High precision measurements of beta decay observables play an important role in beyond the standard model (BSM) physics searches, as they allow us to probe couplings other than of the $V-A$ type, which could appear at the low energy scale. Experiments using cold and ultra-cold neutrons [1–4], nuclei [5–8], and meson rare decays [9], are being performed, or have been planned, that can reach the per mil level or even higher precision. Effective field theory (EFT) allows one to connect these measurements and BSM effects generated at TeV scales. In this approach that complements collider searches, the new interactions are introduced in an effective Lagrangian describing semi-leptonic transitions at the GeV scale including four-fermion terms, or operators up to dimension six for the scalar, tensor, pseudo-scalar, and V+A interactions (for a review of the various EFT approaches see Ref.[10]). Because the strength of the new interactions is defined with respect to the strength of the known SM interaction, the coefficients of the various terms, $\epsilon_i$, ($i = S, T, P, L, R$) depend on the ratio $m_W^2/\Lambda_i^2$, where $\Lambda_i$ is the new physics scale relevant for these non-standard interactions, and $m_W^2$ enters through $G_F = g^2/(4\sqrt{2}m_W^2)$. Therefore, the precision with which $\epsilon_i \propto m_W^2/\Lambda_i^2$, is known determines a lower limit for $\Lambda_i$. The scalar ($S$) and tensor ($T$) operators, in particular, contribute linearly to the beta decay parameters through their interference with the SM amplitude, and they are therefore more easily detectable. The matrix elements/transition amplitudes between neutron and proton states of all quark bilinear Lorentz structures in the effective Lagrangian which are relevant for beta decay observables, involve products of the BSM couplings, $\epsilon_i$, and the corresponding hadronic charges, $g_i$, i.e. considering only terms with left-handed neutrinos, $C_S = G_F V_{ud} \sqrt{2} \epsilon_S g_S$, and $C_T = 4G_F V_{ud} \sqrt{2} \epsilon_T g_T$. $g_S(T)$ can be parameterized in terms of nucleon form factors which cannot be measured directly, being chiral odd.

Various approaches have been developed so far to calculate these quantities including lattice QCD [11–15], and most recently Dyson-Schwinger Equations [16, 17]. Lattice QCD provides the most reliably calculated values for the isovector scalar and tensor charges with precision levels of $\Delta g_S/g_S \approx 15\%$, and $\Delta g_T/g_T \lesssim 4\%$, respectively. Following the analysis in Ref.[18], these values are well below the minimum accuracy that is required not to deteriorate the per mil level constraints from decay experiments.

In this Letter we call attention to the fact that the nucleon form factors which are relevant for BSM physics searches using neutron beta decay at the scale $t = (M_n - M_p)^2 \approx 0$, can now also be measured accurately in deep inelastic processes that occur at the multi-GeV scale. This novel development emerges from recent experimental and theoretical advances in the study of the 3D structure of the nucleon. We focus on $g_T$ that appears at leading order in the hadroproduction cross section, and we evaluate both the uncertainty from the experimental extraction of this quantity, and its impact on the determination of the elementary tensor coupling, $\epsilon_T$. Current and future planned experiments on dihadron semi-inclusive and deeply virtual exclusive pseudoscalar meson ($\pi^0$ and $\eta$) electroproduction at Jefferson Lab [19, 20] and COMPASS [21, 22] allow us to measure $g_T$ with an improved accuracy. The main outcome of the analysis presented here is that the new, more precise measurements of the tensor charge provide for the first time a constraint from experiment on the hadronic matrix element in BSM searches.
The tensor form factor is derived from an integral relation involving the transversity (generalized) parton distribution function, or the probability to find a quark with a net transverse polarization in a transversely polarized proton,

\[ g_T^q(t, Q^2) = \int_0^1 dx \left[ H_T^q(x, t, Q^2) - H_T^\perp(x, t, Q^2) \right] \]

where \( h_T^q(x, Q^2) \) and \( H_T^\perp(x, t, Q^2) \) are the quark (anti-quark) transversity Parton Distribution Function (PDF) and Generalized Parton Distribution (GPD), respectively; \( Q^2 \) is the virtual photon’s four momentum squared in the deep inelastic processes defining each object, while \( t = (p - p')^2 \) is the four-momentum transfer squared between the initial \( p \) and final \( p' \) proton, \( t = 0 \) for a PDF which corresponds to the imaginary replica. Transversity cannot be measured in an ordinary deep inelastic scattering process because it is a chiral-odd quantity, but it has been measured with large errors in one-pion jet semi-inclusive deep inelastic scattering (SIDIS) with transversely polarized targets (see review in [29]). Recent progress in both dihadron SIDIS and exclusive deep virtual meson electroproduction (DVMP) experiments have, however, relaunched the possibility of obtaining a precise experimental determination of \( g_T^q \). The main reason why these processes can provide a cleaner measurement is that they are not sensitive to intrinsic transverse momentum dependent distributions and fragmentation functions, and they therefore connect more directly to the tensor charge while obeying simpler factorization theorems in QCD.

Dihadron SIDIS off transversely polarized targets,

\[ l + N \rightarrow l' + H_1 + H_2 + X \]

where \( l \) denotes the (unpolarized) lepton beam, \( N \) the nucleon target, \( H_1 \) and \( H_2 \) the produced hadrons, allows one to access the helicity charge \( h \), through the modulation from the azimuthal angle \( \phi_S \) of the target polarization component in both the virtual-photon and target momenta, and the azimuthal angle of the transverse average momentum of the pion pair \( \phi_R \) w.r.t. the virtual photon direction. In this process, the observable can be written as the product of \( h_T^q \), and a chiral odd fragmentation function called \( H_{1q}^{\perp} \)

\[ F_{UT}^{\sin(\phi_R + \phi_S)} = x \sum_q e_q^2 h_T^q(x; Q^2) \frac{|R| \sin \theta}{M_h} H_{1q}^{\perp}. \]

Data for the single-spin asymmetry related to the modulation of interest here are available from HERMES [28] and COMPASS [21, 22] on both proton and deuteron target allowing for a \( u \) and \( d \) quarks flavor separation, whereas the chiral-odd DiFF have been extracted from the angular distribution of two pion pairs produced in \( e^+e^- \) annihilations at Belle [33]. Using these data sets, in Ref. [34, 35], the transversity PDF has been determined for different functional forms, and using the replica method for the error analysis. As for future extractions, the dihadron SIDIS will be studied in CLAS12 at JLab on a proton target and in SoLID on a neutron target [19] that will give both an improvement of \( \sim 10\% \) in the ratio \( \Delta g_T/g_T \) thanks to a wider kinematical coverage and
better measurement of the $d$ quarks contribution. The results from this extraction are shown in Figure 1.

Deeply virtual exclusive pseudoscalar meson production (DVMP),

$$l + N \rightarrow l' + \pi^o(\eta) + N',$$

was proposed as a way to access transversity GPDs assuming a (twist three) chiral odd coupling ($\propto \gamma_5$) for the $\pi^o(\eta)$ prompt production mechanism [36, 38–42]. Three additional transverse spin configurations are allowed in the proton besides transversity which can be described in terms of combinations of GPDs called $E_T, \tilde{H}_T, \tilde{E}_T$ [25]. The GPDs enter the observables at the amplitude level, convoluted with complex coefficients at the leading order, thus forming the generalized form factor (GFFs). A careful analysis of the helicity amplitudes contributing to DVMP has to be performed in order to disentangle the various chiral odd GFFs from experiment [13].

The ideal set of data to maximally constrain the tensor charge in the chiral odd sector are from the transverse target spin asymmetry modulation [36],

$$F_{UT}^{\sin(\phi - \phi_s)} = 3m \left[ \mathcal{H}_T(2\mathcal{H}_T + \mathcal{E}_T) \right]$$

where $\phi$, is the angle between the leptonic and hadronic planes, and $\phi_s$, the angle between the lepton’s plane and the outgoing hadron’s transverse spin. In Ref. [36] the tensor charge was, however, extracted by fitting the unpolarized $\pi^o$ production cross section [20], using a parametrization constrained from data in the chiral even sector to guide the functional shape of the in principle unknown chiral odd GPDs. Notice that the tensor charge was obtained with a relatively small error because of the presence of these constraints. The results from this extraction are also shown in Fig. 1.

Finally, in Fig. 1 we quote also the value obtained in single pion SIDIS [37], although this is known to contain some unaccounted for corrections from TMD evolution [44, 45].

The impact on the extraction of $\epsilon_T$, of both the lattice QCD and experimental determinations of $g_T$ is regulated by the most recent limit [10, 17].

$$|\epsilon_T g_T| < 6.4 \times 10^{-4} \quad (90\%)$$

Assuming no error on the extraction/evaluation of $g_T$, yields $\Delta \epsilon_{T,\min} = 6.4 \times 10^{-4}/g_T$. Since the errors on $g_T$ in both the lattice QCD and experimental extractions are affected by systematic/theoretical uncertainty, alternatives to the standard Hessian evaluation have been adopted in recent analyses [15] which are based on the R-fit method [48, 49]. By introducing the error on $g_T$, we obtain $\Delta \epsilon_T \geq \Delta \epsilon_{T,\min}$. The amount by which $\Delta \epsilon_T$ deviates from the minimum error depends, however, on the relative error $\Delta g_T/g_T$ as well as on the central value of $g_T$, and on $C_T$. We find that within the range of parameters extracted from our analysis of exclusive and semi-inclusive experiments, knowing the tensor charge up to a
moderate accuracy, $\Delta g_T/g_T \lesssim 20\%$, does not deteriorate the limits set by current experiments. This situation is illustrated in Fig. 2, where we show $\epsilon_T$ vs. $\Delta g_T/g_T$, for the various determinations.

In conclusion, the possibility of obtaining the scalar and tensor form factors and charges directly from experiment with sufficient precision, gives an entirely different leverage to neutron beta decay searches. While lattice QCD provides the only means to calculate quantities that are unattainable in experiment, for the tensor charge the situation is different. In this case, the hadronic matrix element is the same which enters the DIS observables measured in precise semi-inclusive and deeply virtual exclusive scattering off polarized targets. Most importantly, the error on the elementary tensor coupling, $\epsilon_T$, depends on both the central value of $g_T$ as well as on the relative error, $\Delta g_T/g_T$, therefore, independently from the theoretical accuracy that can be achieved, experimental measurements are essential since they simultaneously provide a testing ground for lattice QCD calculations.

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