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Status and Future Prospects in Searches for New Interactions in Neutron and Nuclear Beta-decay, Muon- and Pion-decay

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The interest, the status and the perspectives of various experiments in neutron and nuclear beta-decay, muon-decay and pion-decays are discussed. The talk is segmented into a discussion of the decay-rates and of the energy-spectra and correlations. The impact on various scenarios of "new physics" is briefly mentioned ; left-right symmetric models are discussed in more detail and the informations gained from the considered experiments is compared to those from other sources.

1 Decay-rates

1.1 Muon-decay

The muon decay rate $(1/\tau_\mu)$ is directly related to the Fermi coupling constant G_F, a fundamental quantity of the Standard Model : $(1/\tau_\mu) = G_F$K where the factor K contains mass-terms and radiative corrections [1]. It was stressed by L.B. Okun that G_F is an important quantity as it is directly related to the vacuum expectation value of the Higgs field which sets the fundamental mass-scale of the Standard Model [2]. The relative precision to which G_F was known was, up to recently, 17 ppm, where 9 ppm is of experimental origin and 15 ppm was an estimate of the 2-loop corrections in the factor K. Recently, these corrections were evaluated to high precision [3] and by now the imprecision in G_F is dominated by the experimental error.

Various groups plan to remesure the muon decay constant with improved precision. In particular, a Bologna-CERN-ETH-PSI-ULB/LBL collaboration developed a fine-grained fiber scintillation target and will use the unique muon beam of PSI to measure the decay constant to a precision of 2 ps, an order of magnitude improvement over the present one [4].

It should be noted that the relation between the decay constant and G_F could be modified by deviations from the Standard Model [5]. E.g. a right-handed scalar coupling of a relative importance of p would modify G_F by 0.02 p ! As the transverse polarization of the decay positrons is sensitive to such deviations

[a]The numerous colleagues who kindly helped providing information and criticism are thankfully acknowledged at the end of the text

from the Standard Model, an experiment is performed presently at PSI to measure p or to set an upper limit to it at the %-level [6].

1.2 Pion beta-decay

The importance of the precision study of superallowed pure Fermi decays to check the unitarity of the Cabibbo-Kobayashi-Maskawa matrix was stressed by I. Towner in this conference [7]. He noted also that the investigated nuclear beta-decays results in a 2.2 standard deviation from unitarity. He stressed also that the error of this determination is dominated by radiative and nuclear structure corrections.
In order to overcome the need for these corrections, an experiment is under way to determine the rate of the superallowed Fermi-decay of the pion [8]. A measurement of this branching ratio, with a precision comparable to the ones obtained in nuclear beta-decays, is very difficult as this decay branch is only 10^{-8}. Having constructed a spectrometer of nearly 4 π coverage and profiting from the high pion flux at PSI, D. Pocanic and his colleagues aim, in the first phase of the experiment, to obtain a 0.5 % precision on the branching ratio.

1.3 Ratio of the electron/muon decay-rate of the pion

In the Standard V-A Model this ratio is helicity-suppressed to the 10^{-4} level and its precise determination verifies not only the universality of the electron/muon coupling strenghts, but also the absence of particles beyond the Standard Model [9 10].
The combination of the TRIUMF [9] and PSI [11] precision experiments results in a ratio of (1.2312 +/- 0.0037)10^{-4} to be compared to the Standard Model prediction of (1.2352 +/- 0.0005)10^{-4}. The comparison verifies the universality of the electron-muon coupling (g_e/g_μ = 0.9989 +/- 0.0016) and excludes new particles with mass-bounds in the TeV-region (cfr references quoted above). As the precision of the test is now limited by the experimental contribution, a 6-fold improvement in the measurement is planed at TRIUMF [12].

1.4 Neutron life-time

The decay rate of the neutron is an interesting quantity because of its cosmological impact on the synthesis of the light elements [13] and because, combined with the electron asymmetry, it provides, in the Standard Model, a direct determination of the semileptonic vector- and axial-vector coupling constants (cfr 2.3.1). The confrontation of the vector coupling obtained by this procedure

with the one extracted from the decay rate of the superallowed Fermi transitions can observe (or place constraints) on physics beyond the Standard Model (cfr 3.3).
P. Geltenbort communicated to this conference the most recent result of L.N. Bondarenko et al. [14] : τ_n = 885.4 +/- 0.9 (stat) +/- 0.4 (syst.) sec resulting in a world average of τ_n = 885.8 +/- 0.9 sec. Improvement of this precision are planed both at ILL [15] and at NIST where a factor of 10 improvement is expected using superfluid helium both to produce ultracold neutrons and to detect their decay [16].

2 Spectra and Correlations

2.1 The Michel parameters in muon-decay

The Michel-parameters are phenomenological quantities which describe the various observables in muon-decay [5]. They can be related to the leptonic coupling constants, only one of them (g^V_{LL}) being non-zero in the Standard Model. As a consequence, precision measurements of these parameters test physics beyond the Standard Model [17], cfr. also section 3.3.
In addition to a measurement of the ρ parameter by the MEGA collaboration which is under analysis [18], three different precision experiments are progressing (D. Gill et al., TRIUMF Exp. E614, W. Fetscher et al., PSI Exp. R-94.10 and R. Prieels et al., PSI Exp. R-97.06). In table 1, their precision aims are compared to the present precision of the Michel parameters.

2.2 Electron-neutrino directional correlations in beta-decay

We refer to the paper of J.D. Jackson et al. [19] for the dependency of the various beta-decay observables on the four-fermion coupling constants C_i and C'_i. In the Standard Model only $C_V = C'_V = 1$ and $C_A = C'_A$ are non-zero and so precision measurements of the various observables can observe or constrain physics beyond the Standard Model [20 21].
In particular, electron-neutrino directional correlation measurements in pure Gamow-Teller (Fermi) transitions can observe or constrain the absolute value of $C_{T(s)}$. Such couplings could originate in the exchange of leptoquarks or charged scalar bosons [20]. The pure Gamow-Teller decay of ^{6}He was investigated by C.H. Johnson *et al.* [22]. The radiative corrections to this decay were revisited recently [23] and it is now the corrected experimental value of the correlation coefficient a = 0.3310 +/- 0.0030 which should be compared to the one expected for a pure axial interaction : a = 0.3333. The experiment allows a tensor coupling-strength which can be up to 0.8 % (at 68 % CL) of the axial one.

Table 1: Present precision (in 10^{-3}) of the various Michel parameters and precision aims of the ongoing experiments

	Part. Data 98	TRIUMF E614	PSI R-94.10	PSI R-97.06
ρ	3	0.1		
$P_\mu \xi$	9	0.14		
δ	4	0.3		
$\xi\delta/\rho$	3			
η	13	3	~ 3	
P_T (T-odd)	23		~ 5	
P_T (T-even)	85		~ 30	
P_L : [ξ']	45			
P_L : [ξ"/(ξ' ξ)]	360			~ 2

In pure Fermi decays the correlation coefficient was deduced from the recoil energy of the residual nucleus observing either its gamma-decay [24] or its proton-decay [25]. This latter technique was further improved [26] and reached by now a statistical precision of 0.005 on the correlation coefficient. The systematic contribution to the error is still under investigation and variants of the experiment are considered at other laboratories.

Because of the small recoil-energy to be observed, optical or electromagnetic traps are particularly promising for these experiments. The most advanced project is the trapping of ^{38m}K at TRIUMF which will allow to constrain possible scalar couplings [27]. Another similar experiment is in preparation at LANL on ^{82}Rb [30]. Electromagnetic traps with similar objectives are under construction at ANL [28] and ISOLDE [29]. If the trapped nuclei are polarized, they can also be used for asymmetry-measurements [30].

2.3 Polarization observables

Neutron beta-decay asymmetries

Polarized neutrons allow to observe both the electron and neutrino emission asymmetries (A_n and B_n). In the Standard Model these asymmetries depend only from the ratio of the axial- and vector coupling constants $\lambda = G_A/G_V$, the dependency of A_n being stronger than that of B_n : $\sigma_A/\sigma_\lambda = 0.36$ and $\sigma_B/\sigma_\lambda = 0.08$. As a consequence a measurement of A_n, combined with that of

the neutron life-time, allows a determination of G_V, i.e. a verification of the unitarity of the Cabibbo-Kobayashi-Maskawa matrix independently of nuclear structure corrections (cfr 1.2). Using G_V obtained from nuclear beta-decay, it allows a control of left-right symmetric extensions of the Standard Model (cfr 3.3). A measurement of B_n, practically independent of G_A/G_V, is however better suited for this second purpose.
Unfortunately the various results of the A_n-measurements scatter beyond statistics. Let us mention for illustration the four latest (and most precise) results : A_n = - 0.1160 +/- 0.0014 [31], A_n = - 0.1189 +/- 0.0012 [32], A_n = - 0.1135 +/- 0.0014 [33] and finally, presented at this meeting, A_n = - 0.1187 +/- 0.0008 [34]. The weighted average of all the available results is - 0.11721 +/- 0.00053 ; the χ^2/n is however too high : 3.3. A value with inflated errors (0.001) will be used in section 3.3 for further analysis ; the situation is however unsatisfactory. One of the critical points of the experiment is the determination of the neutron polarization ; experiments are under way at ILL to compare various methods to determine this polarization [35]. Also relative precisions of about 1 % for A_n are claimed but the corrections to the measured values were of the order of 10 % (about 1% in the case of PERKEO II 98). A novel and ambitious experiment is started at LANSCE which, in its first phase, will measure A_n to 0.2 % with corrections of only 0.16 % [36]. The increase of neutron-flux expected from the superfluid helium moderator (cfr 1.4) will further increase the possibilities of the experiment and allow to measure also other neutron-decay observables.
For B_n a final result was submitted to this conference by I. Kuznetsov *et al.* ($B_n = 0.9796 +/- 0.0044$) which results in a world average of $B_n = 0.9816 +/- 0.0040$. This value is somewhat smaller than the (V-A)-prediction ($\Delta = 0.0064 +/- 0.0041$) which has an impact on the discussions on right-handed currents (section 3.3).
We shall not expand here upon the measurements of the emission-asymmetry (and absolute electron-polarization) measurements in nuclear decays [21]. As these are absolute measurements, it is difficult to obtain a good accuracy. Various corresponding experiments are however in preparation (cfr our remarks on traps in section 2.2).

Beta-decay asymmetry/polarization correlations

2.3.2.1. Nuclear beta-decay
A novel type of experiments was proposed by P. Quin and T. Girard [37] which consists in comparing the longitudinal polarization of the decay-electrons (positrons) emitted in opposite directions by polarized nuclei. (A variant was proposed by J. Govaerts et al. [38], consisting in the comparison of the electron-polarization

for polarized and unpolarized nuclei). These experiments are relative experiments and so avoid the need to determine the absolute polarization of the sample. They are, moreover, very sensitive to physics beyond the Standard Model [38]. E.g. for a pure Gamow-Teller transition and neglecting recoil order terms, the Standard Model value of the polarization ratio R_0 takes the form [38 39] :

$$R_0 = \frac{P_L(-J)}{P_L(J)} = \frac{1}{1 - A_{exp}} \frac{\beta^2(2 - A_{exp}) - A_{exp}}{\beta^2(2 - A_{exp}) + A_{exp}} \tag{1}$$

where β is the positron velocity and A_{exp} is the experimental asymmetry which, as we shall see, has not to be known with good precision. The ratio of the experimental value of R compared to the Standard Model value R_0 is then :

$$\frac{R}{R_0} = 1 - k_A \frac{\Delta_A}{1 + 4\frac{A_{exp}}{\beta^2(2-A_{exp})+A_{exp}}\Delta_A} \tag{2}$$

where Δ_A is a measure of a deviation from the Standard Model and

$$k_A = 8\frac{\beta^2 A_{exp}(2 - A_{exp})}{\beta^4(2 - A_{exp})^2 - A_{exp}^2} \tag{3}$$

is an enhancement factor which can be large indeed if A_{exp} is close to unity (i.e. if the transition is well chosen and the polarization is sizeable). An enhancement factor of k_A = 5-7 was readily achieved in the study of ^{117}In [40 41] and higher enhancement factors are hoped for in a similar experiment in preparation at CERN-ISOLDE (CERN/ISC 96-11, ISC/P80). Similar precisions on Δ_A (though with a smaller enhancement factor k_A) were obtained at PSI with ^{12}N [42 39]. At the level of precision obtained the impact of the nuclear structure dependent recoil-order corrections is negligible. The impact of these measurements on left-right symmetric models will be illustrated in section 3.3.

2.3.2.2. Muon-decay

A similar situation can be expected in muon-decay with the additional (experimental) bonus that muons are produced strongly polarized in pion-decay at rest. Indeed, for "backward" positrons near the spectrum end-point (the reduced positron-energy x=1), we have [43] :

$$P_L(x = 1, cos\theta = -1) = \xi' + \frac{-P_\mu \xi}{1 - P_\mu} \frac{\xi'' - \xi\xi'}{\xi} \tag{4}$$

where the symbols ξ, ξ' and ξ'' are Michel parameters introduced already in section 2.1. Note that the combination $(\xi'' - \xi\xi'/\xi)$ is zero in the Standard Model and that the enhancement factor $(-P_\mu\xi)/(1 - P_\mu\xi)$ can be large for strongly polarized muons. We mentioned already in section 2.1 the PSI experiment R-95-06 of R. Prieels et al., which will exploit this sensitivity to search physics beyond the Standard Model. This will be further illustrated in section 3.3.

3 Impact on New Physics beyond the Standard Model

3.1 Exotic fermions, charged Higgs, s-lepton exchange

We did not expand on these scenarios of physics beyond the Standard Model and refer the reader to the recent review paper of P. Herczeg [20] and to the many references provided in it.

3.2 Leptoquark exchange

In view of the interest raised recently in scenarios involving leptoquarks, let us stress (in addition of refering agin to the review-paper of P. Herczeg), that the helicity-dependent observables such as the ones discussed in section 2.3.2.1, allow also to constrain masses and coupling-strength of various classes of leptoquarks [21 44 45]

3.3 Left-right symmetric model

Soon after the discovery of parity-violation in weak interactions and its incorporation into the $SU(2)_L$x U(1) gauge-group of the Standard Model, scenarios were proposed to recover parity-symmetry at higher energies (for a discussion of these attempts and corresponding references we refer to the review-papers of P. Herczeg as well as J. Deutsch and P. Quin already quoted). For illustration we shall first consider the so-called manifest left-right symmetric models, which contain only two parameters and discuss in a second section the generalization of these models.

Manifest left-right symmetric models

3.3.1.1. Nuclear beta-decay
In this model (refs. cfr. above) a second gauge boson is introduced with a mass (m_2) larger than that of the observed W (m_1 = 80 GeV). This second gauge boson has a predominantly right-handed coupling. Formally the flavor coupling states $W_{L(R)}$ are written as

$$W_L = cos\zeta W_1 + sin\zeta W_2 \qquad W_R = -sin\zeta W_1 + cos\zeta W_2 \tag{5}$$

(the mixing-angle ζ being small). We shall introduce the notation $\delta = (m_1/m_2)^2$.

Writing the left(right) handed fermion covariants as L(R), for small mixing and $q^2 << m_1$, we obtain a hamiltonian of the following form :

$$\begin{aligned} H &= (g^2/8)\left\{\left[\frac{cos^2\zeta}{q^2+m_1^2}+\frac{sin^2\zeta}{q^2+m_2^2}\right]LL \right. \\ &\quad +\left[\frac{sin^2\zeta}{q^2+m_1^2}+\frac{cos^2\zeta}{q^2+m_2^2}\right]RR \\ &\quad \left. + sin\zeta cos\zeta\left[-\frac{1}{q^2+m_1^2}+\frac{1}{q^2+m_2^2}\right][LR+RL]\right\} \qquad (6) \end{aligned}$$

One notes immediately that for small momentum-transfer q the left-handed coupling will dominate (as readily observed). For high values of the momentum-transfer however ($q^2 \cong m_2^2$) the interaction becomes parity-symmetric. Traces of this "primordial" recovery of mirror-symmetry could eventually be observed even in the laboratory, at small q^2 , as a small deviation from full parity-violation.

The first investigations of this eventuality are due to M.A.B. Beg et al [46 47 48]. Early decay-asymmetry measurements of Ne^{19} and of the neutron seemed to indicate a deviation from the Standard Model at the 2.5 σ-level which could have been explained by the interplay of a right-handed gauge-boson in the 250 GeV mass-region [49 50]. The conclusion drawn from the Ne^{19}-asymmetry is very sensitive to the ft-value of the transition ; the most precise result of the neutron-asymmetry measurements which dominated this conclusion was since modified (cfr 2.3.1) illustrating the difficulty of absolute parity-symmetry tests. Prompted by this observation, relative parity-violation tests were initiated. The comparison of the longitudinal positron-polarisation of Fermi- and Gamow-Teller emitters [51 52] gave strong constraints in the (δ - ζ)-plane but did note exclude the possible non-zero value of δ . This is illustrated in Fig. 1 which shows also the other exclusion regions provided by the most up-to-date values of both absolute and relative measurements. This figure shows also the constraint obtained in the beta polarization/asymmetry measurements discussed in section 2.3.2.1.

The exclusion plot combining all nuclear beta-decay tests is shown (at 90 % CL) in Fig. 2. No indication for a predominantly right-handed gauge boson can be noted, the lower limits of its mass being 320 GeV (at 90 % CL). Let us note the ISOLDE-experiment mentioned in section 2.3.2.1 aims at improving this limit to about 450 GeV.

This can be compared to the interesting limits deduced from the energetics of SN1987A which (provided the right-handed neutrino is light enough) could not accomodate right-handed bosons heavier than about 500 GeV (unless they are in the inaccessible multi-TeV region) [53].

3.3.1.2. Muon-decay

For the indications that muon-decay observables provide on manifest left-right symmetric models we recall the references given in section 2.1 and the note of J. Govaerts [43]. A mesurement of the positron asymmetry near the end-point of the spectrum provided a value of $P_\mu \xi\delta/\rho = 0.99790$ +/- 0.00088 [54], 2.4 standard deviations away from the Standard Model value of 1. Considering however the possible systematic effects involved in this absolute measurement, the authors do not consider this deviation as genuine and (for $\xi = 0$) derive a mass limit of 430 GeV to the right-handed gauge-boson. The TRIUMF experiment E614, also an absolute one, has a precision aim of 800 GeV.
The relative asymmetry-polarization experiment PSI-R 97-06 is also sensitive to right-handed gauge-bosons (cfr. proposal PSI R-97-06 and the quoted note of J. Govaerts). Considering that $(\xi''/\xi\xi') - 1 = 4\delta^2$, a first phase of the experiment (a relative one !) is expected to provide already an upper limit of 500 GeV.

3.3.1.3. Constraints of other origin

The $K_L - K_S$ mass-difference constrains the right-handed gauge boson mass in manifest left-right symmetric models to 1.6 TeV [55] or even above 3 TeV [56]. Direct collider-searches of a second gauge-boson yielded also upper limits of 650 GeV (at 95 % CL) by CDF [57] and 720 MeV (at 95 % CL) by DO [58].
Let us note that limits derived from the absence of neutrinoless double beta-decay [59] do not apply in our scenario of light right-handed neutrinos (cfr. 3.3.2).

Generalized left-right symmetric models

In generalized left-right symmetric models the parameter-space (δ, ζ) is enlarged allowing for differences of the gauge-couplings, of the Cabibbo-Kobayashi-Maskawa matrix elements and of the (massif) neutrino mixing in the left- and right-handed sectors. In addition to the review papers and other references already quoted, we wish to call attention to the note of P. Langacker and S. Uma Sankar [60] who show not only that the mass-bound of the right-handed boson deduced from the $K_L - K_S$ mass difference can be avoided in these generalized models, but also that the mass-bound deduced from the absence of neutrinoless double-beta-decay does not apply for light right-handed neutrinos (the only ones one could hope to observe in low- and intermediate-energy experiments !).
As for the limits deduced from colliders, it was noted by P. Herczeg (private

communcication), that they limit the product of the production cross-section of the W-boson and its branching-ratio into lepton-pairs and that this provides a different combination of the parameters than the beta-decay or muon-decay observables [61 62]. We illustrate in Fig. 3 the effect of this difference assuming similar values for the Cabibbo-Kobayashi-Maskawa matrices of the two helicity-sectors, but assuming that the gauge-coupling ratio g_R/g_L differs from unity. As can be seen, for a ratio larger than 2, the beta-decay experiments become complementary to the collider-ones.
A similar conclusion can be drawn from a scenario where the gauge coupling constants are identical but the Cabibbo-Kobayashi-Maskawa matrix elements differ. In this scenario, illustrated in Fig. 4, the beta-decay experiments could exclude right-handed gauge-bosons of a mass similar to (or smaller than) the known one of 80 GeV. The consistency of such a scenario with other constrains was not yet explored [63].
Nuclear beta-decay tests have to assume light enough right-handed electron neutrinos. As the muon-decay tests have to assume this also for muon-neutrinos, the two types of experiments are complementary. It should also be noted that in muon-decay the asymmetry-measurement (PSI R-97.076) test different combinations of the right-handed neutrino sector [61] making these two experiments complementary in generalised left-right symmetric models.

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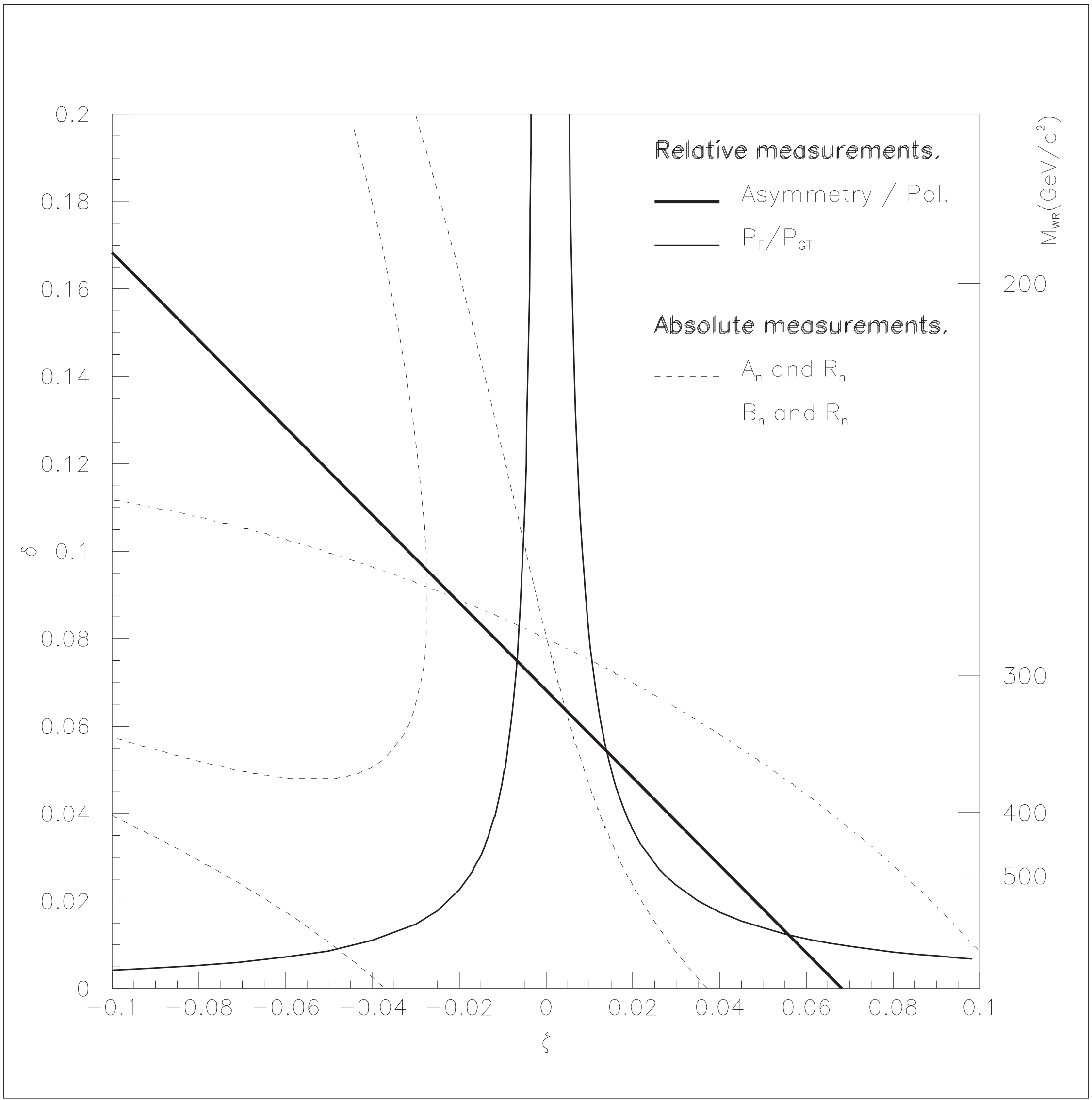

Figure 1: Comparative exclusion plots of the manifest left-right symmetric model parameters provided by various absolute and relative nuclear beta-decay tests at their present levels of precision (90% CL). R_n is the ratio of the neutron-and Fermi decay ft-values

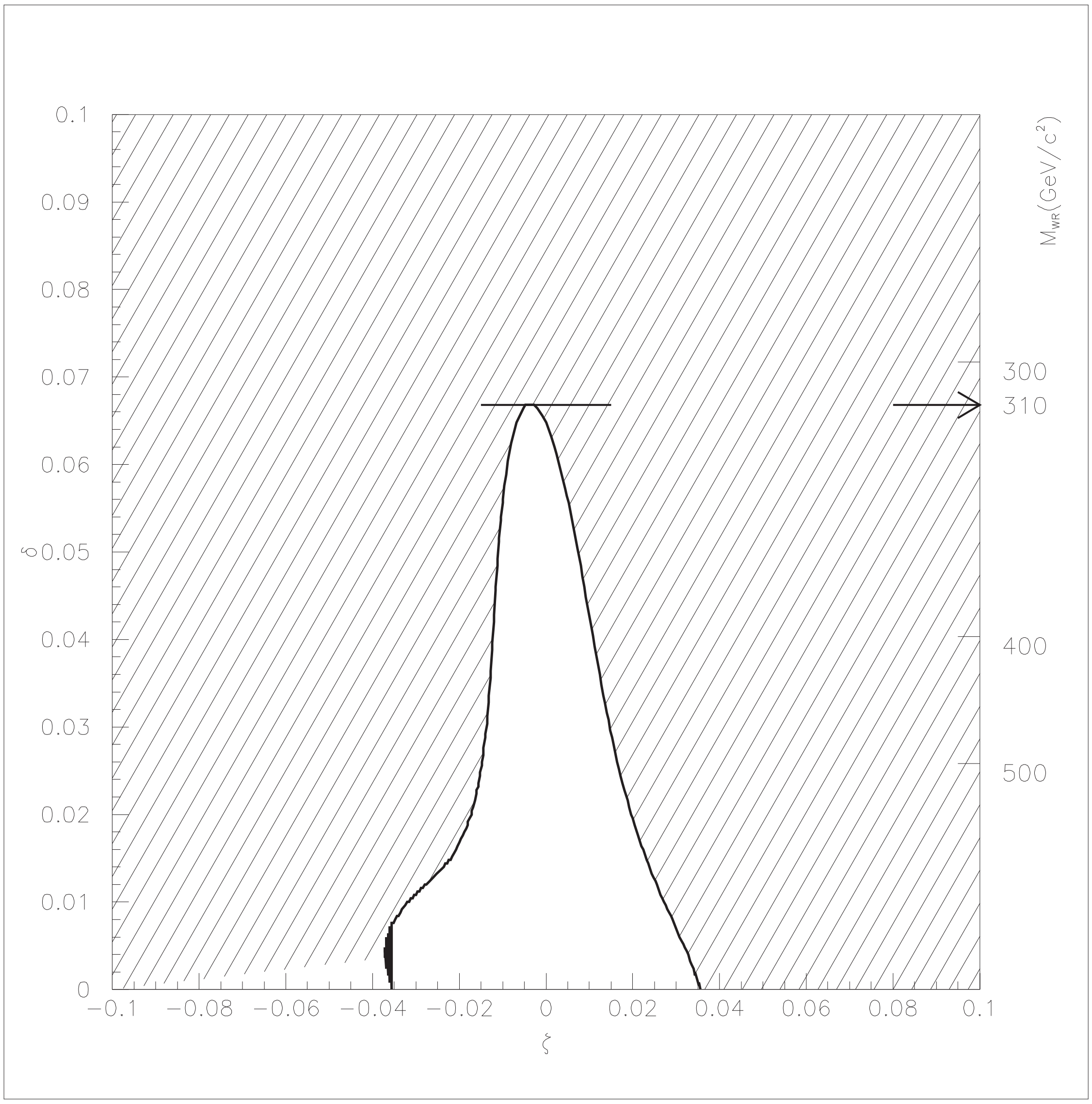

Figure 2: Combination of the constraints presented in Figure 1 on the 90 % CL. The lower limit of the right handed gauge boson mass (independently of the mixing parameter) is represented by an arrow.

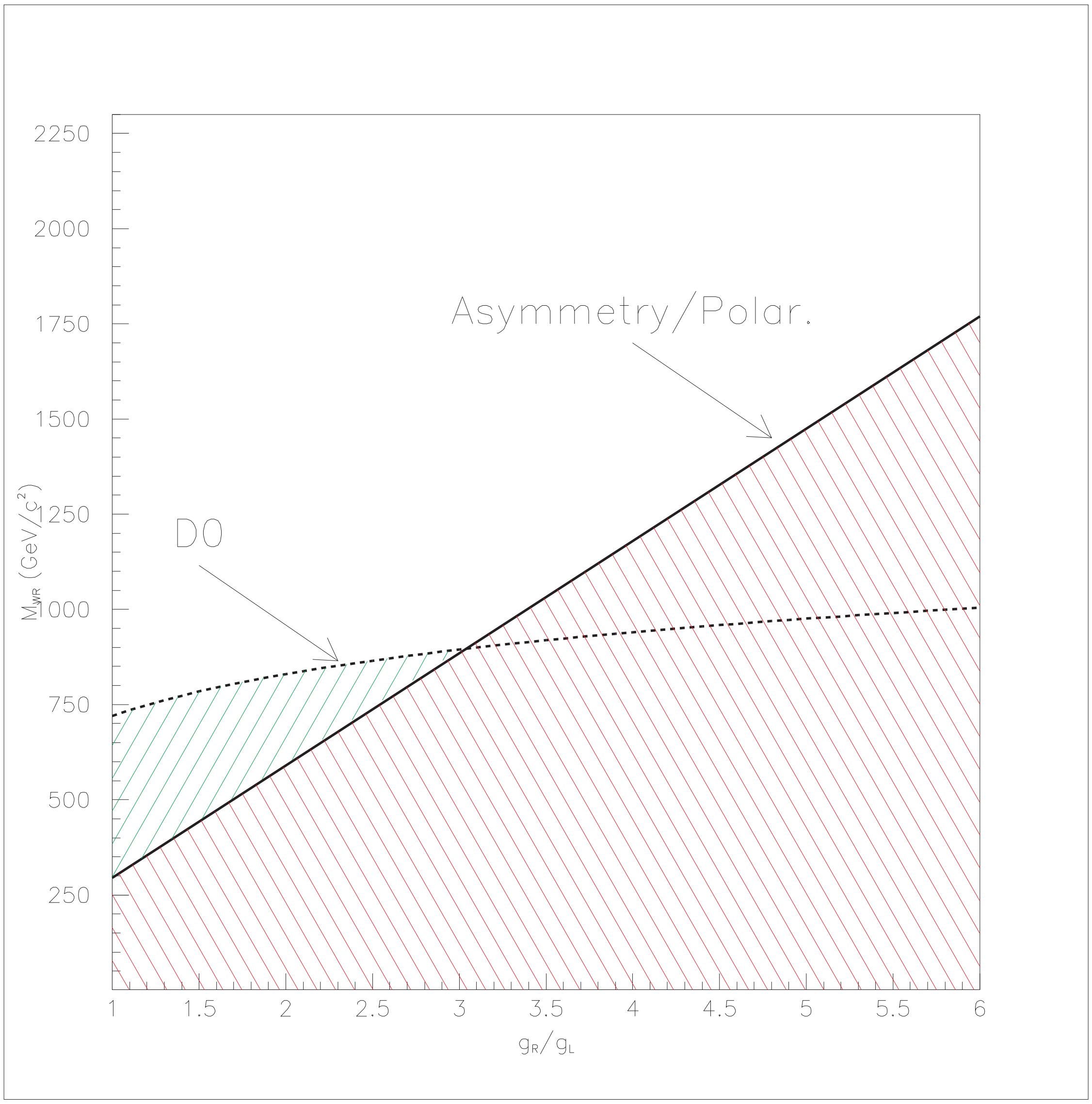

Figure 3: Right-handed gauge-boson limits (at 90% CL) deduced from collider-experiments and nuclear beta-decay of the type discussed in 2.3.2.1 (for $\zeta = 0$) as a function of the gauge-coupling ratio of the right (-left)-handed sectors.

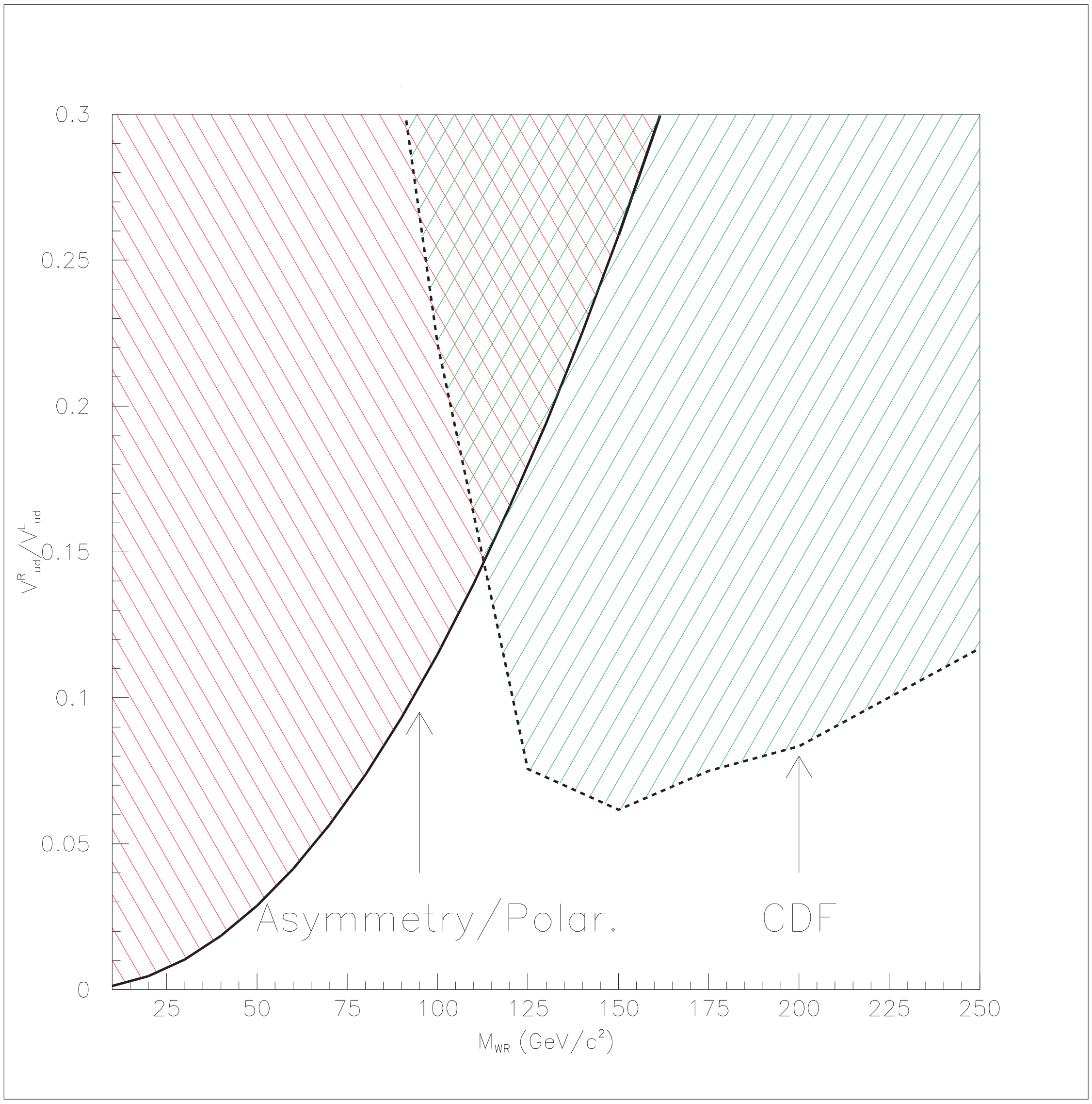

Figure 4: Exclusion-plots of the right(left)-handed Cabibbo-Kobayashi-Maskawa matrix-element ratio as a function of a (light) right-handed gauge-boson mass.