Standard Model

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SM - V-VI

Electroweak Theory.

1. First observation of W/Z and what did it test for the Standard Model?

2. Need for the Higgs boson and formulation of $SU(2) \times U(1)$ with the Higgs.

3. Indirect limits on the Higgs mass from precision measurements and implication of the signal for a 'boson' at the LHC.

An aside:

Massive gauge bosons have a problem. Amplitudes like $\nu_e \bar{\nu}_e \to W^+ W^-$ grow with energy and can violate unitarity.

One can show that this violation of unitarity can be tamed by adding a neutral spin 1 boson which ZW^+W^- couplings as expected in the (Glashow) $SU(2)_L \times U(1)_Y$ model!

Cornwall, Tiktopolous (1974, 1975); Llewellyn Smith (1973), S.D. Joglekar (1973)

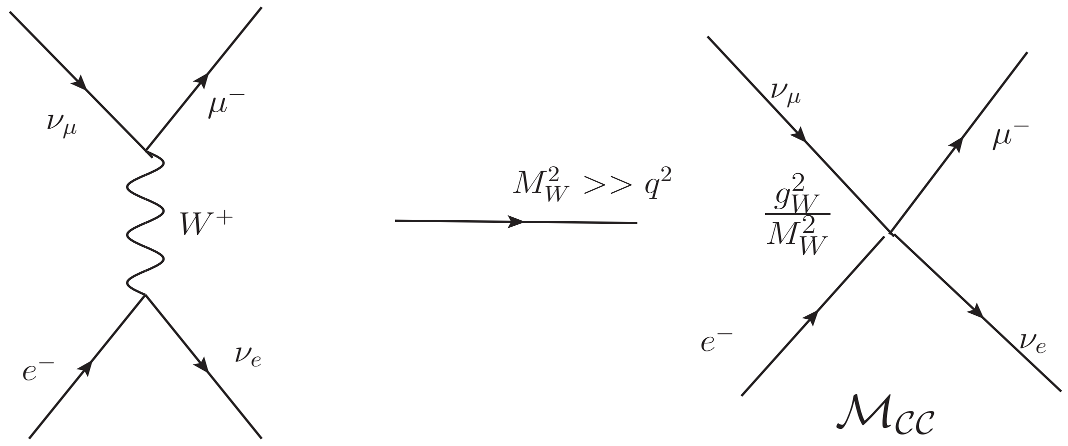
Glashow did not attempt to generate M_W, M_Z, in a gauge invariant manner.

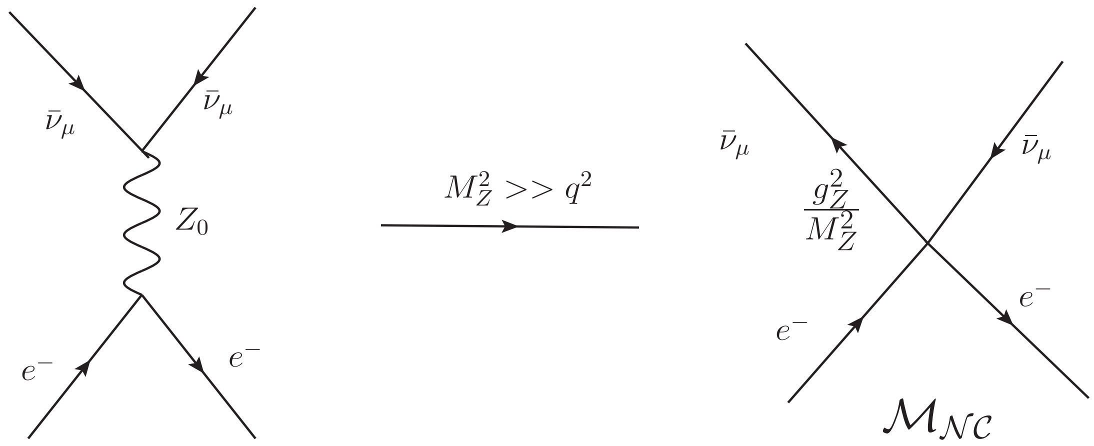
Glashow's model did fix the problem with $\nu_e \bar{\nu}_e \to W^+ W^-$ process violating unitarity.

Alternative mechansims to do that without neutral currents had existed eg. Georgi model which predict a new heavy neutral lepton. This is ruled out by Gargamelle data.

Neutral current discovery means that between the two solutions to restore unitarity to weak processes, the one with new massive neutral gauge boson seems to be called for.

Weinberg and Salam made use of Higgs mechanism to generate masses in a gauge invariant manner AND could predict M_Z in terms of M_W and θ_W !





$$\rho = \frac{g_Z^2}{2g_W^2}\frac{M_W^2}{M_Z^2}$$
$$= \frac{M_W^2}{M_Z^2 \cos^2\theta_W}$$

ρ measures the ratio of strengths of the coupling in $\mathcal{M}_{\mathcal{CC}}$ and $\mathcal{M}_{\mathcal{NC}}$.

For the WS model $\rho = 1$.

‘

Study of Neutral current processes confirming model predictions for couplings, including $\rho \simeq 1$, fetched Nobel prize for Glashow, Salam and Weinberg in 1979.

Non zero M_W, M_Z break gauge invariance.

Mass terms for fermions contains $\bar{\psi}_L \psi_R$, Left handed and Right handed fields have diff rent $SU(2)_L$, $U(1)_Y$ charges. So clearly a fermion mass term breaks gauge invariance too!

Weinberg and Salam, separately, used the Higgs mechanism to generate masses for fermions and gauge bosons in a gauge invariant way. Prediction for both M_W, M_Z in terms of g_1, g_2 and $\sin\theta_W$.

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

gets nonzero vacuum expectation value

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Symmetry spontaneously broken. Vaccum not symmetric but the Lagrangian still is. Scattering amplitudes are gauge invariant. (The Nambu Jona Lasinio mechanism at the heart of this: Nobel prize 2008)

Predictions: M_W, M_Z

$$M_W = \left(g_2^2\sqrt{2}/8G_F\right)^{1/2} = \frac{37.4}{\sin\theta_W}, \ M_Z = \frac{M_W}{\cos\theta_W}; \rho = 1$$

(Weinberg paper Phys. Rev. Lett. 19, 1264,1967) How to determine $\sin\theta_W$?. Couplings g_Z, g_W of W, Z to all fermions predicted in terms of $\sin\theta_W$ and G_F.

Determine $\sin^2\theta_W$ using data from 1) $\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$; 2)$\nu_\mu e^- \to \nu_\mu e^-$; 3)$\bar{\nu}_e e^- \to \bar{\nu}_e e^-$; 4) $e^+e^- \to \mu^+\mu^-$.

g_V, g_A functions of $\sin\theta_W^2$ and q_f. Using this $\sin^2\theta_W$ predict M_W, M_Z.

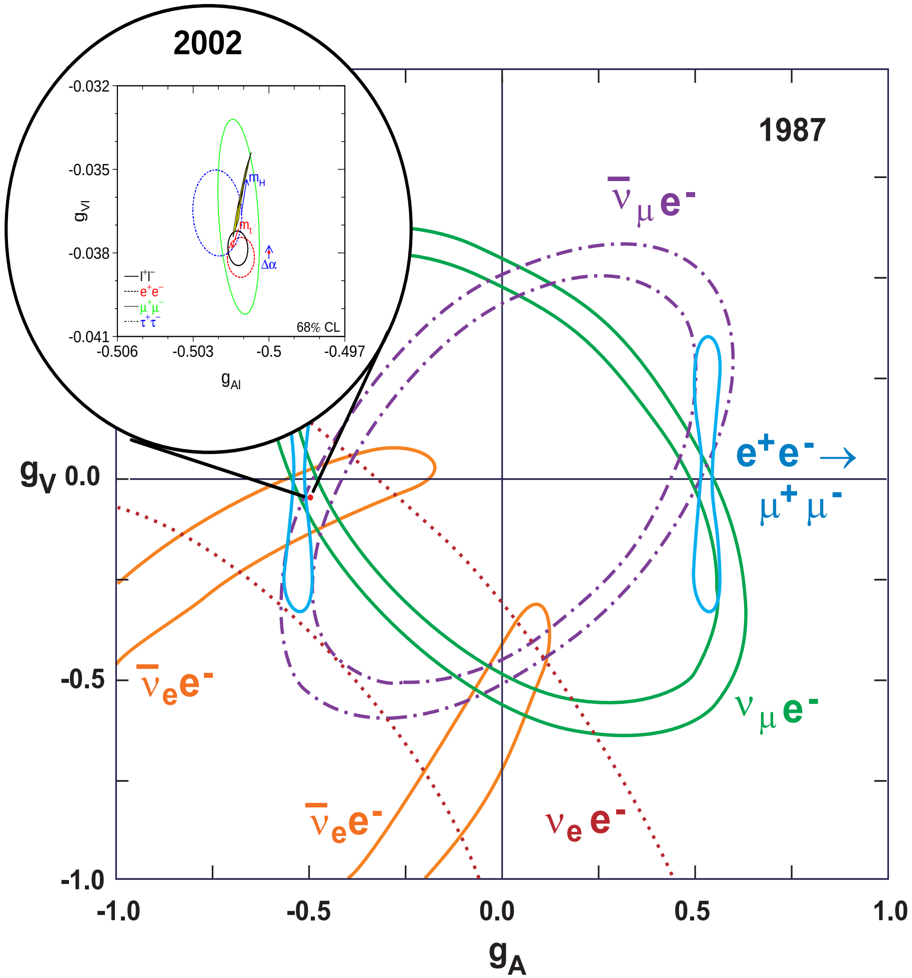
$M_W = 82 \pm 2$ GeV/c^2

$M_Z = 92 \pm 2$GeV/c^2

UA-1 and UA-2 experiments found W/Z with these masses, thus consistent with $\rho \sim 1$.

(Carlo Rubbia + Van der Meer Nobel Prize) (1984)

Proof of Weinberg Salam Glashow model!



We can not discuss it in detail. Before summarising the technical details let me give a simple argument.

We saw in lecture 3 that for massive spin 1/2 ferrmions one can change a state with spin parallel to direction of motion to the case with spin antiparallel with simple Lorentz transformation.

We also saw in lecture 4 that weak interactions treat left handed fermions and right handed fermions differently. This would then mean that existence of weak interactions with properties depending on handedness of the particle would produce conflicts with special theory of relativity for massive particles.!

Higgs mechanism provides a way to allow left handed fermions to change their handedness and hence can make the differential treatment of fermions with two handedness compatible with special theory of relativity.

The SM Higgs, should be a $I_W = 1/2$ doublet.

Must have spin $= 0$, CP $= +1$

Higgs coupling to all particles is $\propto$ their masses. This is intimately related to the Electroweak symmetry breaking.

Higgs mass not predicted by the theory. All the other masses in the SM, related to the vacuum expectation value of the Higgs field v.

$G_F \sqrt{(2)} = 1/v^2 \Rightarrow v \simeq 246$ GeV.

Gauge symmetry predicts precise form of the ZWW coupling.

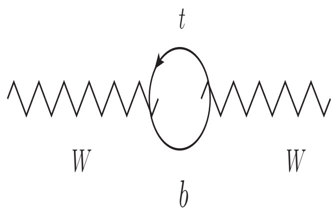
The interaction of the Higgs bosons with all the other particles is decided by the symmetry breaking mechanism, the interaction of everything with W/Z decided by the symmetry itself!

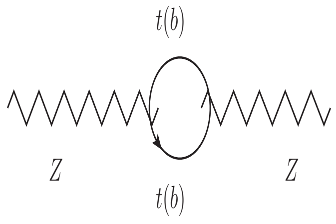
To produce Higgs most favourable couplings are $WW\phi, ZZ\phi$ and $f\bar{f}\phi$ where f is a heavy fermion (top).

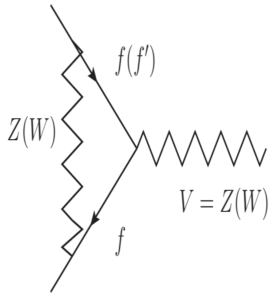
$$M_W = \left(g_2^2\sqrt{2}/8G_F\right)^{1/2} = \frac{37.4}{\sin\theta_W}\mathrm{GeV}/c^2, \quad M_Z = \frac{M_W}{\cos\theta_W}; \rho = 1.0$$

G_F Fermi coupling constant in the β decay (also called G_μ sometimes). Value extracted using muon life time τ_μ.

These relations change due to quantum corrections. Renormalisabity gurantees that the corrections are finite! The renormalisability in the end is guranteed by Gauge Invariance.







$$\rho_{corr} = 1 + \Delta\rho$$

$$\Delta\rho \simeq \frac{3G_F M_t^2}{8\pi^2\sqrt{2}} = 0.01$$

There is also a diagram with ϕ in the loop.

The corrections for the Z and W are different. The dominant corrections come from loop containing the heaviest quarks t, b (and sub dominant ones from ϕ) ρ changes from value 1. (Veltman: screening theorem about the ϕ contribution being small) Before top quark was found, its value was indirectly obtained from measuring ρ.

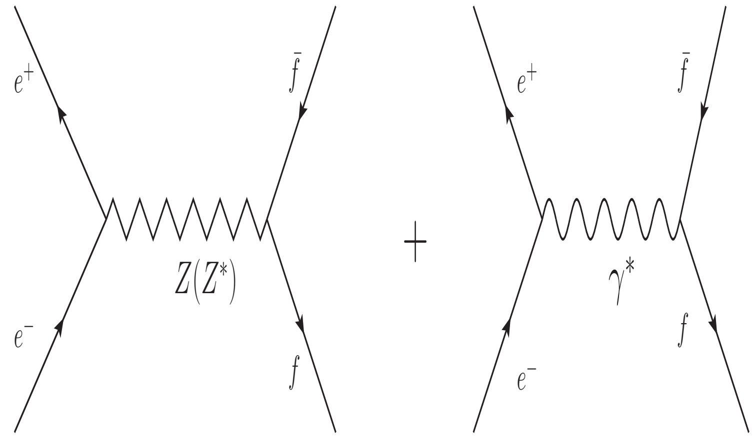
The corrections can be calculated only if theory is renormalisable. Renormalisability proved by 't Hooft and Veltman (Nobel prize 1999)

Precision measurements happened at the Large Electron Positron Collider (LEP) and Stanford Linear Collider (SLC). (Z factories!)

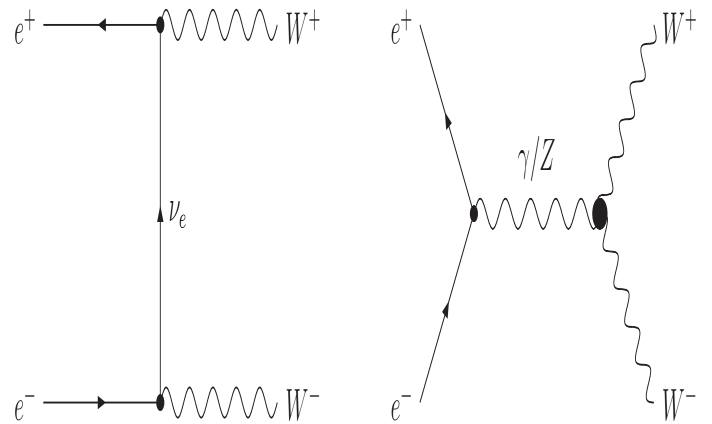
LEP-I: Simple and precision measurement of $e^+e^- \to f\bar{f}$

10 million Z's collected by four experiments.

1. Measure the couplings of the Z to all the SM fermions accurately, to establish the nature of the 'weak' neutral current to great accuracy. Study $e^+e^- \to Z^*/\gamma^* \to f\bar{f}$.



2. $SU(2)_L$ symmetry means specific values for ZWW coupling. Can one directly measure ZWW coupling? Need to measure $e^+e^- \to Z^*/\gamma^* \to W^+W^-$.



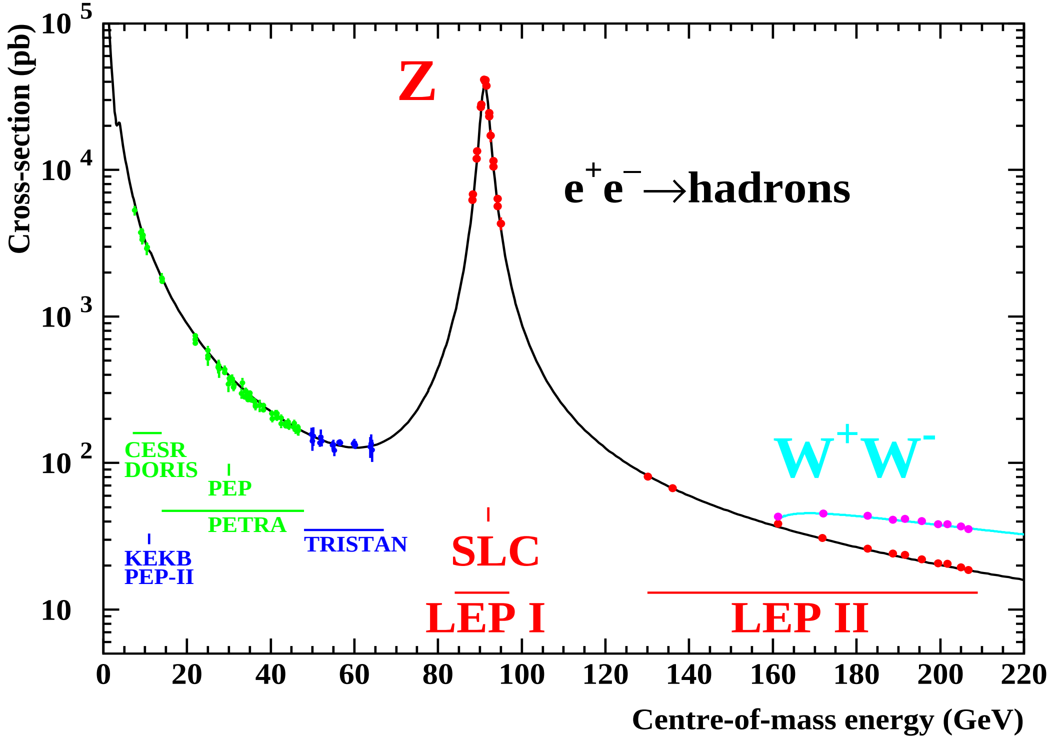
3. Find the Higgs in $e^+e^- \to \phi Z$: LEP did not do this job!

High precision measurements require high precision calculations.

Higher order QED and QCD corrections highly important and non-trivial.

Good understanding of QCD to calculate correctly what the detectors observe: jets.

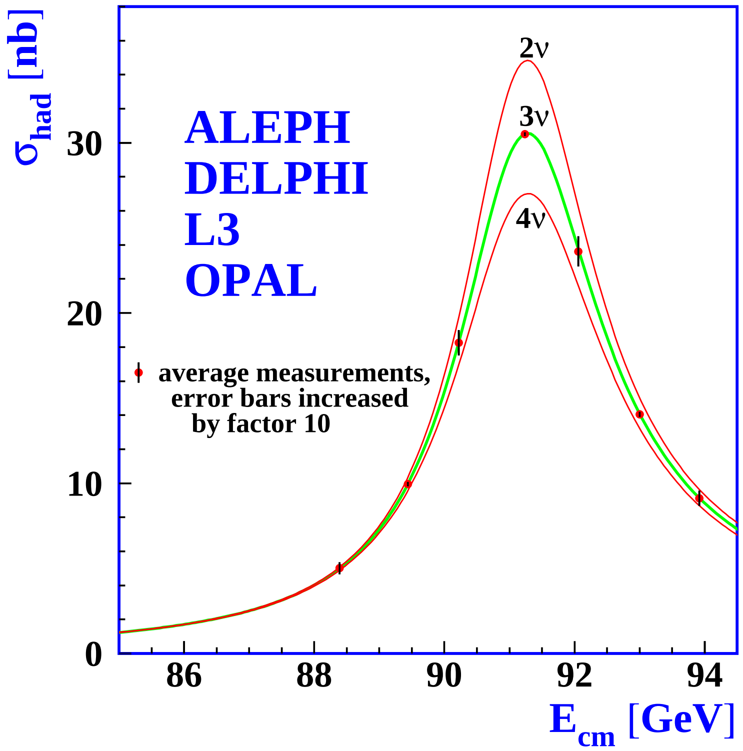
Extensive collaborative studies between experimentalists and theorists LEP Yellow Reports.



Solid line is the SM fit. Phys. Rept. 427, 257 (2006).

Large electromagnetic and QCD radiative corrections,

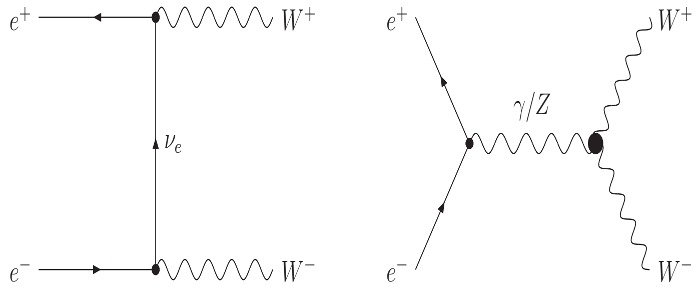
Initial state radiation makes the curve asymmetric near the resonance.

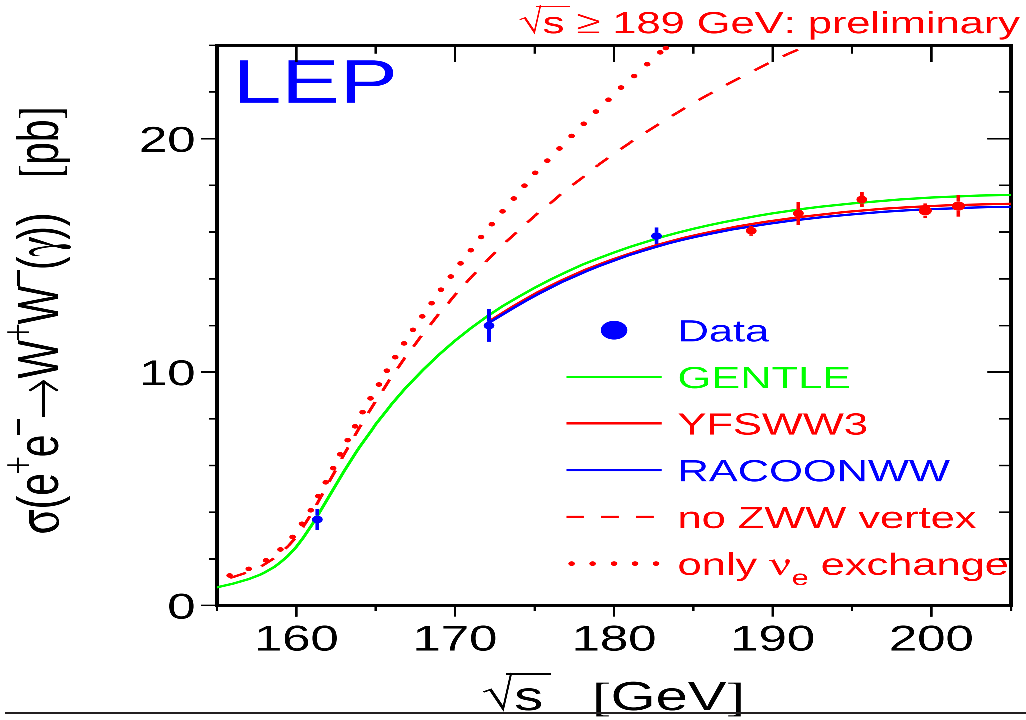


Width of the Z measured accurately, rules out 4th mass less neutrino generation.

Phys. Rept. 427, 257 (2006).

Direct 'Proof' of Symmetry and Symmetry breaking!!



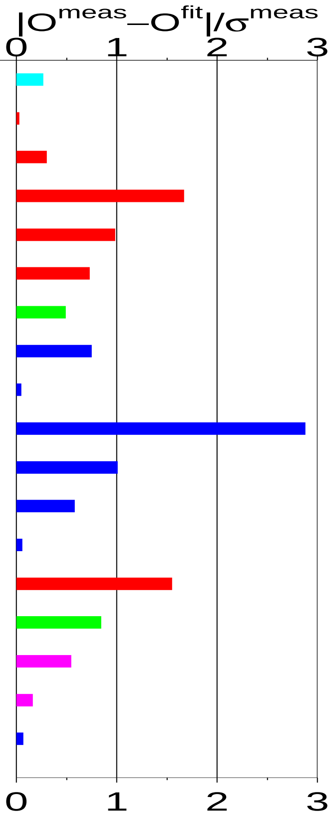


Proof that Electroweak symmetry exists and that it is broken.

The triple gauge boson ZWW coupling tames the bad high energy behaviour of the cross-section caused by the t-channel diagram. Direct proof for the ZWW coupling.

This observation at LEP-II and precision testing at the LEP-I, confirm basics of the SM

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	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]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26



March 2011

see http://lepewwg.web.cern.ch

Measurements of the various observables to one per mill value and agreement of the same with the theoretical prediction within same precision.

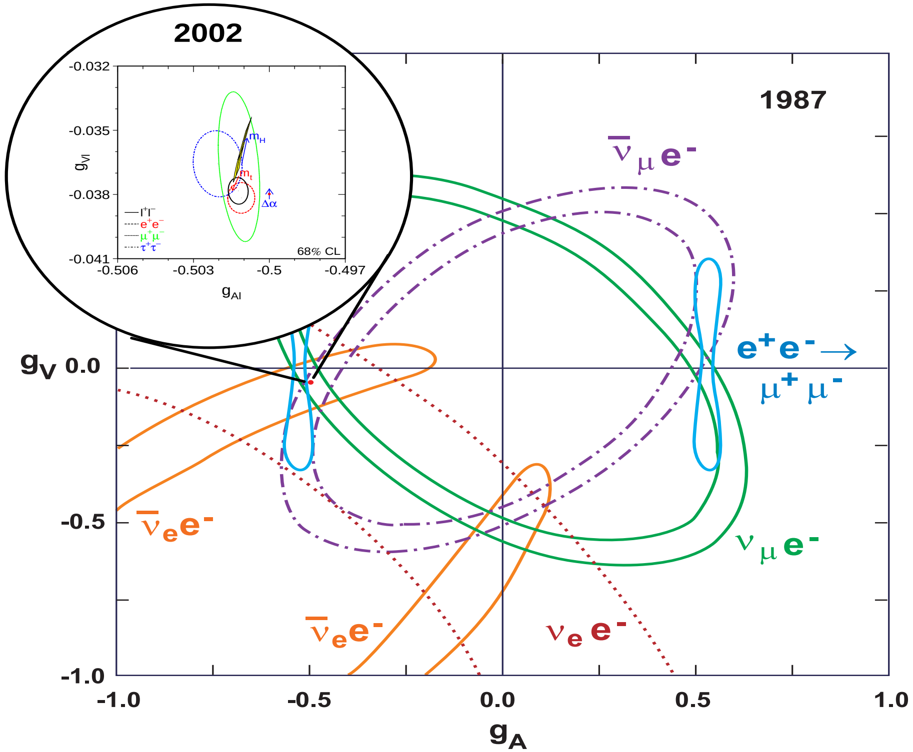
$\Delta\alpha_{em} = 0.02758 \pm 0.00035$ $(measured)$ $0.02767 (theory)$

$\Gamma_Z = 2.4952 \pm 0.0023 GeV$ $(measured)$ $2.4959 GeV (theory)$

$M_W = 80.404 \pm 0.030 GeV$ $(measured)$ $80.376 GeV (theory)$

$m_t = 172.5 \pm 2.3 GeV$ $(measured)$ $172.9 GeV (theory)$

How this is different from yesterday's comparison of $(37.4/\sin\theta_W)$ GeV with the measured M_W.



Enormously more precise measurements.

Agreement with SM prediction would have been impossible unless the predicted values included higher order corrections, calculated in perturbation theory.

Recall correction to $\Delta\rho$ is 1% . The measurement is accuarte to 1 part in 1000 or better.

Analog of $(g-2)_\mu$ for QED!

Logical steps in Precision testing of the SM and the indirect limits:

- SM has three parameters g_2, g_1 and v. All the SM couplings, gauge boson masses functions of these.

- A large number of EW observables measured quite accurately.

- M_Z, α_{em} and G_F are most accurately measured. Trade g_2, g_1 and v for these.

- All observables depend on these three apart from M_f (mainly M_t) *and* M_ϕ, and of course α_s.

- Calculate all observables using **1 loop EW** radiative corrections which can be computed in a renormalisable quantum field theory.

- Compare with data, make a SM fit. Tests the SM at loop level.

Absence of FCNC ⇒ quarks must come in isospin doublets, charm was predicted and top was expected to be present once b was found

Indirect information on M_c, M_t from flavour changing neutral processes. Agreement with experimentally measured values 'proves' gauge theory.

CP violation in meson systems can be explained in terms of the SM parameters and measured CKM mixing in quark sector.

M_W, M_Z predicted in terms of $\sin\theta_W$

M_t predicted from precision measurement of M_W, M_Z.

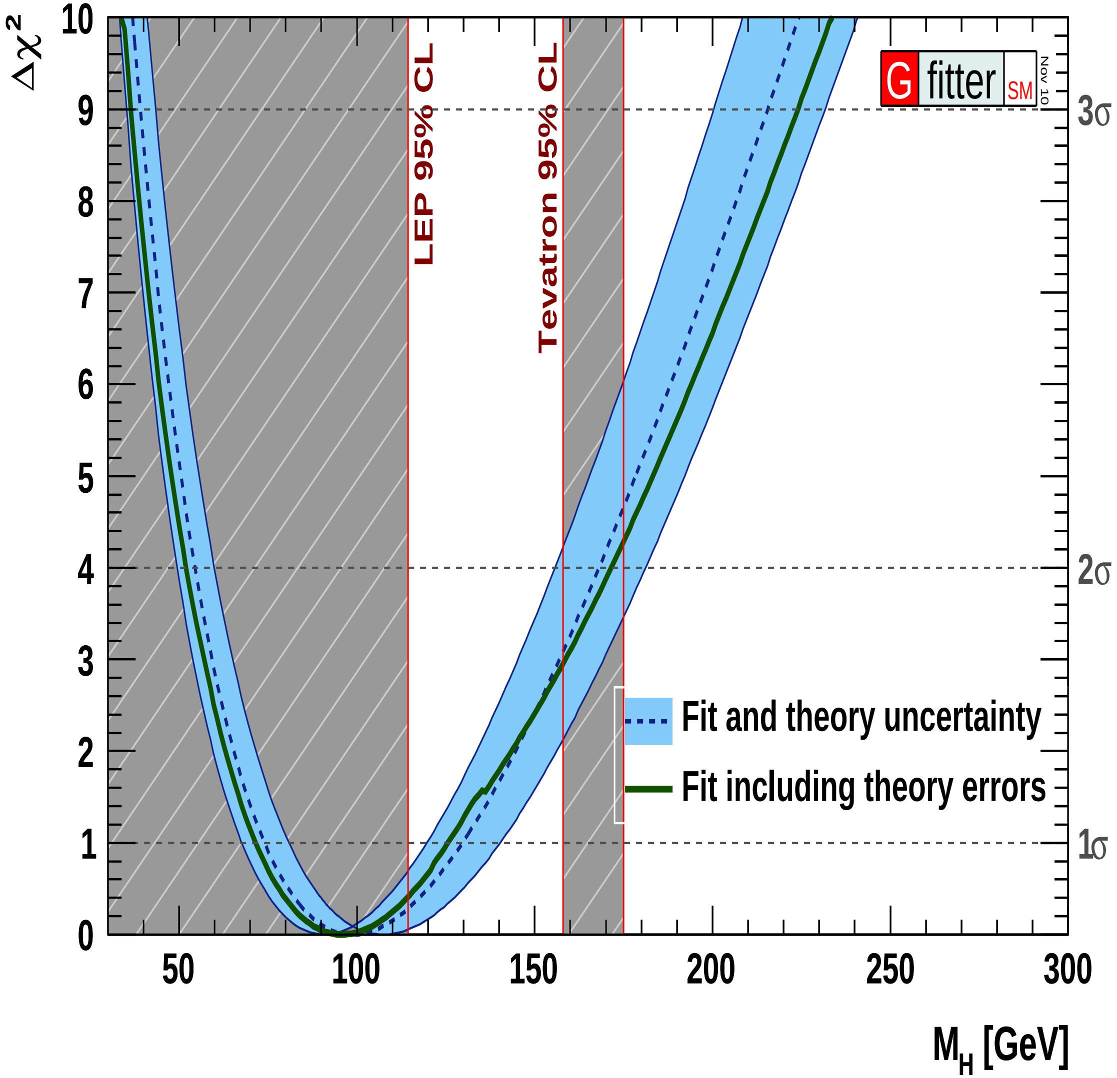
Now that we know that the top is heavy and know its mass, can we use precision measurements to obtain information on the Higgs mass?

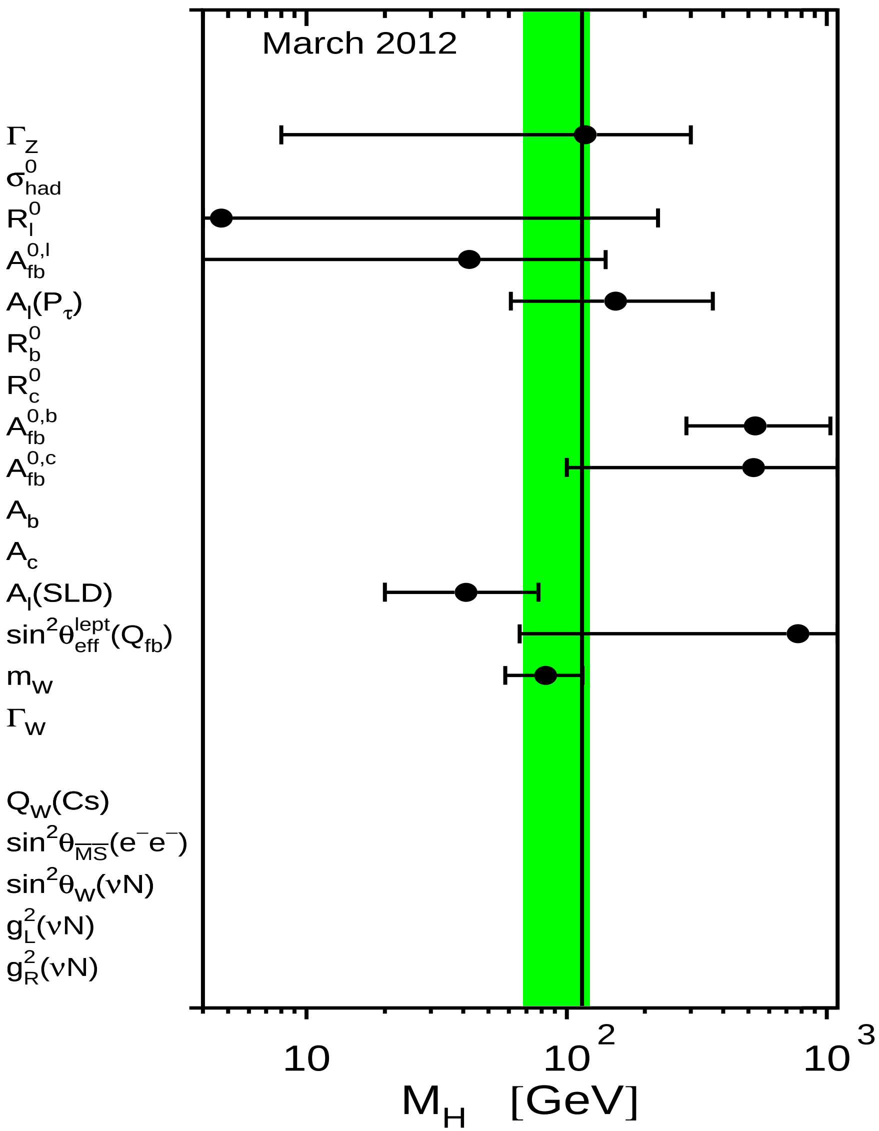
What does this all mean for the Higgs?

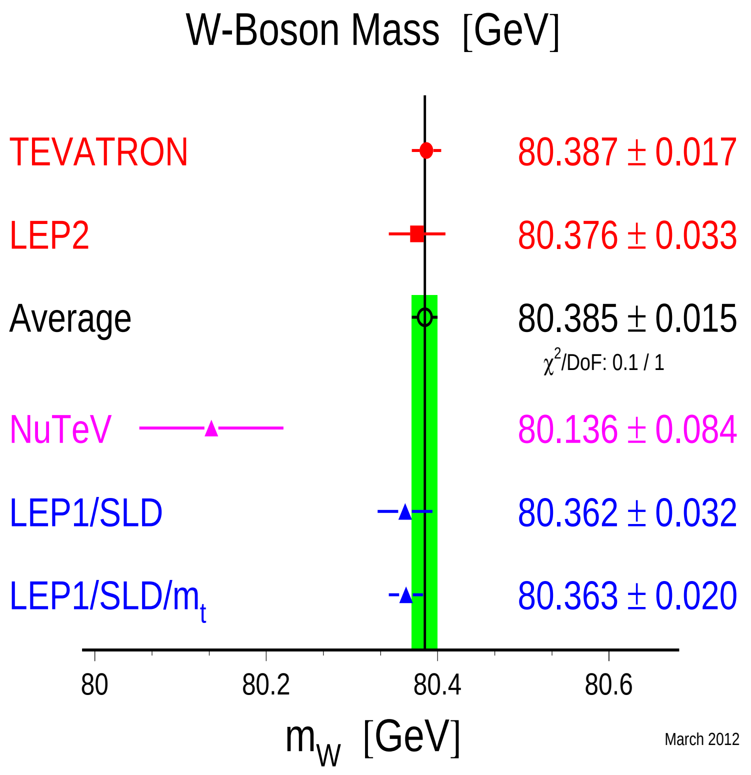
The loop corrections depend on the Higgs mass. Since that is the only unknown these measurements indirectly constrain the Higgs mass.

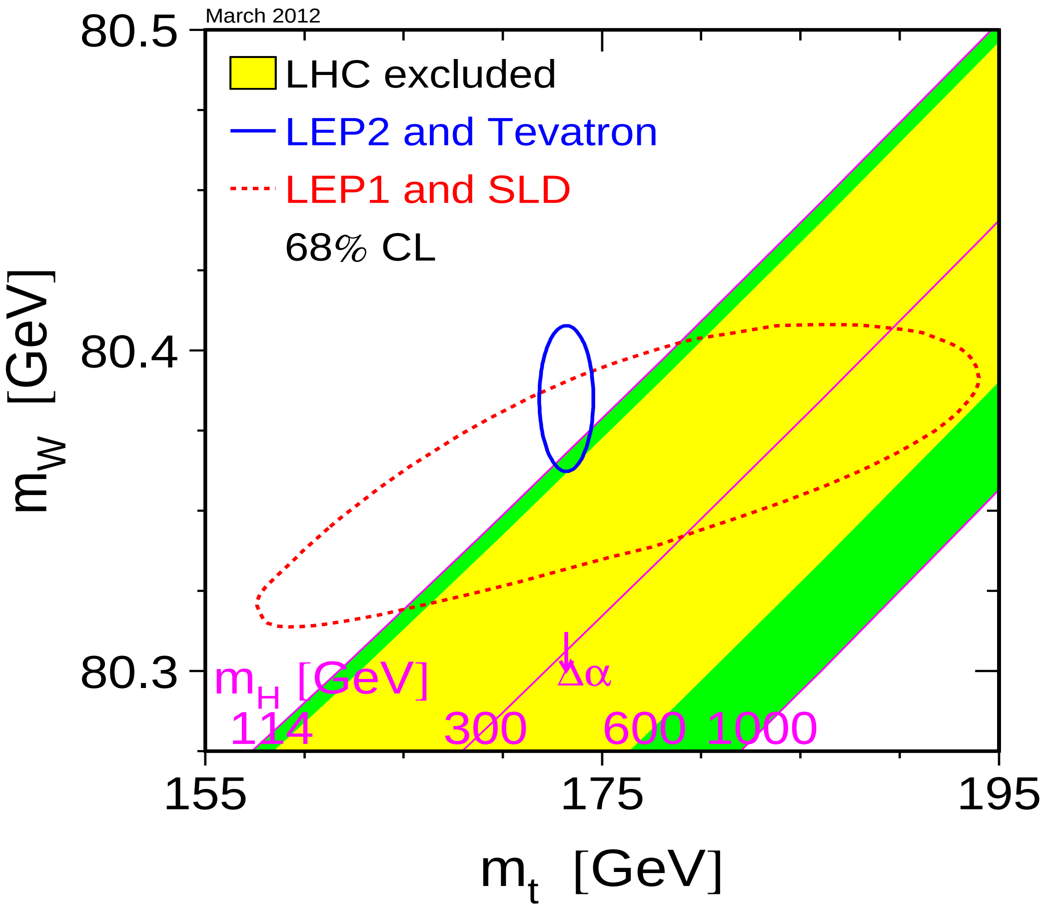
If all the current information is put together the Higgs mass should be less than 150 GeV. (**indirect experimental limit!**)

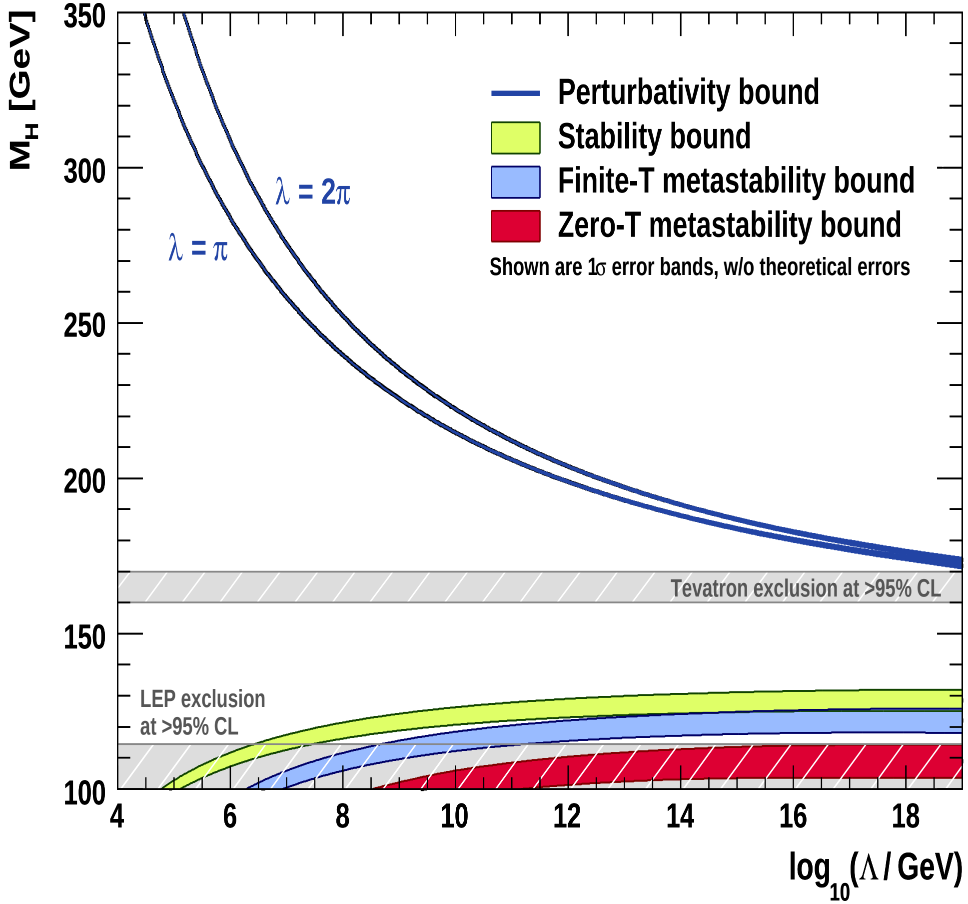
From the Gfitter web page.




March 2012
Γ_Z
σ^0_{had}
R^0_l
$A^{0,l}_{fb}$
$A_l(P_\tau)$
R^0_b
R^0_c
$A^{0,b}_{fb}$
$A^{0,c}_{fb}$
A_b
A_c
A_l(SLD)
$\sin^2\theta^{lept}_{eff}(Q_{fb})$
m_W
Γ_W
Q_W(Cs)
$\sin^2\theta_{\overline{MS}}(e^-e^-)$
$\sin^2\theta_W(\nu N)$
$g^2_L(\nu N)$
$g^2_R(\nu N)$
10
10^2
10^3
M_H [GeV]


W-Boson Mass [GeV]
TEVATRON
80.387 ± 0.017
LEP2
80.376 ± 0.033
Average
80.385 ± 0.015
χ²/DoF: 0.1 / 1
NuTeV
80.136 ± 0.084
LEP1/SLD
80.362 ± 0.032
LEP1/SLD/mt
80.363 ± 0.020
80
80.2
80.4
80.6
mW [GeV]
March 2012

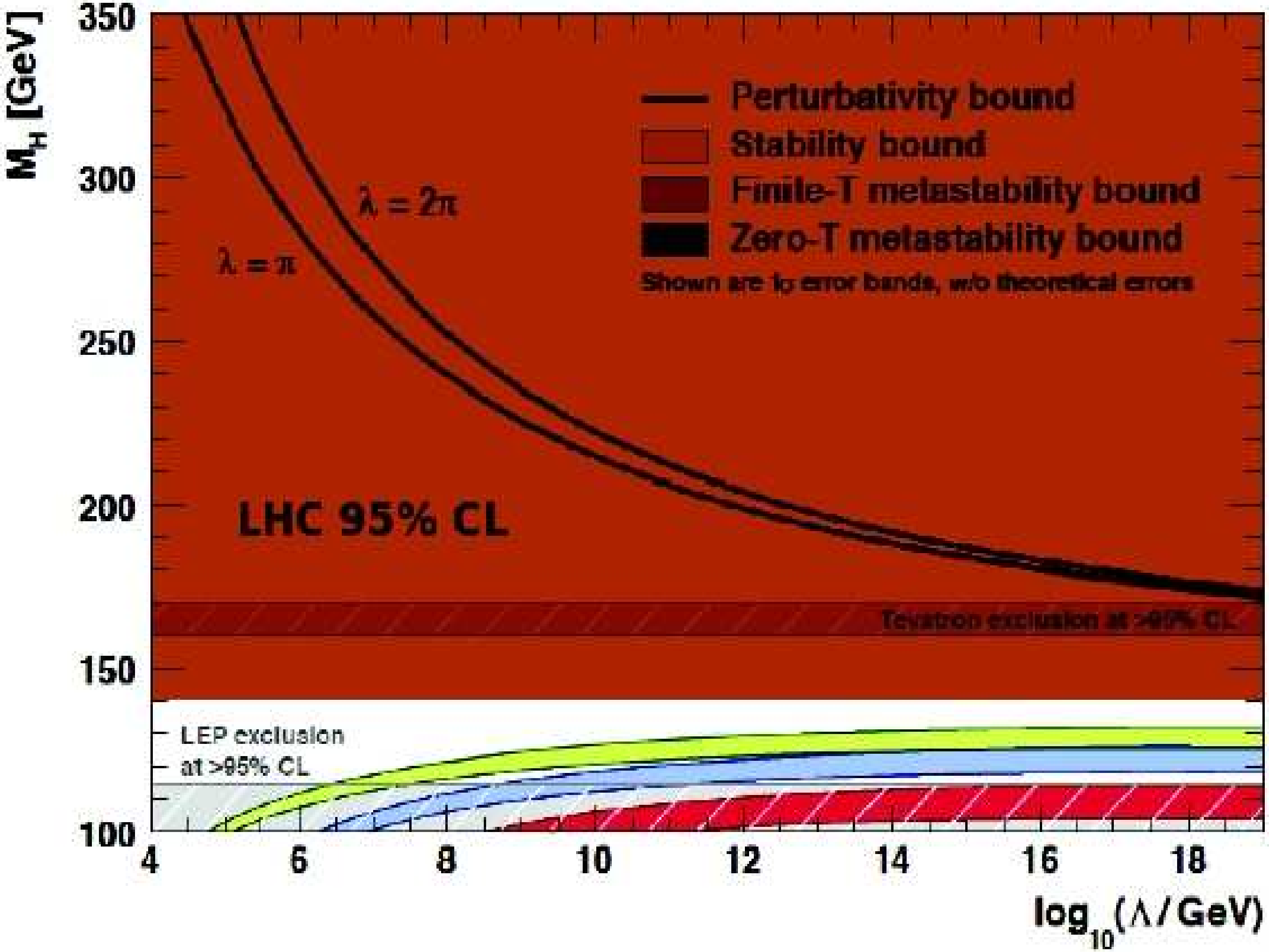

March 2012
LHC excluded
LEP2 and Tevatron
LEP1 and SLD
68% CL
80.5
80.4
80.3
mW [GeV]
mH [GeV]
114
300
600 1000
Δα
155
175
195
mt [GeV]



One limit mainly comes from demanding that the '$WW \to WW$ scattering amplitude does not violate unitarity. B.W. Lee, C. Quigg and H.B. Thacker, Phys. Rev. D16 (1977) 1519

Similar limit comes from demanding that the quartic coupling in the Higgs potential remains perturbative.

If there is physics beyond the SM these limits can be affected.


350
300
250
200
150
100
M_H [GeV]
Perturbativity bound
Stability bound
Finite-T metastability bound
Zero-T metastability bound
Shown are 1σ error bands, w/o theoretical errors
λ = 2π
λ = π
LHC 95% CL
Tevatron exclusion at >95% CL
LEP exclusion
at >95% CL
4
6
8
10
12
14
16
18
$\log_{10}(\Lambda/\mathrm{GeV})$

So finally the main role of the Higgs is to

1)Make the scattering amplitudes involving gauge bosons in the theory respect unitarity, even for massive gauge bosons.

2)Make gauge theories renormalisable.

At the LHC look for the Higgs

We seem to have found it! It is light exactly as we wanted!

Then we will like to explain 'theoretically' why it is light.

Further, almost all the BSM options affect Higgs properties. So study of the Higgs sector is THE LHC goal. May be that will shine the path beyond the SM.

In any case the days of Standard Model are coming to an end in some sense!

Hopefully the case will be 'The King is Dead', 'Long live the King'!

1] Lot of detailed information on the flavour sector is now available. We do not as yet understand it from first principles. SM does not have the capability to explain it from first principles.

2]CP violation required to explain the matter-antimatter asymmetry does seem to require physics outside the SM.

3]Dark Matter seems to exist. Most of the BSM models seem to have almost always a DM candidate automatically.

LHC will tell!