EWSB sector of Higgs-less and Composite Higgs models

Slava Rychkov

(Univ. Pierre et Marie Curie &
École Normale Supérieure, Paris)

Some contributors (surely forgot someone, sorry)

Weinberg; Susskind; Appelquist; CCWZ; Casalbuoni, De Curtis, Dominici, Dolce; Bagger et al; Csaki, Grojean, Pilo, Terning; Barbieri, Rattazzi, Pomarol…

Giorgi, Kaplan, Dimopoulos, Banks, Arkani-Hamed, Cohen, Katz, Nelson, Nomura, Pomarol, Sundrum, Contino, Agashe, Da Rold, Luty, Rattazzi, Carena, Wagner, Santiago, Ponton…

Some contributors (surely forgot someone, sorry)

Weinberg; Susskind; Appelquist; CCWZ; Casalbuoni, De Curtis, Dominici, Dolce; Bagger et al; Csaki, Grojean, Pilo, Terning; Barbieri, Rattazzi, Pomarol…

Giorgi, Kaplan, Dimopoulos, Banks, Arkani-Hamed, Cohen, Katz, Nelson, Nomura, Pomarol, Sundrum, Contino, Agashe, Da Rold, Luty, Rattazzi, Carena, Wagner, Santiago, Ponton…

Disclaimer

-no (warped) extra dimensions

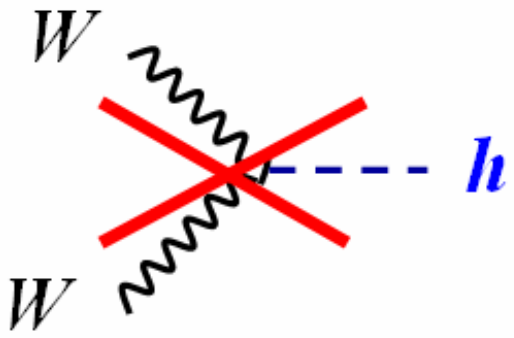
-no Little Higgs

Terminology

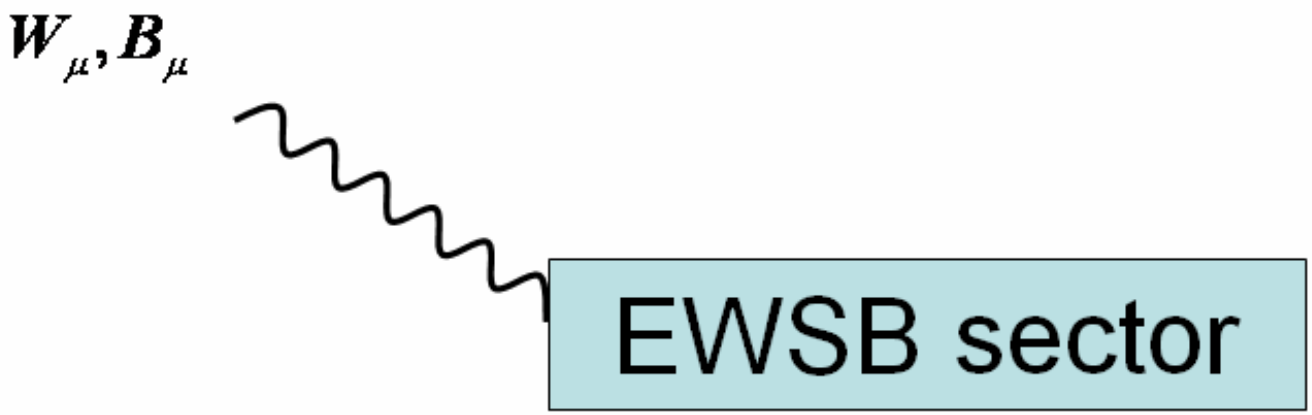
- *Higgs-less* models

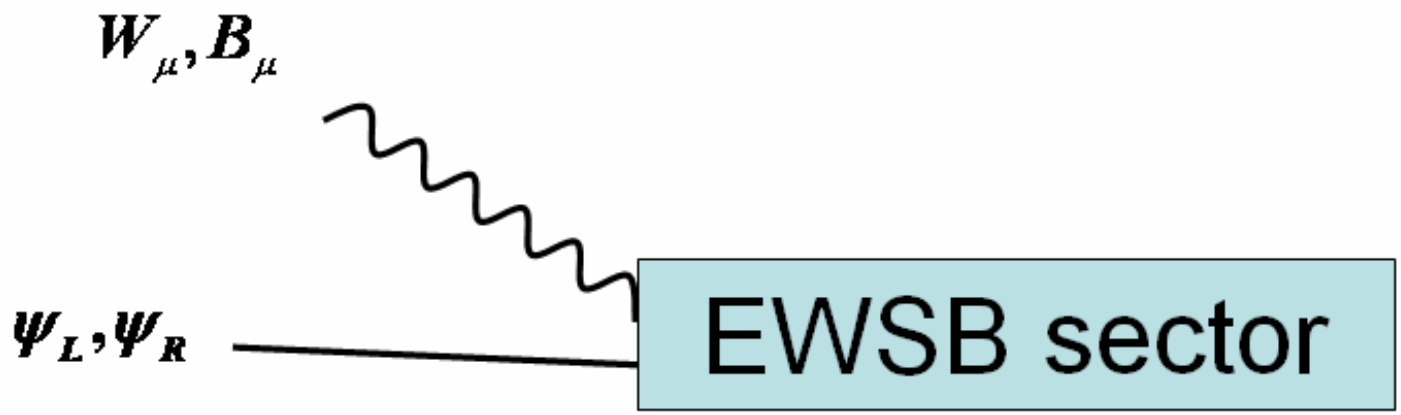
  = models without Higgs boson

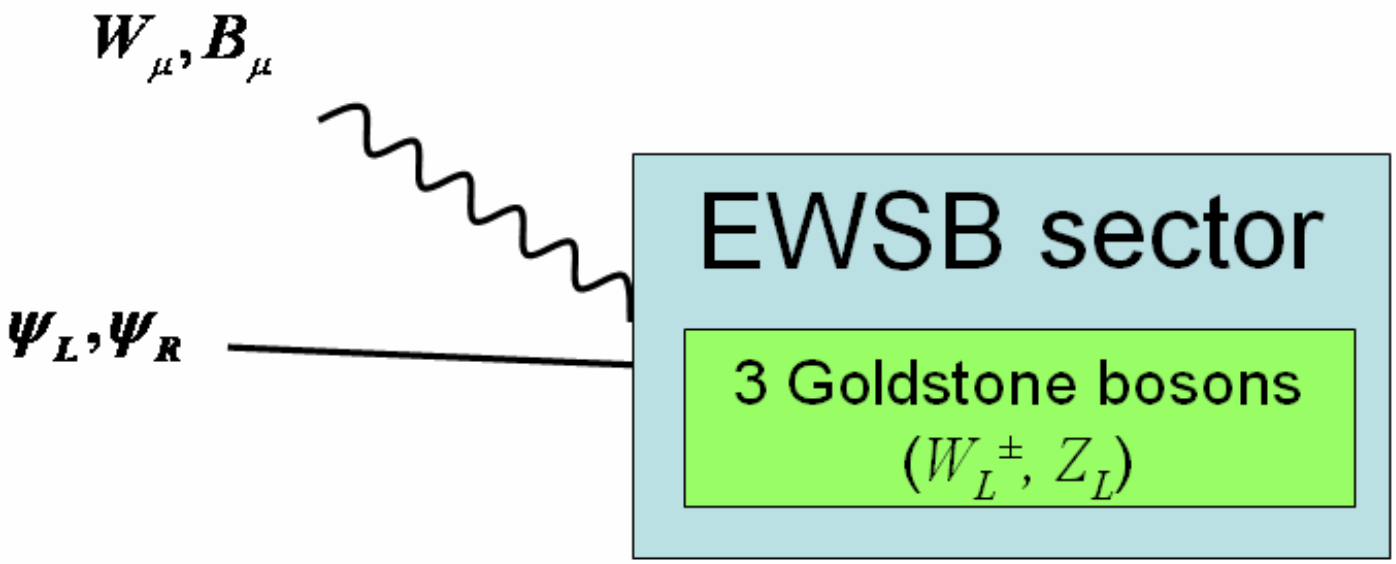
i.e. no CP-even scalar
with significant coupling to WW

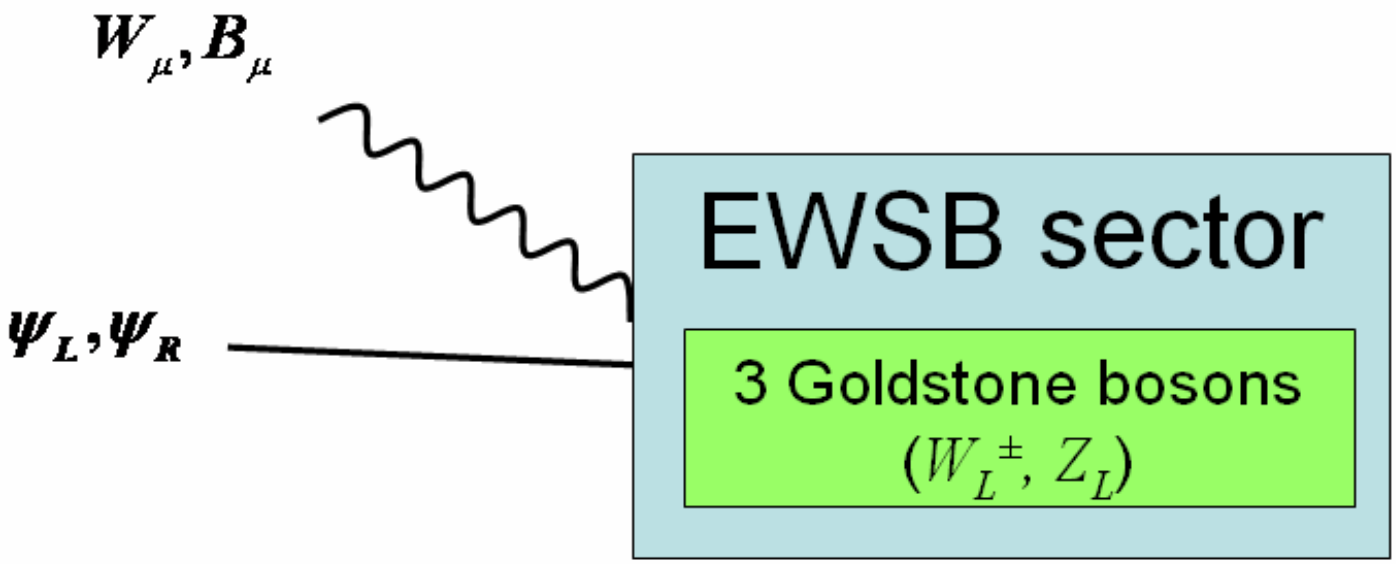


EWSB sector


W_μ, B_μ
EWSB sector


W_μ, B_μ
ψ_L, ψ_R
EWSB sector


W_μ, B_μ
ψ_L, ψ_R
EWSB sector
3 Goldstone bosons
$(W_L^{\pm}, Z_L)$



Goldstones must be related by symmetry
(to explain ρ=1.00…)

⇒ Symmetry breaking pattern (at least)

$$SO(4) \to SO(3)$$

"custodial symmetry"

Minimal EWSB sector

(just Goldstones)

= nonlinear $SO(4)/SO(3)$ sigma-model for Goldstone interactions

$$\phi_1^{\,2} + \phi_2^{\,2} + \phi_3^{\,2} + \phi_4^{\,2} = v^2 \qquad v = 174\,\mathrm{GeV}$$

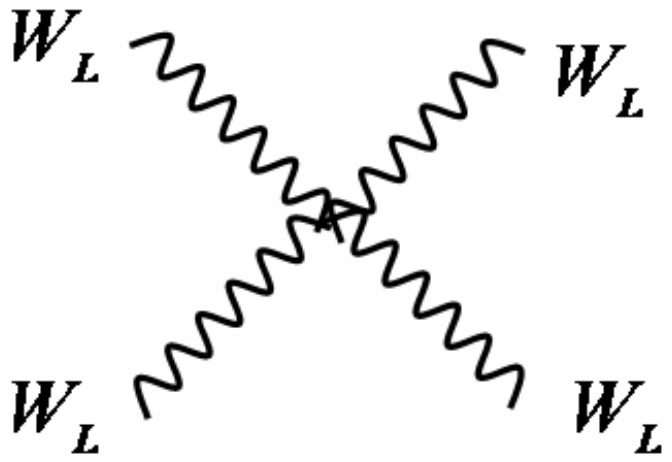
Minimal EWSB sector

(just Goldstones)

= nonlinear $SO(4)/SO(3)$ sigma-model for Goldstone interactions

$$\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 = v^2 \qquad v = 174\,\mathrm{GeV}$$

- not UV-complete
- $W_L W_L$ scattering violates perturbative unitarity:

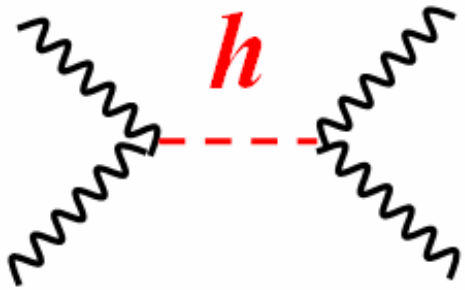


$$\sim \frac{s}{v^2}$$

SM - weakly coupled UV-completion

$$L_{SM} = |\partial H|^2 + \lambda(|H|^2 - v^2)^2$$

- Just 1 extra scalar (Higgs boson)
- Unitarizes *WW* scattering



- Model valid up to arbitrary high energies
- Disfavored by naturalness

Technicolor – strongly coupled UV-completion

QCD-like scaled up to TeV:

$$L_{TC} = \frac{1}{g^2}(F^a_{\mu\nu})^2 + \sum_{i=1}^{N_f} \bar{\Psi}^i D \Psi^i$$

Technicolor – strongly coupled UV-completion

QCD-like scaled up to TeV:

number of new fermions feeling the technicolor force

$$L_{TC} = \frac{1}{g^2}(F^a_{\mu\nu})^2 + \sum_{i=1}^{N_f} \bar{\Psi}^i D \Psi^i$$

Technicolor – strongly coupled UV-completion

QCD-like scaled up to TeV:

number of new fermions feeling the technicolor force

$$L_{TC} = \frac{1}{g^2}(F^a_{\mu\nu})^2 + \sum_{i=1}^{N_f} \bar{\Psi}^i D \Psi^i$$

Chiral symmetry breaking: $SU(N_f) \times SU(N_f) \to SU(N_f)$

$$\cong SO(4) \to SO(3) \quad \text{for} \quad N_f = 2$$

Technicolor – strongly coupled UV-completion

QCD-like scaled up to TeV:

number of new fermions feeling the technicolor force

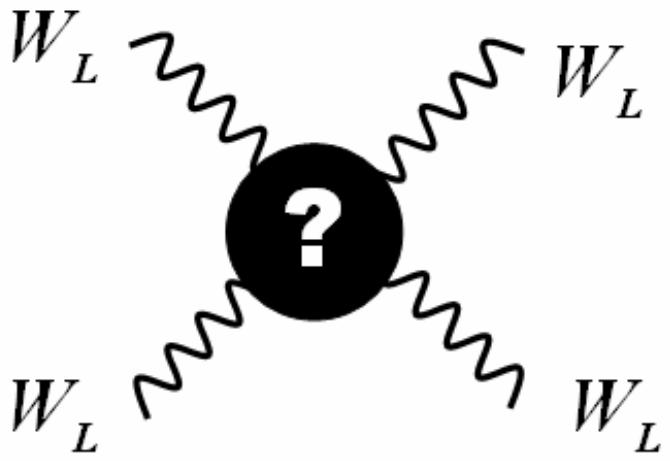
$$L_{TC} = \frac{1}{g^2}(F^a_{\mu\nu})^2 + \sum_{i=1}^{N_f} \bar{\Psi}^i D \Psi^i$$

Chiral symmetry breaking: $SU(N_f) \times SU(N_f) \to SU(N_f)$

$$\cong SO(4) \to SO(3) \quad \text{for} \quad N_f = 2$$

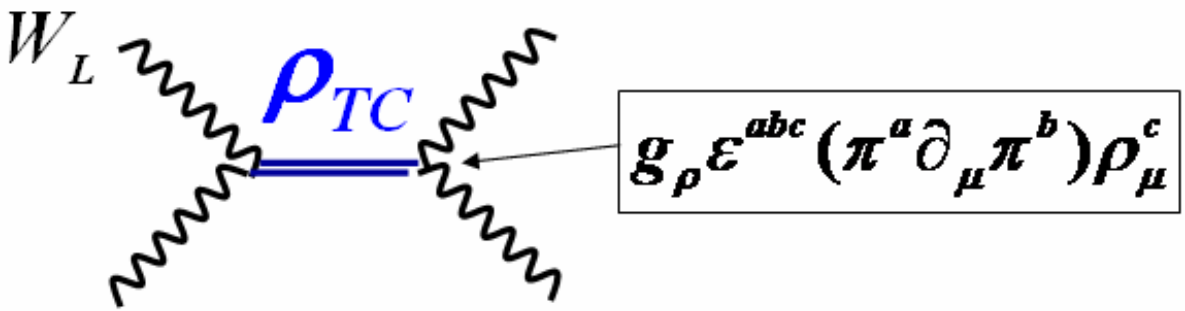
- EW scale neatly explained via dimensional transmutation
- no *a priori* reason to expect a light scalar resonance (thus Higgs-less)

A basic question



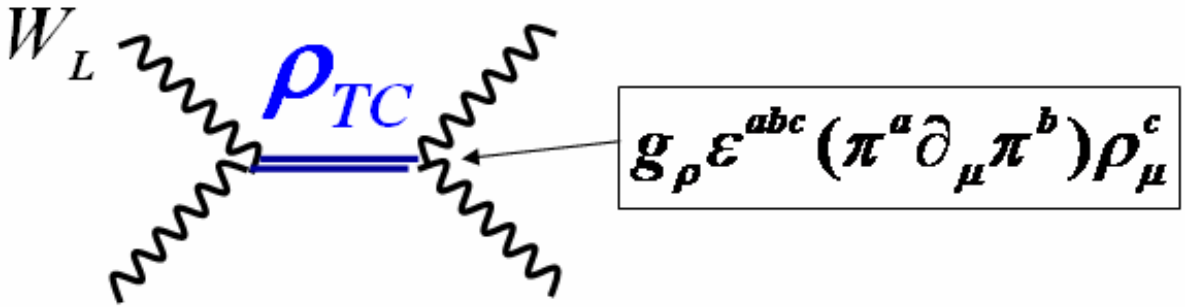
Who unitarizes the $W_L W_L$ scattering in Higgs-less models?

Heavy vector resonances (techni-rho)



- After scalar, the only other way to restore unitarity
  (however, not fully perfect)

Heavy vector resonances (techni-rho)

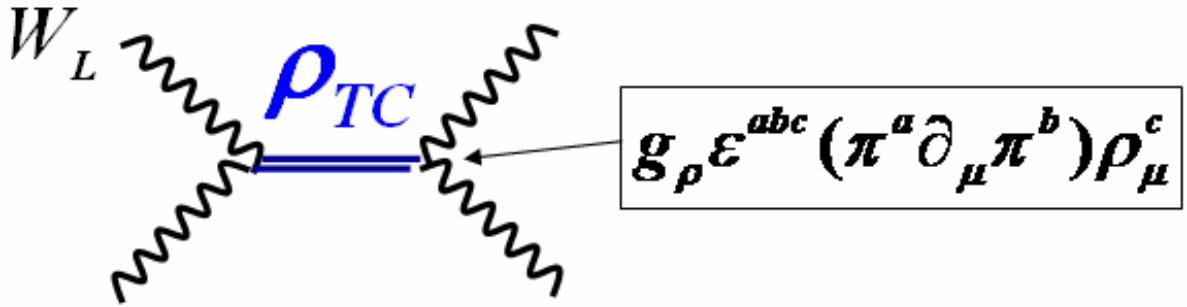


- After scalar, the only other way to restore unitarity (however, not fully perfect)
- mass, coupling, width relation:

$$M_\rho = 0.5 \div 2\ \text{TeV} \quad \leftrightarrow \quad g_\rho \quad \leftrightarrow \quad \Gamma(\rho \to \pi\pi) = 4\% \left(\frac{M_\rho}{\text{TeV}} \right)^2$$

50% for Higgs boson

Heavy vector resonances (techni-rho)

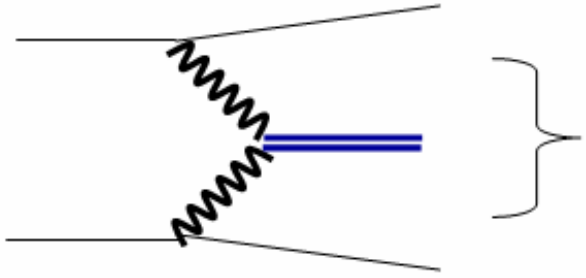


- After scalar, the only other way to restore unitarity (however, not fully perfect)
- mass, coupling, width relation:

$$M_\rho = 0.5 \div 2\ \text{TeV} \quad \leftrightarrow \quad g_\rho \quad \leftrightarrow \quad \Gamma(\rho \to \pi\pi) = 4\% \left(\frac{M_\rho}{\text{TeV}}\right)^2$$

50% for Higgs boson

- can be detected in VBF at $O(100)$ fb^{-1}



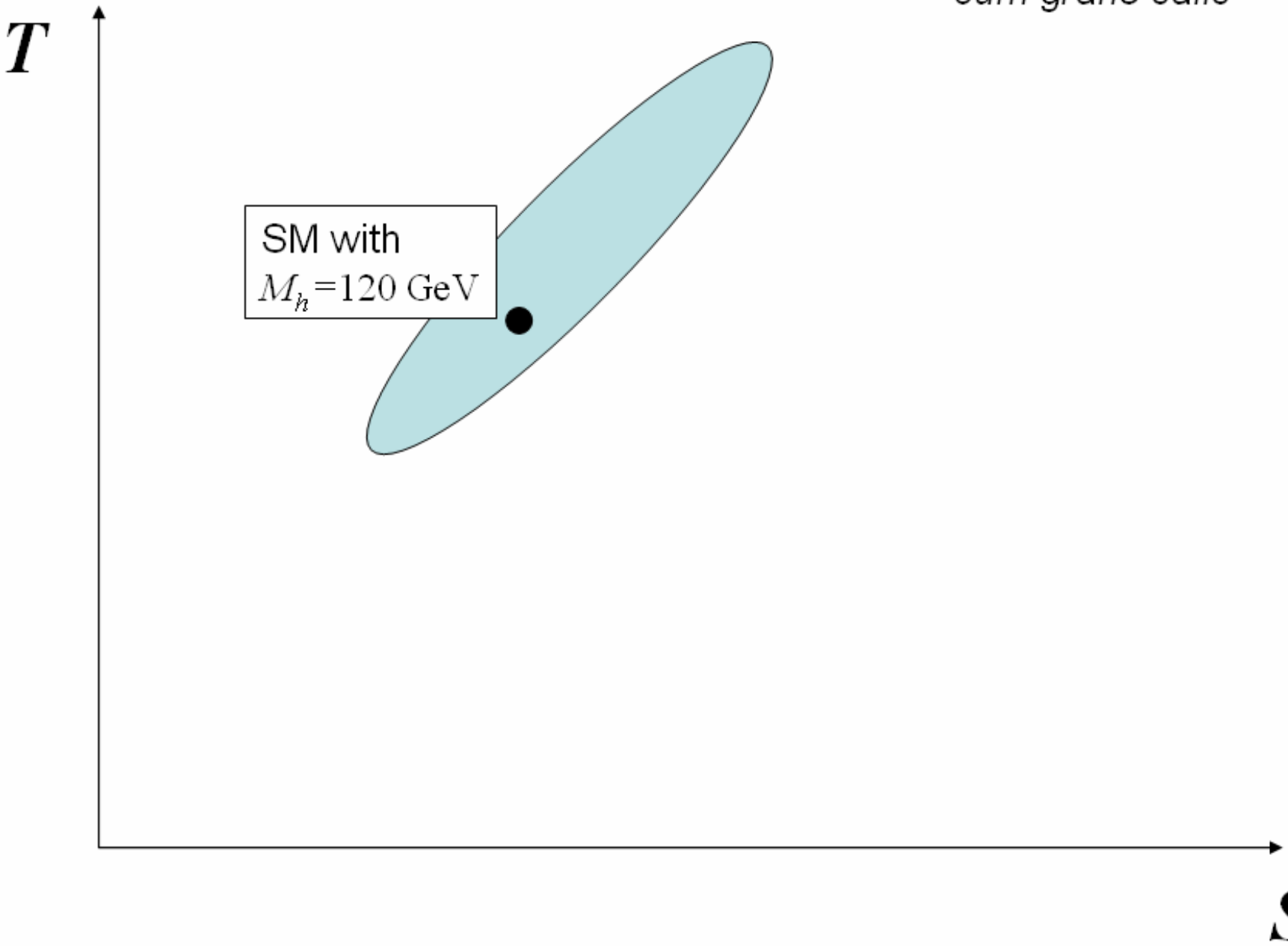
$\rho^+ \to WZ$

$\rho^0 \to W^+W^-$

unlike heavy Higgs, no ZZ decay

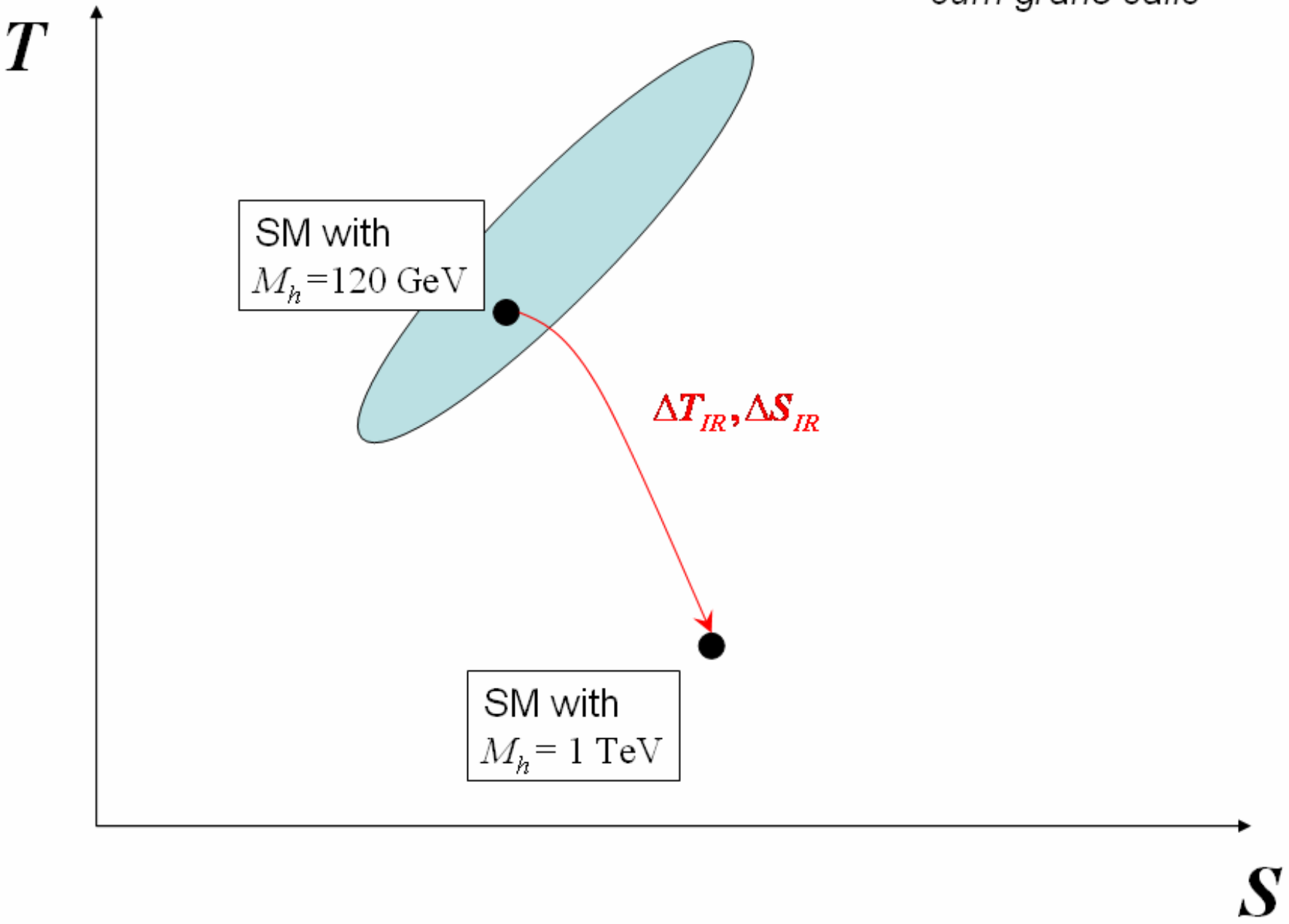
EW precision tests

cum grano salis



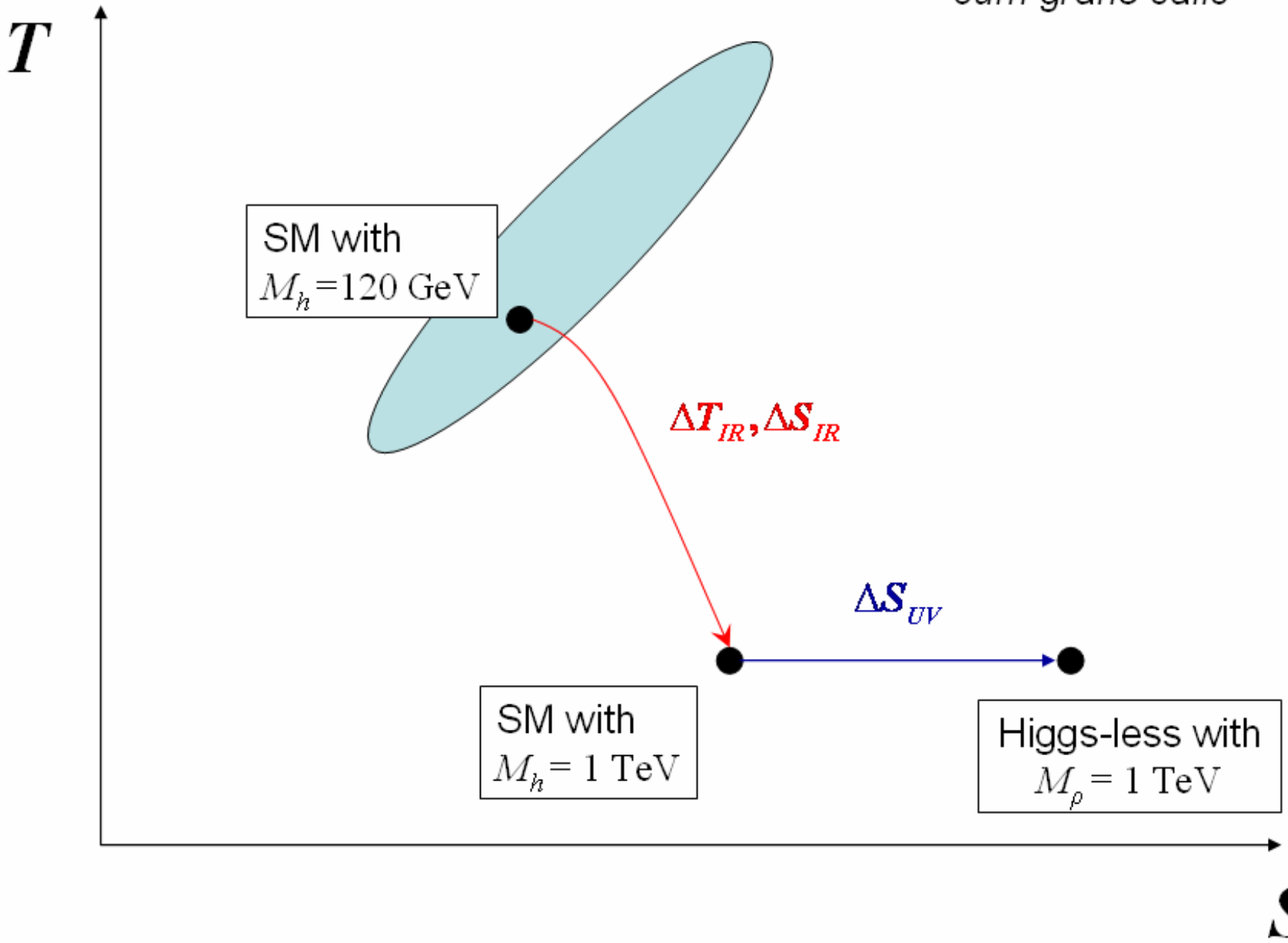
EW precision tests

cum grano salis



EW precision tests

cum grano salis

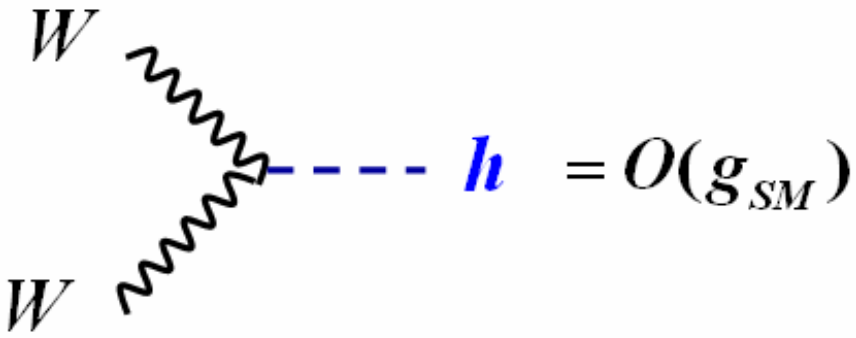


Terminology

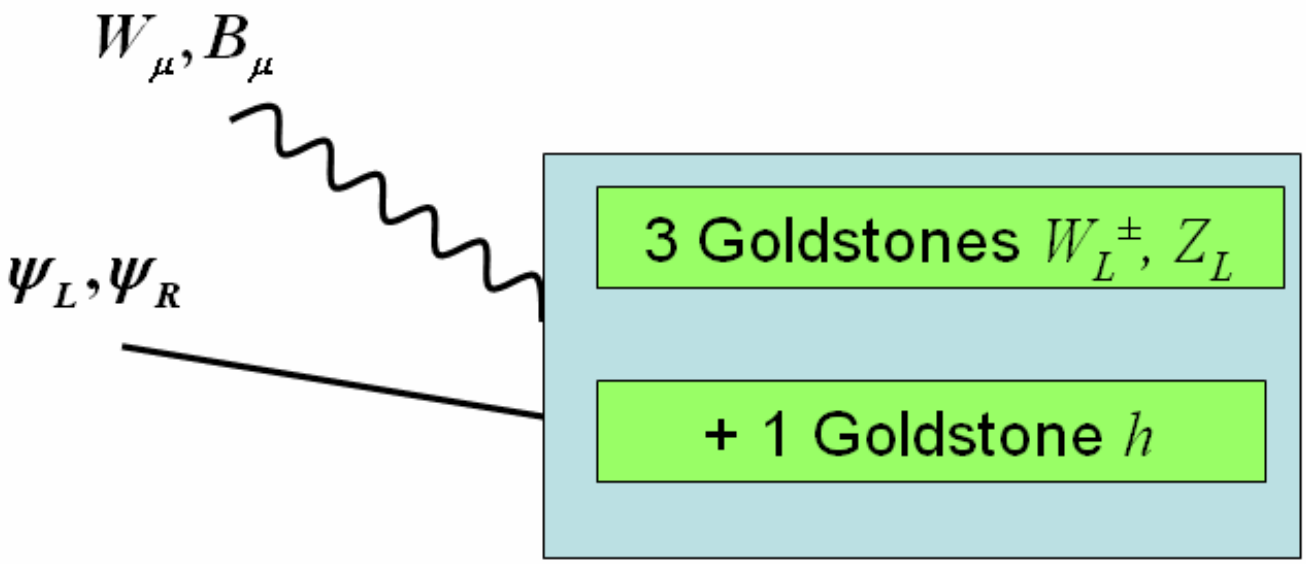
Composite Higgs model

= ‘pseudo-Goldstone Higgs’

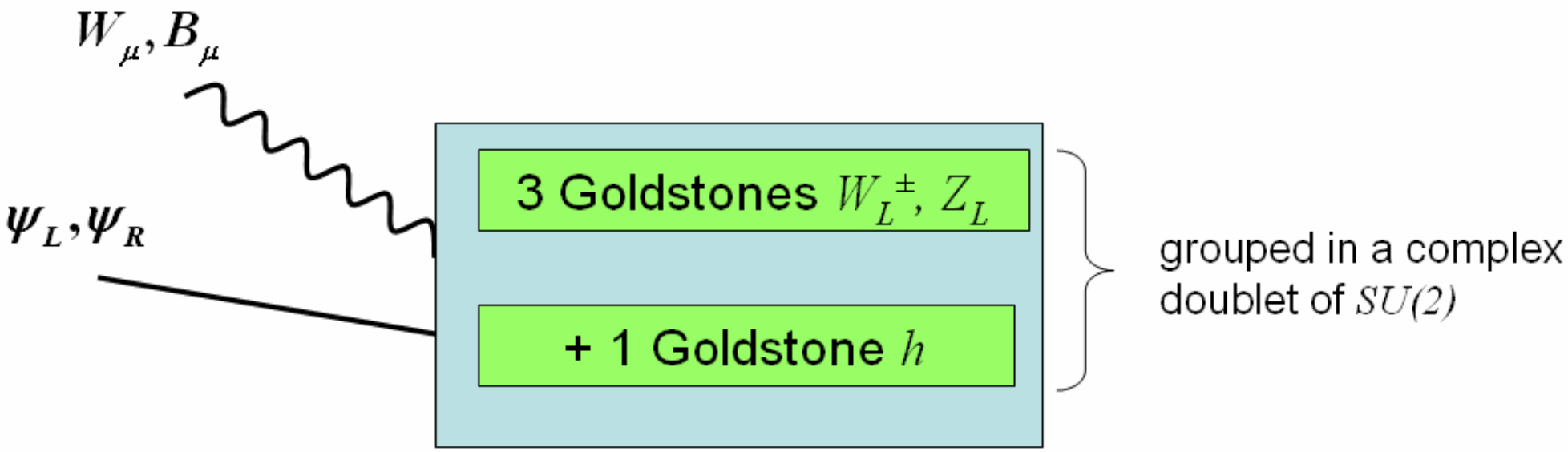
= light CP-even scalar with SM-like couplings, mass protected by (approximate) spontaneously broken global symmetry



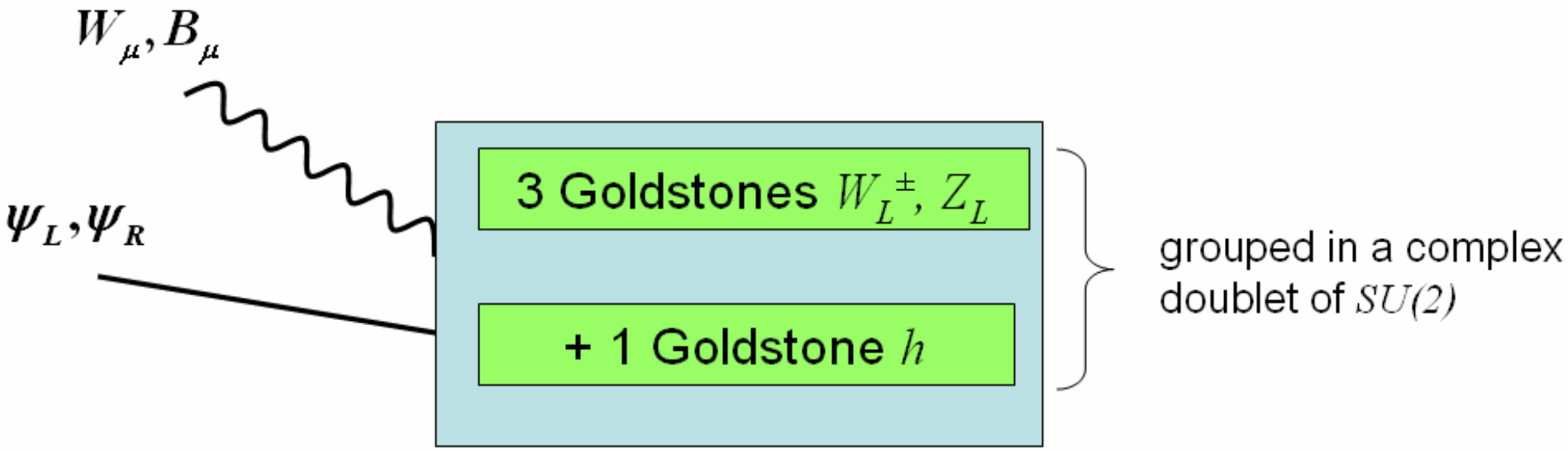
EWSB sector with composite Higgs



EWSB sector with composite Higgs

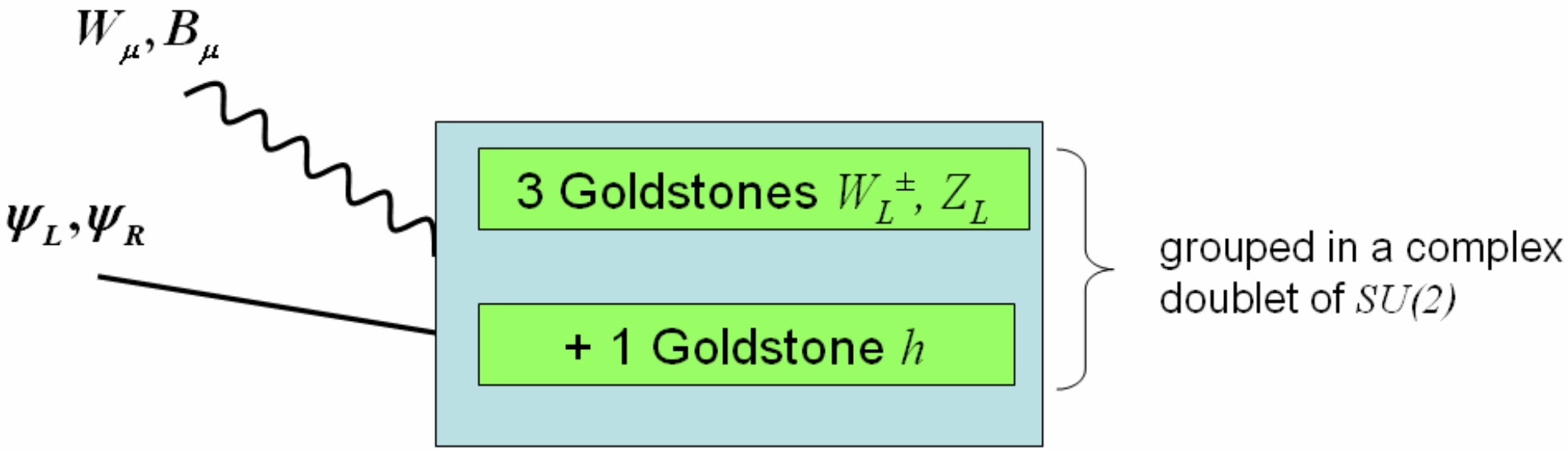


EWSB sector with composite Higgs



$\Rightarrow$ Symmetry breaking pattern (at least) $\quad SO(5) \rightarrow SO(4)$

EWSB sector with composite Higgs



$\Rightarrow$ Symmetry breaking pattern (at least) $\quad SO(5) \to SO(4)$

Many non-minimal models are possible

$SO(6) \to SO(5)$

$SO(6) \to SO(4) \times SO(2)$ $\quad \Rightarrow$ extended Higgs sectors

$SO(7) \to SO(6)$ ...

Minimal Composite Higgs: $SO(5)/SO(4)$

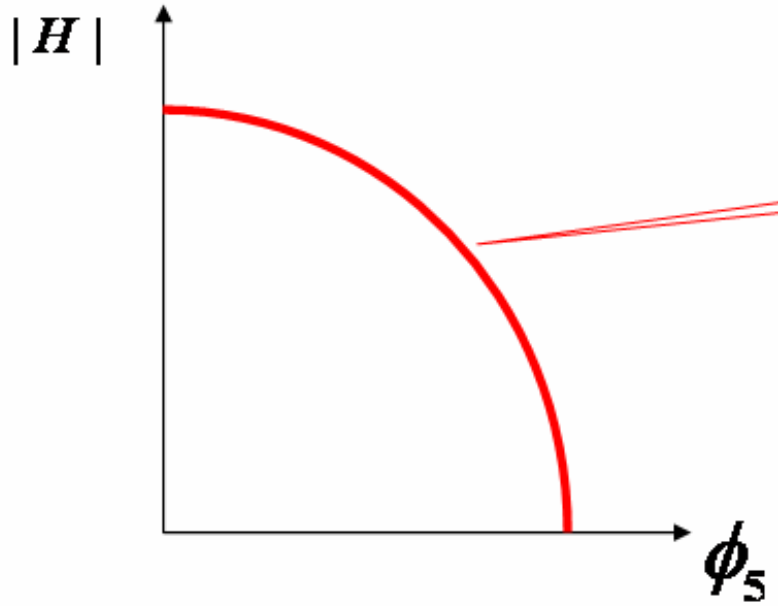
Minimal Composite Higgs: $SO(5)/SO(4)$

$$\Phi = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \\ \phi_5 \end{pmatrix} \Bigg\} H$$

"Goldstone Higgs doublet"

$$SO(4) \supset SU(2)_w \times U(1)_Y$$

EWSB via vacuum disalignment:



moduli space of vacua

$$\Phi^T \Phi \equiv |H|^2 + \phi_5^{\,2} = f^2$$

$$f = (\text{few}) \times v$$

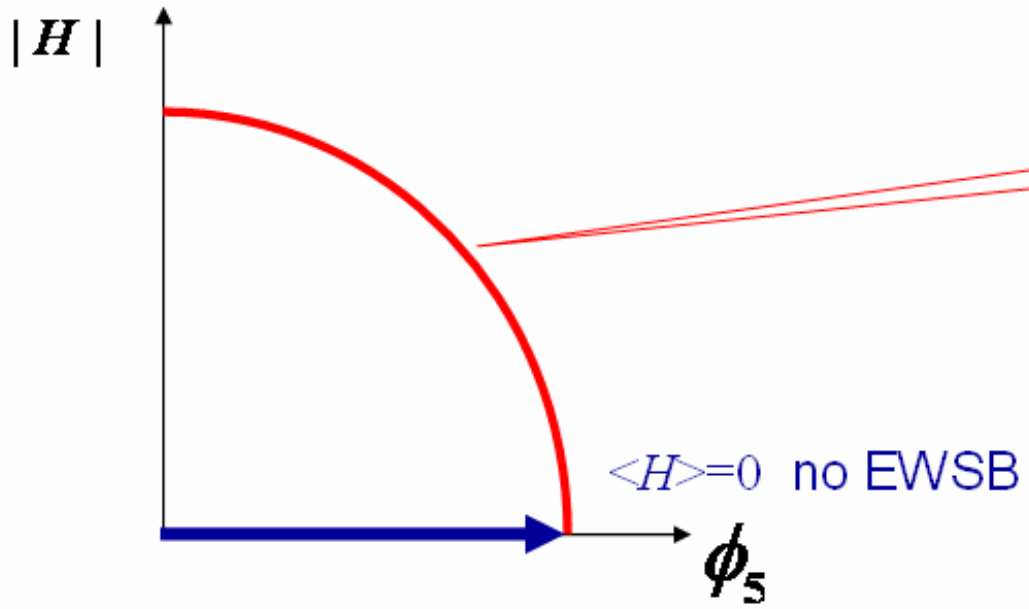
Minimal Composite Higgs: $SO(5)/SO(4)$

$$\Phi = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \\ \phi_5 \end{pmatrix} \Bigg\} H$$

"Goldstone Higgs doublet"

$$SO(4) \supset SU(2)_w \times U(1)_Y$$

EWSB via vacuum disalignment:



moduli space of vacua

$$\Phi^T \Phi \equiv |H|^2 + \phi_5^{\,2} = f^2$$

$$f = (\text{few}) \times v$$

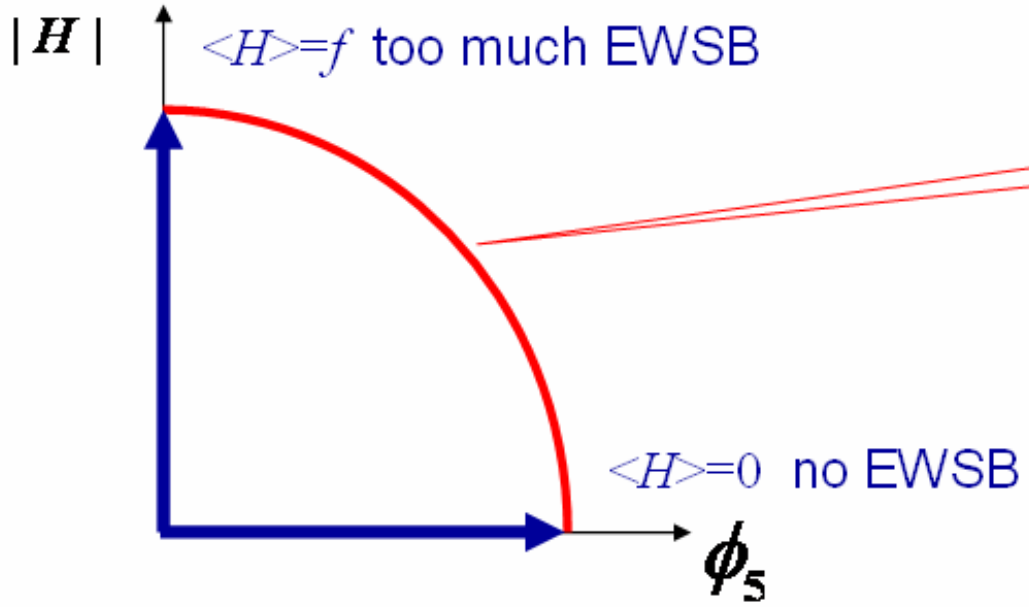
Minimal Composite Higgs: $SO(5)/SO(4)$

$$\Phi = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \\ \phi_5 \end{pmatrix} \quad \left.\begin{matrix} \\ \\ \\ \\ \end{matrix}\right\} \; H$$

"Goldstone Higgs doublet"

$$SO(4) \supset SU(2)_w \times U(1)_Y$$

EWSB via vacuum disalignment:



moduli space of vacua

$$\Phi^T\Phi \equiv |H|^2 + \phi_5^{\,2} = f^2$$

$$f = (\text{few}) \times v$$

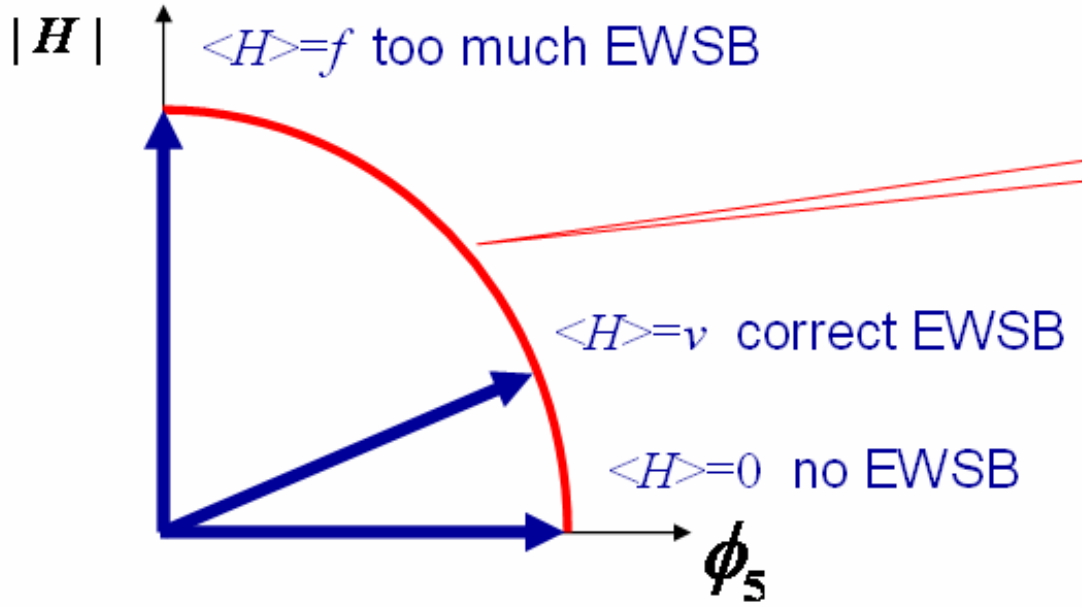
Minimal Composite Higgs: $SO(5)/SO(4)$

$$\Phi = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \\ \phi_5 \end{pmatrix} \quad \left.\begin{matrix} \\ \\ \\ \\ \\ \end{matrix}\right\} \; H$$

"Goldstone Higgs doublet"

$$SO(4) \supset SU(2)_w \times U(1)_Y$$

EWSB via vacuum disalignment:



moduli space of vacua

$$\Phi^T\Phi \equiv |H|^2 + \phi_5^{\,2} = f^2$$

$$f = (\text{few}) \times v$$

Deviations in Higgs couplings

Consequence of nonlinear structure:

$$O_H = \frac{c_H}{f^2}\partial(H^2)\partial(H^2)$$

$$O_Y = \frac{c_Y}{f^2}H^2(\bar{\psi}_L H \psi_R)$$

with model-dependent coefficients $c_H, c_Y = O(1)$ [e.g. $c_H = 1$ for SO(5)/SO(4)]

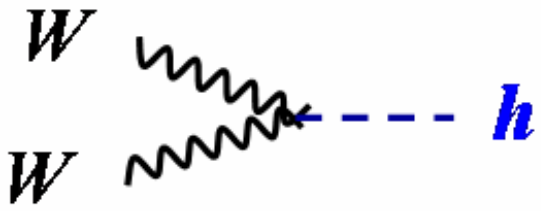
Deviations in Higgs couplings

Consequence of nonlinear structure:

$$O_H = \frac{c_H}{f^2}\partial(H^2)\partial(H^2)$$

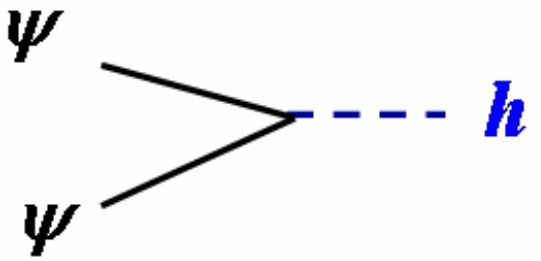
$$O_Y = \frac{c_Y}{f^2}H^2(\bar{\psi}_L H \psi_R)$$

with model-dependent coefficients $c_H, c_Y = O(1)$ [e.g. $c_H = 1$ for SO(5)/SO(4)]



$$g_{WWh} = \left(1 - c_H \xi\right) g_{SM}$$

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



$$g_{\psi\psi h} = \left(1 - (c_H + c_Y)\xi\right) g_{SM}$$

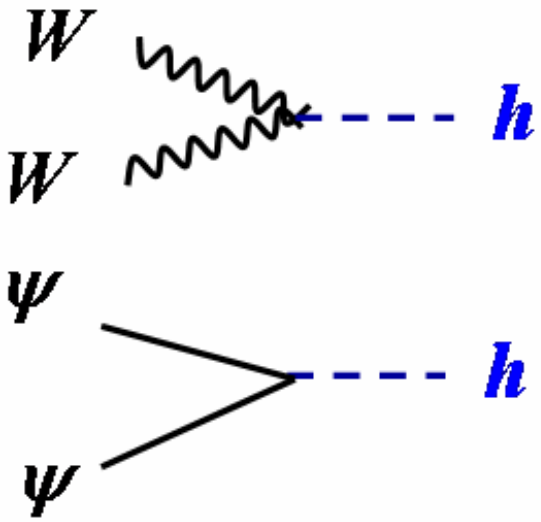
Deviations in Higgs couplings

Consequence of nonlinear structure:

$$O_H = \frac{c_H}{f^2}\partial(H^2)\partial(H^2)$$

$$O_Y = \frac{c_Y}{f^2}H^2(\bar{\psi}_L H \psi_R)$$

with model-dependent coefficients $c_H, c_Y = O(1)$ [e.g. $c_H = 1$ for SO(5)/SO(4)]



$$g_{WWh} = \left(1 - c_H \xi\right) g_{SM}$$

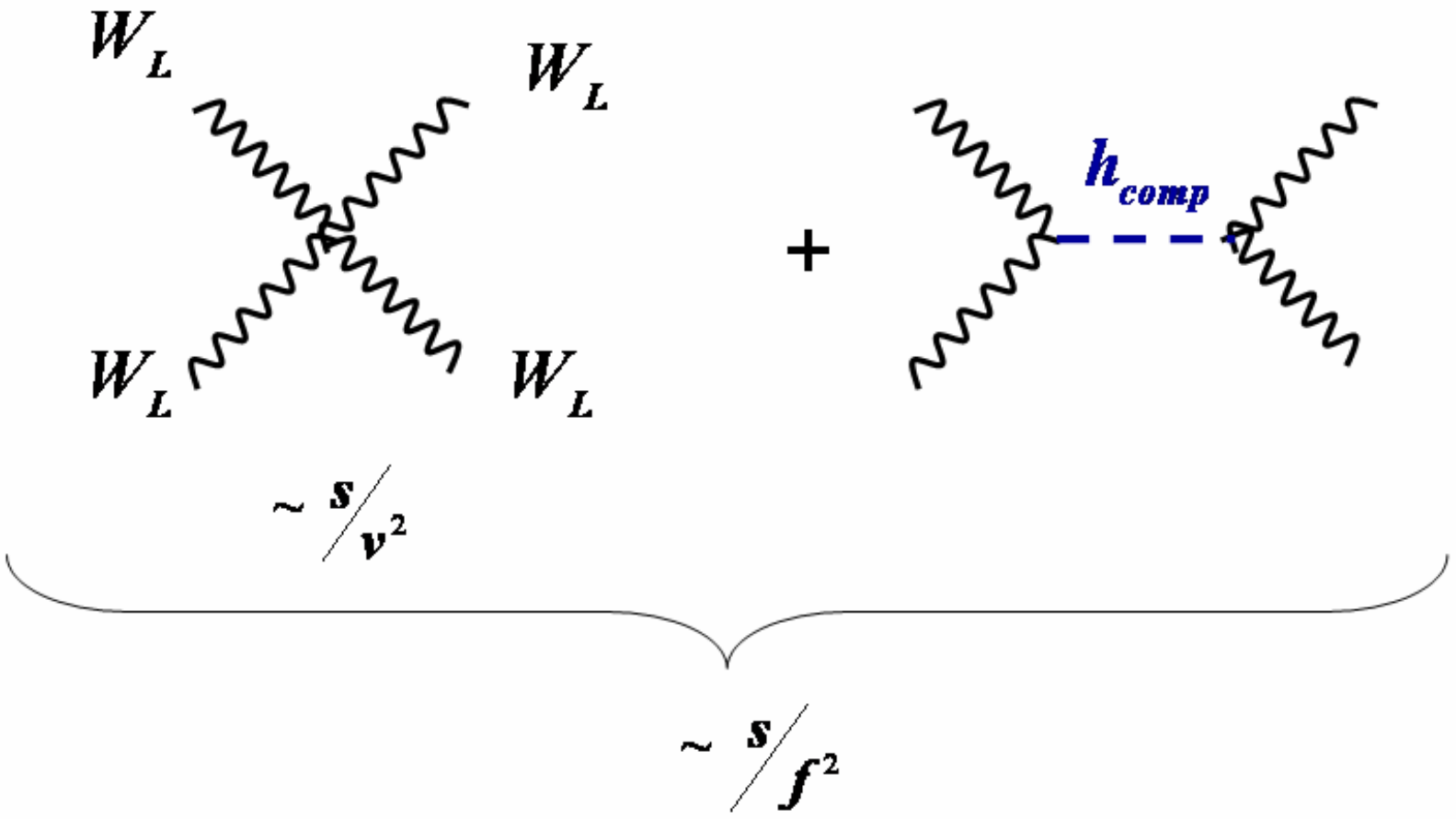
$$g_{\psi\psi h} = \left(1 - (c_H + c_Y)\xi\right) g_{SM}$$

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

predicted positive, i.e. couplings reduced

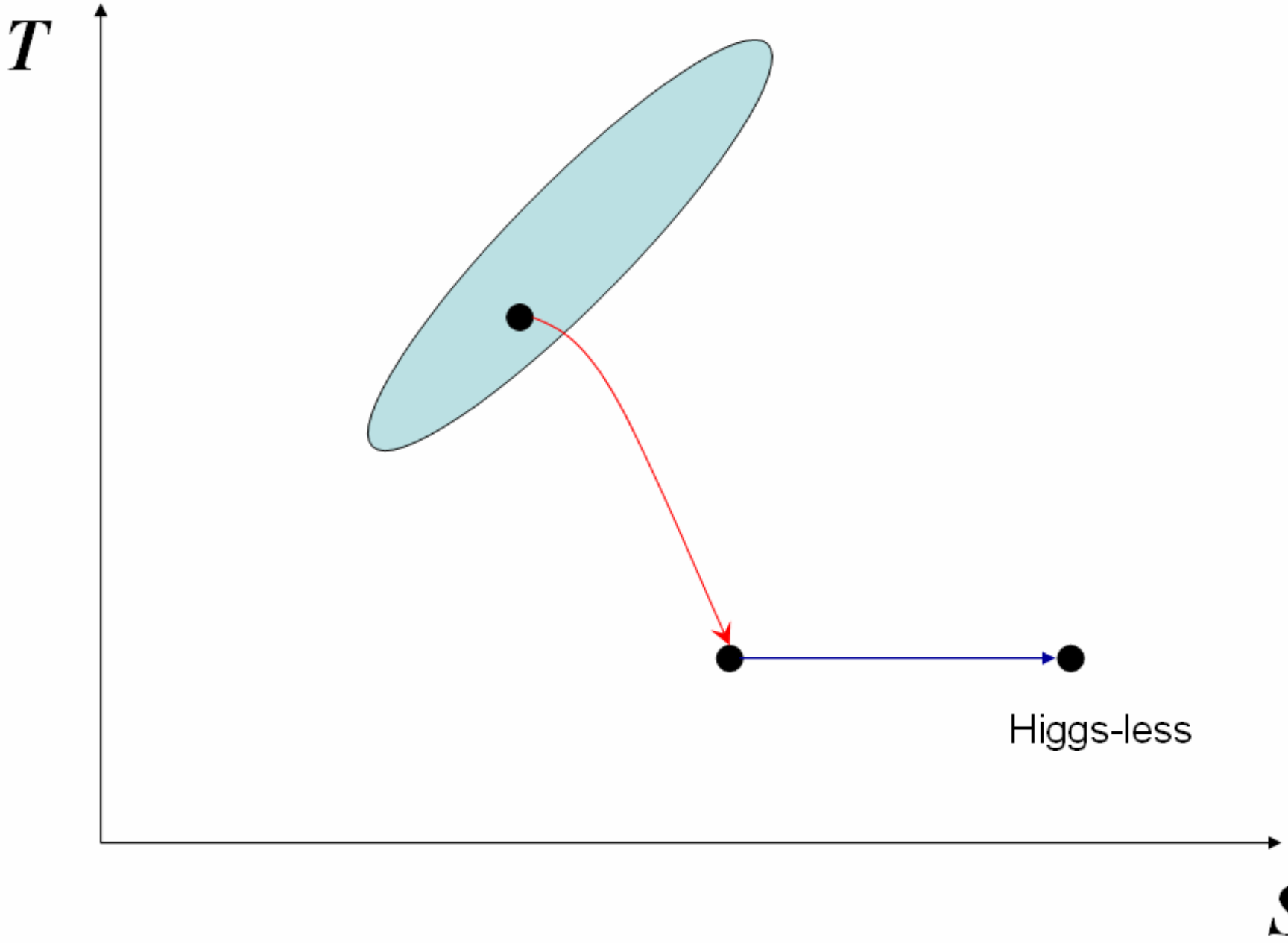
Low, Rattazzi, Vichi

Incomplete unitarization

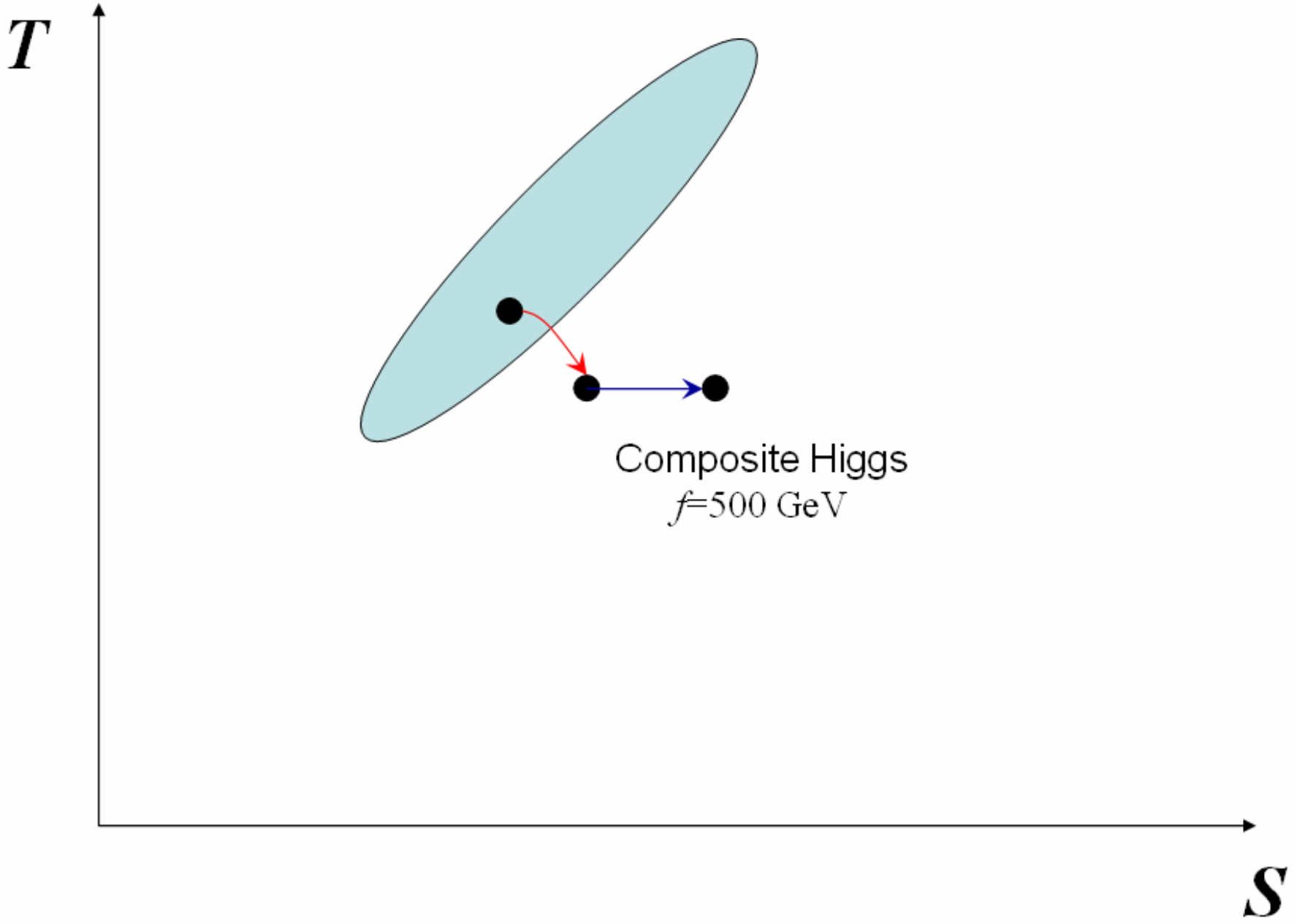


[presumably restored completely by super-heavy vectorial resonances with mass beyond LHC reach]

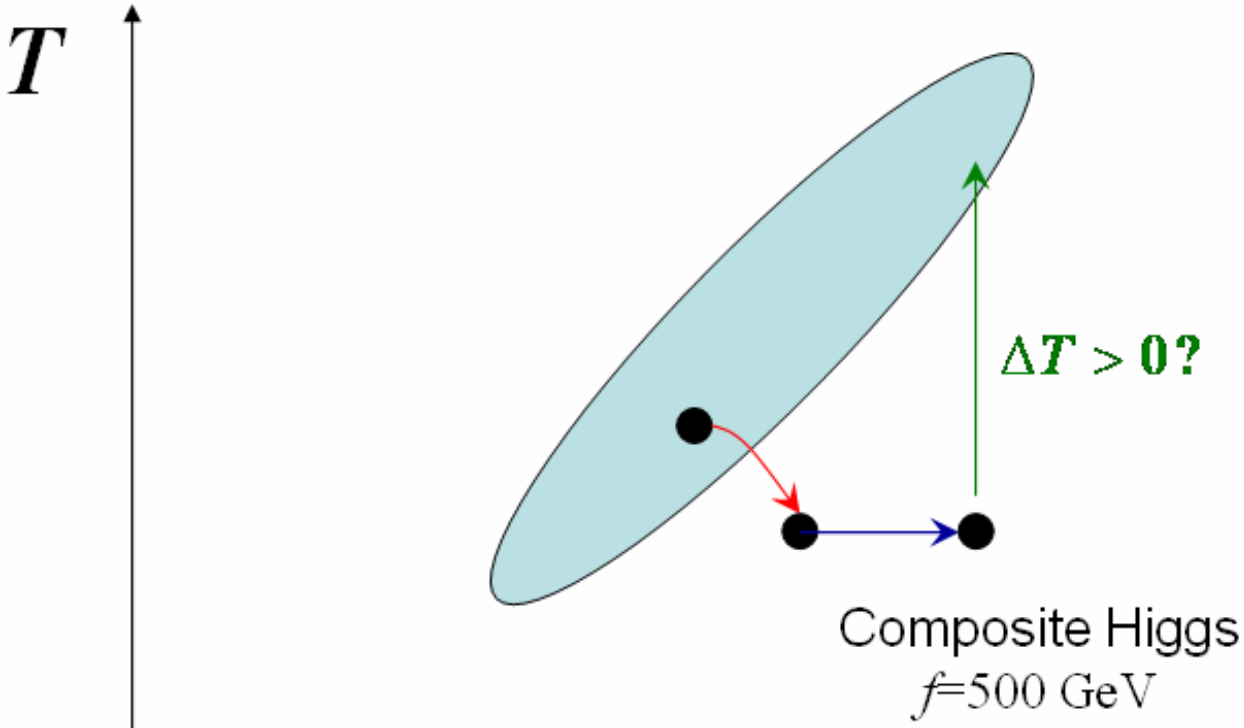
EW precision tests



EW precision tests



EW precision tests

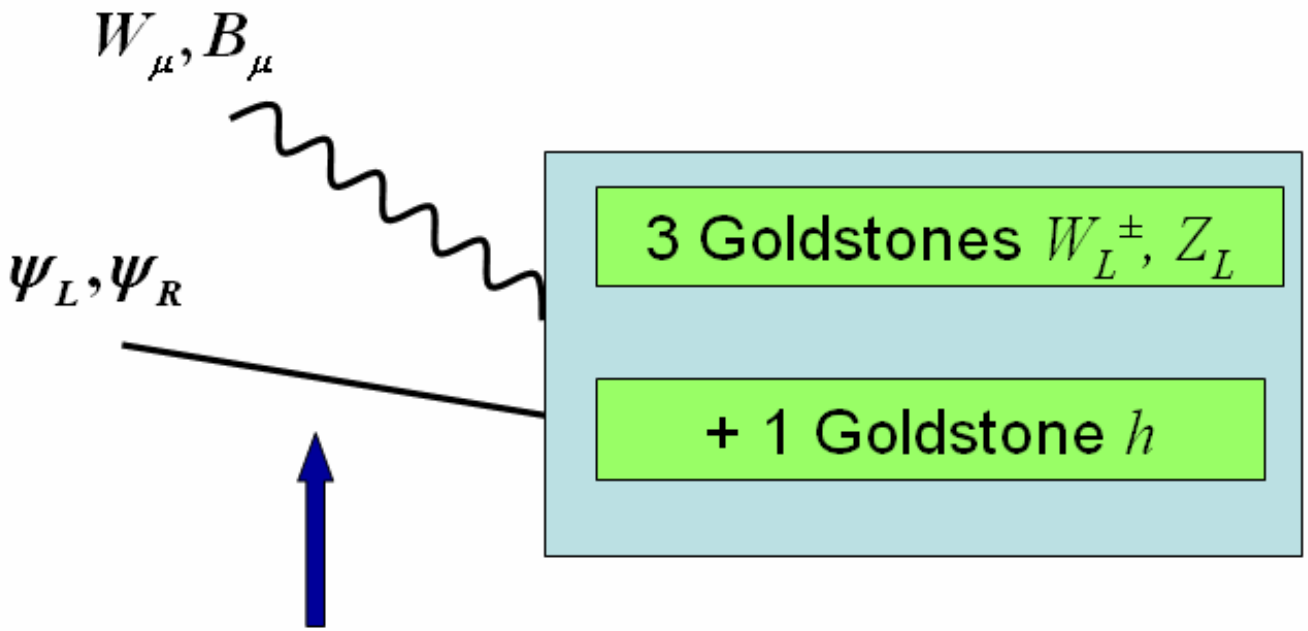


$\Delta T > 0$ from "top partners" – extra vector-like quarks:

Carena, Ponton, Santiago, Wagner;
Barbieri, Bellazzini, S.R., Varagnolo;
Lodone; Gillioz; Pomarol, Serra;
Anastasiou, Furlan, Santiago

EWSB via vacuum disalignment

What causes it?



$SO(5)/SO(4)$

These couplings necessarily break global $SO(5)$, generate potential $V(h)$

In simplest models, f/v hierarchy requires mild finetuning

$$O(v^2 / f^2) \sim 10\%$$

Summary of composite Higgs pheno

EWSB sector

- Lightish (100-200 GeV) SM-like Higgs boson
- O(10-20%) reductions in main Higgs boson couplings $hWW, h\bar{t}t, h\bar{b}b, h\bar{\tau}\tau$

  $\Rightarrow$ changes in production cross sections and BR (including $h \to \gamma\gamma$)
- In non-minimal models,
  more pseudo-Goldstones $\Rightarrow$ extended Higgs sector
  [e.g. in SO(6)/SO(5) pseudo-scalar η which may appear in $h \to \eta\eta$,
  in SO(6)/SO(4)xSO(2) two Higgs doublets etc.]

Summary of composite Higgs pheno

EWSB sector

- Lightish (100-200 GeV) SM-like Higgs boson
- O(10-20%) reductions in main Higgs boson couplings $hWW, h\bar{t}t, h\bar{b}b, h\bar{\tau}\tau$

  $\Rightarrow$ changes in production cross sections and BR (including $h \to \gamma\gamma$)
- In non-minimal models,
  more pseudo-Goldstones $\Rightarrow$ extended Higgs sector
  [e.g. in SO(6)/SO(5) pseudo-scalar η which may appear in $h \to \eta\eta$,
  in SO(6)/SO(4)xSO(2) two Higgs doublets etc.]

100 fb^{-1} stuff…
Bock,Lafaye,Plehn,Rauch,D.Zerwas,P.Zerwas

Summary of composite Higgs pheno

EWSB sector

- Lightish (100-200 GeV) SM-like Higgs boson
- O(10-20%) reductions in main Higgs boson couplings $hWW, h\bar{t}t, h\bar{b}b, h\bar{\tau}\tau$

  $\Rightarrow$ changes in production cross sections and BR (including $h \to \gamma\gamma$)

- In non-minimal models,
  more pseudo-Goldstones $\Rightarrow$ extended Higgs sector
  [e.g. in SO(6)/SO(5) pseudo-scalar η which may appear in $h \to \eta\eta$,
  in SO(6)/SO(4)xSO(2) two Higgs doublets etc.]

100 fb^{-1} stuff…
Bock,Lafaye,Plehn,Rauch,D.Zerwas,P.Zerwas

Extended quark sector ("top partners")… subject of another talk

Conclusions

- Higgs-less scenarios – keep in the back of your mind

  - need O(100 fb^{-1}) to explore the likely mass region of vectorial resonances

- Composite Higgs is a more likely possibility

  - need O(100 fb^{-1}) to test crucial predictions of nonlinear structure in EWSB sector