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Higgs Boson and Electroweak Symmetry Breaking

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Electroweak Symmetry Breaking

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Outline:

- Electroweak symmetry breaking (EWSB): Generalities
- The Higgs mechanism
- Higgsless approach: Technicolor and EWSB by extra dimensions
- Composite Higgs: Pseudo-Goldstone particle:
  - Holographic Higgs
  - Little Higgs
- EWSB at the LHC

I. EWSB: Generalities

Lets start having a look at the EW sector
without any "theoretical prejudice"

Experimental data tell us that particle physics is very well described by a gauge theory:

Gauge SU(3)xSU(2)xU(1)

3 families of
$$\left\{\begin{array}{r} Q_L: \ (3,2,1/3) \\ u_R: \ (3,1,4/3) \\ d_R: \ (3,1,-2/3) \\ l_L: \ (1,2,-1) \\ e_R: \ (1,1,-2) \end{array}\right.$$

+ symmetry-breaking terms:

$$m_q\,\bar{q}_L q_R + m_e\,\bar{e}_L e_R + m_W^2 |W_\mu^+|^2 + \frac{1}{2} m_Z^2 Z_\mu^2$$

All information on EWSB:

$$\underbrace{m_q\,\bar{q}_L q_R + m_e\,\bar{e}_L e_R}_{} + m_W^2 |W_\mu^+|^2 + \frac{1}{2} m_Z^2 Z_\mu^2$$

Plenty of information: But, up to now, not very illuminating: Flavor Puzzle
(only the heaviness of the top gives us suggestions on EWSB)

All information on EWSB:

$$m_q\,\bar{q}_L q_R + m_e\,\bar{e}_L e_R + \underbrace{m_W^2|W_\mu^+|^2 + \frac{1}{2}m_Z^2 Z_\mu^2}$$

Focus on this part:

$$m_W^2|W_\mu^+|^2 + \frac{1}{2}m_Z^2(W_\mu^3 c_{\theta_W} - B_\mu s_{\theta_W})^2$$

$\downarrow$ Absorbing the couplings into the kinetic terms

$$\frac{m_W^2}{g^2}|W_\mu^+|^2 + \frac{1}{2}\frac{m_Z^2 c_{\theta_W}^2}{g^2}(W_\mu^3 - B_\mu)^2$$

Breaks SU(2)xU(1) but preserves a U(1): $Q=(T_3+Y)/2$

Intriguing experimental relation:

$$\frac{m_W^2}{m_Z^2 c_{\theta_W}^2} \equiv \rho \simeq 1.0$$

Possible origin: A remnant global SU(2) under which (W_1, W_2, W_3) form a triplet = Custodial symmetry

Force equal masses for the $W_{1,2,3}$

But symmetry not respected by gauge boson B

Nor for fermions

Lets, from empirical facts, assume this symmetry

Mass terms: $$\frac{m_W^2}{g^2}\mathrm{Tr}\left[W_\mu - \frac{\sigma_3}{2}B_\mu\right]^2 \qquad W_\mu \equiv \frac{\sigma^a}{2}W_\mu^a$$

Redefinition: $$W_\mu \to \Sigma W_\mu \Sigma^\dagger - i\Sigma\partial_\mu\Sigma^\dagger$$

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

2x2 unitary matrix of Det=1

(d.o.f.: 3 real scalars $G_{1,2,3}$)

$$\longrightarrow \quad \frac{m_W^2}{g^2}\mathrm{Tr}\left|\partial_\mu\Sigma + iW_\mu\Sigma - i\Sigma\frac{\sigma_3}{2}B_\mu\right|^2 = \frac{m_W^2}{g^2}\mathrm{Tr}\left|D_\mu\Sigma\right|^2$$

Invariant if: $$\Sigma \to U_L\Sigma U_Y^\dagger \qquad U_Y = e^{i\sigma_3\theta_Y}$$

Assets:

- EW symmetry realized, ... but not in the vacuum:

$$\langle \Sigma \rangle = 1 \to U_L U_Y^\dagger$$ broken generators: $T_{1,2}$ and T_3-Y

- No mass term allowed for Σ: $\mathrm{Tr}\Sigma\Sigma^\dagger \sim 1$

  G= Goldstones of the symmetry associated to each broken generator

- "Accidental" larger global symmetry:

$$\Sigma \to U_L \Sigma U_R^\dagger \qquad U_R \in SU(2)_R$$

broken by the vacuum to a global SU(2) ($U_L = U_R$)

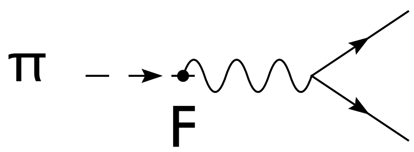
and the gauging of Hypercharge (B-field)

Definition of the decay-constant F of the Goldstones

$$\frac{m_W^2}{g^2} \equiv \frac{1}{4} F^2 \longrightarrow \mathcal{L}_G = \frac{F^2}{4} \mathrm{Tr} |D_\mu \Sigma|^2$$

F ~ 246 GeV

In QCD leads to the pion decay:



Similarly for fermions:

$$m_u \bar{u}_L u_R + m_d \bar{d}_L d_R = \frac{m_u + m_d}{2} \bar{Q}_L Q_R + \frac{m_u - m_d}{2} \bar{Q}_L \sigma_3 Q_R$$

where $Q_{L,R} = \begin{pmatrix} u_{L,R} \\ d_{L,R} \end{pmatrix}$ under hypercharge:

$$Q_L \to e^{i\theta_Y/3} Q_L$$

$$Q_R \to e^{i(1/3+\sigma_3)\theta_Y} Q_R$$

introducing Σ
by field redefinitions

$$\frac{m_u + m_d}{2} \bar{Q}_L \Sigma Q_R + \frac{m_u - m_d}{2} \bar{Q}_L \Sigma \sigma_3 Q_R$$

Breaks the custodial symmetry

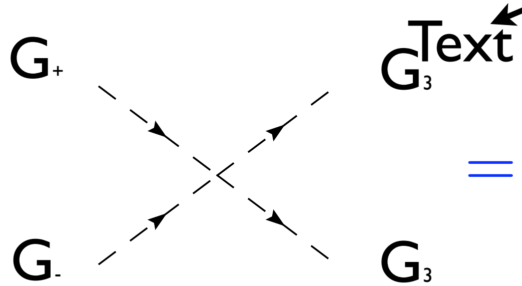
So far, so good...

Nevertheless, unitarity problems:

Lets expand in terms of the Goldstones:

$$\frac{F^2}{4}\mathrm{Tr}|\partial_\mu \Sigma|^2 = F^2\left[\frac{1}{2}(\partial_\mu G_a)^2 + \frac{1}{12}(G_a \overleftrightarrow{\partial_\mu} G_a)^2 + \cdots\right]$$

Self-Interactions



$$= \frac{s}{F^2}$$

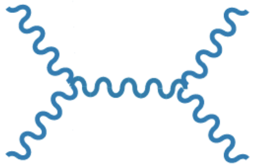
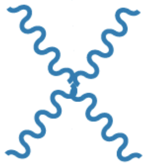
Grows with the energy an violates unitarity at high-energies: $E \gtrsim 1\ TeV$

➔ Theory valid up to energies Λ ~ 1 TeV

Λ= cutoff of the theory

Not a problem associated by introducing Σ

In the unitary gauge Σ=1:

WW→ZZ :  +  $\sim \dfrac{g^2 s}{4m_W^2}$

at large energies

Can we live with this theory (and wait till the LHC tells us what is there at the TeV to UV-complete the theory)?

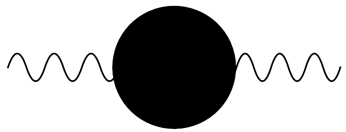
First simple question: What about quantum corrections (loops)?

The theory can be quantized and loops can be calculated (similar to the chiral lagrangian in QCD)

If infinities appear in loop diagrams, counterterms must be added

If we look for physics at energies $E<\Lambda$, the number of counterterms are finite $\rightarrow$ PREDICTIONS!

Most important effects of quantum corrections are those to the propagator of the gauge boson: Vacuum polarization

 $\equiv \Pi_{ij}(q^2)$

Highly constrained by LEP!

Assuming new physics scale $\Lambda \gg M_W$, we can expand in q/Λ:

$$\mathbf{\Pi_a(q) = \Pi_a(0) + q^2\Pi'_a(0) + \frac{q^4}{2}\Pi''_a(0) + \ldots}$$

SM gauge boson self-energies

$$\Pi_{W+} = \Pi_{W+}(0) + q^2\Pi'_{W+}(0) + \frac{q^4}{2}\Pi''_{W+}(0) + \cdots$$

$$\Pi_{W_3} = \Pi_{W_3}(0) + q^2\Pi'_{W_3}(0) + \frac{q^4}{2}\Pi''_{W_3}(0) + \cdots$$

$$\Pi_{B} = \Pi_{B}(0) + q^2\Pi'_{B}(0) + \frac{q^4}{2}\Pi''_{B}(0) + \cdots$$

$$\Pi_{W_3B} = \Pi_{W_3B}(0) + q^2\Pi'_{W_3B}(0) + \frac{q^4}{2}\Pi''_{W_3B}(0) + \cdots$$

Up to order q^4:	**4×3=12** parameters
Masslessness of the photon	**-2**
Absorbed by g, g', v^2	**-3**
.	————————
Independent parameters	**7**

	Form factors	custodial	$SU(2)_L$
$\hat{T}$ =	$\frac{g^2}{M_W^2}\left[\Pi_{W_3}(0)-\Pi_{W+}(0)\right]$	$-$	$-$
$\hat{U}$ =	$g^2\left[\Pi'_{W_3}(0)-\Pi'_{W+}(0)\right]$	$-$	$-$
V =	$\frac{g^2M_W^2}{2}\left[\Pi''_{W_3}(0)-\Pi''_{W+}(0)\right]$	$-$	$-$
$\hat{S}$ =	$g^2\ \Pi'_{W_3B}(0)$	$+$	$-$
X =	$\frac{g'gM_W^2}{2}\ \Pi''_{W_3B}(0)$	$+$	$-$
W =	$\frac{g^2M_W^2}{2}\ \Pi''_{W_3}(0)$	$+$	$+$
Y =	$\frac{g'^2M_W^2}{2}\ \Pi''_{B}(0)$	$+$	$+$

Keep the leading one in the q^2 expansion:

Barbieri,A.P.,Rattazzi,Strumia

Form factors	custodial	$SU(2)_L$
$\hat{T} = \frac{g^2}{M_W^2}\left[\Pi_{W_3}(0) - \Pi_{W+}(0)\right]$	$-$	$-$
$\hat{U} = g^2\left[\Pi'_{W_3}(0) - \Pi'_{W+}(0)\right]$	$-$	$-$
$V = \frac{g^2 M_W^2}{2}\left[\Pi''_{W_3}(0) - \Pi''_{W+}(0)\right]$	$-$	$-$
$\hat{S} = g^2\, \Pi'_{W_3B}(0)$	$+$	$-$
$X = \frac{g' g M_W^2}{2}\, \Pi''_{W_3B}(0)$	$+$	$-$
$W = \frac{g^2 M_W^2}{2}\, \Pi''_{W_3}(0)$	$+$	$+$
$Y = \frac{g'^2 M_W^2}{2}\, \Pi''_{B}(0)$	$+$	$+$

Keep the leading one in the q^2 expansion: $\hat{S}, \hat{T}, W, Y$

Barbieri,A.P.,Rattazzi,Strumia

All these effects nicely parametrized in terms of 4 quantities:

Peskin, Takeushi
Barbieri, AP, Rattazzi, Strumia

$$\begin{aligned}
\hat{T} &= \frac{g^2}{M_W^2}\left[\Pi_{W_3}(0) - \Pi_{W+}(0)\right] \\
\hat{S} &= g^2\ \Pi'_{W_3B}(0) \\
W &= \frac{g^2 M_W^2}{2}\ \Pi''_{W_3}(0) \\
Y &= \frac{g'^2 M_W^2}{2}\ \Pi''_{B}(0)
\end{aligned}$$

All these effects nicely parametrized in terms of 4 quantities:

Peskin, Takeushi

Barbieri, AP, Rattazzi, Strumia

$$\boxed{\begin{aligned} \hat{T} &= \frac{g^2}{M_W^2}\left[\Pi_{W_3}(0) - \Pi_{W^+}(0)\right] \\ \hat{S} &= g^2\, \Pi'_{W_3B}(0) \end{aligned}}$$

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

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

Most important in EWSB physics

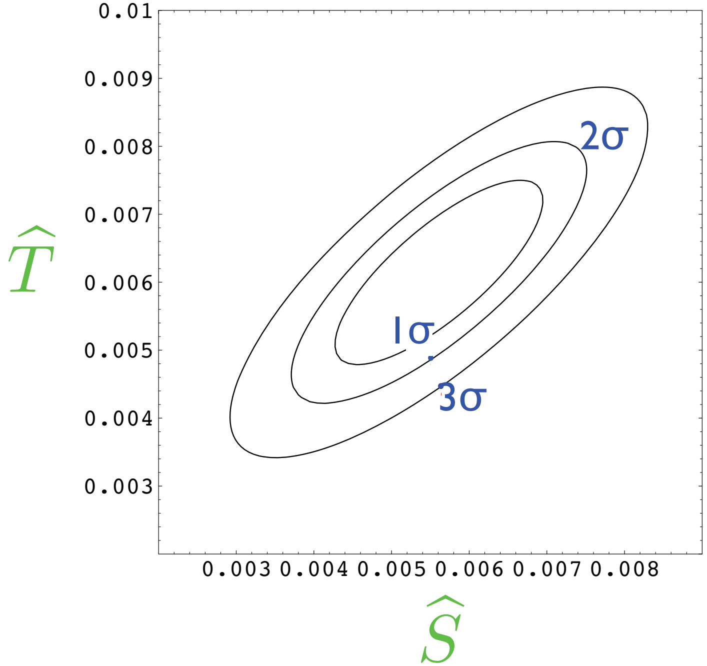
Generated only if EWSB

$\hat{T}$=0 for custodial invariant theories

From LEP and Tevatron:

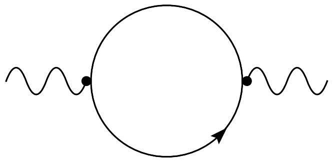
$$\hat{S} = g^2\, \Pi'_{W_3 B}(0)$$

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



Effects on $\hat{T}$:

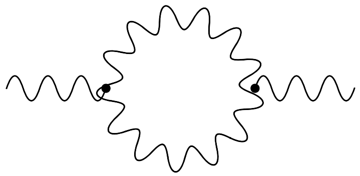
- No contribution from loops of Goldstone bosons
- Largest contribution from the top



$$\hat{T} \simeq \frac{3m_t^2}{16\pi^2 F^2} \simeq 0.008$$

Finite!

- Logarithmic divergent contribution from B-loops

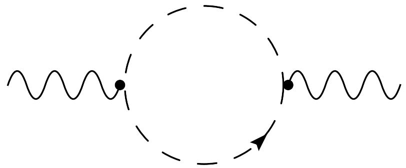


$$\hat{T} \simeq \frac{-3g'^2}{64\pi^2} \ln\left(\frac{\Lambda^2}{m_W^2}\right)$$

Counterterm exists: $c_t F^2 \,\mathrm{Tr}^2[\sigma_3 \Sigma D_\mu \Sigma^\dagger]$

Effects on $\hat{S}$:

- Contribution from Goldstone-loops logarithmically divergent

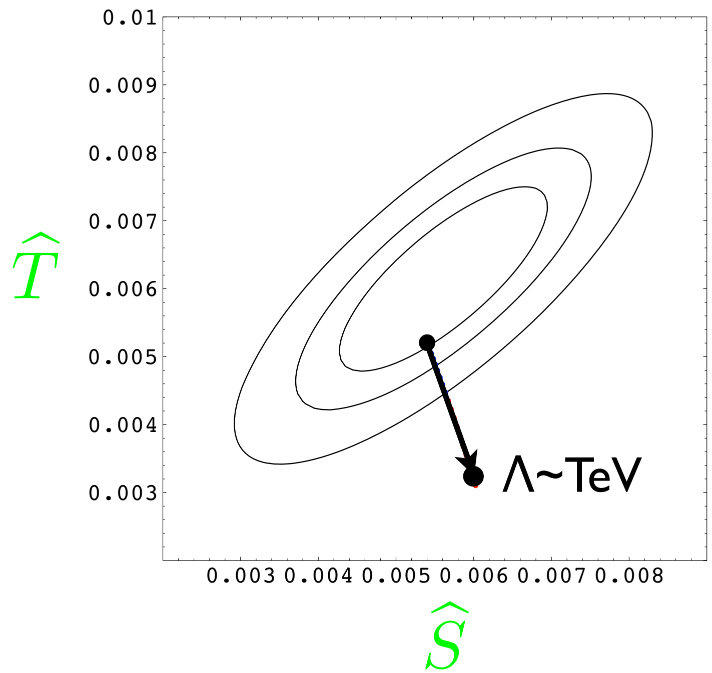


$$\hat{S} \simeq \frac{g^2}{192\pi^2} \ln\left(\frac{\Lambda^2}{m_W^2}\right)$$

Counterterm:

$$c_s \mathrm{Tr}[W_{\mu\nu}\Sigma\frac{\sigma_3}{2}B_{\mu\nu}\Sigma^\dagger]$$

Assuming $c_s = c_t = 0$, we obtain:



EWPT prefers
small Λ !

Possible UV-completions of the EW sector

How to recover unitarity?

EWSB sector must contain new states

I. Higgs mechanism

Brute force approach ➔ Find the minimal number of states needed to have well-behaved amplitudes (at high-energies)

Adding a scalar: h with a coupling $hF(\partial_\mu G_a)^2$

$$\frac{s}{F^2} \qquad - \frac{s^2}{s - m_h^2}\frac{1}{F^2} \xrightarrow{\text{large s}} -\frac{m_h^2}{F^2}$$

Do not grow with the energy!

One finds that a single scalar can "repair" all amplitudes

Easy to introduce:

$$\mathcal{L}(\Sigma, \ldots) \to \mathcal{L}(\underbrace{\Sigma(1+h/F)}_{\frac{\Sigma\,\phi}{F} \equiv \frac{M}{F}}, \ldots)$$

$$\phi = F + h$$

$$\langle \phi \rangle = v = F$$

Why unitarity is restored?

$$M = \phi e^{i\vec{\sigma}\cdot\vec{G}} = \phi(\cos G + i\vec{\sigma}\cdot\frac{\vec{G}}{G}\sin G) \quad \xrightarrow[\text{field redefinition}]{} \quad \phi + i\vec{\sigma}\cdot\vec{G}$$

We have now:

$$\frac{1}{4}\mathrm{Tr}|\partial_\mu M|^2 = \frac{1}{2}(\partial_\mu\phi)^2 + \frac{1}{2}(\partial_\mu G_a)^2$$

It is just only the kinetic term of four scalar! No self-interactions!

This is usually refer as the linear-model

It was easy, but...

now a mass term is allowed for ϕ:

$$m^2\,\mathrm{Tr}[MM^\dagger] = 2m^2\phi^2 + \cdots$$

and we must have this mass of the order of W-mass

this operator is not protected by any symmetry: Difficult to keep it smaller than other big scales in physics (GUT-scale, Planck-scale,..)

➡ HIERARCHY PROBLEM

requires more stuff at the TeV (SUSY?)

Last redefinition: $M = \sqrt{2}(i\sigma_2 H^*, H)$

where H is a Higgs doublet multiplet (Y=1):

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} G_1 - iG_2 \\ \phi - iG_3 \end{pmatrix}$$

Transformation rules: $H \rightarrow U_L H$

$$\rightarrow U_Y H$$

One can proof:

a) $\frac{1}{4}\mathrm{Tr}|D_\mu M|^2 = |D_\mu H|^2$

b) $V(M) = \frac{m^2}{4}\mathrm{Tr} M M^\dagger + \frac{\lambda}{16}\mathrm{Tr}^2 M M^\dagger$

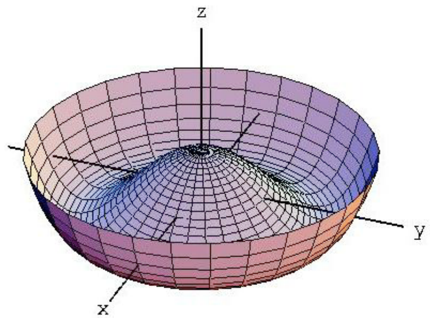
equals to $V(H) = m^2|H|^2 + \lambda|H|^4$

Same dimension-4 lagrangian terms as the Higgs of the SM

Custodial symmetry an accidental symmetry of the Higgs potential and interactions with W. Prediction of the Higgs-doublet: ρ=1 (at tree-level)

Higgs VEV can be written as a function of the Higgs potential parameters

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



$$v^2 = \frac{-m^2}{\lambda}$$

$$m_h^2 = 2\lambda v^2$$ Physical Higgs mass unknown

recall how was introduced:

Higgs couplings:

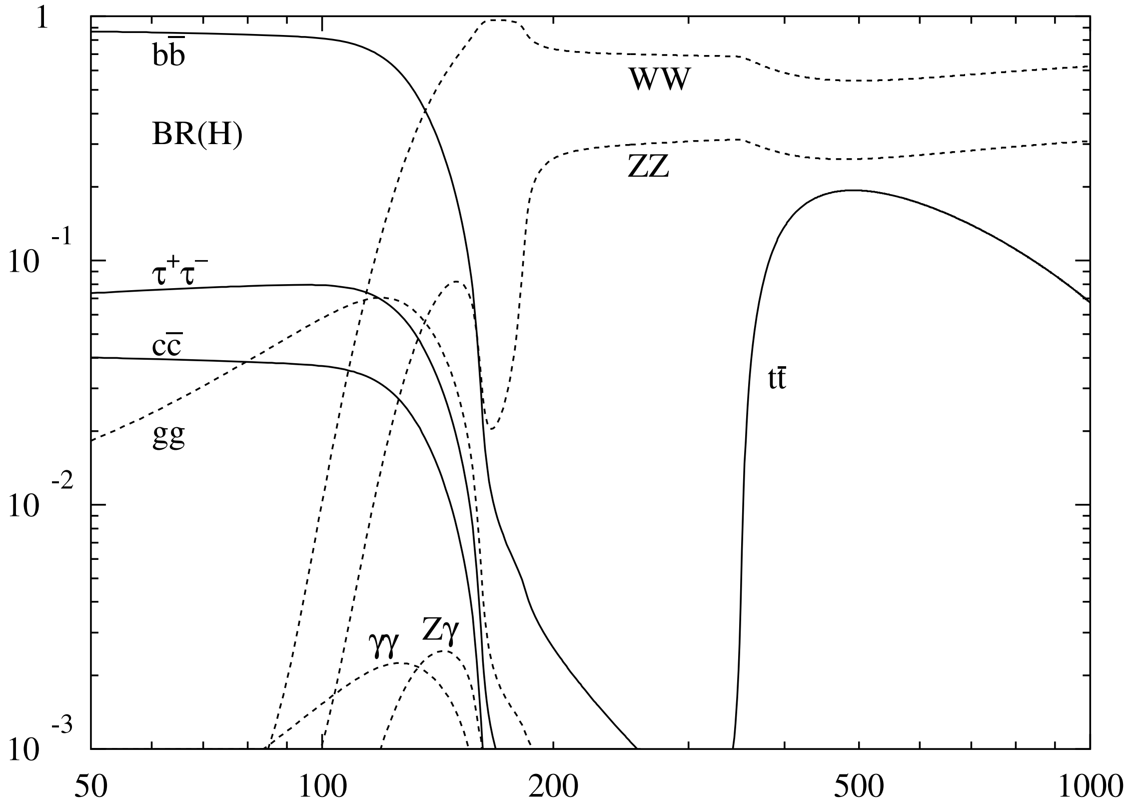
$$\Sigma \to \Sigma(1+h/v)$$

higgs-fermion-fermion: $\dfrac{m_f}{v}$

higgs-WW(ZZ): $\dfrac{m^2_{W,Z}}{v}$

- "Difficult" to be produced in colliders due to its small coupling to light fermions
- Decays to the heaviest particle (allowed kinematically)

Higgs branching ratios:



Higgs mass

Present bounds

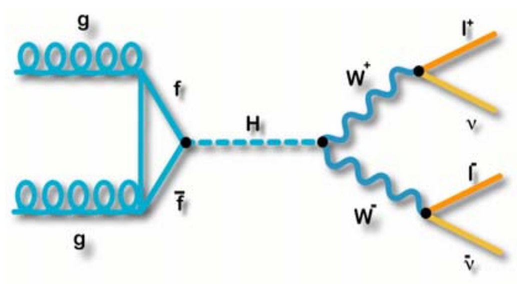
a) LEP:

Direct searches: $m_h > 114.4\ GeV$ (95% CL)

EWPT: $m_h < 185\ GeV$

b) Tevatron Higgs excluded in the region:

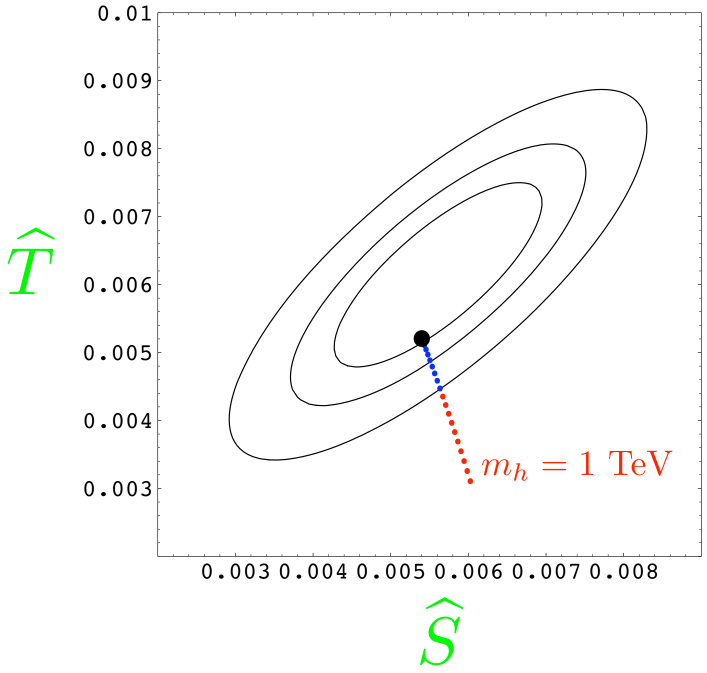
$$160\ GeV < m_h < 170\ GeV$$



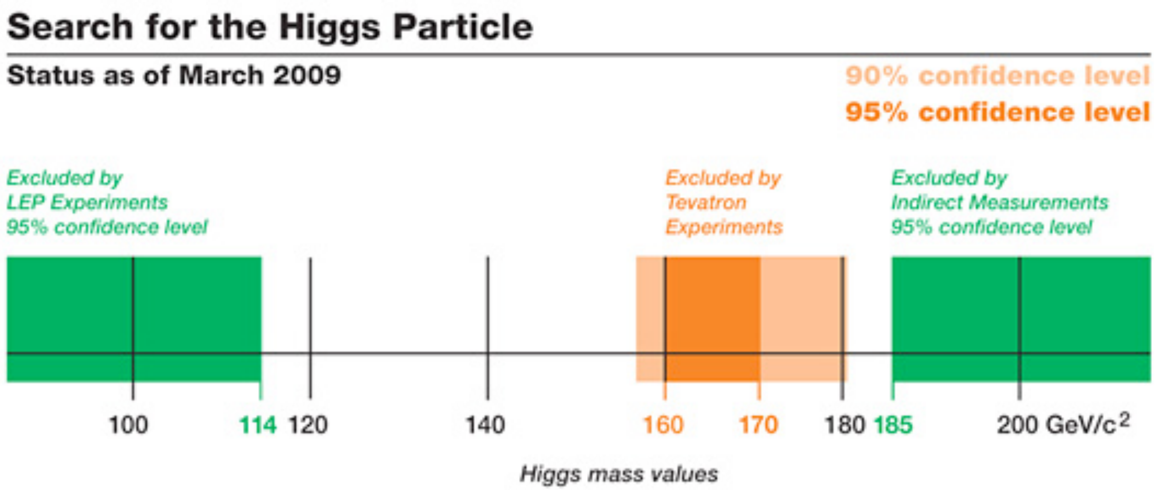
Radiative corrections:

Finite contributions to S and T:

Λ-scale $\rightarrow$ Higgs mass



EWPT prefers light Higgs!


Search for the Higgs Particle
Status as of March 2009
90% confidence level
95% confidence level
Excluded by
LEP Experiments
95% confidence level
Excluded by
Tevatron
Experiments
Excluded by
Indirect Measurements
95% confidence level
100
114
120
140
160
170
180
185
200 GeV/c2
Higgs mass values

More Higgs? Why not

But one must be careful with the ρ-parameter

(Higgs-doublet was special)

1) Adding more Higgs doublets (e.g. MSSM):

Higgs-W interactions preserve the custodial symmetry

But not the 2 Higgs-doublet potential:

Effects on ρ at the loop-level small enough

2) Higgs triplet or higher reps. leads to $\rho \neq 1$
If present, they must get a small VEV

II. Higgsless theories

Technicolor models for EWSB: Achievements and pitfalls

TC is inspired by QCD, a model of dynamical EWSB:

SU(3) theory of two massless quarks: $\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} u_R \\ d_R \end{pmatrix}$

Accidental global symmetry of QCD: $SU(2)_L \times SU(2)_R \times U(1)$

Chiral symmetry breaking by the quark condensate:

$$\langle \bar{u}_L u_R \rangle = \langle \bar{d}_L d_R \rangle \neq 0$$

$$SU(2)_L \times SU(2)_R \times U(1) \to SU(2)_V \times U(1)$$

3 Goldstone bosons: π^+, π^-, π^0

'tHooft

Large N QCD $\longrightarrow$ Theory of infinite resonances, $\rho, \rho', \ldots$

"dual" description

massive $m_\rho \sim 1\ GeV$

and weakly coupled $g_\rho \sim 1/\sqrt{N}$

$\mathcal{L}_{\rm QCD}(q, G) \longleftrightarrow \mathcal{L}(\pi^a, \rho, \rho', \ldots)$ Only known by exp.

$\alpha_s N \gg 1$ $\qquad$ $g_\rho \ll 1$

'tHooft

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$\alpha_s N \gg 1 \qquad\qquad g_\rho \ll 1$

Both must lead to the same generating functional of current correlators

$$Z\left[A^L_\mu, A^R_\mu\right] = \int \mathcal{D}q\mathcal{D}G \exp\left[iS_{\rm QCD} + i\int d^4x (j^\mu_L A^L_\mu + j^\mu_R A^R_\mu)\right]$$

$$= \int \mathcal{D}\pi\mathcal{D}\rho\cdots \ \exp\left[iS_{\rm reson} + iM\int d^4x \rho^\mu (A^L_\mu + A^R_\mu) + \cdots\right]$$

$A^L_\mu = W_\mu \ , \ A^R_\mu = B_\mu\sigma_3 + \cdots$ treated as external fields

At low-energies, $E \ll m_\rho$, we can integrate out all the resonances and write the effective theory for the pions (chiral lagrangian)

$$U = e^{i\sigma^a \pi^a / f_\pi}$$

$$\mathcal{L}_{\rm eff} = f_\pi^2 \Big[\frac{1}{4} |D_\mu U|^2 + \frac{c_S}{m_\rho^2} {\rm Tr}[W^L_{\mu\nu} U W^{R\,\mu\nu} U^\dagger] + \cdots \Big]$$

We present the only terms that will give contributions to the external field propagator

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We present the only terms that will give contributions to the external field propagator

$$\langle U \rangle = 1$$

$$m_W^2 = \frac{1}{4} g^2 f_\pi^2 \quad , \; m_Z^2 = \frac{1}{4\cos^2\theta_W} g^2 f_\pi^2$$

Since the W gauge bosons are a 3 of $SU(2)_V$ they receive equal masses for g'=0

"custodial" symmetry

At low-energies, $E \ll m_\rho$, we can integrate out all the resonances and write the effective theory for the pions (chiral lagrangian)

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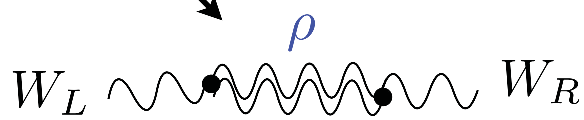
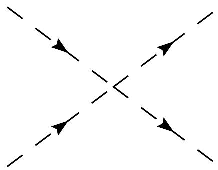
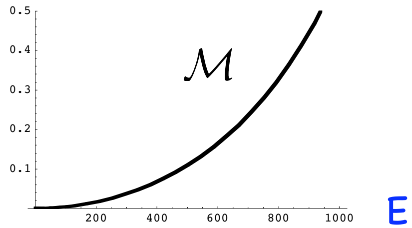


$\pi\pi \longrightarrow \pi\pi$ grows with the energy:

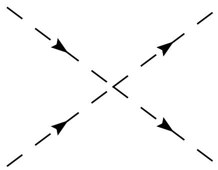


$$\mathcal{M} \propto \frac{s}{f_\pi^2}$$



So who unitarizes this amplitude at high-energy?

$\pi\pi \longrightarrow \pi\pi$ grows with the energy:



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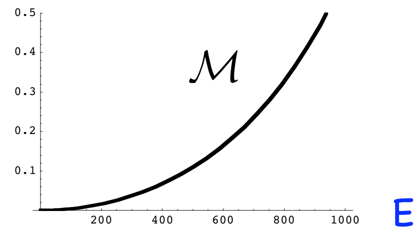
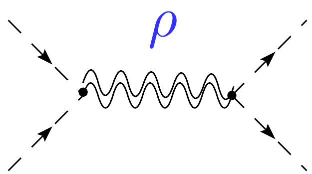
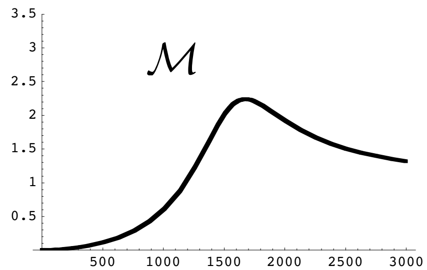


So who unitarizes this amplitude at high-energy?

QCD resonances come to recover unitarity:



$$+ \quad \cdots$$



one needs infinite of them !

Lessons from QCD:

- Simple example of EWSB with $m_W \sim \Lambda_{\rm QCD} \ll M_P$
- Unitarity without a Higgs (there are QCD scalar resonances but none behave like a Higgs)

Technicolor theories: a QCD-like theory at the TeV

Weinberg, Susskind '79

$$\pi_a \longrightarrow G_a$$

$$QCD \;\rightarrow\; TC$$

$$F_\pi \simeq 100\ MeV \;\rightarrow\; v = 246\ GeV \equiv \frac{2m_w}{g}$$

$$Chiral\ breaking \;\rightarrow\; EWSB$$

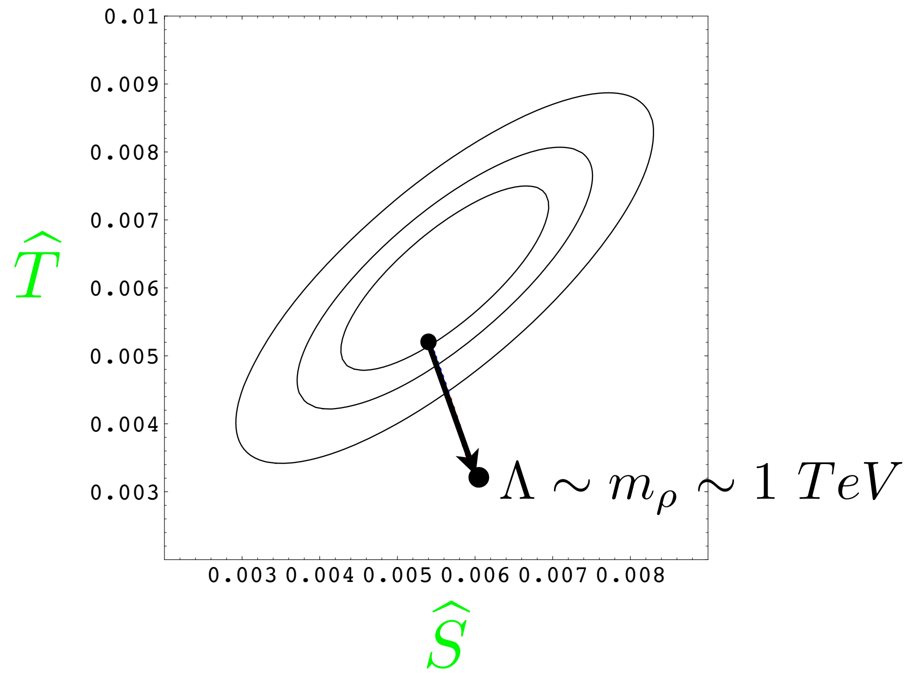
$$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$$

$$Resonances:\ \rho, \rho^{'} \ldots \;\rightarrow\; \rho, \rho^{'} \ldots$$

$$m_\rho \sim 700\ MeV \;\rightarrow\; m_\rho \sim 1.5\ TeV$$

First problem: EW precision tests

Goldstone contributions:

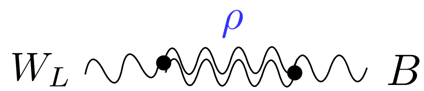


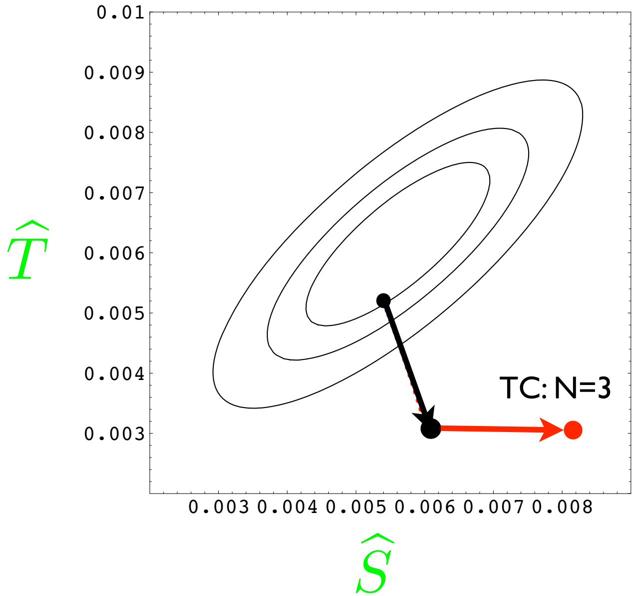
Contributions from heavy resonances:

$$\widehat{T} = 0 \qquad \text{at tree-level, due to the custodial symmetry}$$

$$\widehat{S} = -g^2 c_S \frac{f_\pi^2}{m_\rho^2} \simeq 2.3 \cdot 10^{-3} \left(\frac{N}{3}\right)$$

taking values from QCD





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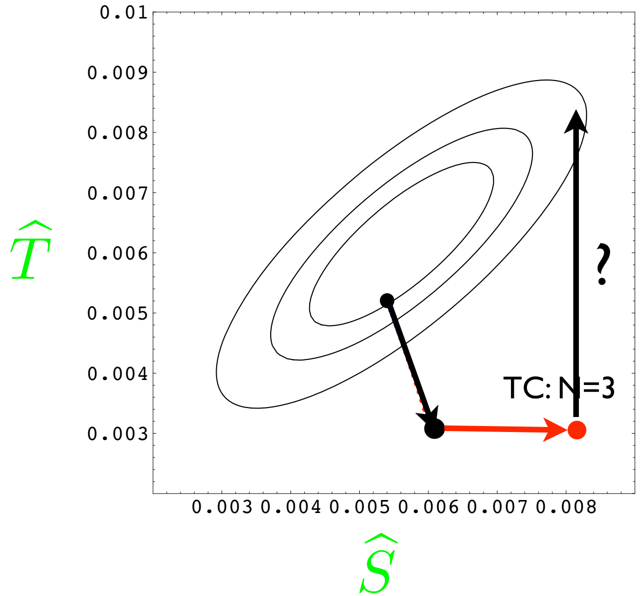
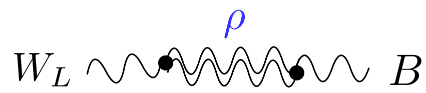


taking values from QCD



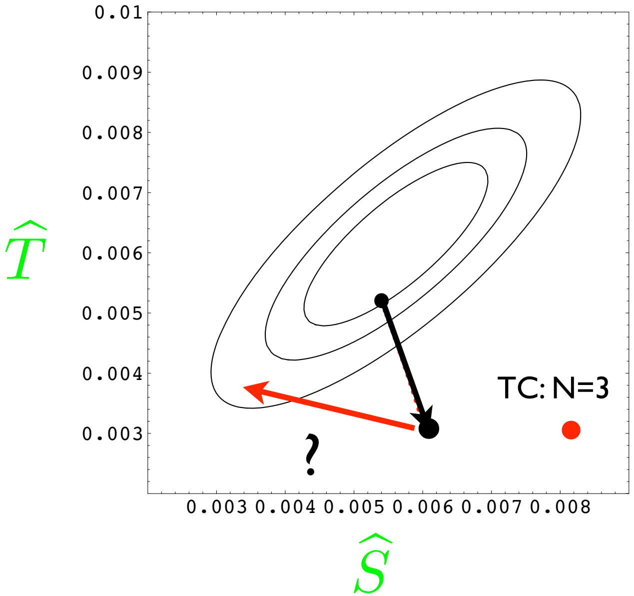
WAY OUTS:

can a one-loop contribution to T put it back in the ellipse?

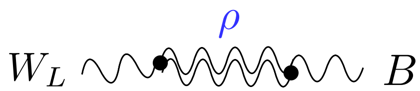
Contributions from heavy resonances:

$\widehat{T} = 0$ at tree-level, due to the custodial symmetry

$$\widehat{S} = -g^2 c_S \frac{f_\pi^2}{m_\rho^2} \simeq 2.3 \cdot 10^{-3} \left(\frac{N}{3}\right)$$



taking values from QCD



WAY OUTS:

can a TC model be different from QCD and give you small or negative S?

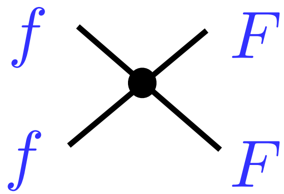
Difficult to answer this questions
within strongly interacting theories:
Absence of calculability !

Second problem: Fermion masses

New sector must be introduced to mix the SM fermions (f) to the TC-quark (F) condensate that breaks the EWSB

Done by an Extended TC gauge sector: $W^{\mu}_{ETC}\bar{F}\gamma_{\mu}f$

Integrating them out:

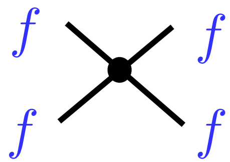


SM fermion masses:

$$m_f \sim \frac{\langle \bar{F}F \rangle}{M^2_{ETC}}$$

BUT:

- ETC also induce:



gives too large flavor transitions (FCNC)

e.g., $K-\bar{K}$ mixing

- Top mass to large to be induced by a higher-dim operator

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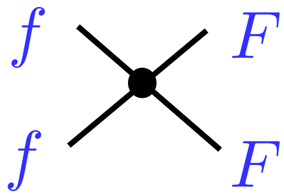

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BUT:

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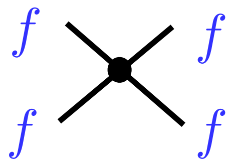


gives too large flavor transitions (FCNC)

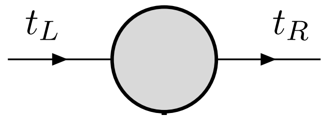
Solution proposed: Walking TC

- Top mass to large to be induced by a higher-dim operator

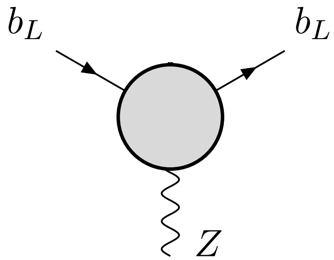
Solution proposed: Topcolor

Even if the top mass is large enough, still one must check that Zbb coupling is not corrected:

whatever generates



must not generate



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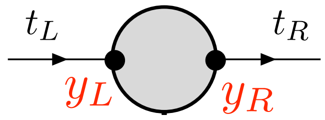
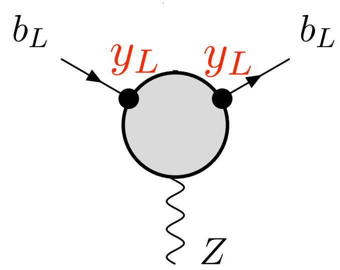


must not generate

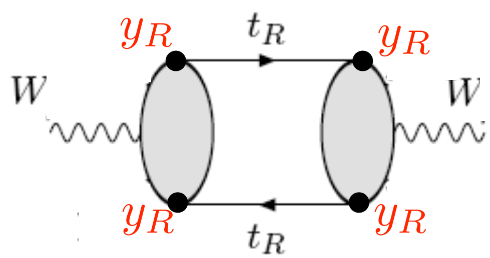


Difficult since t_L is with b_L in the same weak doublet

Estimate: $$\frac{\delta g_b}{g_b} \sim \frac{y_L}{y_R}\frac{m_t}{m_\rho} \sim 0.07$$ Too large!

$y_L \sim y_R$

If $y_R \gg y_L$, possible large loop contributions to T-parameter



$$\hat{T} \sim \frac{y_R^4}{16\pi^2}\frac{m_\rho^2}{v^2} \sim y_R^4$$

Summary of the difficulties in TC Higgsless models:

- S-parameter too large, unless a contribution to T-parameter is also large
- Sizable FCNC
- Top mass
- Corrections to Zbb

Difficult to tackle: These are strongly coupled theories (perturbative methods cannot apply)

Recent progress: explicit weakly-coupled examples of Higgsless theories using extra dimensions

III. Composite Higgs

Idea:

The strong sector does not break the EWSB symmetry (as in TC) but has a "Higgs" in its spectrum (composite state) that will be responsible for EWSB

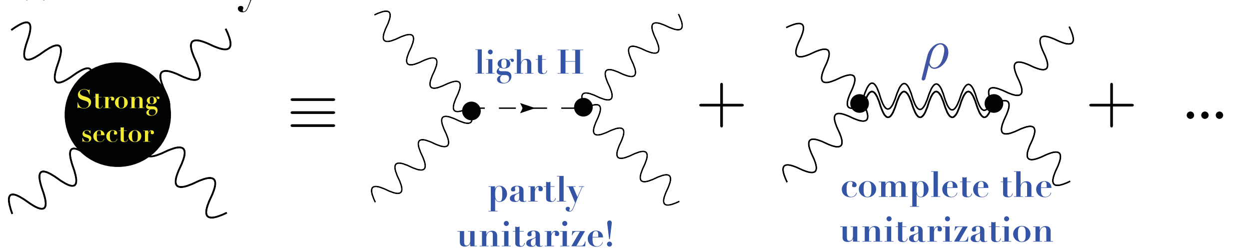
Georgi,Kaplan

There is a Higgs but it is not elementary: It's a composite particle!

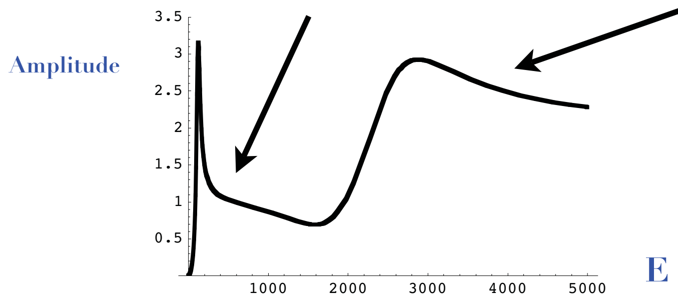
H is "almost" a Higgs (its couplings deviate from a point-like scalar)

no naturalness problem

WW unitarity:



What we gain?



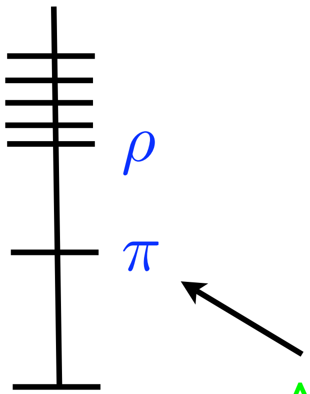
The heavy states ρ are needed to unitarize WW at an energy higher that 1 TeV
Having bigger masses, they give smaller effects to the SM gauge boson propagators

1st important question of this scenario:

Why the Higgs mass will be smaller than m_ρ?

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

Spectrum:



Are not true Goldstones
are Pseudo-Goldstone bosons (PGB):

Get small masses from the explicit breaking
of the chiral symmetry

Can the light Higgs be a kind of a pion
from a new strong QCD-like sector?

Example (minimal case):

1) Global symmetry breaking of the new strong sector:

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

4 Goldstones = a doublet of SU(2) = Higgs

$$\Sigma = \langle\Sigma\rangle e^{\Pi/f_\pi} \ , \qquad \langle\Sigma\rangle = (0,0,0,0,1) \ , \qquad \Pi = \begin{pmatrix} 0_4 & H \\ -H^T & 0 \end{pmatrix}$$

2) Not a true Goldstone since the gauging of SM SU(2) $\in$ SO(5) breaks the global SO(5) symmetry:

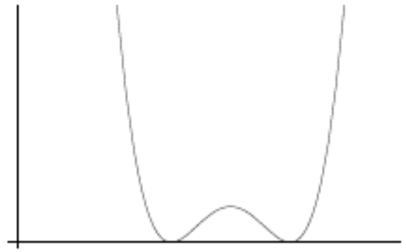
3) SM Fermion must couple to the strong sector:

This must also break the SO(5)

A Higgs potential is generated V(h) but at the one-loop level

Origin of EWSB

Higgs potential induced by gauge loops + top loops



$$V(h) \sim -\frac{Y_t^2 m_\rho^2}{16\pi^2} h^2 + \cdots$$

A heavy top essential to break EWSB!

The physical Higgs mass is one-loop smaller than other resonance masses: m(h)~100-200 GeV

Main problem with this scenario:

How to go further: Calculate spectrum, check consistency with EWPTs, fermion sector (flavor problem),...

i.e. how to calculate within strongly coupled theories

$\boxed{\text{Lack of predictability !!}}$

Recent progress: explicit weakly-coupled examples

- Extra dimensions : Holographic Higgs — Contino,Nomura, AP; Agashe, Contino,AP
- Little Higgs — Arkani-Hamed, Cohen, Katz, Nelson

Predictive models!

EWSB with extra dimensions

Recent new tool to calculate within strongly coupled theories:

Maldacena 97

$\boxed{\text{AdS/CFT correspondence}}$

Strongly coupled 4D theories in the large-N limit $\xleftrightarrow{\text{duality}}$ **Weakly coupled string theories in 10D**

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Maldacena 97

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Strongly coupled 4D theories in the large-N limit $\xleftrightarrow{\text{duality}}$ **Weakly coupled string theories in 10D**

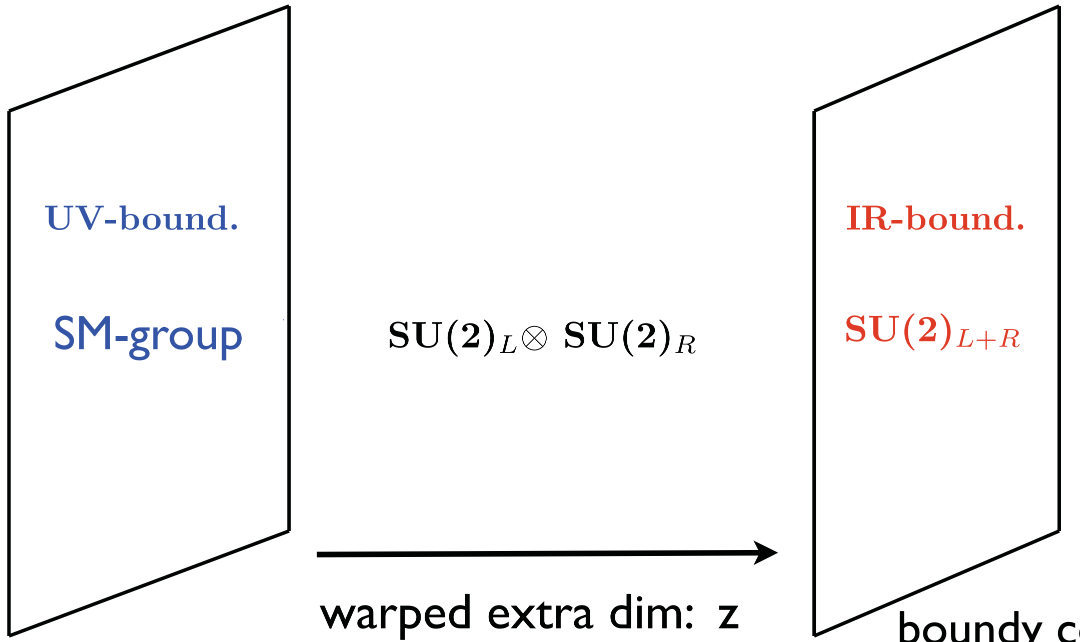
Can we find dual examples of TC-like models for EWSB?

Yes, the Sakai-Sugimoto model

D4-D8 system with chiral symmetry breaking:

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

At low-energy, this theory is equivalent to a gauge theory in 5D
with chiral breaking on the z=0 boundary



boundy conditions:

Dirichlet: $A_L^\mu - A_R^\mu = 0$

Neumann: $F_L^{\mu 5} + F_R^{\mu 5} = 0$

Taking $N_F = 2$, the SS-model can be considered the dual model of dynamical EW breaking

Carone,Erlich,Sher
Hirayama,Yoshioka

Weakly coupled theory where the KK-states are the mesons

We can calculate physical quantities such as the S-parameter

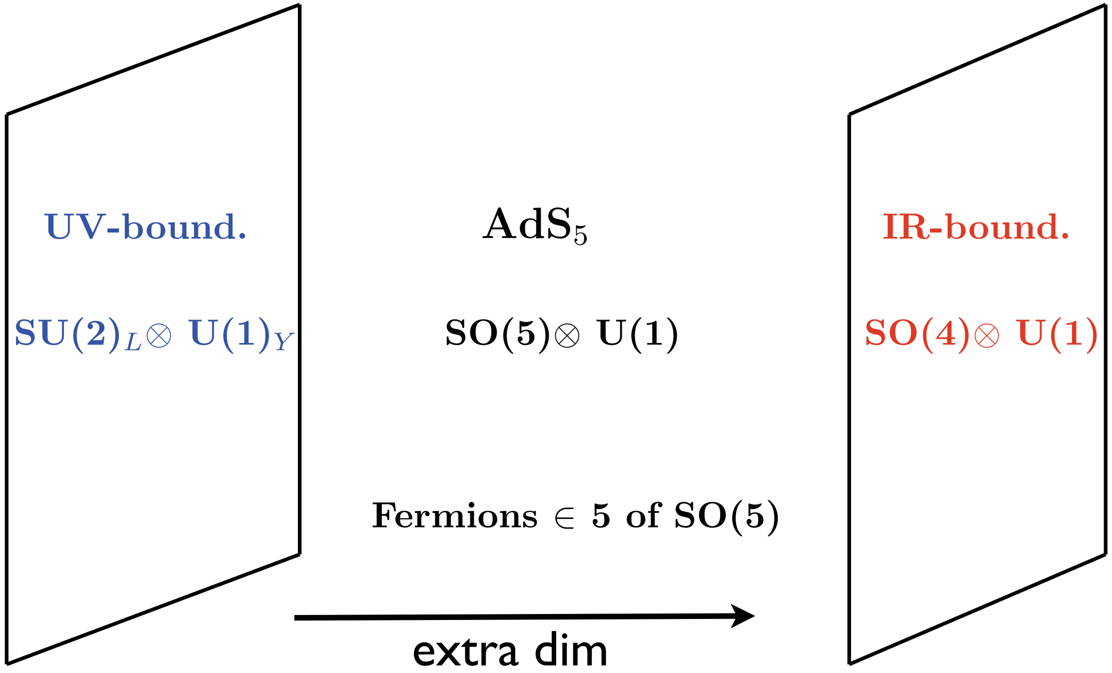
We obtain:

$$\widehat{S} \simeq 3 \cdot 10^{-3} \left(\frac{N}{3} \right)$$

~ 30% more than in QCD!

Holographic composite Higgs

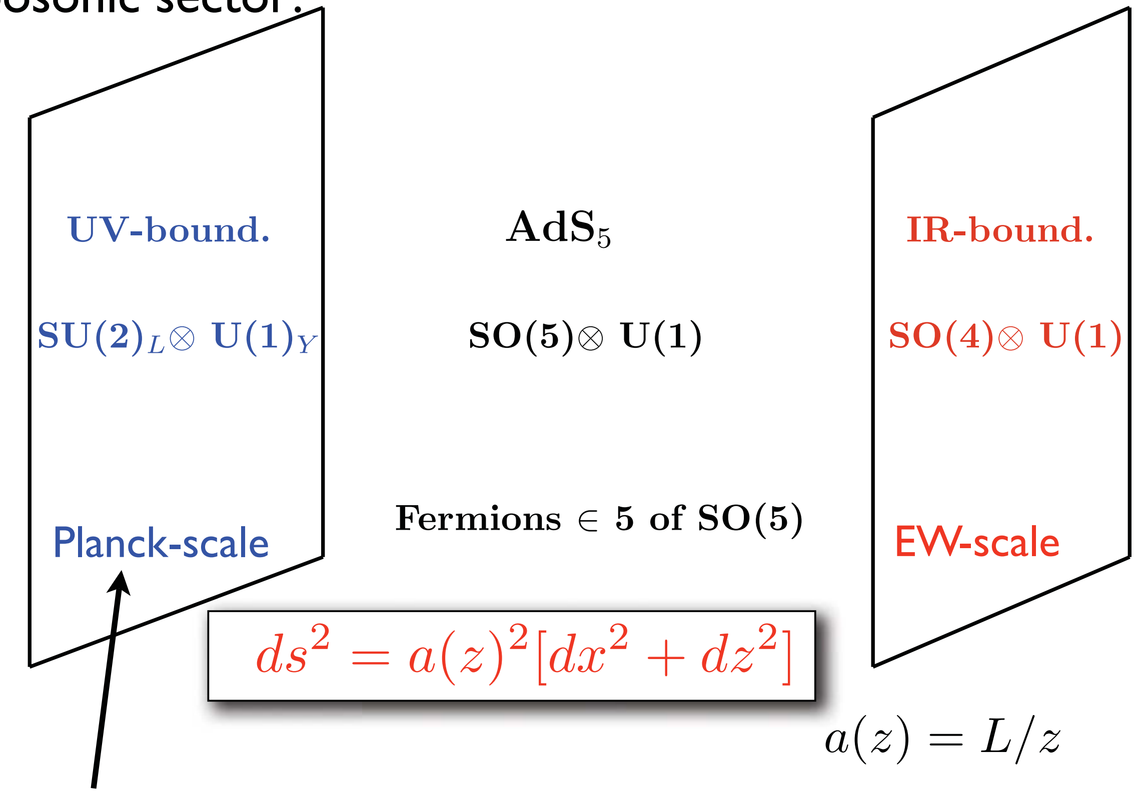
A benchmark model: Minimal 5D composite Higgs



Agashe,Contino,A.P.

A benchmark model: Minimal 5D composite Higgs

The bosonic sector:



Randall-Sundrum solution to the hierarchy problem:
Graviton localized on the Planck-brane

Why this symmetry breaking pattern?

We are in 5D: $\mathbf{A_M} = (\mathbf{A}_\mu, \mathbf{A_5})$

<u>Massless boson spectrum:</u>

- $\mathbf{A}_\mu$ **of** $\mathbf{SU(2)}_L \otimes \mathbf{U(1)}_Y$ = **SM Gauge bosons**
- $\mathbf{A_5}$ **of** $\mathbf{SO(5)/SO(4)}$ = **2 of** $\mathbf{SU(2)}_L$ = **SM Higgs**

$\hookrightarrow$ $\boxed{\textbf{Higgs-gauge unification}}$

Hosotani mechanism

Higgs mass protected by 5D gauge invariance!

$$A_5 \to A_5 + \partial_5\theta$$

shifts as a PGB

The fermionic sector: We have to choose the bulk symmetry representation of the fermions and b.c. giving only the 4D massless spectrum of the SM

Up-quark sector: $\mathbf{5}_{2/3}$ of $\mathrm{SO}(5){\times}\mathrm{U}(1)_X$.

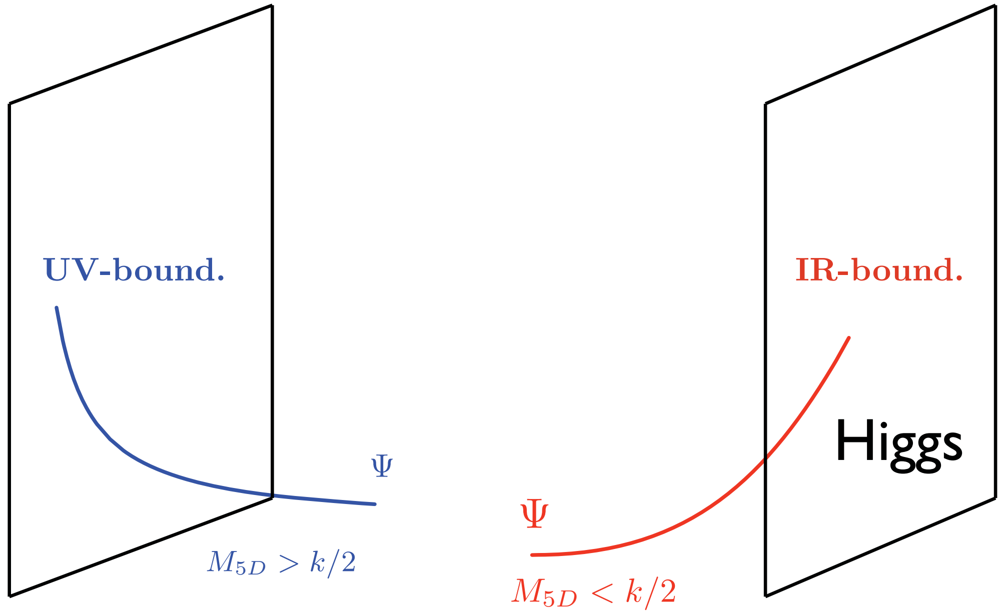
$$\xi_q = (\Psi_{q\,L}\ ,\Psi_{q\,R}) = \begin{bmatrix} (\mathbf{2},\mathbf{2})^{\mathbf{q}}_{\mathbf{L}} = \begin{bmatrix} q'_L(-+) \\ q_L(++) \end{bmatrix} & , & (\mathbf{2},\mathbf{2})^{\mathbf{q}}_{\mathbf{R}} = \begin{bmatrix} q'_R(+-) \\ q_R(--) \end{bmatrix} \\ & & \\ (\mathbf{1},\mathbf{1})^{\mathbf{q}}_{\mathbf{L}}(--) & , & (\mathbf{1},\mathbf{1})^{\mathbf{q}}_{\mathbf{R}}(++) \end{bmatrix}$$

$$\xi_u = (\Psi_{u\,L}\ ,\Psi_{u\,R}) = \begin{bmatrix} (\mathbf{2},\mathbf{2})^{\mathbf{u}}_{\mathbf{L}}(+-) & , & (\mathbf{2},\mathbf{2})^{\mathbf{u}}_{\mathbf{R}}(-+) \\ (\mathbf{1},\mathbf{1})^{\mathbf{u}}_{\mathbf{L}}(-+) & , & (\mathbf{1},\mathbf{1})^{\mathbf{u}}_{\mathbf{R}}(+-) \end{bmatrix},$$

IR-bound. mass:

$$\widetilde{m}_u\,\overline{(\mathbf{2},\mathbf{2})}^{\mathbf{q}}_{\mathbf{L}}(\mathbf{2},\mathbf{2})^{\mathbf{u}}_{\mathbf{R}} + \widetilde{M}_u\,\overline{(\mathbf{1},\mathbf{1})}^{\mathbf{q}}_{\mathbf{R}}(\mathbf{1},\mathbf{1})^{\mathbf{u}}_{\mathbf{L}} + h.c.$$

Depending on the 5D mass the wave-function of the SM fermion can be picked towards the UV-bound., having a small overlapping with the IR-bound., and then small masses, or be picked towards the IR and get large masses



Nice "geometrical" solution to the flavor problem

Fermion masses, Higgs potential and S-parameter
can be calculated

They are low-energy quantities and can be treated with
perturbation theory (5D)

Higgs potential: $\mathbf{V}(\mathbf{h}) = \alpha \ \mathbf{sin}^2\left(\frac{\mathbf{h}}{\mathbf{F}_\pi}\right) + \beta \ \mathbf{sin}^4\left(\frac{\mathbf{h}}{\mathbf{F}_\pi}\right)$

Minimum at $\sin^2\frac{h}{F_\pi} = \sqrt{\frac{-\alpha}{2\beta}}$

α, β loop quantities depending on

Parameters:

g_{5D} : **5D gauge coupling**

$c_{q,u}$: **5D top masses**

$$\left.\begin{array}{l}\tilde{m}_u \\ \tilde{M}_u\end{array}\right\} \textbf{boundary masses}$$

and the overall scale (compactification scale): L_1

Higgs decay-constant:

$$F_\pi = \frac{2}{g_{5D}}\frac{1}{L_1}$$

KK-mass: $m_\rho \simeq \frac{3\pi}{4}\frac{1}{L_1}$

Important constraint: S-parameter

$$\hat{S} \simeq 0.2 \left(\frac{v}{m_\rho}\right)^2 \leq 2 \cdot 10^{-3}$$

$$\hookrightarrow \frac{v}{m_\rho} \leq \frac{1}{10}$$

Exists certain tension!

$\hat{T}=0$ by the custodial symmetry

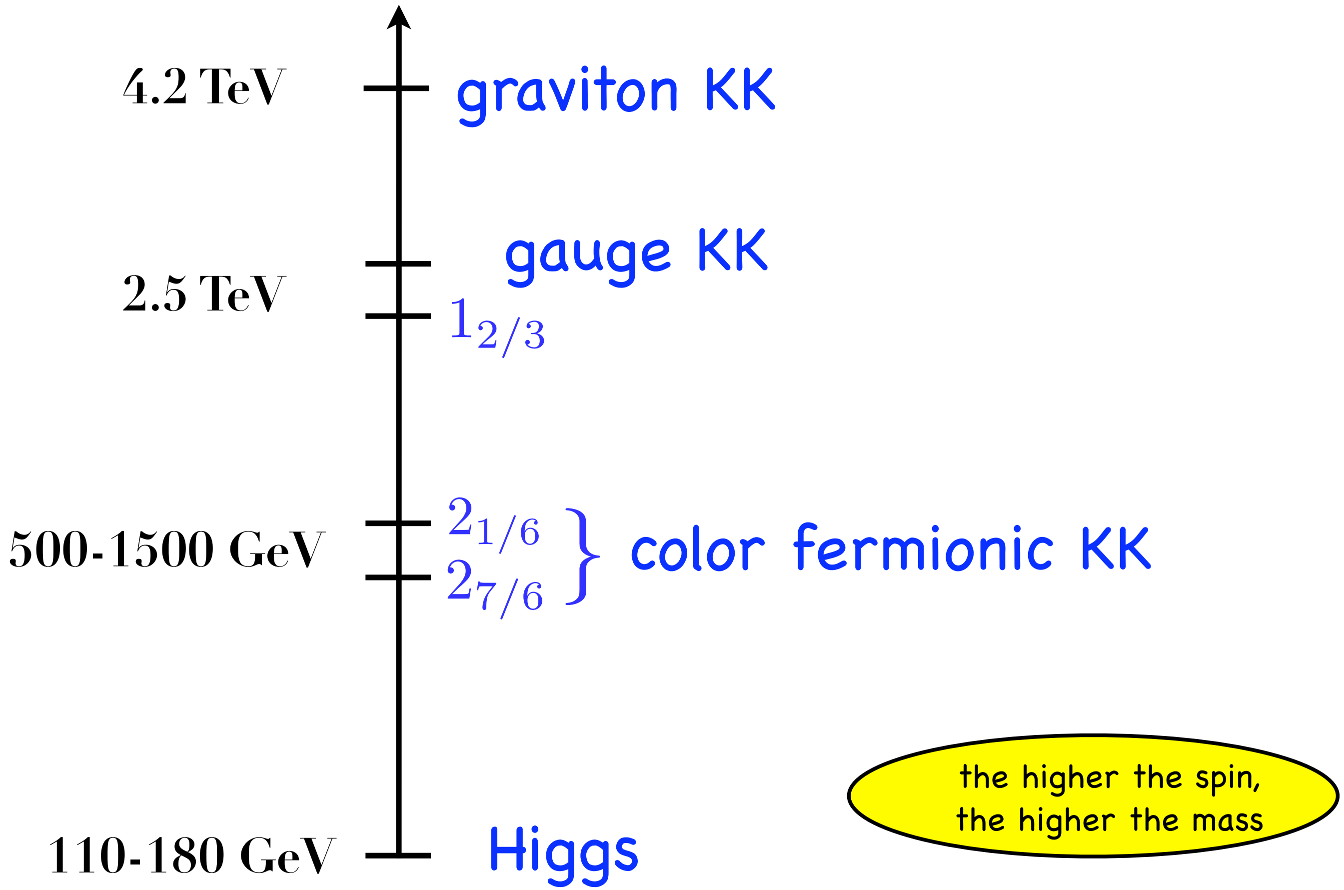
Predictions

Light Higgs $+$ **KK resonances for each SM field in complete reps of the bulk group SO(5)**

top: $5 = 2_{7/6} + 2_{1/6} + 1_{2/3}$

exotic states of Q=5/3

Spectrum


4.2 TeV
graviton KK
gauge KK
2.5 TeV
$1_{2/3}$
$2_{1/6}$
$2_{7/6}$
500-1500 GeV
color fermionic KK
the higher the spin,
the higher the mass
110-180 GeV
Higgs

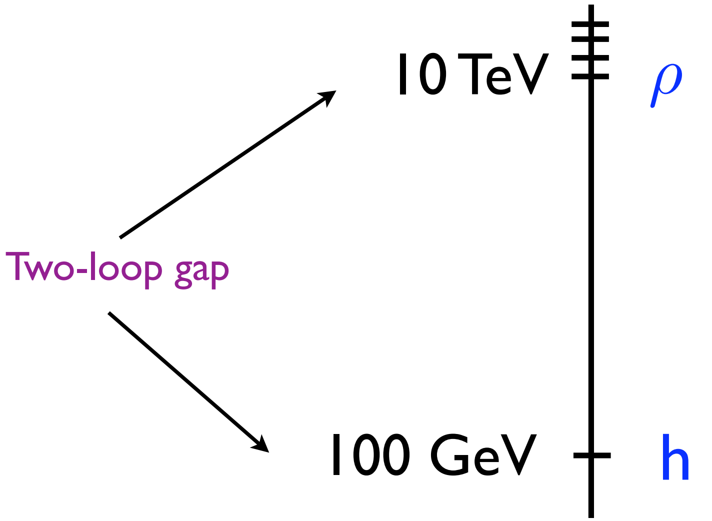
Little Higgs

Engineer a model where

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

two-loops

one-loop

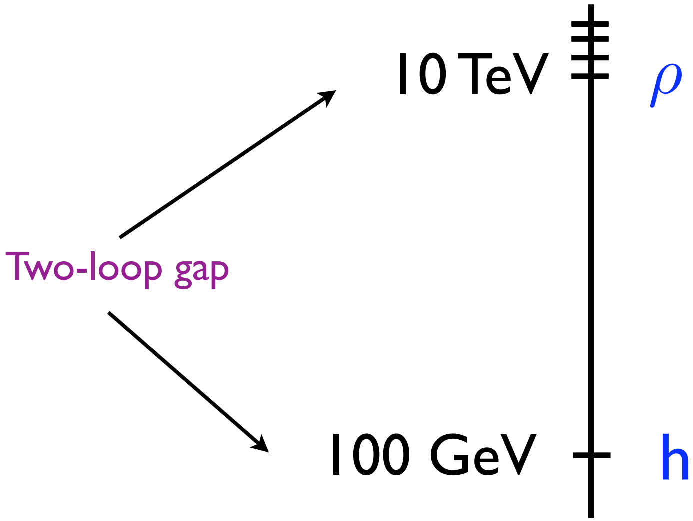


Arkani-Hamed, Cohen, Georgi

Little Higgs!

How?

Collective breaking: Demand two gauge couplings needed to break the PGB symmetry



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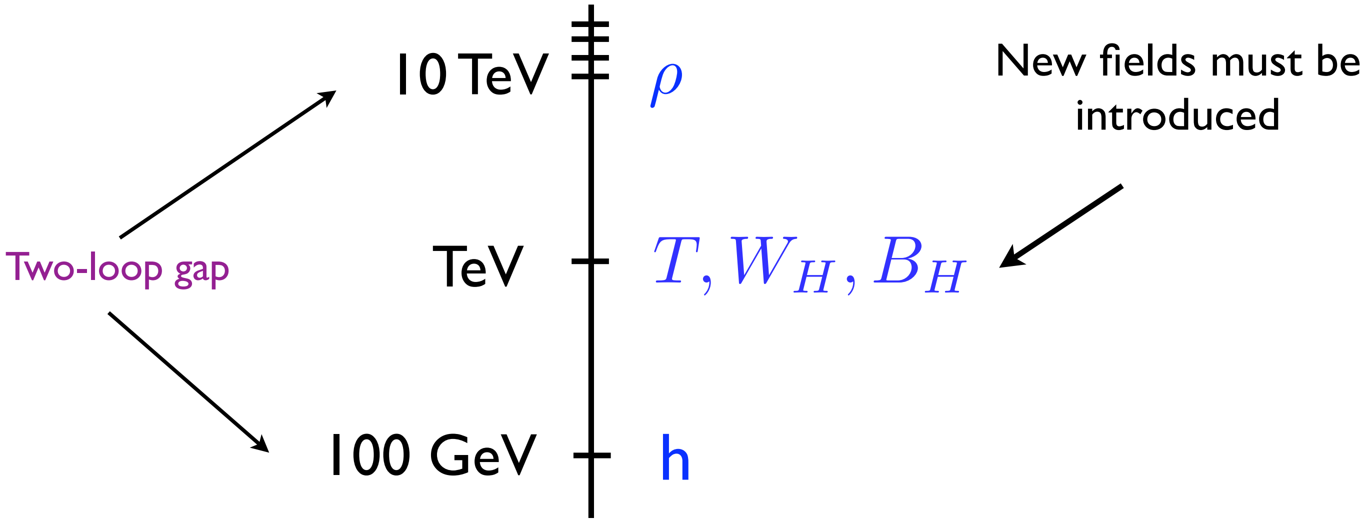


IV. EWSB at the LHC

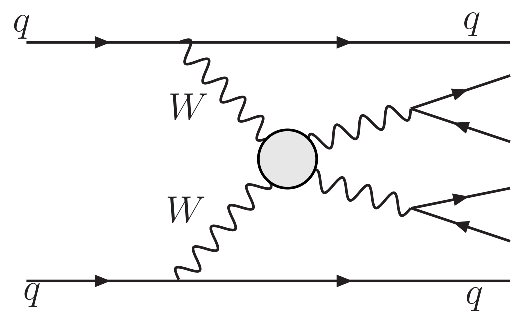
Type of searches:

Model Independent: WW-scattering, Higgs searches: Measure of its couplings to see if they differ from a SM (elementary) Higgs

Model Dependent: Extra resonances around TeV with SM quantum numbers: W', Z', t', b', ... and other exotics

WW-scattering at the LHC

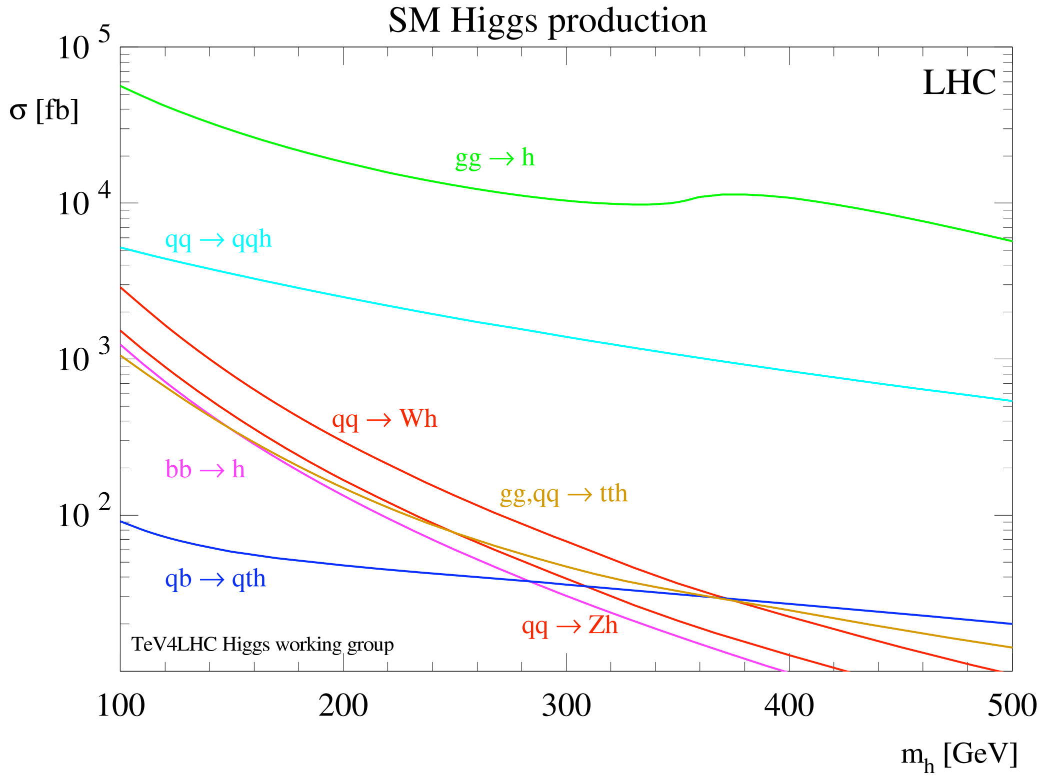
Accomando et al Phys.Rev.D75:113006,2007



M_{cut}	NoHiggs		M(H)=200 GeV		Ratio
800 GeV	31	(14,17)	12	(7,5)	2.59
900 GeV	25	(12,13)	8	(5,3)	3.12
1.0 TeV	19	(9,10)	6	(4,2)	3.16
1.1 TeV	16	(7,9)	5	(3,2)	3.20
1.2 TeV	13	(6,7)	3	(2,1)	4.33
1.3 TeV	11	(5,6)	2	(1,1)	5.50
1.4 TeV	9	(4,5)	2	(1,1)	4.50

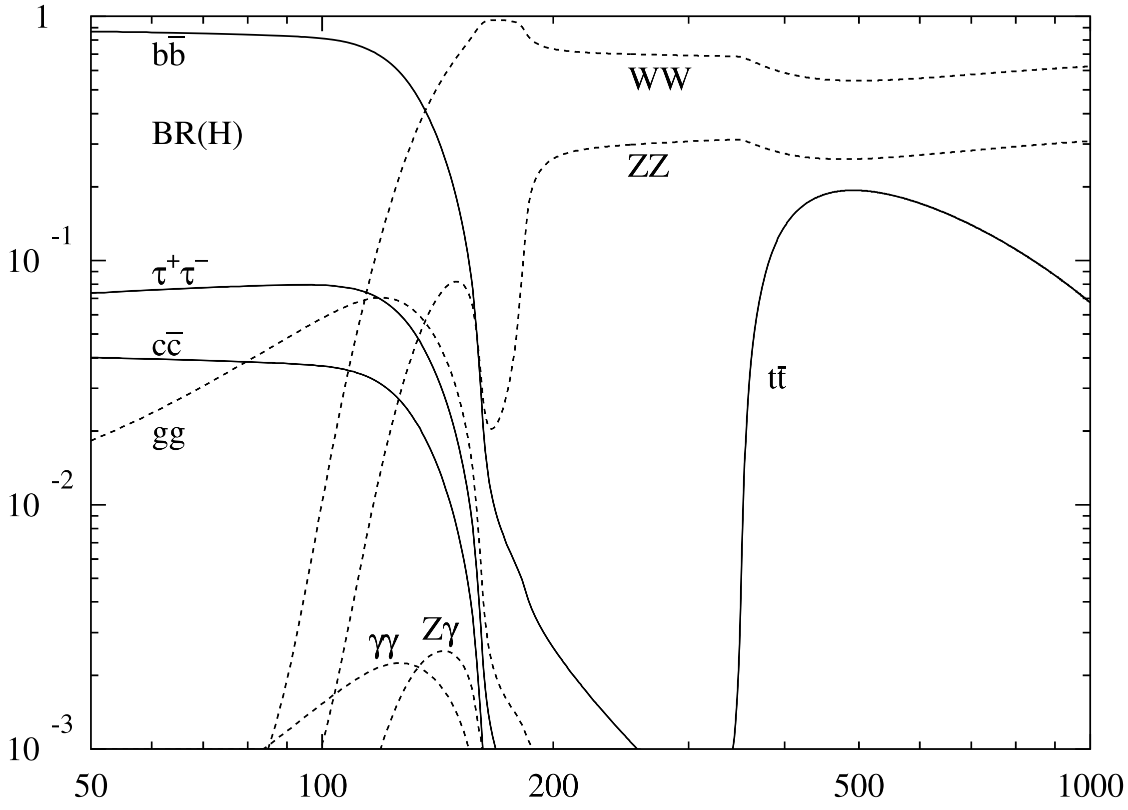
TABLE V: Number of events as a function of the minumum invariant mass of the $ZV \to \mu^+\mu^- jj$ pair for L=100 fb^{-1}. All events satisfy $|\eta(Z_{ll})| < 2$ and $|\eta(q_V)| < 2$. In brackets we show the contribution of the (ZW,ZZ) final states.

Higgs searches



SM Higgs production
LHC
σ [fb]
10 5
10 4
10 3
10 2
gg → h
qq → qqh
qq → Wh
bb → h
gg,qq → tth
qb → qth
qq → Zh
TeV4LHC Higgs working group
100
200
300
400
500
m_h [GeV]

Higgs branching ratios:



Higgs mass

If the Higgs is (PGB) composite state,
its coupling will deviate from SM coupling

Deviations can be parametrized by 4 dimension-six operators

Giudice,Grojean,A.P.,Rattazzi

$$\frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right)+\frac{c_T}{2f^2}\left(H^\dagger\overleftrightarrow{D^\mu}H\right)\left(H^\dagger\overleftrightarrow{D}_\mu H\right)$$

$$-\frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3+\left(\frac{c_y y_f}{f^2}H^\dagger H\bar{f}_L H f_R+\text{h.c.}\right)$$

c_H, c_T, c_6, c_y : **model-dependent coefficients**

f can be as small as ~ 500 GeV

Measuring the compositeness of the Higgs:

$$\xi \equiv \frac{v^2}{f^2}$$

Definite modifications of Higgs decay widths:

$$\Gamma\left(h \to f\bar{f}\right)_{\mathrm{SILH}} = \Gamma\left(h \to f\bar{f}\right)_{\mathrm{SM}} \left[1 - \xi\left(2c_y + c_H\right)\right]$$

$$\Gamma\left(h \to W^+W^-\right)_{\mathrm{SILH}} = \Gamma\left(h \to W^+W^{(*)-}\right)_{\mathrm{SM}} \left[1 - \xi\left(c_H - \frac{g^2}{g_\rho^2}\hat{c}_W\right)\right]$$

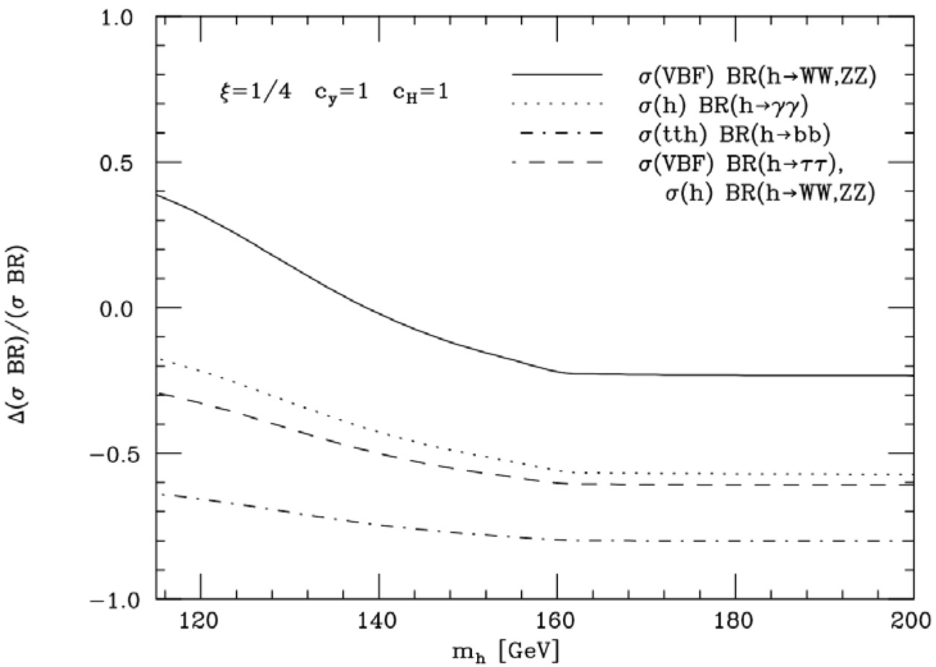
$$\Gamma\left(h \to ZZ\right)_{\mathrm{SILH}} = \Gamma\left(h \to ZZ^{(*)}\right)_{\mathrm{SM}} \left[1 - \xi\left(c_H - \frac{g^2}{g_\rho^2}\hat{c}_Z\right)\right]$$

$$\Gamma\left(h \to gg\right)_{\mathrm{SILH}} = \Gamma\left(h \to gg\right)_{\mathrm{SM}} \left[1 - \xi\,\mathrm{Re}\left(2c_y + c_H + \frac{4y_t^2 c_g}{g_\rho^2 I_g}\right)\right]$$

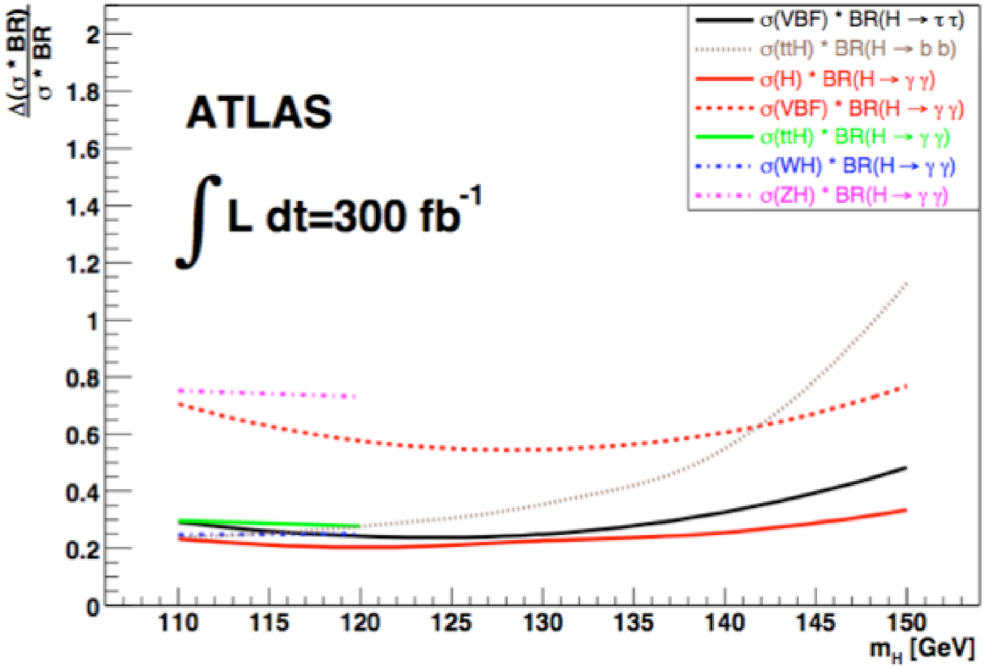
$$\Gamma\left(h \to \gamma\gamma\right)_{\mathrm{SILH}} = \Gamma\left(h \to \gamma\gamma\right)_{\mathrm{SM}} \left[1 - \xi\,\mathrm{Re}\left(\frac{2c_y + c_H}{1 + J_\gamma/I_\gamma} + \frac{c_H - \frac{g^2}{g_\rho^2}\hat{c}_W}{1 + I_\gamma/J_\gamma} + \frac{\frac{4g^2}{g_\rho^2}c_\gamma}{I_\gamma + J_\gamma}\right)\right]$$

$$\Gamma\left(h \to \gamma Z\right)_{\mathrm{SILH}} = \Gamma\left(h \to \gamma Z\right)_{\mathrm{SM}} \left[1 - \xi\,\mathrm{Re}\left(\frac{2c_y + c_H}{1 + J_Z/I_Z} + \frac{c_H - \frac{g^2}{g_\rho^2}\hat{c}_W}{1 + I_Z/J_Z} + \frac{4c_{\gamma Z}}{I_Z + J_Z}\right)\right]$$

Deviations from the SM:



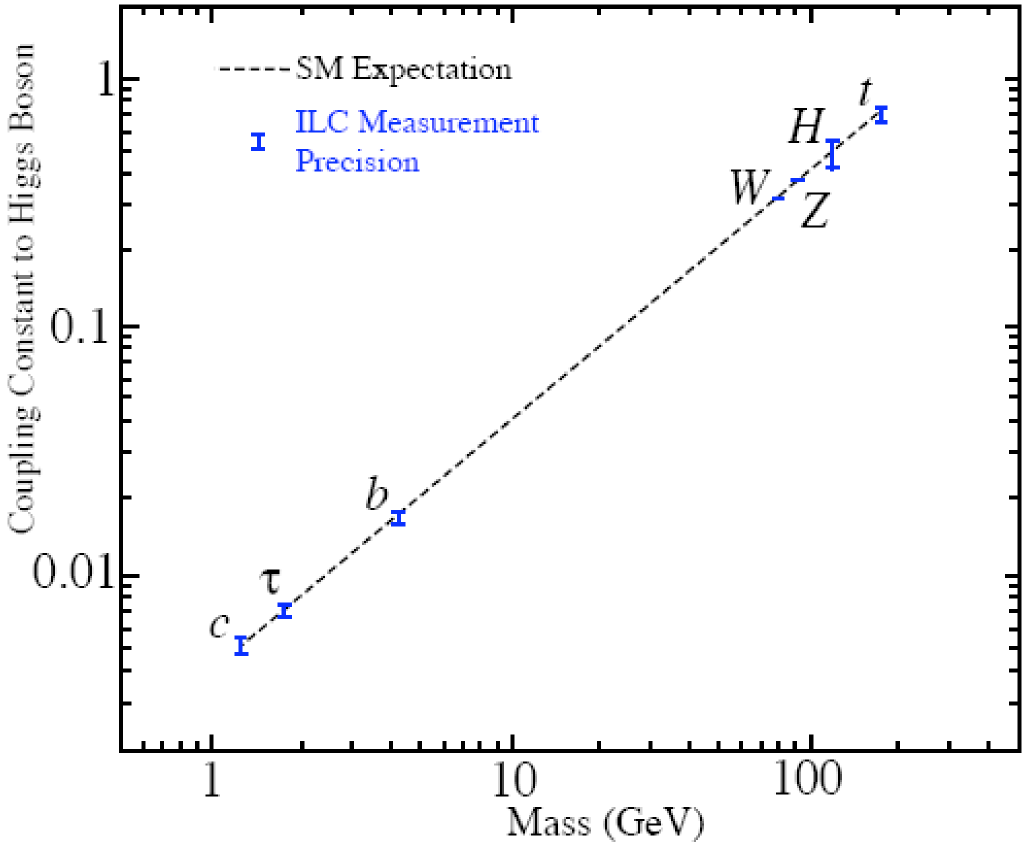
Visible at LHC?



Duhrssen 03

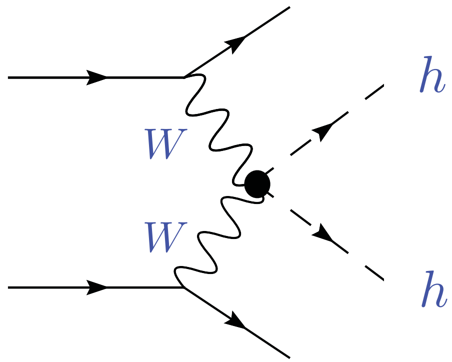
...certainly if they are of order 20-40%

ILC would be a perfect machine to test these scenarios:
effects could be measured up to a few %



SM Expectation
ILC Measurement Precision
Coupling Constant to Higgs Boson
Mass (GeV)
1
0.1
0.01
1
10
100
c
τ
b
W
Z
H
t

2 Higgs-production also grows with s:

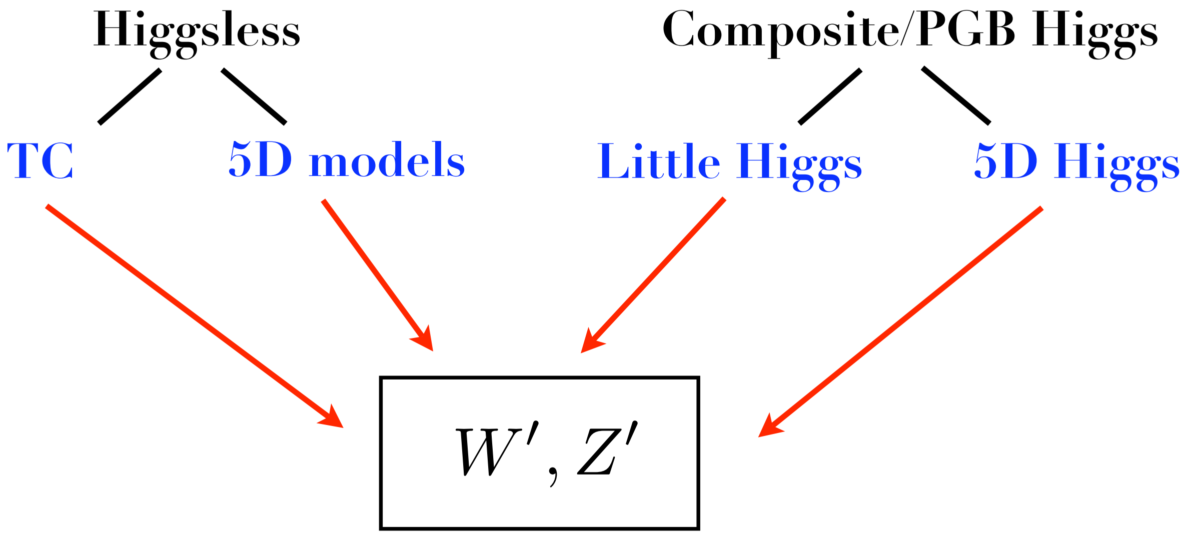


$$\mathcal{A}\left(Z_L^0 Z_L^0 \to hh\right) = \mathcal{A}\left(W_L^+ W_L^- \to hh\right) = \frac{c_H s}{f^2}.$$

Challenging!

Detection of new Resonances


Higgsless
TC
5D models
Composite/PGB Higgs
Little Higgs
5D Higgs



Higgsless
Composite/PGB Higgs
TC
5D models
Little Higgs
5D Higgs
W', Z'

Higgsless

TC | **5D models**

Composite/PGB Higgs

Little Higgs | **5D Higgs**

$$\boxed{W', Z'}$$

Decay:

$$W', Z' \to \text{leptons}$$

$$W', Z' \to \text{tops}, W_{long}, Z_{long}, h$$

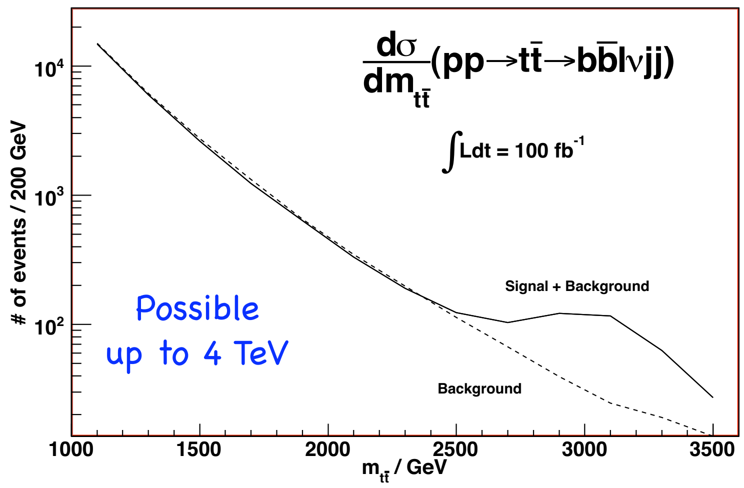
Possible to see up to 2-3 TeV

Higgsless — TC, 5D models

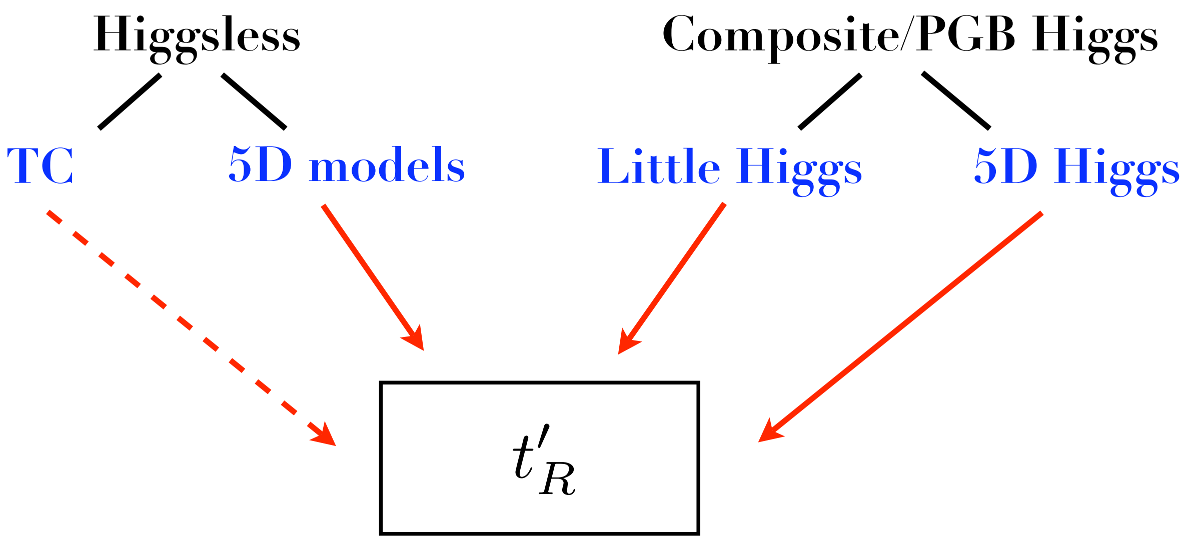
Composite/PGB Higgs — Little Higgs, 5D Higgs

$$\boxed{g'}$$

Decay: $g' \to t\bar{t}$



Agashe et al



Decay: $t'_R \to W_{long} b$

feasible to see up to 1-2 TeV

Higgsless

TC   5D models

Composite/PGB Higgs

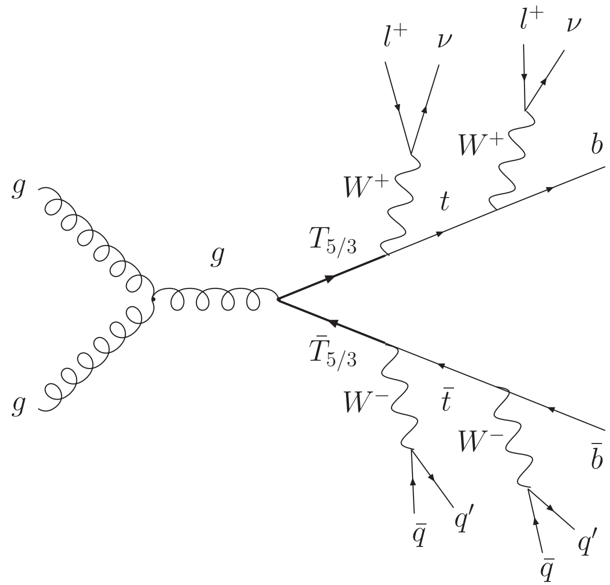
Little Higgs   5D Higgs

$$\boxed{T_{5/3}}$$

Decay: $T_{5/3} \rightarrow W_{long} t$

feasible to see up to 1-2 TeV

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



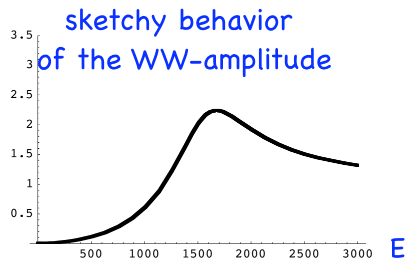
masses up to 1 TeV reached with an integrated luminosity of 20/fb

Contino,Servant

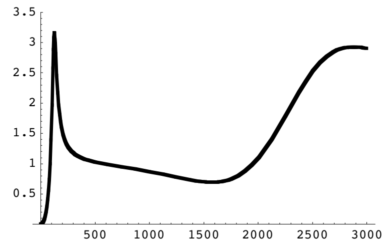
Conclusions

Three possibilites that could UV-complete the experimentally known SM:

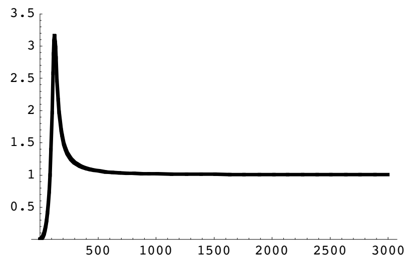
1) No Higgs



2) Composite Higgs

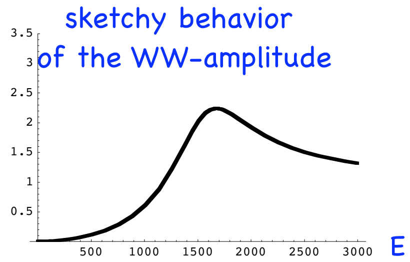


3) Elementary Higgs

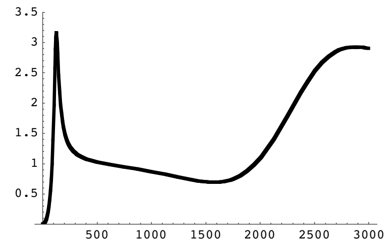


Three possibilites that could UV-complete the experimentally known SM:

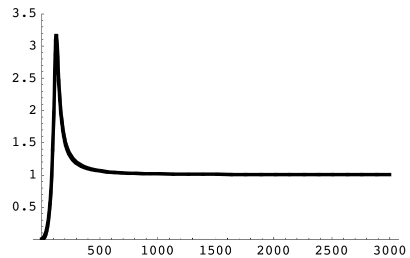
1) No Higgs



2) Composite Higgs



3) Elementary Higgs



We hope soon the LHC will deliver the verdict !