Prospects for precision measurements in nuclear $\beta$ decay at the LHC era

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Abstract

Precision measurements in nuclear $\beta$ decay offer a sensitive window to search for new physics beyond the standard electroweak model and allow also the determination of the fundamental weak vector coupling in processes involving the lightest quarks. Searches for new physics are also a strong motivation for experiments carried out at the high energy frontier reached at the most powerful particle colliders. It is instructive to confront results from the low energy and the high energy frontiers in order to look for possible complementarities and orient new avenues for experiments at low energies. We review here the status of constraints on new physics obtained from nuclear and neutron decays and compare them to those from other semi-leptonic processes and from the LHC. We stress the requirements of new precision experiments in $\beta$ decay in order to impact the search for new physics at the light of current and projected LHC results. We describe recent experimental results and ongoing developments in nuclear and neutron $\beta$ decay, with emphasis on their planned goals to improve present limits on exotic weak couplings.

1 Introduction

Searches for physics beyond the Standard electroweak Model (SM) are carried out both at the high energy frontier, attained at the most powerful particle colliders, as well as at the high precision frontier, looking for deviations from SM predictions in low background environments, where high sensitivities to small effects can often be achieved.

Nuclear $\beta$ decay and neutron decay have played a crucial role in the development of the “$V - A$” theory of the weak interaction, which was eventually embedded in the wider framework of the SM \[1, 2\]. Today, one of the main motivations for improving the experimental sensitivities of precision experiments in nuclear and neutron decays is the search for possible non-SM or “exotic” interactions that would manifest themselves through genuine scalar or tensor terms in semi-leptonic weak processes.

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The tests of the SM and the searches for New Physics (NP) in nuclear and neutron decays have been the subject of several recent reviews, with focus either on experiments in nuclear $\beta$ decay \[2, 3, 4, 5\] or on experiments using cold or ultra-cold neutrons \[6, 7, 8\].

A recurrent question addressed to precision measurements carried out at low energies concerns their sensitivity to NP as compared with results obtained at high energy, and currently at the Large Hadron Collider (LHC).

In this paper we review first the status of constraints on scalar and tensor couplings obtained from precision measurements in nuclear and neutron decays. We stress the observation that, for the most precise measurements, the only relevant parameter providing stringent constraints on exotic interactions is the Fierz interference term, through its contribution to other correlation coefficients.

We confront next the most precise results obtained in $\beta$ decay with constraints obtained from other semi-leptonic processes and also with results from the LHC\[9, 10, 11\], paying special attention to those observables that are linear on the exotic couplings. The use of an Effective Field Theory (EFT) framework allows us to bridge through the low energy and the high energy searches and to compare their sensitivities to new physics.

Considerable experimental effort using neutrons and nuclei are underway worldwide with the aim to improve the precision on decay observables. We describe recent experimental results and current developments in nuclear and neutron decays, and discuss their precision goals and sensitivities to exotic weak couplings.

2 Theoretical description

In the SM, semi-leptonic processes at the quark-lepton level are described by the exchange of the charged vector bosons, $W^{\pm}$. Since the mass of the bosons are significantly larger than the energies involved in nuclear and neutron $\beta$ decays, the interaction Lagrangian for these processes takes the usual $(V - A) \times (V - A)$ form

$$\mathcal{L}_{\text{SM}} = -\frac{G_F V_{ud}}{\sqrt{2}} \bar{e}_\mu (1 - \gamma_5) \nu_e \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d, \quad (1)$$

where $G_F$ is the Fermi coupling and $V_{ud}$ is the element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix involved in the weak coupling of the lightest quarks. This Lagrangian provides the framework for the calculations of observables to leading order, that will be compared with experimental results. However, due to the precision of current experiments, the calculation of SM predictions requires to take into account corrections to this contact form arising from the finiteness of the $W$ mass and from electroweak radiative corrections \[13, 12\].

For the inclusion of NP effects in nuclear and neutron $\beta$ decays, it is very useful to follow an EFT approach. This model-independent framework allows us to compare the sensitivity of these processes with other low-energy charged-current observables and also with measurements carried out at high energy colliders.

2.1 Quark-level Effective Lagrangian

Assuming that the particles not included in the SM are much heavier than the energy scales relevant for nuclear and neutron $\beta$ decay, they can again be integrated out along with the $W$
boson and the rest of heavy SM particles. The low-scale $O(1 \text{ GeV})$ effective Lagrangian for semi-leptonic transitions is then given by \cite{9,10}.

$$
L_{\text{eff}} = -\frac{G_F V_{ud}}{\sqrt{2}} \left[ (1 + \epsilon_L) \bar{e} \gamma_\mu (1 - \gamma_5) \nu_e \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d 
+ \epsilon_L \bar{e} \gamma_\mu (1 + \gamma_5) \nu_e \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d 
+ \epsilon_R \bar{e} \gamma_\mu (1 - \gamma_5) \nu_e \cdot \bar{u} \gamma^\mu (1 + \gamma_5) d 
+ \epsilon_S \bar{e} (1 + \gamma_5) \nu_e \cdot \bar{u} d 
- \epsilon_P \bar{e} (1 - \gamma_5) \nu_e \cdot \bar{u} \gamma_5 d 
+ \epsilon_T \bar{e} \sigma_{\mu\nu}(1 - \gamma_5) \nu_e \cdot \bar{u} \sigma^{\mu\nu}(1 - \gamma_5) d 
+ \tilde{\epsilon}_T \bar{e} \sigma_{\mu\nu}(1 + \gamma_5) \nu_e \cdot \bar{u} \sigma^{\mu\nu}(1 + \gamma_5) d \right] + \text{h.c.}.
$$

The $\epsilon_i$ and $\tilde{\epsilon}_i$ complex coefficients are functions of the masses and couplings of the new particles, in the same way that the Fermi constant $G_F$ is a function of the weak coupling and the $W$ mass. The specific expressions of these coefficients within the minimal supersymmetric standard model can be found in e.g. Ref. \cite{14}.

For the sake of generality we have included right-handed (RH) neutrinos in the low-energy particle content, but they can easily be removed setting $\epsilon_{L,R,S,P,T} = 0$. It is worth noticing that operators involving RH neutrinos contribute quadratically to the observables, what makes their effect on the experiments much smaller.

The effective Lagrangian in Eq. (2) describes the effect of NP not only in nuclear and neutron $\beta$ decay, but also in other processes like for example $\pi^\pm \rightarrow \pi^0 e^\pm \nu$. The details of the hadronization are obviously different, with different form factors needed in each process, but the underlying dynamics is the same.

After removing an overall phase, we have ten real couplings and nine phases that can be probed comparing precise low-energy experiments and accurate SM calculations. Given the smallness of these couplings it is useful to work at linear order in them to identify their main effect on the different observables. As explained above, in this approximation we can neglect the $\tilde{\epsilon}_i$ couplings, since they involve RH neutrinos. Moreover, in nuclear and neutron decays the pseudo-scalar coupling $\epsilon_P$ can also be neglected since the associated hadronic bilinear vanishes in the non-relativistic approximation. In this approximation the low-energy effective Lagrangian can be written as

$$
L_{\text{eff}} = -\frac{G_F V_{ud}}{\sqrt{2}} \left[ 1 + \text{Re}(\epsilon_L + \epsilon_R) \right] \times
\times \left\{ \bar{e} \gamma_\mu (1 - \gamma_5) \nu_e \cdot \bar{u} \gamma^\mu [1 - (1 - 2\epsilon_R) \gamma_5] d 
+ \epsilon_S \bar{e} (1 + \gamma_5) \nu_e \cdot \bar{u} d 
+ \epsilon_T \bar{e} \sigma_{\mu\nu}(1 - \gamma_5) \nu_e \cdot \bar{u} \sigma^{\mu\nu}(1 - \gamma_5) d \right\} + \text{h.c.},
$$

where an overall phase has been omitted.

Furthermore, in neutron decay it is usual to extract the axial-vector form factor $g_A$ (or the so-called mixing ratio in the case of nuclear decays) from experiments. The extracted quantity for the sake of simplicity we do not considered operators involving $\nu_\mu$ or $\nu_\tau$. The generalization is straightforward and the general formulae can be found in Ref. \cite{10}.
contains an unobservable NP contribution \[9, 15\]

\[ g_A \rightarrow g_A \operatorname{Re} \left[ \frac{1 + \epsilon_L - \epsilon_R}{1 + \epsilon_L + \epsilon_R} \right] \approx g_A [1 - 2\operatorname{Re}(\epsilon_R)] + \mathcal{O}(\epsilon^2) \ , \tag{4} \]

that can only be probed if a precise lattice calculation of \( g_A \) becomes available.

All in all, we see that there are six couplings left in this approximation:

- The real part of \( \epsilon_L + \epsilon_R \) that produces a shift in the overall normalization and can be absorbed in a redefinition of \( V_{ud} \), with the only consequence being the violation of the unitarity condition of the first row of the CKM quark mixing matrix, \(|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \neq 1\).

- The real parts of the scalar \( \epsilon_S \) and tensor \( \epsilon_T \) couplings that modify the energy distributions and CP-even correlation coefficients.

- The imaginary parts of the axial-vector \( \epsilon_R \), scalar \( \epsilon_S \) and tensor \( \epsilon_T \) couplings that modify CP-odd correlation coefficients.

These six couplings represent the only linear NP effects in nuclear and neutron \( \beta \) decay. Consequently we expect strong bounds on them, whereas weak bounds are expected to be obtained for the rest of the couplings.

### 2.2 Nucleon-level effective couplings

The next step in the theoretical description is matching the quark-level effective Lagrangian, Eq. (2), onto a nucleon-level effective Lagrangian. Working at leading order in momentum transfer, the neutron-to-proton matrix elements can be written as

\[ \langle p|\bar{u}\Gamma d|n \rangle = g_T \bar{\psi}_p \Gamma \psi_n \ , \tag{5} \]

with \( \Gamma = 1, \gamma_5, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu} \). Proceedings in this way, the Lee-Yang effective Lagrangian is obtained \[16, 17\] \[4\]

\[ -\mathcal{L}_{n\rightarrow pe^-\nu_e} = \bar{p} n \left( C_S \bar{e} \nu_e - C'_S \bar{e} \gamma_5 \nu_e \right) + \bar{p}\gamma_\mu n \left( C_V \bar{e} \gamma_\mu \nu_e - C'_V \bar{e} \gamma_5 \gamma_\mu \nu_e \right) + \bar{p}\sigma_{\mu\nu} n \left( C_T \bar{e} \sigma_{\mu\nu} \nu_e - C'_T \bar{e} \gamma_5 \sigma_{\mu\nu} \nu_e \right) - \bar{p}\gamma_5 n \left( C_A \bar{e} \gamma_5 \gamma_5 \nu_e - C'_A \bar{e} \gamma_\mu \nu_e \right) + \bar{p}\gamma_5 n \left( C_P \bar{e} \gamma_5 \nu_e - C'_P \bar{e} \nu_e \right) + \text{h.c.} \ . \tag{6} \]

\[4\] Notice that the original paper of Lee and Yang \[16\] uses a different definition of \( \gamma_5 \) that we do not follow here. The definitions of all the couplings, \( C_i^{(0)} \) used here and in Refs. \[15, 17\] are however the same.
The effective couplings $C_i, C'_i$ ($i \in \{V, A, S, T\}$) can be expressed in terms of the parton-level parameters as

$$C_i = \frac{G_F}{\sqrt{2}} V_{ud} C_i$$  \hspace{1cm} (7)

$$\overline{C}_V = g_V (1 + \epsilon_L + \epsilon_R + \tilde{\epsilon}_L + \tilde{\epsilon}_R)$$  \hspace{1cm} (8)

$$\overline{C}_V' = g_V (1 + \epsilon_L + \epsilon_R - \tilde{\epsilon}_L - \tilde{\epsilon}_R)$$  \hspace{1cm} (9)

$$\overline{C}_A = -g_A (1 + \epsilon_L - \epsilon_R - \tilde{\epsilon}_L + \tilde{\epsilon}_R)$$  \hspace{1cm} (10)

$$\overline{C}_A' = -g_A (1 + \epsilon_L - \epsilon_R + \tilde{\epsilon}_L - \tilde{\epsilon}_R)$$  \hspace{1cm} (11)

$$\overline{C}_S = g_S (\epsilon_S + \tilde{\epsilon}_S)$$  \hspace{1cm} (12)

$$\overline{C}_S' = g_S (\epsilon_S - \tilde{\epsilon}_S)$$  \hspace{1cm} (13)

$$\overline{C}_P = g_P (\epsilon_P + \tilde{\epsilon}_P)$$  \hspace{1cm} (14)

$$\overline{C}_P' = g_P (\epsilon_P - \tilde{\epsilon}_P)$$  \hspace{1cm} (15)

$$\overline{C}_T = 4 g_T (\epsilon_T + \tilde{\epsilon}_T)$$  \hspace{1cm} (16)

$$\overline{C}_T' = 4 g_T (\epsilon_T - \tilde{\epsilon}_T)$$  \hspace{1cm} (17)

The use of this Lagrangian to study NP effects is fully justified due to the small magnitude of such effects. On the other hand, in order to have a precise determination of the SM contributions one has, again, to take into account higher order terms in the momentum transfer expansion, like weak-magnetism, as well as other sub-leading corrections like electromagnetic effects [13, 12, 18].

Using these relations and the results of Ref. [19] one can work out the dependence of neutron and nuclear $\beta$ decay observables on the short-distance parameters $\epsilon_i$ and $\tilde{\epsilon}_i$.

For the hadron-level coefficients, the results of Sec. 2.1 indicate that the only quantities that can affect linearly the observables are (i) the real part of $(C_V + C'_V)$ that shifts the value of $V_{ud}$, (ii) the real and imaginary parts of the combinations $(C_S + C'_S)/C_V$ and $(C_T + C'_T)/C_A$ and (iii) the relative phase between $C_V$ and $C_A$.

The precise knowledge of both vector and axial-vector charges $g_{V,A}$ is needed to accurately calculate the SM contribution. The vector charge is $g_V = 1$ up to second-order isospin symmetry breaking corrections that can be safely neglected. The axial-vector charge $g_A$ cannot be accurately calculated from first principles, and the usual strategy is to keep it as an independent parameter that can be extracted from experiments with high precision.

The presence of exotic scalar and tensor interactions introduces two additional form factors $g_{S,T}$ that we need to know in order to convert the measured quantities into the quark-level parameters $\epsilon_{S,T}$. In the rest of this article we will use the recent lattice QCD determinations $g_S = 0.8 \pm 0.4$ and $g_T = 1.05 \pm 0.35$ in the $\overline{MS}$ scheme and at the renormalization scale $\mu = 2 \text{ GeV}$ [9]. Notice that, given the smallness of the scalar and tensor couplings $\epsilon_{S,T}$, it is not necessary to have such a precise determination of $g_{S,T}$ as for the $g_{V,A}$ couplings.

The bounds derived for $\epsilon_{S,T}$ depend both on our ability to accurately calculate the $g_{S,T}$ form factors and to perform precise experiments that can put strong constraints on the hadronic couplings $C_i$. The level of precision needed in the lattice determination so that the final bounds on $\epsilon_{S,T}$ would be dominated by experimental errors has been studied in Ref. [9], assuming a determination of the Fierz term $b$ (see below) at the $10^{-3}$ level in future neutron decay experiments. That study concluded that an improvement by a factor of two in the current lattice...
error will be necessary, what has motivated a renewed effort in the lattice QCD community to improve the present results [9, 20].

2.3 Nuclear matrix elements

An additional step is necessary for nuclear decays to connect the hadron-level effective Lagrangian, Eq.(6), with the nuclei involved in the transition.

Working at leading order in the non-relativistic approximation, this step can be done in a simple way and only two new quantities are needed: (i) the Fermi nuclear matrix element, $M_F$, that encodes the nuclear effects in the vector- and scalar-mediated transitions, and (ii) the Gamow-Teller nuclear matrix element, $M_{GT}$, that plays the same role in transitions mediated by tensor and axial-vector interactions. In this same limit the pseudo-scalar nuclear matrix element vanishes. Moreover $M_F$ (and other terms in the momentum transfer expansion, like weak-magnetism) can be calculated exactly in the isospin symmetry limit.

Once again the use of this approximation is justified to study the effect of NP at the current level of precision, whereas sub-leading corrections have to be taken into account in the calculation of the SM contribution. This includes higher order terms in the momentum transfer expansion like weak-magnetism [21], electromagnetic effects or nuclear structure dependences [13, 22, 23]. Forbidden effects in allowed transitions, associated with an orbital angular momentum of the lepton pair $\ell \neq 0$, are in principle negligible at the current level of precision due to the $(qR)^\ell$ suppression, where $R$ is the nucleus radius. However if the allowed matrix elements $M_F$ or $M_{GT}$ happen to be suppressed, the forbidden effects could become significant what could be the case for nuclear decays with large $ft$-values.

2.4 Weak-scale operator basis

The effective Lagrangian given in Eq.(2) allows us to compare the NP sensitivity of different low-energy experiments, even when the hadrons involved are different, like pion decay and neutron decay. Under some reasonable assumptions such a comparison can be done also with experiments performed at much higher energies and with some processes involving neutral currents, due to the $SU(2)$ gauge invariance.

Indeed, if we assume that the new fields introduced by the theory that supersedes the SM are not only heavier than the scales relevant for $\beta$ decay experiments but also heavier than the energy scale of current collider experiments, we can then describe the physics at that scale also through an effective Lagrangian. This high-energy effective Lagrangian includes all SM fields as active degrees of freedom and has the following structure [24, 10]

$$L_{eff} = L_{SM} + \frac{1}{\Lambda^2} \sum_i \alpha_i O_i^{(6)} + \ldots,$$

where $O_i^{(6)}$ are $SU(2)_L \times U(1)_Y$-invariant dimension-six effective operators generated by the exchange of the new fields that we integrated out, $\alpha_i$ are the associated Wilson coefficients and $\Lambda$ is the characteristic NP scale.

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5Given the R-fit method used in Ref. [9], the lower bounds of $g_{S,T}$ are actually a better indicator of the final $\epsilon_{S,T}$ bounds than the errors $\delta g_{S,T}$. It is thus technically more accurate to say that a future determination of $\epsilon_{S,T}$ from a measurement of $b_n$ at the level of $10^{-3}$ will be dominated by the experimental error as long as $g_{S}^{\min} > 0.64$ and $g_{T}^{\min} > 0.84$. 


It is possible to identify twelve effective operators that generate a tree-level contribution to nuclear and neutron $\beta$ decay, either through a modification of the $W$ boson vertex to fermions or introducing a new four-fermion interaction. It is then possible to relate the Wilson coefficients of both theories, i.e. $\epsilon_i = f(\alpha_j)$ and likewise for $\tilde{\epsilon}_i$. These matching conditions, which can be found in Ref. [10], allow us to understand the implications of collider searches for low-energy experiments and vice versa.

3 Correlations in allowed $\beta$ decay

The relations between the experimentally accessible angular and energy distributions and the hadronic couplings $C_i$ and $C'_i$ was established in the seminal paper of Jackson, Treiman and Wyld (JTW) for allowed nuclear transitions [17, 19]. Their formalism is also valid for neutron decay when making the appropriate substitutions for the Fermi and Gamow-Teller matrix elements.

The decay rate distributions are expressed in terms of the total energies $E_i$ and the momenta $p_i$ of the decay products, with $i = e, \nu$ for the $\beta$ particle and the neutrino respectively, and also the spins $J$ and $\sigma_e$ of the decaying system and of the $\beta$ particle. Those distributions include correlation terms which are scalar, pseudo-scalar or mixed products of the kinematic vectors. For example, the angular and energy distribution of the electron and neutrino in the decay of unpolarized nuclei or neutrons has the form [19]

$$\omega(E_e) = \omega_0(E_e) \xi \left( 1 + b \frac{m}{E_e} + a \frac{p_e \cdot p_\nu}{E_e E_\nu} \right),$$

(19)

where the function $\omega_0(E_e)$ includes the phase space factor and the Fermi function, $m$ is the electron mass and the coefficients $\xi$, $b$, and $a$ contain the dynamics of the decay. This includes the nuclear matrix elements, $M_F$ and $M_{GT}$, and the effective couplings $C_i$ and $C'_i$ [17, 19]. Any specific experimental configuration fixes the magnitude of the various correlation terms and then the sensitivity to the coefficients, $a$, $b$, etc.

For a quick reference to the most common correlations coefficients, Fig. 1 shows a pictorial representation, in the form of a tetrahedron. The vertices correspond to the kinematic vectors, the edges to the two-fold correlations and the faces to the three-fold correlations.

![Figure 1: Pictorial representation of the two-fold (edges) and three-fold (sides) correlation coefficients between the kinematic vectors (vertices). Adapted from Ref. [8].](image-url)
At leading order in the approximations discussed above, the SM corresponds to \( C'/C = C'/A = 1 \), all other parameters being zero. Deviations of experimental results from the values of the coefficients predicted in the SM would provide an indication for new physics or a departure from the allowed approximation for nuclear decays.

It can easily be seen from the expressions of the coefficients \(^{[19]}\) that all of them receive linear NP contributions which are not suppressed to order \( \alpha \) except the coefficients \( a, A, G \). Among those, the coefficients that have been accessed experimentally, either directly or in conjunction with other coefficients are: the Fierz interference term \( b \), the neutrino asymmetry parameter \( B \), the polarization-spin correlation \( N \), the \( \beta \) longitudinal polarization from polarized nuclei \( Q \) and the triple correlations \( R \) and \( D \). These latter are sensitive to a possible relative phase between the couplings arising from time-reversal violation.

Measurements of \( N \) and \( Q \) require the analysis of the spin of \( \beta \) particles emitted from polarized neutrons or nuclei, what makes such experiments very demanding and challenging.

In most experimental conditions, the measured coefficients receive a linear contribution via the Fierz term of the form
\[
\tilde{X} = \frac{X}{1 + b\langle m/E_e \rangle}, \tag{20}
\]
where \( X = a, A, B \), etc. stands for any of the correlation coefficients and \( \langle \rangle \) denotes the weighted average over the observed part of the \( \beta \) energy spectrum. Such a contribution arises for instance in measurements of the \( \beta \nu \) angular correlation, \( a \), which is quadratic on the exotic couplings. For \( C_i^{(\ell)} \ll 1 \), the sensitivity of \( \tilde{a} \) to those couplings becomes then dominated by the contribution due to the Fierz term. Under such conditions, the factor \( \langle m/E_e \rangle \) becomes an important quantity since it can suppress or enhance significantly the NP sensitivity. This factor depends on the transition and the details of the experiment, and is typically in the range \( 0.2 - 0.7 \) \(^{[2]}\).

The contribution of the Fierz term can however adversely affect the sensitivity of other coefficients. For example, for pure Gamow-Teller transitions, which are sensitive to tensor contributions, the \( b \) and \( B \) coefficients have the form \(^{[19]}\)
\[
b_{GT} = \pm \gamma \Re \left( \frac{C_T + C_T'}{C_A} \right), \tag{21}
\]
\[
B_{GT} = \lambda_{\ell', J} \left[ \pm 1 + \frac{\gamma m}{E_e} \Re \left( \frac{C_T + C_T'}{C_A} \right) \right], \tag{22}
\]
where \( \lambda_{\ell', J} \) is a spin factor \(^{[17]}\), \( \gamma = \sqrt{1 - (\alpha Z)^2} \) with \( Z \) the atomic number of the daughter nucleus and the upper (lower) sign refers to electron (positron) decay. Following Eq. (20) we have then
\[
\tilde{B}_{GT} \approx B_{GT} \left( 1 - \frac{m}{E_e} b_{GT} \right) \approx \pm \lambda_{\ell', J}. \tag{23}
\]

This shows that the measured coefficient looses then the linear sensitivity to tensor couplings for such transitions. A similar, albeit partial, suppression of sensitivity has been observed for \( B \) in neutron decay \(^{[9]}\). These suppressions are due to the fact that \( B \) and \( b \) have similar (linear) dependence on the exotic couplings.

The sensitivity of \( B \) to the couplings actually depends on the initial spin of the transition, on the spin sequence and on the mixing ratio \( \rho = C_A M_{GT}/(C_V M_F) \) between the Gamow-Teller
and Fermi contributions. Thus the cancellation due to the contribution of $b$ to $\tilde{B}$ observed in pure Gamow-Teller processes does not necessarily happen in all mixed transitions.\footnote{It is certainly conceivable to perform simultaneous measurements of ratios of coefficients, like $B/a$, so that the linear sensitivity to the NP contribution in $B$ is not lost. However, such a measurement has not yet been performed.}

In summary, the discussion above shows that the sensitivity of correlation coefficients which are linear in the exotic couplings can strongly be affected by the contribution of the Fierz term. For coefficients that depend quadratically on the couplings, the dominant sensitivity to these couplings will arise from the contribution of the Fierz. For transitions with large end-point energies, the contribution of the Fierz term can however be strongly weaken. We illustrate this quantitatively in the next sections.

4 Constraints from nuclear and neutron $\beta$ decay

We review here the most stringent constraints on NP from the measurement of energy and angular distributions in nuclear and neutron decays.

The use of the hadronic-level couplings $C_i^{(p)}$ of JTW is convenient at this stage because the comparison of sensitivity between different observables and measurements does not require the knowledge of the form factors $g_{V,A,S,T}$. However in the next section we will convert the most precise results to the quark-level notation $\epsilon_i$ and $\tilde{\epsilon}_i$ in order to be able to compare the NP sensitivity of these decays with other low- and high-energy observables.

Following the results of Sec. 2.2 we present here the constraints on quantities that can affect linearly the observables, namely: (i) the real part of the vector couplings $(C_V + C_V')$; (ii) the real parts of the scalar and tensor couplings $(C_S + C_S')/C_V$ and $(C_T + C_T')/C_A$; and (iii) the imaginary parts of the scalar and tensor couplings as well as the relative phase between $C_V$ and $C_A$.

4.1 Limits on real vector couplings

The effect of the NP contribution to the real part of $(C_V + C_V')$ shifts the value of $V_{ud}$ and can be probed through the unitarity test of the CKM matrix.

The most precise determination of $V_{ud}$ comes from the study of super-allowed Fermi transitions \cite{23, 3}. Together with the recent determinations of $V_{us}$ and $V_{ub}$ \cite{25}, it offers a very precise test of the CKM unitarity condition

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.0001(10) \quad (90\% \; CL),$$

which results in

$$\text{Re} \left( \frac{C_V + C_V'}{2} \right) = 1.000(1) \quad (90\% \; CL),$$

in perfect agreement with the SM prediction.
4.2 Limits on real scalar and tensor couplings

The most stringent limits on scalar couplings obtained from nuclear and neutron $\beta$ decays arise from the contribution of the Fierz interference term to the $F_t$-values of super-allowed pure Fermi transitions [23]. The value of the Fierz term extracted from this set reads

$$b_F = -\text{Re} \left( \frac{C_S + C'_S}{C_V} \right) = -0.0022(43) \quad (90\% \text{ CL}) \ ,$$  

(26)

and the constraints are shown by the light blue lines in Fig. 2. The error on this value is determined by the individual errors of the $F_t$-values which are fitted to search for a possible deviation from a constant. The $Q_{EC}$ values in these transitions increase with the mass of the parent nucleus so that transitions in lighter nuclei have a stronger weight in the extraction of $b_F$ due to the $\langle m/E_e \rangle$ factor. The contributions to the error on $b_F$ given in Eq.(26) are then due to the experimental data and to theoretical corrections which have here an important effect. The opportunities for improving the errors of the $F_t$-values have recently been discussed in Ref. [3] in connection with the determination of $V_{ud}$ from pure Fermi transitions for the unitarity test of the CKM matrix.

![Diagram](image)

Figure 2: Constraints on real scalar couplings obtained from most precise observables in nuclear $\beta$ decay. The straight lines are deduced from the Fierz interference term in super-allowed pure Fermi transitions [23]. The circular bounds are deduced from the measurement of the $\beta\nu$ angular correlation in $^{38m}K$ decay [26]. The limits are calculated at the 90% CL.

The other measured observable providing complementary constraints to those resulting from the $F_t$-values is the $\beta\nu$ angular correlation $a$. The most precise result obtained so far was in the pure Fermi decay of $^{38m}K$. The experiment used the TRIUMF Neutral Atom Trap setup [26] which is a Magneto Optical Trap (MOT) system composed of two traps. The $\beta\nu$ correlation was determined from the shape of the time-of-flight spectra of recoil ions measured in coincidence relative to the $\beta$ particle. Since $^{38m}K$ is a positron emitter, the detection of positively charged recoil ions relies on the double or multiple shake-off of electrons following $\beta$ decay. The statistical precision of the result is $3 \times 10^{-3}$ and the systematic error is comparable, arising from several instrumental sources [26]. A similar precision has been achieved with an indirect method, by measuring the energy spectrum shape of the delayed proton in the decay of $^{32}Ar$ [27].
bounds obtained from the $^{38m}$K experiment are shown by the circles in Fig. 2 and are extracted from

$$\tilde{a} = \frac{a}{1 + b(m/E_e)}.$$  

(27)

It is interesting to stress that the abscissa, $x_C$, and ordinate, $y_C$, of the center of the circles in Fig. 2 are essentially given by $x_C \approx y_C \approx \langle m/E_e \rangle/2$, and that the mean radius of the circular band, $R_M$, is given by $R_M \approx \langle m/E_e \rangle/\sqrt{2}$. This indicates the importance of the value of the sensitivity factor $\langle m/E_e \rangle$ of the Fierz term, in defining the exclusion plot and hence the interval of allowed values for the exotic couplings.

The value for a possible real scalar coupling obtained from the most recent global analysis [2] including data from experiments in nuclear and neutron decays translates into

$$\text{Re} \left( \frac{C_S + C'_S}{C_V} \right) = 0.0026(42) \ (90\% \ CL),$$  

(28)

for a three parameters fit with left-handed couplings ($C_S = C'_S$). The fit also includes data from $F_t$-values and the measurement of $\tilde{a}$ in $^{38m}$K and $^{32}$Ar decays discussed above. Although the compilation of $F_t$-values used in Ref. [2] was not the same than for the value quoted in Eq. (26), the result in Eq. (28) is clearly dominated by the $F_t$-values.

The most stringent limits on tensor couplings arising from single observables is obtained from the ratio between polarizations of $\beta$ particles emitted from pure Fermi and pure Gamow-Teller transitions $P_F/P_{GT}$. The longitudinal polarizations are governed by the correlation coefficients $G$ of each decay, and the ratio provides constraints on both scalar and tensor contributions. These experiments were motivated by the search for deviations from maximal parity violation due to the presence of e.g. right-handed currents which would couple through $V$ and $A$ interactions. The polarization ratio $P_F/P_{GT}$ has been measured with high precision by two groups [28, 29, 30]. The first experiment compared the longitudinal polarization of positrons from $^{26}$Al and $^{30}$P decays using Bhabha scattering in a magnetized foil [28]. The second group detected positrons from $^{10}$C and $^{14}$O [29, 30] and used the polarimetry technique based on time-resolved spectroscopy of hyperfine positronium decay. Here again, it is the contribution of the Fierz term to $G$ that provides the constraints on exotic couplings deduced from these experiments. At the 90% CL, the value deduced for the difference between the scalar and tensor terms reads [30]

$$\text{Re} \left( \frac{C_S + C'_S}{C_V} \right) - \text{Re} \left( \frac{C_T + C'_T}{C_A} \right) = 0.003(18).$$  

(29)

Since the scalar couplings are more severely constrained by the $F_t$-values from pure Fermi transitions, Eq. (26), these experiments provide constraints on the tensor contribution. The limits are shown by the orange straight lines in Fig. 3. It is remarkable that the most stringent limits on tensor couplings from nuclear $\beta$ decay arise from two experiments that were performed in the 1980’s, even though that was not the main motivation of those experiments.

The $\beta\nu$ angular correlation provides also here complementary constraints to those obtained from $P_F/P_{GT}$. The most precise measurement carried out so far was in the pure Gamow-Teller decay of $^{6}$He, fifty years ago [31]. This experiment measured the energy spectrum of the recoil ions in singles with an electromagnetic spectrometer. The relative precision achieved in this measurement was $10^{-2}$. The result has been revisited by Glück to include order-$\alpha$ radiative corrections and the effect of induced weak currents to the recoil spectrum [32].
Figure 3: Constraints on real tensor couplings obtained from most precise single observables in nuclear β decay. The straight lines are deduced from the Fierz interference term contributing to the longitudinal polarization of β particles in Fermi and Gamow-Teller transitions \[30\]. The circular bounds are deduced from the measurement of the βν angular correlation in \(^{6}\)He decay \[31\]. All limits are calculated at the 90% CL.

limits obtained from this measurement are shown by the green circles on Fig. 3. It is seen that the (absolute) values of the coordinates \((x_C, y_C)\) of the center of the circles and the mean radius, \(R_M\), of the circular band are here larger than in \(^{38}\)mK decay (Fig. 2), because the sensitivity factor \(\langle m/E_e \rangle\) is a factor 1.8 larger. Although the relative error on the measurement of \(\tilde{a}\) in \(^{6}\)He decay is a factor of about 2 larger than in \(^{38}\)mK, the width of the circular band is smaller due its larger sensitivity. As expected, the interval for the allowed values of \(\text{Re}(C_T + C'_T)/C_A\) from the \(^{6}\)He experiment is dominated by the contribution of the Fierz term to \(\tilde{a}\). Moreover, it appears that the sensitivity factors for the measurement of \(\tilde{a}\) in \(^{6}\)He and of \(P_F/P_{GT}\) in \(^{10}\)C and \(^{14}\)O are the same within 2% \[2\]. Therefore the ratio between the bounds on \(\text{Re}(C_T + C'_T)/C_A\) is provided directly by the ratio between the relative uncertainties of the experimental results.

The value for a possible real tensor coupling as deduced from the global analysis of Ref. \[2\], for a three parameters fit with left-handed couplings \(C_T = C'_T\), is

\[
\text{Re} \left( \frac{C_T + C'_T}{C_A} \right) = 0.007(11) \quad (90\% \text{ CL}) .
\]  

(30)

The error resulting from this fit is somewhat smaller than the one obtained in the measurements of \(P_F/P_{GT}\) alone, Eq. (29). This is attributed to the contribution of the Fierz term to the β asymmetry parameter, \(\tilde{A}\), in neutron decay which has a significant impact on the global fit. For the data used in Ref. \[2\], the sensitivity to the Fierz term through the factor \(\langle m/E_e \rangle\) is about 2 times larger for the \(\tilde{A}\) coefficient in neutron decay than for \(P_F/P_{GT}\) \[2\].

Measurements of other correlations do not provide more stringent limits compared to those presented above. As already mentioned, the coefficients which are linear in the real parts of exotic couplings and that have been measured are \(B, Q\) and \(N\).

The coefficient \(B\) has been measured in \(^{37}\)K \[33\] and in neutron decay \[34, 35\]. As discussed in Sec. 3, the sensitivity of \(B\) to exotic couplings can be strongly suppressed due to the contribution
of the Fierz term. These experiments were however motivated by the search for right-handed currents with vector and axial-vector couplings.

The same goal motivated measurements of the longitudinal polarization of $\beta$ particles emitted from polarized nuclei, which is dominated by the $Q$ coefficient and contains also a small contribution of $N$ \[36\]. The measurements were carried out in $^{107}$In \[37\] and $^{12}$N \[38, 39\]. Since these are relative measurements, the contribution of the Fierz term cancels and the remaining sensitivity to exotic left-handed couplings is strongly suppressed.

Finally, the $N$ coefficient has been measured in neutron decay \[40\] as a control parameter of a polarimeter dedicated to the measurement of the triple correlation $R$. The achieved experimental error combined with the small value of $N$ under the conditions of that experiment do not provide significantly improved constraints on scalar or tensor couplings.

Absolute measurements of the $\beta$ asymmetry parameter, $A$, have recently been performed in Gamow-Teller decays with the explicit purpose to probe tensor couplings via the Fierz term \[41, 42\]. The experiments used the low-temperature nuclear orientation technique in the decays of $^{114}$In \[41\] and $^{60}$Co \[42\]. These transitions have a relatively low end point energies and hence large sensitivity to the Fierz term. However, the allowed Gamow-Teller matrix element is strongly reduced in $^{60}$Co decay. The SM value of the asymmetry parameter has therefore a theoretical uncertainty which is of the same order of magnitude than the experimental error \[42\] due to the contribution of recoil corrections. The total relative uncertainties achieved were respectively 1.4% and 2.0% at 1$\sigma$ for $^{114}$In and $^{60}$Co and do not significantly improve the limits obtained from $P_F/P_{GT}$.

In neutron decay, a global analysis of data has been performed in order to assess the sensitivity to exotic couplings \[43\]. It appears that, since the ratio $g_A/g_V$ has to be determined from the same data, the constraints are less stringent than those obtained from the global fit including nuclear data \[2\]. A similar conclusion was recently obtained in the analysis of $\tilde{a}$, $\tilde{A}$, and $\tilde{B}$, in neutron decay \[44\]. It is to note that in the global fit of Ref. \[2\], the determination of the ratio $g_A/g_V$ results essentially from the comparison between the $Ft$-value from pure Fermi transitions and the neutron lifetime so that all correlation in neutron decay, and in particular $A$ serve to constraint exotic couplings.

To summarize, we have shown that the most stringent limits obtained on the real scalar and tensor couplings result solely from the contribution of the Fierz term to the observables. This applies to the total decay rate through the $Ft$-values, to the $\beta\nu$ angular correlation coefficient $\tilde{a}$ in Fermi and Gamow-Teller transitions and to the $\beta$ particle longitudinal polarization $\tilde{G}$ which enters the ratio $P_F/P_{GT}$.

### 4.3 Limits on imaginary couplings

The presence of imaginary phases between the couplings is related to the violation under time-reversal \[19\]. In nuclear and neutron decays, searches for time-reversal violation have traditionally been focused on the $D$ and $R$ triple correlation coefficients (Fig. 1).

Since the $\beta\nu$ angular correlation depends quadratically on the NP couplings, it is also sensitive to possible imaginary parts in them. Considering that measurements of the $Ft$-values in Fermi transitions and of the polarization ratio $P_F/P_{GT}$, provide stringent constraints on the Fierz terms associated respectively with scalar, and tensor couplings, Eqs. (26) and (29), it is possible to extract constraints on the imaginary parts from the $\beta\nu$ correlation measurements, by neglecting here the contributions of the Fierz terms.
Figure 4: Constraints on imaginary scalar couplings obtained from most precise single experiments in nuclear and neutron decays. The straight lines are deduced from the triple correlation measurement in neutron decay \[40\]. The circular bound is deduced from the measurement of the $\beta\nu$ angular correlation in $^{38m}$K decay \[26\]. The limits are calculated at the 90% CL.

Figure 4 shows the constraints on imaginary scalar couplings extracted from the $\beta\nu$ angular correlation in $^{38m}$K decay \[26\] and from the measurement of the triple correlation coefficient, $R$, in neutron decay \[40\]. The determination of this coefficient requires the measurement of the transverse polarization of $\beta$ particles emitted perpendicular to the neutron spin. The experiment was performed using a polarized cold neutron beam and the transverse electron polarization was analyzed from the asymmetry in Mott scattering at backward angles using a thin lead foil. The total absolute error reached in this measurement is $\delta R_n = 1.3\%$, generating the following 90% CL constraint

$$\text{Im} \left( \frac{C_S + C'_S}{C_V} \right) - 1.5 \text{Im} \left( \frac{C_T + C'_T}{C_A} \right) = -(1.8 \pm 5.9) \times 10^{-2} .$$

(31)

Using the stronger constraint on the tensor contribution obtained from the measurement of $R$ in $^{8}$Li decay (see below), we obtain the limit on the imaginary part of the scalar interaction shown in Fig. 4.

Notice that the quadratic dependence of the $\beta\nu$ angular correlation provides here a competitive constraint. The region allowed by the $^{38m}$K result (disk inside the red circle) has been somewhat reduced by the constraint obtained from the new measurement of the triple correlation in neutron decay.

The constraints on the imaginary tensor couplings are shown in Fig. 5. They are extracted from the $\beta\nu$ angular correlation in $^{6}$He decay \[31\] and from the measurement of the triple correlation coefficient $R$ in $^{8}$Li decay \[45\]. This measurement used polarized $^{8}$Li nuclei produced by polarization transfer reactions from a vector-polarized deuteron beam on a $^{7}$Li target. The target was cooled close to liquid helium temperatures in order to achieve long relaxation times. The transverse polarization of the decay electrons was also deduced here from the Mott scattering asymmetry at backward angles using a lead foil as analyzer. The absolute precision reached in this measurement was $\delta R^{(8}\text{Li}) = 2.2 \times 10^{-3}$ and the result has been corrected for the effects of final state interactions, $R_{FSI} = 0.7(1) \times 10^{-3}$. The 90% CL value of the imaginary part of
tensor couplings obtained from this measurement reads

$$\text{Im} \left( \frac{C_T + C'_T}{C_A} \right) = (0.27 \pm 1.08) \times 10^{-2}.$$  \hfill (32)

Figure 5: Constraints on imaginary tensor couplings obtained from most precise single experiments in nuclear $\beta$ decay. The straight lines are deduced from the triple correlation measurement in $^8\text{Li}$ decay [45]. The circular bound is deduced from the measurement of the $\beta\nu$ angular correlation in $^6\text{He}$ decay [31]. The limits are calculated at the 90% CL.

The situation for the constraints on tensor couplings, Fig. 5, is quite different from the scalar couplings exclusion plot. The strongest constraints are those arising from the measurement of $R$, which has an uncertainty a factor of 6 smaller than in neutron decay.

The measurement of the $D$ triple correlation coefficient requires the use of mixed transitions and the determination of the neutrino momentum through the observation of the recoil. In nuclear $\beta$ decay, the $D$ coefficient has been measured in $^{19}\text{Ne}$ decay. The combined result from all runs provided the value $D(^{19}\text{Ne}) = (1 \pm 6) \times 10^{-4}$ [46]. The $D$ coefficient has also been measured by two groups in neutron decay [47, 48]. The most recent and precise result is $D_n = (-0.9 \pm 2.1) \times 10^{-4}$ [48] and provides the following 90% CL bounds for a possible phase between the vector and axial couplings

$$\text{Im}(C_V C_A^*) = (-2.1 \pm 8.0) \times 10^{-4}.$$  \hfill (33)

This completes the review of the current status of the six couplings left in the approximation introduced in Sec. 2.1 that affect linearly the observables.

5 Comparison with other low- and high-energy experiments

5.1 CP-conserving vector/axial couplings

As explained in Sec. 2.1, the linear effects produced by CP-conserving vector and axial-vector interactions, which are represented by $\epsilon_{L,R}$ and $\tilde{\epsilon}_{L,R}$ can be re-expressed as an overall shift in the effective Lagrangian and an unobservable shift in the axial-vector form factor $g_A$. The only
observable effect is then a NP contribution to $V_{ud}$ that can be probed through the test of the unitarity condition of the CKM matrix.

The value obtained in Eq. (25) translates into the following strong bound

$$|\text{Re}(\epsilon_L + \epsilon_R)| < 0.5 \times 10^{-3} \quad (90\% \ CL) \ ,$$

where once again we have neglected $O(\epsilon_i, \tilde{\epsilon}_i)^2$ contributions. In the high-energy effective theory, this bound corresponds to an effective NP scale of 11 TeV that represents a more stringent bound than those from LEP and LHC analysis on the same effective interactions [49, 10].

Given a specific NP model this stringent bound translates in severe constraints on the masses and couplings of the new particles, as explicitly shown in various (mostly supersymmetric) extensions of the SM during the last decades [50, 51, 52, 53, 54, 55].

### 5.2 CP-conserving scalar and tensor couplings

The rest of non-standard interactions can be probed by measuring normalized angular and energy distributions, as described in Sec. 4.

For scalar interactions, the most stringent bound comes from the determination of the Fierz term in super-allowed Fermi decays given in Eq. (26). This translates into

$$-1.0 \times 10^{-3} < g_S \text{Re}(\epsilon_S) < 3.2 \times 10^{-3} \quad (90\% \ CL) \ ,$$

represented in Fig. 6 with a horizontal green band.

In the case of tensor interactions, we saw in Sec. 4.2 that the best bound from nuclear $\beta$ decays arises from measurements of the ratio $P_F/P_{GT}$ of longitudinal polarization of positrons emitted in the decay of pure Fermi and pure Gamow-Teller transitions [30, 28]. These experiments are sensitive to the difference between Fierz terms and generate the following 90% CL bound

$$-2.6 \times 10^{-3} < \frac{g_S}{3} \text{Re}(\epsilon_S) + g_T \text{Re}(\epsilon_T) < 3.2 \times 10^{-3} .$$

This is represented in Fig. 5 by the wide red diagonal band. The contribution of other observables in nuclear and neutron decays that can possible improve this limit require a global fit as presented in Ref. [2].

More stringent bounds on tensor interactions can be obtained from the analysis of the Dalitz plot of the radiative pion decay $\pi^+ \rightarrow e^+ \nu e \gamma$ done by the PIBETA collaboration [56]

$$-1.1 \times 10^{-3} < \text{Re}(\epsilon_T) < 1.4 \times 10^{-3} \quad (90\% \ CL) \ ,$$

represented in Fig. 6 by the vertical yellow band.

Another promising process to probe both scalar and tensor interactions is the measurement of the Fierz term in neutron decay [9]. The purple area in Fig. 6 shows the impact of future determinations of this parameter with a sensitivity at the level of $|\delta b| \leq 10^{-3}$. It will offer the most stringent bound on tensor interactions, after taking into account the strong bounds existing on $b_F$, Eq. (26).

Finally it is worth mentioning that, although not shown in Fig. 6, the ratio $R_\pi = \Gamma(\pi \rightarrow e\nu)/\Gamma(\pi \rightarrow \mu\nu)$ is also a very powerful probe of scalar and tensor interactions since they generate radiatively a pseudo-scalar interaction [58]. More details can be found in Refs. [9, 10].

\footnote{For the associated hadronic form factor we use $f_T = 0.24(4)$, obtained in Ref. [57], using a large-$N_c$-inspired resonance-saturation model.}
Figure 6: 90% CL limits on the scalar and tensor NP couplings $\text{Re}(\epsilon_{S,T})$ from super-allowed nuclear decays [23] (green), radiative pion decay [56] (yellow) and measurements of the ratio $P_F/P_{GT}$ [30, 28] (red), along with the expected bound from future measurements of the Fierz term $b$ in neutron decay (purple).

### 5.3 CP-violating interactions

The three CP-violating phases with a linear effect on the nuclear $\beta$ decay observables are represented in the quark-level effective Lagrangian by the imaginary parts of the coefficients $\epsilon_{R,S,T}$. They parameterize the relative phase between the purely vector interaction in the hadronic bilinear and axial-vector, scalar and tensor interactions, respectively.

The 90% CL bounds on the imaginary parts of scalar and tensor interactions obtained from measurements of the $R$ parameter in neutron and in $^8\text{Li}$ decays were given in Eqs.(31) and (32). They can be trivially re-expressed as

$$g_S \text{Im}(\epsilon_S) + 4.7 \ g_T \text{Im}(\epsilon_T) = -(0.9 \pm 3.0) \times 10^{-2}$$

$$g_T \text{Im}(\epsilon_T) = -(0.4 \pm 1.7) \times 10^{-3}.$$  

Using the recent lattice QCD determination of the form factors $g_{S,T}$ [9] we obtain the bounds shown in Fig. 7.

Likewise, the bound on the relative phase between $C_V$ and $C_A$ given in Eq.(33) from the measurement of the $D$ correlation coefficient in neutron decay [18] can be casted in the quark-level language as

$$\text{Im}(\epsilon_R) = -(1.1 \pm 4.0) \times 10^{-4} \quad (90\% \text{ CL}) .$$

It is worth mentioning that additional T-odd correlations with potential NP sensitivity can be constructed in the radiative $\beta$ decay of nuclei and neutron, as shown in Refs. [59, 60].

Like for the CP-conserving coefficients, the ratio $R_\pi = \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$ offers strong constraints on $\text{Im}(\epsilon_{S,T})$ since they generate radiatively a non-zero $\text{Im}(\epsilon_F)$ [11].

Using the high-energy effective Lagrangian of Eq.(18), it is possible to show that the same $SU(2)_L \times U(1)_Y$ invariant effective operators that generate at low-energy the coefficients $\epsilon_{R,S,T}$
Figure 7: 90% CL limits on the CP-violating scalar and tensor NP couplings $\text{Im}(\epsilon_{S,T})$ from measurements of the triple correlation $R$ in neutron decay [40] (diagonal maroon band) and $^8\text{Li}$ [45] (vertical green band). Notice that both $\epsilon_S$ and $\epsilon_T$ scales are different than in Fig. 6.

also generate contributions to different EDMs [61], what generates much stronger bounds than those given in Eqs. (38)-(40). In fact, the indirect limit on the $D$ coefficient from the current neutron EDM bound is of the order $10^{-7}$ [61], whereas for the $R$ coefficient the current Thallium EDM bound implies an indirect bound at the level of $10^{-8}$ [62]. These bounds from EDMs could be avoided assuming an almost complete cancellation with other effective operators contributing to the EDMs. Although such a scenario is very unnatural from a purely EFT point of view, in a specific NP model the different Wilson coefficients are related to the more fundamental coupling constants and masses and such a cancellation could occur in a less unnatural way. In this sense, direct bounds from $\beta$ decays complement EDM experiments in the search of new sources of CP-violation. Moreover, this comparison with EDM relies on the use of the high-energy effective Lagrangian of Eq. (18), that in turn relies on some assumptions about the structure of the underlying NP.

We can see that the situation is very different from the CP-conserving coefficients, where direct limits from $\beta$ decays are very competitive and for some interactions they actually offer the best bound.

5.4 Limits from the LHC

If the new particles are too heavy to be produced on-shell at the LHC we can connect collider searches with low-energy experiments in an elegant model-independent way using the high-energy effective Lagrangian of Eq. (18) to analyze collider data. The natural channel to study at the LHC is the search for electrons and missing transverse energy (MET), $pp \rightarrow e + \text{MET} + X$, since the underlying partonic process is the same as in $\beta$ decay ($\bar{u}d \rightarrow e\bar{v}$) and so we expect it to be sensitive to the same kind of NP.

Using the matching conditions between Wilson coefficients of the low- and high-energy effec-
It is possible to express collider observables in terms of the coefficients of the low-energy effective theory, $\epsilon_i$ and $\bar{\epsilon}_i$. In particular the cross-section $\sigma(pp \rightarrow e + \text{MET} + X)$ with transverse mass higher than $m_T$ takes the following form:

$$\sigma(m_T > m_T) = \sigma_W \left[ 1 + |\epsilon_L^{(v)}|^2 + |\bar{\epsilon}_L|^2 + |\epsilon_R|^2 \right] - 2 \sigma_{WL} \text{Re} \left( \epsilon_L^{(c)} + \epsilon_L^{(o)} \epsilon_L^{(c)} \right) + \sigma_R \left[ |\bar{\epsilon}_R|^2 + |\epsilon_L^{(c)}|^2 \right] + \sigma_S \left[ |\epsilon_S|^2 + |\bar{\epsilon}_S|^2 + |\epsilon_P|^2 + |\bar{\epsilon}_P|^2 \right] + \sigma_T \left[ |\epsilon_T|^2 + |\bar{\epsilon}_T|^2 \right], \tag{41}$$

where $\sigma_W(m_T)$ represents the SM contribution and $\sigma_{WL,R,S,T}(m_T)$ are new functions, which explicit form can be found in Ref. [10]. The crucial feature is that they are several orders of magnitudes larger than the SM contribution, what compensates for the smallness of the NP couplings and makes possible to put significant bounds on them from these searches. On the other hand, the lack of such an enhancement makes this search not very sensitive to $\epsilon_L^{(o)}$, $\bar{\epsilon}_L$ and $\epsilon_R$.

The most recent search for electrons and missing transverse energy in the final state was done by the CMS collaboration using 20 fb$^{-1}$ of data recorded at $\sqrt{s} = 8$ TeV [64]. In this analysis they found one single event with a transverse mass above 1.5 TeV, to be compared with the SM expectation of $1.99 \pm 0.27$ events. This absence of an excess of high-$m_T$ events in this channel can be translated into bounds on the different NP couplings using Eq. (41), as shown in Fig. 8 for scalar and tensor couplings.

Assuming that only one operator at a time is present we obtain the following 90% CL bounds:

$$|\epsilon_S,P|, |\bar{\epsilon}_S,P| < 5.8 \times 10^{-3}, \tag{42}$$

$$|\epsilon_T|, |\bar{\epsilon}_T| < 1.3 \times 10^{-3}, \tag{43}$$

$$|\bar{\epsilon}_R|, |\text{Im } \epsilon_L^{(c)}| < 2.2 \times 10^{-3}, \tag{44}$$

$$\text{Re } \epsilon_L^{(c)} \in (-1.1, 4.5) \times 10^{-3}. \tag{45}$$

The bounds presented in Figs. 6 and 8 show an interesting competition between low- and high-energy searches looking for new CP-conserving scalar and tensor interactions involving LH neutrinos. On the other hand, interactions involving RH neutrinos are more strongly constrained by the LHC, as shown in Table 1.

In the case of non-standard (axial-)vector interactions with LH neutrinos, the combination $\text{Re}(\epsilon_L + \epsilon_R)$ is strongly constrained by CKM unitarity tests, as shown in Eq. (34), but the orthogonal combination $\text{Re}(\epsilon_L - \epsilon_R)$ cannot be probed by $\beta$ decay experiments. Although current LHC searches cannot improve the CKM unitarity limit, they are sensitive to the contact interaction part of $\epsilon_L$ providing in this way complementary information. For (axial-)vector interactions with RH neutrinos, we see from Table 1 that the LHC dominates the search in the case of $\epsilon_R$, whereas the bounds obtained on $\epsilon_L$ from nuclear $\beta$ decays are the most competitive, even if they are above the per-cent level.

Finally, for the pseudoscalar couplings $\epsilon_P$ and $\bar{\epsilon}_P$ the ratio $R_\pi = \Gamma(\pi \rightarrow e\nu)/\Gamma(\pi \rightarrow \mu\nu)$ represents by far the best probe, providing bounds of order $10^{-4}$ [10].

All in all, we see that only the combination of both low- and high-energy searches can give us a complete picture of non-standard charged current interactions.

\[\text{Notice that high-energy searches probe separately the vertex correction } \epsilon_L^{(o)} \text{ and contact } \epsilon_L^{(c)} \text{ contributions to the coupling } \epsilon_L, \text{ defined in Ref. [10].} \]
Figure 8: The red (blue) solid line gives the 90% C.L. limits on the scalar and tensor NP couplings \(|\epsilon_{S,T}|\) obtained with 5 fb\(^{-1}\) (20 fb\(^{-1}\)) of data recorded at \(\sqrt{s} = 7\) TeV (8 TeV) by the CMS collaboration in the \(pp \to e + \text{MET} + X\) channel [63, 64]. The dotted line gives an estimated future bound obtained with higher luminosity and energy.

Table 1: Summary of 90% CL bounds (in units of \(10^{-2}\)) on the non-standard couplings \(\tilde{\epsilon}_i\) from low- and high-energy searches.

| \(\tilde{\epsilon}_L\) | \(\tilde{\epsilon}_R\) | \(\tilde{\epsilon}_P\) | \(\tilde{\epsilon}_S\) | \(\tilde{\epsilon}_T\) |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Low energy [2, 10] | 6 | 6 | 0.03 | 14 | 3.0 |
| LHC (this work) | - | 0.2 | 0.6 | 0.6 | 0.1 |

Needless to say, this interplay becomes much more interesting if a non-zero result is obtained for one of the Wilson coefficients, either in the low-energy experiments or in collider searches. This was explained in Ref. [9], where it was shown that a hypothetical scalar resonance found at the LHC in the \(pp \to e^\pm + \text{MET} + X\) channel would imply a lower bound in the value of \(|\epsilon_S|\) that should then be confirmed in nuclear and neutron decay experiments.

6 Experimental activities

Detailed accounts of new results and ongoing activities have been provided in several recent reviews [2, 4, 5, 6, 7, 8]. In this section we focus on current experiments or projects aiming at improving present limits on exotic couplings for both the real and imaginary parts. The purpose is to review the anticipated precision goals of such efforts in order to confront them with the current most precise limits and with the estimated reach at the LHC.

6.1 The \(\beta\nu\) angular correlation, \(a\)

As already indicated, the information about the angular correlation between the \(\beta\) particle and the neutrino is contained in the momentum spectrum of the recoiling daughter nucleus. This
correlation can be obtained by detecting the recoiling nuclei either in singles or in coincidence with the $\beta$ particles.

There are currently two experiments aiming at improving the precision on scalar couplings in Fermi transitions.

The first uses the Weak Interaction Trap for CHarged particles spectrometer (WITCH) installed at ISOLDE-CERN \cite{65}. The setup includes two Penning traps located in the same magnetic field. The first trap serves for cleaning and preparation of the ion cloud and the second to store the ions during their decay. In the WITCH spectrometer, the energy spectrum of the recoil ions is measured in singles using a magnetic spectrometer which contains several electrostatic retardation electrodes. The operation of this type of spectrometer is complicated by the possible presence of local Penning traps, where ions or electrons can be confined. This is caused by the electromagnetic field configuration inside the system and by secondary ionization processes. Such effects require the operation of the spectrometer under ultra-high vacuum conditions. The candidate nucleus considered for this experiment is $^{35}$Ar which is also a positron emitter. The detection of positively charged recoil ions from singly charged trapped ions relies on the single or multiple shake-off process of the bound electrons. A first measurement of a recoil spectrum from stored $^{124}$In$^+$ ions has been reported \cite{66}. The precision goal of this experiment is to reach the level of $\delta a \approx 5 \times 10^{-3}$ \cite{65}. When achieved, this will slightly improve the limit on scalar interactions obtained from $^{38}$mK, Fig. 2, and $^{32}$Ar decays.

In order to calculate the level of precision required in a measurement of $\tilde{a}_F$ from a pure Fermi transition, such as to compete with the direct extraction of the Fierz term from the $Ft$-values in super-allowed pure Fermi transitions, Eq. (26), we refer once again to the only linear sensitivity of $\tilde{a}$ to scalar interactions through the contribution of the Fierz term, Eq. (27). This leads to

$$\left| \frac{\delta \tilde{a}_F}{\tilde{a}_F} \right| \approx |\delta b_F| \left| \frac{m}{E} \right|.$$  

(46)

Taking $\delta b_F$ at 1$\sigma$ from Eq. (26) and assuming $\langle m/E \rangle \sim 0.2$ as an estimate, Eq. (46) gives $|\delta \tilde{a}_F/\tilde{a}_F| \sim 0.5 \times 10^{-3}$. This is an order of magnitude smaller than the current level of precision in $^{38}$mK \cite{26} and $^{32}$Ar \cite{27} and the anticipated goal in $^{35}$Ar \cite{65}.

The second experiment will use the Texas A&M University TRAP (TAMUTRAP) which is also a Penning trap system currently under construction \cite{67}. The experimental program of TAMUTRAP includes measurements of $\tilde{a}$ in a set of super-allowed pure Fermi transitions with isospin $T = 2$, which are $\beta$-delayed proton emitters, like $^{32}$Ar decay. The measuring principle relies on the broadening of the delayed proton energy spectrum, which is affected by the correlation between the $\beta$ particle and the neutrino \cite{27}. The Penning trap setup employs an optimized length-to-radius ratio in the electrode structure providing a 90 mm large inner radius \cite{67}.

The fact that the constraints on tensor couplings are considerably weaker than those on scalar ones (Figs. 2 and 3) has motivated a number of new experiments for precision measurements in Gamow-Teller transitions, most of them focused on the measurement of the $\beta\nu$ correlation coefficient in the decay of $^6$He.

A new measurement of $\tilde{a}$ has been carried out at the Grand Accélérateur National d’Ions Lourds (GANIL), Caen in the $\beta$ decay of $^6$He \cite{68}. The ions were stored in a transparent Paul

\footnote{The projections of the future experimental precision goals do not always specify the statistical CL. Unless explicitly stated otherwise, it is assumed that the quoted experimental errors and the projected precision goals are at 1$\sigma$.}
trap (LPCTrap) \[69\] and the \(\beta\nu\) correlation was deduced from the time-of-flight spectrum of \(^6\)Li recoils detected in coincidence with the \(\beta\) particles \[70\]. Three data production runs have been completed with this setup including a measurement of the shake-off probability of the singly bound electron in the recoiling ions following \(\beta\) decay \[71\]. A relative statistical error of 2% has been obtained from the analysis of the first run \[68\] with a systematic error of comparable size.

Since no limit on tensor couplings has been quoted in Ref. \[68\] we review here the result in order to further stress the sensitivity to the linear contributions of the exotic couplings via the Fierz term. The experimental result from Ref. \[68\] reads \(\tilde{a} = -0.334(10)\) where the statistical and systematic errors have been added in quadrature. For a Gamow-Teller transition, the expression of \(b\) in Eq. (27) is given in Eq. (21). Assuming first that the sensitivity to tensor couplings arises only via the Fierz term, we then set \(a \approx a_{SM} \approx -1/3\). The value of the term \(\langle m/E_e \rangle\) under the conditions of that experiment is \(\langle m/E_e \rangle = 0.20\) \[10\]. Assuming \(C_T = C'_T\), the limit obtained from this measurement is then
\[
|C_T/C_A| < 0.13 \quad (90\% \text{ CL, first run LPCTrap}).
\]

(47)

If, in contrast, the contribution of the Fierz term is ignored, the limit extracted from the quadratic contribution to \(a\) would be \(|C_T/C_A| < 0.23\) what is a factor of about 2 weaker. We see that, even if the sensitivity to the Fierz term is here only \(\langle m/E_e \rangle = 0.20\), it remains nevertheless dominant in the extraction of constraints on exotic couplings from the expression of \(\tilde{a}\).

A new measurement has been carried out with the LPCTrap at GANIL, resulting in a relative statistical precision \(\delta a/a = 4.5 \times 10^{-3}\) at 1\(\sigma\) \[72\]. Assuming that the final systematic error will be of comparable magnitude than the statistical one, the result will provide the following bound
\[
\left| \text{Re} \left( \frac{C_T + C'_T}{C_A} \right) \right| \lesssim 0.052 \quad (90\% \text{ CL}).
\]

(48)

This will finally improve the fifty-year old measurement of \(a\) in \(^6\)He decay \[31\], but will still be a factor of 2.5 away from the current limit obtained from \(P_F/P_{GT}\), Eq. (29).

A high intensity gaseous source of \(^6\)He has been developed at the Center for Experimental Nuclear Physics and Astrophysics (CENPA) in Seattle \[73\]. The measured extracted rate of atomic \(^6\)He available at a low background experimental area was about \(10^6\) atoms/s. The source has been used for a high precision measurement of the \(^6\)He half-life \[73\], with the atoms confined in a cylindrical storage volume. The physics plans include a measurement of \(a\) and of the Fierz interference term \[73\]. The measurement of \(a\) will be performed with atoms confined in a MOT \[75\] and by detecting the \(\beta\) particles in coincidence with the recoil ions. The goal of this project is to reach the precision level of 1% in a first phase and reach an ultimate precision of 0.1% after possible improvements of the setup \[75\]. Such a total precision would entail the following bound on tensor interactions
\[
\left| \text{Re} \left( \frac{C_T + C'_T}{C_A} \right) \right| \lesssim 0.0082 \quad (90\% \text{ CL}).
\]

(49)

This would improve the bound from nuclear and neutron decays, Eq. (30), by a factor of about 2. The current bound from radiative pion decay given in Eq. (37) would still be slightly stronger though.

\[10\] For the purpose followed here, the value of \(\langle 1/E_e \rangle = \langle 1/(T_e + m_e) \rangle\) was extracted from the spectrum of the measured kinetic energy, \(T_e\), without deconvoluting the detector response function.
An electrostatic ion beam trap is currently being built at the Weizmann Institute of Science, in Rehovot [76]. The program around this trap includes a measurement of $a$ in $^6$He decay. The ions will be trapped by mirror potentials, and the $^6$Li recoil ions and the $\beta$ particles will be detected in coincidence in a field free region [76]. The project envisages to take advantage of the high yields of radioactive nuclei that will become available at the Soreq Applied Research Accelerator Facility [81].

The $\beta$-$\alpha$-$\alpha$ correlation from $^8$Li decay has since long been known to offer an attractive scheme in order to circumvent the detection of the recoil nucleus [77] although early results were not selective enough to distinguish between different interaction types. After establishing that the decay was dominated by a Gamow-Teller transition, a first limit on a possible tensor contribution has been provided [78] from the measurement of the $\alpha$ particle momenta. An additional advantage of this correlation in $^8$Li decay is that, when the $\alpha$ and $\beta$ particles are detected along the same direction, the sensitivity to the quadratic contributions of the tensor interaction is enhanced by a factor of 3 [78] as compared to a direct measurement of $a$ in a Gamow-Teller transition. This decay has recently been reconsidered at Argonne National Laboratory using ions stored in a longitudinal Paul trap [79]. The $\alpha$ and $\beta$ particles are detected in coincidence and the shape of the $\alpha$ particle energy shift distribution is analyzed. The experiment has obtained a first result [80] corresponding to a limit $|C_T/C_A|^2 < 0.026$ at 90% CL. It is expected that, with an upgraded detection system, the limit on $|C_T/C_A|^2$ can be improved by an order of magnitude [80]. This would then result in a limit on the tensor couplings a factor of about 2 larger than given in Eq. (48). Note that, since the $\beta$ particle end-point energy is rather large in $^8$Li decay (16.1 MeV) the sensitivity to the Fierz term via the factor $\langle m/E_e \rangle$ is 3.3 times smaller than in $^6$He decay.

Several experiments are currently ongoing aiming at improved measurements of $a$ in neutron decay [82, 83, 84]. Such efforts are primarily motivated by the extraction of the ratio $g_A/g_V$ using another observable than the $\beta$ asymmetry parameter, $A$, in order to determine the $V_{ud}$ matrix element from the neutron lifetime. The anticipated precision goals on $\delta a/a$ of these experiments are $\pm 1\%$ for $a$CORN [83] $\pm 0.5\%$ for $a$SPECT [82] and $0.1\%$ for Nab [84]. This last collaboration also aims a direct determination of the Fierz term that we address here below.

In summary, the most precise experiments in Fermi transitions have reached a level of of few $10^{-3}$ at $1\sigma$ for the measurements of $a$ [27, 26]. Comparable levels of precision have been anticipated by new projects [63] and it is reasonable to expect that these will soon be achieved. It appears challenging that the new round of measurements of $a$ would be able to improve the bounds on scalar couplings set by the Fierz term extracted from the $F_t$-values in pure Fermi transitions, Eq. (26). However, this constraint has a stronger dependence to theoretical uncertainties related to nuclear structure and radiative corrections than those obtained from correlation coefficients. Since the nuclear matrix elements cancel to first order in the correlation coefficients, it is expected that nuclear effects would manifest at the level of induced weak currents. This leaves significant room for improvements in precision for measurements of correlation coefficients.

For pure Gamow-Teller transitions, considering the number of ongoing experiments in $^6$He, $^8$Li and neutron decays and the anticipated precision goals on a longer time scale [75, 84], it is expected that the next round of measurements of $a$ could reach a precision at the $0.1\%$ level. This should have a significant impact to further constraint possible tensor contributions.
6.2 The Fierz interference term, $b$

The Fierz term can be accessed directly by measurements of the shape of the $\beta$ energy spectrum. Such measurements are very challenging, in particular because of instrumental difficulties associated with the detection of $\beta$ particles at low energies such as backscattering, out-scattering, detector dead-layers, noise, etc.

The physics program of the CENPA group around the high intensity $^6\text{He}$ source includes a measurement of $b$ in $^6\text{He}$ decay [73]. The technical details of the detection system to be used for such a measurement and the sensitivity level of the experiment have not yet been anticipated.

The problems associated with the scattering of $\beta$ particles in matter and the limited precision of available data on low-energy electron scattering that is required for precise Monte-Carlo simulations, have motivated the development of a new and compact $\beta$ spectrometer (miniBETA) by groups from Krakow and Leuven [85]. The system is based on an ultra-light multi-wire drift chamber combined with energy sensitive detectors. Precision measurements of the shape of $\beta$ energy spectra for transitions with relatively low endpoint energies are being considered [86].

The Fierz term has never been measured in neutron decay and there are currently two projects aiming a direct determination from the shape of the $\beta$ energy spectrum.

The Nab collaboration will use a cold neutron beam at the Fundamental Neutron Physics Beamline of the Spallation Neutron Source in Oak Ridge [84]. The setup uses a field-expansion magnetic spectrometer that confines electrons and protons toward segmented Si detectors. The anticipated precision goal for the direct measurement of $b$ is $\delta b = 3 \times 10^{-3}$ [84] and is aimed to provide an independent limit on exotic tensor couplings.

The second project is the UCNb experiment at Los Alamos National Laboratory [87] and uses ultra-cold neutrons confined in a $4\pi$ box made of plastic scintillators. This experiment aims a precision of $\delta b \approx 10^{-3}$ [87].

6.3 Time-reversal violating correlations

A new measurement of the time-reversal violating triple correlation coefficient $R$ has been carried out in $^8\text{Li}$ decay at ISAC-TRIUMF [88]. The nuclear polarization is obtained by collinear laser optical pumping of a low-energy beam which is then ionized an implanted on a Pt foil. The $\beta$ particle transverse polarization is analyzed by Mott scattering on a lead foil and the particles are tracked using planar wire chambers. The precision goal of this experiment is to reach the level of final state interactions which, as already indicated, are at $10^{-4}$ level for this decay [45].

7 Summary and Outlook

We have reviewed the status of the searches for physics beyond the SM by precision measurements in nuclear and neutron $\beta$ decays. For the description of such processes at the quark-level, we have used a model-independent EFT approach, assuming that the NP would emerge at much higher energies, not only compared to those available in $\beta$ decays but also those currently accessed or projected to be accessed at the LHC. An attractive feature of this approach is that it provides a unified framework to describe the effects of NP in nuclear, neutron and pion decays as well as in collider physics.

It was shown that only three CP-conserving and three CP-violating NP couplings can contribute linearly to the observables in $\beta$ decay, and so only those couplings can be strongly probed with precision experiments at low energies.
We have then review the constrains on these six couplings from precise measurements in nuclear and neutron decays, using the hadron-level coefficients. Except for the $Ft$-values deduced from pure Fermi transitions, which combines results from a large set of experiments and for several nuclear transitions, we have selected the most precise results from single experiments. A more detailed analysis would require a new global fit of all currently available data. When analyzing the sensitivity of the most stringent constraints on scalar and tensor couplings provided by measurements of correlations or decay rates, we found that the only relevant parameter for all constraints is the Fierz interference term. This term is linear in the couplings and contribute to the measured correlations in most experimental conditions, offering then the dominant sensitivity to those couplings.

With the most precise results, we have then moved to a quark-level description in order to compare first with results obtained from other semi-leptonic processes but also with results obtained from measurements at the LHC. This illustrates the benefit of the EFT approach for the sensitivity comparison between different hadronic probes, such as pions, nucleons, and nuclei. For the CP-conserving coefficients, direct limits from $\beta$ decay appear to be very competitive. Next we discussed the interplay with results from the LHC and we stressed the complementary of precision measurements in $\beta$ decay as probes of new physics. An interesting competition with results from the LHC arises since the effective scale probed by low energy experiments overlaps with the LHC reach. The most attractive scenario of such interplay would be that in which a non-zero result would be observed for an exotic effective coupling either at low energies or in the collider searches. If a new particle were found at the LHC, experiments in $\beta$ decays will play an important role in disentangling the properties of the NP dynamics. We also presented the projected sensitivities to be reached at LHC which are important to orient new precision goals for measurements at low energies.

We have finally reviewed the current experimental efforts looking for signatures of NP in measurements of correlations or spectrum shapes in nuclear and neutron decays. The purpose was to project the sensitivity level of those efforts and confront them with the future LHC reach. We have stressed again the importance of the Fierz term in those searches and gave simple quantitative illustrations in the measurement of $a$ in Fermi and Gamow-Teller transitions. Although recent measurements of the $\beta$ asymmetry parameter $A$ in Gamow-Teller transitions have explicitly relied on the sole contribution of the Fierz term in the search for tensor interactions, the role this term does not appear to have been generally incorporated for the optimization of current experiments and for the design of new projects.

The sensitivity goal imposed by future LHC reach is very challenging but possibly within reach by next generation experiments, where precisions at the level of $10^{-3}$ or below are needed on the Fierz term. For the comparison with the SM predictions of the measured observables, accurate theoretical calculations are fundamental. These require the inclusion of radiative corrections and recoil order effects and, whenever necessary, of nuclear structure corrections. The errors on these corrections set the next theoretical limit of sensitivity for future measurements and leave still a large window for improvements for experiments measuring correlations or spectrum shapes in nuclear and neutron decays.

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