Symmetry violation in neutron and nuclear β decay

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KKV *et al.*, accepted Rev. Mod. Phys.

Motivation

"V-A" structure of the weak interaction.

Parity violating, only left-handed W coupling

$$\mathcal{L}_{\rm SM} = \frac{g^2 V_{ud}}{8 m_W^2} \bar{e}\gamma_\mu (1-\gamma_5)\nu_e \bar{u}\gamma^\mu (1-\gamma_5) d + {\rm h.c.}\ ,$$

Many models of new physics.

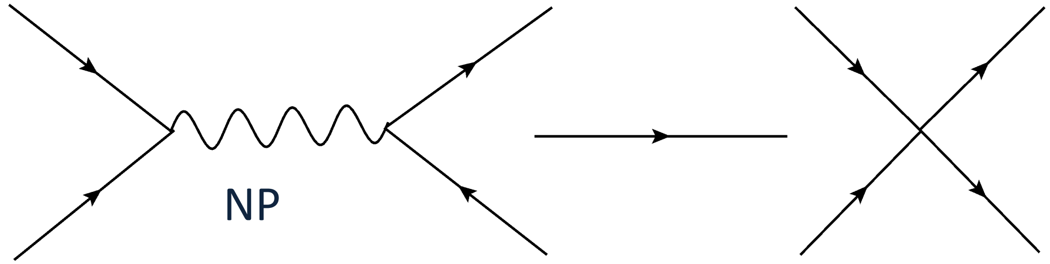
- Direct detection of new particles at high energy.
- Via high-precision low-energy experiments.

Role of beta decay in the LHC era?

Role of beta decay in searches for Lorentz violation?

Parametrization of new physics: EFT

- ✓ Model independent.
- ✓ Only SM fields with gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$



- ✓ New interactions included as higher dimensional terms.

Grzadkowski *et al.*, 2010

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c_5}{\Lambda} O_5 + \sum_i \frac{c_6^i}{\Lambda^2} O_6^i$$

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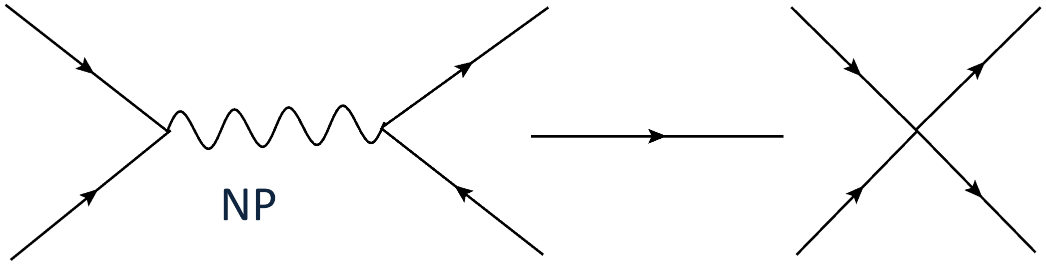

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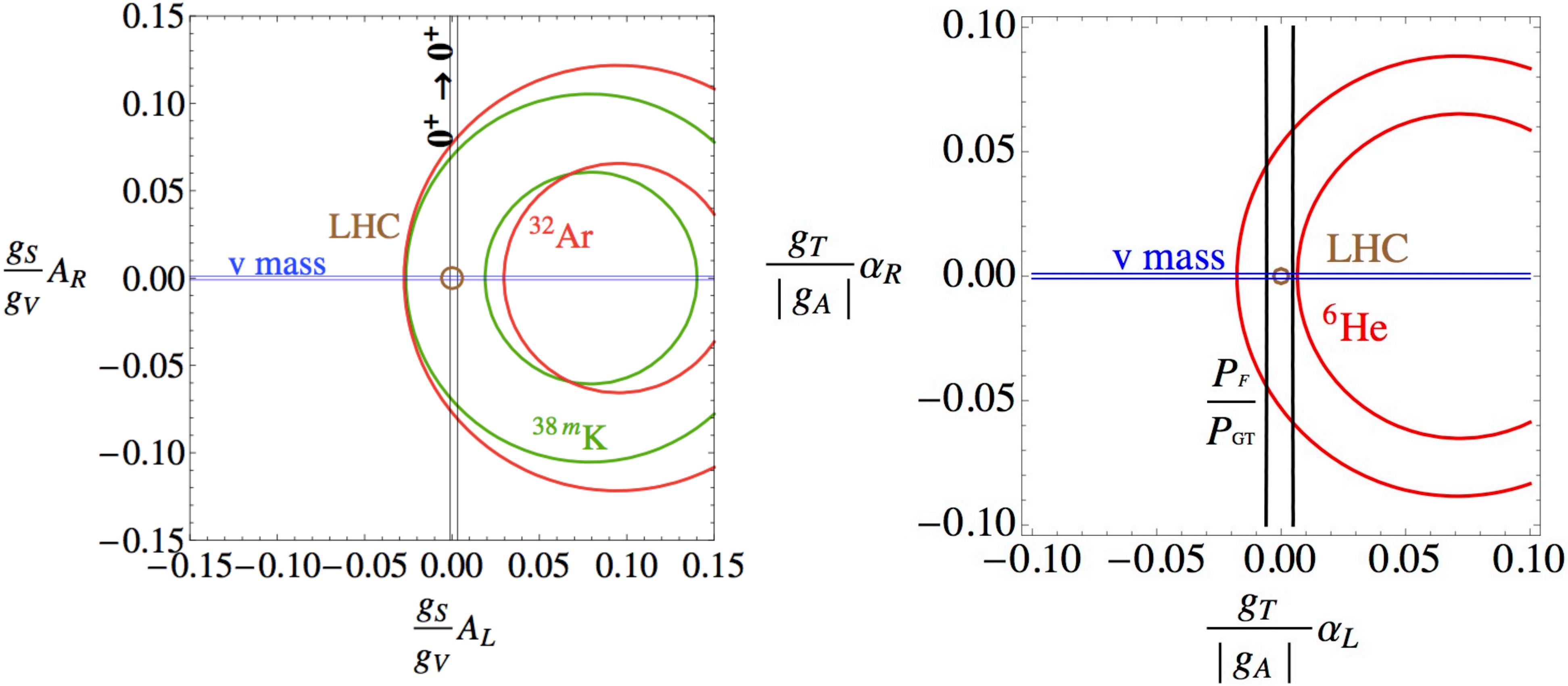
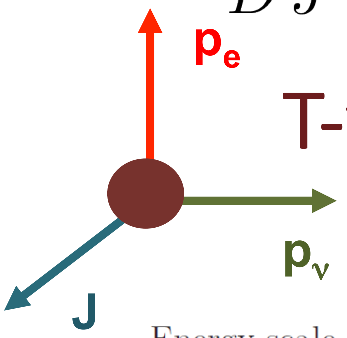
SEARCHES FOR EXOTIC COUPLINGS

Current status

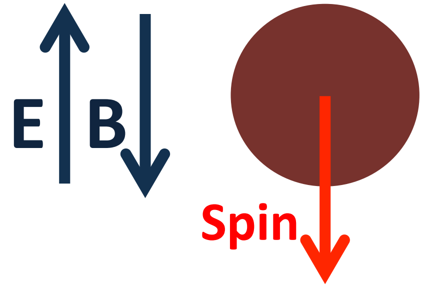


$D\,\vec{J}\cdot(\vec{p}_e \times \vec{p}_\nu)$

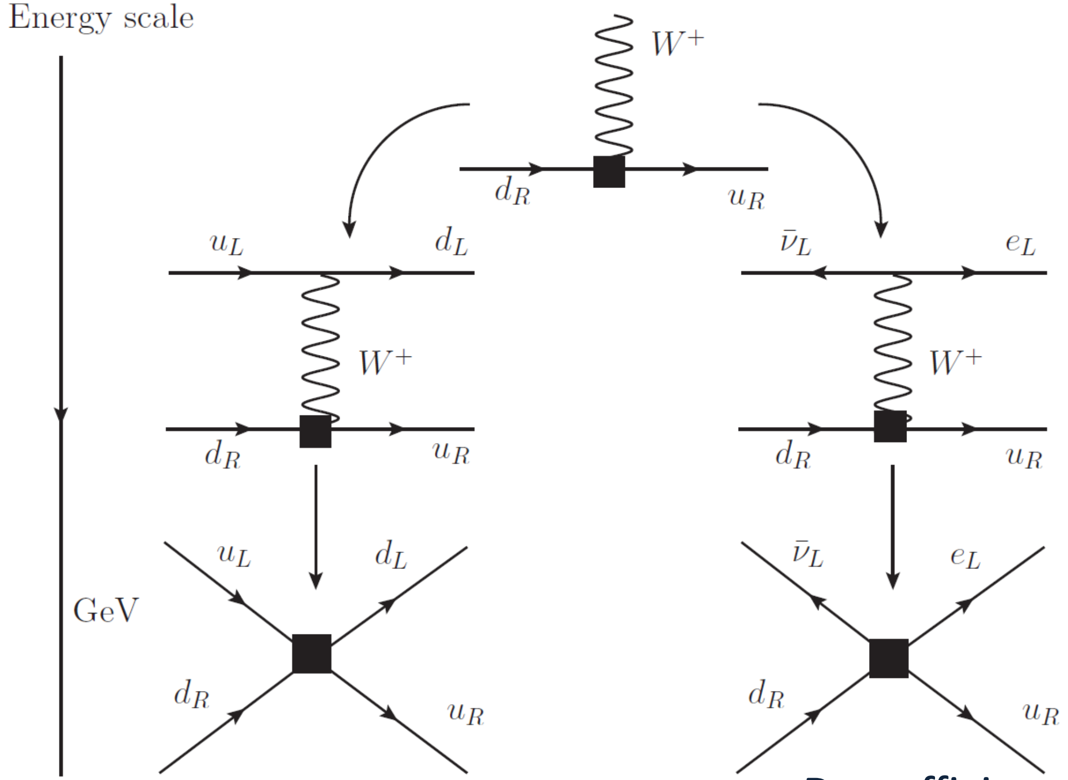


T-violation: EDM versus β decay

Ng and Tulin, 2012
KKV, et al. Rev. Mod. Phys. 2015



P-odd and T-odd



Neutron EDM

D-coefficient

Generated by same dimension-6 operator.

EDMs limit the same imaginary couplings as β decay.

Bounds from EDM limits are two orders of magnitude better than those from beta decay.

Outlook

Discussed the role of β decay in the LHC era.

- Only possible to evade bounds in finetuned or specific models (no dim-6)

- LHC experiments will give stronger constraints.
- EDMs will be improved with factor 10-100 in the near future.
- β-decay experiments best for left-handed scalar/tensor:
  - -β shape spectrum measurements.
  - -Superallowed Fermi decays (also Vud)/mirror nuclei.

SEARCHES FOR LORENTZ VIOLATION

Lorentz violation in the weak interaction

Viable scenarios for Lorentz symmetry breaking in some quantum gravity theories.

- Mechanism for CPT violation.

Can be probed in low-energy precision experiments.

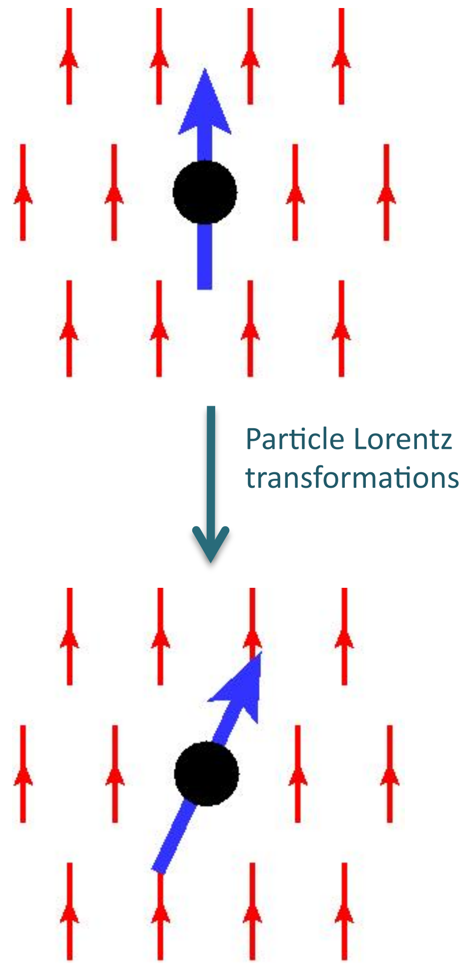
- Use effective field theory.

✓ Observer invariance maintained.

- Coordinate independence.

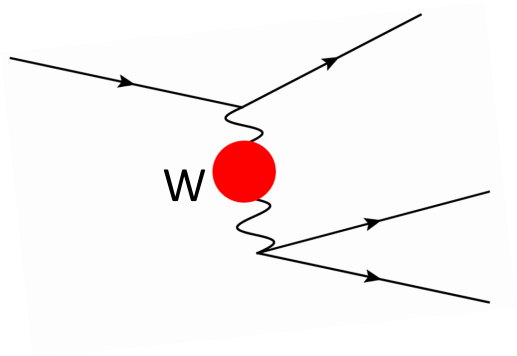
× Breaking of particle Lorentz transformation.

- Boost or rotations.



Lorentz violation in the weak interaction

Theoretical framework ⟶ modified W-boson propagator.



General Lorentz-violating tensor

$$\langle W^{\mu+}(p) W^{\nu-}(-p) \rangle = \frac{-i(g^{\mu\nu} + \chi^{\mu\nu})}{M_W^2}$$

Broad class of Lorentz violation, also vertex corrections.

- Originally to study β decay, since then also electron capture, pion decay, nonleptonic decays, muon decay.

- χ momentum-independent and CPT-even.

-First experiment in allowed β decay discussed in next talk.

S. E. Muller *et al.,* Phys. Rev. D 88, 071901(R)(2013). A. Sytema *et al.*, in preparation. J.P. Noordmans *et al.,* PRL 111, 171601 (2013). KKV *et al*, PLB 729, 112 (2014). B. Altschul, Phys.Rev. D 88, 076015 (2013). J.P. Noordmans and KKV, Phys. Rev. D89, 101702(R) (2014).

Lorentz violation in the weak interaction

Best currents bounds from forbidden β decays:

$$\chi_r^{\mu\nu} = \begin{bmatrix} 10^{-6} & 10^{-7} & 10^{-7} & 10^{-8} \\ 10^{-7} & 10^{-6} & 10^{-6} & 10^{-6} \\ 10^{-7} & 10^{-6} & 10^{-6} & 10^{-6} \\ 10^{-8} & 10^{-6} & 10^{-6} & 10^{-6} \end{bmatrix}, \quad \text{and} \quad \chi_i^{\mu\nu} = \begin{bmatrix} \times & - & - & - \\ - & \times & 10^{-8} & 10^{-7} \\ - & 10^{-8} & \times & 10^{-7} \\ - & 10^{-7} & 10^{-7} & \times \end{bmatrix}.$$

What can still be done?

- High statistics necessary to improve existing constraints.
- Unconstrained coefficients.

Lorentz violation in β decay

Example Fermi decay

$$dW_F = dW_0 \left\{ 1 + b\frac{m_e}{E_e} + 2\chi_r^{00} + 2\chi_r^{0l}\frac{p_e^l}{E_e} + (a + 2\chi_r^{00})\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + 2\chi_i^{0l}\frac{(\vec{p}_e \times \vec{p}_\nu)^l}{E_e E_\nu} + \cdots \right\}$$

Anisotropic emission.

$$\mathcal{A} = \frac{W^+ - W^-}{W^+ + W^-}$$

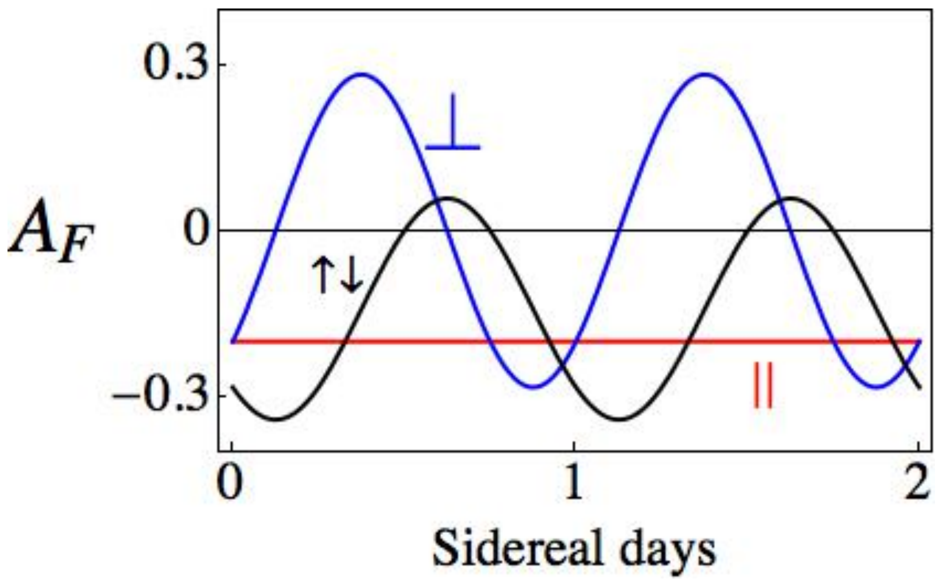
Possible to probe different coefficients directly!

-In contrast to forbidden decays

Can be done in parallel to BSM searches.

Unique experimental signature:

- sidereal variations



Lorentz violation in β decay

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Anisotropic emission.

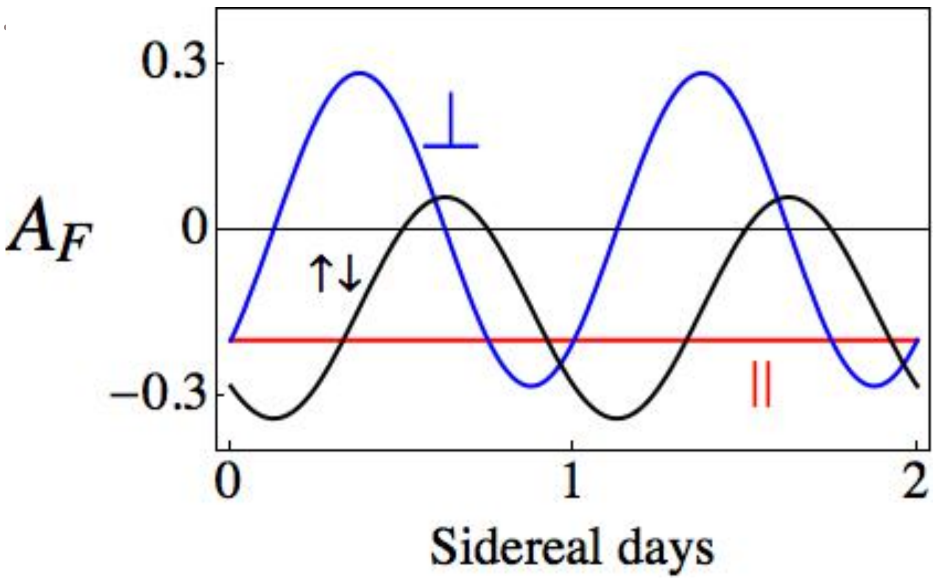
- Preferred fermion direction.

$$\mathcal{A} = \frac{W^+ - W^-}{W^+ + W^-}$$

Study in parallel with βν-correlation a..

Gamow-Teller decays sensitive to

$$\mathcal{A}_{GT} = \tfrac{2}{3}\beta(\chi_r^{0l} + \tilde{\chi}_i^l)\hat{p}_e^l$$



Lorentz violation in β decay

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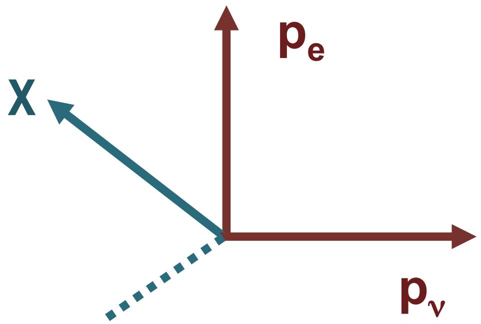
Anisotropic emission.

- Preferred reaction plane.



Unconstrained coefficients, most difficult to probe.

For polarized decays also possible to consider

$$\chi_i^{0s}(\hat{I} \times \vec{p}_e)^s$$

KKV *et al.*, submitted
B. Altschul, Phys. Rev. D88, 076015 (2013).
KKV *et al.,* Phys. Rev. C . 91, 038501 (2015).

Discussion

Established a program to test LV in weak decays.

Lorentz violation could be studied parallel to BSM physics in β decay.

High statistics necessary to improve existing constraints

Use γ^2 enhancement.

$$\frac{dW}{dW_0} = 1 + 2\gamma^2(\chi_r^{TT} + 2\chi_r^{TJ}\hat{v}_J + \chi_r^{JK}\hat{v}_J\hat{v}_K)$$

- Future beta beam facilities or LHC!

Electron capture.

- Spin polarized or recoil detection.

Thank you for your attention

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D. Colladay and V.A. Kostelecky, Phys. Rev. D 58, 116002 (1998)

EFT approach: the Standard Model Extension (SME)

Most general EFT and gauge invariant (also dim-3 and dim-4)

CPT-odd Lorentz violating

$$\mathcal{L}^{(3)} = -m\bar{\varphi}\varphi - \boxed{a_\mu}\bar{\varphi}\gamma^\mu\varphi - \boxed{b_\mu}\bar{\varphi}\gamma^\mu\gamma_5\varphi$$

CPT-even Lorentz violating

$$\mathcal{L}^{(4)} = i\bar{\varphi}\gamma_\nu\partial^\nu\varphi + \boxed{c_{\mu\nu}}\bar{\varphi}\gamma^\mu\partial^\nu\varphi + \boxed{d_{\mu\nu}}\bar{\varphi}\gamma_5\gamma^\mu\partial^\nu\varphi$$

+ W boson coefficients + gauge sector + ...

Keep “nice” features of the SM.

Searches for exotic couplings

“V+A” or right-handed W-coupling

$$\mathcal{L}^{(\mathrm{eff})} = \frac{G_F V_{ud}}{\sqrt{2}} \left[\sum_{\epsilon,\delta=L,R} \{4a_{\epsilon\delta}\bar{e}\gamma^{\mu}\nu_e^{\epsilon} \cdot \bar{u}\gamma_{\mu}d_{\delta}\} \right.$$

Scalar

$$+\underline{A_L}\ \bar{e}(1-\gamma_5)\nu_e \cdot \bar{u}d + \underline{A_R}\ \bar{e}(1+\gamma_5)\nu_e \cdot \bar{u}d$$

$$\left. +\underline{\alpha_L}\ \bar{e}\frac{\sigma^{\mu\nu}}{\sqrt{2}}(1-\gamma_5)\nu_e \cdot \bar{u}\frac{\sigma^{\mu\nu}}{\sqrt{2}}(1-\gamma_5)d + \underline{\alpha_R}\ \bar{e}\frac{\sigma^{\mu\nu}}{\sqrt{2}}(1+\gamma_5)\nu_e \cdot \bar{u}\frac{\sigma^{\mu\nu}}{\sqrt{2}}(1+\gamma_5)d \right]$$

Tensor

T (CP)-violation probed by imaginary couplings