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PRECISION TESTS OF THE ELECTROWEAK INTERACTIONS

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The status of the precision test of the ElectroWeak interactions is reviewed in this paper. Special emphasis is put on new results at low Q^2: the anomalous magnetic moment of the muon from E821 at Brookhaven and new measurements of $\sin^2\theta_{eff}$. The status of the measurements at high Q^2 is also reviewed, and the internal consistency of the Minimal Standard Model is discussed.

1. Introduction

In the context of the Minimal Standard Model (MSM), any Electroweak (EW) process can be computed at tree level from α (the fine structure constant measured at values of Q^2 close to zero), M_W (the W-boson mass), M_Z (the Z-boson mass), and V_{jk} (the Cabbibo-Kobayashi-Maskawa flavor-mixing matrix elements).

When higher order corrections are included, any observable can be predicted in the "on-shell" renormalization scheme as a function of:

$$O_i = f_i(\alpha, \alpha_s, M_W, M_Z, M_H, m_f, V_{jk})$$

and contrary to what happens with "exact gauge symmetry theories", like QED or QCD, the effects of heavy particles do not decouple. Therefore, the MSM predictions depend on the value of the top mass and to less extend to the value of the Higgs mass, or to any kind of "heavy new physics".

The subject of this letter is to show how the high precision achieved in the EW measurements allows testing the MSM beyond the tree level predictions and, therefore, how these measurements are able to indirectly determine the value of m_{top} and M_W, to constrain the unknown value of M_H, and at the same time to test the consistency between measurements and theory. At present the uncertainties in the theoretical predictions are dominated by the precision on the input parameters.

1.1. *Parameters of the MSM*

The W mass is one of the input parameters in the "on-shell" renormalization scheme.

It is known with a precision of about 0.04%, although the usual procedure is to take $G\mu$ (the Fermi constant measured in the muon decay) to predict M_W as a function of the rest of the input parameters and use this more precise value. Therefore, the input parameters are chosen to be the ones shown in Table 1.

Table 1 Values and uncertainties of the MSM input parameters

Input Parameters	Value	Relative Uncertainty
$\alpha^{-1}(M^2_Z) =$	128.936(46)	0.036%
$\alpha_s(M^2_Z) =$	0.118(2)	1.1%
$G\mu =$	$1.16637(1)\times10^{-5}$ GeV^{-2}	0.0009%
$M_Z =$	91.1875(21) GeV	0.0023%
$m_{top} =$	178.0(43) GeV	2.4%
$M_H >$	114 GeV @95 CL	-

Notice that the less well known parameters are m_{top}, α_s and, of course, the unknown value of M_H. The next less well known parameter is $\alpha^{-1}(M^2_Z)$, even though its value at $Q^2 \approx 0$ is known with an amazing relative precision of 3×10^{-9}, ($\alpha^{-1}(0) = 137.03599877(40)$). The reason for this loss of precision when one computes the running of α, is the large contribution from the light fermions loops to the photon vacuum polarization. The contribution from leptons and top quark loops is well known.

But for the light quarks non-perturbative QCD corrections are large at low energy scales. The method so far has been to use the measurement of the hadronic cross section through one-photon exchange, normalized to the point-like muon cross-section, R(s), and evaluate the dispersion integral:

$$\Delta\alpha_{hadron} = -\frac{\alpha}{3\pi}\int_{4m_\pi^2}^{\infty}\frac{m_Z^2 \, d\acute{s}}{\acute{s}\left[\acute{s}-m_Z^2\right]}\frac{\sigma(e^+e^-\to\gamma^*\to\overline{q}q)}{\sigma(e^+e^-\to\gamma^*\to\mu^+\mu^-)}$$

giving [1] $\Delta\alpha_{hadron} = 0.02761 \pm 0.00036$, the error being dominated by the experimental uncertainty in the cross section measurements.

Several new "*theory driven*" calculations have reduced this error, by extending the regime of applicability of Perturbative QCD (PQCD). These new calculations have been validated by the most recent data from BES II, CMD-2 and KLOE included in the evaluation in reference [1]. The most precise determination is $\Delta\alpha_{hadron} = 0.02747 \pm 0.00012$, from reference [2], which would be used for comparison. In any case, the inclusion in the analysis of the data collected at $\sqrt{s}\approx1$-7 GeV, in particular BES II measurements, has reduced the error such that $\Delta\alpha_{hadron}$ is not anymore the limiting factor in the predictions of the high Q^2 observables.

The situation, alas, is not the same for the prediction of the anomalous magnetic moment of the muon, where the typical scale is $Q^2\approx m_\mu^2$, and the relevant data is at $\sqrt{s} < 1$ GeV, in particular around the ρ resonance. It was suggested [3] to use tau decays and isospin symmetry to improve the uncertainty in this prediction. However, both data sets disagree significantly in the region above the ρ resonance, see Figure 1. The source of this disagreement is not understood, but the fact that the latest results from CMD-2 agree perfectly with the just released results from KLOE [4] using radiative events strongly suggest that the use of the tau data in the calculation of the running of α may be more difficult than anticipated. Therefore, the updated contributions to the anomalous magnetic moment of the muon are taken to be [5]:

a_μ (QED) $= (11658472.07\pm0.11)\times10^{-10}$

a_μ (Had,LO)	=	$(693.4\pm6.4)\times10^{-10}$
a_μ (Had,HO)	=	$(-10.0\pm0.6)\times10^{-10}$
a_μ (Had,LBL)	=	$(12.0\pm3.5)\times10^{-10}$
a_μ (Weak)	=	$(15.4\pm0.3)\times10^{-10}$

giving a total contribution of

$a_\mu = (11659182.8\pm7.3)\times 10^{-10}$.

The uncertainty is dominated by the experimental errors in the determination of the hadronic contribution at $\sqrt{s}< 1$GeV. More experimental data in this energy region will help to clarify the situation.
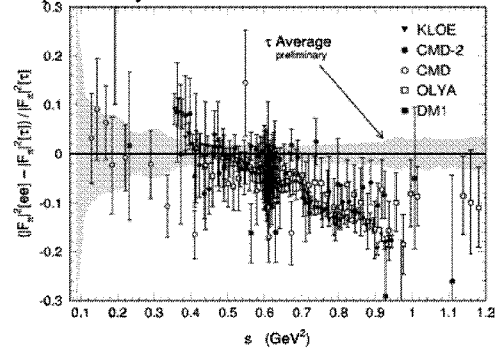

Figure 1 Comparison of the pion form factor calculated using e^+e^- data and tau decays as a function of Q^2.

2. Tests of the Electroweak Interactions at low Q^2

2.1. *Anomalous magnetic moment: g_μ-2*

In the presence of an electro-magnetic field the spin of the muon precess relative to the muon momentum according to

$$\vec{\omega}_a=\vec{\omega}_s-\vec{\omega}_c = \frac{e}{m_\mu c}\left[a_\mu\vec{B}-\left(a_\mu-\frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E}\right]$$

Here ω_s and ω_c are the angular frequencies of spin rotation and momentum rotation (or cyclotron angular frequency), respectively. In the absence of electric field (E), only two quantities need to be measured to determine the anomalous magnetic moment of the muon: ω_a and B. However, in order to minimize the dependence of a given muon's precession rate

on its exact trajectory in the storage ring, the E821 collaboration follows the previous CERN approach of using a quadrupole electrostatic field to provide focusing. Fortunately, at the "magic" γ=29.3, or p_μ = 3.094 GeV, the dependence on the electric field (E) cancels out, so the E821 experiment chose to run exactly at this "magic" energy.

The B-field in the storage region was mapped by the E821 collaboration every three to four days with 17 NMR probes mounted transversely on a movable cable-driven trolley. A relative precision of ~0.4 ppm was achieved in the determination of the B field.

The number of electrons (positrons) from muons (antimuons) decays has energies in the range 0 to 3.1 GeV. In the muon rest frame the higher energy electrons are preferentially emitted parallel to the direction of the spin of the muon. Hence, when the muon spin is parallel to the muon momentum, there will be more high energy muons in the lab frame than when the direction is anti-parallel. The number of electrons (positrons) in the lab frame above a given energy threshold versus time therefore oscillates at the precession frequency ω_a.

The E821 experiment at Brookhaven released in 2004 the new results using a sample of four billion μ^- decays. The result [6],

$$a\mu^- = (11659214 \pm 6(\text{stat}) \pm 5(\text{syst}))\times 10^{-10}$$

compares very well with their previous result using a sample of more than 5 billion μ^+,

$$a\mu^+ = (11659203 \pm 6(\text{stat}) \pm 5(\text{syst}))\times 10^{-10}.$$

The average of the two results,

$$a\mu = (11659208 \pm 5(\text{stat}) \pm 4(\text{syst}))\times 10^{-10}$$

is shown in Figure 2 and compared with the updated theoretical prediction discussed in the previous section. The inclusion of the μ^- data collected in the year 2001 has increased the significance of the discrepancy from 1.9σ to 2.7σ.
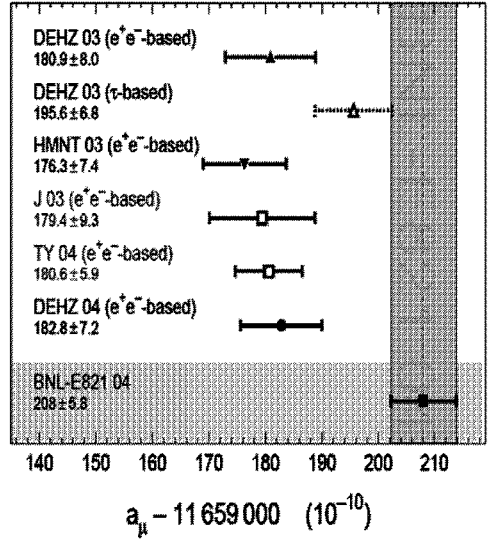

Figure 2 Comparison between different theoretical predictions of the anomalous magnetic moment of the muon, and the experimental measurement from E821

2.2. $Sin^2\theta_{eff}$ at low Q^2

We can define $\sin^2\theta_W$ in the on-shell renormalization scheme in terms of the ratio of the W and Z on-shell mass measured experimentally as,

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

Radiative corrections modify this relation. It is convenient to define the effective $\sin^2\theta_{eff}$ as $\kappa(Q^2)\sin^2\theta_W$. The function $\kappa(Q^2)$ depends on the value of Q^2 at which the measurements are performed. For instance, $\kappa(m_Z^2)\approx1.04$, while at very low Q^2, $\kappa(0)\approx1.07$, as it can be seen in Figure 3. The main contribution is again the running of α discussed in the previous sections. The contribution from pure Weak radiative corrections is only at the per mile level. Nevertheless, it is interesting to measure $\sin^2\theta_{eff}$ at different Q^2 values as new physics of the type of Z', contact interactions, etc... will modify this relation at the Born level.

2.2.1. *Moller scattering (E158):*

The E158 collaboration at SLAC has used 50GeV polarized electrons (up to 80% polarization) scattered of atomic electrons to measure the angular distribution of the outgoing electrons. Comparing both polarizations they can determine as a function of the polar angle (θ), the Left-Right asymmetry, which is given by:

$$A_{ee} = mE \frac{\rho G_F}{\sqrt{2}\pi\alpha} \frac{16\sin^2\theta}{(3+\cos^2\theta)^2} \left(\frac{1}{4} - \kappa(Q^2)\sin^2\theta_W \right) + \dots$$

Their measurement using all data accumulated during the three running periods of the experiment is compared in Figure 3 with the expected value, and corresponds to [7]:

$\sin^2\theta_{eff}(Q^2 \approx 0.026 \text{GeV}^2) = 0.2403 \pm 0.0010(\text{stat.}) \pm 0.0009(\text{syst.})$

2.2.2. *Neutrino-Nucleon scattering (NuTeV):*

In the same Figure 3 the result from the NuTeV collaboration at Fermilab is also shown. They have measured the ratio of neutral to charged currents in neutrino (antineutrino) scattering with nucleons. The results have been known for a while to disagree with the SM predictions:

$$R^\nu = \frac{\sigma(\nu N \to \nu X)}{\sigma(\nu N \to \mu^- X)} = 0.3916 \pm 0.0007 \pm 0.0011$$

$$R^{\bar{\nu}} = \frac{\sigma(\bar{\nu} N \to \bar{\nu} X)}{\sigma(\bar{\nu} N \to \mu^+ X)} = 0.4050 \pm 0.0016 \pm 0.0022$$

while the SM predictions are 0.3950 (-2.6σ) for neutrinos and 0.4066 (-0.6σ) for antineutrinos. The NuTeV collaboration exploits the Paschos-Wolfenstein relation between these two quantities to extract the value of $\sin^2\theta_W$ with reduced systematic uncertainties:

$\sin^2\theta_W = 0.2276 \pm 0.0013(\text{stat.}) \pm 0.0008(\text{syst.})$

which is 2.8σ away from the SM prediction, $\sin^2\theta_W = 0.2229$. However, several authors have pointed out several sources of uncertainties that

have been neglected in the extraction of $\sin^2\theta_W$. An updated calculation of the EW corrections needed to interpret these ratios in terms of $\sin^2\theta_W$ indicates that the NuTeV central value could move by about 1σ. Similarly, the asymmetry of the strange sea contents of the nucleon, which has been neglected in the NuTeV analysis, could also change the value significantly. Last, but not least, the difference between the u-quark density in the proton compared with the d-quark density in the neutron, assumed to cancel out in the NuTeV analysis, may change the value by about 1σ [8]. Hence, it is clear to me that before a careful re-assessment of all theoretical uncertainties by the NuTeV collaboration, the 2.8σ discrepancy with the SM cannot be taken at face value. The good news presented at this conference is that the NOMAD collaboration at CERN is performing an analysis with their already recorded neutrino data, and a preliminary study shows similar sensitivity than NuTeV using only neutrinos [9]. As has been show before, most of the discrepancy is coming from the NuTeV neutrino data; hence an independent cross-check of the systematic uncertainties is more than welcome.
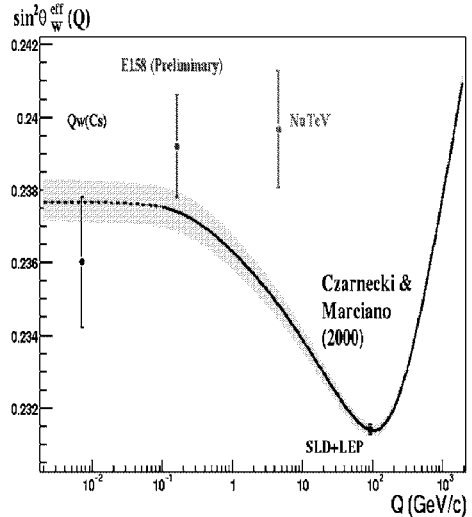

Figure 3 Expected dependence of $\sin^2\theta_{eff}$ on Q^2, compared with the experimental determinations from E158 and NuTeV.

3. Tests of the Electroweak Interactions at high Q^2

Large statistics of Z and W bosons have been collected at e^+e^- colliders, hadron colliders and lepton-hadron colliders during the last ten to twenty years. LEP has collected about 20 million of Zs, and about 40k Ws. Since 2001, the RUN II at TeVatron has accumulated around 400 pb^{-1}, corresponding to about 200k Z's and about 2 million W's decaying into leptons. Also, HERA II has started collecting data; more than 20 pb^{-1} of polarized positron-hadron collisions have been recorded, allowing testing the dependence with the polarization of the charged and neutral currents [10].

3.1. *Z/W boson production*

The Weak Vector Boson production in all these environments has been found to be in agreement with the MSM predictions. In particular, new results from the RUN II at TeVatron allow testing the production of Z and W bosons in hadronic collisions at unprecedented levels, O(0.1pb) [11].

3.2. *Z couplings to fermions*

The data collected at e^+e^- colliders, LEP and SLC has allowed a precise determination of the couplings of fermions to the Z boson. The ratio of the vector and axial lepton couplings is just a function of $\sin^2\theta_{eff} = \frac{1}{4}$ $(1-g^l_V/g^l_A)$. All the asymmetries measured at LEP and SLC are just a measurement of this ratio, or more precisely a measurement of the parameter:

$$A_f \equiv \frac{2\left(\dfrac{g^f_V}{g^f_A}\right)}{1+\left(\dfrac{g^f_V}{g^f_A}\right)^2}$$

Combining all the leptonic asymmetries measured at LEP and SLC gives, $A_l = 0.1501\pm0.0016$, with a $\chi^2/dof=1.6/2$, which corresponds to a measurement of $\sin^2\theta_{eff} = 0.23113\pm0.00021$. Similarly, one can obtain the ratio of lepton couplings from asymmetries involving b-quarks and c-quarks in the final state, because they are proportional to A_e, as the initial state are electrons and positrons. Combining the forward-backward asymmetries measured with b and c-quarks gives, $\sin^2\theta_{eff} = 0.23213\pm0.00029$. The two determinations of $\sin^2\theta_{eff}$ differ by 2.8σ [12]. This is the most significant discrepancy of the many tests of the EW interactions at high Q^2. While the leptonic asymmetries would prefer a very low value of the Higgs mass, as can be seen in Figure 4, the quark-asymmetries would prefer a large value. As will be seen in the forthcoming sections, all the rest of measurements at high Q^2 would prefer a low value of the Higgs mass.
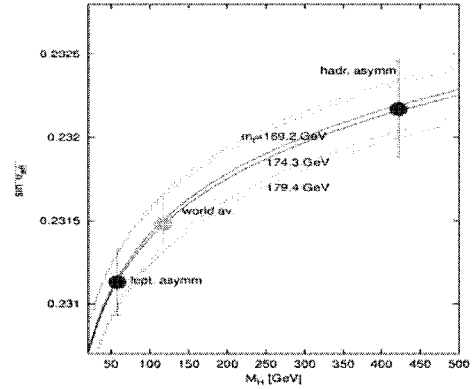

Figure 4 Comparison of the measured values of $\sin^2\theta_{eff}$ using leptonic and hadronic asymmetries with the MSM prediction as a function of the Higgs mass.

3.3. *W decays and mass*

Since 1996 up to 2000 LEP has been running at energies above the W-pair production threshold and about 40k W-pairs have been detected by the LEP experiments.

The cross-section for the process $e^+ e^- \rightarrow W^+ W^-$ has been measured with a precision of 1%. The theoretical calculations have been updated to match with this precision, confirming the indirect evidence for Gauge Boson Couplings predicted by the MSM [13].

More interesting in the context of this talk, is the improvement on the W mass accuracy, previously measured in hadronic collisions.

3.3.4. W mass at hadron colliders

At hadron colliders, the W mass is obtained from the distribution of the W transverse mass, which is the invariant mass of the W decay products evaluated in the plane transverse to the beam. This is because the longitudinal component of the neutrino momentum cannot be measured in a hadron collider. On the other hand, the transverse momentum of the neutrino can be deduced from the vector sum of the transverse momentum of the charged lepton and the transverse momentum of the system recoiling against the W.

The uncertainty on the W mass is dominated by the uncertainty in the lepton energy/momentum calibration. The combination of the measurements at FERMILAB (CDF/D0), and CERN (UA2) gives: $M_W = 80.454 \pm 0.059$ GeV, where the error is dominated by the systematic uncertainty (50 MeV) [14].

3.3.5. W mass at LEP

The W-pair production cross-section near the threshold has a strong dependence on the W mass. The first data collected at LEP just above threshold has been used to get a measurement of the W mass: $M_W = 80.40 \pm 0.22$ GeV.

But the most precise measurement of the W mass comes from the kinematical reconstruction of the W decay products at LEP. The precise knowledge of the c.o.m. energy is used to improve the experimental resolutions. The W mass is extracted from a comparison between data and Monte Carlo simulation for different values of the W mass giving [15]: $M_W = 80.447 \pm 0.042$ GeV.

The measurement is dominated by systematic uncertainties (30 MeV). The main systematic uncertainty is due to the hadronization model (18 MeV) and to the knowledge of the

LEP c.o.m. energy (17 MeV) which affects both channels in a coherent way: 4q channel where both W's decay into quarks, and 2q channel when one of the W's decay into a lepton and a neutrino.

There are other systematic sources related to the hadronization model that only affect the 4q channel. In particular, the separation of the decay vertices is about 0.1 fm, which is small compared with the typical hadronization scale of 1 fm. This fact may lead to non-perturbative phenomena interconnecting the decays of the two W's and introducing a source of systematic uncertainties in the measurement.
The study of the particle flow distribution in the region between jets from different
W's in the same event tends to favor models with a small fraction of Colour Reconnection (CR). From these studies a maximum shift of 100 MeV is quoted in the 4q channel from CR. Similarly, the study of the 4-momentum difference (Q) between like-sign particles coming from different W's in the same event tends to favor models without Bose-Einstein correlations (BE), predicting shifts smaller than 15 MeV on the W mass.

The most promising strategy to reduce these uncertainties is to modify the jet clustering algorithm to dismiss the information from those particles in the region between the two W's. The four LEP experiments are following similar approaches and the small lost in statistical precision is more than compensated by the reduction in the CR systematic uncertainty [15].

However, these new results are not yet available from the LEP collaborations. Hence, the world average value for the W mass is still, $M_W = 80.425 \pm 0.034$ GeV.

One can compare the measured value with the indirect prediction using the values of $\cos\theta_W$ and M_Z: $M_W = M_Z \cos\theta_W$. Using the value of $\cos\theta_W$ measured by the leptonic asymmetries gives, $M_W = 80.414 \pm 0.026$ GeV in perfect agreement with the direct measurement. Using the value of $\cos\theta_W$ measured by the hadronic asymmetries gives, $M_W = 80.290 \pm 0.042$ GeV

which is about 2.5σ away from the direct measurement.

3.4. *Top quark mass*

As it will become clear in section 4.2 the most important limitation in the indirect determination of the Higgs mass from the MSM fit is the precision on the Top quark mass.

Recently, the D0 collaboration at TeVatron has reevaluated their RUN I measurement using a much more detailed event-by-event likelihood [16].

The new measurement has a smaller statistical uncertainty (5.2 GeV is reduced to 3.6 GeV), and more relevant for the combination with CDF, has reduced the systematic uncertainties (4.9 GeV to 3.9 GeV). As the systematic uncertainties between CDF and D0 are strongly correlated, and the combined measurement is dominated by systematic uncertainties, the more precise measurement of D0 translates into a new combination with CDF:

m_{top} = 178.0 ± 2.7 ± 3.3 GeV, improving the previous precision on m_{top} from 5.1 GeV down to 4.3 GeV. Incidentally, the most probable value for m_{top} has shifted upwards by 4 GeV, which due to the strong correlation with $\log(M_H)$, about 70%, corresponds to an upward shift of about 20 GeV in the most probable value of M_H.

4.   Consistency with the Standard

The MSM predictions are computed using the programs TOPAZ0[17] and ZFITTER[18]. They represent the state-of-the-art in the computation of radiative corrections, and incorporate recent calculations such as the QED radiator function to $O(\alpha^3)$, four-loop QCD effects, non-factorisable QCD-EW corrections, and two-loop corrections, resulting in a significantly reduced theoretical uncertainty compared to the work summarized in reference[19].

4.1. *Are we sensitive to radiative corrections other than Δα?*

This is the most natural question to ask if one pretends to test the MSM as a Quantum Field Theory and to extract information on the only unknown parameter in the MSM, M_H.

The MSM prediction of R_b neglecting radiative corrections is R^0_b=0.2183, while the measured value, R_b = 0.21646±0.00065, is about 2.8σ lower. The MSM prediction depends only on m_{top} and allows determining indirectly it's mass to be m_{top} =155±20 GeV, in agreement with the direct measurement (m_{top}=178.0±4.3GeV). This indirect determination of m_{top} can be seen in Figure 5.

The measurement of the leptonic width disagrees with the prediction without weak corrections by about 4.7σ, showing evidence for radiative corrections in the ρ parameter, Δρ = 0.005±0.001. The most sensitive measurement to the unknown M_H is $\sin^2\theta_{eff}$. Surprisingly, the difference between the MSM prediction corrected by Δα and the measurement only disagrees by 1.7σ, showing no clear evidence for pure weak radiative corrections. This is because in the MSM there is a strong cancellation between the contribution from m_{top} and M_H.

However, the most striking evidence for pure weak radiative corrections is not coming from Z^0 physics, but from M_W and its relation with G_μ. The value measured at LEP and TEVATRON is M_W =80.425±0.034 GeV. From this measurement and through the relation

$$m_W^2 \sin^2(\theta_W) = \frac{\pi\alpha}{\sqrt{2}G_\mu}(1 + \Delta r)$$

one gets a measurement of Δr = 0.034± 0.002, and subtracting the value of Δα, given in section 1.1, one obtains Δr_W = Δr-Δα = -0.023±0.002, which is about 12σ different from zero.

In Figure 5 one can see the indirect determination of m_{top} and M_H for these four sets

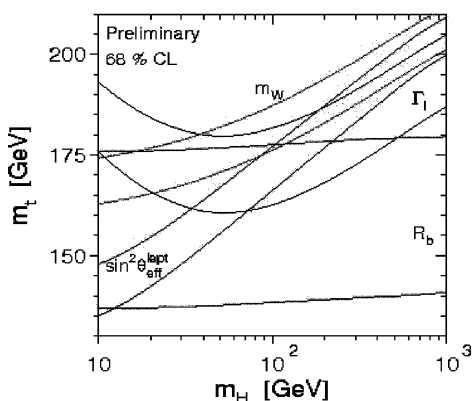of measurements sensitive to weak radiative corrections.

Figure 5 Indirect determination of the Top and Higgs mass from the four set of measurements described in the text: W mass, leptonic Z width, $\sin^2\theta_{eff}$ and Rb.

4.2 Fit to the MSM predictions

Having shown that there is sensitivity to pure weak corrections with the accuracy in the measurements achieved so far, one can envisage fitting the values of the unknown Higgs mass and the less well known top mass in the context of the MSM predictions.

The fit is done using the measurements at high Q^2 described in section 3 and the results are [20]

$m_{top} = 178.2 \pm 3.9$ GeV

$\log(M_H/\text{GeV}) = 2.06 \pm 0.21$

$\quad (M_H = 114^{+69}_{-45}$ GeV$)$

$\alpha_s = 0.1186 \pm 0.0027$

with a $\chi^2/\text{dof} = 15.8/13$. The χ^2 distribution is shown in Figure 6 and the distribution of the pulls of each measurement is shown in Figure 7.
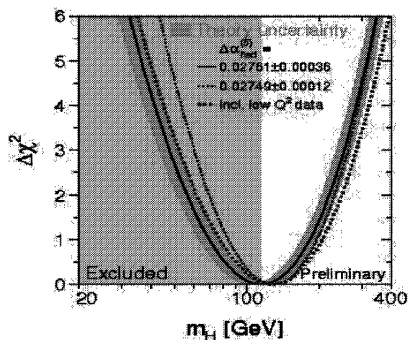

Figure 6 $\Delta\chi^2$ of the MSM fit as a function of the Higgs mass.

Taking into account the theoretical uncertainties (about ±0.05 in $\log(M_H/\text{GeV})$), implies a one-sided 95% C.L. limit of: $M_H < 260$ GeV which does not take into account the limits from direct searches, $M_H > 114.1$ GeV @95 C.L.

As it is shown in Figure 5, one can divide the measurements sensitive to the Higgs mass into three different groups: Asymmetries ($\Delta\kappa$), Widths ($\Delta\rho$) and the W mass (Δr). They test conceptually different components of the radiative corrections and it is interesting to check the internal consistency. Given the discrepancies between hadronic and leptonic measurements of the Z^0 asymmetries, it is instructive to quote separate results for the asymmetries.

Repeating the MSM fit shown in the previous section for the three different groups of measurements with the additional constraint: $\alpha_s = 0.118 \pm 0.002$, gives the results shown in Figure 8.

The indirect determination of M_H from the Z^0 lineshape, from the leptonic asymmetries and from the W mass are in amazing agreement, and prefer a very low value of the Higgs mass. Only the hadronic asymmetries, somehow, contradict this tendency.

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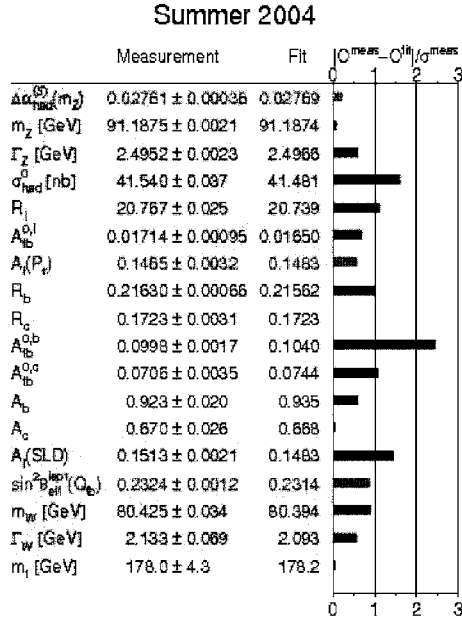|	Measurement	Fit	$|O^{meas}-O^{fit}|/\sigma^{meas}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02769	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4966	
σ_{had}^0 [nb]	41.540 ± 0.037	41.481	
R_l	20.767 ± 0.025	20.739	
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01650	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1483	
R_b	0.21630 ± 0.00066	0.21562	
R_c	0.1723 ± 0.0031	0.1723	
$A_{fb}^{0,b}$	0.0998 ± 0.0017	0.1040	
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0744	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.026	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1483	
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.425 ± 0.034	80.394	
Γ_W [GeV]	2.133 ± 0.069	2.093	
m_t [GeV]	178.0 ± 4.3	178.2	

Figure 7 Pulls of the individual measurements with respect to the best MSM fit.

In table 2 it is shown the different contributions to the uncertainty in $\log(M_H/\text{GeV})$. It is clear that any future improvement on the indirect determination of the Higgs mass needs a more precise determination of the Top mass.

Table 2 Contributions to the uncertainty of $\log(M_H/\text{GeV})$.

	$[\Delta\log(m_H)]^2$		$[\Delta exp]^2+[\Delta mt]^2+[\Delta\alpha]^2+[\Delta\alpha_s]^2$
$\text{Sin}^2\theta_{eff}$	$[0.22]^2$	$=$	$[0.15]^2+[0.12]^2+[0.10]^2+[0.01]^2$
All meas.	$[0.21]^2$	$=$	$[0.12]^2+[0.13]^2+[0.10]^2+[0.04]^2$

5. Outlook and Conclusions.

The MSM of the ElectroWeak interactions describes all the precision measurements up to the 0.1% level. The precision is such that pure Weak radiative corrections are needed, and are able to constraint indirectly the values of the Top and Higgs masses:

$m_{top} = 178.2 \pm 3.9$ GeV
$M_H = 114^{+69}_{-45}$ GeV
($M_H < 260$ GeV @95%C.L.)
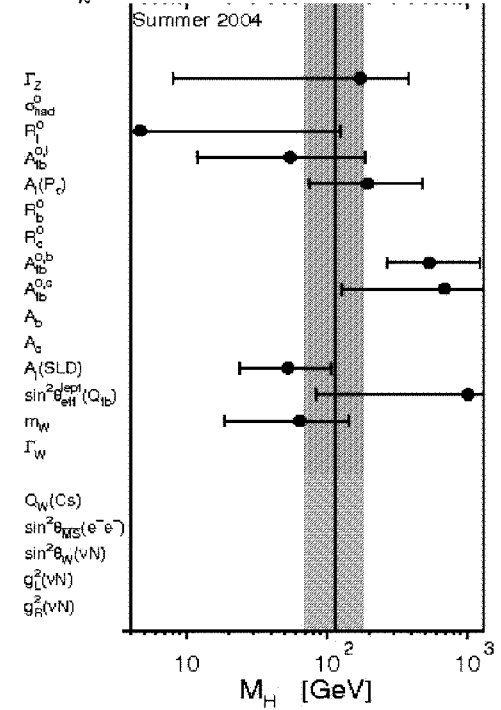with a $\chi^2/\text{dof}=16/13$.

Figure 8 Individual indirect determinations of the Higgs mass.

Any significant improvement on this indirect determination of M_H, needs a significant improvement on the measurement of m_{top}.

The largest contribution to the χ^2 is A_{FB}^b with a 2.4σ contribution. It pulls for a large value of M_H in opposition to the rest of the measurements: leptonic asymmetries, W mass and leptonic Z width.

The biggest discrepancy with the MSM fit is on the interpretation of the ratio of Neutral and Charged Currents measured at NuTeV as a determination of $\sin^2\theta_{eff}$. However this interpretation depends on theoretical uncertainties that must be reevaluated, before the 3σ discrepancy can be taken at face value.

In my opinion, the biggest challenge to the supremacy of the MSM describing the EW processes (leaving aside neutrino oscillations), is the deviation observed in the measurement of the anomalous magnetic moment of the muon:

$$a\mu \ (Exp) = (11659208 \pm 6 \ ) \times 10^{-10}$$
$$a\mu(\ Th) = (11659183 \pm 7 \ ) \times 10^{-10}$$

which is 2.7σ away from theory. The theoretical prediction is now much more robust, even though the discrepancy when using tau decays is not really understood.

The medium-term future in our field is bright. The precision EW measurements tells us that something has to happen at energy scales of $O(1\text{TeV})$. It may be a light Higgs boson, it maybe SUSY, or it may even be something else, but the energy scale is determined by the precision measurements at LEP, SLC and TeVatron.

Acknowledgments

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