Elementary or Composite: The particle physics dilemma

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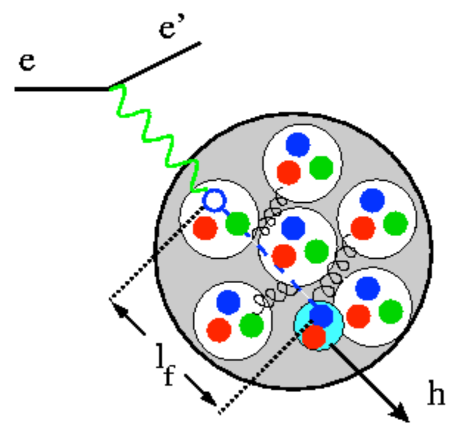
Composite vs Elementary

Dilemma since the beginning of particle physics

Search for structure by probing states at shorter distances (high-energies)



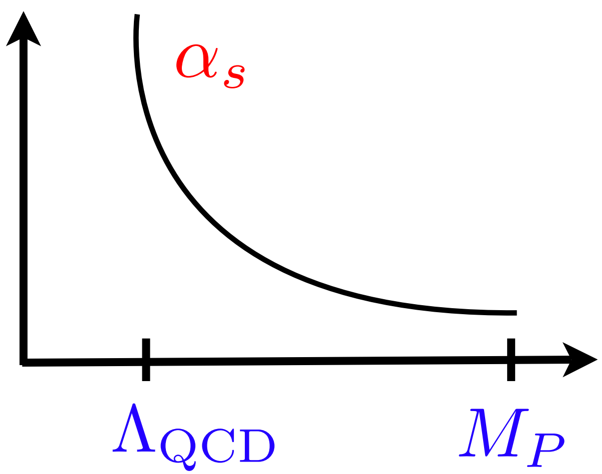
At present, extra motivation in the SM:

Why $M_W \ll M_P$? (hierarchy problem)

Up to now, the only possible dynamical answer comes from "dimensional transmutation":

Quantum running of a dimensionless coupling generates a new scale

An example: YM theory ~ QCD:



Explains why

$\Lambda_{\rm QCD} << M_P$

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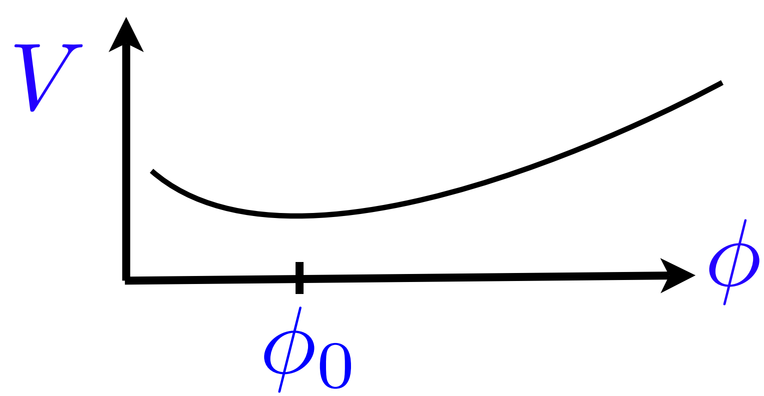
Another example: Coleman-Weinberg mechanism:

$$V = \lambda\phi^4 \underset{\text{quantum level}}{\longrightarrow} \lambda(\phi)\phi^4$$



Can generate $\phi_0 \ll M_P$

But if ϕ has dim=1, exists a relevant operator: $M^2\phi^2$

Possible if $\mathcal{O} \equiv \phi^2$ composite operator of dim=2

The smallness of the EW scale suggests the existence of a new strong sector, giving an important motivation for searching for **compositeness** in the SM particles

Question to address here:

Are there SM states coming (as composites) from this strong sector?

→ *Similarly as in the old good days, when exploring physics below the GeV: muon, pions, kaons,...*

e.g. in the known examples

Technicolor: W_L, Z_L

Supersymmetry: None (strong sector hidden from the SM)

Here I center in a strong sector at around the TeV-scale such that is possible to be probed at the LHC

Approach this question theoretically:

Impossible to answer today

Hard to get predictions from strongly-interacting theories

New tools:

- Supersymmetry (e.g. Seiberg dualities)
- AdS/CFT correspondence:

Strongly-coupled systems
i.e. Large N_c
Large $\lambda \equiv g^2 N_c$

→

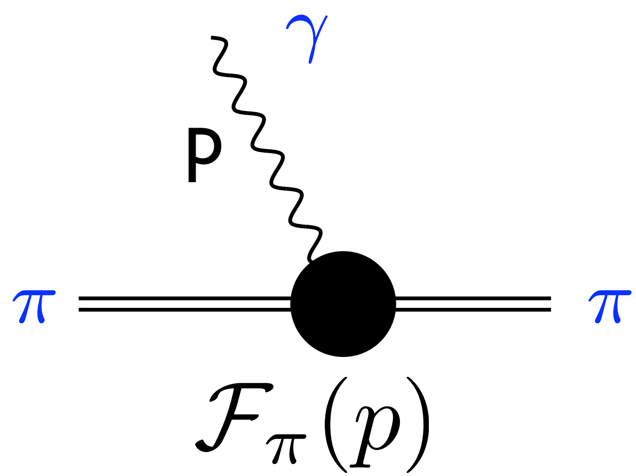
Weakly-coupled Gravitational systems in higher-dimensions

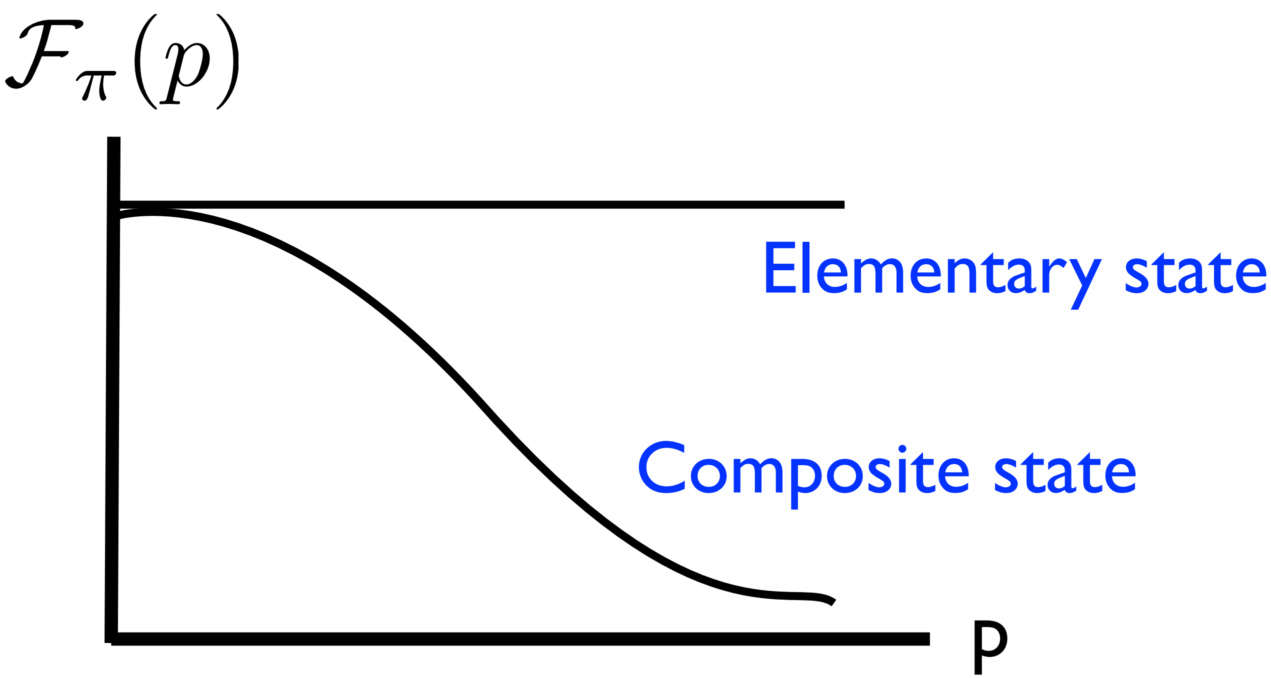
Very useful to derive properties of composite states from studying weakly-coupled fields in extra-dimensional models

Approach this question experimentally:

Easy in an **ideal** collider:

As we do it with pions in QCD:



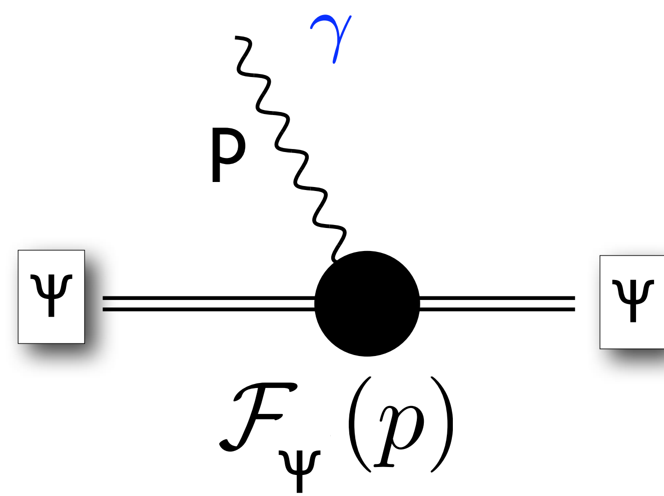


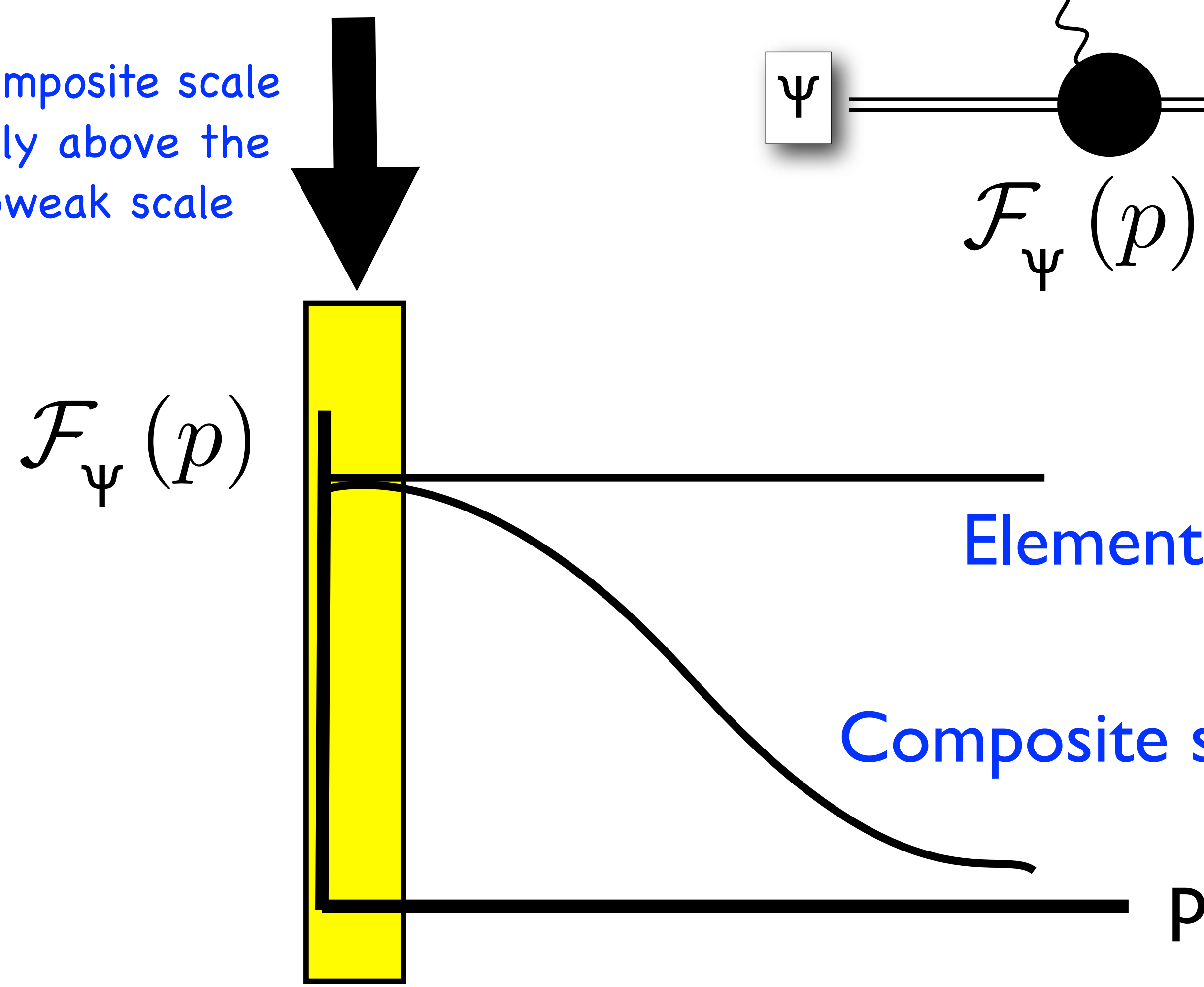
Approach this question experimentally:

In a **real** collider:

Only access up to few TeV

If the composite scale is slightly above the electroweak scale





At least, this simplifies the approach since we can make use of effective field theories expanding in powers of Energy/Composite-scale: Deviations from elementary states parametrized by higher-dimensional operators added to the SM:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\mathcal{O}_{d=6} + \cdots$$

Two types of operators:

a) Extra powers of $\dfrac{\partial^2}{\Lambda^2}$ Λ = scale of the strong-sector

e.g. $(\partial_\rho F_{\mu\nu})^2$

b) Extra powers of $\dfrac{g_\rho^2\,\psi^2}{\Lambda^2} \equiv \dfrac{\psi^2}{f^2}$ g_ρ = coupling of the composite states

e.g. $\dfrac{(\bar{q}^i_L\gamma_\mu q^j_L)^2}{f^2}$

since $g_\rho \gg 1 \to f \ll \Lambda$, operators type (b) are dominant

➥ all these operators lead to deviations from SM predictions

What past and present experiments tell us?

(what SM particles “smell” composite or elementary?)

How well the SM particles are tested?

First reaction, one answers "extremely well"

Extensive LEP, SLAC LC, Tevatron,... legacy:

$\sqrt{s}$ (GeV)	Quantity	Average value	SM	Δ
130	$\sigma(q\bar{q})$	82.1±2.2	82.8	-0.3
130	$\sigma(\mu^+\mu^-)$	8.62±0.68	8.44	-0.33
130	$\sigma(\tau^+\tau^-)$	9.02±0.93	8.44	-0.11
130	$A_{FB}(\mu^+\mu^-)$	0.694±0.060	0.705	0.012
130	$A_{FB}(\tau^+\tau^-)$	0.663±0.076	0.704	0.012
136	$\sigma(q\bar{q})$	66.7±2.0	66.6	-0.2
136	$\sigma(\mu^+\mu^-)$	8.27±0.67	7.28	-0.28
136	$\sigma(\tau^+\tau^-)$	7.078±0.820	7.279	-0.091
136	$A_{FB}(\mu^+\mu^-)$	0.708±0.060	0.684	0.013
136	$A_{FB}(\tau^+\tau^-)$	0.753±0.088	0.683	0.014
161	$\sigma(q\bar{q})$	37.0±1.1	35.2	-0.1
161	$\sigma(\mu^+\mu^-)$	4.61±0.36	4.61	-0.18
161	$\sigma(\tau^+\tau^-)$	5.67±0.54	4.61	-0.06
161	$A_{FB}(\mu^+\mu^-)$	0.538±0.067	0.609	0.017
161	$A_{FB}(\tau^+\tau^-)$	0.646±0.077	0.609	0.016
172	$\sigma(q\bar{q})$	29.23±0.99	28.74	-0.12
172	$\sigma(\mu^+\mu^-)$	3.57±0.32	3.95	-0.16
172	$\sigma(\tau^+\tau^-)$	4.01±0.45	3.95	-0.05
172	$A_{FB}(\mu^+\mu^-)$	0.675±0.077	0.591	0.018
172	$A_{FB}(\tau^+\tau^-)$	0.342±0.094	0.591	0.017
183	$\sigma(q\bar{q})$	24.59±0.42	24.20	-0.11
183	$\sigma(\mu^+\mu^-)$	3.49±0.15	3.45	-0.14
183	$\sigma(\tau^+\tau^-)$	3.37±0.17	3.45	-0.05
183	$A_{FB}(\mu^+\mu^-)$	0.559±0.035	0.576	0.018
183	$A_{FB}(\tau^+\tau^-)$	0.608±0.045	0.576	0.018
189	$\sigma(q\bar{q})$	22.47±0.24	22.156	-0.101
189	$\sigma(\mu^+\mu^-)$	3.123±0.076	3.207	-0.131
189	$\sigma(\tau^+\tau^-)$	3.20±0.10	3.20	-0.048
189	$A_{FB}(\mu^+\mu^-)$	0.569±0.021	0.569	0.019
189	$A_{FB}(\tau^+\tau^-)$	0.596±0.026	0.569	0.018

$\sqrt{s}$ (GeV)	Quantity	Average value	SM	Δ
192	$\sigma(q\bar{q})$	22.05±0.53	21.24	-0.10
192	$\sigma(\mu^+\mu^-)$	2.92±0.18	3.10	-0.13
192	$\sigma(\tau^+\tau^-)$	2.81±0.23	3.10	-0.05
192	$A_{FB}(\mu^+\mu^-)$	0.553±0.051	0.566	0.019
192	$A_{FB}(\tau^+\tau^-)$	0.615±0.069	0.566	0.019
196	$\sigma(q\bar{q})$	20.53±0.34	20.13	-0.09
196	$\sigma(\mu^+\mu^-)$	2.94±0.11	2.96	-0.12
196	$\sigma(\tau^+\tau^-)$	2.94±0.14	2.96	-0.05
196	$A_{FB}(\mu^+\mu^-)$	0.581±0.031	0.562	0.019
196	$A_{FB}(\tau^+\tau^-)$	0.505±0.044	0.562	0.019
200	$\sigma(q\bar{q})$	19.25±0.32	19.09	-0.09
200	$\sigma(\mu^+\mu^-)$	3.02±0.11	2.83	-0.12
200	$\sigma(\tau^+\tau^-)$	2.90±0.14	2.83	-0.04
200	$A_{FB}(\mu^+\mu^-)$	0.524±0.031	0.558	0.019
200	$A_{FB}(\tau^+\tau^-)$	0.539±0.042	0.558	0.019
202	$\sigma(q\bar{q})$	19.07±0.44	18.57	-0.09
202	$\sigma(\mu^+\mu^-)$	2.58±0.14	2.77	-0.12
202	$\sigma(\tau^+\tau^-)$	2.79±0.20	2.77	-0.04
202	$A_{FB}(\mu^+\mu^-)$	0.547±0.047	0.556	0.020
202	$A_{FB}(\tau^+\tau^-)$	0.589±0.059	0.556	0.019
205	$\sigma(q\bar{q})$	18.17±0.31	17.81	-0.09
205	$\sigma(\mu^+\mu^-)$	2.45±0.10	2.67	-0.11
205	$\sigma(\tau^+\tau^-)$	2.78±0.14	2.67	-0.042
205	$A_{FB}(\mu^+\mu^-)$	0.565±0.035	0.553	0.020
205	$A_{FB}(\tau^+\tau^-)$	0.571±0.042	0.553	0.019
207	$\sigma(q\bar{q})$	17.49±0.26	17.42	-0.08
207	$\sigma(\mu^+\mu^-)$	2.595±0.088	2.623	-0.111
207	$\sigma(\tau^+\tau^-)$	2.53±0.11	2.62	-0.04
207	$A_{FB}(\mu^+\mu^-)$	0.542±0.027	0.552	0.020
207	$A_{FB}(\tau^+\tau^-)$	0.564±0.037	0.551	0.019

Background	% of $W \to \mu\nu$ data	δm_W (MeV) m_T fit	p_T fit	$\not{p}_T$ fit
$Z/\gamma^* \to \mu\mu$	6.6 ± 0.3	6	11	5
$W \to \tau\nu$	0.89 ± 0.02	1	7	8
Decays in flight	0.3 ± 0.2	5	13	3
Hadronic jets	0.1 ± 0.1	2	3	4
Cosmic rays	0.05 ± 0.05	2	2	1
Total	7.9 ± 0.4	9	19	11

without lepton universality	
χ^2/N_{df} = 32.6/27	
m_Z [GeV]	91.1876± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
σ_h^0 [nb]	41.541 ± 0.037
R_e^0	20.804 ± 0.050
R_μ^0	20.785 ± 0.033
R_τ^0	20.764 ± 0.045
$A_{FB}^{0,e}$	0.0145 ± 0.0025
$A_{FB}^{0,\mu}$	0.0169 ± 0.0013
$A_{FB}^{0,\tau}$	0.0188 ± 0.0017

	Lepton non–universality			Lepton universality
Experiment	$\mathcal{B}(W \to e\bar{\nu}_e)$ [%]	$\mathcal{B}(W \to \mu\bar{\nu}_\mu)$ [%]	$\mathcal{B}(W \to \tau\bar{\nu}_\tau)$ [%]	$\mathcal{B}(W \to \text{hadrons})$ [%]
ALEPH	10.81 ± 0.29*	10.91 ± 0.26*	11.15 ± 0.38*	67.15 ± 0.40*
DELPHI	10.55 ± 0.34*	10.65 ± 0.27*	11.46 ± 0.43*	67.45 ± 0.48*
L3	10.78 ± 0.32*	10.03 ± 0.31*	11.89 ± 0.45*	67.50 ± 0.52*
OPAL	10.40 ± 0.35	10.61 ± 0.35	11.18 ± 0.48	67.91 ± 0.61
LEP	10.66 ± 0.17	10.60 ± 0.15	11.41 ± 0.22	67.49 ± 0.28
χ^2/d.o.f.	6.8/9			15.0/11

Background	% of $W \to e\nu$ data	δm_W (MeV) m_T fit	p_T fit	$\not{p}_T$ fit
$W \to \tau\nu$	0.93 ± 0.03	2	2	2
Hadronic jets	0.25 ± 0.15	8	9	7
$Z/\gamma^* \to ee$	0.24 ± 0.01	1	1	0
Total	1.42 ± 0.15	8	9	7

without lepton universality	
Γ_{had} [MeV]	1745.8 ±2.7
Γ_{ee} [MeV]	83.92±0.12
$\Gamma_{\mu\mu}$ [MeV]	83.99±0.18
$\Gamma_{\tau\tau}$ [MeV]	84.08±0.22

$\sqrt{s}$ (GeV)	WW cross-section (pb) ALEPH	DELPHI	L3	OPAL	LEP	χ^2/d.o.f.
161.3	4.23 ± 0.75*	$3.67^{+0.99}_{-0.87}$ *	$2.89^{+0.82}_{-0.71}$ *	$3.62^{+0.94}_{-0.84}$ *	3.69 ± 0.45 *	} 1.3 / 3
172.1	11.7 ± 1.3 *	11.6 ± 1.4 *	12.3 ± 1.4 *	12.3 ± 1.3 *	12.0 ± 0.7 *	} 0.22/ 3
182.7	15.90 ± 0.63*	16.07 ± 0.70*	16.53 ± 0.72*	15.43 ± 0.66*	15.89 ± 0.35 *	26.4/24
188.6	15.76 ± 0.36*	16.09 ± 0.42*	16.17 ± 0.41*	16.30 ± 0.39*	16.03 ± 0.21 *	
191.6	17.10 ± 0.90 *	16.64 ± 1.00*	16.11 ± 0.92 *	16.60 ± 0.99	16.56 ± 0.48	
195.5	16.61 ± 0.54 *	17.04 ± 0.60*	16.22 ± 0.57 *	18.59 ± 0.75	16.90 ± 0.31	
199.5	16.90 ± 0.52 *	17.39 ± 0.57*	16.49 ± 0.58 *	16.32 ± 0.67	16.75 ± 0.30	
201.6	16.65 ± 0.71 *	17.37 ± 0.82*	16.01 ± 0.84 *	18.48 ± 0.92	17.00 ± 0.41	
204.9	16.79 ± 0.54 *	17.56 ± 0.59*	17.00 ± 0.60 *	15.97 ± 0.64	16.78 ± 0.31	
206.6	17.36 ± 0.43 *	16.35 ± 0.47*	17.33 ± 0.47 *	17.77 ± 0.57	17.13 ± 0.25	

How well the SM particles are tested?

First reaction, one answers "extremely well"

Extensive LEP, SLAC LC, Tevatron,... legacy:

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Hadronic jets	0.25 ± 0.15	8	9	7
$Z/\gamma^* \to ee$	0.24 ± 0.01	1	1	0
Total	1.42 ± 0.15	8	9	7

universality
745.8 ±2.7
83.92±0.12
83.99±0.18
84.08±0.22

However, a lot of the data is redundant (measure the same SM sector), so we have some parts of the SM very well-tested and others not at all

L3	$10.78 \pm 0.32^*$	$10.03 \pm 0.31^*$	$11.89 \pm 0.45^*$	$67.50 \pm 0.52^*$
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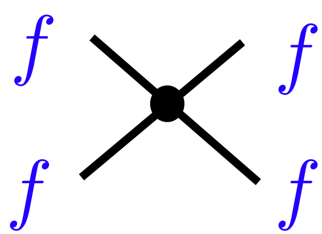
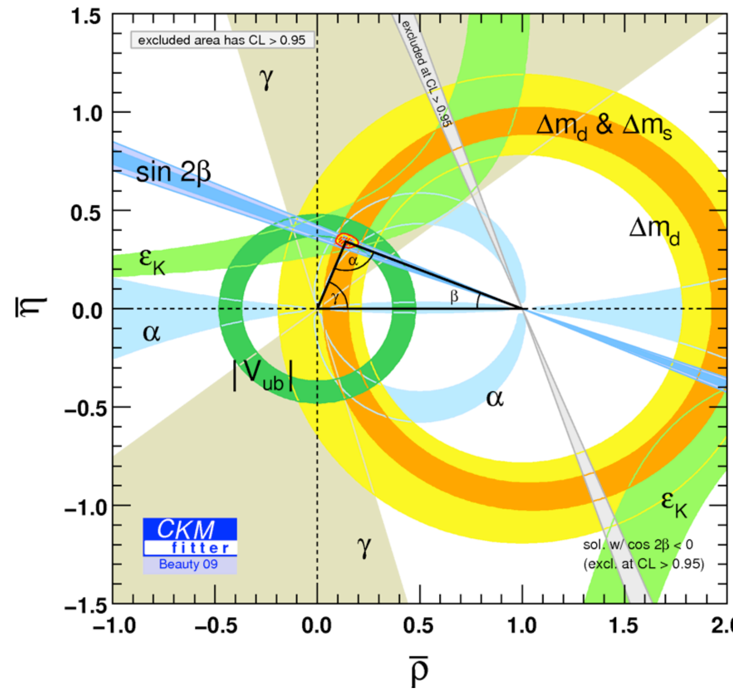
$W \to \tau\nu$	0.89 ± 0.02	1	7	8
Decays in flight	0.3 ± 0.2	5	13	3
Hadronic jets	0.1 ± 0.1	2	3	4
Cosmic rays	0.05 ± 0.05	2	2	1
Total	7.9 ± 0.4	9	19	11

$\sqrt{s}$ (GeV)	WW cross-section (pb) ALEPH	DELPHI	L3	OPAL	LEP	χ^2/d.o.f.
161.3	$4.23 \pm 0.75^*$	$3.67\,^{+0.99}_{-0.87}\,^*$	$2.89\,^{+0.82}_{-0.71}\,^*$	$3.62\,^{+0.94}_{-0.84}\,^*$	$3.69 \pm 0.45^*$	1.3 / 3
172.1	$11.7 \pm 1.3^*$	$11.6 \pm 1.4^*$	$12.3 \pm 1.4^*$	$12.3 \pm 1.3^*$	$12.0 \pm 0.7^*$	0.22/ 3
182.7	$15.90 \pm 0.63^*$	$16.07 \pm 0.70^*$	$16.53 \pm 0.72^*$	$15.43 \pm 0.66^*$	$15.89 \pm 0.35^*$	26.4/24
188.6	$15.76 \pm 0.36^*$	$16.09 \pm 0.42^*$	$16.17 \pm 0.41^*$	$16.30 \pm 0.39^*$	$16.03 \pm 0.21^*$	
191.6	$17.10 \pm 0.90^*$	$16.64 \pm 1.00^*$	$16.11 \pm 0.92^*$	16.60 ± 0.99	16.56 ± 0.48	
195.5	$16.61 \pm 0.54^*$	$17.04 \pm 0.60^*$	$16.22 \pm 0.57^*$	18.59 ± 0.75	16.90 ± 0.31	
199.5	$16.90 \pm 0.52^*$	$17.39 \pm 0.57^*$	$16.49 \pm 0.58^*$	16.32 ± 0.67	16.75 ± 0.30	
201.6	$16.65 \pm 0.71^*$	$17.37 \pm 0.82^*$	$16.01 \pm 0.84^*$	18.48 ± 0.92	17.00 ± 0.41	
204.9	$16.79 \pm 0.54^*$	$17.56 \pm 0.59^*$	$17.00 \pm 0.60^*$	15.97 ± 0.64	16.78 ± 0.31	
206.6	$17.36 \pm 0.43^*$	$16.35 \pm 0.47^*$	$17.33 \pm 0.47^*$	17.77 ± 0.57	17.13 ± 0.25	

Main lessons from experiments

1) Flavor universality:



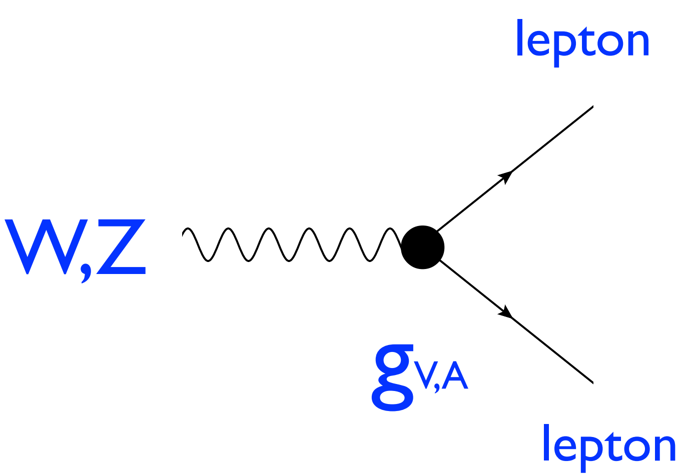


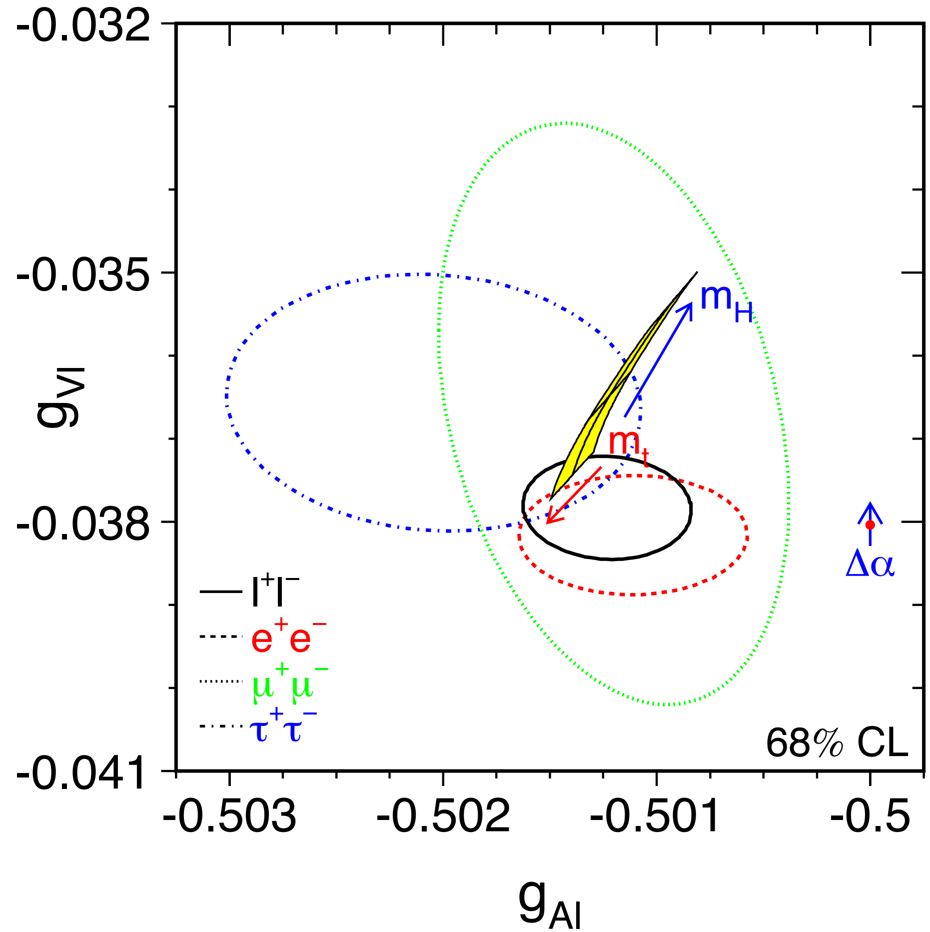
$$\frac{(\bar{q}^i_L \gamma_\mu q^j_L)^2}{f^2}$$

➡ Dimension-6 operators must be flavor diagonal (i=j)

only exception, could be the top, whose properties not yet well-measured

2) No sign of compositeness for **leptons**:
Properties very-well measured (per mille level)





3) Similarly for **q_L** = left-handed quarks:

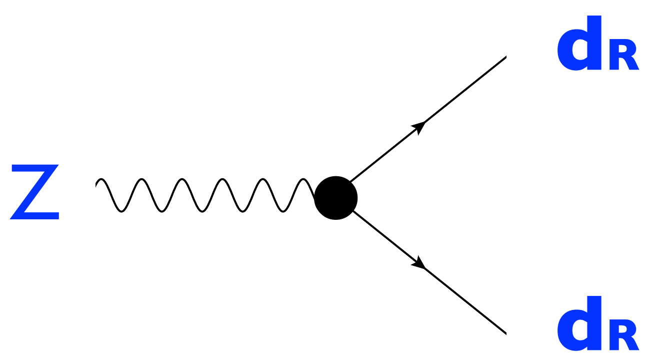
LEP gave already good bounds, but recent KLOE results put a very stringent bound on quark-lepton universality of the W interactions

$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2 = 0.9999(6)$$

$$\Rightarrow \quad \frac{G_F|_{quarks}}{G_F|_{leptons}} - 1 < 10^{-3}$$

4) $\mathbf{d_R}$ = right-handed down-quarks:

Not well-measurement of couplings, due to their small values



$$g_R = Q_d \sin^2\theta_W \sim 0.08$$

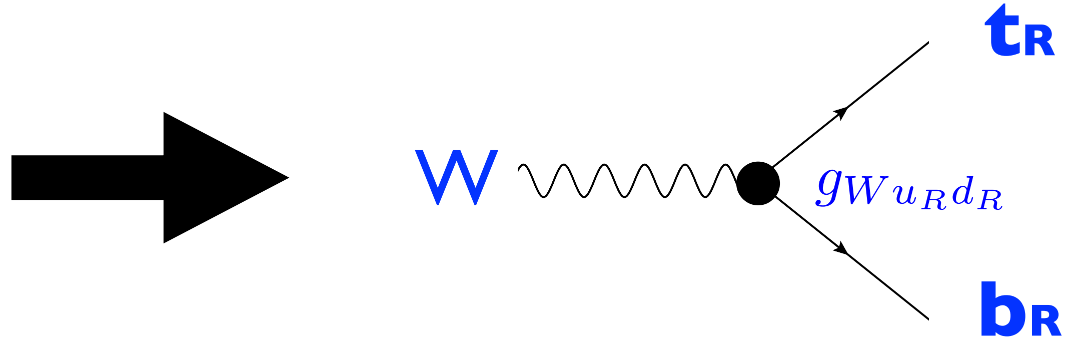
Best measurement for $\mathbf{b_R}$ that gives a ~3 sigma discrepancy with the SM value:

Needed: $$\frac{\delta g_R}{g_R} \sim 0.2$$

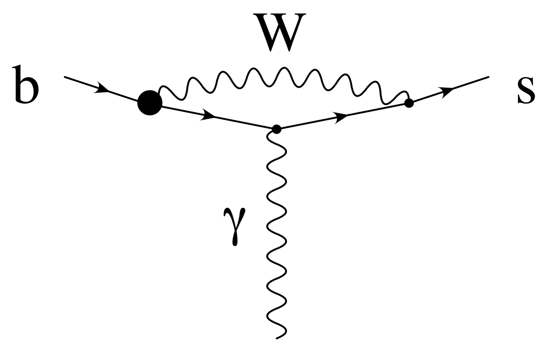
similarly for $\mathbf{u_R}$ = right-handed up-quarks

But important indirect bound on their coupling to W:

$$H^\dagger D_\mu \widetilde{H} \bar{b}_R \gamma^\mu t_R$$



Affects b →sγ:



Chirality flip by the top:

m_t/m_b-enhancement
with respect the SM loop

$$g_{W u_R d_R} < 4 \cdot 10^{-3}$$

Avoidable if the strong sector has a
custodial global SU(2) symmetry under which

$W_\mu \in \mathbf{3}$, $u_R\ d_R \in \mathbf{1}$

that implies $g_{W u_R d_R} = 0$

5) Gauge bosons:

Effects on the propagators nicely parametrized in terms of 4 quantities:

Peskin, Takeushi

Barbieri, AP, Rattazzi, Strumia

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

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

$$W = \frac{g^2 M_W^2}{2}\, \Pi''_{W_3}(0)$$

$$Y = \frac{g'^2 M_W^2}{2}\, \Pi''_B(0)$$

Important to separate longitudinal part from transverse:

Stueckelberg formalism (EW symmetry non-linearly realized):

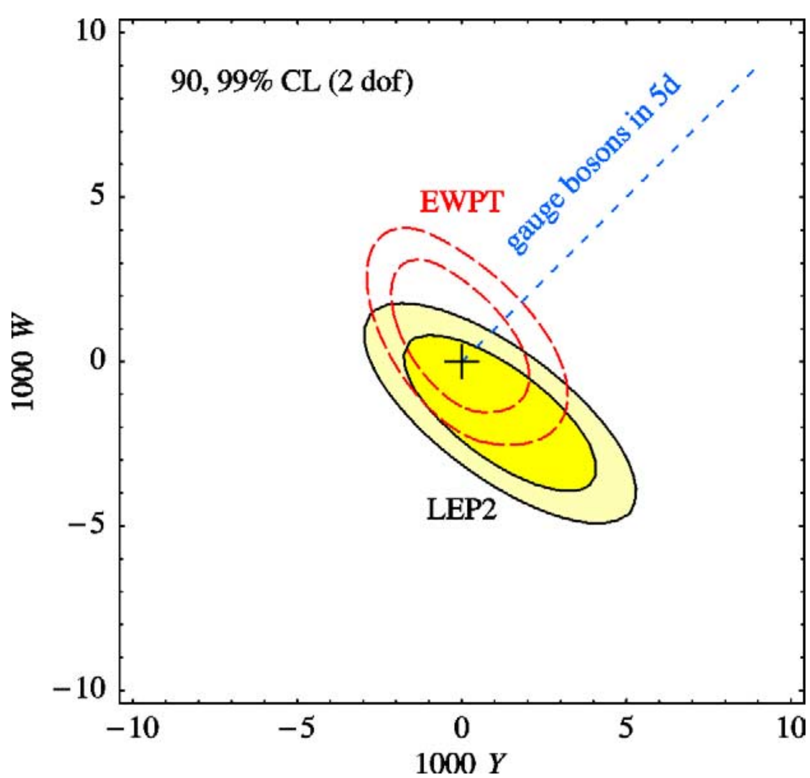
$$W_\mu \to \Sigma W_\mu \Sigma^\dagger - i\Sigma\partial_\mu\Sigma^\dagger \qquad \Sigma = e^{i\sigma_a G_a}$$

Goldstone bosons

5a) Transverse part of gauge bosons:

$$Y \leftrightarrow (\partial_\rho B_{\mu\nu})^2$$

$$W \leftrightarrow (D_\rho W_{\mu\nu})^2$$



bounds at the per mille level:
gauge bosons look like elementary!

5a) Longitudinal part of gauge bosons: SM Goldstones

$$\widehat{T} \leftrightarrow \mathrm{Tr}^2[\sigma_3 \Sigma D_\mu \Sigma^\dagger]$$

$$\Sigma = e^{i\sigma_a G_a}$$

Goldstone bosons

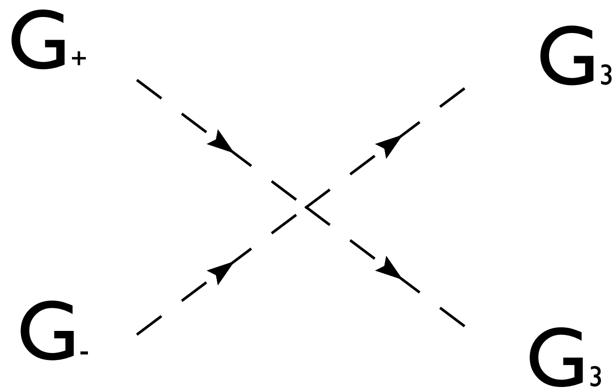
➥ G  G

Measures deviation between the propagator of the charged and neutral G

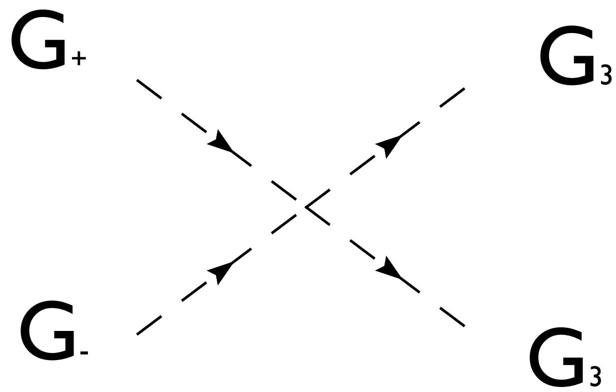
$$\widehat{S} \leftrightarrow \mathrm{Tr}[W_{\mu\nu} \Sigma \sigma_3 \Sigma^\dagger] B_{\mu\nu}$$

➥ W_μ  B_μ

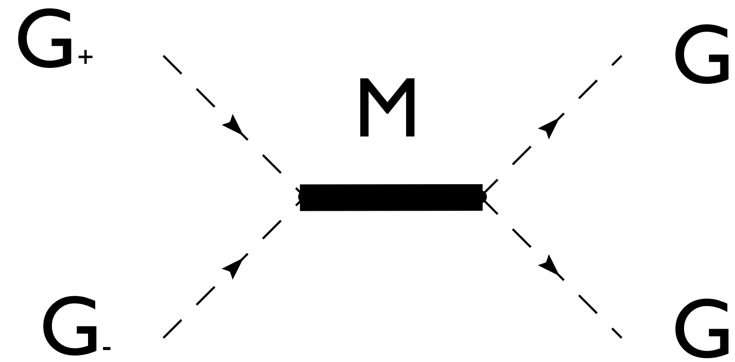
Goldstone contributes to this operator at the loop level, making the contributions log-sensitive to whatever unitarize G-cross sections



grows with E^2



+



grows with E^2

extra state M needed to unitarize

grows with E^2 extra state M needed to unitarize

M = moderator of the G-cross section

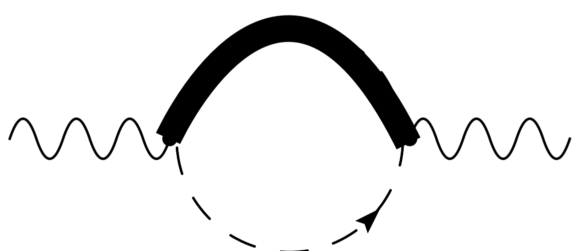
(M = Higgs in the SM)

grows with E^2

extra state M needed to unitarize

M = moderator of the G-cross section

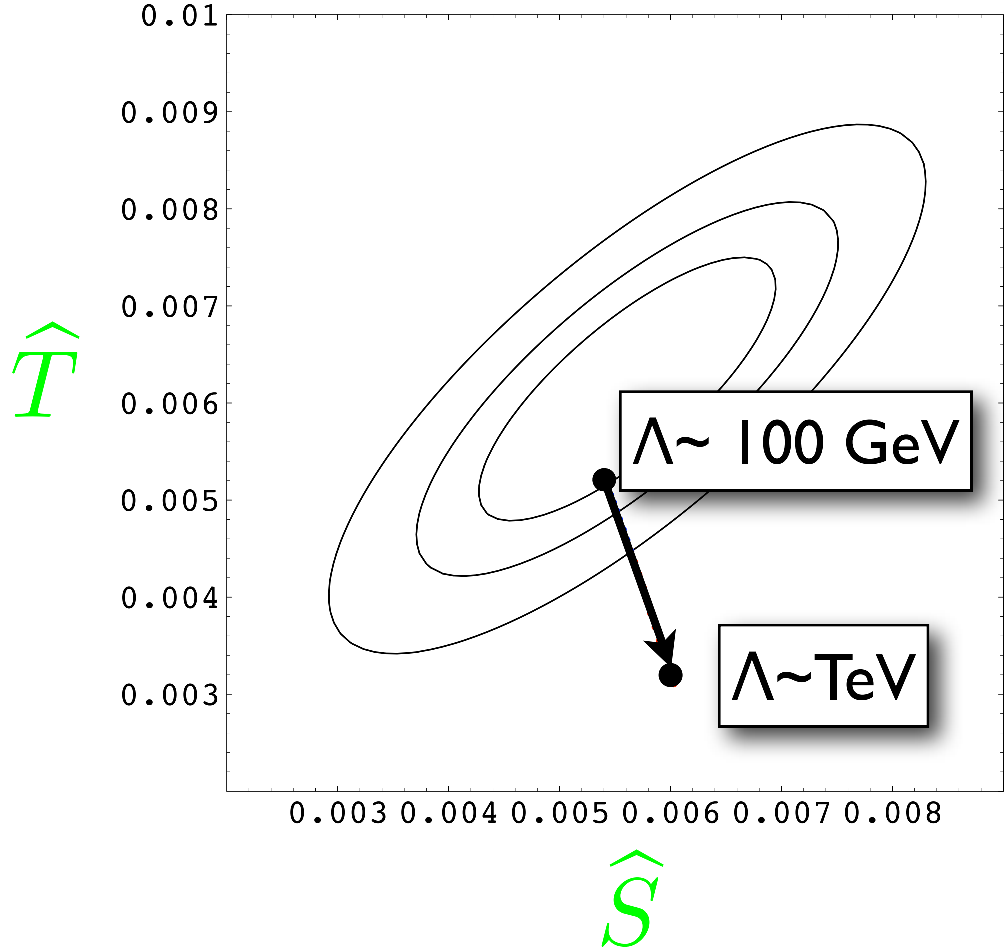
(M = Higgs in the SM)



$$\hat{S} \simeq \frac{g^2}{192\pi^2} \ln\left(\frac{\Lambda^2}{m_W^2}\right)$$

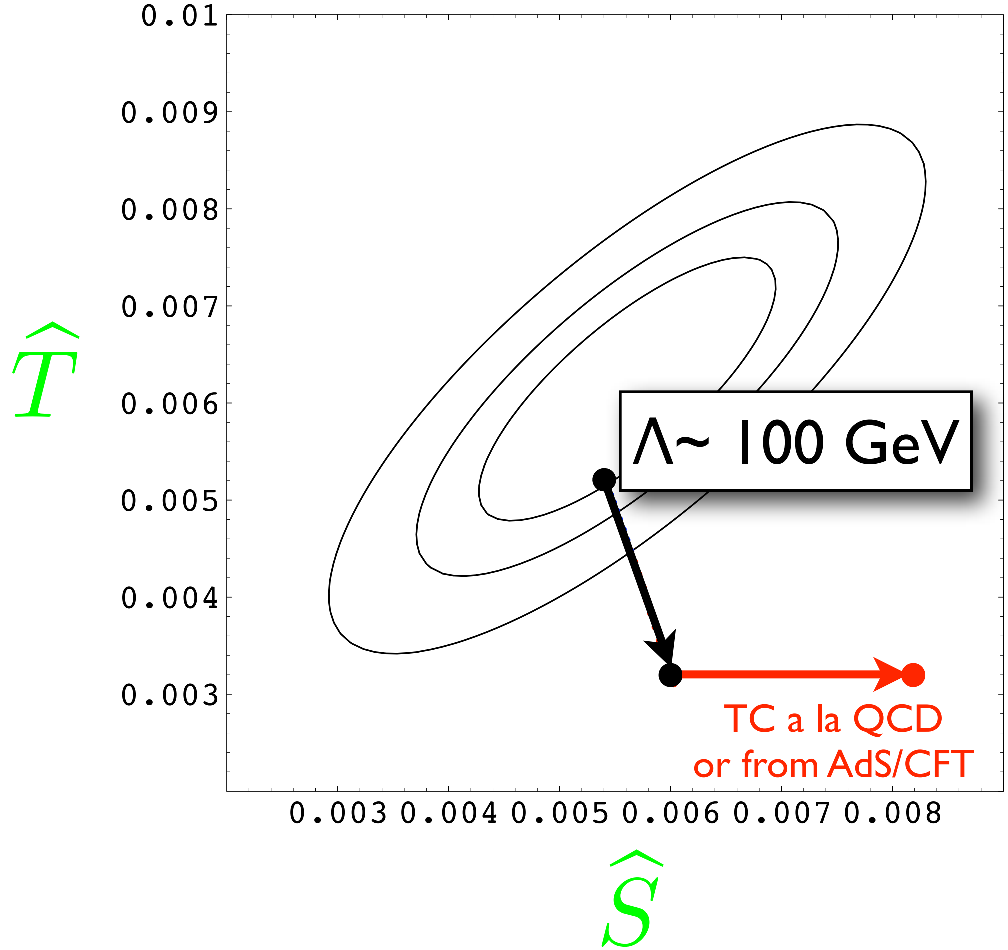
Λ=mass of M

From experiments:



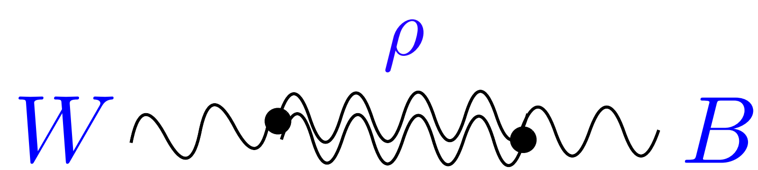
➥ Data tell us that the 3 Goldstone must form a triplet under some global symmetry (custodial) and the moderator of the SM cross-section must be light!

From experiments:



➥ Data tell us that the 3 Goldstone must form a triplet under some global symmetry (custodial) and the moderator of the SM cross-section must be light!

If M=spin-one state (as in Higgsless), can be tree-level contribution to S:



Summing up:

Only **right-handed quarks** and **W_L , Z_L**
can be considered composite states
of a strong sector at ~TeV, if:

- Strong sector has a global SU(2)-symmetry with the W,Z transforming as a triplet
- Contain a light scalar playing the role of the Higgs

➥ **Composite Higgs**

Implications

If **right-handed quark** are composite states...

If right-handed quark are composite states:

Best test at the LHC:

pp→ qq → jet+jet affected at high-energy by $\frac{(\bar{u}_R\gamma_\mu u_R)^2}{f^2}$

Already testing it! New data (17-Nov):

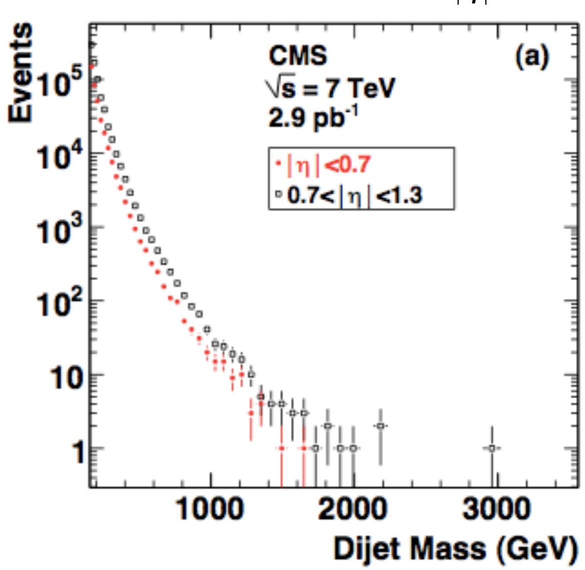
Quark compositeness/QCD

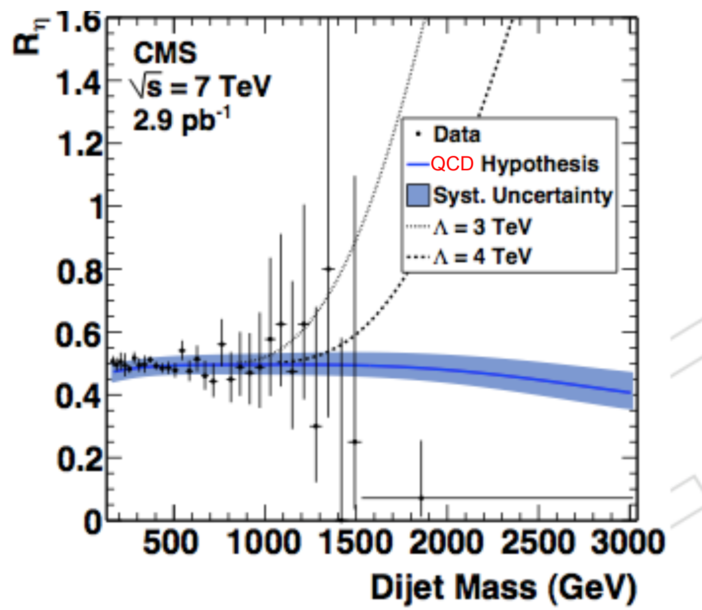
Centrality ratio

$$R_\eta = \frac{\sum_{|\eta|<0.7} Dijets}{\sum_{0.7<|\eta|<1.3} Dijets}$$

Contact interaction: excluded for Λ<4 TeV (higher than expected −2.9 TeV- due to fewer-than-expected events at high Dijet mass)

→ f >1 TeV





Composite Higgs

The idea of composite Higgs has an extra motivation

➥ Elementary scalars not naturally light:

Supersymmetry must be invoked

But in the susy SM (MSSM)

Higgs is predicted to be "too light"

(below exp. bound ~114 GeV)

unless certain tuning in the spectrum is required

(usually tuning < 1-10%)

Naturally Light Scalars from a Strong sector

Either from spontaneous breaking of...

1) a global symmetry: G→H
Pseudo-Goldstone Boson (PGB) = G/H coset

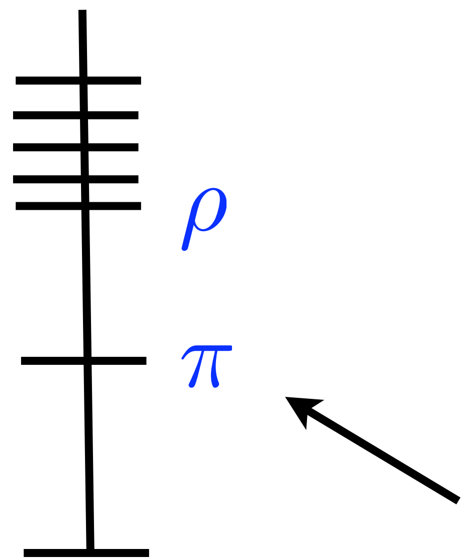
2) dilatations → Dilaton

of a (scale-invariant) strong sector (or a Warped Extra Dimensional AdS_5)

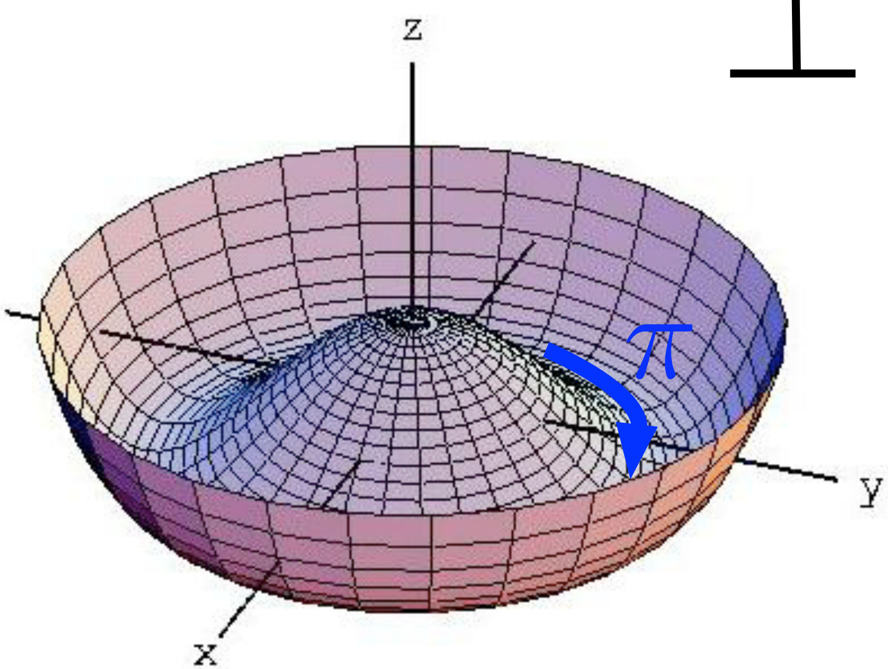
First option:

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

Spectrum:



Are Pseudo-Nambu-Goldstone bosons (PNGB)



Mass protected by the global QCD symmetry!

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

First option:

Higgs arising as Pseudo-Goldstone Bosons (PGB) from the breaking of global symmetry of a strong sector (or WED):

$$G \rightarrow H$$

Higgs (h) and company = PGB = coset G/H

From the strong sector (or AdS5): $V(h)=0$ $(h \rightarrow h+\alpha)$

Explicit breaking from SM fields: $V(h/f) \neq 0$ at the loop level

➥ $\langle h \rangle \sim f$ (PGB-decay constant)

As we will see, $f \sim 500$ GeV → Higgs masses 100-300 GeV

This is similar but not the little-Higgs approach!

Requirements for the group G and H:

a) H must contain the SM gauge group

b) G must contain an SU(2)xSU(2) ~ SO(4) symmetry
under which a PGB is a Higgs doublet is a (2,2) ~ 4

P.Sikivie, L.Susskind, M.B.Voloshin, V.I.Zakharov

$$H = \begin{pmatrix} 0 \\ 0 \\ 0 \\ v \end{pmatrix}$$

} SO(3) unbroken subgroup: "Custodial" symmetry

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} SO(3) unbroken subgroup: "Custodial" symmetry

We could know more on G and H if we know the elementary states of the strong sector

e.g. For a strong SU(N) sector:

Minimal fund. fermion content: 4 (Ψ_L,Ψ_R) then G=SU(4)xSU(4) → H=SU(4)

But we are not yet able to know a strong sector that successfully explains all EWSB masses

→ We must a take a more modest approach and explore the different possibilities fulfilling (a) and (b)

Possible symmetry patterns:

G	H	PGB
SO(5)	O(4)	4=(2,2)
SO(6)	SO(5)	5=(2,2)+(1,1)
	O(4)xO(2)	8=(2,2)+(2,2)
SO(7)	SO(6)	6=(2,2)+(1,1)+(1,1)
	G_2	7=(1,3)+(2,2)
...	...	...

times $SU(3)_c \times U(1)$ of SM

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Agashe, Contino, AP

one doublet

times $SU(3)_c \times U(1)$ of SM

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Gripaios, AP, Riva, Serra

One doublet
+ Singlet

times $SU(3)_c$ x U(1) of SM

Possible symmetry patterns:

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Two doublets

J.Mrazek, A. P., R. Rattazzi, M. Redi, J. Serra and A. Wulzer, in preparation

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Two doublets

J.Mrazek, A. P., R. Rattazzi, M. Redi, J. Serra and A. Wulzer, in preparation

times $SU(3)_c \times U(1)$ of SM

Good: Scalar (PGB) spectrum fixed by symmetries

Bad: Not clear which G/H should be considered

➡ **Minimality is not a guide**

Bosonic Part:

Although the dynamics of the strong sector can be unknown, the low-energy effective lagrangian for PGB Higgses can be determined by symmetries (as chiral lagrangian for pions physics).

Lowest dim operator:

$$\frac{f^2}{8}\,\mathrm{Tr}\,|D_\mu \Sigma|^2$$

$$e^{iT_a h_a}$$ G/H coset

By expanding around the EWSB minimum, gives Higgs self-couplings and couplings to gauge bosons

Fermionic Part: Couplings to SM fermions

More model dependent!

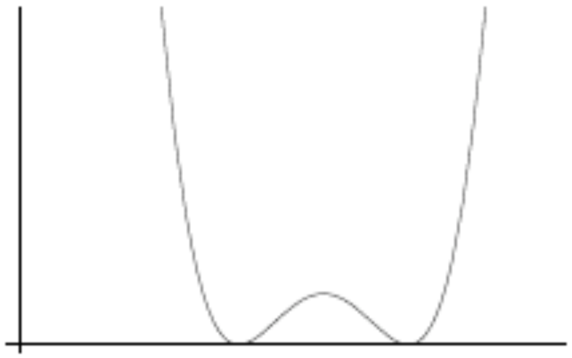
Inspired by AdS/CFT:

Assume that elementary SM fermions couple to fermionic resonances of the strong sector

$$\mathcal{L}_{\rm int} = \lambda \psi_{\rm SM} \Psi_{compo}$$

Explicitly break G, generating a potential at one-loop level for h

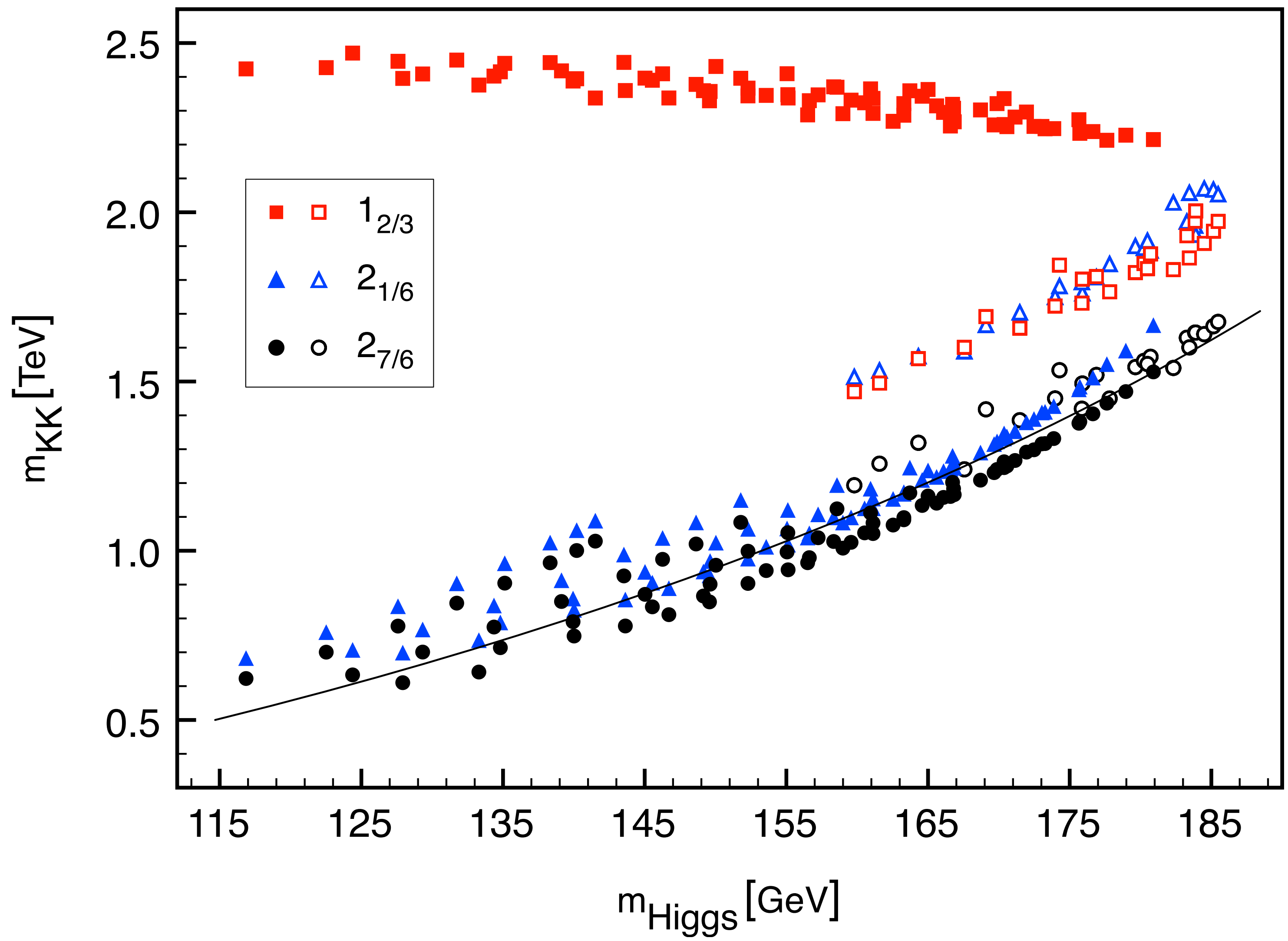
Higgs potential induced by gauge loops + top loops



$$V(h) = -m^2 h^2 + \ldots$$

EWSB thanks to the heavy top!

Precise predictions from AdS/CFT:



Correlation between the masses of the Higgs and the resonances of the top

Back to the Bosonic Part:

SO(5)/SO(4) model: One Higgs = h

$$\frac{f^2}{8}\mathrm{Tr}|D_\mu\Sigma|^2 = \frac{f^2}{2}(\partial_\mu h)^2 + \frac{f^2}{2}\frac{(h\partial_\mu h)^2}{1-h^2}$$

$$+\frac{g^2 f^2}{4}h^2\left[W^{\mu+}W^-_\mu + \frac{1}{2\cos^2\theta_W}Z^\mu Z_\mu\right] + \cdots$$

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:

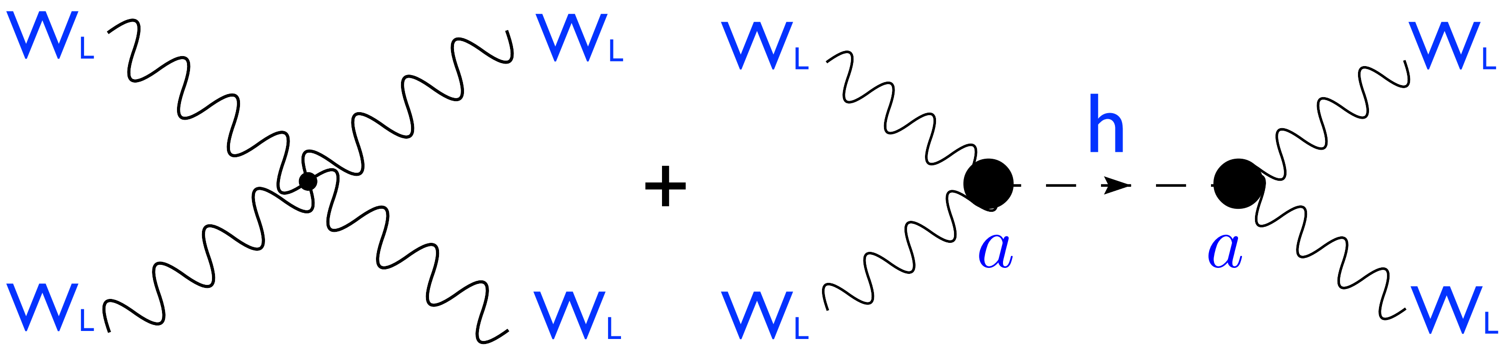
Giudice,Grojean,AP,Rattazzi 07

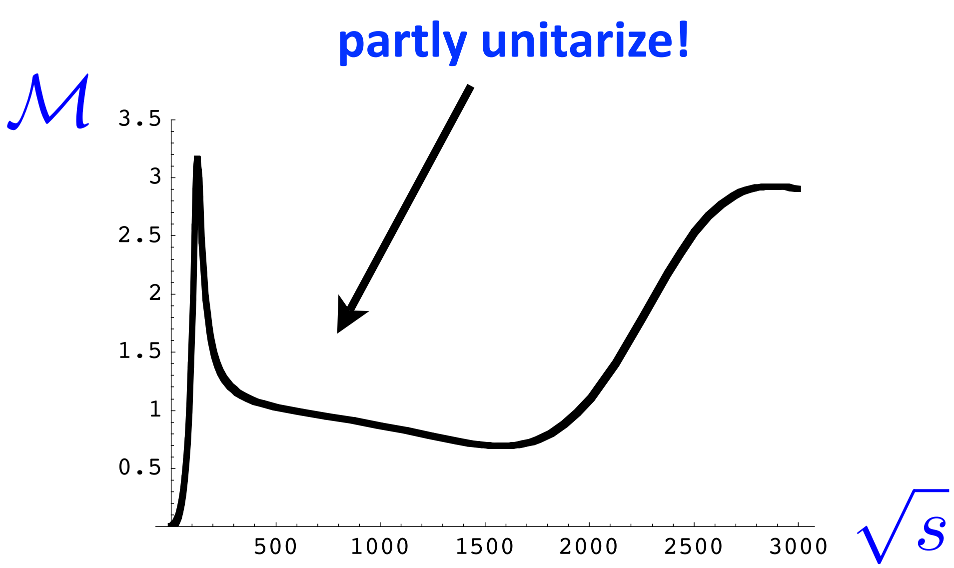
$$a = \sqrt{1 - \frac{v^2}{f^2}} \qquad b = 1 - \frac{2v^2}{f^2} \qquad c = \sqrt{1 - \frac{v^2}{f^2}}$$

effective 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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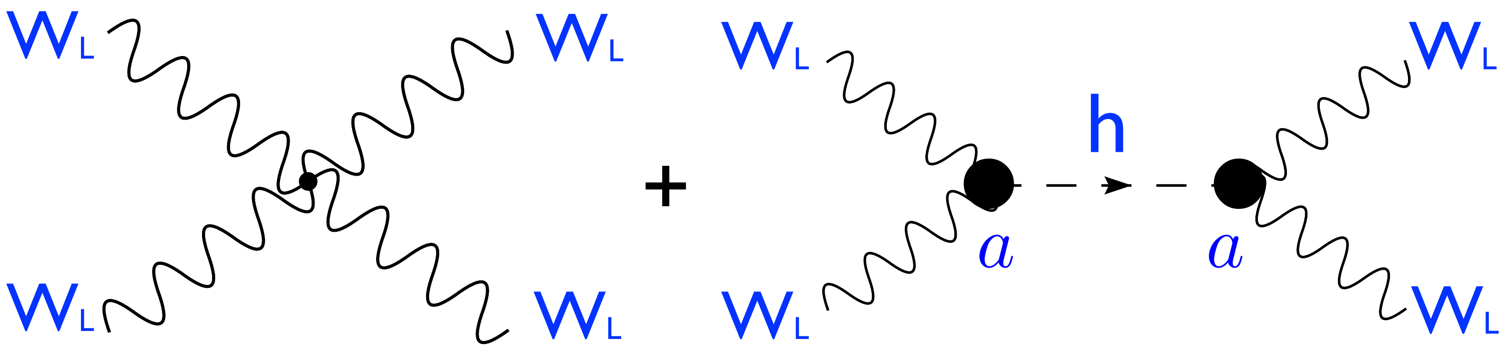
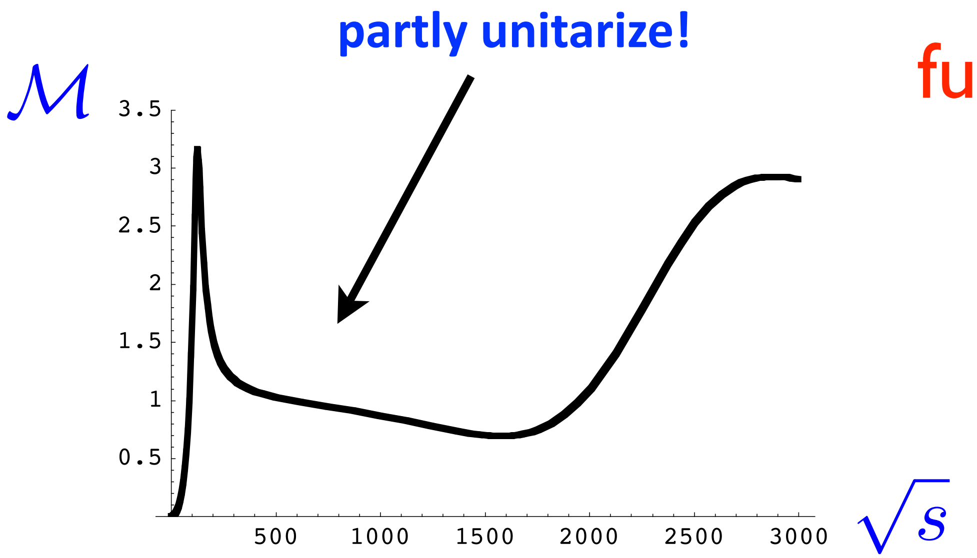
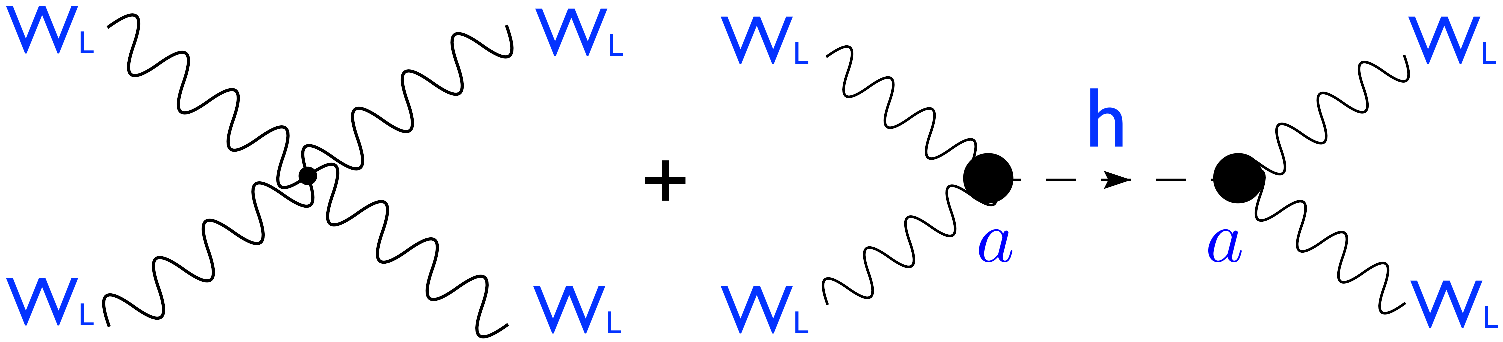
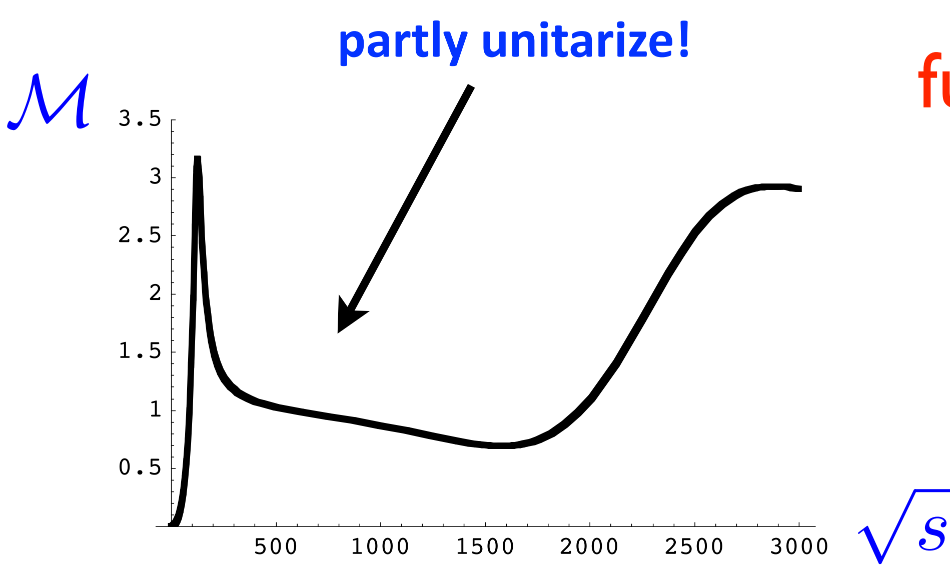




Extra states needed to fully unitarize (for consistency)!

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





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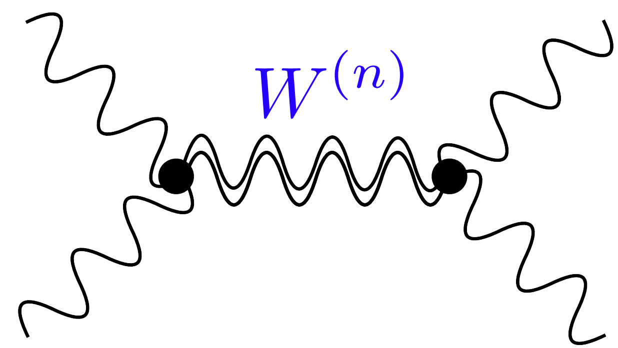
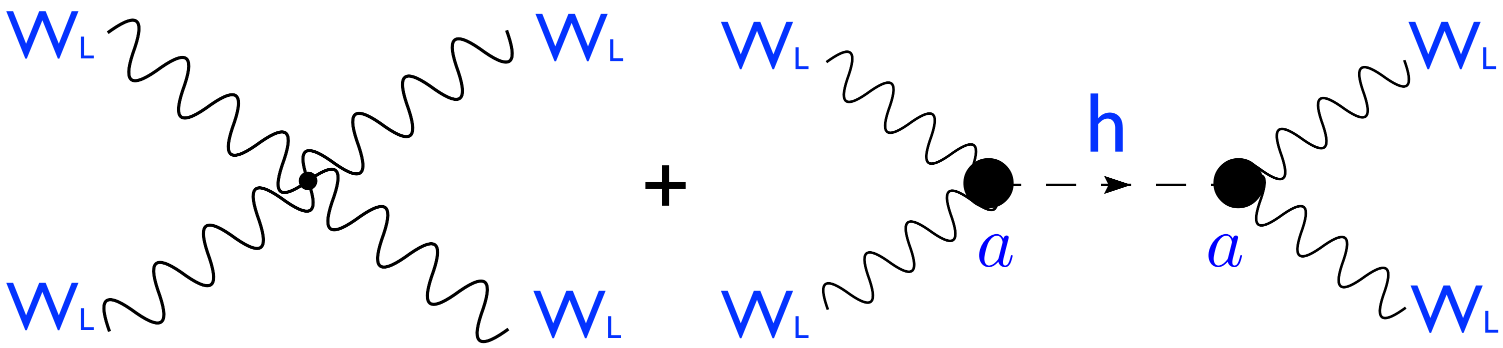


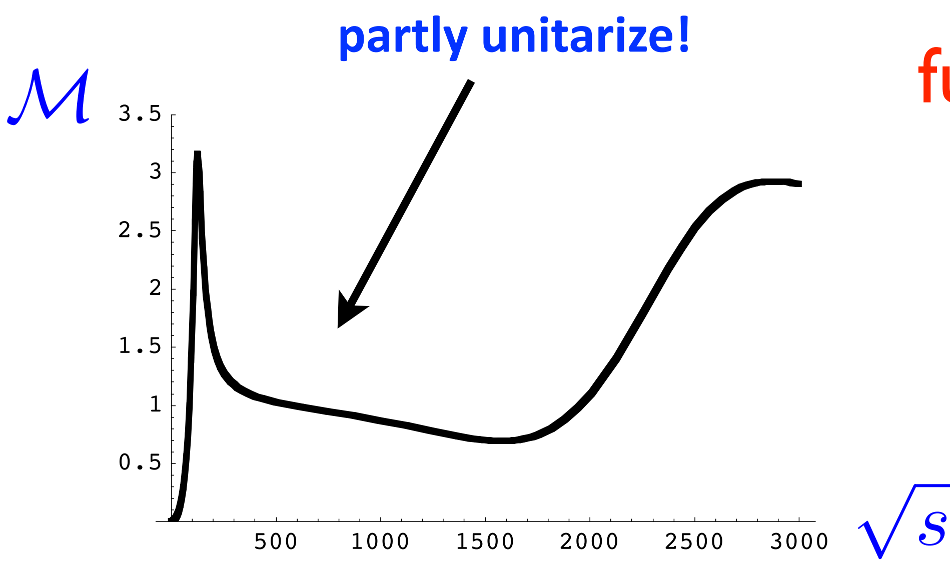
Extra resonances

(or Kaluza-Klein states of the W)

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

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





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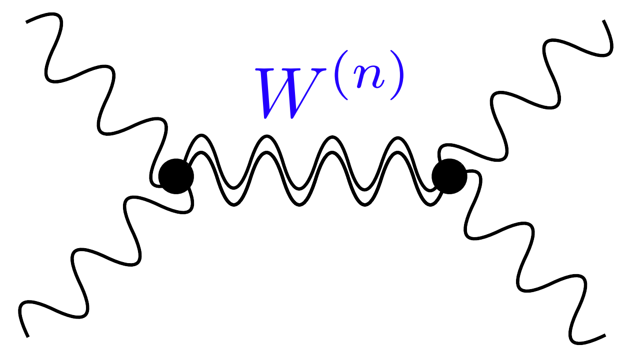
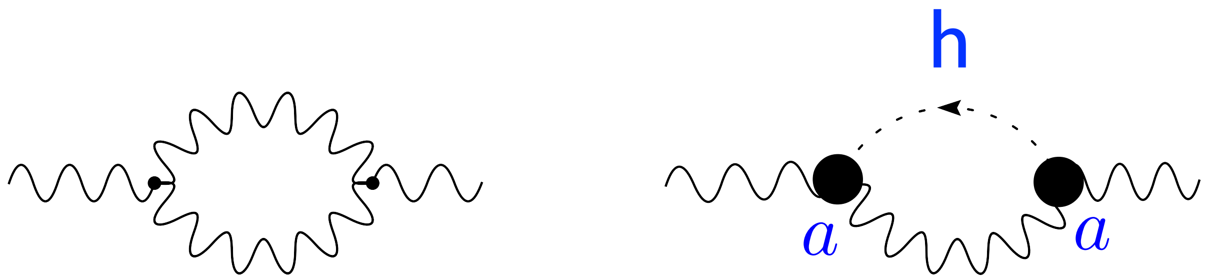


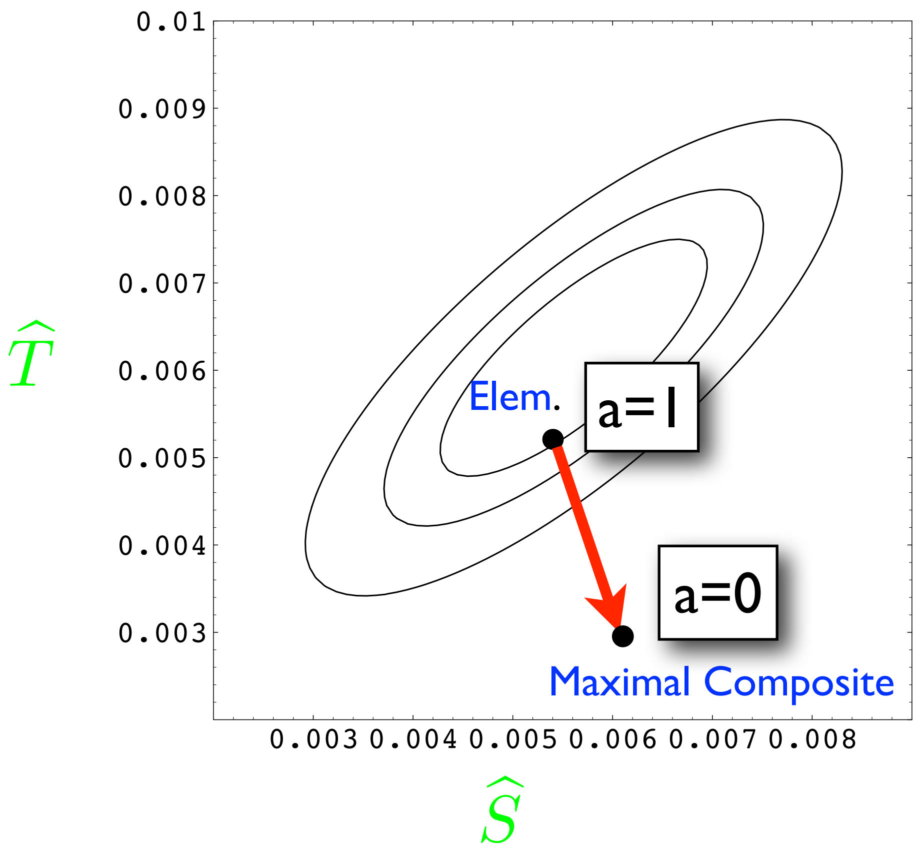
Extra resonances
(or Kaluza-Klein states of the W)

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



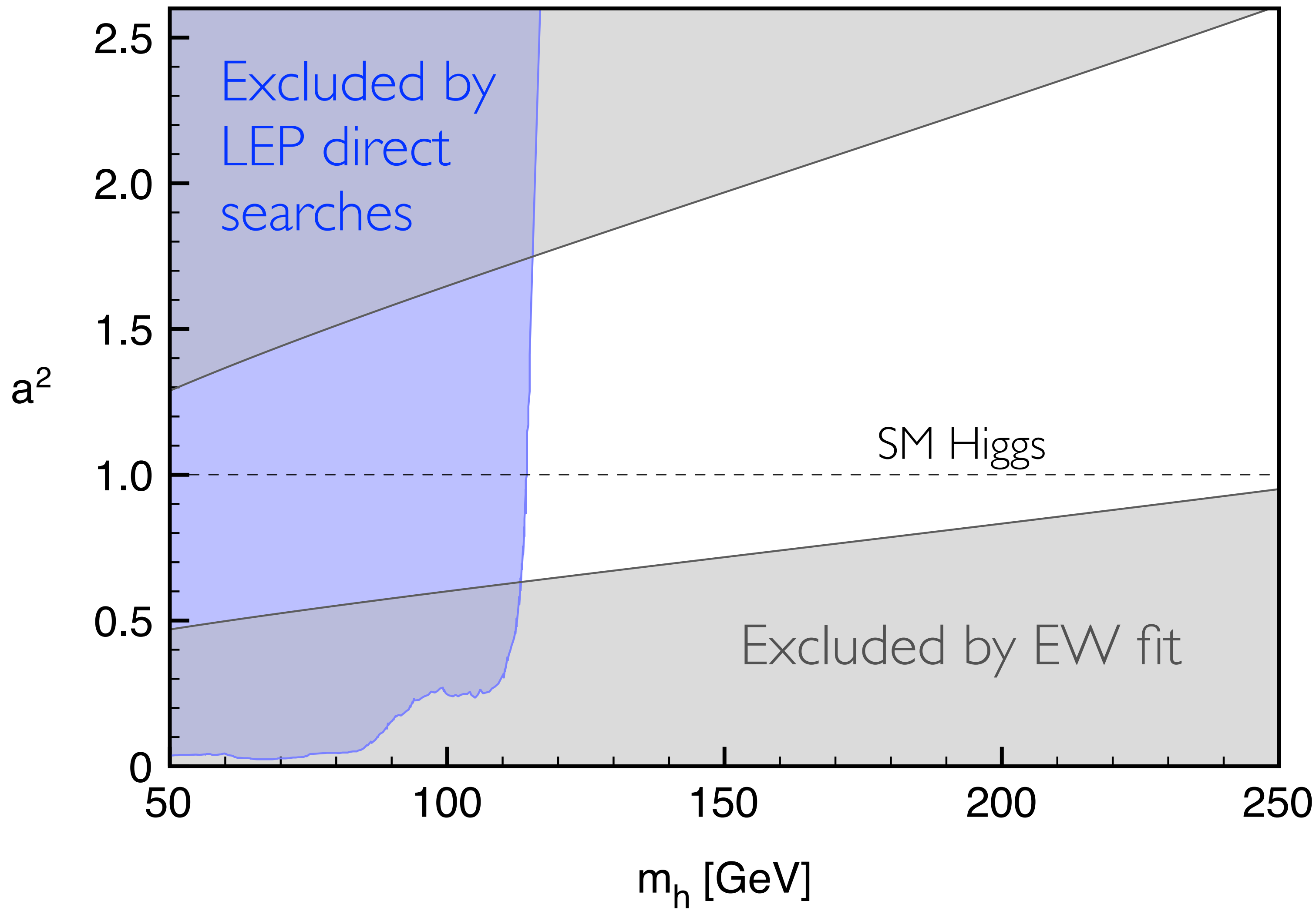


➠ a > 0.8

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

More precise:

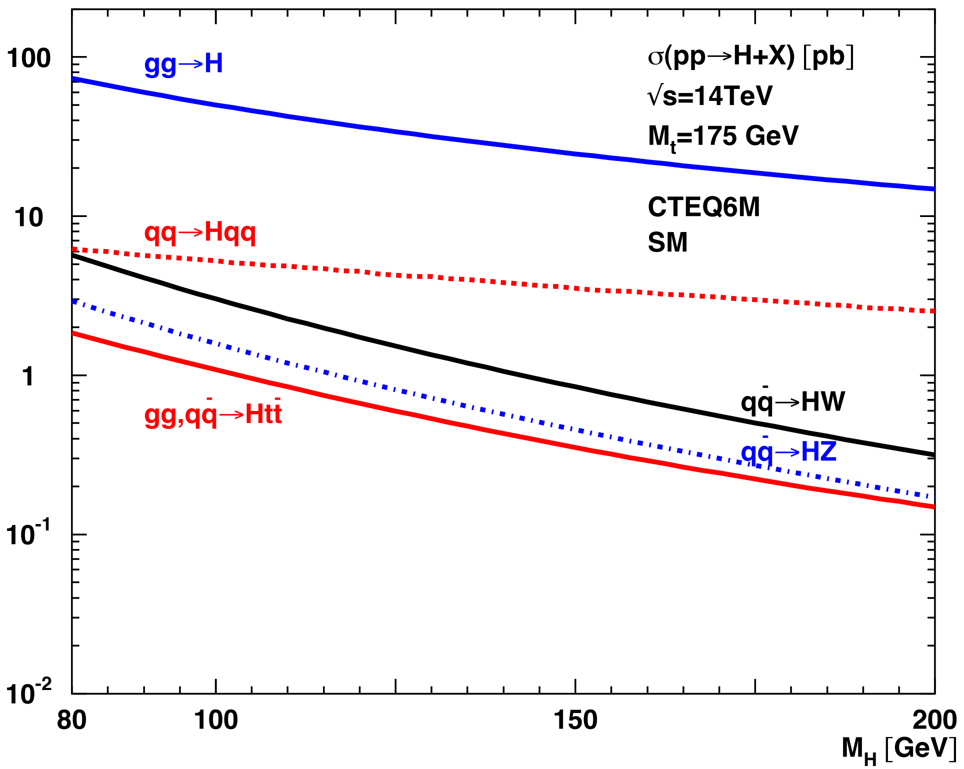
Contino at Planck10



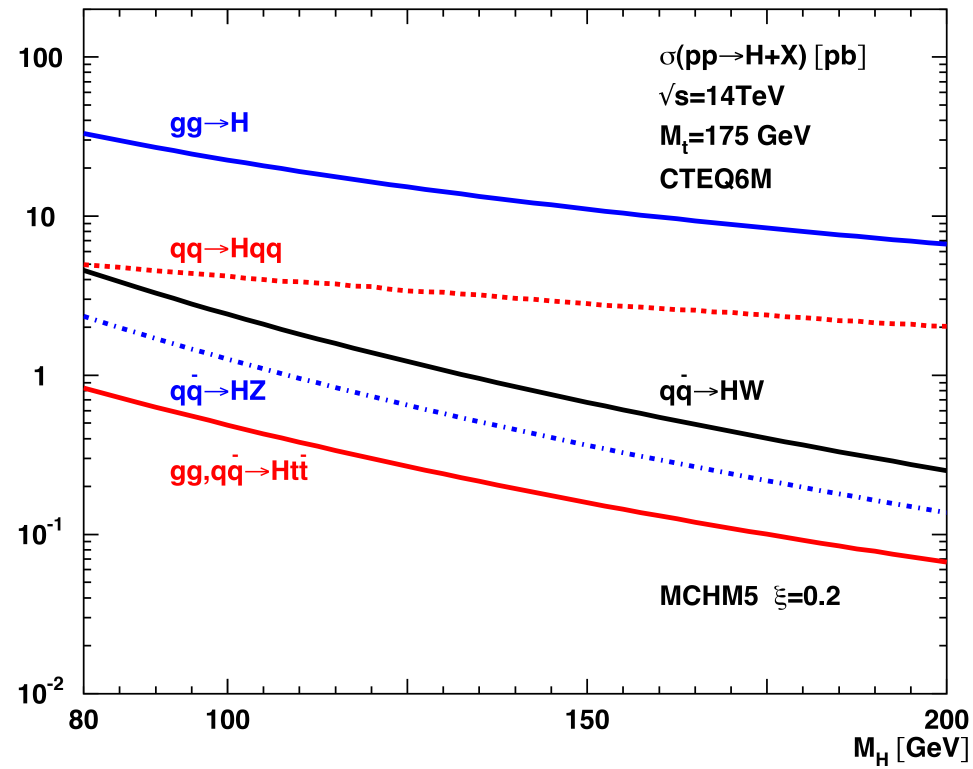
If the Higgs is **composite**, how it will change LHC predictions?

Bad news: Reduction of rates!

SM Higgs



Compo. PGB Higgs a=0.9



Grojean,Espinosa,Muhlleitner 10

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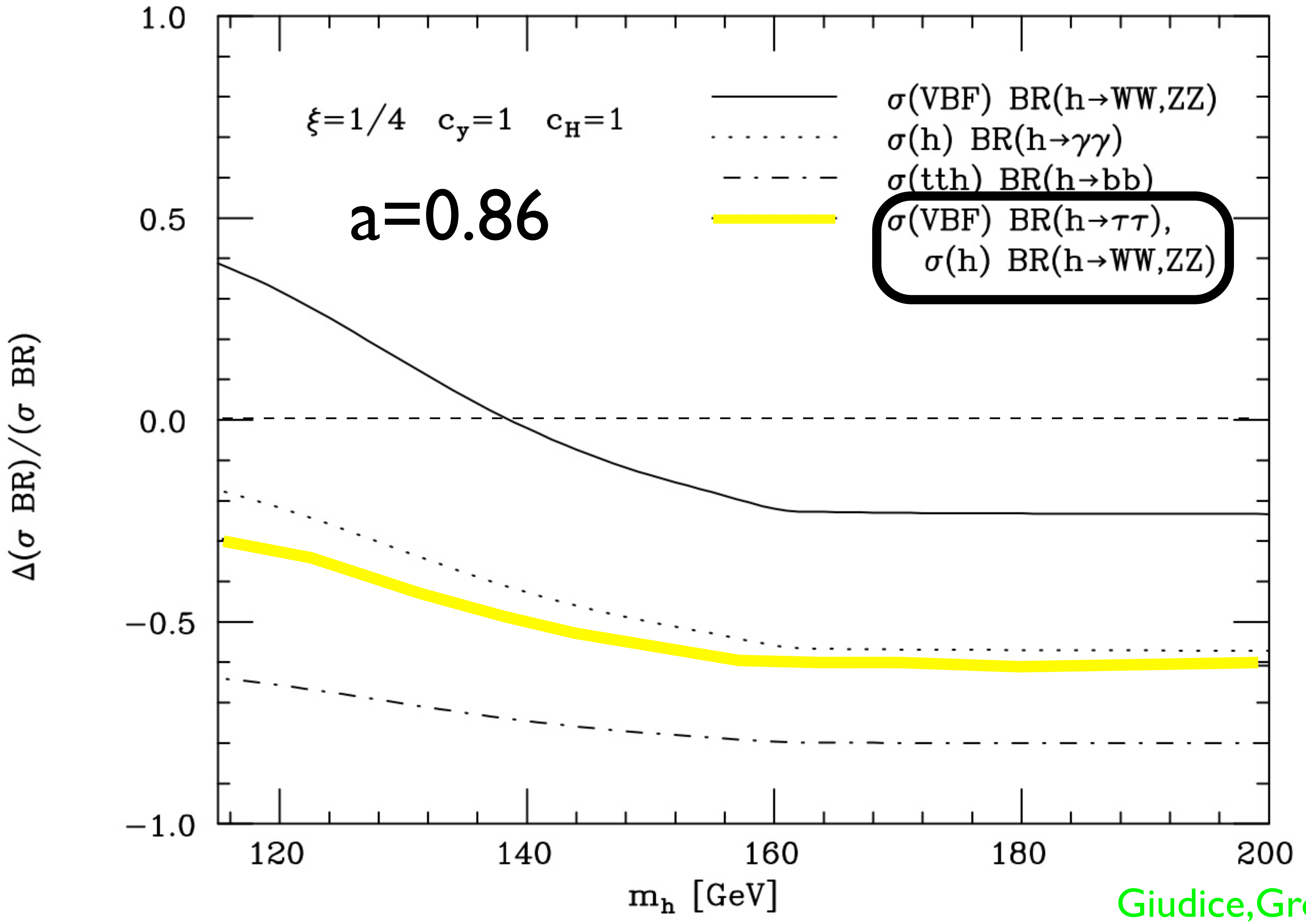
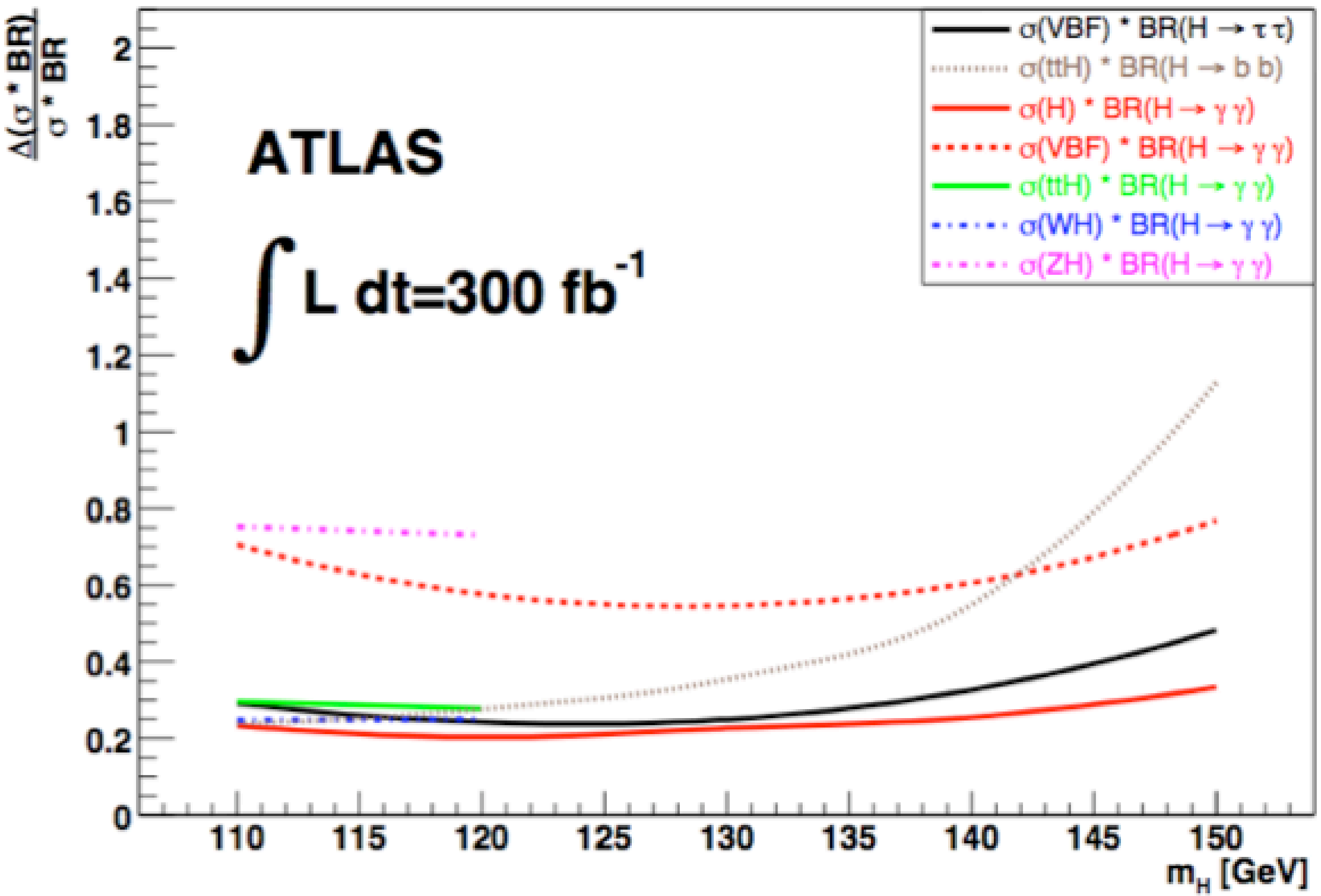


Giudice,Grojean,AP,Rattazzi 07



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 %

SO(6)/SO(5) model: Doublet h + Singlet η

$$\frac{f^2}{8}\,\mathrm{Tr}|D_\mu \Sigma|^2 = \frac{f^2}{2}(\partial_\mu h)^2 + \frac{f^2}{2}(\partial_\mu \eta)^2 + \frac{f^2}{2}\frac{(h\partial_\mu h + \eta\partial_\mu \eta)^2}{1 - h^2 - \eta^2}$$

$$+ \frac{g^2 f^2}{4} h^2 \left[W^{\mu +} W^-_\mu + \frac{1}{2\cos^2\theta_W} Z^\mu Z_\mu \right]$$

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Gripaios, AP, Riva, Serra

$h\eta\eta$ coupling:

$$-\frac{f^2\langle h\rangle}{2}\eta^2\partial_\mu^2 h$$

Fixed by symmetries !!

Possibility for a new Higgs decay:

(depending on the η-mass)

$h \to \eta\eta \to b\bar{b}b\bar{b}$ or $\tau\bar{\tau}\tau\bar{\tau}$

In all these cases, Higgs h can be lighter than LEP bound 114 GeV

Chang, Dermisek, Gunion, Weiner

SO(6)/[SO(4)xSO(2)] model: 2 Doublets: $H_{1,2}$
(spectrum: h, H, A, H^+)

$$\frac{f^2}{8}\mathrm{Tr}|D_\mu\Sigma|^2 = \cdots - \frac{g^2}{24}\left[|W_\mu|^2 + \frac{Z_\mu^2}{2\cos^2\theta_W}\right][(h^2+H^2)^2 + A^4] - \frac{g^2 Z_\mu^2}{8\cos^2\theta_W}h^2A^2$$
$$- \frac{gZ^\mu}{6\cos\theta_W}h^2 H\partial_\mu A + \cdots$$

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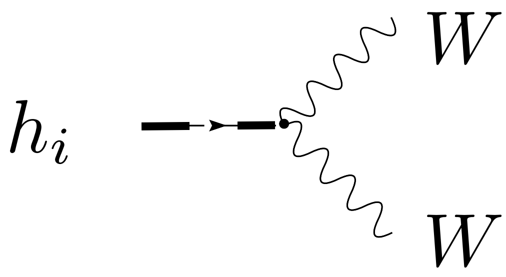
$$-\frac{gZ^\mu}{6\cos\theta_W}h^2H\partial_\mu A + \cdots$$

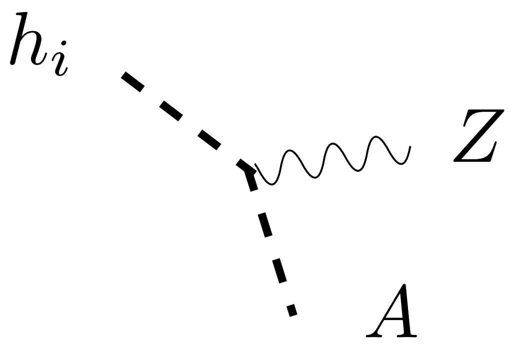
New couplings or deviations on renormalizable couplings of THDM of order $(v/f)^2 \sim 0.2$

Changes in the Higgs-coupling sum rules

In renormalizable THDM:



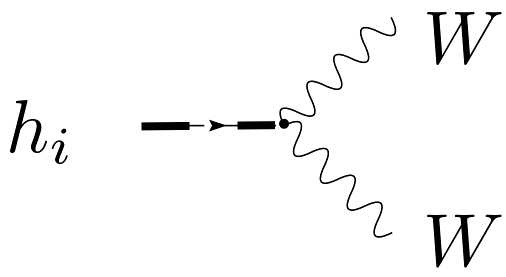
$$\sum_i g^2_{h_i WW} = g^2 m^2_W$$



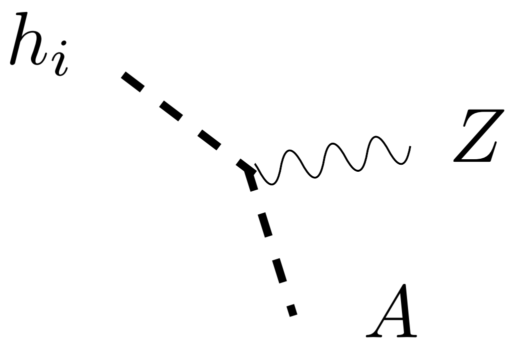
$$\sum_i g^2_{h_i AZ} = \frac{g}{\cos\theta_W}$$

Changes in the Higgs-coupling sum rules

In PGB Higgs:



$$\sum_i g^2_{h_i WW} = g^2 m_W^2 \left(1 - \frac{2}{3}\frac{v^2}{f^2}\right)$$



$$\sum_i g^2_{h_i AZ} = \frac{g}{\cos\theta_W}\left(1 - \frac{1}{6}\frac{v^2}{f^2}\right)$$

Possible 20% corrections!

Second option:

Light "Higgs" arising from the spontaneous breaking of dilations in a strong sector (or WED): Dilaton

Not, a priori, naturally light!

Under dilations: $x \rightarrow \lambda x$

$$\Phi(x) \rightarrow \lambda^d \Phi(\lambda x)$$

Spontaneous breaking of dilations: $\langle\Phi\rangle \equiv M^d \neq 0$

Dilaton: $\pi \rightarrow \pi(\lambda x) + \ln \lambda$

or $\varphi = e^{\pi} \rightarrow \lambda e^{\pi}$

Allows a non-linear realization of scale-transformations

Replace scales, Λ, by $\varphi\Lambda$: Transforms as a field of dim=1

A cosmological constant $\kappa \rightarrow \kappa\varphi^4$

potential for the dilaton allowed: $V=\kappa\varphi^4$ κ=const

Minimum with φ = const$\neq$0 only if κ=0 (tuning!) Fubini 76

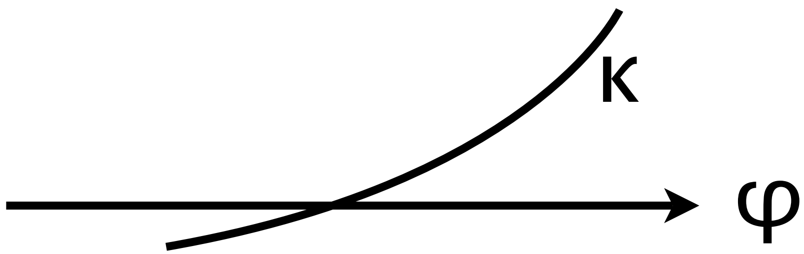
Explicit breaking must be introduced to the CFT:

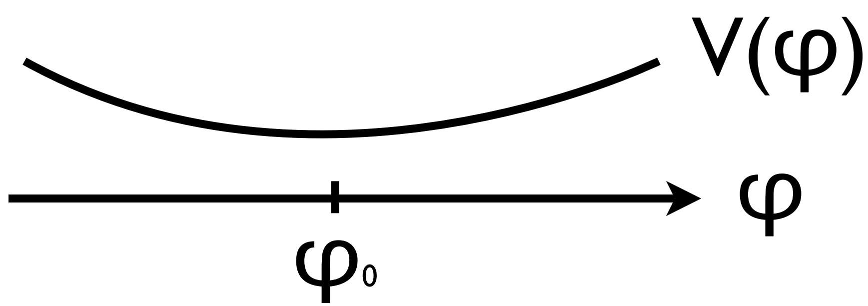
Add αO_d that "runs" $\beta(\alpha)\neq 0$

Now we have: $V(\varphi)=\kappa(\alpha(\varphi))\,\varphi^4$ (Coleman-Weinberg potential)

Non-trivial minimum if $\kappa(\alpha(\varphi))$ crosses zero:

Rattazzi,Contino,A.P.





Small dilaton mass → Flattish potential → slow running of κ → slow running of α

α must be an almost marginal deformation of the CFT

$\mathrm{Dim}[\alpha]=\varepsilon \;\rightarrow\; m_\varphi^2\sim \beta(\alpha)\sim\varepsilon$ (Not like in QCD)

The AdS/CFT dictionary, tells us how to be realized in AdS spaces (RS-setup):

$CFT_4 \rightarrow AdS_5$

Dilaton $\rightarrow$ Radion

$V(\varphi) \rightarrow T(\varphi)$ tension of the IR-brane

$Dim[\alpha]=\varepsilon \rightarrow$ Scalar with mass ~ ε

PGB in 5D!!

If the EW scale arises Mw/g arises from a scale-inv. sector, the dilaton couplings to the SM fields are fixed:

$$\mathcal{L} = M_W^2 W^\mu W_\mu + \frac{1}{2} M_Z^2 Z^\mu Z_\mu + m_f \bar{\psi}_i \psi_i$$

$$\mathcal{L} = \frac{\varphi^2}{f_D^2} M_W^2 W^\mu W_\mu + \frac{1}{2}\frac{\varphi^2}{f_D^2} M_Z^2 Z^\mu Z_\mu + \frac{\varphi}{f_D} m_f \bar{\psi}_i \psi_i$$

Expanding around the vacuum: $\frac{\varphi}{f_D} \to 1 + \frac{\varphi}{f_D}$

we obtain the coupling of the dilaton to the SM fields

Parametrization of deviations from SM Higgs couplings

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

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

Dilaton:

Goldberger, Grinstein, Skiba 07

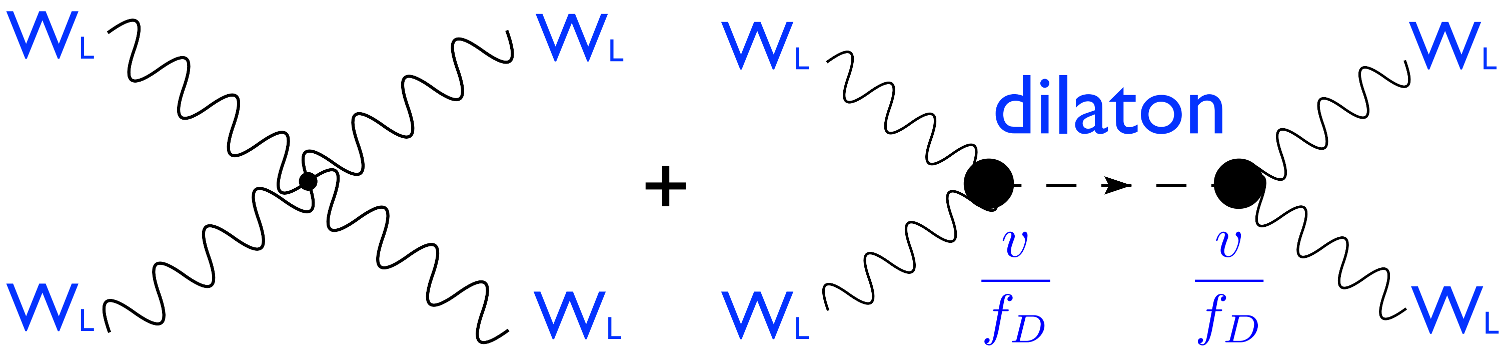
$$a = \sqrt{b} = c = \frac{v}{f_D} \sim \mathcal{O}(1)$$

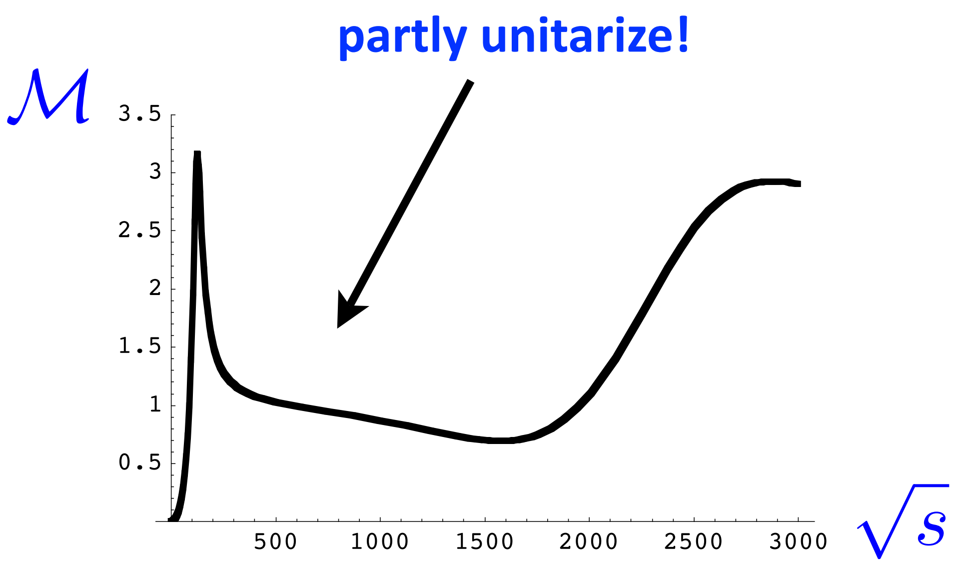
Scale related to the composite-scale

For $f_D \to v$ = 246 GeV, the dilaton behaves as a Higgs!

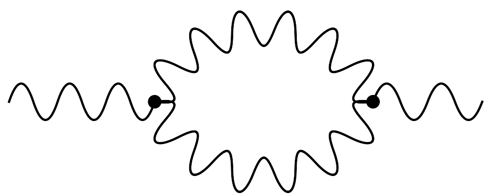
(Although has nothing to do with EWSB)

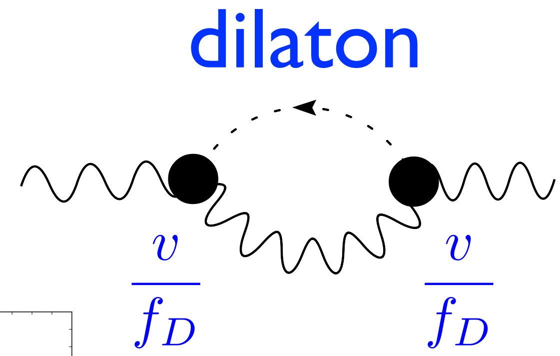
The **dilaton** “helps” to partly unitarize the WW-amplitude

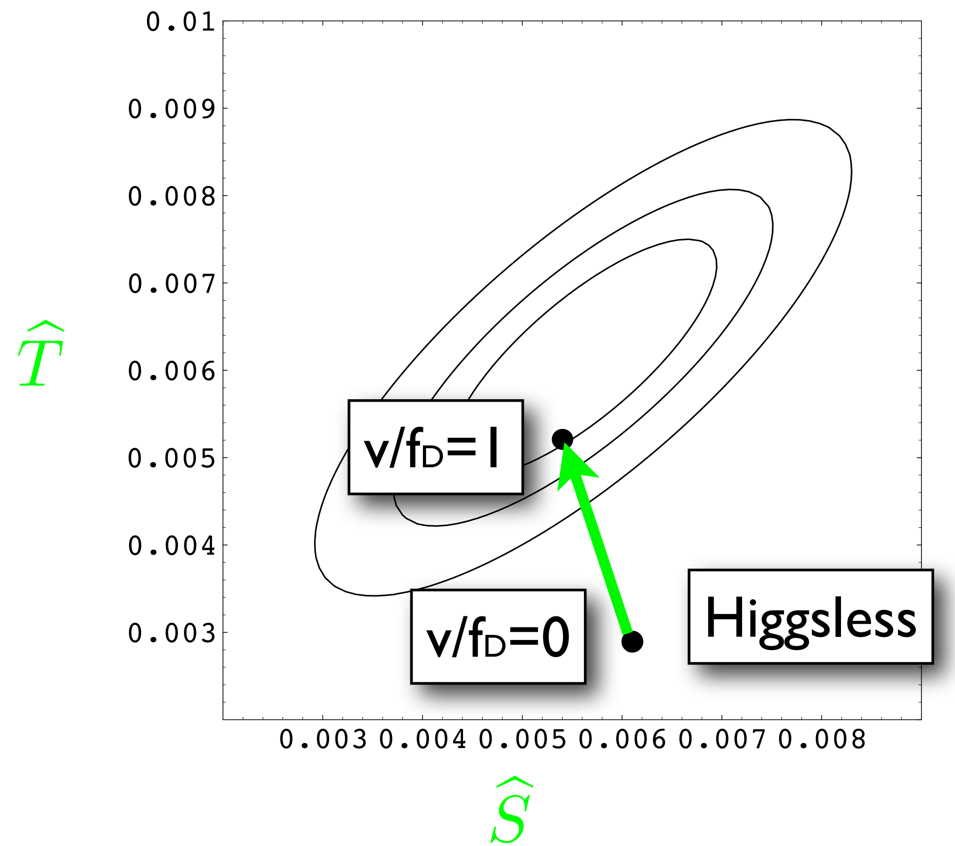




and helps to satisfy EWPT



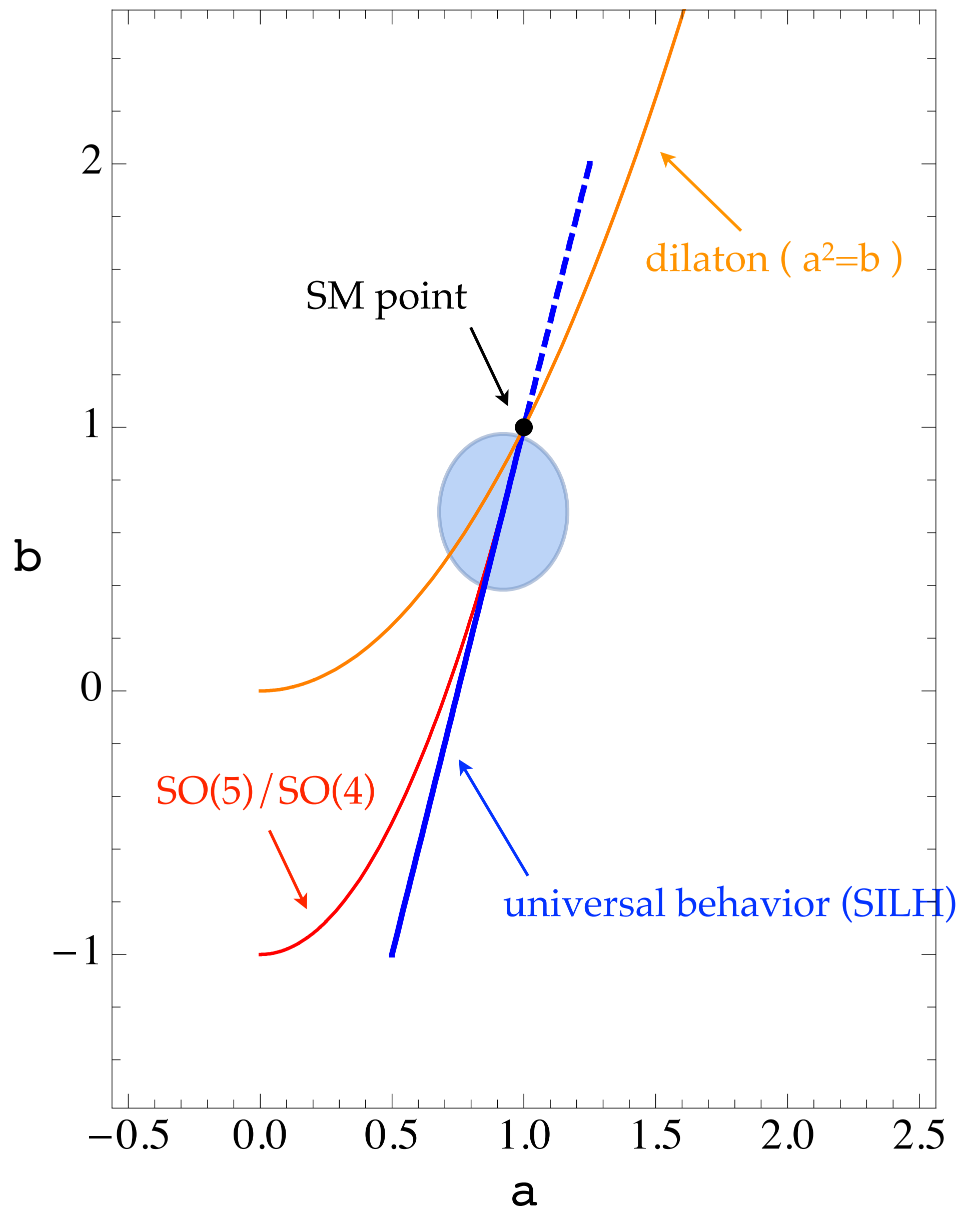




➠ $v/f_D > 0.8$

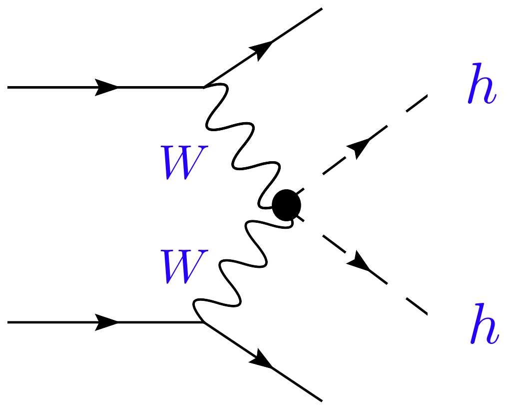
Put a bound on the scale of compositeness: $f_D > 500$ GeV

Contino at Planck10



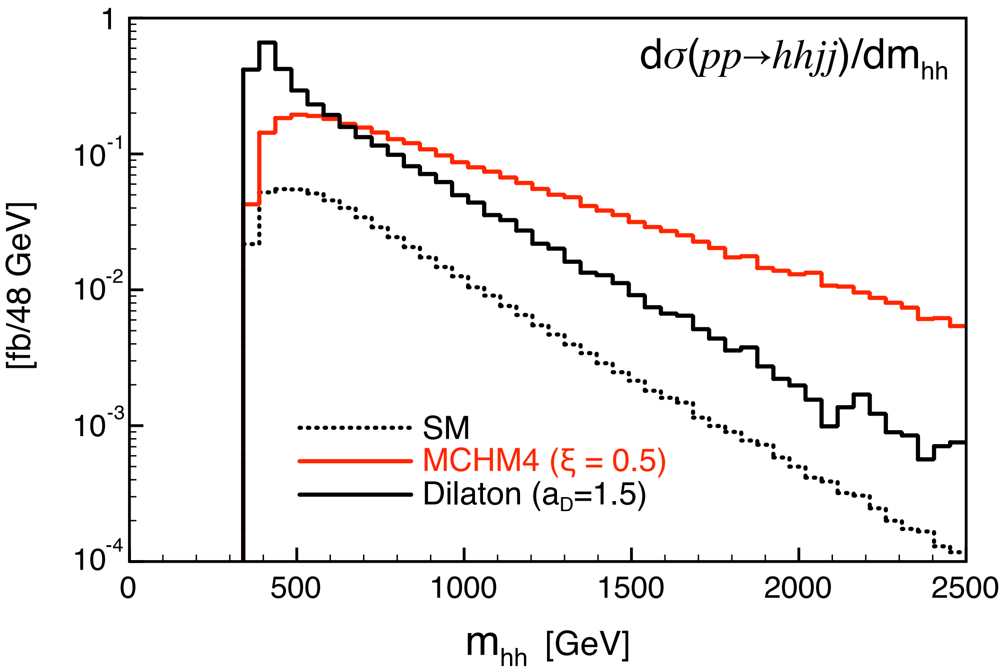
$$\mathcal{L} = \frac{M_V^2}{2} V_\mu^2 \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - m_f \bar{\psi}_L \psi_R \left(1 + c\frac{h}{v}\right) + \cdots$$

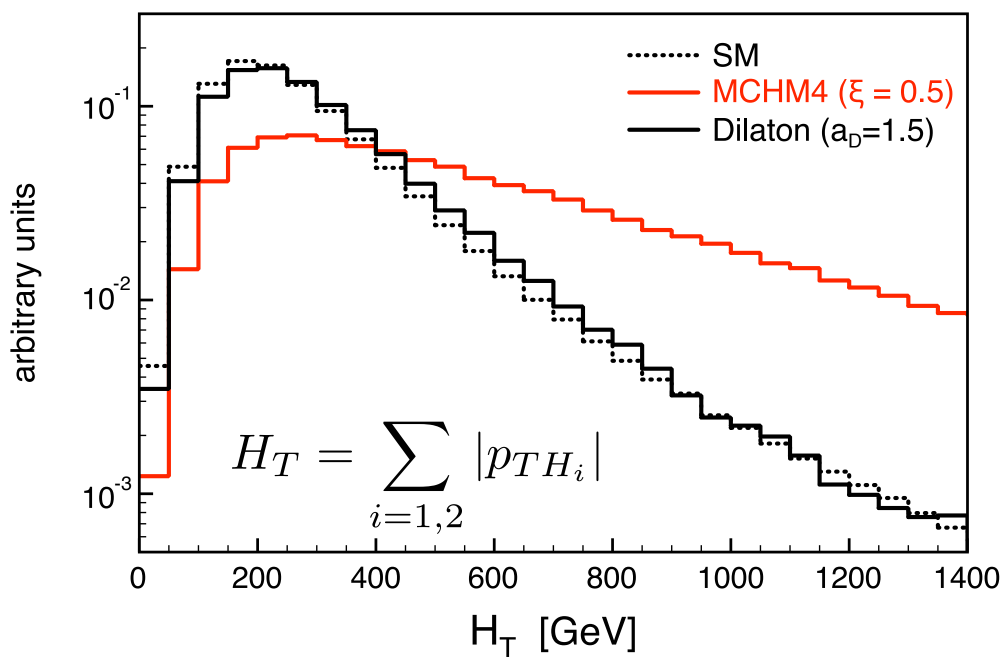
Distinguishing a SM Higgs from PGB Higgs or a dilaton by Double-Higgs production



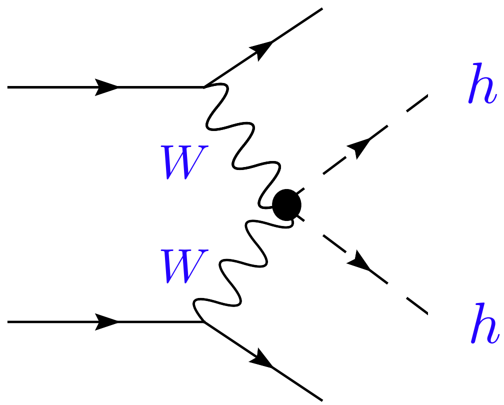
Contino et al 10

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





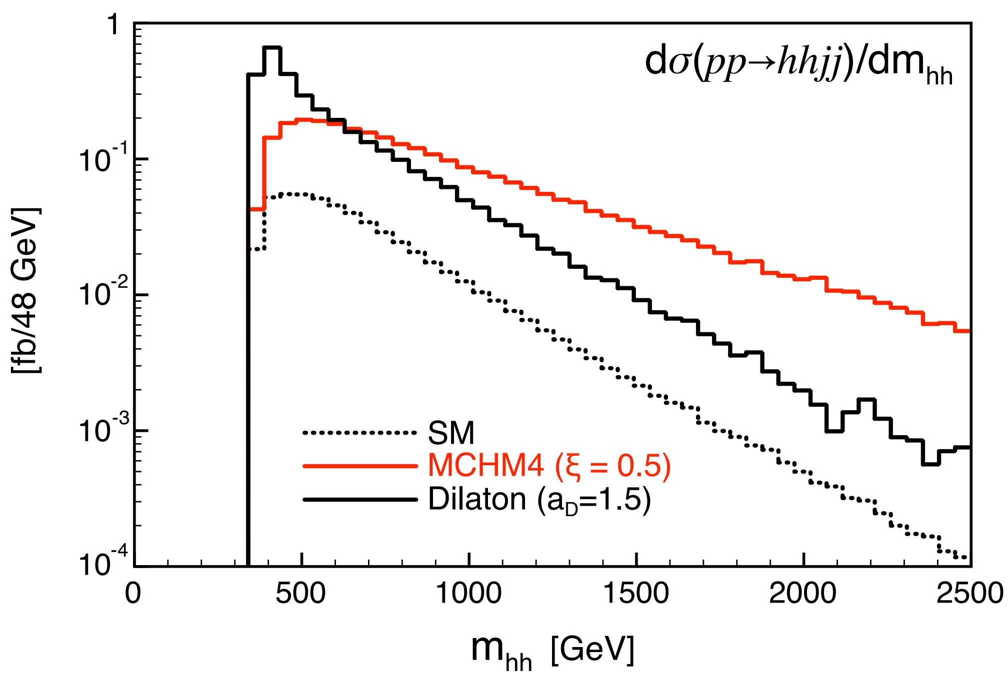
Distinguishing a SM Higgs from PGB Higgs or a dilaton by Double-Higgs production

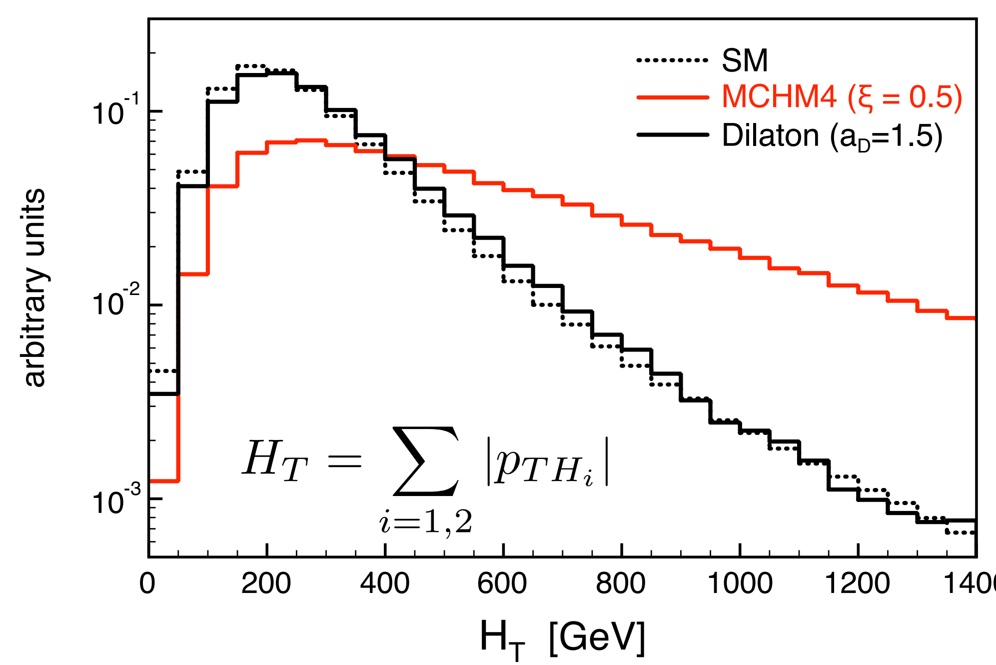


$$pp \to hhjj \to 4Wjj \to \begin{cases} l^+l^+l^-l^- \not{E}_T + 2j \\ l^+l^-l^\pm \not{E}_T + 4j \\ l^{+(-)}l^{+(-)} \not{E}_T + 5j\,(6j) \end{cases}$$

Contino et al 10

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





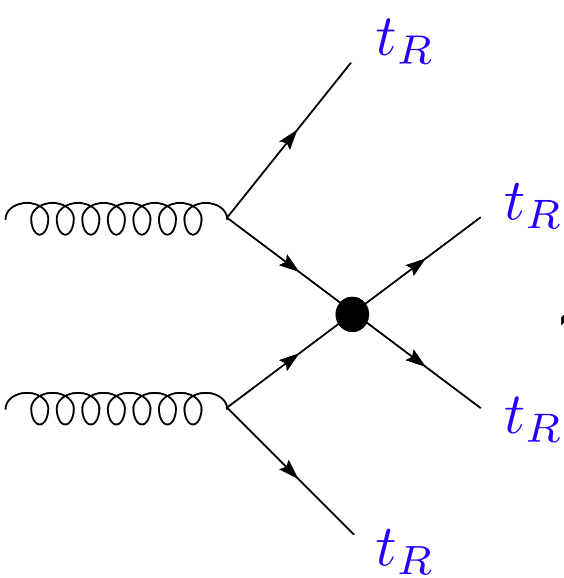
Composite Higgs implies Partly-Composite top

Since large top mass implies large coupling of the top to the Higgs (strong or KK-sector)

Important to measure deviations from elementary top predictions

In particular, 4-top production at the LHC:

$$pp \to t_R \bar{t}_R t_R \bar{t}_R$$



~ grows with (E/f)

Conclusions

- If the origin of the EW scale is due to a new strong sector, it is possible that the Higgs (and W_L , Z_L) arise from this sector

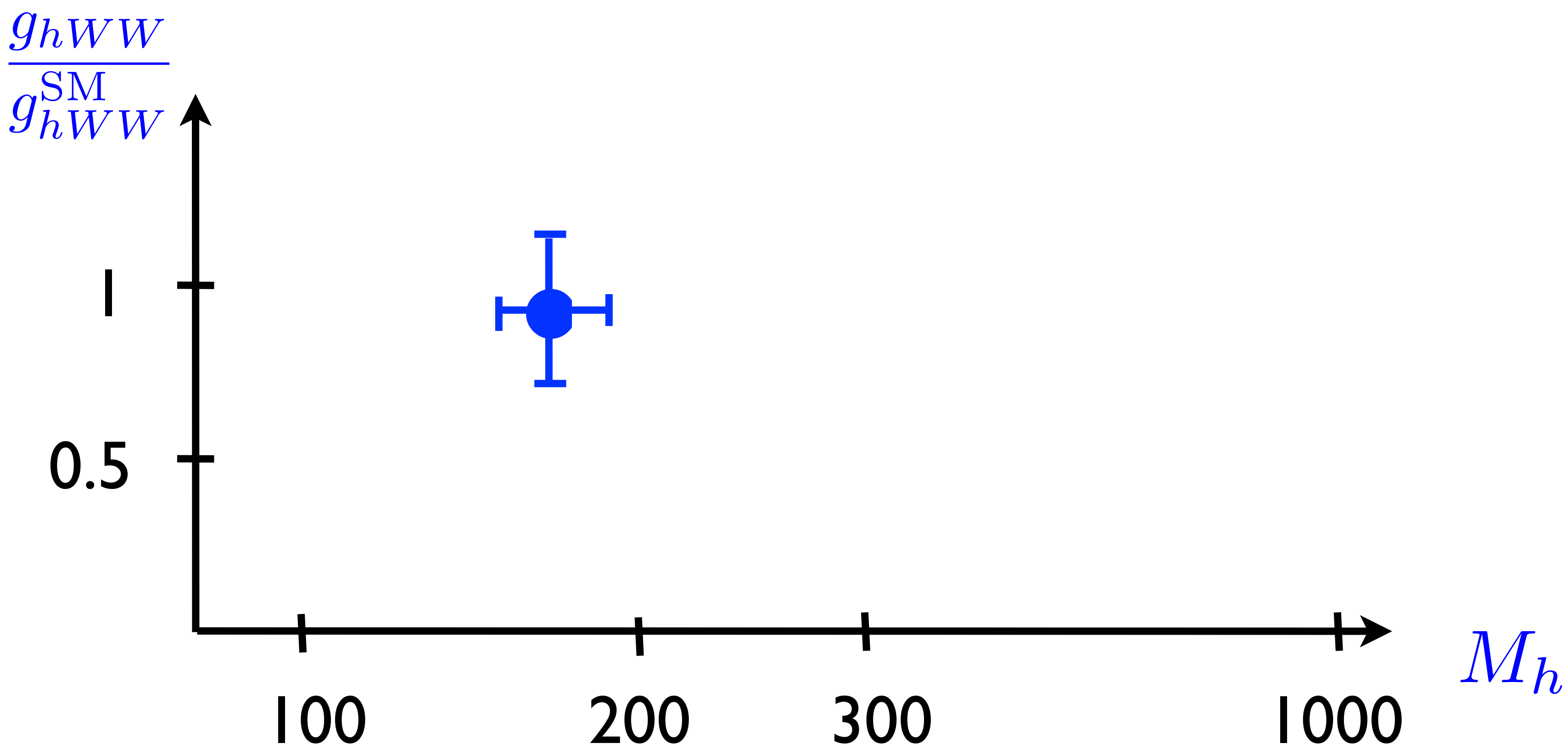
- Higgs will show properties of compositeness
  → deviations from ordinary SM Higgs couplings

- Rich Higgs spectrum and pheno if more PGB are present:
  Fixed by G/H

- Possibility of a light dilaton mimicking the Higgs

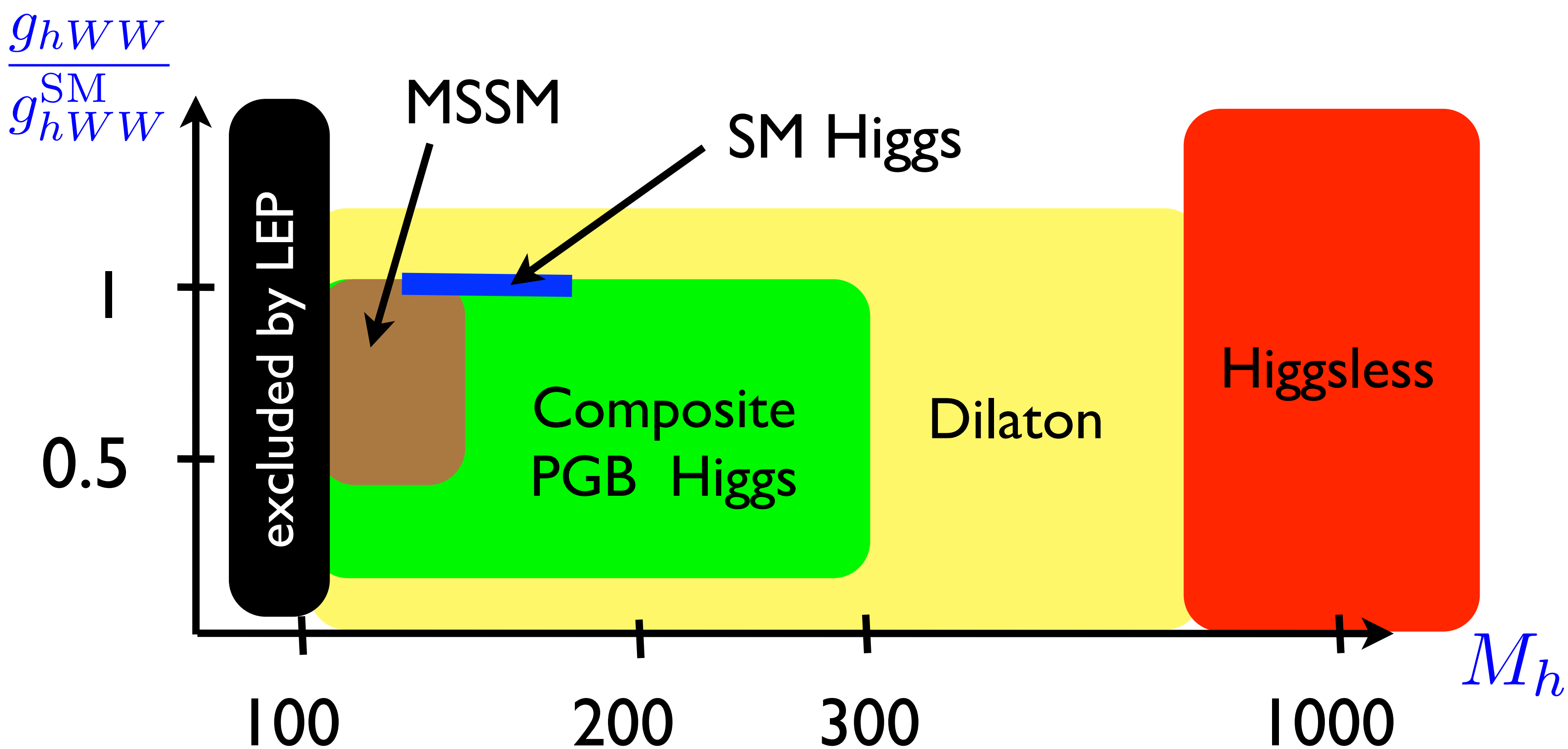
Then if at the LHC a **Higgs-like** state is found,
it will crucial to determine its role in EWSB...

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



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

A rough perspective of different theoretical scenarios:



... it will take some time!

- Right-handed quarks could also be composite but this we will know it soon...