Snowmass2021 - Letter of Interest
Probing Scalar and Tensor Interactions at the TeV Scale

Topical Groups:

■ (EF04) EW Physics: EW Precision Physics and constraining new physics
■ (EF05) QCD and strong interactions:Precision QCD
■ (EF09) BSM: More general explorations
■ (EF10) BSM: Dark Matter at colliders
■ (RF02) BSM: Weak decays of strange and light quarks
■ (RF03) Fundamental Physics in Small Experiments
■ (TF02) Effective field theory techniques
■ (TF05) Lattice gauge theory
■ (TF06) Theory techniques for precision physics
■ (CompF2) Theoretical Calculations and Simulation

Contact Information:
Rajan Gupta (Los Alamos National Laboratory) [rajan@lanl.gov]:
Emanuele Mereghetti (Los Alamos National Laboratory) [emereghetti@lanl.gov]
Collaboration: Precision Neutron Decay Matrix Elements (PNDME) and Nucleon Matrix Elements (NME)

Authors:
Simone Alioli (Universita' degli Studi di Milano-Bicocca) [simone.alioli@unimib.it]
Tanmoy Bhattacharya (Los Alamos National Laboratory) [tanmoy@lanl.gov]
Radja Boughezal (Argonne National Laboratory) [rboughezal@anl.gov]
Vincenzo Cirigliano (Los Alamos National Laboratory) [cirigliano@lanl.gov]
Rajan Gupta (Los Alamos National Laboratory) [rajan@lanl.gov]
Yong-Chull Jang (Brookhaven National Laboratory) [ypj@bnl.gov]
Huey-Wen Lin (Michigan State University) [hwlin@pa.msu.edu]
Emanuele Mereghetti (Los Alamos National Laboratory) [emereghetti@lanl.gov]
Santanu Mondal (Los Alamos National Laboratory) [santanu@lanl.gov]
Sungwoo Park (Los Alamos National Laboratory) [sungwoo@lanl.gov]
Saori Pastore (Washington University, St. Louis) [saori@wustl.edu]
Frank Petriello (Northwestern University) [f-petriello@northwestern.edu]
Boram Yoon (Los Alamos National Laboratory) [boram@lanl.gov]
Albert Young (North Carolina State University) [aryoung@ncsu.edu]

Abstract: Novel scalar and tensor interactions (fundamental or loop effects) at the TeV scale can be probed, both at the LHC and through precision measurements of neutron decay combined with lattice QCD calculations of the isovector scalar and tensor charges of the neutron. Progress in all three areas in the last five years have significantly improved constraints on these interactions. In this LOI, we motivate the calculations and outline the progress expected over the next decade in improving the precision of the measurements of the helicity flip parameters b and b_ν in neutron decay and in lattice QCD calculations of the charges of the nucleon. With these expected improvements, and results from the LHC, we estimate that possible BSM couplings ε_S and ε_T can be constrained at the 10^{-4} level.

Motivation and Physics Goals The Standard Model does not contain fundamental scalar or tensor interactions. However, loop effects and new interactions at the TeV scale can generate effective interactions at the hadronic scale that can be probed in decays of neutrons, and at the TeV scale itself at the LHC. In a low-energy effective theory, nonstandard scalar and tensor charged-current interactions are parametrized by the dimensionless couplings $\epsilon_{S,T}$[7;10]:

$$\mathcal{L}_{\rm CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \left[\epsilon_S \, \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}d + \epsilon_T \, \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \right] . \quad (1)$$

These couplings can be constrained by a combination of low energy precision beta-decay measurements (of the pion, neutron, and nuclei) combined with Lattice QCD results for their isovector charges $g_S^{\rm u-d}$ and $g_T^{\rm u-d}$, as well at the Large Hadron Collider (LHC) through the reactions $pp \to e\nu + X$ and $pp \to e^+e^- + X$. The LHC constraint is valid provided the mediator of the new interaction is heavier than a few TeV.

In the neutron decay distribution, such scalar and tensor interactions contribute to the helicity-flip parameters b and b_ν[7]. To leading order, the relation is

$$b^{\rm BSM} \approx 0.34 \, g_S \, \epsilon_S + 5.22 \, g_T \, \epsilon_T \qquad\qquad b_\nu^{\rm BSM} \approx 0.44 \, g_S \, \epsilon_S - 4.85 \, g_T \, \epsilon_T \quad (2)$$

Thus, by combining the calculation of the scalar and tensor charges with the measurements of b and b_ν in low energy experiments, one can put constraints on novel scalar and tensor interactions at the TeV scale as described in Ref.[7] and reproduced in Fig. 1. To optimally bound such scalar and tensor interactions using measurements of b and b_ν parameters in planned experiments targeting 10^{-3} precision[2;22;26], the level of precision required in g_S^{u-d} and g_T^{u-d} is at the 10% level as explained in Refs.[2;7;22;26].

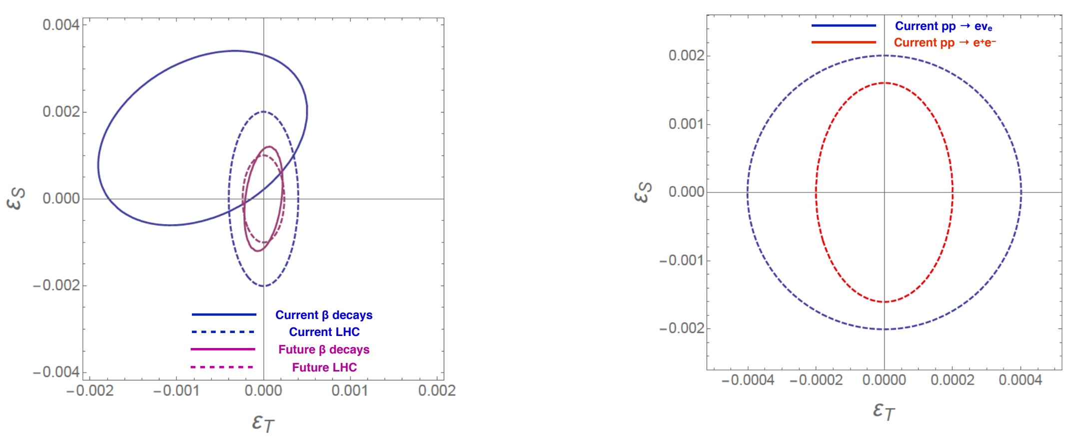

Figure 1: Current and projected 90% C.L. constraints on ϵ_S and ϵ_T defined at 2 GeV in the $\overline{MS}$ scheme. (Left) The beta-decay constraints are obtained from the recent review article Ref.[12]. The current analysis includes all existing neutron and nuclear decay measurements, while the future projection assumes measurements of the various decay correlations with fractional uncertainty of 0.1%, the Fierz interference term at the 10^{-3} level, and neutron lifetime with uncertainty $\delta\tau_n = 0.1s$. The current and future LHC bounds are obtained from the analysis of the $pp \to e + MET + X$. We have used the ATLAS results[1] at $\sqrt{s} = 13$ TeV and integrated luminosity of 36 fb^{-1}. We find that the strongest bound comes from the cumulative distribution with a cut on the transverse mass at 2 TeV. The projected future LHC bounds are obtained by assuming that no events are observed at transverse mass greater than 3 TeV with an integrated luminosity of 300 fb^{-1}. (Right) Comparison of current LHC bounds from $pp \to e + MET + X$ versus $pp \to e^+e^- + X$.

Neutron beta decay Experiments: Recent measurements from the UCNA collaboration [16;17;25] and PERKEO III [24] have provided the first direct constraints on Fierz interference terms in neutron decay that can be produced by exotic S- and T-couplings. Experiments are under construction (or in early stages of development) using conventional detector methods such as the Nab magnetic spectrometer instrumented with thick Si detectors [9;21] and Cyclotron Resonance Emission Spectroscopy [4;11] to improve these limits. CRES, in particular, may permit a direct measurement of the spectrum with constraints below the 10^{-3} level for a possible Fierz term.

Scalar and tensor interactions at colliders: In the next ten years, the LHC Run 3 will collect data with 300 fb^{-1} of integrated luminosity at $\sqrt{S} = 14$ TeV, and, towards the end of the decade, the High Luminosity LHC will start taking data. Constraints from these data on scalar and tensor currents will be studied in the framework of the SMEFT. In addition to the total cross section at high invariant mass, we will study differential distributions, including angular distributions, which might offer smoking-gun evidence for scalar and tensor interactions. We will then study the impact of dimension-8 SMEFT operators on global fits to charged- and neutral-current Drell-Yan (DY) data. Since scalar and tensor interactions do not interfere with the SM (modulo tiny mass corrections which are negligible at the LHC), and thus contribute quadratically to DY cross sections, the inclusion of dimension-8 operators is necessary for a consistent treatment. A consistent global fit might unveil free directions in parameter space, with implications for the complementarity of high-energy and low-energy experiments (including beta decays and high-luminosity colliders such as the EIC).

Lattice QCD calculations: The lattice QCD calculations of g_S and g_T are part of a comprehensive calculation of matrix elements of various low energy effective local and non-local operators composed of quarks and gluons. They address many interesting quantities including axial vector [13;19] and electromagnetic [18] form factors of the nucleon that enter in the analysis of neutrino and electron scattering; the flavor diagonal axial [20], scalar and tensor [15], charges that are needed to study the interaction of dark matter particles off nuclear targets; and the contribution of novel CP violating operators to the neutron electric dipole moment (nEDM) [5;23]. In a series of papers [5;6;8;14;15;20], we have shown that the methodology for lattice-QCD calculations is well established and we have reached a level of control over all sources of systematic errors needed to yield the tensor charge with about 5% precision ($g_T^{u-d} = 0.989(32)(10)$ and scalar with about 10% ($g_S^{u-d} = 1.022(80)(60)$) [14]. The status of nucleon charges has been reviewed in the Flavour Lattice Averaging Group (FLAG) Review 2019 [3]. With the ongoing calculations, we anticipate reducing the errors in both g_S^{u-d} and g_T^{u-d} by a factor of two in the next 2–3 years. Over the next decade, with the anticipated a 10–100 fold increase in computing resources, we will be able to provide all isovector and flavor diagonal charges of the nucleon with 1% accuracy. Having g_S^{u-d} and g_T^{u-d} at the 1% level will complement the measurements of b and b_ν parameters at the 10^{-4} precision. With these milestones, low-energy constraints on ε_S and ε_T will reach the 10^{-4} level.

Nuclear physics calculations: Scalar and tensor interactions can also be sensitively probed by measuring the Fierz interference term in pure Fermi and pure Gamow-Teller nuclear beta decays. In the next decade, several experiments aim at achieving spectral measurements with accuracy at better than the permill level. To claim the discovery of new physics, or constrain new physics models at the TeV scale, it is necessary that nuclear theoretical calculation of the beta spectra reach the same accuracy, demanding control of recoil and radiative corrections. Nuclear Effective Field Theories (EFT), especially chiral EFT, provide a systematic framework for the calculations of these corrections, in a power counting scheme which allows reliable estimation of the theoretical error. We will compute the beta spectrum in the decay of ^{6}He and provide solid estimates of the Standard Model background to searches for the b interference term.

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