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TESTS OF THE STANDARD MODEL (AND BEYOND) FROM SPIN PHYSICS

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typical accuracy of several results is in general a few per cent or more, which in fact only represents a test of the model at "tree level". To achieve a more severe comparison of theory and experiment, one will not have to wait for a long time, since a new generation of high precision measurements is expected to produce its first results in the coming years, a fact that will then allow us to test the model at its next, one-loop, level. This point has been thoroughly discussed and generally investigated in the last few years, and excellent reviews exist on the subject³. Here I will consider, in this philosophy, the very specific example of the measurements of the Z couplings to a generic fermion f. In the MSM, they are given by the following expression:

$$J_\mu^Z(g) = \bar{f} \gamma_\mu [\nu_f + a_f \gamma_5] f \quad (1)$$

with the understanding that (universality):

$$\begin{aligned} (\nu, a)_e &= (\nu, a)_\mu = (\nu, a)_\tau \\ (\nu, a)_{\nu_e} &= (\nu, a)_{\nu_\mu} = (\nu, a)_{\nu_\tau} \\ (\nu, a)_u &= (\nu, a)_c = (\nu, a)_t \\ (\nu, a)_d &= (\nu, a)_s = (\nu, a)_b \end{aligned} \quad (2)$$

but:

$$(\nu, a)_e \neq (\nu, a)_\nu \neq (\nu, a)_u \neq (\nu, a)_d \quad (3)$$

The experimental situation in this sector has been discussed by several authors. From a recent analysis⁴ one sees that for leptons the picture is the following:

$$a_e/a_e^{\text{MSM}} = 1.00 \pm 0.08 \quad (4)$$

$$a_\mu/a_e = 1.10 \pm 0.15 \quad (5)$$

$$a_\tau/a_e = 0.97 \pm 0.21 \quad (6)$$

while ν_e is very poorly determined apart from the qualitative confirmation of its expected smallness, $(\nu_e/a_e) \ll 1$.

For quarks, assuming $a_e/a_e^{\text{MSM}} = 1$, one finds (forgetting at this stage the strong interaction effects in the final state):

$$a_c/a_e^{\text{MSM}} = 1.14 \pm 0.36 \quad (7)$$

$$a_b/a_e^{\text{MSM}} = 0.98 \pm 0.20 \quad (8)$$

Figure 1 shows a pictorial representation of Eqs. (7) and (8). The conclusion is that the accuracy of the measurements in the sector of

INTRODUCTION

The fact that spin physics can provide crucial tests of the Standard Model should be no surprise for all those physicists who still remember the fundamental SLAC-Yale experiment¹, that was based on the scattering of longitudinally polarized high-energy electrons off unpolarized deuterium nuclei and succeeded in measuring the related polarization asymmetry, thus demonstrating unambiguously the existence of an interference between electromagnetic and weak neutral current. What is, in a sense, less obvious is the fact that spin physics might also be able to demonstrate unambiguously the existence of, at least, certain kinds of New Physics that would be considered as a "natural" generalization of the Standard Model, and that are still, in principle, not contradicted by the available experimental evidence nowadays.

To understand the latter statement more quantitatively, one has to be a little more specific. The relevant experiments that I will consider here would imply high precision measurements of special longitudinal polarization asymmetries on top of Z resonance in e^+e^- scattering. Since these quantities would actually measure certain combinations of Z couplings to fermions, I will try to introduce them and justify their use starting from a short review of some of the existing experimental evidence in favour of the Standard Model in this specific Z couplings sector (Section 2). In Section 3 I will show the main properties of the relevant asymmetries that would make them, potentially, powerful tests of the Standard Model. Finally, in Section 4, I will show why these quantities could also act as unique and clean detectors of some specific and theoretically motivated models of New Physics, in particular, as one would imagine, of models that lead to a substantial modification of the Z couplings to fermions already at the tree level.

Z COUPLINGS TO FERMIONS IN THE MINIMAL STANDARD MODEL

As of today, all the known electroweak experiments do not contradict the commonly used minimal version of the Standard $SU(3)_C \times SU(2)_L \times U(1)_Y$ Model, i.e., that in which three families of quarks and leptons interact via exchanges of massive and massless gauge bosons, in the (virtual or real) presence of one physical Higgs scalar belonging to an $SU(2)_L$ doublet². It is true, though, that the

Z couplings to fermions varies from ten per cent (lepton case) to more than thirty per cent (quark case). Clearly, a more accurate comparison between theory and experiment would be rather interesting.

POLARIZED ASYMMETRIES ON Z RESONANCE AS MEASUREMENTS OF Z COUPLINGS TO FERMIONS IN THE MSM

The previous results on couplings⁴ were all derived from measurements of forward-backward asymmetries in e^+e^- scattering at energies well below the Z resonance. This suggests, intuitively, that measuring asymmetries on Z resonance, where statistics will be much higher, would be a good way to obtain improved information on Z couplings. To see this in some detail, one has only to compute a number of differential cross-sections in the very simplified Z exchange approximation, certainly a good one on resonance. Allowing the initial beam to be longitudinally polarized, with polarization degree P, one can define the following polarization asymmetries:

$$A_{LR}^f \equiv A = \frac{1}{P} \frac{\sigma_P^f - \sigma_{-P}^f}{\sigma_P^f + \sigma_{-P}^f} \quad (9)$$

$$A_{FB}^f(\text{pol}) \equiv A^f = \frac{1}{P} \frac{(N_{FP}^f - N_{\bar{F}P}^f) - (N_{B\bar{P}}^f - N_{B\bar{P}}^f)}{(N_{FP}^f + N_{\bar{F}P}^f) + (N_{B\bar{P}}^f + N_{B\bar{P}}^f)} \quad (10)$$

(F, B $\equiv$ forward, backward)

These asymmetries have rather special features that make them particularly interesting and that have been thoroughly discussed in recent papers^{5,6} and also in a more complete dedicated review on polarization at LEP⁷. The simplest and most spectacular property is the fact that, to a very good approximation, the first asymmetry, Eq. (9), measures a certain combination of couplings of Z to the initial electron state, while the second quantity, Eq. (10), measures their combination of couplings of Z to the final f state. In other words:

$$A = \chi_e + \text{"small"} \quad (11)$$

$$A^f = \frac{3}{4} \chi_f + \text{"small"} \quad (12)$$

where

$$\chi_i = \frac{-2v_i a_i}{v_i^2 + a_i^2} \quad (13)$$

is the i-chirality and the "small" terms are computable (and have been computed^{5,6}) to one loop. Note that, in the case of an

unpolarized forward-backward asymmetry, the product of the initial and of the final coupling is always measured, which does not allow such a clear separation as in the polarized case.

In practice, once the experimental error on Eqs. (9) and (10) is estimated, the residual theoretical uncertainty comes mostly from the fact that the top and the Higgs masses are (still) unknown⁸. This leads to a theoretical prediction for the asymmetries represented in Figs. 2 and 3 for $t = b, c$. As one sees, a comparison between theory and experiment would now represent a rather severe test for the Minimal Standard Model, roughly a factor ten more precise than in the cases illustrated in Fig. 1 and in Eqs. (4)-(6). In particular, assuming that the MSM is absolutely correct, one might derive stringent self-consistency bounds for the values of the top and Higgs masses from a measurement of A (A^f) are much less sensitive to variations of these parameters). This would lead to several interesting possibilities, the most popular of which is that of combining the measurement of A with that of the W mass⁹ to obtain, in the plane of these observables, a bidimensional figure that represents, so to say, the MSM "fiducial domain" shown in Fig. 4. If the experimental point should fall outside the domain, the MSM would be in trouble, and one would definitely need some kind of New (or alternative?) Physics. If this were the case, then the previous asymmetries would, again, play a rather unique rôle.

POLARIZED ASYMMETRIES AS CLEAN DETECTORS OF NEW GAUGE VECTOR BOSONS

The fact that the previously defined polarized asymmetries might be used to identify signals of New Physics free of possible contaminations from unknown MSM effects (in particular from a possible large top mass) was first stressed by Gvetic and Lynn⁹. The simple starting point is the observation that, on resonance, the potentially dangerous one-loop oblique corrections (that contain a term quadratic in the top mass) appear in all asymmetries as a universal "block" multiplied by known (different) numerical coefficients. Therefore, one can immediately define two linear combinations of A, A^f for which this effect has been washed out. Numerically, it turns out that to a very good approximation these combinations can be written as:

$$\tilde{A}^b = A^b - \frac{1}{15} A \quad (14)$$

$$\tilde{A}^c = A^c - \frac{9}{25} A \quad (15)$$

The operation that kills the oblique corrections in Eqs. (14) and (15) has a number of fundamental and pleasant consequences. First of all, it obviously eliminates automatically every similar potentially dangerous contribution coming from possible new heavy and split families or "sfamilies"⁹. Next, it eliminates in practice, i.e., it reduces drastically the dependence of the Born terms of Eqs. (14) and (15) on the Salam-Weinberg angle θ_W^2 , making them practically equal

to (known) constants¹⁰. Finally, it eliminates also a certain possible dependence (at tree level) on a hypothetically more complex Higgs structure of the theory¹¹. Since the contributions of QED and of the strong interaction of the final states is completely under control^{5,6,12,13}, the conclusion emerges that the only possible deviations of the experimental measurements of $\tilde{\chi}(b,c)$ from the "known" predictions can come from models of New Physics which can produce effects different from the previously discussed kinds of contaminations (heavy top, etc.). An immediate and almost obvious possibility in this case is represented by those models that predict the existence of (at least) one new vector boson Z' . One of the effects of such models is, in fact, that of generating a mixing between the mathematical MSM Z_0 and the new Z'_0 , leading to a physical Z whose couplings with fermions would be different from those of Z_0 . This difference would already appear at tree level, and from the previous considerations a couple of "natural" observables to be measured in order to reveal such an effect appear to be the polarized asymmetries $\tilde{\chi}(b,c)$.

A final and welcome feature of Eqs. (14) and (15) appears when the (large) class of the relevant models that predict the existence of a new Z' is considered. It turns out, in fact, that for all those "alternative" models based either on a composite Z picture¹⁴ or on a strongly interacting electroweak sector¹⁵ (that would both allow for a description of electroweak processes without any Higgs) the overall strength of the Z couplings, Eq. (1), is simply to redefine the overall effects cannot influence Eqs. (14) and (15) and, as a consequence of this, $\tilde{\chi}(b,c)$ would be "blind" to this kind of New Physics. In practice, therefore, they would only feel effects coming from a new Z' of extended gauge origin, that are in general more complicated than the previous ones.

The complete discussion of these effects has been given in Ref. 11 for the cases of a Z' generated from a previous E_6 symmetry¹⁶ or from a left-right symmetric $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model¹⁷. In general, both cases can be characterized by two free parameters, i.e., by a mixing angle θ_M and a second suitably chosen quantity. Defining the two observables:

$$x = \tilde{A}^{(b)(exp)} - \tilde{A}^{(b)(MSM)} \quad (16)$$

$$y = \tilde{A}^{(c)(exp)} - \tilde{A}^{(c)(MSM)} \quad (17)$$

one would therefore expect that a certain set of possible non-zero values of the two free parameters of each model selects a certain domain in the (x,y) plane. This is actually true for the E_6 case, that can be characterized by two angles θ_M, β , where β is free and θ_M is in fact bounded for every β value by the already existing

experimental limitations¹⁸. The expressions of x, y in terms of θ_M, β read¹¹:

$$x^{(E_6)} = \frac{2}{15} \theta_M \left[\frac{\sqrt{10}}{3} \sin \beta + \frac{10}{16} \cos \beta \right] \quad (18)$$

$$y^{(E_6)} = \frac{9}{50} \theta_M \left[-\frac{\sqrt{10}}{3} \sin \beta + \frac{10}{16} \cos \beta \right] \quad (19)$$

Taking into account the existing limitations leads to the following Fig. 5¹⁹; clearly, if the experimental point fell into this characteristic "banana", there would be a strongly unambiguous evidence in favour of this model for New Physics.

A final gift provided by $\tilde{\chi}(b,c)$ becomes evident if one repeats the previous analysis for the most general left-right symmetric case. Using the notation of Durkin and Langacker²⁰, one easily finds:

$$\delta A^{(LR)} \simeq \theta_M \left[\alpha - 2/\alpha \right] \quad (20)$$

$$\delta A^{b(LR)} \simeq \theta_M \left[\frac{1}{5} \alpha + \frac{2}{15} \frac{1}{\alpha} \right] \quad (21)$$

$$\delta A^{c(LR)} \simeq \theta_M \left[\frac{18}{25} \alpha - \frac{9}{25} \frac{1}{\alpha} \right] \quad (22)$$

where the parameter α is defined as

$$\alpha = \sqrt{\left(\frac{g_R}{g_L}\right)^2 \left(\frac{1 - \frac{1}{3} \frac{g_W^2}{g_L^2}}{\frac{1}{3} \frac{g_W^2}{g_L^2}}\right) - 1} \quad (23)$$

and depends on the arbitrary ratio g_R/g_L . The (surprising?) bonus is that, in the combinations of asymmetries that are considered, Eqs. (14) and (15), the dependence on θ_M and α is the same (apart from known coefficients), i.e.:

$$x^{(LR)} = 4/15 \theta_M \left[\alpha + 1/\alpha \right] \quad (24)$$

$$y^{(LR)} = 9/25 \theta_M \left[\alpha + 1/\alpha \right] \quad (25)$$

This means that, in the (x,y) plane, the most general left-right symmetric model, for every choice of g_L/g_R will fall onto the "universal left-right symmetric line"¹⁹:

$$\left[y/x \right]^{(LR)} = 27/20 \quad (26)$$

represented in Fig. 5. This final spectacular property would therefore allow one to use a measurement of $\tilde{\chi}(b,c)$ as a first immediate and simple yes/no test of this class of models of New Physics.

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FIGURE CAPTIONS

- Fig. 1 Experimental values of a_b/a_b^{MSM} , a_c/a_c^{MSM} taken from Ref. 4.
- Fig. 2 Theoretical prediction of A versus M_Z , taken from Ref. 5.
- Fig. 3 Theoretical predictions of $A^{b,c}$ versus M_Z , taken from Ref. 6.
- Fig. 4 Plot of A versus M_W for the typical value $M_Z = 92$. Data are from Ref. 5. The figure is taken from Ref. 2.
- Fig. 5 Allowed region for an E_6 -generated Z' in the (x,y) plane, taken from Ref. 19.

CONCLUSIONS

The conclusion of this talk is that precision measurements of the longitudinal polarization asymmetries, Eqs. (9) and (10), on top of Z resonance, can provide very severe tests of the MSM but can also eventuate spectacular and unexpectedly simple signals of some model of New Physics beyond it, in a realistic and reasonably clean way. This certainly explains the vast theoretical and experimental effort in the related area and authorizes a reasonably optimistic person to conclude by saying:

"SE SON ROSE, FIORIRANNO"

which, in the specific case, means that if reality corresponds to these theoretical dreams, it will make itself evident manifestly and beautifully in this spin physics sector.

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- Fig. 1 -

- Fig. 2 -

- Fig. 3 -

- Fig. 5 -

- Fig. 4 -