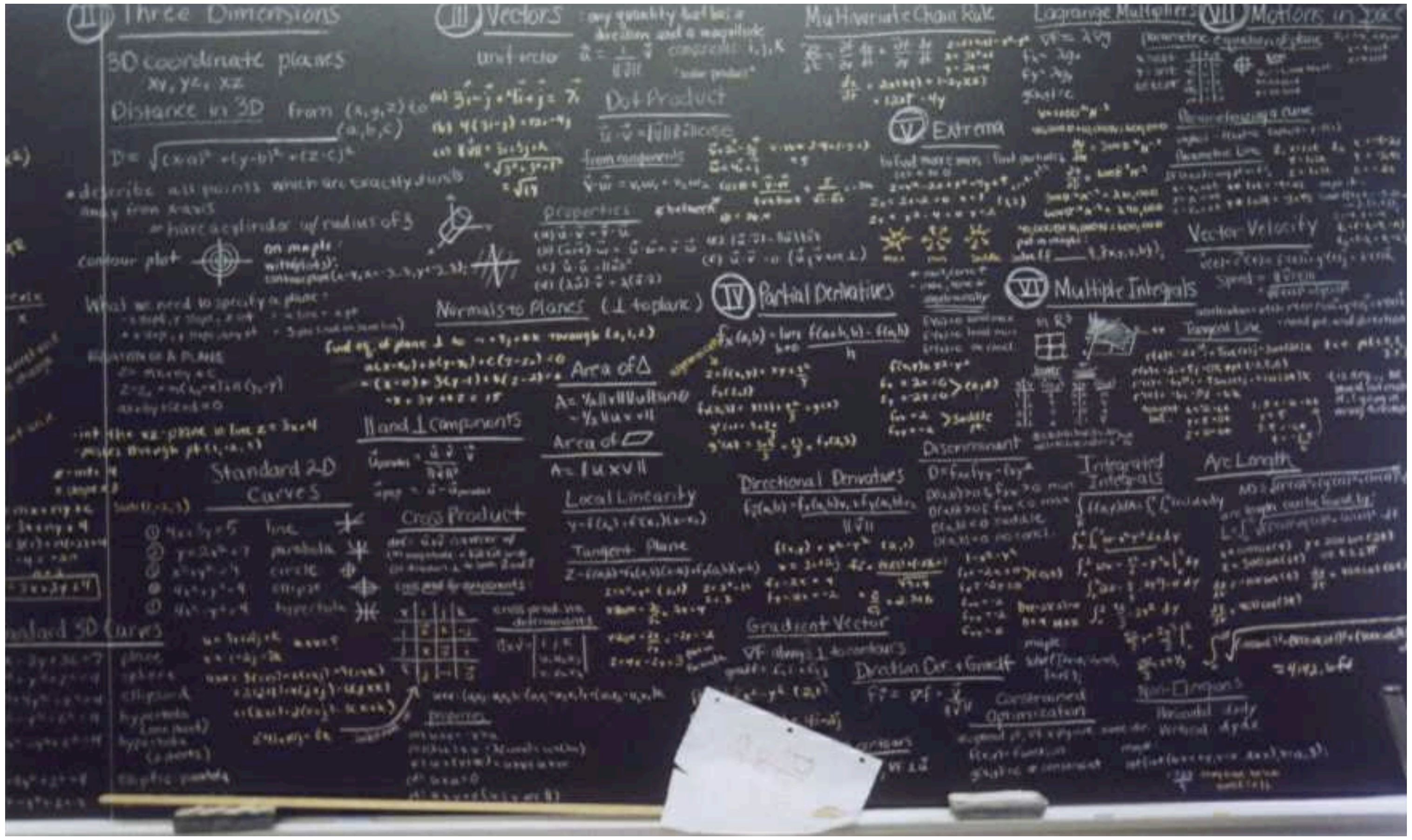
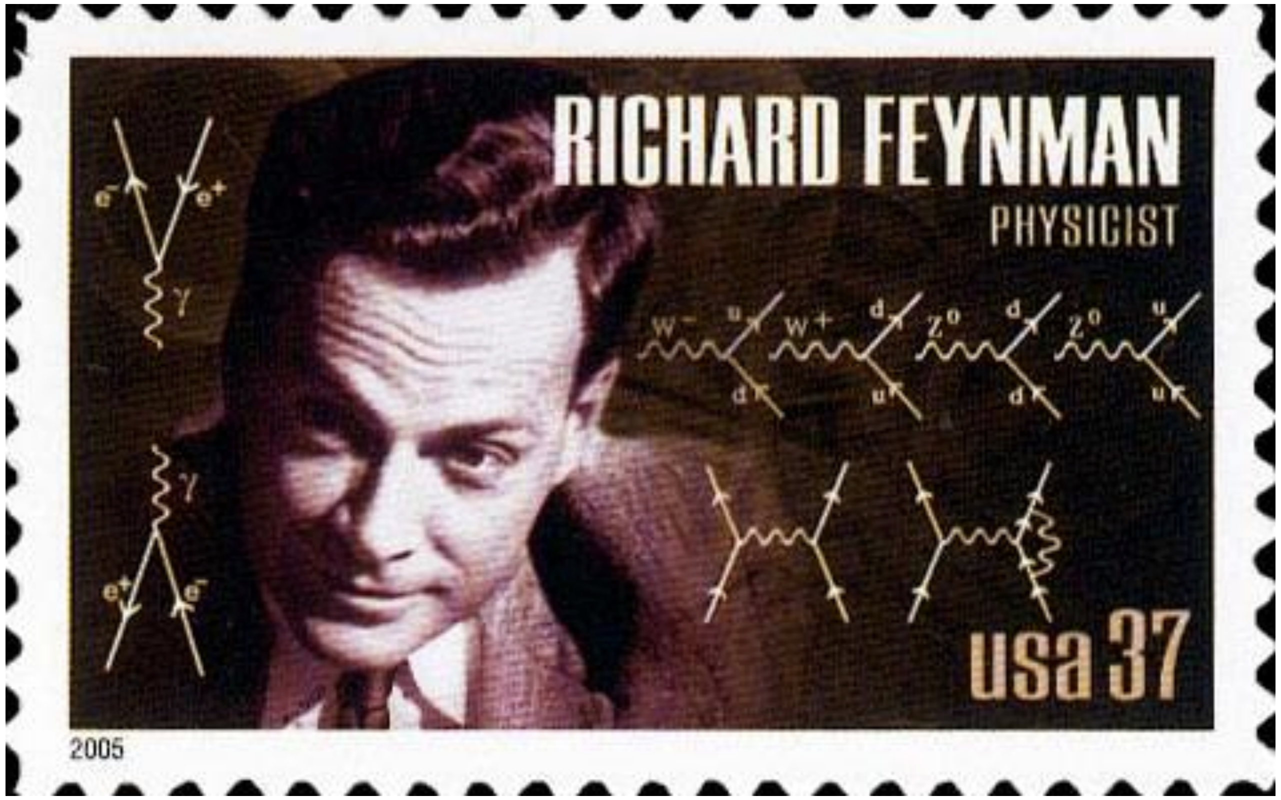
Higgs and alternatives



Alex Pomarol (Univ. Autonoma Barcelona)

Part of the enormous success of particle physics in the last 50 years has grounded in **gauge theories**

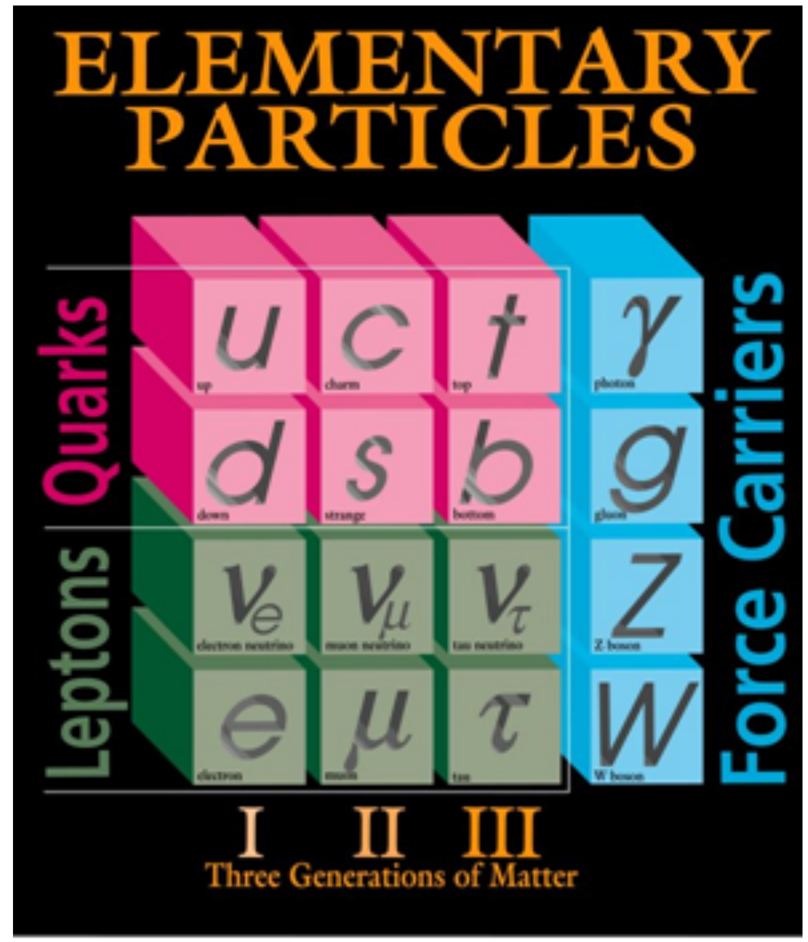
Impressive **calculability**



e.g. **QED**: g_e-2=0.0023193043

Gauge theories have allowed to explain the properties of the **particle zoo**

at 2010:



interactions dictated by a **gauge theory** based on the SU(3)xSU(2)xU(1) symmetry....

Gauge theories have allowed to explain the properties of the **particle zoo**

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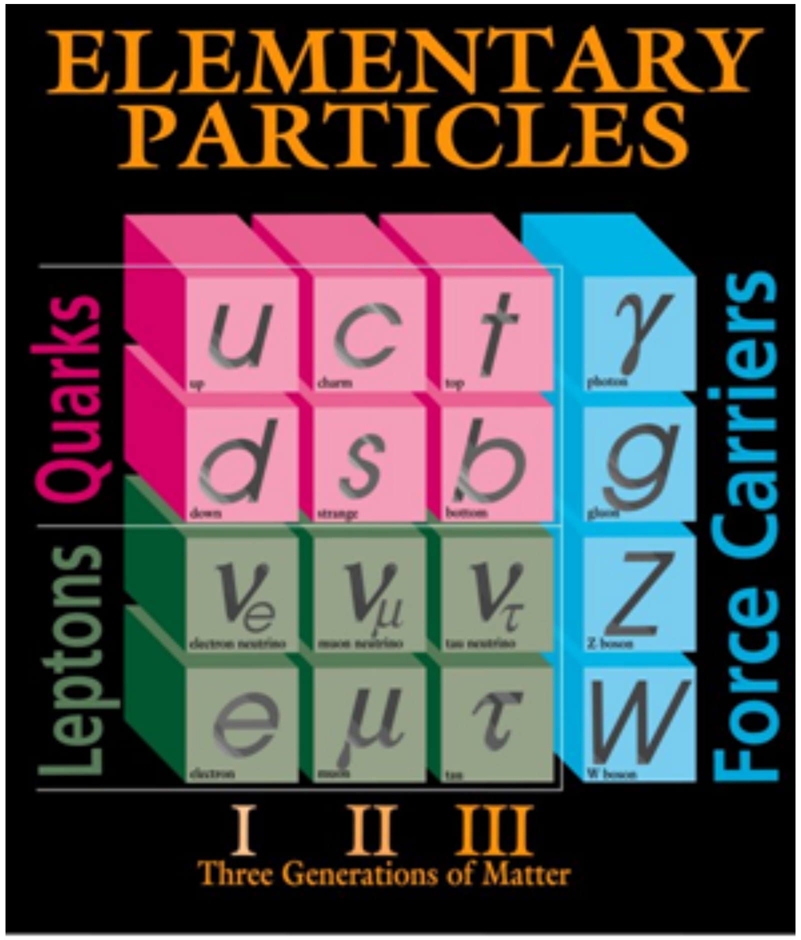


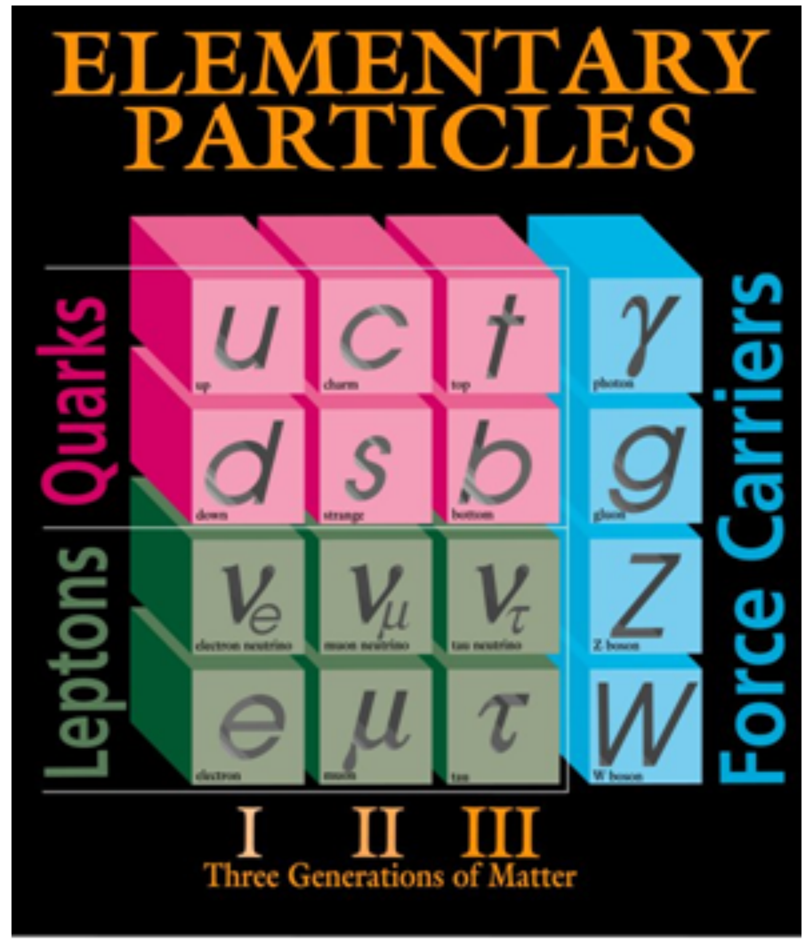
interactions dictated by a **gauge theory** based on the SU(3)xSU(2)xU(1) symmetry....

Up to mass terms!

Don't respect the SU(2)xU(1) symmetries

Gauge theories have allowed to explain the properties of the **particle zoo:**

at 2010:



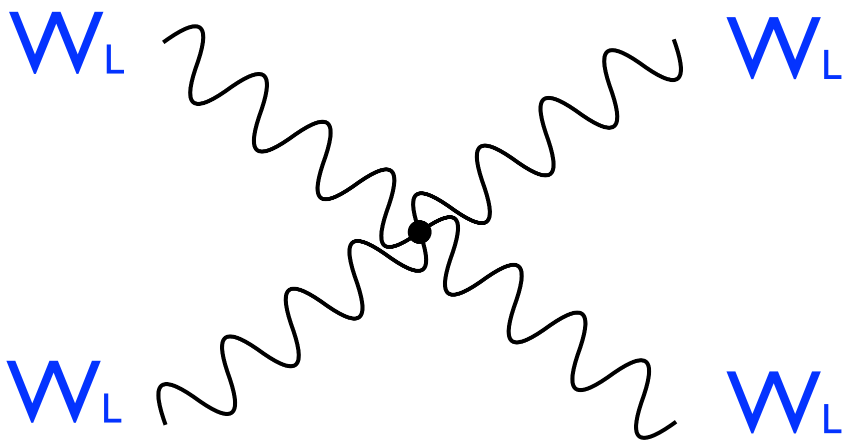
interactions dictated by a **gauge theory** based on the SU(3)xSU(2)xU(1) symmetry....

Massive W and Z have 3 polarizations:
New physical states: W_L , Z_L

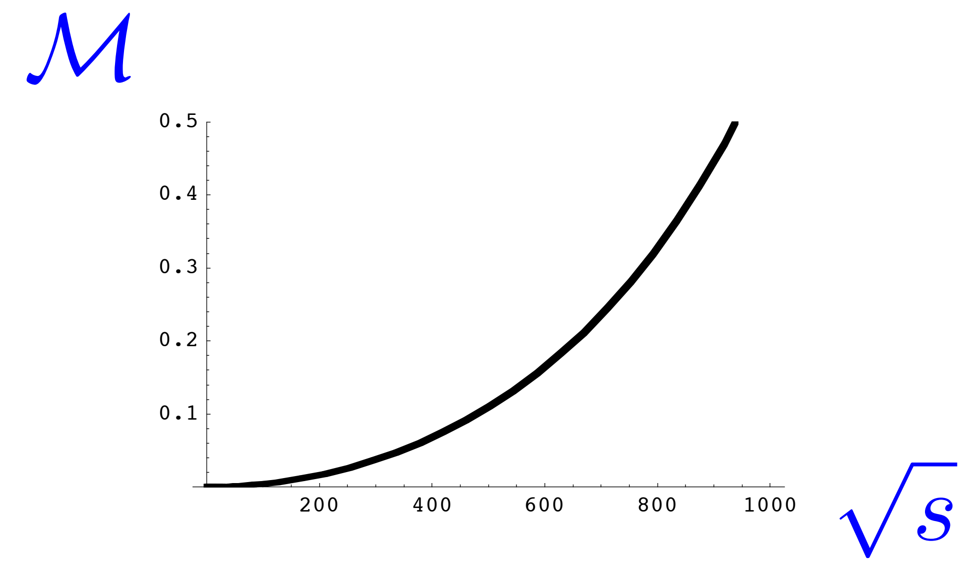
These new states W_L, Z_L (that must be present even if the masses were tiny) **spoil** the nice properties of gauge theories

Calculability is lost!

a)

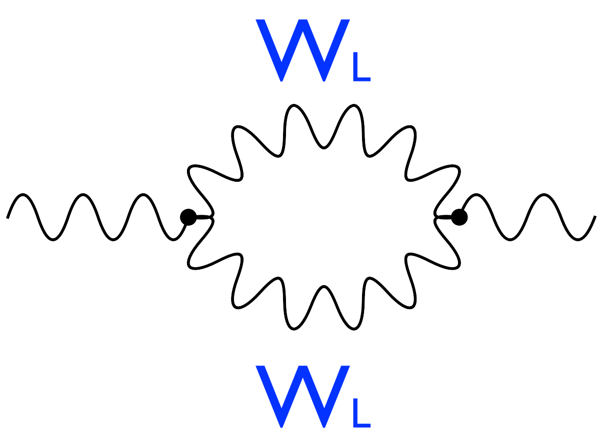


$$\propto \frac{s}{v^2}$$



Unitarity is lost at high-energies

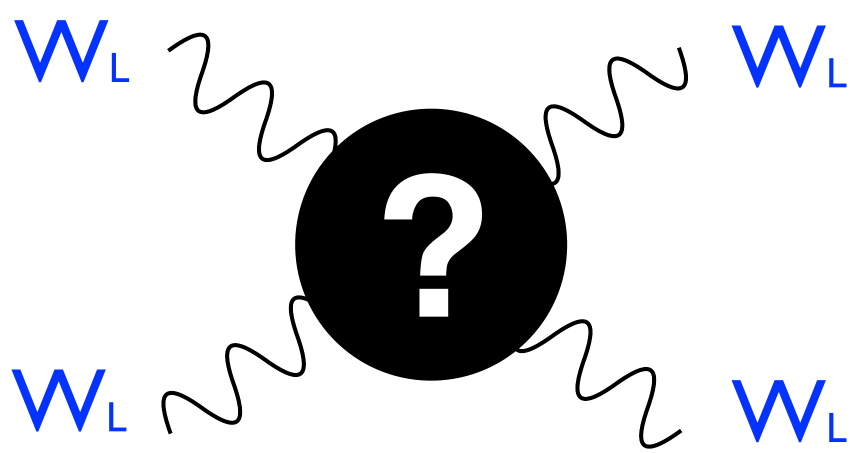
b)



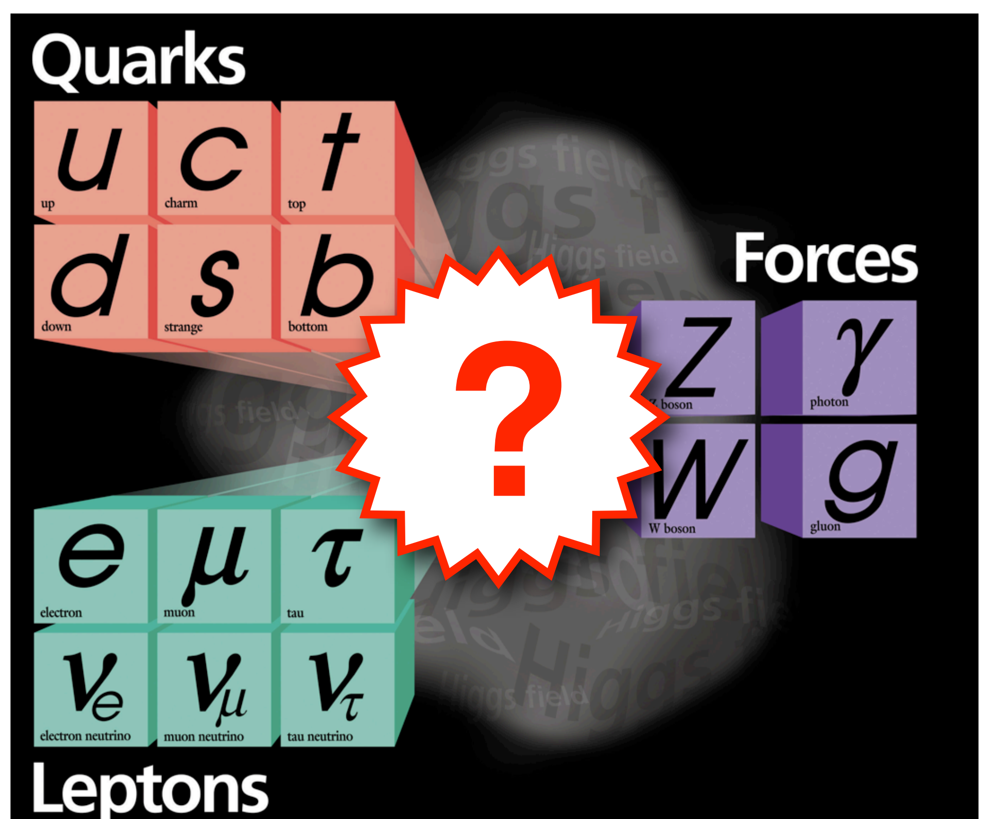
Loops are not finite!

Do not allow for precision calculations as in QED

There is a missing ingredient
in the **observed** particle content



To find this missing piece (or pieces) in the
particle zoo is the **main mission** of the LHC !



What this missing piece(s) could be?

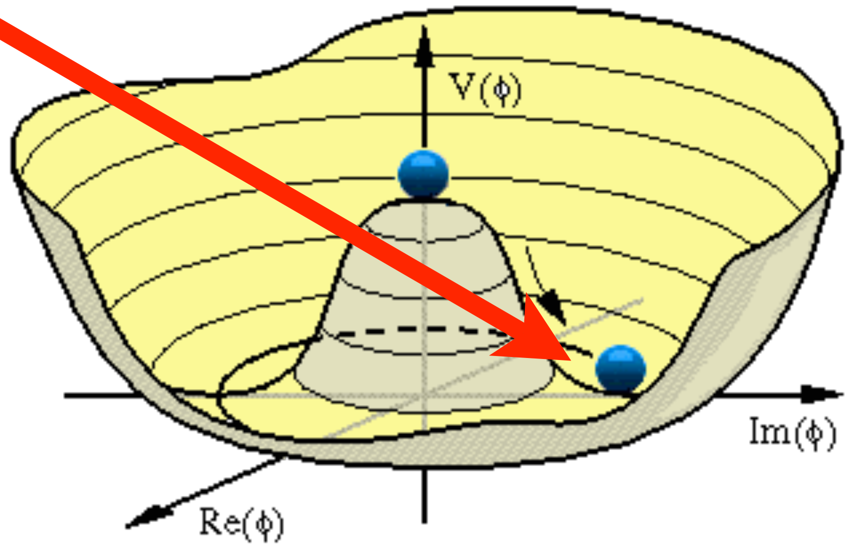
Simple Option:

Blame it on the vacuum

Simple Option:

Blame it on the vacuum

Not invariant under
the EW symmetry



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EW Symmetry restoration

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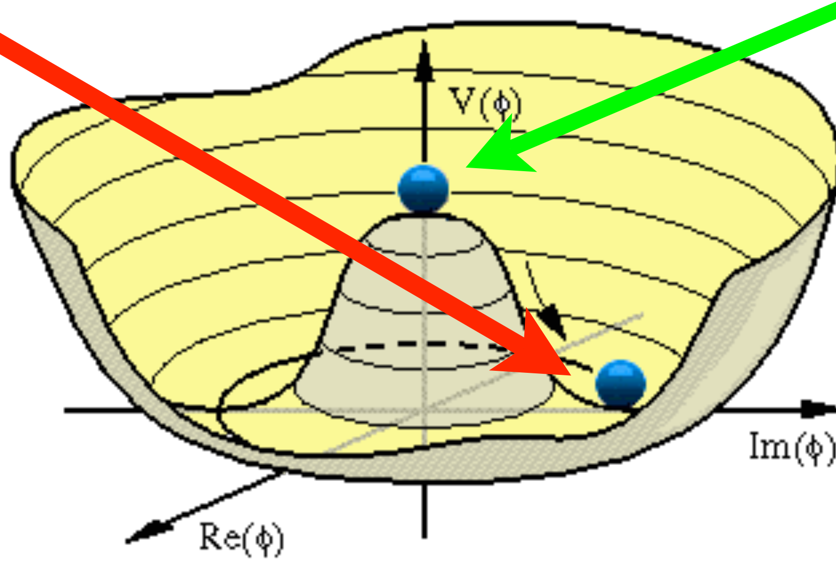

The theory, before set
in its minimum,
was SU(2)xU(1) symmetric

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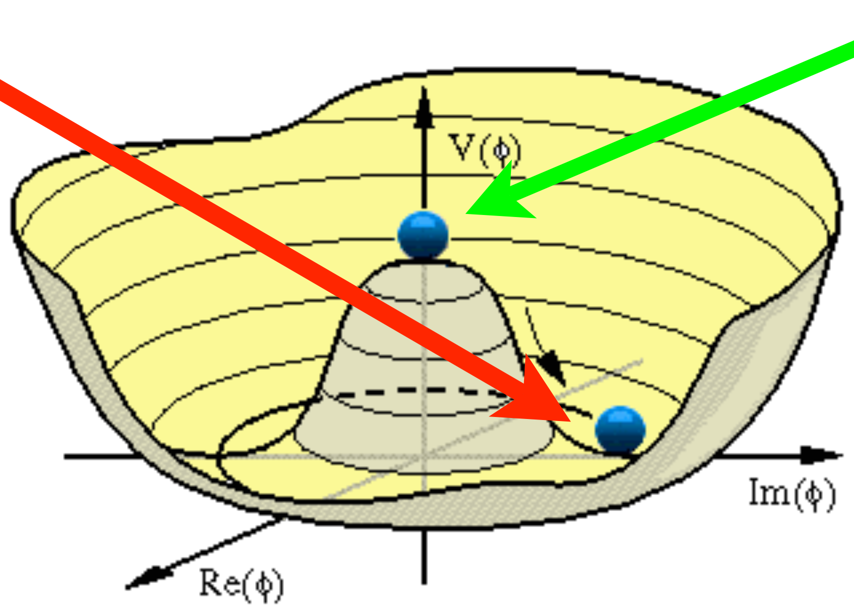

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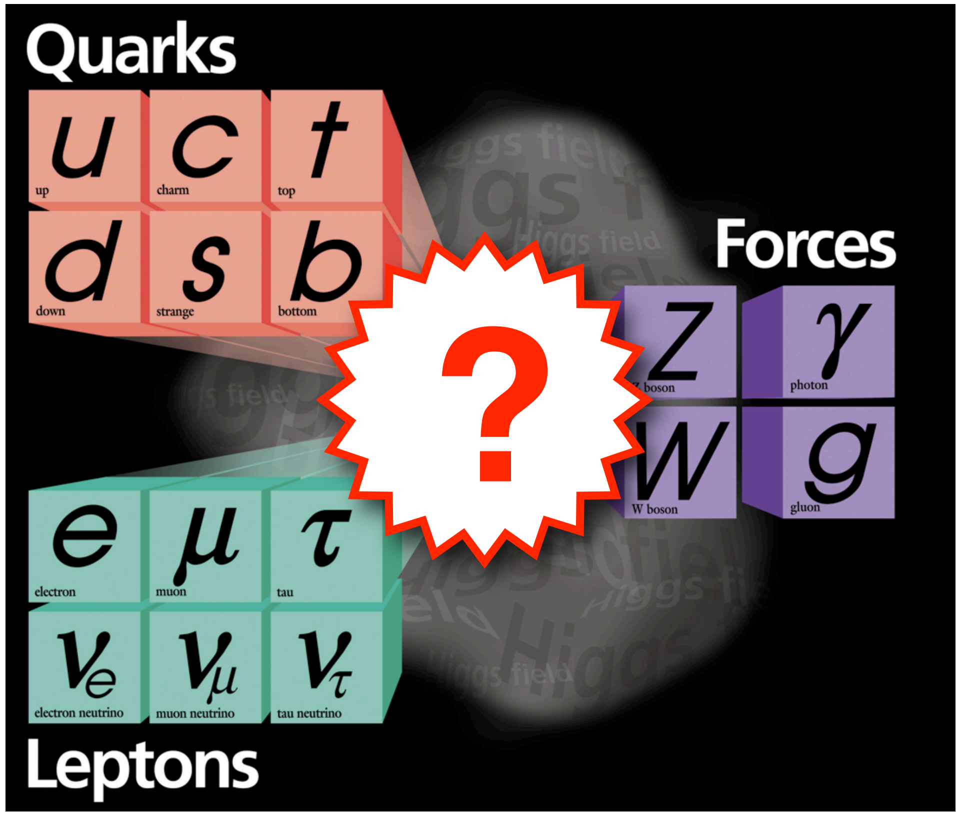
Gauge symmetry restoration possible if an extra scalar is present



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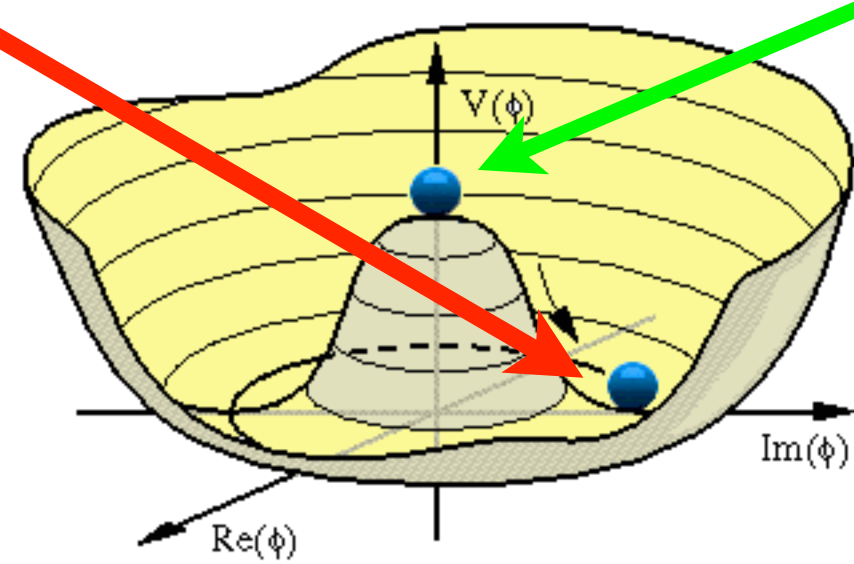

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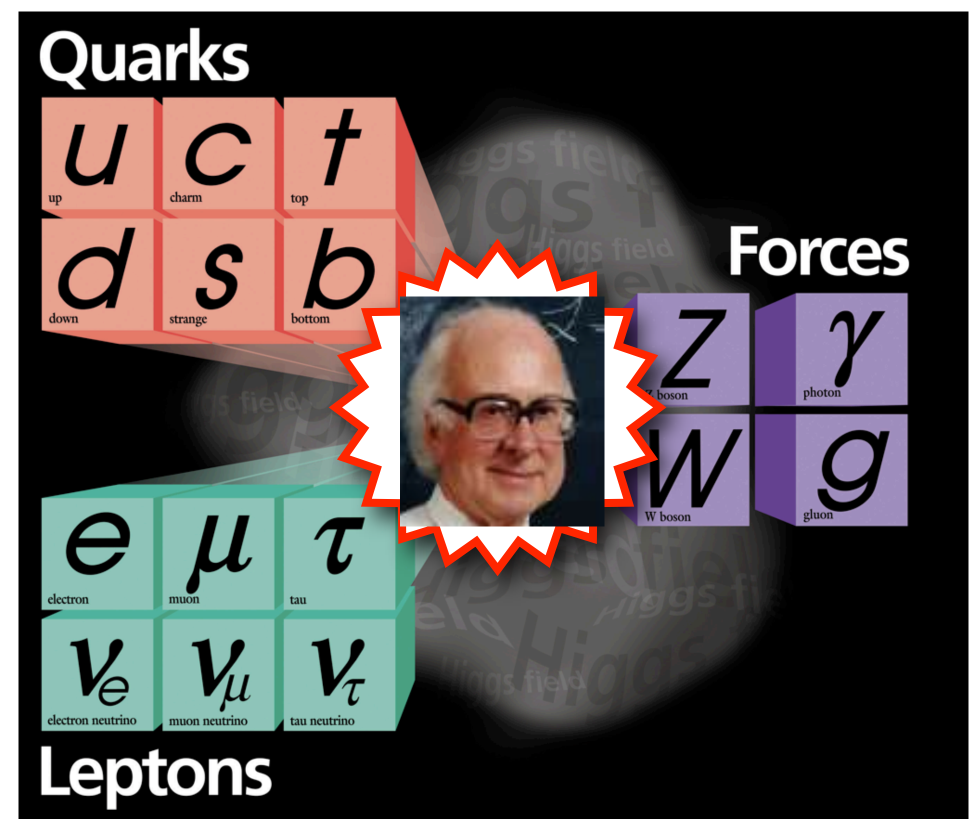
Gauge symmetry restoration possible if an extra scalar is present = the **Higgs boson**

Completes the SM:



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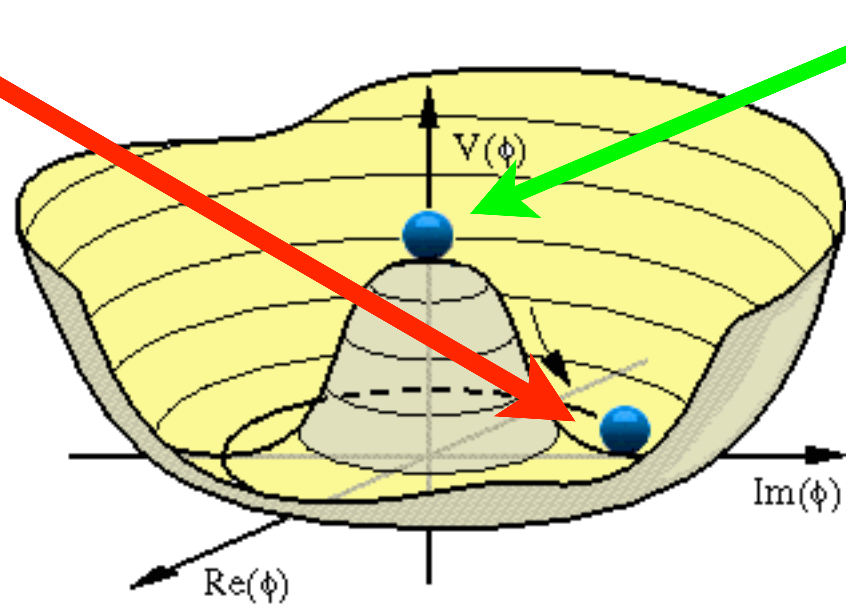

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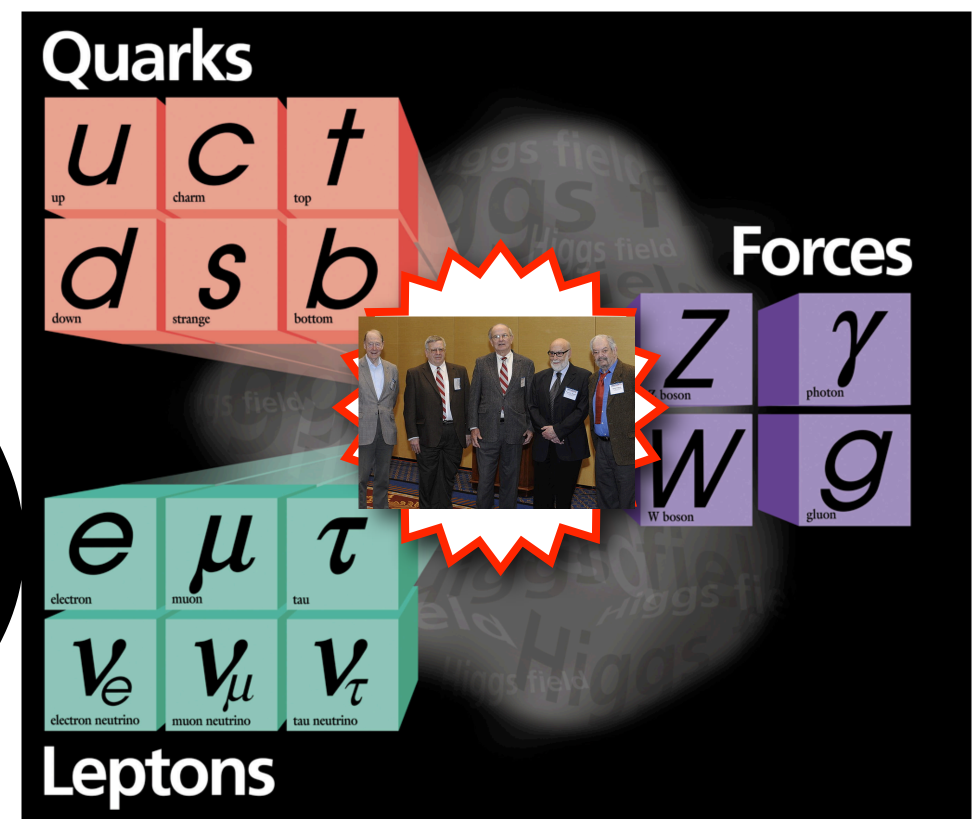
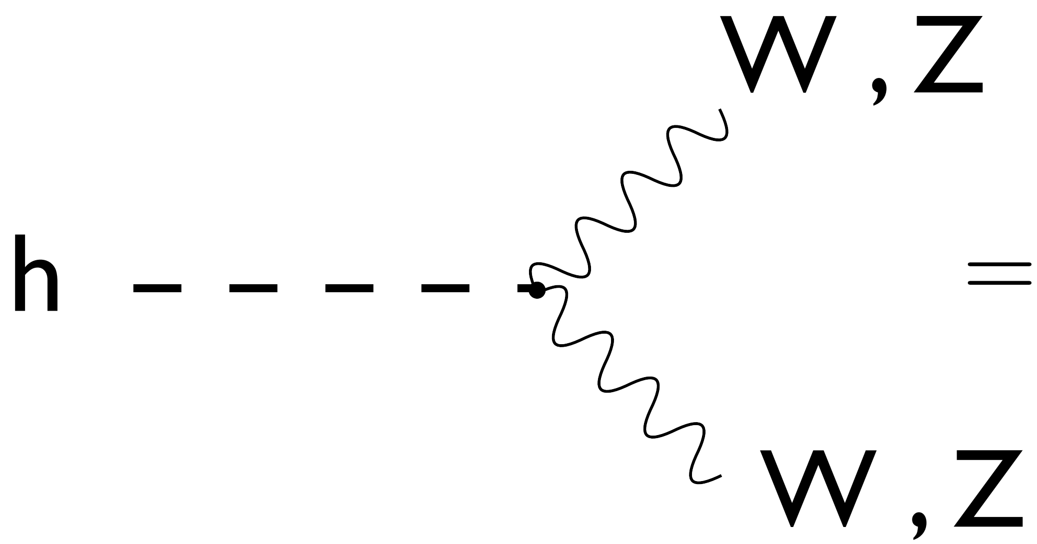


(or, more fair, the
Hagen-Englert-Guralnik-Higgs-Brout-Kibble
boson)

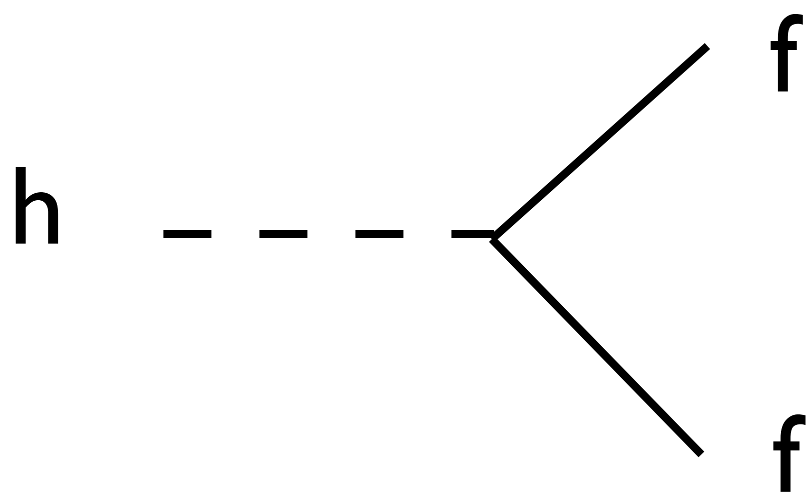
according to Wikipedia and Sakurai-Prize committee

The Higgs is a very special scalar:

Likes to couple to heavy particles:



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

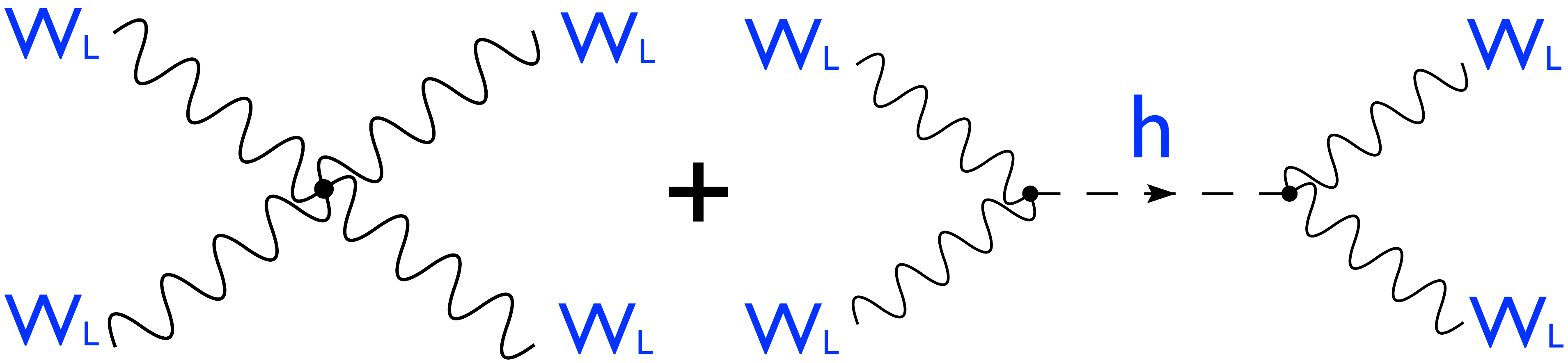


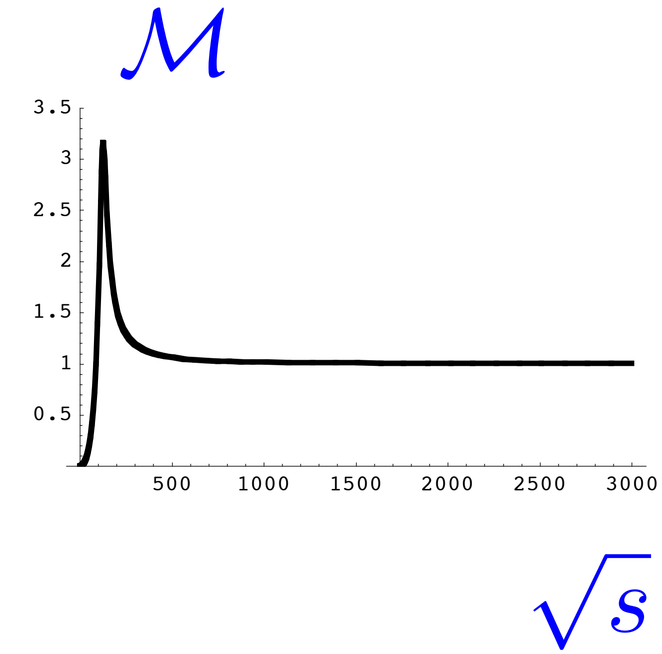
$$= \quad \frac{gM_f}{2M_W}$$

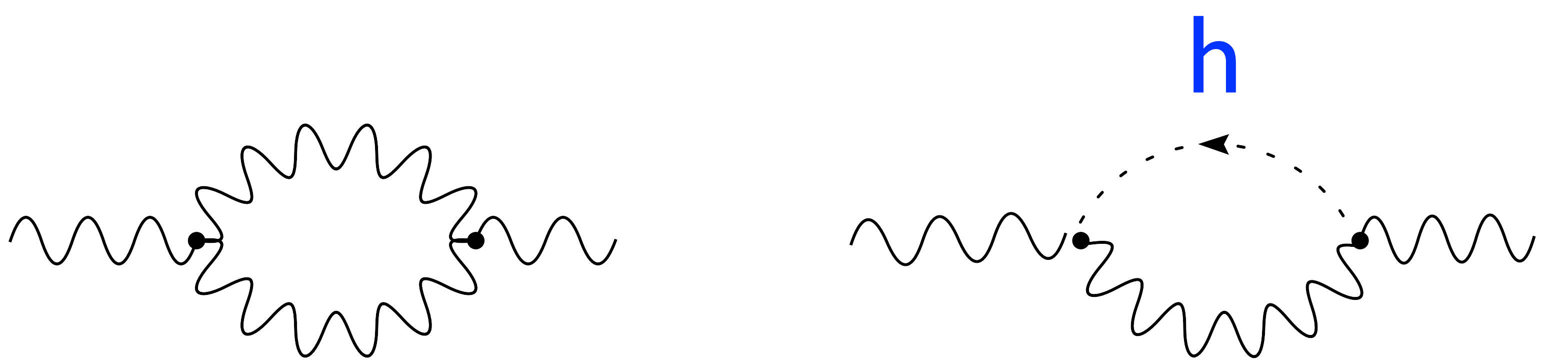
At tree-level the couplings must be **exactly** this ones to make the SM a **consistent** theory

Otherwise is **NOT** the Higgs = **“Impostor”**

With the Higgs **calculability** is recovered:







Finite results!

Back to the prediction era!

Only one unknown parameter:

The Higgs mass

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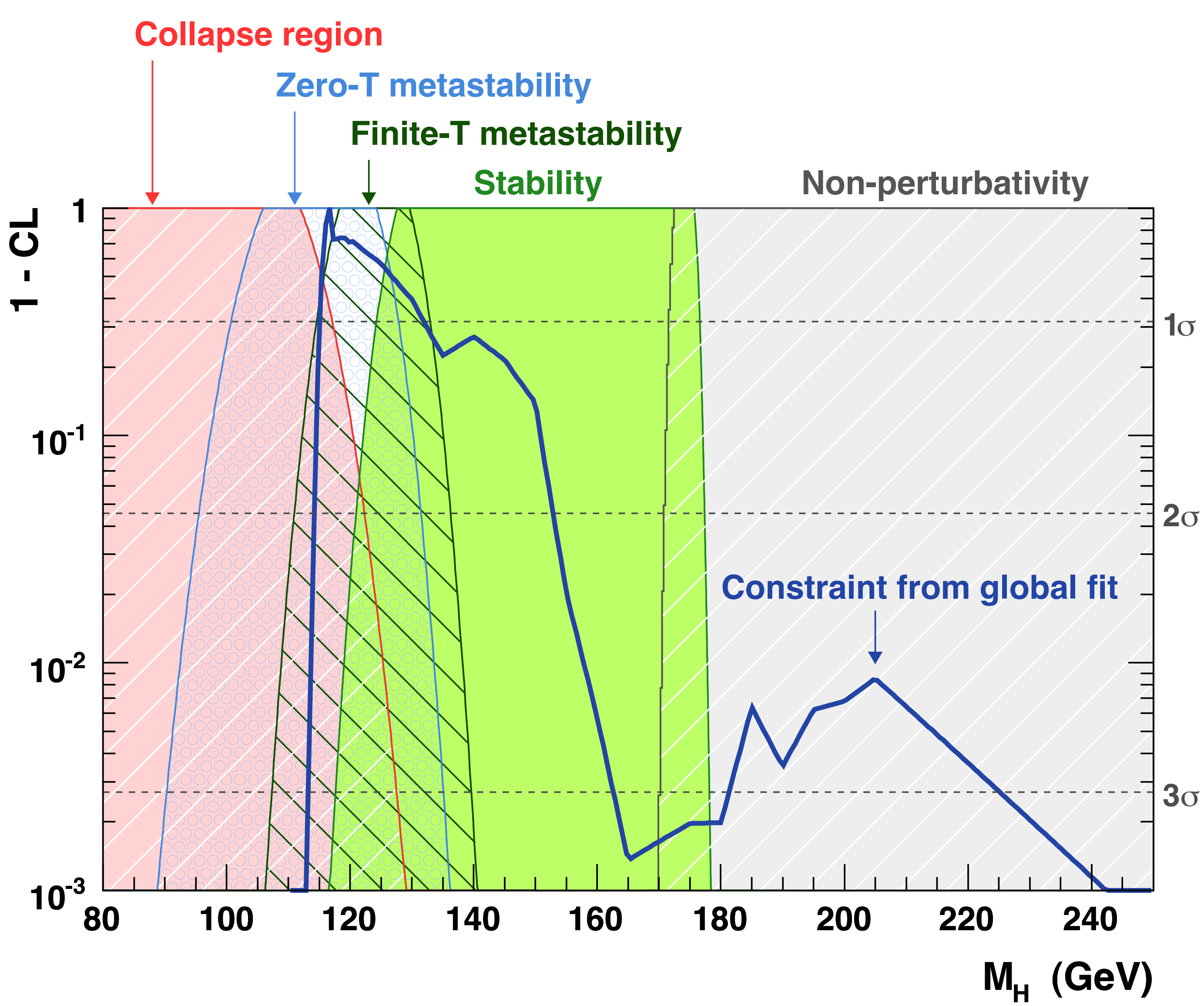
The Higgs mass

a) Theoretical bounds:

If we want the SM to be a theory valid up to the Planck scale:



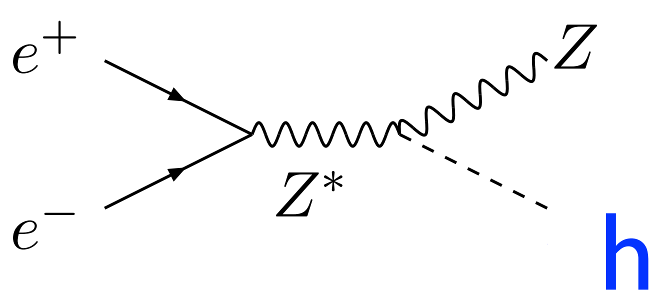
J.Ellis et al

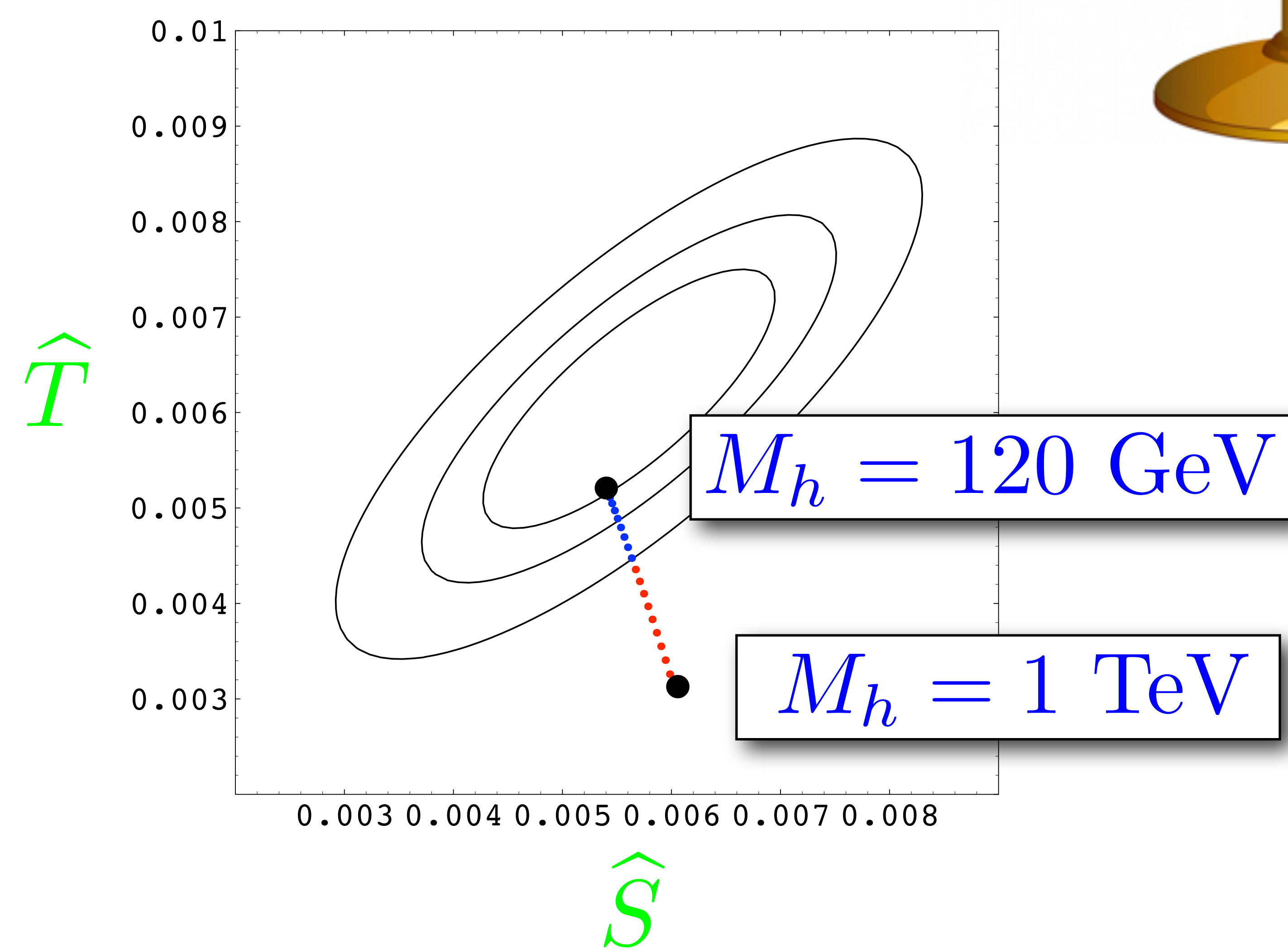
Only one unknown parameter:

The Higgs mass

b) Experimental bounds:

LEP searches + EW Precision Tests



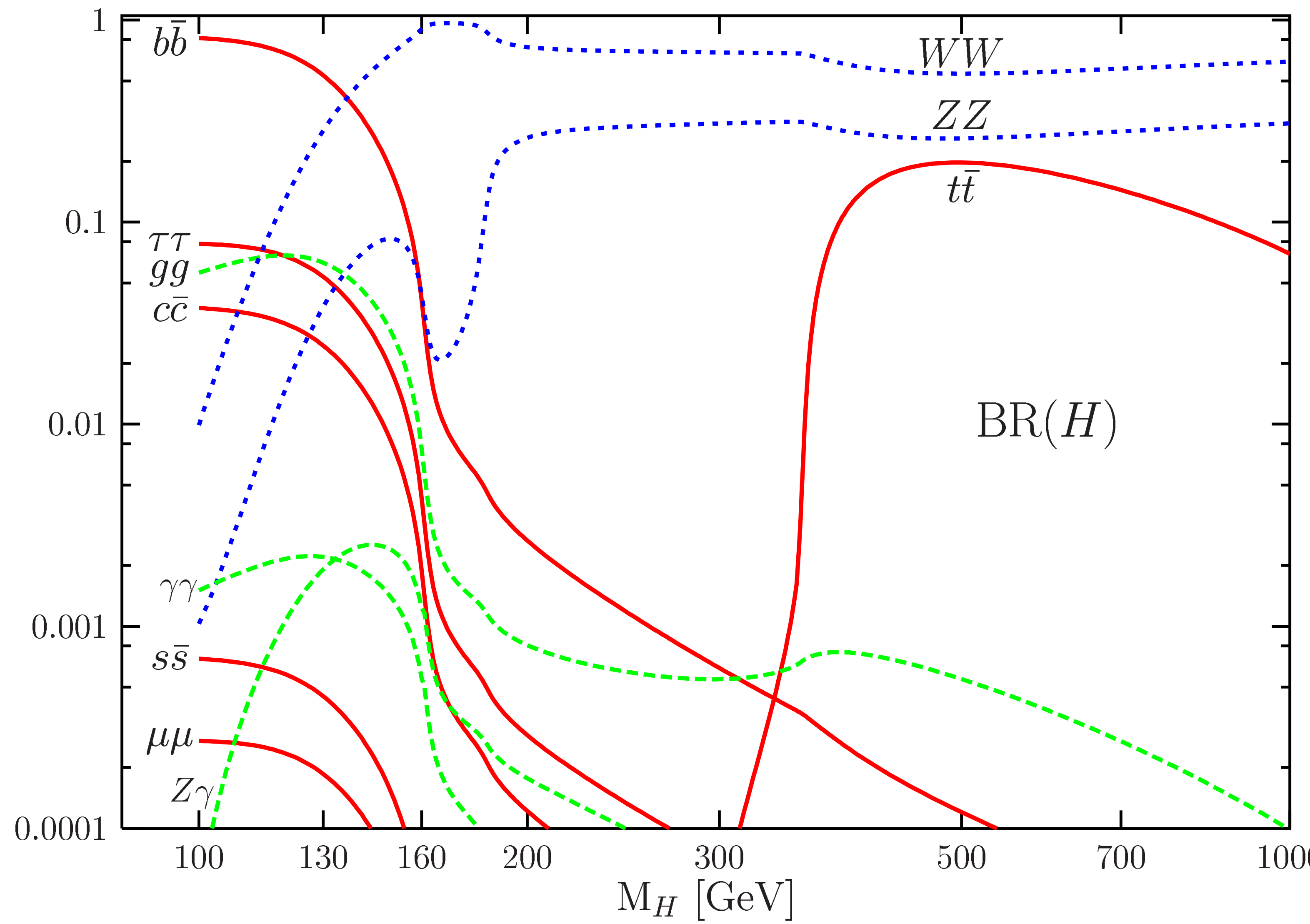


➥ 114 GeV < M_h < 157 GeV (95%CL)

Higgs hunting at the LHC

A precise theory, gives a precise prediction
for Higgs physics at the LHC

Higgs BR



Small uncertainties in present calculations: < 5%

Higgs production cross-section

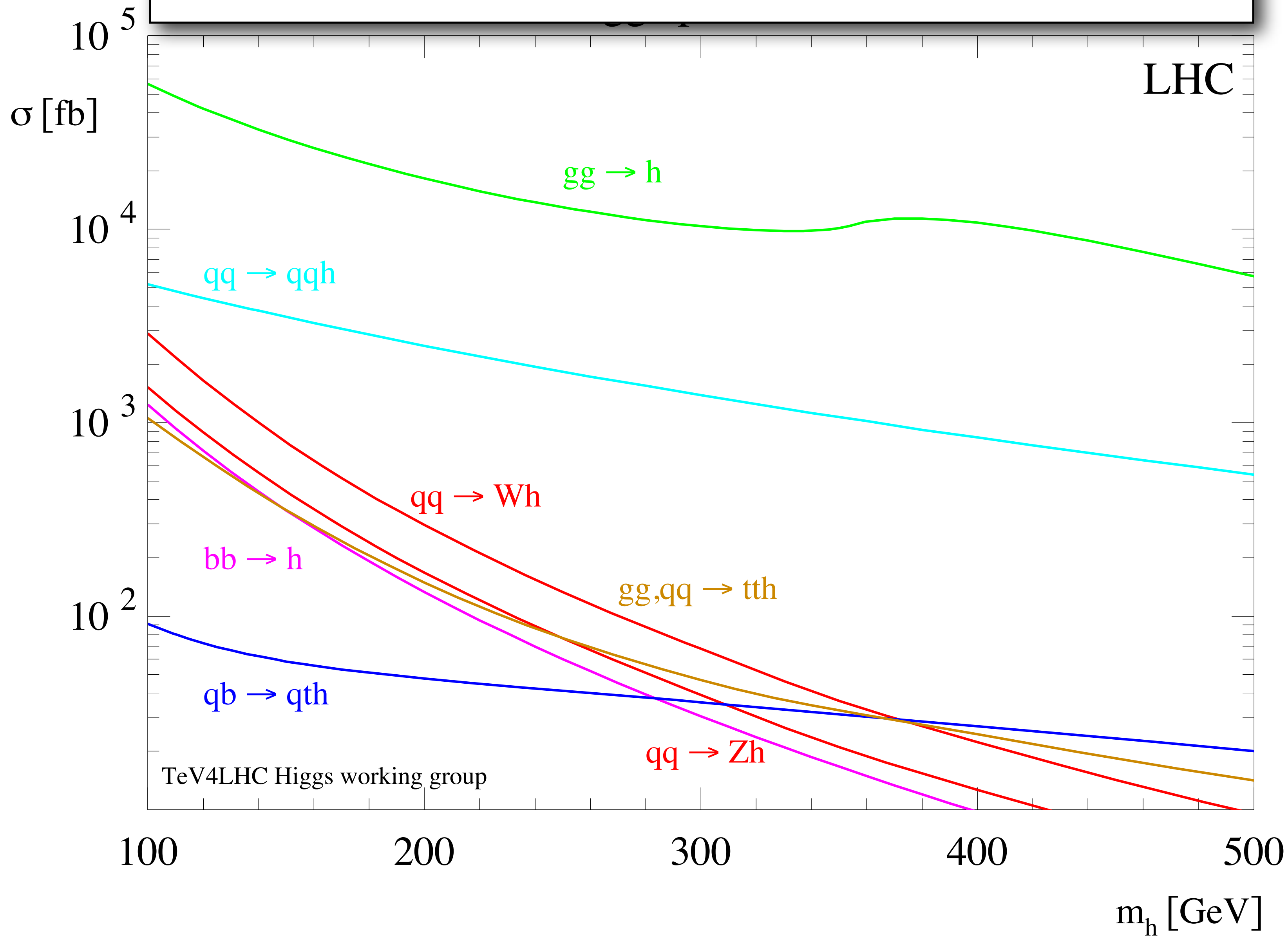
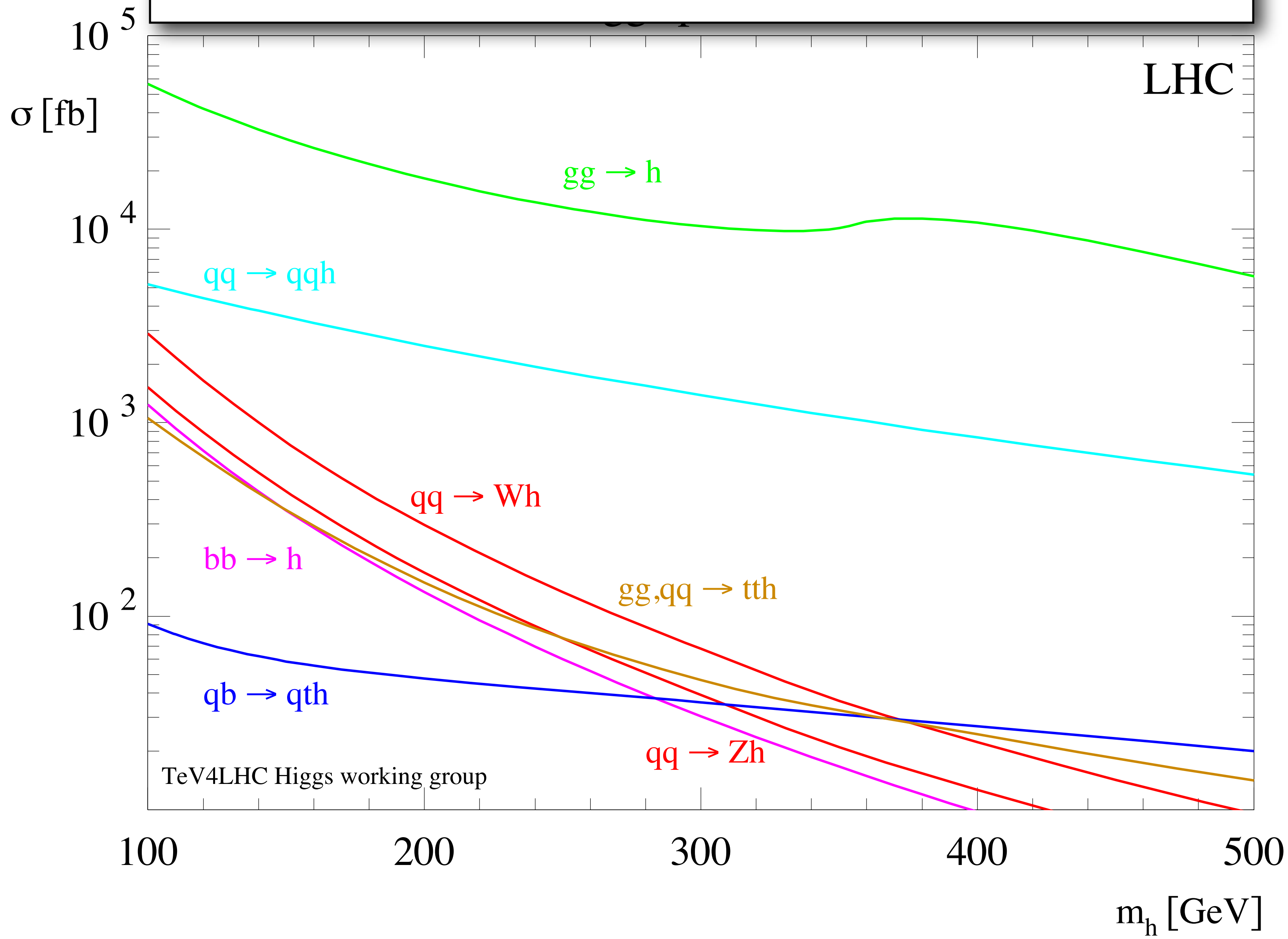


Fig. 1: Total cross sections for Higgs production at the LHC. The gluon fusion result is NNLO QCD with soft gluon resummation effects included at NNLL and uses MRST2002 PDFs with renormalization/factorization scales equal to m_h. The vector boson fusion curve is shown at NLO QCD with CTEQ6M PDFs and renormalization/factorization scales equal to m_h. The Vh results ($V = W, Z$) include NNLO QCD corrections and NLO EW corrections and use MRST2002 PDFs with the renormalization /factorization scales equal to the $m_h - M_V$ invariant mass. The $b\bar{b} \to h$ result is NNLO QCD, with MRST2002 PDFs, renormalization scale equal to m_h and factorization scale equal to $m_h/4$. The results for $t\bar{t}h$ production are NLO QCD, use CTEQ6M PDFs and set the renormalization/factorization scale to $m_t + m_h/2$ [100].

Higgs production cross-section



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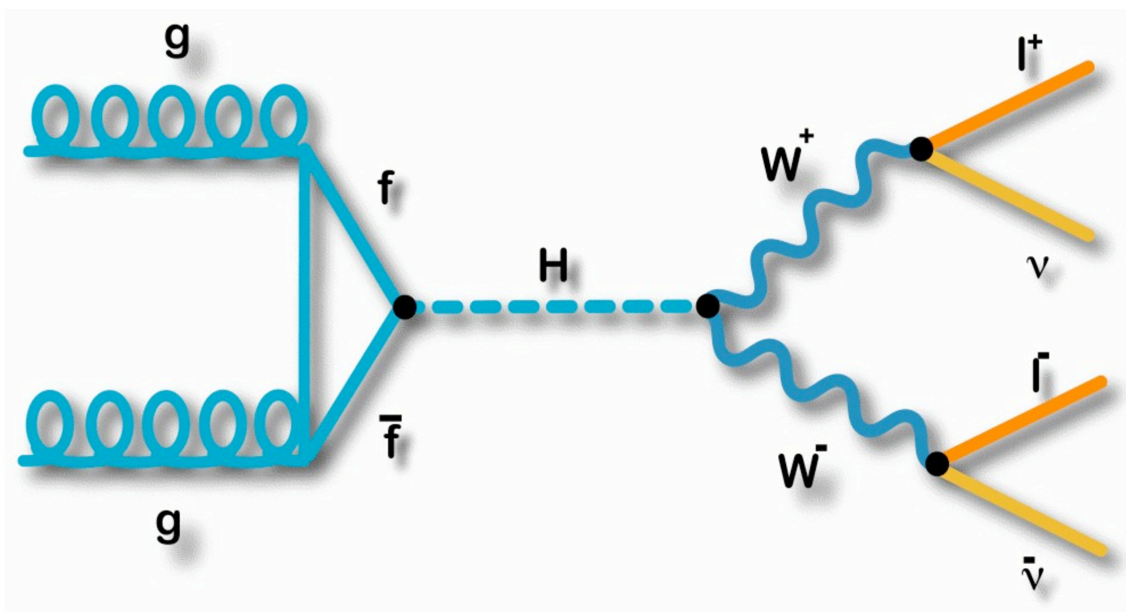
Uncertainties < 15% from strong corrections

Best scenario:

Production from color particles

+ Decay to colorless states:



ATLAS (talk at Planck10) for $\sqrt{s}$=7 TeV and 1/fb:

"Higgs: 3σ evidence in the mass range 145-180GeV"

... but full coverage in the long run

Is the Higgs a “hunting piece” worthy enough the LHC cost?

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Theoretical viewpoint:

There must be more than a single Higgs

Although the SM is consistent, it is not "natural"

In QFT is difficult to keep scalar masses small as compared to other large scales

($M_h << M_P$)

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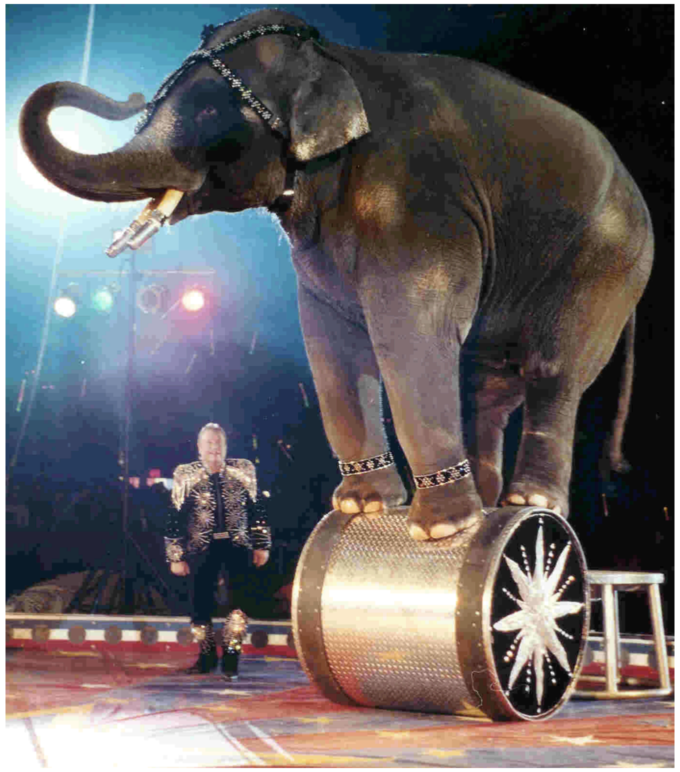
Hierarchy problem!



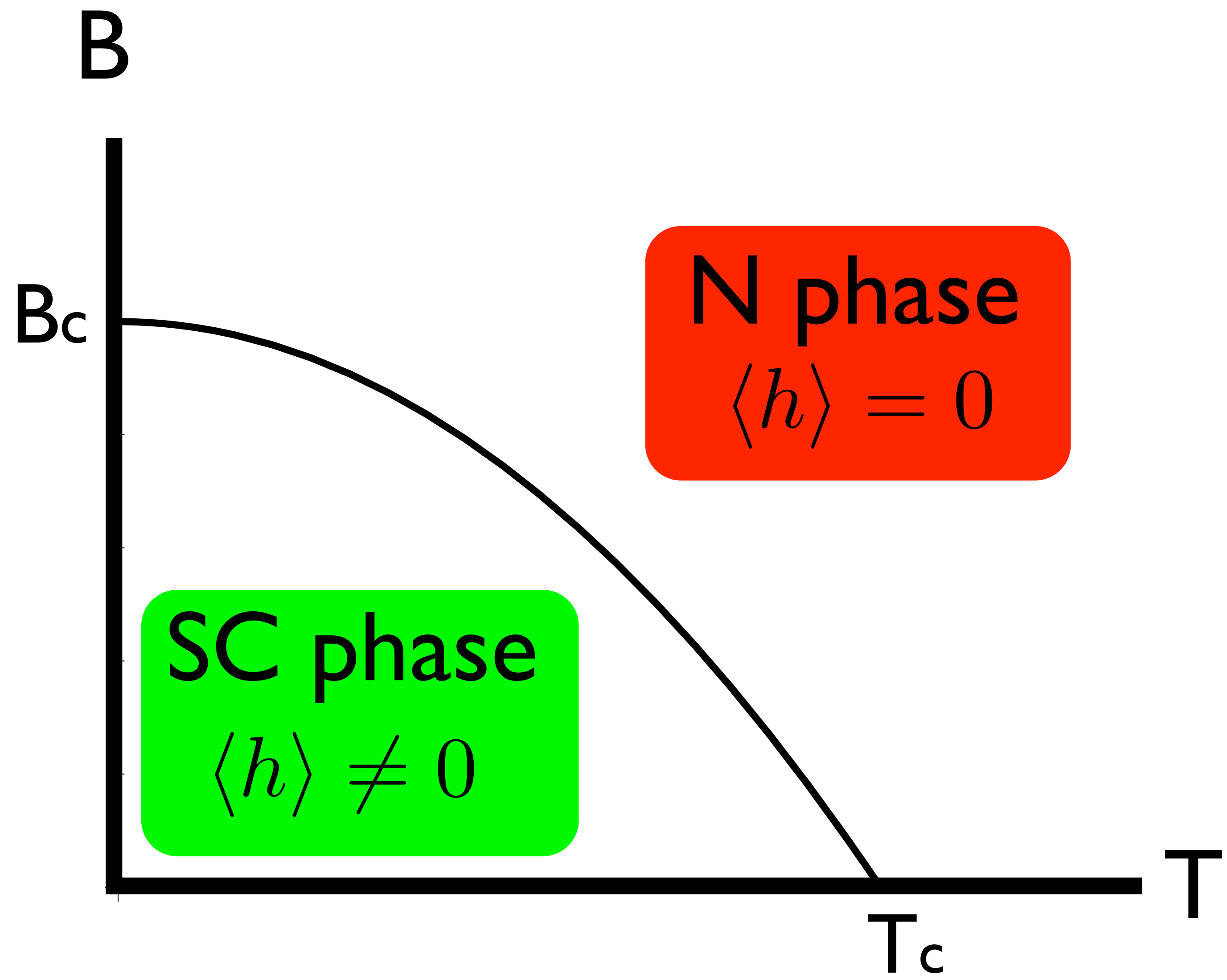
Example of fine-tuning

Analogy with Superconductivity

EWSB ⇔ Breaking of U(1)$_{EM}$

Higgs Model ⇔ Landau Model $\langle h \rangle = \langle e^- e^- \rangle$

$$V(h) = m^2|h|^2 + \lambda|h|^4$$



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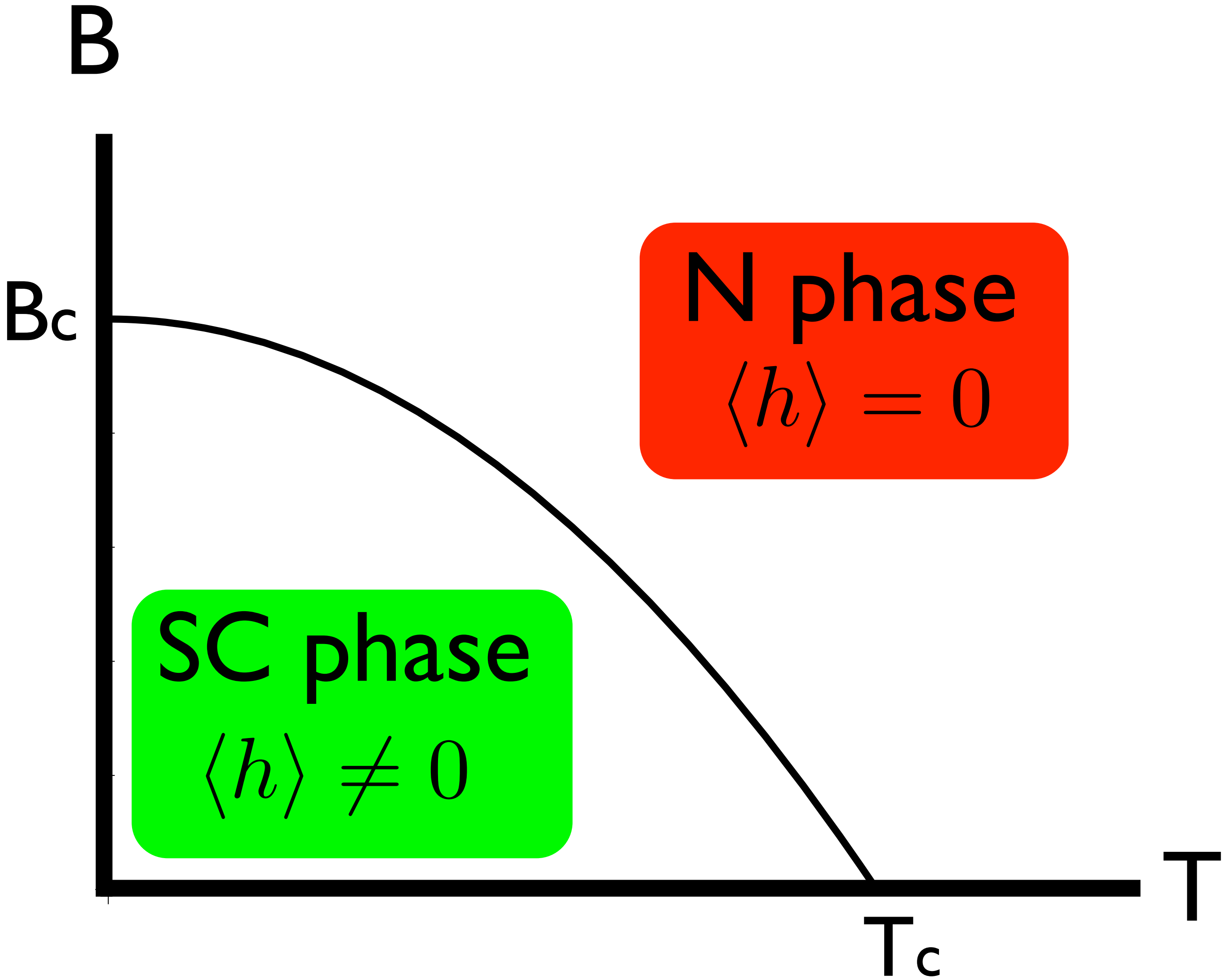
Give Landau Model a good description of superconductors?



Analogy with Superconductivity

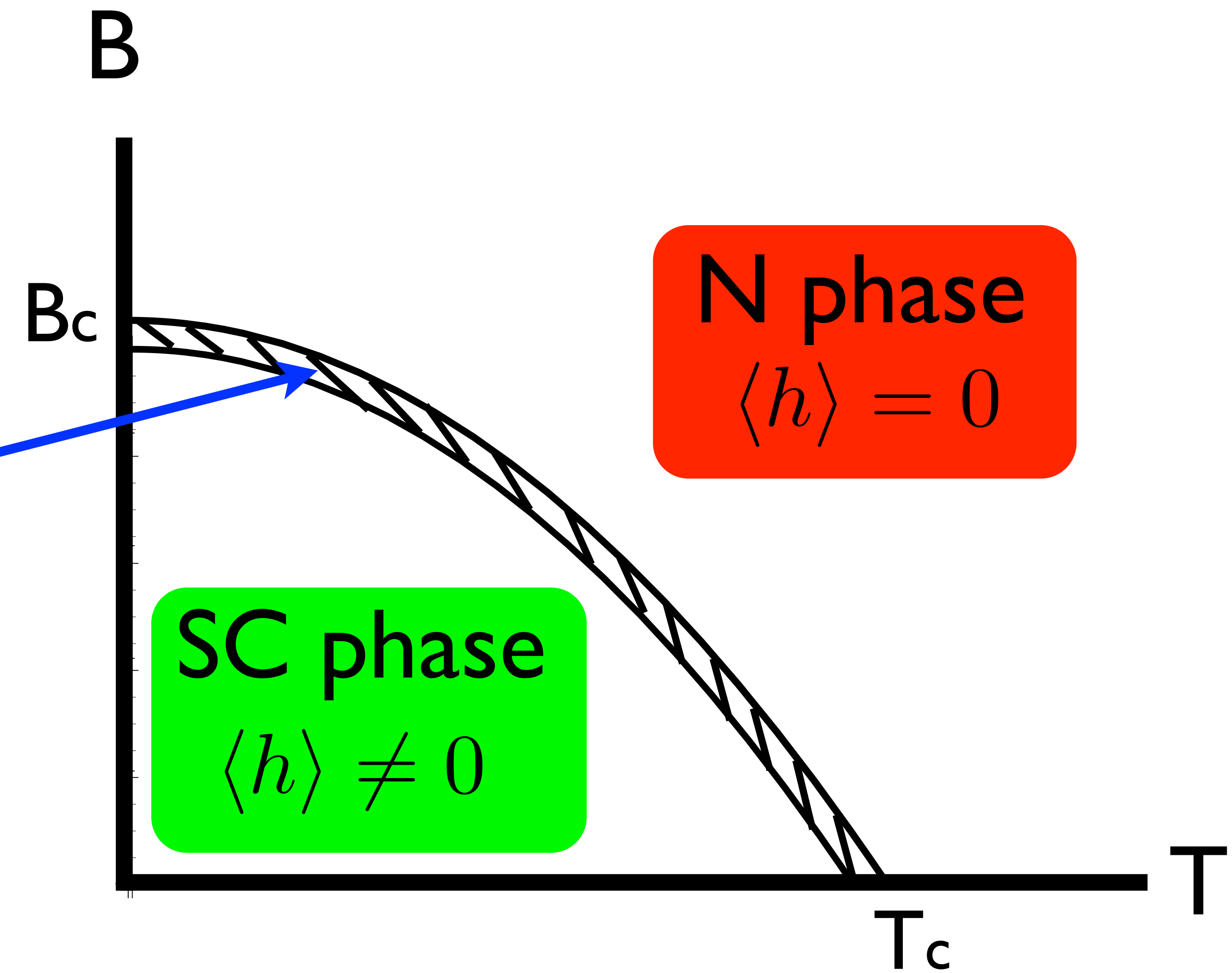
EWSB $\Leftrightarrow$ Breaking of U(1)$_{EM}$

Higgs Model $\Leftrightarrow$ Landau Model $\langle h \rangle = \langle e^- e^- \rangle$

Give Landau Model a good description of superconductors?

NO, it only works close to the critical line

only there $\langle h \rangle$ is small and it makes sense to Taylor-expand the potential:



$$V(h) = m^2|h|^2 + \lambda|h|^4 + \cdots$$

Possibilities that theorists envisage to tackle the Hierarchy Problem:

1) **Supersymmetry**: Stabilize the Higgs potential

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

As in superconductivity: h ~ ee

or QCD: pions ~ $q\bar{q}$

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

Supersymmetry = MSSM

Supersymmetry = MSSM

Brings Predictions:

1) **Extra** doublet needed: $h \;+\; H,\ A,\ H^{+}$

Supersymmetry = MSSM

Brings Predictions:

1) **Extra** doublet needed: $\underbrace{h \;+\; H}_{\text{Both play the role of the SM Higgs}}, A, H^{+}$

Supersymmetry = MSSM

Brings Predictions:

1) **Extra** doublet needed: $\underbrace{h \;+\; H}_{\text{Both play the role of the SM Higgs}}, A, H^+$

2) One Higgs , h, always **light**: $M_h \lesssim 130 \text{ GeV}$

Good: Since EWPT favors a light Higgs

Bad: Since LEP Higgs bounds rule out a big chunk of the MSSM parameter space (~ 90% or more)

MSSM Higgs hunting at the LHC

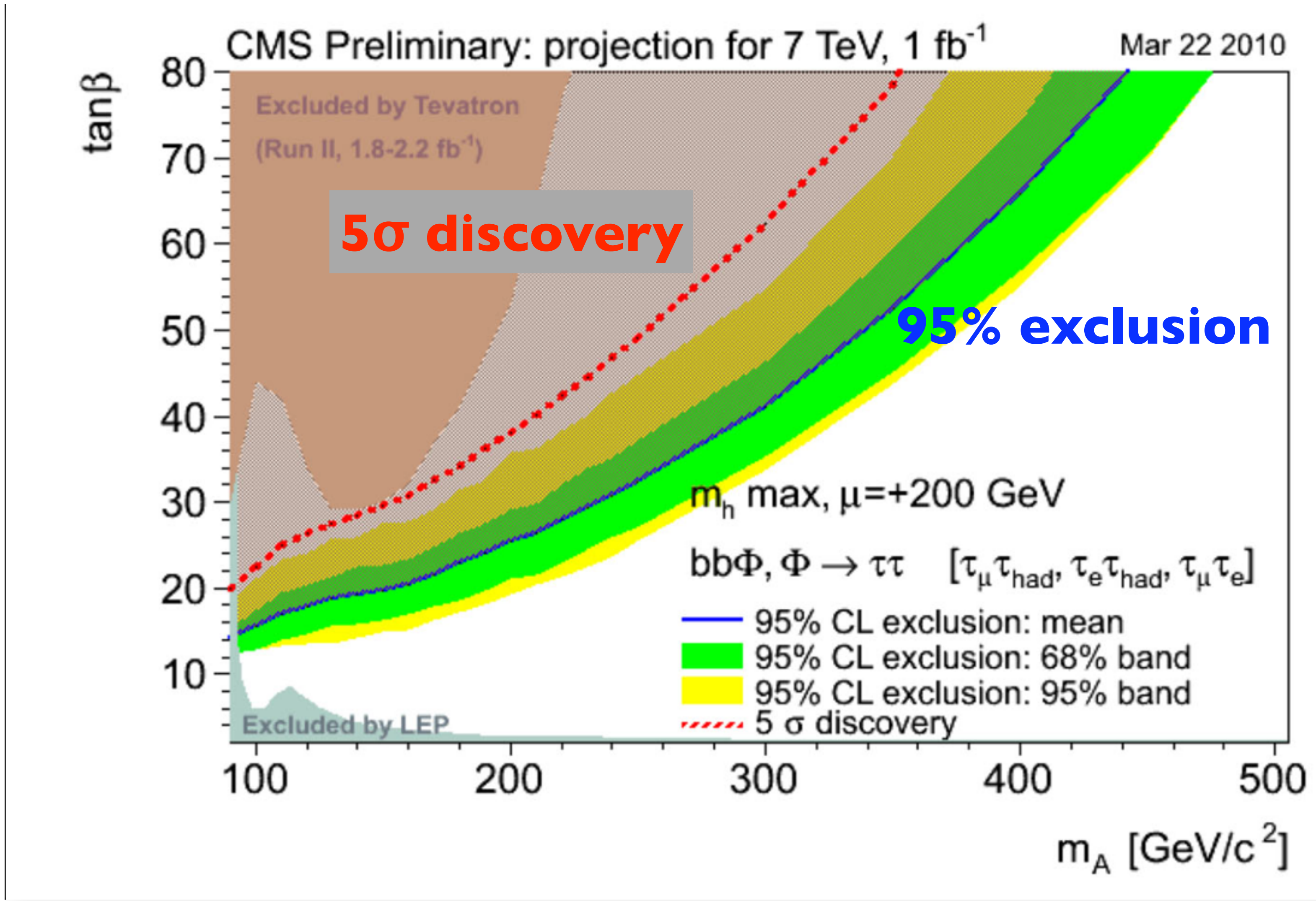
Bad news: h too light to decay to WW/ZZ

A, H^+ have very small couplings to VV

H small regions with sizable couplings to WW/ZZ

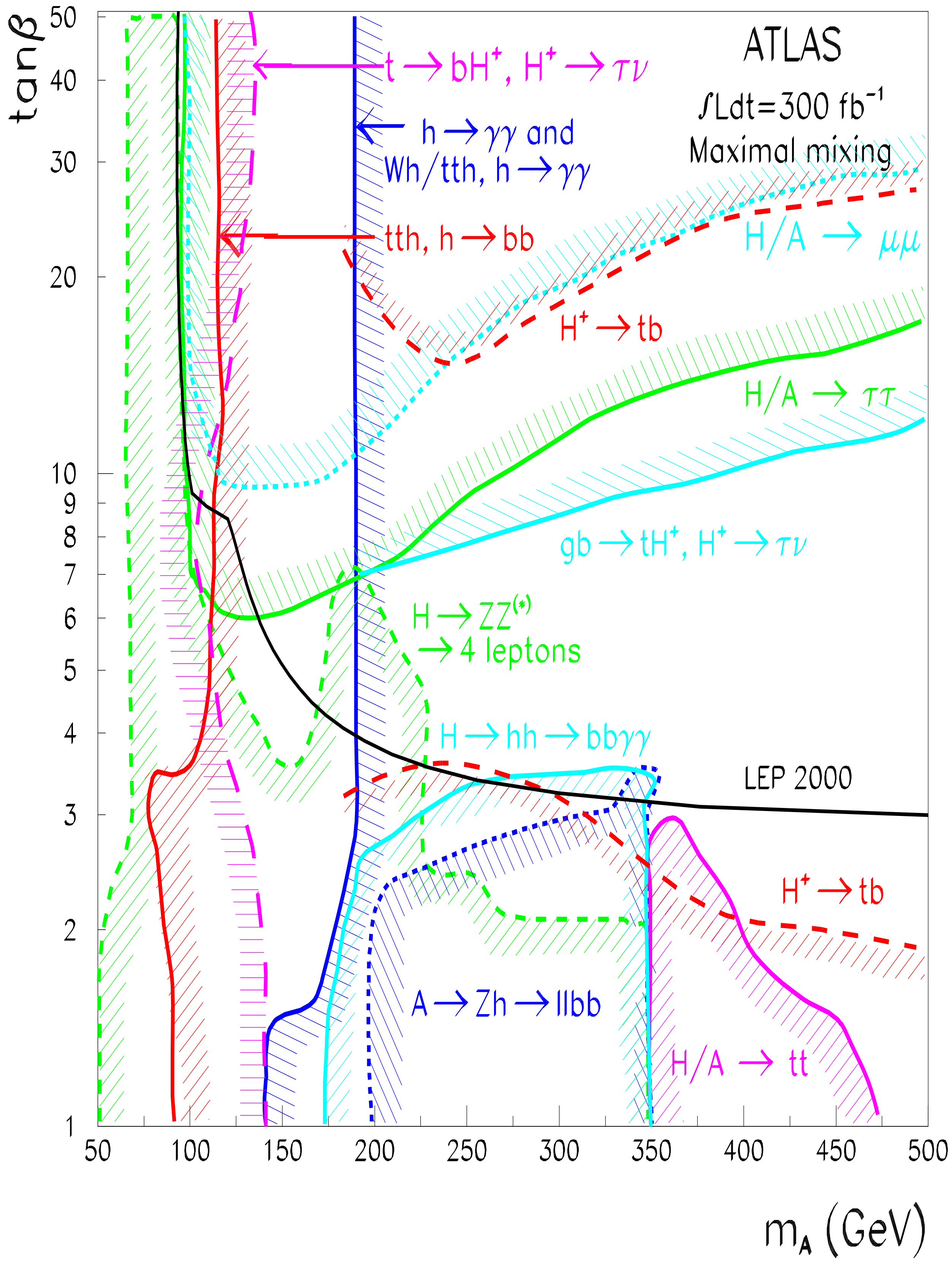
Good news: Regions where the decays of H, A, H^+ to leptons are enhanced (Large Tanβ region)

Near future:



CMS Preliminary: projection for 7 TeV, 1 fb^{-1}
Mar 22 2010
tanβ
Excluded by Tevatron
(Run II, 1.8-2.2 fb^{-1})
5σ discovery
95% exclusion
m_h max, μ=+200 GeV
bbΦ, Φ → ττ [$\tau_\mu\tau_{had}$, $\tau_e\tau_{had}$, $\tau_\mu\tau_e$]
95% CL exclusion: mean
95% CL exclusion: 68% band
95% CL exclusion: 95% band
5 σ discovery
Excluded by LEP
m_A [GeV/c^2]

In the long run....



Composite Higgs

Composite Higgs

Two attitudes:

Positive: We already have examples like this in nature:

QCD: $m_\pi << M_P$

Negative: Not again **strong dynamics**!

calculations are difficult

Composite Higgs

Two attitudes:

Positive: We already have examples like this in nature:

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Negative: Not again **strong dynamics**!

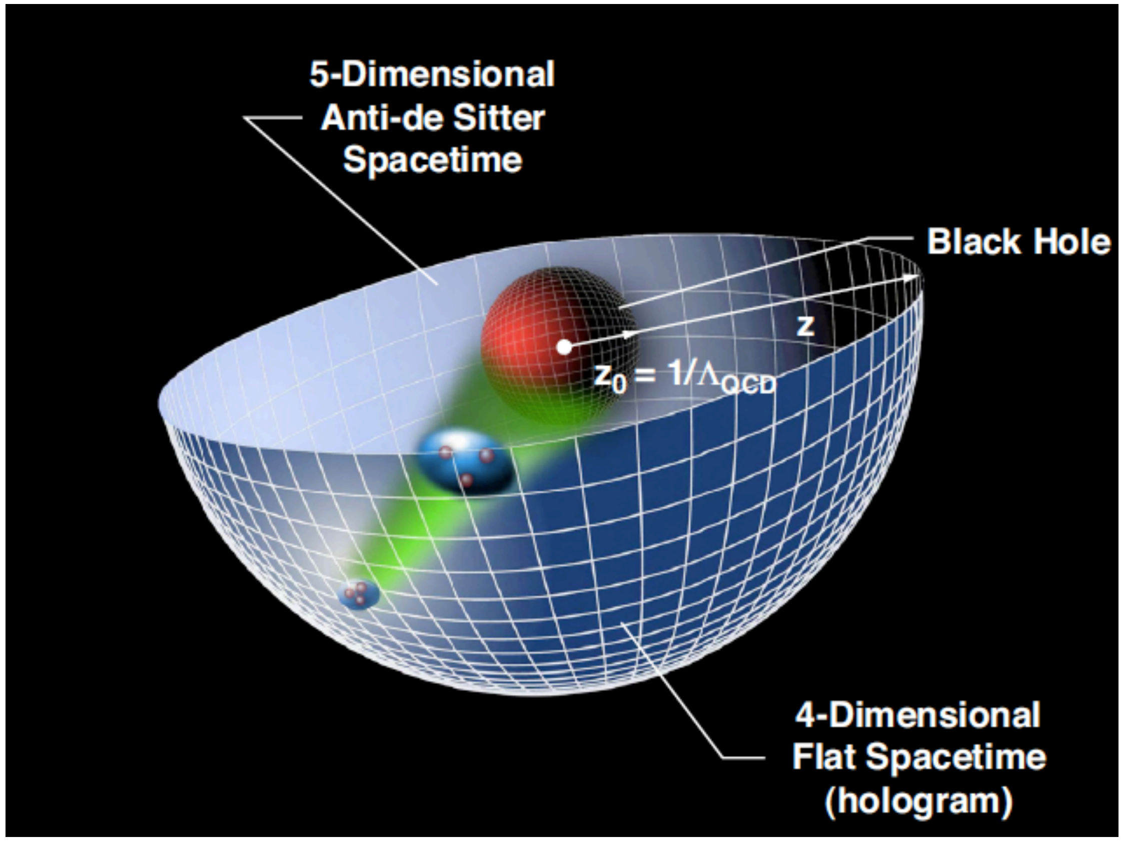
calculations are difficult

Picture from
G.F. de Teramond

"Sexier" approach to composite Higgs:

Higgs as an "hologram"

Contino,Nomura,AP 03



The 4D compositeness properties of the Higgs are due to its 5D nature

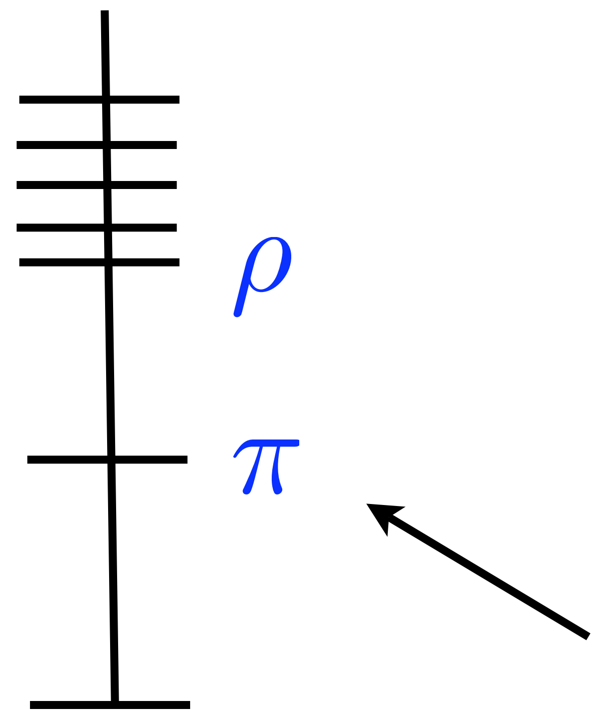
(AdS/CFT correspondence)

Maldacena 98

Composite Higgs scenario is inspired by QCD where one observes that the (pseudo) scalar are the lightest states

Kaplan,Georgi '80

QCD spectrum:

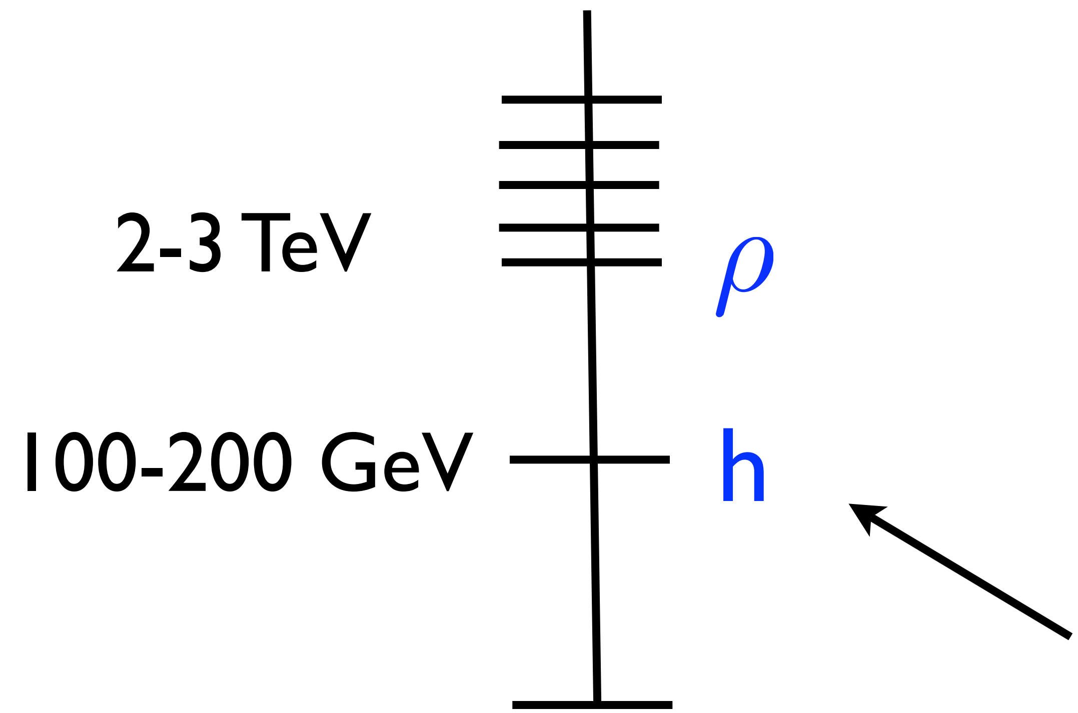


Are Pseudo-Goldstone bosons (PGB)

Mass protected by global symmetries in QCD!

Spectrum of the new QCD-like sector:

Kaplan,Georgi '80



Pseudo-Goldstone bosons (PGB)

Mass protected by a global symmetry G

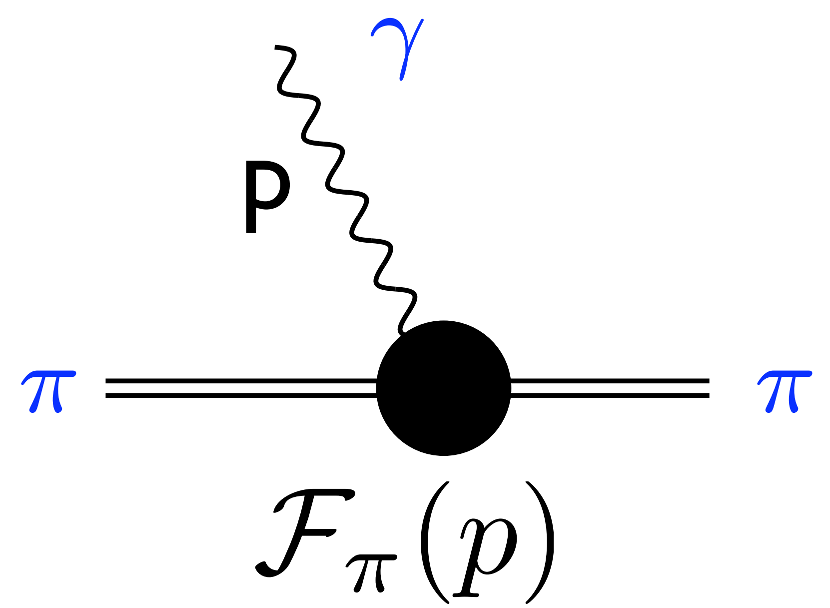
Similar but slightly different approach: **Little Higgs**

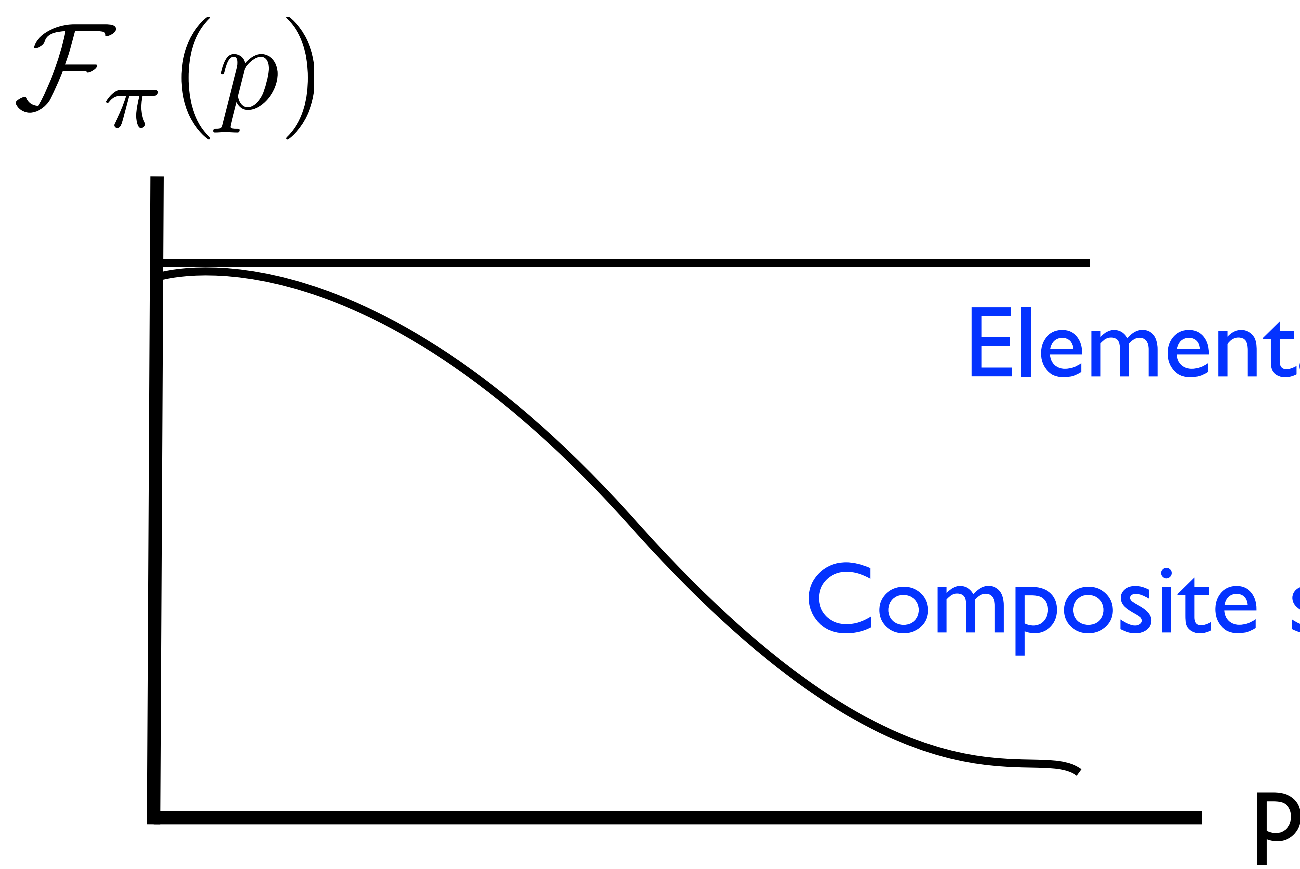
Arkani-Hamed,Cohen,Georgi

How to unravel the **composite** nature of the Higgs?

Easy in an **ideal** collider:

As we do it with pions in QCD:

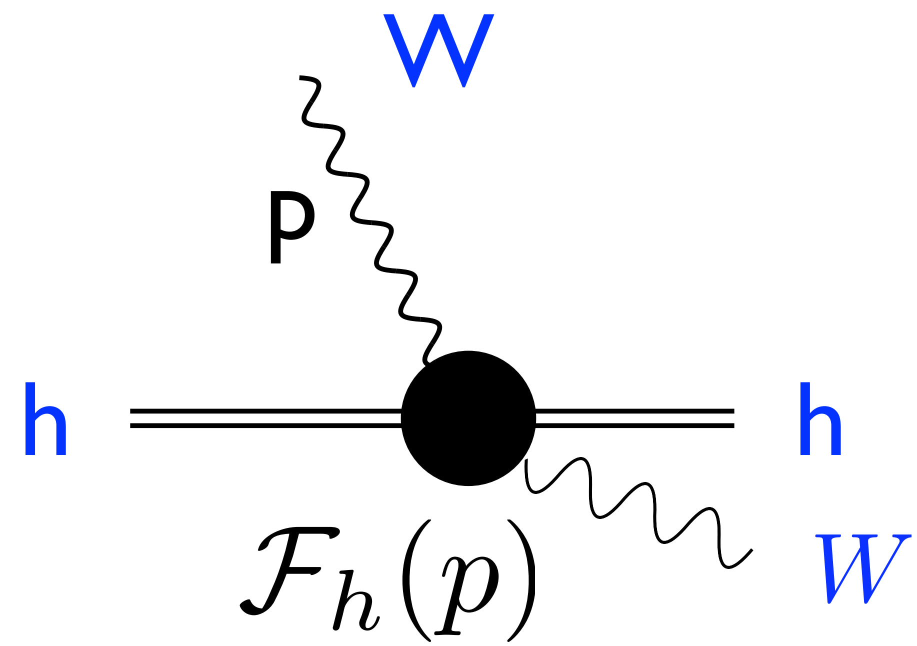


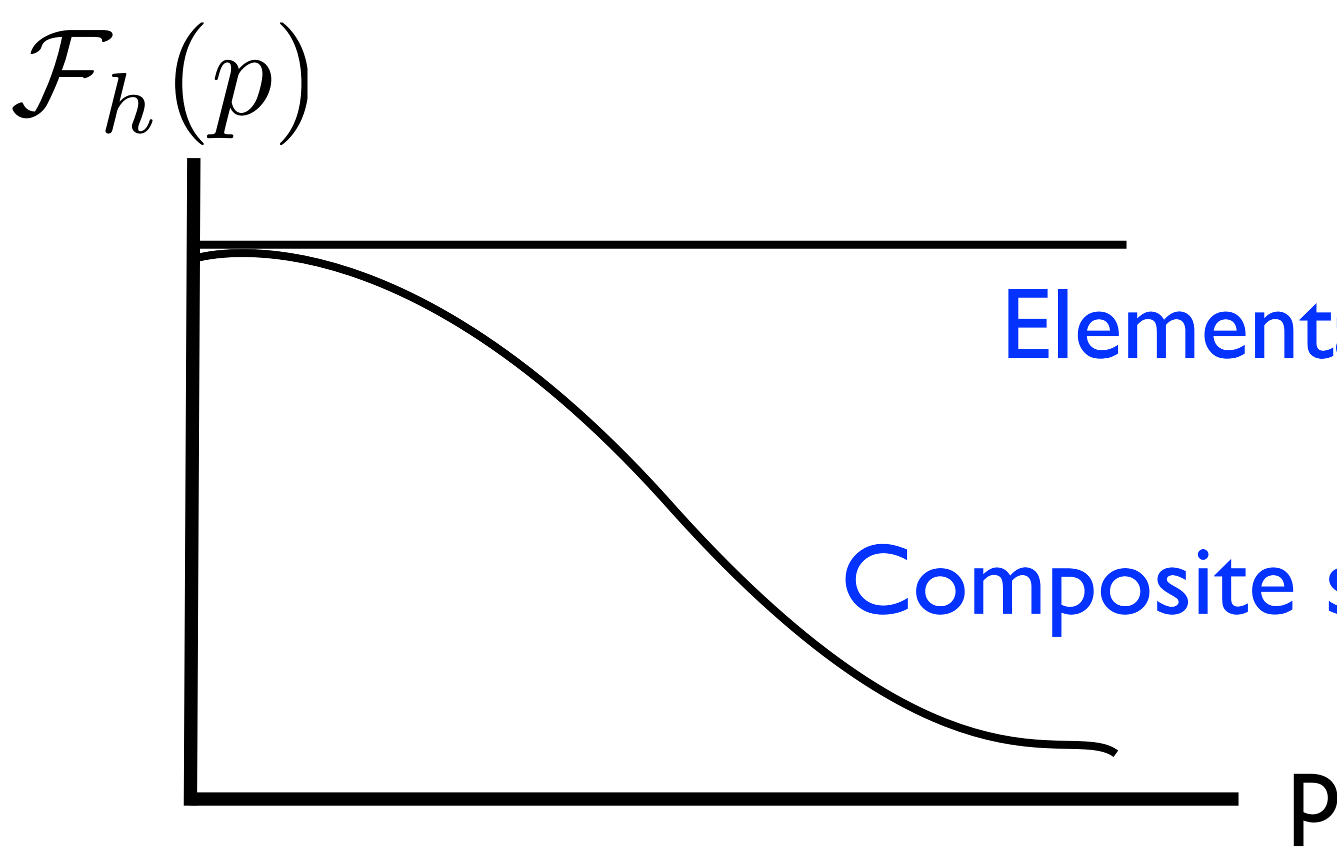


How to unravel the **composite** nature of the Higgs?

Easy in an **ideal** collider:

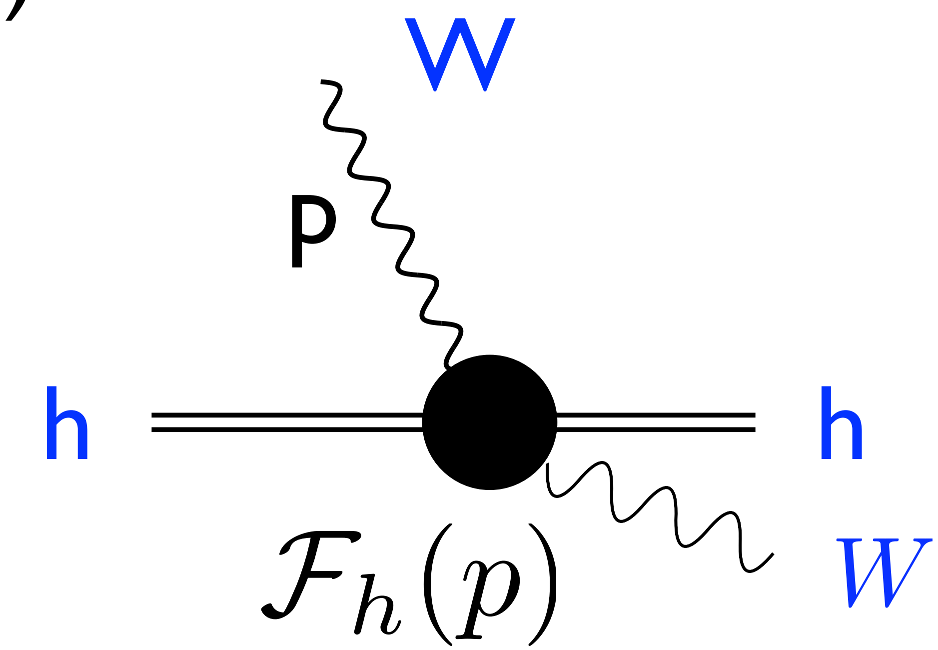
Similarly for the Higgs:



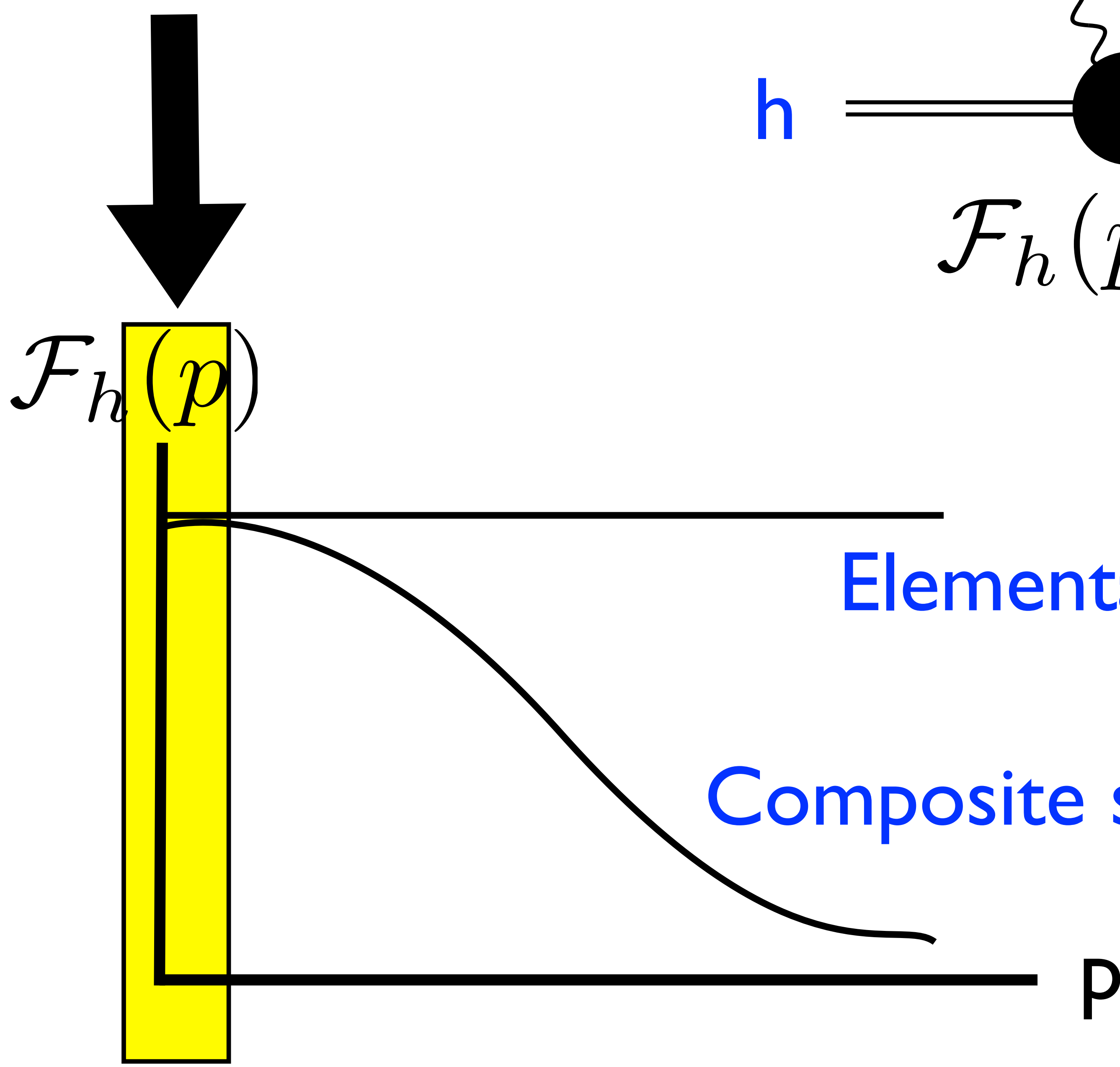


How to unravel the **composite** nature of the Higgs?

But in a **real** collider (LHC):



Only access up to few TeV



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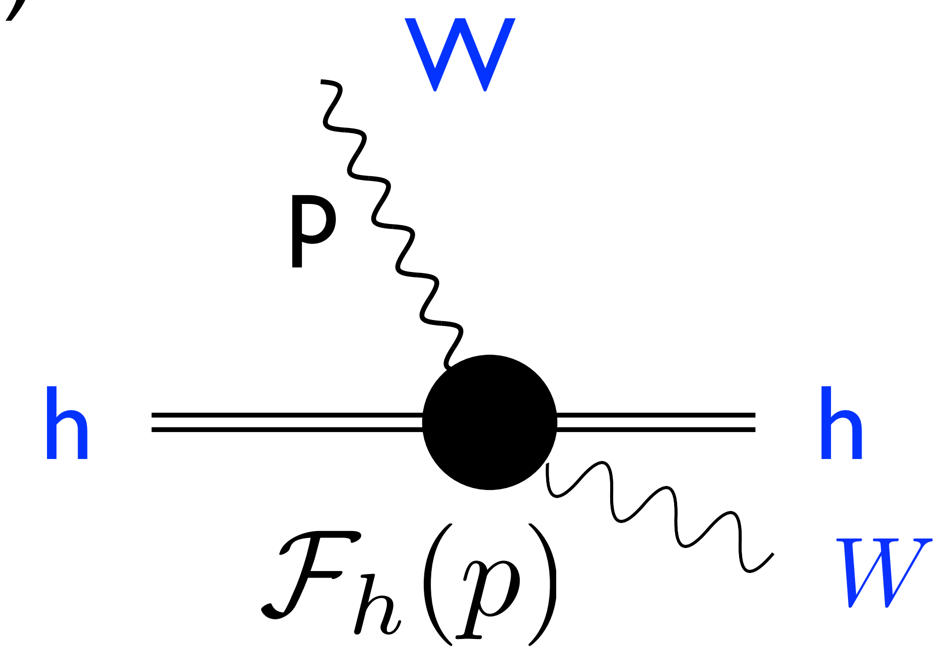

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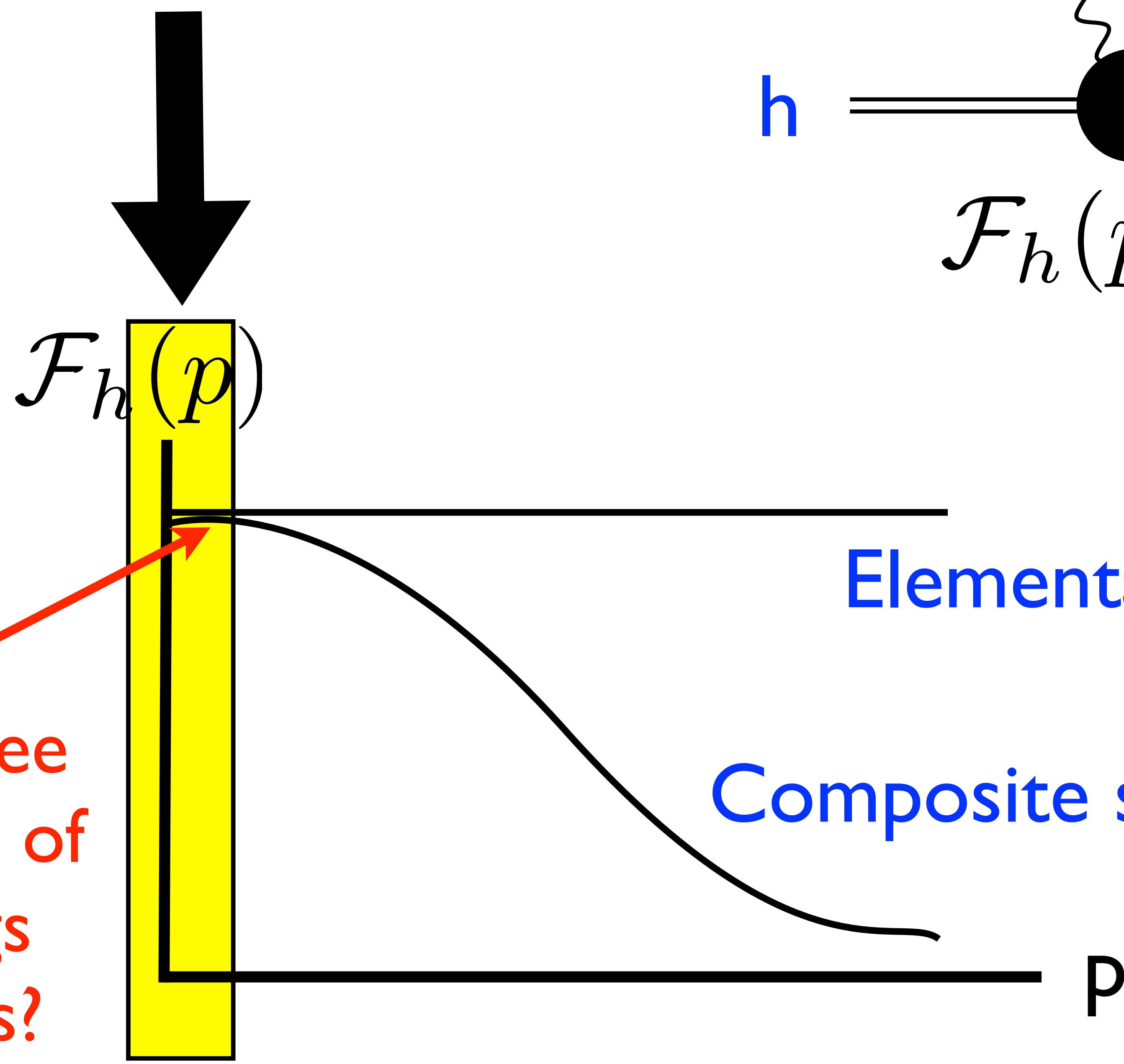


Can we see deviations of the Higgs couplings?

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:

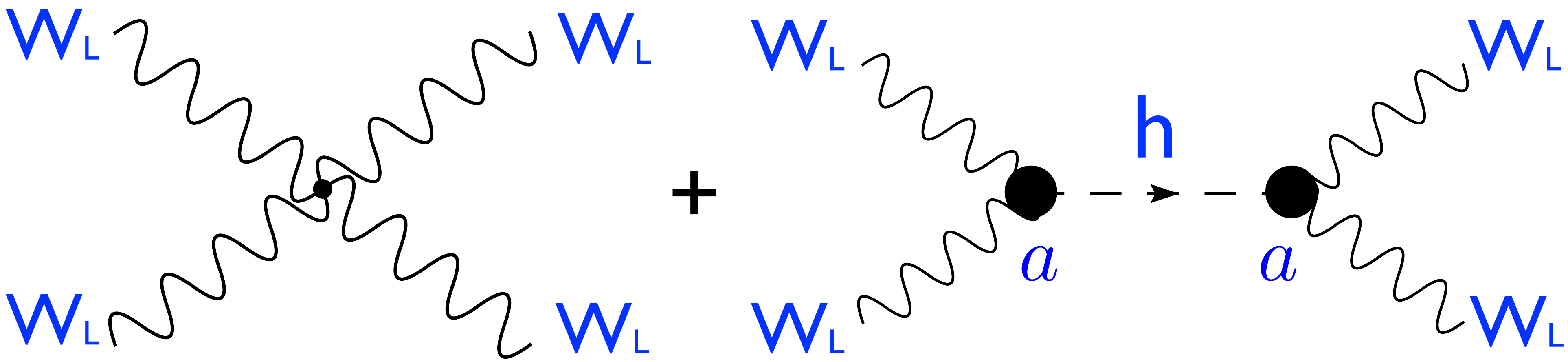
Giudice,Grojean,AP,Rattazzi 07

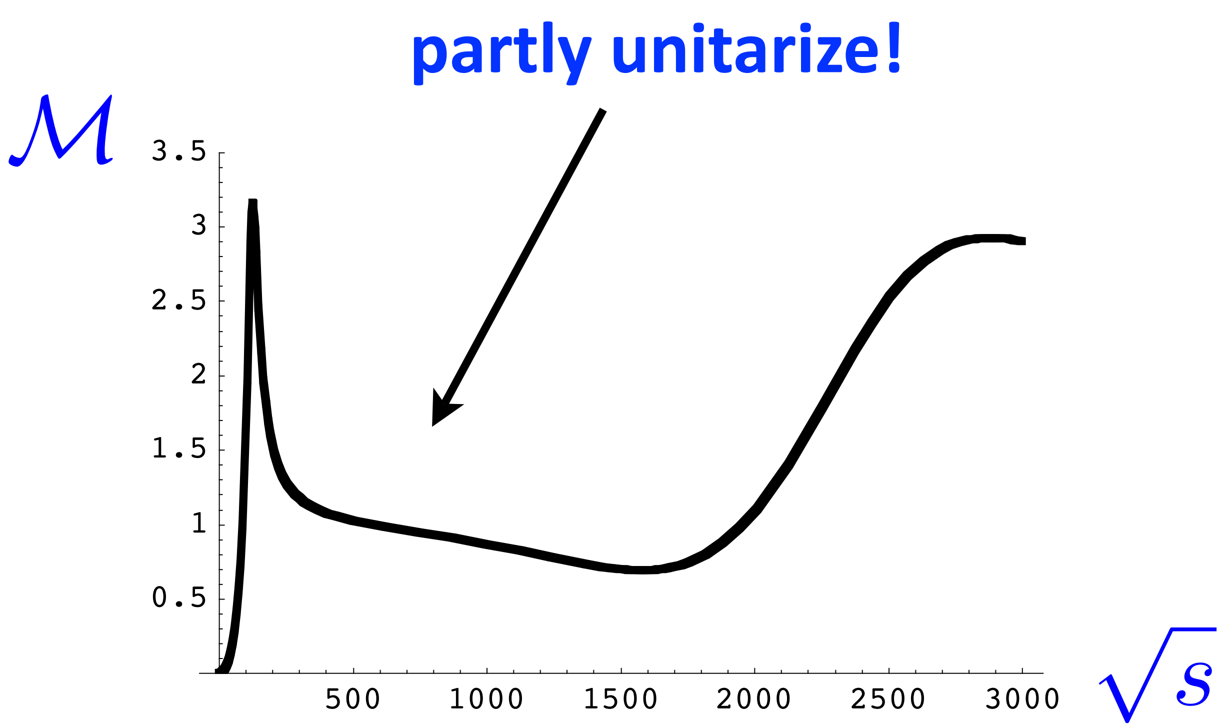
$$a = \sqrt{1 - \frac{v^2}{f^2}} \qquad b = 1 - \frac{2v^2}{f^2} \qquad c = \sqrt{1 - \frac{v^2}{f^2}}$$

Scale related to the composite-scale

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

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





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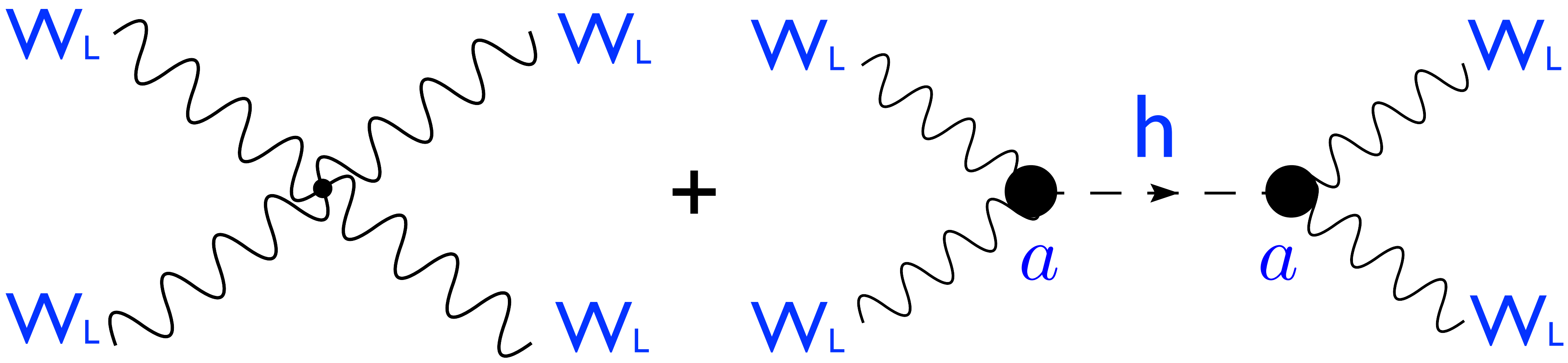

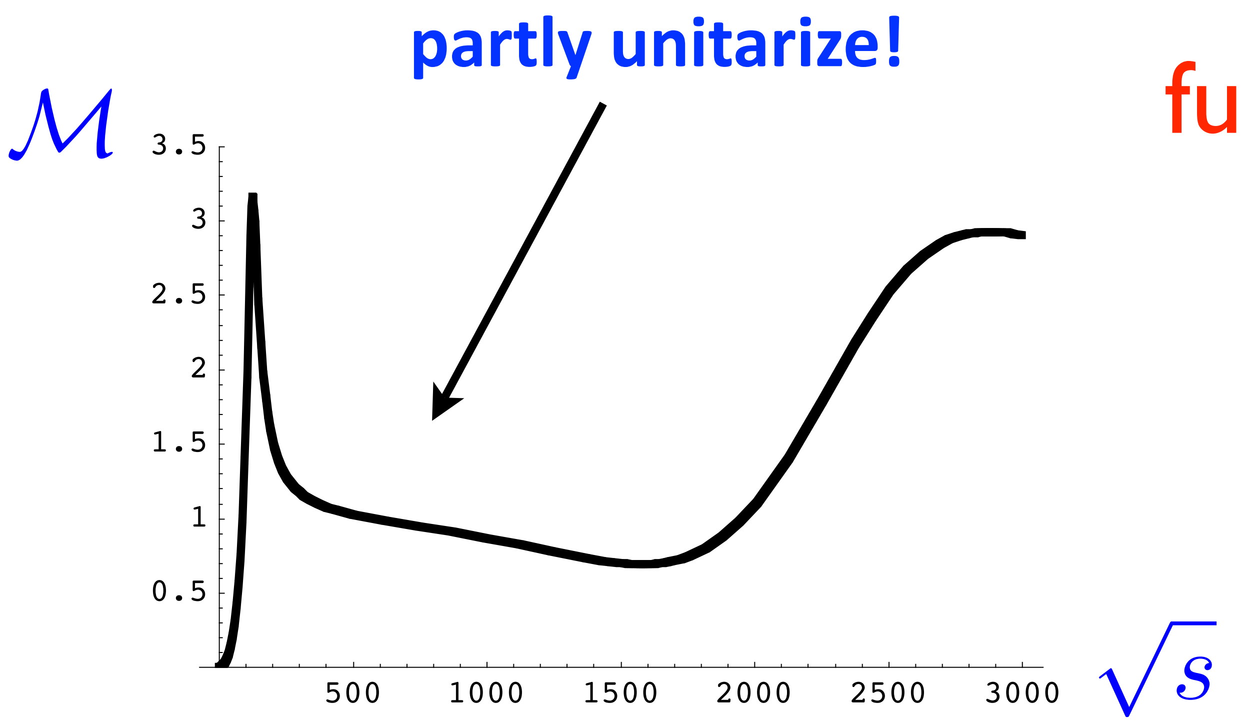

Extra states needed to
fully unitarize (for consistency)!

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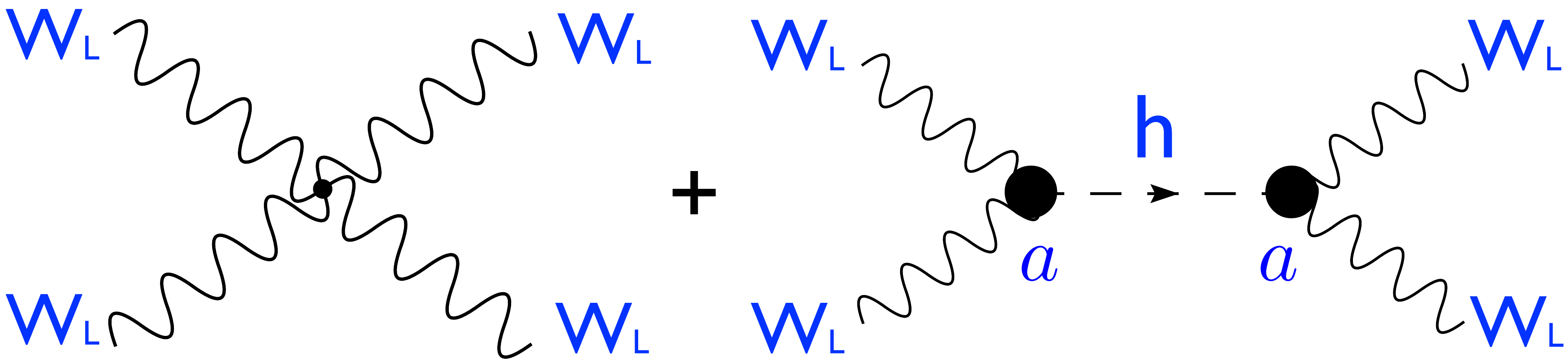

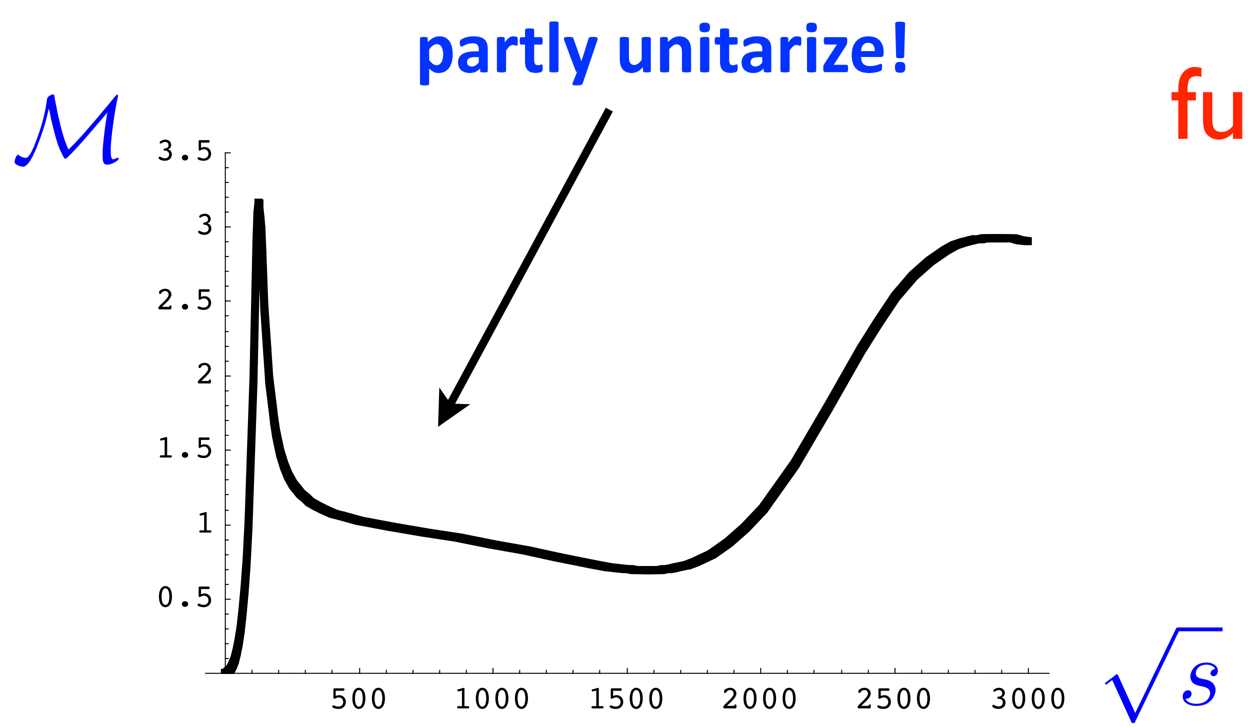

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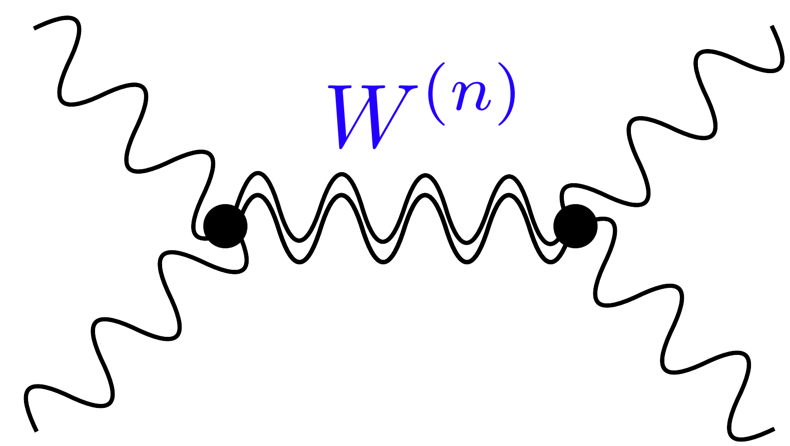

Extra resonances
(or Kaluza-Klein states of the W)

$$M_{\rm KK} \lesssim \frac{2\ \text{TeV}}{\sqrt{1-a^2}}$$

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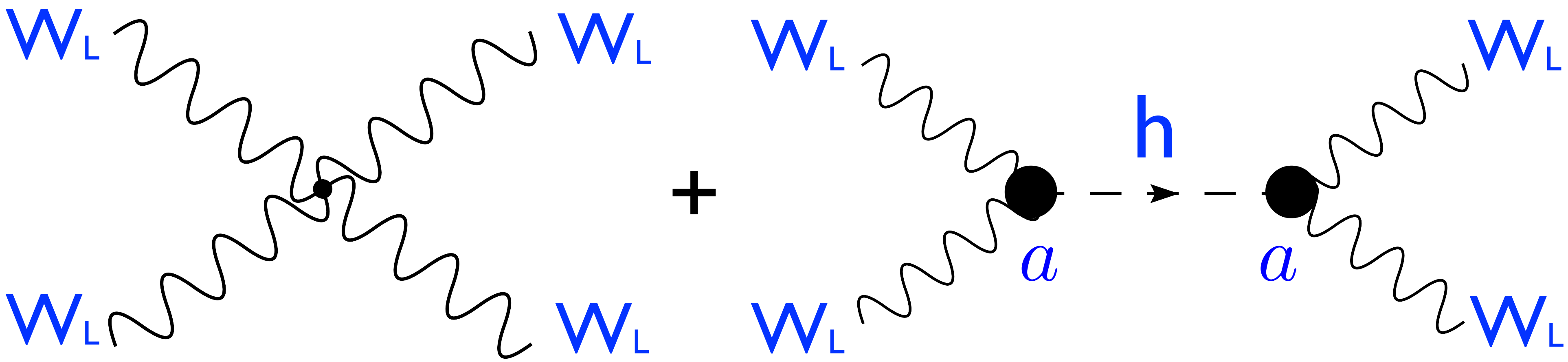

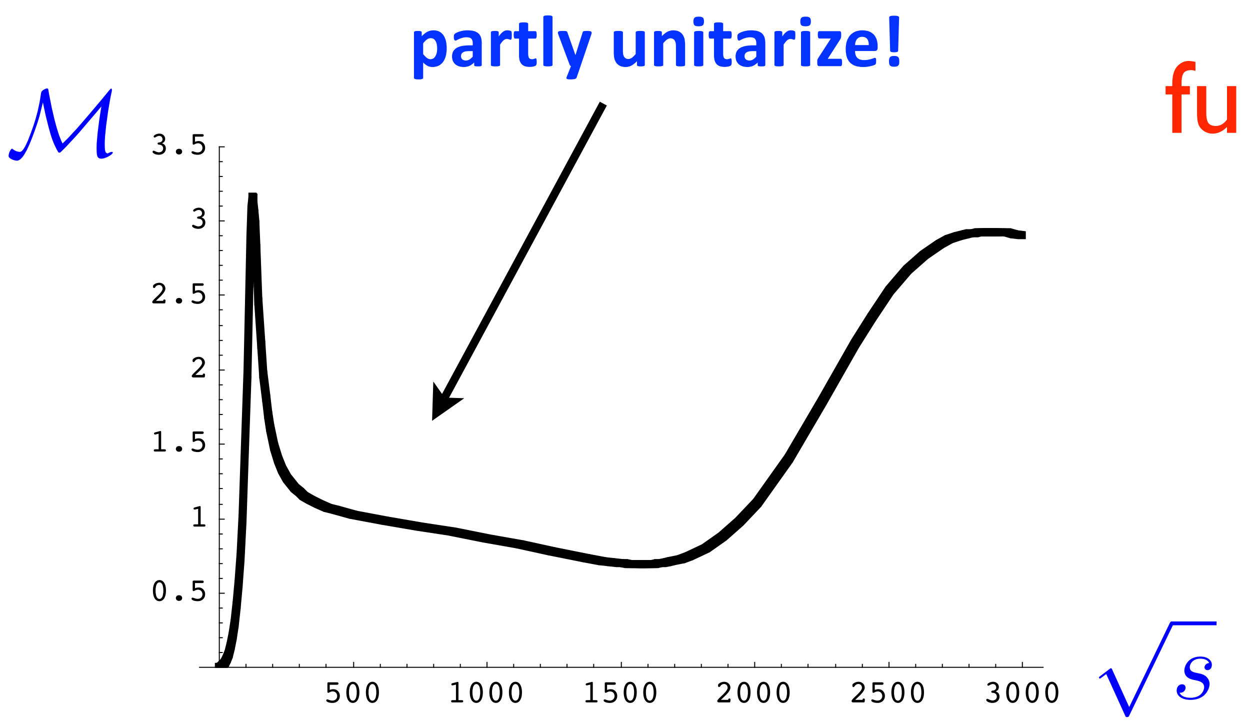

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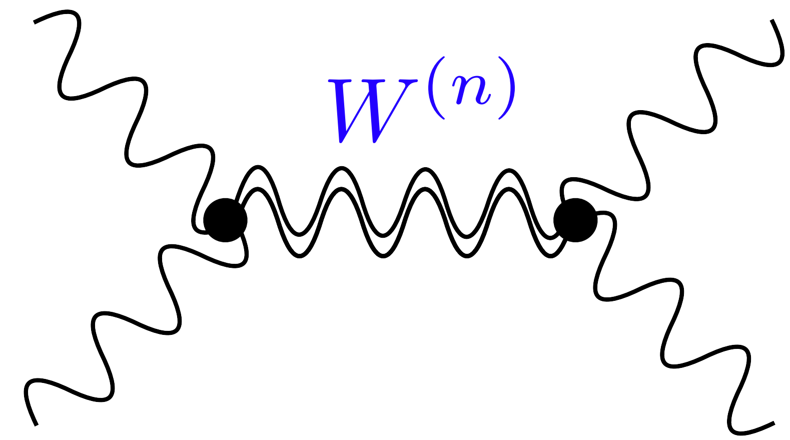


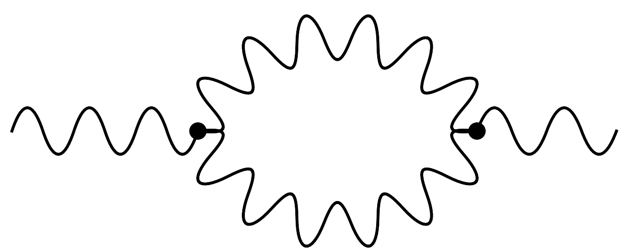
Extra resonances

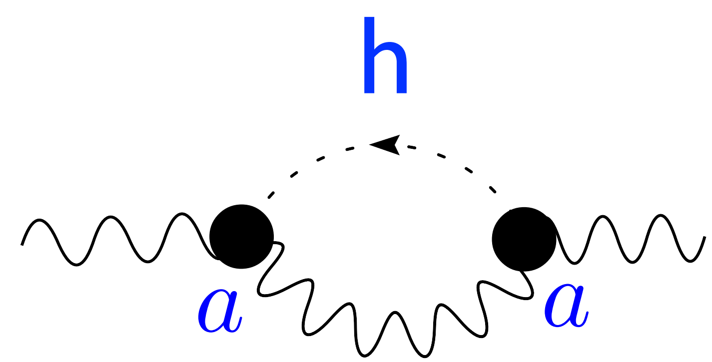
(or Kaluza-Klein states of the W)

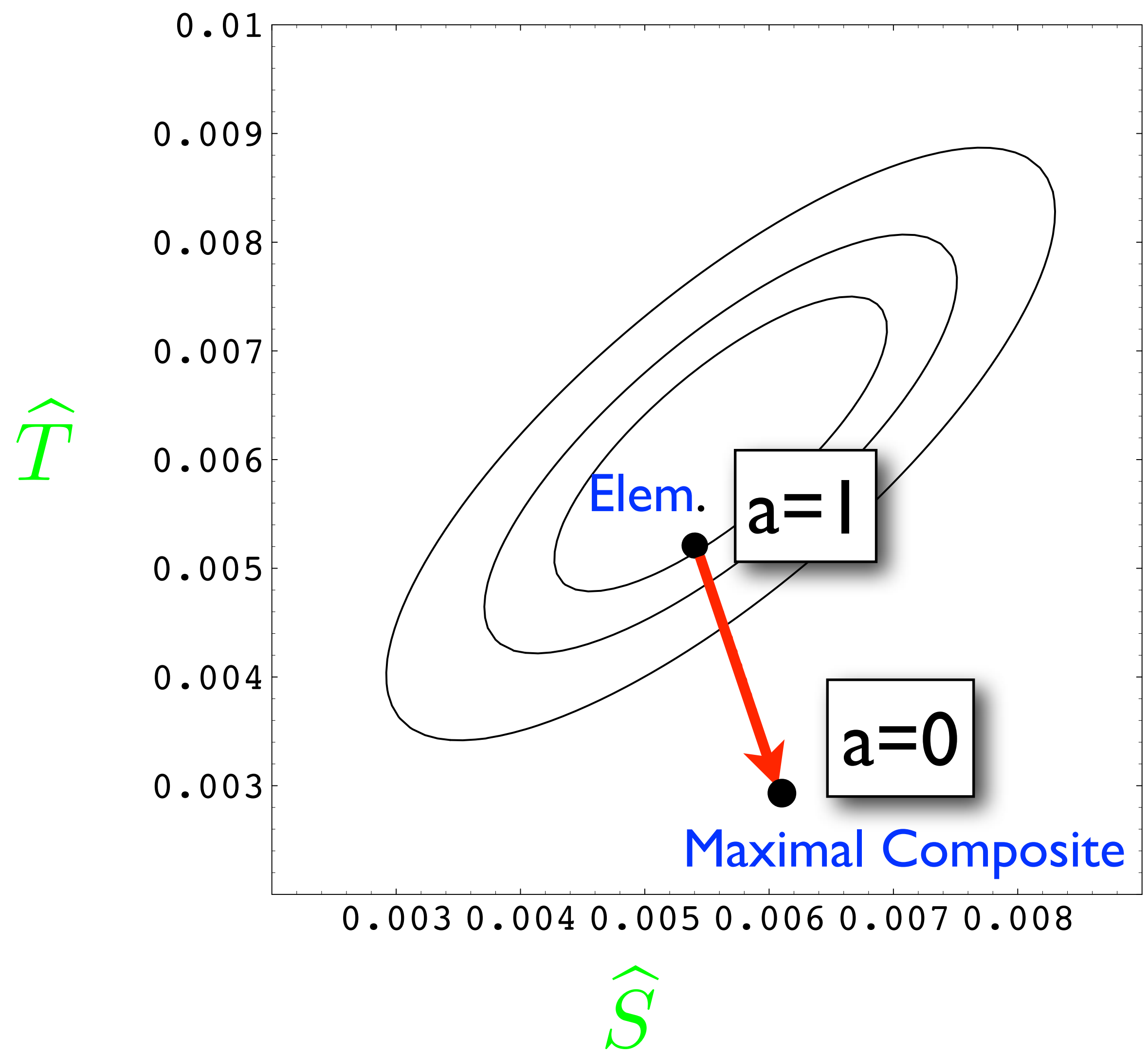
In the limit a=0 (~ **Higgsless**)
KK do all the job!

$$M_{\rm KK} \lesssim \frac{2\ {\rm TeV}}{\sqrt{1-a^2}}$$

Maximal degree of compositeness not allowed by EWPT







➠ a > 0.86

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

Higgsless (a=0) disfavored

Of course, extra contributions can make a~0 case **consistent with EWPT**

EXAMPLE: Extra state **Dilaton**

Goldberger, Grinstein, Skiba 07

(present in certain theories with spontaneous breaking of scale invariance)

Higgs-like state with:

$$a = \sqrt{b} = c = \frac{v}{f_D} \sim \mathcal{O}(1)$$

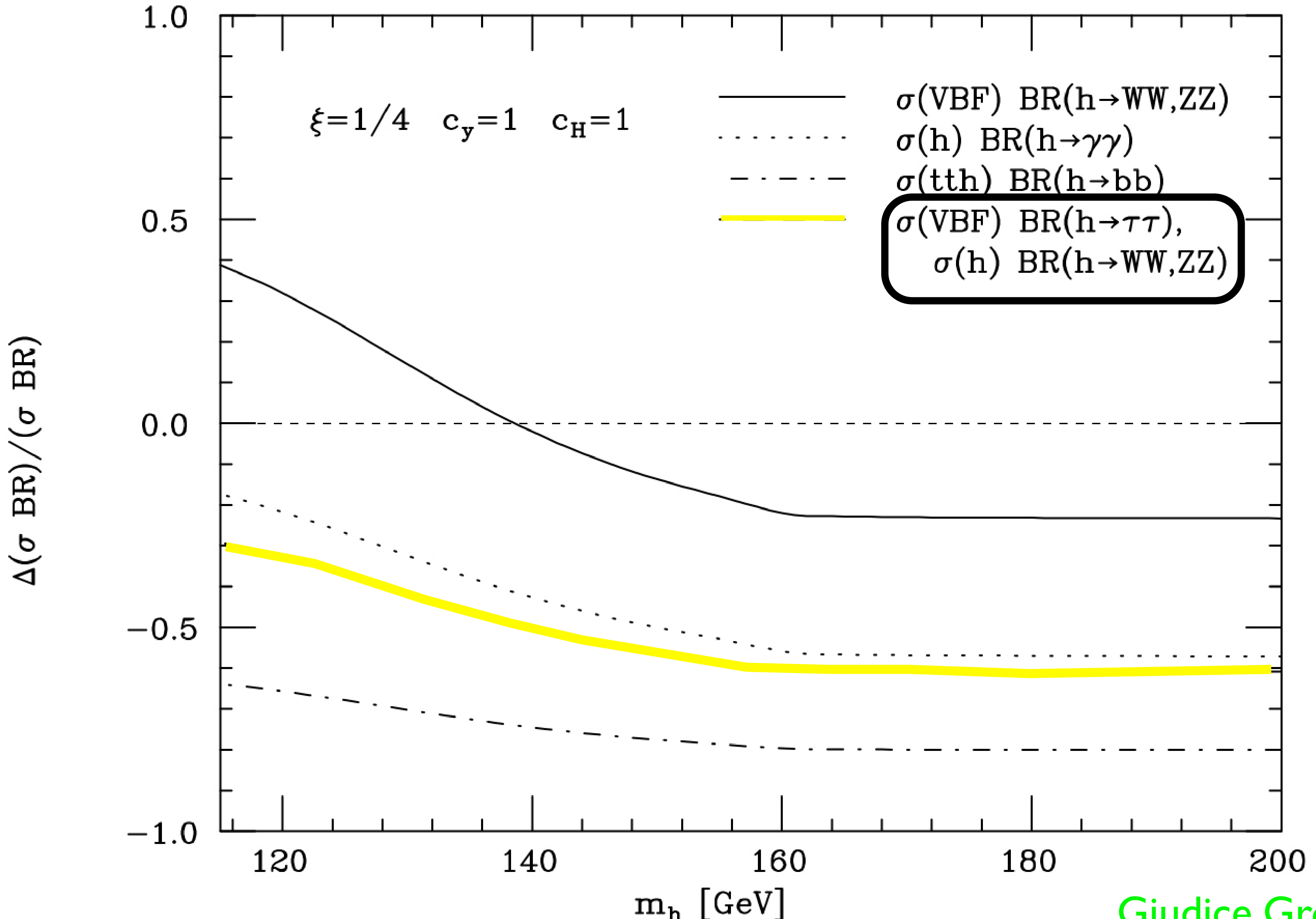
Helps for EWPT

Acts like a Higgs but has nothing to do with EWSB

The most serious Higgs **impostor**!

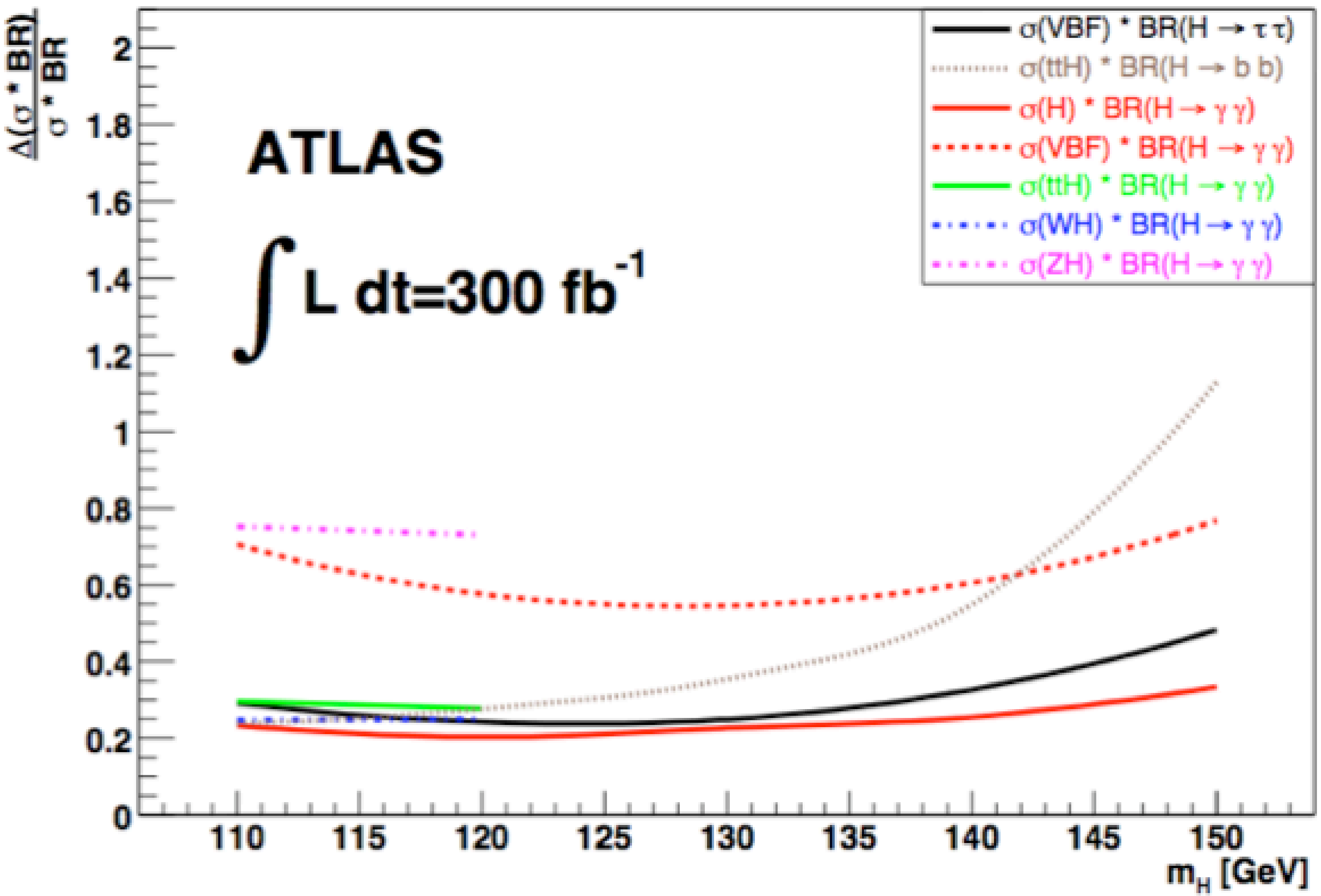
If the Higgs is **composite**, how it will change LHC predictions?

Bad news: Reduction of rates!



Giudice,Grojean,AP,Rattazzi 07

see also, Grojean,Espinosa,Muhlleitner 10



Duhrssen 03

Higgs coupling measurements ~ 20-40%

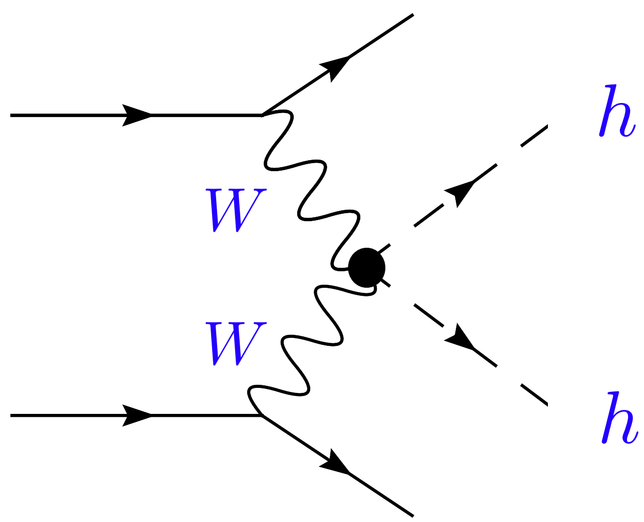
recent studies Lafaye,Plehn,Rauch,Zerwas,Duhrssen 09

ILC would be a perfect machine to test these scenarios:
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



Contino et al 10

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

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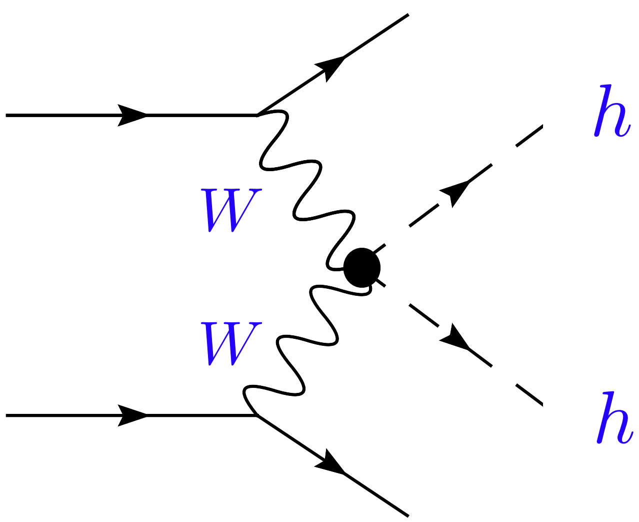


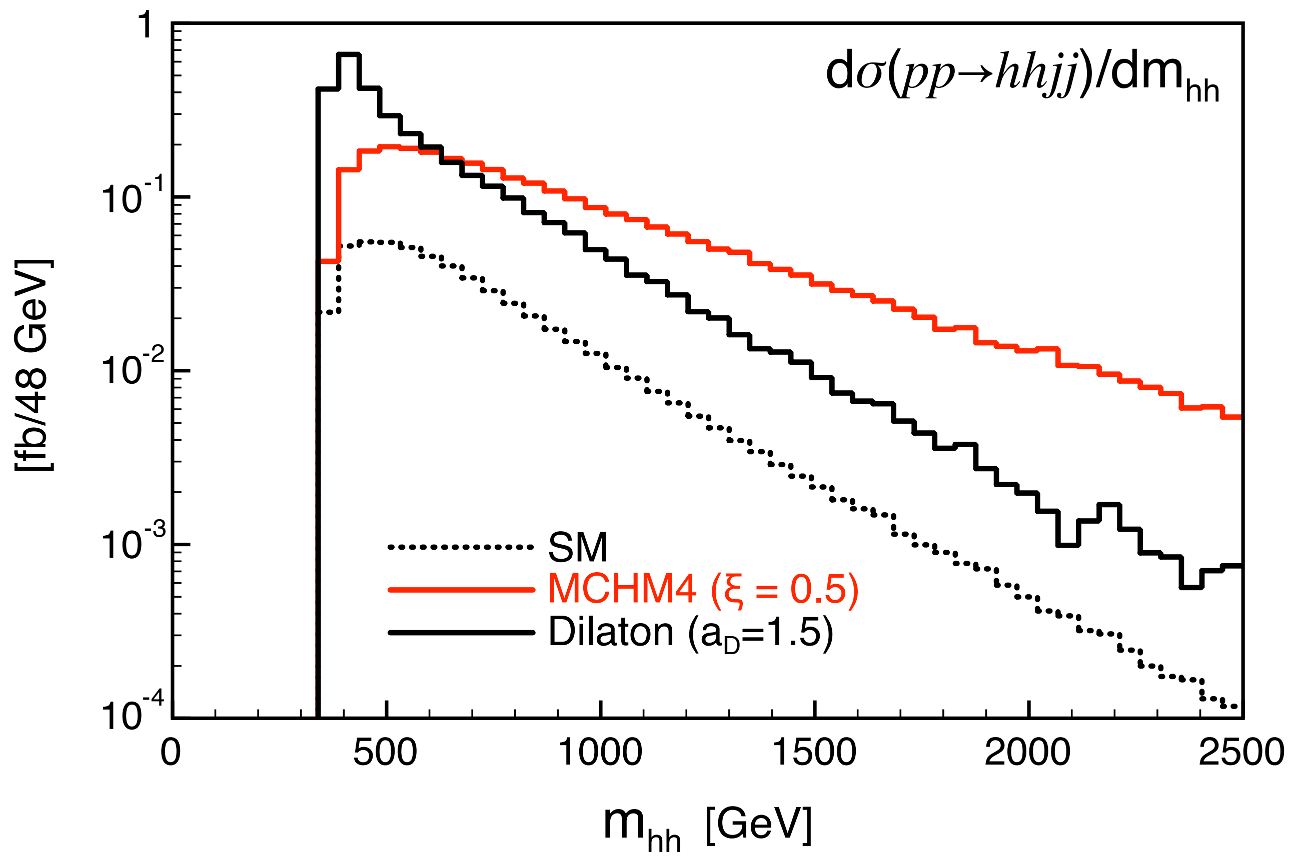
Contino et al 10

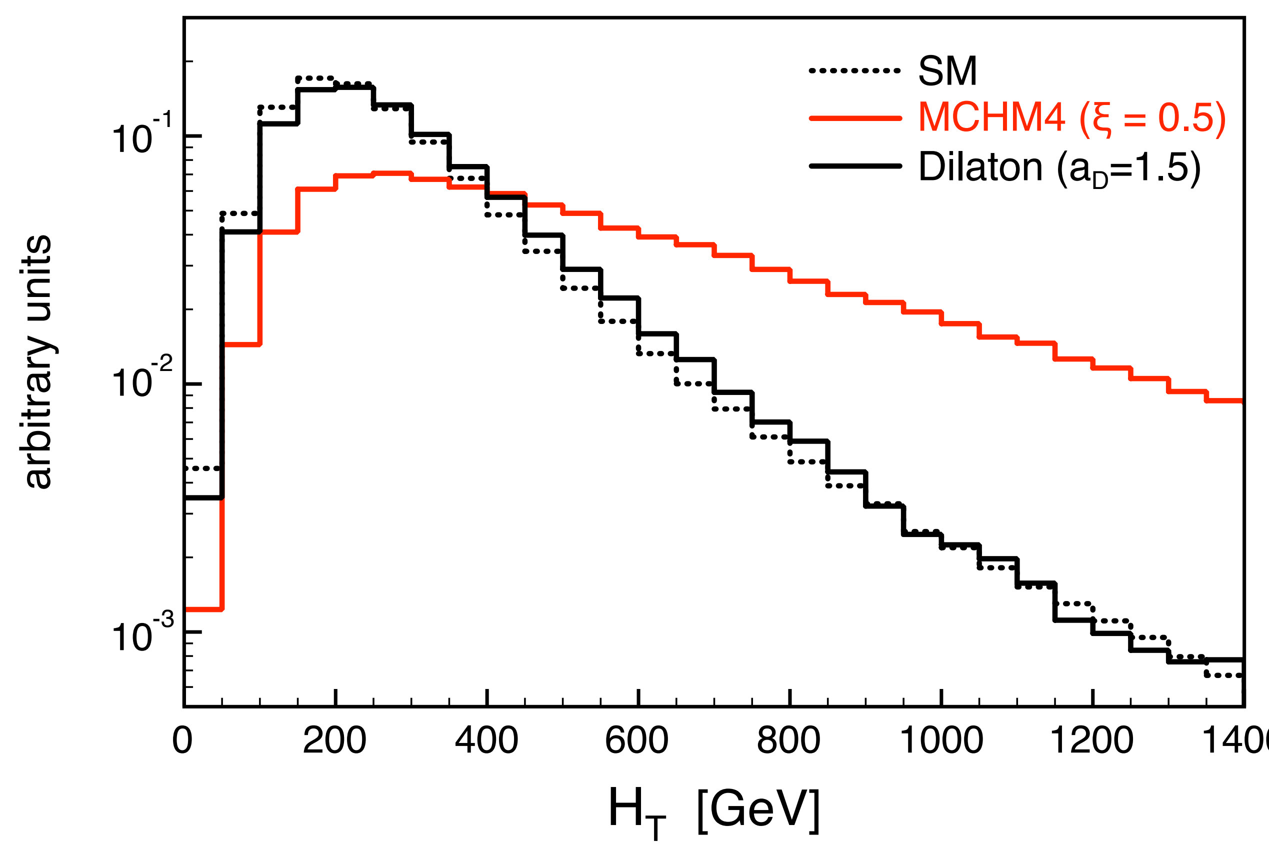
$$pp \to hhjj \to 4Wjj \to \begin{cases} l^+l^+l^-l^- \not{E}_T + 2j \\ l^+l^-l^\pm \not{E}_T + 4j \\ l^{+(-)}l^{+(-)} \not{E}_T + 5j\ (6j) \end{cases}$$

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

Distinguishing a SM Higgs, a composite Higgs and a dilaton

Contino et al 10





$$H_T = \sum_{i=1,2} |p_{T H_i}|$$

The **composite Higgs** can have PGB companions

Gripaios, AP, Riva, Serra

In certain models: One Higgs doublet (h) + Singlet (η)

Possibility for a new Higgs decay:

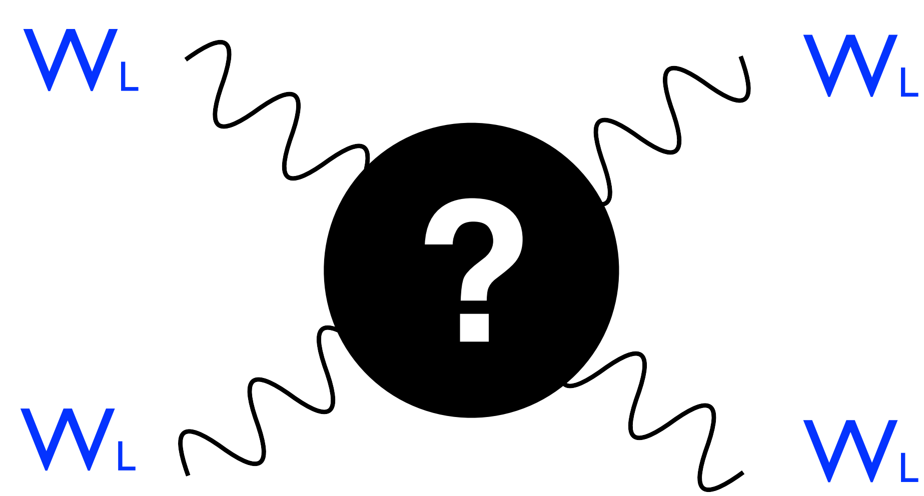
$$h \to \eta\eta \to b\bar{b}b\bar{b}$$ or $$\tau\bar{\tau}\tau\bar{\tau}$$ (depending on the η-mass)

Similar signatures in non-minimal Susy Higgs models

Dermisek, Gunion

Conclusions

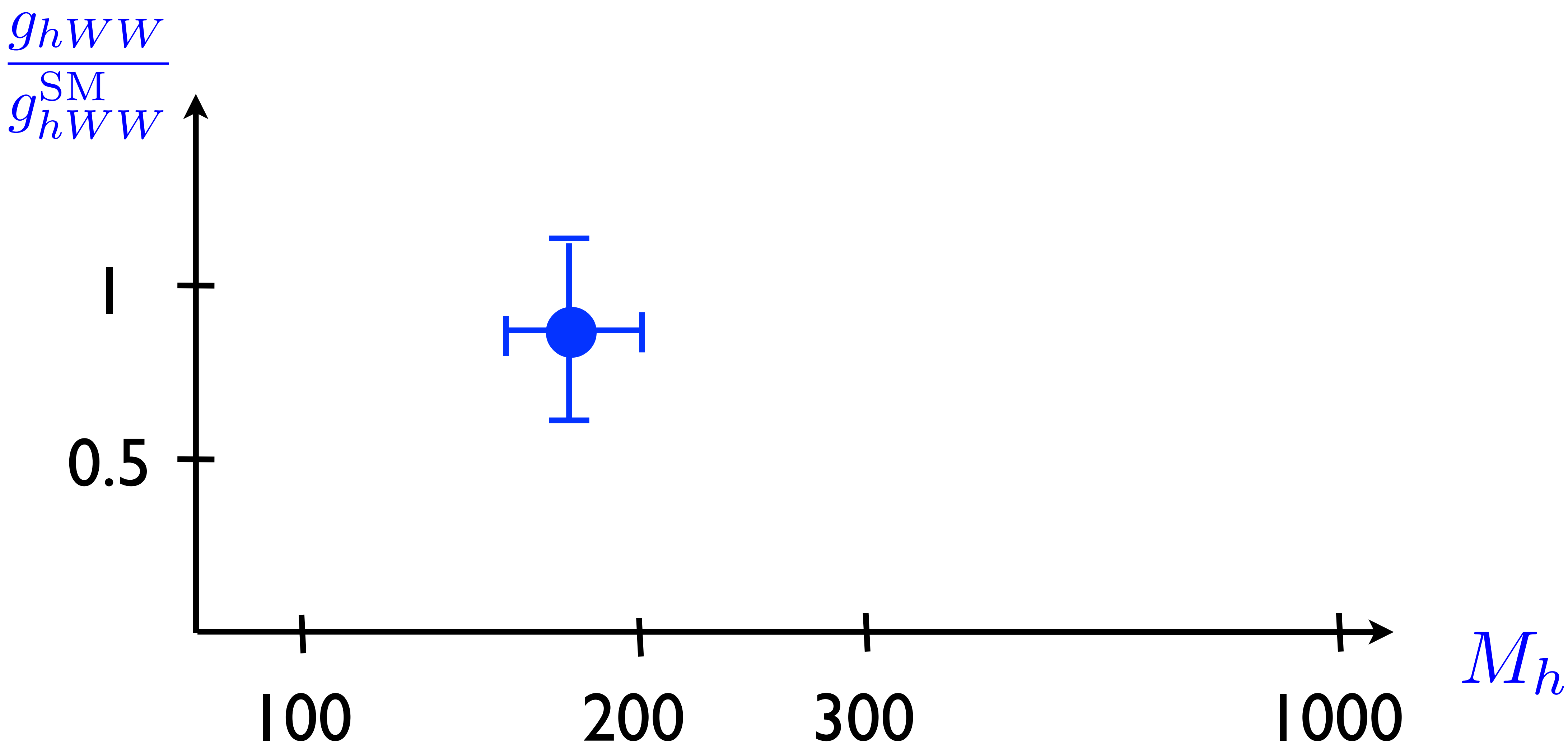
LHC **must** (and will) find the missing piece(s) of the SM



Conclusions

When a **Higgs-like** state is found, it will 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: