THE HIGGS BOSON

Elementary or Composite ?

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OUR CURRENT DESCRIPTION OF FUNDAMENTAL INTERACTIONS

- 1860's Theory of Electromagnetism
- 1896 Discovery of Radioactivity
- 1897 Discovery of the electron
- 1930 Neutrino hypothesis
- 1934 Theory of β-decay
- 1940's QED
- 1957 Discovery of Parity Violation
- 1964 Discovery of CP Violation
- 1960's The Standard Model
- 1960's-1970's Discovery of matter triplication
- 1960-70's Discovery of Quarks and QCD
- 1971-72 The SM renormalizable
- 1973 Discovery of Neutral Currents
- 1983 Discovery of Weak Bosons
- 2000 Neutrino Masses

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + \bar{\Psi}\, i\not{D}\, \Psi$$

$$+ M^2 A_\mu A^\mu + m_\Psi \bar{\Psi}\Psi$$

TWO OPEN PROBLEMS

- Mechanism of ElectroWeak Symmetry Breaking $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$

  how matter and weak vector bosons acquire mass ?

- Origin of the Planck-ElectroWeak Hierarchy $M_W/M_{Pl} \sim 10^{-17}$

  why M_W is so small compared to the Planck scale M_{Pl}?

SPONTANEOUSLY BROKEN SYMMETRIES

Let U be an element of a symmetry group G that leaves the Hamiltonian $\mathcal{H}$ invariant:

$$U^\dagger \mathcal{H} U = \mathcal{H}$$

Consider two states $|A\rangle$ and $|B\rangle$ such that:

$$\Phi_A|0\rangle = |A\rangle \qquad \Phi_B|0\rangle = |B\rangle \qquad U\,\Phi_A\,U^\dagger = \Phi_B$$

There are two possibilities:

- the vacuum is invariant under G:

$$U|0\rangle = |0\rangle$$

then $|A\rangle$ and $|B\rangle$ are degenerate:

$$U|A\rangle = U\Phi_A|0\rangle = \Phi_B U|0\rangle = |B\rangle$$

$$E_A = \langle A|\mathcal{H}|A\rangle = \langle B|\mathcal{H}|B\rangle = E_B$$

- the vacuum is not invariant:

symmetry G <u>not</u> manifest in the spectrum of energy levels

selection rules still follow from the invariance of the Hamiltonian

$\partial^\mu J^a_\mu(x) = 0$ conserved currents (Noether)

$U\Phi_i U^\dagger = R_{ij}\Phi_j$ $\langle 0|\Phi_i|0\rangle \neq \langle 0|U\Phi_i U^\dagger|0\rangle \simeq \langle 0|\Phi_i|0\rangle + i\alpha^a\langle 0|T^a_{ij}\Phi_j|0\rangle$

$\langle 0|T^a_{ij}\Phi_j|0\rangle \neq 0$

<u>Theorem</u> (Goldstone)

$\forall\, T^a \;/\; \langle 0|T^a_{ij}\Phi_j|0\rangle \neq 0$ there is a massless state π^a

$\langle 0|J^a_0|\pi^a\rangle \neq 0$

(Nambu-Goldstone boson)

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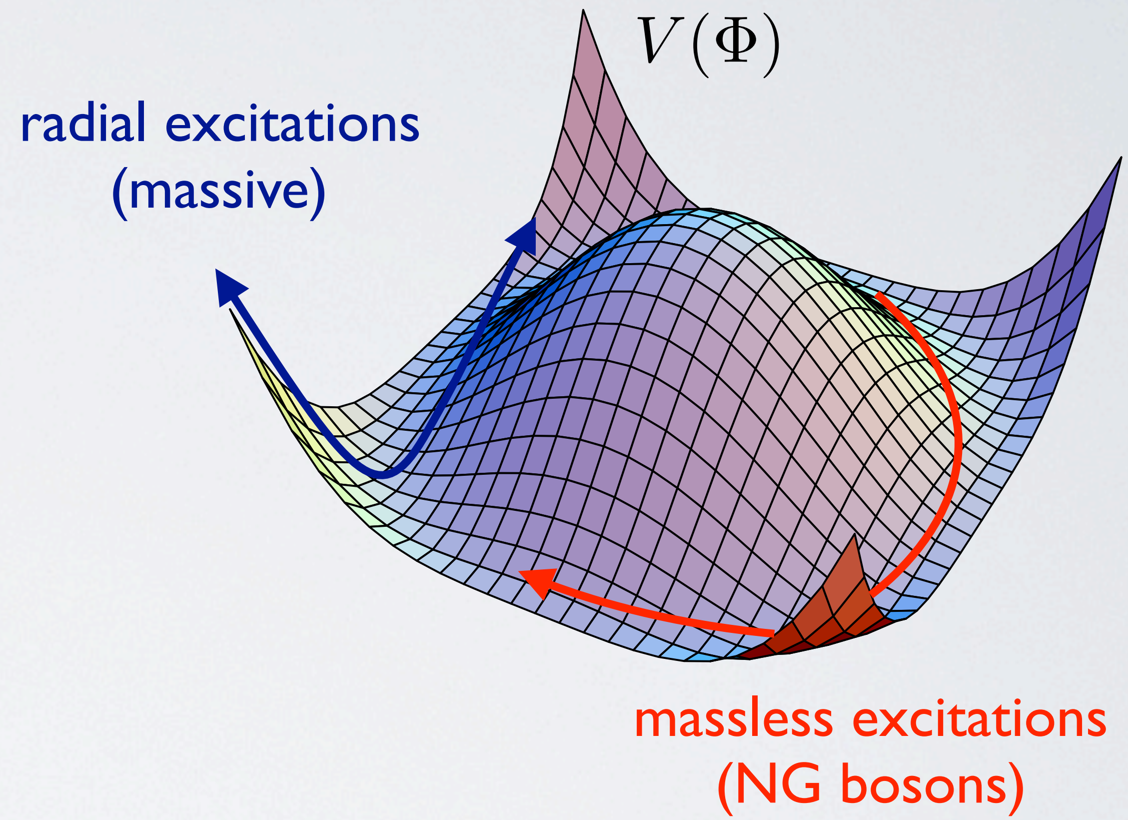

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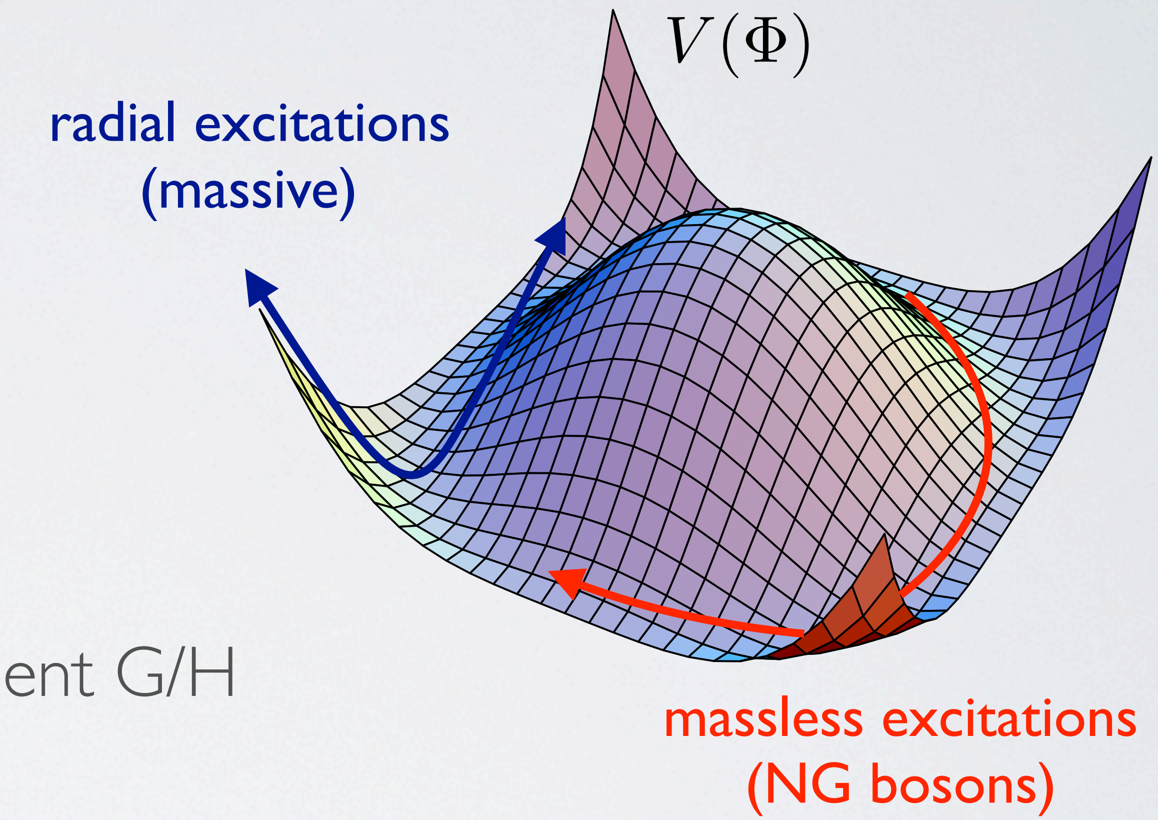
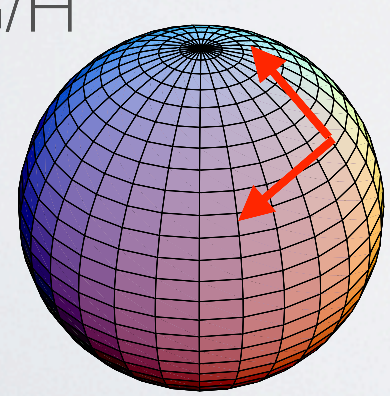


Nambu-Goldstone bosons live on the quotient G/H

G/H



$$\langle 0|T^a_{ij}\Phi_j|0\rangle = 0 \qquad T^a \in \mathrm{Alg}(H)$$

$$\langle 0|T^{\hat{a}}_{ij}\Phi_j|0\rangle \neq 0 \qquad T^{\hat{a}} \in \mathrm{Alg}(G/H)$$

- the vacuum is not invariant:

symmetry G <u>not</u> manifest in the spectrum of energy levels

selection rules still follow from the invariance of the Hamiltonian

$$\partial^\mu J_\mu^a(x) = 0$$

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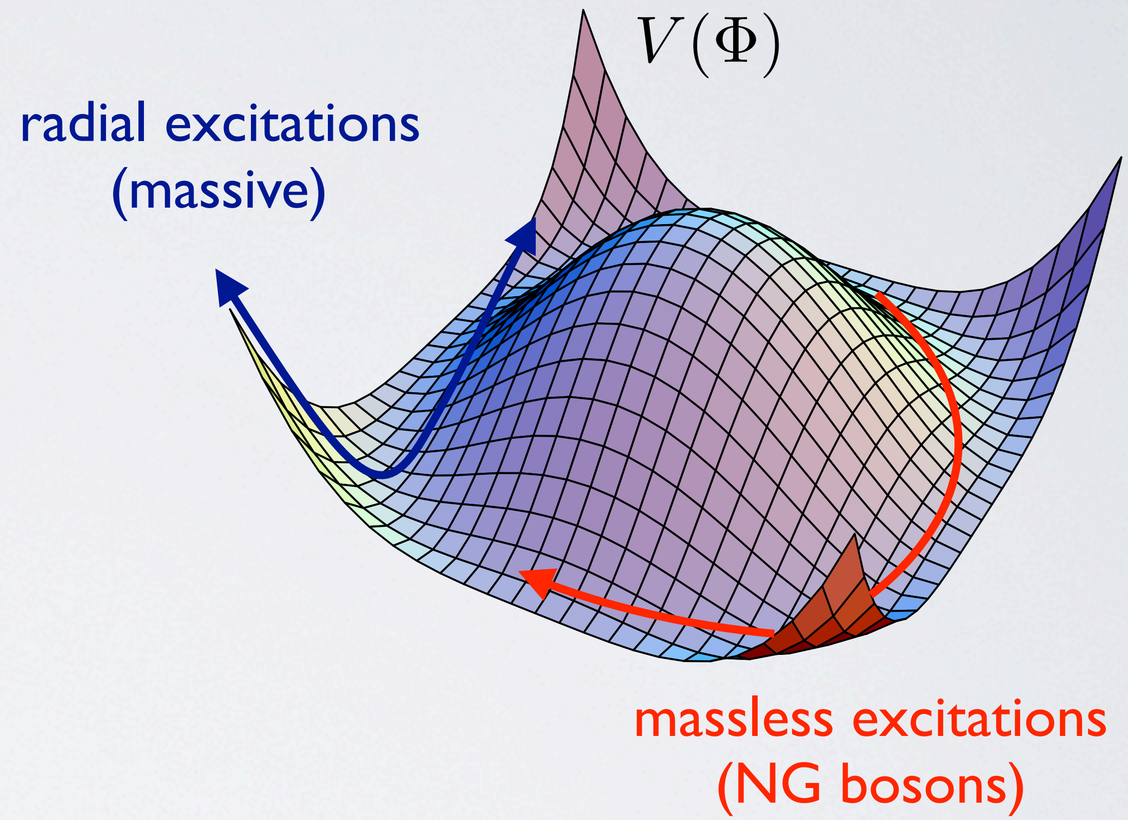
$$\langle 0|T_{ij}^a \Phi_j|0\rangle \neq 0$$



Theorem (Higgs)

If the symmetry is gauged the NG bosons are 'eaten' to form the longitudinal polarizations of the gauge field, which becomes massive

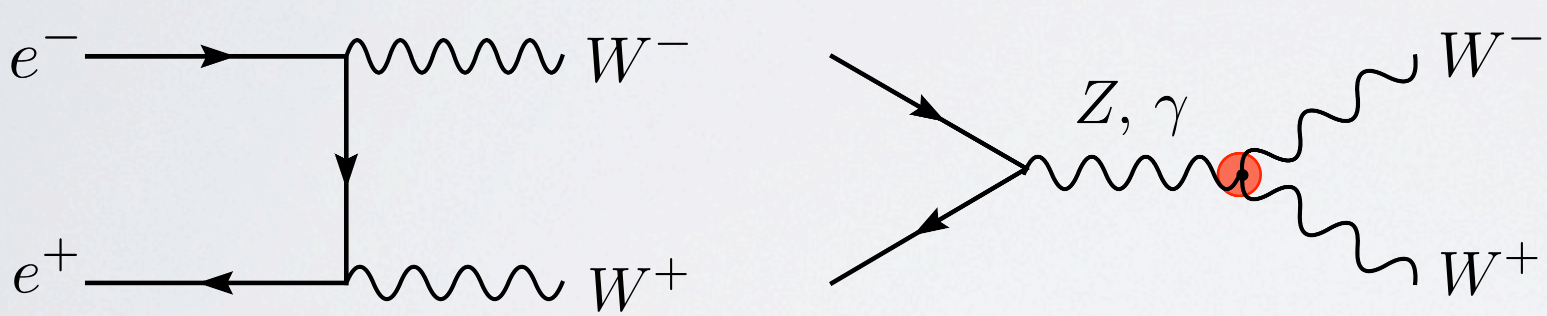
$$\pi^a \rightarrow A_L^{\mu\, a}$$

SPONTANEOUSLY BROKEN ELECTROWEAK SYMMETRY

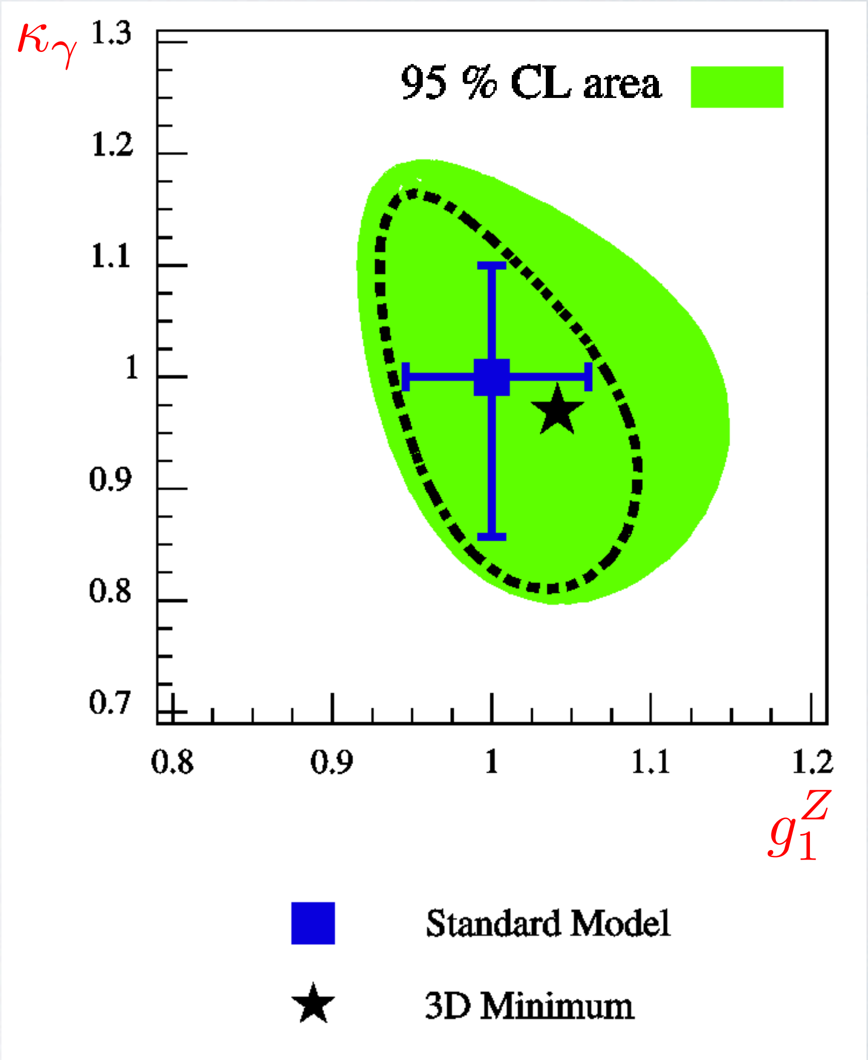
Interactions invariant under $SU(2)_L \times U(1)_Y$

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

Ex: Triple gauge couplings tested at LEP



$$i\mathcal{L} = e \cot\theta_W \left[g_1^Z\, Z^\mu (W^-_{\mu\nu} W^{+\,\nu} - W^+_{\mu\nu} W^{-\,\nu}) + \kappa_Z\, W^+_\mu W^-_\nu Z^{\mu\nu} + \lambda_Z\, W^{+\,\rho}_\nu W^-_{\rho\mu} Z^{\mu\nu} \right] + e \left[\kappa_\gamma\, W^+_\mu W^-_\nu \gamma^{\mu\nu} + \lambda_\gamma\, W^{+\,\rho}_\nu W^-_{\rho\mu} \gamma^{\mu\nu} \right]$$



SPONTANEOUSLY BROKEN ELECTROWEAK SYMMETRY

Interactions invariant under $SU(2)_L \times U(1)_Y$

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

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

Mass spectrum has a smaller $U(1)_{em}$ invariance

THE $SU(2)_L \times U(1)_Y$ SYMMETRY IS "HIDDEN"

MAKING THE $SU(2)_L \times U(1)_Y$ SYMMETRY MANIFEST

- Reintroduce the NG-boson (and choose a non-unitary gauge):

$$\Sigma = \exp\left(i\sigma^a \chi^a / v\right) \qquad D_\mu \Sigma = \partial_\mu \Sigma - i g_2 \frac{\sigma^a}{2} W_\mu^a \Sigma + i g_1 \Sigma \frac{\sigma_3}{2} B_\mu$$

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

$$\mathcal{L}_{mass} = \boxed{\frac{v^2}{4}\mathrm{Tr}\left[(D_\mu\Sigma)^\dagger (D^\mu \Sigma)\right] + \frac{a_T}{8} v^2 \, \mathrm{Tr}\left[\Sigma^\dagger D_\mu \Sigma \, \sigma^3\right]^2} - \frac{v}{\sqrt{2}} \sum_{i,j} (\bar{u}_L^{(i)} \; \bar{d}_L^{(i)}) \Sigma \begin{pmatrix} \lambda_{ij}^u u_R^{(j)} \\ \lambda_{ij}^d d_R^{(j)} \end{pmatrix} + h.c.$$

$$\boxed{\begin{aligned} M_W^2 &= \frac{v^2}{4} g_2^2 \\ M_Z^2 &= \frac{v^2}{4}(g_1^2 + g_2^2)(1 + a_T) \end{aligned}}$$

TWO IMPORTANT CLUES FROM LEP

[1.] CUSTODIAL SYMMETRY

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

Experimentally: $(\rho - 1) \lesssim 2 \times 10^{-3}$

Predicted: $\rho = \dfrac{1}{1 + \cancel{a_T}}$

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

$$+\cancel{\frac{a_T}{8}v^2\,\mathrm{Tr}[\Sigma^\dagger D_\mu\Sigma\,\sigma^3]^2}$$

must be SMALL

TWO IMPORTANT CLUES FROM LEP

[1.] CUSTODIAL SYMMETRY

- For $a_T = 0$, in the limit $g_1 = 0$, $\lambda^u = \lambda^d$, there is a larger SU(2)L x SU(2)R global symmetry $\quad \Sigma \to U_L \Sigma U_R^\dagger$

$$\Sigma = \exp\left(i\sigma^a \chi^a / v\right) \qquad D_\mu \Sigma = \partial_\mu \Sigma - i g_2 \frac{\sigma^a}{2} W_\mu^a \Sigma + i g_1 \Sigma \frac{\sigma_3}{2} B_\mu$$

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

- The vacuum $\langle \Sigma \rangle = 1$ breaks SU(2)LxSU(2)R→SU(2)V

  the NG bosons χ^a transform as a triplet under the custodial SU(2)V $\longrightarrow$ $M_W = M_Z$ for $g_1 = 0$

TWO IMPORTANT CLUES FROM LEP

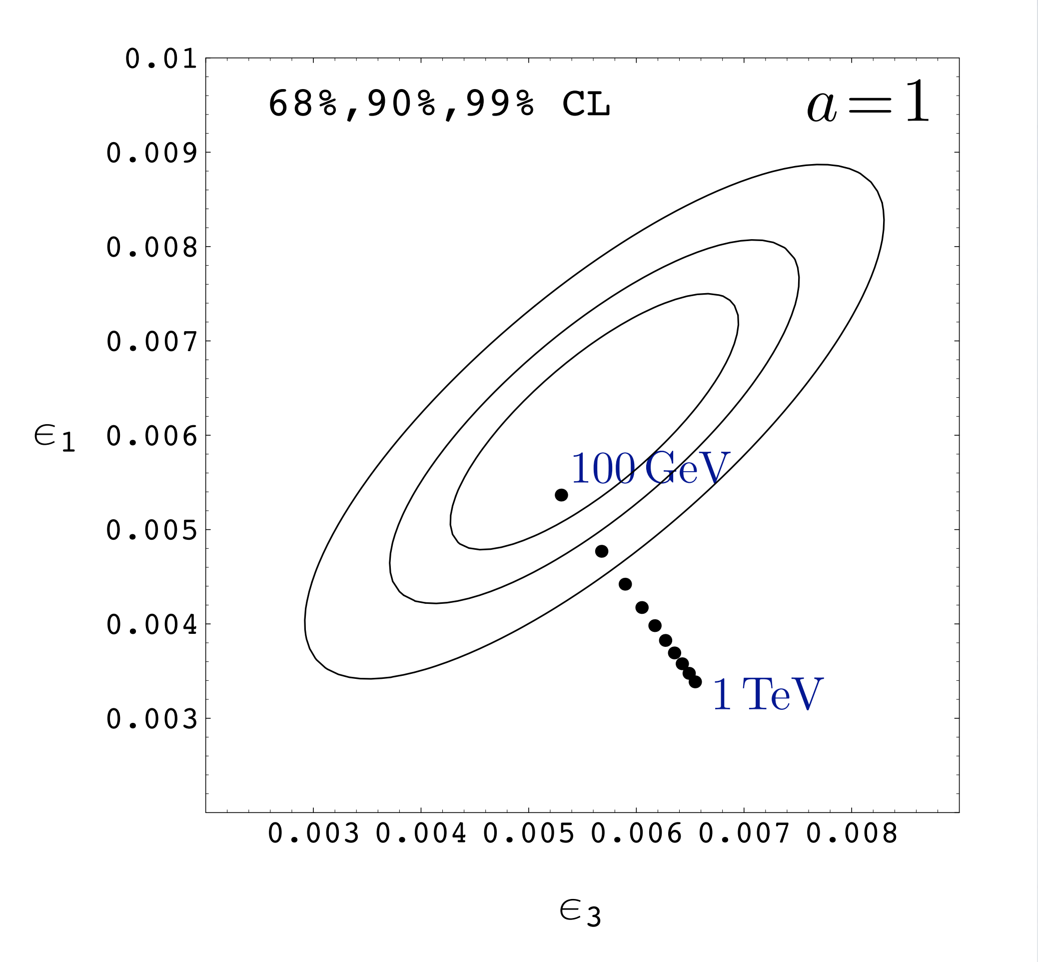
[2.] `EVIDENCE` FOR A LIGHT HIGGS BOSON

- Add an $SU(2)_L \times SU(2)_R$ scalar singlet h

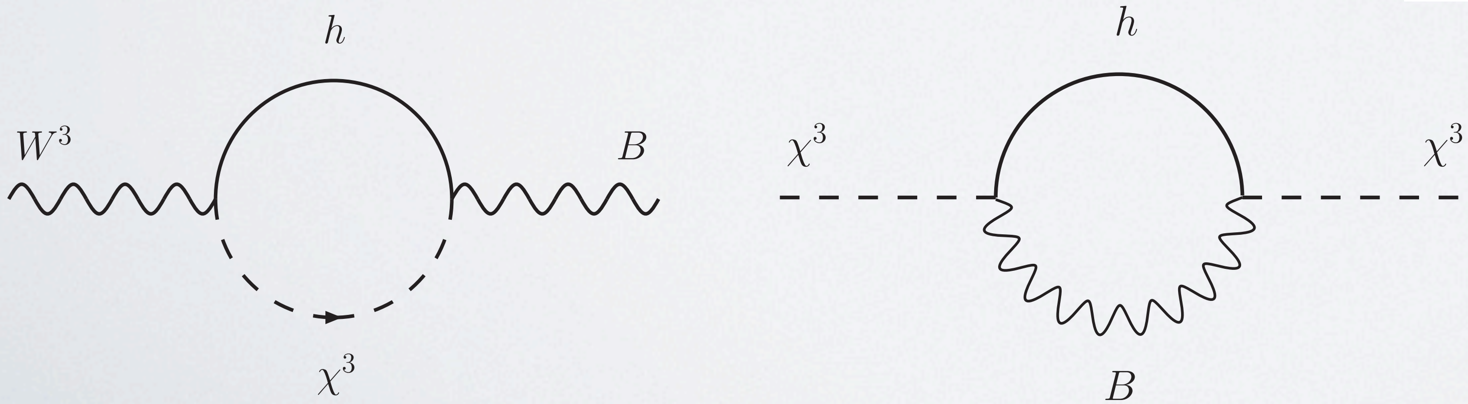
$$\mathcal{L}_{EWSB} = \frac{v^2}{4} \mathrm{Tr}\left[D_\mu \Sigma^\dagger D^\mu \Sigma\right] \left(1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + \cdots \right)$$

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

a, b, c are free parameters



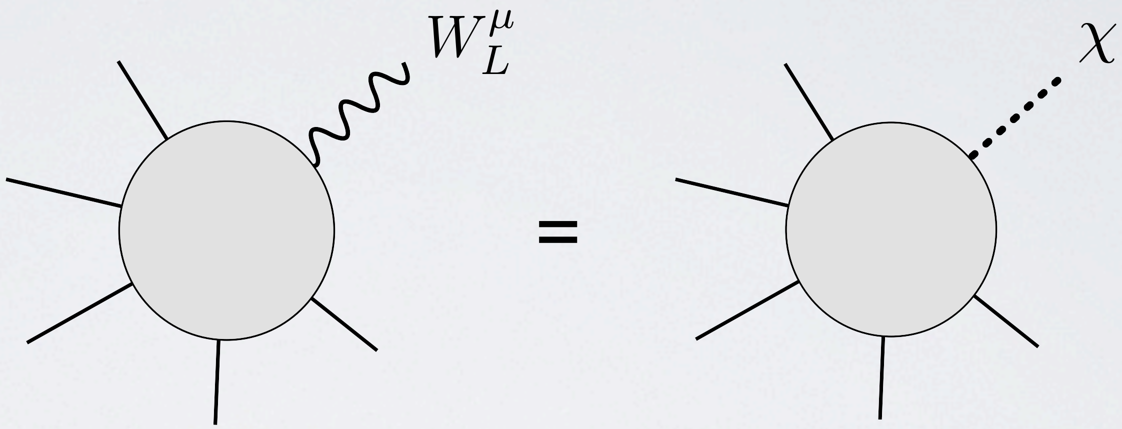
- $\mathrm{Log}(m_h)$ dependence through loop effects



NEED FOR AN EWSB SECTOR

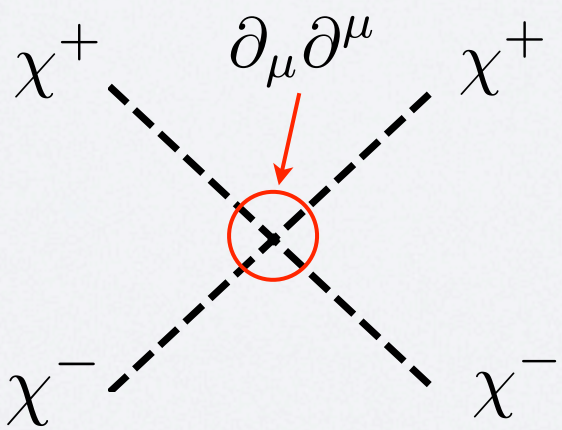
- New dynamics needed at large energy: Theory not unitary or strongly coupled

Most easily seen using the Equivalence Theorem:



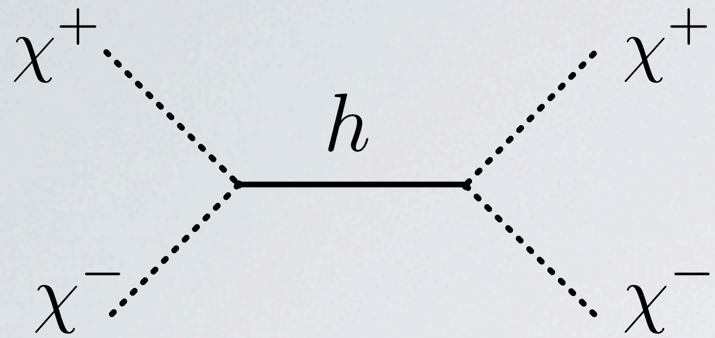
$$\left(1 + O\left(\frac{M_W^2}{E^2}\right)\right)$$

Perturbative unitarity violated at $E \gg M_W$ in the scattering of two NG bosons:



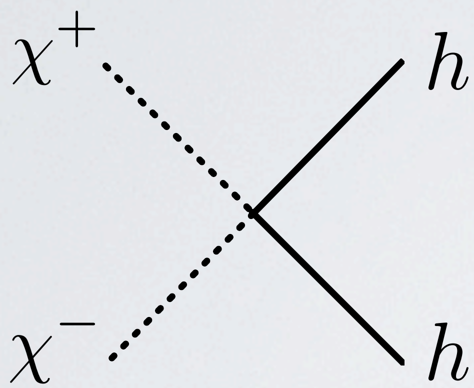
$$A(\chi^+\chi^- \to \chi^+\chi^-) = \frac{1}{v^2}\,(s+t)$$

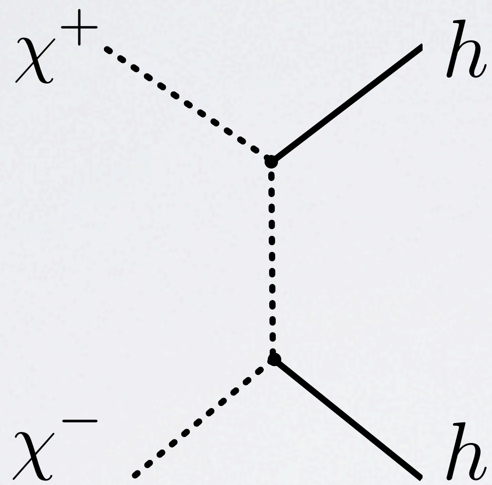
A scalar h can restore perturbative unitarity:



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

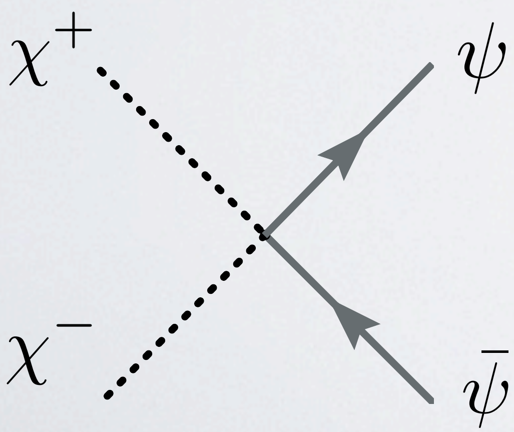
unitarity for: a=1

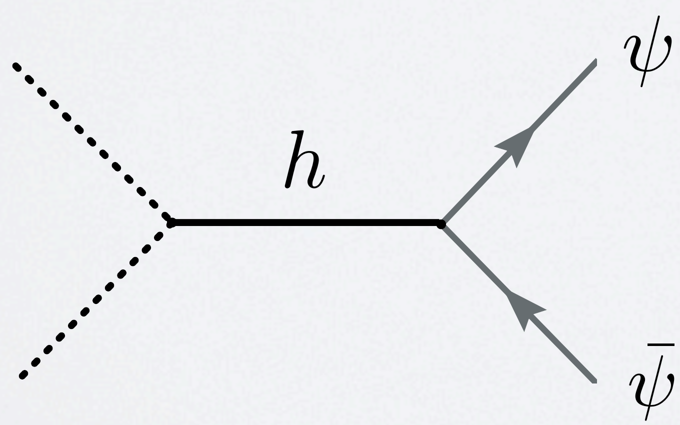




$$\mathcal{A}(\chi^+\chi^- \to hh) \simeq \frac{s}{v^2}\boxed{(b - a^2)}$$

unitarity for: a^2=b





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

unitarity for: a=c

- a=b=c=1 defines the Higgs model, whose Lagrangian can be rewritten in terms of the $SU(2)_L$ doublet H:

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

- Unitarity of the model follows from its renormalizability

- There is an unbroken custodial symmetry SO(3):

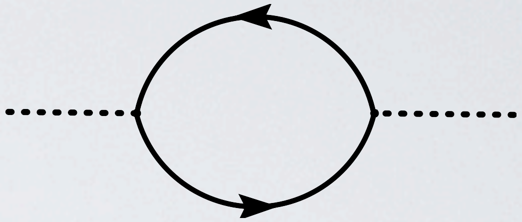
$$H = \begin{pmatrix} w_1 + i\, w_2 \\ w_3 + i\, w_4 \end{pmatrix} \qquad H^\dagger H = \sum_i (w_i)^2$$

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

$\langle H^\dagger H \rangle = v^2$ breaks $SO(4) \rightarrow SO(3) \sim SU(2)_V$

HIGGS BOSON: ELEMENTARY ?

- A light elementary scalar is highly unnatural in absence of a symmetry protection



Higgs mass naturally of order $\sim \Lambda$

$$\delta m_h^2 = \left[6\, y_t^2 - \frac{3}{4}\left(3\, g_2^2 + g_1^2\right) - 6\, \lambda_4 \right] \frac{\Lambda^2}{8\pi^2}$$

The larger Λ the less natural a light Higgs is

- Not an accident: No elementary scalar has been found so far !

- The cutoff Λ might be low: the Higgs model should be perhaps regarded as a parametrization rather than a mechanism of EWSB

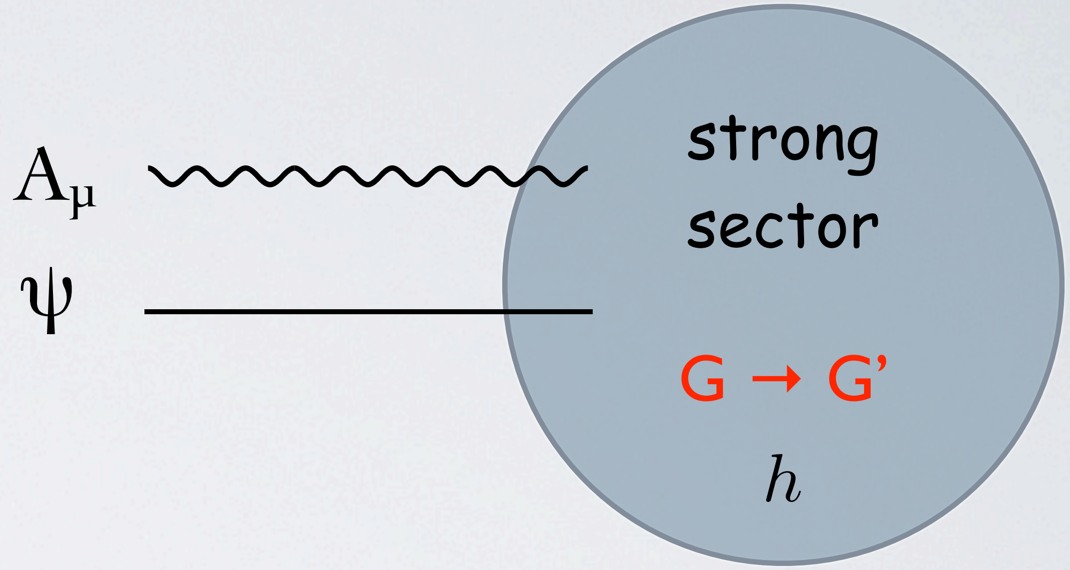
THE COMPOSITE HIGGS

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

[Georgi & Kaplan, `80]

Motivations:

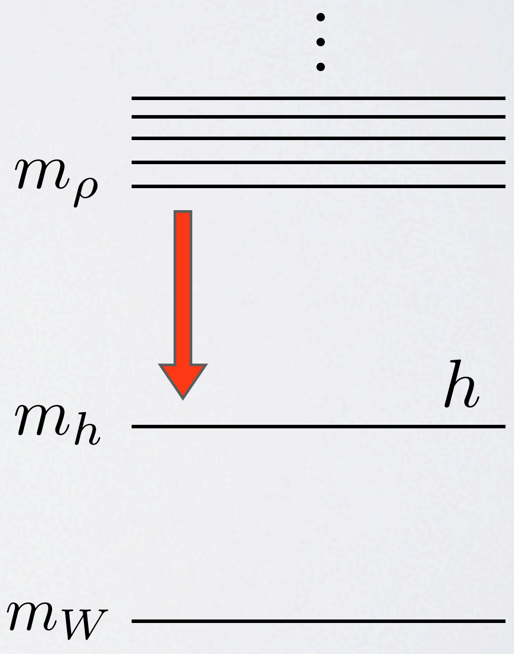
- A composite Higgs solves the hierarchy problem
- A light Higgs is preferred by the EW fit



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

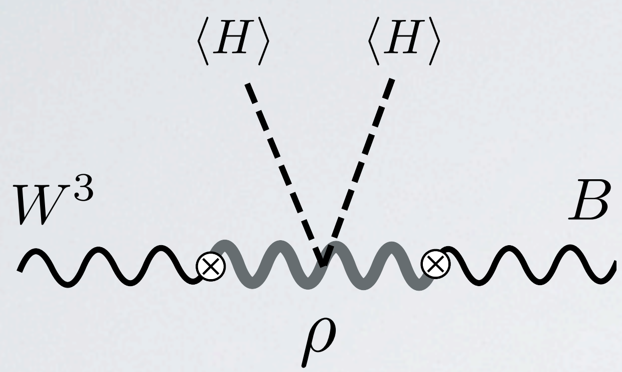
enlarge the global symmetry of the strong sector to have a full $SU(2)_L$ doublet

ex: SO(5) → SO(4)

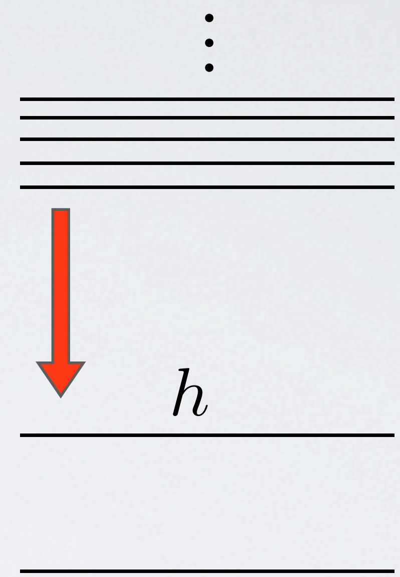


[Agashe, RC, Pomarol, NPB 719 (2005) 165]

- Composite Higgs lighter than the other resonances required by LEP precision tests



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



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

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

m_W

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

new parameter compared to TC
(fixed by dynamics)

$\xi \to 0$
$[\, f \to \infty \,]$

decoupling limit

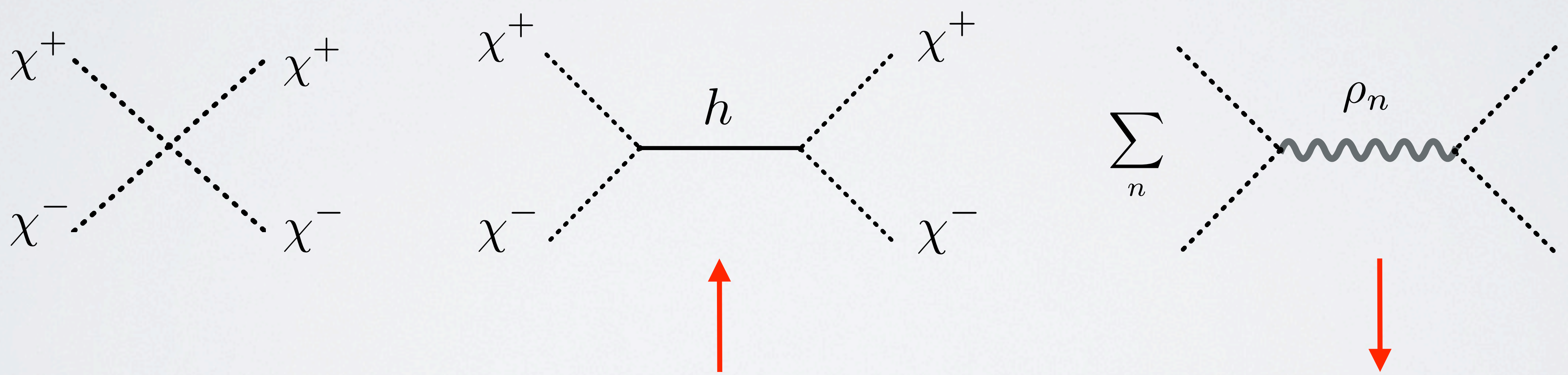
All ρ's become heavy and one reobtains the SM

Shifts in the Higgs couplings at $O(\xi)$

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

Ex: SO(5) → SO(4)

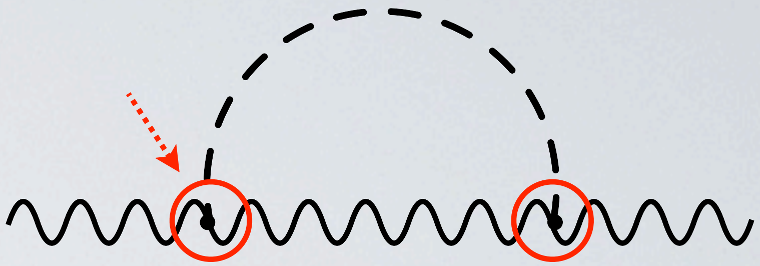
$$a = \sqrt{1-\xi}\,, \qquad b = (1 - 2\,\xi)$$



composite Higgs partially unitarizes WW scattering

other resonances can be heavier

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



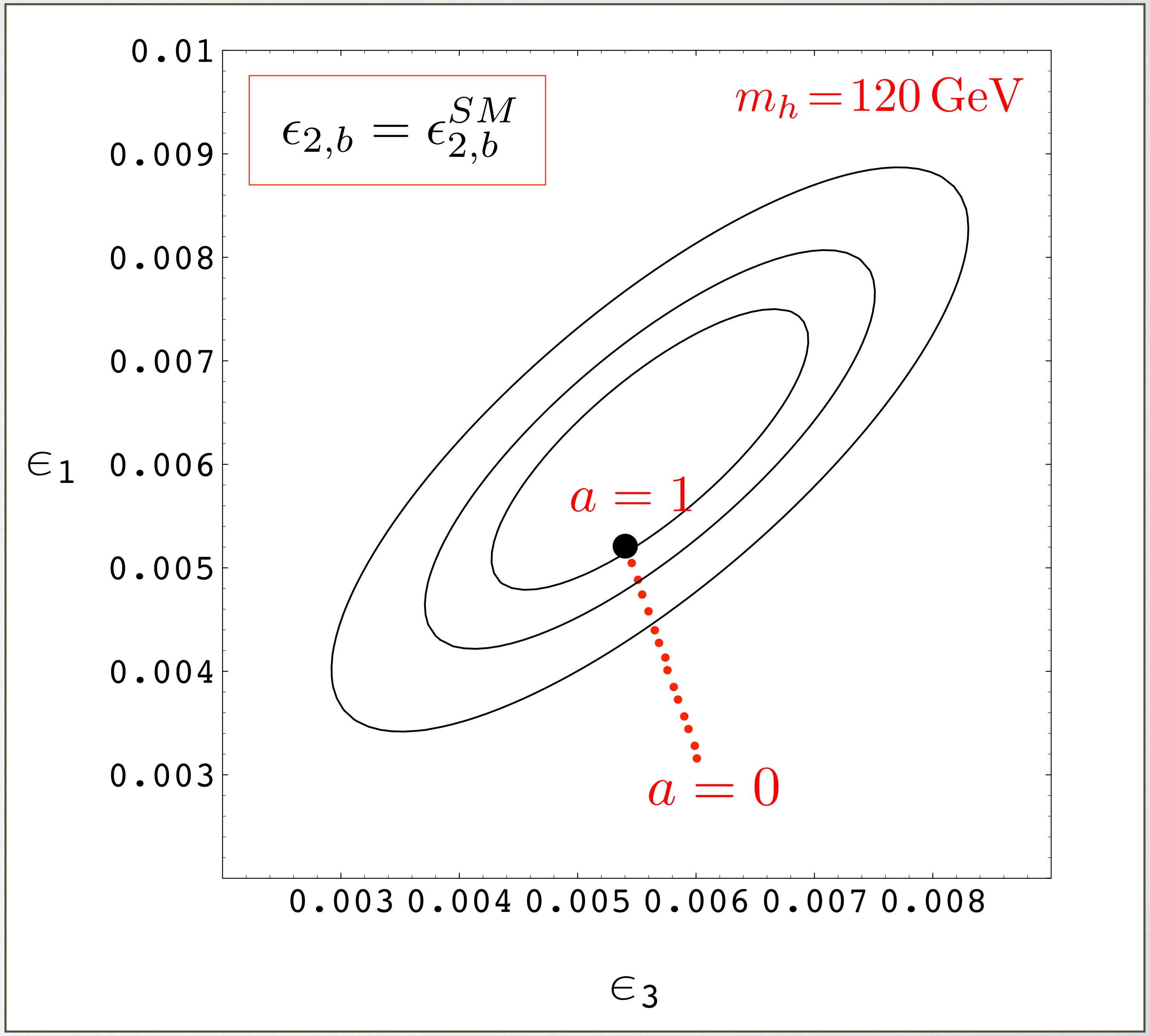
$$\epsilon_{1,3} = c_{1,3} \log\left(\frac{M_Z^2}{\mu^2}\right) - c_{1,3}\, a^2 \log\left(\frac{m_h^2}{\mu^2}\right) - c_{1,3}\,(1-a^2) \log\left(\frac{m_\rho^2}{\mu^2}\right) + \text{finite terms}$$

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

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

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

$$0.8 \lesssim a^2 \lesssim 1.6 \qquad @\ 99\%\ \text{CL}$$



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

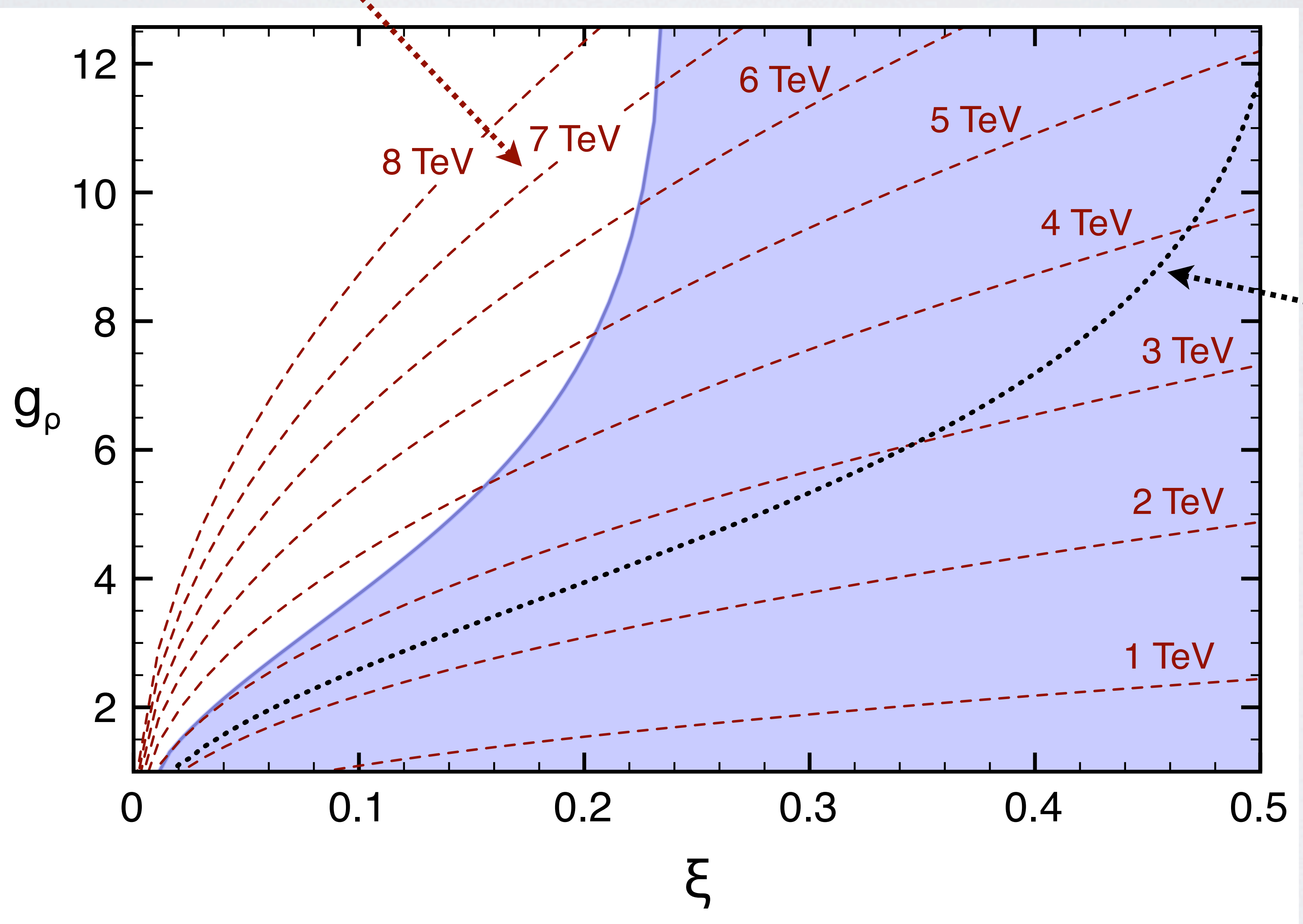
■ Composite Higgs vs LEP data

Ex: SO(5) → SO(4)

[Agashe, RC, Pomarol, NPB 719 (2005) 165]

$$m_\rho = \frac{3}{8\pi}\frac{g_\rho v}{\sqrt{\xi}} \qquad a = \sqrt{\xi - 1}$$

isocurves of constant m_ρ



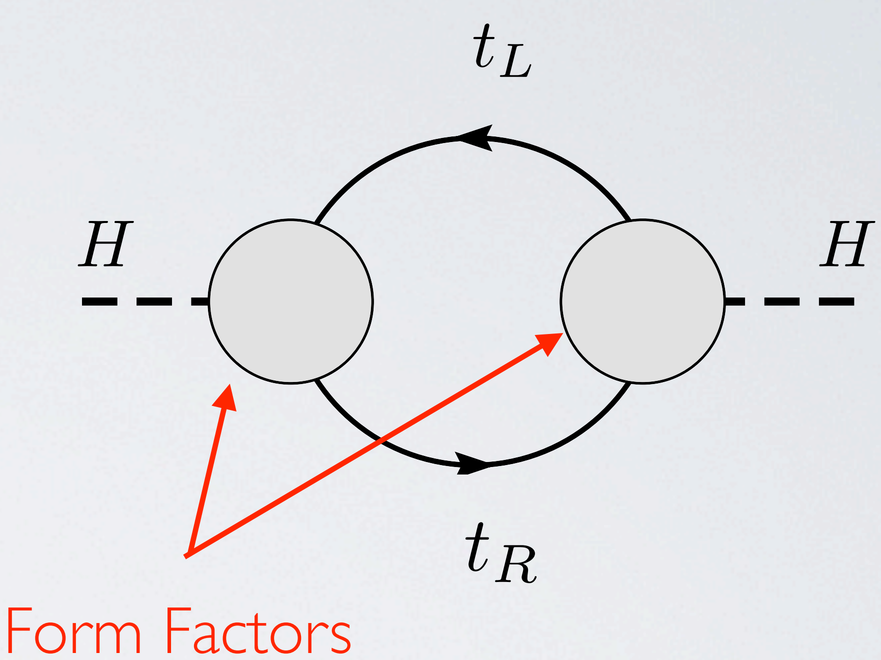
adding an extra

$\Delta\rho = +2 \times 10^{-3}$

1-LOOP POTENTIAL FOR THE PSEUDO-NG HIGGS

- Only loops of elementary fields generate a potential

- Higgs couplings switch off at large momenta → finiteness

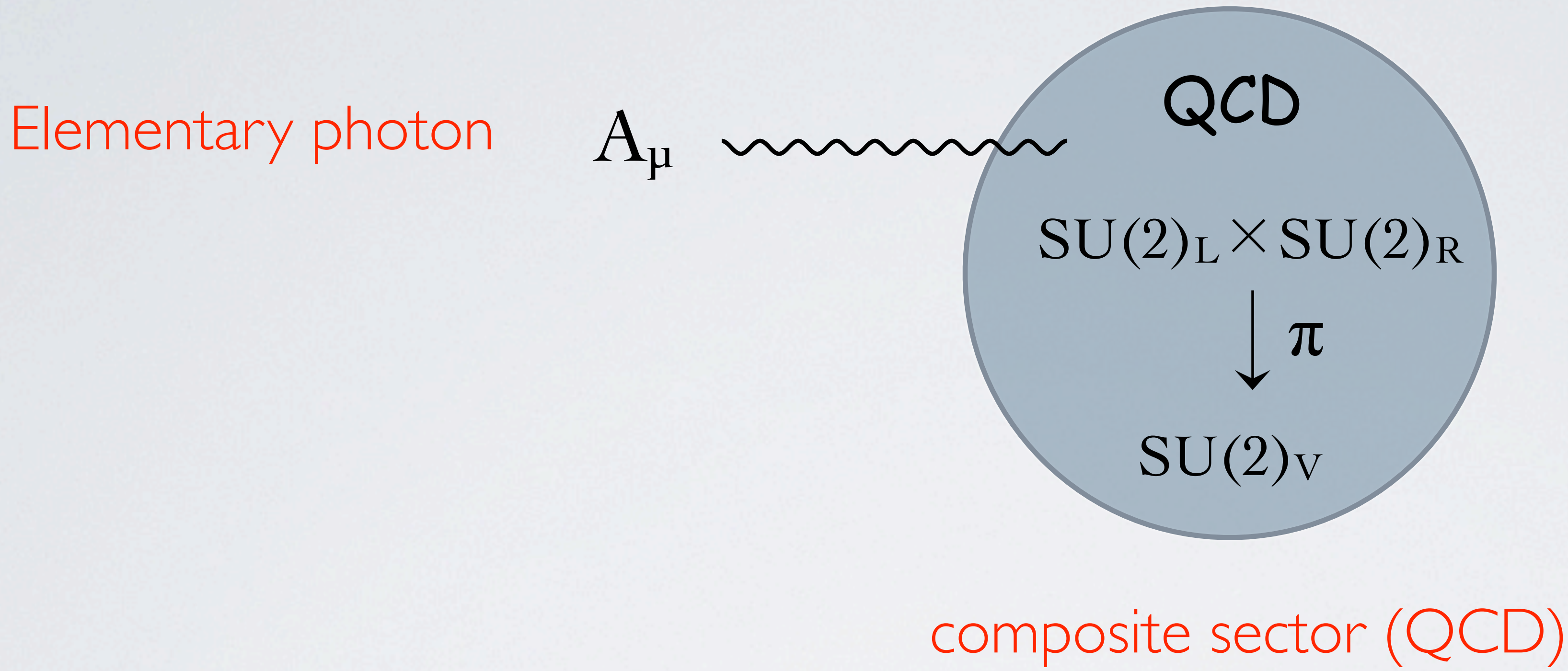


periodic function $(H \in G/G')$

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

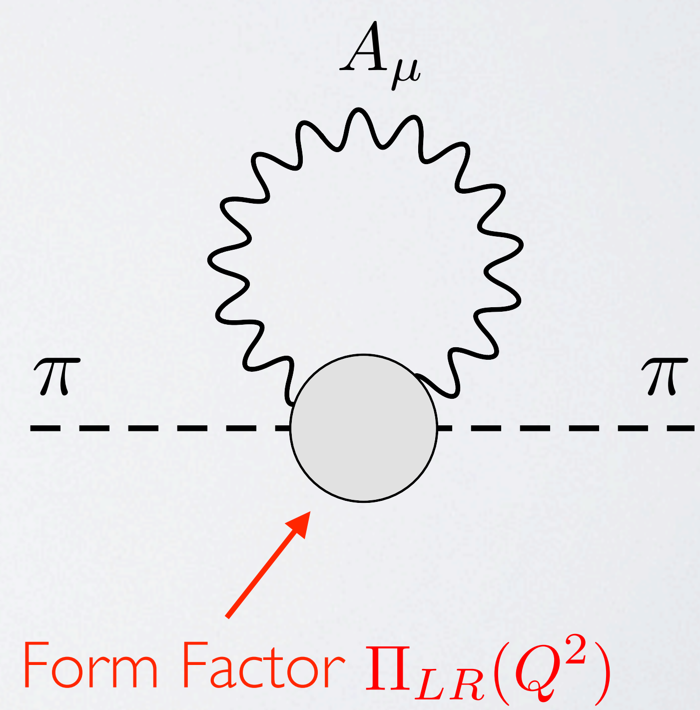
The scale v is dynamically generated

A QCD ANALOG: THE PION



- Photon loops generate a potential for the pion w/o breaking $U(1)_{em}$

$$V(\pi) \simeq \frac{3\alpha_{em}}{8\pi^2} \sin^2\left(\frac{\pi}{f_\pi}\right) \int_0^\infty dQ^2 \; \Pi_{LR}(Q^2)$$

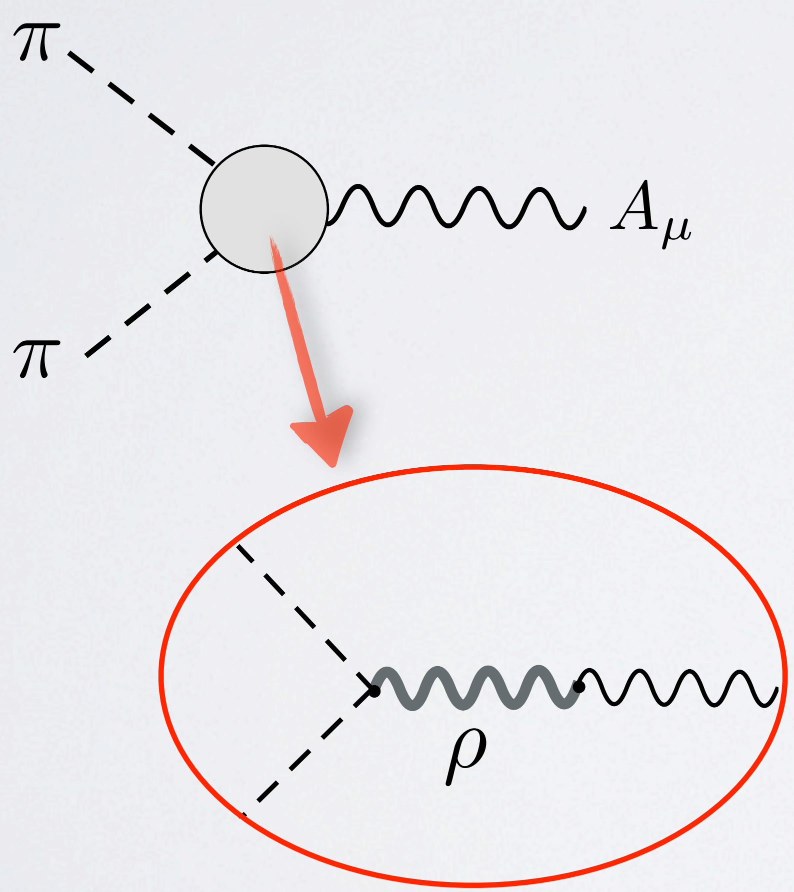


- Estimate for charged pion mass works:

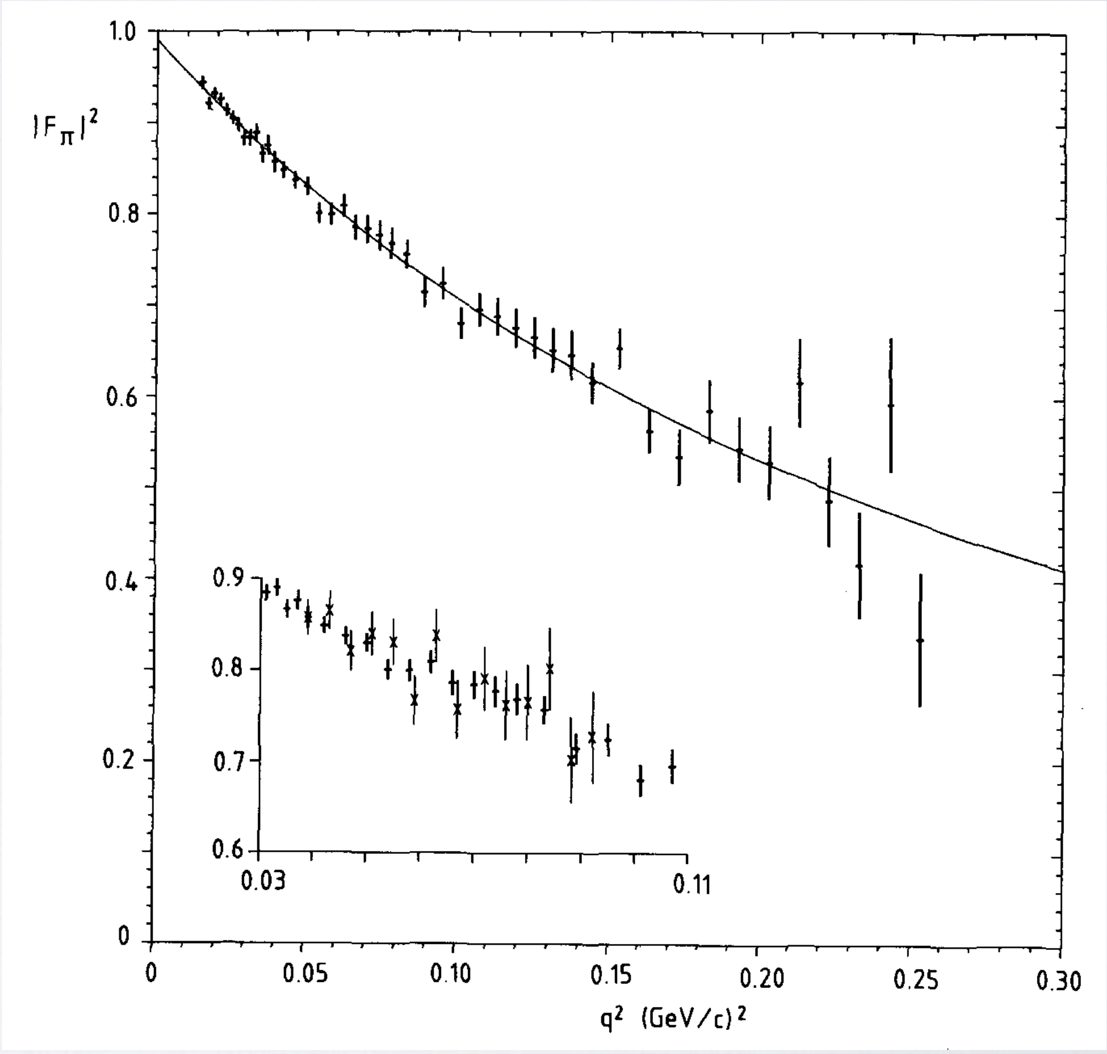
$$(m_{\pi^\pm} - m_{\pi_0})|_{\mathrm{TH}} \simeq 5.8\,\mathrm{MeV}$$

$$(m_{\pi^\pm} - m_{\pi_0})|_{\mathrm{EXP}} \simeq 4.6\,\mathrm{MeV}$$

- Pion compositeness means momentum-dependent couplings:



Ex: Pion electromagnetic form factor



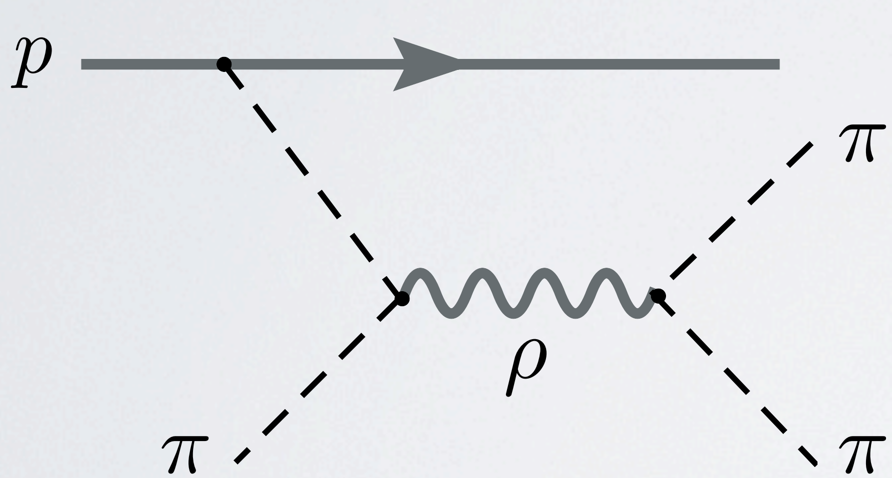
[NA7 Collaboration (1986)]

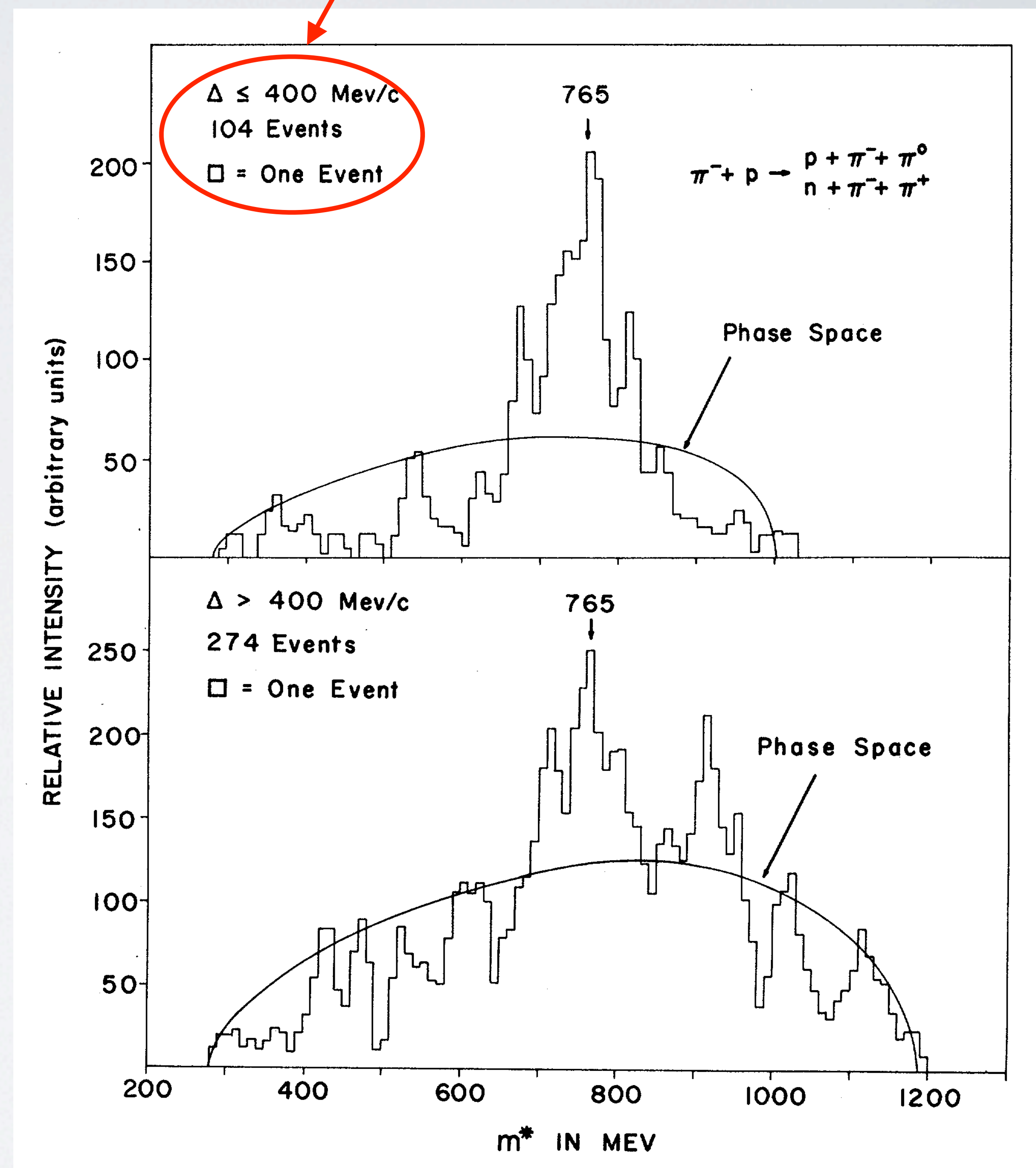
- Historically : ρ discovered in pi-pi scattering

(predicted by Nambu and Frazer and Fulco)

events with small transfer momentum

$$\pi^- + p \rightarrow \begin{matrix} p + \pi^- + \pi^0 \\ n + \pi^- + \pi^+ \end{matrix}$$

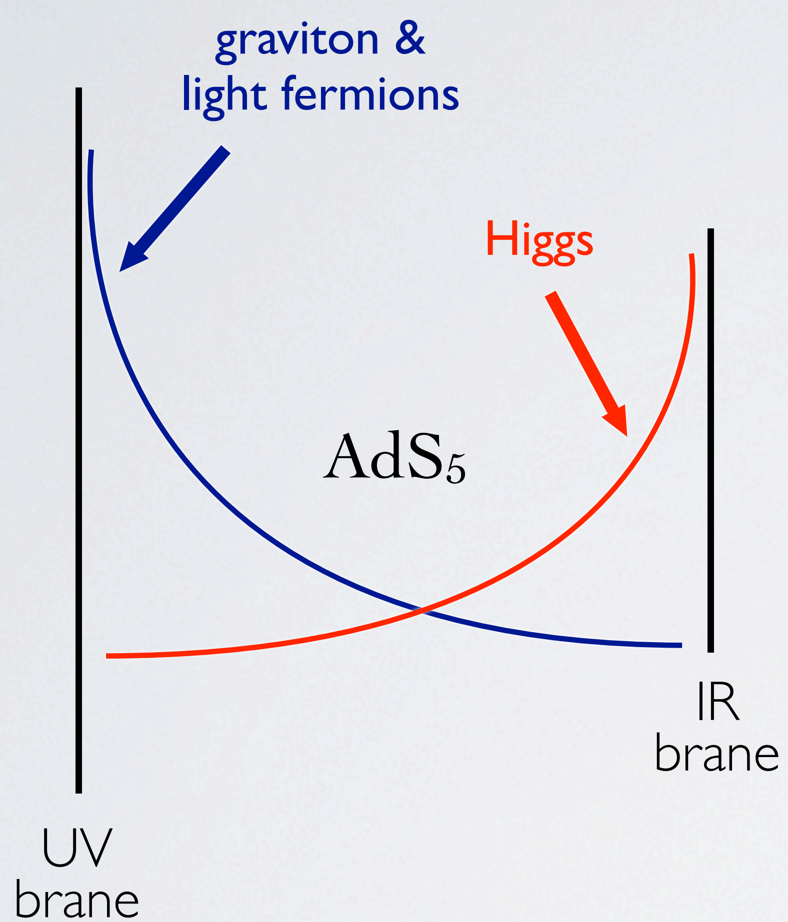




[Erwin et al. , Phys Rev Lett 6 (1961) 628]

A FASCINATING POSSIBILITY: COMPOSITENESS FROM HIGHER DIMENSIONS

Consider a 5-dimensional field theory in a curved background: (Randall-Sundrum)



warp factor

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

$$0 \leq y \leq \pi R$$

- Scales depend on the position:

  translation of y ⇔ 4D rescaling

- EW/Planck hierarchy from geometry:

  EW scale = redshifted Planck scale

$$\mathrm{TeV} \sim e^{-2k\pi R} M_{\mathrm{Pl}}$$

- Fourier decomposition gives towers of massive 4D fields

$$\Phi(x^\mu, x^5) = \sum_n f_n(x^5)\, \phi^{(n)}(x)$$

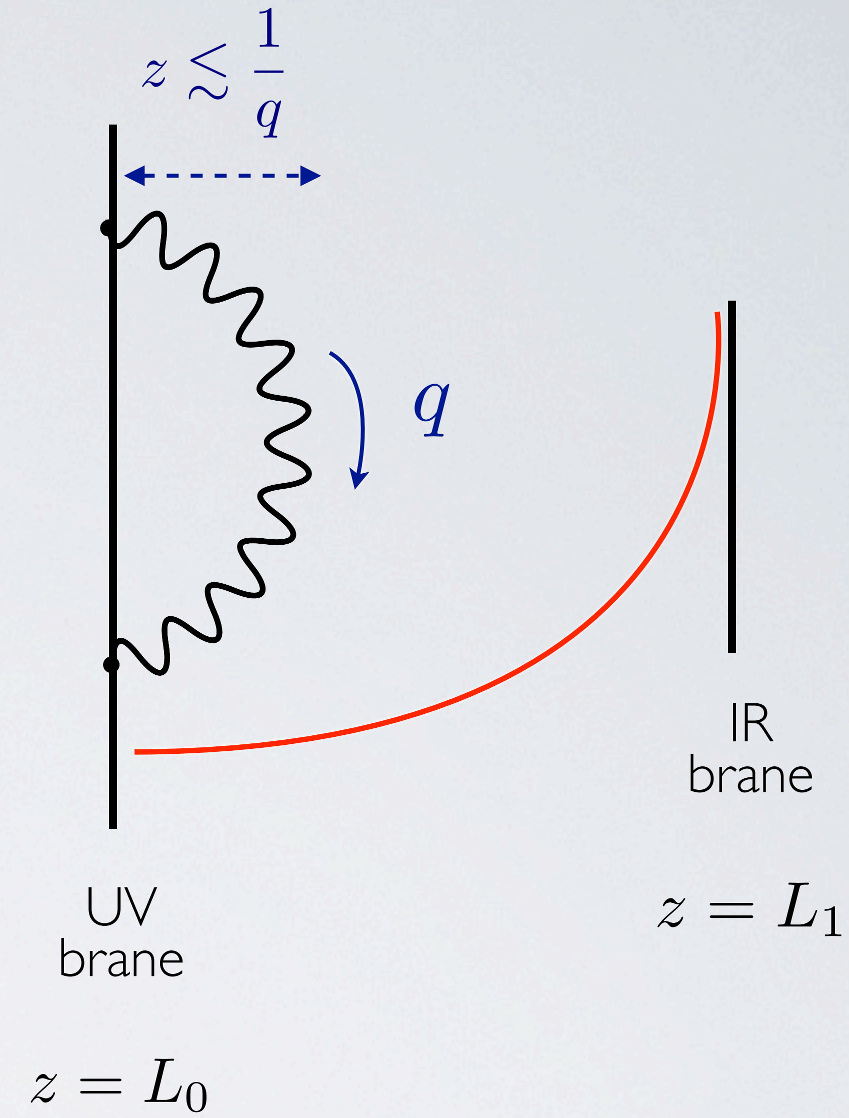
5D - 4D duality

Kaluza-Klein excitations ⟷ Resonances of the strong sector

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 momentum

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

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

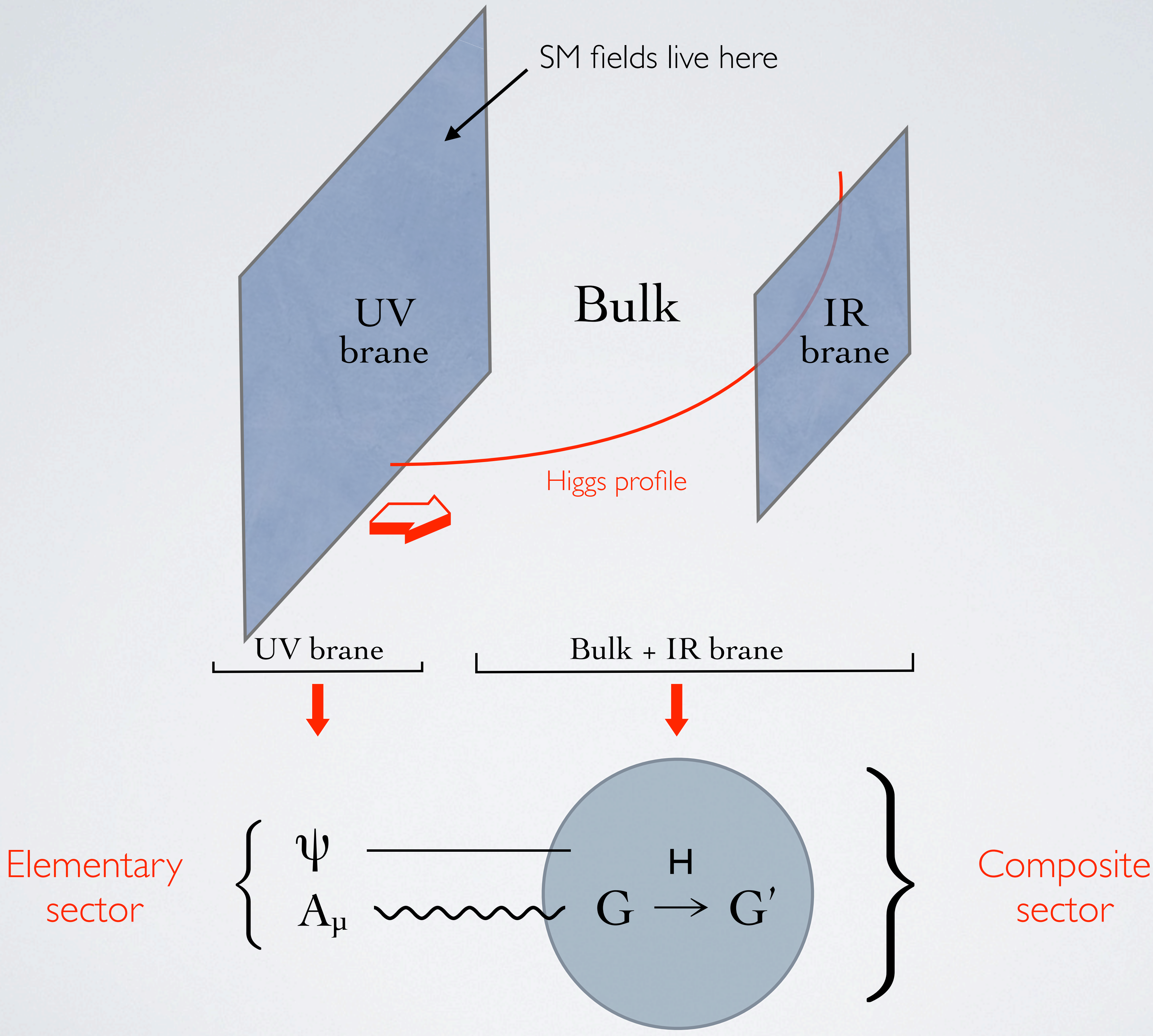


the Higgs structure along the extra dimension

appears like a form factor

for an observer on the UV brane

THE HOLOGRAPHIC DESCRIPTION



CONCLUSIONS

- LHC goal: Unraveling the mechanism of EWSB

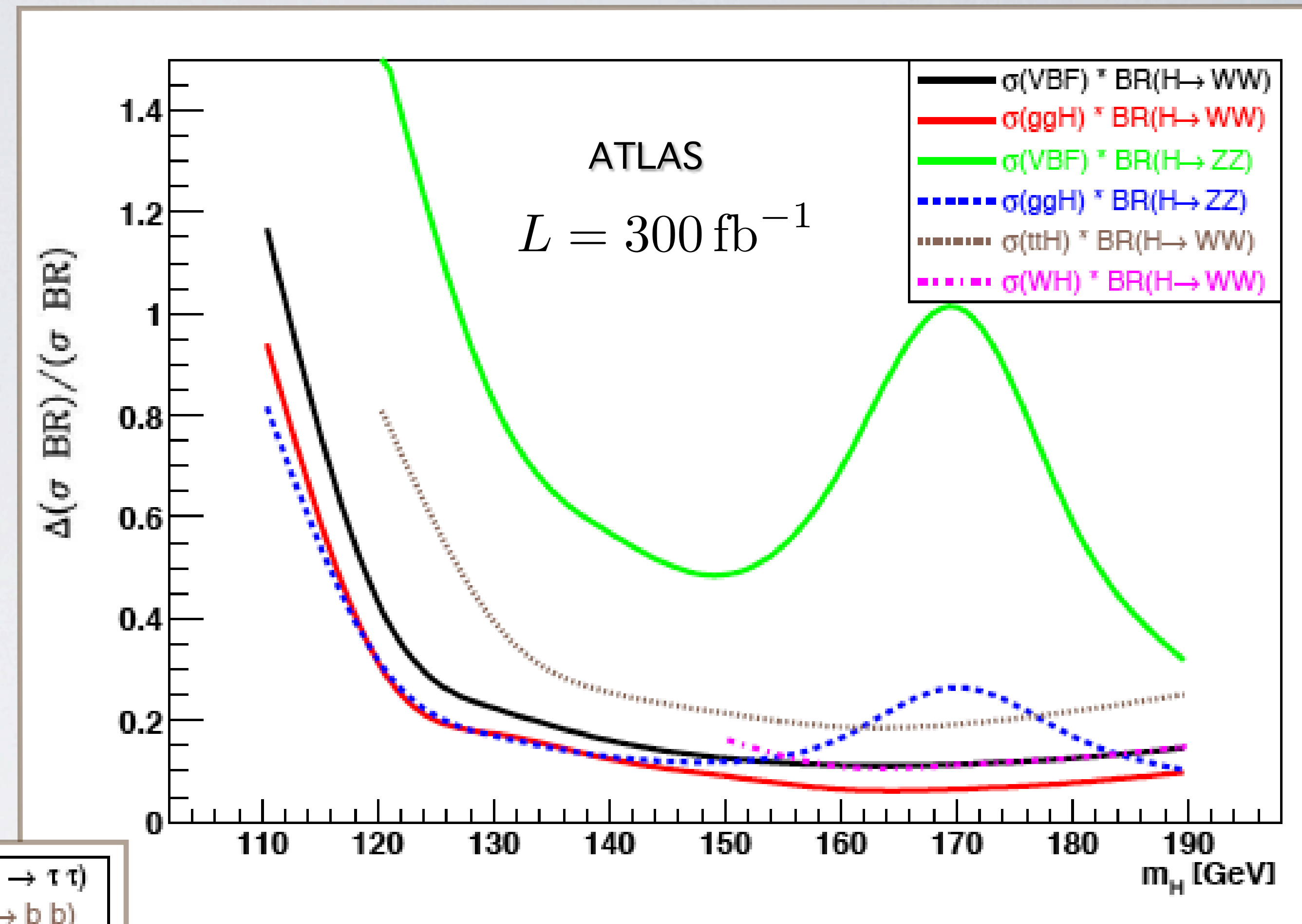
  main question: weak or strong ?

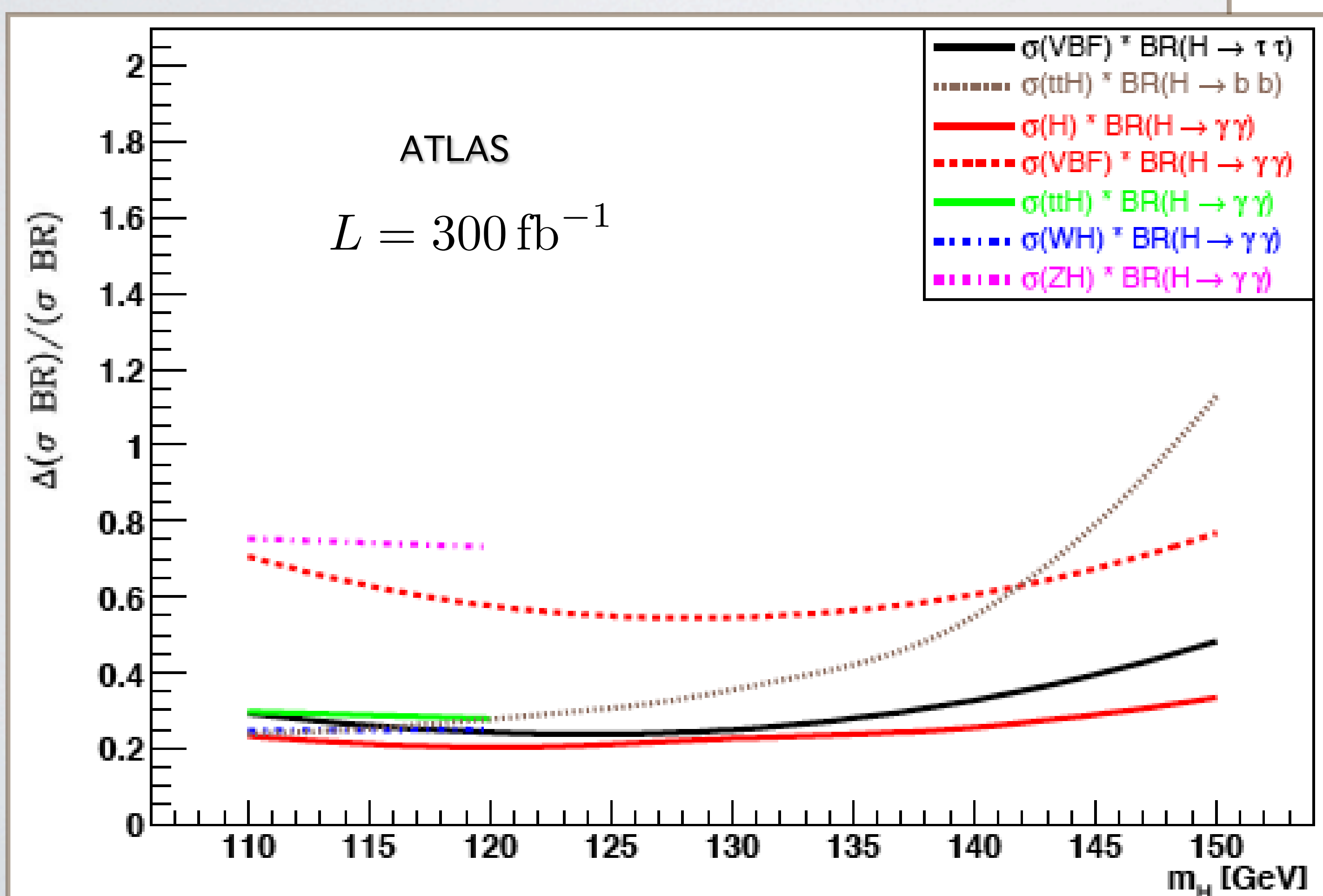
- Standard Model with an elementary Higgs boson does not explain the origin of EWSB nor address the Planck/EW hierarchy

- Watch out for deviations in Higgs couplings and WW scattering as evidence of compositeness and new dynamics

BACK UP SLIDES

MEASURING THE HIGGS COUPLINGS AT THE LHC





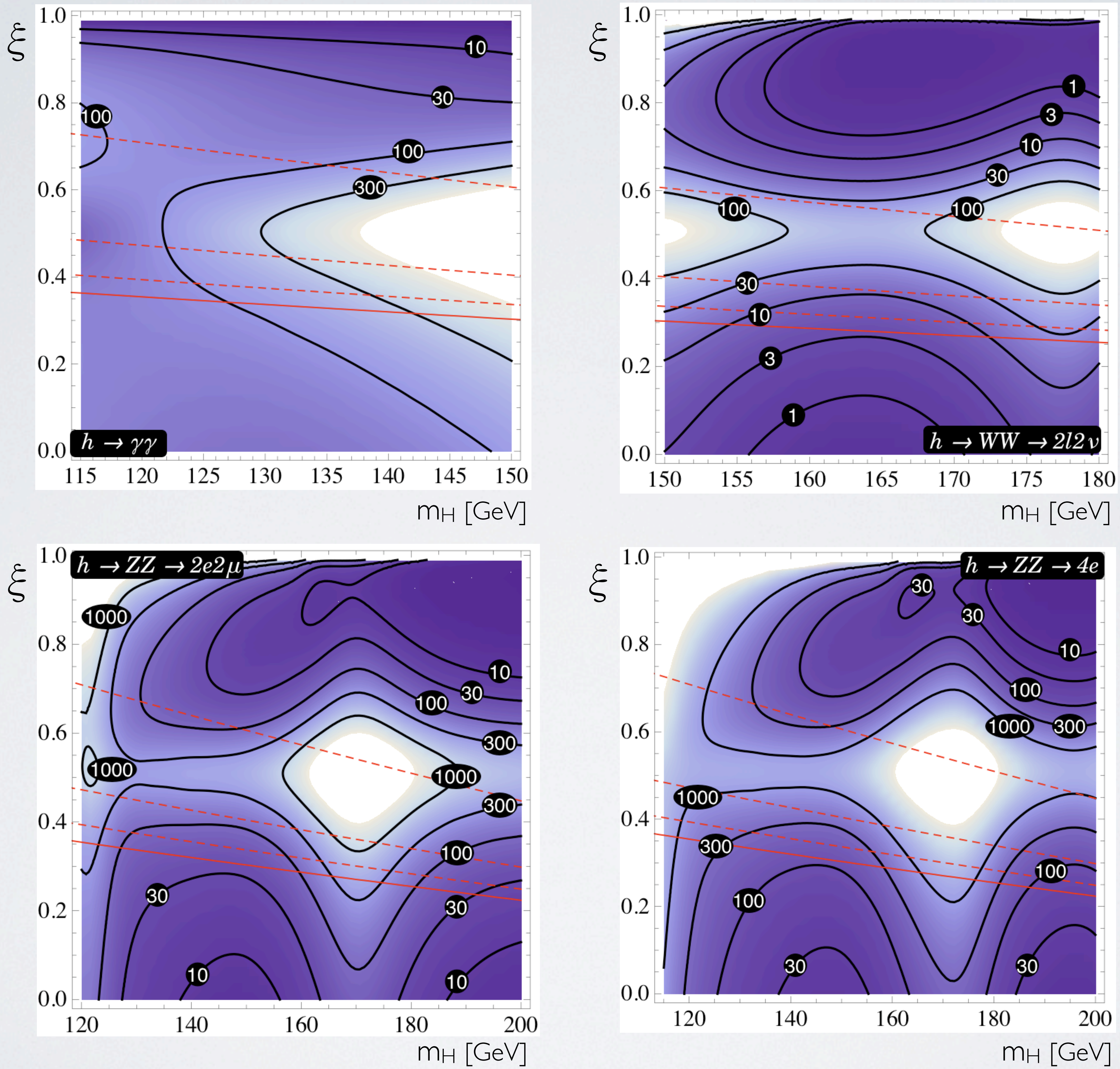
LHC sensitive up to

$$\xi \sim 0.2 - 0.4$$

[Duhrssen ATL-PHYS-2003-030]

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

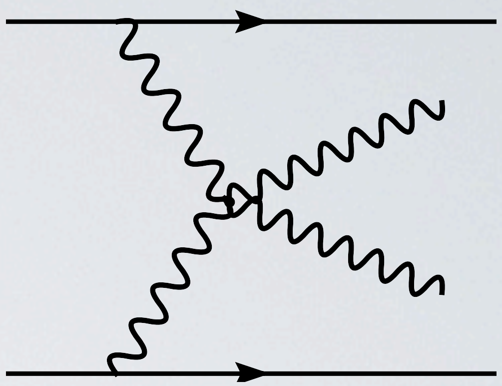
LHC DISCOVERY REACH ON THE COMPOSITE HIGGS (MCHM5)



from: C. Grojean, arXiv:0910.4976

STRONG VS WEAK EWSB: HOW THE LHC CAN TELL

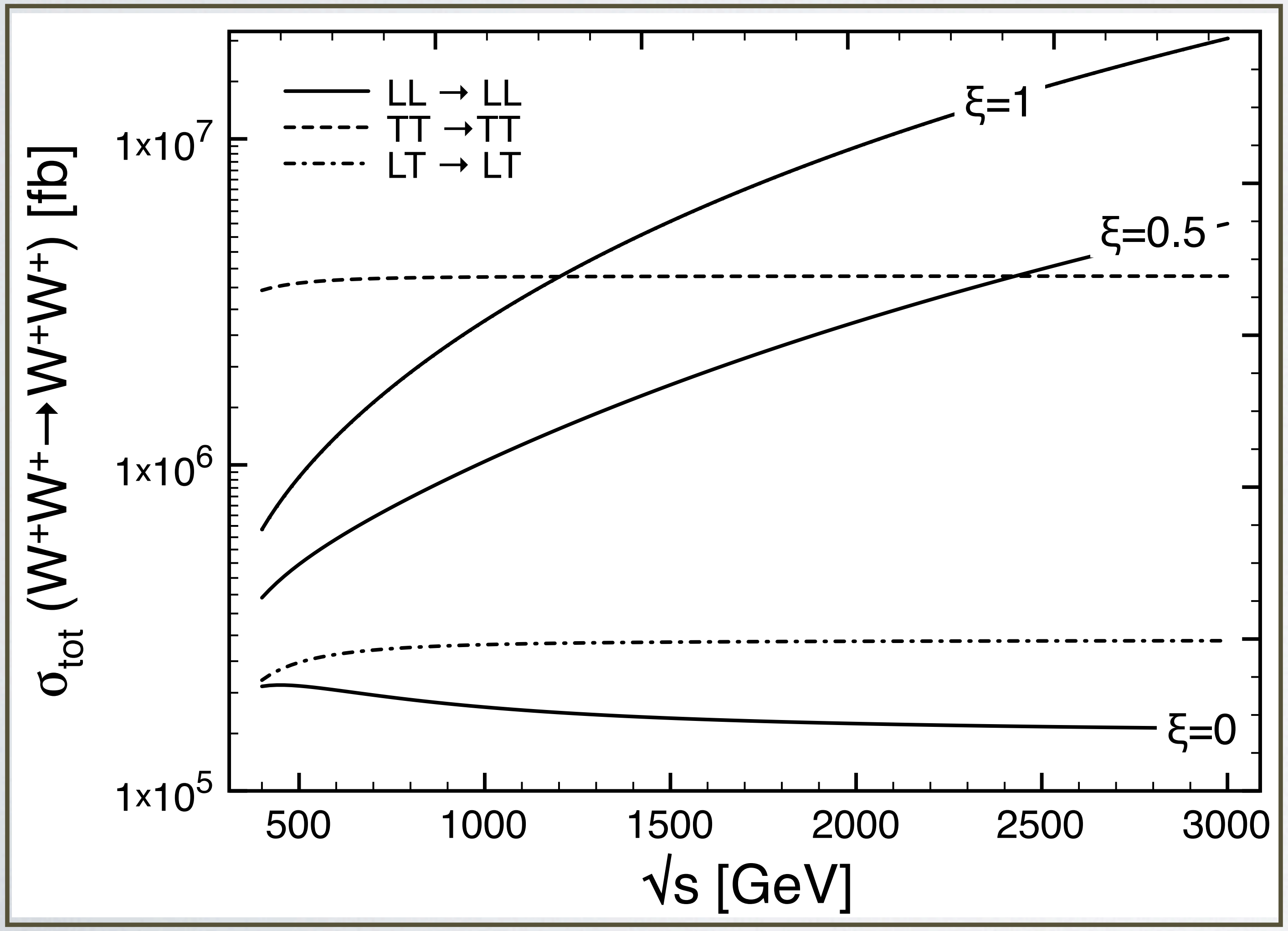
2. Detecting an excess of events in $WW \to WW$ scattering (determines a)



- 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

PARTON LEVEL



	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]

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

Barger, Han, Langacker, McElrath,Zerwas 03

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

Coupling	$M_H = 120\,\mathrm{GeV}$	$140\,\mathrm{GeV}$
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.*

- 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

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

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

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

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