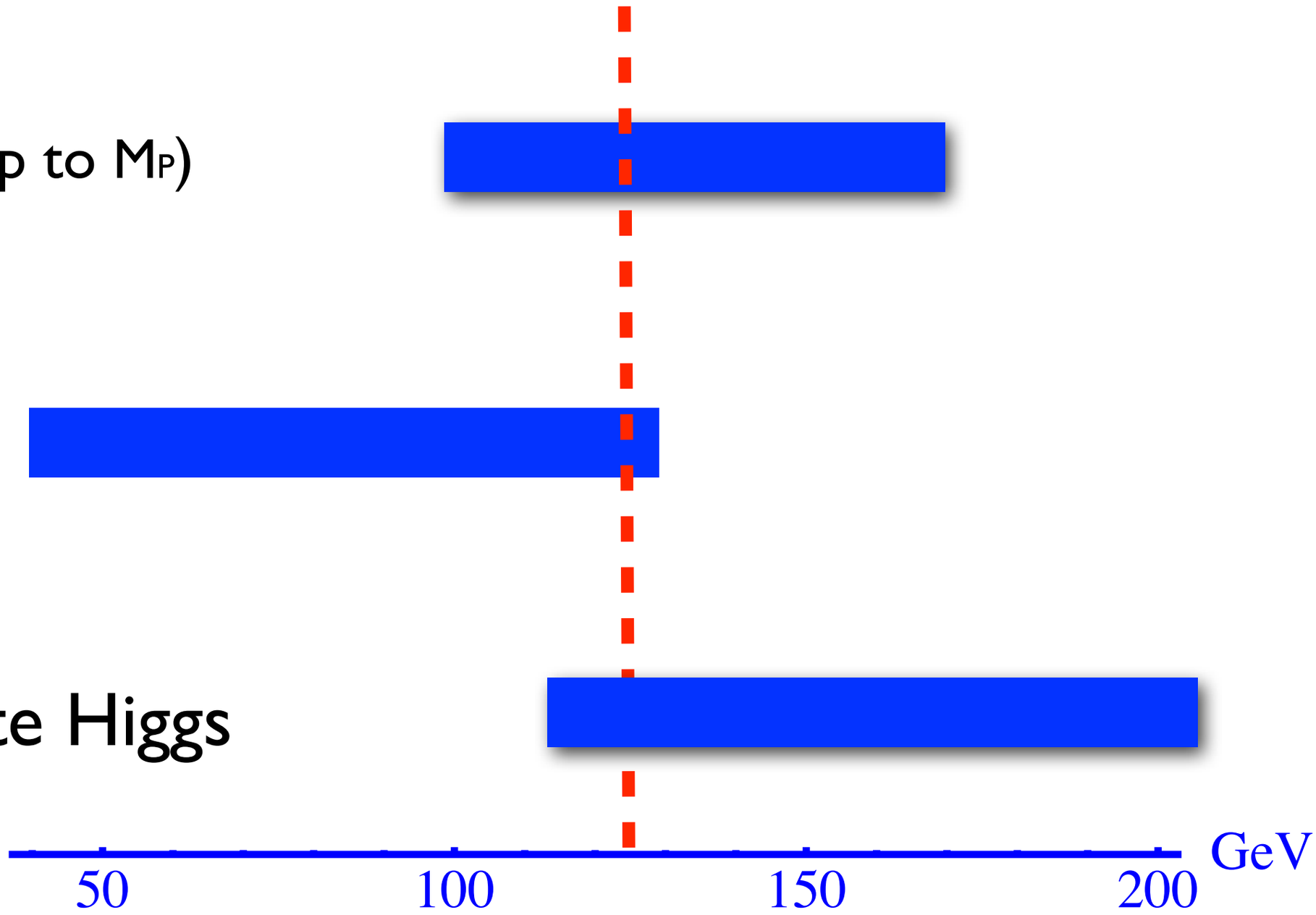
Couples as a Higgs up to an overall scale → **A Higgs impostor**

# Higgs mass range

SM (valid up to $M_P$)

MSSM

Composite Higgs

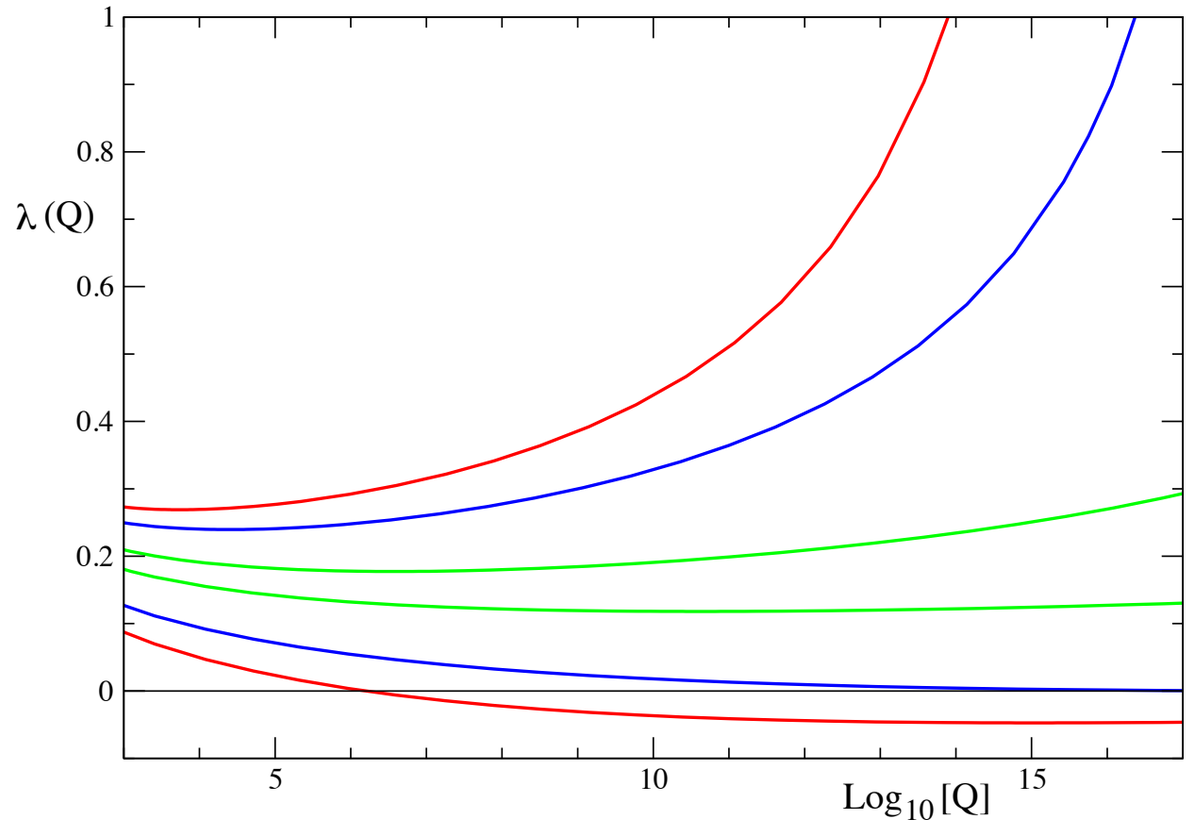


# 125 GeV SM Higgs

# In the SM:

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

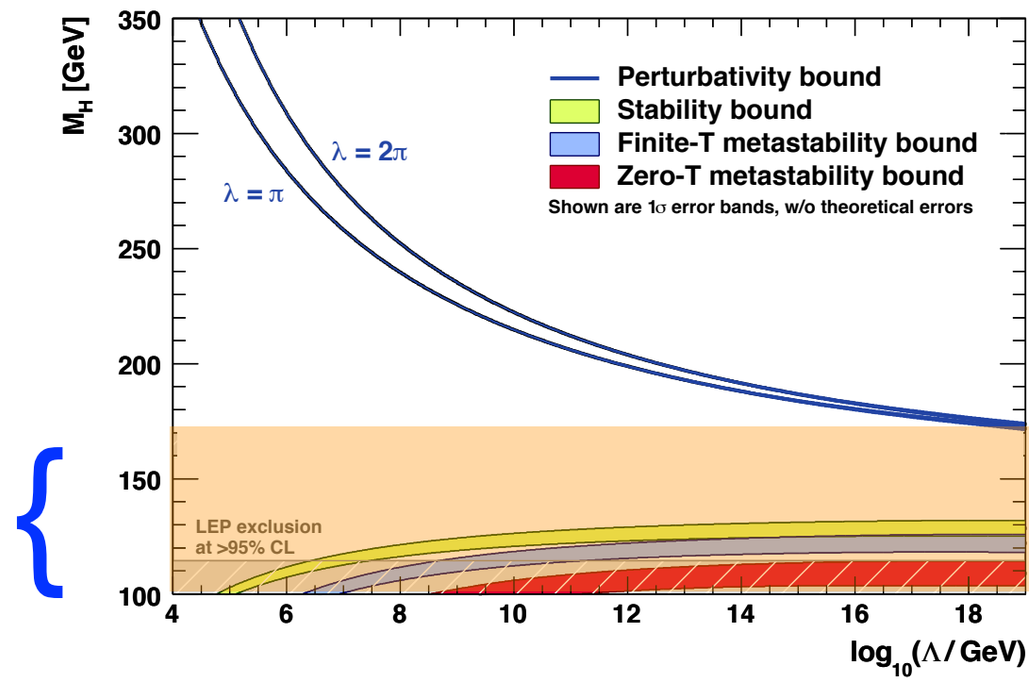
Evolves with the energy




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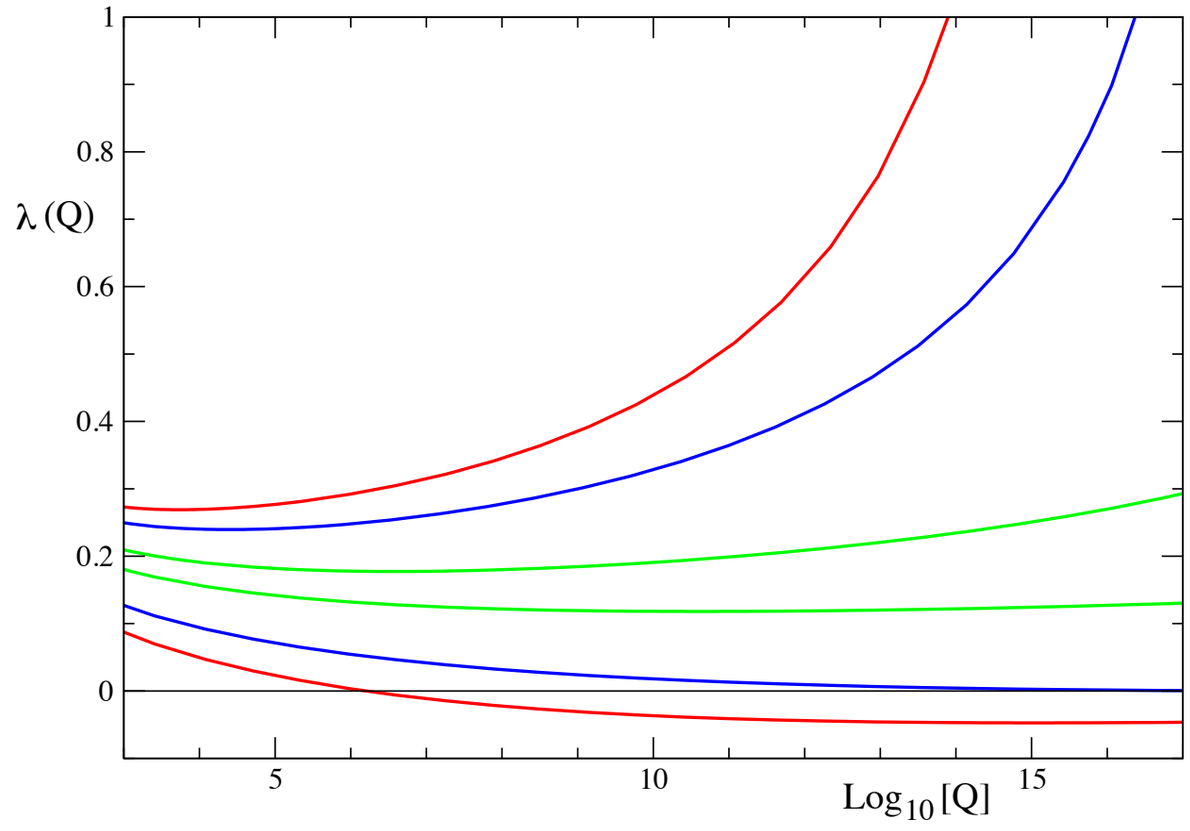
$$m_H^2 = \lambda v^2$$

Evolves with the energy

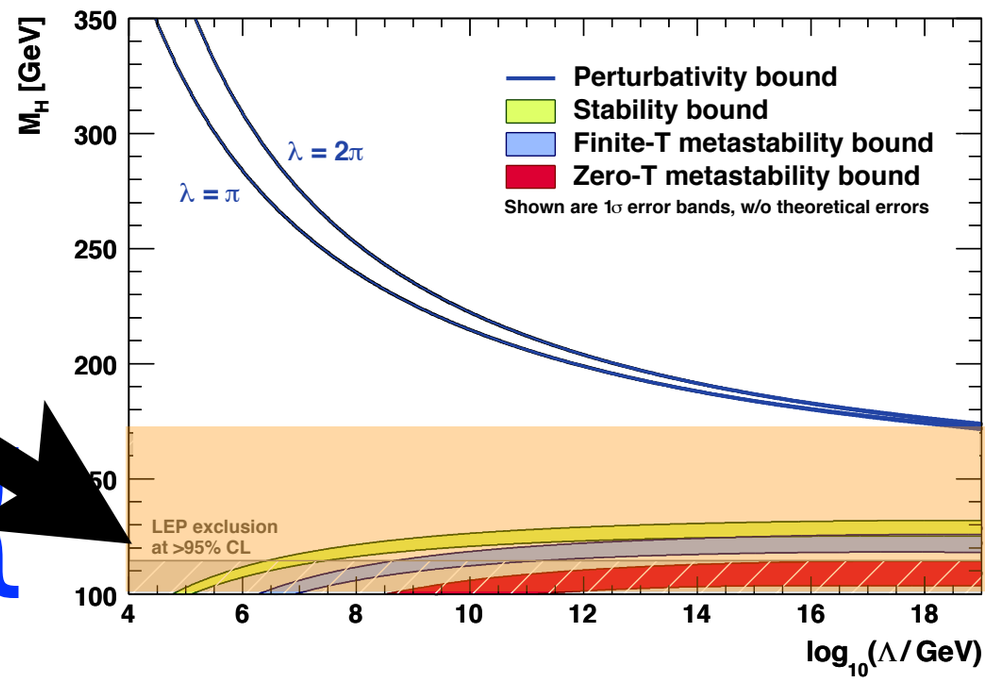



Demanding λ not too large (keep perturbativity),
not too negative that destabilizes the Higgs potential

from Phys.Lett. B679 (2009) 369

**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:

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

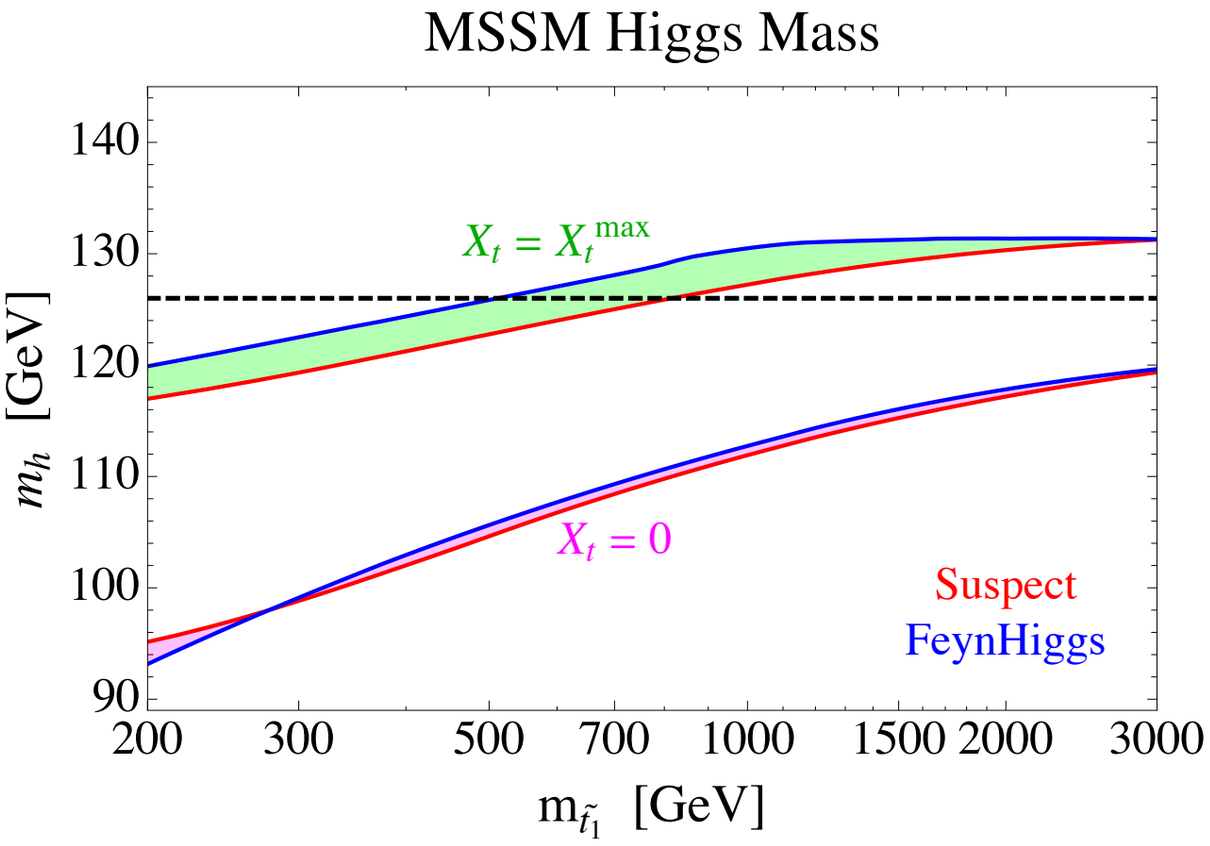
➥ susy breaking term (at one-loop)

$\mathbf{(125\ GeV)^2}$ $\mathbf{(91\ GeV)^2}$ $\mathbf{(86\ GeV)^2}$

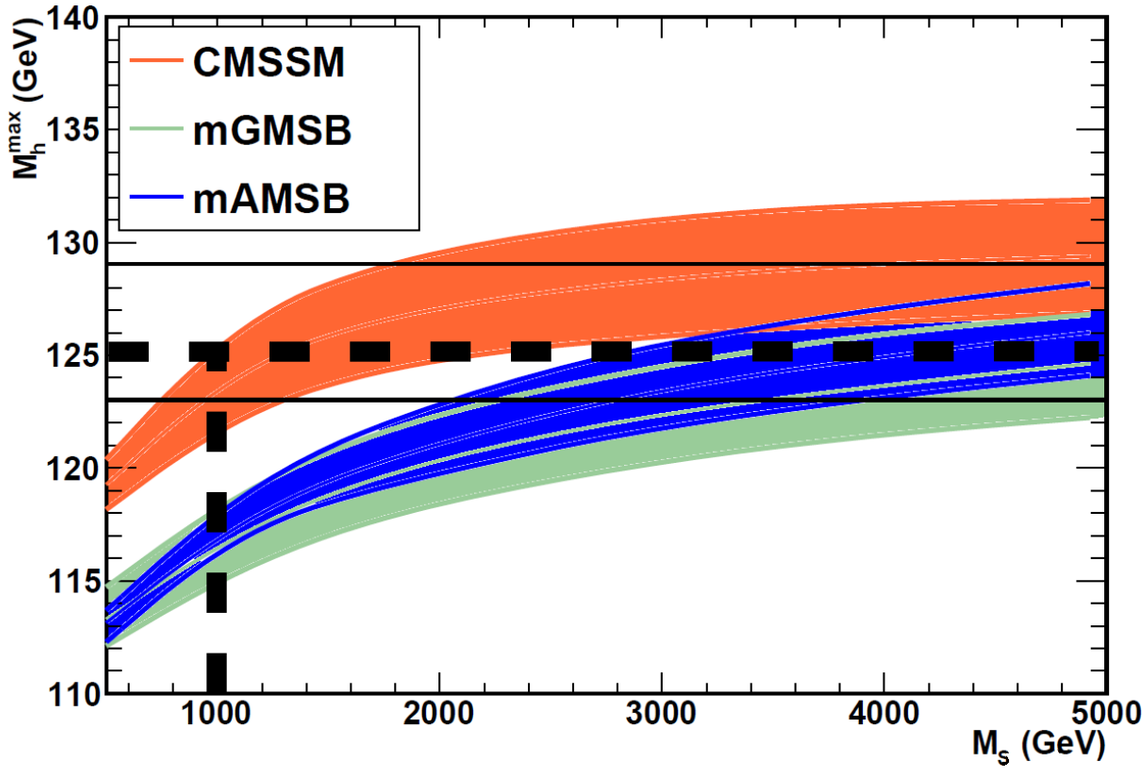
both have similar size:
Susy must be "badly" broken!

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

➥**The MSSM is becoming unnatural**

(>99% parameter space excluded)

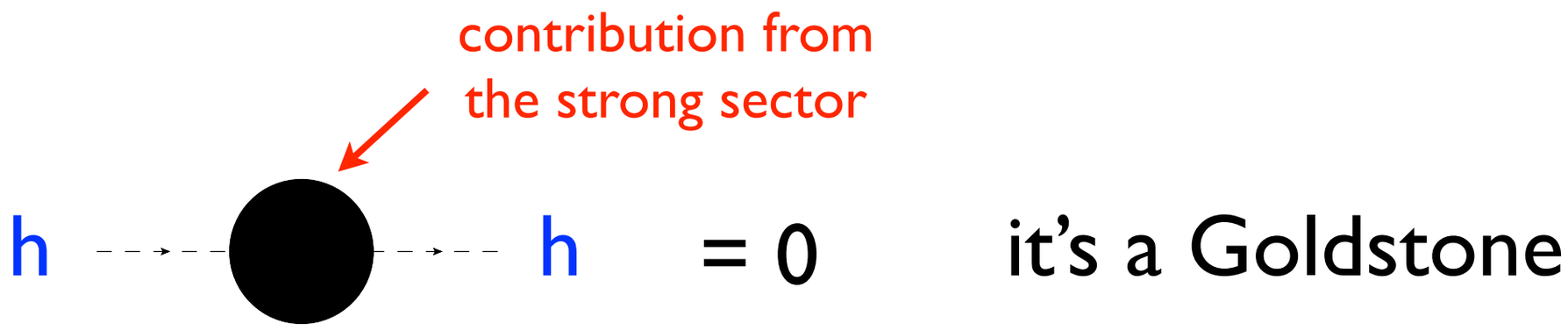
**Directions to go** (see Sundrum's Talk):

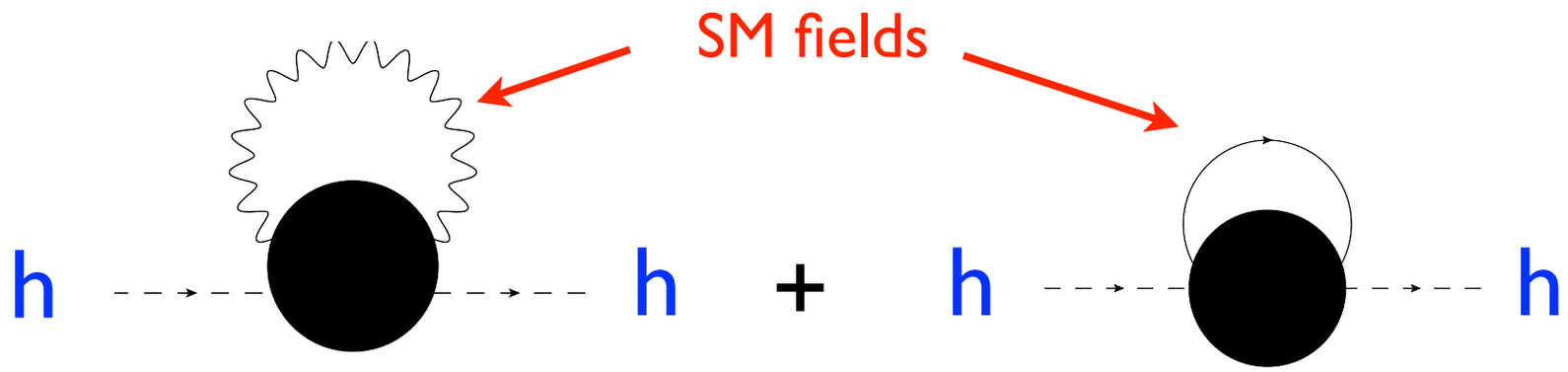
**Beyond the MSSM:**

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

# 125 GeV Composite PGB Higgs

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




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

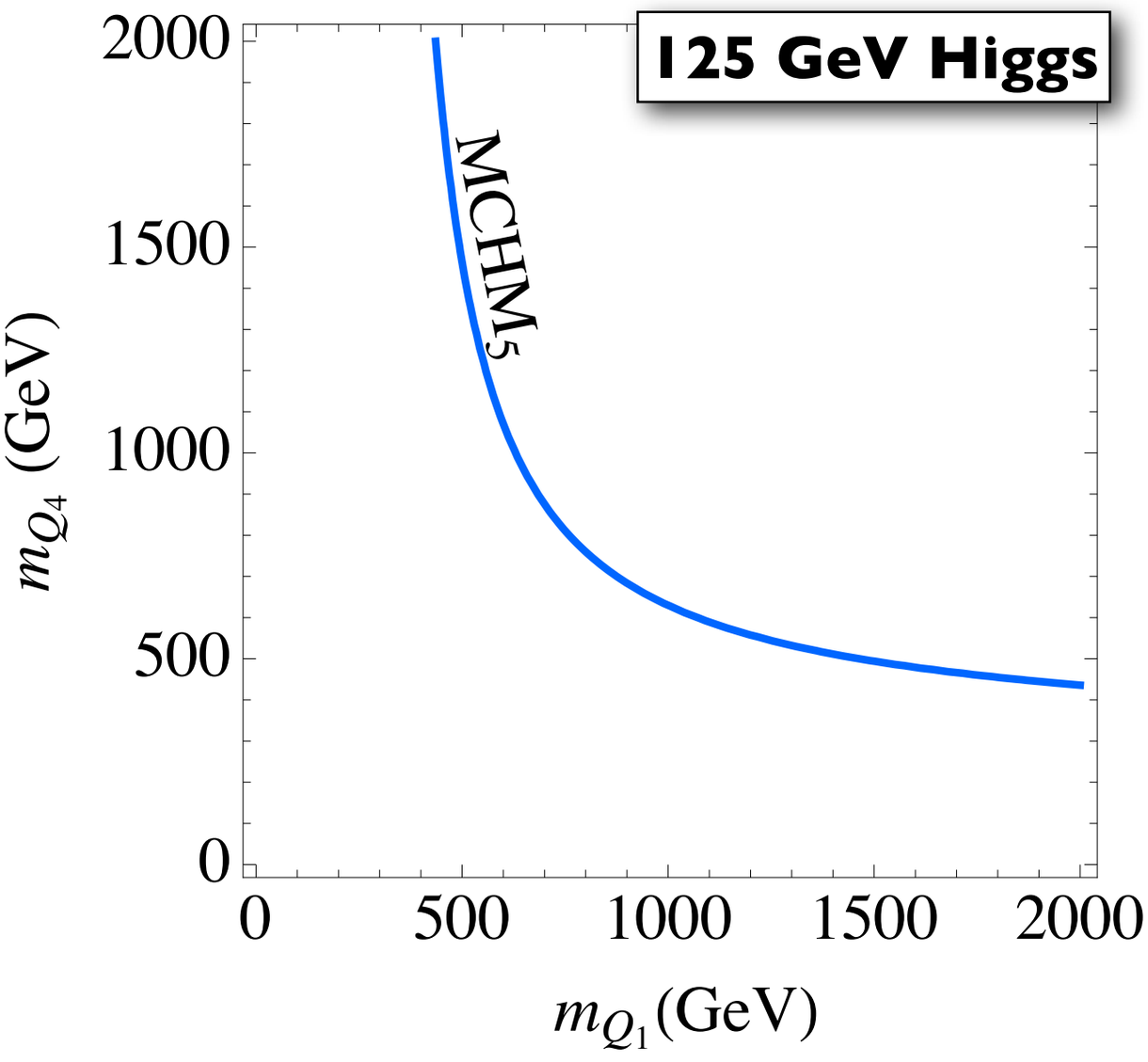
Difficult to get predictions due to the intractable **strong** dynamics**!**

Using similar techniques as in the 60s (Das at al 67)
to calculate the charged pion mass, one obtains (in the minimal model):

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

arXiv:1205.0770
arXiv:1205.6434
see also
arXiv:1204.6333
arXiv:1205.0232

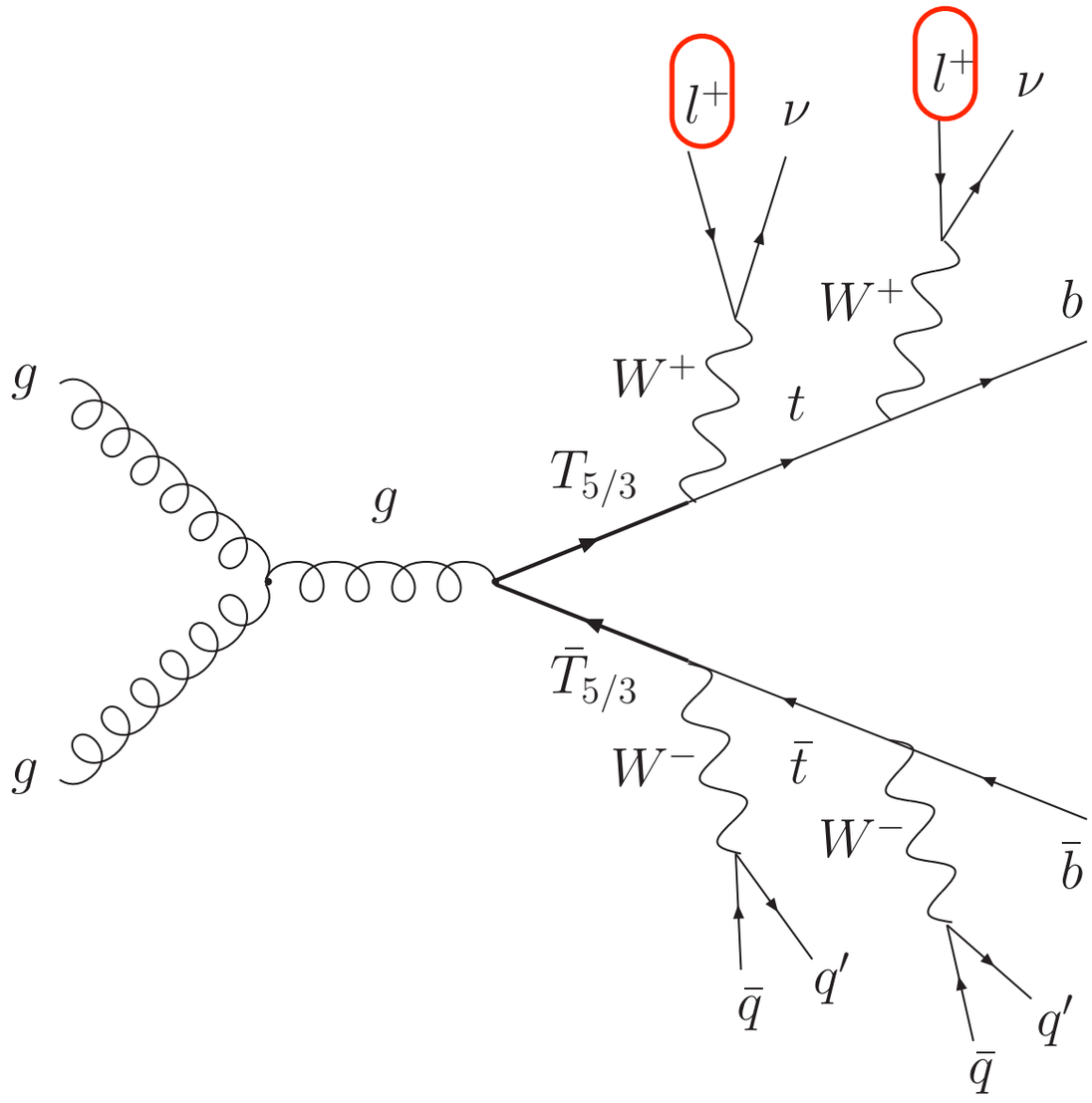
mass of color vector-like fermions
with EM charges 5/3,2/3,-1/3




Fermion resonances
around 500-700 GeV

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

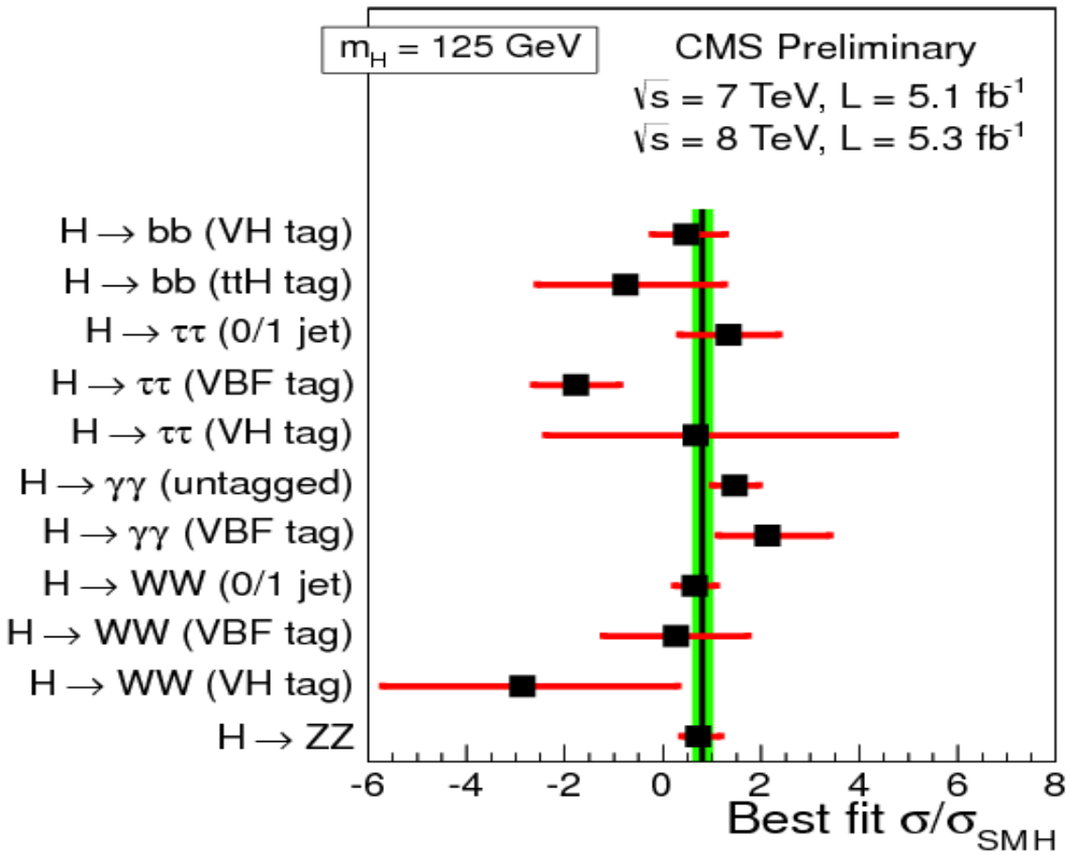
If this fermion is light, it can be double produced:

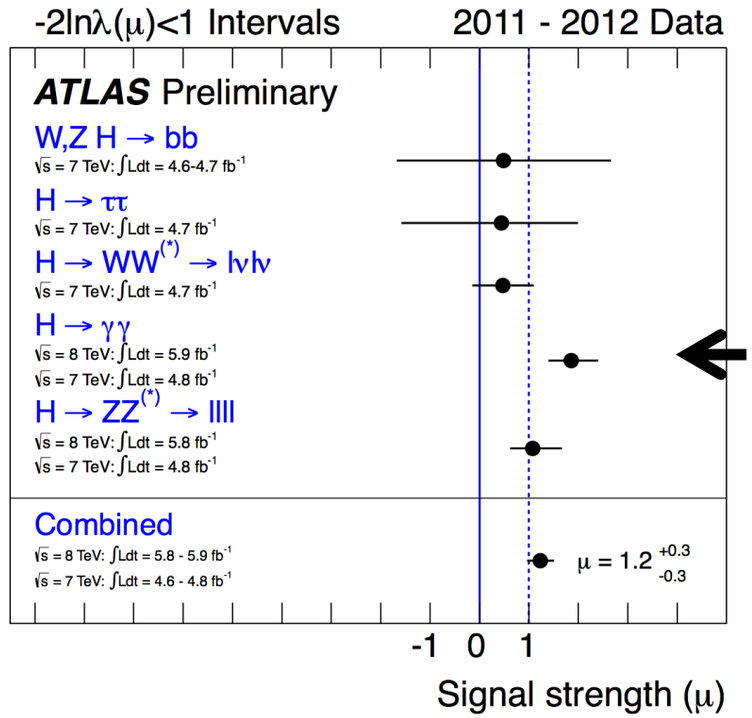



same-sign di-leptons

from JHEP 0806 (2008) 026

# What the Higgs couplings tells us?

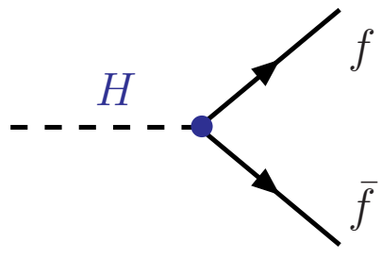



**Not significant deviations from a SM Higgs**

(The **more** natural the Higgs sector is,
the **more** we expect
deviations from the SM Higgs couplings)

# Main pieces of information to be extracted from data:

1) 

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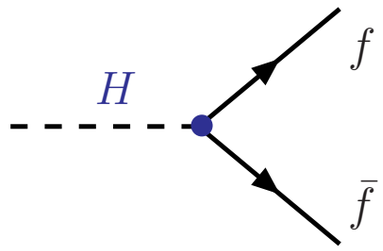
2) 

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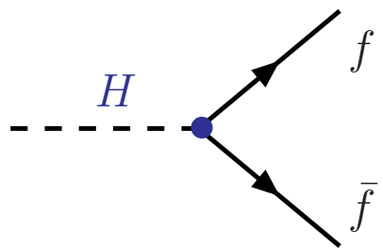
3) 

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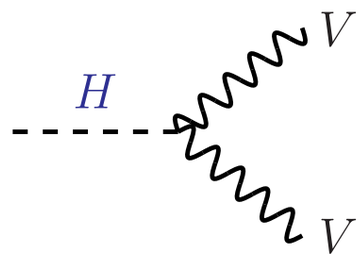
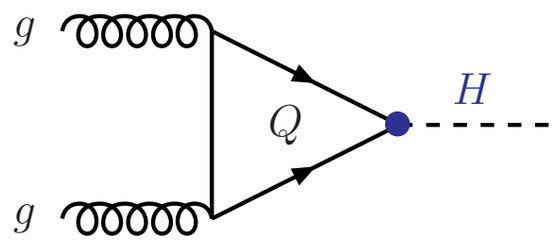
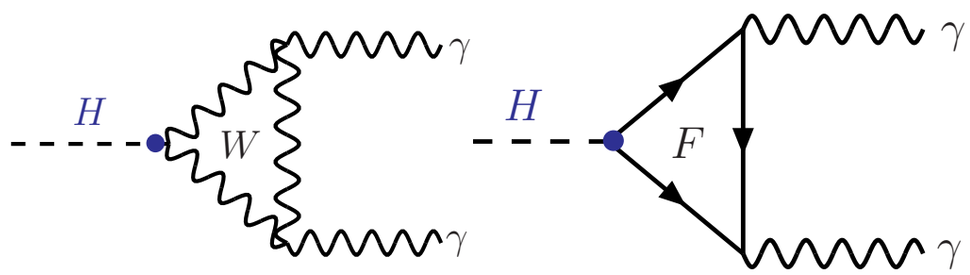
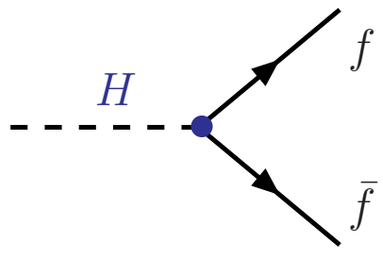
4) 


5) 


6) 

# Main pieces of information to be extracted from data:

at present
only indirectly from

1) 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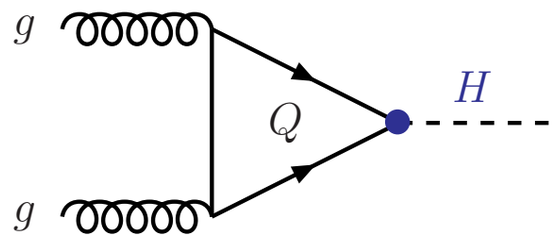
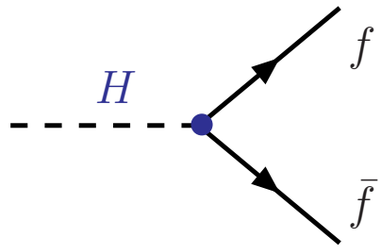
5) 


2) 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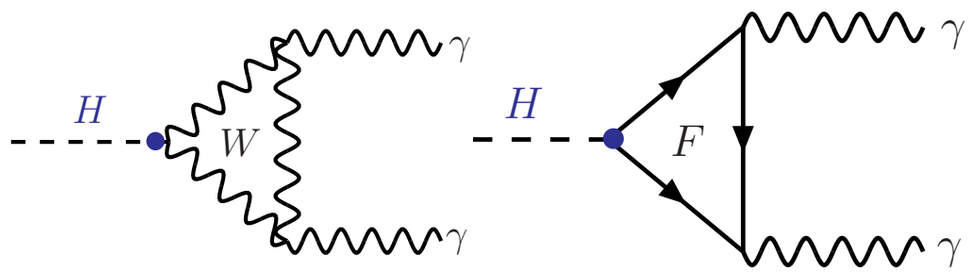
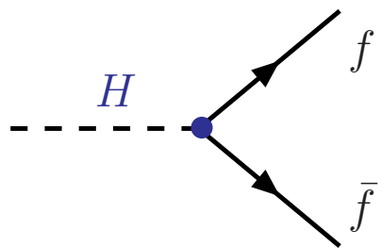
6) 


3) 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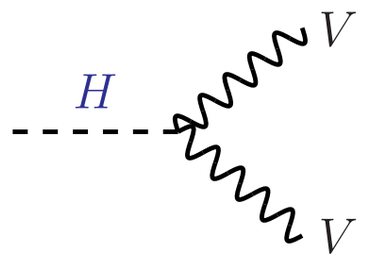
4) 

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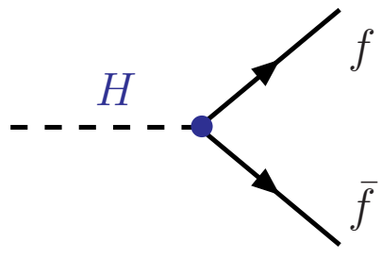
1) 

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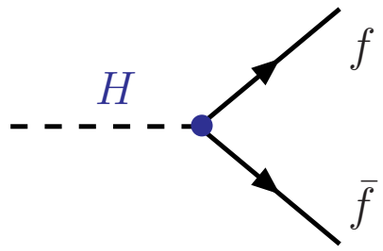
2) 

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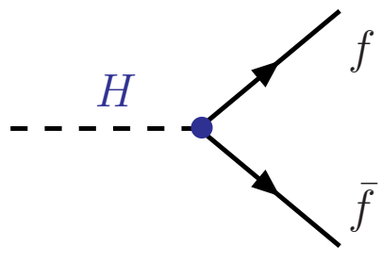
3) 

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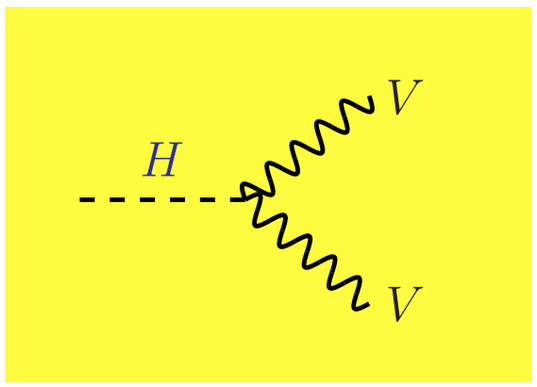
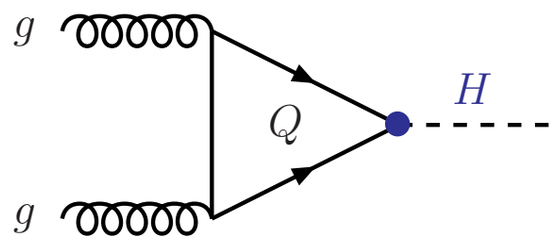
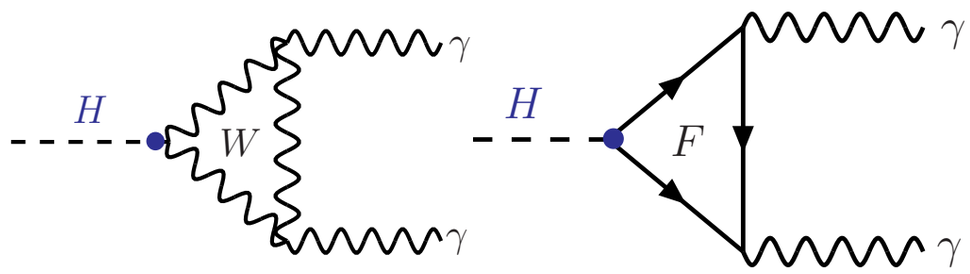
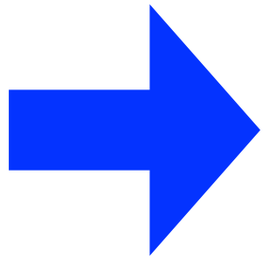
4) 

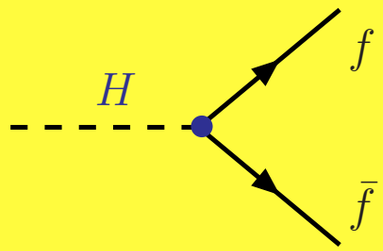

5) 


6) 

Most genuine Higgs coupling
(determines its role in EWSB)

# Main pieces of information to be extracted from data:

1) 

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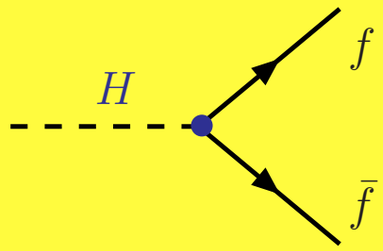
2) 

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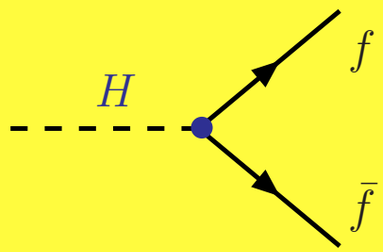
3) 

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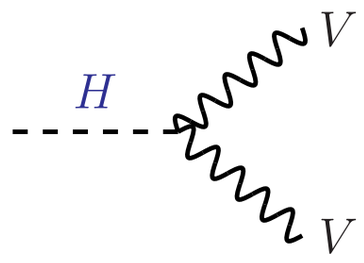
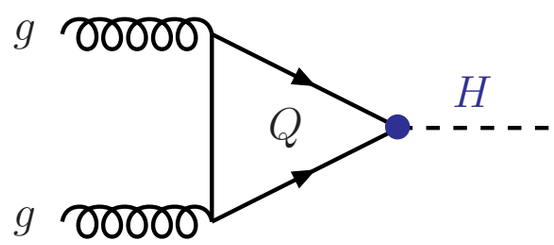
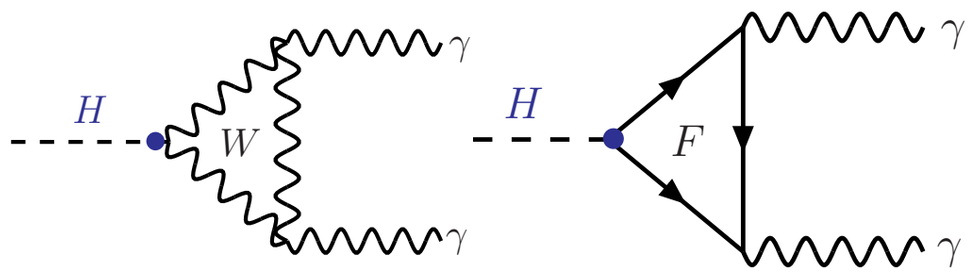
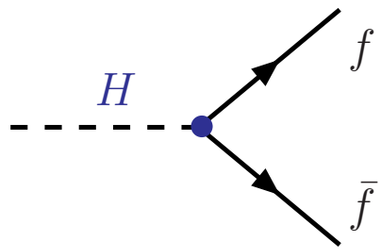
4) 


5) 


6) 


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

# Main pieces of information to be extracted from data:

1) 

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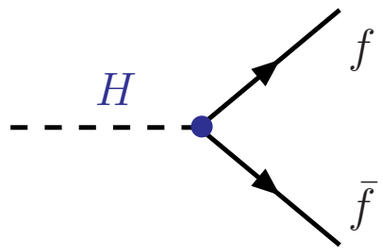
2) 

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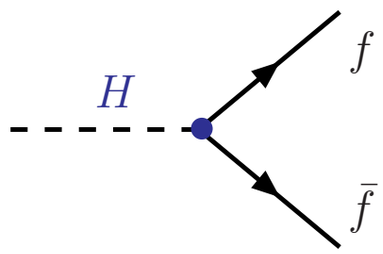
3) 

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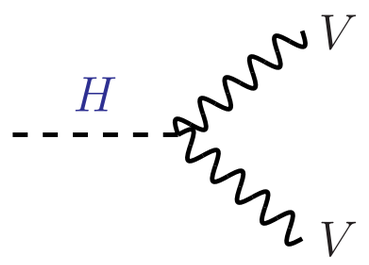
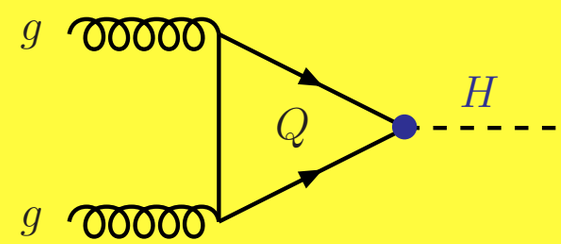
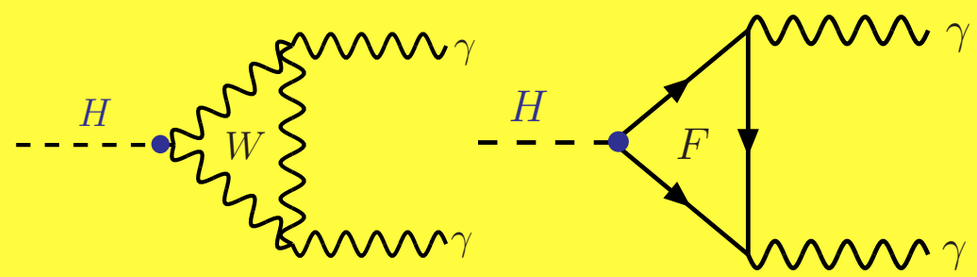
4) 

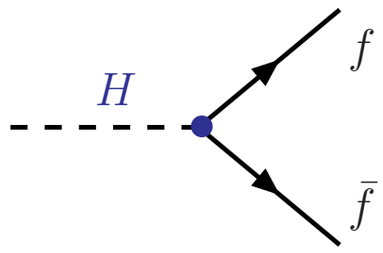

5) 


6) 


Sensitive to new states

(not necessary related with EWSB)

# Main pieces of information to be extracted from data:

1) 

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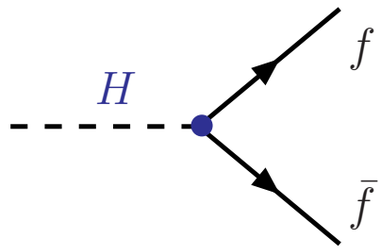
2) 

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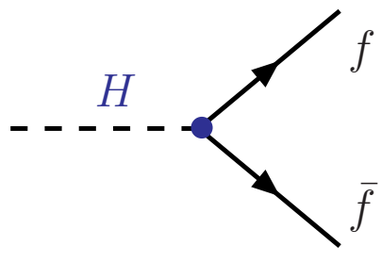
3) 

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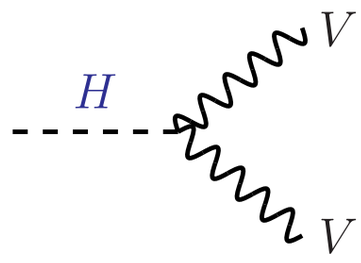
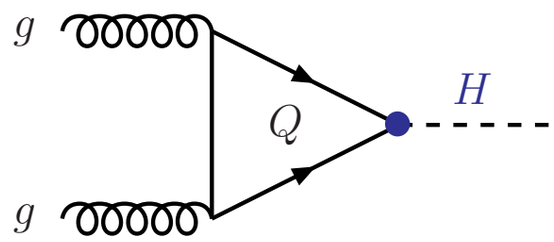
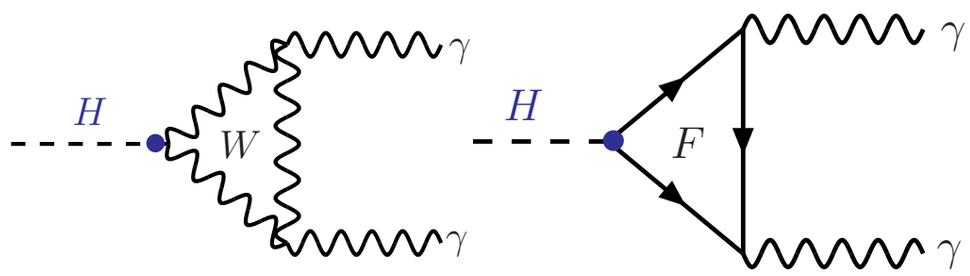
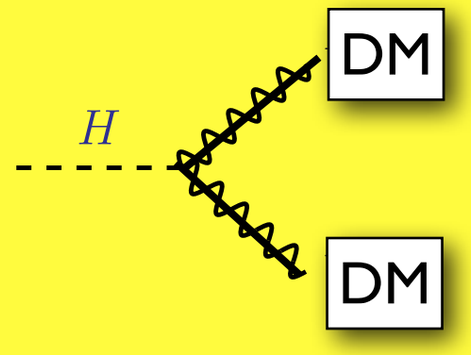
4) 


5) 


6) 


## Also indirectly:

7) 

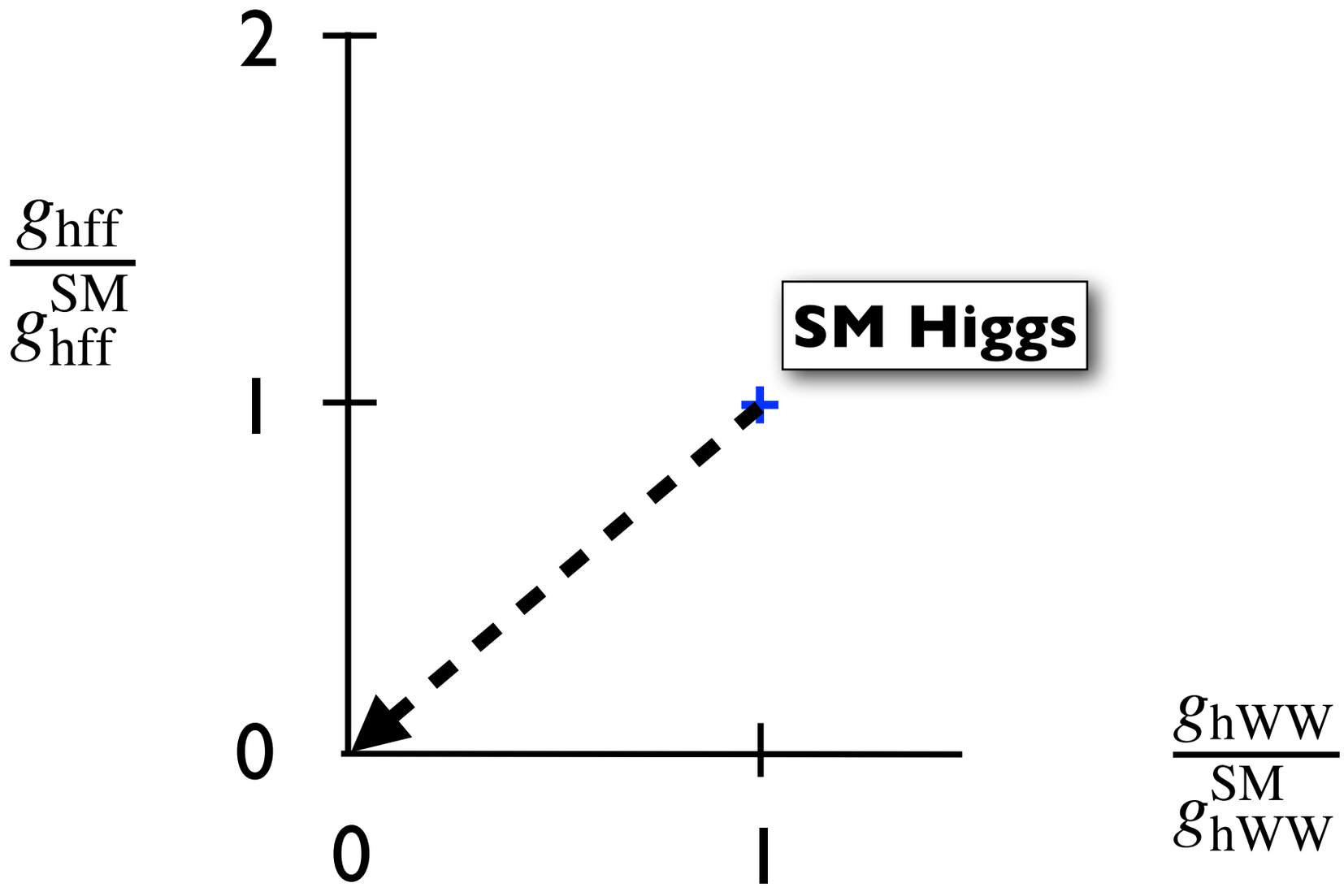
$\Gamma_{\text{inv}}$

Depending on the type of Higgs (or impostor)
different predictions in this 7 dimensional parameter space

Depending on the type of Higgs (or impostor)
different predictions in this 7 dimensional parameter space

**Few very simple examples:**

1) Higgs mixes with some other (inert) scalar:



Depending on the type of Higgs (or impostor)
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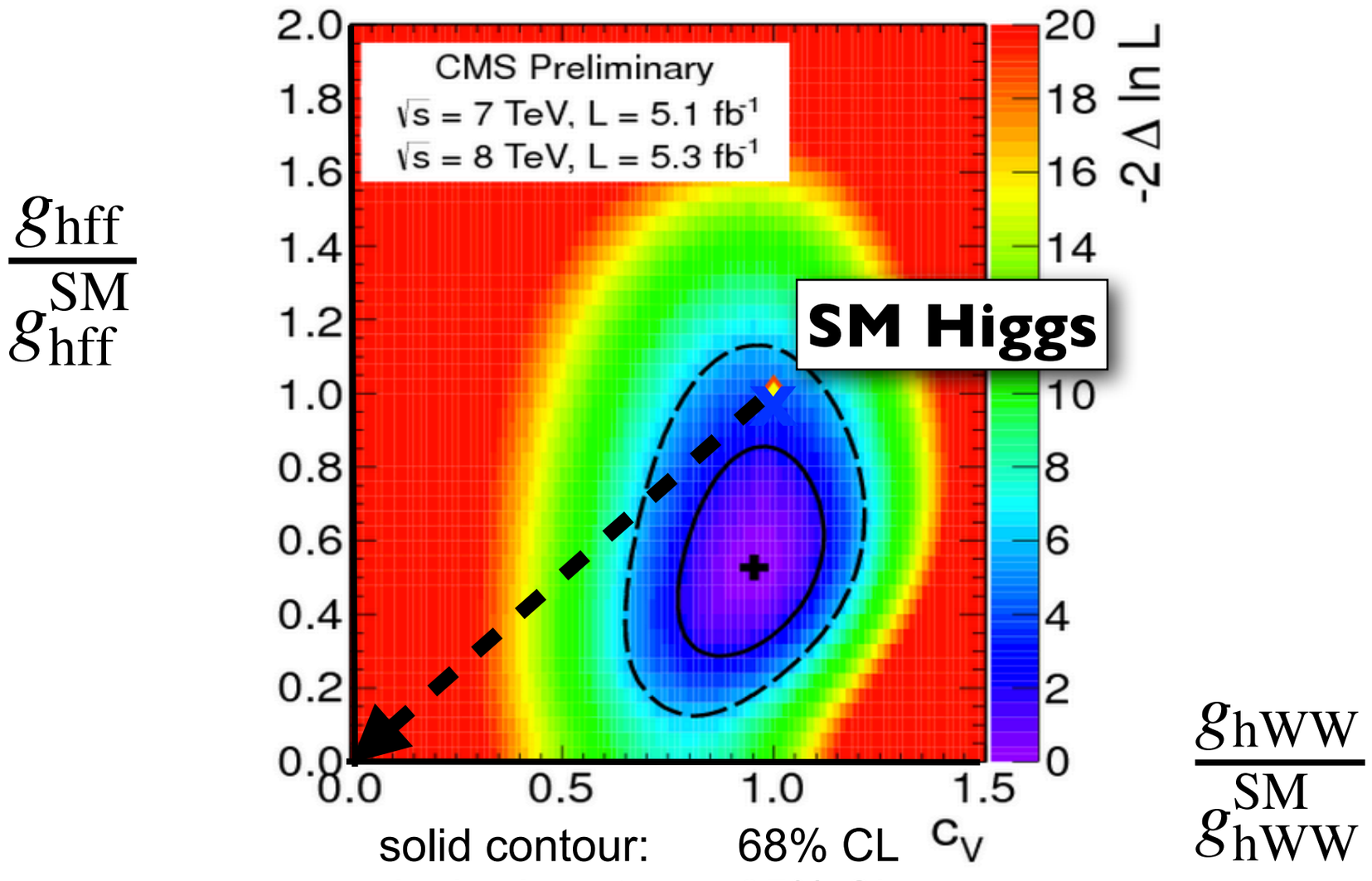
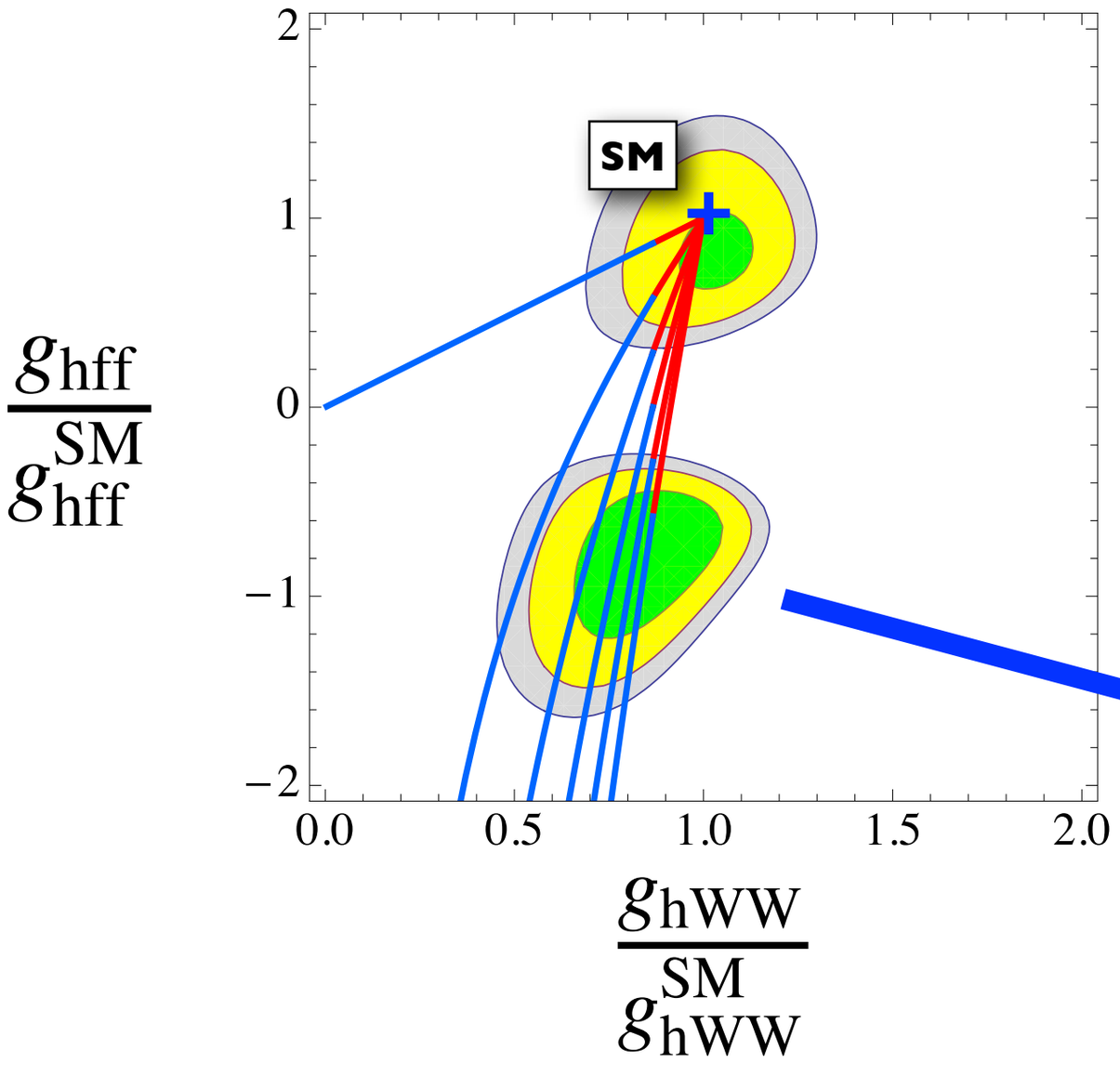


Depending on the type of Higgs (or impostor) different predictions in this 7 dimensional parameter space

# Few very simple examples:

## 2) Composite Higgs:




Montull,Riva (preliminary) using:

(previous studies: JHEP 1204 (2012) 127 JHEP 1205 (2012) 097)

| CMS | Cuts | $\hat{\mu}^7$ | $\hat{\mu}^8$ |
|---|---|---|---|
| $\gamma\gamma_0$ | I | $2.1^{+2.0}_{-1.6}$ | $1.5^{+1.3}_{-1.3}$ |
| $\gamma\gamma_1$ | I | $0.6^{+1.0}_{-0.9}$ | $1.5^{+1.1}_{-1.1}$ |
| $\gamma\gamma_2$ | I | $2.2^{+1.5}_{-1.4}$ | $1.0^{+1.2}_{-1.2}$ |
| $\gamma\gamma_3$ | I | $0.6^{+1.8}_{-1.7}$ | $3.8^{+1.8}_{-1.8}$ |
| $\gamma\gamma_{jj}$ | $\text{VBF}_{3.3\%G}$ | $3.6^{+2.2}_{-1.6}$ | - |
| $\tau\tau$ | I | $0.6^{+1.1}_{-1.3}$ | - |
| $bb$ | A | $1.2^{+2.1}_{-1.9}$ | - |
| $WW_{0j}$ | G | $0.1^{+0.6}_{-0.6}$ | $1.3^{+0.8}_{-0.6}$ |
| $WW_{1j}$ | G | $1.7^{+1.2}_{-1.0}$ | $0.0^{+0.8}_{-0.8}$ |
| $WW_{2j}$ | VBF | $0.0^{+1.3}_{-1.3}$ | $1.3^{+1.7}_{-1.3}$ |
| $ZZ$ | I | $0.6^{+1.0}_{-0.6}$ | - |

| ATLAS | Cuts | $\hat{\mu}^7$ | $\hat{\mu}^8$ |
|---|---|---|---|
| $\gamma\gamma$ | I | $1.6^{+0.8}_{-0.7}$ | - |
| $\tau\tau$ | I | $0.2^{+1.7}_{-1.8}$ | - |
| $bb$ | A | $0.5^{+2.1}_{-2.0}$ | - |
| $WW$ | I | $0.6^{+0.7}_{-0.7}$ | - |
| $ZZ$ | I | $1.4^{+1.3}_{-0.8}$ | - |

| CDF & D0 | Cuts | $\hat{\mu}^{1.96}$ | - |
|---|---|---|---|
| $\gamma\gamma$ | I | $3.6^{+3.0}_{-2.5}$ | - |
| $bb$ | A | $2.0^{+0.7}_{-0.6}$ | - |
| $WW$ | I | $0.3^{+1.2}_{-0.3}$ | - |

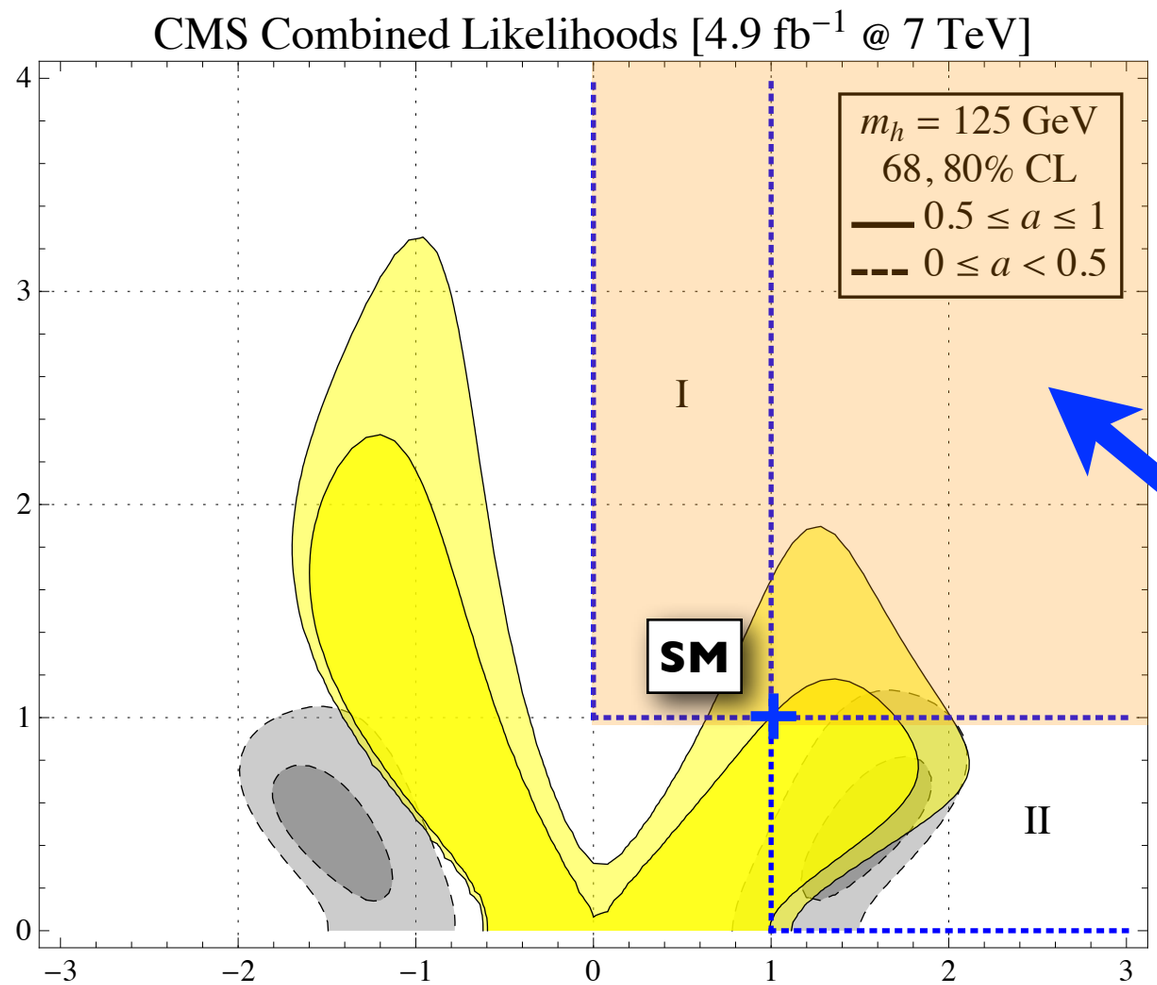
Allowed area where constructive interference between top and W loops enhancing the $\gamma\gamma$ channel

Depending on the type of Higgs (or impostor)
different predictions in this 7 dimensional parameter space

**Few very simple examples:**

## 3) MSSM Higgs with heavy spectrum:

arXiv:1206.1058
(2011 data)



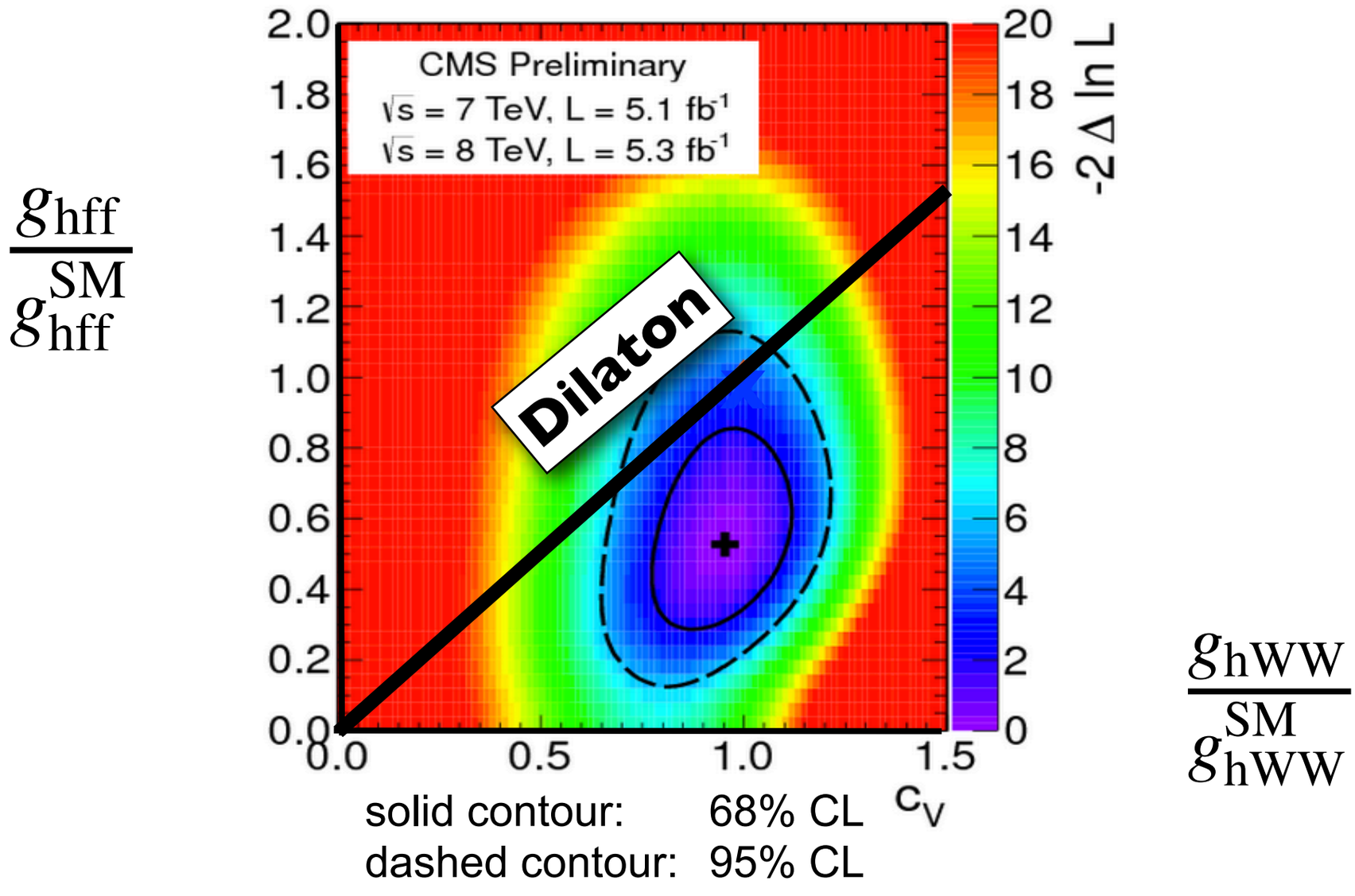

$$a \equiv \frac{g_{hWW}}{g_{hWW}^{SM}}$$

MSSM
with tanβ>1

Depending on the type of Higgs (or impostor)
different predictions in this 7 dimensional parameter space

**Few very simple examples:**

4) Dilaton (that couples as the SM Higgs up to an overall factor)



# Conclusions

**Data is finally here to learn about EWSB**

**A lot of questions to address:**

- Is it the SM Higgs?
- Are there indications for compositeness?
- Are there indications for mixing with other Higgs (sharing the role of EWSB)?
- Is it an impostor?
- Does it decay invisibly?
- ....

**A new era has begun ...**

# Thank you !

"Sit down before fact as a little child,
be prepared to give up every preconceived notion,
follow humbly wherever and to whatever abysses nature leads,
or you shall learn nothing"

**Thomas Henry Huxley**