The Higgs boson: elementary or composite ?

Roberto Contino

Università di Roma La Sapienza

1. Weak or Strong EWSB ?

The physics discovered so far : $\mathcal{L}_{SM} = \mathcal{L}_0 + \mathcal{L}_{mass}$

$$\mathcal{L}_0 = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\,\mu\nu} - \frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \sum_{j=1}^{3}\left(\bar{\Psi}^{(j)}_L i\not{D}\Psi^{(j)}_L + \bar{\Psi}^{(j)}_R i\not{D}\Psi^{(j)}_R\right)$$

$$\begin{aligned}\mathcal{L}_{mass} =& M_W^2\, W^+_\mu W^{-\,\mu} + \frac{1}{2}M_Z^2\, Z^\mu Z_\mu \\ & - \sum_{i,j}\left\{\bar{u}^{(i)}_L M^u_{ij} u^{(j)}_R + \bar{d}^{(i)}_L M^d_{ij} d^{(j)}_R + \bar{e}^{(i)}_L M^e_{ij} e^{(j)}_R + \bar{\nu}^{(i)}_L M^\nu_{ij} \nu^{(j)}_R + h.c.\right\}\end{aligned}$$

The $SU(2)_L xU(1)_Y$ symmetry is non-linearly realized (or "hidden"):

Interactions are invariant under $SU(2)_L xU(1)_Y$

The mass spectrum is not

$$\mathcal{L}_{mass} = M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z^\mu Z_\mu - \sum_{i,j} \left\{ \bar{u}_L^{(i)} M_{ij}^u u_R^{(j)} + \bar{d}_L^{(i)} M_{ij}^d d_R^{(j)} + h.c. \right\}$$

In fact, an additional term that breaks the LR symmetry has been omitted since $\rho_{exp} \simeq 1$

$$\mathcal{L}_{mass} = \frac{v^2}{4} \mathrm{Tr}\left[(D_\mu \Sigma)^\dagger (D^\mu \Sigma) \right] - \frac{v}{\sqrt{2}} \sum_{i,j} (\bar{u}_L^{(i)}\ \bar{d}_L^{(i)}) \Sigma \begin{pmatrix} \lambda_{ij}^u u_R^{(j)} \\ \lambda_{ij}^d d_R^{(j)} \end{pmatrix} + h.c. + a\, v^2\, \mathrm{Tr}\left[\Sigma^\dagger D_\mu \Sigma\, T^3 \right]^2$$

$$\Sigma = \exp\left(i \sigma^a \chi^a / v \right)$$

$$D_\mu \Sigma = \partial_\mu \Sigma - i g_2 \frac{\sigma^a}{2} W_\mu^a \Sigma + i g_1 \Sigma \frac{\sigma_3}{2} B_\mu$$

$\rho = 1$ follows from a larger global $SU(2)_L \times SU(2)_R$ approximate invariance

$$\Sigma \to U_L\, \Sigma\, U_R^\dagger$$

broken only by g_1 and $\lambda^u \neq \lambda^d$

- The $SU(2)_L \times U(1)_Y$ symmetry is now manifest, though non-linearly realized

$$\Sigma \to U_L\, \Sigma\, U_Y^\dagger \qquad U_L(x) = \exp(i\, \alpha_L^a(x) \sigma^a / 2) \qquad U_Y(x) = \exp(i\, \alpha_Y(x) \sigma^3 / 2)$$

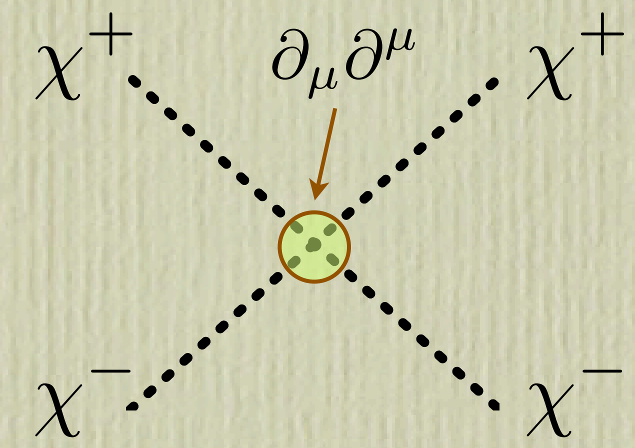
- In the unitary gauge $\langle \Sigma \rangle = 1$, $\mathcal{L}_{mass}$ equals the original mass Lagrangian with :

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$$

This formulation makes the problem most transparent:

There is a violation of perturbative unitarity

in the scattering of the Goldstone bosons:

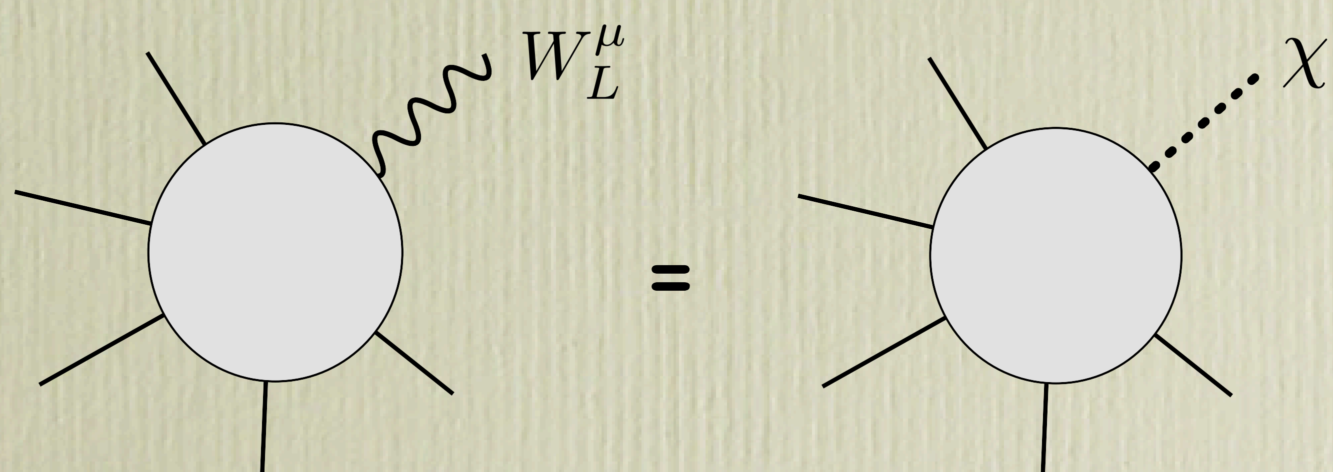


$$A(\chi^+\chi^- \to \chi^+\chi^-) = \frac{1}{v^2}\,(s+t)$$

which is in fact linked to the non-renormalizability of the Lagrangian

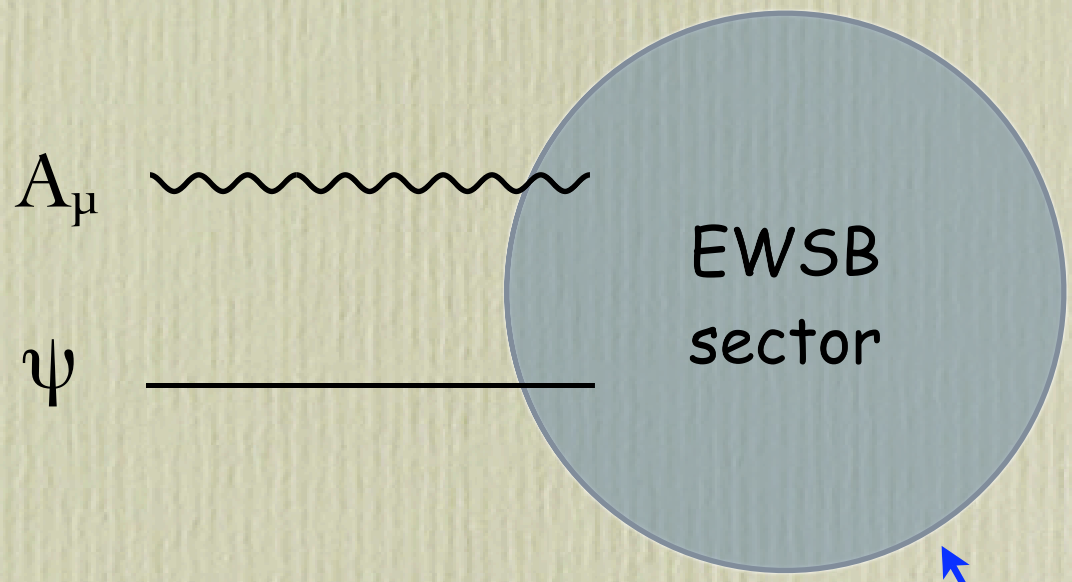
The Equivalence Theorem implies that this corresponds to the scattering of

longitudinal vector bosons:



$$\left(1 + O\left(\frac{M_W^2}{E^2}\right)\right)$$

☞ We need a new EWSB sector that acts as a UV completion of the EW chiral Lagrangian and restores unitarity



$$= \left\{ \chi^a + \dots \right\}$$

must respect the custodial symmetry

Q: is such new sector weakly or strongly interacting ?

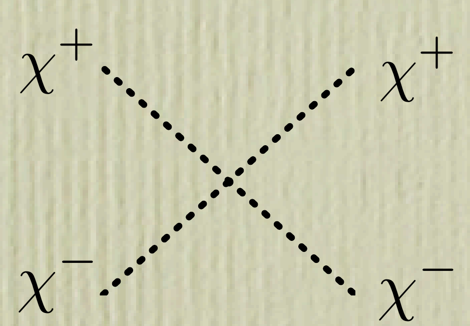
The Higgs model as a prototype of weak EWSB dynamics :

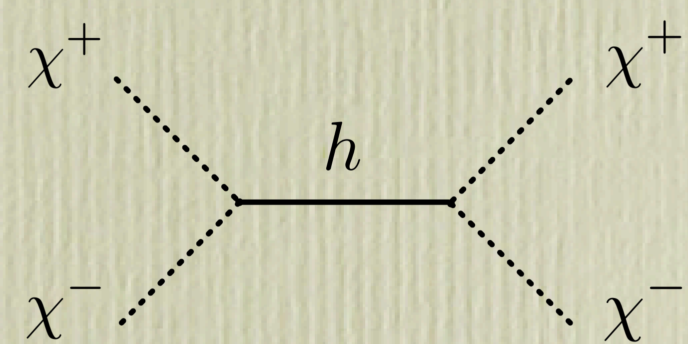
EWSB sector $= \{ \; \chi^a, \; h \; \}$

Most economical addition :

1 scalar field singlet under $SU(2)_L \times SU(2)_R$

$$H = \frac{1}{\sqrt{2}} \, e^{i\sigma^a \chi^a / v} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$





$$A(\chi^+\chi^- \to \chi^+\chi^-) \simeq -\frac{g_2^2 m_h^2}{4M_W^2}$$

✓ good agreement with EW precision tests

✗ theoretically unsatisfactory (UV instability of Higgs mass term)

The Higgs model as a prototype of weak EWSB dynamics :

EWSB sector $= \{ \; \chi^a, \; h \; \}$

Most economical addition :

1 scalar field singlet under SU(2)$_L$ x SU(2)$_R$

$$H = \frac{1}{\sqrt{2}} e^{i\sigma^a \chi^a / v} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

There is an unbroken custodial symmetry SO(3) preserved by the Higgs vev that leads to $\rho = 1$

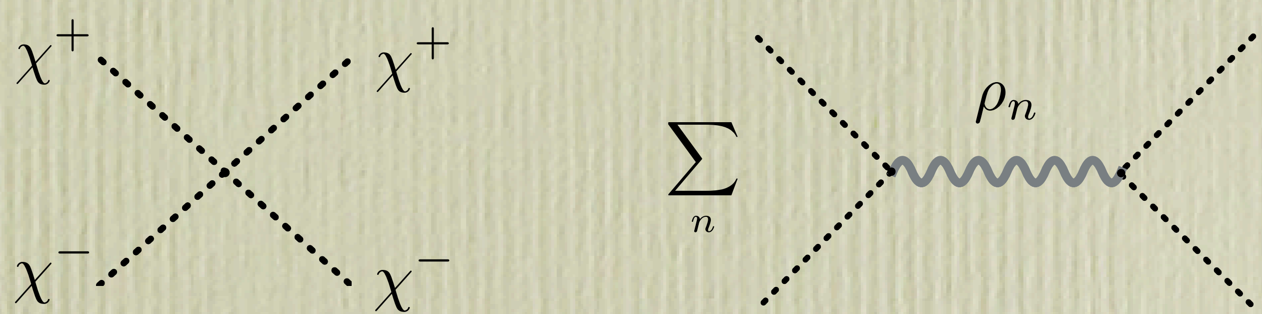
$$H = \begin{pmatrix} w_1 + i\, w_2 \\ w_3 + i\, w_4 \end{pmatrix} \qquad H^\dagger H = \sum_i (w_i)^2$$

$V(H^\dagger H)$ is SO(4)~SU(2)$_L$xSU(2)$_R$ invariant

$\langle H^\dagger H \rangle = v^2$ breaks SO(4)⟶SO(3)

Technicolor as a prototype of strong EWSB dynamics :

EWSB sector = { Confining SU(N_{TC}) with bound states in the IR; χ^a are composite NG bosons (like π in QCD) }

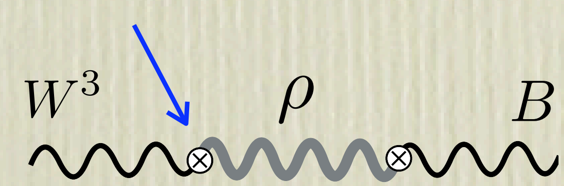


Scattering cross section grows strong until the resonances exchange restores unitarity at the SU(N_{TC}) confining scale

✓ theoretically satisfactory

✗ naively at odds with EW precision tests

$$\langle 0|J_\mu|\rho\rangle = \epsilon^r_\mu\, f_\rho\, m_\rho$$



2. Composite Higgs

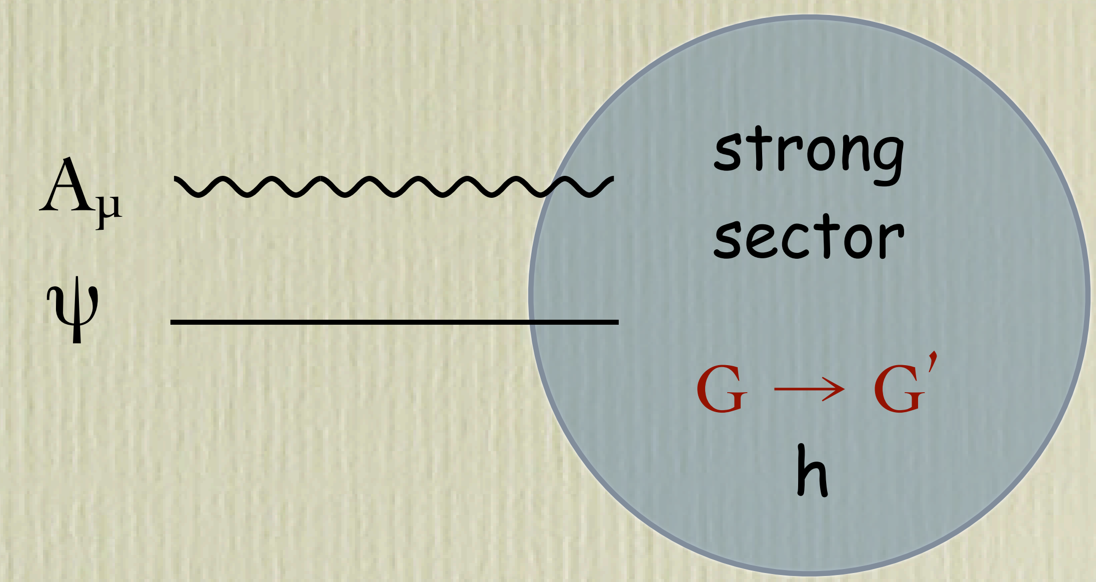
The Composite Higgs

It is also possible that a light Higgs-like scalar arises as a bound state from a strongly-interacting EWSB sector

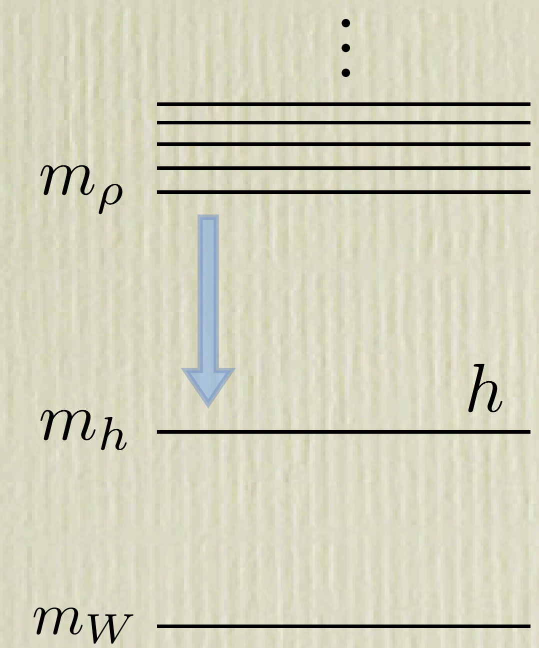
[Georgi & Kaplan, `80s]

Motivations:

- A composite Higgs solves the hierarchy problem
- A light Higgs is preferred by the electroweak fit

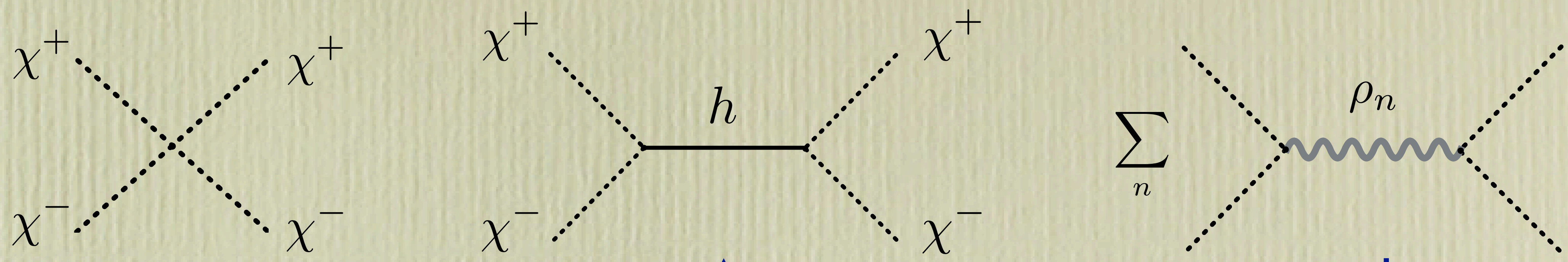


☞ A light composite Higgs can naturally arise as a (pseudo) Nambu-Goldstone boson



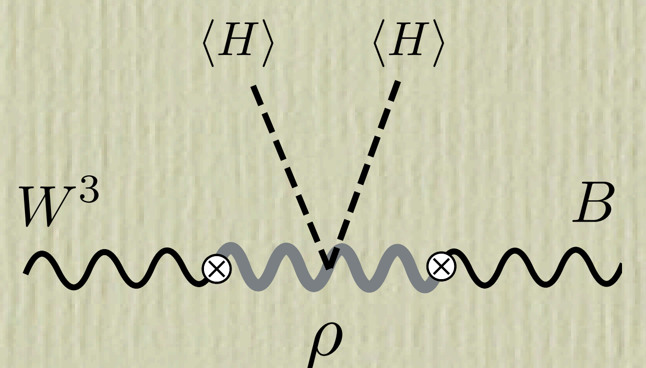
enlarge the global symmetry of the strong sector to have a full SU(2) doublet

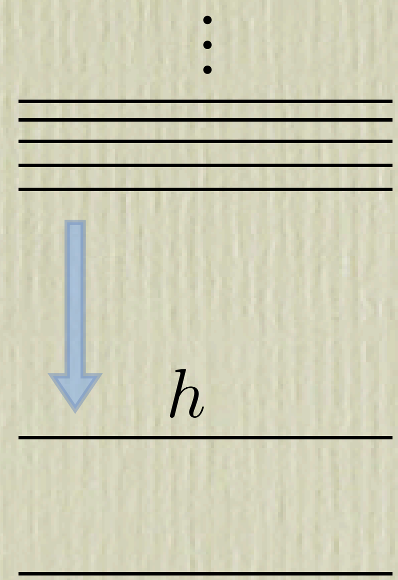
ex: $SO(5) \to SO(4)$



composite Higgs partially unitarizes WW scattering

other resonances can be heavier





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

$$m_h^2 = \lambda_4 \, v^2 \sim \frac{g_{SM}^2}{16\pi^2} \, g_\rho^2 \, v^2$$

$$m_W$$

$$\Delta\epsilon_3 \equiv \hat{S} \sim \frac{m_W^2}{m_\rho^2} \sim \frac{g^2}{16\pi^2} \times \frac{16\pi^2}{g_\rho^2} \times \frac{v^2}{f^2}$$

$$\boxed{\xi = \left(\frac{v}{f}\right)^2}$$

$\longleftarrow$ new parameter compared to TC (fixed by the dynamics)

$\xi \to 0$

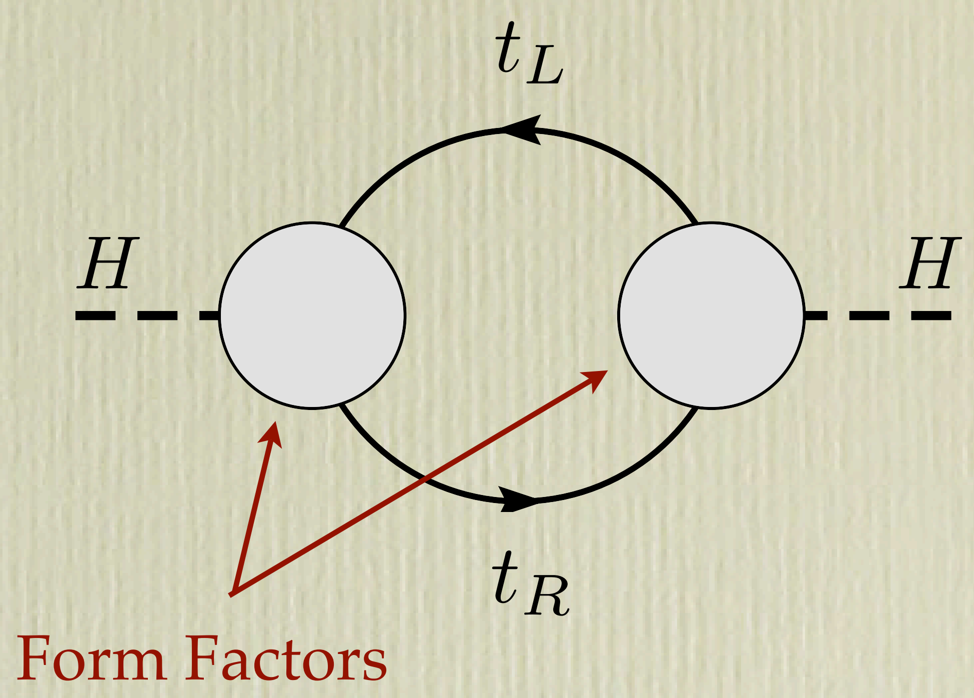
$[\, f \to \infty \,]$

decoupling limit:

All ρ's become heavy and one re-obtains the SM

1-loop potential for the pseudo-Goldstone Higgs

- only loops with virtual elementary fields generate a potential
- Higgs couplings switch off at large momenta ➞ finiteness



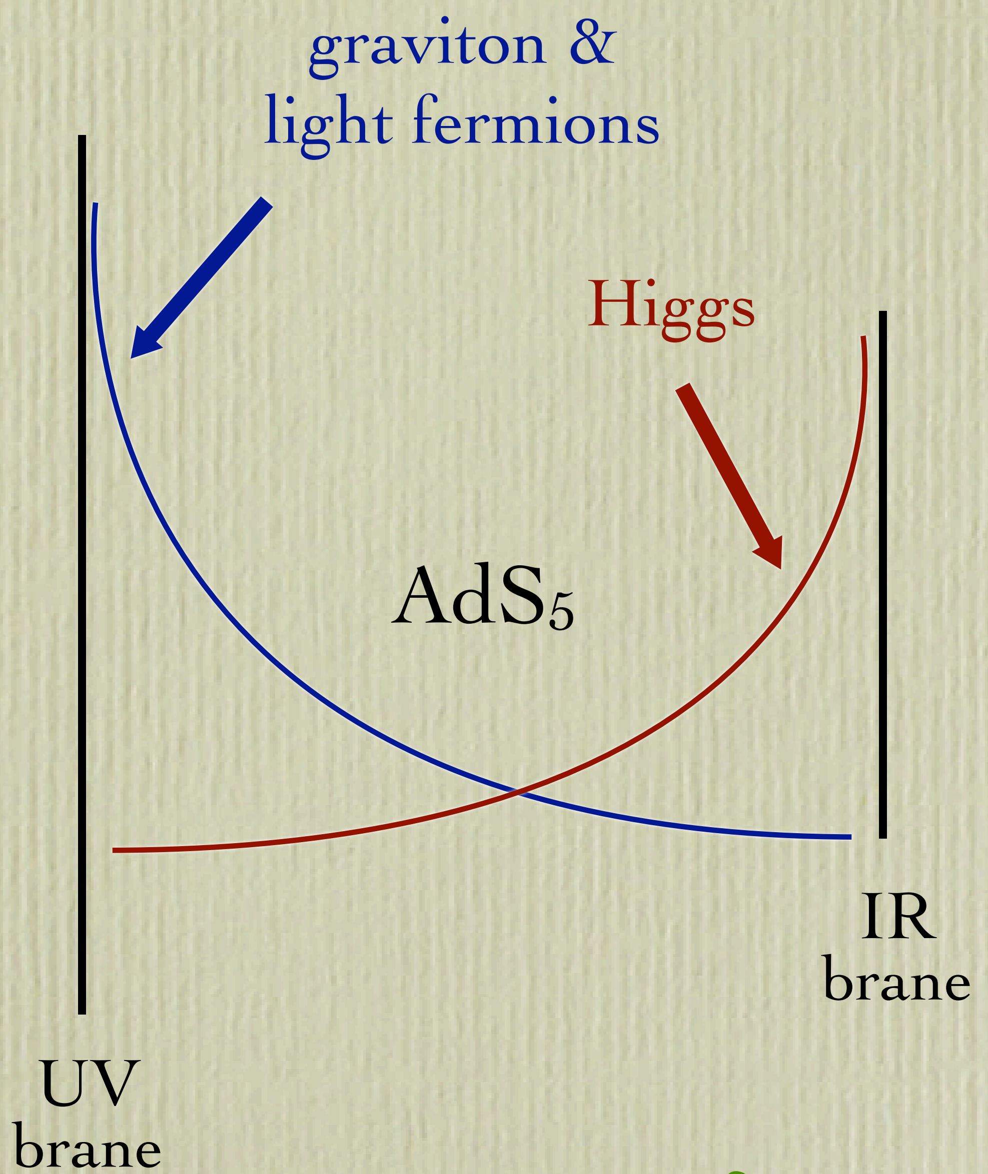
periodic function $(H \in G/G')$

$$V(h) \approx \frac{3\, y_t^2}{16\pi^2}\, m_\rho^2\, f^2\, \zeta(h/f) \qquad \lambda_4 \sim \frac{3}{16\pi^2}\, y_t^2\, g_\rho^2$$

Explicit models built in the context of 5D warped field theories (Randall-Sundrum compactifications)

[R.C., Nomura, Pomarol, NPB 671 (2003) 148]

[Agashe, R.C., Pomarol, NPB 719 (2005) 165]



warp factor

$$ds^2 = e^{-2ky}\, dx^\mu dx^\nu \eta_{\mu\nu} - dy^2$$

$$0 \le y \le \pi R$$

- Scales depend on the position:

  translation in y ⇔ 4D rescaling

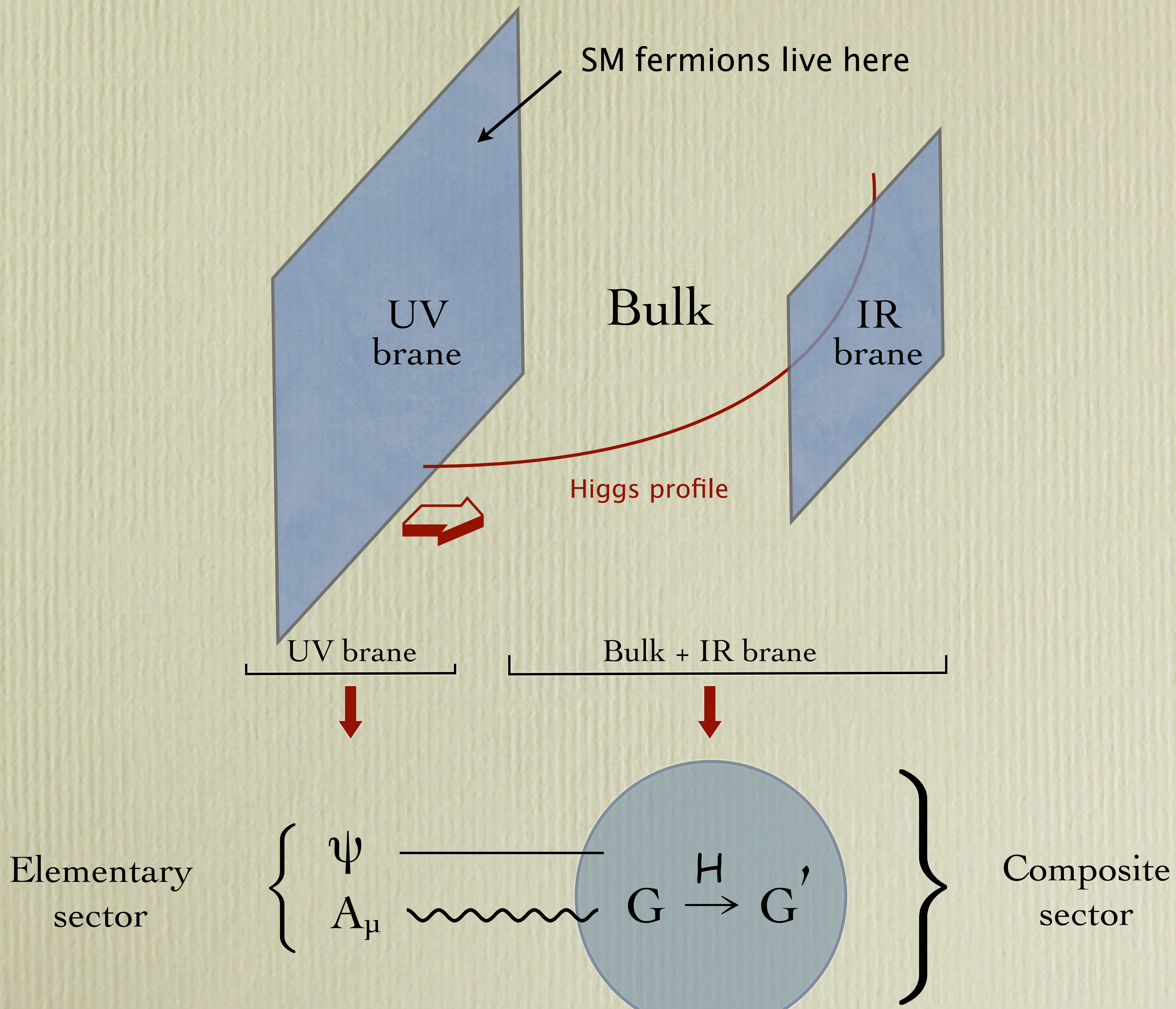
- Solution to the Hierarchy Problem

  geography of wave functions in the bulk

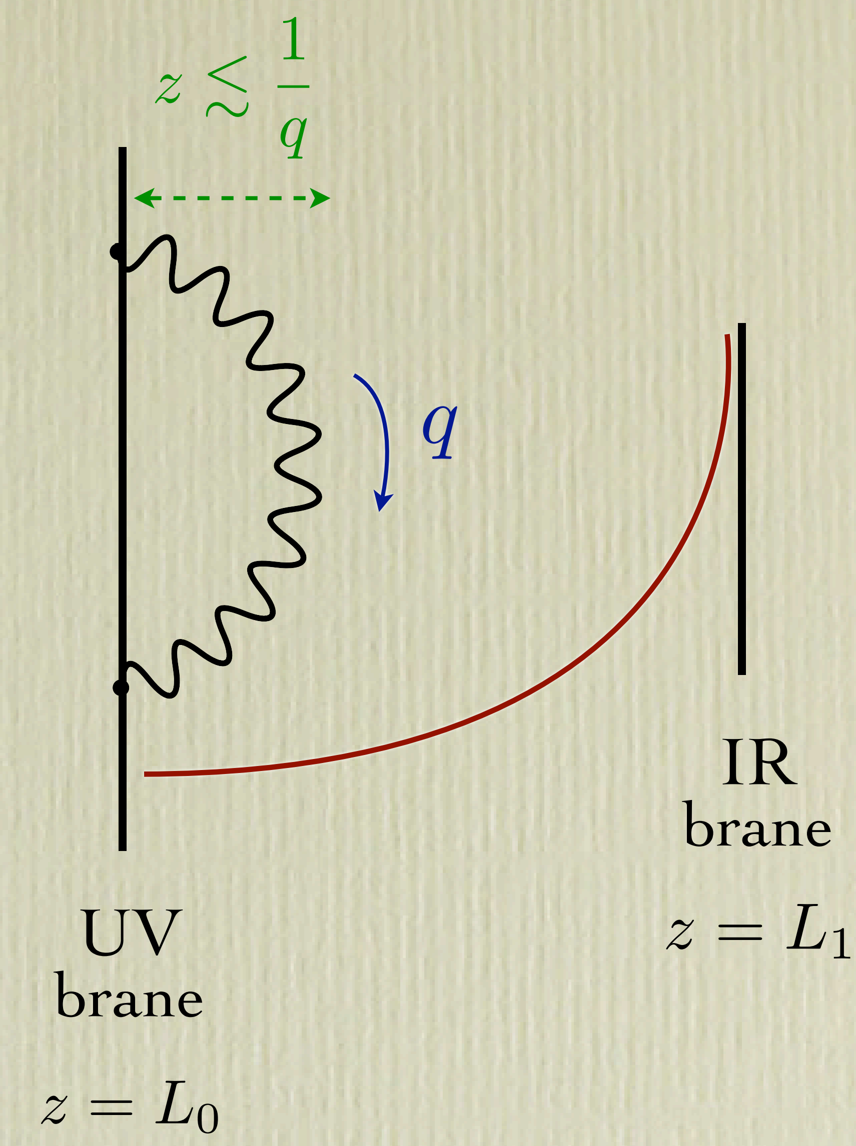
$$k \sim M_{\rm Pl}$$

$$k\, e^{-2k\pi R} \sim \text{TeV}$$

The holographic description



A brane-to-brane propagator between two sources on the UV boundary "probes" only up to distances $z \sim 1/q$, where q is the 4D exchanged momentum:



$$G(q, L_0, z) \sim e^{-qz} \quad \text{for} \quad qz \gg 1$$

$$z = k^{-1}\, e^{-yk}$$

the Higgs structure along the extra dimension

appears like a form factor

for an observer on the UV brane

Generic low-energy parametrization for a light scalar :

a, b, c are free parameters

$$\mathcal{L}_{EWSB} = \frac{v^2}{4} \mathrm{Tr}\left[D_\mu \Sigma^\dagger D^\mu \Sigma\right] \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right)$$

$$- m_i \bar{\psi}_{Li} \Sigma \left(1 + c\frac{h}{v}\right) \psi_{Ri} + h.c. + V(h)$$

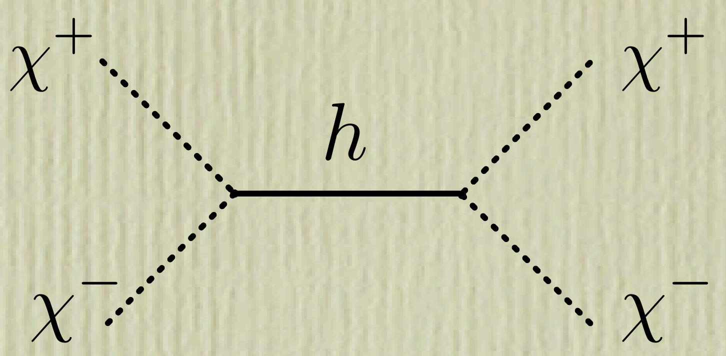
- Given the σ-model Lagrangian, a, b are predicted in terms of ξ.

For example, for SO(5)→SO(4):

$$a = \sqrt{1-\xi}\,, \qquad b = (1 - 2\,\xi)$$

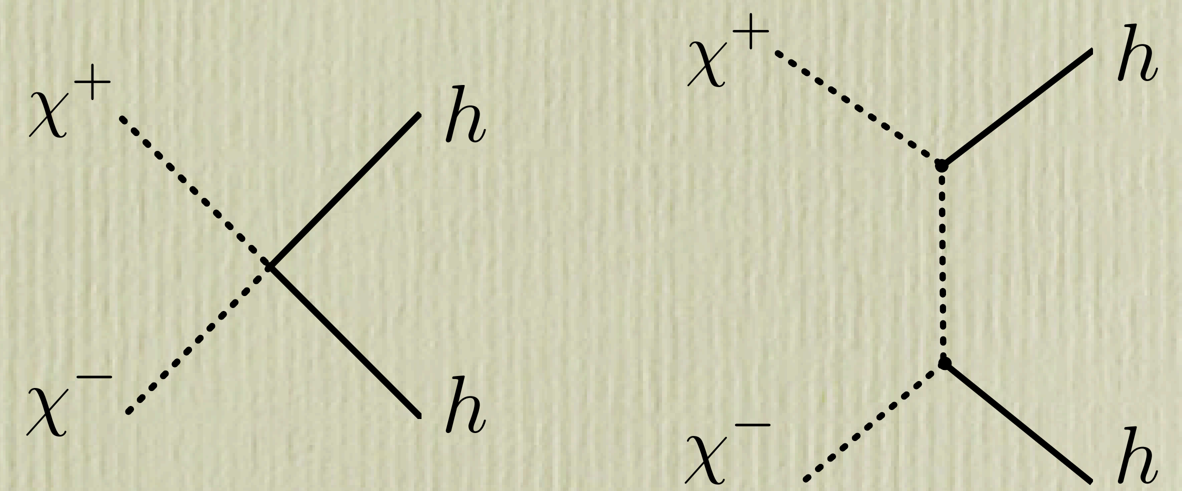
- c is also a function of ξ but more model dependent

- For $a^2 = 1$ the scalar exchange unitarizes the WW scattering



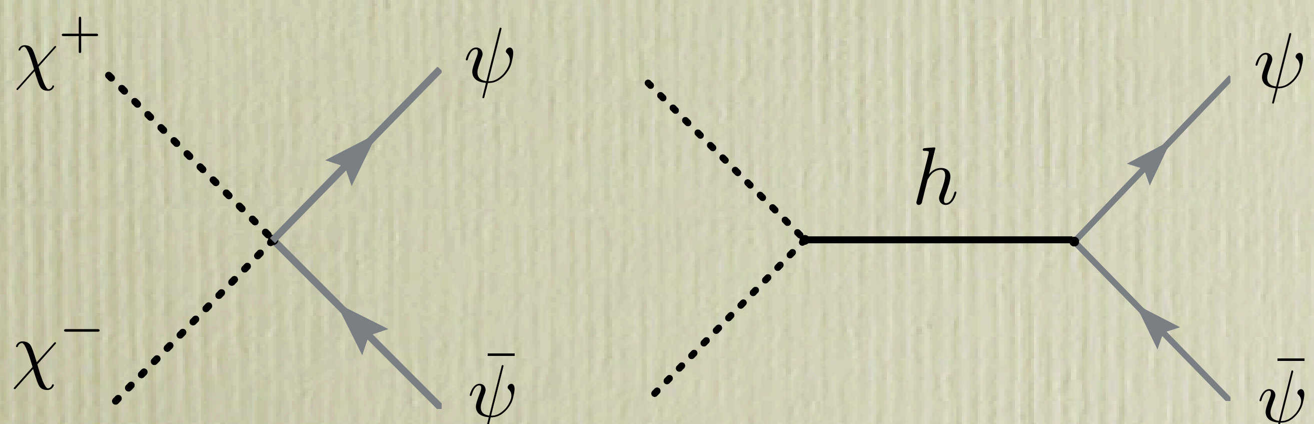
$$\mathcal{A}(\chi^+\chi^- \to \chi^+\chi^-) \simeq \frac{1}{v^2}\left[s - \frac{a^2 s^2}{s - m_h^2} + (s \leftrightarrow t)\right]$$

- For $b = a^2$ the inelastic channel respects unitarity



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

- For $ac = 1$ also the $WW \to \psi\bar{\psi}$ scattering is unitarized



$$\mathcal{A}(\chi^+\chi^- \to \psi\bar{\psi}) \simeq \frac{\sqrt{m_\psi s}}{v^2}(1 - ac)$$

☞ Only for $a = b = c = 1$ the EWSB sector is weakly coupled

ex: WW scattering becomes strong at $\sqrt{s} \approx \dfrac{4\pi v}{\sqrt{1-a^2}}$

$a = b = c = 1$ defines the Higgs Model

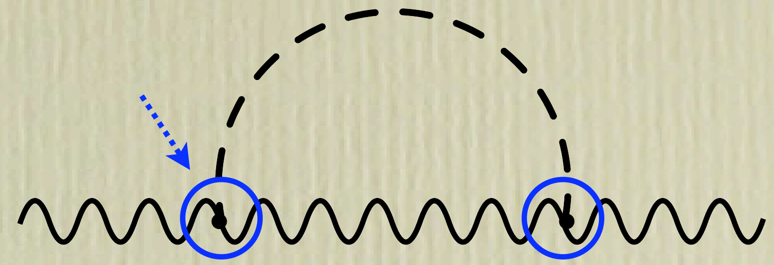
☞ The study of $VV \to VV$, $VV \to hh$ and $VV \to \psi\bar{\psi}$

tests three different parameters

ex: $VV \to hh$ allows one to distinguish a composite Higgs from the case of a light dilaton ($a^2 = b = c^2$)

$$\mathcal{L} = e^{2\phi/f_D} \left[\frac{1}{2} (\partial_\mu \phi)^2 + \frac{v^2}{4} \mathrm{Tr} \left(D_\mu \Sigma^\dagger D^\mu \Sigma \right) \right] \qquad \frac{v}{a} \equiv f_D \,, \qquad e^{\phi/f_D} = 1 + \frac{h}{f_D}$$

- The parameter a controls the size of the IR contribution to $\epsilon_{1,3}$:

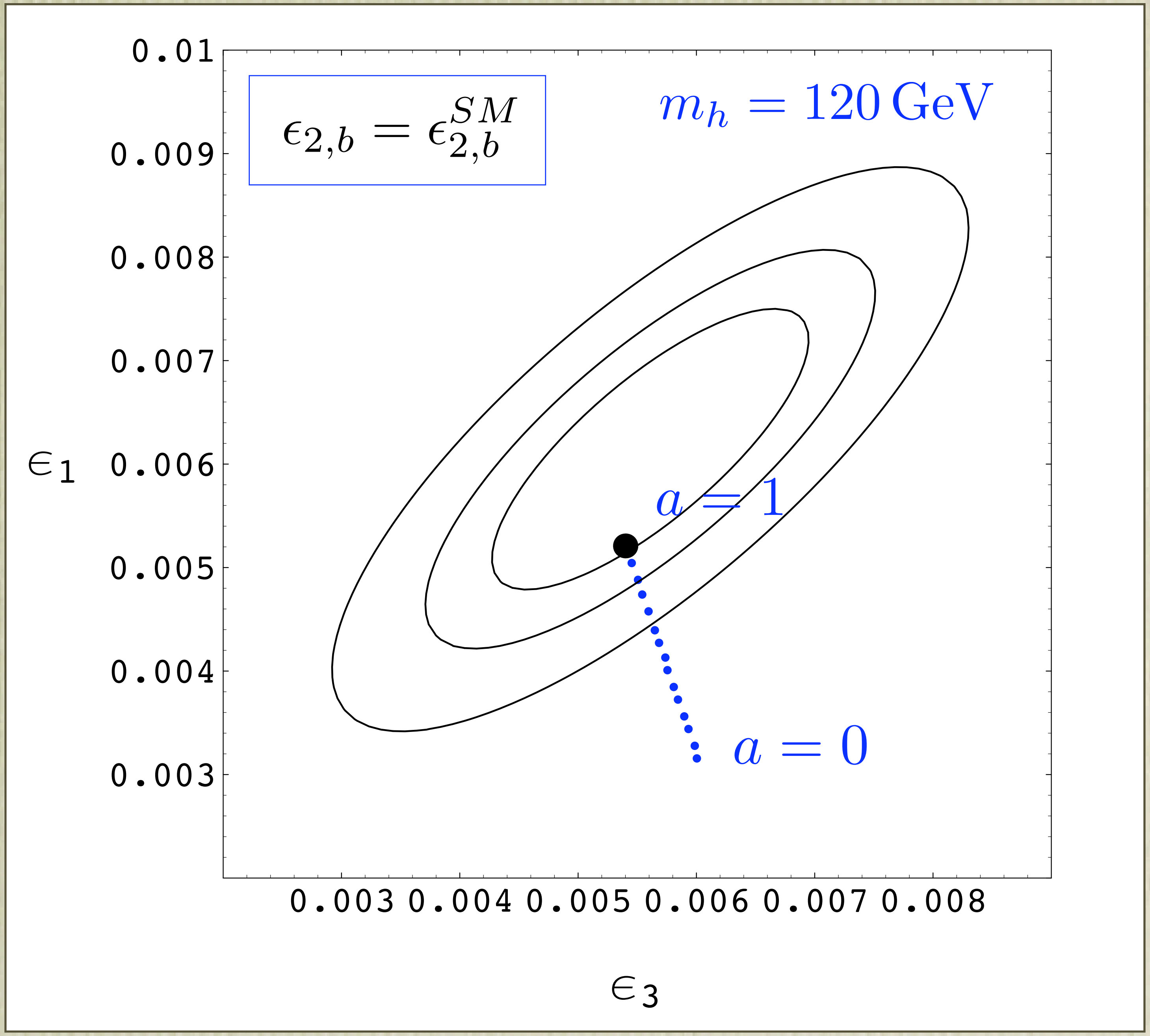


$$\epsilon_{1,3} = c_{1,3}\,\log\left(\frac{M_Z^2}{\mu^2}\right) - c_{1,3}\,a^2\log\left(\frac{m_h^2}{\mu^2}\right) - c_{1,3}\,(1-a^2)\log\left(\frac{m_\rho^2}{\mu^2}\right) + \text{finite terms}$$

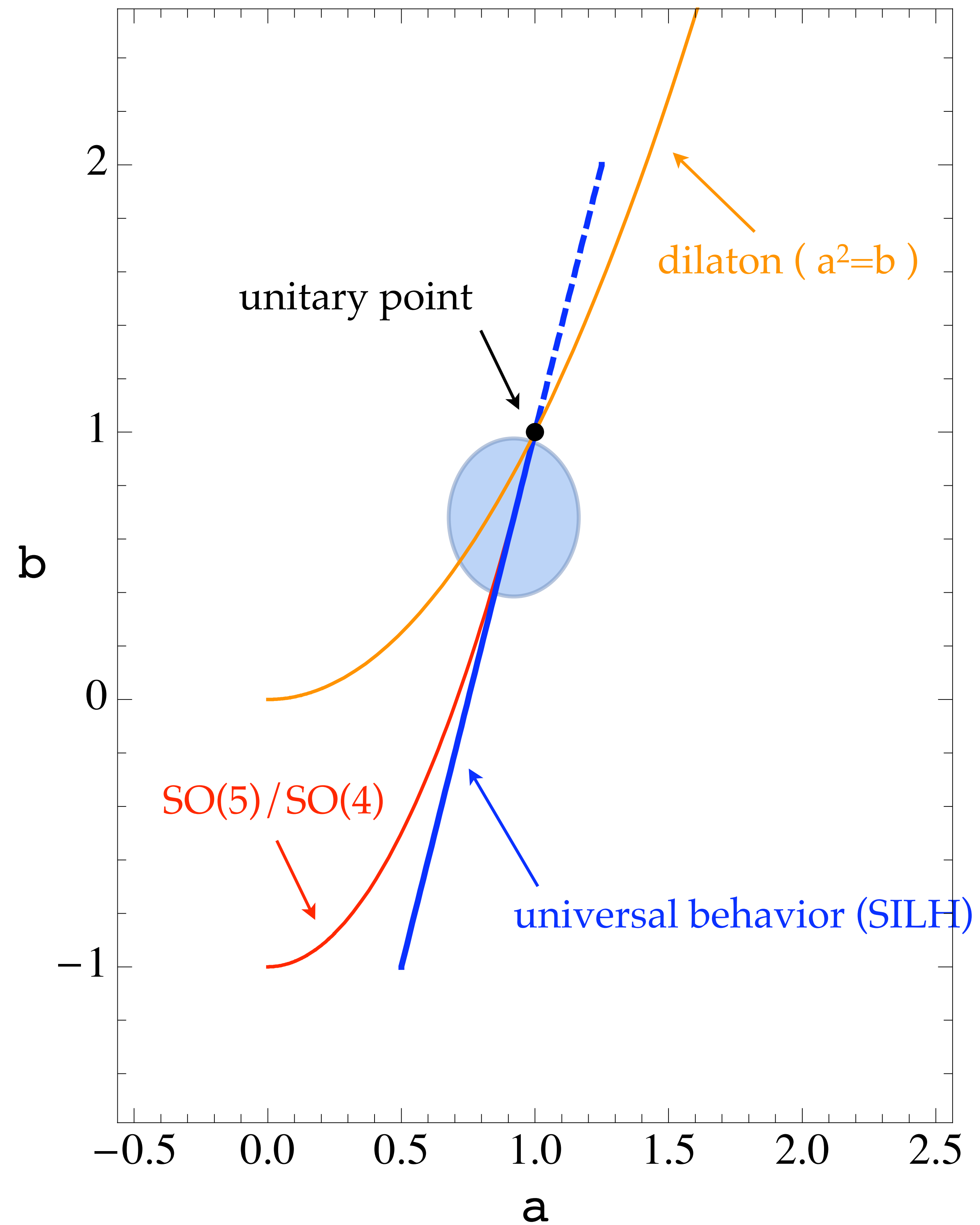
$$c_1 = +\frac{3}{16\pi^2}\,\frac{\alpha(M_Z)}{\cos^2\theta_W}$$

$$c_3 = -\frac{1}{12\pi}\,\frac{\alpha(M_Z)}{4\sin^2\theta_W}$$

$$\Delta\epsilon_{1,3} = -c_{1,3}\,(1-a^2)\log\left(\frac{m_\rho^2}{m_h^2}\right)$$



see: Barbieri et al. PRD 76 (2007) 115008



unitary point
dilaton (a²=b)
SO(5) / SO(4)
universal behavior (SILH)
b
a
2
1
0
−1
−0.5
0.0
0.5
1.0
1.5
2.0
2.5

An effective Lagrangian for the Strongly Interacting Light Higgs

built along the rules of the chiral expansion:

Giudice, Grojean, Pomarol, Rattazzi
JHEP 0706:045 (2007)

1. each extra Goldstone leg is weighted by a factor $1/f = g_\rho/m_\rho$
2. each derivative is weighted by a factor $1/m_\rho$
3. higher dimensional operators that violate the non-linear symmetry of the σ-model must be suppressed by g_{SM}

at the level of dimension-6 operators:

strong constraint from LEP

$\Delta\rho = c_T \xi$

$$\mathcal{L}_{\rm SILH} = \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)$$
$$- \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.}\right)$$

probe strong coupling

$$+ \frac{ic_W g}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{ic_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right)$$

1-loop suppressed →

$$+ \frac{ic_{HW} g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{ic_{HB} g'}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

more than 1-loop suppressed →

$$+ \frac{c_\gamma g'^2}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{c_g g_S^2}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}$$

form factors

dominant effect:

shift in the Higgs couplings

subdominant role in scattering amplitudes

one combination constrained by LEP: $\hat{S} = (c_W + c_B)\frac{m_W^2}{m_\rho^2}$

$$
\begin{aligned}
\mathcal{L}_{\text{SILH}} = & \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\
& - \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.}\right) \\
& + \frac{i c_W g}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i c_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
& + \frac{i c_{HW} g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i c_{HB} g'}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
& + \frac{c_\gamma {g'}^2}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g g_S^2}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}
\end{aligned}
$$

directly affect Higgs gluon production and Higgs decay to photons

(subdominant compared to c_H)

shifts in the Higgs couplings:

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

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

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

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

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

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

$$\left[\hat{c}_W = c_W + \left(\frac{g_\rho}{4\pi}\right)^2 c_{HW}\,,\quad \hat{c}_Z = \hat{c}_W + \tan^2\theta_W\left[c_B + \left(\frac{g_\rho}{4\pi}\right)^2 c_{HB}\right],\quad c_{\gamma Z} = \frac{c_{HB} - c_{HW}}{4\sin 2\theta_W}\right]$$

3. Elementary or Composite ?

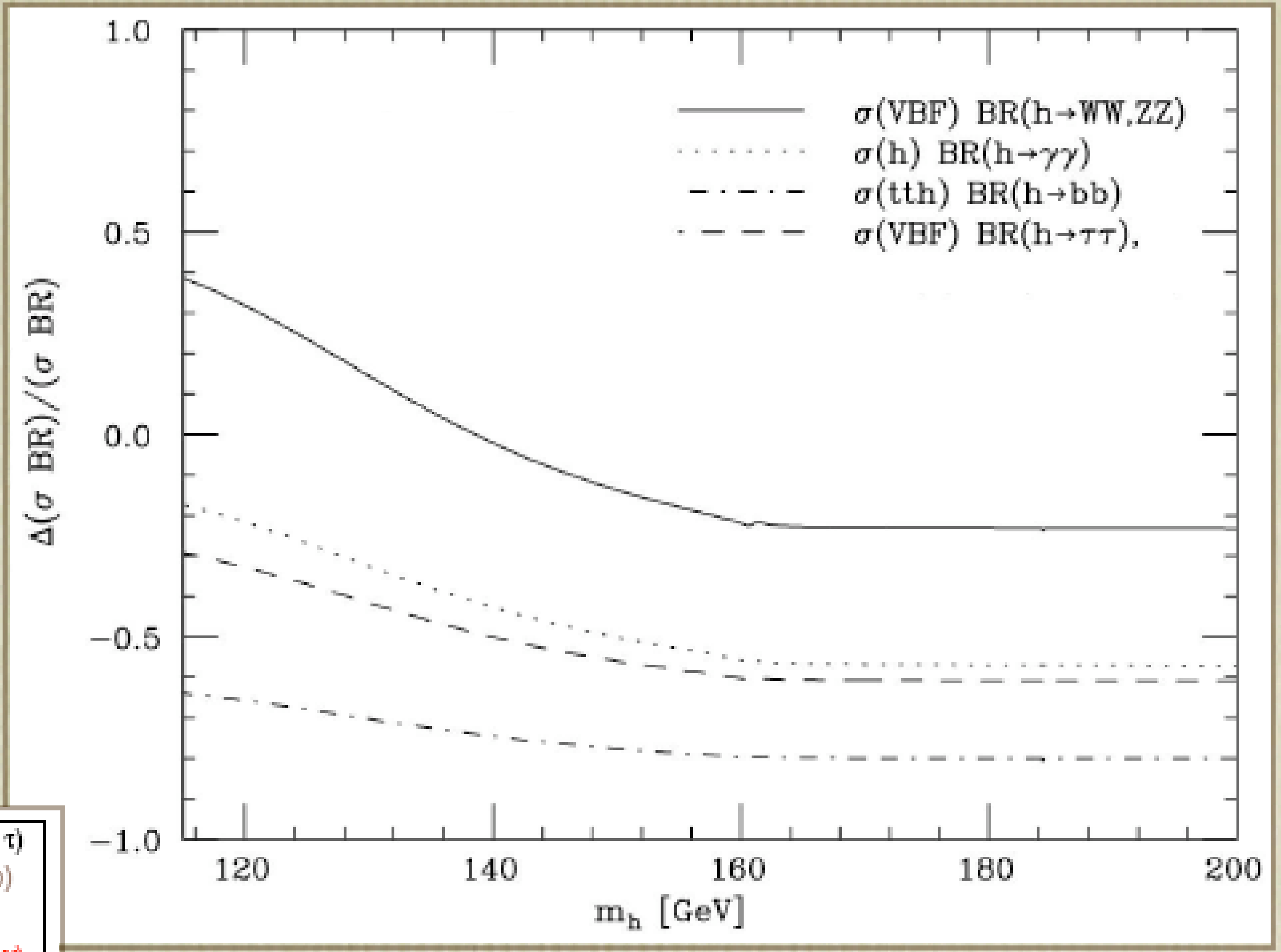
1. Measuring the Higgs couplings (determines a, c)

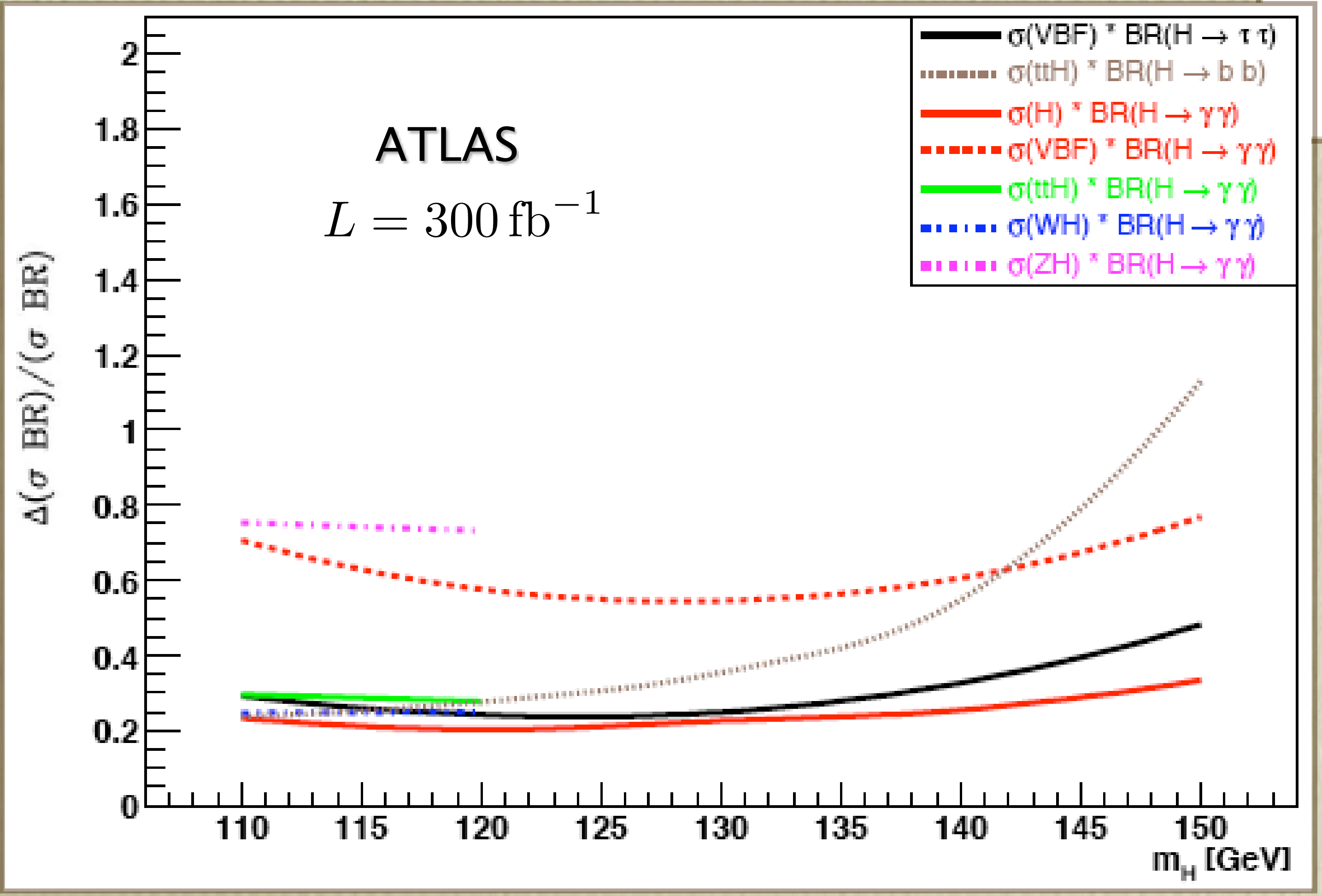
prediction for an SO(5)/SO(4) model

[$c_y/c_H = 1$] with $c_H\xi = 0.25$ →

[Giudice et al. JHEP 0706:045, 2007]

[R.C., DaRold, Pomarol PRD 75 (2007) 055014]





← LHC sensitive up to

$$\xi = 0.2 - 0.4$$

[Duhrssen ATL-PHYS-2003-030]

[Giudice et al. JHEP 0706:045, 2007]

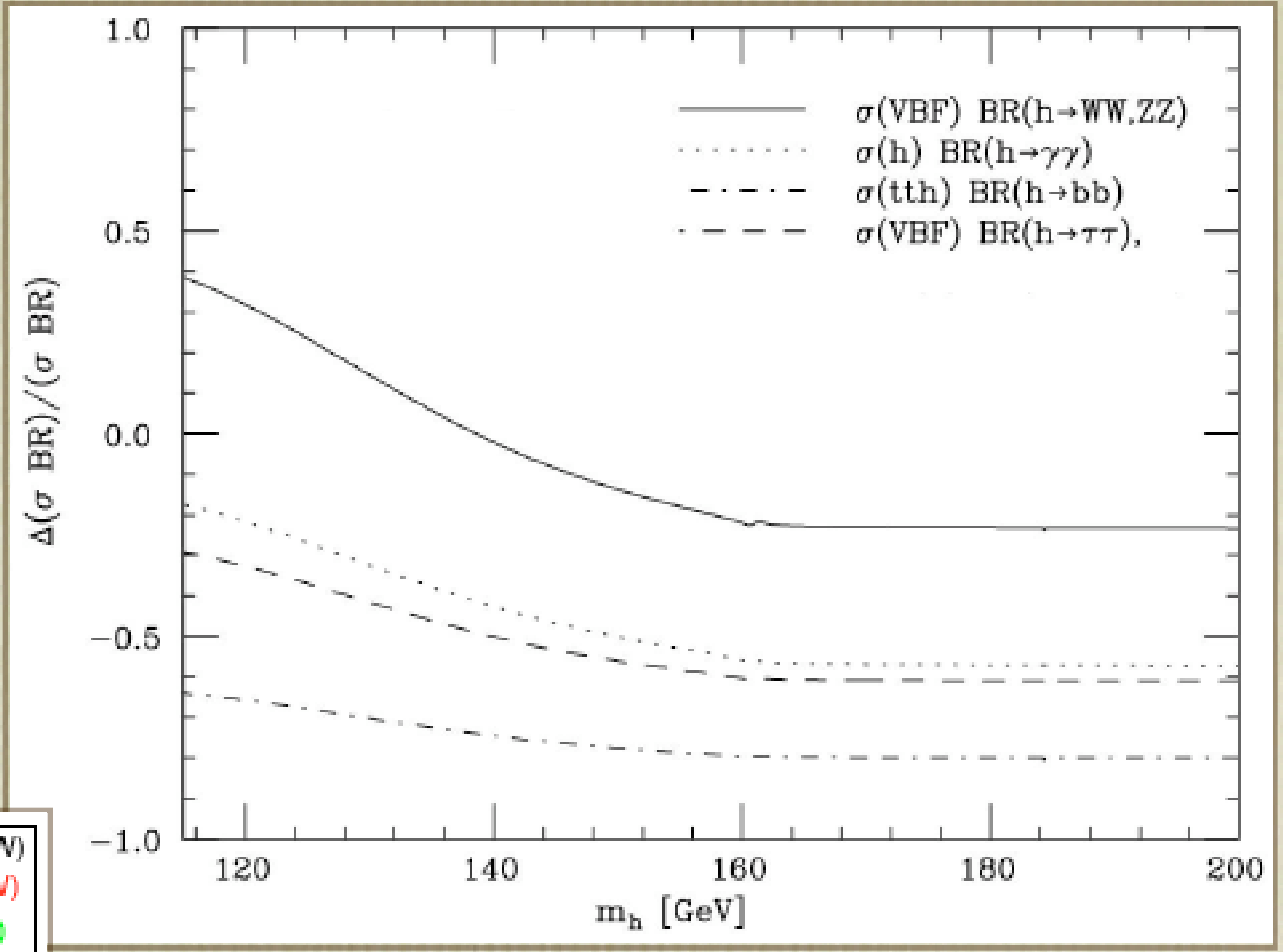
1. Measuring the Higgs couplings (determines a, c)

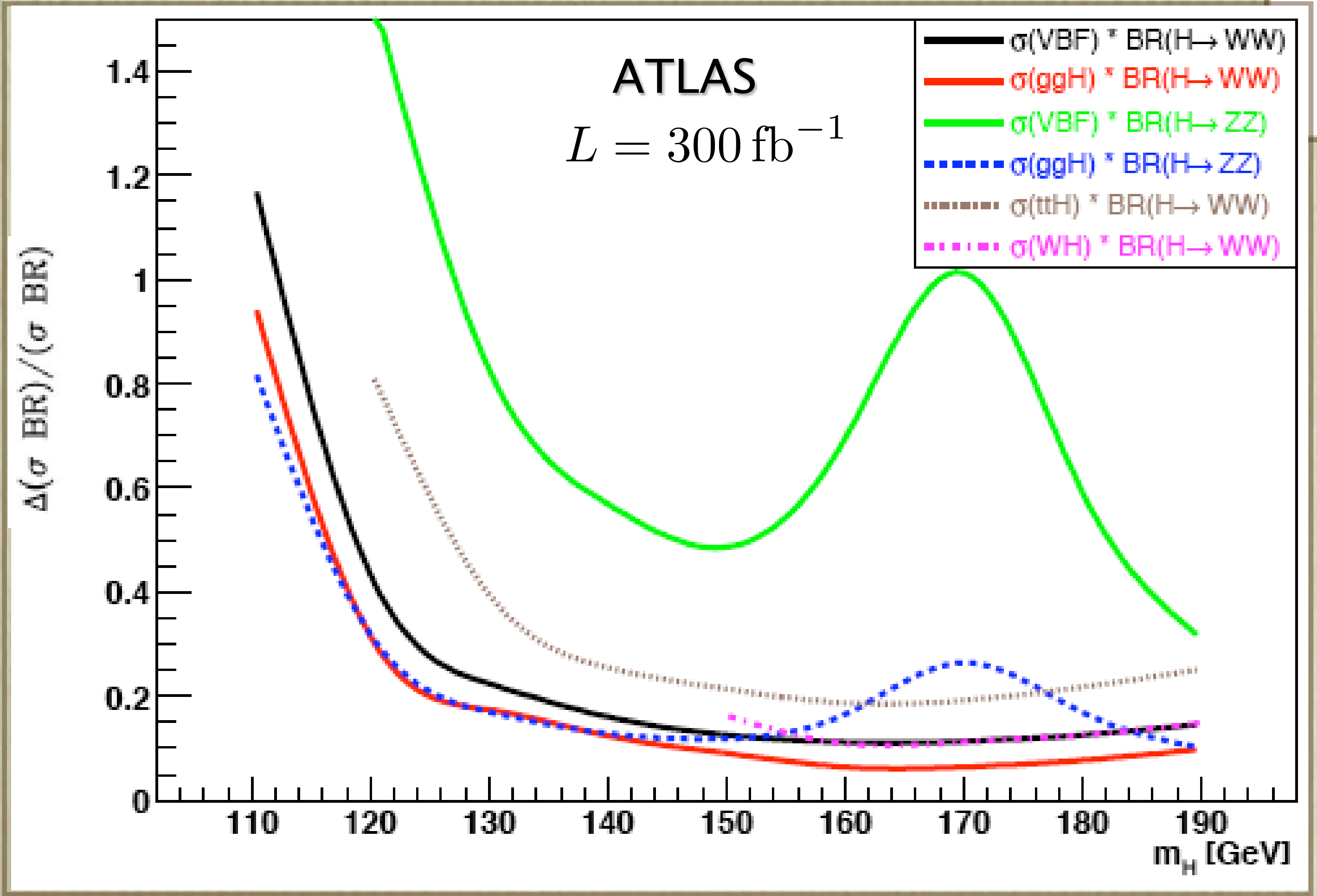
prediction for an SO(5)/SO(4) model

[$c_y/c_H = 1$] with $c_H\xi = 0.25$ →

[Giudice et al. JHEP 0706:045, 2007]

[R.C., DaRold, Pomarol PRD 75 (2007) 055014]





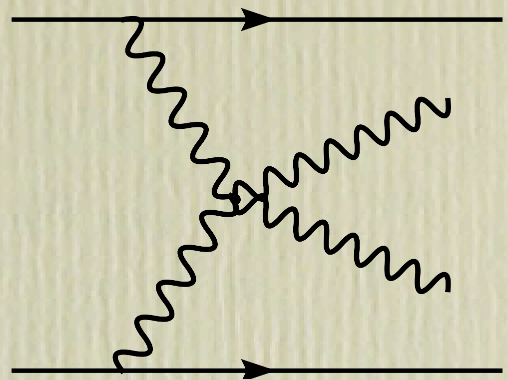
← LHC sensitive up to

$$\xi = 0.2 - 0.4$$

[Duhrssen ATL-PHYS-2003-030]

[Giudice et al. JHEP 0706:045, 2007]

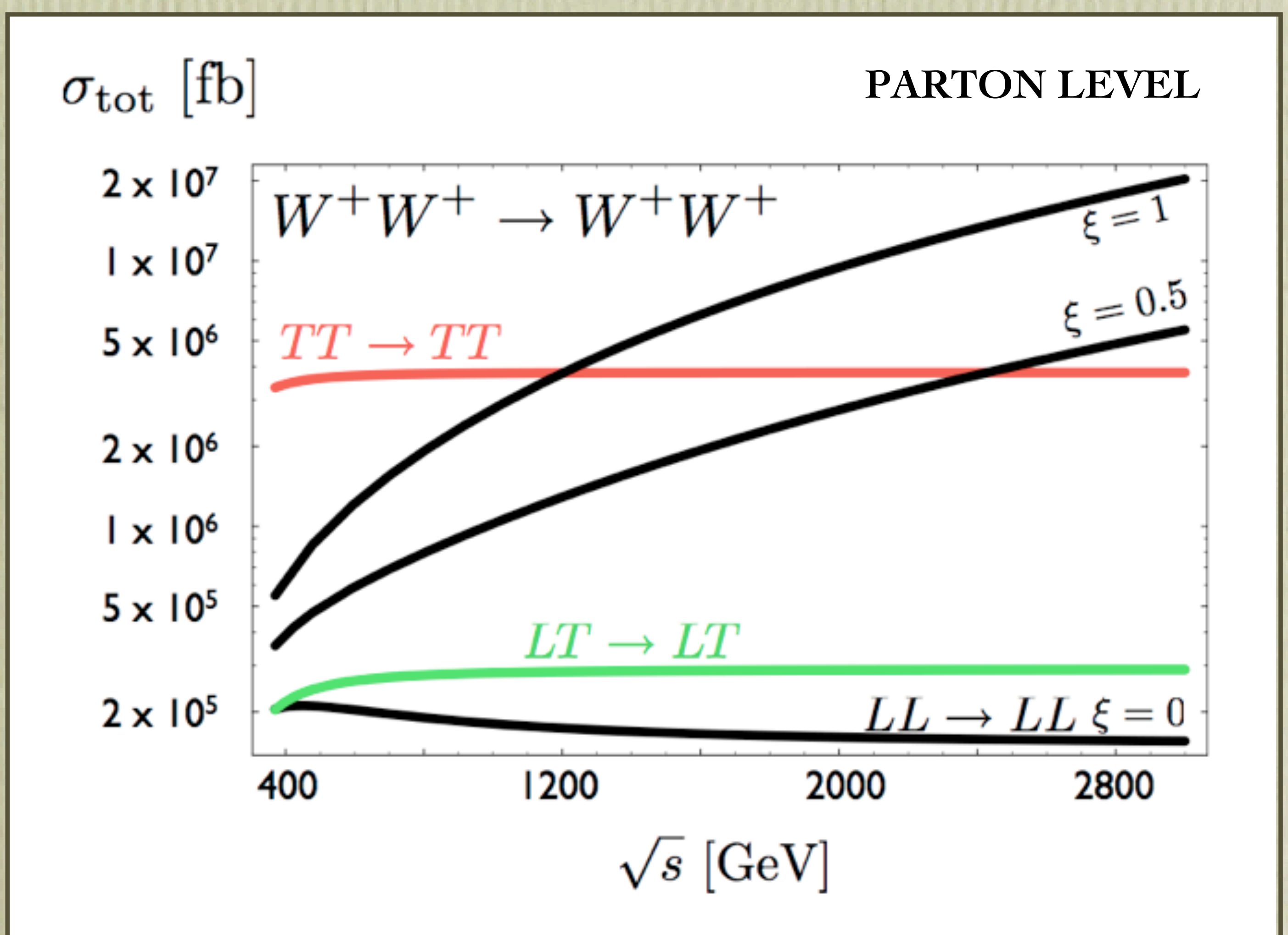
2. Study of $WW \to WW$ (determines a)



- Strong "pollution" from transverse polarizations
- The onset of the strong scattering is delayed to larger energies

Events per 100 fb^{-1} in the golden purely leptonic decay modes

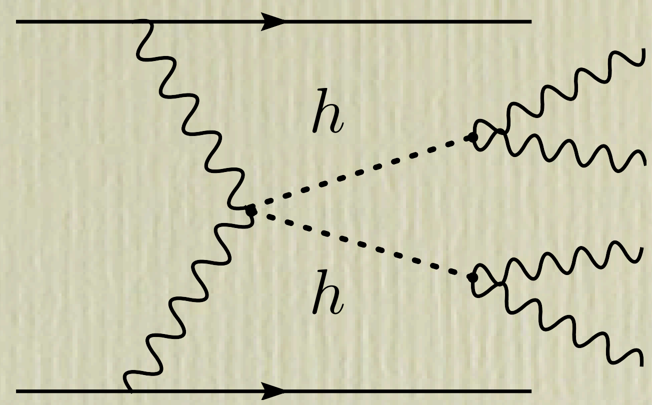
	signal $a=0$	SM	SM bckg
ZZ	1.5	9	0.7
W^+W^-	5.8	27	12
$W^\pm Z$	3.2	1.2	4.9
$W^\pm W^\pm$	13	5.6	3.7



$$\sigma(W_L W_L \text{ signal}) \equiv \sigma(a=0) - \sigma(\text{SM } m_h = 100\,\text{GeV})$$

[Bagger et al. PRD 52 (1995) 3878]

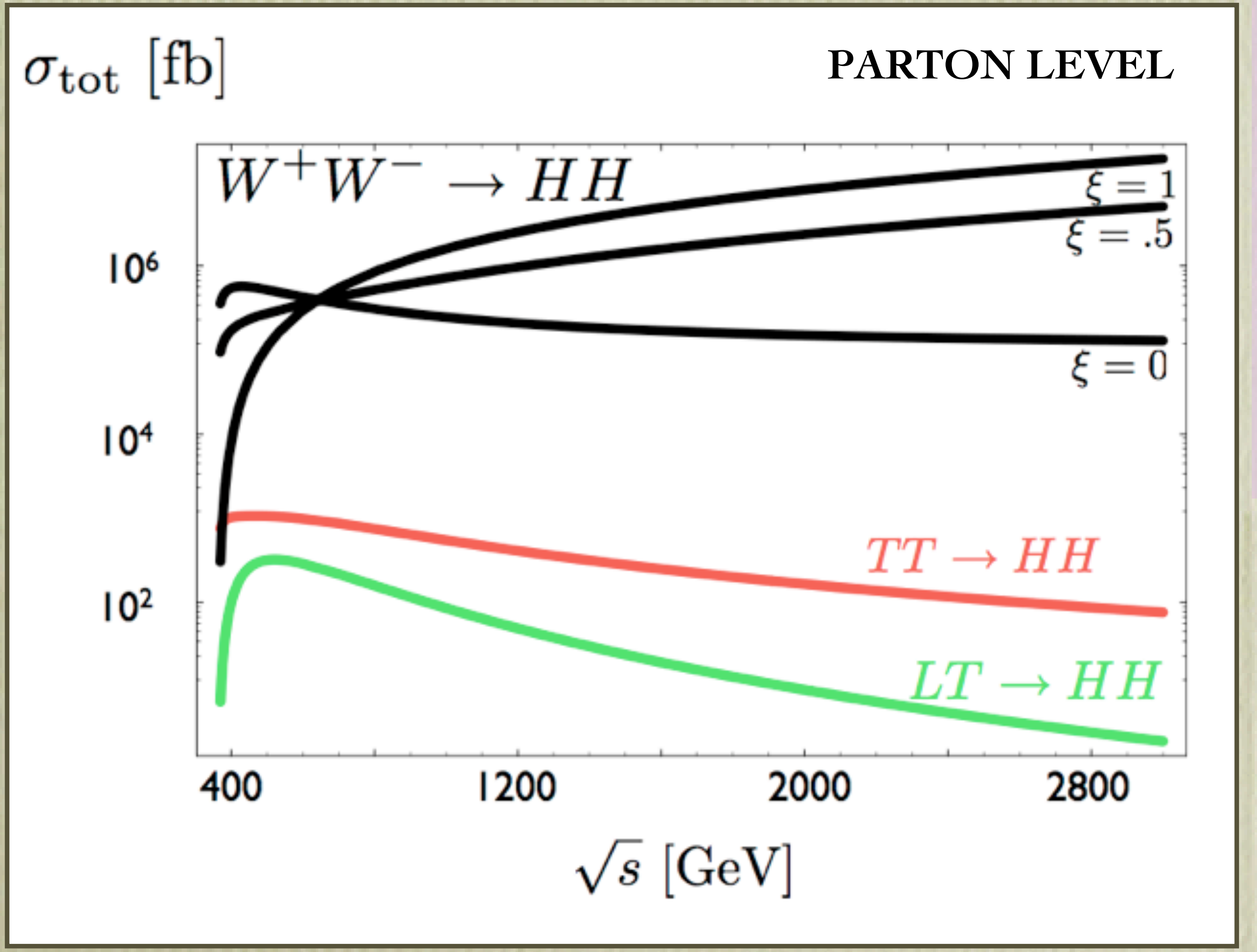
3. Study of $WW \to hh$ (determines b)



- Despite the more complex final state $WW \to hh$ is competitive with $WW \to WW$ to probe the Higgs strong interaction

Preliminary results for $m_h = 180\,\text{GeV}$

		N_{ev} (300 fb^{-1})	σ (300 fb^{-1})
3 leptons	$\xi = 1.0$	7.4	3.7
	$\xi = 0.8$	5.0	2.6
	$\xi = 0.5$	2.3	1.2
	Background	1.5	–
2 same-sign leptons	$\xi = 1.0$	23.6	4.0
	$\xi = 0.8$	16.0	2.8
	$\xi = 0.5$	7.6	1.3
	Background	26.2	–



[work in progress with Grojean, Moretti, Piccinini, Rattazzi]

Backup slides

CERN-OPEN-2008-020
December 2008

Supersymmetry 1513
Supersymmetry Searches 1514
Data-Driven Determinations of W, Z and Top Backgrounds to Supersymmetry 1525
Estimation of QCD Backgrounds to Searches for Supersymmetry 1562
Prospects for Supersymmetry Discovery Based on Inclusive Searches 1589
Measurements from Supersymmetric Events 1617
Multi-Lepton Supersymmetry Searches 1643
Supersymmetry Signatures with High-p_T Photons or Long-Lived Heavy Particles 1660
Exotic Processes 1695
Dilepton Resonances at High Mass 1696
Lepton plus Missing Transverse Energy Signals at High Mass 1726
Search for Leptoquark Pairs and Majorana Neutrinos from Right-Handed W Boson Decays in Dilepton-Jets Final States 1750
Vector Boson Scattering at High Mass 1769
Discovery Reach for Black Hole Production 1803

Expected Per

A detailed
ATLAS de
missing ene
of b-taggin
interesting
examined.
of the detec
the data exp

Process	Cross section (fb)		Luminosity (fb^{-1})		Significance
	signal	background	for 3σ	for 5σ	for 100 fb^{-1}
$WW/WZ \to \ell\nu\ jj$, $m = 500$ GeV	0.31 ± 0.05	0.79 ± 0.26	85	235	3.3 ± 0.7
$WW/WZ \to \ell\nu\ jj$, $m = 800$ GeV	0.65 ± 0.04	0.87 ± 0.28	20	60	6.3 ± 0.9
$WW/WZ \to \ell\nu\ jj$, $m = 1.1$ TeV	0.24 ± 0.03	0.46 ± 0.25	85	230	3.3 ± 0.8
$W_{jj}Z_{\ell\ell}$, $m = 500$ GeV	0.28 ± 0.04	0.20 ± 0.18	30	90	5.3 ± 1.9
$W_{\ell\nu}Z_{\ell\ell}$, $m = 500$ GeV	0.40 ± 0.03	0.25 ± 0.03	20	55	6.6 ± 0.5
$W_{jj}Z_{\ell\ell}$, $m = 800$ GeV	0.24 ± 0.02	0.30 ± 0.22	60	160	3.9 ± 1.2
$W_jZ_{\ell\ell}$, $m = 800$ GeV	$0.27 \pm 0.02 \pm 0.05$	$0.23 \pm 0.07 \pm 0.05$	38	105	4.9 ± 1.1
$W_jZ_{\ell\ell}$, $m = 1.1$ TeV	$0.19 \pm 0.01 \pm 0.04$	$0.22 \pm 0.07 \pm 0.05$	68	191	3.6 ± 1.0
$W_{\ell\nu}Z_{\ell\ell}$, $m = 1.1$ TeV	0.070 ± 0.004	0.020 ± 0.009	70	200	3.6 ± 0.5
$Z_{\nu\nu}Z_{\ell\ell}$, $m = 500$ GeV	0.32 ± 0.02	0.15 ± 0.03	20	60	6.6 ± 0.6

Table 10: Approximate signal and background cross sections expected after the analyses. An approximate value of the luminosity required for 3σ and 5σ significance, and the expected significance for 100 fb^{-1} are shown. The uncertainties, when given, are due to Monte Carlo statistics only.

- At the ILC one would test $\frac{v^2}{f^2}$ 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

Table 2.2.6: *Relative accuracy on Higgs couplings and their ratios obtained from a global fit (see text). An integrated luminosity of 500 fb^{-1} at $\sqrt{s} = 500$ GeV is assumed except for the measurement of g_{Htt}, which assumes 1000 fb^{-1} at $\sqrt{s} =$ 800 GeV in addition.*

Barger, Han, Langacker, McElrath, Zerwas 03

Aguilar-Saavedra et al. ECFA/DESY LC Physics WG

- Also test deviation from SM in Higgs potential $\frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3$: $\frac{c_6\lambda}{f^2} < 20\%$

ILC can rule out Higgs compositeness scale $4\pi f$ below $30\ \mathrm{TeV}$

[From Rattazzi, talk at Princeton 07]

Trilinear vector boson couplings

$$\mathcal{L}_V = -ig\cos\theta_W g_1^Z Z^\mu \left(W^{+\nu}W^-_{\mu\nu} - W^{-\nu}W^+_{\mu\nu}\right) \\ -ig\left(\cos\theta_W \kappa_Z Z^{\mu\nu} + \sin\theta_W \kappa_\gamma A^{\mu\nu}\right) W^+_\mu W^-_\nu$$

$$g_1^Z = \frac{m_Z^2}{m_\rho^2}\left[c_W + (\frac{g_\rho}{4\pi})^2 c_{HW}\right]$$

$$\kappa_\gamma = \frac{m_W^2}{m_\rho^2}\left(\frac{g_\rho}{4\pi}\right)^2 (c_{HW} + c_{HB}), \qquad \kappa_Z = g_1^Z - \tan^2\theta_W \kappa_\gamma$$

other trilinears $\lambda_{Z,\gamma} \sim \frac{\alpha_W}{4\pi} k_{Z,\gamma}$ → negligible

LHC with 100 fb^{-1} can test down to $g_1^Z = 1\%$, $k_{Z,\gamma} = 5\%$

weaker sensitivity on m_ρ than from direct production of heavy states

or than LEP bound $\widehat{S} < 2 \times 10^{-3}$

[From Rattazzi, talk at Princeton 07]