Non-Standard Charged-Current Interactions in β Decay: Sources and Prospects

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Topics in Context

We consider how "non-standard" charged-current interactions can ...

(i) modify β decay observables that respect SM symmetries

(ii) generate β decay observables that are "null" in the SM **(T odd!)**

Testing the V-A law has spanned **decades**, employing

$$\mathcal{H}_{int} = (\bar{\psi}_p \psi_n)(C_S \bar{\psi}_e \psi_\nu + C'_S \bar{\psi}_e \gamma_5 \psi_\nu) + (\bar{\psi}_p \gamma_\mu \psi_n)(C_V \bar{\psi}_e \gamma^\mu \psi_\nu + C'_V \bar{\psi}_e \gamma^\mu \gamma_5 \psi_\nu)$$
$$-(\bar{\psi}_p \gamma_\mu \gamma_5 \psi_n)(C_A \bar{\psi}_e \gamma^\mu \gamma_5 \psi_\nu + C'_A \bar{\psi}_e \gamma^\mu \psi_\nu) + (\bar{\psi}_p \gamma_5 \gamma_\mu \psi_n)(C_P \bar{\psi}_e \gamma_5 \psi_\nu + C'_P \bar{\psi}_e \psi_\nu)$$
$$+\frac{1}{2}(\bar{\psi}_p \sigma_{\lambda\mu} \psi_n)(C_T \bar{\psi}_e \sigma^{\lambda\mu} \psi_\nu + C'_T \bar{\psi}_e \sigma^{\lambda\mu} \gamma_5 \psi_\nu) + h.c.$$

[Lee and Yang, 1956; note also Gamow and Teller, 1936]

to confront decay correlations. For the neutron: [Jackson, Treiman, and Wyld, 1957]

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \xi S(p_e, E_e)[1 + a\frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + \boldsymbol{\sigma_n} \cdot (A\frac{\boldsymbol{p}_e}{E_e} + B\frac{\boldsymbol{p}_\nu}{E_\nu} + D\frac{\boldsymbol{p}_e \times \boldsymbol{p}_\nu}{E_e E_\nu})]$$

N.B. the V-A Law: $C'_A = C_A$, $C'_V = C_V$, with all others zero.

[Feynman and Gell-Mann, 1958; Sudarshan and Marshak, 1958]

$$\text{Note} \quad b\xi = \pm 2\text{Re}[C_S C_V^* + C'_S C'^*_V + 3(C_T C_A^* + C'_T C'^*_A)]$$

EFT Analysis Framework for β Decay

$$\mathcal{L}^{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{1}{\Lambda_i^2} O_i \Longrightarrow \mathcal{L}_{\rm SM} + \frac{1}{v^2} \sum_i \hat{\alpha}_i O_i \,,$$

with $\hat{\alpha}_i = v^2/\Lambda_i{}^2$. [Buchmuller & Wyler, 1986; Grzadkowski et al., 2010; Cirigliano, Jenkins, González-Alonso, 2010; Cirigliano, González-Alonso, Graesser, 2013]

$$\begin{aligned}
\mathcal{L}^{\rm eff} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \Big[& \left(1+\delta_\beta\right) \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
+ \quad & \epsilon_L \, \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d + \tilde{\epsilon}_L \, \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
+ \quad & \epsilon_R \, \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d + \tilde{\epsilon}_R \, \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\
+ \quad & \epsilon_S \, \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}d + \tilde{\epsilon}_S \, \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}d \\
- \quad & \epsilon_P \, \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d - \tilde{\epsilon}_P \, \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d \\
+ \quad & \epsilon_T \, \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d + \tilde{\epsilon}_T \, \bar{e}\sigma_{\mu\nu}(1+\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1+\gamma_5)d \\
+ \quad & \text{h.c.}
\end{aligned}$$

Right-handed currents $\tilde{\epsilon}_i$ enter as $|\tilde{\epsilon}_i|^2$ in β decay.
δ_β is the SM radiative correction. [Sirlin, 1974, 1978; Marciano & Sirlin, 1986, 2006; Czarnecki et al., 2004]
There is a one-to-one map between these operators and Lee & Yang.

Connecting to Lee and Yang

$$
\begin{aligned}
\langle p(p')|\bar{u}\gamma^\mu d|n(p)\rangle &\equiv \bar{u}_p(p')\left[g_V(q^2)\gamma^\mu - i\frac{f_2(q^2)}{M}\sigma^{\mu\nu}q_\nu + \frac{f_3(q^2)}{M}q^\mu\right]u_n(p)\,,\\
\langle p(p')|\bar{u}\gamma^\mu\gamma_5 d|n(p)\rangle &\equiv \bar{u}_p(p')\left[g_A(q^2)\gamma^\mu\gamma_5 - i\frac{g_2(q^2)}{M}\sigma^{\mu\nu}\gamma_5 q_\nu + \frac{g_3(q^2)}{M}\gamma_5 q^\mu\right]u_n(p)\,,\\
\langle p(p')|\bar{u}d|n(p)\rangle &\equiv \bar{u}_p(p')g_S(q^2)u_n(p)\,,\\
\langle p(p')|\bar{u}\sigma_{\mu\nu}d|n(p)\rangle &\equiv \bar{u}_p(p')\Big[g_T(q^2)\sigma^{\mu\nu} + g_T^{(1)}(q^2)(q^\mu\gamma^\nu - q^\nu\gamma^\mu)\\
&\quad + g_T^{(2)}(q^2)(q^\mu P^\nu - q^\nu P^\mu) + g_T^{(3)}(q^2)(\gamma^\mu \not{q}\gamma^\nu - \gamma^\nu\not{q}\gamma^\mu)\Big]u_n(p)\,,
\end{aligned}
$$

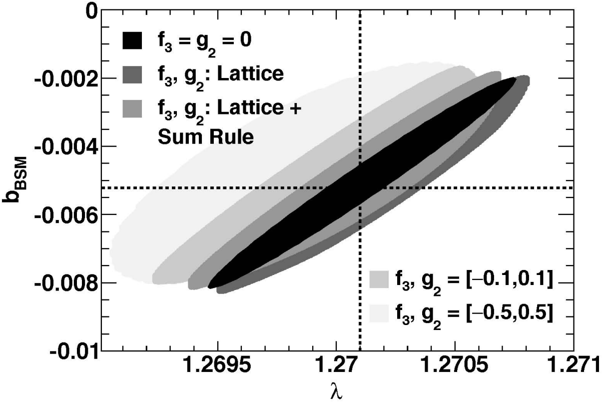
at leading recoil order yield the matching conditions (note $C_i = (G_F^{(0)}/\sqrt{2})\,V_{ud}\,\bar{C}_i$), e.g.,

$$
\begin{aligned}
\bar{C}_V &= g_V\,(1+\delta_\beta+\epsilon_L+\epsilon_R+\tilde{\epsilon}_L+\tilde{\epsilon}_R)\\
\bar{C}_V' &= g_V\,(1+\delta_\beta+\epsilon_L+\epsilon_R-\tilde{\epsilon}_L-\tilde{\epsilon}_R)\\
\bar{C}_A &= -g_A\,(1+\delta_\beta+\epsilon_L-\epsilon_R-\tilde{\epsilon}_L+\tilde{\epsilon}_R)\\
\bar{C}_A' &= -g_A\,(1+\delta_\beta+\epsilon_L-\epsilon_R+\tilde{\epsilon}_L-\tilde{\epsilon}_R)\\
\bar{C}_S &= g_S\,(\epsilon_S+\tilde{\epsilon}_S)\\
\bar{C}_S' &= g_S\,(\epsilon_S-\tilde{\epsilon}_S)\\
\bar{C}_T &= 4\,g_T\,(\epsilon_T+\tilde{\epsilon}_T)\\
\bar{C}_T' &= 4\,g_T\,(\epsilon_T-\tilde{\epsilon}_T)
\end{aligned}
$$

Lattice QCD evaluations of g_S and g_T sharpen the impact of beta decay experiments. [Bhattacharya et al., arXiv:1306.5435; González-Alonso & Camalich, arXiv:1309.4434]

Resolving the limits of the V-A Law

The precision of the experiments imply that $g_A/g_V \equiv \lambda$ must be fit.
Poorly known recoil-order matrix elements (SM) can mimic S, T effects.
Treating these as theory errors in a maximum likelihood fit á la "CKMFitter" [RFit] of Monte Carlo pseudodata for a and A (assuming anticipated PERC precision) with the largest empirically allowed tensor term yields [Hoecker et al., 2001; Charles et al., 2005 – here SG & Plaster, 2013]



T-odd Observables at Low Energies....

For the neutron: [Jackson, Treiman, and Wyld, 1957]

$$d^3\Gamma \propto E_e|\boldsymbol{p}_e|(E_e^{\max} - E_e)^2 \times$$
$$[1 + a\frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + \boldsymbol{\sigma}_N \cdot (A\frac{\boldsymbol{p}_e}{E_e} + B\frac{\boldsymbol{p}_\nu}{E_\nu} + D\frac{\boldsymbol{p}_e \times \boldsymbol{p}_\nu}{E_e E_\nu})]dE_e d\Omega_e d\Omega_\nu$$

A and B are P odd, T even, whereas D is (pseudo)T odd, P even.

Limits on permanent EDMs of nondegenerate systems and T-odd correlations in β-decays probe new sources of CP violation — all these observables involve spin....

In *radiative* β-decay we can form a T-odd correlation from momenta alone: $\mathbf{p}_\gamma \cdot (\mathbf{p}_e \times \mathbf{p}_\nu)$, so that we probe new physics sources which are not constrained by EDM limits. [SG and Daheng He, 2012]

N.B. decay correlations can only be motion-reversal odd.
Thus they are not – and cannot be – true tests of T.

In β decay, the mimicking FSI are **electromagnetic** and can be computed.

Anomalous interactions at low energies

What sort of interaction gives rise to a $\mathbf{p}_\gamma \cdot (\mathbf{p}_e \times \mathbf{p}_\nu)$ correlation at low energy?

Harvey, Hill, and Hill: Gauging the axial anomaly of QCD under $SU(2)_L \times U(1)_Y$ makes the baryon vector current anomalous and gives rise to "Chern-Simons" contact interactions (containing $\varepsilon^{\mu\nu\rho\sigma}$) at low energy.

[Harvey, Hill, and Hill (2007, 2008)]

In a chiral Lagrangian with nucleons, pions, and a complete set of electroweak gauge fields, the requisite terms appear at N^2LO in the chiral expansion. [Hill (2010); note also Fettes, Meißner, Steininger (1998) (isovector)]

Integrating out the $W^\pm$ yields

$$-\frac{4c_5}{M^2}\frac{eG_F V_{ud}}{\sqrt{2}}\varepsilon^{\sigma\mu\nu\rho}\bar{p}\gamma_\sigma n\bar{\psi}_{eL}\gamma_\mu\psi_{\nu_e L}F_{\nu\rho}\,,$$

which can infere with (dressed by a bremsstrahlung photon)

$$\frac{G_F V_{ud}}{\sqrt{2}}g_V\bar{p}\gamma^\mu n\bar{\psi}_e\gamma_\mu(1-\gamma_5)\psi_{\nu_e}\,,$$

Thus the weak vector current can mediate parity violation, too.

Radiative β-Decay

In $n(p_n) \to p(p_p) + e^-(l_e) + \overline{\nu}_e(l_\nu) + \gamma(k)$ decay the interference of the c_5 term with the leading $V - A$ terms yields

$$|\mathcal{M}|^2_{c_5} = 256 e^2 G_F^2 |V_{ud}|^2 \mathrm{Im}\,(c_5\, g_V) \frac{E_e}{l_e \cdot k} (\mathbf{l}_e \times \mathbf{k}) \cdot \mathbf{l}_\nu + \dots \,,$$

neglecting corrections of radiative and recoil order.
Note EMIT II limits $\mathrm{Im}\, g_V < 7 \cdot 10^{-4}$ (68%CL). [Mumm et al., 2011; Chupp et al., 2012]
First row CKM unitarity yields $\mathrm{Im}\, g_V < 2 \cdot 10^{-2}$ (68%CL).
Defining $\xi \equiv (\mathbf{l}_e \times \mathbf{k}) \cdot \mathbf{l}_\nu$, we form an asymmetry:

$$\mathcal{A}(\omega_{\min}) \equiv \frac{\Gamma_+(\omega_{\min}) - \Gamma_-(\omega_{\min})}{\Gamma_+(\omega_{\min}) + \Gamma_-(\omega_{\min})} \,,$$

where $\Gamma_\pm$ contains an integral of the spin-averaged $|\mathcal{M}|^2$ over the region of phase space with $\xi \gtrless 0$, respectively, neglecting corrections of recoil order.

Results

Table: T-odd asymmetries in units of $\mathrm{Im}\,[g_V(c_5/M^2)]\,[\mathrm{MeV}^{-2}]$ for neutron, $^{19}\mathrm{Ne}$, and $^{35}\mathrm{Ar}$ radiative β decay.

$\omega_{\min}(\mathrm{MeV})$	$\mathcal{A}^{\mathrm{HHH}}(n)$	$\mathrm{BR}(n)$	$\mathcal{A}^{\mathrm{HHH}}(^{19}\mathrm{Ne})$	$\mathrm{BR}(^{19}\mathrm{Ne})$
0.01	-5.61×10^{-3}	3.45×10^{-3}	-3.60×10^{-2}	4.82×10^{-2}
0.05	-1.30×10^{-2}	1.41×10^{-3}	-6.13×10^{-2}	2.82×10^{-2}
0.1	-2.20×10^{-2}	7.19×10^{-4}	-8.46×10^{-2}	2.01×10^{-2}
0.3	-5.34×10^{-2}	8.60×10^{-5}	-0.165	8.86×10^{-3}

Limits on $\mathrm{Im}(c_5)$ come only from the empirical radiative β decay BR: $|\mathrm{Im}(c_5/M^2)| < 12\,\mathrm{MeV}^{-2}$ **at 68% C.L.**

In constrast the Lee-Yang Hamiltonian yields ($C_i^{(\prime)} \equiv G_F V_{ud}\tilde{C}_i^{(\prime)}/\sqrt{2}$)

$$|\mathcal{M}|^2_{\mathrm{T-odd,LY}} = 16e^2 G_F^2 |V_{ud}|^2 M \mathbf{l}_\nu \cdot (\mathbf{l}_e \times \mathbf{k}) \frac{1}{l_e \cdot k} \mathrm{Im}[\tilde{C}_T(\tilde{C}_S'^* + \tilde{C}_P'^*) + \tilde{C}_T'(\tilde{C}_S^* + \tilde{C}_P^*)]$$

With $\mathrm{Im}\,\mathcal{C}_{\mathrm{LY}} \equiv \mathrm{Im}[\tilde{C}_T(\tilde{C}_S'^* + \tilde{C}_P'^*) + \tilde{C}_T'(\tilde{C}_S^* + \tilde{C}_P^*)]$, we have for $\omega^{\min} = 0.3\,\mathrm{MeV}$, in units of $\mathrm{Im}\,\mathcal{C}_{\mathrm{LY}}$

$$\mathcal{A}^{\mathrm{LY}}(n) = 5.21\times10^{-6} \quad ; \quad \mathcal{A}^{\mathrm{LY}}(^{19}\mathrm{Ne}) = 4.53\times10^{-7} \quad ; \quad \mathcal{A}^{\mathrm{LY}}(^{35}\mathrm{Ar}) = 8.63\times10^{-7}$$

These asymmetries are negligible cf. to $\mathrm{Im}(c_5)$.

Electromagnetic Simulation of T-Odd Effects

We first compute $\overline{|\mathcal{M}|^2}_{\mathrm{T-odd}}$ and then the asymmetry. We work in $\mathcal{O}(\alpha)$ and in **leading recoil order**.

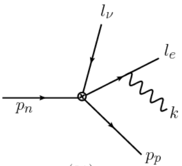
$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{tree}}|^2 + \mathcal{M}_{\mathrm{tree}} \cdot \mathcal{M}^*_{\mathrm{loop}} + \mathcal{M}_{\mathrm{loop}} \cdot \mathcal{M}^*_{\mathrm{tree}} + \mathcal{O}(\alpha^2)$$

$$\overline{|\mathcal{M}|^2}_{\mathrm{T-odd}} \equiv \frac{1}{2} \sum_{\mathrm{spins}} |\mathcal{M}|^2_{\mathrm{T-odd}} = \frac{1}{2} \sum_{\mathrm{spins}} (2\mathrm{Re}(\mathcal{M}_{\mathrm{tree}} i \mathrm{Im} \mathcal{M}^*_{\mathrm{loop}}))$$

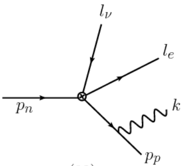
Note "Cutkosky cuts" [Cutkosky, 1960]

$$\mathrm{Im}(\mathcal{M}_{\mathrm{loop}}) = \frac{1}{8\pi^2} \sum_n \int d\rho_n \sum_{s_n} \mathcal{M}_{fn} \mathcal{M}^*_{in} = \frac{1}{8\pi^2} \int d\rho_n \sum_{s_n} \mathcal{M}_{fn} \mathcal{M}_{ni}$$

There are many cancellations. At tree level

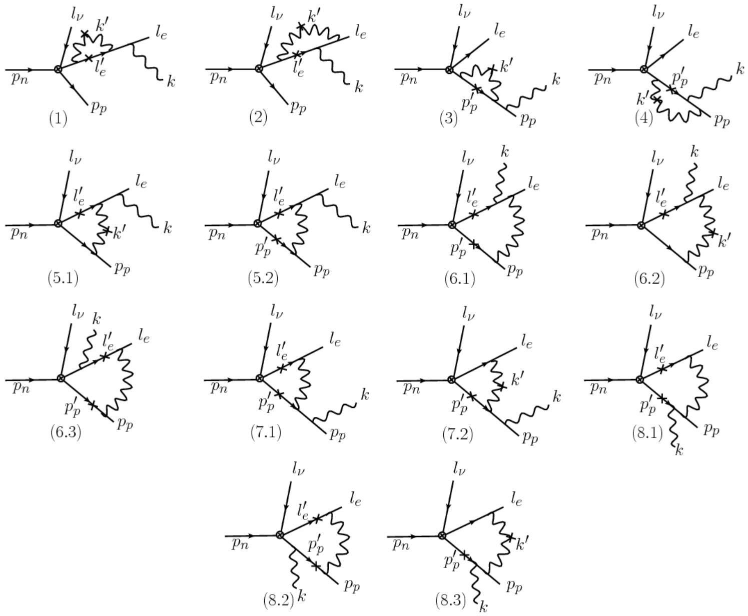


(01)



(02)

The Family of Two-Particle Cuts in $\mathcal{O}(e^3)$



Results

Table: Asymmetries from SM FSI in various weak decays. The range of the opening angle between the outgoing electron and photon is chosen to be $-0.9 < \cos(\theta_{e\gamma}) < 0.9$.

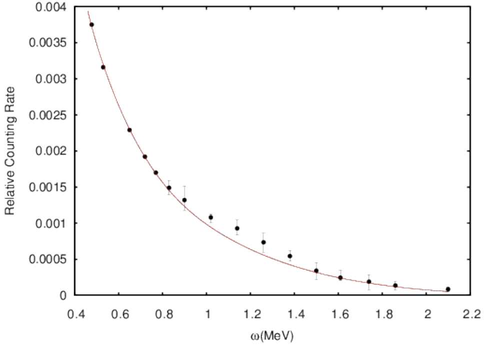
$\omega_{\min}$(MeV)	$\mathcal{A}^{\rm FSI}(n)$	$\mathcal{A}^{\rm FSI}(^{19}{\rm Ne})$	$\mathcal{A}^{\rm FSI}(^{35}{\rm Ar})$
0.01	1.76×10^{-5}	-2.86×10^{-5}	-8.35×10^{-4}
0.05	3.86×10^{-5}	-4.76×10^{-5}	-1.26×10^{-3}
0.1	6.07×10^{-5}	-6.40×10^{-5}	-1.60×10^{-3}
0.3	1.31×10^{-4}	-1.14×10^{-4}	-2.55×10^{-3}

The computation of the nuclear FSI proceeds similarly; the final results depend on the Z of the daughter.

$\mathcal{A}_\xi^{\rm SM}$ is proportional to $(1-\lambda^2)$, with $\lambda = g_A/g_V = 1.267$ for neutron β decay. The observed quenching of the Gamow-Teller strength in nuclear decays can also suppress $\mathcal{A}_\xi^{\rm SM}$. One can use the lifetime or the β asymmetry to infer $\lambda^{\rm eff}$. **The SM asymmetries are sufficiently small as to be negligible for present purposes.**

Nuclear Radiative β-Decay

Very little data exist. $^6\mathrm{He}$ decay offers a proof-of-principle experiment?



Data from the 1960's.

For $^6\mathrm{He}$ β-decay (GT!):

$\omega_{\mathrm{min}}(\mathrm{MeV})$	A_ξ^{SM}
0.01	7.00×10^{-5}
0.05	1.14×10^{-4}
0.1	1.52×10^{-4}
0.2	2.13×10^{-4}
0.3	2.63×10^{-4}
0.4	3.07×10^{-4}
0.5	3.45×10^{-4}
0.6	3.79×10^{-4}
0.7	4.07×10^{-4}

Now we turn to models which can generate $\mathrm{Im}\, c_5$.

Hidden Sector Models

Many variants exist....

Hermetic

Dark matter which is neutral under all SM gauge interactions. Suppose it possesses an exact hidden U(1). DM (here a hidden sector stau) is self-interacting and thus subject to observational constraints... e.g., $\alpha_\chi < 10^{-7}$ for $M_\chi \sim 1$ GeV.

[Feng, Kaplinghat, Tu, Yu, arXiv:0905.3039; Feng, Tu, Yu, arXiv:0808.2328]

Models with Abelian Connectors

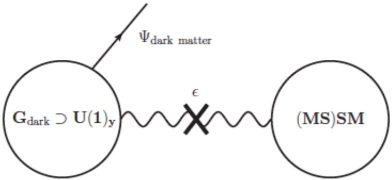
Astrophysical anomalies prompts models which mix with $U(1)_Y$.

[Essig, Schuster, Toro, 2009; Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2009; Baumgart, Cheung, Ruderman, Wang, Yavin, 2009]

Models with non-Abelian Connectors

[Baumgart, Cheung, Ruderman, Wang, Yavin, 2009; SG and He, arXiv:1302.1862]

U(1) Kinetic Mixing with a Hidden Sector



[Baumgart et al., 2009]

Let A' be the gauge field of a massive dark $\mathrm{U}(1)'$ gauge group

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} - \frac{1}{4} F'^{,\mu\nu} F'_{\mu\nu} + m_{A'}^2 A'^{\mu} A'_{\mu}$$

With $A_\mu \to \tilde{A}_\mu = A_\mu - \epsilon A'_\mu$, the A' gains a tiny electric charge ϵe.

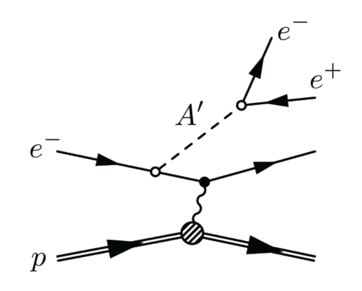
[Holdom, 1986]

The A' can be discovered in fixed-target experiments....

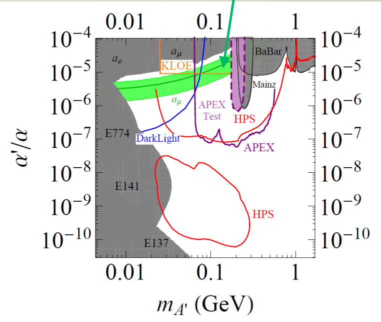
[Bjorken, Essig, Schuester, Toro, arXiv:0906.0580]

New Opportunity: Search for A' at JLab

Search for new forces mediated by ~100 MeV vector boson A' with weak coupling to electrons:



g – 2 preferred!



Irrespective of astrophysical anomalies:

- New ~GeV–scale force carriers are important category of physics beyond the SM
- Fixed-target experiments @JLab (FEL + CEBAF) have unique capability to explore this!

[R. McKeown, GHP 2011, April APS] [Note M. Pospelov for $g-2$ connection.]

Consider an operator Φ which transforms under the adjoint rep of a non-Abelian dark group. Then $\mathrm{tr}(\Phi F_{\mu\nu})\mathrm{tr}(\tilde{\Phi}\tilde{F}_{\mu\nu})$ can connect the sectors.

[Baumgart et al., 2009]

This operator should become more important at low energies.

We model this as (noting the hidden local symmetry model of QCD)

[Bando, Kugo, Uehara, Yamawaki, Yanagida, 1985]

$$\mathcal{L}^{\pm}_{mix} = -\frac{1}{4}\rho^{+\,\mu\nu}\rho^{-}_{\mu\nu} - \frac{1}{4}\rho'^{+\,\mu\nu}\rho'^{-}_{\mu\nu} + \frac{\epsilon}{2}\left(\rho^{+\,\mu\nu}\rho'^{-}_{\mu\nu} + \rho^{-\,\mu\nu}\rho'^{+}_{\mu\nu}\right) + \frac{g_\rho}{\sqrt{2}}(\rho^{+}_{\mu}J^{+\,\mu} + \rho^{-}_{\mu}J^{-\,\mu})\,.$$

Under $\tilde{\rho}^{\pm}_{\mu} = \rho^{\pm}_{\mu} - \epsilon\rho'^{\pm}_{\mu}$, the baryon vector current couples to $\rho'^{\pm}$....

One can hope to detect the ρ' through its possible CP-violating effects.

A Tale of Two Models

The notion of new physics in QCD is vintage. [Okun, 1980; Bjorken, 1979; Gupta, Quinn, 1982]
Note much more recent "quirk" models:
quirks are charged under "infracolor" and are supposed to have mass $M_Q \sim 100 - 1000$ GeV, with $M_Q > \Lambda \Longrightarrow$ macroscopic strings!
The two sectors connect via

$$\mathcal{L}_{\rm eff} \sim \frac{g^2 g'^2}{16\pi^2 M_Q^4} F_{\mu\nu}^2 F_{\mu\nu}'^2$$

[Kang and Luty, arXiv:0805.4642]

For $M_Q \gtrsim 100$ GeV, weaker than the weak interactions!

Expect collider signatures only!

In our model we suppose hidden quarks crudely comparable to m_q in mass but with $\Lambda' < \Lambda$ and thus $m_{\rho'} < m_\rho$

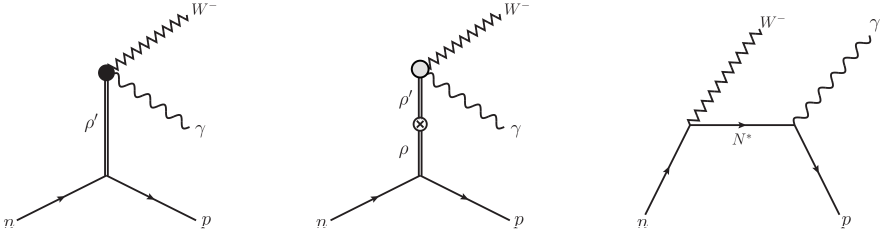
Expect collider effects to be hidden under hadronization uncertainties!

Expect low-energy signatures only!

New physics can be an emergent low-energy feature... to be discovered at the Intensity Frontier!

Radiative β decay revisited

The low-energy constant c_5 can be generated in different ways....



The first graph mediates radiative decay in the physical ρ basis, an experimental limit on the asymmetry translates as $\mathrm{Im}(c_5/M^2) = 2\epsilon\mathrm{Im}\epsilon g^2_{\rho^0}/(16\pi^2 m^2_{\rho'})$.

Collider studies can constrain away the colored scalars we used to build our "connector" to the hidden sector, i.e., they can kill **specific** models that generate low-energy effects — but not all.

Summary and Outlook

(i) An EFT analysis with lattice QCD calculations of g_S and g_T sharpen the ability to limit new scalar and tensor interactions in beta decay experiments. Although SM recoil order terms that break isospin are parametrically small, they can limit the ability to resolve the limits of the V-A law.

(ii) The study of a spin-independent T-odd correlation coefficient is possible via radiative β decay and allows access to CP-violating effects associated with the baryon vector current.

The triple-product momentum correlation is P-odd and pseudo-T-odd but does not involve the nucleon spin; the constraints offered through its study in neutron (and nuclear) radiative β-decay yields constraints independent of those from EDMs.

Backup Slides

T-odd Correlations

In neutron β decay, triple product correlations are spin dependent.
Major experimental efforts have recently been concluded.

D term [Mumm et al., 2011; Chupp et al., 2012]

D probes $\boldsymbol{J} \cdot (\boldsymbol{p}_e \times \boldsymbol{p}_\nu)$ and is T-odd, P-even.
$D = [-0.94 \pm 1.89(\text{stat}) \pm 0.97(\text{sys})] \times 10^{-4}$ (best ever!)
D_{FSI} is well-known (N^3LO) and some $10\times$ smaller. [Callan and Treiman, 1967; Ando et al., 2009]
D limits the phase of C_A/C_V...

R term [Kozela et al., 2009; Kozela et al., 2012]

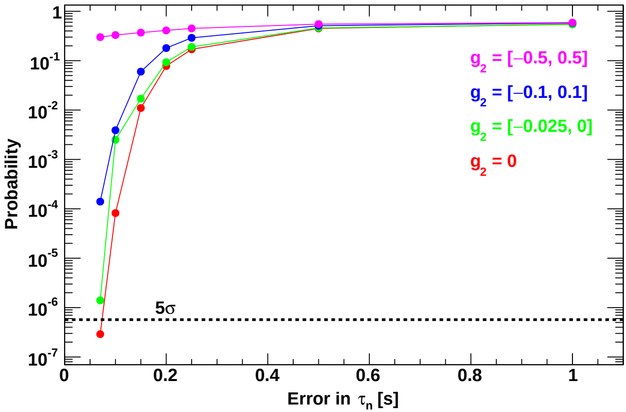
Here the transverse components of the electron polarization are measured.

R probes $\boldsymbol{J} \cdot (\boldsymbol{p}_e \times \hat{\boldsymbol{\sigma}})$ and is T-odd, P-odd.
N probes $\boldsymbol{J} \cdot \hat{\boldsymbol{\sigma}}$ and gives a non-zero check.

$R = 0.004 \pm 0.012(\text{stat}) \pm 0.005(\text{sys})$
R limits the imaginary parts of scalar, tensor interactions...

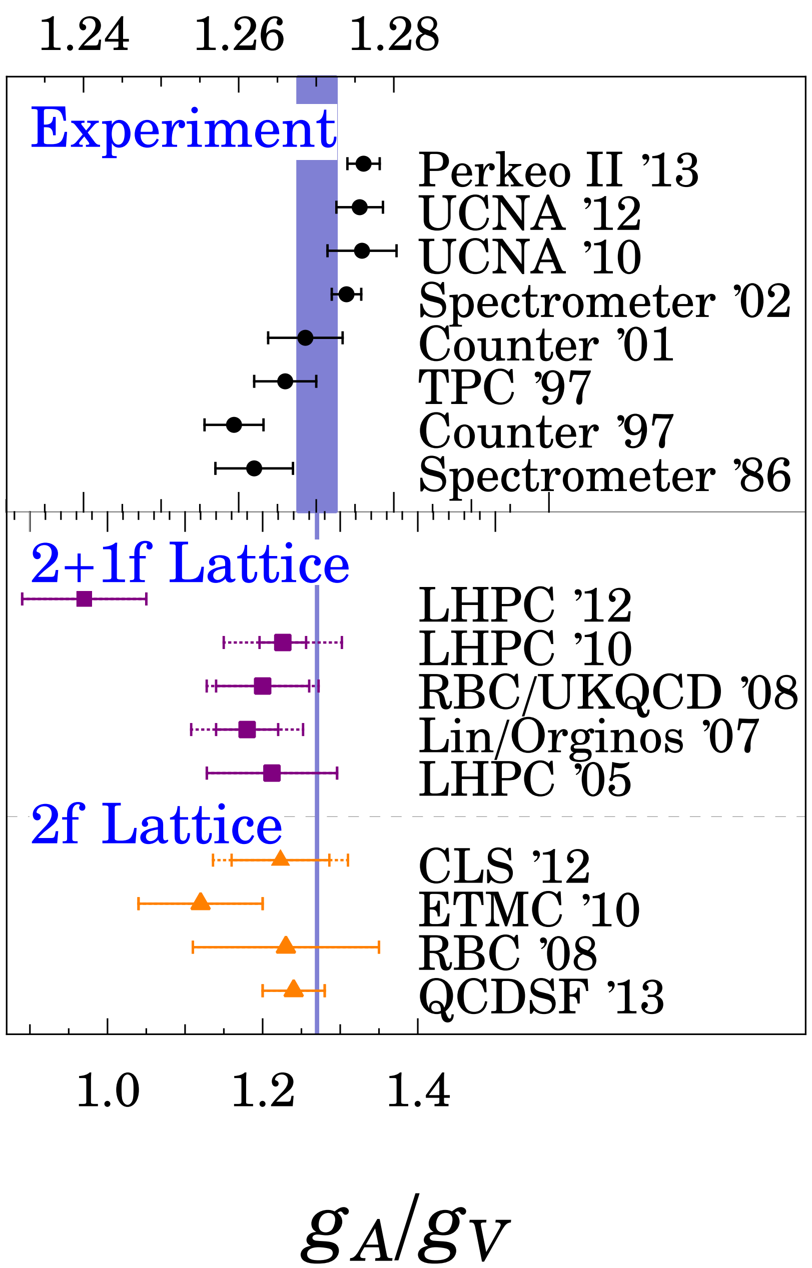
In contrast, in radiative β-decay one can form a T-odd correlation from momenta alone, $\mathbf{p}_\gamma \cdot (\mathbf{p}_e \times \mathbf{p}_\nu)$, so that the spin does not enter.

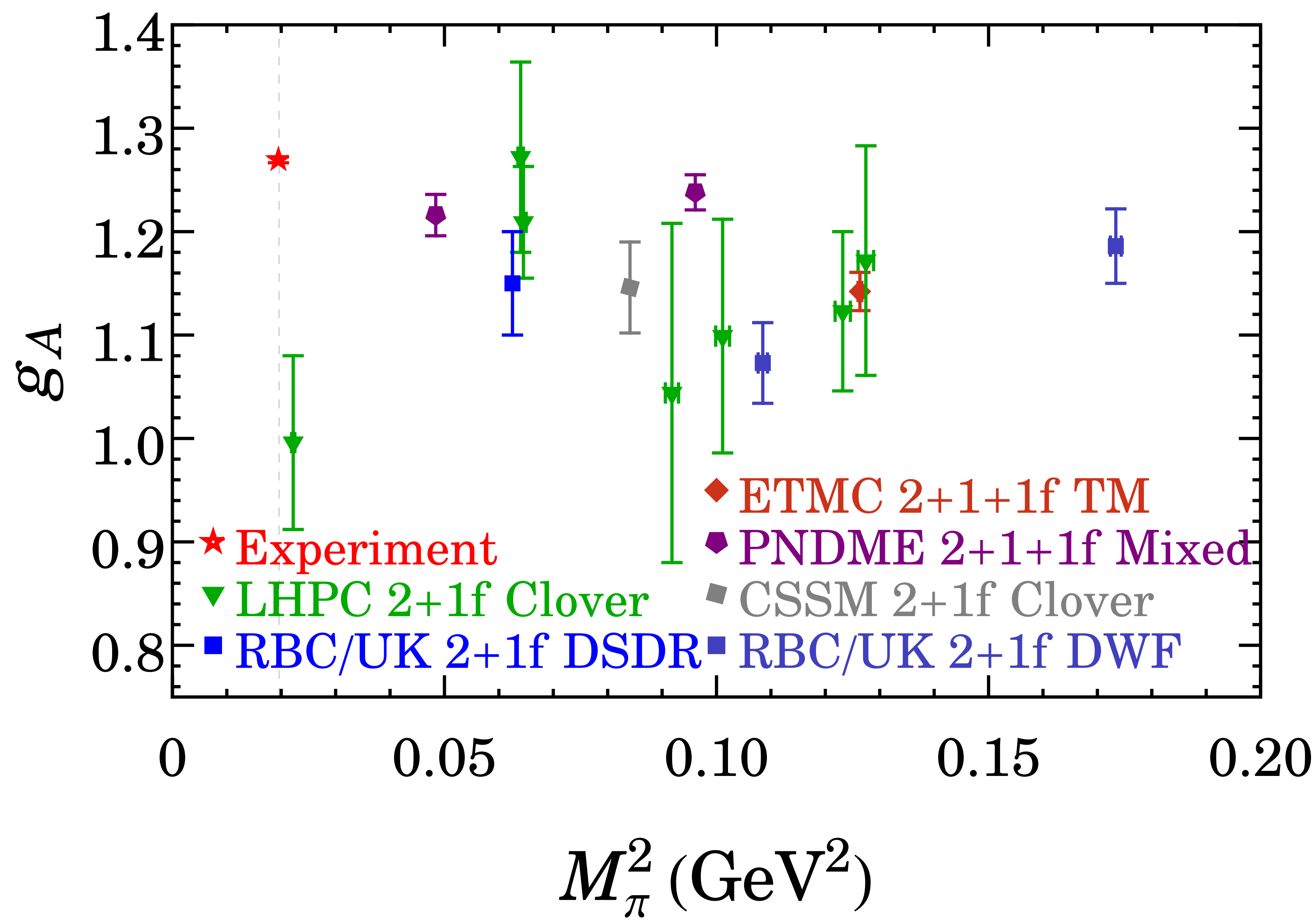
Using the neutron lifetime as well, a test statistic for falsifying the SM can be constructed:



Definitely would like a better assessment of g_2!

The axial vector coupling





[Bhattacharya et al., arXiv:1306.5435]

In beta-decay we must fit for SM and BSM physics simultaneously

[SG, Plaster, arXiv: 1305.0014]

Resolving the limits of the V-A Law

Poorly known recoil-order matrix elements can mimic S,T effects

The second-class current (SCC) terms are particularly poorly known

From QCD sum rules: $g_2/g_A = -0.0152 \pm 0.0053$ [Shiomi, 1996]

$$g_2 = g_A[-0.026, -0.0046] = [-0.033, -0.006]$$

From Lattice QCD $(|\Delta S| = 1)$:

$\Xi^0 \to \Sigma^+ l \bar{\nu}$ [Sasaki and Yamazaki, 2009]

$$g_2/g_A = 0.68 \pm 0.18 \; ; \; f_3/g_V = 0.14 \pm 0.09$$

$$g_2 \approx 0.05 g_A[0.32, 1.04] = [0.020, 0.066] \longrightarrow g_2 = [-0.033, 0.066]$$

$$f_3 \approx 0.05[-0.04, 0.32] = [-0.002, 0.016]$$

Union of both methods

Resolving the limits of the V-A Law

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 \xi$$
$$\times \left[1 + b\frac{m_e}{E_e} + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} \right.$$
$$\left. + \langle \vec{\sigma}_n \rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right]$$

$$\lambda \equiv \frac{g_A}{g_V}$$

$$\Xi = 1 + 3\lambda^2 + (g_S \epsilon_S)^2 + 3(4 g_T \epsilon_T)^2 ,$$

$$a = a_1 + a_2 \beta \cos\theta_{e\nu}$$

$$a_0 = \frac{(1-\lambda^2) - (g_S\epsilon_S)^2 + (4g_T\epsilon_T)^2}{(1+3\lambda^2) + (g_S\epsilon_S)^2 + 3(4g_T\epsilon_T)^2} ,$$

$$a_1 = a_0 + f(g_A, f_2, g_2, f_3, E_e)$$

$$b_{\rm BSM} = \frac{2(g_S\epsilon_S) - 6\lambda(4g_T\epsilon_T)}{(1+3\lambda^2) + (g_S\epsilon_S)^2 + 3(4g_T\epsilon_T)^2} ,$$

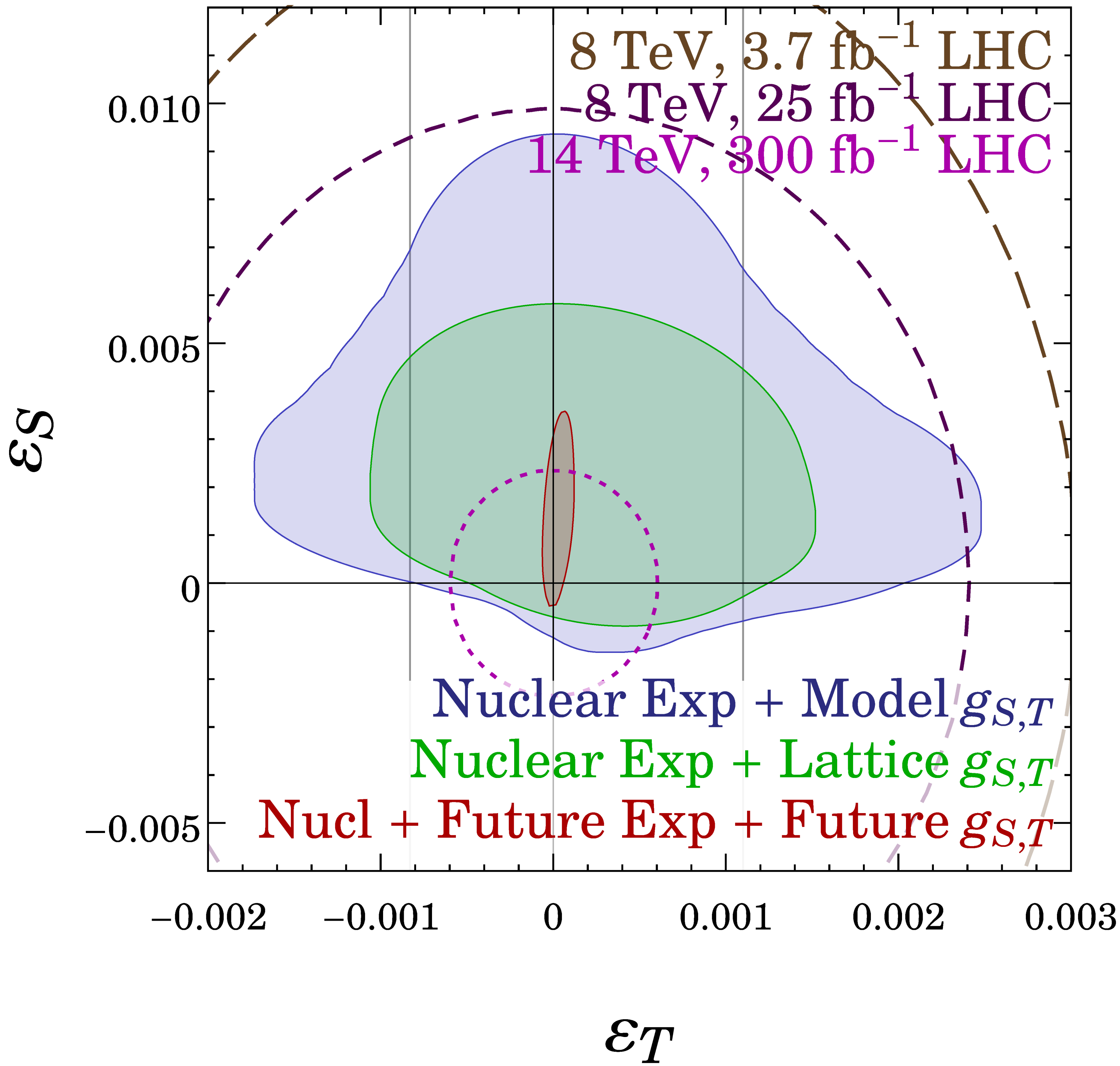
$$a_{\rm exp} \equiv \frac{N(\cos\theta_{e\nu} > 0) - N(\cos\theta_{e\nu} < 0)}{N(\cos\theta_{e\nu} > 0) + N(\cos\theta_{e\nu} < 0)}$$
$$= \frac{1}{2}\beta \frac{a_1}{1 + b_{\rm BSM}\frac{m_e}{E_e} + \frac{1}{3}a_2\beta^2} ,$$

$$a_2 = \frac{3(\lambda^2 - 1)}{(1+3\lambda^2)} \frac{E_e}{M}$$

$$A_{\rm exp} \equiv \frac{N(\cos\theta_e > 0) - N(\cos\theta_e < 0)}{N(\cos\theta_e > 0) + N(\cos\theta_e < 0)}$$
$$= \frac{1}{2}\beta \frac{A}{1 + b_{\rm BSM}\frac{m_e}{E_e}} .$$

Scalar and Tensor Charges

Lattice QCD sharpens the impact of beta decay experiments



[Bhattacharya et al., arXiv:1306.5435]