The Higgs boson

as a window to Beyond the Standard Model Physics

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I. what have we discovered so far ...

... and why we need an EWSB sector

The physics discovered so far can be powerfully classified according to a gauge principle, except for the terms responsible for the particles' masses

$$\mathcal{L}_{SM} = \mathcal{L}_0 + \mathcal{L}_{mass}$$

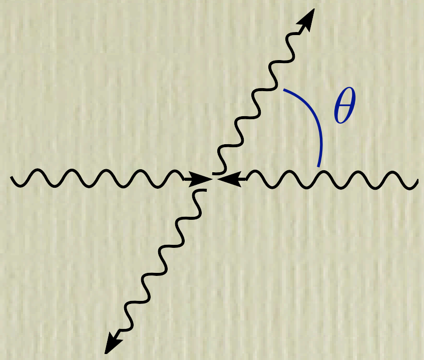
$$\mathcal{L}_0 = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a\,\mu\nu} - \frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \sum_{j=1}^{3} \left(\bar{\Psi}_L^{(j)} i \not{D} \Psi_L^{(j)} + \bar{\Psi}_R^{(j)} i \not{D} \Psi_R^{(j)} \right)$$

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

Mass terms are not invariant under the local $SU(2)_L \times U(1)_Y$ symmetry

Mass terms are responsible for the inconsistency of the theory at high energies:

The scattering of longitudinal W's and Z's violates unitarity at high energy



The optical theorem

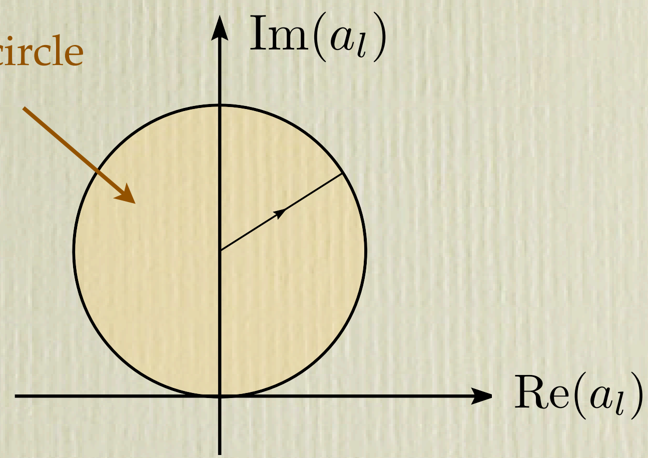
$$\frac{E}{p}\,\frac{1}{s}\,\mathrm{Im}\left(A(\theta=0)\right)=\sigma_{tot}(WW\to\text{anything})$$

requires for each partial wave:

$$\mathrm{Im}(a_l(s))=|a_l(s)|^2+|a_l^{in}(s)|^2$$

$$\mathrm{Re}(a_l(s))\leq\frac{1}{2}$$

physical amplitudes bound within the unitarity circle

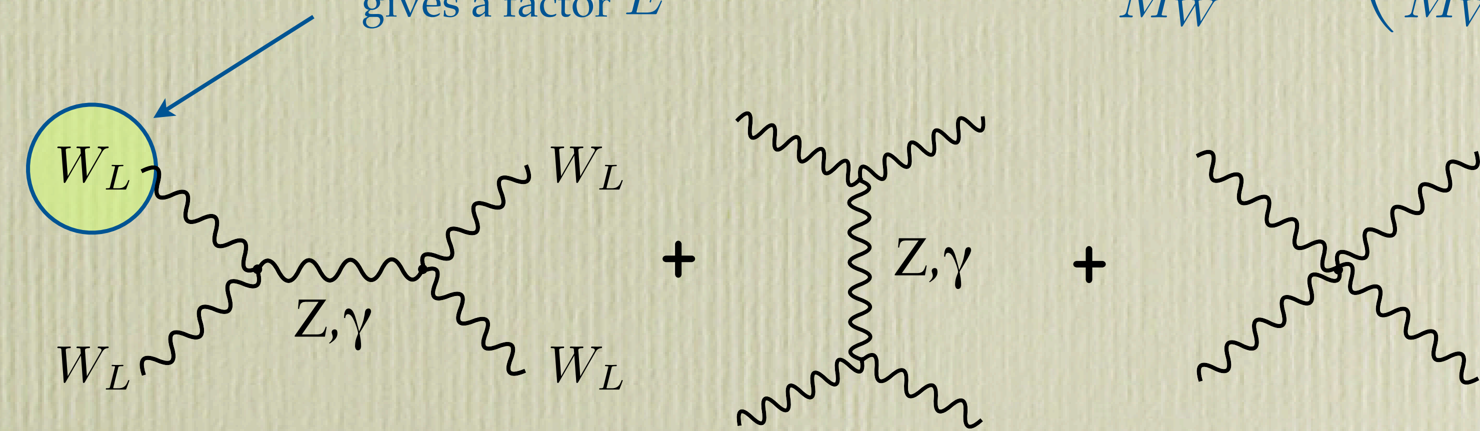


The amplitude for scattering of longitudinal W's and Z's grows with the energy and eventually violates the unitarity bound:

Ex: $$A(W_L^+ W_L^- \to W_L^+ W_L^-) = \frac{g_2^2}{4M_W^2}(s+t)$$

each longitudinal polarization gives a factor E

$$\epsilon_L^\mu = \frac{p^\mu}{M_W} + O\left(\frac{E}{M_W}\right)$$



Unitarity is violated at $\sqrt{s} \simeq \Lambda = 1.2\,\mathrm{TeV}$

The breaking of gauge invariance is in fact a fake: the symmetry is just hidden

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

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

$\rho = 1$ 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 $\lambda^u \neq \lambda^d$

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

$$+ a \, v^2 \, \mathrm{Tr}\left[\Sigma^\dagger D_\mu \Sigma \, T^3 \right]^2$$

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

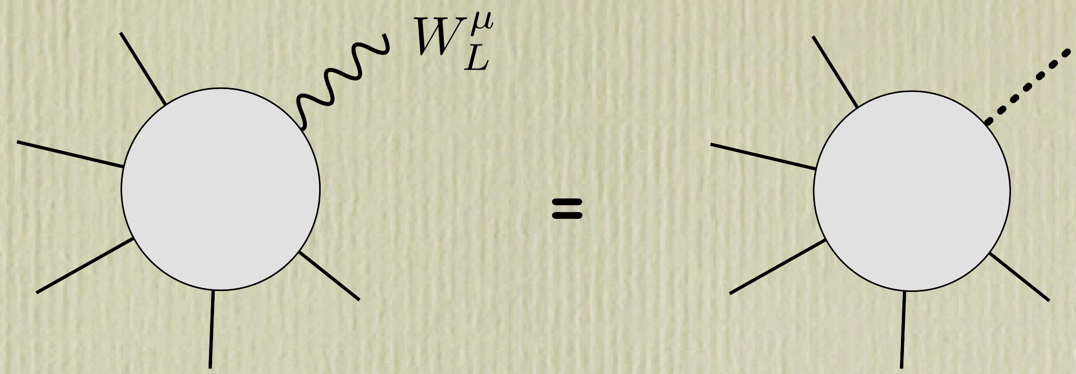
- The $SU(2)_L \times U(1)_Y$ symmetry is now manifest, although non-linearly realized

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

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

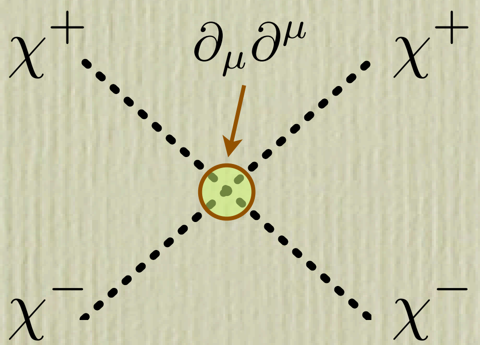
$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = 1$$

Violation of unitarity, thanks to the Equivalence Theorem,



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

can be traced back to the scattering of the Goldstone bosons:



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

and it is linked to the non-renormalizability of the Lagrangian

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

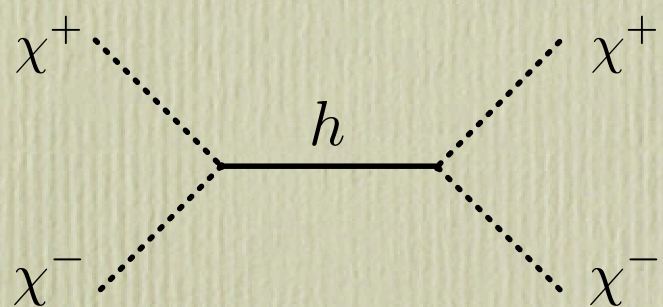
II. Restoring unitarity by adding 1 new field: the Higgs model

The most economical EWSB sector consists of 1 scalar field singlet under the $SU(2)_L x SU(2)_R$ (and the local $SU(2)_L x U(1)_Y$) symmetry :

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

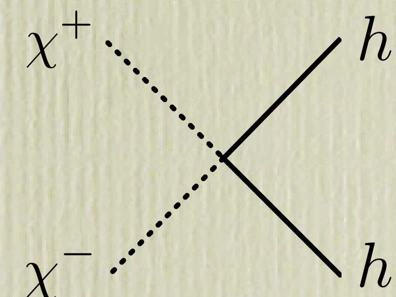
a and b are free parameters

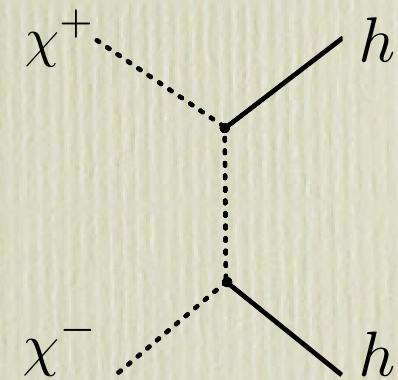
- For a=1 the scalar exchange unitarizes the WW scattering



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

- For b=1 also the inelastic channels respect unitarity





a=b=1 defines the Higgs Model, whose Lagrangian can be rewritten in the standard form in terms of the $SU(2)_L$ doublet

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

Unitarity of the Higgs Model can be traced back to its renormalizability

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 $SO(4) \sim SU(2)_L \times SU(2)_R$ invariant

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

1. Unitarity bound on Higgs mass

$$A(W_L^+W_L^- \to W_L^+W_L^-) = -\frac{g_2^2\, m_h^2}{4M_W^2}\left[\frac{s}{s-m_h^2} + \frac{t}{t-m_h^2}\right] \to -\frac{g_2^2\, m_h^2}{4M_W^2}$$

Unitarity of WW scattering requires:

$$m_h \leq \sqrt{\frac{8\pi\sqrt{2}}{5G_F}} \simeq 780\,\mathrm{GeV}$$

The heavier the Higgs is, the more strongly it couples $\lambda_4 = \dfrac{m_h^2}{2v^2}$

and the broader it is $\Gamma(h \to W^+W^-) \simeq \dfrac{1}{16\pi}\dfrac{m_h^3}{v^2}$

☞ As a general rule: the later unitarity is cured, the more strongly coupled the EWSB sector will be

2. Bounds on the Higgs mass through the quartic coupling

The physical Higgs mass is set by the quartic coupling, which is a running parameter $m_h^2 = 2\lambda_4 v^2$

$$16\pi^2 \frac{d}{d\log Q}\lambda_4 = 24\,\lambda_4^2 - \left(3g'^2 + 9g^2 - 12y_t^2\right)\lambda_4 + \frac{3}{8}\,g'^4 + \frac{3}{4}\,g'^2 g^2 + \frac{9}{8}\,g^4 - 6\,y_t^4 + \cdots$$

- For a too heavy Higgs, the first term dominates and drives λ_4 to a Landau pole at large energy scales

$$m_h^2 \lesssim \frac{4\pi^2 v^2}{3\log(\Lambda/v)}$$

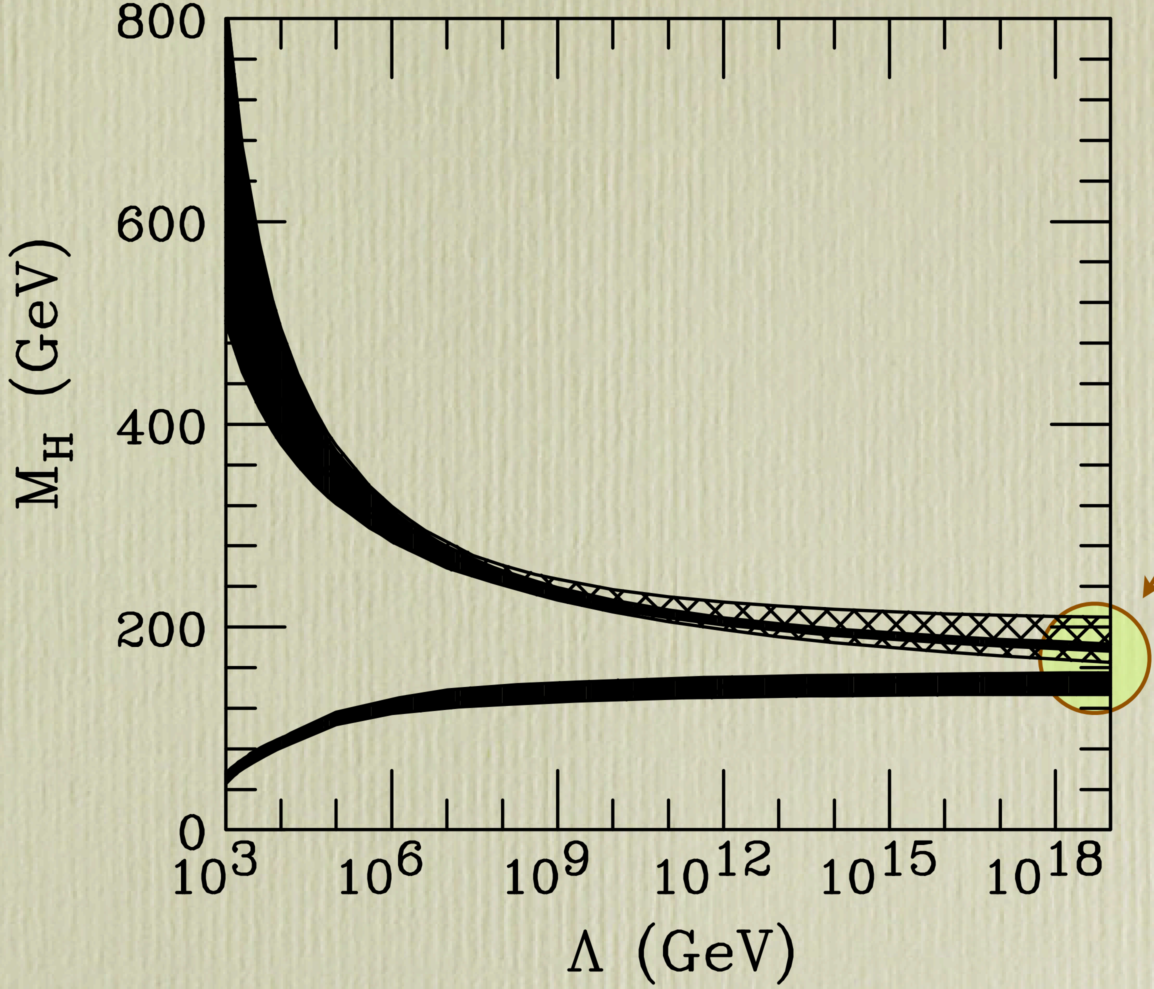
TRIVIALITY BOUND

largest scale of validity of the theory (cutoff scale)

- For a too small Higgs, the last term dominates and drives λ_4 negative at large energy scales

$$m_h^2 \gtrsim \frac{3y_t^4 v^2}{4\pi^2}\log(\Lambda/v)$$

VACUUM STABILITY BOUND



perturbativity up to the Planck scale requires

$$m_h < 180\,\mathrm{GeV}$$

$$\Lambda = 10^{19}\,\mathrm{GeV}$$

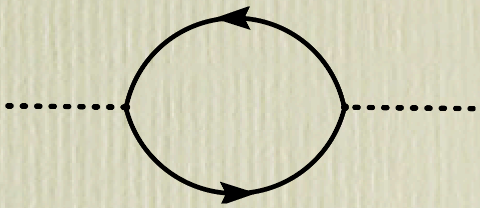
from: T. Hambye, K. Riesselmann Phys Rev, D55 (1997) 7255

3. UV instability of the Higgs mass term

[aka: the Hierarchy Problem]

The Higgs mass term receives quadratically divergent corrections from SM loops, making the physical mass highly sensitive to the value of the cutoff scale:

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



The larger Λ, the less natural a light Higgs is

☞ The cutoff might be low: the Higgs model should be perhaps regarded as a parameterization rather than a dynamical explanation of EWSB

3. LEP constraints on m_h and Λ

If the Higgs model is considered as an effective field theory, New Physics effects are encoded in higher order (non-renormalizable) operators :

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i,p} \frac{c_i}{\Lambda^p} O_i^{(4+p)}$$

$$O_i^{(6)} \in \{ (H^\dagger T^a H) W^a_{\mu\nu} B^{\mu\nu}, \; |H^\dagger D_\mu H|^2, \; (\bar{\Psi}\gamma^\mu \Psi)^2, \; (\bar{\Psi}\gamma^\mu \Psi)(H^\dagger D_\mu H) \}$$

S parameter

T parameter ($\Delta\rho$)

”oblique” corrections

4-fermion operators

vertex corrections

Notice: those above are flavor and CP-conserving operators

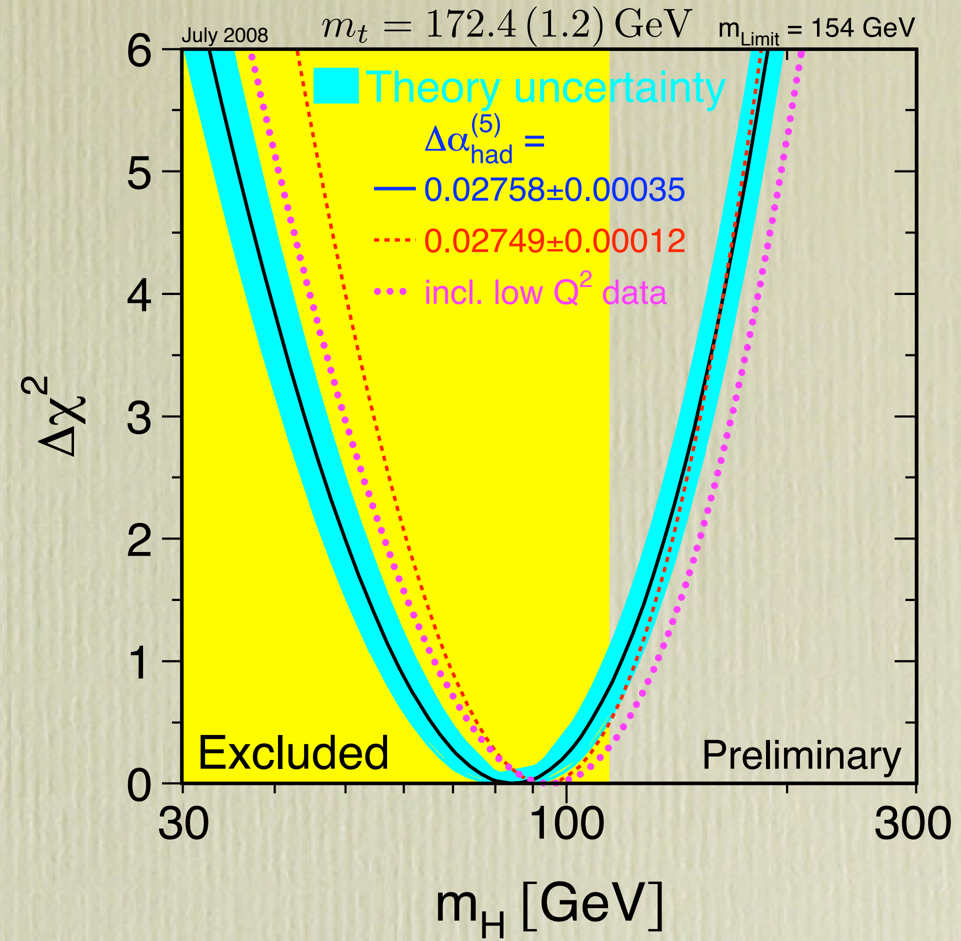
The EW precision measurents performed at LEP, SLD and Tevatron

Γ_Z	total Z width
σ_h	$e\bar{e}$ hadronic cross section at Z peak
R_h	$\Gamma(Z \to \text{hadrons})/\Gamma(Z \to \mu^+\mu^-)$
R_b	$\Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$
R_c	$\Gamma(Z \to c\bar{c})/\Gamma(Z \to \text{hadrons})$
A_P^τ	τ polarization asymmetry
A_{LR}^e	Left/Right asymmetry in $e\bar{e}$
A_{LR}^b	LR Forward/Backward asymmetry in $e\bar{e} \to b\bar{b}$
A_{LR}^c	LR FB asymmetry in $e\bar{e} \to c\bar{c}$
A_{FB}^ℓ	Forward/Backward asymmetry in $e\bar{e} \to \ell\bar{\ell}$
A_{FB}^b	Forward/Backward asymmetry in $e\bar{e} \to b\bar{b}$
A_{FB}^c	Forward/Backward asymmetry in $e\bar{e} \to c\bar{c}$
M_Z	pole Z mass
G_F	Fermi constant for μ decay
m_t	pole top mass
M_W	pole W mass
$\alpha_s(M_Z)$	strong coupling
$\alpha_{em}^{-1}(M_Z)$	electromagnetic coupling

can be used to test the Higgs Model and put constraints on m_h and Λ

Global fit to the Higgs Model

[from the LEP EWWG]



The dependence upon the Higgs mass is logarithmic and comes in through loop effects

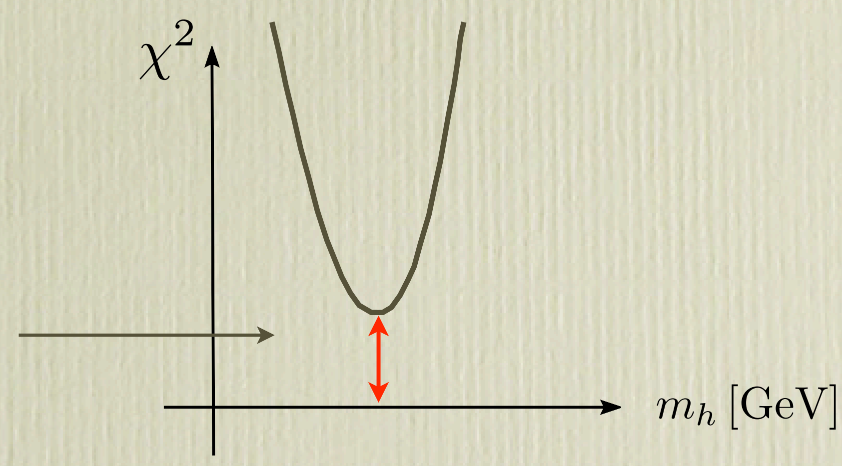
On the whole the Standard Model performs rather well, with a clear indication for a light Higgs

$$m_h \lesssim 154\,\mathrm{GeV} \quad @\ 95\%\ \mathrm{CL}$$

yet the fit is not entirely satisfactory:

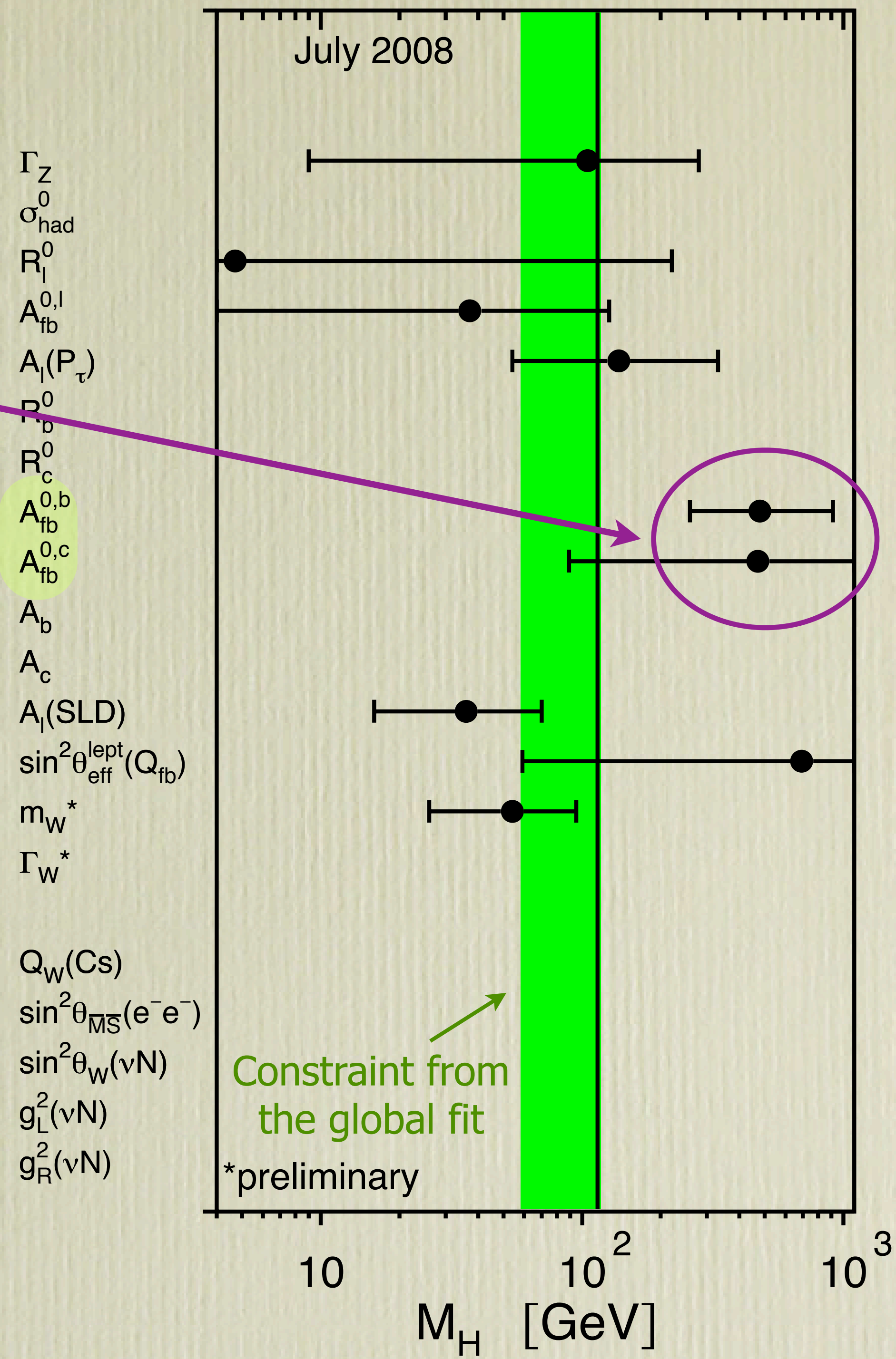
P~4.5% $$\frac{\chi^2_{min}}{ndf}(all) = \frac{28.0}{17}$$

P~15% $$\frac{\chi^2_{min}}{ndf}(only-high) = \frac{18.2}{13}$$



Best fit $m_h = 87^{+36}_{-27}\,\mathrm{GeV}$ is the result of a tension between leptonic and hadronic asymmetries

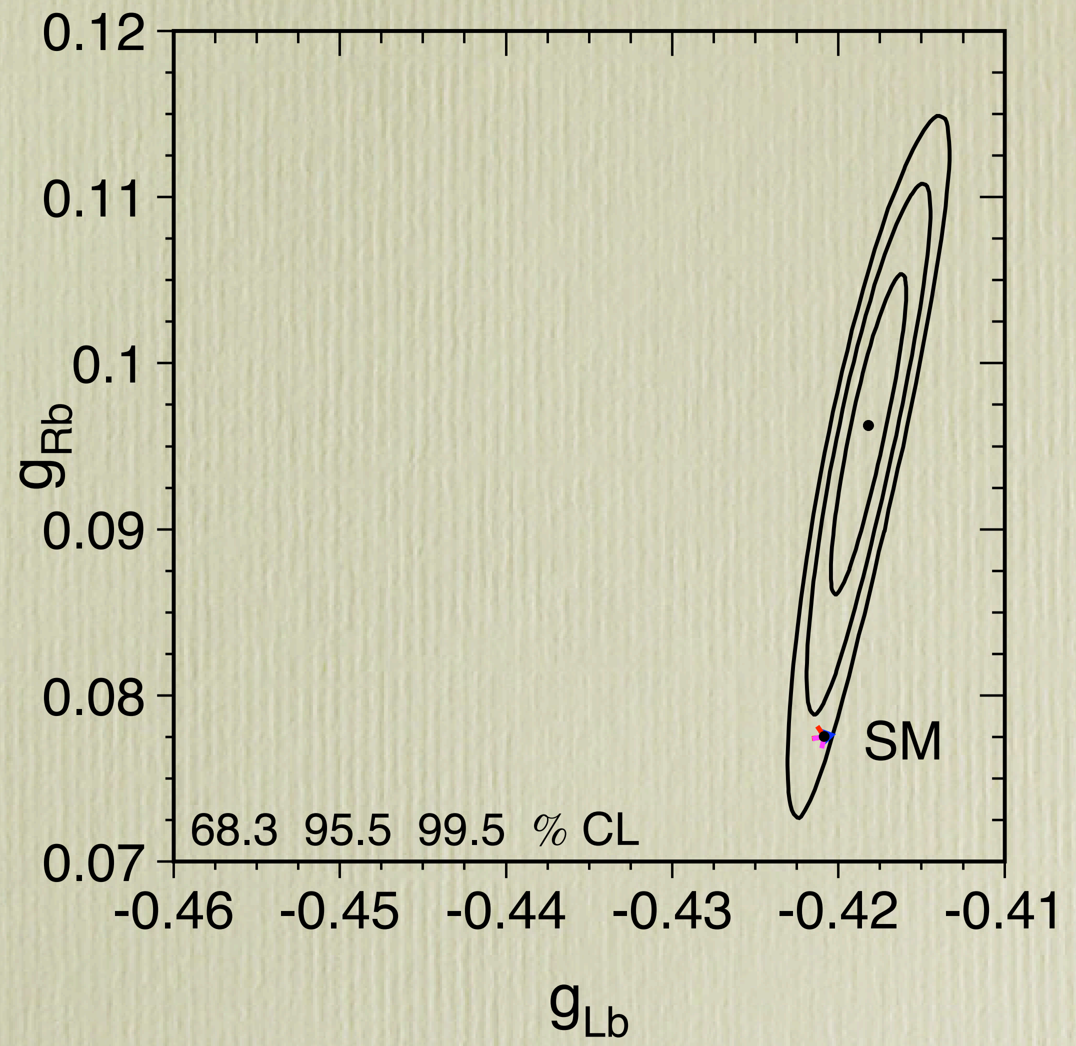
Only the hadronic asymmetries (and the NuTeV result) push for a high Higgs mass



removing $A_{\rm fb}^{0,b}$ from the fit gives a better χ^2 but also :

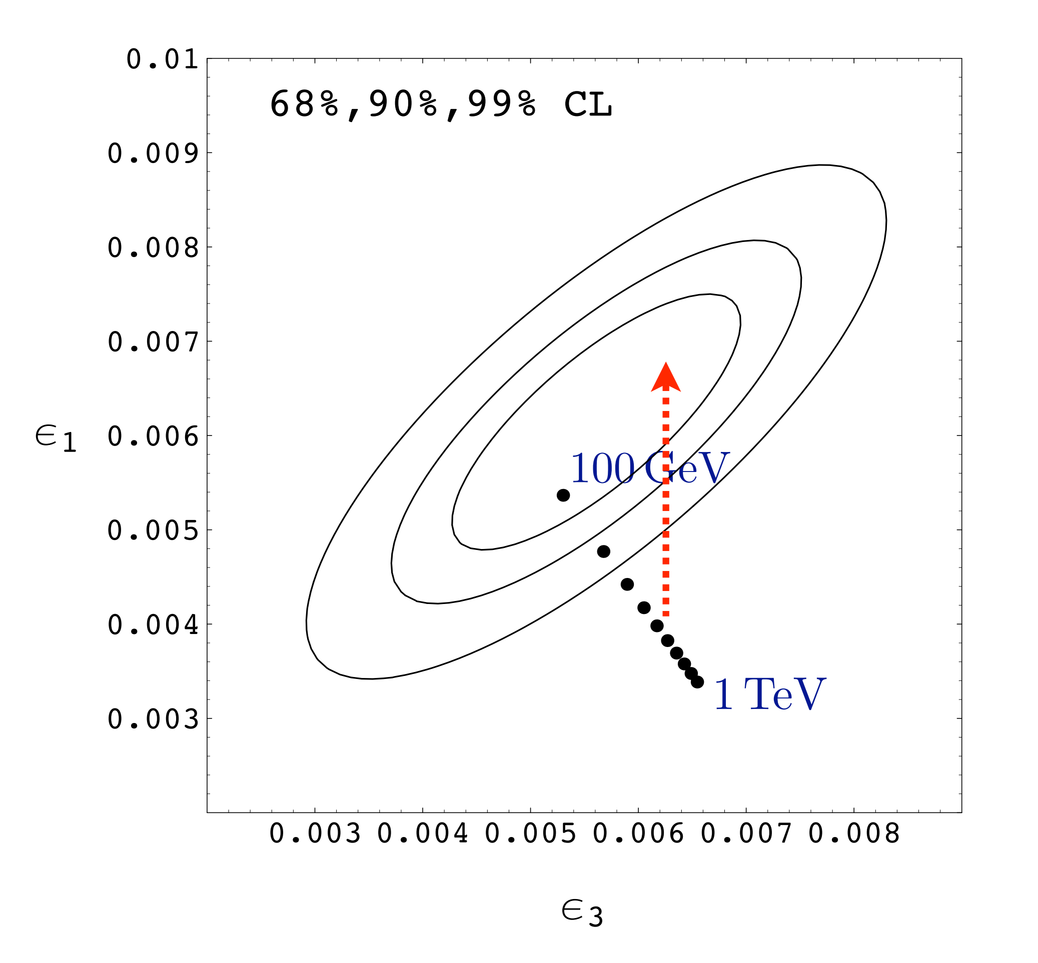
$$m_h = 55^{+30}_{-20}\,\mathrm{GeV}$$

The fit improves allowing for a (large) δg_{Rb} from New Physics



☞ However: very few examples of New Physics leading to a large δg_{Rb} and very small positive δg_{Lb}

Moral: The Higgs boson is light, unless New Physics is of a very special kind



If the Higgs is light: bound on each individual coefficient is strong

[LEP "paradox"]

Dimensions six operators			$m_h = 115\,\text{GeV}$ $c_i = -1$	$c_i = +1$
$\mathcal{O}_{WB}$	=	$(H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$	9.7	10
$\mathcal{O}_H$	=	$\lvert H^\dagger D_\mu H \rvert^2$	4.6	5.6
$\mathcal{O}_{LL}$	=	$\frac{1}{2}(\bar{L}\gamma_\mu \tau^a L)^2$	7.9	6.1
$\mathcal{O}'_{HL}$	=	$i(H^\dagger D_\mu \tau^a H)(\bar{L}\gamma_\mu \tau^a L)$	8.4	8.8
$\mathcal{O}'_{HQ}$	=	$i(H^\dagger D_\mu \tau^a H)(\bar{Q}\gamma_\mu \tau^a Q)$	6.6	6.8
$\mathcal{O}_{HL}$	=	$i(H^\dagger D_\mu H)(\bar{L}\gamma_\mu L)$	7.3	9.2
$\mathcal{O}_{HQ}$	=	$i(H^\dagger D_\mu H)(\bar{Q}\gamma_\mu Q)$	5.8	3.4
$\mathcal{O}_{HE}$	=	$i(H^\dagger D_\mu H)(\bar{E}\gamma_\mu E)$	8.2	7.7
$\mathcal{O}_{HU}$	=	$i(H^\dagger D_\mu H)(\bar{U}\gamma_\mu U)$	2.4	3.3
$\mathcal{O}_{HD}$	=	$i(H^\dagger D_\mu H)(\bar{D}\gamma_\mu D)$	2.1	2.5

☞ Possible conclusions:

1. more than one operator contribute

2. coefficients c_i are small (= New Physics is weakly coupled)

III. Curing the UV sensitivity of the Higgs model

Fact: mass of fermions and gauge bosons are UV-stable because protected by a symmetry

Strategy: relating the Higgs to fermions or gauge fields to gain the symmetry protection

CHIRAL SYMMETRY ⟶ SUSY $h \subset \begin{pmatrix} \tilde{h} \\ h \end{pmatrix}$

(fermion protection)

GAUGE SYMMETRY ⟶ GAUGE-HIGGS UNIFICATION $h = A_5$

(gauge protection)

[requires extra dimensions]

SUSY in a nutshell:

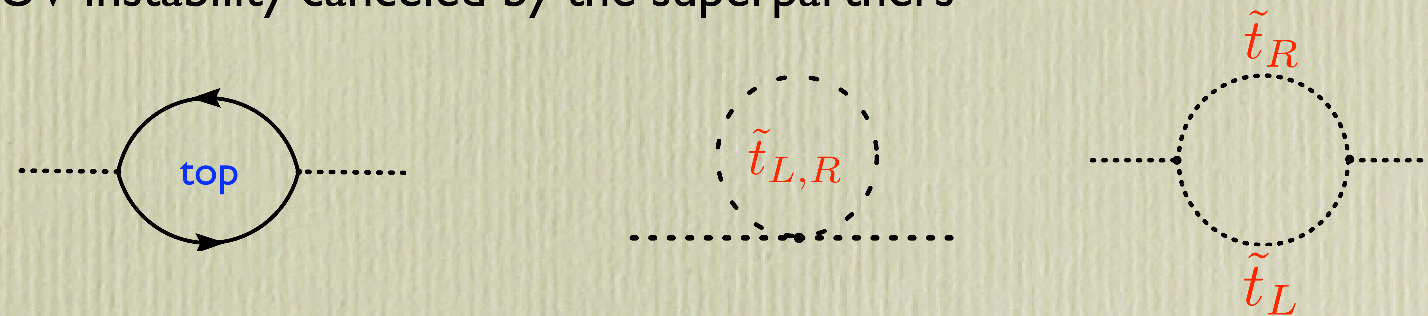
- each SM particle has a superpartner with opposite statistics

$\begin{pmatrix} \psi \\ \tilde{\psi} \end{pmatrix}$ sfermions (scalar)

$\begin{pmatrix} h \\ \tilde{h} \end{pmatrix}$ higgsinos (fermion)

$\begin{pmatrix} A_\mu \\ \tilde{A} \end{pmatrix}$ gauginos (fermion)

- UV instability canceled by the superpartners



- internal consistency + anomaly cancellation require 2 Higgs doublets

h comes along with: $H^\pm,\ H,\ A$

- dynamical explanation for EWSB: m_H^2 driven negative by top loops via RG evolution

- Higgs must be light:

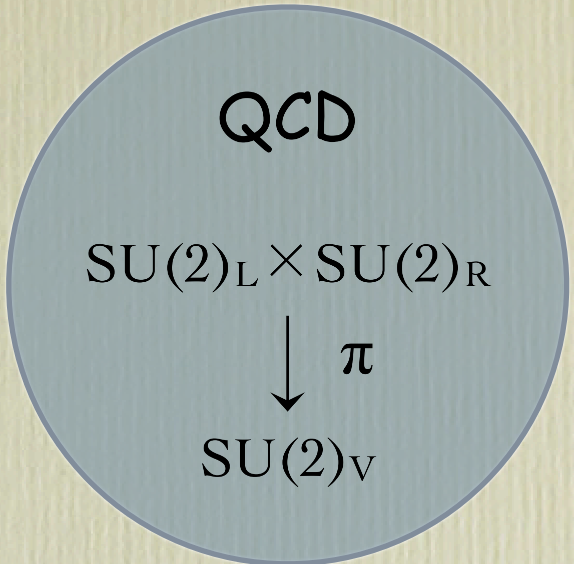
$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{N_c}{2\pi^2}\frac{m_t^4}{v^2}\log\left(\frac{\tilde{m}_t^2}{m_t^2}\right)^2$$

$$m_h \lesssim 135\,\mathrm{GeV}$$

IV. Restoring unitarity by adding an infinite number of new states

The QCD analogy:

QCD is a remarkable example of a (strongly-interacting) sector which leads to a chiral Lagrangian in the low-energy limit



- For m_q=0 QCD with 2 flavors has an $SU(2)_L x SU(2)_R$ invariance

$$\mathcal{L}_{QCD} = \sum_{q=u,d} \bar{q}\,\gamma^\mu \left(i\partial_\mu - g_3\,\lambda^a G^a_\mu\right) q$$

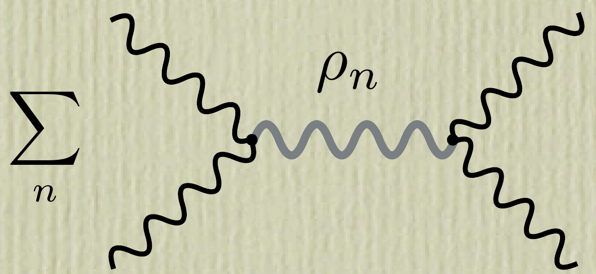
- $SU(2)_L x SU(2)_R$ spontaneously broken to $SU(2)_V$ at low energy by the $\langle \bar{q} q \rangle$ condensate

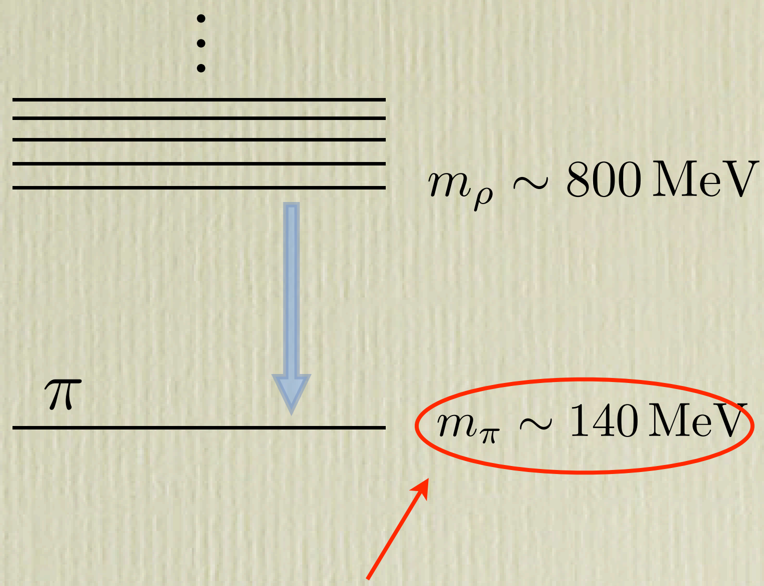
$$\mathcal{L}_\chi = \frac{f_\pi^2}{4} \mathrm{Tr}\left[\partial_\mu \Sigma^\dagger \partial^\mu \Sigma\right]$$

- the three pions π^a are the composite Goldstone bosons of the chiral symmetry breaking

$$\Sigma(x) = e^{i\sigma^a \pi^a(x)/f_\pi} \qquad f_\pi = 92\,\mathrm{MeV}$$

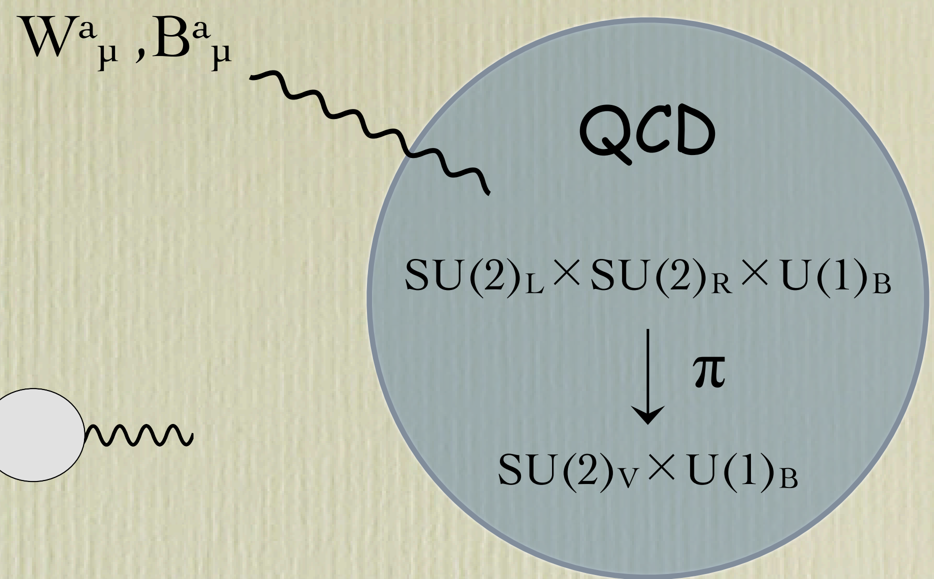
Unitarity of $\pi\pi$ scattering is enforced by the contribution of the heavier vector and axial resonances :

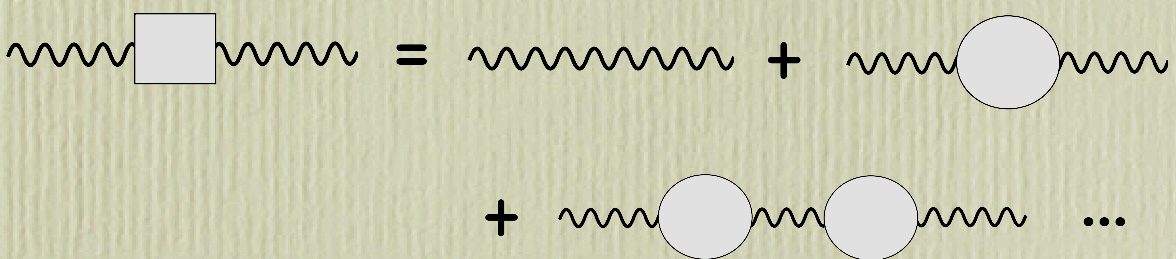




the pion lighter because
is a (pseudo)-Goldstone

After turning on the $SU(2)_L x U(1)_Y$ gauging, the pions are in fact eaten to give mass to the W and Z:





$$G^{\mu\nu}(q) = \frac{-i}{q^2}\frac{1}{1-g_2^2\,\Pi(q^2)}\left(\eta^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right)$$

$$i\Pi^{\mu\nu}(q) = -\int d^4q\; e^{-iqx}\langle T\left\{J^\mu(x)J^\nu(0)\right\}\rangle$$

$$\Pi^{\mu\nu}(q) = \Pi(q^2)\left(q^2\eta^{\mu\nu} - q^\mu q^\nu\right)$$

✓ $U(1)_Q$ unbroken: massless photon

✓ custodial symmetry ⇒ ρ=1

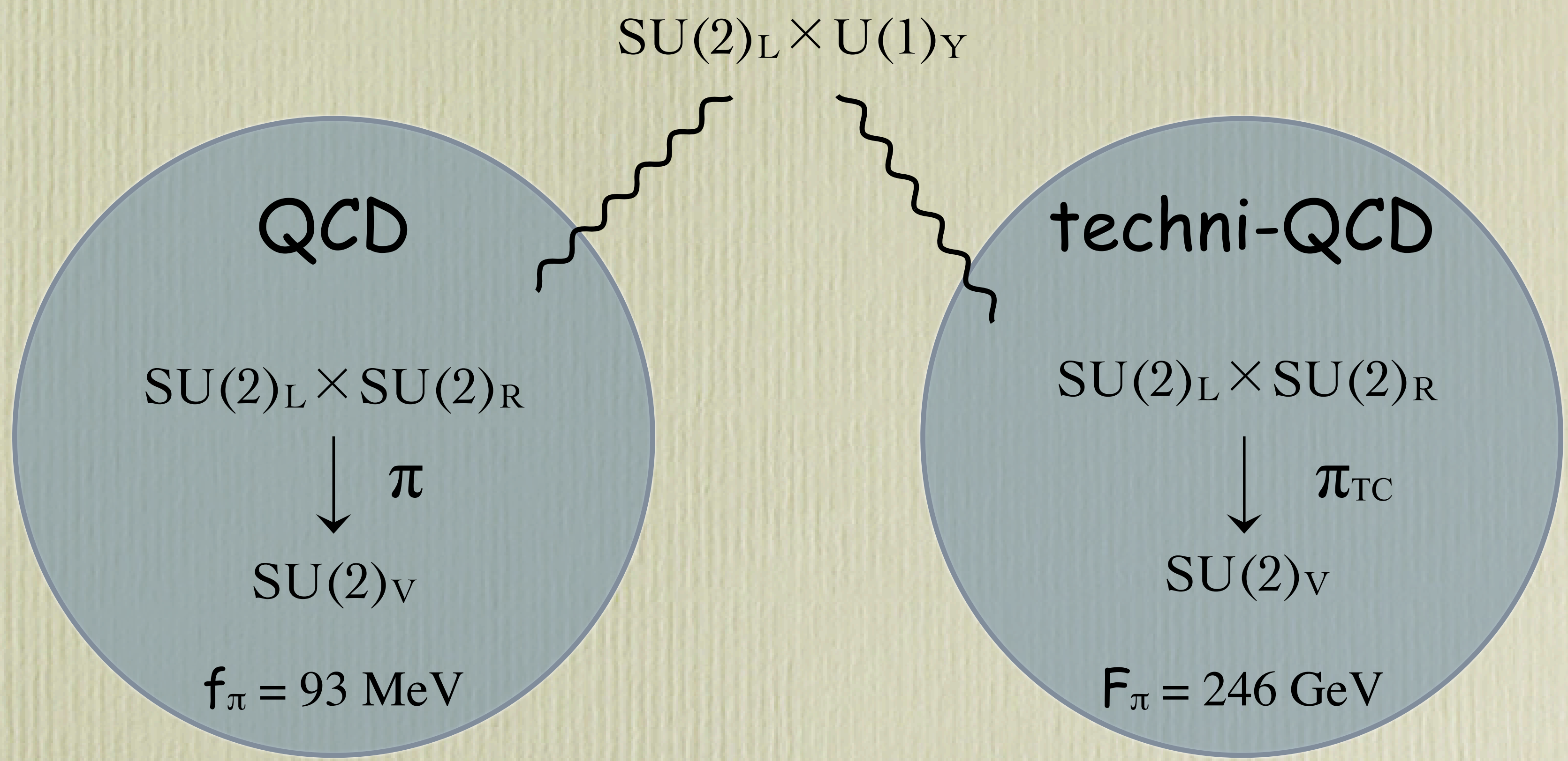
☹ Problems:

1) f_π =92MeV ⇒ $M_W = g\, f_\pi/2$ =30 MeV !

2) we do observe the pions !

The technicolor paradigm:

[Weinberg, Susskind]



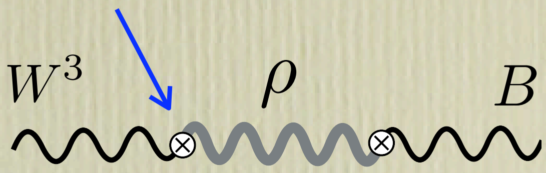
✓ $F_\pi \gg f_\pi$ ⇨

1) W_{long}, Z_{long} mostly from π_{TC} : $M_W \simeq g\, F_\pi/2 = 80$ GeV

2) still a physical pion in the spectrum, mostly π

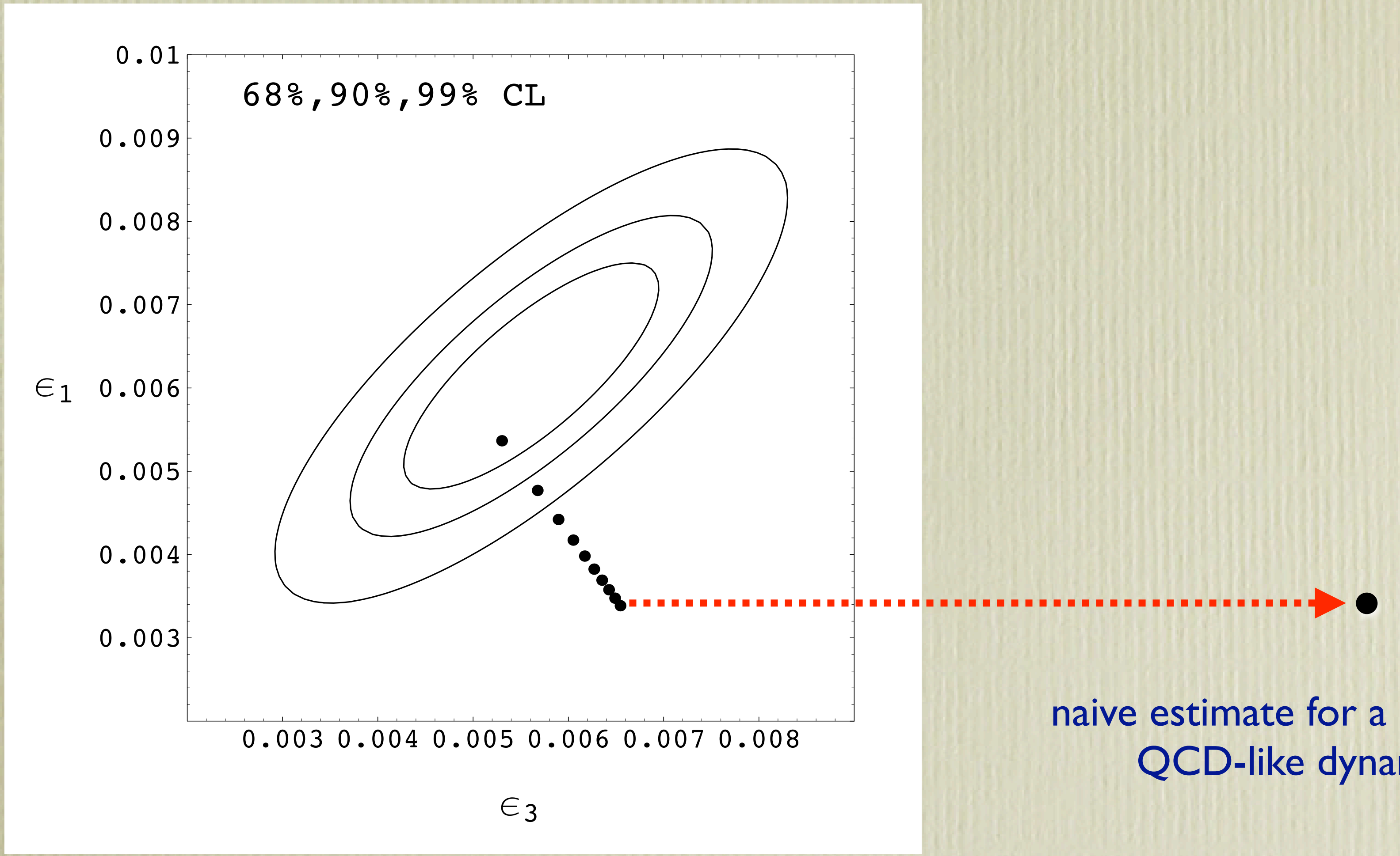
Naive Technicolor does not work

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



Large corrections to the S parameter

$$\Delta\mathcal{L} = \frac{S}{32\pi} W^3_{\mu\nu} B_{\mu\nu} \qquad S \sim 16\pi \left(\frac{v}{m_\rho}\right)^2 \sim \frac{N}{\pi}$$



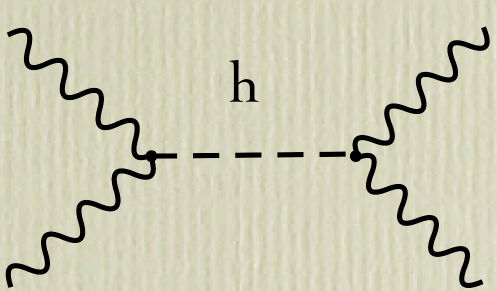
naive estimate for a scaled-up QCD-like dynamics

☞ A possible solution to the EWPT problem:

suppose the strong dynamics has also a light scalar bound state playing the role of the Higgs

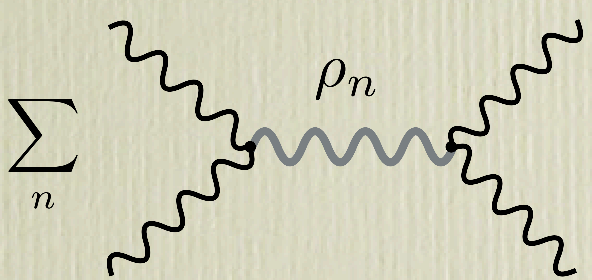
the composite Higgs partially unitarize

the WW scattering until a scale $\Lambda' = \frac{\Lambda}{\sqrt{\xi}}$



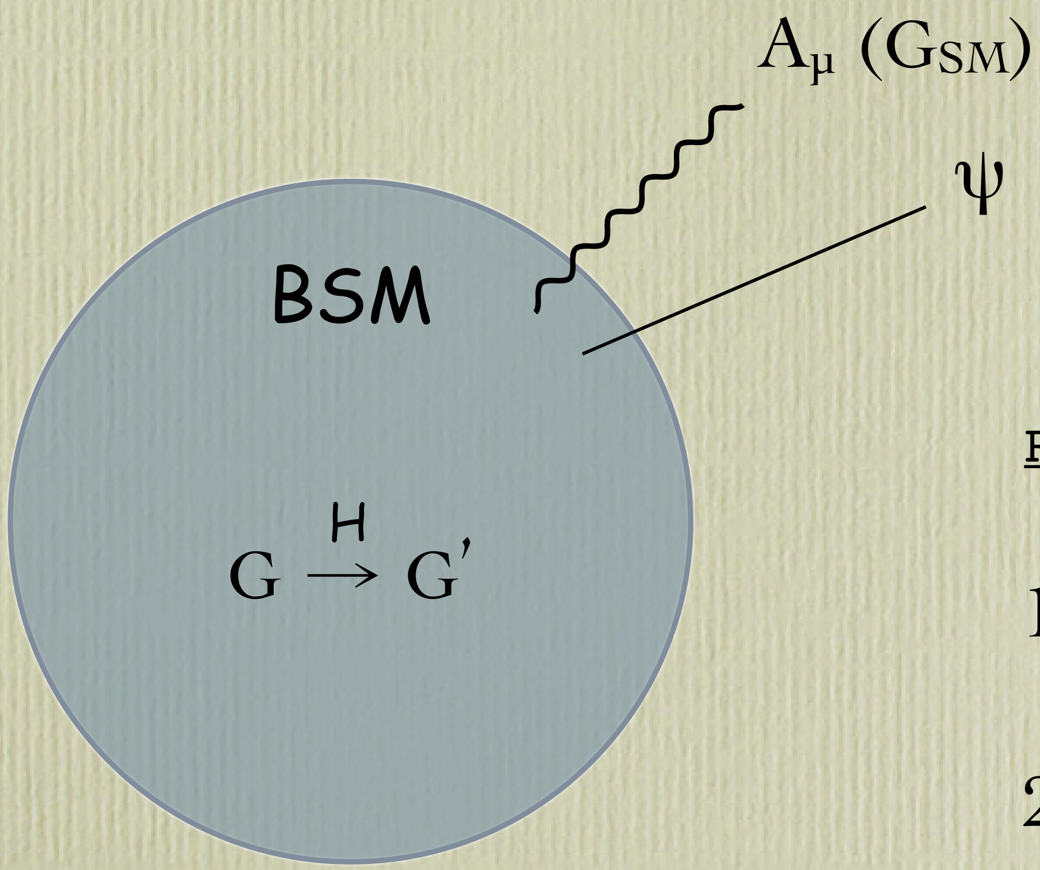
$$g_{hWW} = g^{SM}_{hWW}(1 + O(\xi))$$

... until the vector resonances take on



Composite Higgs models

[Georgi & Kaplan, `80s]



Requirements:

1) $G_{SM} \subset G'$

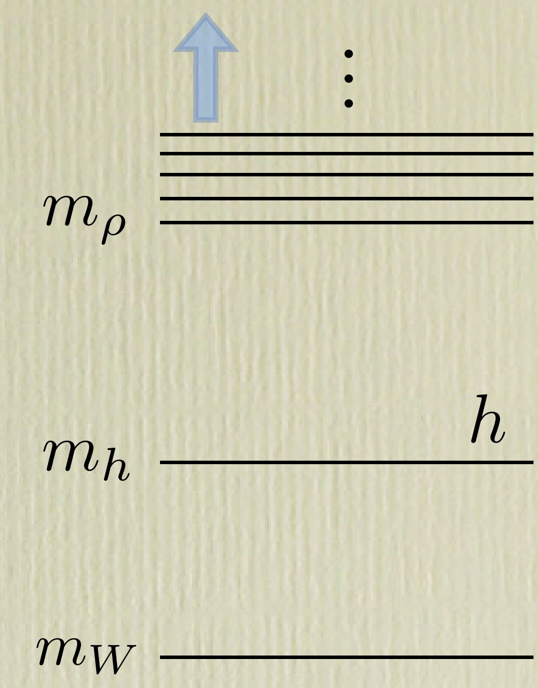
2) H is a doublet of $SU(2)_L$

Example: $SO(5) \rightarrow SO(4) \sim SU(2)_L \times SU(2)_R$

gives 4 real Goldstones: one $SU(2)_L$ doublet H

- vector resonances can be heavier:

  → smaller corrections to EWPO

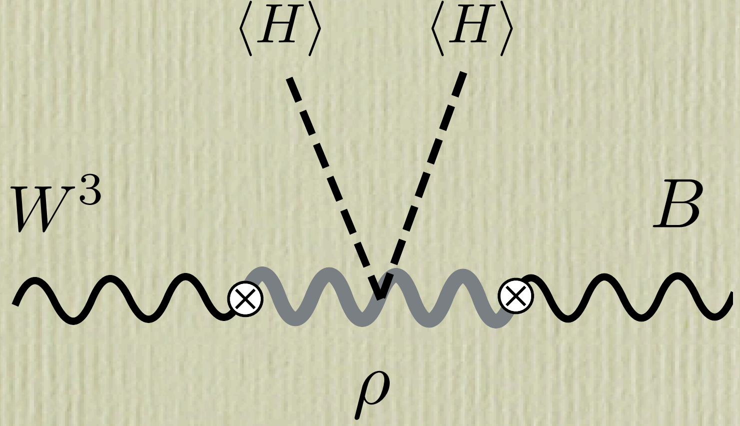


- the Higgs is composite:

  → Planck/TeV Hierarchy solved

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

new parameter compared to TC
(fixed by the dynamics)



$$m_\rho \sim \frac{4\pi f}{\sqrt{N}}$$

$$S \sim 16\pi \left(\frac{v}{m_\rho}\right)^2 \sim \xi \, \frac{N}{\pi}$$

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

decoupling limit:

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

LHC will tell us which path

Nature has chosen !

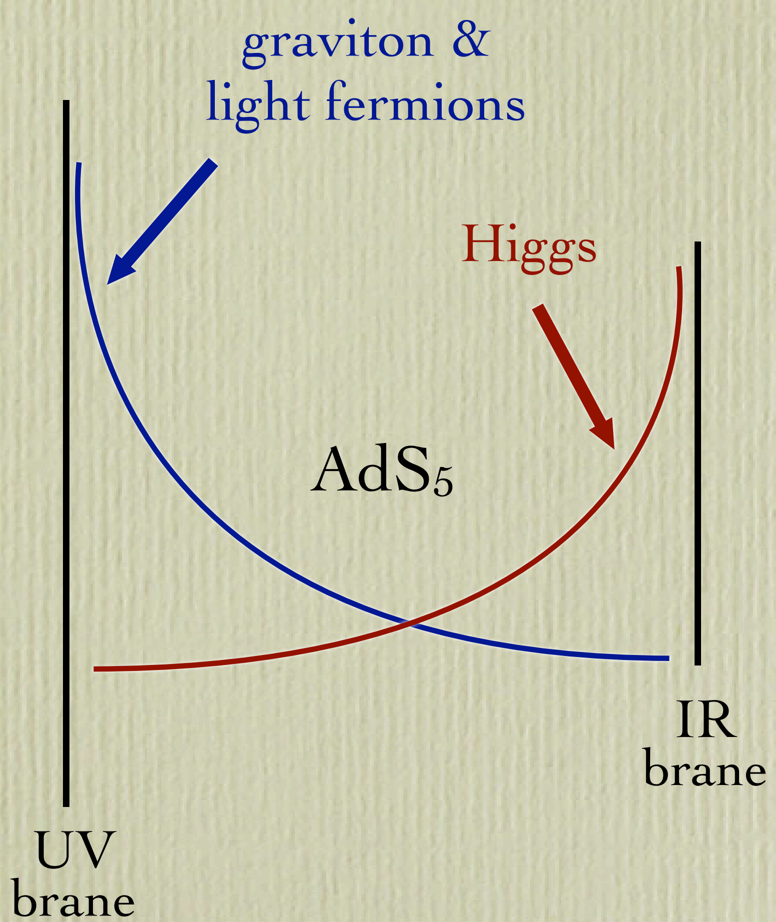
(The End)

Extra Slides

Field theories with a curved fifth dimension give an explicit realization of 4D composite Higgs models

Resonances of the strong sector ⟷ Kaluza-Klein excitations

Example of strong dynamics: a Randall-Sundrum setup



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 in y ⇔ 4D rescaling

- Solution to the Hierarchy Problem

  geography of wave functions in the bulk

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

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

The holographic description