Theory of the ElectroWeak Interactions

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1. The Standard Model: the "indirect" informations

2. "Higgsless" Grojean

3. The Higgs boson as a PGB Grojean

4. Beyond mSUGRA Pokorski

All at a hopefully simple and self-contained level,
to be complemented by other lectures this same week

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 flavor 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)

Anybody NOT familiar with this?

Almost all the focus of these lectures on (3),
with, maybe, an incursion on (2) towards the end

The impact of the Large Hadron Collider on EWSB

1. The first thorough exploration of the energy scales well above $G_F^{-1/2}$

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

2. No comparable prior situation at the SppS or at the TEVATRON

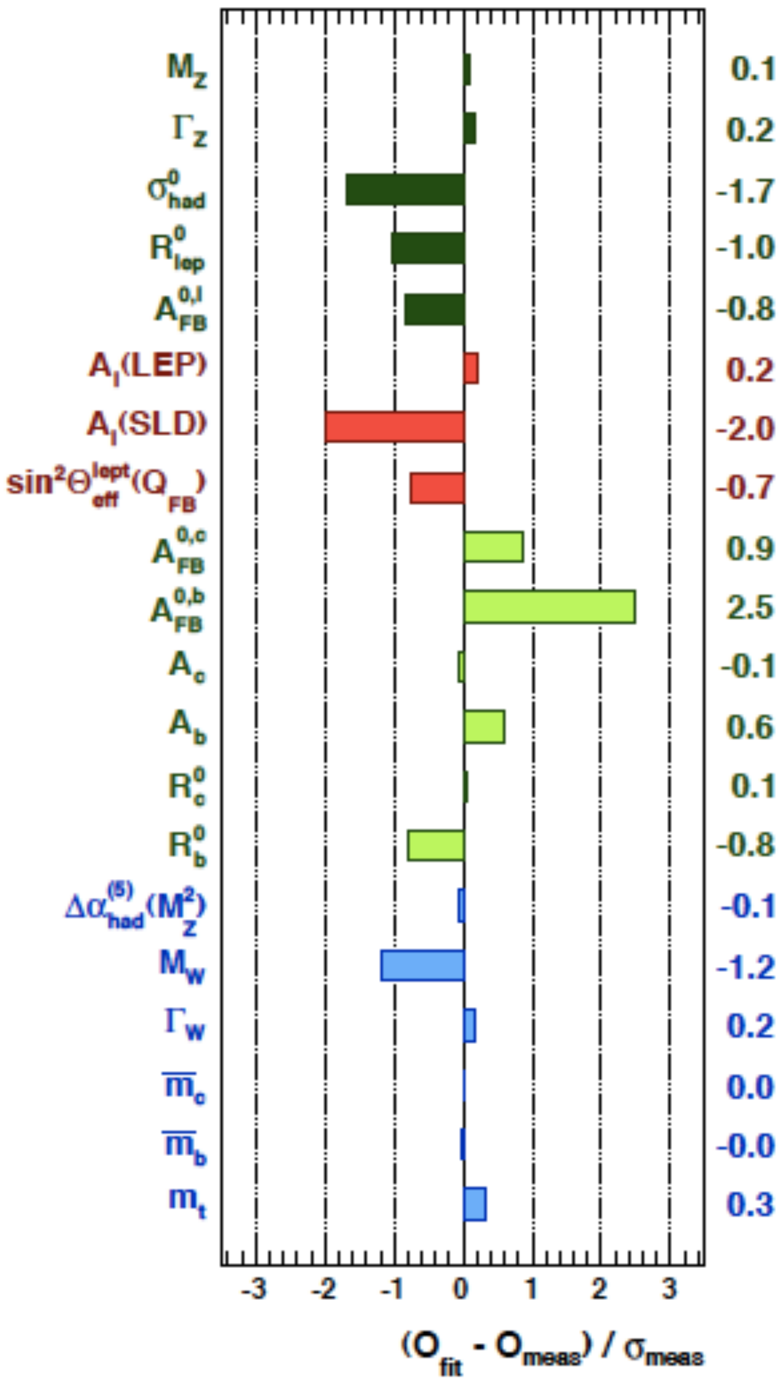
1984: W, Z

1994: top

201?: the Higgs boson of the SM

Which "indirect" informations so far?

The famous ElectroWeak Precision Tests



the Gfitter group

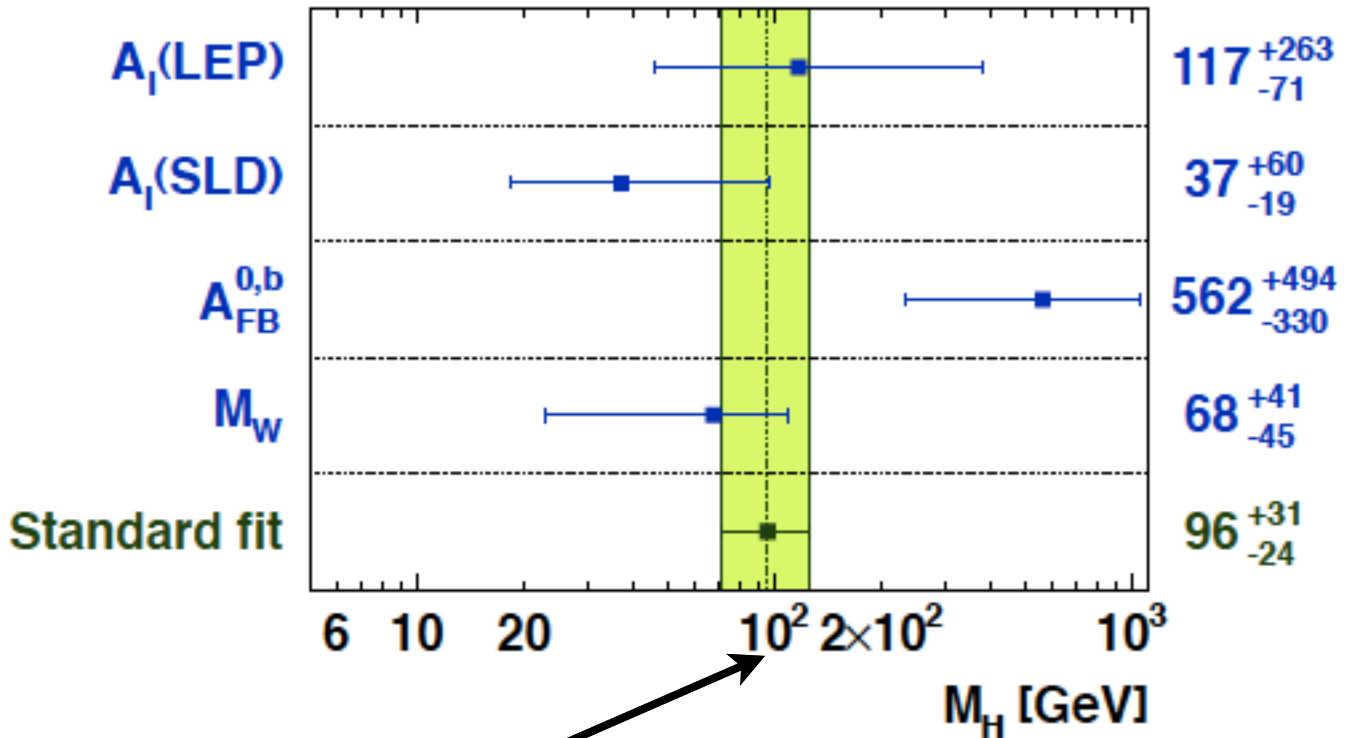
CERN-Fermilab-Stanford

precision often better than 10^{-3}

In fact:
from $l_{max} \approx 10^{-8} cm$ (APV)
to $l_{min} \approx 10^{-16} \div 10^{-17} cm$

A "naive p-value" of 0.23

The Higgs boson mass in the SM



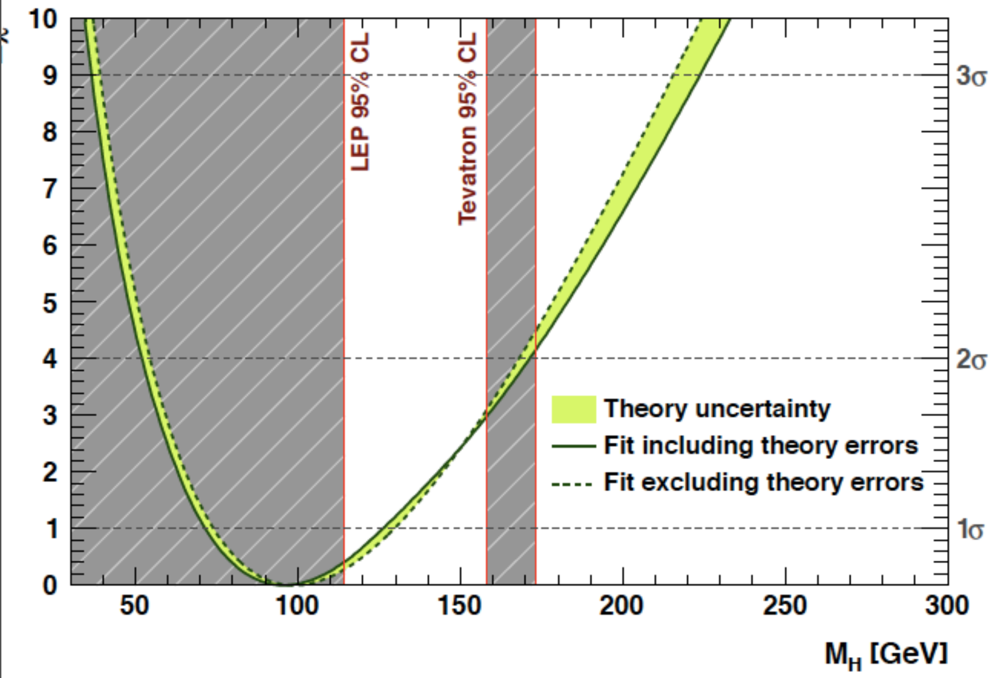
$$M_{Higgs} = 96^{+31}_{-24}\ GeV$$

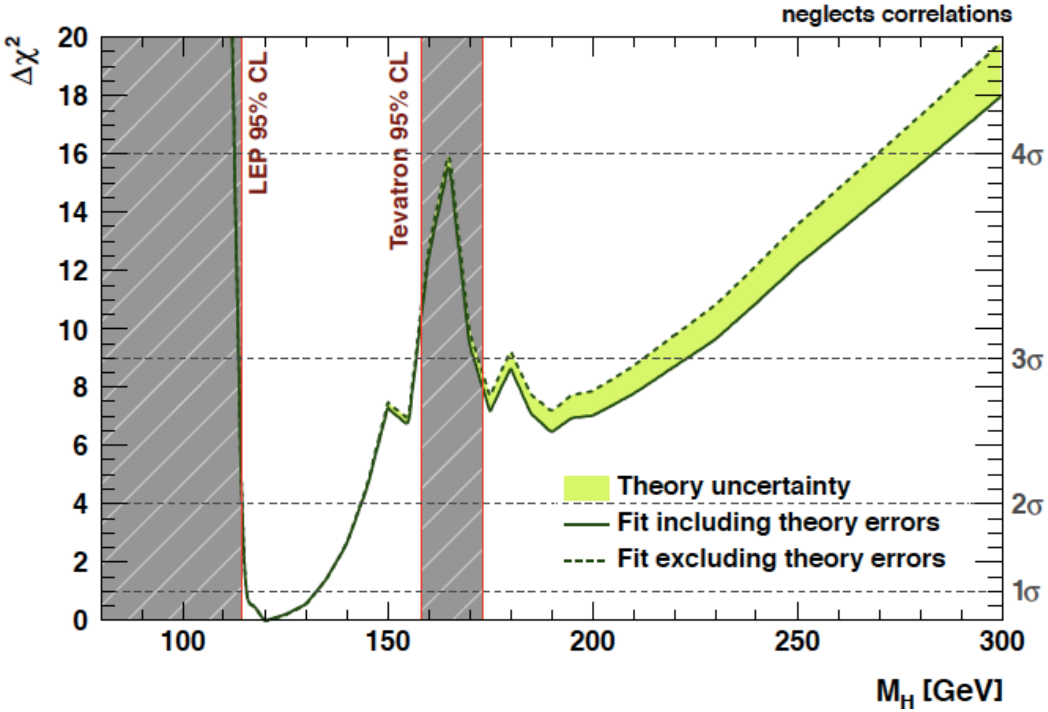
$$M_{Higgs} = 120^{+12}_{-5}\ GeV$$

with LEP and Tevatron direct searches included

χ^2-distributions

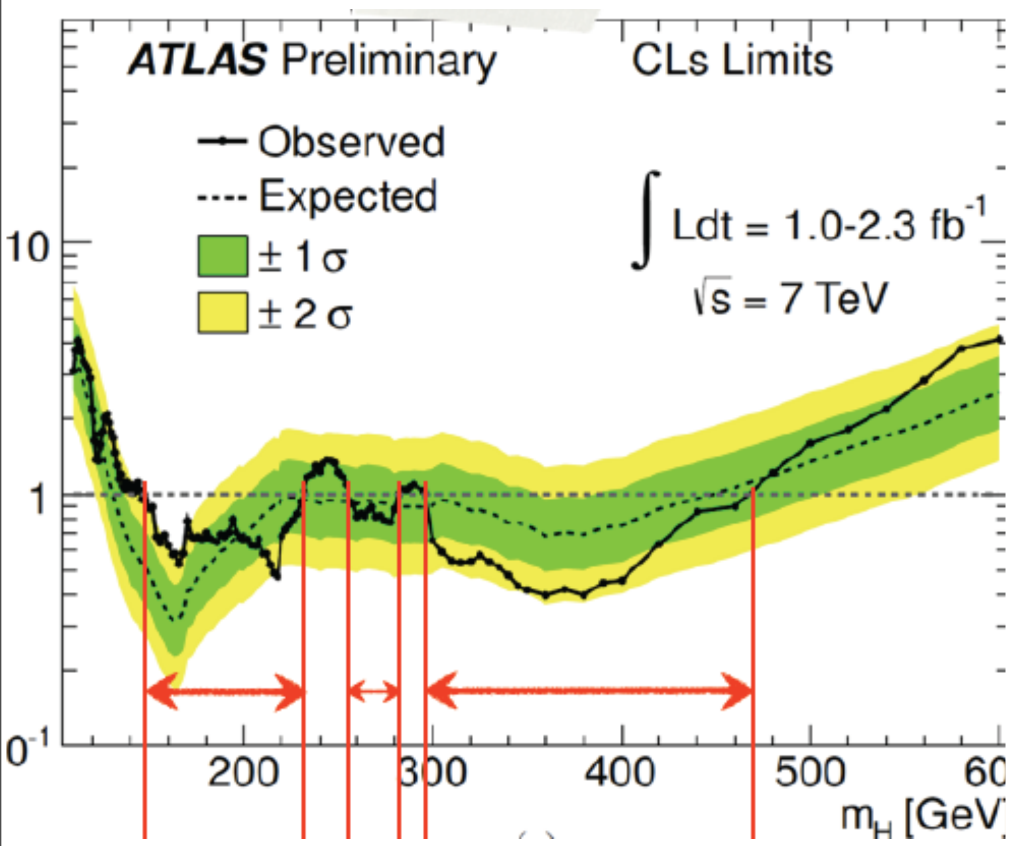
the Gfitter group

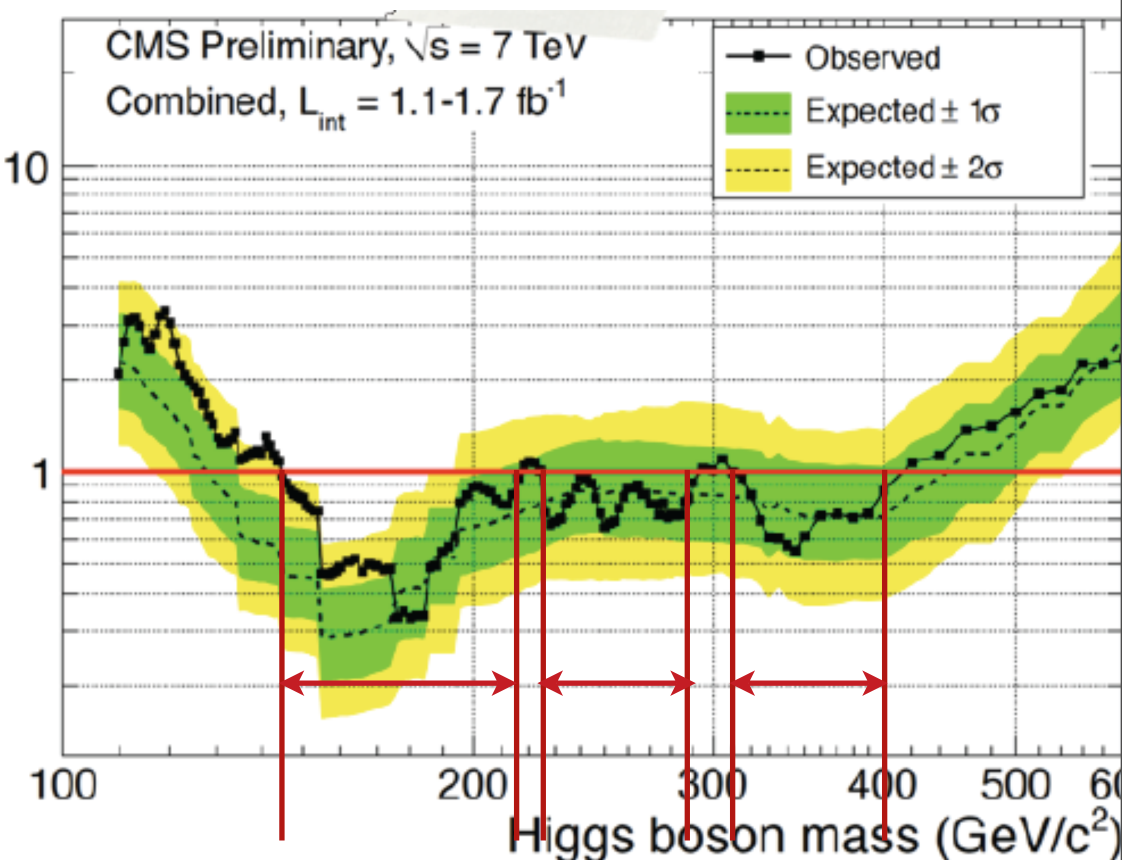




(ATLAS and CMS not included)

LHC exclusion plots



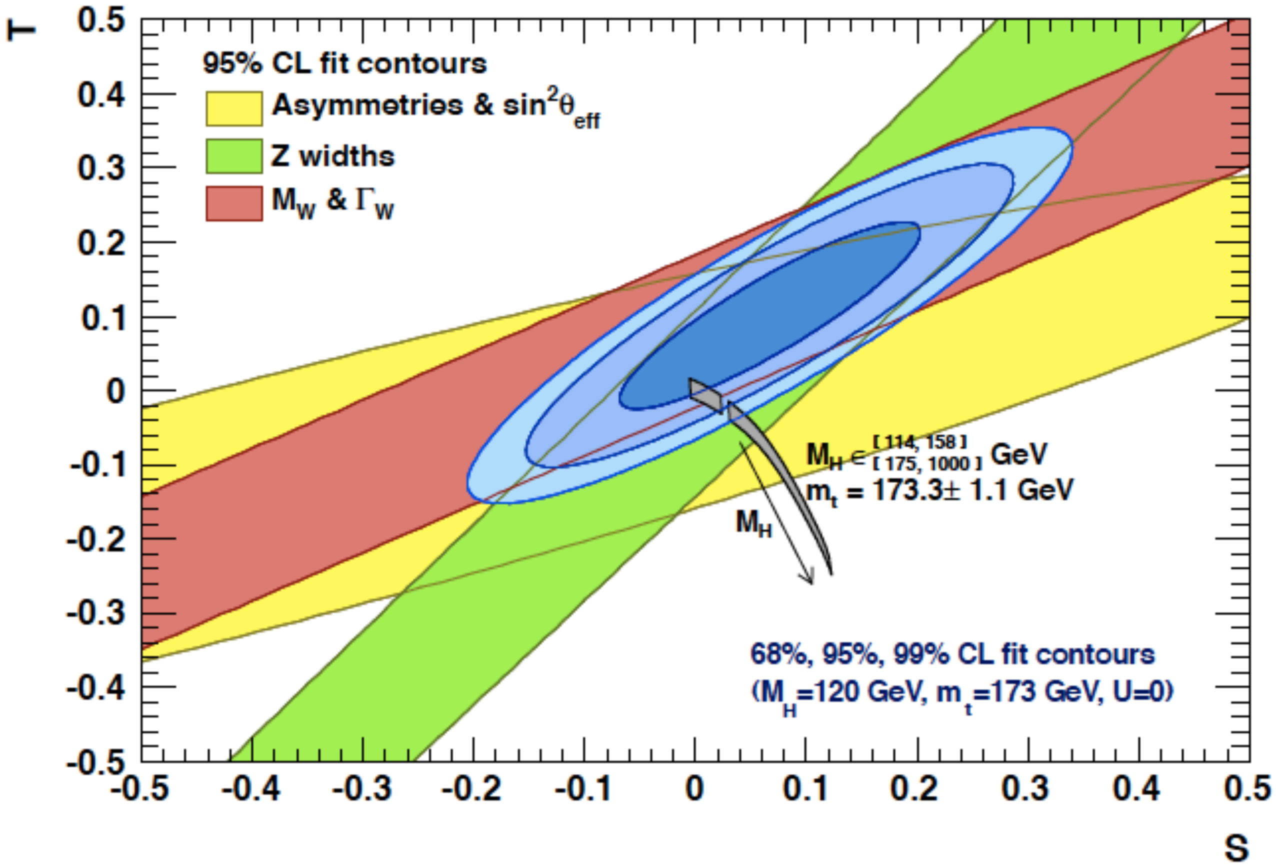


95% CL limits on $\frac{\sigma}{\sigma_{SM}}$

The indirect determination of the Higgs mass

Rad Corr predict m_W and m_t well. Also m_h ?

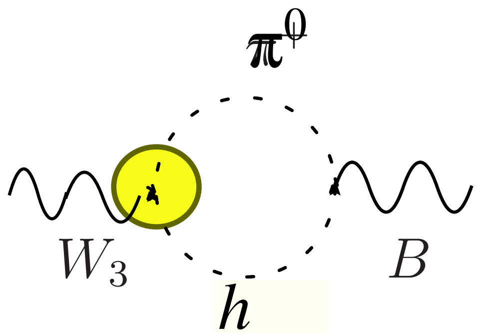
"th" $\Rightarrow$	$m_t = 176.8 \pm 3.3$	$m_W = 80.362(13)$	$M_{Higgs} = 96^{+31}_{-24}\ GeV$
exp $\Rightarrow$	$m_t = 173.3 \pm 1.1$	$m_W = 80.399(23)$	?

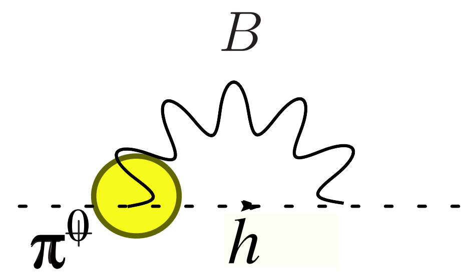


(the exact meaning of this plot in a while)

The main Standard Model effects summarized

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

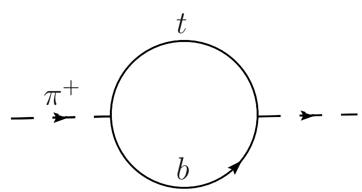


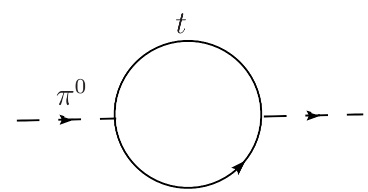


$$\pi^0 \approx W_3$$

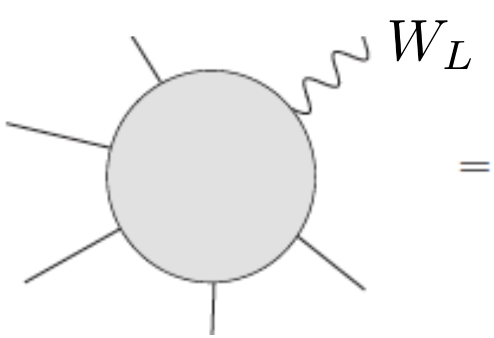
$$\hat{S} \approx \frac{G_F m_W^2}{12\sqrt{2}\pi^2}\log m_h \qquad \hat{T} \approx -\frac{3G_F m_W^2}{4\sqrt{2}\pi^2}\tan^2\theta \log m_h$$

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





"Equivalence Theorem"



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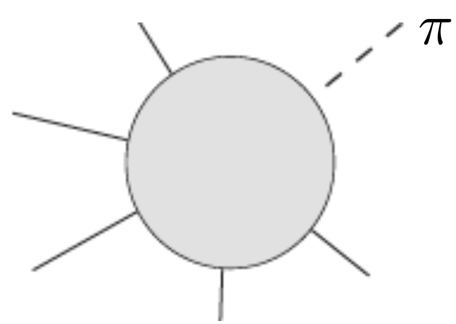
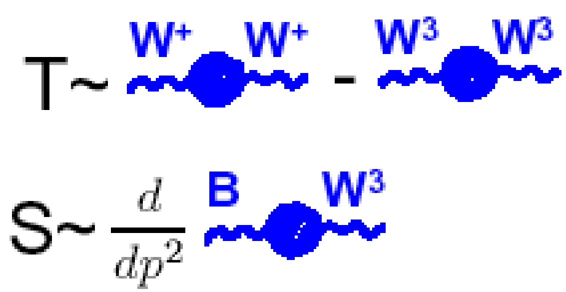


$$\times \left(1 + O\left(\frac{m_W^2}{E^2}\right)\right)$$

A more general use of the EWPT

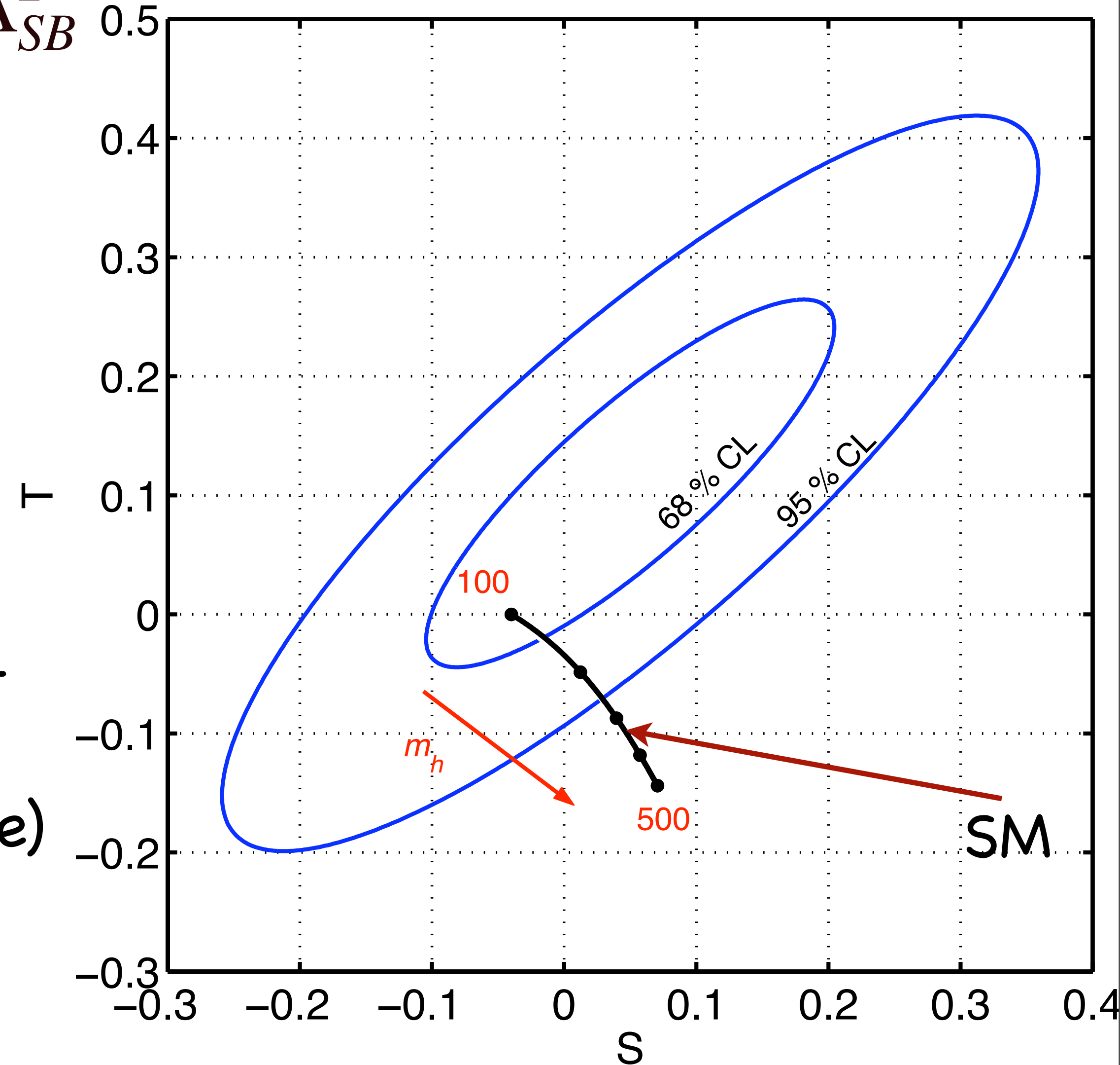
1 $\Rightarrow$ Consider a theory characterized by a scale Λ_{SB} with its virtual effects likely significant in the vac. pol. amplitudes of the vector bosons. At $q^2 < \Lambda_{SB}^2$

The dominant effects in:



(with some care when extra light particles, $\mathcal{O}(m_W)$, are present)

($T \approx \epsilon_1,\ S \approx \epsilon_3$, although not quite)



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 considering one operator at a time

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

	operator $\mathscr{O}$	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→	$\lvert H^\dagger D_\mu H\rvert^2$	$\theta_{\rm W}$ in M_W/M_Z	5 TeV
S→	$(H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$	$\theta_{\rm W}$ 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

flavour (see below)

More conservatively: $\Lambda >$ ~5 TeV

Current flavour constraints

2000÷2010: The CKM picture quantitatively successful

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

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

Operator	Bounds on c_i ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	9×10^{-7}	3×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L\, d_R)$	7×10^{-9}	3×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	6×10^{-7}	1×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L\, u_R)$	6×10^{-8}	1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	3×10^{-6}	1×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L\, d_R)$	6×10^{-7}	2×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	8×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L\, s_R)$	1×10^{-5}		Δm_{B_s}

Isidori, Nir, Perez 2010

A problem and an opportunity

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

The naturalness problem of the Fermi scale

There is certainly New Physics (NP) at short distances

$\Lambda_{NP} = \ldots, M_{GUT}, M_{Pl}$ $\qquad\qquad$ $\Lambda_{NP} >> G_F^{-1/2}$

to be included in a suitably Extended SM (ESM)

How to keep the beautiful consistency of the SM with exp.s?

No problem, even not knowing which NP at all, provided:

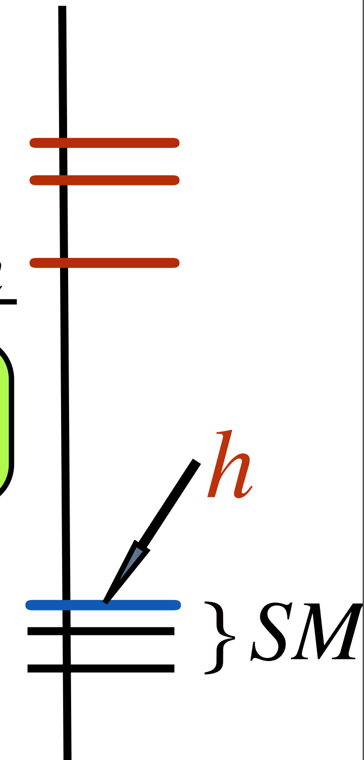
1. SU(3)×SU(2)×U(1) kept intact

2. The "low energy" spectrum of the ESM coincides with the one of the SM, <u>with the inclusion of the Higgs boson</u>

Why this is the case?
≡ the naturalness problem of the Fermi scale

Why the focus on the Higgs boson only?

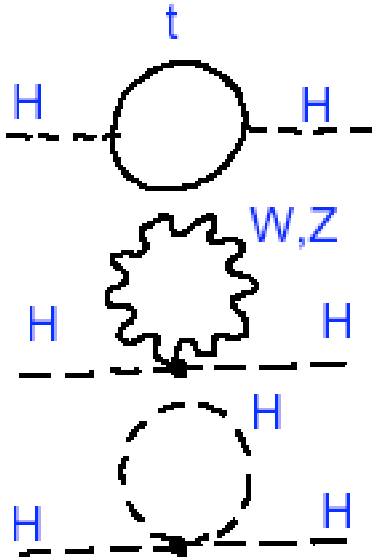
Why we call this "a problem"?



Why "a problem"?

1. To address it at all, need a "calculable" Higgs mass

2. In the SM



$$\delta m_h^2 = \alpha_t \Lambda_t^2 + \alpha_g \Lambda_g^2 + \alpha_h \Lambda_h^2 \quad (*)$$

with known coeff.s for a given cut-off

3. Even though $\Lambda \to \infty$,
whatever will cutoff these div.s is likely to leave a significant contribution to m_h^2 (see below) Too big?

4. Using the naive estimate of $(*)$
and barring accidental cancellations $\Rightarrow$

$$\Lambda_t \approx 3.5\, m_h$$
$$\Lambda_g \approx 9\, m_h > \Lambda_t$$
$$\Lambda_h \approx 1.3 \text{ TeV}$$

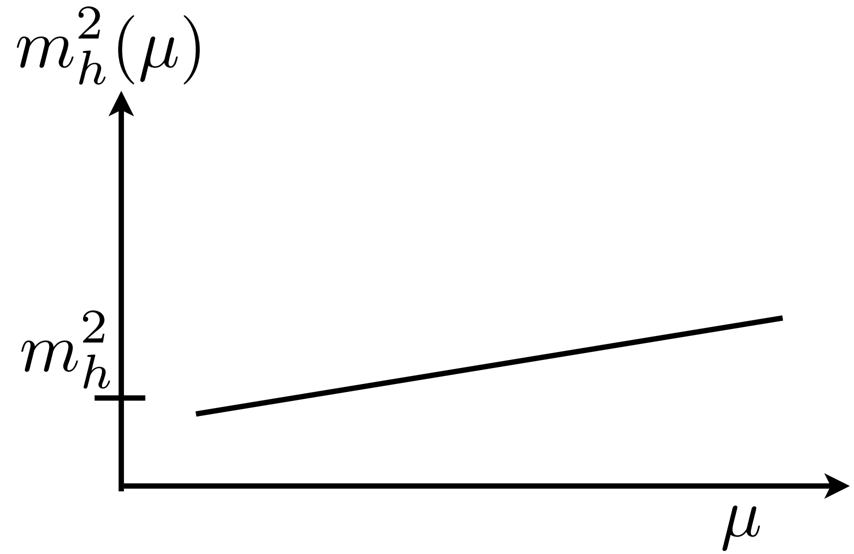
5. Especially Λ_t low enough that one might have already seen its (indirect)signs

A “more refined” analysis

SM in isolation

$$m_h^2(phys) = m_0^2 + \alpha_t \Lambda^2 + \dots$$

$$\mu\frac{d}{\mu}m_h^2(\mu) = \alpha_t m_h^2(\mu), \quad \mu > m_h > m_t$$

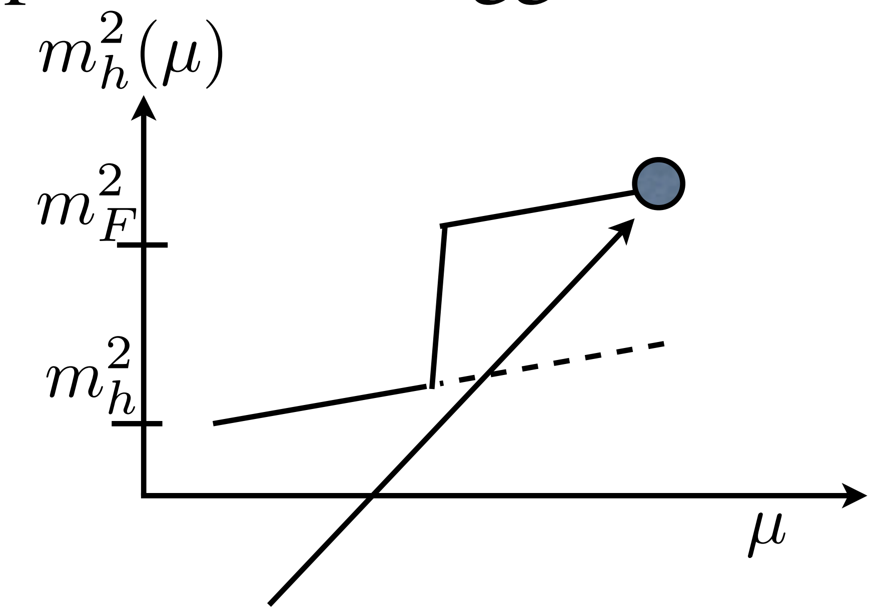


SM + (e.g.) a heavy Fermion coupled to the Higgs boson

$$m_h^2(phys) = m_0^2 + \alpha_F \Lambda^2 + \dots$$

$$\mu\frac{d}{\mu}m_h^2(\mu) = \alpha_F m_h^2(\mu), \quad \mu < m_F$$

$$\mu\frac{d}{\mu}m_h^2(\mu) = \alpha_F m_F^2, \quad \mu > m_F$$



⇒ a very precise initial condition at the high scale if $m_F >> m_h$ on a physical “renormalized” quantity

The Fine Tuning problem of the Fermi scale

1999: "the LEP Paradox"

B, Strumia

2001: "the little hierarchy" problem

While all indirect tests (EWPT, flavour) indicate no new scale below several TeV's, the Higgs boson mass is apparently around the corner and is normally sensitive to any such scale

$$m_h \approx 115\ GeV \left(\frac{\Lambda_{cutoff}}{400\ GeV}\right) \qquad \Lambda_{NP} \gtrsim ?\ TeV$$

$$\Lambda_{NP} \overset{?}{\approx} \Lambda_{cutoff}$$

2011: the problem still there, more than ever, driving our view about what can/will happen at the LHC

The (many) reactions to the FT problem

0. Ignore it and view the SM in isolation (untenable)

In case you doubted of its relevance:

1. Cure it by symmetries: SUSY, Higgs as PGB, little Higgs
2. A new strong interaction nearby
3. A new strong interaction not so nearby: quasi-CFT
4. Warp space-time: RS
5. Saturate the UV nearby: ADD, classicalons
6. Accept it: the multiverse, the 10^{120} vacua of string theory

Anything else?

The proposed relevant symmetries

1 $\Rightarrow$ Supersymmetry

$$(\phi, \psi) \Rightarrow \cancel{m^2\phi^2} \quad \text{if } \psi \text{ massless}$$

2 $\Rightarrow$ Global symmetry

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

3 $\Rightarrow$ Gauge symmetry in higher dim.s

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

$$h = A_5$$

(likely related to 2 anyhow)

EWSB: “weak” or “strong”?

“weak”

a relatively light Higgs boson exists

perturbativity extended →high E (M_{GUT}, M_{Pl})

perhaps (probably) embedded in susy

gauge couplings (perhaps) unify

“strong”

EWSB related to new forces, new degrees of freedom
or even new dimensions opening up in the TeVs

perturbativity lost in the multi-TeV range

high E extrapolation highly uncertain