# Lecture II

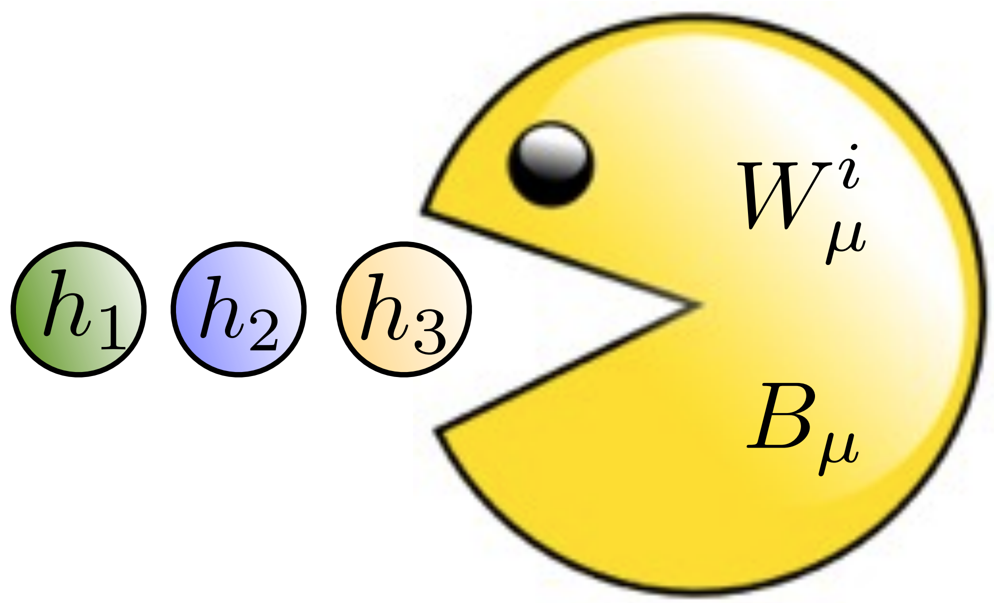
- Electroweak symmetry breaking from a new strong dynamics
- Models with a light composite Higgs boson: theory and phenomenology

# Higgs mechanism

| | | | |
|---|---|---|---|
| # of states | 4 | $2 \times 4$ | $= 12$ |

$$\begin{pmatrix} h_1 + ih_2 \\ h + ih_3 \end{pmatrix} \qquad W^i_\mu\,,\ B_\mu \quad \text{massless}$$

EWSB




$$h \qquad W^\pm_\mu\,, Z^0_\mu \qquad A_\mu$$

| | | | | |
|---|---|---|---|---|
| # of states | 1 | $3 \times 3$ | 2 | $= 12$ |

$m_{W,Z} \neq 0$ 3 polarizations = $2_{\perp}$ + $1_{\parallel}$

eaten Goldstones

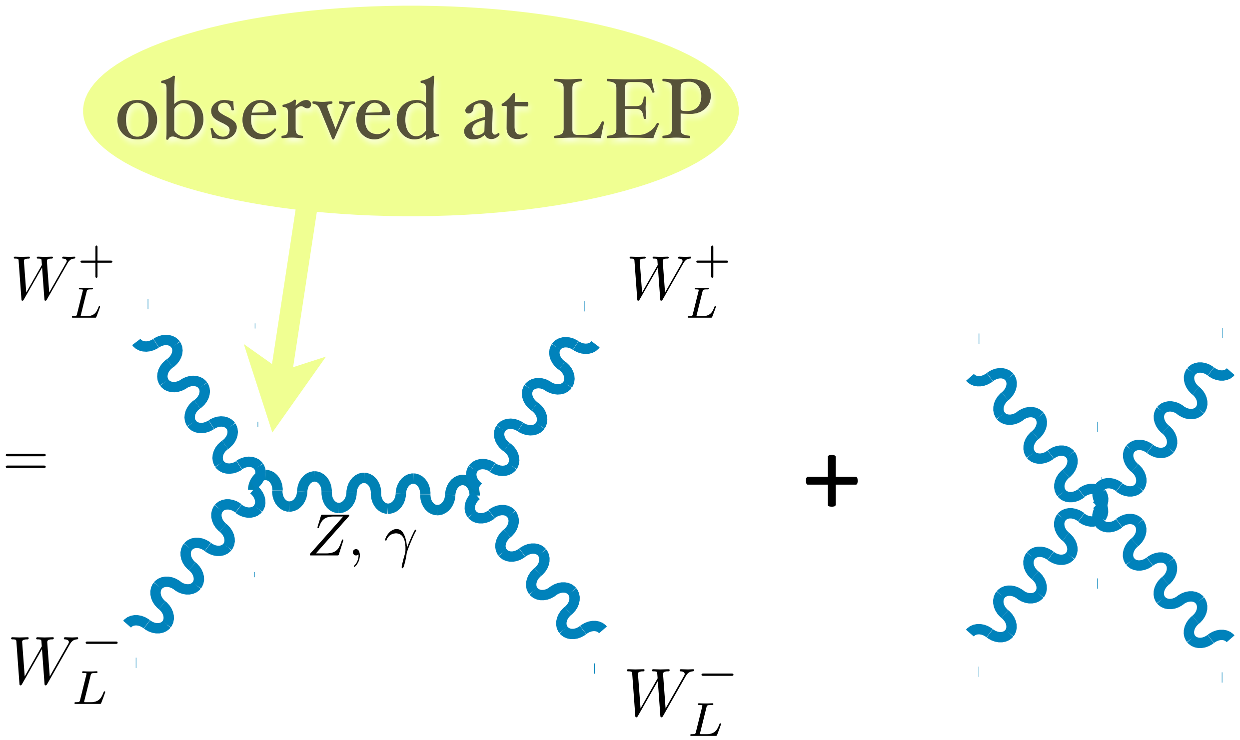
The eaten Goldstones are essential to provide the 3rd polarization

But why do we need the neutral scalar *h*?

What happens if we eliminate *h* from the spectrum ?

Consider the scattering of longitudinally polarized vectors $W_L^\pm \sim h^\pm$

$A(W_L^+ W_L^- \to W_L^+ W_L^-) =$




$= \left(\dfrac{\sqrt{s}}{174\,\text{GeV}}\right)^2$

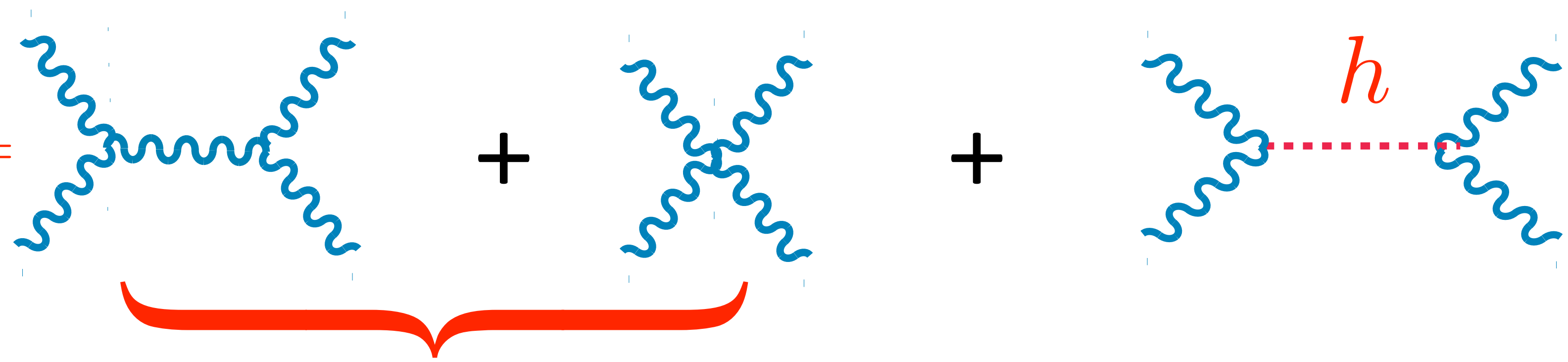
interactions among longitudinal modes become strong at around 2 TeV

Higgsless SM

- ✦ A new strong dynamics exists below 2 TeV!
- ✦ New states expected around same scale

# Putting the Higgs scalar back

$\mathcal{A}(V_L V_L \to V_L V_L) =$




$$\frac{s}{v^2} - \frac{s}{v^2}\frac{s}{s-m_h^2} \overset{s\to\infty}{=} \frac{m_h^2}{v^2}$$

Higgs boson acts as a **moderator** in the interaction strength

It allows SM to be extrapolated to arbitrarily high scale Λ

# No-loose theorem

Either a Higgs boson is discovered

or

a new strong force shows up around the TeV scale

# Technical interlude : custodial symmetry

$$H = \begin{pmatrix} h_1 + ih_2 \\ h \ \ + ih_3 \end{pmatrix} \equiv \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \qquad H \longrightarrow U_L H$$

useful to consider $SO(4) = SU(2)_L \times SU(2)_R$

$$\Phi \equiv \begin{pmatrix} H^{0*} & H^+ \\ -H^{+*} & H^0 \end{pmatrix} \qquad \Phi \longrightarrow U_L \Phi U_R^\dagger$$

Notice: $SU(2)_L$ is a gauge symmetry but $SU(2)_R$ is not

The SM lagrangian, neglecting Yukawa and hypercharge couplings, is accidentally invariant under the full SO(4) symmetry

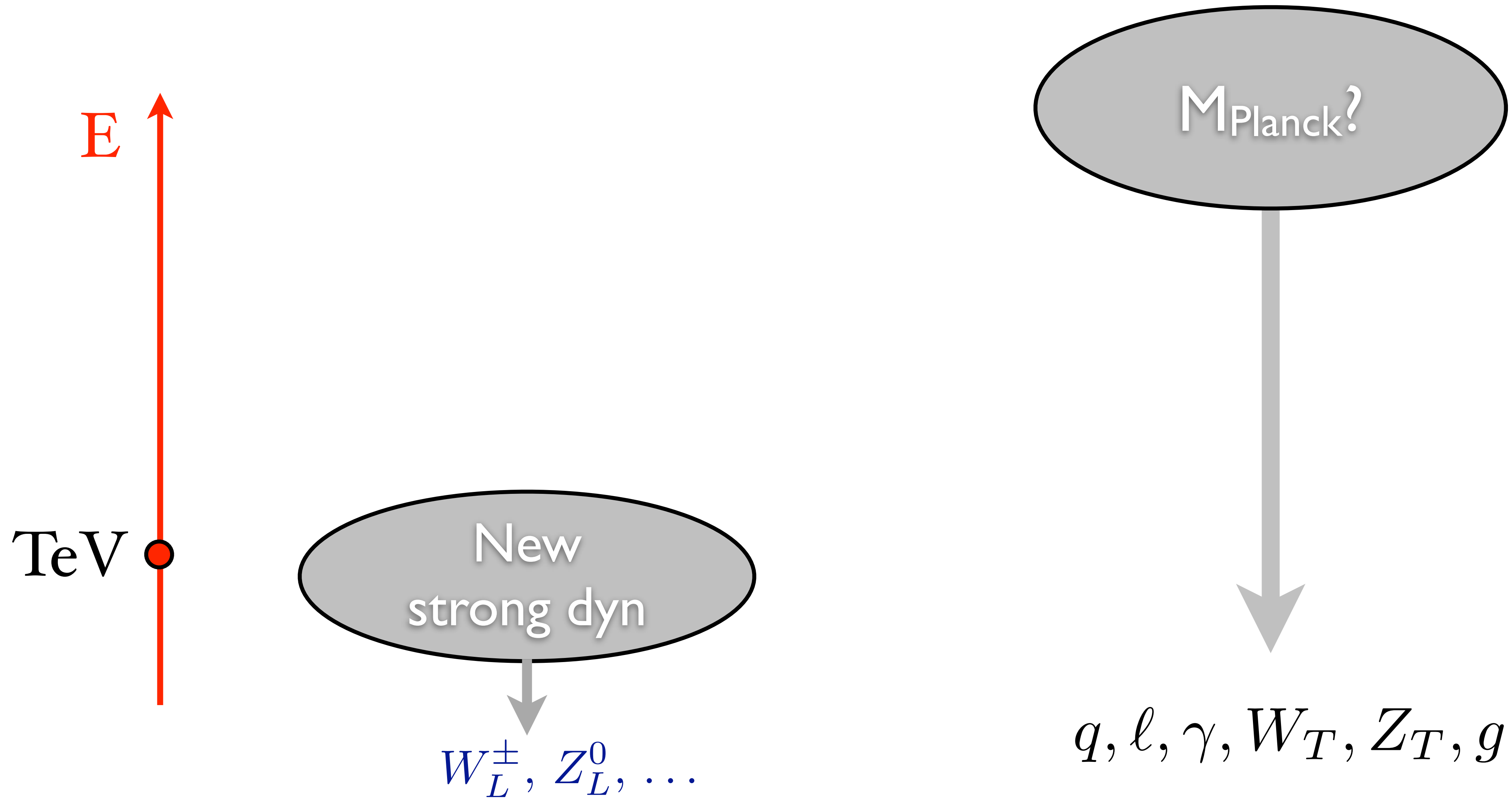
$$\langle \Phi \rangle = \begin{pmatrix} v & 0 \\ 0 & v \end{pmatrix} \qquad SU(2)_L \times SU(2)_R \longrightarrow SU(2)_{L+R}$$

custodial symmetry

$$\mathcal{L}_{mass} = \frac{v^2}{4} \begin{pmatrix} W_\mu^1 & W_\mu^2 & W_\mu^3 & B_\mu \end{pmatrix} \begin{pmatrix} g_2^2 & & & 0 \\ & g_2^2 & & \\ & & g_2^2 & g_2 g_Y \\ 0 & & g_2 g_Y & g_Y^2 \end{pmatrix} \begin{pmatrix} W_\mu^1 \\ W_\mu^2 \\ W_\mu^3 \\ B_\mu \end{pmatrix}$$

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} = 1$$

# The basic scenario

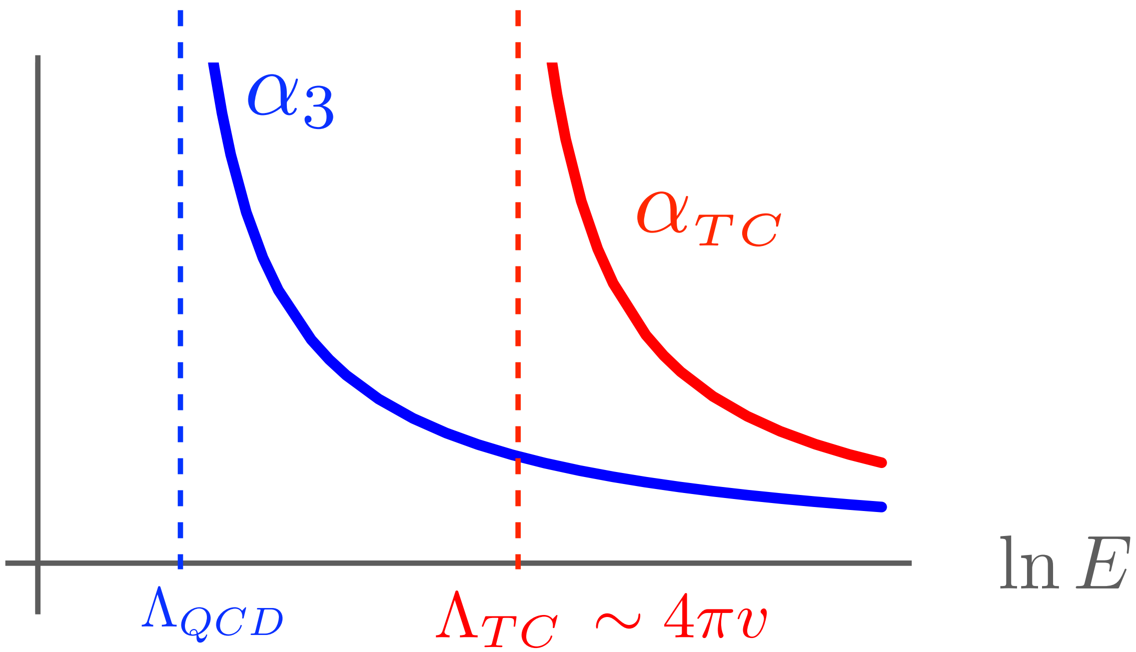



The longitudinal polarizations (eaten Goldstones) arise as bound states of a new strong force at TeV scale

Simplest realization : Technicolor

A new gauge force mimicking the dynamics of QCD

$$G_{total} = SU(N)_{TC} \times SU(3) \times SU(2)_L \times U(1)_Y$$




## Technifermions

$$\begin{pmatrix} U_L \\ D_L \end{pmatrix} = (N,\ 1,\ 2,\ 0)$$

$$U_R = (N,\ 1,\ 1,\ +1)$$

$$D_R = (N,\ 1,\ 1,\ -1)$$

meson field $\mathbf{\Phi}$ plays Higgs role

$$\mathbf{\Phi} \equiv \begin{pmatrix} \bar{U}_R U_L & \bar{D}_R U_L \\ \bar{U}_R D_L & \bar{D}_R D_L \end{pmatrix} \qquad \mathbf{\Phi} \xrightarrow{SU(2)_L \times SU(2)_R} U_L \mathbf{\Phi} U_R^\dagger$$

vacuum dynamics breaks EW symmetry, preserving a custodial SU(2) !

$$\langle \mathbf{\Phi} \rangle = \Lambda_{TC}^3 \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad SU(2)_L \times SU(2)_R \longrightarrow SU(2)_{L+R}$$

particles ‘created’ by $\mathbf{\Phi}$

$\pi_1,\ \pi_2,\ \pi_3$

3 massless Goldstone bosons eaten in Higgs mech

strongly coupled & wide resonances with mass

$\gtrsim \Lambda_{TC} \sim 4\pi v_F$

$$\mathbf{\Phi} = \Lambda_{TC}^3\, e^{i\pi_a \sigma^a}$$

$SU(2)_L$ x U(1) is non-linearly realized

No light Higgs scalar $h$

# Beautiful !

... but there were 2 (now probably 3) problems with TC

# Problem 1: Flavor

**SM**

$$Y_{ij}\,\bar\psi_L^i\,\mathbf{H}\,\psi_R^j \quad\to\quad m_{ij} = Y_{ij}\,v_F$$

$d = 1$

**TC**

$d = 3$

$$\lambda_{ij}\,\frac{(\bar\psi_L^i\psi_R^j)(\bar U_R U_L)}{\Lambda_F^2} \quad\to\quad m_{ij} = \lambda_{ij}\,\frac{v_F^3}{\Lambda_F^2}$$

Fermion masses do not arise at renormalizable level in TC

The scale $\Lambda_F$ must be close to weak scale

otherwise quarks & leptons are too light

Expect extra dangerous Flavor violating effects from physics at scale $\Lambda_F$ ☹

# Problem 2: electroweak precision tests (EWPT)

- $G_F|_Z = G_F|_\mu (1 + \varepsilon_1)$ → quantum corrections + New Physics

$\varepsilon_1 \equiv \delta\rho$ breaks custodial

- different definitions of Weinberg angle

$$(1 - s_W^2) s_W^2 \equiv \frac{\pi \alpha_{EM}}{\sqrt{2}\, G_F|_\mu\, m_Z^2}$$

$$(1 - \tilde{s}_W^2) \tilde{s}_W^2 \equiv \frac{m_W^2}{m_Z^2}\left(1 - \frac{m_W^2}{m_Z^2}\right)$$

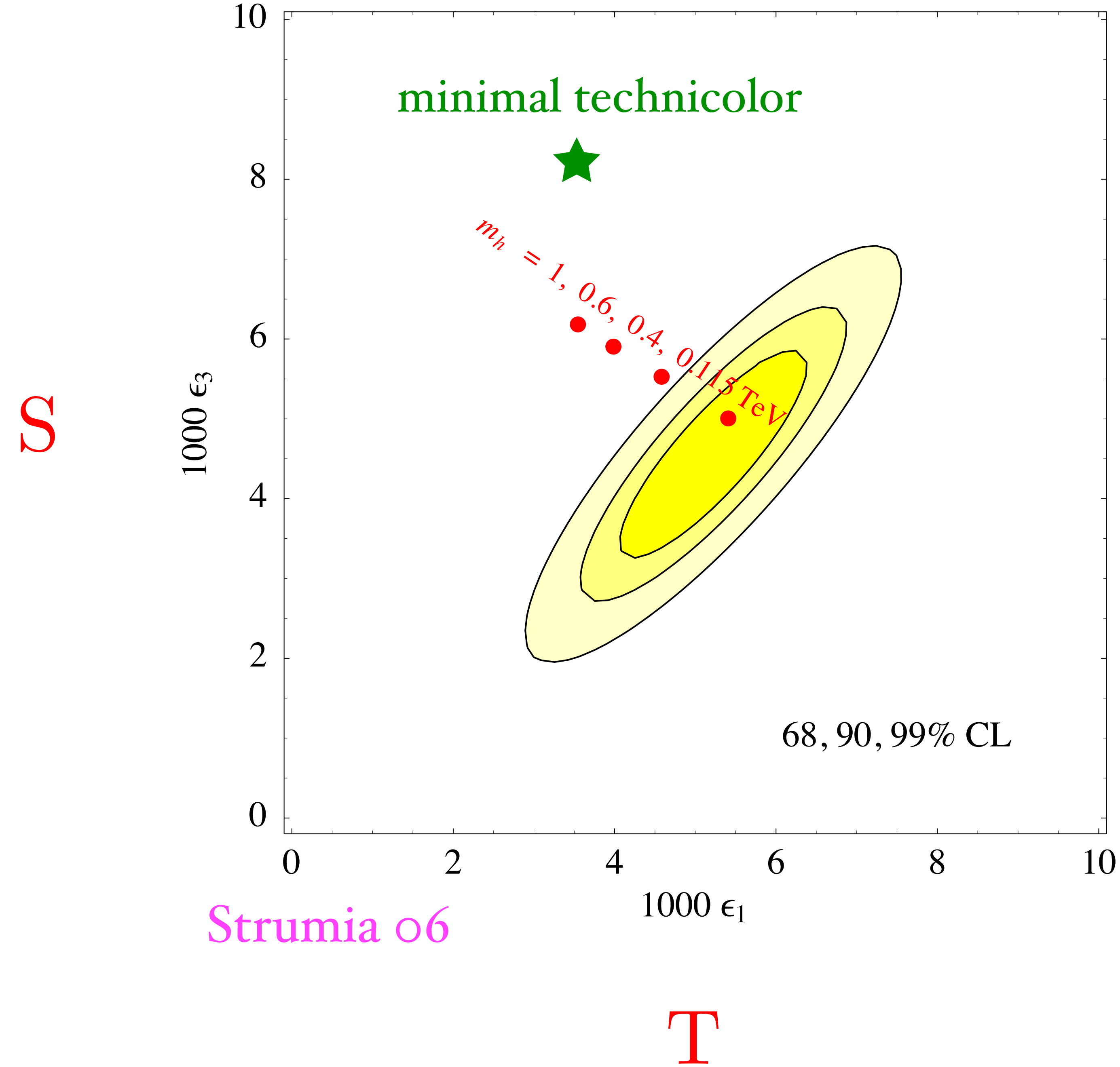
$$-\frac{1}{2} + 2\bar{s}_W^2 \equiv g_V$$

at tree level

$$s_W^2 = \tilde{s}_W^2 = \bar{s}_W^2$$

the relative mismatch between 3 definitions ⇒ 2 precision parameters $\varepsilon_2$, $\varepsilon_3$

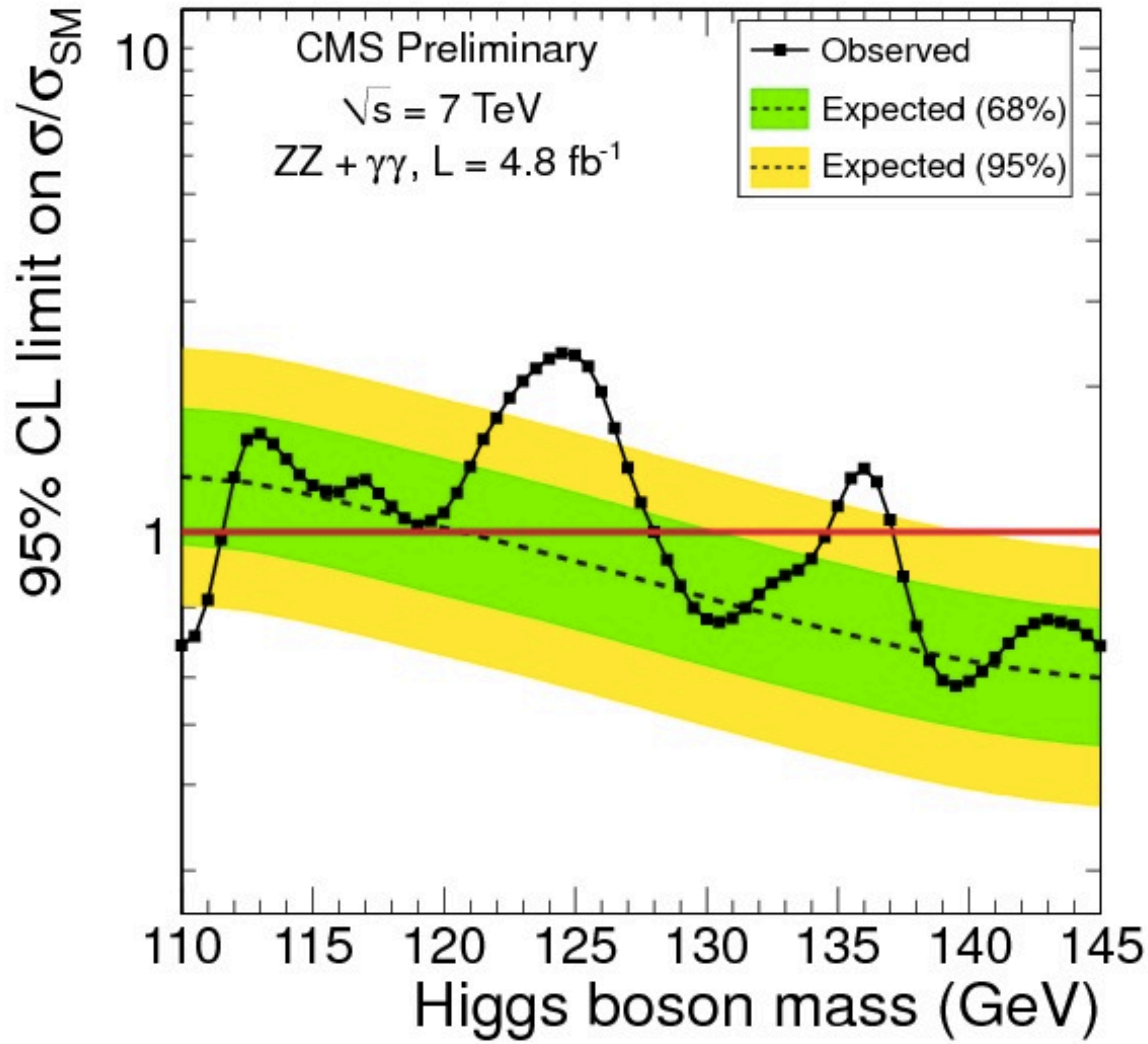
sensitive to quantum corrections and to New Physics




$$\Delta\epsilon_3\big|_{TC} \sim \frac{g^2}{96\pi^2} N_{TF} N_{TC}$$

large and positive
little space to argue

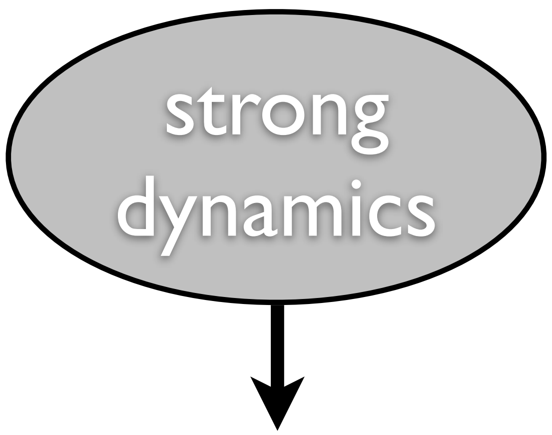
# Problem 3


CMS Preliminary
$\sqrt{s}$ = 7 TeV
ZZ + γγ, L = 4.8 fb$^{-1}$
Observed
Expected (68%)
Expected (95%)
95% CL limit on σ/σ$_{SM}$
10
1
110
115
120
125
130
135
140
145
Higgs boson mass (GeV)

# A significant improvement: models with a composite light Higgs

basic idea: in addition to the 3 eaten massless bosons there is a fourth one, only approximately massless, and playing the role of the SM neutral Higgs

Georgi, Kaplan '84
Banks '84
Arkani-Hamed, Cohen, Katz, Nelson '02
Agashe, Contino, Pomarol '04




$$\begin{pmatrix} h_1 + ih_2 \\ h \;\; + ih_3 \end{pmatrix}$$ =light pseudo-Goldstone bosons from spontaneous breaking of a group $\mathcal{G}$ down to a subgroup $\mathcal{H}$

- minimal example $SO(5) \rightarrow SO(4)$

no fully realistic model purely based on 4-dimensional gauge theories
though an extremely interesting partial example exists

Galloway, Ewans, Luty, Tacchi 2010

several realistic models based on 5-dimensional models
in warped spacetime (Randall-Sundrum models)

Agashe, Contino, Pomarol '04

the 5-D models are loosely related to 4-D theories thanks
to the AdS/CFT correspondence

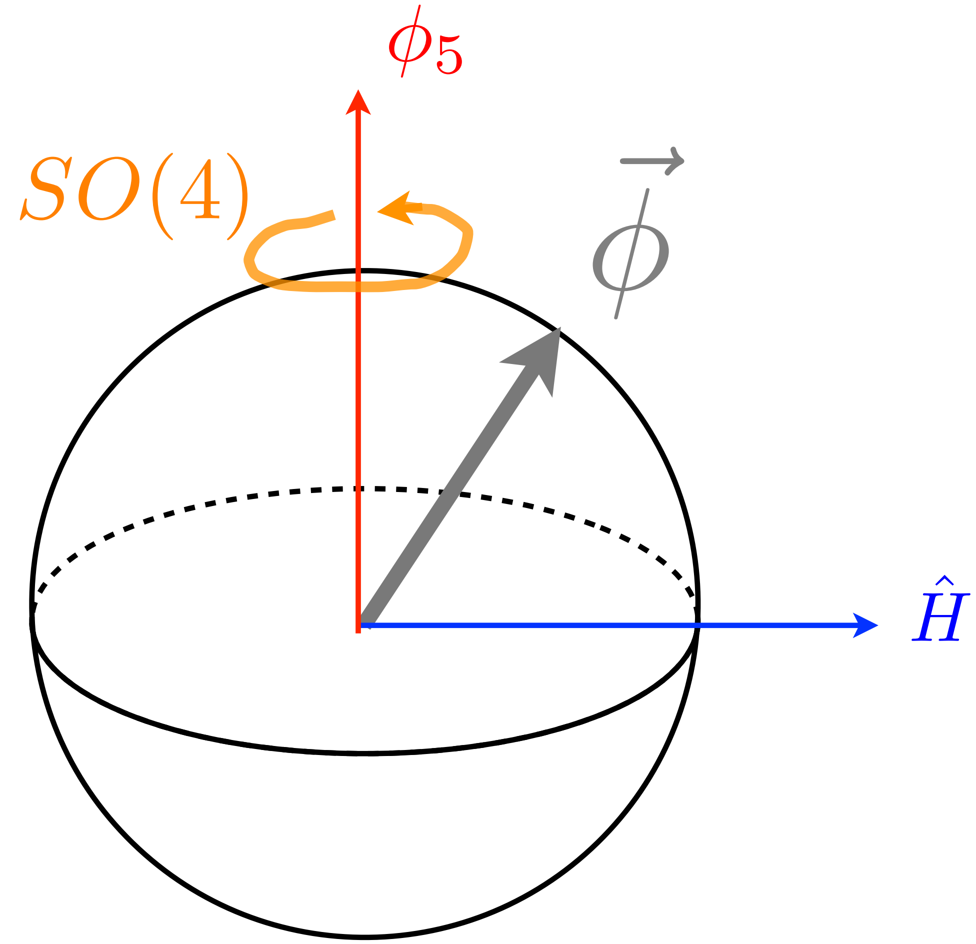
Arkani-Hamed, Porrati, Randall 2000
Rattazzi, Zaffaroni 2000

# $SO(5)/SO(4)$

$$\vec{\phi} = (\phi_1,\, \phi_2,\, \phi_3,\, \phi_4,\, \phi_5)$$

$$\vec{\phi}\cdot\vec{\phi} = f^2 = \text{const}$$

$$\hat{H} = \begin{pmatrix} h_1 \\ h_2 \\ h_3 \\ h \end{pmatrix} \equiv \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \end{pmatrix}$$



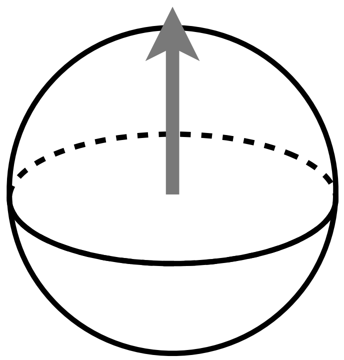

$g_{SM} = Y_{SM} = 0$ ⇒ all points on the 5-sphere equivalent, $V(\hat{H}) = 0$

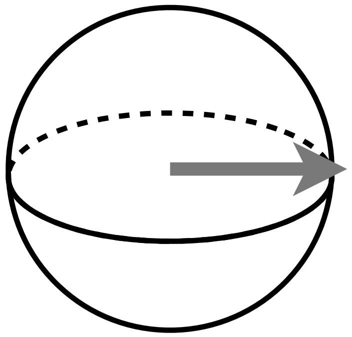
$g_{SM} \neq 0 \quad \lambda_t \neq 0$ ⇒ $V(\hat{H}) \neq 0$

possibilities for $v \equiv \langle H \rangle$

unbroken $SU(2)_L \times U(1)$

maximally broken

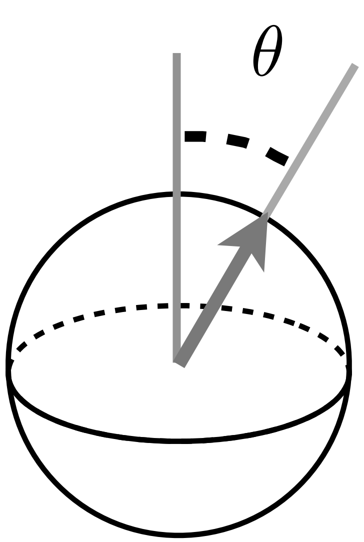




$v = 0$

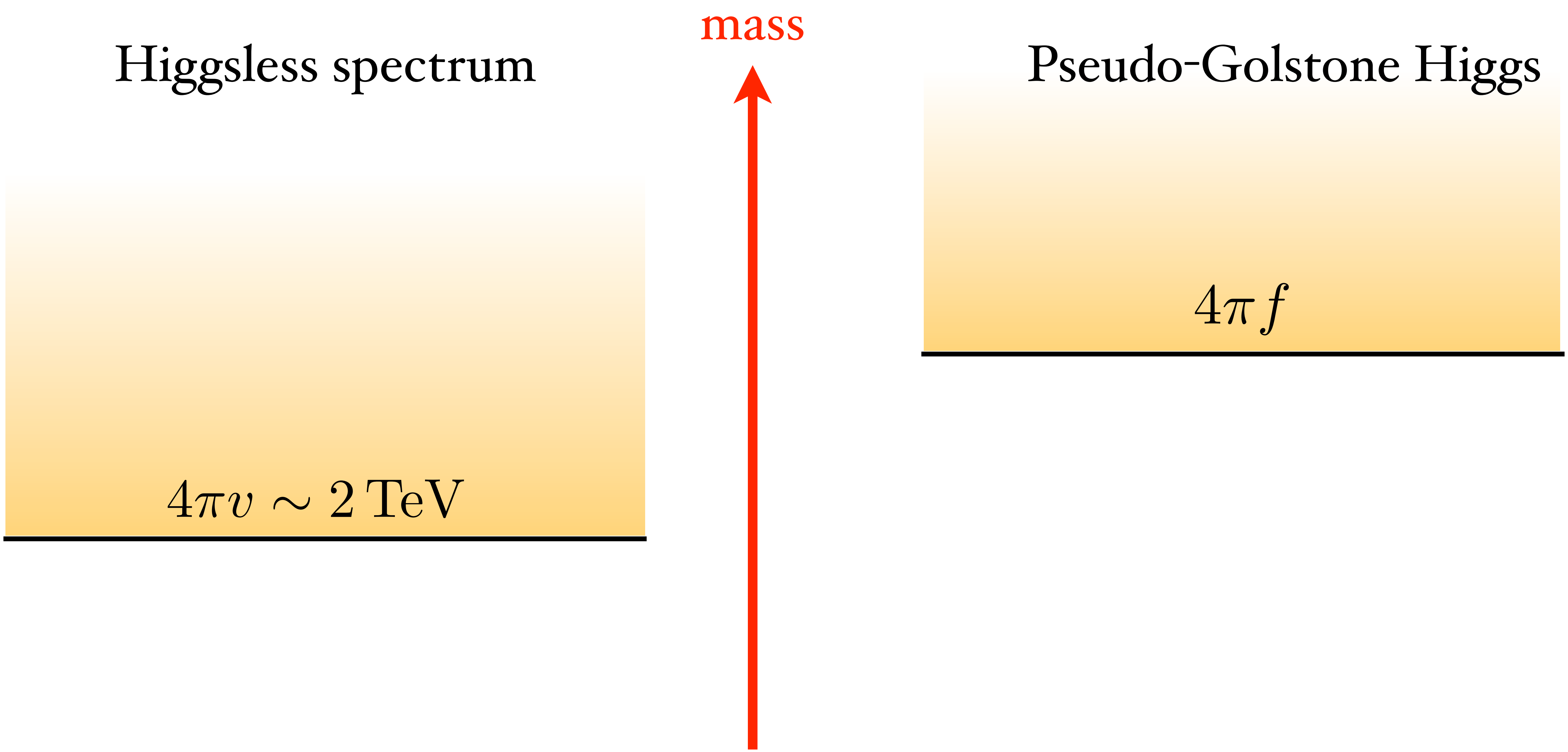
$v = f$

# ideal




$$v = f \sin\theta \ll f$$

- effects in EWPT are under control
- in practice $v/f \lesssim 0.3$ is enough
- either by mild tuning or
- by clever construction (Little Higgs)



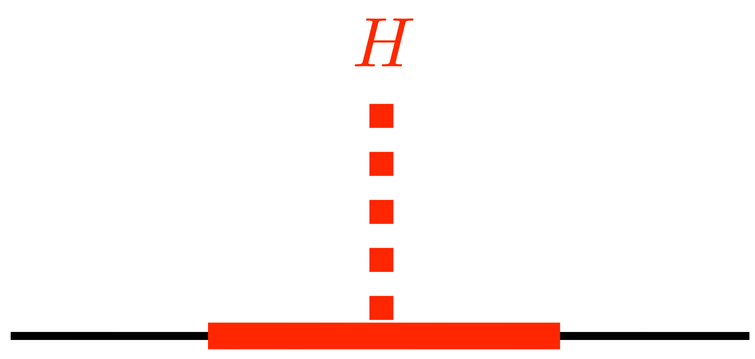

$$S_{CH} \sim S_{TC} \times \frac{v^2}{f^2}$$

$\frac{v^2}{f^2} \ll 1$ and existence of light Higgs ⇒ EWPT satisfied

# Flavor from partial compositeness

D.B. Kaplan '91
....
Huber, Shafi '00
RS with bulk fermions

$$\mathcal{L}_{Yukawa} = \epsilon_q^i q_L^i \Psi_q^i + \epsilon_u^i u_L^i \Psi_u^i + \epsilon_d^i d_L^i \Psi_d^i$$



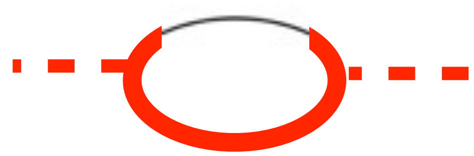
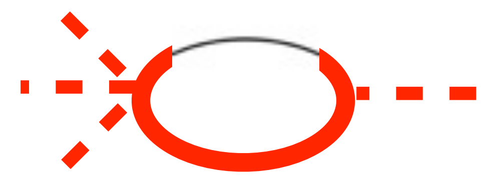
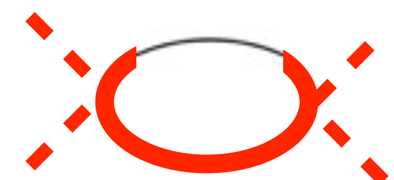

$$Y_u^{ij} \sim \epsilon_q^i \epsilon_u^j g_*$$

$$Y_d^{ij} \sim \epsilon_q^i \epsilon_d^j g_*$$

$\Psi$ = composite with dimension $\sim \frac{5}{2}$ ⇒ $\epsilon_q^i,\ \epsilon_u^i,\ \epsilon_d^i$ = dimensionless

Problems of minimal technicolor greatly alleviated
Qualitative prediction for the pattern of deviation from CKM paradigm

- $\Psi^i$ rich spectrum of composite fermionic resonances
- most interesting ones related to top quark = top partners T
- $t_R$ preferred to be fully composite
- $m_T$ related to physical Higgs mass

$V(H) =$  $+$  $+$  $+ \ldots$

rough estimate $$m_h^2 \sim \frac{3\lambda_t^2}{4\pi^2} \int_0^{M_T^2} dp^2 \sim \frac{3\lambda_t^2}{4\pi^2} M_T^2$$

allowing for some cancellations $$M_T \sim 450\,\mathrm{GeV} \times \frac{m_h}{125\,\mathrm{GeV}} \times \frac{1}{\sqrt{\epsilon_{tune}}}$$

A relatively light Higgs as hinted by LHC prefers relatively light top partners ( < 1 TeV)

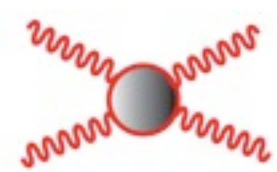
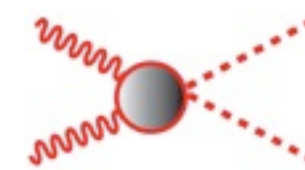
EWPTs on the contrary prefer bosonic resonances to be in the multi TeV range

If the scenario of Composite Higgs is realized in Nature it is clear that the underlying theory must be significantly more complex than a generic rescaled version of QCD

# Phenomenology

- production of resonances (vectors, top partners,...)

see lectures by G. Servant

- strong interactions in WW scattering  

- anomalous Higgs (top) couplings → Effective Lagrangian

# General parametrization of *Higgslike scalar h*

Contino, Grojean, Moretti, Piccinini, RR '10

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 + \frac{M_V^2}{2}\mathrm{Tr}\left(V_\mu V^\mu\right)\left[1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \dots\right] - m_i \bar{\psi}_{Li}\left(1 + c\frac{h}{v}\right)\psi_{Ri} + \mathrm{h.c.}$$
$$+ \frac{1}{2}m_h^2 h^2 + d_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4 \frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \dots$$
$$+ c_g \frac{\alpha_s}{4\pi}\frac{h}{v}G_{\mu\nu}G^{\mu\nu} + c_\gamma \frac{\alpha}{4\pi}\frac{h}{v}F_{\mu\nu}F^{\mu\nu}$$

$c$ flavor universal in minimal flavor violating set up

✦ Standard Model: $a = b = c = d_3 = 1$ $c_g = c_\gamma = 0$

✦ $h$ = pseudo-Goldstone implies additional constraints

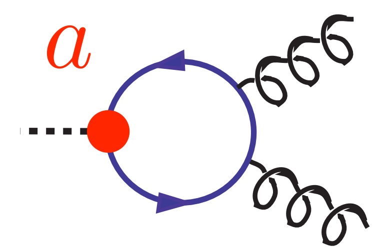
# $SO(5)/SO(4)$ Pseudo-Goldstone Higgs

Agashe, Contino, Pomarol '04

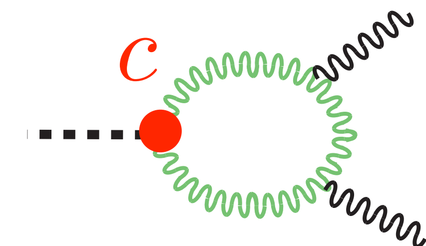
3 parameters

$$a = \sqrt{1 - v^2/f^2} \qquad b = 1 - 2v^2/f^2$$ model independent

$$c,\ d_3 \ = \ 1 + O(v^2/f^2)$$ model dependent




$$c_g,\ c_\gamma \ \sim \ \frac{\alpha_t}{4\pi}$$ controlled by small explicit SO(5) breaking
NEGLIGIBLE!




✦ Leading order in $v^2/f^2$ ➡ 3 independent effective operators

$$\mathcal{L}_{eff} = \frac{1}{2f^2}\partial^\mu \left(H^\dagger H\right) \partial_\mu \left(H^\dagger H\right) + y\left(\frac{c_y}{f^2} H^\dagger H\, \bar{\psi}_L H \psi_R + \text{h.c.}\right) - \frac{c_6 \lambda}{f^2}\left(H^\dagger H\right)^3$$

$$a = 1 - \frac{1}{2}\frac{v^2}{f^2} \qquad b = 1 - 2c_H\frac{v^2}{f^2} \qquad c = 1 - \left(\frac{c_H}{2} + c_y\right)\frac{v^2}{f^2}$$

# Deviations in Higgs production and decay controlled by a and c

$$\frac{\Gamma(h \to gg)}{\Gamma(h \to gg)|_{SM}} = \frac{\Gamma(h \to f\bar{f})}{\Gamma(h \to f\bar{f})|_{SM}} = c^2 \qquad \frac{\Gamma(h \to VV)}{\Gamma(h \to VV)|_{SM}} = a^2$$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)|_{SM}} = a^2 \left[1 + R(1 - c/a)\right]^2 \sim a^2 \qquad R \sim 0.22 \div 0.28$$

- LHC with 300 fb$^{-1}$ sensitive to $\xi \equiv \frac{v^2}{f^2} \sim 0.1 - 0.4$
- In principle pseudo-Goldstone hypothesis can be tested by suitable ratios of rates
- A robust prediction of a large class of models is that all the couplings are reduced with respect to the SM

# Composite $h$ fails to fully unitarize VV scattering

Goldstone

$$\mathcal{A}(VV \to VV) = \frac{s}{v^2}(1 - a^2) = \frac{s}{f^2}$$

$$\mathcal{A}(VV \to hh) = \frac{s}{v^2}(a^2 - b) = \frac{s}{f^2}$$

I. strong VV scattering direct signal of Higgs compositeness

$$\sigma\left(pp \to V_L V_L' X\right) = \left(\frac{v^2}{f^2}\right)^2 \sigma\left(pp \to V_L V_L' X\right)_{\not{H}}$$

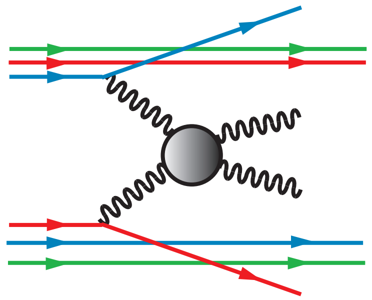
sensitivity with 300 $fb^{-1}$

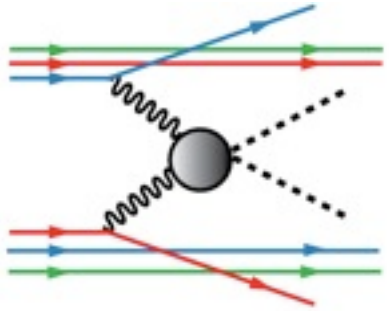
$$\frac{v^2}{f^2} = 0.5 - 0.7$$

Bagger et al., '95

II. Strong double Higgs production related to strong VV scattering by custodial O(4) symmetry

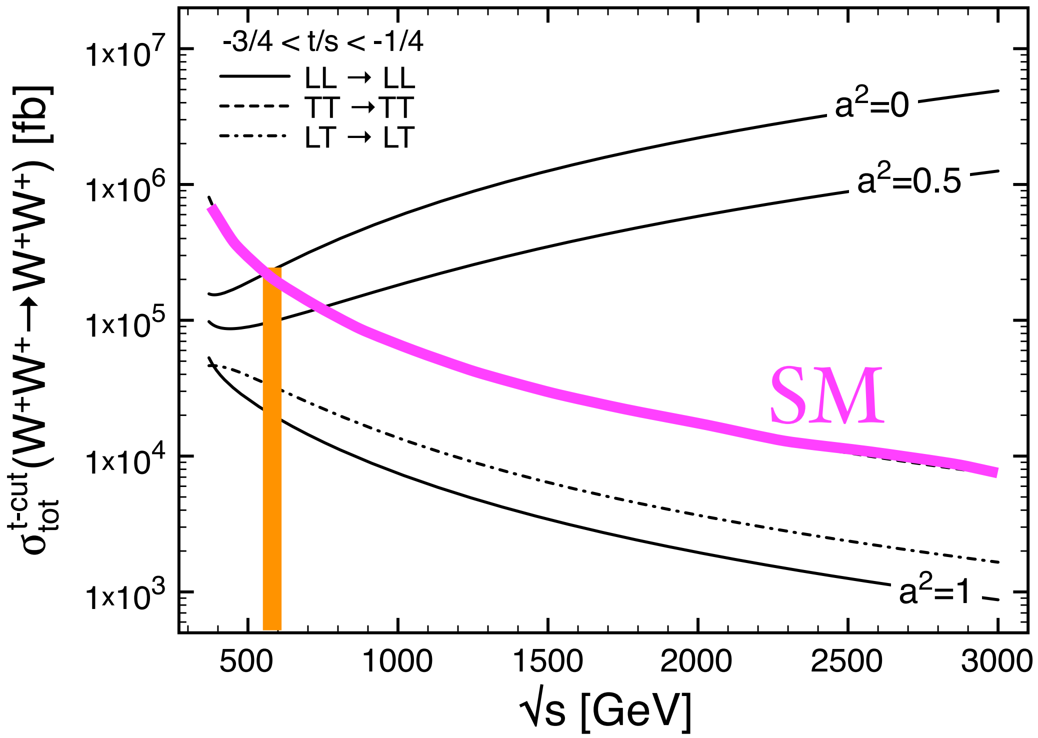
# VV ➔ VV versus VV ➔ hh

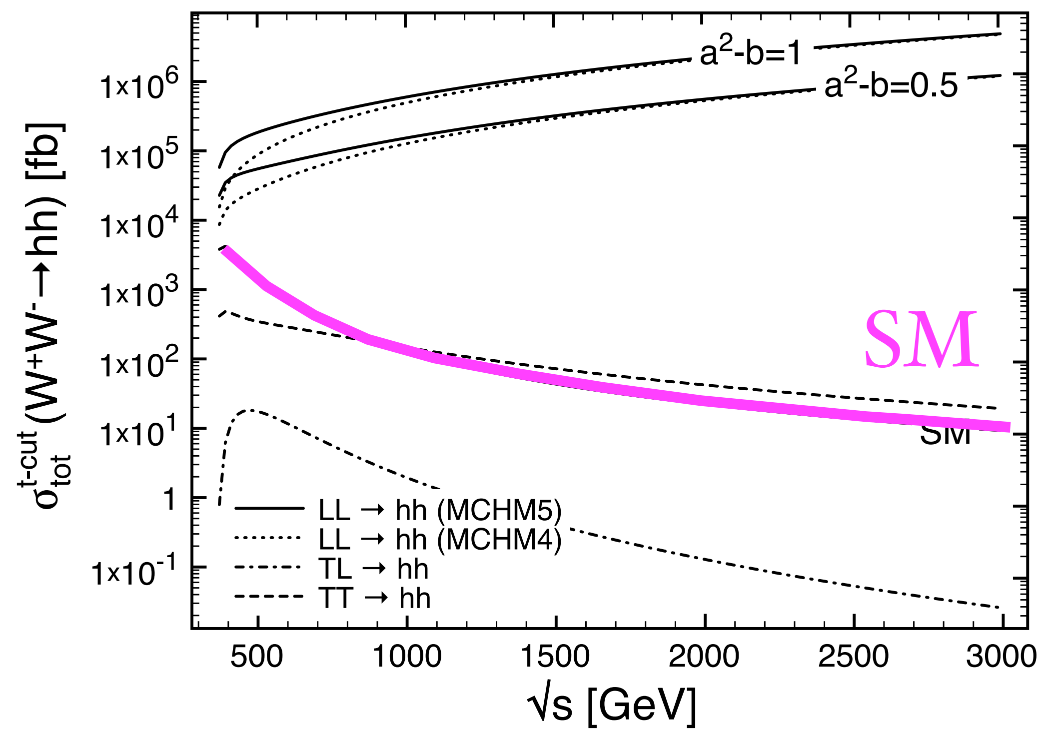




$$\mathcal{A}(VV \to VV) \simeq \frac{s}{v^2}(1 - a^2)$$

$$\mathcal{A}(VV \to hh) \simeq \frac{s}{v^2}(b - a^2)$$



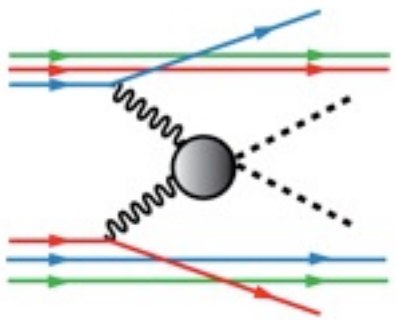

$$\sigma(V_T V_T \to V_T V_T)$$

large in SM by
'numerical accident'

$$\sigma(VV \to hh)$$

beats SM as expected
but final state
more difficult to detect

# VV➔ hh at the LHC



Contino, Grojean, Moretti, Piccinini, RR
arXiv:1002.1011

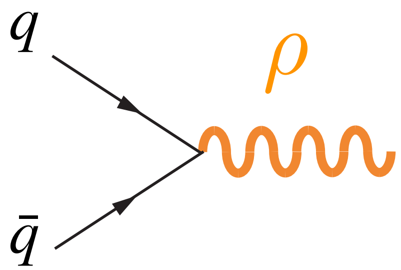
- $hh \rightarrow bbbb$ QCD background too big
- $hh \rightarrow 4W \rightarrow \text{leptons} + \text{jets} + \not{E}_T$ doable...

Visible signal for $\dfrac{v^2}{f^2} = 0.5$ at luminosity upgrade (not too encouraging)

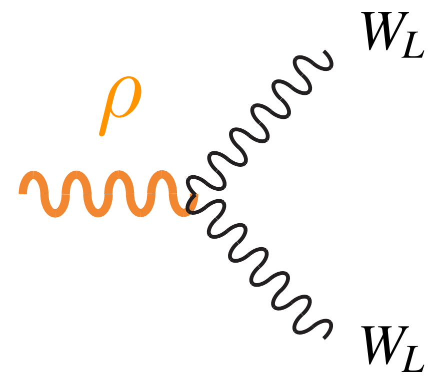
| Significance | | 3 leptons | 2 leptons |
|---|---|---|---|
| MCHM4 | $\xi = 1$ | 3.1 (10.3) | 3.2 (10.3) |
| | $\xi = 0.8$ | 2.1 (7.2) | 2.1 (6.9) |
| | $\xi = 0.5$ | 0.9 (3.4) | 1.0 (3.2) |
| MCHM5 | $\xi = 0.8$ | 2.5 (8.2) | 2.5 (8.2) |
| | $\xi = 0.5$ | 1.5 (5.3) | 1.6 (5.2) |

$3\ ab^{-1}$

# Vector resonances in WW channel: the $\rho$ (Not quite a Z' !!)




$$= \frac{g_W^2}{g_\rho} \ll g_W$$



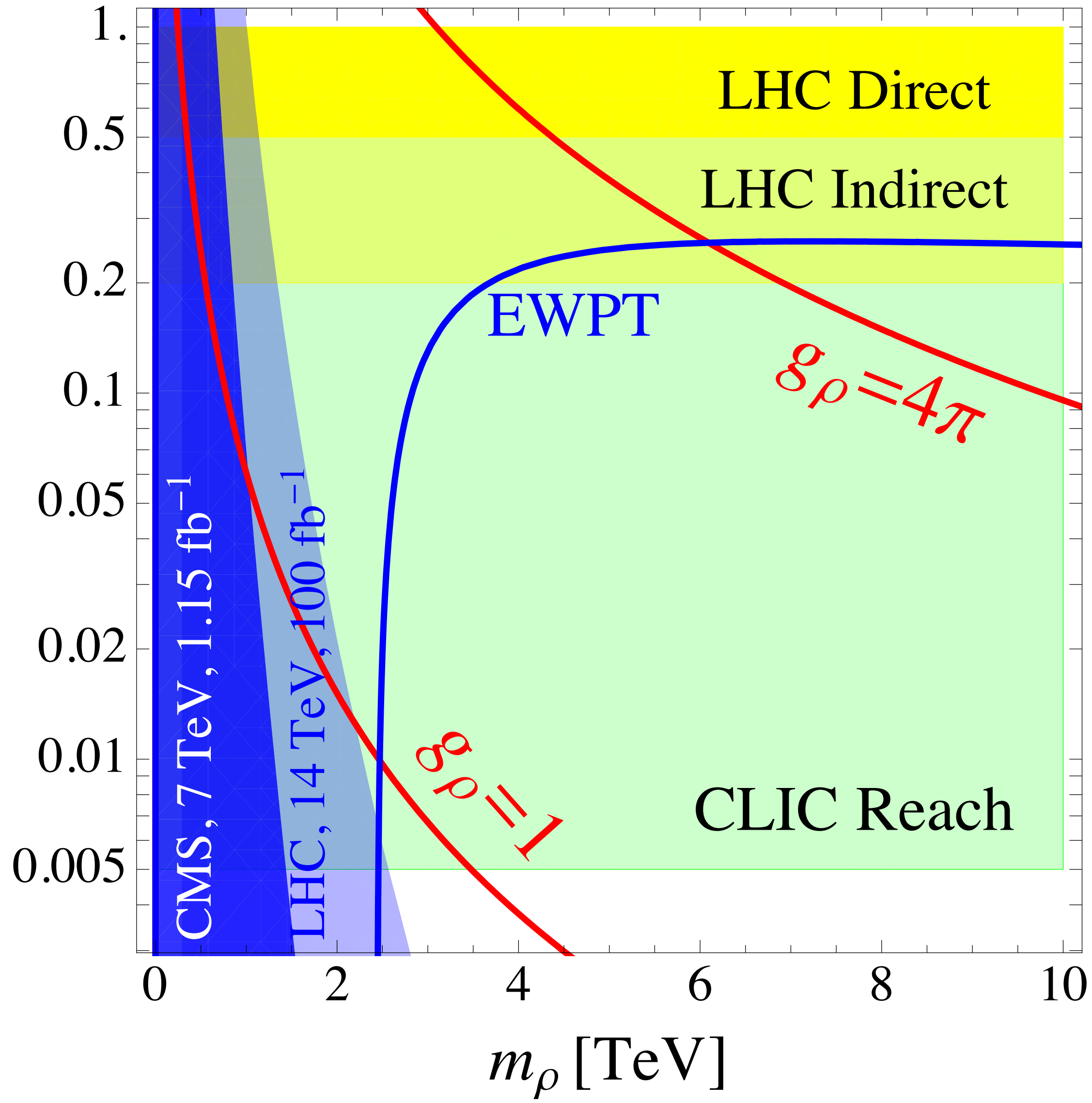

$$= g_\rho$$

$g_\rho$ large → resonances couple 'superweakly' to light fermions

$$\sigma\left(pp \to \rho_H^\pm + X\right) = \left(\frac{4\pi}{g_\rho}\right)^2 \left(\frac{3\ \mathrm{TeV}}{m_\rho}\right)^6 0.5\ \mathrm{fb}$$

resonances are increasingly harder to see as $g_\rho \to 4\pi$

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




$$m_\rho \sim g_\rho f$$

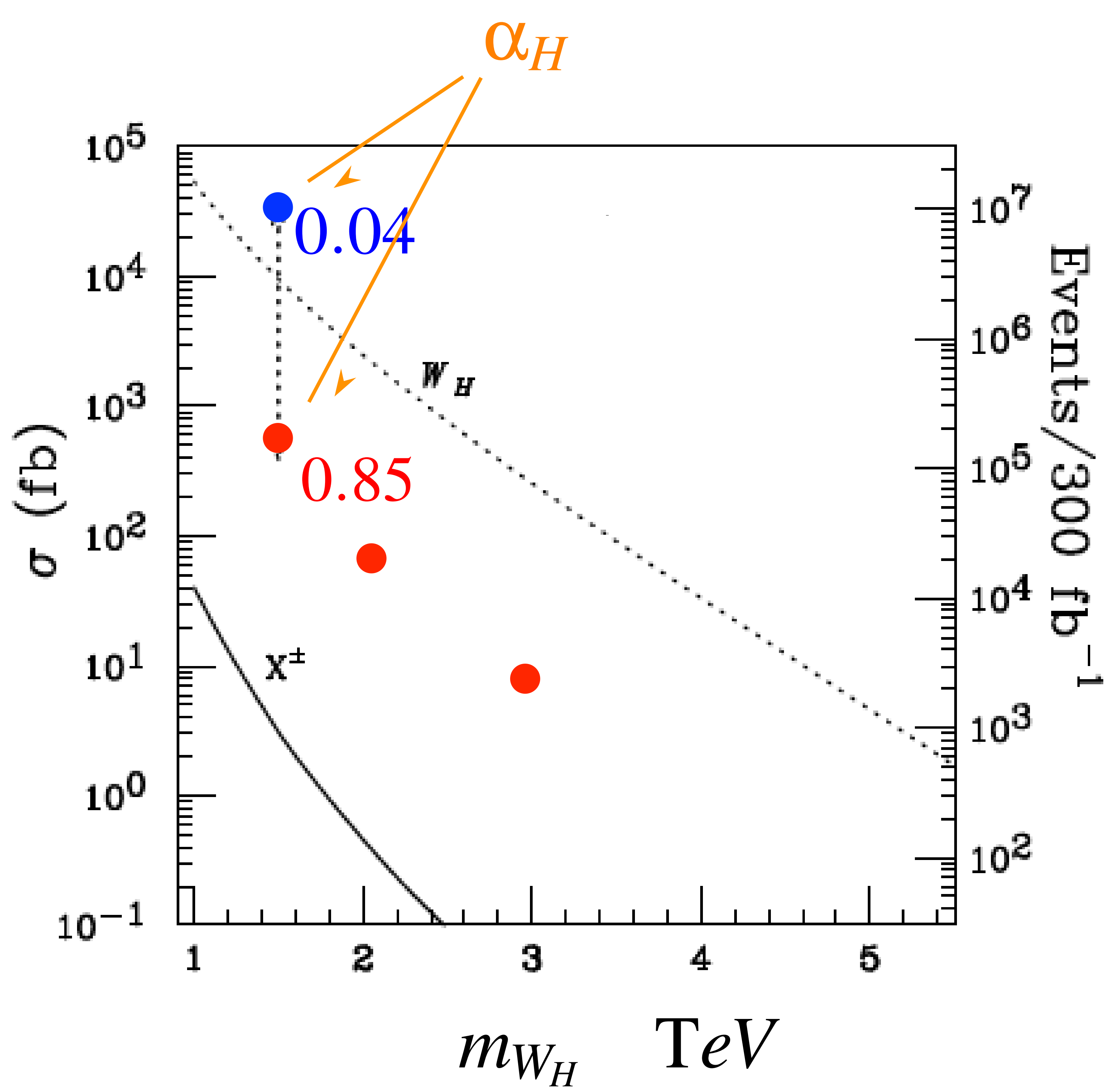
$\frac{v^2}{f^2} > 0.1$ LHC
- deviations from SM in Higgs couplings
- top partners

$\frac{v^2}{f^2} < 0.1$

LHC just top partners

CLIC Higgs couplings and WW➔ hh

LHC33TeV all the resonances



αH
0.04
0.85
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
σ (fb)
W H
X±
10^7
10^6
10^5
10^4
10^3
10^2
Events/300 fb^-1
1
2
3
4
5
mWH TeV