Probing New Physics with Neutrino Tridents

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Neutrino induced production of a charged lepton pair in the Coulomb field of a heavy nucleus

Induced by electro-weak interactions at tree level → sensitive to EW-scale new physics

A rare process: cross section is many orders of magnitude smaller than the inclusive neutrino-nucleus scattering cross section (2 → 4 vs 2 → 2)

(Will focus on muon-neutrino induced processes in the following)
\[
\nu_\mu \rightarrow \nu_\mu e^- e^+
\]

not observed so far
$\nu_\mu \rightarrow \nu_e \mu^- e^+$

not observed so far

($\mu^+ e^- \text{ from muon anti-neutrinos}$)
\[ \nu_\mu \rightarrow \nu_\mu \mu^- \mu^+ \]

observation claimed at
CHARM II ('90)
CCFR ('91)
can integrate out W and Z bosons and describe the interaction through a 4 fermion operator

\[
\mathcal{H}_{\text{eff}} = \frac{2G_F}{\sqrt{2}} \left( \bar{\mu} \left[ C_V \gamma_\alpha + C_A \gamma_\alpha \gamma_5 \right] \mu \right) (\bar{\nu}_\mu \gamma^\alpha P_L \nu_\mu)
\]

connect to nucleus via a virtual photon

need to calculate the full \( 2 \rightarrow 4 \) process. Equivalent photon approximation was found to introduce sizable uncertainties

(Magill, Plestid 1612.05642; Ge et al. 1702.02617; Ballet et al. 1807.10973)
experimental signature of coherent scattering on a nucleus:

- two opposite sign leptons without any hadronic activity

\[ d\sigma_{\text{coh.}} \propto Z^2 \alpha_{\text{em}}^2 G_F^2 |F_N(q^2)| \]

- enhanced by \( Z^2 \)

- for scattering on spin 0 nuclei, need the electric form factors of the nuclei
Electric form factors of nuclei are very well measured.

We use nuclear charge densities from De Vries, De Jager, De Vries ’87.

Different parameterizations lead to $< 1\%$ shifts in the results.
Incoherent Scattering on Individual Nucleons

Experimental signature of incoherent scattering on nucleons:

- Two opposite sign leptons + proton or neutron that is kicked out from nucleus

\[ d\sigma_{\text{incoh.}} \simeq \Theta(|\vec{q}|)(Zd\sigma_p + (A - Z)d\sigma_n) \]

- \( \Theta \) is a Pauli blocking factor, derived by approximating the nucleus as an ideal Fermi gas (Lovseth, Radomski, PRD 3, 2686 (1971)). Approximation should work at the \( \sim 20\% \) level (Llewellyn Smith, Phys Rept 3, 261 (1972)).

- For scattering on protons and neutrons, need the electric and magnetic form factors (very well known, e.g. Alberico et al. 0812.3539, Ye et al. 1707.09063).
coherent scattering has largest cross section, followed by incoherent scattering on protons, then scattering on neutrons

main uncertainties from higher order EW (coherent), and nuclear modeling (incoherent)
**Existing Measurements**

First signal claimed at CHARM II:
neutrinos with average energy
$\sim 20$ GeV on glass

$\sigma_{\text{CHARM II}}/\sigma_{\text{SM}} = 1.58 \pm 0.57$

Similar significance at CCFR:
neutrinos with average energy
$\sim 160$ GeV on iron

$\sigma_{\text{CCFR}}/\sigma_{\text{SM}} = 0.82 \pm 0.28$

No conclusive signal at NuTeV:
neutrinos with average energy
$\sim 160$ GeV on iron

$\sigma_{\text{NuTeV}}/\sigma_{\text{SM}} = 0.72^{+1.73}_{-0.72}$
Issues with the CCFR Result?

NuTeV analysis identified an additional background that was not included by CCFR

Furthermore, the neutrino trident process must be considered in combination with the expected signal from diffractive charm production in experiments that are only sensitive to two-muon final states. This point has not been recognized in previous measurements of neutrino tridents.

and improved signal modeling

This procedure incorporated all possible kinematic correlations between the two muons and represents an improvement over previous methods.


How reliable is the CCFR result?
Neutrino Tridents and New Physics
My Favorite Model for $R_{K(\ast)}$

$Z'$ based on gauging $L_\mu - L_\tau$
with effective flavor violating couplings to quarks

WA, Gori, Pospelov, Yavin 1403.1269; WA, Yavin 1508.07009

$\frac{g' Y_{Qb} Y_{Qs}^\ast \langle \phi \rangle^2}{2m^2_Q}$

$Q$: heavy vectorlike fermions with mass $\sim 1 - 10$ TeV

$\phi$: scalar that breaks $L_\mu - L_\tau$

(see also recent extended model WA, Davighi, Nardecchia 1909.02021)
My Favorite Model for $R_{K(\ast)}$

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predicted Lepton Universality Violation in rare B decays!

$g' Y_Q b Y_{Qs} \langle \phi \rangle^2 / 2m_Q^2$

$Q$: heavy vectorlike fermions with mass $\sim 1 - 10$ TeV

$\phi$: scalar that breaks $L_\mu - L_\tau$

(see also recent extended model WA, Davighi, Nardecchia 1909.02021)
$Z'$ contributes to $(g - 2)_\mu$

at the 1-loop level

\[ \Delta a_\mu \simeq \frac{(g')^2}{12\pi^2} \frac{m_\mu^2}{m_{Z'}^2} + \mathcal{O}\left(\frac{m_\mu^4}{m_{Z'}^4}\right) \]

Can it explain the long standing discrepancy?

\[ \Delta a_\mu \simeq (2.9 \pm 0.9) \times 10^{-9} \]
Can obtain bounds from measured $Z \to 4\mu$ branching ratio

(WA, Gori, Pospelov, Yavin, 1406.2332)
LHC Searches

Can obtain bounds from measured \( Z \rightarrow 4\mu \) branching ratio

(WA, Gori, Pospelov, Yavin, 1406.2332)

recent dedicated search for the \( L_\mu - L_\tau \) gauge boson (CMS 1808.03684)

extension to lower masses possible?

(Elahi, Martin 1511.04107)
Direct Search at B-factories

$e^+ e^- \rightarrow 2\mu Z' \rightarrow 4\mu$

BaBar 1606.03501
(Can be improved at Belle II)

$g'$ vs. $m_{Z'}$ (GeV)
Direct Search at B-factories

\[ e^+ e^- \rightarrow 2\mu Z' \rightarrow 4\mu \]

What about the region below the di-muon threshold?

\[ e^+ e^- \rightarrow \mu^+ \mu^- + E_{\text{miss}} \]
Modified Z Couplings to Leptons

loops involving the $Z'$
lead to corrections of the
couplings of the SM $Z$ to
muons, taus and neutrinos

→ constraints from
LEP measurements

WA, Gori, Pospelov, Yavin 1403.1269
Borexino measures the scattering rate of solar neutrinos on electrons

\[ \nu_{\mu,\tau} \rightarrow \nu_{\mu,\tau} \]

\[ \rightarrow \ Z' \]

\[ \rightarrow \ \mu, \tau \]

\[ \rightarrow \ \gamma \]

\[ \rightarrow \ e \]

\[ \rightarrow \ e \]

tiny momentum transfer
⇒ \( Z' \) can mix with photon

relevant constraint at low masses

Kamada, Yu 1504.00711
The $Z'$ contributes to trident production effect has some dependence on the neutrino beam spectrum

\[
\frac{\sigma_{\text{CCFR}}}{\sigma_{\text{SM}}} \approx \frac{1.13 + \left( 1 + 4s_W^2 + \frac{2v^2(g')^2}{M_{Z'}^2} \right)^2}{1.13 + (1 + 4s_W^2)^2}
\]

(for $Z'$ masses $\gtrsim$ few GeV)

\[
\frac{\sigma_{\text{DUNE}}}{\sigma_{\text{SM}}} \approx \frac{1.54 + \left( 1 + 4s_W^2 + \frac{2v^2(g')^2}{M_{Z'}^2} \right)^2}{1.54 + (1 + 4s_W^2)^2}
\]

(for $Z'$ masses $\gtrsim$ few hundred MeV)

(WA, Gori, Martin-Albo, Sousa, Wallbank 1902.06765)
Summary of Current Constraints on $L_\mu - L_\tau$

WA, Gori, Pospelov, Yavin, 1406.2332; WA, Gori, Martin-Albo, Sousa, Wallbank 1902.06765

$g'\ (\text{GeV})$

$B_B\text{N}$

$Borexino$

$CCFR$

$(g-2)_\mu$

$\text{BBN}$

$\text{LEP}$

$\text{LHC}$

$m_Z' (\text{GeV})$

$\text{BaBar}$
Neutrino Tridents at DUNE

WA, Gori, Martin-Albo, Sousa, Wallbank 1902.06765

expect $\sim 700 \nu_\mu \rightarrow \nu_\mu \mu^+ \mu^-$ trident events after 3 years in the DUNE near detector

main challenge:

huge background from $\nu_\mu N \rightarrow \mu^- N' \pi$

developed event selection based on simple kinematical cuts

using only information from the LArTPC, we find that DUNE should be able to measure the trident cross section with at least $\sim 40\%$ accuracy
Expected DUNE Sensitivity to $L_\mu - L_\tau$

WA, Gori, Martin-Albo, Sousa, Wallbank 1902.06765
Model Independent Sensitivity to New Physics

parameterize effects of heavy new physics model independently through four fermion contact interactions
(corresponds to NSI of muon neutrinos with muons)

\[ \mathcal{H}_{\text{eff}}^{\text{SM}} = \frac{G_F}{\sqrt{2}} \left( g_{\mu\mu\mu\mu}^V (\bar{\nu}_\mu \gamma_\alpha P_L \nu_\mu)(\bar{\mu} \gamma_\alpha \mu) \right. \\
\left. + g_{\mu\mu\mu\mu}^A (\bar{\nu}_\mu \gamma_\alpha P_L \nu_\mu)(\bar{\mu} \gamma_\alpha \gamma_5 \mu) \right) \]

\[ g_{\mu\mu\mu\mu}^V = 1 + 4 \sin^2 \theta_W + \Delta g_{\mu\mu\mu\mu}^V \]

\[ g_{\mu\mu\mu\mu}^A = -1 + \Delta g_{\mu\mu\mu\mu}^A \]

WA, Gori, Martin-Albo, Sousa, Wallbank
1902.06765
Neutrino tridents have unique sensitivity to new muonic forces

Existing measurements constrain $Z'$ solutions of the $(g - 2)_\mu$ anomaly, but still leave viable parameter space ($m_{Z'} \lesssim \text{few hundred MeV}$)

DUNE should be able to probe most of the remaining open parameter space