Electroweak physics and the LHC

an introduction to the Standard Model (II)

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Outline

- Prologue on weak interactions
- Express review of gauge theories
- (I) SM gauge sector
- Hidden symmetries
- SM Higgs sector (structure & consequences)
- Precision tests of the SM
- anomalous magnetic moments
- (II) Computing G_F
- Global fit and the Higgs mass
- Electroweak physics at LHC

Particle physics in one page

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

$$\left(+N_i M_{ij} N_j \right)$$ The ν-mass sector (4) (if Majorana)

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

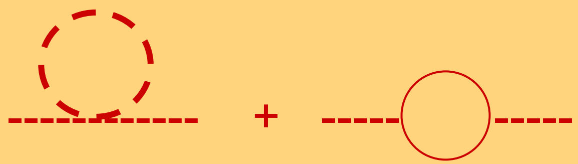
Can it be the end of the story?

Riccardo Barbieri

Naturalness of the SM

Electron mass shift in QED $m_e = m_{e,0} [\, 1 + 3\alpha/2\pi \;\ln \Lambda/m_{e,0} + ...]$
similarly in SM. Even for very large Λ the shift is $O(m_e)$. Chiral symmetry protects the fermion masses

The Higgs sector in SM presents quadratic divergences:

$\delta M_H^2 =$  $+ ... \sim \lambda\Lambda^2 + h_t^2 \Lambda^2 + ...$

Scalar masses are not protected by any symmetry.

$\Lambda \sim M_{Planck} \rightarrow \delta M_H^2 \sim 10^{38} GeV^2$ unnatural

> 30 orders of magnitude **fine tuning**. Why worry? SM is renormalizable!
But look at it from above...

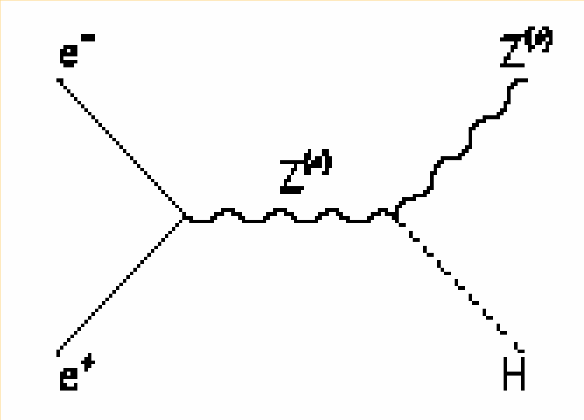
Naturalness has long been guiding principle in extending the SM
Avoid scalars or introduce a symmetry that softens the divergence (susy)

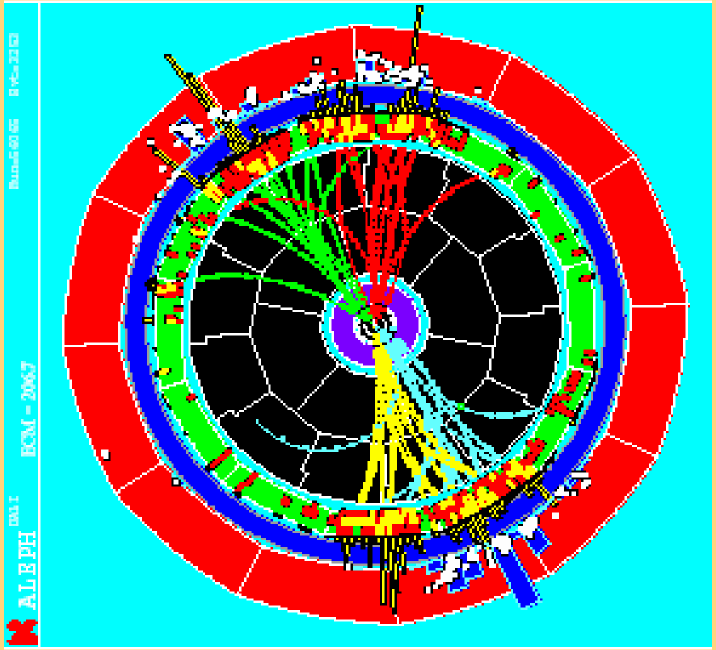
What do we know about the Higgs?

Unlike gauge and flavor sectors, Higgs sector is (almost) unexplored

the Higgs mass parameterizes our ignorance of SSB.

Direct searches at LEP: $M_H > 114.4$ GeV





Small excess observed by Aleph in the last few months of LEP2 with $M_H \sim 115$ GeV, but low statistical significance

Finding the Higgs and verifying its couplings would confirm the SSB mechanism and help understanding how to complete the SM

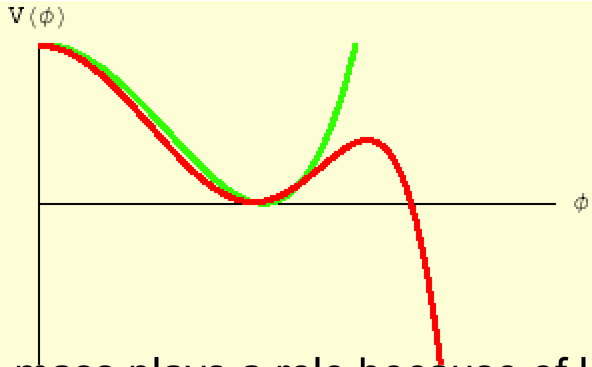
Theory bounds on M_H (I)

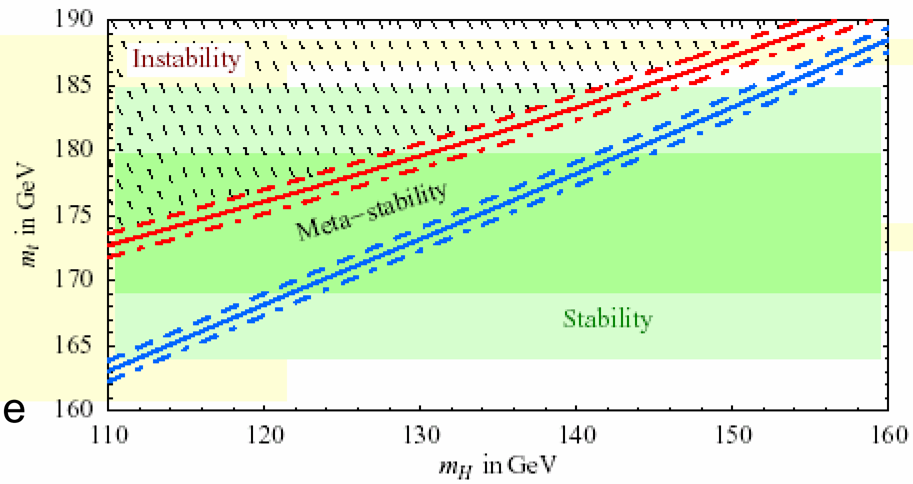
Theory bounds follow from EXTRAPOLATING the SM to higher scales and demanding consistency.

The SM vacuum is sensitive to quantum corrections that deform the Higgs potential

Require SM valid up to the Planck scale and stable (or sufficiently long–lived) vacuum The request $\lambda(\phi \sim \Lambda \gg v)>0$ depends on initial conditions: m_H.

$\Rightarrow$ LOWER BOUND $m_H \gtrsim 115$ GeV (Isidori, Ridolfi, Strumia, 2001)





Top mass plays a role because of large h_t that drives λ down

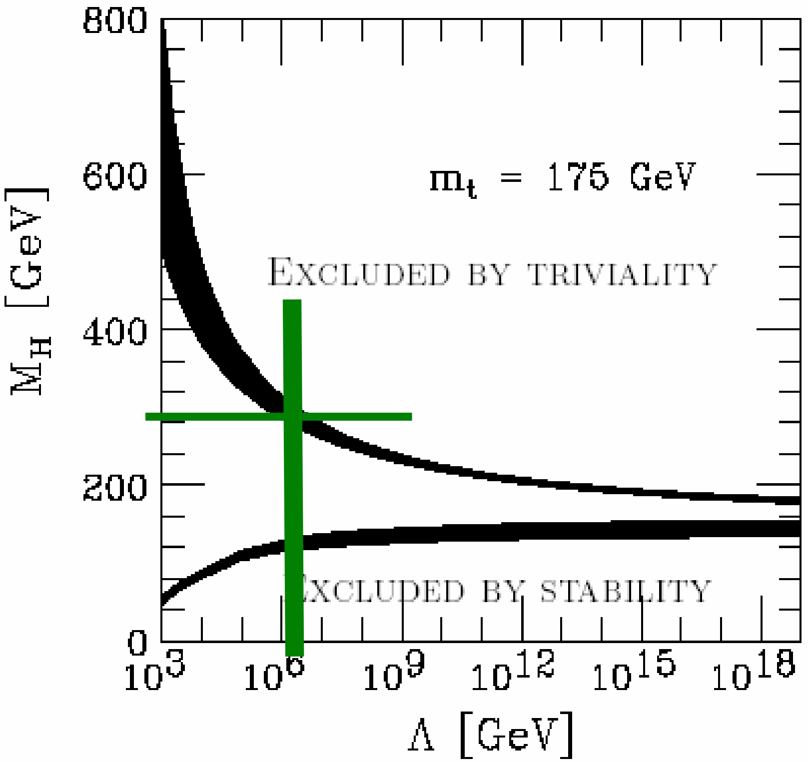
Theory bounds on M_H (II)

The Higgs field self-coupling is

$$\lambda = \frac{m_H^2}{2v^2}$$

The coupling of $\lambda\phi^4$ grows with energy up to a *Landau pole* at Λ, where it blows up.

The SM cannot be extrapolated beyond Λ, which depends on the initial value, i.e. m_H $m_H \lesssim 600$ GeV



Discovering the Higgs boson would imply bounds on the SM cutoff: the scale at which New Physics becomes necessary (as far as we can trust these bounds)

Why we don't believe in the SM

As we'll see in a moment, the SM is quite successful, yet...

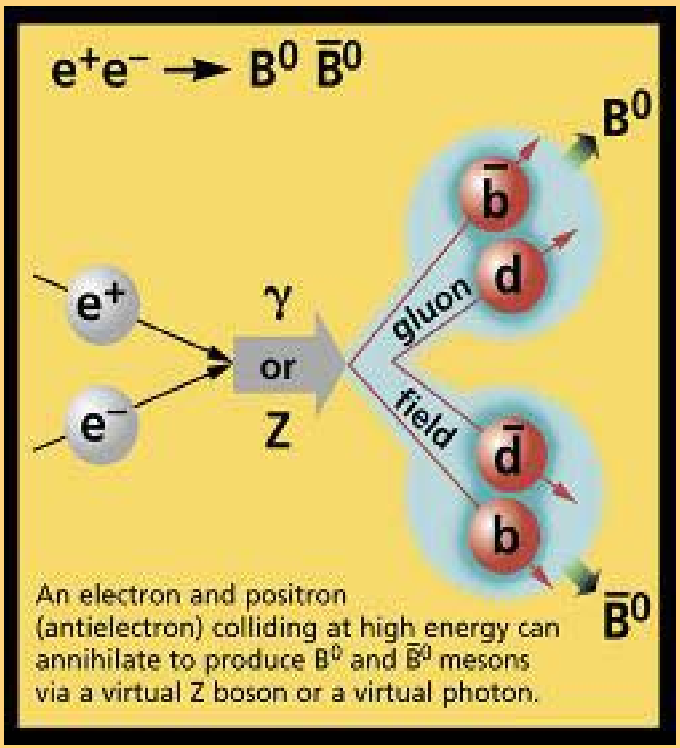
- ✓ it has many parameters (18), 3 replicas with no apparent reason
- ✓ it is incomplete: and gravity? Why is it so weak?
- ✓ it does not account for **neutrino** masses, nor explains their smallness
- ✓ it cannot explain **dark matter**, nor baryogenesis
- ✓ its extrapolation to very high energies is problematic: the huge hierarchy between Fermi and Planck scale is unstable

  naturalness hints at new physics $\sim$ TeV, but **do we understand naturalness?**

the SM must have a UV completion that we don't know yet:
it is a (renormalizable!) low-energy effective theory.
Dependence on the cutoff is power suppressed

Two complementary approaches to new physics

Direct production

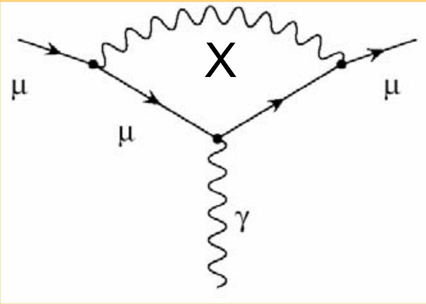


Indirect search

Virtual effects of heavy particles (e.g. the Higgs boson) can be detected by precision measurements, despite the loop or power suppression.

Historically, **indirect signals** have often anticipated the discovery of new particles: charm, top...

new physics in muon g-2?



Precision tests of the SM

Serve **double purpose**: check SM (nowadays in particular SSB) and look for extensions. Having testing the main architecture of SM, current exps aim at detecting & studying virtual corrections (ex W,Z,t, H loops, possibly new physics): weak loops $\sim$ 1% ➔ need O(0.1%) accuracy

Need **sophisticated perturbative calculations**: $O(g^2, g^2\,\alpha_s, g^2\,h_t^2, \ldots)$ QED/QCD radiation, etc. Need clean quantities, that can be computed with high accuracy. In a few cases complete 2loop EW calculations (M_W, $\sin^2\theta_{eff}^{lept}$)

The SM is a renormalizable theory: we are screened from whatever completes it. The **screening is power-like** and roughly determines the precision required to probe New Physics scales $\gg M_W$

$\Gamma_Z \sim \alpha\, m_W^2/\Lambda^2$: tests scales beyond weak scale ~ 1%

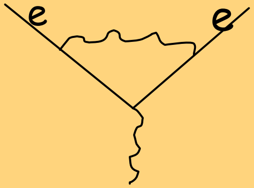
Different exps test different sectors of the SM: EWSB, Flavour
Low energy EW exps: g-2, NC ($e^- e^-$, APV, ν N), **Z pole observables** (LEP, SLC): Z properties and couplings, $\mathbf{M_W}$ (LEP2, Tevatron), $\mathbf{M_t}$ (Tevatron)

The prototypical precision test

Dirac theory (1928) predicts $g_e=2$
Since 1947, the anomalous magnetic moment $a_e=(g_e-2)/2$
is a fantastic test of Quantum Field Theory (QED)

$$a_e^{SM} = \frac{\alpha}{2\pi} - 0.328\left(\frac{\alpha}{\pi}\right)^2 + 1.181\left(\frac{\alpha}{\pi}\right)^3 - 1.75\left(\frac{\alpha}{\pi}\right)^4 + 1.7\times 10^{-12}$$

Hadr & ew loops

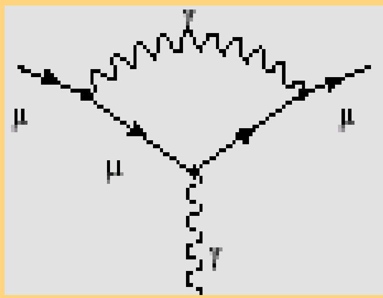


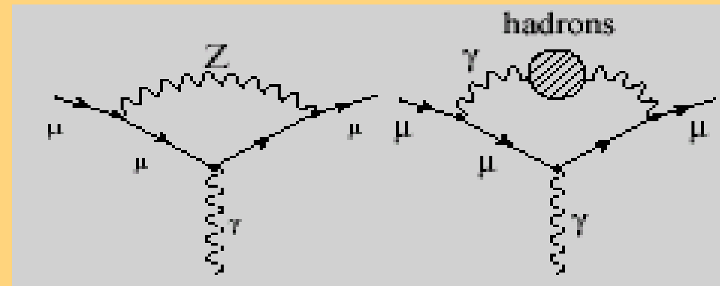
a_e^{exp} = 1159652188(4) x 10^{-12} **Exp precision challenged theorists for 50 yrs**

Presently gives the **best determination of α**, with rel accuracy 4×10^{-9},
5x more precise than Quantum Hall effect, 2x better than atom beam interferometry

Effect of virtual particles ~ $(m_e/M)^2$:
QED is a renormalizable theory, **screened** from the UV completion

The muon anomalous magnetic moment: can we test the SM?





Non-QED effects are suppressed by m_μ^2/Λ^2 but starting at 2loops Λ can also be the scale of strong interactions $\Lambda \sim M_\rho \sim 700$MeV !

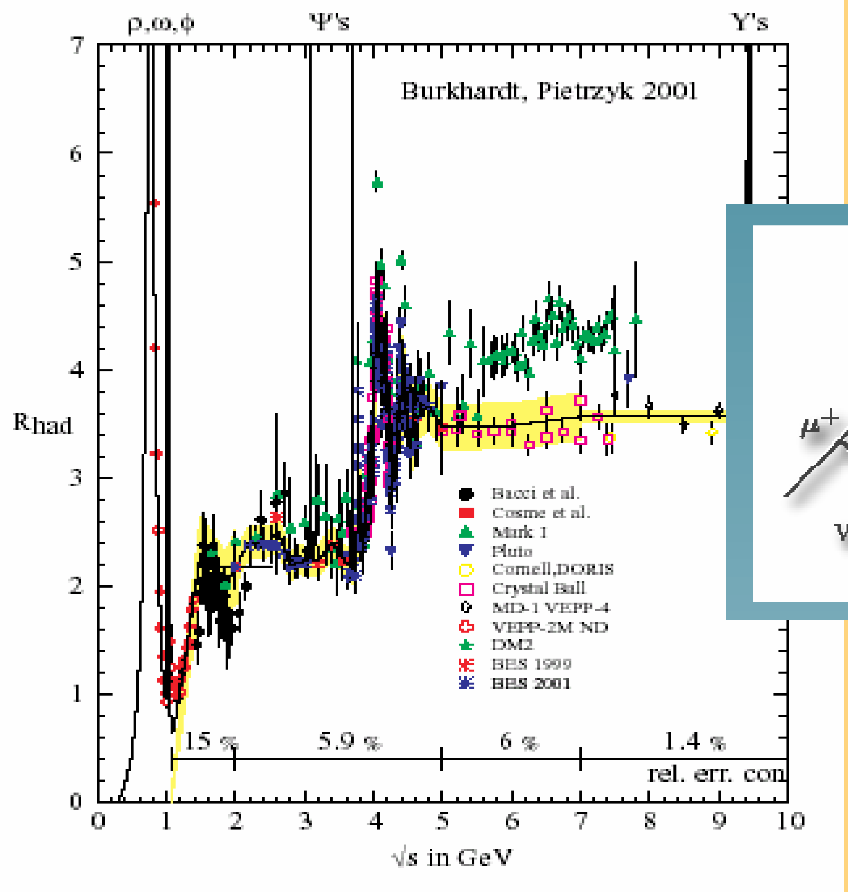
$$a_\mu^{exp} = 116\ 592\ 080(60)\times 10^{-11}$$

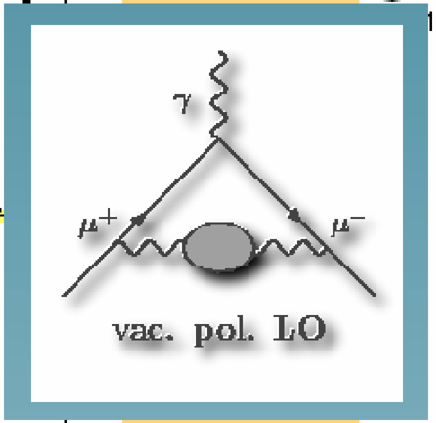
$$a_\mu^{SM} = [116\ 584\ 706(3)_{QED} + 154(2)_{W,Z,H} + 6831(73)_{hadrons}]\times 10^{-11}$$

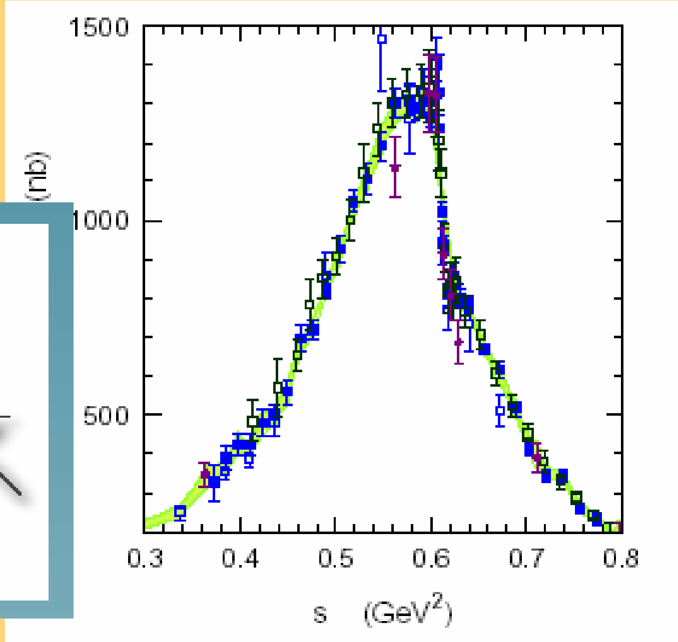
~2-3σ discrepancy: **New Physics** (Supersymmetry?) or
due to **uncalculable strong interaction effects**?

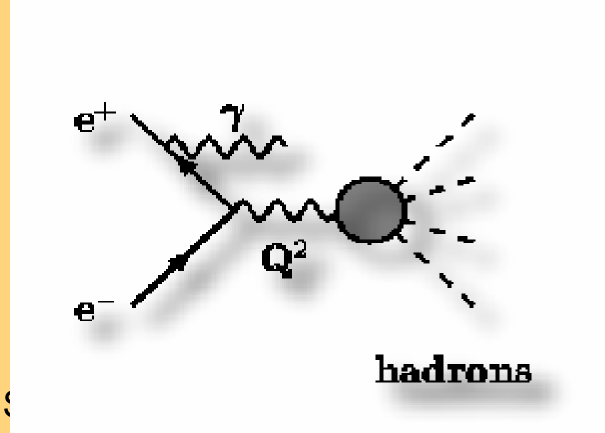
Excellent place for new physics, low M_H sensitivity: loop effects $\sim m^2_\mu/\Lambda^2$ but needs chiral enhancement: SUSY natural candidate at moderate/large tanβ

The spectral function









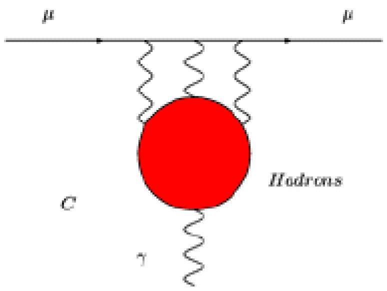
The spectral function can be measured in
$e^+ e^- \to$ hadr, in τ decays, and with radiative return

Status of $(g-2)_\mu$

$a_\mu^{SM} \times 10^{11}$	$(a_\mu^{EXP} - a_\mu^{SM}) \times 10^{11}$	σ		HLO Reference
116591789 (76)	291 (98)	3.0	⟨2.5⟩	[1] (e^+e^-)
116591803 (95)	277 (114)	2.4	⟨2.0⟩	[2] (e^+e^-)
116591779 (76)	301 (98)	3.1	⟨2.6⟩	[3] (e^+e^-)
116591799 (63)	281 (89)	3.1	⟨2.7⟩	[4] (e^+e^-)
116591962 (70)	118 (95)	1.3	⟨0.7⟩	[5] (τ)

a_μ^{HHO}(lbl) = 80 (40) x 10^{-11} in all table except angle brackets. → a_μ^{HHO}(lbl) = 136 (25) x 10^{-11}

[1] A. Hoecker@ICHEP04, hep-ph/0410081.
[2] F. Jegerlehner, Nucl. Phys. Proc. Suppl. 126 (2004) 325.
[3] Hagivara, Martin, Nomura & Teubner, PRD69 (2004) 09300
[4] J.F. de Troconiz and F.J. Yndurain, PRD71 (2005) 073008.
[5] Davier, Eidelman, Hoecker and Zhang, EPJC31 (2003) 503.



BUT still many disagreements between various experiments: eg new Belle results

M. Passera - 19.05.06

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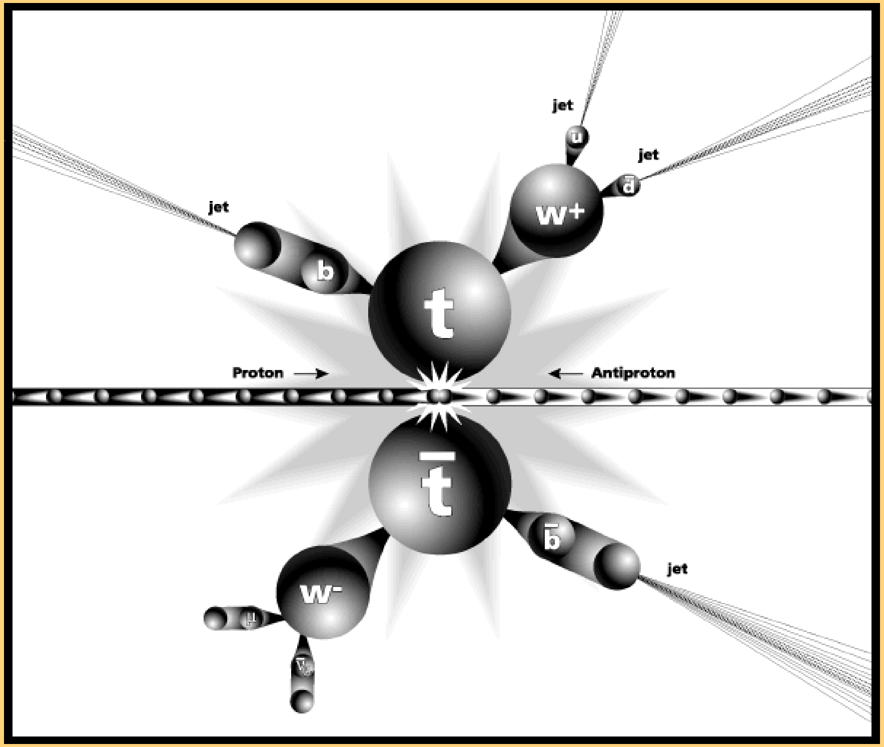
Precision tests and the top

1994: fits to precision measurements (LEP etc.) give
M_{top}=177±11±19 GeV

1994: top quark discovery at Fermilab with
M_{top}=174±10±13 GeV

Great success of SM and of the experimental program



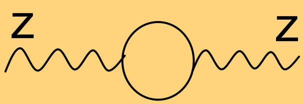
➡ Can it be repeated with the Higgs boson?

Unfortunately the sensitivity is much lower ~log M_H

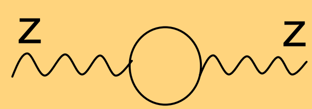
Decoupling and the SM

- **Decoupling theorem**: the effects of heavy particles are power-suppressed (up to a redefinition of the coupling) if theory remains renormalizable and no coupling is prop to the heavy masses. Ex. QED and QCD at low energy

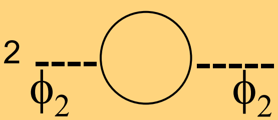
- What with **heavy top**?
  - SM not renormalizable any longer (gauge symmetry broken)
  - $h_t \propto m_t$ and W_L, Z_L couple like pseudo-Goldstone bosons



$\propto m_t^2\, g^{\mu\nu}$



$\propto \partial/\partial q^2$



$(q^2=0)$

$m_t^2 \sim 5M_W^2$ relatively large, often dominant correction (also $Z \to bb$)

$$\rho = 1 + \Delta\rho = \frac{3G_\mu(m_t^2 - m_b^2)}{8\pi^2\sqrt{2}} + \dots$$ universal m_t^2 corr.

- What with **heavy Higgs**? only logs in ew corrections

  difference with top: m_t-m_b breaks expl O(4) custodial symmetry of Higgs potential that guarantees ρ=1. Higgsless SM: non linear σ model

Precision tests (II)

Question was: can we determine M_H from precision observables?

18 SM parametrs (+ ν masses & mixings)	g $=e/s_w$	g' $=g/c_w$	v $=2c_wM_z/g$	λ	g_s	6+3 masses	4 CKM
	α or $\alpha(M_z)$	$\sin^2\theta_W$,	M_Z	M_H	$\alpha_s(M_z)$	M_t, others mostly irrilevant	Irrilevant for flavor diag
Relative precision	10^{-9} or 3.5 10^{-4}	depends on def.	2 10^{-5}	?	2-3%	1.3%...	...

Other best known EW observables:

$G_\mu(0.9\ 10^{-5})$; $M_W(4\ 10^{-3})$; $\sin^2\theta_{eff}^{lept}\ (0.8\ 10^{-3})$; $\Gamma_l\ (10^{-3})$

Info on M_H can be extracted from

$\alpha(M_z), M_t, G_\mu, M_w \rightarrow M_H$

or $\alpha(M_z), M_t, G_\mu, \sin^2\theta_{eff}^{lept} \rightarrow M_H$

etc. : all exp and th uncertainties contribute to $\delta \log M_H$

Natural relations

Mass-coupling relation ($\rho=1+O(g^2)$)

$$\frac{e_0^2}{g_0^2} = 1 - \frac{M_{W0}^2}{M_{Z0}^2} = \sin^2\theta_W^0$$

between bare quantities: have same divergences, finite rad corrections

since $G_\mu^0 = \frac{g_0^2}{4\sqrt{2}M_{W0}^2}$

$$G_\mu = \frac{\pi\alpha(M_Z)}{\sqrt{2}M_W^2(1-\frac{M_W^2}{M_Z^2})}\frac{1}{(1-\Delta r)}$$

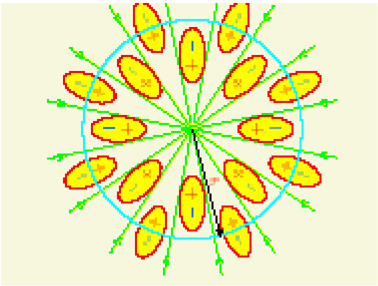
$$G_\mu = \frac{\pi\alpha(M_Z)}{\sqrt{2}M_Z^2\cos^2\theta_{eff}^{lept}\sin^2\theta_{eff}^{lept}}\frac{1}{(1-\Delta r_{eff})}$$

Δr, Δr_{eff} are two observables with very different top, H dependence !
They can be calculated with theory precision close to 10^{-4}

Masses here are always **pole masses** (real part of the propagator pole)
Not a convenient parameter for the top mass (large higher orders)

Why $\alpha(M_z)$?

Running α (I)



$$\alpha \equiv \frac{e^2(0)}{4\pi} = \frac{e_0^2}{4\pi(1+\pi(0))} = 1/137.03599890(50)$$

$$\alpha(s) = \frac{\alpha}{1-\Delta\alpha(s)} \qquad \Delta\alpha(s) = \Pi(s) = \Pi_\gamma(0) - \mathrm{Re}\Pi_\gamma(s)$$

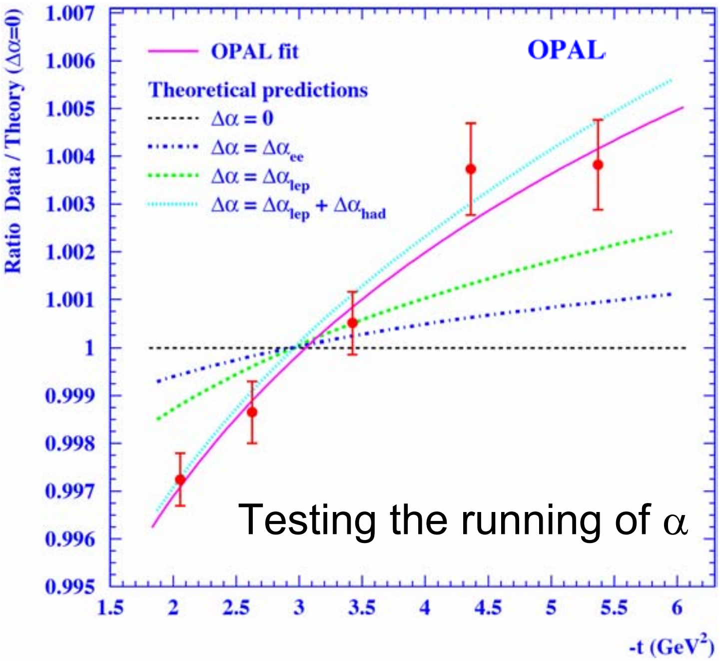
$$\Delta\alpha^{\mathrm{pert}}(s) = \frac{\alpha}{3\pi}\sum_f Q_f^2 N_{Cf}\left(\log\frac{s}{m_f^2} - \frac{5}{3}\right)$$

$$\Delta\alpha(s) = \Delta\alpha(s)_l + \Delta\alpha(s)_h + \Delta\alpha(s)_t$$

$$\Delta\alpha(s)_l = 0.0331421\ ; \quad \Delta\alpha(s)_t = \frac{\alpha}{3\pi}\frac{4}{15}\frac{m_Z^2}{m_t^2} = -0.000061$$

$\Delta\alpha^{(5)}_{\mathrm{hadrons}}(M_Z^2)$	$=$	0.02777 ± 0.00034	
Jegerlehner		0.02761 ± 0.00036	BP 01
$\alpha^{-1}(M_Z^2)$	$=$	128.925 ± 0.046	
		128.936 ± 0.046	BP 01

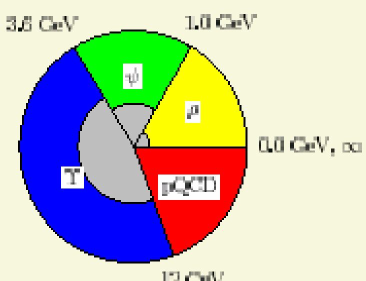
Setting scale of α typically means avoiding & resumming large QED logs



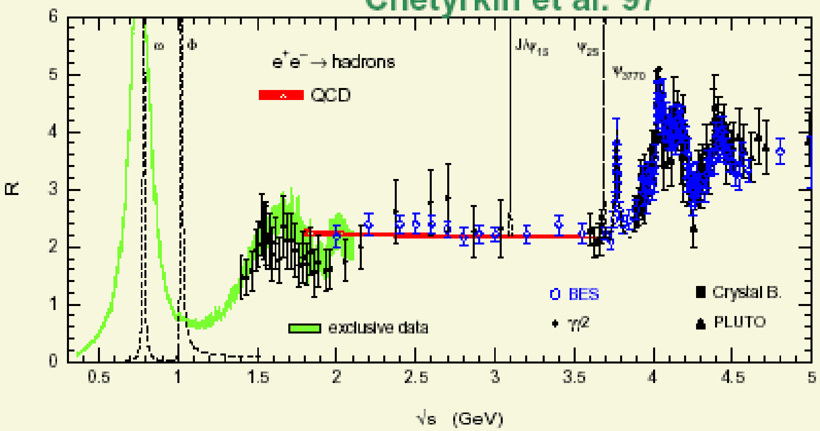
Running α (II)

Non-perturbative hadronic contributions $\Delta\alpha^{(5)}_{\rm had}(s)$ can be evaluated in terms of $\sigma(e^+e^- \to {\rm hadrons})$ data via dispersion integral:

$$\Delta\alpha^{(5)}_{\rm had}(s) = -\frac{\alpha s}{3\pi}\left(\int_{4m_\pi^2}^{E^2_{\rm cut}} \!\!\!\!\!\! P \; ds' \frac{R^{\rm data}_\gamma(s')}{s'(s'-s)} + \int_{E^2_{\rm cut}}^{\infty} \!\!\!\! P \; ds' \frac{R^{\rm pQCD}_\gamma(s')}{s'(s'-s)} \right)$$

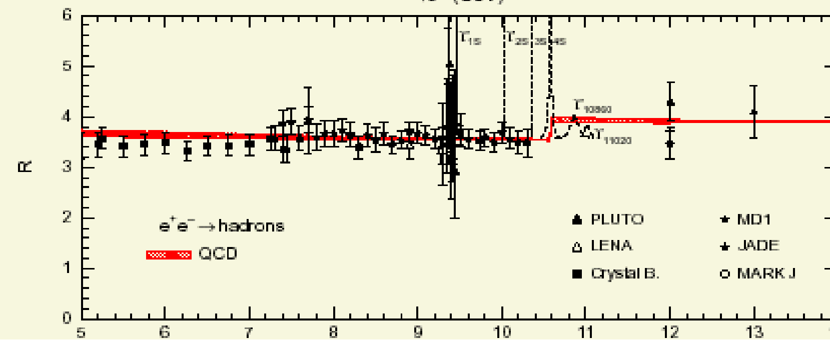


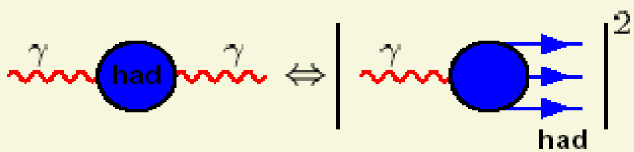
Compilation: Davier, Eidelman et al. 02
Theory = pQCD: Groshny et al. 91, Chetyrkin et al. 97



where

$$R_\gamma(s) \equiv \frac{\sigma^{(0)}(e^+e^- \to \gamma^* \to {\rm hadrons})}{\frac{4\pi\alpha^2}{3s}}$$

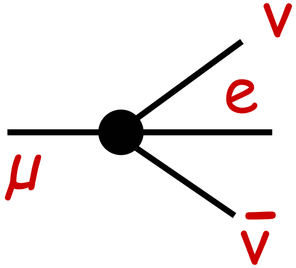




$\Pi'_\gamma(q^2)$ $\qquad\sim \sigma^{\rm had}_{\rm tot}(q^2)$

Computing the Fermi constant (I)

Muon decay in the Fermi Theory...



$$\tau_\mu^{-1} = \frac{G_\mu^2 m_\mu^5}{192\pi^3} f\left(\frac{m_e^2}{m_\mu^2}\right)\left(1+\frac{3}{5}\frac{m_\mu^2}{m_W^2}\right)(1+RC)$$

$$RC = \frac{\alpha}{2\pi}\left(\frac{25}{4}-\pi^2\right)\left(1+\frac{\alpha}{\pi}\left(\frac{2}{3}\ell n\frac{m_\mu}{m_e}-3.7\right)+\left(\frac{\alpha}{\pi}\right)^2\left(\frac{4}{9}\ell n^2\frac{m_\mu}{m_e}-2.0\ell n\frac{m_\mu}{m_e}\right)\right)+\cdots$$

$G_\mu = 1.16637(1)\times 10^{-5}\ \mathrm{GeV}^{-2}$ Wilson coefficient of Fermi operator

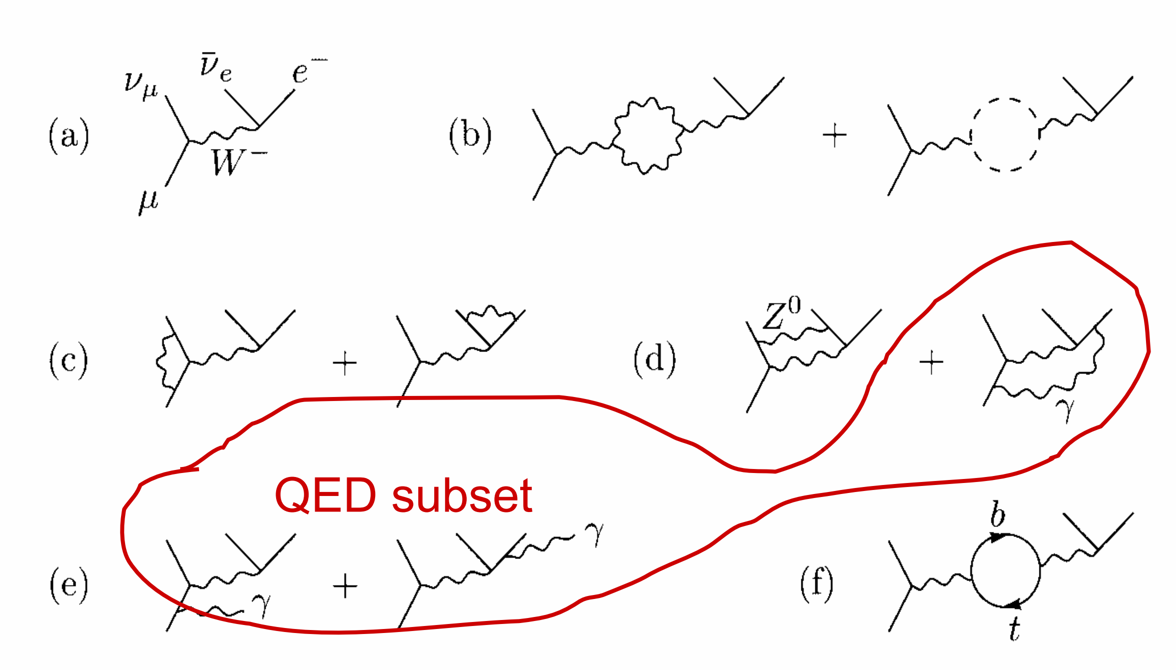
Δr gives radiative corrs to μ decay after subtracting QED effects

RC insensitive to UV physics: QED corrections to muon decay are FINITE

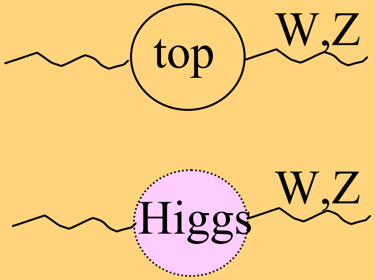
Fermi operator of muon decay does not run with QED Hence $\alpha(M_z)$

Exp: Δr =-0.0282±0.0022 **Electroweak corrections are observed**

Computing the Fermi costant (II)



plus counterterms:



Exp: Δr =-0.0282±0.0022

SM:

$$\Delta r = -\frac{c_W^2}{s_W^2}\frac{3G_\mu M_t^2}{8\sqrt{2}\pi^2} + \frac{11}{12}\frac{G_\mu M_W^2}{\sqrt{2}\pi^2}\log\frac{M_H^2}{M_W^2} + \ldots$$

Using the measured M_{top} and M_W $\Delta r\ (M^2_{top})$=-0.031±0.002

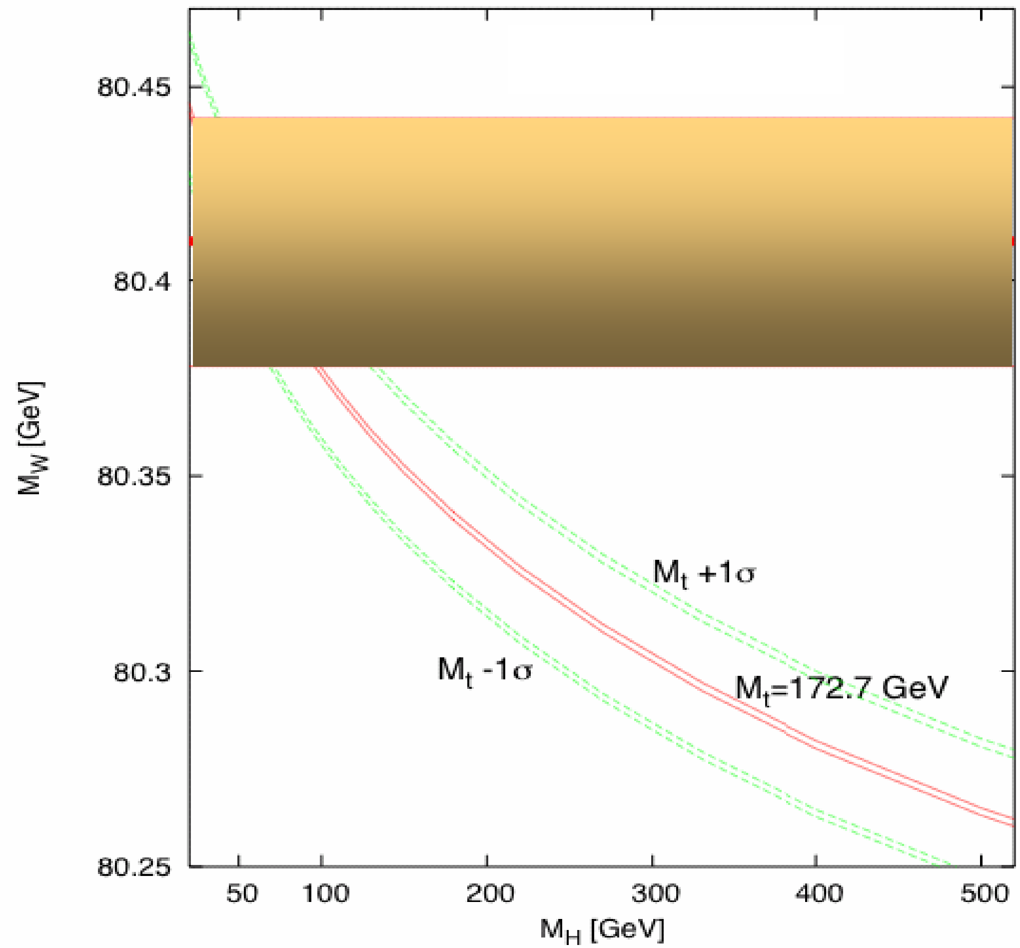
Residual terms small ➔ **M_H cannot be large**, M_{top} close to exp

A detailed complete calculation leads to:

$$m_W/(\text{GeV}) = 80.409 - 0.507\left(\frac{\Delta\alpha_h^{(5)}}{0.02767} - 1\right) + 0.542\left[\left(\frac{m_t}{178\text{GeV}}\right)^2 - 1\right]$$
$$-0.05719\ell n(m_H/100\ \text{GeV}) - 0.00898\ell n^2(m_H/100\ \text{GeV})$$

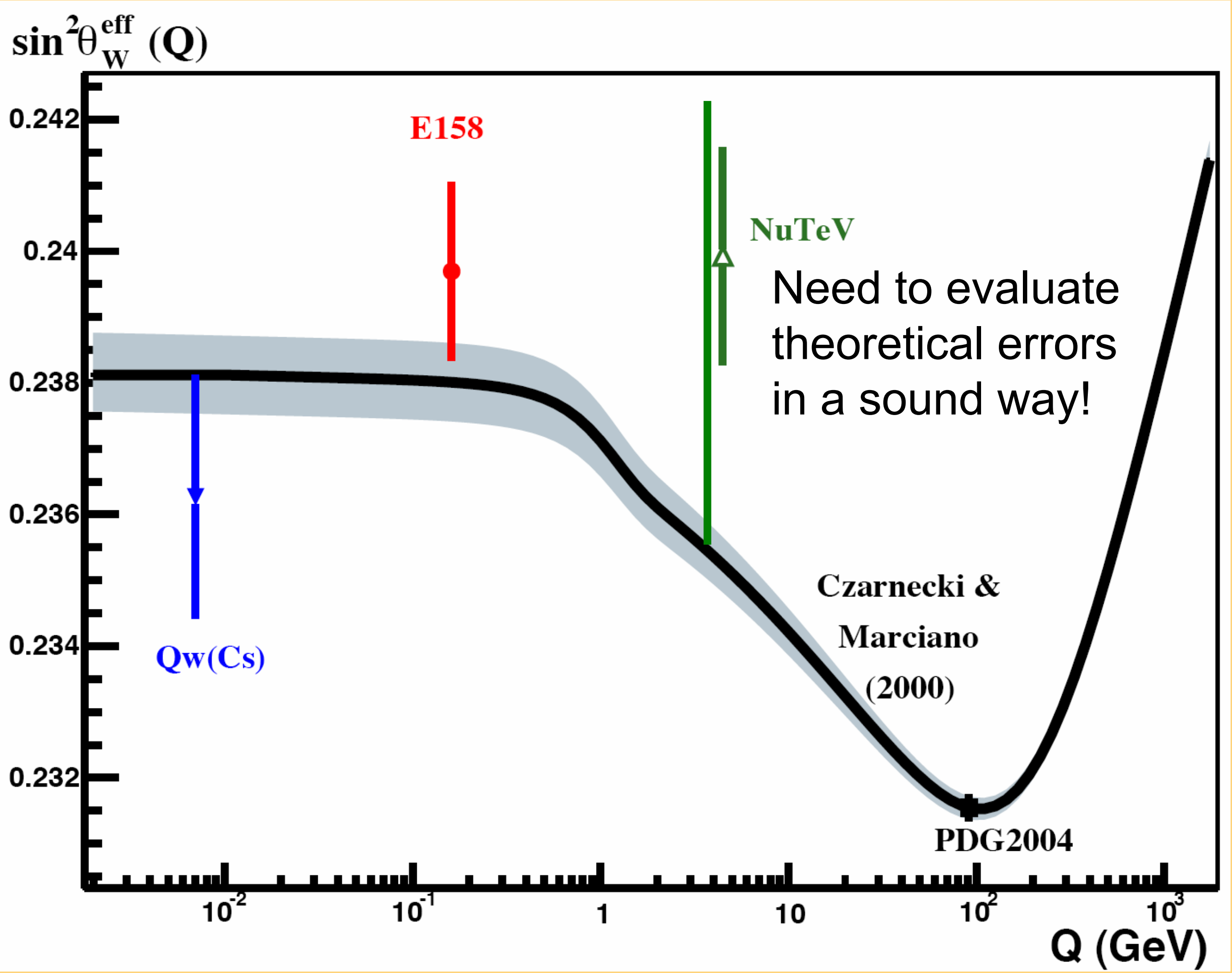
m_W points to a light Higgs!

Like $[\sin^2\theta_{eff}]_l$



Low energy tests of NC couplings

Low energy measurements of $\sin^2\theta_W$ can be presented as tests of its running

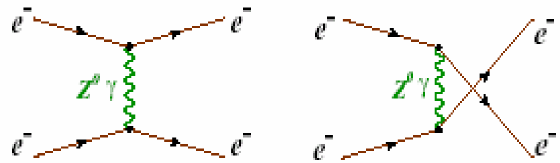


Need to evaluate theoretical errors in a sound way!

PV in Møller scattering

- Scatter polarized 50 GeV electrons off *unpolarized* atomic electrons
- Measure $A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -A_{LR}$
- Small tree-level asymmetry

$$A_{PV} = -mE \frac{G_F}{\sqrt{2}\pi\alpha} \frac{16\sin^2\Theta}{(3+\cos^2\Theta)^2}\left(\frac{1}{4} - \sin^2\theta_W\right)$$



E158 at SLAC
first measurement of PV in Møller sc.

huge luminosity
high polarization (~80%)

At tree level, $A_{PV} \approx 280\ 10^{-9}$

Suppressed → very sensitive to $\sin^2\theta_w$ Large radiative corrections, ≈-40% Czarnecki-Marciano,Denner-Pozzorini,Petriello,Ferroglia et al

Large theory uncertainty from γZ VP ≈5%can and should be reduced

Sensitive to new physics orthogonal or complementary to collider physics (PV contact interations, loops…)

The NuTeV EW result

NuTeV measures ratios of NC/CC cross-sections in ν DIS

$$R_\nu \equiv \frac{\sigma(\nu\mathcal{N}\to\nu X)}{\sigma(\nu\mathcal{N}\to\mu X)} = g_L^2 + r g_R^2$$

$$R_{\bar\nu} \equiv \frac{\sigma(\bar\nu\mathcal{N}\to\bar\nu X)}{\sigma(\bar\nu\mathcal{N}\to\bar\mu X)} = g_L^2 + \frac{1}{r} g_R^2,$$

$$r \equiv \frac{\sigma(\bar\nu\mathcal{N}\to\bar\mu X)}{\sigma(\nu\mathcal{N}\to\mu X)}$$

R^{exp} differ from these because of n_e contamination, cuts,NC/CC misID, 2nd generation, non isoscalar target, QCD-EW corr.: need detailed MC

NuTeV main new feature is having both ν and $\bar\nu$ beams. R_ν most sensitive to $\sin^2\theta_W$, $R_{\bar\nu}$ control sample → m_c. Approximately corresponds to **PASCHOS-WOLFENSTEIN** ratio

$$R_{PW} \equiv \frac{R_\nu - r R_{\bar\nu}}{1-r} = \frac{\sigma(\nu\mathcal{N}\to\nu X)-\sigma(\bar\nu\mathcal{N}\to\bar\nu X)}{\sigma(\nu\mathcal{N}\to\ell X)-\sigma(\bar\nu\mathcal{N}\to\bar\ell X)} = g_L^2 - g_R^2 = \frac{1}{2} - \sin^2\theta_W$$

$\mathbf{s^2_w}$(NuTeV)=$0.2276\pm0.0013_{stat}\pm0.0006_{syst}\pm0.0006_{th}$

where $\mathbf{s^2_w=1-M^2_w/M^2_w}$ (on-shell) Global fit: $\mathbf{s^2_w}= 0.2229\pm0.0004$

a ~2.8σ discrepancy but with many theoretical open issues

Asymmetric sea and NuTeV

Without assumptions on the parton content of target

$$R_{PW} = \frac{1}{2} - s_W^2 + \frac{\tilde{g}^2}{Q^-}\left[u^- - d^- + c^- - s^-\right]\{1 + O(\alpha_s)\}$$

Davidson,Forte,PG,Rius,Strumia

$\tilde{g}^2 \approx 0.23$ $Q^- \approx 0.18$ $q^- = \int dx\, x(q(x)-\bar{q}(x))$

Isospin violation

Non-isoscalar target: accounted by NuTeV. Uncertainty originally underestimated Kulagin '03

Isospin violation in the pdfs

$$u_p(x) \neq d_n(x)$$

Naturally of O(1%),
$\delta s^2_w \approx 0.002$
exp constraints very weak

Different models give this order of magnitude $\delta s^2_w < 0$,
Sather,Rodionov et al,Londergan&Thomas

We cannot rely on models!

Such a strange asymmetry

$$R_{PW} = \frac{1}{2} - s_W^2 + \frac{\tilde{g}^2}{Q^-}\left[u^- - d^- + c^- - s^-\right]\{1 + O(\alpha_s)\}$$

Strange quark asymmetry
Non-perturbatively induced by p <-> KΛ
A positive s^- reduces the anomaly

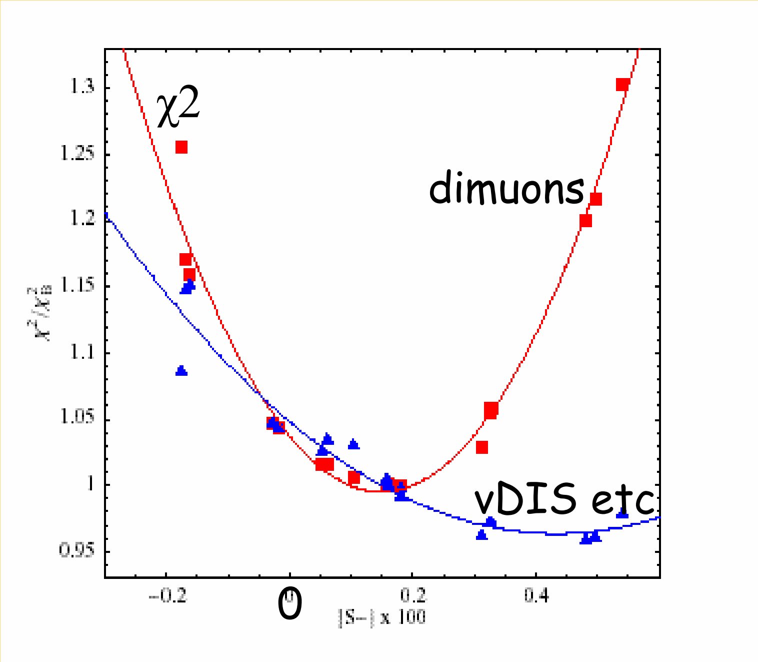
Only ν-induced processes
are sensitive to $s^-(x)$

<u>Inclusive ν-DIS</u>

<u>Dimuons (charm production)</u>

NuTeV has found $s^- = -0.0027 \pm 0.0013$
but the analysis is **inconsistent**

NEW CTEQ analysis
- explores full range of parametrns
- includes all available data

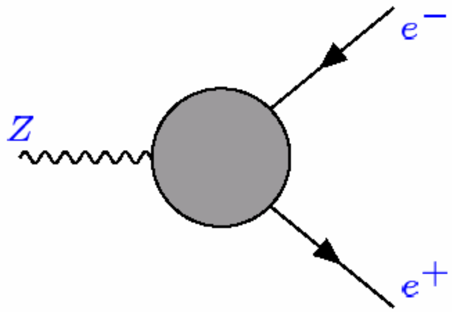


Kretzer, Olness, Pumplin, Stump, Tung et al.

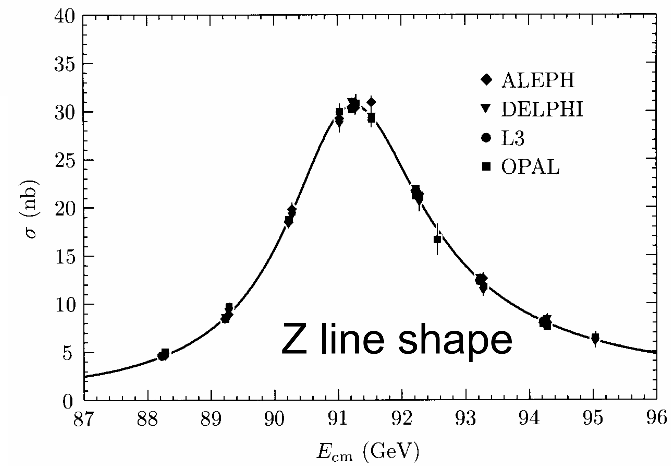
Bottom line on NuTeV

- Large sea uncertainties and other theoretical uncertainties reduce strongly the discrepancy
- Given present understanding of hadron structure, NuTeV is no good place for high precision physics
- **Useful lesson for LHC!**

Asymmetries at the Z^0 pole



$$= \quad \bar{u}_l \, \gamma_\mu \, (g_v + g_a \, \gamma_5) \, v_l \, \epsilon_Z^\mu$$



$$A_{FB}^{0,f} = \frac{3}{4} \mathcal{A}_e \mathcal{A}_f \qquad A_f = \frac{2 g_A g_V}{g_A^2 + g_V^2}$$

$$g_V^\mu / g_A^\mu \quad = \quad 1 - 4 \sin^2 \theta_{eff}^{\text{lept}} \ll 1$$

$$\sin^2 \theta_{\text{eff}}^{\text{lept}} = \frac{1}{4} \left[1 - \text{Re} \left(\frac{g_v}{g_a} \right) \right]$$

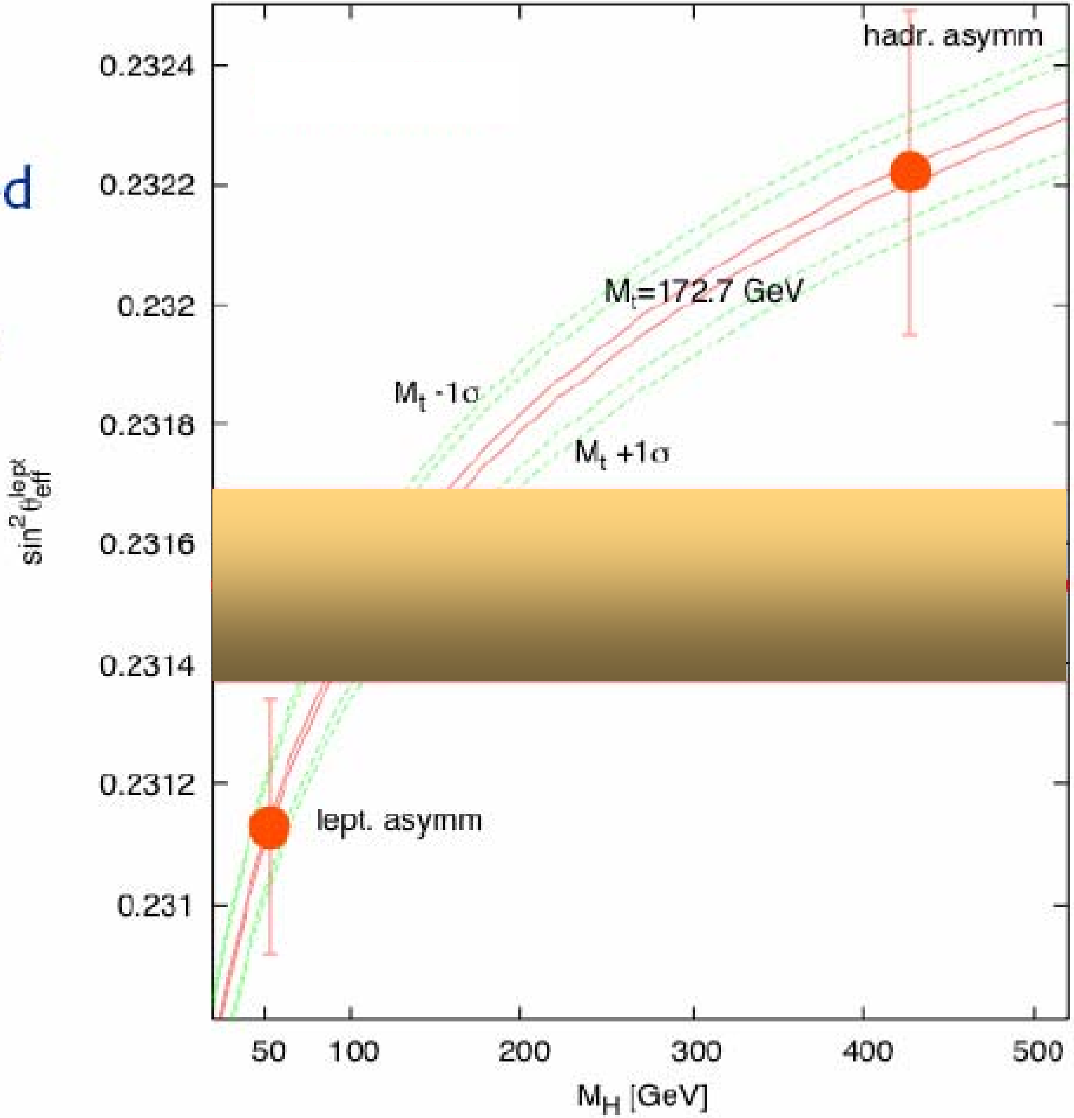
different asymmetries (tau polarization, LR, LRFB) measure differently the same coupling factors. Assuming lepton univ. there is only one eff $\sin^2 \theta^{\text{lept}}$ that can be measured also from A_{FB}^b:

$$\frac{1}{A_e} \frac{\partial A_e}{\partial \sin^2 \theta_W} \sim -55 \gg \frac{1}{A_b} \frac{\partial A_b}{\partial \sin^2 \theta_W} \sim -0.7$$

Plot $\sin^2\theta_{eff}$ vs m_H

Exp. values are plotted at the m_H point that better fits given m_{texp}

Clearly leptonic and hadronic asymm.s push m_H towards different values

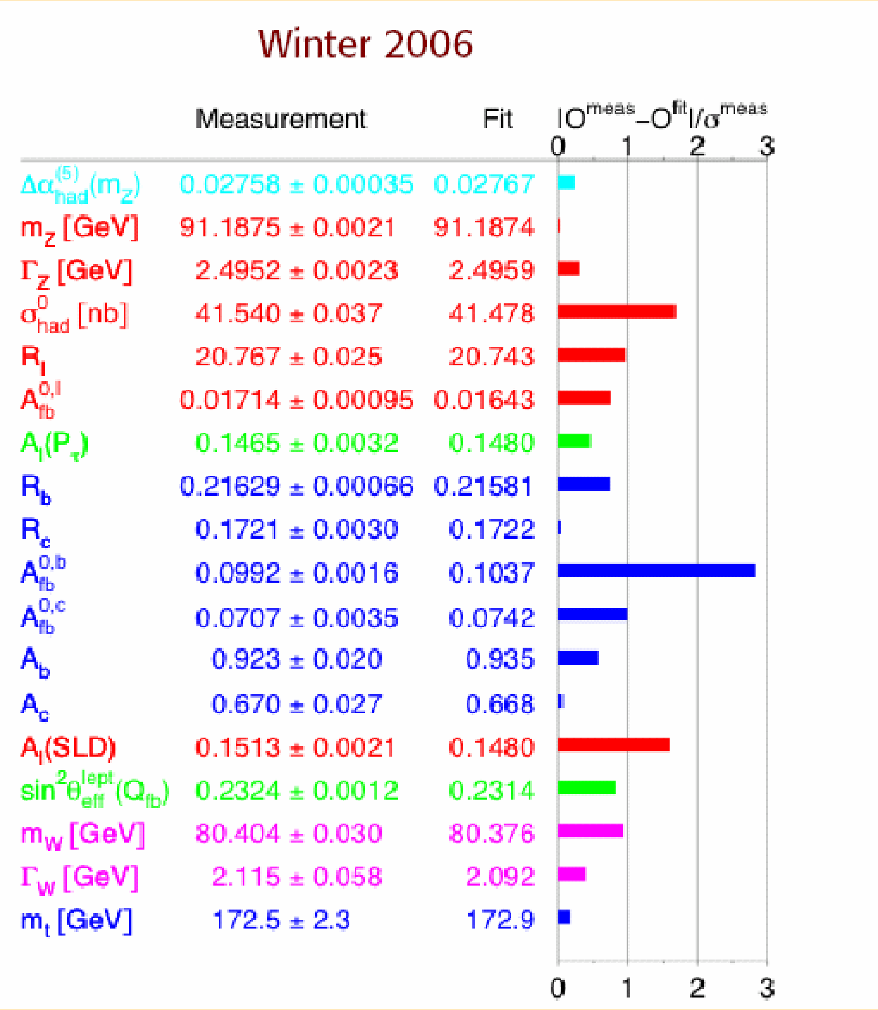


The "global" EWWG fit

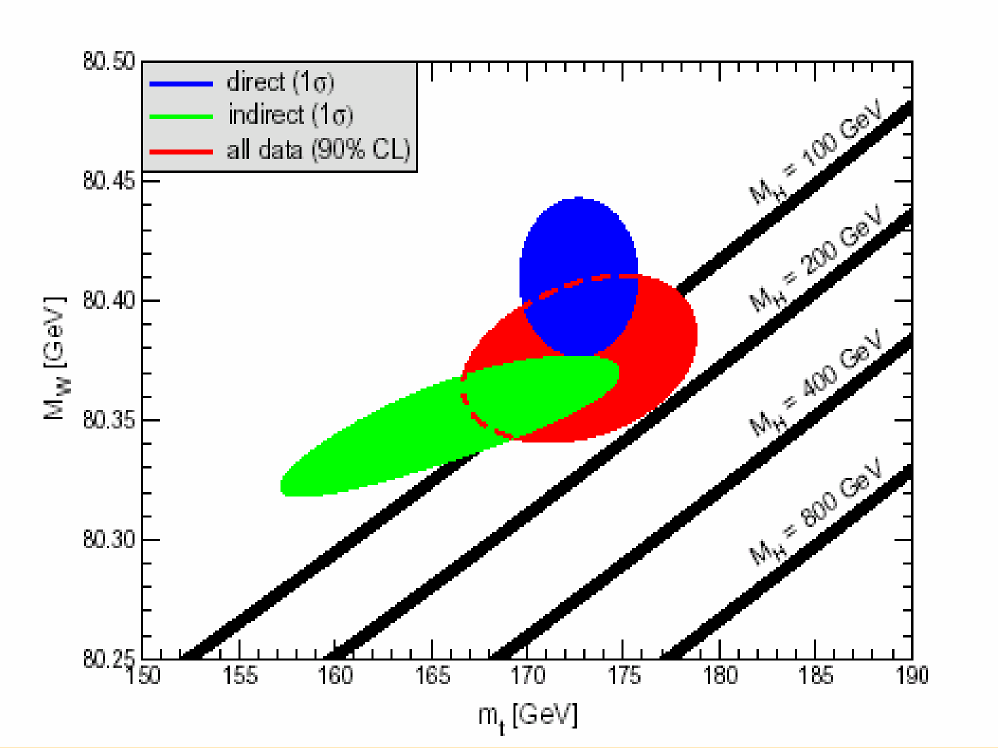
M_H^{fit}=89 GeV, M_H<175 GeV at 95%CL
χ^2/dof=17.5/13 17.7% prob

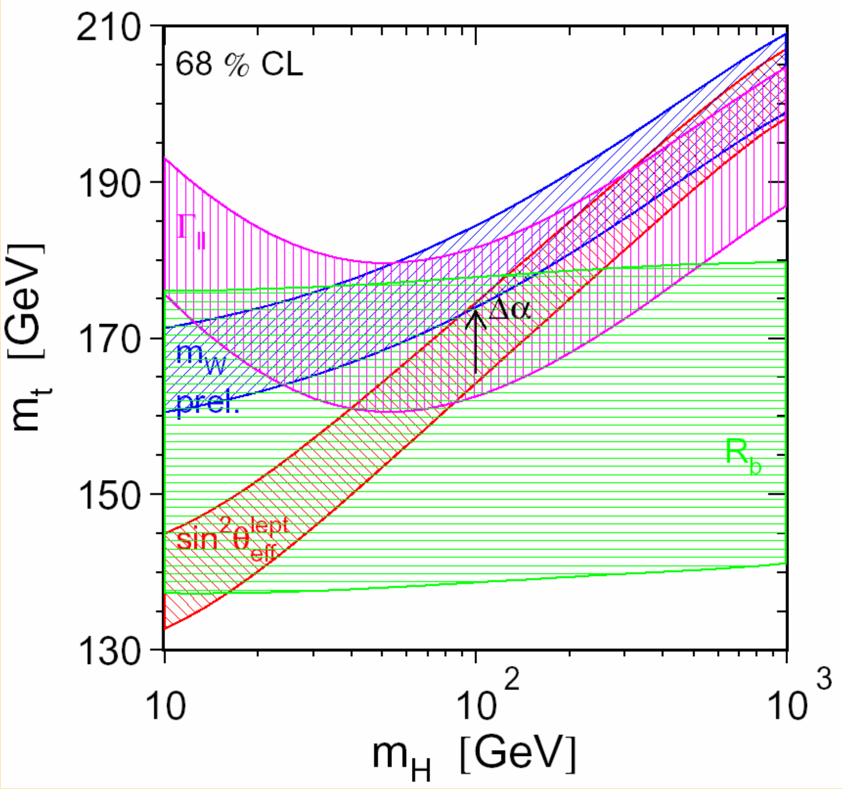
Clear preference for light Higgs, below 200 GeV

OVERALL, SM fares well
(does not include NuTeV, APV, g-2)



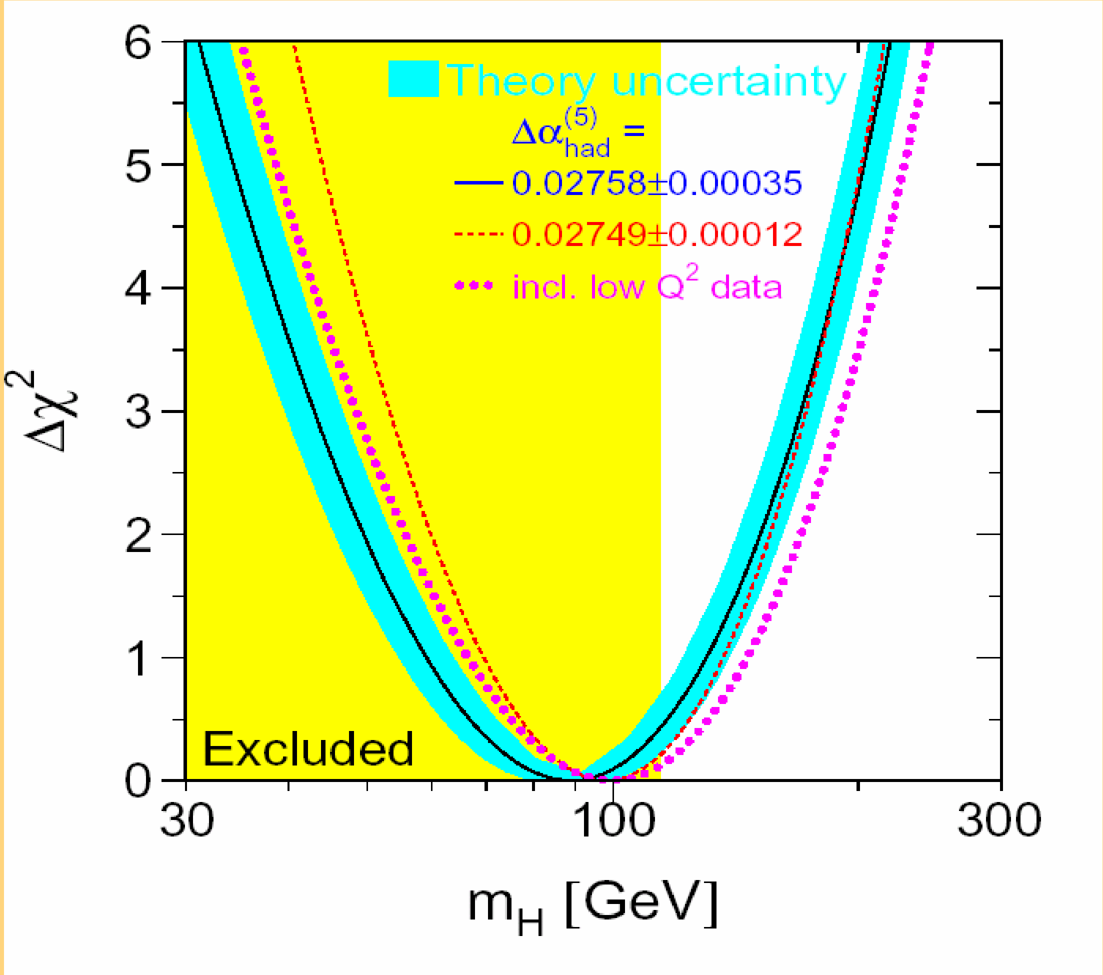
M_t-M_W and M_t-M_H correlations





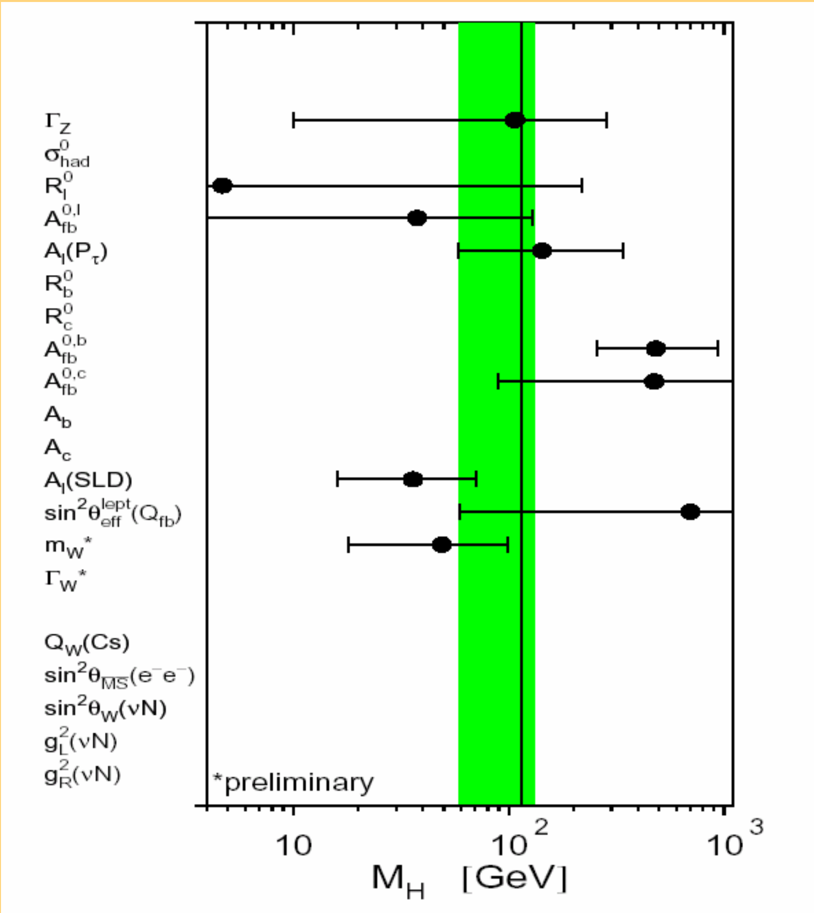
Constraining power of M_W and $\sin^2\theta_{eff}$ is similar at current precision ➔

The blue band



LEP-SLD EW Working Group

The M_H fit

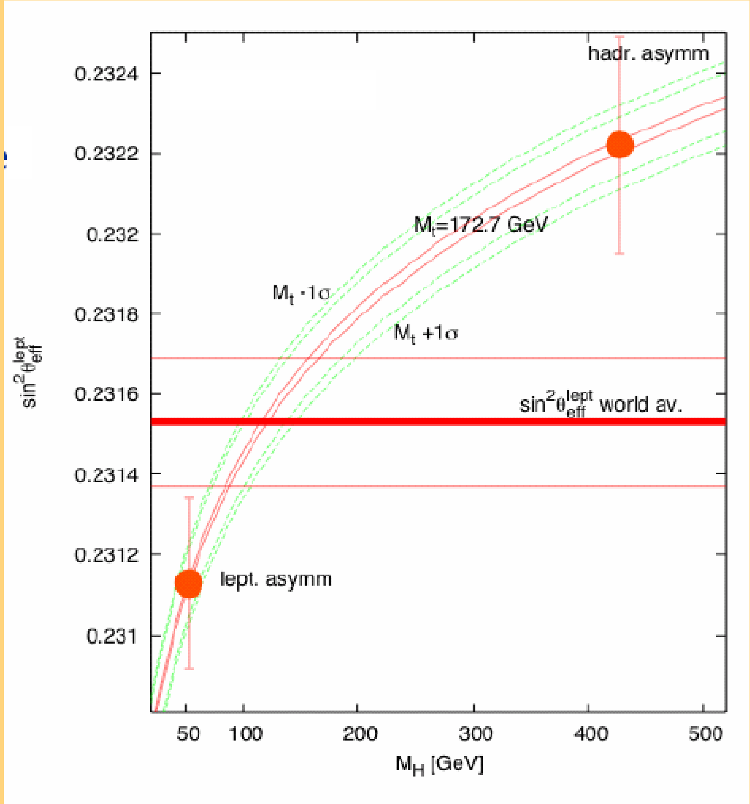


EWWG fits an arbitrary set
no $(g\text{-}2)_\mu$, no universality, no $b\rightarrow s\gamma$

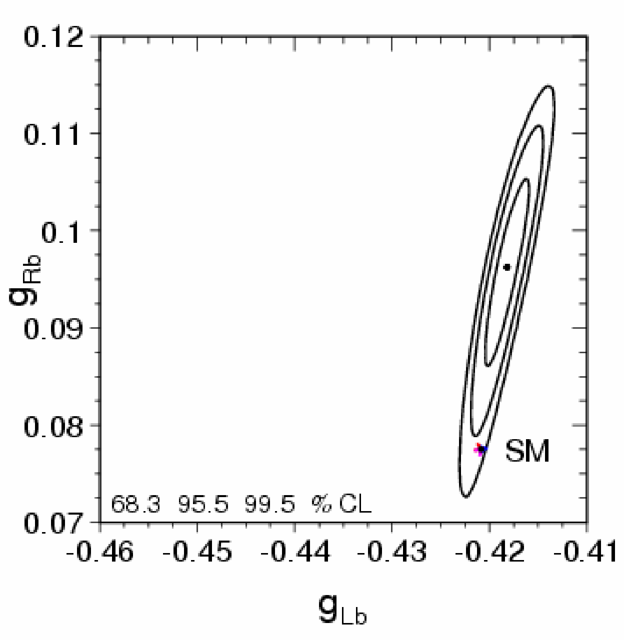
Only a subset of observables
is sensitive to M_H

A fit to only the observables sensitive to M_H has the **same central value** and **much LOWER probability O(1-2%)**

New physics in the b couplings?



Root of the problem: old ~3σ discrepancy between LR asymmetry of SLD and FB b asymmetry of LEP: in SM they measure the **same quantity, $\sin^2\theta^{eff}$** (A_b is practically fixed in SM)



Needs **tree level NEW Physics**
such that $|\delta g_R^b|>>|\delta g_L^b|$
Problematic and ad-hoc Choudhury et al, He-Valencia

The Chanowitz argument

2 possibilities, both involving new physics:

a) $A_{FB}(b)$ points to new physics

b) it's a fluctuation or is due to unknown systematics

without $A_{FB}(b)$, the M_H fit is very good, but in conflict with direct lower bound M_H>114.4 GeV

M_H^{fit}=51 GeV, M_H<110 GeV at 95%CL

Even worse if $\alpha(M_Z)$ from tau is used

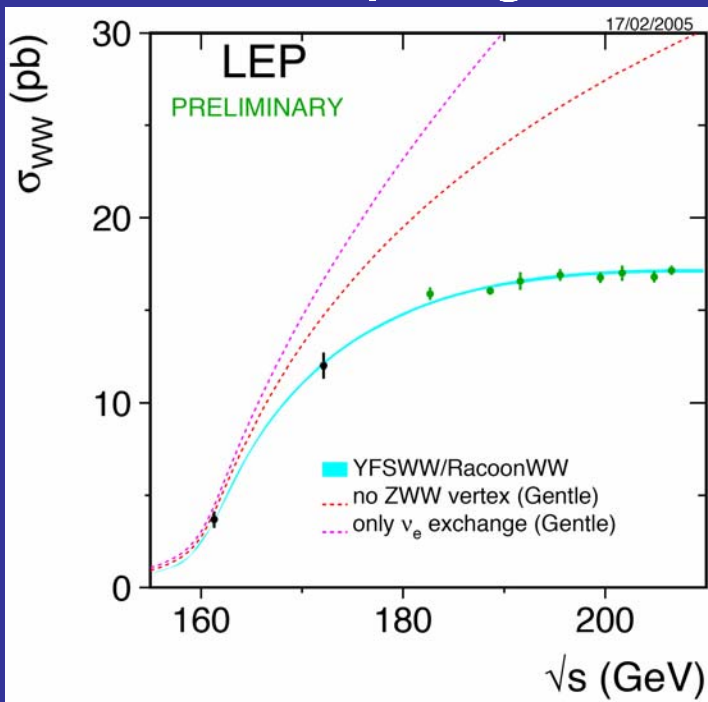
If true, not difficult to find NP that mimics a light Higgs.
Non-trivially, SUSY can do that with light sleptons, tanβ>4

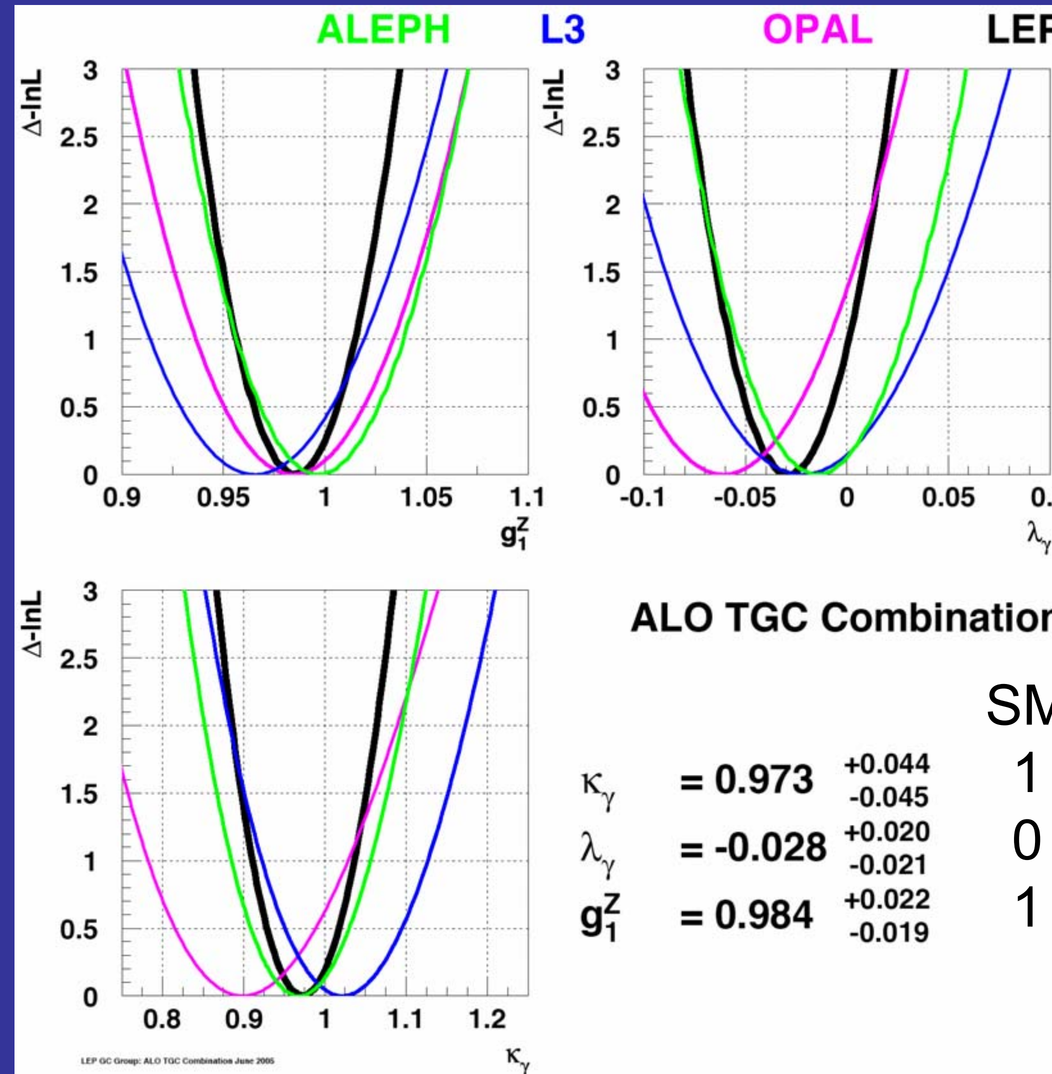
Altarelli et al

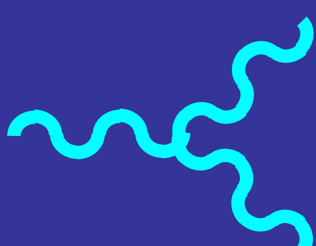
Statistically weak at the moment is 5% small enough?
Very sensitive to M_t

Other tests that do not enter the fit

Z W γ
self couplings



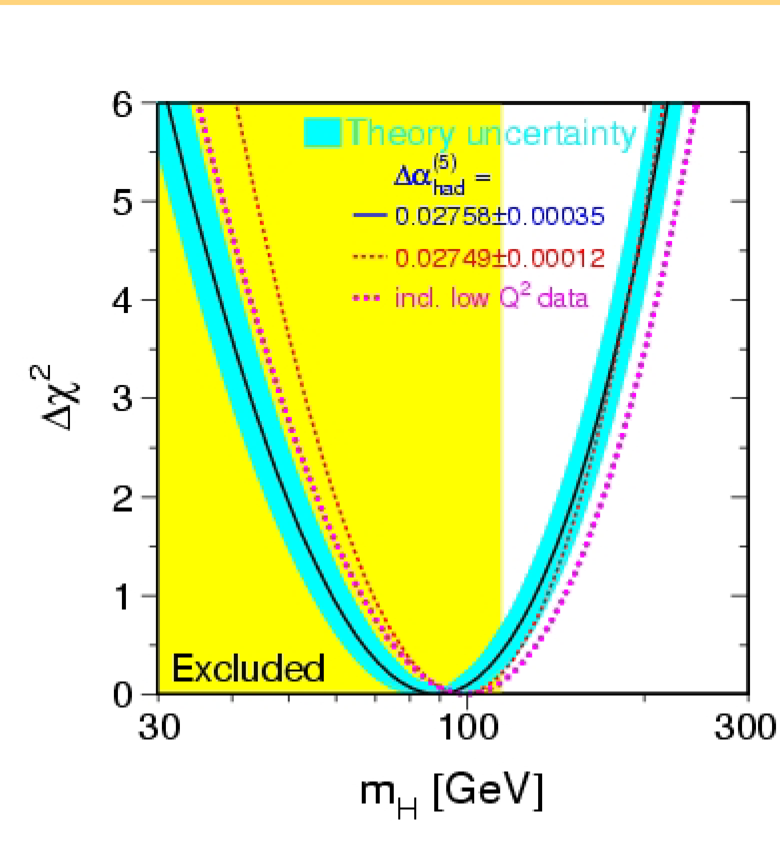




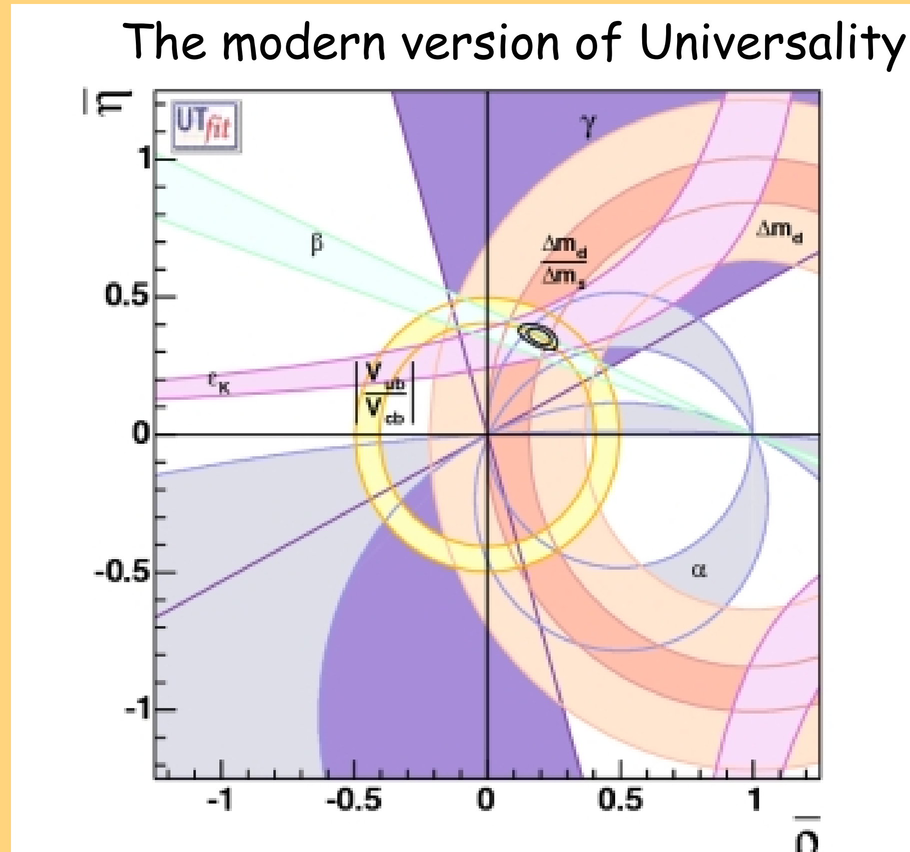
Based on WW cross section and angular distribution

Overview of precision tests

EWSB: $O(0.1\%)$, $\Lambda > 5$ TeV (roughly)



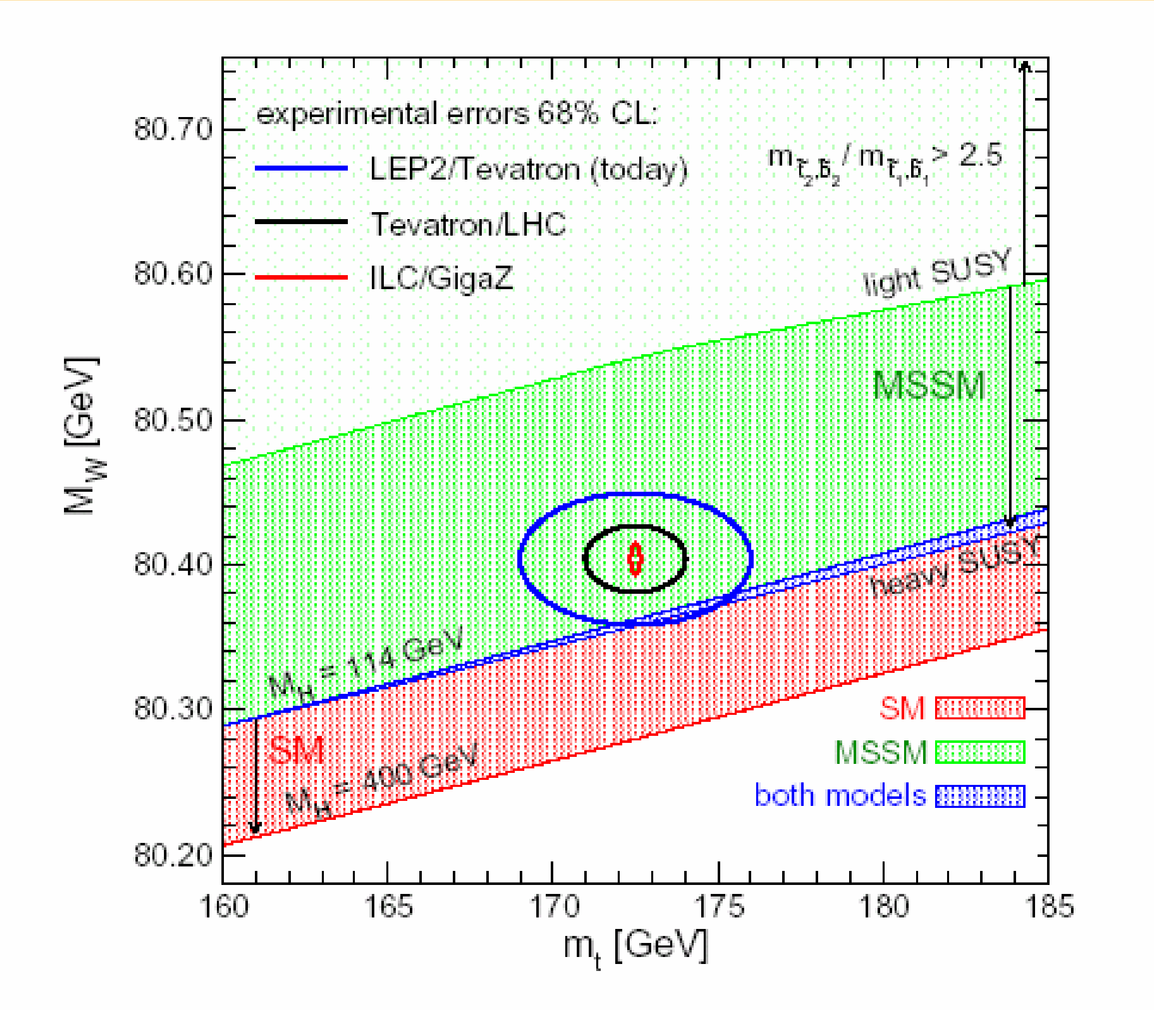
Flavor: $O(2\text{-}10\%)$, $\Lambda > 2$ TeV (roughly)



Electroweak physics at LHC

* determination of Higgs properties (mass, width, couplings even a rough measurement can distinguish between 2HDM and SM)
* **W mass** (goal 10 MeV) and width
* **top mass** (probably th limited) and couplings
* $\sin^2\theta_{eff}^{lept}$ from FB asymmetries
* WW,WZ,ZZ production (triple gauge couplings)
* Large EW effects (Sudakov logs)

Possible impact of LHC ew measurements



Summary

* The SM is a **beautiful and successful** theory built on solid ground. Appreciation of its limitations does not exclude admiration for the ingenuity that went into it.

* Gauge symmetry is verified with excellent accuracy. The SM mechanism of SSB will be **verified only by the Higgs discovery**, although most present indications point to a light Higgs boson in the SM framework. Higgs discovery or disproval remains the first task for LHC.

* Despite the lack of serious evidence, **new physics within the reach of LHC remains likely**: we have good th reasons for that. Yet, new physics must respect the precise experi-ments that agree with SM. Only delicate improvements on Higgs and flavor sectors seem plausible.

* New discoveries will have to be put in the context and ***interpreted***. That's why a strong program of precision EW physics is necessary.

The way to the future