Precision Electroweak Measurements Circa 2002*

Paolo Gambino[a †]

[a] Theory Division - CERN
CH 1211, Geneve 23, Switzerland

Present global fits to electroweak data are characterized by two results that differ from Standard Model (SM) expectations by about 3σ, the NuTeV measurement of $\sin^2\theta_W$ and the FB b quark asymmetries measured at LEP. I review possible SM and new physics explanations of these anomalies and the implications for the indirect determination of the Higgs mass.

1. The global Standard Model fit

There is not so much going on in electroweak physics nowadays, apart from the muon $g-2$, it is tempting to say. Not quite so: the latest Standard Model (SM) fit performed by the LEP Electroweak Working Group [1] looks remarkably different from the one from last year. The main new result comes from the NuTeV Collaboration [2]: their measurement of the electroweak mixing angle in ν-N Deep Inelastic Scattering (DIS) differs about 3σ from theoretical expectations. The χ^2/d.o.f. of the global fit is 29.7/15, corresponding to 1.3% 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^b_{FB}, at LEP. The best fit [1] points to a fairly light Higgs boson, with mass $M_H = 81$ GeV, while the 95% CL upper bound on M_H, including an estimate of theoretical uncertainty, is about 190 GeV. Interestingly, the information on the Higgs mass is almost insensitive to the NuTeV result: a fit performed excluding this new result gives practically the same constraints on M_H, but of course the quality of the fit improves significantly, with χ^2/d.o.f.=20.5/14, corresponding to a probability of 11.4%. One would conclude that the SM fit is quite satisfactory, if not for NuTeV. Let us therefore start this (incomplete) status review with a look at the intriguing NuTeV *anomaly*.

2. The NuTeV electroweak result

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

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

where $r \equiv \frac{\sigma(\bar\nu N\to\bar\mu X)}{\sigma(\nu N\to\mu X)}$ and $g^2_{L,R}$ are average effective left and right-handed ν-quark couplings. The actual experimental ratios $R^{exp}_{\nu,\bar\nu}$ 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 MonteCarlo including most of these effects relates $R^{exp}_{\nu,\bar\nu}$ to $R_{\nu,\bar\nu}$. It is useful to note that most uncertainties and $O(\alpha_s)$ effects drop in the Paschos-Wolfenstein (PW) ratio [3]

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

which equals $g_L^2 - g_R^2 = \frac{1}{2} - \sin^2\theta_{\rm W}$ and therefore could provide a clean measurement of $\sin^2\theta_{\rm W}$, if experimentally accessible. NuTeV do not measure R_{PW} directly, but, using the fact that $R_{\bar\nu}$ is

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†Marie Curie Fellow

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 $\sin^2\theta_W$. To first approximation, the NuTeV procedure corresponds to a measurement of R_{PW}. The result is expressed as a test on the on-shell $s_W^2 \equiv 1 - M_W^2/M_Z^2$ definition of $\sin^2\theta_W$:

$$s_W^2(\mathrm{NuTeV}) = 0.2277 \pm 0.0013 \pm 0.0006 \pm 0.0006, \quad (1)$$

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 dependence in the above equation. The above value must be compared to the one obtained using the results of the global fit, $s_W^2 = 0.2226 \pm 0.0004$, which is about 3σ away.

QED corrections are important and their implementation in NuTeV could be improved, but they seem at the moment an unlikely explanation. Electroweak corrections, on the other hand, are small and under control.

A potentially very important source of uncertainty are the parton distribution functions (PDFs) employed in the analysis. NuTeV work 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 PDFs self-consistently fitted in the experiment, with little external input.

Is the NuTeV estimate of the PDFs uncertainty reliable? We have seen that R_{PW} is independent of the details of first generation PDFs. As long as the NuTeV result is equivalent to a measurement of R_{PW}, even with cuts and second generation quarks, the small uncertainty attributed by NuTeV might be realistic [4]. The problem is that NuTeV do *not* really measure R_{PW} and there are indications [4] that this might be relevant at the required level of accuracy.

We have seen that NuTeV do not employ NLO QCD corrections. Are they necessary? The answer is very similar to the previous one: no, if you are measuring R_{PW}, which is not corrected at $O(\alpha_s)$. But any CC/NC or $\nu/\bar{\nu}$ asymmetry (introduced by cuts, differences in the energy spectra and in the sensitivity, *etc.*) spoils delicate cancellations (ordinary NLO corrections are 5-10%, while here a better than 0.5% precision is required). As the NuTeV measurement seems to differ enough from that of R_{PW}, the analysis needs to be consistently upgraded to NLO. This would allow the implementation of different sets of NLO PDFs, and would simplify the discussion of other issues, such as the PDFs uncertainty and the contribution of an asymmetric quark sea.

2.1. Asymmetric sea

In the previous section I have implicitly used the assumptions, generally made in the extraction of PDFs 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 terms [4]

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

where q^- is the asymmetry in the momentum carried by the quark species q in an isoscalar target, $q^- = \int_0^1 x\,[q(x) - \bar{q}(x)]\,dx$, $\tilde{g}^2 \approx .23$ a coupling factor, and $Q^- = (u^- + d^-)/2 \approx 0.18$. While there is no reason in QCD to expect $s^- = 0$, for an isoscalar target $u^- - d^-$ is of the order of isospin violation. In fact, eq.(2) tells us that even quite small values of these two asymmetries could change significantly the value of s_W^2 measured by NuTeV.

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 $p \leftrightarrow \Lambda K^+$[5]. Unfortunately, the strange quark sea is mainly constrained by (mostly old) νN DIS data, which are usually not included in standard PDFs fits. In fact, MRST and CTEQ use an *ansatz* $s = \bar{s} = (\bar{u} + \bar{d})/4$. Barone et al. (BPZ) [6] have reanalyzed at NLO all νN DIS together with ℓN and Drell-Yan data. They have a much higher sensitivity to strange sea than the standard fits and find a strange $s(x)$ larger than usual at high-x. This feature contrasts with NuTeV dimuon results, not included in the BPZ fit which was prior to their release, but agrees well with positivity constraints from polarized DIS [7]. Allowing for a strange asymmetry improves BPZ

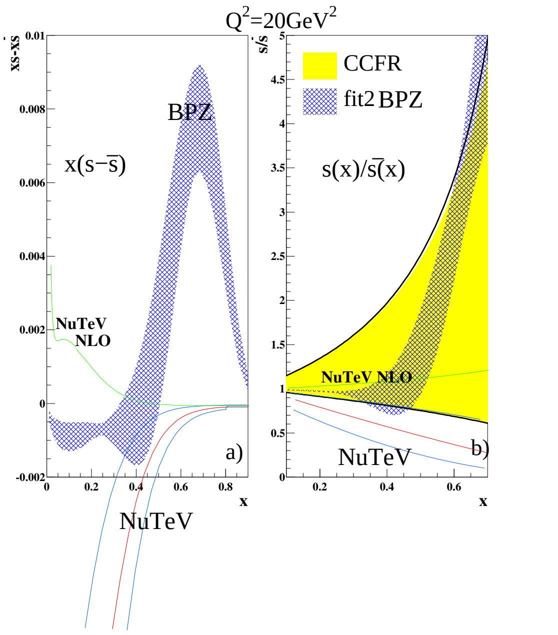

Figure 1. Strange sea asymmetry at NLO from BPZ fit [6] (no dimuons, blue band), at LO in the NuTeV *cross section model* from dimuons only [8] (red line, with errors in blue), and the same at NLO from [9] (green line, error not available). The yellow band on the rhs represents the CCFR dimuon result.

best fit drastically and could explain a large fraction of the discrepancy. The result, $s^- \approx 0.002$, is compatible with theory estimates [5] and is driven by cross section measurements by CDHSW (νN) and BCDMS ($\mu\, p$).

I have already mentioned that BPZ do not include NuTeV data, especially those on dimuon events (tagged charm production), a rather sensitive probe of the strange sea. NuTeV has analyzed them, claiming $s^- = -0.0027 \pm 0.0013$, which would *increase* the anomaly to 3.7σ [8]. The NuTeV strange asymmetry is compared to the BPZ fit in Fig. 1, which makes their incompatibility apparent. Because of various shortcomings, such as strong dependence on underlying PDFs, violation of strangeness (evident in Fig. 1) and other sources of model dependence (see note added to [4]), the above estimate *cannot* be interpreted as a measurement of s^- and should not be compared to that of BPZ. NLO corrections, in particular, are very important for dimuons, as shown by a preliminary NLO analysis of NuTeV dimuons [9]. This new analysis is in better agreement with BPZ, both on the total size and on the asymmetry of $s(x)$ (see Fig. 1). The use of the NuTeV s^- in the s^2_W extraction is also highly questionable, even in the context of NuTeV improved LO model, because it assumes that the restricted set of dimuon events available be representative of the whole kinematic range employed in the s^2_W analysis. At least, a generous theory error should be attached to this procedure, perhaps of the order of the effect itself, 0.7σ, and much larger than the theory error in eq. (1).

The bottom line is that we presently know very little on the strange sea. Before any conclusion can be drawn on its asymmetry and the effect on the NuTeV s^2_W result, a global NLO fit including all dimuons and ν-N DIS data is needed. A precise $s(x), \bar{s}(x)$ determination will be possible at a neutrino factory [10].

A violation of isospin of the form $u_p(x) \neq d_n(x)$ would also affect the PW relation according to eq. (2). A rough estimate for its size is $(m_u - m_d)/\Lambda_{QCD} \approx 1\%$. So small a violation of charge symmetry would give no visible effect in any present experiment, apart from the NuTeV measurement of s^2_W, where it could explain a fraction of the anomaly – about a third, according to eq. (2). Explicit model calculations [11] vary widely in their results for a shift in s^2_W. Estimates giving a very small shift are generally due to subtle cancellations of much larger contributions and should be handled with care.

The relevant momentum asymmetries in the quark sea are therefore only weakly constrained and could have a significant impact on s^2_W extracted by NuTeV. It has been shown [8] that these effects are somewhat diluted in the actual NuTeV analysis compared to the direct use of eq. (2), precisely because NuTeV differs from a measurement of R_{PW}. They nevertheless introduce an unwelcome uncertainty very hard to estimate.

I should also mention that several attempts at explaining the NuTeV anomaly with nuclear effects like nuclear shadowing have been made [12], but no convincing case has so far been presented.

3. New Physics vs NuTeV

A New Physics explanation of the NuTeV anomaly requires a $\sim$ 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 [4].

In particular, supersymmetry, with or without R parity, cannot help, because it is strongly constrained by other precision measurements (often at the permille level) and by direct searches. The same is generally true of models inducing only oblique corrections or only anomalous Z couplings [4]. Realistic and well-motivated examples of the latter are models with ν_R mixing [4,13]. Models with ν_R mixing *and* oblique corrections have been considered in [14] and found to fit well all data including NuTeV.[3] But finding sensible new physics that provides oblique corrections in the preferred 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 $\pi \to \mu\bar{\nu}_\mu$, 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 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). A viable possibility that could alleviate the NuTeV anomaly and at the same time explain part of the $(g-2)_\mu$ anomaly [15], is based on an abelian gauge symmetries $B - 3L_\mu$ [4]. The Z' must have very small mixing with the Z^0 because of the bounds on oblique parameters and on the anomalous Z couplings [4,16] (see [17] for an explicit $L_\mu - L_\tau$ model and [18] for technicolor models).

[3] Can the necessary oblique corrections be provided by a heavy SM Higgs boson? No, as it is also clear from a careful reading of [14] (contrary to what stated by prominent NuTeV members, there is *no* conflict between [14] and [4]). 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. However, solving the NuTeV anomaly at the expense of the very precise measurement of M_W is hardly an improvement.

4. The SM fit to M_H is not satisfactory

The global fit without NuTeV has an 11% probability. This gives us an idea of the overall consistency of the data, but if we are interested in extracting information on the Higgs mass, it is clear that 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 $M_H^{fit} = 90$ GeV, $M_H <$ 195 GeV at 95% C.L., and χ^2/dof=13/4, corresponding to a 1% 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* satisfactory, even without NuTeV.

5. Another unwelcome anomaly

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

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 $\sin^2\theta_{eff}^{lept}$ at the value measured by the leptonic asymmetries, A_{FB}^b corresponds to a measurement of a combination of b couplings, $\mathcal{A}_b = 0.882 \pm 0.017$; the same combination is also tested by A_{LR}^{FB} at SLD, yielding $\mathcal{A}_b = 0.922 \pm 0.020$. One should compare

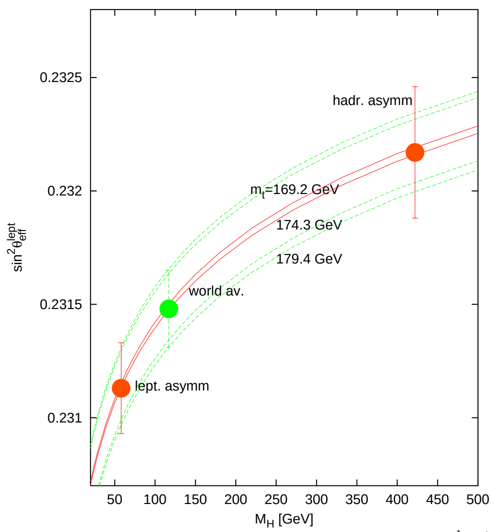

Figure 2. Higgs mass dependence of $\sin^2\theta_{eff}^{lept}$ extracted from leptonic and hadronic asymmetries, for three M_t values.

these two values to the very precise SM prediction, $\mathcal{A}_b^{SM} = 0.935 \pm 0.002$: SLD result is compatible with the SM and at $1.5\,\sigma$ from the value extracted from A_{FB}^b; (ii) the value of $\mathcal{A}_b$ extracted from A_{FB}^b would require a $\sim 30\%$ correction to the b vertex, i.e. tree level physics; (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, $|\delta g_R^b| \gg |\delta g_L^b|$. 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 b quark [19], and LR models that single out the third generation [20], but even these *ad-hoc* models have problems in passing all experimental tests. Difficult to explain in the most popular new physics models, both NuTeV and A_{FB}^b are in this sense two *unwelcome* anomalies.

6. Too light a Higgs

An even-handed option to handle the discrepancy between A_{LR} and A_{FB}^b is to enlarge their error according to the PDG prescription. The result is a slight decrease in the central M_H value of the fit [21]. But we have seen that their preference for a heavy Higgs really singles out the hadronic asymmetries. It is then instructive 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 $M_H^{fit} = 40$ GeV fits perfectly all data and one obtains an upper bound $M_H < 109$ GeV at 95% CL. If really M_W, Γ_ℓ, M_t, and the leptonic asymmetries are consistent data and the SM is correct, why hasn't the Higgs been found at LEP, which set a lower bound $M_H > 114$ GeV [22,23]?

The inconsistency with the direct lower bound marginally depends on the value of the hadronic contributions to $\alpha(M_Z)$ used in the fit, but even in the most unfavorable case the 95% CL upper bound is no more than 120 GeV. Similarly, current estimates of the theoretical error agree that it cannot shift up $M_H^{95\%}$ more than ~ 20 GeV [24]. The inconsistency would be alleviated if the top mass turned out to be heavier than the present central value, a possibility soon to be tested at Tevatron, but the fit does not suggest this possibility at all. One can quantify the inconsistency computing the combined probability of the global fit *and* of having $M_H > 114$ GeV: it is the same with or without A_{FB}^b [22].

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 $\epsilon_{2,3} < 0$ [22,23]. A non-degenerate unmixed fourth generation with a heavy neutrino with $m_N \approx 50$ GeV would easily work [25]. More interestingly, the MSSM offers rapid decoupling (small corrections), M_W always higher than in SM, and $\sin^2\theta_{eff}^{lept}$ lower than in SM. A plausible MSSM scenario involves light sneutrinos and sleptons, heavy squarks, and $\tan\beta \gtrsim 5$ [23]. The required mass spectrum cannot be obtained in minimal SUGRA models with universal soft masses, though alternatives exist, and could be discovered at Tevatron. Other susy scenarios have also been presented [13].

7. Conclusions

The NuTeV experiment aims at high precision in a complex hadronic environment. Its measurement of $\sin^2\theta_W$ is affected by theoretical systematics not fully under control or untested, such as a small strange/antistrange asymmetry and isospin violation. The analysis should be upgraded to NLO.

Even excluding the NuTeV electroweak result, the SM fit to M_H is not satisfactory. What we know on the Higgs boson mass depends heavily on the b quark FB asymmetries, an even more puzzling experimental anomaly. Removing the two deviant results from the SM fit leads however to inconsistency with the direct lower bound on M_H.

Both the NuTeV $\sin^2\theta_W$ and A^b_{FB} require new tree level effects which are difficult to accommodate in reference scenarios of physics beyond the SM. For instance, supersymmetry with or without R parity cannot explain them. Proposed interpretations rely on *ad-hoc* exotic models and it is always problematic to reconcile them with other precision data. Keeping also in mind the discrepancy of the measured $(g-2)_\mu$ with the SM prediction, the SM looks definitely under strain, although a clear-cut, compelling case for new physics has yet to be made.

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