Particules Élémentaires, Gravitation et Cosmologie
Année 2007-'08

Le Modèle Standard et ses extensions

The Precision Tests

Particle Physics in one page

$$\mathcal{L}_{\sim SM} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i\bar{\psi} \not{D} \psi$$

The gauge sector (1)

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

The flavour sector (2)

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

The EWSB sector (3)

$$+N_i M_{ij} N_j$$

The ν-mass sector (if Majorana) (4)

The quadrant of nature whose laws can be summarized in one page with absolute precision and empirical adequacy

One century to develop it, from Maxwell on

Can it be the end of the story?

The tree level predictions from the gauge sector

v, g, g' $\Rightarrow$ the boson masses, M_W, M_Z , their self-interactions and their interactions with matter, all read off from $\mathcal{L}$

$$gW_\mu^+ J_\mu^- + h.c., \quad J_\mu^- = \bar{u}\gamma_\mu d + \bar{\nu}\gamma_\mu e$$

$$eA_\mu J_\mu^{em}, \quad J_\mu^{em} = 2/3\bar{U}\gamma_\mu U - 1/3\bar{D}\gamma_\mu D - \bar{E}\gamma_\mu E, \quad e = g\sin\theta$$

$$\frac{g}{\cos\theta} Z_\mu J_\mu^Z, \quad J_\mu^Z = \bar{\Psi}\gamma_\mu (T_3 - Q\sin^2\theta)\Psi$$

$$U = u + (u_c)^C \equiv U_{Dirac}$$

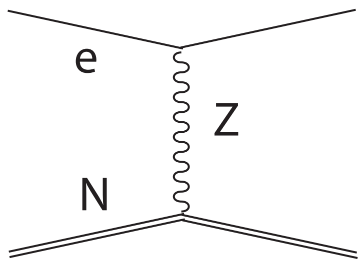
Highly predictive: a great variety of phenomena from

$l_{max} \approx 10^{-8} cm$ (Atomic Parity Violation) to

$l_{min} \approx 10^{-16} \div 10^{-17} cm$ (HERA, LEP, TEVATRON)

[Note, however, that $l_{min} \approx G^{1/2}$]

An example: Atomic Parity Violation

1. From 

to ΔH_{PV}

ΔH_{PV} must be local and proportional to G

$$\Rightarrow \quad \Delta H_{PV} = \frac{G}{\sqrt{2}m_e} Q_W \sigma \cdot \nabla \delta^3(\mathbf{r}) \quad \text{or} \quad A_{PV} = \frac{G}{\sqrt{2}m_e} Q_W \sigma \cdot \mathbf{q}$$

2. From the Z-exchange diagram and $\mathcal{L}$

$$A_{PV} = \frac{G}{\sqrt{2}} (\bar{E}\gamma_\mu\gamma_5 E)(c_u \bar{U}\gamma_\mu U + c_d \bar{D}\gamma_\mu D)$$

$$c_u = -1/2 + 4/3 \sin^2\theta$$
$$c_d = 1/2 - 2/3 \sin^2\theta$$

so that, by comparison, in the NRL

$$Q_W = -2(c_u n_u + c_d n_d) = (2 - 4\sin^2\theta)Z - A$$

3. From the measured S-P mixing in Ce_{55}^{133} induced by ΔH_{PV}

$$Q_W|_{exp} = 72.69(48) \qquad Q_W|_{th} = 73.19(3)$$

The prototype examples of empirical adequacy

$$\frac{(g-2)_e}{2} \equiv a_e = a_e(QED) + a_e(\not{had}) + a_e(\not{EW})$$

$$a_e(QED) = \Sigma_n C_n^e (\frac{\alpha}{\pi})^n$$

$$a_e(exp) = 11596521808.5(7.6) \cdot 10^{-13} \quad \Leftarrow 2006$$

$$a_e(th) = 11596521823(85) \cdot 10^{-13}$$

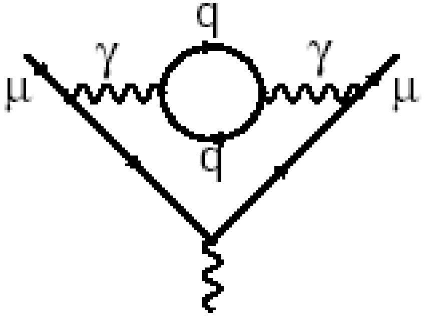
remarkable !, but a pure QED effect

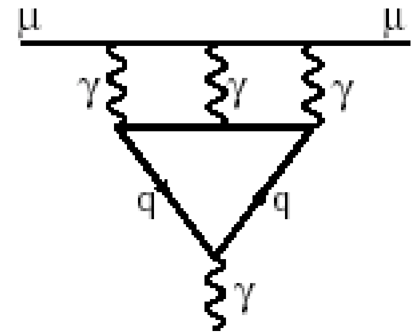
$$\frac{(g-2)_\mu}{2} \equiv a_\mu = a_\mu(QED) + a_\mu(had) + a_\mu(EW)$$

$$\sigma[a_\mu(exp)] = (63)\cdot 10^{-11}$$

$$a_\mu(had)^{vac\ pol} = 6951(56)\cdot 10^{-11}$$

$$a_\mu(had)^{LbL} = 120(35)\cdot 10^{-11}$$





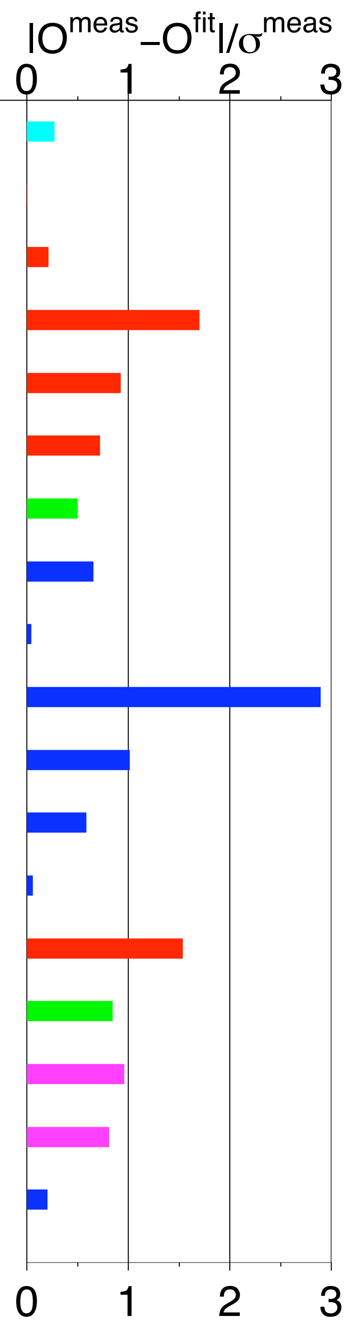
$a_\mu(th)$ includes $a_\mu(EW) = 154\cdot 10^{-11}$

$$a_\mu(exp) - a_\mu(th) = 275(91)\cdot 10^{-11}$$!!??

and maybe?? $a_\mu(susy) \approx 250\cdot 10^{-11}\left(\frac{\tan\beta}{50}\right)\left(\frac{500\ GeV}{m_{susy}}\right)^2$

The famous ElectroWeak Precision Tests

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^{0} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3



CERN-Fermilab-Stanford

precision often better than 10^{-3}

In fact:

from $l_{max} \approx 10^{-8} cm$ (APV)

to $l_{min} \approx 10^{-16} \div 10^{-17} cm$

15% χ^2 probability

Infact the EWPT bring together:

A. The gauge sector $(\frac{g^2}{4\pi}, \frac{g'^2}{4\pi})$

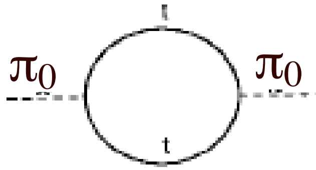
B. The flavor sector, through $\lambda_t Q_3 t \phi \quad (\frac{\lambda_t^2}{4\pi} = \frac{G m_t^2}{8\pi^2\sqrt{2}})$

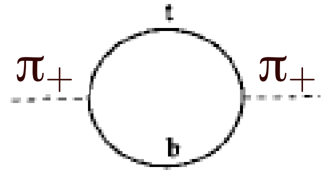
C. The EWSB sector, mostly through $\frac{g^2}{4\pi} \log m_h$

About A - In principle not different from the standard $\frac{e^2}{4\pi}$ expansion of QED, but with exchanged W's and Z's

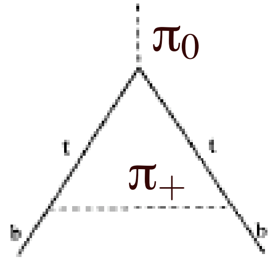
About B - In fact, these effects (the dominant part) can be most easily computed with g = g' =0, hence in a theory of top/bottom quarks, the Higgs h and the (unphysical) Goldstones (π's)

The leading corrections of type B





$$\Rightarrow \quad \frac{M_W^2}{M_Z^2 \cos^2\theta} \equiv \rho = \frac{Z_2^+}{Z_2^0} = 1 + 3x$$



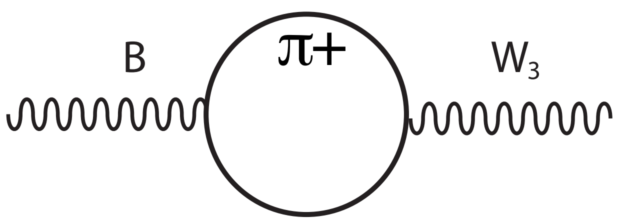
$$\Rightarrow \quad \delta V_\mu(Z \to b\bar{b}) \equiv \frac{g}{2\cos\theta}\tau\gamma_\mu \frac{1+\gamma_5}{2} \qquad \tau = \frac{Z_1}{Z_2^b} = -2x$$

where $\quad x = \dfrac{G m_t^2}{8\pi^2\sqrt{2}} \approx 0.5\%$

$\Rightarrow$ clearly visible effects, used to get a range of top masses before the actual discovery (in 1993 $m_t = 120 \div 160 GeV$), now almost a background

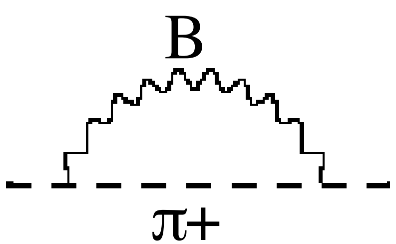
About the Higgs mass dependence

In the limit of infinite Higgs mass, $(m_h^2 = 4\lambda v^2 : \quad \lambda \to \infty)$ divergences appear: log's at 1 loop, quadratic at 2 loops. In the perturbative regime ($\lambda \leq 4\pi$ or m_h $\leq$ 1-2 TeV) the log's dominate, with 2 effects only:



$$= \Pi_{W_3 B}(p^2) g_{\mu\nu} + p_\mu p_\nu - terms$$

$$\Rightarrow \ \widehat{S} \equiv \Pi'_{W_3 B}(0) = \frac{\alpha}{24\pi \sin^2\theta} \log\Lambda$$



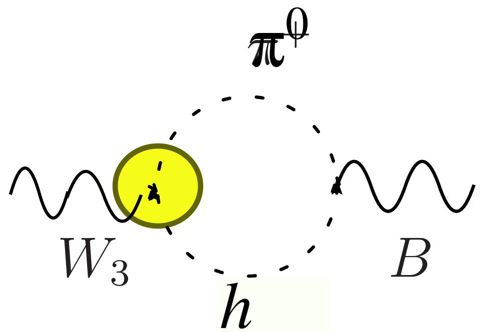
$$= \Pi_+(p^2)$$

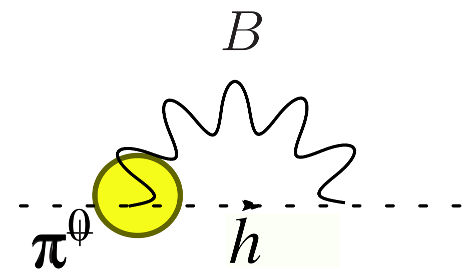
$$\Rightarrow \ \widehat{T} \equiv \Pi'_+(0) = -\frac{3\alpha}{8\pi \sin^2\theta} \log\Lambda$$

which spread in the various observables with $\log\Lambda \to \log m_h$

The main Standard Model effects summarized

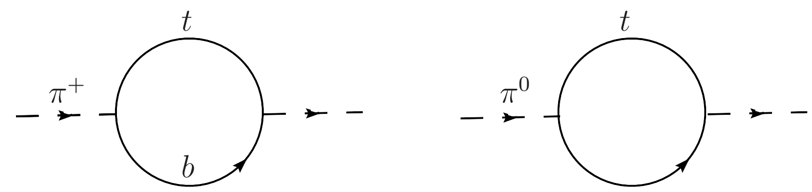
$$\hat{S} = \frac{g}{g'}\Pi'_{30}(0) \qquad \hat{T} = \frac{\Pi_{33}(0) - \Pi_{WW}(0)}{m_W^2}$$





$$\hat{S} \approx \frac{G_F m_W^2}{12\sqrt{2}\pi^2}\log m_h \qquad \hat{T} \approx -\frac{3G_F m_W^2}{4\sqrt{2}\pi^2}\tan^2\theta \log m_h$$

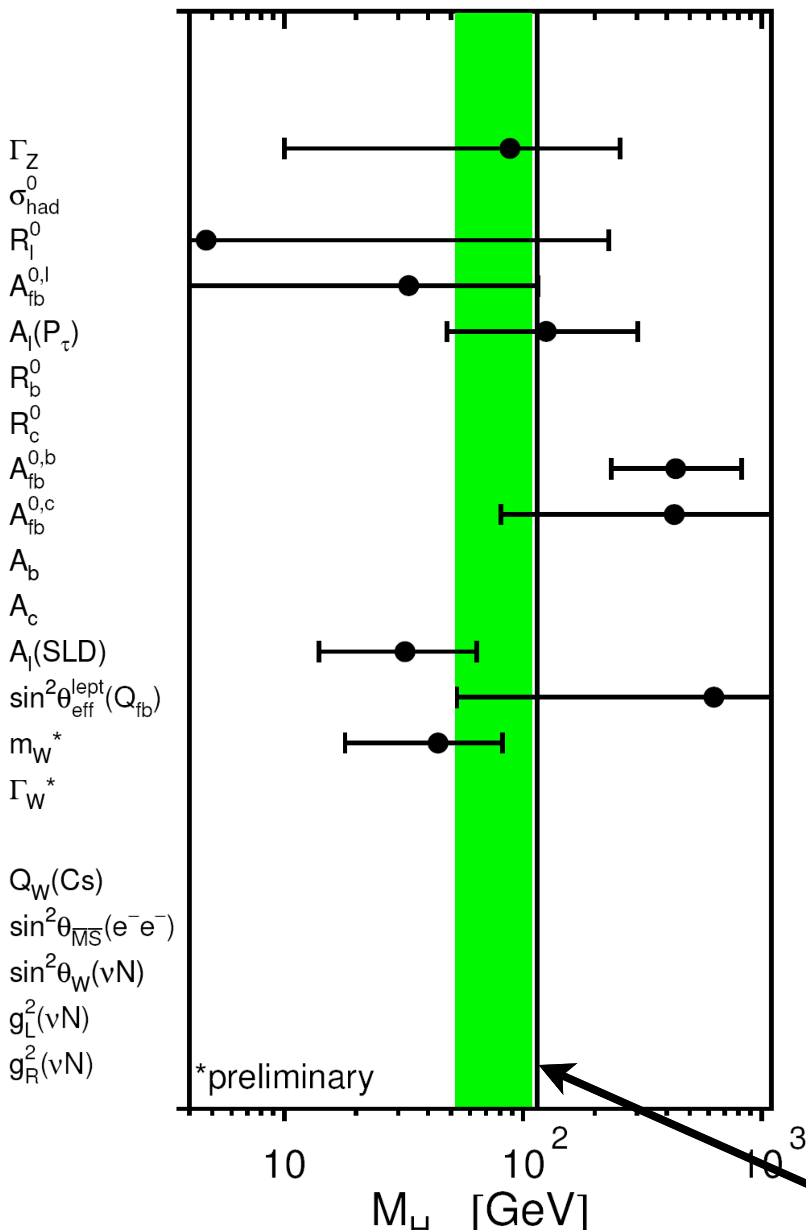
$$\rho - 1 = \hat{T} = 1 + \frac{3G_F m_t^2}{8\sqrt{2}\pi^2}$$

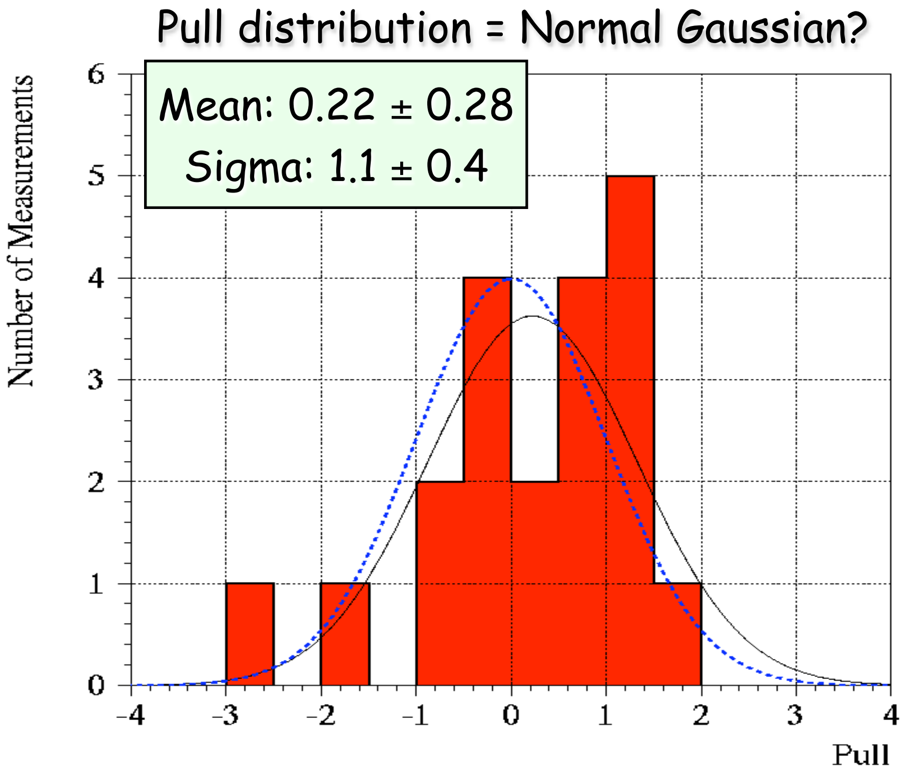


The Higgs boson mass in the SM

$$M_{Higgs} = (85^{+37}_{-27})\ GeV/c^2$$

$$M_{Higgs} \leq 144\ GeV/c^2 \quad 95\%\ CL$$





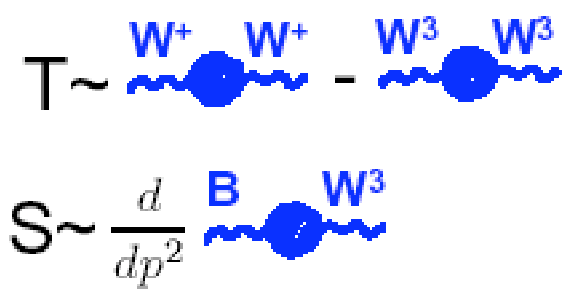
$$M_{Higgs}|_{direct} \geq 114.4 GeV$$

LEPHWG

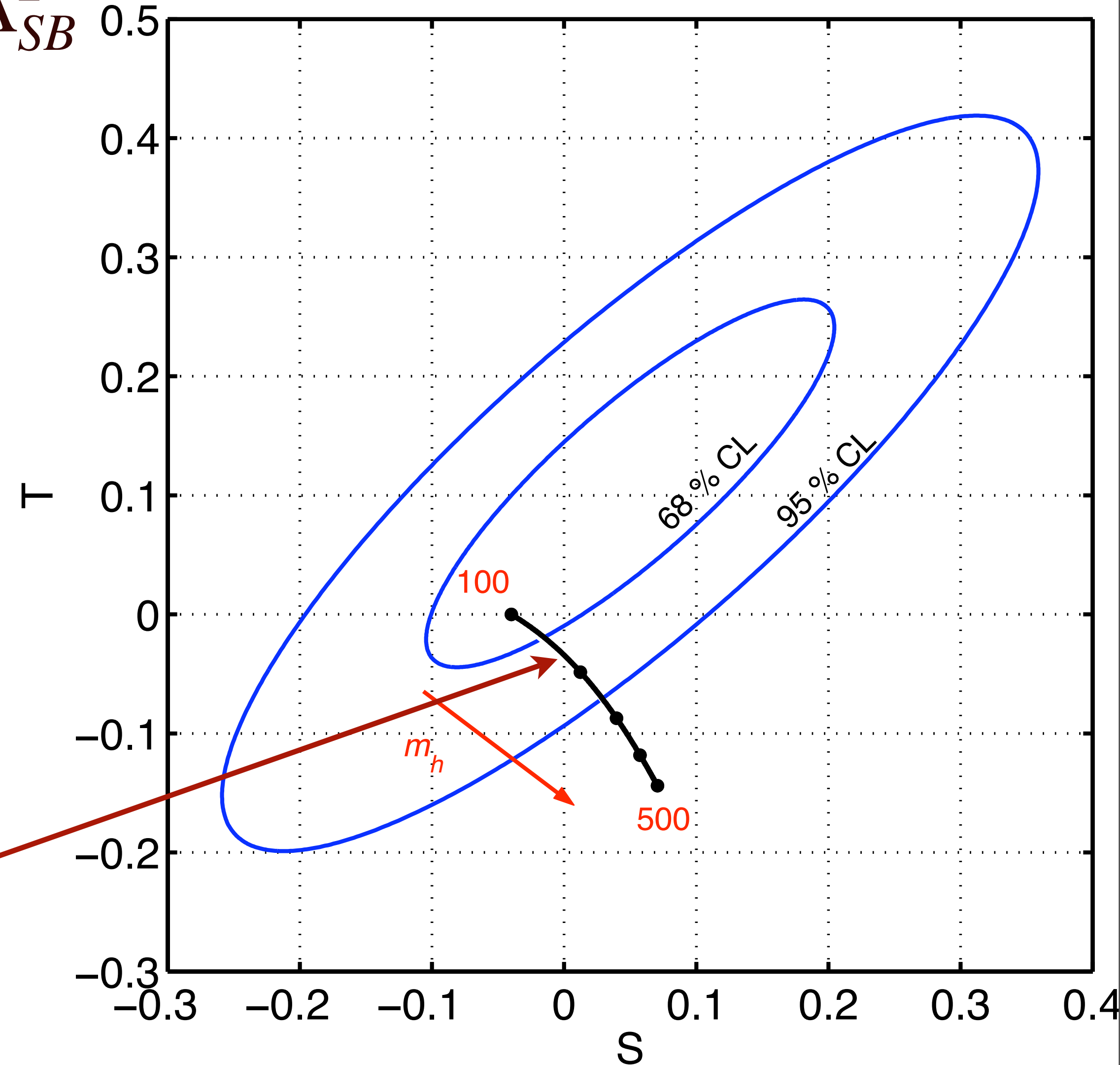
A more general use of the EWPT

1 ⇒ 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 $q^2 < \Lambda_{SB}^2$

The dominant effects in:



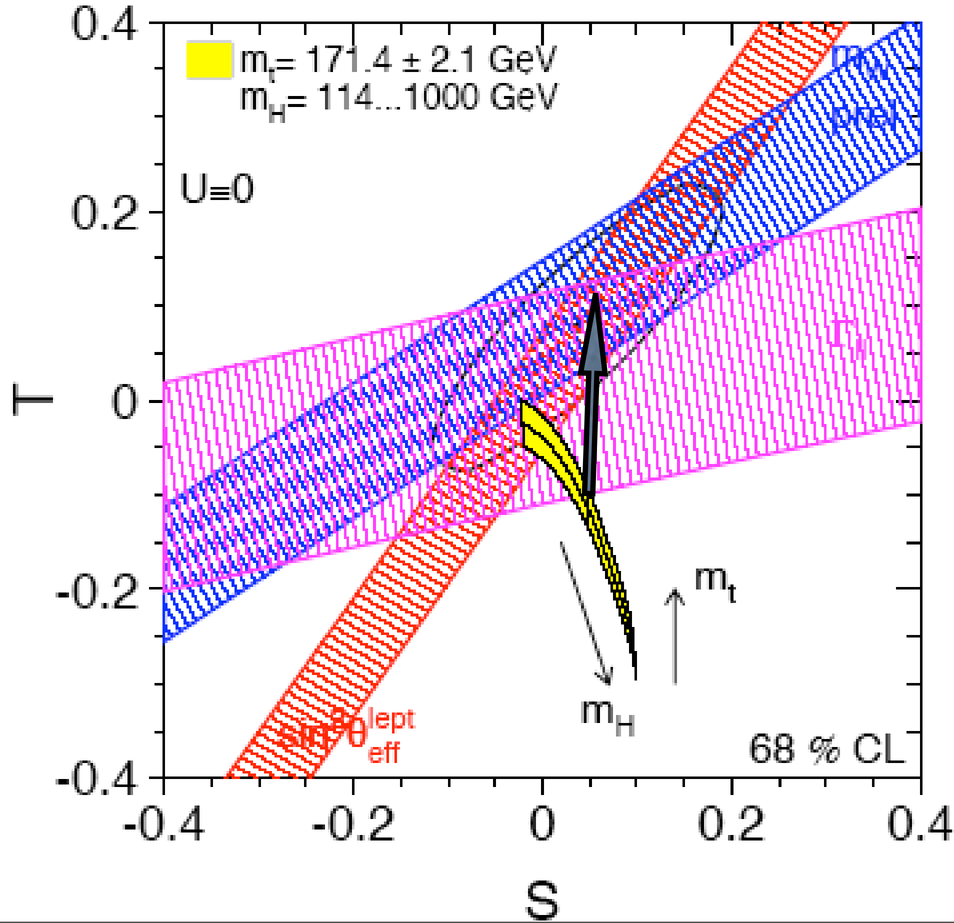
The SM as function of the Higgs boson mass in GeV



The indirect determination of the Higgs mass

Rad Corr predict m_W and m_t well. Also m_h ?

predicted $\Longrightarrow$	$m_t = 177.6^{+12}_{-9}$	$m_W = 80.361(20)$	$m_h = 85^{+39}_{-28}$
measured $\Longrightarrow$	$m_t = 171.4 \pm 2.1$	$m_W = 80.392(29)$	?



A heavier Higgs would require a positive ΔT

LEPEWWG - Summer 2006

2

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \mathcal{L}_{eff}^{NP}$$

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

Taking $c_i = \pm 1$ and <u>considering one operator at a time</u>

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

	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
⇒	$H^\dagger(\bar{D}\lambda_D \lambda_U \lambda_U^\dagger \gamma_{\mu\nu} Q) F^{\mu\nu}$	$b \to s\gamma$	10 TeV
⇒	$\frac{1}{2}(\bar{Q}\lambda_U \lambda_U^\dagger \gamma_\mu Q)^2$	B mixing	10 TeV

1σ-bounds ⊕ a light Higgs

More conservatively: $\Lambda > \sim 5$ TeV

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

Conclusions (tentative)

1. The full gauge sector of the SM successfully tested at the quantum level

2. A significant, although indirect, evidence emerges for the existence of the Higgs boson

3. The Higgs boson, if it exists, is probably relatively light

4. Any deviation from the SM pretty tightly constrained
(A problem for a "natural" Fermi scale?)

⇒ The Large Hadron Collider is meant to validate all this (or show where it is wrong)