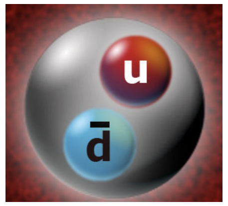
Composite Higgs

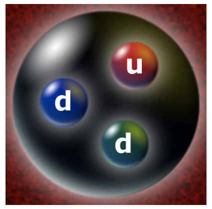
Pseudo Goldstone Boson (PGB)

Inspired by QCD where we see **light scalars** without problems of naturalness:

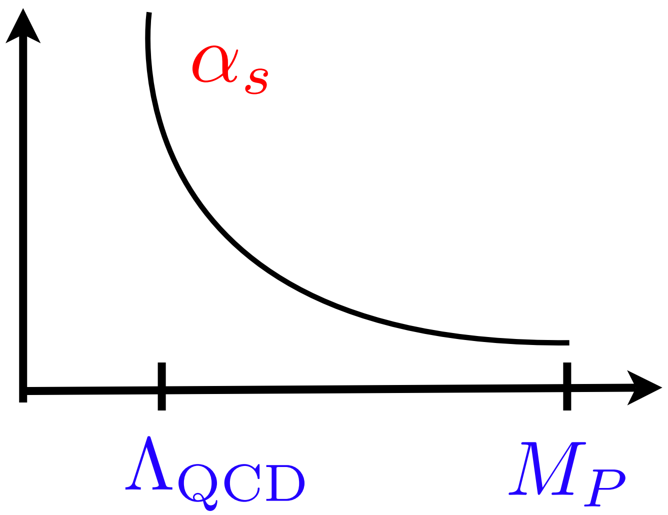
$$m_\pi,\ m_K,\ m_{a_0}, ... << M_P$$

Reason: they are composite states at $\Lambda_{\rm QCD} << M_P$,





defined by the scale at which the strong gauge-coupling becomes large:

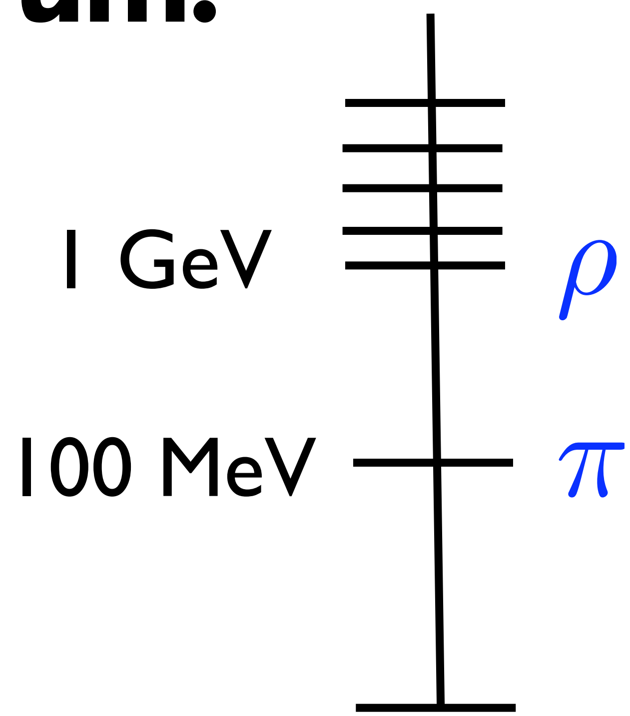


Furthermore,

the lightest states in QCD are the (pseudo) scalars:

(spin=0 particles like the Higgs)

QCD Spectrum:



Why the lightest?

Because they are
Pseudo-Goldstone bosons (PGB)

Pseudo-Goldstone bosons (PGB) in QCD

QCD, considering only two quarks in the massless limit,

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

has an accidental global symmetry:

$$SU(2)_L \times SU(2)_R$$

It is broken by the quark condensate: $\langle q\bar{q} \rangle \neq 0$

$$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$$ *Isospin*

3 Goldtones:

π^+, π^-, π^0 **Massless!!**

In reality, they are not massless since quark masses break explicitly $SU(2)_L \times SU(2)_R$ giving the pions a mass:

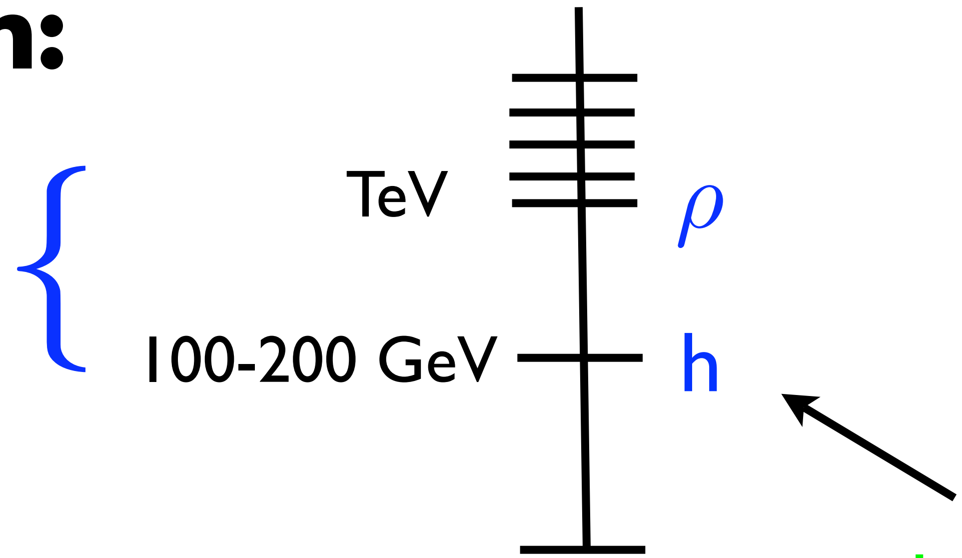
$$m_\pi^2 \propto m_q$$

Lets try the same for the Higgs

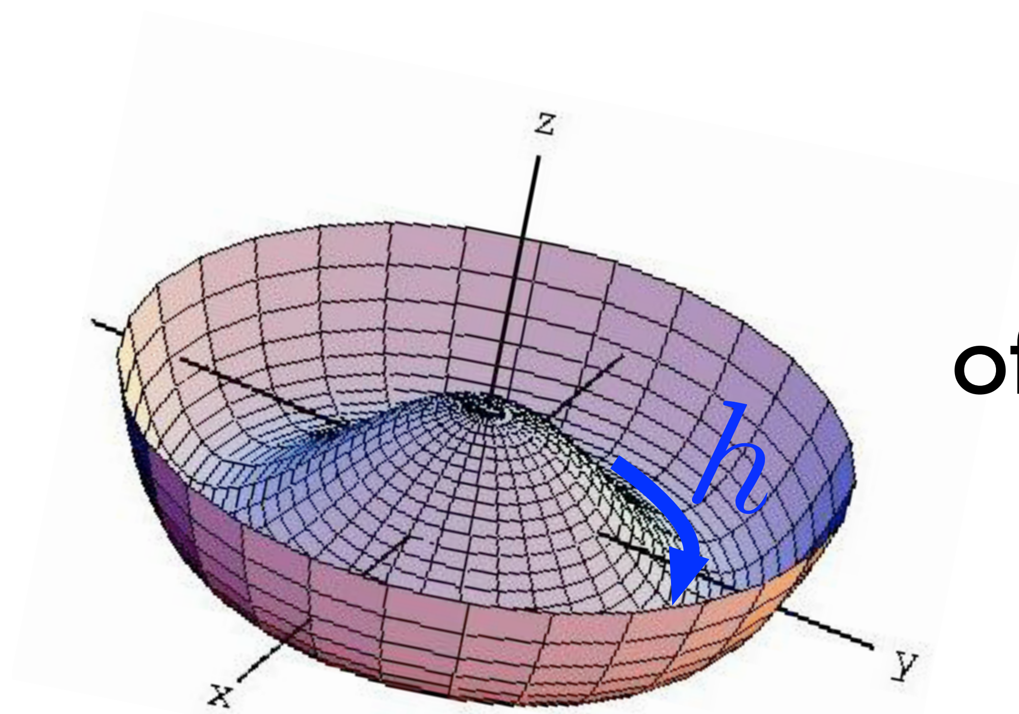
➠ Assume that there is a **New Strong sector** (QCD-like) at around the TeV-scale:

Spectrum:

Mass gap: Would explain the absence of new states at colliders before the LHC



Lets ask for the Higgs to be a Pseudo-Goldstone bosons (PGB)



Symmetry breaking pattern of this **New Strong Sector**:

$$SO(5) \rightarrow SO(4)$$

4 Goldstones = Higgs doublet

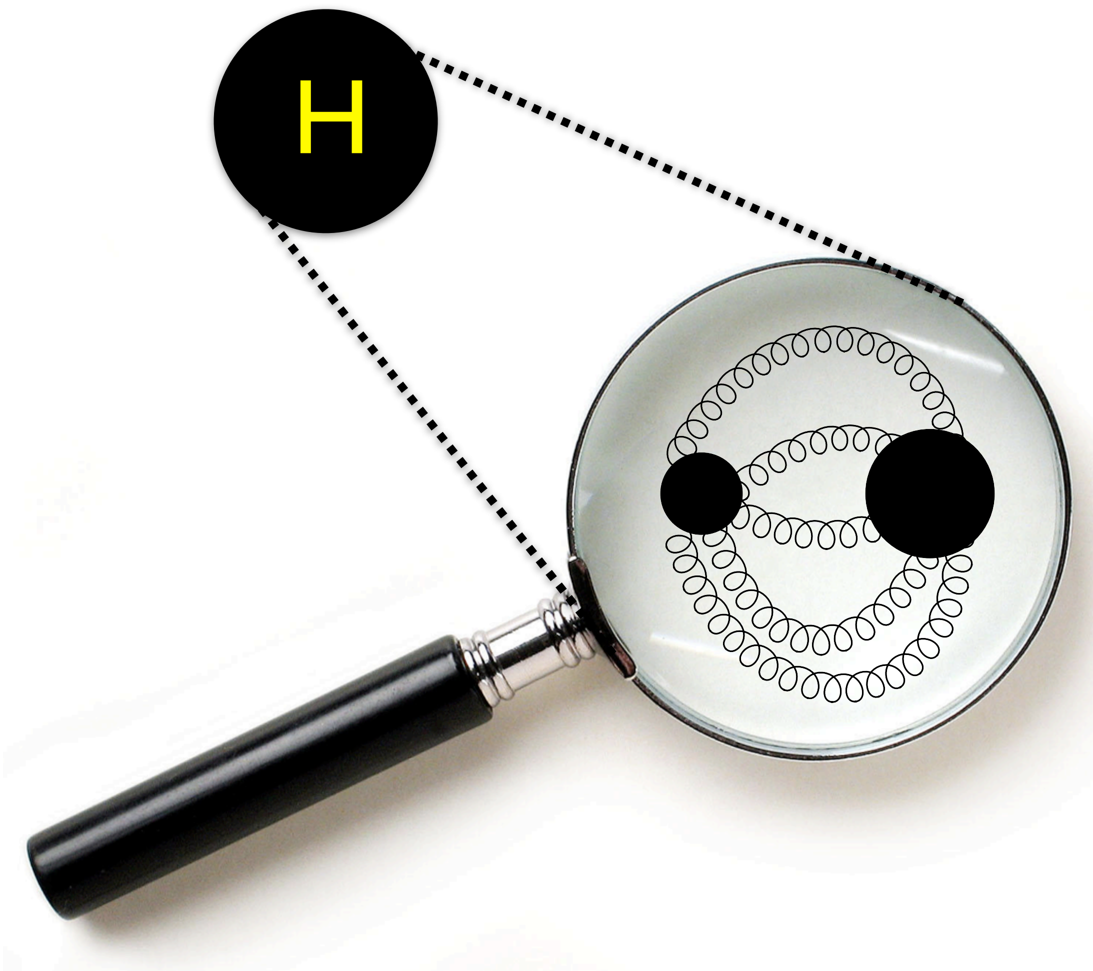
Main difference with QCD pions → It gets a VEV

Similar but slightly different approach:

Arkani-Hamed, Cohen, Georgi

Little Higgs

How to unravel the composite nature of the Higgs?

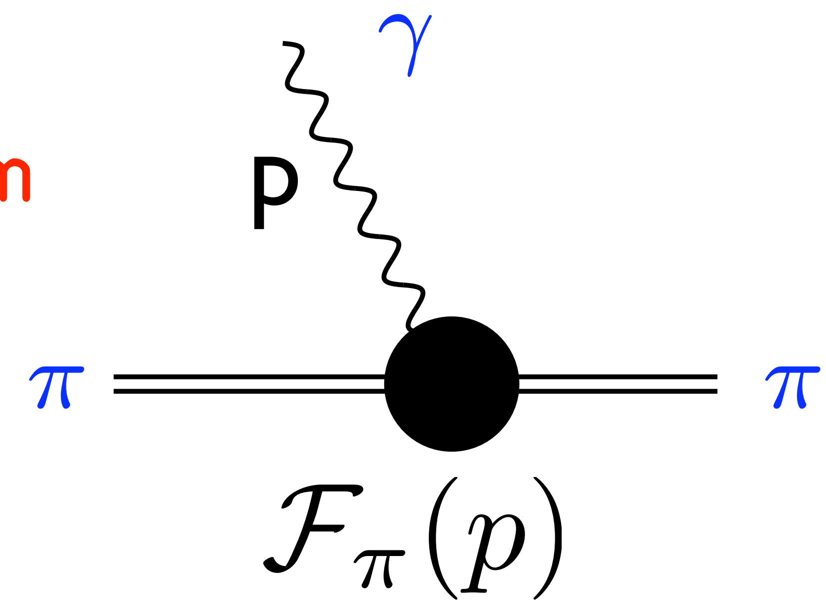


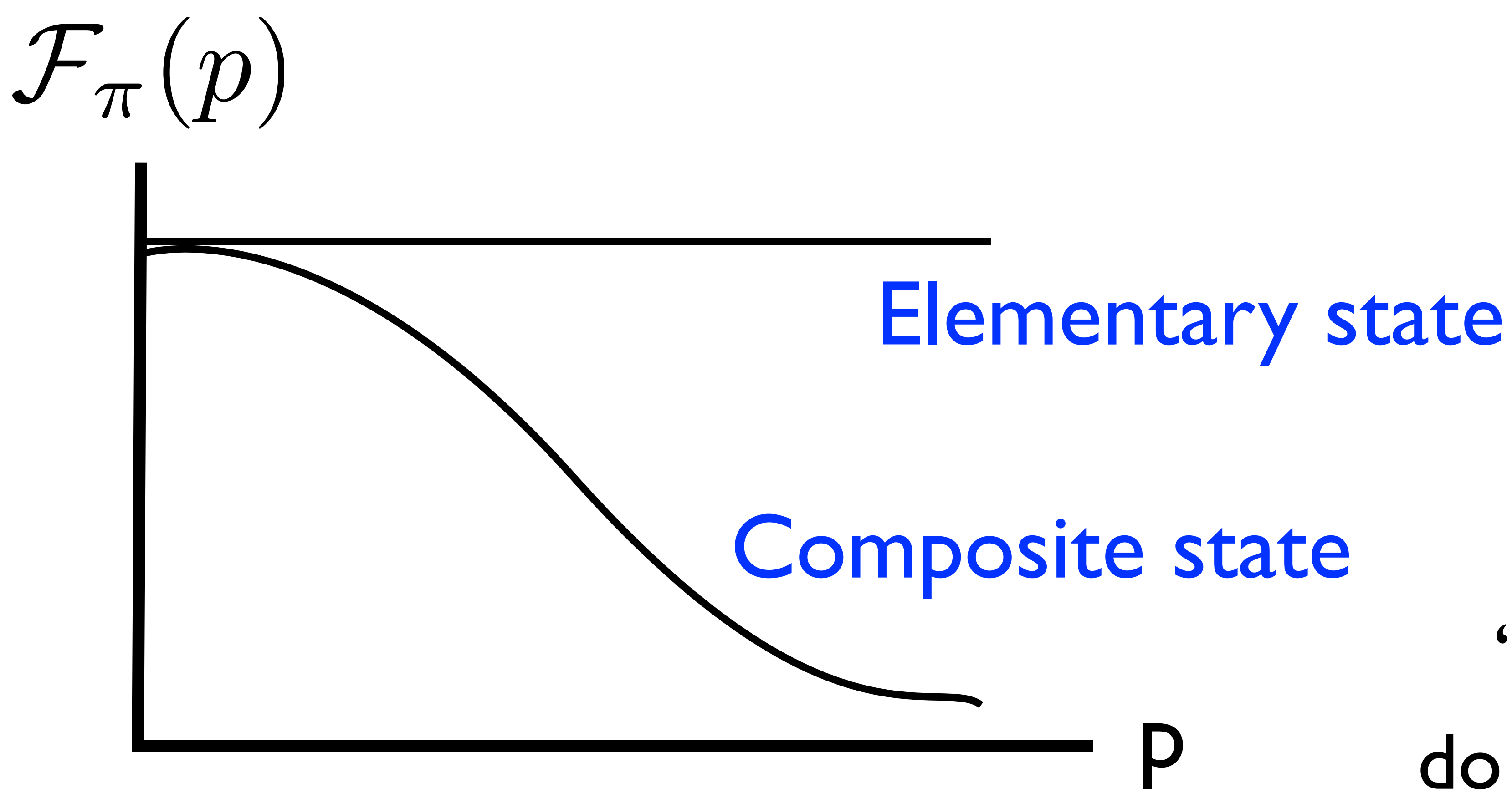
?

How to unravel the composite nature of the Higgs?

Easy in an ideal collider:

Do it as we do with pions in QCD:
probe it with photons at high-momentum



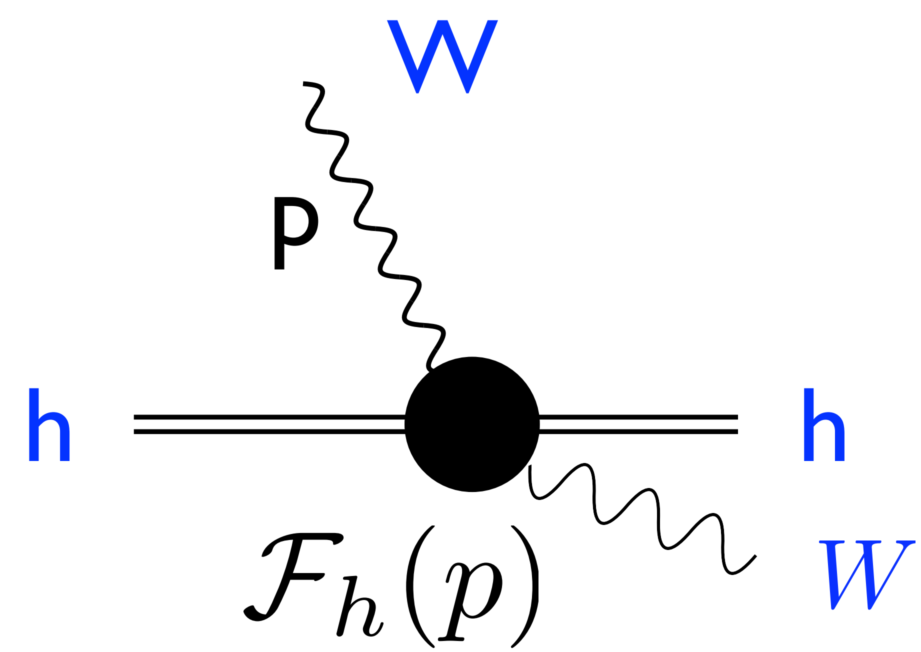


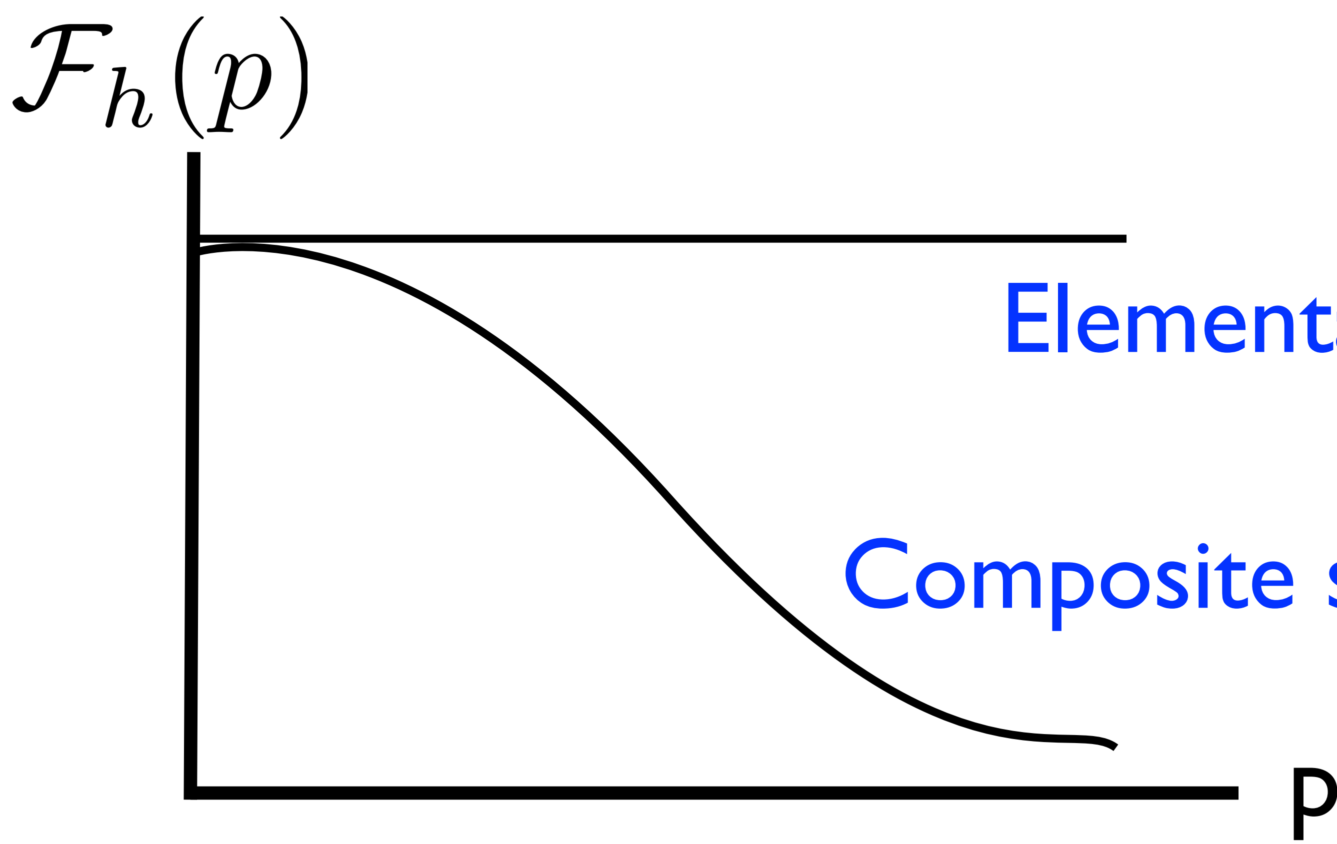
→ QM analog of
"High-frequency waves
do not see big soft objects"

How to unravel the composite nature of the Higgs?

Easy in an ideal collider:

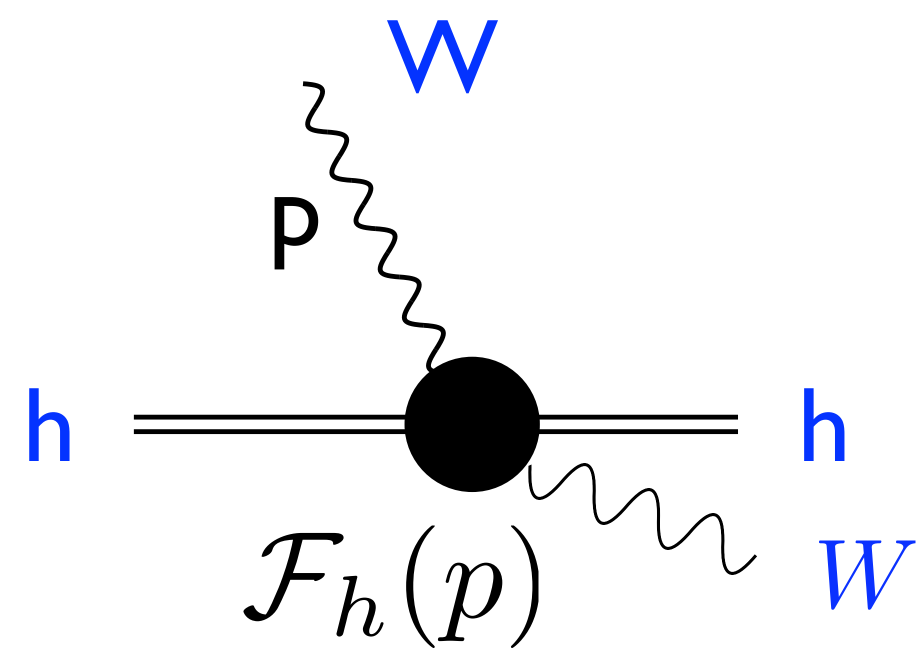
Similarly for the Higgs:

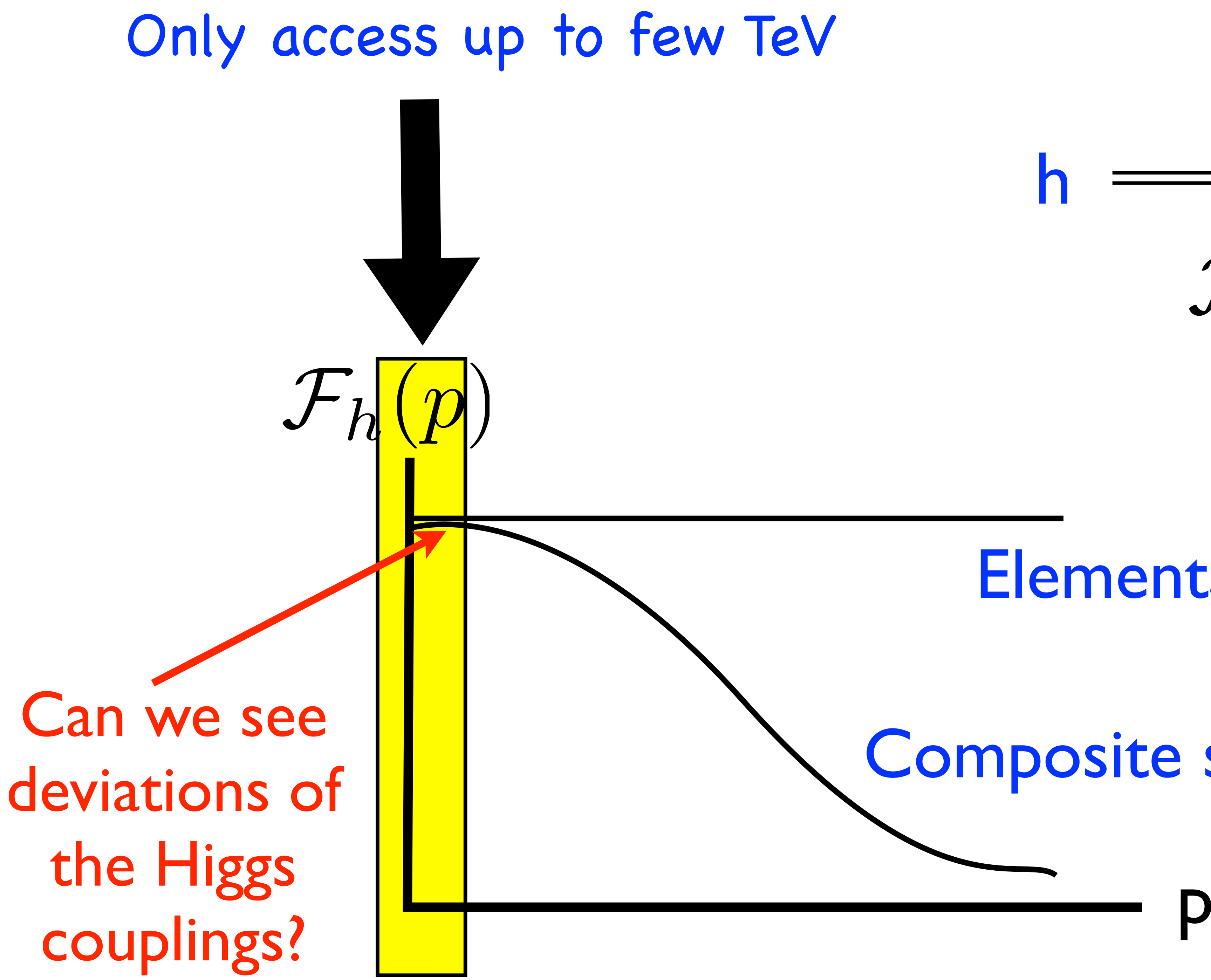




How to unravel the composite nature of the Higgs?

But in a real collider (LHC):





Parametrization of deviations from SM Higgs couplings

Contino et al 10

$$\mathcal{L} = \frac{M_V^2}{2} V_\mu^2 \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - m_f \bar{\psi}_L \psi_R \left(1 + c\frac{h}{v}\right) + \cdots$$

SM Higgs: $a = b = c = 1$

Composite Higgs:

Giudice,Grojean,AP,Rattazzi 07

$$a = \sqrt{1 - \frac{v^2}{f^2}} \qquad b = 1 - \frac{2v^2}{f^2} \qquad c = \sqrt{1 - \frac{v^2}{f^2}}$$

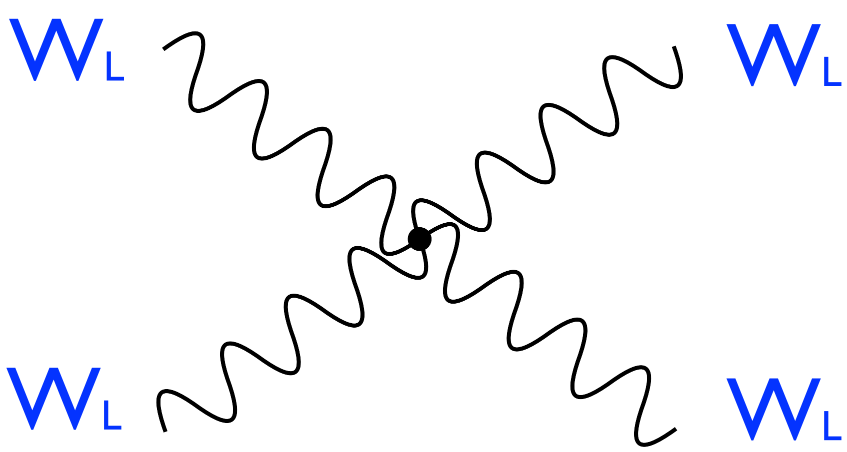
Scale related to the composite-scale

Since its couplings are different, it's **NOT** a true Higgs

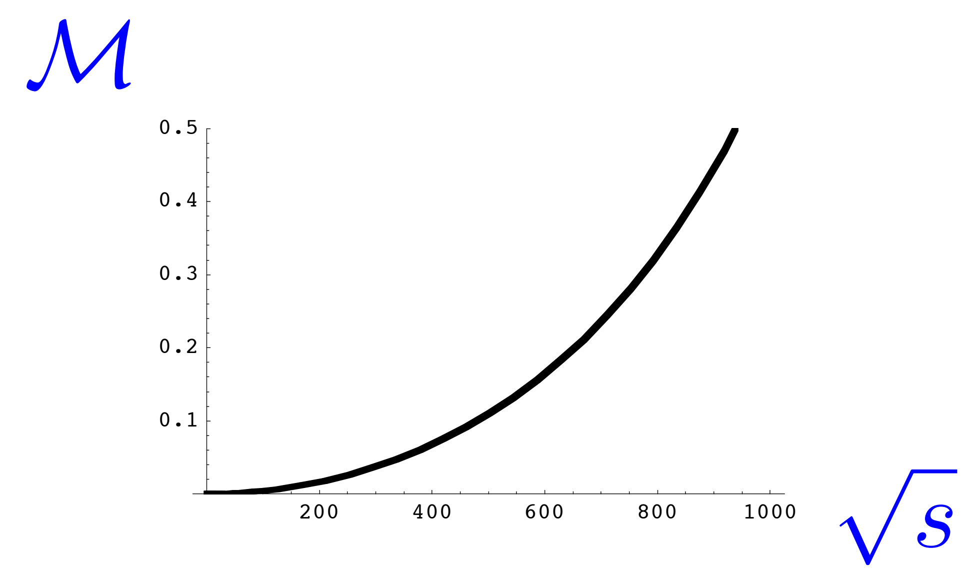
The Higgs plays an important role in the consistency of the SM

Without the physical Higgs: $M_h \to \infty$

a)

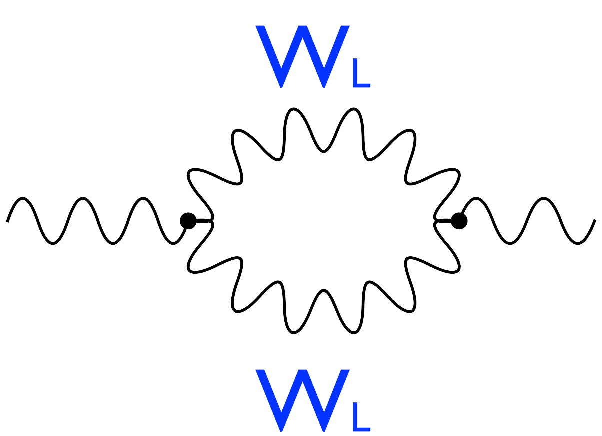


$$\propto \frac{s}{v^2}$$



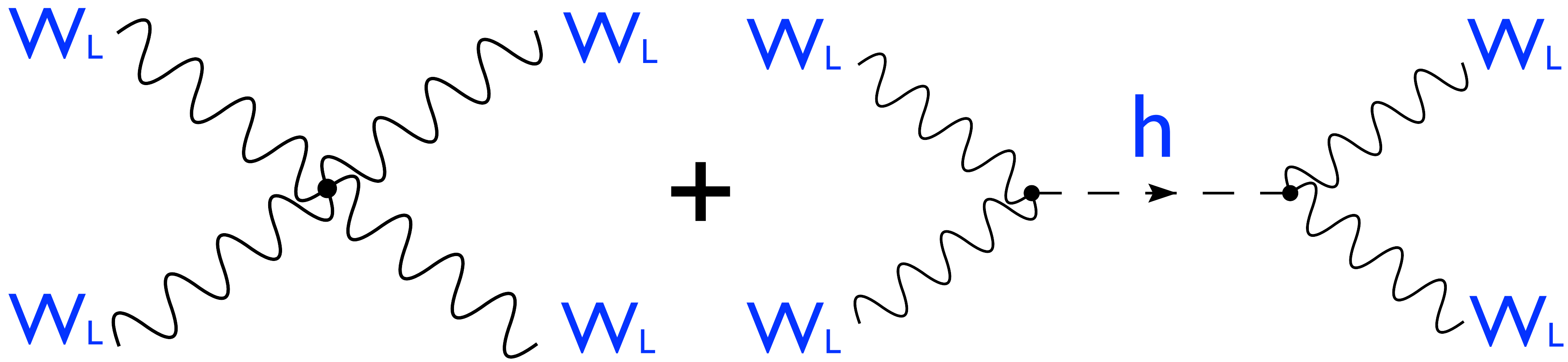
Unitarity is lost at high-energies

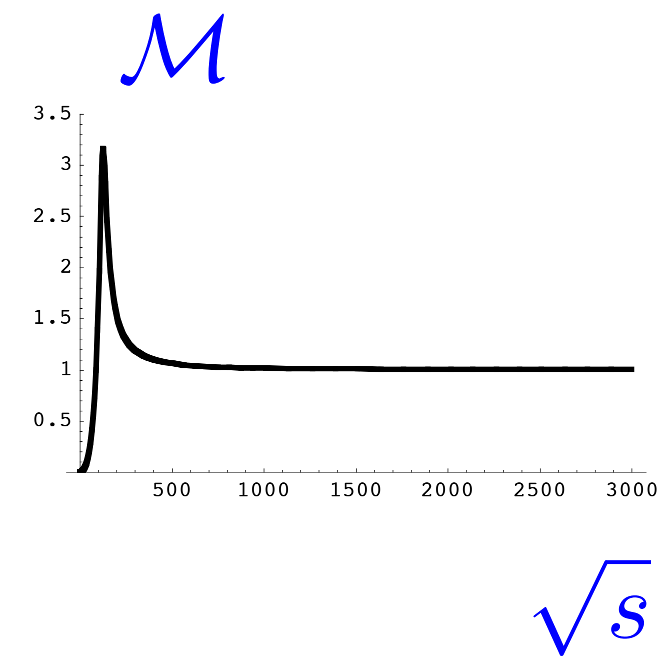
b)

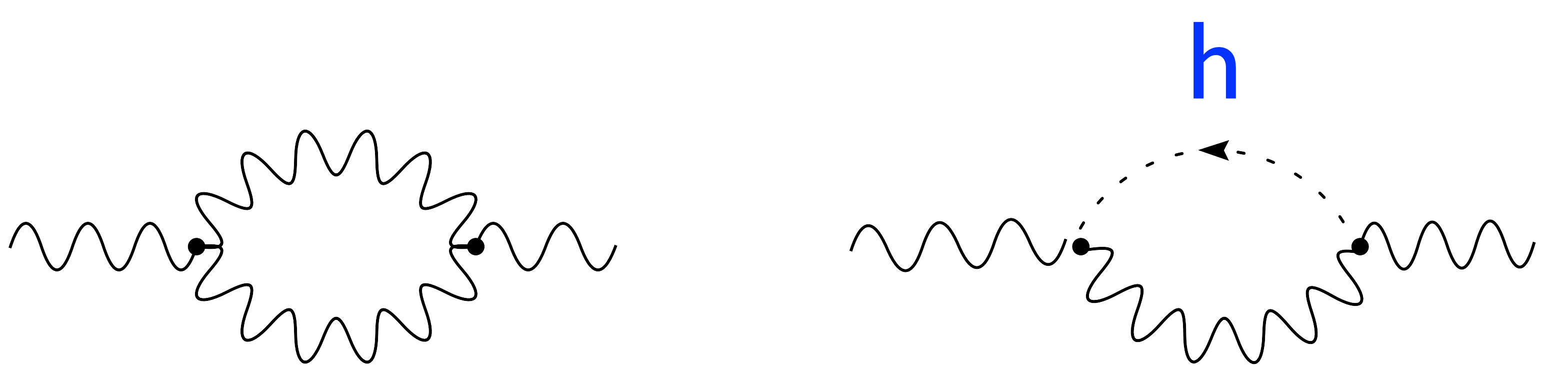


Loops are not finite!

With the Higgs **calculability** is recovered:

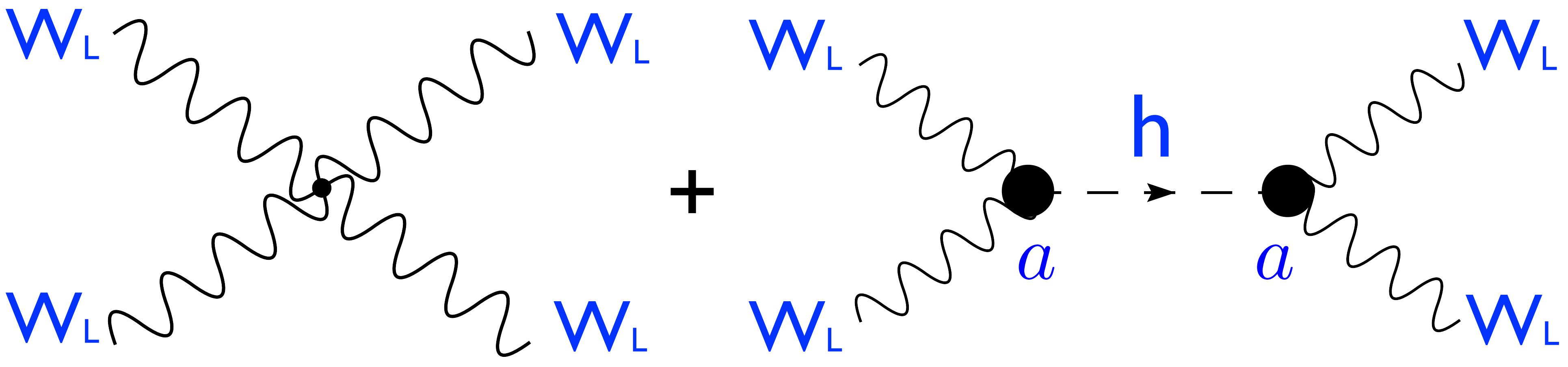


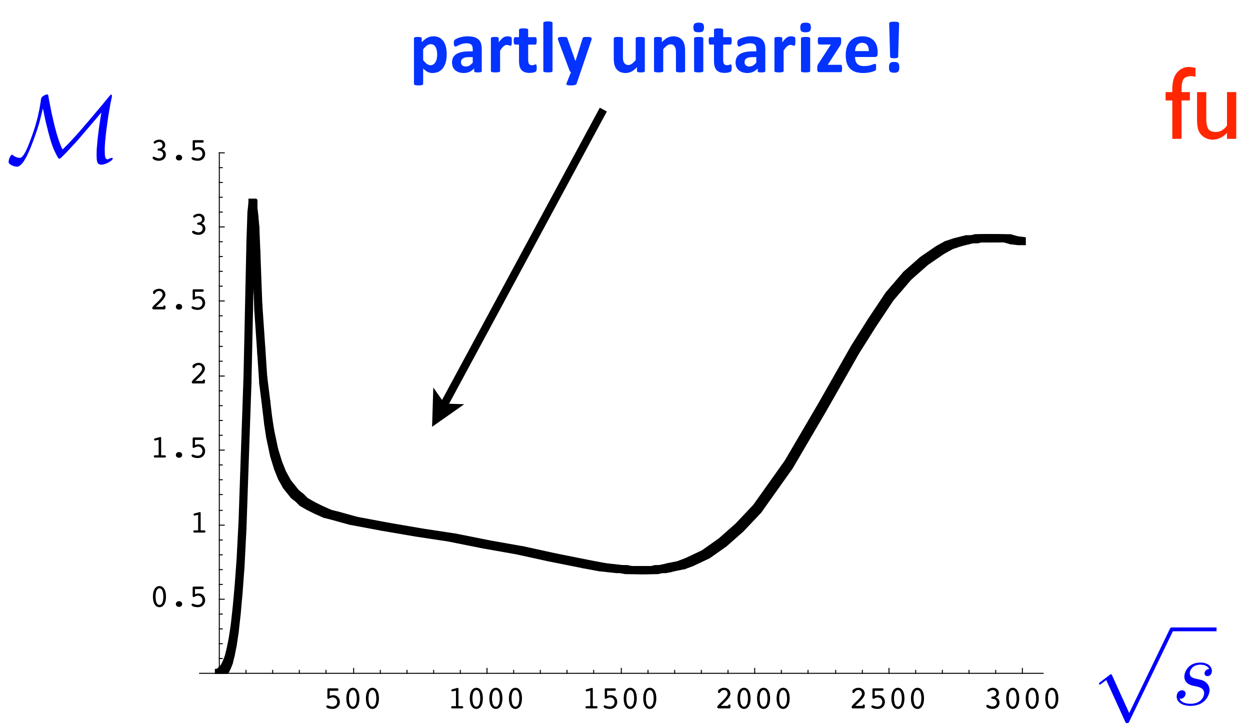




Finite results!

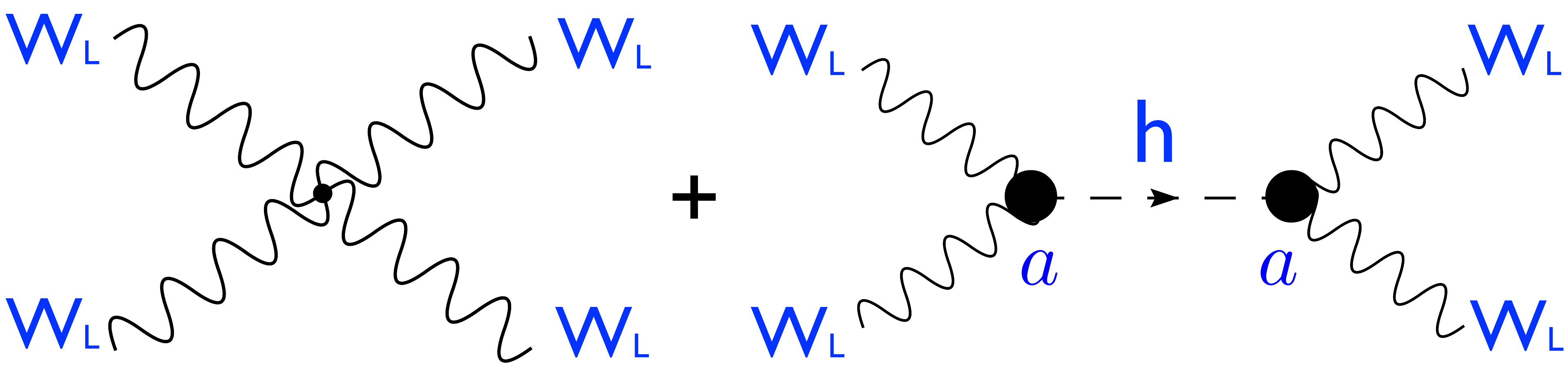
Composite Higgs only partly does the job of a **true** Higgs

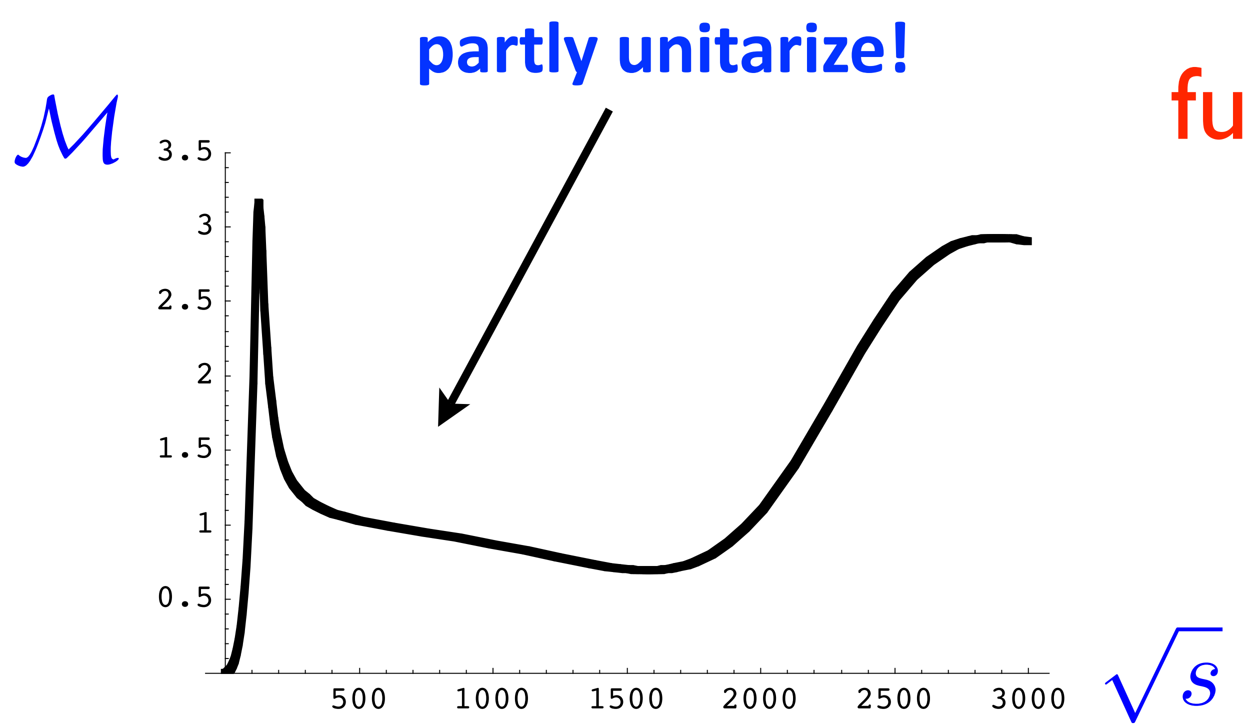




Extra states needed to fully unitarize (for consistency)!

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





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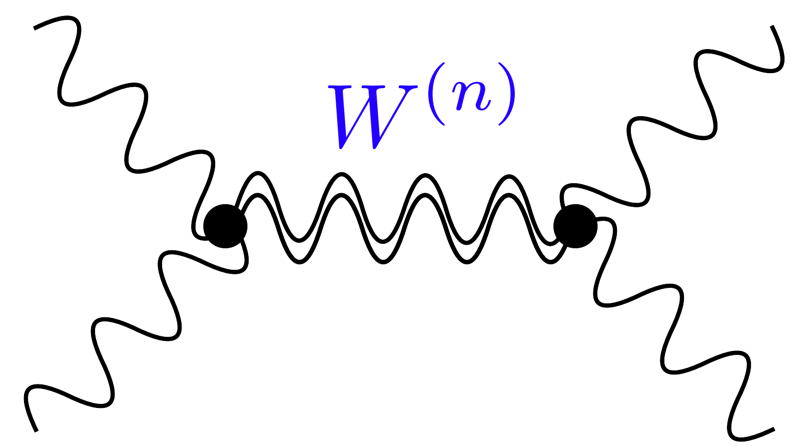
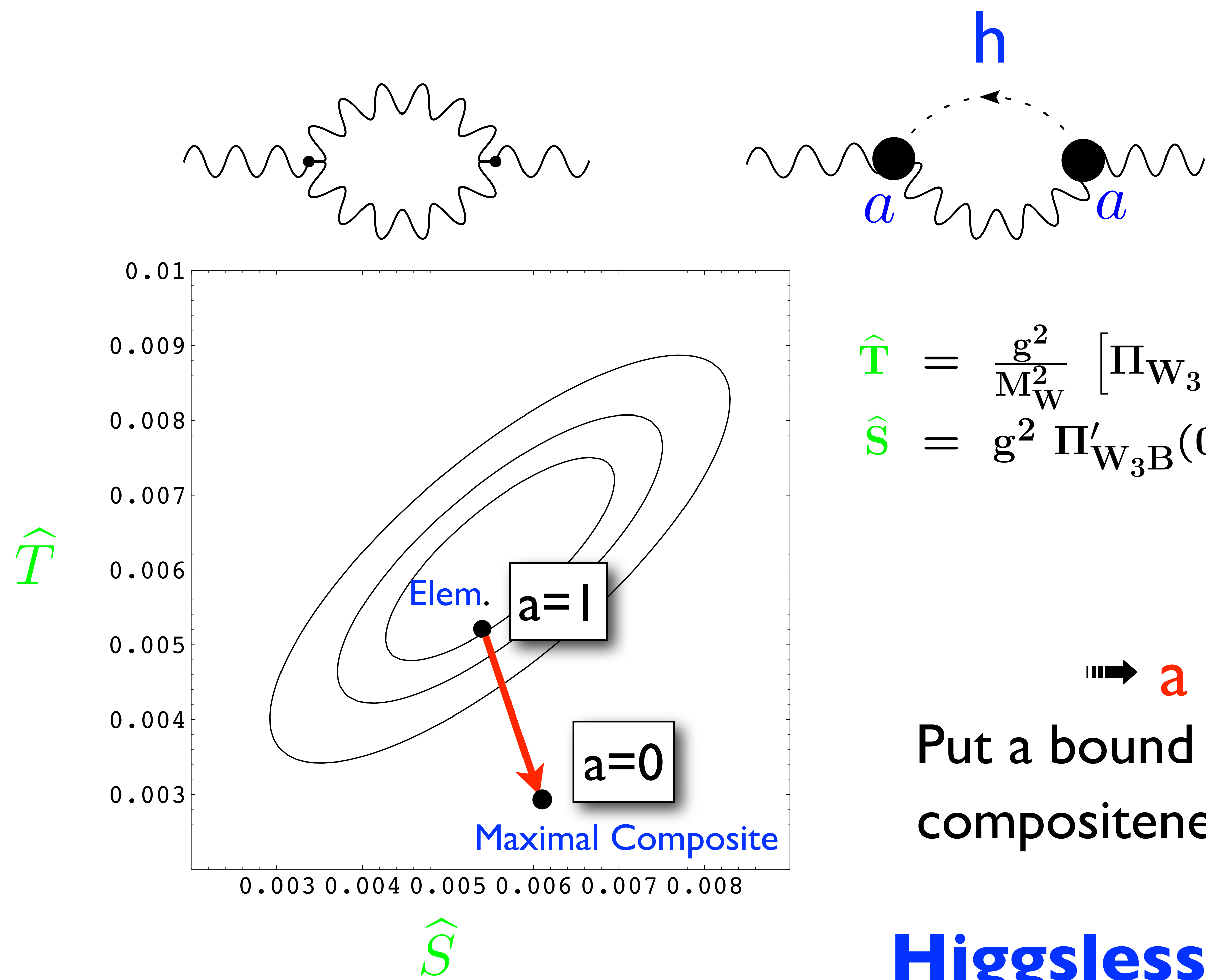


Extra resonances
(as in QCD)

$$M_{W^{(n)}} \simeq \frac{2\ \text{TeV}}{\sqrt{1-a^2}}$$

In the limit a=0 (~ **Higgsless**)
composite Higgs not at all a Higgs
Resonances do all the job!

Maximal degree of compositeness not allowed by EWPT



$$\hat{T} = \frac{g^2}{M_W^2}\left[\Pi_{W_3}(0) - \Pi_{W+}(0)\right]$$

$$\hat{S} = g^2\, \Pi'_{W_3 B}(0)$$

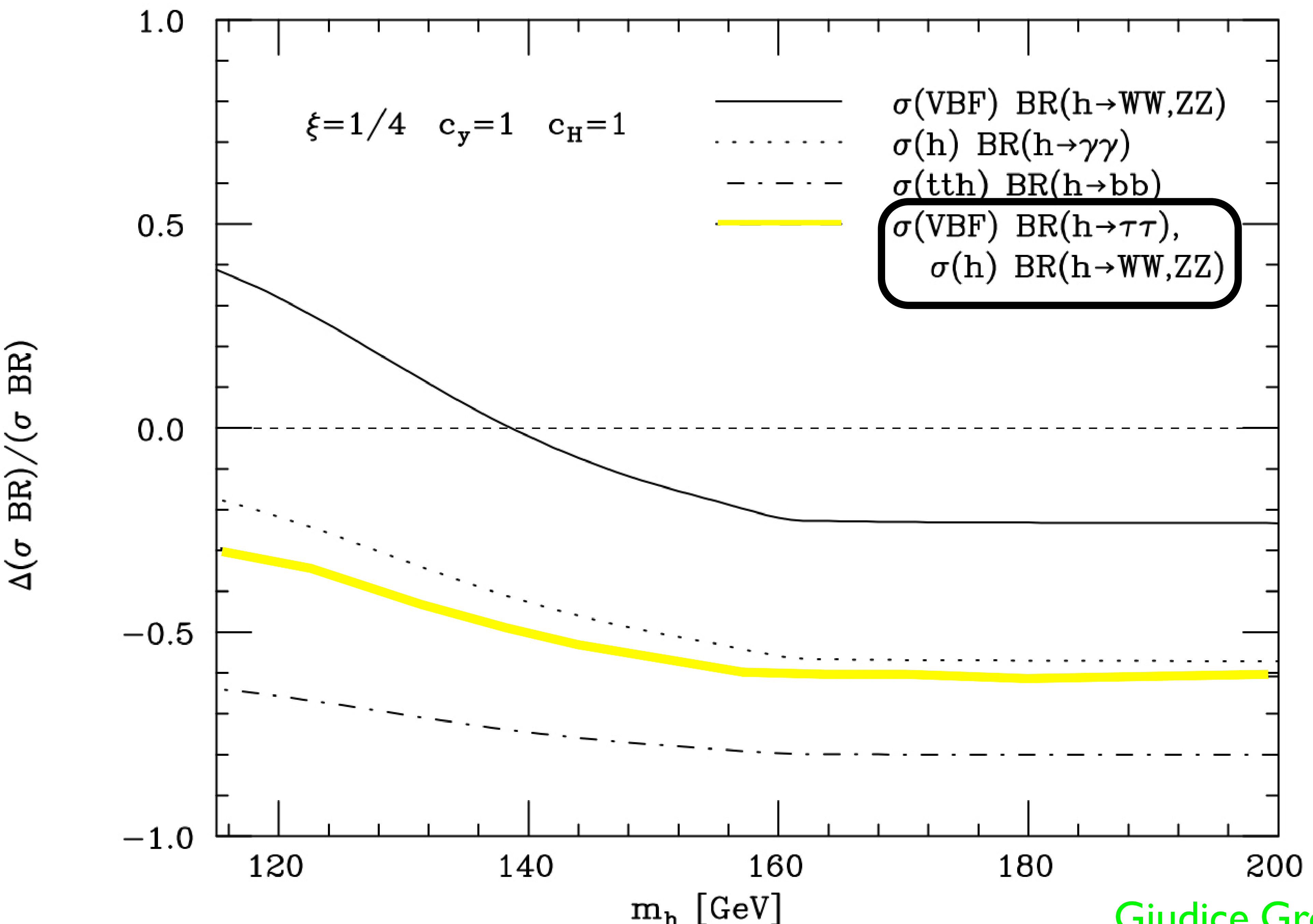
➡ a > 0.86

Put a bound on the scale of compositeness: f>500 GeV

Higgsless (a=0) disfavored

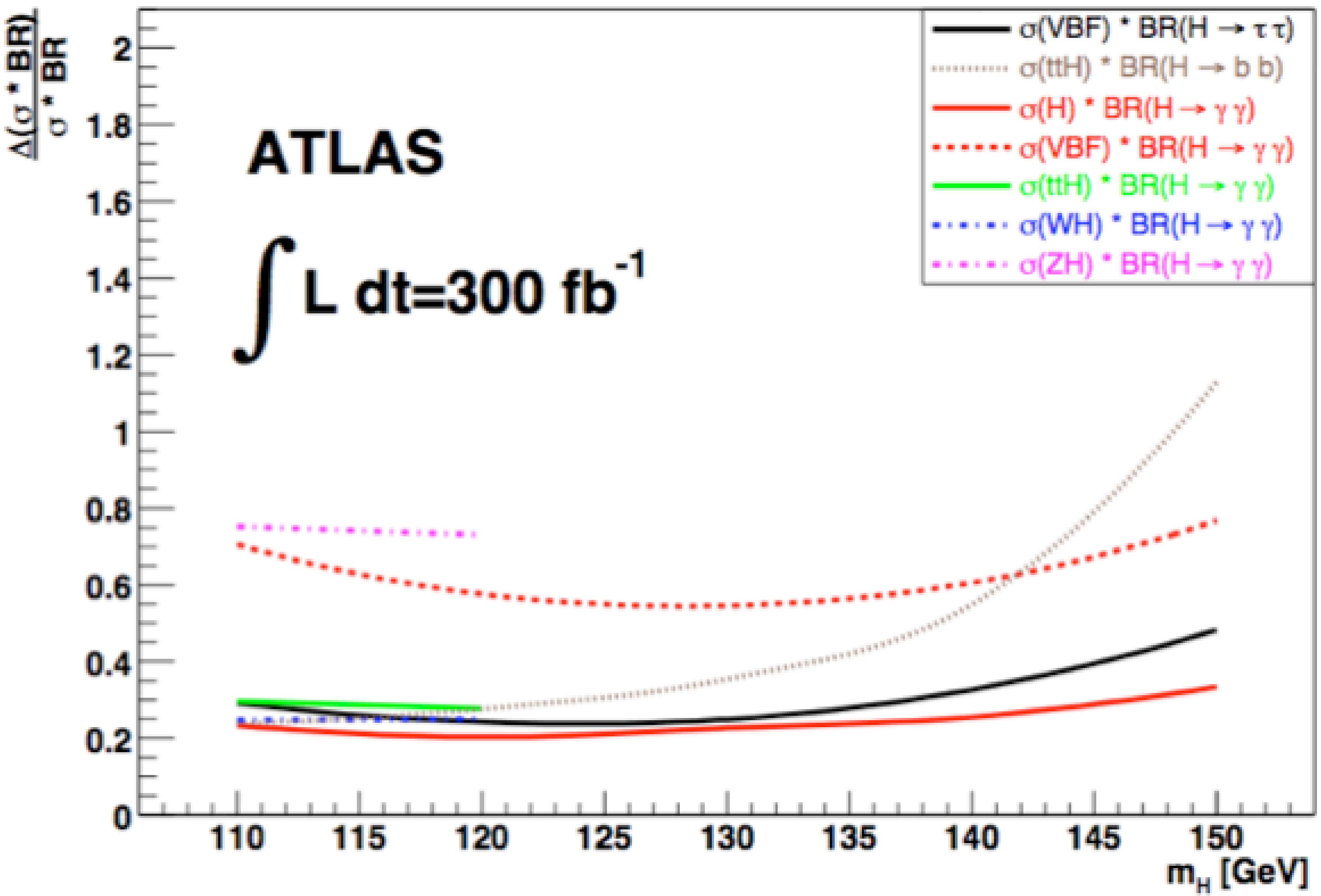
If the Higgs is **composite**, how it will change LHC predictions?

Bad news: Reduction of rates!



Giudice,Grojean,AP,Rattazzi 07

see also, Grojean,Espinosa,Muhlleitner 10



Duhrssen 03

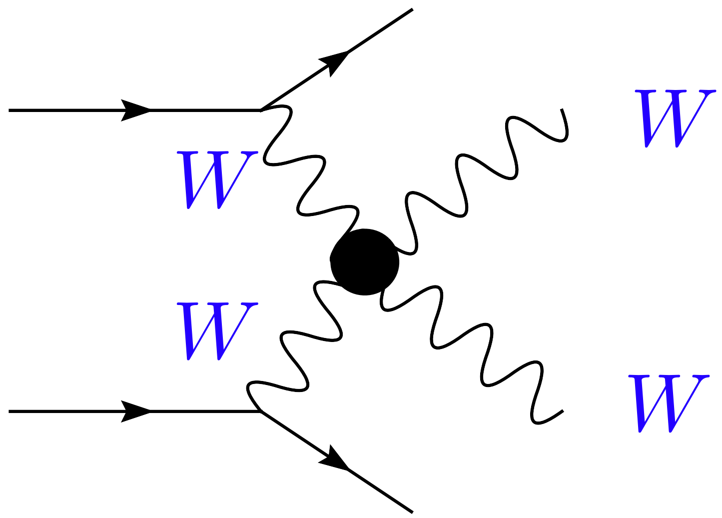
Higgs coupling measurements ~ 20-40%

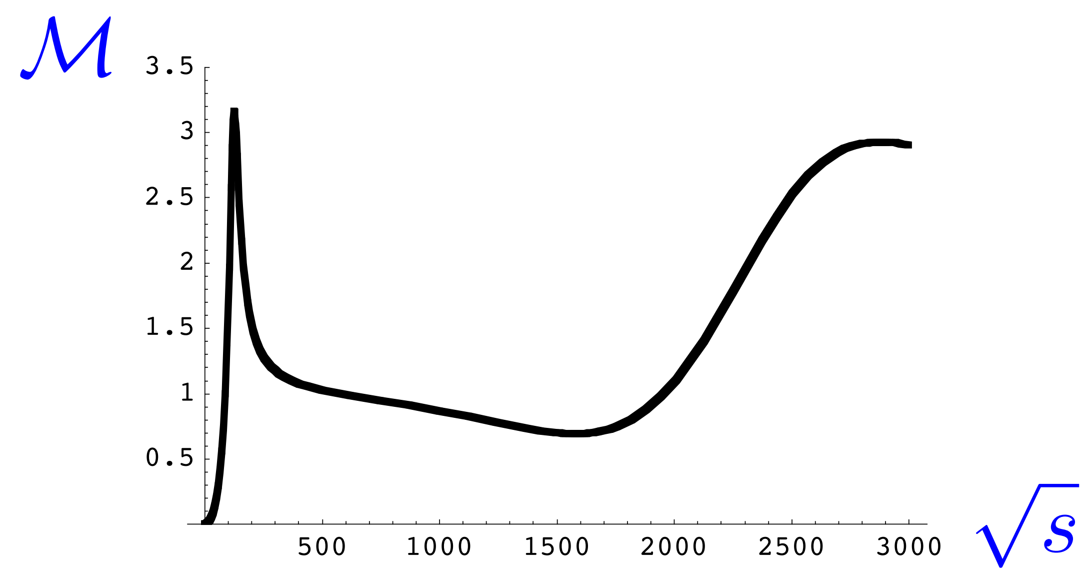
recent studies Lafaye,Plehn,Rauch,Zerwas,Duhrssen 09

ILC would be a perfect machine to test this scenario: effects could be measured up to a few %

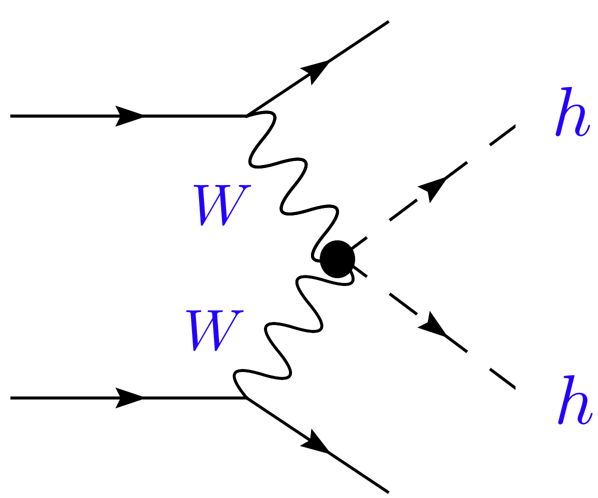
Genuine properties of the **composite** nature of the Higgs

1) $W_L W_L$ -scattering grows at high energy





2) Double-Higgs production grows at high energy



$$pp \to hhjj \to 4Wjj \to \begin{cases} l^+l^+l^-l^- \not{E}_T + 2j \\ l^+l^-l^\pm \not{E}_T + 4j \\ l^{+(-)}l^{+(-)} \not{E}_T + 5j\,(6j) \end{cases}$$

Contino et al 10

In the best cases "3σ signal significance with 300/fb collected at a 14 TeV LHC"

What about indirect signatures?

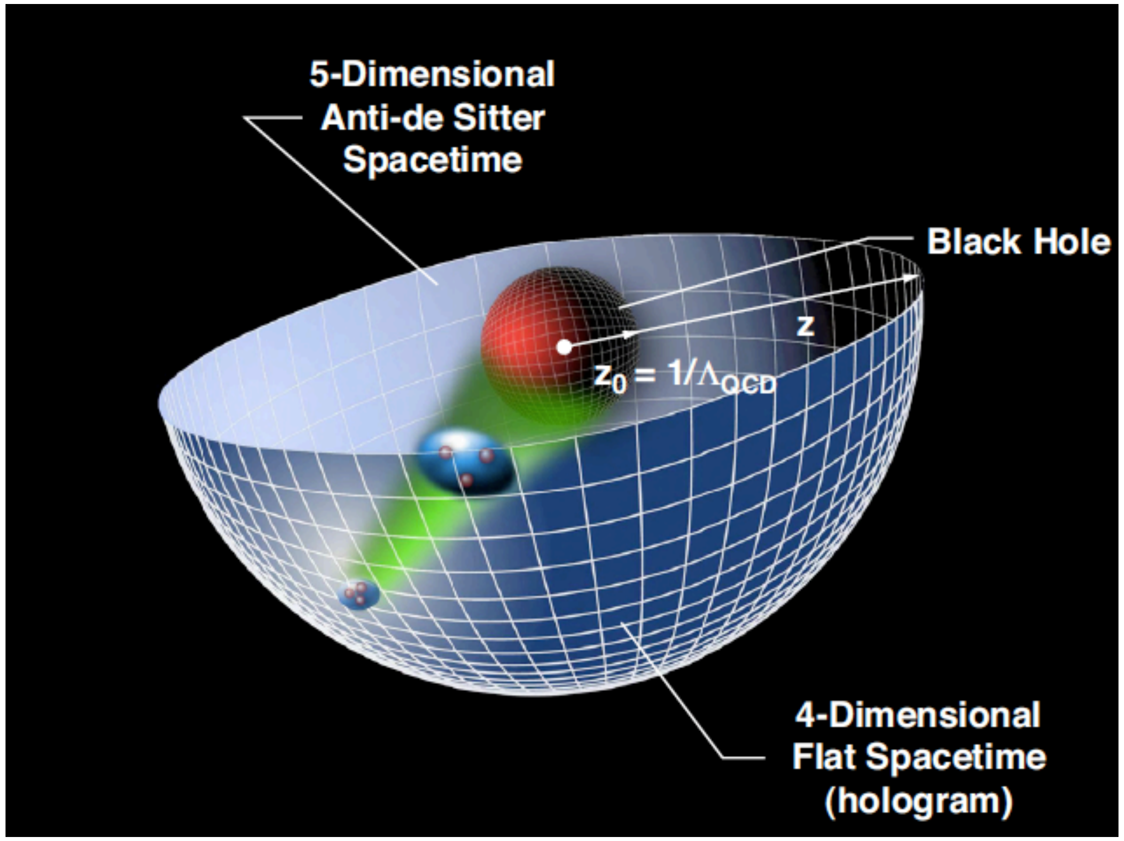
As in QCD, detecting other hadrons was also an indication of pion compositeness

But very difficult to calculate the spectrum in **strongly-interacting theories**

Recent progress:

Explicit weakly-coupled approaches to PGB Higgs

Picture from G.F. de Teramond



"Sexier" approach to composite Higgs:

Higgs as an "hologram"

Contino,Nomura,AP 03

The 4D composite properties of the Higgs are due to its 5D nature (AdS/CFT correspondence)

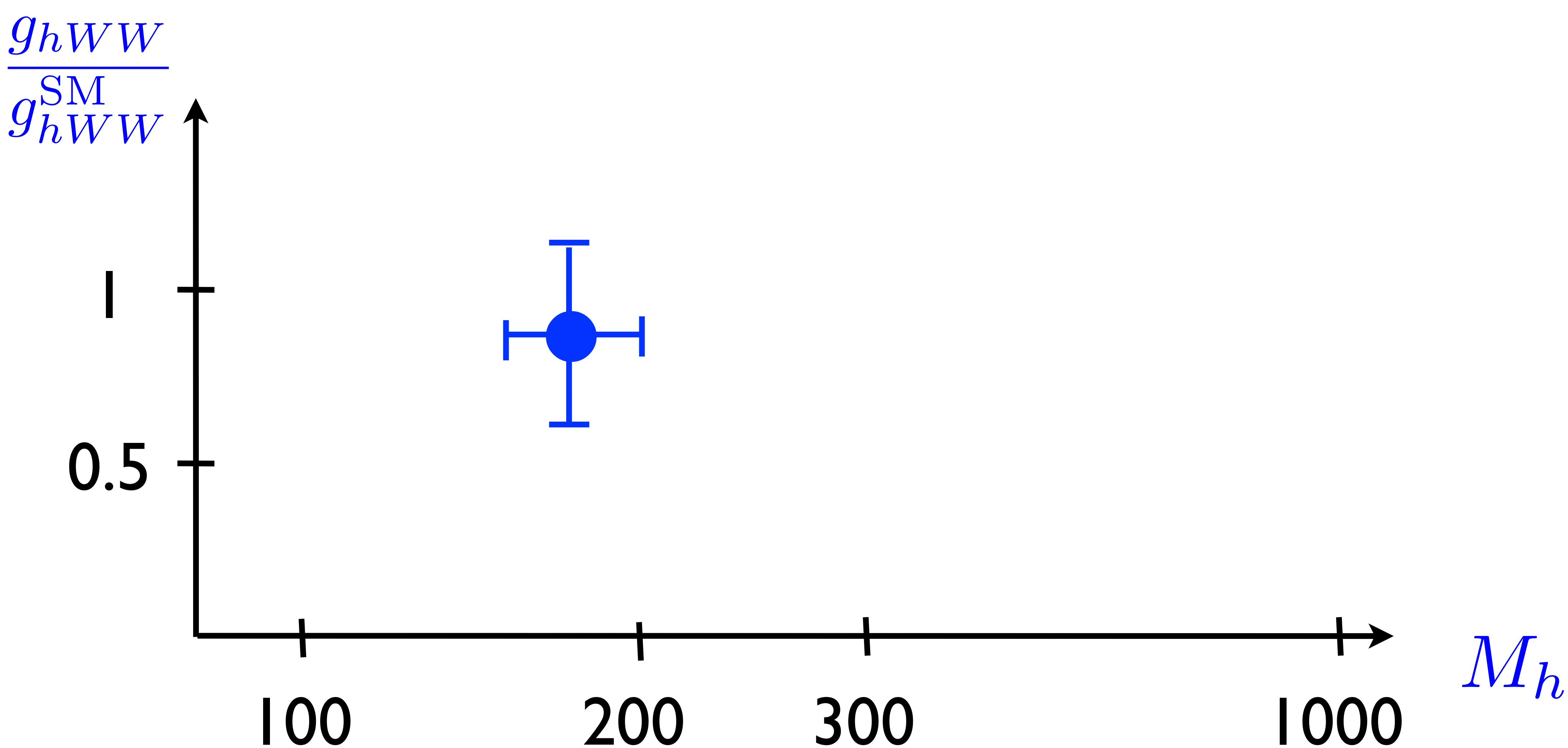
Maldacena 98

we will see it later...

One of the Main Messages:

Once a **Higgs-like** state is found, it will be crucial to determine its role in EWSB

e.g. where it **sits** in this plane!



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A rough perspective of different theoretical scenarios: