

THE TOP PRIORITY: PRECISION ELECTROWEAK PHYSICS FROM LOW TO HIGH ENERGY

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Overall, the Standard Model describes electroweak precision data rather well. There are however a few areas of tension (charged current universality, NuTeV , $(g-2)_\mu$, b quark asymmetries), which I review emphasizing recent theoretical and experimental progress. I also discuss what precision data tell us about the Higgs boson and new physics scenarios. In this context, the role of a precise measurement of the top mass is crucial.

Precision electroweak physics lies at the intersection of many specialized fields and involves experiments performed at hugely different energies. In testing the consistency between all data within the Standard Model (SM) framework, we hope to uncover signs of physics beyond the SM. However, as we will see, the main problem is the precision of the theoretical predictions with which we confront the experimental data. Almost invariably, long-distance hadronic interactions enter the game, so we often take great pains to try to make sense of extremely precise experiments.

In the following I will try to summarize the main recent progress in the field, concentrating on the unsettled questions. For some of the topics I will not have space to cover, see the References.^{1,2}

1. Parity Violation in Møller Scattering

Let us start from low-energy experiments. The E158 experiment at SLAC³ has measured for the first time parity violation (PV) in polarized Møller (e^-e^-) scattering. The PV asymmetry $A_{LR} = (\sigma_L - \sigma_R)/(\sigma_L + \sigma_R)$ is extremely small in the SM, $\approx 10^{-7}$, due to an extra suppression factor $1/4 - \sin^2\theta_W$. It can be measured at SLAC thanks to the huge luminosity and the high polarization of the beam. A_{LR} is very sensitive to $\sin^2\theta_W$ and the goal of E158 is to measure it with 8% precision, equivalent to an error of 0.001 on $\sin^2\theta_W$. Such a precision is not competitive with LEP and SLD determinations, but one should keep in mind that a low-energy measurement would test completely different radiative corrections, and would be sensitive to new physics complementary or orthogonal to collider experiments.

E158 is currently performing a last and third

run and expect to be able to reach the aimed precision. The preliminary result of Run I (at $Q^2 = 0.027 \text{ GeV}^2$),

$$A_{LR} = [151.9 \pm 29.0(\text{stat}) \pm 32.5(\text{syst})] \times 10^{-9},$$

translates into $\sin^2\hat{\theta}_W^{\overline{\text{MS}}}(M_Z) = 0.2296 \pm 0.0038$, in good agreement with the global average, $\sin^2\hat{\theta}_W^{\overline{\text{MS}}}(M_Z) = 0.2312 \pm 0.0003$. Radiative corrections⁴ reduce A_{LR} by about 40%. A large theoretical uncertainty comes from the $\gamma - Z$ hadronic vacuum polarization, which cannot be computed perturbatively. The current estimate, inducing $\approx 5\%$ error on A_{LR} , can and should be updated in view of E158's final result, expected next year.

2. Universality of Charged Currents

This is a very old subject.⁵ Universality in the leptonic sector is verified at the 0.2% level.⁶ Charged currents in the quark sector, on the other hand, involve also the CKM matrix elements. One can however test accurately the unitarity relation

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1. \quad (1)$$

Since the last term on the lhs is $O(10^{-5})$, the test concerns the consistency of Cabibbo angle measurements from V_{ud} and V_{us} .

The most precise method to measure V_{ud} is to use Superaligned Fermi Transitions, i.e. $0^- \rightarrow 0^-$ nuclear β decays. There are several experiments in good agreement, yielding $\delta V_{ud} \sim 0.0005$. Neutron β decay is also becoming competitive: the present $\delta V_{ud} \sim 0.0013$ will be improved at PERKEO⁷. A promising mode is pion decay, currently at $\delta V_{ud} \sim 0.005$, which is theoretically cleaner and will soon be improved by PIBETA⁸. The consistent picture that

emerges from these experiments can be expressed, using Eq. (1), as

$$|V_{us}|(\text{unitarity}) = 0.2269 \pm 0.0021. \quad (2)$$

The most precise direct measurement of $|V_{us}|$ is given on the other hand by $K \rightarrow \pi \ell \nu$ decays ($K_{\ell 3}$). Here the experimental situation is not as consistent as for V_{ud} : the recent E865 result for K^+ decays disagrees with a series of old experiments by more than 2σ . While the E865 result agrees well with the unitarity prediction, Eq. (2), the older results and a recent preliminary K^0 measurement by KLOE all yield a smaller Cabibbo angle. Upcoming analyses from KLOE, NA48, and KTeV should tell us whether grossly underestimated isospin breaking corrections are the cause of this situation, or there is an experimental problem. Averaging the old published data only, one obtains

$$|V_{us}|_{K_{\ell 3}} = 0.2201 \pm 0.0024,$$

but the result changes little if one includes also E865 and KLOE results. Alternative promising strategies to extract $|V_{us}|$ are provided by τ and hyperon decays. In particular, measurements of the τ spectral functions at the B factories will make the first method competitive with $K_{\ell 3}$, while the use of hyperon decays requires a careful assessment of SU(3) breaking effects, which could be helped by lattice simulations.

In summary, a puzzling violation of unitarity persists at the level of $\sim 2\sigma$, despite new data. Fortunately, upcoming experimental results are likely to shed light on this problem. For a more detailed discussion, see elsewhere.⁹

3. The NuTeV Electroweak Result

NuTeV measures ratios of Neutral (NC) to Charged Current (CC) cross sections in νN DIS.¹⁰ Ideally, in the parton model with only one generation of quarks and an isoscalar target

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

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

where $r \equiv \frac{\sigma(\bar{\nu} N \rightarrow \bar{\mu} X)}{\sigma(\nu N \rightarrow \mu X)}$ and $g_{L,R}^2$ are average effective left- and right-handed ν -quark couplings. The actual experimental ratios $R_{\nu,\bar{\nu}}^{exp}$ differ from $R_{\nu,\bar{\nu}}$ because

of ν_e contamination, experimental cuts, NC/CC misidentification, the presence of second generation quarks, the non-isoscalarity of steel target, QCD and electroweak corrections, etc.. In the NuTeV analysis, a Monte Carlo including most of these effects relates $R_{\nu,\bar{\nu}}^{exp}$ to $R_{\nu,\bar{\nu}}$. It is useful to note that most uncertainties and $O(\alpha_s)$ effects drop out in the Paschos-Wolfenstein (PW) ratio¹¹

$$R_{PW} \equiv \frac{R_\nu - r R_{\bar{\nu}}}{1 - r} = \frac{\sigma(\nu N \rightarrow \nu X) - \sigma(\bar{\nu} N \rightarrow \bar{\nu} X)}{\sigma(\nu N \rightarrow \ell X) - \sigma(\bar{\nu} N \rightarrow \bar{\ell} X)}$$

which equals $g_L^2 - g_R^2 = \frac{1}{2} - \sin^2 \theta_W$ and therefore could provide a clean measurement of $\sin^2 \theta_W$, if experimentally accessible. NuTeV do not measure R_{PW} directly, but, using the fact that $R_{\bar{\nu}}$ is almost insensitive to $\sin^2 \theta_W$, they extract from it the main hadronic uncertainty, an effective charm mass. The weak mixing angle is then obtained from R_ν . In practice, NuTeV fit for m_c^{eff} and $\sin^2 \theta_W$. This procedure certainly approximates a measurement of R_{PW} , but it is not clear to what extent exactly.

The NuTeV result provides a test of the on-shell $s_W^2 \equiv 1 - M_W^2/M_Z^2$ definition of $\sin^2 \theta_W$:

$$s_W^2(\text{NuTeV}) = 0.2276 \pm 0.0013 \pm 0.0006 \pm 0.0006, \quad (3)$$

where the three errors are statistical, systematic and theoretical respectively. Because of accidental cancellations, the choice of the on-shell scheme implies very small top and Higgs mass dependences in Eq. (3). The above value must be compared to the result of the global fit, $s_W^2 = 0.2229 \pm 0.0004$, which is 2.8σ away.

NuTeV works at Leading Order (LO) in QCD in the context of a *cross section model* which effectively introduces some Next-to-Leading-Order (NLO) improvement. They use LO PDF's self-consistently fitted in the experiment, with little external input. There are a number of theoretical systematics which could have been underestimated in Eq. (3), and considerable work has been devoted to study the most obvious among them.

- i) *Uncertainties in the parton distribution functions* (PDF's): neglecting for the moment asymmetric sea contributions (see later) they are small in R_{PW} with the cuts used.^{12,13}
- ii) *NLO QCD corrections*:¹³⁻¹⁵ vanish in R_{PW} , and effects introduced by asymmetric cuts and differences in the $\nu, \bar{\nu}$ energy spectra seem small.

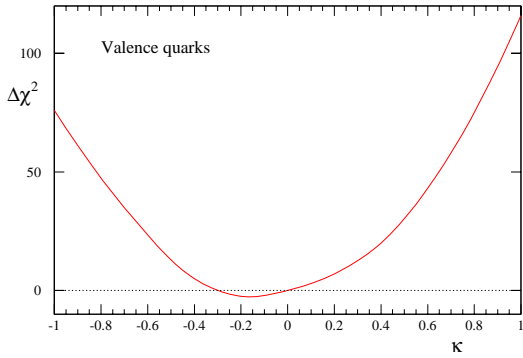


Figure 1. MRST fit of isospin violation in valence PDF's.

Again, this refers to the ideal observable R_{PW} . Only a complete NLO analysis can ensure that the same conclusions apply to the NuTeV fit. For instance, the phenomenological cross section model used by NuTeV may distort in an important way cancellations among QCD corrections.¹⁵ Estimating the actual effect on s_W^2 would require refitting the PDF's at NLO. In summary, the analysis needs to be consistently upgraded to NLO, and the NuTeV collaboration is investigating this possibility.

iii) *Electroweak corrections* (mainly photonic): the NuTeV analysis is largely based on very old code, which needs to be checked against recently developed tools.¹⁶

3.1. Asymmetric Sea

I have so far used the assumptions, generally made in the extraction of PDF's from the data, of isospin symmetry and of a symmetric strange and charm sea ($s = \bar{s}$, $c = \bar{c}$). If we drop these assumptions, the PW relation is explicitly violated by new terms¹²

$$R_{PW} = \frac{1}{2} - s_W^2 + \frac{\tilde{g}^2}{Q^-} (u^- - d^- + c^- - s^-), \quad (4)$$

where q^- is the asymmetry in the momentum carried by the quark species q in an isoscalar target, $q^- = \int_0^1 x [q(x) - \bar{q}(x)] dx$, $\tilde{g}^2 \approx 0.23$ a coupling factor, and $Q^- = (u^- + d^-)/2 \approx 0.18$. The non-isoscalarity of the target gives a contribution to $u^- - d^-$ that is obviously taken into account by NuTeV, although the uncertainty on this correction seems to have been somewhat underestimated.¹⁷ There are, however, less

standard and potentially more dangerous contributions: there is no reason in QCD to expect $s^- = 0$, and for an isoscalar target $u^- - d^-$ is of the order of the isospin violation. Eq. (4) tells us that even quite small values of these two asymmetries could change significantly the value of s_W^2 measured by NuTeV.^a

A violation of isospin of the form $u_p(x) \neq d_n(x)$ would induce a u^- different from d^- even in an isoscalar target and affect the PW relation according to Eq. (4). A rough estimate for its size is $(m_u - m_d)/\Lambda_{QCD} \approx 1\%$. This could explain a fraction of the anomaly – about a third, according to Eq. (4). Isospin violation is very weakly constrained by experiment, as demonstrated by a new MRST analysis.¹⁸ MRST have performed a global fit to the PDF's deforming the valence distributions by a contribution proportional to a function, $f(x)$, with zero first moment: $u_n^-(x) = d_p^-(x) + \kappa f(x)$ and $d_n^-(x) = u_p^-(x) - \kappa f(x)$. The fit to κ , shown in Fig. 1, gives a mild indication for a negative κ , but with very large uncertainty (MRST use $\Delta\chi^2 = 50$ to define a 90% CL). The central value $\kappa \approx -0.2$ corresponds to a reduction of the NuTeV anomaly by about a third, and has the expected order of magnitude. Amusingly, the MRST central value leads to a shift in s_W^2 very close to that of a recent analysis in the context of nucleon models.¹⁹ Using similar models, NuTeV claim a much smaller isospin breaking shift.²⁰ In any case, it is clear that model calculations,²¹ though sometimes useful to understand the size of an effect, cannot be relied upon for a precision measurement. We are therefore left with a substantial uncertainty unaccounted for in Eq. (3).

What do we know about the strange quark asymmetry? An asymmetry s^- of the sign needed to explain NuTeV can be induced non-perturbatively (*intrinsic strange*) by fluctuations of the kind $p \leftrightarrow \Lambda K^+$.²² Unfortunately, the strange quark sea is mainly constrained by (mostly old) νN DIS data, which are usually not included in standard PDF's fits. In fact, MRST and CTEQ use an *ansatz* $s = \bar{s} = (\bar{u} + \bar{d})/4$. Barone *et al.* (BPZ)²³ reanalyzed, a few years ago, a host of νN DIS together with ℓN and Drell-Yan data at NLO. Allowing for a strange asymmetry improved the BPZ best fit drastically and could explain a large fraction of the NuTeV discrepancy.

^aThese effects are somewhat diluted in the actual NuTeV analysis compared to the direct use of Eq. (4),²⁰ precisely because NuTeV differs from a measurement of R_{PW} .

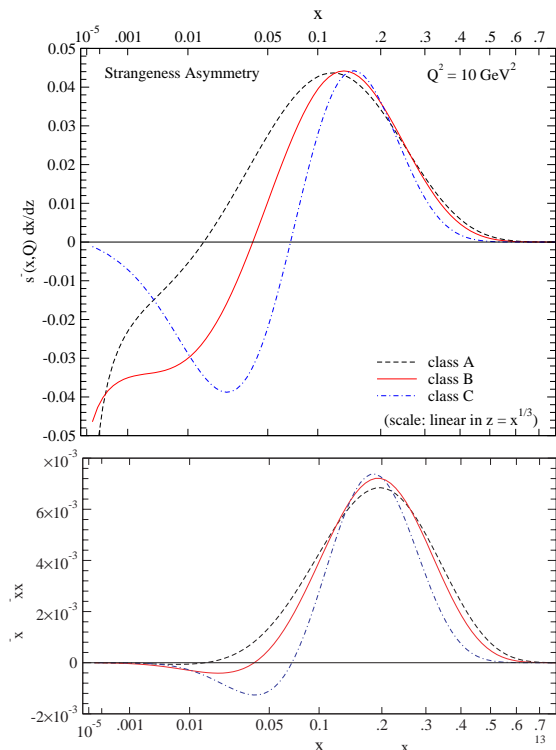


Figure 2. CTEQ fit of the strangeness asymmetry using different low- x behaviors.

ancy. The result, $s^- \approx 0.0018 \pm 0.0005$, was compatible with theory estimates²² and was driven by cross section measurements by CDHSW (νN) and BCDMS (μp). The BPZ analysis was recently updated with the inclusion of CCFR cross sections, leading to a quite different result, $s^- \approx 0.0002 \pm 0.0004$.

The inclusive analysis pioneered by BPZ should however be supplemented by data on dimuon events (tagged charm production), a rather sensitive probe of the strange sea. The most precise dimuon data come from the CCFR/NuTeV Collaboration,²⁴ which has analyzed them at LO with the specific aim of constraining the strange asymmetry. Their result, $s^- = -0.0027 \pm 0.0013$, would *increase* the anomaly to 3.7σ ,²⁰ but it suffers from various shortcomings, detailed in the note added to S. Davidson *et al.*¹² and elsewhere.²⁵ The main problem is in the parameterization, which does not satisfy the condition

$$\int_0^1 dx [s(x) - \bar{s}(x)] = 0 \quad (5)$$

that ensures zero strangeness quantum number for the nucleon. As the dimuon data are concentrated at $x < 0.3$, the evidence for a small negative strange

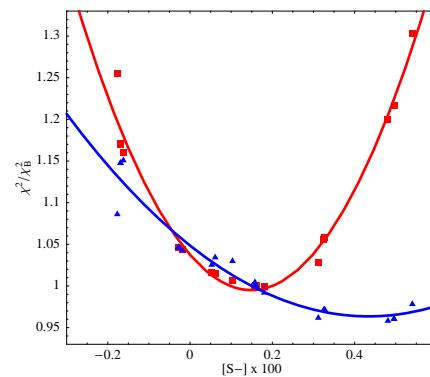


Figure 3. CTEQ fit of the strange momentum asymmetry s^- .

asymmetry at low x would imply, if the condition given by Eq. (5) is imposed, a *positive* asymmetry at large x , and hence a *positive* momentum asymmetry. This is illustrated in Fig. 2,²⁵ which shows strange asymmetries with the above qualitative features but different shapes. The NuTeV analysis of dimuon data is not reliable.

A dedicated global fit that employed both inclusive and dimuon data in a consistent way was therefore necessary. The CTEQ Collaboration has presented at this conference the preliminary results of one such analysis.²⁵ The inclusion of the CCFR-NuTeV dimuon data in the CTEQ global fit is presently done using NuTeV software developed at LO in QCD. Dimuon data are therefore included at LO, which should not influence the main qualitative conclusions. CTEQ explored the full range of parameterizations of $s(x) - \bar{s}(x)$ that satisfy Eq. (5), studying for instance different low- x behavior, as shown in Fig. 2. They perform a new global fit to all PDF's using all available inclusive and dimuon data, although they do not reanalyze old νN data in detail, as was done by BPZ. The preliminary result of the s^- fit is shown in Fig. 3 for the best performing (class B) parameterization. While inclusive data alone show only a mild preference for a positive s^- , the dimuon data have real discriminating power. The central value of the global class B fit is $s^- \approx 0.002$, and corresponds to the indicated line in Fig. 2. In general, all acceptable fits have central values $0.001 < s^- < 0.003$. Negative s^- are disfavored, but $s^- = 0$ cannot be excluded. CTEQ estimate that the likely impact on the NuTeV s_W^2 extraction would be a reduction of s_W^2 by 0.0012 to 0.0037. Note that if a strange asymmetry shifted s_W^2 by 0.002 ± 0.002 , the NuTeV result would

be at 1σ from the SM. Although a more detailed study is under way with the active participation of the NuTeV Collaboration, two firm conclusions are that: *i*) the strange asymmetry is a strong candidate to explain part or most of the NuTeV anomaly; and *ii*) one cannot avoid the related, substantial uncertainty.

Given the present understanding of hadron structure, R_{pW} does not seem to be a good place for high precision electroweak physics. In fact, the relevant momentum asymmetries in the quark sea induce an error in the extraction of s_W^2 of the same order as the experimental error. Improved analyses of dimuon data would certainly constrain s^- better, and data from CHORUS might also be useful – if not for measuring s_W^2 , at least for constraining the sea asymmetries.²⁶ Useful input could also come from associated charm- W production at the Tevatron and RHIC. In the long term, a precise $s(x), \bar{s}(x)$ determination will be possible at a neutrino factory.²⁷

I should also mention that several attempts at explaining the NuTeV anomaly with nuclear effects like nuclear shadowing have been made,²⁸ but no convincing case has so far been presented.

3.2. New Physics vs NuTeV

A new physics explanation of the NuTeV anomaly requires a ~ 1 -2% effect, and naturally calls for tree level physics. It is very difficult to build realistic models that satisfy all present experimental constraints and explain a large fraction of the anomaly.¹²

In particular, Supersymmetry, with or without R-parity, cannot help, because it is strongly constrained by other precision measurements (often at the 10^{-3} level) and by direct searches.^{12,29} The same is generally true of models inducing only oblique corrections or only anomalous Z couplings.¹² Realistic and well-motivated examples of the latter are models with ν_R mixing.^{12,30} Models with ν_R mixing *and* oblique corrections have been considered by W. Loinaz *et al.*³¹ and found to fit well all data including NuTeV.^b However finding sensible new physics that provides oblique corrections in the pre-

^bCan the necessary oblique corrections be provided by a heavy SM Higgs boson? No, the only way to obtain an acceptable fit with a preference for both ν mixing and a heavy Higgs is to exclude M_W from the data.³¹ However, solving the NuTeV anomaly at the expense of the very precise measurement of M_W is hardly an improvement.

ferred range is far from obvious.

On the other hand, the required new physics can be parameterized by a contact interaction of the form $[\bar{L}_2\gamma_\mu L_2][\bar{Q}_1\gamma_\mu Q_1]$. This operator might be induced by different kinds of short-distance physics. Leptoquarks generally also induce another operator which over-contributes to $\pi \rightarrow \mu\bar{\nu}_\mu$, or have the wrong sign, but SU(2) triplet leptoquarks with non-degenerate masses could fit NuTeV, albeit not very naturally. Another possible new physics contribution inducing the above contact interactions is an unmixed Z' boson. It could be either light ($2 \lesssim M_{Z'} \lesssim 10$ GeV) and super-weakly coupled, or heavy ($M_{Z'} \gtrsim 600$ GeV). The Z' must have very small mixing with the Z^0 because of the bounds on oblique parameters and on the anomalous Z couplings^{12,32} (see E. Ma and D. P. Roy³³ for an explicit $L_\mu - L_\tau$ model and R. S. Chivukula and E. H. Simmons³⁴ for technicolor models).

4. The Ups and Downs of $(g - 2)_\mu$

The anomalous magnetic moment of the muon is an excellent place to look for new physics: it probes unexplored loop effects proportional to m_μ^2/Λ^2 , where Λ is the mass scale characteristic of the new physics. Given the present experimental resolution, in order for us to observe large deviations from the SM, the new physics we need must have a chiral enhancement, of the kind naturally emerging in Supersymmetric models with large $\tan\beta$. Conversely, no deviation from the SM would impose severe constraints on these models. This is at the origin of the great attention this observable has recently received.

The last few years have seen a dramatic progress in the measurement of a_μ , driven by the $g - 2$ experiment at Brookhaven. The present world average

$$a_\mu(\text{w.a.}) = 11659203(8) \times 10^{-10}$$

is dominated by their latest μ^+ result³⁵, released in 2002. The results of the 2001 Run, performed with μ^- , should reduce the error by $\sim 30\%$ and are expected soon.

Figure 4 summarizes the evolution of the measurement and of the theoretical estimates of a_μ . As you will see in a moment, the theoretical prediction of this quantity depends heavily on other experimental results, so the ups and downs are mostly due to the evolution of data and to the corrections of some

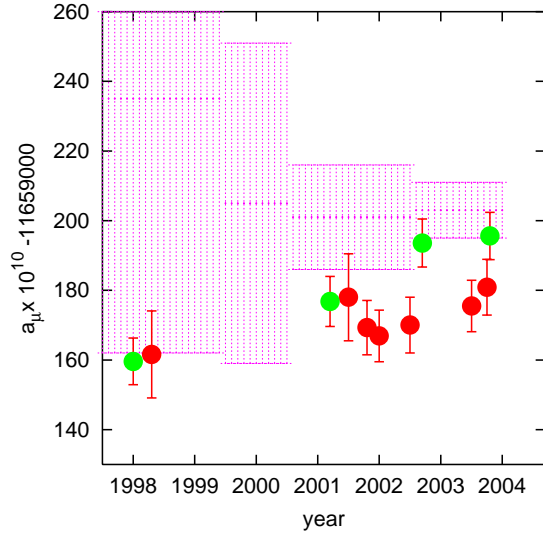


Figure 4. Historical evolution of the measurement and prediction of a_μ . The lighter (green) dots represent estimates based also on τ decay data. The compilation of theoretical estimates is not complete.

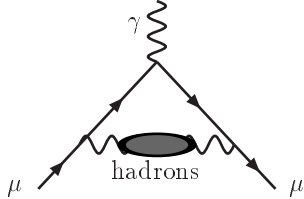


Figure 5. Lowest order vacuum polarization insertion.

unfortunate mistakes.

While most of us have computed the lowest-order QED contribution to a_μ at graduate school, a calculation of a_μ at the current level of precision is a very involved and sophisticated enterprise (there are excellent reviews,³⁶ with references to the original literature). Here I will concentrate only on the general aspects and on recent developments. The various contributions to a_μ , listed with their estimated errors, are:

$$\begin{aligned}
 a_\mu &= 11\,658\,470.35(28) \times 10^{-10} \text{ (QED)} \\
 &+ 694(7) \times 10^{-10} \text{ (had, Leading Order)} \\
 &- 10.0(6) \times 10^{-10} \text{ (had, Higher Order)} \quad (6) \\
 &+ 8(4) \times 10^{-10} \text{ (had, Light by Light)} \\
 &+ 15.4(2) \times 10^{-10} \text{ (EW)}
 \end{aligned}$$

The main component comes from QED without hadronic loops. The four-loop contribution³⁷ is not so small, $\sim 40 \times 10^{-10}$, and has never been checked. But these heroic calculations at least can be done.

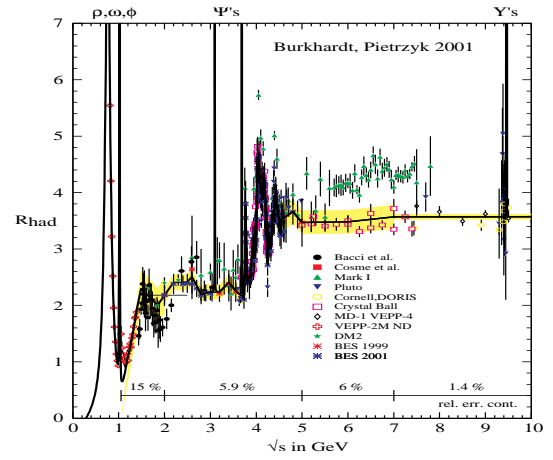


Figure 6. The spectral function.

Not so for the hadronic contributions: hadronic loops enter the second order diagram of Fig. 5 and are characterized by the scale $\Lambda_{QCD} \approx 300$ MeV. They provide the largest uncertainty to the determination of a_μ . As the energy scale is too low to employ perturbative methods, the usual route is to use a dispersive integral of the vector spectral function,

$$a_\mu^{\text{LO, had}} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} R_{\text{had}}(s) K(s) ds \quad (7)$$

where the spectral function $R_{\text{had}}(s)$ is measured from the total hadronic cross section in e^+e^- collisions. A number of experiments have contributed to its measurement, most recently CMD-2, SND, and BES, leading to the situation summarized in Fig. 6. Different strategies are also available to combine the data and their errors – see the References^{38–41} for the most recent and complete analyses. Because of the weight function $K(s)$, the integral given by Eq. (7) is dominated by the low energy region, and in particular by the ρ resonance in the $\pi\pi$ channel. Indeed, the pion form factor (see Fig. 7) alone contributes more than 70% of $a_\mu^{\text{LO, had}}$. The recent CMD-2 reanalysis⁴² of their very precise $\pi\pi$ data, with a revised treatment of QED corrections, is therefore of the utmost importance. It is included in the following updated estimates:^{39–41}

$$\begin{aligned}
 a_\mu^{\text{LO, had}}(\text{HMNT}) &= (691.8 \pm 5.8_{\text{exp}} \pm 2.0_{\text{r.c.}}) \times 10^{-10} \\
 a_\mu^{\text{LO, had}}(\text{DEHZ}) &= (696.3 \pm 6.2_{\text{exp}} \pm 3.6_{\text{r.c.}}) \times 10^{-10} \\
 a_\mu^{\text{LO, had}}(\text{GJ}) &= (694.8 \pm 8.6) \times 10^{-10} \quad (8)
 \end{aligned}$$

where the r.c. error is mostly due to uncertainty in correcting old data for missing radiative corrections.

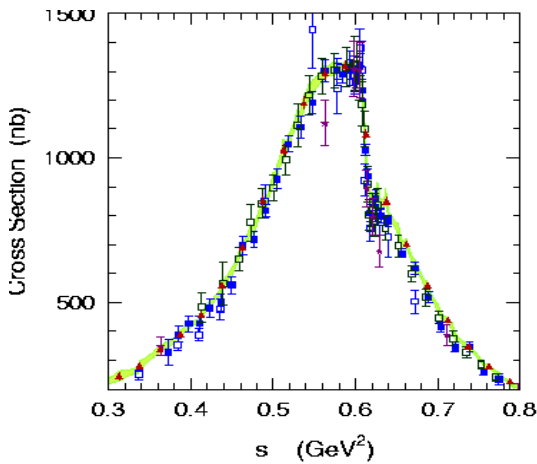
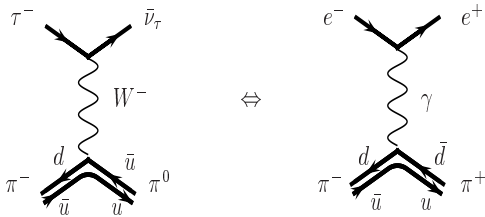


Figure 7. The pion form factor.

Adding all other SM contributions, this translates into a 1.9-2.5 σ discrepancy between SM prediction and experiment.

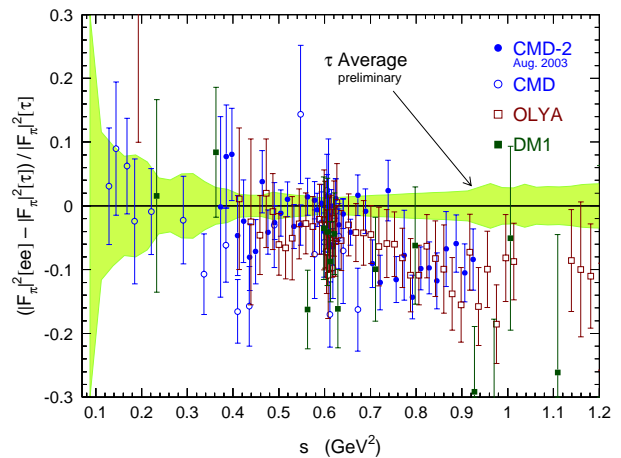
A second way of measuring the spectral function in the crucial region below 1.8 GeV consists of relating the τ hadronic decays to the e^+e^- hadronic cross section using CVC and isospin symmetry, as schematically illustrated in Fig. 8. This method has

Figure 8. The diagrams relating τ hadronic decays to the e^+e^- hadronic cross section.

been explored by M. Davier⁴⁰ *et al.* with data from Aleph, CLEO, and Opal. A series of corrections have been implemented⁴³, leading to

$$a_{\mu}^{\text{LO, had}}(\text{DEHZ}, \tau) = (709.0 \pm 5.1_{\text{exp}} \pm 1.2_{\text{r.c.}} \pm 2.8_{\text{SU}(2)})$$

where the last uncertainty refers to the isospin corrections. This determination is competitive with e^+e^- and leads to a prediction of a_{μ} in much better agreement with experiment (0.7 σ). Figure 9 from M. Davier⁴⁰ *et al.* shows a comparison of the spectral function extracted from e^+e^- and τ data: although the CMD2 revision has much improved the situation below 850 MeV, there is still a discrepancy between 0.85 and 1 GeV. The problem could be in the data

Figure 9. Comparison of the spectral function extracted from τ decay and e^+e^- data (relative difference).

or in the theoretical framework. While a recent paper advocates the second possibility,^{41,44} hinting at underestimated isospin breaking, an important check of the CMD2 e^+e^- results has come from the first results of a third method to measure the spectral function, the radiative return.

The idea behind radiative return is that a photon radiated off the initial e^+ or e^- (ISR) reduces the effective energy of the collision, see Fig. 10. Provided

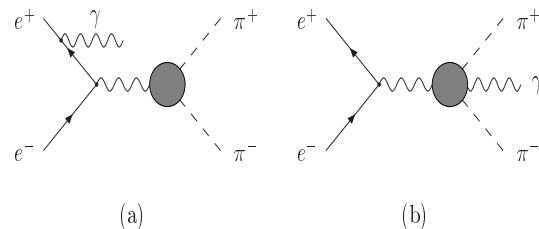


Figure 10. Examples of ISR and FSR.

the photon momentum is measured, a fixed energy collider can investigate a whole q^2 range, with obvious advantages over the energy scan experiments. The large luminosities at DAΦNE and at the B -factories compensate the radiative suppression. The potential pollution from FSR at low-energy (see Fig. 10(b)) is circumvented by kinematic cuts. Radiative corrections⁴⁵ play a crucial role here, as they do anyway in the energy scan case. KLOE has announced⁴⁶ the first preliminary results of radiative return: the contribution of the two pions chan-

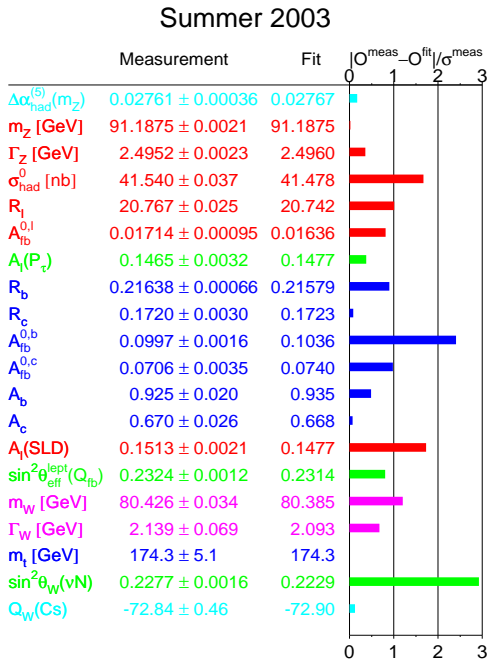


Figure 11. Pulls in the summer 2003 fit by the LEP Electroweak Working Group.

nel to $a_\mu^{\text{LO,hadr}}$ in the range $0.37 < q^2 < 0.93 \text{ GeV}^2$ is, in units 10^{-10} , $378.4 \pm 0.8_{\text{stat}} \pm 4.5_{\text{syst}} \pm 2.6_{\text{th}} \pm 3.8_{\text{FSR}}$, to be compared with the *new* CMD2 result $378.6 \pm 2.6_{\text{stat}} \pm 2.2_{\text{syst\&th}}$. KLOE agrees well with CMD2. The systematic error will soon be further reduced. Radiative return analyses are also expected from Babar, Belle and CLEO-c.

5. The SM Fit and the Higgs Boson Mass

The latest compilation of electroweak data of the LEP Electroweak Working Group¹ is shown in Fig. 11, where the data are compared with the results of a global fit. The main changes with respect to last year are: a revised (lower) M_W value from Aleph, that draws the world average down by 0.5σ , to $M_W(w.a.) = 80.426 \pm 0.034 \text{ GeV}$ and improves the consistency of the global fit; small shifts in the heavy flavor observables; and a new value of atomic PV, due to revised (and hopefully converging) theoretical calculations. The value for M_t , $174.3 \pm 5.1 \text{ GeV}$, is the old one, and does not include the new D0 analysis.⁴⁷ Also the value of $\alpha(M_Z)$, from the conservative estimate,⁴⁸ has not yet been updated to reflect the new CMD2 data, a rather small effect anyway (the new value is $\Delta\alpha_{\text{had}} = 0.02768 \pm 0.00036$).

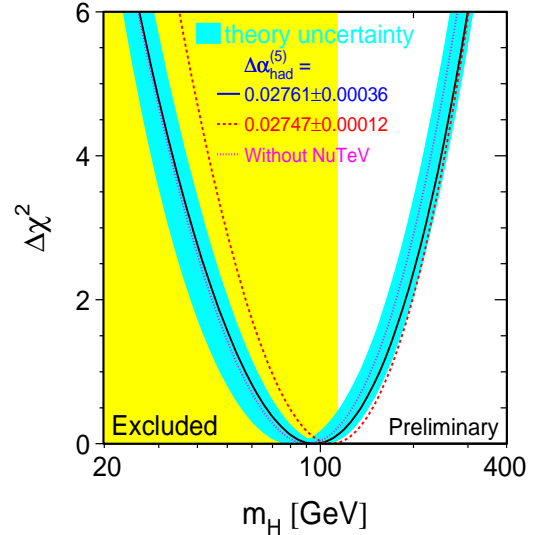


Figure 12. The parabolic darker (blue) band summarizes our indirect information on M_H , while the lighter shaded (yellow) area is excluded by LEP.

Indeed, the spectral function discussed in the previous section enters also the determination of $\alpha(M_Z)$, but higher energy data have more weight. Considerable progress has been achieved in the last few years, and this uncertainty is no more a bottleneck for the present bounds on M_H . An alternative analysis that tries to use the data in a more efficient way^{38,39} yields $\Delta\alpha_{\text{had}} = 0.02769 \pm 0.00018$. It is difficult at the moment to beat this precision: determinations that make use of perturbative QCD down to lower scales in order to reduce the error are penalized by other uncertainties, *e.g.* on the charm mass⁴¹.

The $\chi^2/\text{d.o.f.}$ of the global fit is 25.4/15, corresponding to 4.5% probability. The NuTeV result shares the responsibility for the degradation of the fit with another deviant measurement, that of the bottom quark Forward-Backward asymmetry, A_{FB}^b , at LEP. The best fit¹ points to a fairly light Higgs boson, with mass $M_H = 96 \text{ GeV}$, while the 95% CL upper bound on M_H , including an estimate of theoretical uncertainty, is about 220 GeV. As the uncertainty used for NuTeV is the one given by the experiment, let us consider the fit performed excluding this result. The information on the Higgs mass is almost insensitive to the NuTeV result ($M_H^{\text{fit}} = 91 \text{ GeV}$, $M_H < 202 \text{ GeV}$ at 95%), but of course the quality of the fit

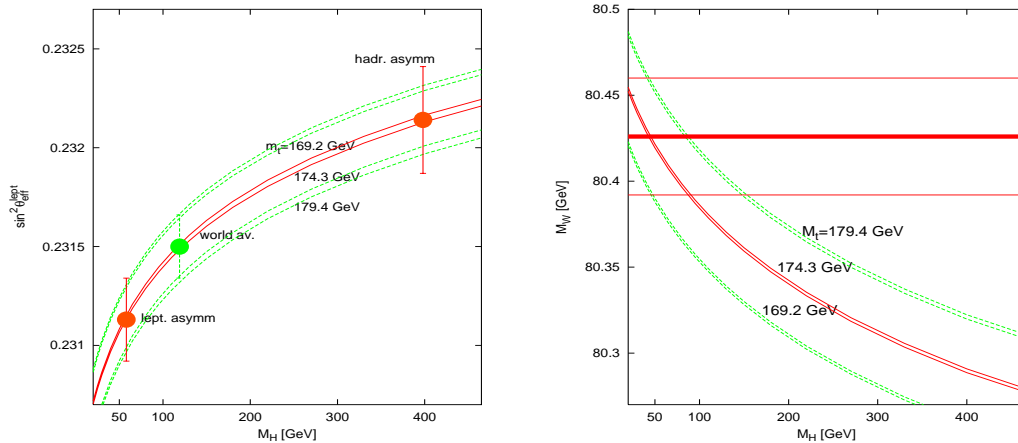


Figure 13. Higgs mass dependence of $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ – extracted from leptonic and hadronic asymmetries – and of M_W , for three M_t values, compared with the experimental values.

improves significantly, with $\chi^2/\text{d.o.f.}=16.8/14$, corresponding to 26.5%. One would conclude that the SM fit is quite satisfactory. The direct and indirect information on the Higgs mass are summarized in Fig. 12, where the lighter shaded (yellow) area, $M_H < 114.4$ GeV, is excluded by LEP.

We have noted that, excluding NuTeV, the data are rather consistent. But the table in Fig. 11 contains an arbitrary set of observables. For example, it does not include a_μ , or $B \rightarrow X_s \gamma$, which are important and precise data. The overall conclusion would not change, in my view. However, if we are interested in extracting information on the Higgs mass, we should concentrate only on the subset of observables that are really sensitive to M_H and, because of a strong correlation, to the top mass, M_t . Using only M_W , M_t , Γ_ℓ , the Z-pole asymmetries, and R_b , one obtains $M_H^{\text{fit}} = 98$ GeV, $M_H < 210$ GeV at 95% CL, and $\chi^2/\text{dof}=11/4$, corresponding to 2.6% probability. In other words, the restricted fit gives the same constraints on M_H of the global fit. However, it is now obvious that the SM fit to the Higgs mass is *not* really satisfactory.

The root of the problem is an old 3σ discrepancy between the Left-Right asymmetry, A_{LR} , measured by SLD and the Forward-Backward b quark asymmetry, A_{FB}^b , measured by the LEP experiments. In the SM these asymmetries measure the *same* quantity, $\sin^2 \theta_{\text{eff}}^{\text{lept}}$, related to the lepton couplings to an on-shell Z^0 . It now happens that all leptonic asymmetries, measured both at LEP and SLD, are mutually consistent and prefer a very *light Higgs* mass

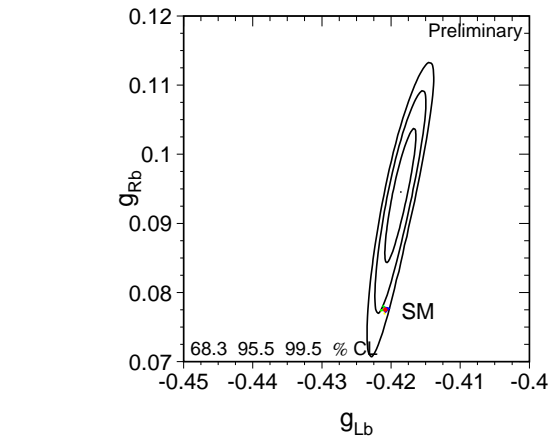


Figure 14. Fit to the left- and right-handed b quark neutral current couplings.

– see Fig. 13. In this sense, they are also consistent with M_W measured at LEP and Tevatron. Only the asymmetries into hadronic final states prefer a *heavy Higgs* (see Fig. 13).

Since the hadronic asymmetries are dominated by A_{FB}^b , and the third generation is naturally singled out in many extensions of the SM, could this be a signal of new physics in the b couplings? After all, QCD and experimental systematics in A_{FB}^b have been carefully considered.¹ New physics in the b couplings seems unlikely for several reasons: (i) fixing $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ at the value measured by the leptonic asymmetries, A_{FB}^b corresponds to a measurement of a combination of b couplings, $\mathcal{A}_b(A_{FB}^b) = 0.886 \pm 0.017$; the same combination is also tested by A_{LR}^{FB} at SLD, yielding $\mathcal{A}_b(A_{LR}^{FB}) = 0.922 \pm 0.020$.

One should compare these two values to the very precise SM prediction, $\mathcal{A}_b^{SM} = 0.935 \pm 0.002$: the SLD result is compatible with the SM and at 1.4σ from the value extracted from A_{FB}^b ; (ii) the value of \mathcal{A}_b extracted from A_{FB}^b would require a $\sim 25\%$ correction to the b vertex, i.e. tree level physics; and (iii) R_b agrees well with the SM and tests an orthogonal combination of b couplings; it follows that new physics should predominantly affect the right-handed b coupling, $|\delta g_R^b| \gg |\delta g_L^b|$, see Fig. 14. All this places strong restrictions on the extensions of the SM that can explain A_{FB}^b . Exotic scenarios that shift only the b_R coupling include mirror vector-like fermions mixing with the b quark,⁴⁹ and LR models that single out the third generation,⁵⁰ but even these *ad hoc* models have problems in passing all experimental tests.

We have seen that their preference for a heavy Higgs really singles out the hadronic asymmetries. This brings us to what can be called the *Chanowitz argument*:^{51,52} there are two possibilities, both involving new physics:

- (a) A_{FB}^b points to new physics; or
- (b) A_{FB}^b is a fluctuation or is due to unknown systematics.

In the second case it is interesting to see what happens if one excludes the hadronic asymmetries from the above restricted Higgs mass fit. Not surprisingly, a consistent picture emerges: a very light Higgs with $M_H^{fit} = 42$ GeV fits perfectly all data and one obtains an upper bound $M_H < 120$ GeV at 95% CL. This would suggest new physics because the direct lower bound on the Higgs boson in the SM is $M_H > 114$ GeV^{51,52}

Although it may be the ringing bell for something more spectacular, the inconsistency with the direct lower bound is statistically rather weak at the moment. It also marginally depends on the value of the hadronic contributions to $\alpha(M_Z)$ used in the fit, although we are already employing the most unfavorable estimate. Similarly, current estimates of the theoretical error agree that it cannot shift up $M_H^{95\%}$ more than ~ 20 GeV.⁵³ The inconsistency would be alleviated if the top mass turned out to be heavier than the present central value, a possibility suggested by the latest D0 analysis of Run-I data (yielding $M_t = 180.1 \pm 5.4$ GeV⁴⁷) and soon to be tested at the Tevatron. Figure 15 illustrates

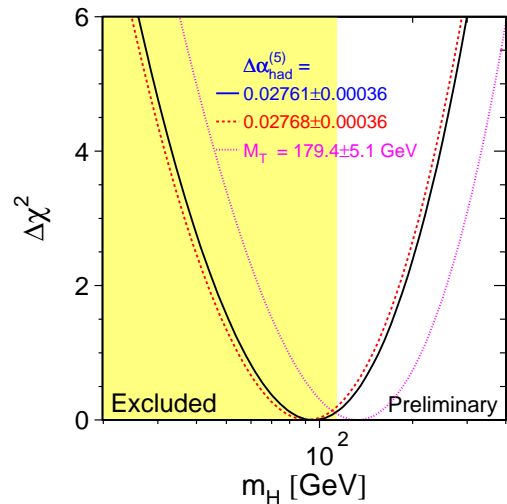


Figure 15. Effect of a 1σ change in M_t on the Higgs mass constraints.

this point by showing the result of a global fit with $M_t = 179.4 \pm 5.1$ GeV.

We have seen that excluding A_{FB}^b (and NuTeV) from the fit the quality of the fit improves considerably, but M_H^{fit} becomes very small. Finding new physics that simulates a very light Higgs is much easier than fixing the two anomalies. An example are oblique corrections: in general it just requires $S < 0$ ($T > 0$) or $\epsilon_{2,3} < 0$.^{51,52} A non-degenerate unmixed fourth generation with a heavy neutrino with $m_N \approx 50$ GeV would easily work. More interestingly, the MSSM offers rapid decoupling (small corrections), M_W always higher than in the SM, and $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ lower than in the SM. A plausible MSSM scenario involves light sneutrinos and sleptons, heavy squarks, and $\tan \beta \gtrsim 5$.⁵²

As illustrated in Fig. 15, the Higgs indirect determination depends strongly on the top mass: a shift of $+5$ GeV in M_t would imply $M_H < 280$ GeV instead of 200 GeV. A factor 2 improvement in the determination of $\alpha(M_Z)$ would lower the 95% CL upper bound on M_H by only about 5 GeV. A factor 2 improvement in the measurement of M_t would lower the 95% CL upper bound on M_H by about 35 GeV. Figure 16 is also instructive: all the main precision observables define almost parallel bands in the M_t, M_H plane. The only important piece of information that can, in the near future, significantly improve the Higgs mass constraints is the top mass. A better M_t measurement would also help clarify the fate of the *Chanowitz argument*.

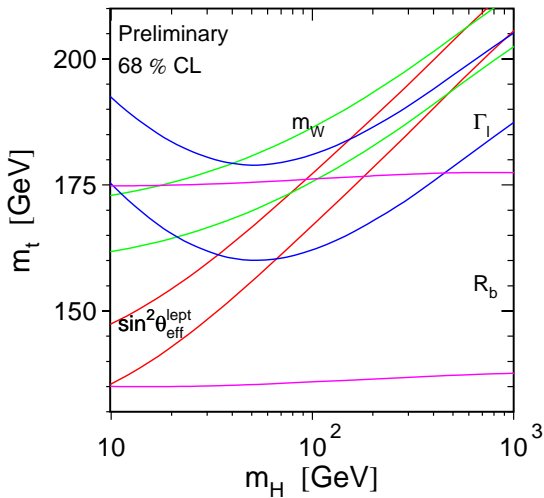


Figure 16. Constraints in the M_t, M_H plane from different observables.

In the future, interesting new data will come from the Tevatron (M_t and M_W), from E158 and QWeak, and later from the LHC and possibly from a Linear Collider. Running the latter on the Z^0 peak (the *Giga-Z* option) would reach a new frontier in precision physics. We will be able to exploit this precision only with a major effort on the theoretical side. After years of studies and despite some progress,⁵⁴ automatic two-loop calculations in the electroweak sector are still confined to special cases: the complete two-loop calculation of the relation between M_W , M_Z and G_μ has just been completed,⁵⁵ and the analogous calculation for $\sin^2 \theta_{lept}^{eff}$ is nowhere in sight.

6. Conclusions

The SM works fine, but there are several areas of tension in the data. None of them gives a convincing indication of new physics. Though each of them could, depending on the evolution of data and theory.

For what concerns the tests of charged current universality, an odd discrepancy persists between the measurements of the Cabibbo angle from $K_{\ell 3}$ and nuclear β decays. The situation, possibly due to underestimated theoretical uncertainties, should soon be clarified by a number of upcoming measurements.

A new global analysis of PDF's favors a positive strange quark asymmetry in the nucleon, that would reduce the NuTeV anomaly. This effect and isospin violation in the PDF's add a substantial uncertainty

to the NuTeV result. Given our present understanding of the nucleon structure, the Paschos-Wolfenstein relation is probably not a good place for electroweak precision physics: NuTeV may end up teaching us more about hadronic structure than short-distance physics.

Revised CMD-2 data have reduced to $\approx 2\sigma$ the discrepancy between the experimental result for $(g-2)_\mu$ and the SM prediction based on e^+e^- data. KLOE has given the first results with the method of radiative return, confirming within errors CMD-2. On the other hand, the spectral function extracted from τ decays still deviates significantly from e^+e^- data in a small \sqrt{s} window, a rather odd result that needs to be confirmed and understood, probably in terms of isospin breaking.

Although the SM fit shows a clear preference for a light Higgs boson, what we know of the Higgs mass and of the kind of new physics we might expect depends heavily on conflicting experimental data. Removing the most deviant result from the SM fit leads to a mild inconsistency with the direct lower bound on M_H . The *top priority* here is a precise measurement of the top mass, and we all expect interesting results from the Tevatron soon.

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