Effective Theories for Physics Beyond the Standard Model

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ETs a useful tool in many different areas of PBSM

E.g.: B- and/or L-violation, flavour physics, etc

Concentrate on EWSB $\Leftrightarrow$ EWPT

(leave out specific models)

Why?

$\Rightarrow$ *LHC will explore* ***for the first time*** *the* ***relevant*** *energy range, well above the Fermi scale*

$$\Lambda_{QCD},\ G_F^{-1/2}$$

Outline

1. The SM as a prototype Effective Theory
2. Making it without a Higgs boson
3. A more naive but also more effective expansion
4. Expanding in operators of higher dimension
5. The “little hierarchy problem”

1. The SM as a prototype Effective Theory

The 2 equivalent ways to define the SM:

1

$$\mathcal{L}_{\sim SM} = -\frac{1}{4}F^a_{\mu\nu}F^{a\,\mu\nu} + i\bar{\psi}D\psi$$

The gauge sector (1)

$$+\psi_i\lambda_{ij}\psi_j h + h.c.$$

The flavor sector (2)

$$+|D_\mu h|^2 - V(h)$$

The EWSB sector (3)

$$+N_i M_{ij} N_j$$

The ν-mass sector (4)
(if Majorana)

2

The SM as the most general renormalizable theory with the given gauge symmetry and particle content

SU_{321} $\qquad$ $3\,\Psi_{16} + 1\,H$

$\Rightarrow$ The good news:

The SM as the unique low energy effective approximation of an infinite number of possible theories

(in the jargon: Ultra-Violet completions)

$\Rightarrow$ The bad news:

How can we possibly think of guessing the right PBSM?

(but wait a moment)

What do we know of the Higgs mass in the SM?

1. Limit from direct search

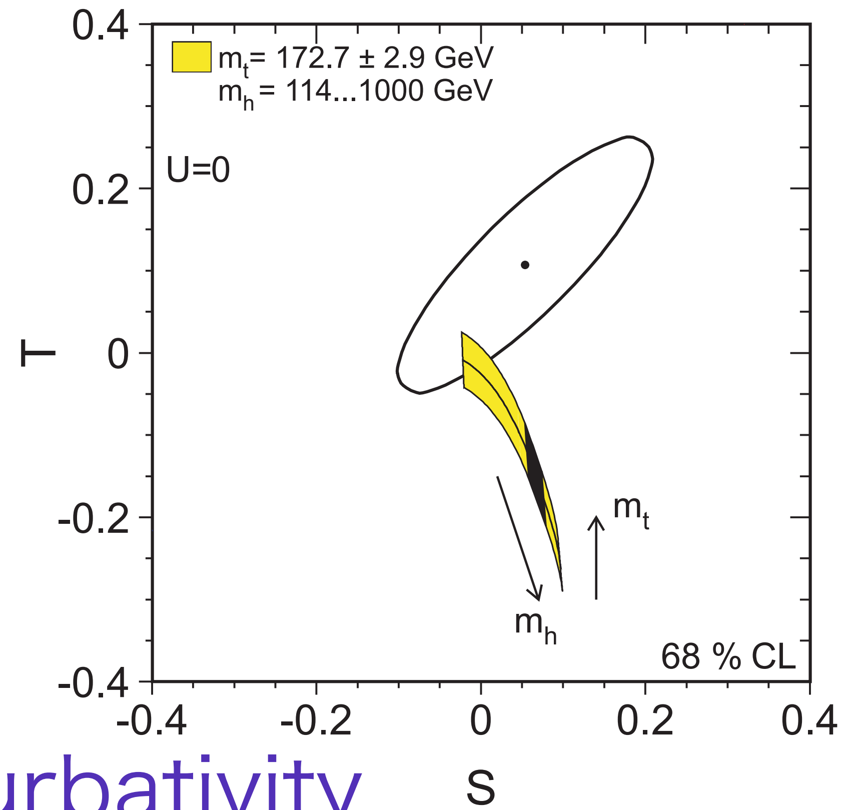
$$m_h > 114.5\ GeV$$

2. EWPT

$$m_h = 88^{+34}_{-26} GeV$$

$$m_h < 185\ GeV$$

$$(m_t = 172.5 \pm 2.3\ GeV)$$



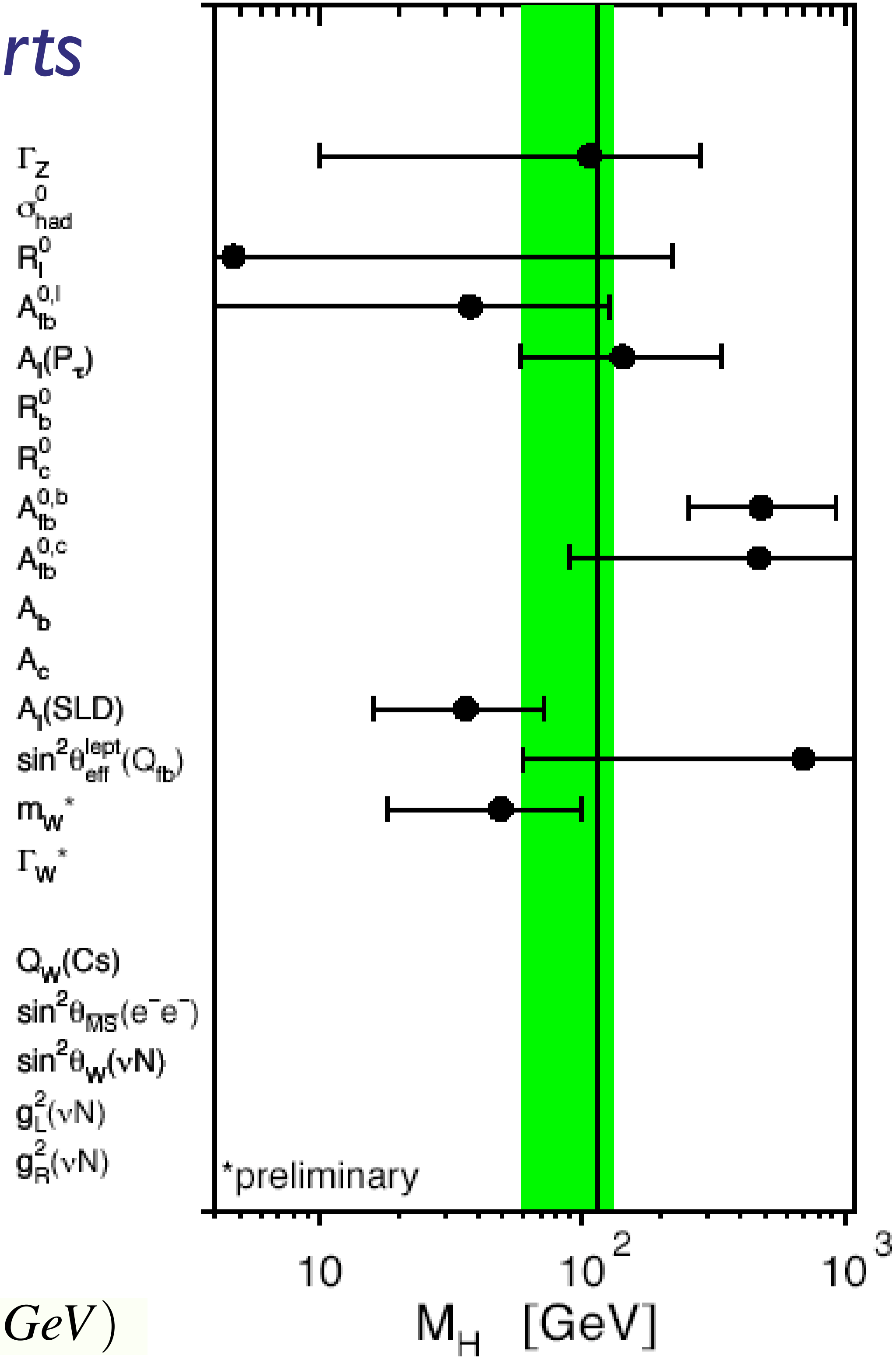
(see below)

LEPEWWG

3. Perturbativity

m_h,GeV	Λ_P,TeV	Λ_L,TeV
400	2.4	80
500	1.8	16
600	1.6	7.5

For non-experts



indirect:

$M_H = 86^{+39}_{-30} GeV$

$M_H < 175\ GeV$

95% CL

direct:

$m_H > 114\ GeV$

LEPEWWG

$(m_t = 172.5 \pm 2.3\ GeV)$

The naturalness problem of the Fermi scale

A non-trivial property of any UV-completion:

The Higgs boson must be in its InfraRed spectrum,
i.e. it must be light relative to any of its mass scales

We only know of approximate symmetries that can explain this. In all explicit examples, barring unwarranted cancellations,

the Higgs mass is at least of the same size of the SM contribution computed with a cut-off scale Λ_{NP}

$$\delta m_h^2 = \alpha_t \Lambda_t^2 + \alpha_g \Lambda_g^2 + \alpha_h \Lambda_h^2 \quad \Rightarrow \quad \begin{array}{l} \Lambda_t \approx 3.5\, m_h \\ \Lambda_g \approx 9\, m_h > \Lambda_t \\ \Lambda_h \approx 1.3 \text{ TeV} \end{array}$$

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My personal view on 1

1. The SM is an effective Lagrangian

2. (not an opinion) The naturalness problem of the Fermi scale is well defined.

3. If it does not have an accidental solution (=no solution), the chances of seeing new physics at the LCH greatly enhanced

Making it without a Higgs

The EW chiral Lagrangian

In the SM: $H_{SM} = \Sigma \begin{pmatrix} 0 \\ v+h \end{pmatrix}$ $\Sigma = \exp i\frac{\pi \cdot \tau}{v}$

invariant under

$H_{SM} \Rightarrow U_L H_{SM}$ $U_L = \exp i\omega_L \cdot \tau/2$ $H_{SM} \Rightarrow \exp(i\omega_Y/2) H_{SM}$

Changing notation:

$\boxed{\Phi \equiv (v+h)\Sigma}$ $\Phi \Rightarrow U_L \Phi$ $\Phi \Rightarrow \Phi \exp(-i\omega_Y \tau_3/2)$

$D_\mu \Phi \equiv d_\mu \Phi - g\hat{W}_\mu \Phi + g' \Phi \hat{B}_\mu$ $\hat{W}_\mu \equiv -i/2 \mathbf{W}_\mu \cdot \tau$ $\hat{B}_\mu \equiv -i/2 B_\mu \cdot \tau_3$

$H^+_{SM} H_{SM} = \frac{1}{2} Tr(\Phi^+ \Phi)$ $|D_\mu H_{SM}|^2 = \frac{1}{2} Tr(D_\mu \Phi)^+ (D_\mu \Phi)$

$\Rightarrow$ Throw away h and even forget the doublet origin of Σ

$\Rightarrow$ EW Chiral Lagrangian

In the g'$\rightarrow$0 limit

$SU(2)_L x SU(2)_R$ $\Sigma \Rightarrow U_L \Sigma U_R^+$

The EW chiral Lagrangian (continued)

An expansion in powers of derivatives and $V_\mu \equiv (D_\mu \Sigma)\Sigma^+$

$$\Sigma = \exp i\frac{\pi\cdot\tau}{v} \qquad T \equiv \Sigma\tau_3\Sigma^+$$

$$\mathcal{L}_{EWCh} = \mathcal{L}_G + \mathcal{L}_{NL} + \Sigma_{i=0}^{10}\mathcal{L}_i$$

$$\mathcal{L}_G = \frac{1}{2}Tr\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu} + \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\right] \qquad \mathcal{L}_{NL} = \frac{v^2}{4}Tr[(D_\mu\Sigma)^+ D_\mu\Sigma]$$

$$\Rightarrow \mathcal{L}_0 = a_0\frac{v^2}{4}\left[Tr\left(TV_\mu\right)\right]^2$$

$$\Rightarrow \mathcal{L}_1 = a_1\frac{igg'}{2}B_{\mu\nu}Tr\left(T\hat{W}^{\mu\nu}\right)$$

$$\Rightarrow \mathcal{L}_2 = a_2\frac{ig'}{2}B_{\mu\nu}Tr\left(T[V^\mu, V^\nu]\right)$$

$$\Rightarrow \mathcal{L}_3 = a_3 g Tr\left(\hat{W}_{\mu\nu}[V^\mu, V^\nu]\right)$$

$$\Rightarrow \mathcal{L}_4 = a_4\left[Tr\left(V_\mu V_\nu\right)\right]^2$$

$$\Rightarrow \mathcal{L}_5 = a_5\left[Tr\left(V_\mu V^\mu\right)\right]^2$$

$$\Rightarrow \mathcal{L}_6 = a_6 Tr\left(V_\mu V_\nu\right) Tr\left(TV^\mu\right) Tr\left(TV^\nu\right)$$

$$\Rightarrow \mathcal{L}_7 = a_7 Tr\left(V_\mu V^\mu\right)\left[Tr\left(TV^\nu\right)\right]^2$$

$$\Rightarrow \mathcal{L}_8 = a_8\frac{g^2}{4}\left[Tr\left(T\hat{W}_{\mu\nu}\right)\right]^2$$

$$\Rightarrow \mathcal{L}_9 = a_9\frac{g}{2}Tr\left(T\hat{W}_{\mu\nu}\right) Tr\left(T[V^\mu, V^\nu]\right)$$

$$\Rightarrow \mathcal{L}_{10} = a_{10}\left[Tr\left(TV_\mu\right) Tr\left(TV_\nu\right)\right]^2$$

$\Rightarrow$ 2V-terms $\quad\Rightarrow$ 3V-terms

$\Rightarrow$ 4V-terms

Important remarks on the EWChL

⇒ Its symmetries:

gauged $SU(2)_L x U(1)_Y$ exact (surprising?)

As g'→0, global $SU(2)_L x SU(2)_R$ conserved by

$$\mathcal{L}_{NL} + \mathcal{L}_g + \Sigma_{i=1}^{5} \mathcal{L}_i$$

⇒ Without knowing the underlying dynamics, 11 unknown parameters $a_0, a_1, ..., a_{10}$

as opposed to a single one in the SM: the Higgs mass m_h

(v, g, g' are in common)

⇒ The SM as $m_h \longrightarrow \infty$ is a particular $\mathcal{L}_{EWCh}$

At one loop, 4 a_i's diverge logarithmically

What is it known of the a_i's experimentally?

V^2 - terms: $a_0,\ a_1,\ a_8 \Leftrightarrow T,\ S,\ U$ see plot and below

(in one-to-one correspondence)

V^3 - terms: $a_2,\ a_3,\ a_9$

Setting $a_9 = 0$ $\quad a_2,\ a_3 \Leftrightarrow g_1^Z,\ k_\gamma$

From $e^+e^- \to W^+W^-$ at LEP2

$$g_1^Z - 1 = -0.016^{+0.022}_{-0.019}$$

$$k_\gamma - 1 = -0.027^{+0.044}_{-0.045}$$

($O(10^{-3})$ in the SM)

LEPEWWG

V^4 - terms: $a_4,\ a_5,\ a_6,\ a_7,\ a_{10}$

Nothing known

$\bigcirc = SU(2)_{L+R}$ conserving

A nearby strong interaction?

$$A(W_L W_L) \approx \quad \underset{\text{Gauge}}{(E/v)^2} \quad - \quad \underset{\text{Higgs}}{(E/v)^2} \approx E^0$$

Without a Higgs, perturbation theory saturated at $E \approx 4\pi v$

Obvious from the point of view of $\mathcal{L}_{EWCh}$

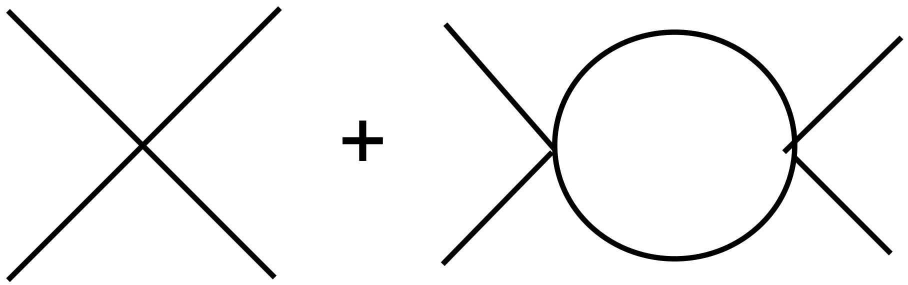
$$\Delta\mathcal{L}_{NL} = v^2/4 |(\partial_\mu + igA_\mu) e^{i\pi^a\tau^a/v}|^2$$

$$\approx g^2 v^2 A_\mu^2 + (\partial_\mu \pi)^2 + \frac{1}{v^2}\pi^2(\partial_\mu \pi)^2 + \ldots$$

$$\Rightarrow \Lambda_4 \sim 4\pi v \sim 4\pi \frac{M_W}{g}$$

Unless something happens below Λ_4

$$\approx g^2 v^2 A_\mu^2 + (\partial_\mu \pi)^2 + \frac{1}{v^2}\pi^2(\partial_\mu \pi)^2 + \ldots$$



$(E/v)^2$

$(E/v)^2 \; (E/v)^2 \frac{1}{16\pi^2}$

$$\Rightarrow \Lambda_4 \sim 4\pi v \sim 4\pi \frac{M_W}{g}$$

An amusing counter-example:
A 5D-gauge theory broken by boundary conditions

Csaki et al

1. Where is the strong dynamics?

$$\mathcal{L}_5 = \frac{1}{4g_5^2} F_{MN} F^{MN}$$

$\frac{1}{g_5^2}$ = [mass]

$$\Rightarrow A_{gauge} \approx \frac{E g_5^2}{24\pi^3}$$

$$\Rightarrow \Lambda_5 \sim \frac{24\pi^3}{g_5^2}$$

2. Compactify the 5-th D without breaking G

(Only IR-physics modified, at 1/R,
Λ_5 determined by short distance physics)

$\Rightarrow$ KK spectrum of vectors $\quad M_n = \frac{n}{R}, \quad n = 0, 1, \ldots$

coupled at $E \leq \frac{1}{R} << \Lambda_5$ with strength $g_4 \sim \frac{g_5}{\sqrt{2\pi R}}$

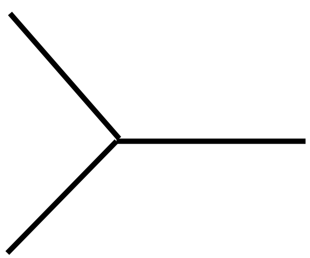
$$\Rightarrow \quad \Lambda_5 \sim \frac{24\pi^3}{g_5^2} = \frac{12\pi^2}{g_4} M_1 = \frac{3\pi}{g_4}\frac{4\pi M_1}{g_4} = \frac{3\pi}{g_4}\Lambda_4$$

by a non trivial dynamics!!!

$$\mathcal{L}_5 = \frac{1}{4g_5^2} F_{MN} F^{MN}$$

$$A_\mu \to g_5\, A_\mu \qquad \mathcal{L}_5 = \frac{1}{4}(d_M A_N - d_M A_N)^2 + g_5 A_M A_N d_M A_N + \ldots$$

$$\Rightarrow \quad [A_M] = m^{3/2} \quad \Rightarrow \qquad \frac{1}{g_5^2} = \text{[mass]}$$



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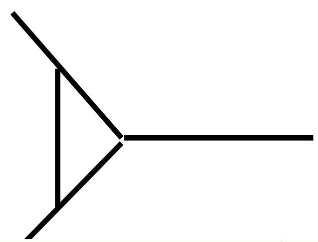

$$g_5 E \qquad g_5 E\ g_5^2 E\ \frac{1}{24\pi^3} \qquad \Rightarrow \Lambda_5 \sim \frac{24\pi^3}{g_5^2}$$

$$\int d^5x \frac{1}{4g_5^2} F_{MN} F^{MN} = \int d^4x\ 2\pi R \frac{1}{4g_5^2} F^0_{MN} F^{MN0} \qquad \Longrightarrow \qquad g_4 \sim \frac{g_5}{\sqrt{2\pi R}}$$

3. Break G by boundary conditions

$0 \quad\quad \pi R$

$$\mathcal{L} = \mathcal{L}_5 + \delta(y)\mathcal{L}_0 + \delta(y-\pi R)\mathcal{L}_\pi$$

$$\Delta\mathcal{L}_\pi = F^2 |(\partial_\mu + igA_\mu)e^{i\Sigma/F}|^2$$
$$\approx g^2F^2A_\mu^2 + (\partial_\mu\pi)^2 + \frac{1}{F^2}\pi^2(\partial_\mu\pi)^2 + \ldots$$

Send F $\rightarrow \infty$

1. Effectively $A_\mu|_{\pi R} = 0$
2. No new strong scale $\Leftarrow$

The vector spectrum $M_n = \dfrac{n+1/2}{R}, \quad n = 0, 1, ..$

If $M_0 = \dfrac{1}{2R} = m_Z$ then $m_{Z1} = \dfrac{3}{2R} = 3m_Z$!!!

4. Take a big kinetic term on the boundary

$g_{bound} \uparrow \qquad \dfrac{M_{n>1}}{M_1} \uparrow$

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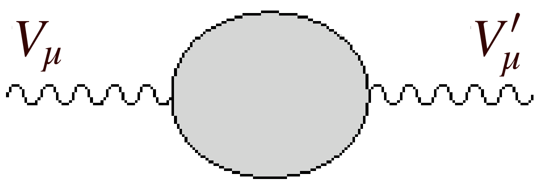
My personal view on 2

1. (not an opinion)Making it without a Higgs is technically possible
2. Without a specified underlying dynamics, a great loss of predictive power relative to the SM

A more naive but also more effective expansion

⇒ Consider a theory characterized by a scale Λ_{SB} with its virtual effects likely significant in the vac. pol. amplitudes of the vector bosons. At $q^2 < \Lambda_{SB}^2$



$$\Pi_V(q^2) \approx \Pi_V(0) + q^2\Pi'_V(0) + \frac{(q^2)^2}{2}\Pi''_V(0) + \ldots$$

where $V = W^+W^-, W_3W_3, BB, W_3B.$

[Note: in general, W and B are the interpolating fields that couple to quarks and leptons, even if many vectors present, provided they couple to fermions through the usual charged and neutral currents: "universal theories"]

Up to $O((q^2)^2)$ the number of coefficients is

$$3 \times 4 = 12 = 3(g, g', v) + 2(m_\gamma = 0, Q = T_3 + Y) + 7$$

$$7 = 1\ (\Pi_V(0)) + 2\ (\Pi'_V(0)) + 4\ (\Pi''_V(0))$$

Their definition and symmetry properties

B, Pomarol, Rattazzi, Strumia

see below

Adimensional form factors			operators			custodial	$SU(2)_L$
$g^{-2}\widehat{S}$	$=$	$\Pi'_{W_3B}(0)$	$\mathcal{O}_{WB}$	$=$	$(H^\dagger\tau^a H)W^a_{\mu\nu}B_{\mu\nu}/gg'$	$+$	$-$
$g^{-2}M_W^2\widehat{T}$	$=$	$\Pi_{W_3W_3}(0)-\Pi_{W^+W^-}(0)$	$\mathcal{O}_H$	$=$	$\lvert H^\dagger D_\mu H\rvert^2$	$-$	$-$
$-g^{-2}\widehat{U}$	$=$	$\Pi'_{W_3W_3}(0)-\Pi'_{W^+W^-}(0)$		$-$		$-$	$-$
$2g^{-2}M_W^{-2}V$	$=$	$\Pi''_{W_3W_3}(0)-\Pi''_{W^+W^-}(0)$		$-$		$-$	$-$
$2g^{-1}g'^{-1}M_W^{-2}X$	$=$	$\Pi''_{W_3B}(0)$		$-$		$+$	$-$
$2g'^{-2}M_W^{-2}Y$	$=$	$\Pi''_{BB}(0)$	$\mathcal{O}_{BB}$	$=$	$(\partial_\rho B_{\mu\nu})^2/2g'^2$	$+$	$+$
$2g^{-2}M_W^{-2}W$	$=$	$\Pi''_{W_3W_3}(0)$	$\mathcal{O}_{WW}$	$=$	$(D_\rho W^a_{\mu\nu})^2/2g^2$	$+$	$+$

- relation with *standard* S, T, U:

$S = 4s_W^2\widehat{S}/\alpha \approx 119\widehat{S},\ T=\widehat{T}/\alpha\approx 129\widehat{T},\ U=-4s_W^2\widehat{U}/\alpha.$

- "custodial": $SU(2)_V$ under which W_μ^a transform as a triplet

and $\Phi = \begin{pmatrix}\phi_0^* & \phi_+\\ -\phi_+^* & \phi_0\end{pmatrix} \Rightarrow e^{i\vec{w}\vec{\sigma}}\Phi e^{-i\vec{w}\vec{\sigma}}$ $\qquad SU(2)_V\subset SU(2)_{L+R}$

- no new class of parameters by going to higher powers of q^2
- 4 emerging: $\widehat{S},\widehat{T},W,Y$

Their determination

- Data 1: the EWPT's at the Z- and W- poles

Can express all effects in terms of 3 observable quantities:

Peskin, Takeuchi
Altarelli, B

$$\frac{m_W^2}{m_Z^2} = \frac{m_W^2}{m_Z^2}\Big|_B (1 + 1.43\epsilon_1 - 1.00\epsilon_2 - 0.86\epsilon_3),$$

$$\Gamma_l = \Gamma_l|_B (1 + 1.20\epsilon_1 - 0.26\epsilon_3),$$

$$A_l^{FB} = A_l^{FB}|_B (1 + 34.72\epsilon_1 - 45.15\epsilon_3),$$

which can then be related to the various form factors:

$$\varepsilon_1 = (+5.3 - 0.86 \ln \frac{m_h}{M_Z} \pm ...)10^{-3} + \widehat{T} - W + 2X \frac{s_W}{c_W} - Y \frac{s_W^2}{c_W^2}$$

$$\varepsilon_2 = (-7.5 - 0.16 \ln \frac{m_h}{M_Z} \pm ...)10^{-3} - \widehat{U} - W + 2X \frac{s_W}{c_W} - V\,,$$

$$\varepsilon_3 = (+4.9 - 0.54 \ln \frac{m_h}{M_Z} \pm ...)10^{-3} + \widehat{S} \frac{c_W}{s_W} - W + \frac{X}{s_W c_W} - Y\,.$$

- Define the various coeff.s as *deviations* from the SM (hence the result is $\log m_h$- dependent)

Their determination (continued)

- Data 2: the $e^+e^- \to f\bar{f}$ at LEP2

The modified Z- γ propagator

$$\begin{array}{cc} & \begin{array}{cc} Z & \gamma \end{array} \\ \begin{array}{c} Z \\ \gamma \end{array} & \begin{pmatrix} G_{ZZ}(s) + \dfrac{\Delta\varepsilon_1}{s - M_Z^2} - \dfrac{\varepsilon_{ZZ}}{M_W^2} & G_{Z\gamma}(s) + \dfrac{c_W^2(\Delta\varepsilon_1 - \Delta\varepsilon_2) - s_W^2 \Delta\varepsilon_3}{s_W c_W (s - M_Z^2)} + \dfrac{\varepsilon_{Z\gamma}}{M_W^2} \\ G_{Z\gamma}(s) + \dfrac{c_W^2(\Delta\varepsilon_1 - \Delta\varepsilon_2) - s_W^2 \Delta\varepsilon_3}{s_W c_W (s - M_Z^2)} + \dfrac{\varepsilon_{Z\gamma}}{M_W^2} & G_{\gamma\gamma}(s) - \dfrac{\varepsilon_{\gamma\gamma}}{M_W^2} \end{pmatrix} \end{array}$$

also expressed in terms of the various form factors:

$$\begin{aligned} \varepsilon_{ZZ} &= c_W^2 W - 2 s_W c_W X + s_W^2 Y, \\ \varepsilon_{\gamma\gamma} &= s_W^2 W + 2 s_W c_W X + c_W^2 Y, \\ \varepsilon_{Z\gamma} &= (c_W^2 - s_W^2) X + s_W c_W (W - Y) \end{aligned}$$

Their determination (finally)

- Limit the fit to the likely dominant terms, $\widehat{S},\widehat{T},W,Y$.
(7 parameters against 3+3 observables would be 1 too much)

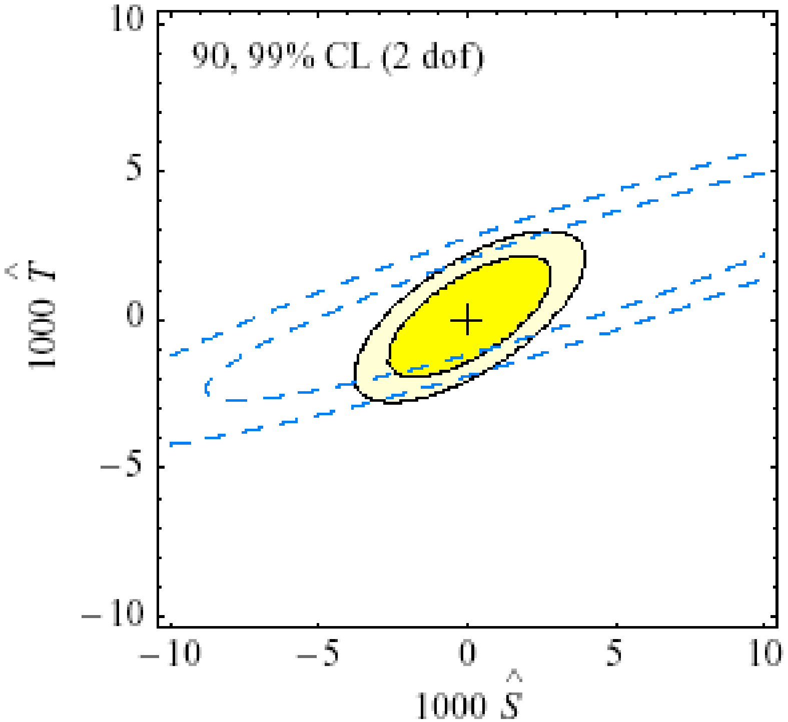
LEP2(~percent)/LEP1(~permille) compensated by $q^2/m_Z^2 \approx 5$

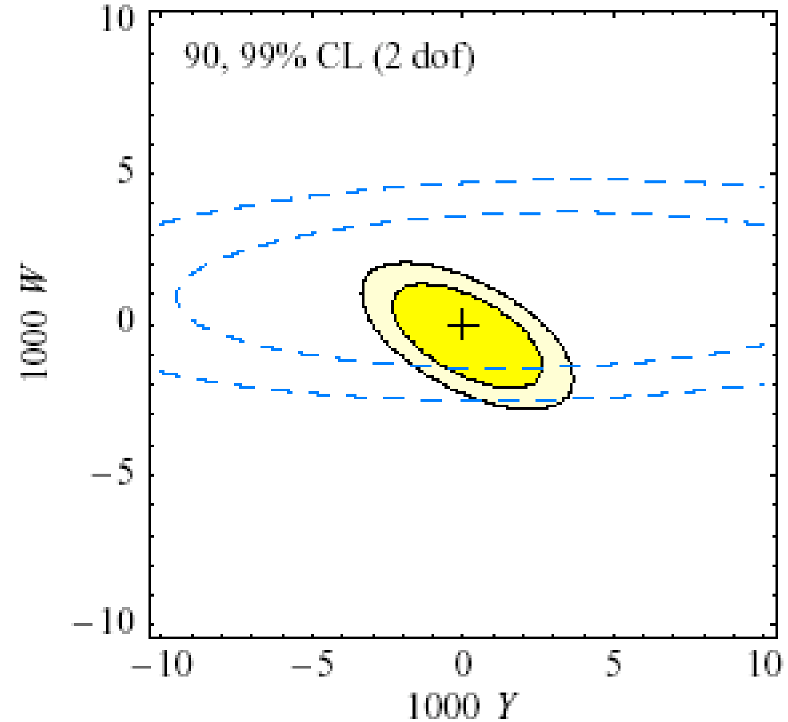
Type of fit	$10^3\widehat{S}$	$10^3\widehat{T}$	$10^3 Y$	$10^3 W$
One-by-one (light Higgs)	0.0 ± 0.5	0.1 ± 0.6	0.0 ± 0.6	-0.3 ± 0.6
One-by-one (heavy Higgs)	—	2.7 ± 0.6	—	—
All together (light Higgs)	0.0 ± 1.3	0.1 ± 0.9	0.1 ± 1.2	-0.4 ± 0.8
All together (heavy Higgs)	-0.9 ± 1.3	2.0 ± 1.0	0.0 ± 1.2	-0.2 ± 0.8

$\Rightarrow$ The deviations from the SM pretty constrained

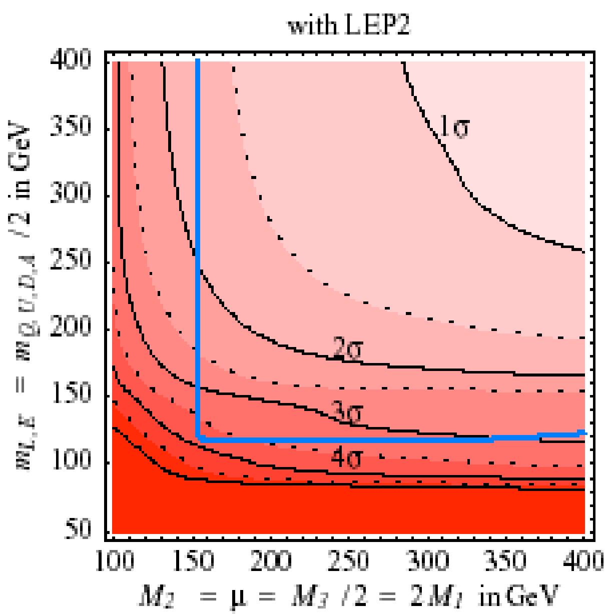
$\Rightarrow$ A heavy Higgs (800 GeV) technically allowed.
Significant? See below

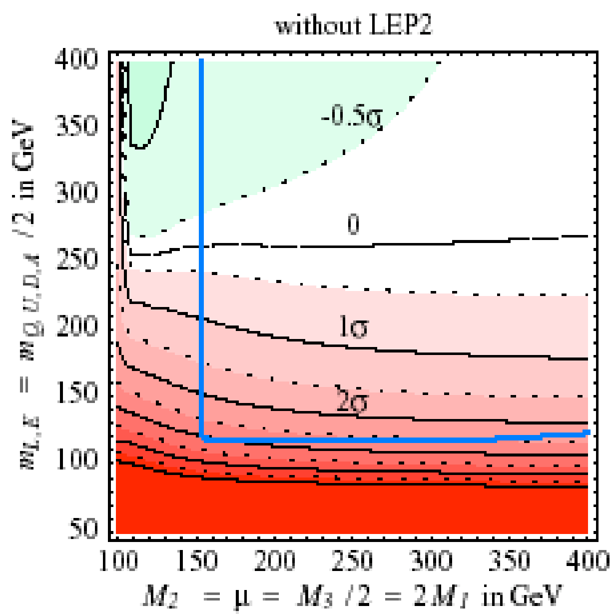
The role of LEP2





(generic fit:
$\widehat{S}, \widehat{T}, W, Y$)





A supersymmetric example

(Marandella, Schappacher, Strumia)

Estimated uncertainties on precision electroweak observables (future)

$sin^2\theta_{eff}(M_t, m_h, \alpha(M_Z))$
$M_W(M_t, m_h, \alpha(M_Z))$

	now	LHC	LC	Giga-Z
$\delta sin^2\theta_{eff}(10^{-5})$	16 (?)	15	?	1.3
$\delta M_W[MeV]$	34	15	10	7
$\delta M_t[GeV]$	4.3	1.0	0.2	0.1
$\Rightarrow \frac{\delta m_h}{m_h}$	60%	15-20%	10-15%	5-10%

the limiting factor is the worst of the (at least) 3 precisely measured quantities

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Expanding in operators of higher dimension

Back to the original observation: The SM as an effective theory

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \mathcal{L}_{eff}^{NP} \qquad \mathcal{L}_{eff}^{NP} = \Sigma_i \frac{c_i}{\Lambda_{NP}^2} O_i$$

E.g. once again:

Adimensional form factors	Operators	Custodial	$SU(2)_L$
$\hat{S} = g^2 \Pi'_{3B}(0)$	$\mathcal{O}_{WB} = (H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}/gg'$	$+$	$-$
$\hat{T} = \frac{g^2}{M_W^2}(\Pi_{33}(0) - \Pi_{+-}(0))$	$\mathcal{O}_H = \|H^\dagger D_\mu H\|^2$	$-$	$-$
$Y = \frac{g'^2 M_W^2}{2} \Pi''_{BB}(0)$	$\mathcal{O}_{BB} = (\partial_\rho B_{\mu\nu})^2/2g'^2$	$+$	$+$
$W = \frac{g^2 M_W^2}{2} \Pi''_{33}(0)$	$\mathcal{O}_{WW} = (D_\rho W^a_{\mu\nu})^2/2g^2$	$+$	$+$

This is in fact the complete set of operators of dim-6 only dep. on Vectors and Higgs

Grinstein, Wise

(but notice that the expansion in powers of q^2 did not require the Higgs boson to exist)

Any evidence for (which limits on) $\mathcal{L}_{eff}^{NP}$?

Taking $c_i = \pm 1$ and considering one operator at a time

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \mathcal{O}/\Lambda^2$$

	operator $\mathcal{O}$	affects	constraint on Λ
	$\frac{1}{2}(\bar{L}\gamma_\mu \tau^a L)^2$	μ-decay	10 TeV
	$\frac{1}{2}(\bar{L}\gamma_\mu L)^2$	LEP 2	5 TeV
T→	$\lvert H^\dagger D_\mu H \rvert^2$	θ_{W} in M_W/M_Z	5 TeV
S→	$(H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$	θ_{W} in Z couplings	8 TeV
	$i(H^\dagger D_\mu \tau^a H)(\bar{L}\gamma_\mu \tau^a L)$	Z couplings	10 TeV
	$i(H^\dagger D_\mu H)(\bar{L}\gamma_\mu L)$	Z couplings	8 TeV
$\Rightarrow$	$H^\dagger(\bar{D}\lambda_D \lambda_U \lambda_U^\dagger \gamma_{\mu\nu} Q) F^{\mu\nu}$	$b \to s\gamma$	10 TeV
$\Rightarrow$	$\frac{1}{2}(\bar{Q}\lambda_U \lambda_U^\dagger \gamma_\mu Q)^2$	B mixing	10 TeV

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On the meaning of these bounds

$$c_i = \pm 1 \quad ?$$

$\Rightarrow$ The stronger case: fermion compositeness at Λ_{NP}

$$c_i \approx 16\pi^2$$

$\Rightarrow$ The weaker case: NP only induced by loop effects

$$c_i \approx \frac{\alpha}{4\pi}$$

$\Rightarrow$ An intermediate case: NP from perturbative tree level

$$c_i \approx 1$$

Need to consider specific models to be more precise
also because of possible cancellations

Outline

1. The SM as a prototype Effective Theory √
2. Making it without a Higgs boson √
3. A more naive but also more effective expansion √
4. Expanding in operators of higher dimension √
5. The "little hierarchy problem"

My personal view on 3,4

1. The perturbative success of the SM is not accidental.

2. Strongly interacting theories of EWSB disfavoured

The "little hierarchy problem"

$\Rightarrow$ Explain relative Higgs lightness (See 1)

$$\Lambda_{nat} < 400\ GeV \frac{m_h}{115\ GeV}\ \Delta^{1/2}$$

with $1/\Delta$ = % of accidental cancellation

$\Rightarrow$ From the success of the SM (See 3-4)

$$\Lambda_{NP} > 10\ TeV$$

although with the mentioned caveats

A clash between these bounds?? B, Strumia

Addressing the "little hierarchy problem"

1. The Higgs boson made light by an <u>approximate</u> symmetry

$\Rightarrow$ Supersymmetry

$\Rightarrow$ Gauge symmetry

$$A_\mu \to A_\mu + d_\mu \alpha \;\Rightarrow\; \cancel{m^2 A_\mu^2}$$

$$h = A_5$$

$\Rightarrow$ Global symmetry

$$h \to h + \alpha \;\Rightarrow\; \cancel{m^2 h^2}$$

($\Rightarrow$ By accident: not an explanation)

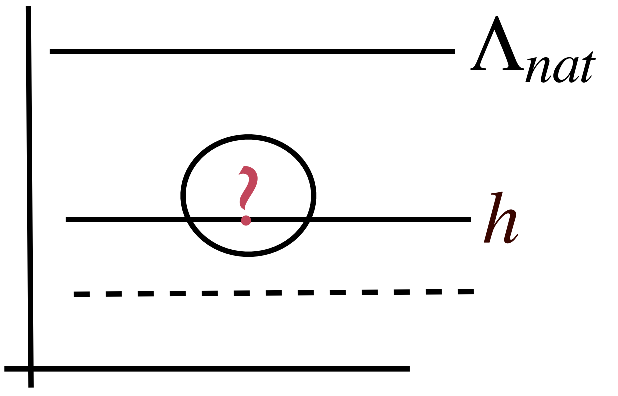
2. How light is the light Higgs?

A Higgs boson in the mass range of 400-600 GeV, if it were consistent with the EWPT, would allow to raise Λ_{nat} to ~1.5 TeV without any cancellation and remaining fully perturbative

Can one raise Λ_{nat} ?

$\downarrow$

What allows to raise m_h ?



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Overview

(in the form of questions)

1. Is it accidental that the SM is the most general renormalizable SU_{321} gauge theory with 3 Ψ_{16} and 1 Higgs doublet in its spectrum?

2. Why the Higgs doublet in the *low-energy* spectrum?

3. Is the perturbative success of the SM accidental?

4. How light is the light Higgs boson?

5. Is there a meaningful clash between Λ_{nat} and Λ_{NP} ?

$\Rightarrow$ *LHC will explore* ***for the first time*** *the* ***relevant*** *energy range, well above the Fermi scale*