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Bounds on the top mass from Z decays into b quarks*

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ABSTRACT

I discuss the information that can be obtained on the top quark mass from high–precision measurements in the decay $Z \to b\bar{b}$ which are performed at LEP. I will show that there are two completely independent ways to constrain this parameter: while the forward–backward asymmetry A^b_{FB} directly measures the top effect stemming from gauge boson self–energies and which affect all electroweak observables, the ratio of decay widths $\Gamma_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ is only sensitive to the top effect due to vertex corrections. Non genuine electroweak effects on the two observables as well as possible effects due to New Physics are also discussed.

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The top quark is one of the missing ingredients of the Standard Model (SM). Its long awaited discovery can only be expected at a future phase of the Tevatron or, in case where it turns out (once again!) to be too heavy, in the next generation of colliders. However, one can already see its virtual effects and obtain some information on its mass from the high–precision measurement of the electroweak radiative corrections which are performed at LEP [1]. It is this issue that I will discuss in this talk, concentrating on two observables in the sector of its weak isospin partner, the b quark.

Let me first summarize the reasons why everybody believes in the existence of the top. There is first an aesthetical reason. We know that the quark structure of the SM is such that, for the two first generations, the left–handed components are in weak isodoublets while the right–handed ones are in weak isosinglets. If the top is absent both b_L and b_R will be isosinglets and it will be too ugly that the third family does not reproduce the pattern of the first ones. There is also a theoretical reason. We all know that a triangular loop which is built up by an axial–vector and two vector charges leads to an anomaly which spoils the renormalizability of the theory. The only way to get rid of it in the SM is to demand that the sum of the charges of the left–handed fermions is zero and this condition is only met if we postulate the existence of the top. Finally, there are some experimental data which provide a very strong evidence that the b quark has a partner. As one might expect, most of these results come from b physics, and here, I will just mention two of them which are both very recent and very convincing. At the Born level, the partial width and the forward–backward asymmetry in the decay $Z \to b\bar{b}$ are given by (for details on b physics at LEP see e.g [2])

$$\begin{aligned} \Gamma(Z \to b\bar{b}) &= \frac{3\alpha}{16 c_W^2 s_W^2}\beta_b \left[\frac{3-\beta_b^2}{2} v_b^2 + \beta_b^2 a_b^2\right] &\simeq \frac{3\alpha}{16 c_W^2 s_W^2}(a_b^2 + v_b^2) \\ A^b_{FB} &= \frac{3}{4}\frac{2a_e v_e}{a_e^2+v_e^2}\beta_b \frac{2a_b v_b}{\beta_b^2 a_b^2 + \frac{3-\beta_b^2}{2}v_b^2} &\simeq \frac{3}{4}\frac{2a_e v_e}{a_e^2+v_e^2}\frac{2a_b v_b}{a_b^2+v_b^2} \end{aligned} \quad (1)$$

where $\beta_b = (1 - 4m_b^2/M_Z^2)^{1/2}$, $s_W^2 = 1 - c_W^2 \equiv \sin^2\theta_W$, a_f and v_f are the axial and vectorial $Zf\bar{f}$ couplings which, in terms of arbitrary weak isospin, are given by

$$v_f = 2(I_f^{3L} + I_f^{3R}) - 4e_f s_W^2 \qquad a_f = 2(I_f^{3L} - I_f^{3R}) \quad (2)$$

Thus clearly, the theoretical predictions for the two observables are different for the two values of the left–handed isospin: $I_b^{3L} = 0$ (isosinglet) and $I_b^{3L} = \pm 1/2$ (isodoublet):

$$\begin{aligned} \Gamma(Z \to b\bar{b})\Big|_{I_b^{3L}=-1/2} &\simeq 380 \text{ MeV} \quad , \quad & A^b_{FB}\Big|_{I_b^{3L}=-1/2} &\simeq 0.08 \\ \Gamma(Z \to b\bar{b})\Big|_{I_b^{3L}=0} &\simeq 30 \text{ MeV} \quad , \quad & A^b_{FB}\Big|_{I_b^{3L}=0} &= 0 \end{aligned} \quad (3)$$

If we now compare with the experimental results of the LEP collaborations which have been given in this conference [3], we clearly see that the case $I_b^{3L} = 0$ is ruled out and that the case $I_b^{3l} = -1/2$ (the minus sign comes from A^b_{FB}) is in perfect agreement with the data. This means that the b needs its $I^{3L} = +1/2$ partner, namely the top.

In fact the previous observables can, not only tell us that the top quark is around, but also how much it weights. Indeed, through radiative corrections, the two quantities receive potentially large contributions from virtual top exchange and in a near future, they will be measured with enough accuracy for these effects to be precisely probed as I will illustrate later. Before that, I briefly discuss all the possible "background" effects which might be important for a very precise measurement.

The first effect which leads to relatively large contributions to the two observables is the one due to strong interactions. These QCD radiative corrections are well known for massive quarks [4] and in the case the b quark, one can use the fact that $m_b \ll M_Z$ and perform an expansion in powers of $\mu = m_b/M_Z$. The correction can then be simply incorporated by making the following substitutions [2]:

$$v_b^2 + a_b^2 \to v_b^2 \left[1 + \frac{\alpha_s}{\pi}\right] + a_b^2 \left[1 + (1 + 3\mu^2 \log\frac{4}{\mu^2})\frac{\alpha_s}{\pi}\right] \ , \ a_b v_b \to a_b v_b \left[1 - (1 - \frac{2}{3}\mu)\frac{\alpha_s}{\pi}\right] \quad (4)$$

which describe the full result with a good accuracy. The coefficient of α_s/π is of order one in both quantities and might lead, because of the relatively poor knowledge of α_s, to ambiguities which are competitive with the interesting top effect that we are looking at. A way to eliminate this ambiguity in the asymmetry is to consider two jet events [2]. Indeed, if one only selects the events where the invariant mass of two jets is less than a small fraction of the total energy, the coefficient of α_s/π, and thus the associated error, can be drastically reduced. This cannot be done for the partial decay width (otherwise the correction blows up) but one can normalize to the total hadronic width which has practically the same α_s dependence

$$\Gamma_b \equiv \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{hadrons})} \simeq \Gamma_b^0 \left[1 + 0.1\frac{\alpha_s}{\pi}\right] \qquad (5)$$

and which only leaves the effect due the finite b mass, which is small enough that one can neglect the associated error. Note that this ratio has also an experimental advantage since all systematic errors common to hadrons cancel. The final state electromagnetic corrections can be copied from the QCD ones by an appropriate change of the couplings: $\alpha_s \to \frac{3}{4}c_b^2\alpha$. Their contribution though, is very small and can be safely neglected. For the initial sate radiation, which in general gives large contributions, it has been shown in the recent LEP workshop [1] that they are well under control.

Another effect that one has to consider in the forward–backward asymmetry is $b\bar{b}$ mixing. Indeed the b asymmetry will be extracted from asymmetry measurements of B mesons and because of the mixing of the latter, there is not a one-to-one correspondence between the two. For instance, if the b's are tagged through their semi-leptonic decay modes, the asymmetries are related by $A_{FB}^l = (1 - 2\bar{\chi})A_{FB}^b$ with $\bar{\chi} \simeq 0.15$ the average mixing parameter which is expected to be measured to better than 10%. This will then lead to an error $\delta A_{FB}^b \simeq 0.003$ which will be the major uncertainty [2].

I come now to the main part of my talk, which is the discussion of the genuine electroweak radiative corrections which contain the top dependence. These corrections are usually divided in two sets. The oblique corrections stemming from the vacuum polarization of the gauge bosons are universal (in the sense that they affect all LEP observables) and, in practically all cases, the most important ones. The direct corrections, coming from fermion self–energy, vertex and box diagrams are process dependent. They are very small except in the case of $b\bar{b}$ final states. All these corrections are available in the literature [1] and here, I give some simple formulae which are very good approximations of the exact results. I will adopt the on shell scheme [5] where one uses α, G_μ and M_Z as input parameters and where $s_W^2 \equiv 1 - M_W^2/M_Z^2$.

If one takes into account the running of α from $q^2 = 0$ to $q^2 = M_Z^2$ by using $\alpha(M_Z^2) \simeq 1/128.8$, the oblique corrections can be simply included by slightly shifting s_W^2

$$s_W^2 \to \bar{s}_W^2 = s_W^2 \left\{\frac{c_W^2}{s_W^2}\Delta\rho + \frac{\alpha}{4\pi s_W^2}\left[\log(1 + m_H/17.3\ \text{GeV} + 1) - 2\right]\right\} \qquad (6)$$

This approximate formulae reproduces the complete result (e.g given by Hollik [6]) to an accuracy better than 0.2%. The logarithmic Higgs contribution is rather small but if s_W^2 is measured with enough accuracy (and once the top mass is fixed), this effect can also be probed. The leading top contribution is contained in the term $\Delta\rho$ (there is also a logarithmic term but its contribution is marginal)

$$\Delta\rho \equiv \frac{\Pi_{ZZ}(0)}{M_Z^2} - \frac{\Pi_{WW}(0)}{M_W^2} \simeq \frac{3}{16 s_W^2 c_W^2}\frac{\alpha}{\pi}\frac{m_t^2}{M_Z^2} \qquad (7)$$

This expression has to be corrected to include the leading two–loop effects which can be important for a very heavy top quark

$$\Delta\rho \to \Delta\rho\left[1 - (2\pi^2 - 19)\frac{\alpha}{3\pi}\frac{m_t^2}{M_Z^2}\right] \times \left[1 - \frac{2\pi^2 + 6}{9}\frac{\alpha_s}{\pi}\right] \qquad (8)$$

where the first bracket describes the leading correction due to Higgs and longitudinal W exchange [7] (which goes like m_t^4) and the second, the correction due to the strong interactions of the quarks inside the loop in the large m_t limit [8].

Contrary to the other final states the direct corrections are very important in the case of the b quark. This is due to the top exchange in the $Zb\bar{b}$ vertex which leads to large contributions [9] and which can be readily incorporated by adding a piece to v_b and a_b

$$v_b \to v_b + \frac{2}{3}\Delta_{bV} \qquad a_b \to a_b + \frac{2}{3}\Delta_{bV} \qquad (9)$$

where, to a very good approximation, Δ_{bV} is given by

$$\Delta_{bV} \simeq \frac{\alpha}{\pi}\left[\frac{m_t^2}{M_Z^2} + \frac{16}{3}\log\frac{m_t^2}{M_W^2}\right] \qquad (10)$$

Note that contrary to the case of the oblique corrections the logarithmic piece is important since its contribution is comparable to the quadratic one for $m_t \sim 200$ GeV. Thus, we have at our disposal two independent quantities where large effects due the top quark occur: $\Delta\rho$ and Δ_{bV}. While the former can be "measured" in all LEP observables (and in general all electroweak processes) the latter can only be probed in Z decays into b quarks. If we now add all these top corrections to our observables [the other contributions which, as discussed previously are well under control, are included in $(A^b_{FB})^0$ and $(\Gamma_b)^0$] we will have

$$\begin{aligned} A^b_{FB} &= (A^b_{FB})^0 + 2\Delta\rho + ... \\ \Gamma_b &= (\Gamma_b)^0 \left[1 - \frac{6}{5}\Delta_{bV}\right] + ... \end{aligned} \qquad (11)$$

where the ellipses stand for the small non leading terms. As a result of an accidental (and welcome!) cancellation, the coefficient of Δ_{bV} in A^b_{FB} and the one of $\Delta\rho$ in Γ_b are so small that their contributions are well below the level of a few per mile, even for top masses of the order of 250 GeV. This leads to the very interesting situation where A^b_{FB} only feels the effects of $\Delta\rho$ while Γ_b is only sensitive to the effects of Δ_{bV}. Since the two effects have completely different origins we will have at our disposal two completely independent ways to look at the top quark [10]. A simultaneous study of the two quantities will then serve as a crucial test of the SM.

To make this statement more quantitative, let me spend few words on the experimental accuracies which can be achieved on the two quantities. For the asymmetry the error has been estimated to be $\delta A^b_{FB} \simeq 0.004$ (for $s^2_W = 0.235$) at the end of the LEP1 runs [11]. For Γ_b, it has been claimed that in a high-luminosity LEP phase and with the help of micro-vertex detectors (which can tag b quarks with an efficiency of 85% and up to a purity of 99%!) the experimental error can be as small as 1% [11]. This would make that, if the validity of the SM is assumed, one can get a value for the top mass with an error less than ± 20 GeV from the asymmetry measurement and that Γ_b would feel the effect of the top if it is heavier than 150 GeV. Of course, the information which will be delivered by the asymmetry will be the best one in the SM. However, the important point that I want to stress again is that the two informations are completely independent and will provide us with an unbiased constraint on m_t even in the presence of New Physics. Indeed the quantities $\Delta\rho$ and Δ_{bV} are affected by different extensions of the SM, to which I turn my attention now.

There are several effects which might introduce a deviation of the ρ parameter from one and which mimic the top effect, some of them have been already discussed by Hollik and Passarino [12]. First of all, the ρ parameter is equal to one at tree level, only if the electroweak symmetry is broken by Higgs doublets or singlets. In the case of triplets for instance, there is a deviation which can be negative and which destroys the present bound on m_t [13]. In fact, even in the case of two–doublets Higgs models (though not for the interesting supersymmetric case), it is possible that the masses of

the various Higgs bosons are such that they generate a negative contribution to ρ at the one loop order [14]. Another possibility is that a new relatively light vector boson Z' is present and mixes with the SM Z boson, altering the value of the ρ parameter [15] (this contribution is, though, always positive). One can also have a fourth family of fermions with a heavy Majorana neutrino. This introduces a shift in $\Delta\rho$ which interferes destructively with that of the top [16]. Finally a large mass splitting between the supersymmetric partners of b and t quarks will also lead to a contribution similar to that of the tb doublet [17]. Thus, when we "measure" $\Delta\rho$ we are not only probing the top effect but also all the previous effects which have nothing to do with this quark.

In the case of Γ_b the situation is different since there are still some new effects which contribute to Δ_{bV} but in most of the cases, they have something to do with the top quark. For instance, in the case of two Higgs doublets models the charged Higgsses give also a contribution which is proportional to m_t^2 but with the same sign as that of the SM [18] (the contribution of the neutral Higgsses is very small for realistic values of the extra parameters). This is also the case in the minimal supersymmetric SM where the dominant contribution of the supersymmetric particles (the one of the charginos) is similar to that of the charged Higgsses [19]. Note that all these contributions are only important if the top is heavy (as opposed to the previous case, where one can have a sizeable $\Delta\rho$ even with a light top). This makes that Δ_{bV} is a genuine top indicator.

There are also some new effects which cannot be cast into Δ_{bV} and/or $\Delta\rho$. This is, for instance, the case of a new Z' boson whichs alters the $Zf\bar{f}$ couplings in a model dependent way. However, one can always built some combinations which are Δ_{bV} and $\Delta\rho$ free and which strongly constrain the new parameters introduced by the Z' as it has been thoroughly discussed in ref. [19]. A similar situation occurs in the case of anomalous ZWW couplings which can be tightly constrained by some specific combinations [20] to the level where they practically have not effect on Γ_b. A special case is the mixing between ordinary and some exotic fermions ones (e.g. E_6 fermions) which is flavor dependent and affect differently all LEP observables. Fortunately its effect in Γ_b is of the same sign as that of the top quark [21].

In conclusion. I have shown that accurate measurements of the process $Z \to b\bar{b}$ at LEP provide us with two independent constraints on the top quark mass even in the presence of New Physics. While the forward–backward asymmetry A^b_{FB} is one of the best measurements of the universal $\Delta\rho$, the ratio $\Gamma_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ measures only the vertex correction Δ_{bV} which is specific to b quarks final states. The information contained in these two quantities are complementary and can serve as a crucial test of the Standard Model.

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References

[1] For a detailed discussion of LEP Physics, see the CERN Yellow Book 89–08, Z Physics at LEP, G. Altarelli, R. Kleiss and C. Verzegnassi, eds.

[2] Heavy Flavors, J. H. Kühn and P. Zerwas [conv.] et al., in [1];
A. Djouadi, J. H. Kühn and P. Zerwas, Z. Phys. C46 (1990) 411;
P. M. Zerwas, "Heavy Flavors", PITHA 90/32 (1990).

[3] See the summary talk given by F. Dydak, these proceedings.

[4] J. Jerzak, E. Laermann and P. Zerwas, Phys. Rev. D25 (1982) 1218;
A. Djouadi, Z. Phys. C39 (1988) 561.

[5] A. Sirlin, Phys. Rev. D22 (1980) 971.

[6] W. Hollik, Fortsch. Phys. 38 (1990) 165.

[7] J. J. van der Bij and F. Hoogeeven, Nucl. Phys. B283 (1987) 477.

[8] A. Djouadi and C. Verzegnassi, Phys. Lett. B195 (1987) 265.

[9] A. Akhundov, D. Bardin and T. Riemann, Nucl. Phys. B276 (1986) 1;
W. Beenakker and W. Hollik, Z. Phys. C40 (1988) 141.

[10] F. Boudjema, A. Djouadi and C. Verzegnassi, Phys. Lett. B238 (1990) 423.

[11] Workshop on High–Luminosity at LEP, J. Thresher et al., proc. to appear.

[12] W. Hollik, these proceedings; G. Passarino, these proceedings.

[13] B. Lynn and E. Nardi, CERN–TH–5876–90 (1990).

[14] A. Denner, R.J. Guth and J. Kühn, Phys. Lett. B240 (1990) 438.

[15] F. Boudjema, F. Renard and C. Verzegnassi, Nucl. Phys. B314 (1989) 301.

[16] S. Bertolini and A. Sirlin, MPI–PAE–74–90 (1990).

[17] see e.g., M. Drees and K. Hagiwara, Phys. Rev. D42 (1990) 1709.

[18] A. Djouadi, J. L. Kneur and G. Moultaka, Phys. Lett. B242 (1990) 265;
A. Denner et al, Preprint MPI–PAE–PTH–1–91 (1991).

[19] A. Djouadi, G. Girardi, W. Hollik, F. M. Renard and C. Verzegnassi, Nucl. Phys. B349 (1991) 48.

[20] G. Belanger, F. Boudjema and D. London, Phys. Rev. Lett. 65 (1990) 2943.

[21] A. Djouadi et al., in preparation.