Higgs ?

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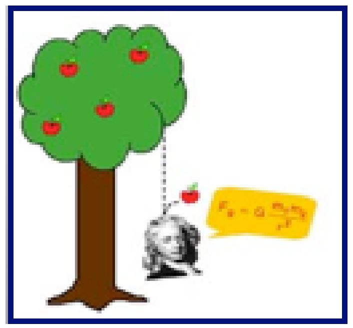
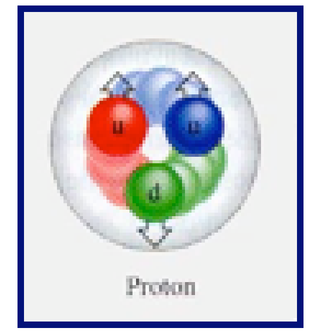
$m_W \neq 0$





$\boxed{?}$

New dynamics necessary for Electroweak Symmetry Breaking

Plausibly new 'principles' associated with it

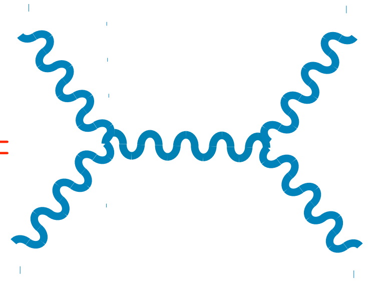
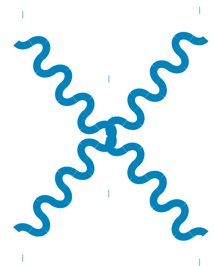
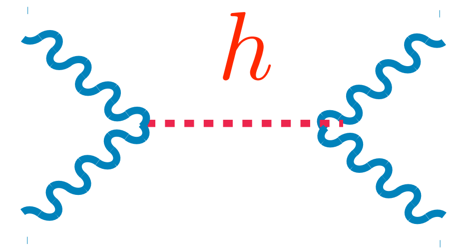
★ Supersymmetry
★ Large extra dimensions

Still worth asking the basic questions on $\boxed{?}$

Is the new dynamics weak or strong ?

in most regards equivalent to

Is there a light Higgs boson or not ?

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

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

strong < 2 TeV

weak up to
ultra-high scale

SM Higgs boson acts as a 'moderator' of the interaction strength

allows model to be extrapolated possibly down to Planck length

to achieve this amazing goal the couplings of the Higgs are extremely constrained and predicted in terms of just one parameter m_h

The Higgs is by all practical means an elementary particle

A beautiful theory with a beautiful problem

The hierarchy

Plausible that a light and narrow ‘Higgs-like’ light scalar exists
but as a bound state of a new strong force at around weak scale

Couplings will deviate from SM

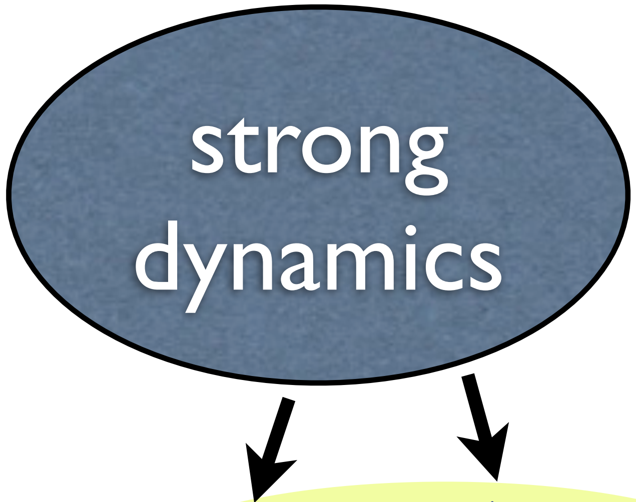
If deviations are observed the issue is to understand
the nature of the new dynamics and the role of the ‘Higgs’

Two examples

★ pseudo-Golstone Higgs (very well motivated)
★ light dilaton (possible)

Pseudo-Goldstone Higgs

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



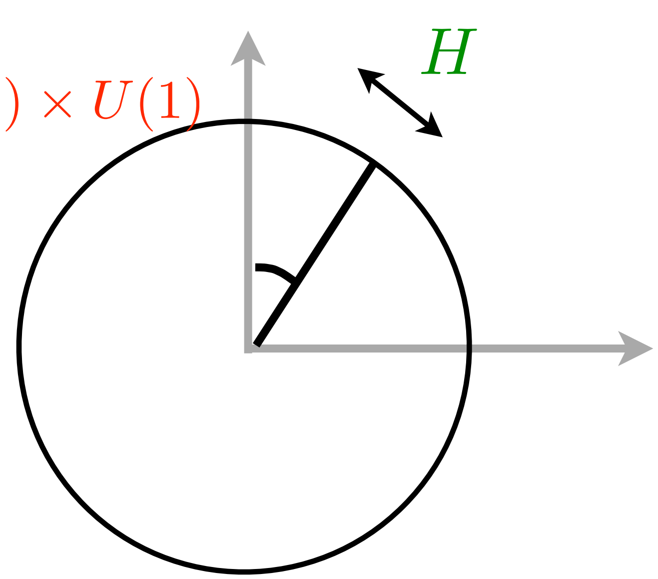
$$H = \quad h \qquad \pi^{\pm},\, \pi^{0} \;\subseteq\; \mathcal{G}/\mathcal{H}$$

- minimal example
  $H = SO(5)/SO(4)$

- technicolor $SU(2)_{TC}$ with 4 fermion doublets
  $H \subset SU(4)/Sp(4)$

$\langle H \rangle \equiv v$ from vacuum alignment in coset space controlled by small explicit breaking of $\mathcal{G}$

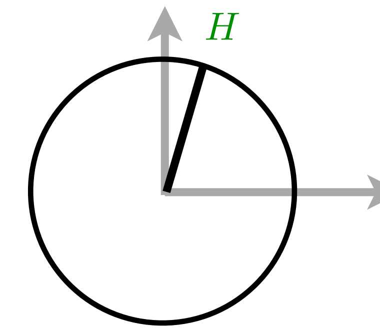
preserved $SU(2) \times U(1)$



$SU(2) \times U(1)$ broken

Conceivable to have v a bit smaller than Goldstone decay const. f

either by mild tuning or by Little Higgs mech



unwanted corrections to S,T,..etc suppressed with respect to technicolor

$$S = S_{TC} \times \frac{v^2}{f^2}$$

- In practice $\frac{v^2}{f^2} \equiv \xi \sim 0.3$ sufficient in explicit models
- but worth keeping a broader perspective $\xi \sim O(1)$

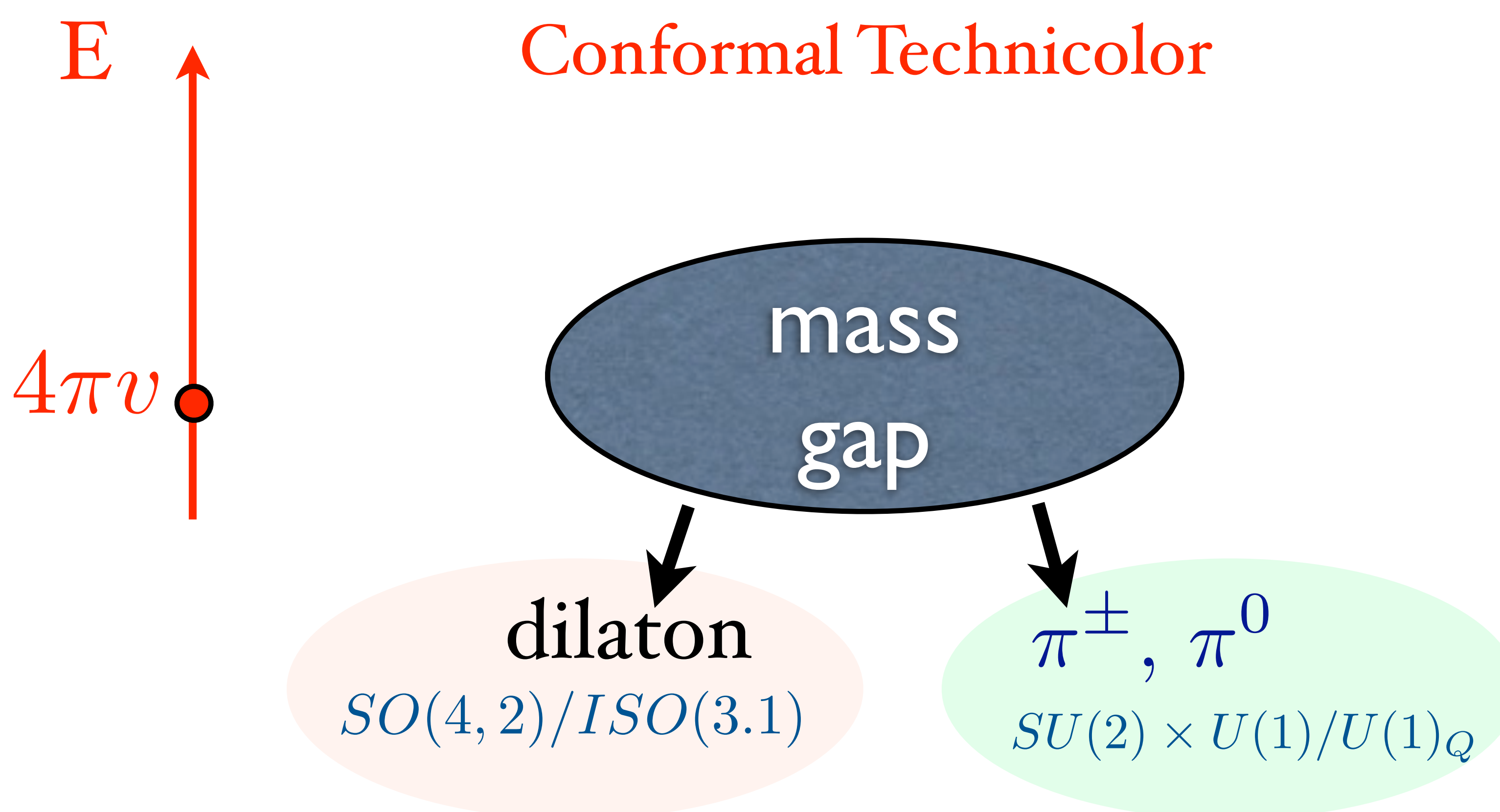
Compositeness scale $4\pi f$ still as low as a few TeV

Low energy phenomenology of pseudo-Goldstone Higgs
constrained by non-linearly realized $\mathcal{G}$
and by the structure of its explicit breaking

Giudice, Grojean, Pomarol, Rattazzi 07

Dilaton as Higgs look-alike

Goldberger, Grinstein, Skiba 07



- ✦ Does not immediately help with EWPT
- ✦ but dilaton intriguingly similar to a Higgs boson
- ✦ can indeed the dilaton be naturally light? $m_D \ll 4\pi v$

ordinary Goldstone	$\varphi(x) \to \varphi(x) + c$	$V(\varphi) = 0$
dilaton	$\varphi(x) \to \varphi(kx) + \ln k$	$V(\varphi) = V_0\, e^{4\varphi}$
canonical dilaton	$\chi \equiv f_D\, e^{\varphi}$	$V_0 \propto f_D^4$

Pattern of SO(4,2) breaking controlled by V_0

Fubini '76

$V_0 = 0$	$\langle\chi\rangle = f_D = \text{const}$	ISO(3,1) Poincaré-4
$V_0 > 0$	$\langle\chi\rangle \propto \frac{1}{z}$	SO(3,2) AdS4
$V_0 < 0$	$\langle\chi\rangle \propto \frac{1}{t}$	SO(4,1) dS4

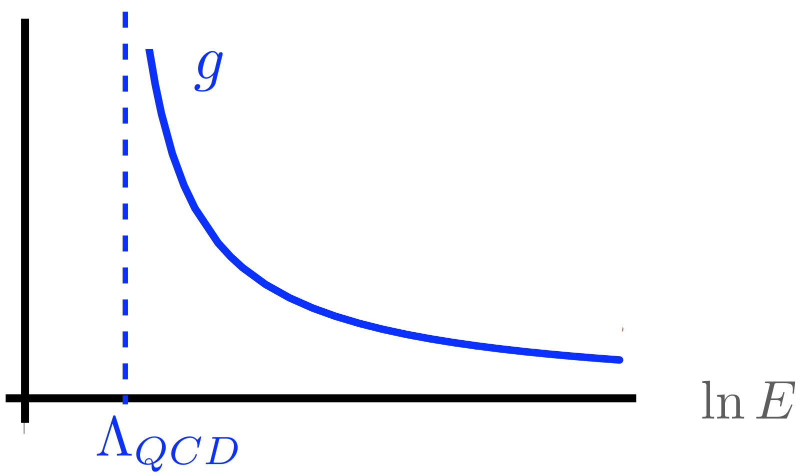
generically (without SUSY) spontaneous SO(4,2) ➔ ISO(3,1) not realized

Need explicit breaking of conformal invariance

$$\mu \frac{d}{d\mu} g \neq 0$$

A) QCD like: no dilaton

$$m_D \sim \Gamma_D \sim \Lambda_{QCD}$$

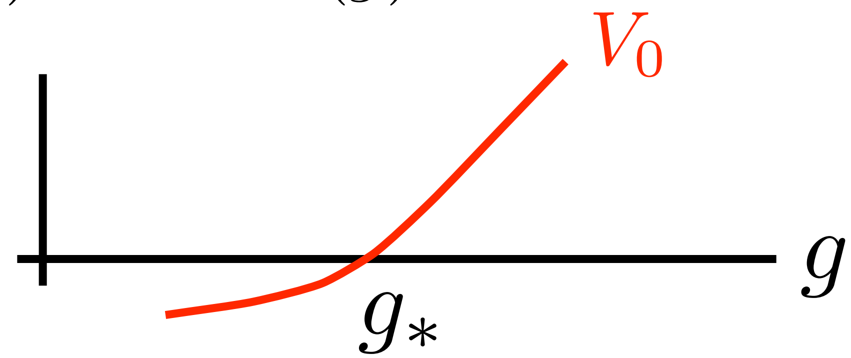


B) naturally light dilaton

discussion with
Contino, Katz, Pomarol

- imagine g exactly marginal $V(\varphi) = e^{4\varphi} V_0(g)$

- generically $\exists$ $V_0(g_*) = 0$



- imagine g acquires small dimension ε over all marginality surface

- scale invariance $V \to e^{4\varphi} V_0(g e^{\epsilon\varphi})$

- relaxation mechanism $g(\varphi) \equiv g e^{\epsilon\varphi} \longrightarrow g_*$ at minimum

$$m_\varphi^2 = O(\epsilon)$$

+ definite prediction for cubic coupling

Dual realization of light dilaton in Randall-Sundrum

Golberger, Wise '99
Rattazzi, Zaffaroni '00

CFT4		AdS5	
g	$\longleftrightarrow$	π	bulk Goldstone boson
$V_0(g)$	$\longleftrightarrow$	$\tau(\pi)$	IR brane tension
dilaton	$\longleftrightarrow$	radion	

General parametrization of *Higgslike* scalar

Contino, Grojean, Moretti, Piccinini, RR '10

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

c flavor universal in minimal flavor violating set up

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

$$\mathcal{A}(VV \to VV) \simeq \frac{s}{v^2}(1 - a^2) \qquad \mathcal{A}(VV \to hh) \simeq \frac{s}{v^2}(b - a^2) \qquad \mathcal{A}(VV \to \psi\bar{\psi}) \simeq \frac{m_\psi\sqrt{s}}{v^2}(1 - ac)$$

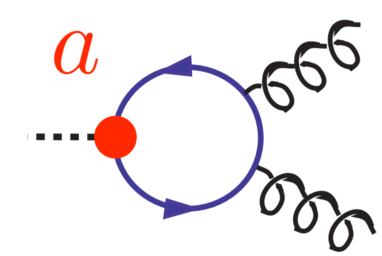
$SO(5)/SO(4)$ Pseudo-Goldstone Higgs

Agashe, Contino, Pomarol '04

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

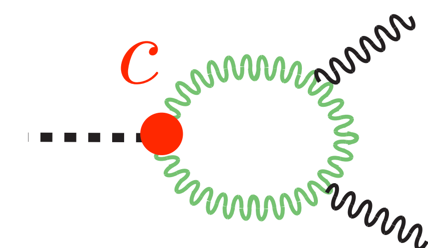
$c = d_3 = \sqrt{1 - v^2/f^2}$ fermions in **4**

$c = d_3 = \dfrac{1 - 2v^2/f^2}{\sqrt{1 - v^2/f^2}}$ fermions in **5**



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

NEGLIGIBLE!



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

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

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

Notice $\boxed{0 < a < 1}$ from group compactness

$b,\ c < 1$ for preferred (small) values of v^2/f^2

$0 < a,\ b,\ c\ < 1$

persists in all Little Higgs models, even though σ-model structure destroyed by exchange of heavy vectors and scalars

Low, RR, Vichi 09

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 10-40% effects

In principle pseudo-Goldstone hypothesis can be tested by suitable ratios of rates

VV scattering relevant with composite light Higgs

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

sensitivity with 300 fb^{-1}

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

Bagger et al., '95

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

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

Dilaton case

Goldberger, Grinstein, Skiba 07
Vecchi, to appear

3 parameters
$$\begin{cases} a = \sqrt{b} = c = \dfrac{v}{f_D} \\ d_3 = \dfrac{5}{3}\dfrac{v}{f_D} + O(\epsilon) \\ c_g,\, c_\gamma = O(v/f_D) \end{cases}$$

$$a,\, b,\, c \lesseqgtr 1$$

$$\frac{\Gamma(h\to VV)}{\Gamma(h\to f\bar{f})} = \frac{\Gamma(h\to VV)|_{SM}}{\Gamma(h\to f\bar{f})|_{SM}}$$

$$\frac{\Gamma(h\to VV)}{\Gamma(h\to \gamma\gamma)}\frac{\Gamma(h\to \gamma\gamma)|_{SM}}{\Gamma(h\to VV)|_{SM}} = a^2/(1+\#c_\gamma)^2 \not\simeq 1$$

different pattern
than pseudo-Goldstone

$$\mathcal{A}(VV\to VV) = s\left(\frac{1}{v^2} - \frac{1}{f_D^2}\right)$$

VV scattering affected

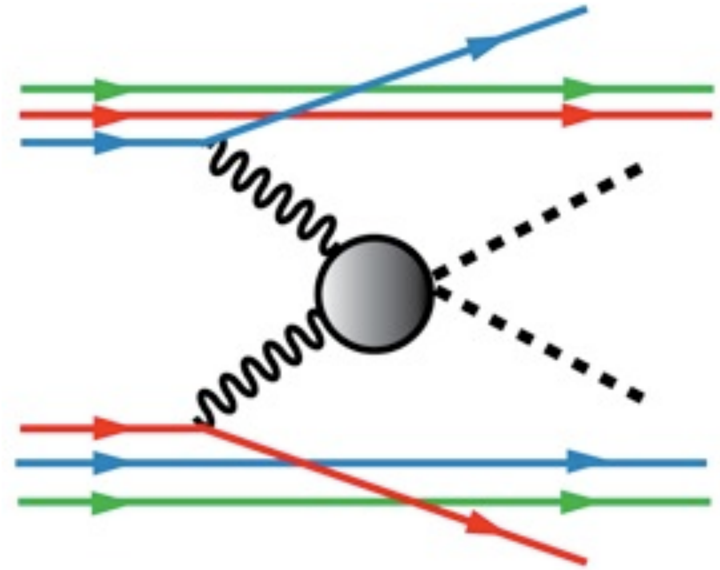
$$a^2 - b = 0$$

$$\boxed{\mathcal{A}(VV\to hh) \sim \text{const}}$$

crucial difference !!

$VV \rightarrow hh$ at the LHC

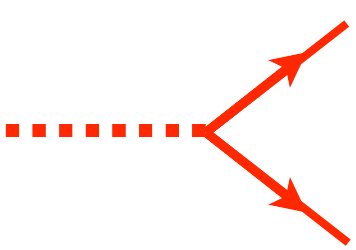
Contino, Grojean, Moretti, Piccinini, RR
in preparation



- $hh \rightarrow bbbb$ QCD background too big

- $hh \rightarrow 4W \rightarrow \text{leptons} + \text{jets} + \not{E}_T$ doable...

- Notice that $h \rightarrow WW$ could also dominate for $m_h < 150\,\text{GeV}$



$$\propto \frac{1-2v^2/f^2}{\sqrt{1-v^2/f^2}}$$

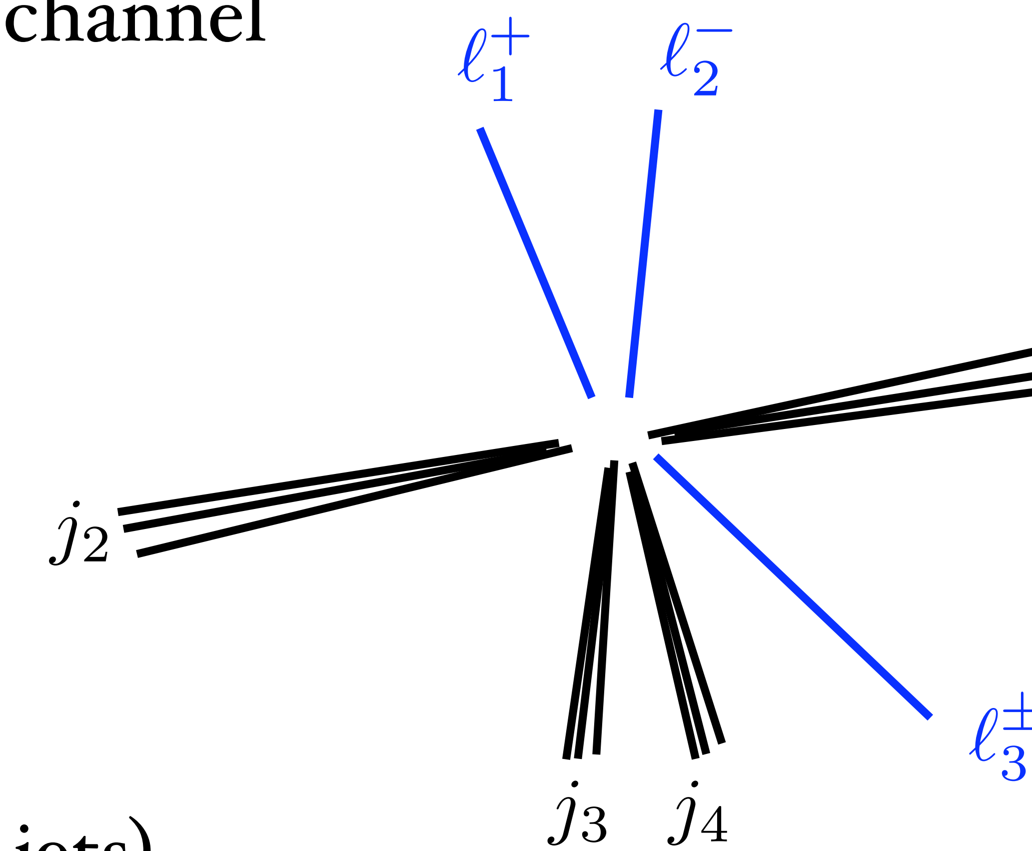
$h \rightarrow bb$ suppressed around $\frac{v^2}{f^2} = \frac{1}{2}$

Trilepton channel

$$pp \to hh\, j_1 j_2$$

$$\quad \hookrightarrow WW \to \ell_1^+ \ell_2^- + \nu\nu$$

$$\quad \hookrightarrow WW \to \ell_3^\pm + \nu + j_3 j_4$$



- ✦ 2 energetic forward jets (reference jets)
- ✦ 4W in central region due to s-wave
- ✦ $\ell_1^+ \ell_2^-$ $\sim$ aligned because of boost and helicity conservation

Signal: $\ell^+ \ell^- \ell^\pm + (j \geq 4)$

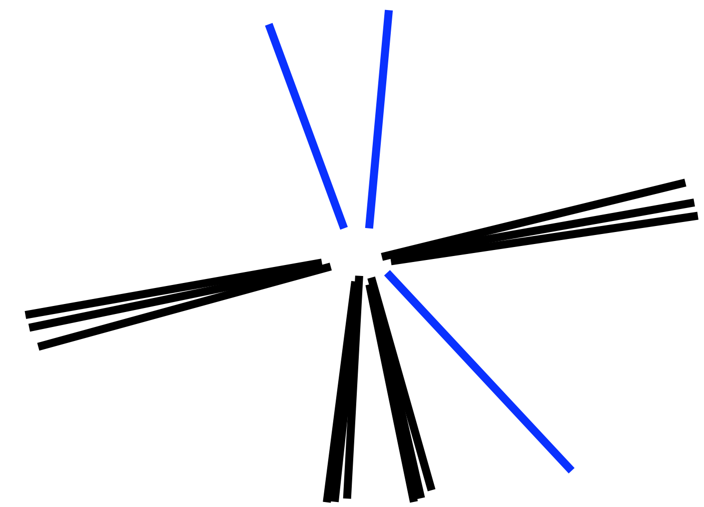
In analysis we define

$\lvert \eta_{j_1} \rvert$	largest
$m_{j_1 j_2}$	largest
$m_{\ell_1^+ \ell_2^-}$	smallest

$m_h \; = \; 180\,\mathrm{GeV}$ *ab*

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

Channel	σ_1	σ_2	σ_3
$\mathcal{S}_3$ ($\xi = 1$)	30.4	27.7	16.4
$\mathcal{S}_3$ ($\xi = 0.8$)	20.4	18.7	11.0
$\mathcal{S}_3$ ($\xi = 0.5$)	9.45	8.64	5.14
$\mathcal{S}_3$ ($\xi = 0$)	1.73	1.34	0.73
Wl^+l^-4j	12.0×10^3	658	2.47
Wl^+l^-5j	3.83×10^3	16.6	0.00
$hl^+l^-jj \to WWl^+l^-jj$	102	29.7	0.49
$WWW4j$	86.2	3.47	0.23
$t\bar{t}Wjj$	408	11.3	0.37
$t\bar{t}Wjjj$	287	2.40	0.09
$t\bar{t}WW$	315	4.48	0.02
$t\bar{t}WWj$	817	28.1	0.89
$t\bar{t}hjj \to t\bar{t}WWjj$	610	8.89	0.38
$t\bar{t}hjjj \to t\bar{t}WWjjj$	329	0.84	0.03
$W\tau^+\tau^-4j$	206	11.5	0.68
Total background	18.9×10^3	775	5.65



acceptance

master

$|\eta_{j_1}| \geq 1.8 \qquad m_{j_1 j_2} \geq 320\ \mathrm{GeV} \qquad |\eta_{j_1} - \eta_{j_2}| \geq 2.9$

$|m_{j_3 j_4} - m_W| \leq 40\ \mathrm{GeV} \qquad m^h_{l_1 l_2} \leq 110\ \mathrm{GeV} \qquad m^h_{j_3 j_4 l_3} \leq 210\ \mathrm{GeV}$

optimization

$m_{SF-OS} \geq 20\,\mathrm{GeV} \qquad |m_{SF-OS} - M_Z| \geq 7\,\Gamma_Z \qquad |m_{j_3 j_4} - m_W| \leq 20\ \mathrm{GeV}$

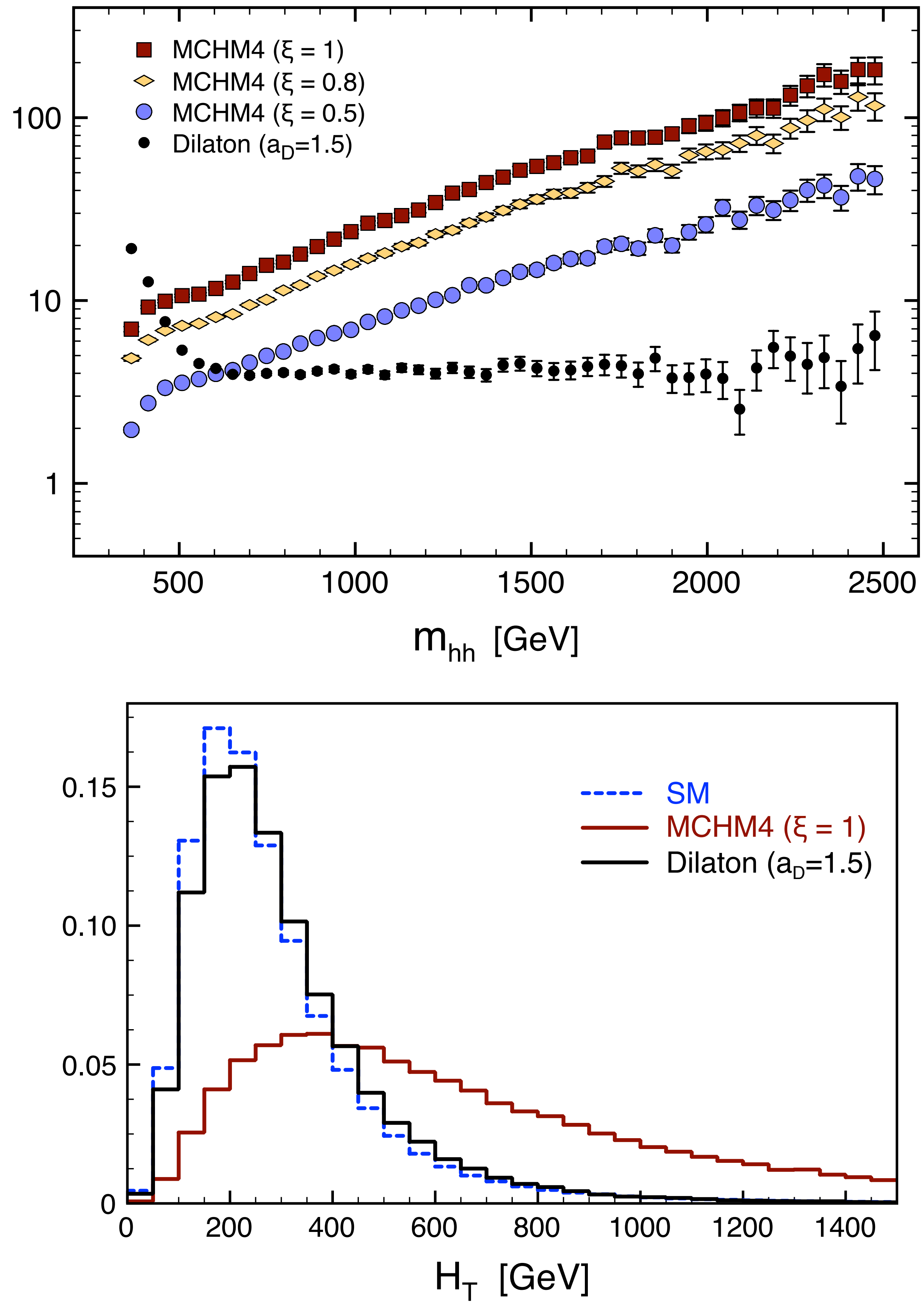
$|\eta_{j_1} - \eta_{j_2}| \geq 4.5 \qquad m_{j_1 j_2} \geq 700\,\mathrm{GeV} \qquad m^h_{j_3 j_4 l_3} \leq 160\,\mathrm{GeV}$

Events with 300 fb^{-1}		3 leptons signal	3 leptons bckg.	2 leptons signal	2 leptons bckg.
MCHM4	$\xi = 1$	4.9	1.1	15.0	16.6
	$\xi = 0.8$	3.3	1.2	10.1	18.3
	$\xi = 0.5$	1.5	1.4	4.9	21.0
MCHM5	$\xi = 0.8$	4.5	1.8	14.3	26.0
	$\xi = 0.5$	2.3	1.2	7.6	18.4
SM	$\xi = 0$	0.2	1.7	0.8	25.4

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)

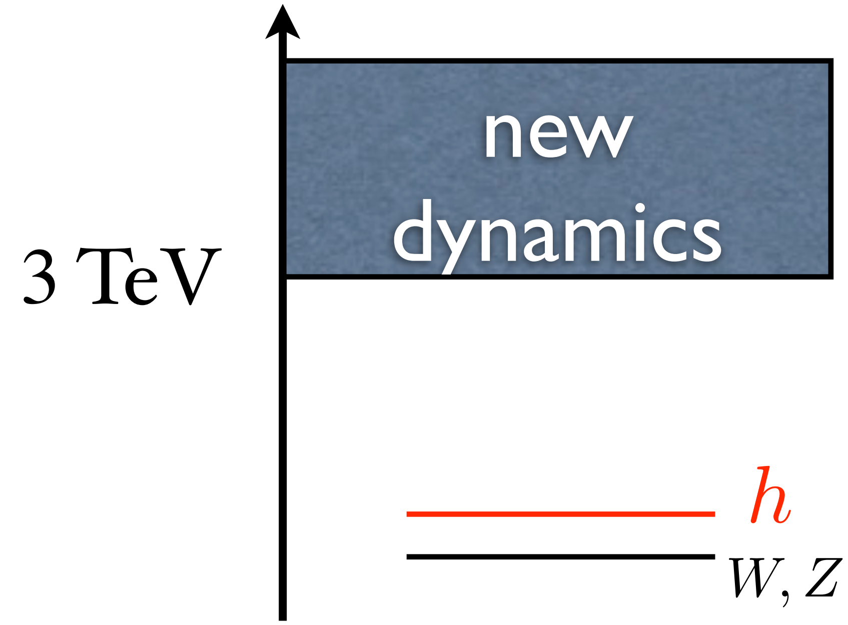
3 ab^{-1}

distinguishing dilaton and pseudo-Goldstone



Summary

A possible scenario at LHC



✦ pseudo-Goldstone Higgs or dilaton are possible SM-Higgs impostors

✦ symmetry constrains deviations from SM to depend on 2-3 parameters

✦ cases can, in principle, be distinguished by study of single Higgs production and decay

✦ LHC with 300 fb^{-1} indirectly sensitive up to compositeness scale $4\pi f \sim 5\,\mathrm{TeV}$

✦ Strong $VV \to VV$ genuine signal of h compositeness

✦ $VV \to hh$ distinguishes dilaton from Goldstone

these studies more realistically with 3 ab^{-1} unless $\dfrac{v^2}{f^2} \sim 1$

✦ Study of indirect signals of Higgs compositeness ideal at ILC $\sim$ Higgs factory

At ILC one would test $\dfrac{v^2}{f^2}$ at % level

Coupling	$M_H = 120$ GeV	140 GeV
g_{HWW}	$\pm$ 0.012	$\pm$ 0.020
g_{HZZ}	$\pm$ 0.012	$\pm$ 0.013
g_{Htt}	$\pm$ 0.030	$\pm$ 0.061
g_{Hbb}	$\pm$ 0.022	$\pm$ 0.022
g_{Hcc}	$\pm$ 0.037	$\pm$ 0.102
$g_{H\tau\tau}$	$\pm$ 0.033	$\pm$ 0.048
g_{HWW}/g_{HZZ}	$\pm$ 0.017	$\pm$ 0.024
g_{Htt}/g_{HWW}	$\pm$ 0.029	$\pm$ 0.052
g_{Hbb}/g_{HWW}	$\pm$ 0.012	$\pm$ 0.022
$g_{H\tau\tau}/g_{HWW}$	$\pm$ 0.033	$\pm$ 0.041
g_{Htt}/g_{Hbb}	$\pm$ 0.026	$\pm$ 0.057
g_{Hcc}/g_{Hbb}	$\pm$ 0.041	$\pm$ 0.100
$g_{H\tau\tau}/g_{Hbb}$	$\pm$ 0.027	$\pm$ 0.042

Barger, Han,Langacker,
McElrath,Zerwas 03

J.A. Aguilar Saavedra et al.
[ECFA/DESY LC Physics WG]

ILC can test Higgs compositeness up to $4\pi f$ around 30 TeV