Probing EM Properties of Neutrinos and the Weak Mixing Angle at the FPF

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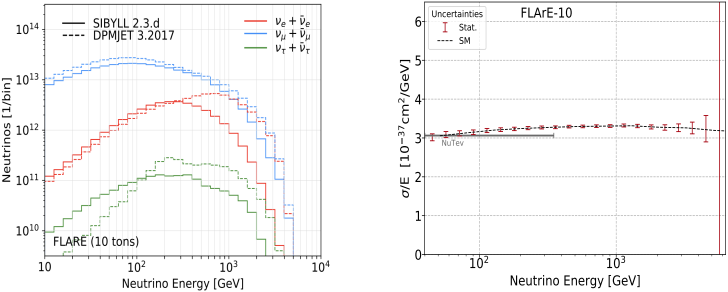
Neutrinos in the Forward Direction

Copious amounts of neutrinos are produced in the forward direction at the LHC.

Precision studies of neutrinos are now possible with the expected high luminosity at FPF.

Neutrino neutral current interactions are also measurable at the LHC.

Ahmed Ismail, RMA, Felix Kling; 2012.10500



Neutrino flux and NC interactions at FLArE10 for $\mathcal{L} = 3\ \text{ab}^{-1}$.

2109.10905, 2203.05090, 2105.08270

Neutrino Electromagnetic (EM) Properties

- Neutrinos have zero electric charge and no tree-level EM interactions.
- They can arise at loop level or via BSM effects.
- The electromagnetic properties of neutrinos can be assembled in the matrix element of the neutrino effective electromagnetic current

$$\nu_f(p_f) j^{\mu}_{\nu,\mathrm{EM}} \nu_i(p_i) = \overline{u}_f(p_f) \Lambda^{\mu}_{fi}(q) u_i(p_i).$$

- In the ultra-relativistic limit,

$$\Lambda^{\mu}_{fi}(q) = \gamma^{\mu}\left(Q_{fi} - \frac{q^2}{6}\left\langle r^2 \right\rangle_{fi}\right) - i\sigma^{\mu\nu} q_{\nu} \mu_{fi}.$$

Q_{fi} = Neutrino millicharge (NMC)
$\left\langle r^2 \right\rangle_{fi}$ = Neutrino Charge Radius (NRC)
μ_{fi} = Neutrino Magnetic Moment (NMM)

1403.6344

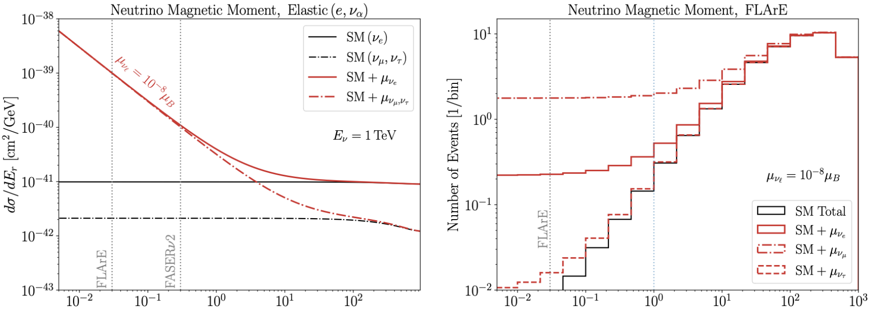
Motivation to Study Neutrino EM Properties

- Electromagnetic properties of neutrinos can also be used to probe new physics.
- Non-zero neutrino masses implies non-zero neutrino magnetic moment, $\mu_\nu^D \sim 10^{-19}(\frac{m_\nu}{1\text{ev}})\mu_B$, and $\mu_\nu^M \sim 10^{-23}\mu_B$.
- Measuring NMM this can shed light on the nature of neutrinos; Dirac - diagonal and transition, Majorana - transition NMM.
- Neutrino EM properties have been used to explain some experimental anomalies.
- Experiments are very close to the SM value of neutrino charge radius.

Modified Rates at FPF - NMM

$$\mathcal{L} \supset \mu_\nu (\bar{\nu} \sigma_{\alpha\beta} \nu) F^{\alpha\beta}$$

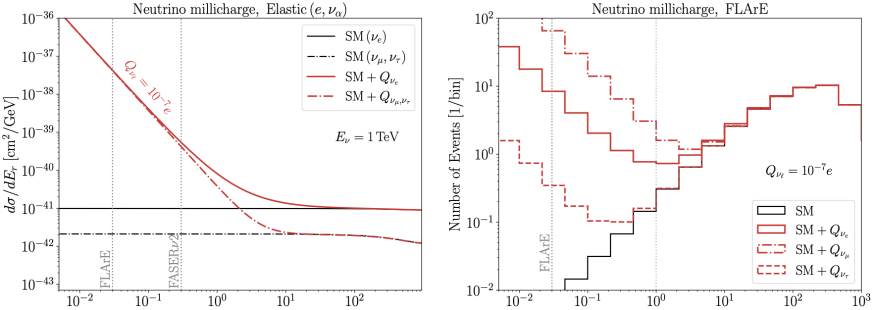
$\left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\rm NMM} \sim \frac{1}{E_r}$; excess events at low electron recoil energies.



RMA, Saeid Foroughi-Abari, Felix Kling, and Yu-Dai Tsai, in prep.

Modified Rates at FPF - NMC

$$\mathcal{L} \supset Q_\nu (\bar{\nu}\gamma_\mu \nu) A^\mu$$

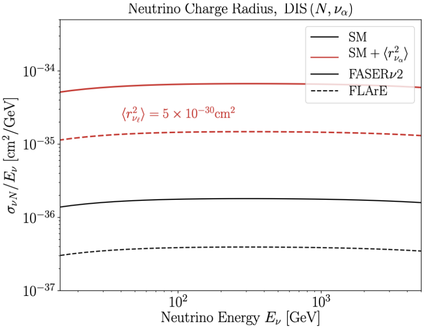


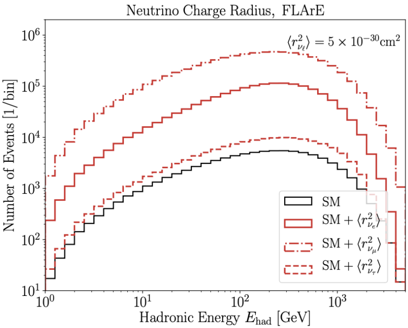
RMA, Saeid Foroughi-Abari, Felix Kling, and Yu-Dai Tsai, in prep.

Modified Rates at FPF - NCR

Vector coupling in the NC DIS is modified as,
$g_V^q \to g_V^q - \frac{2}{3} Q_q m_W^2 \langle r_{\nu_\ell}^2 \rangle \sin^2\theta_w$

We use a heavier target (nuclear scattering) for higher signal event rates.





RMA, Saeid Foroughi-Abari, Felix Kling, and Yu-Dai Tsai, in prep.

Weak Mixing Angle at FPF

If the SM value shifts, $\sin^2\theta_W \to \sin^2\theta_W + \Delta\sin^2\theta_W$, then $g_V^q \to g_V^q - 2Q_q\Delta\sin^2\theta_W$.

Modifies NC DIS similarly to NCR.

Can recast NCR results to measure to the $\sin^2\theta_W$ at the FPF.

Interesting in light of the NuTeV anomaly. Their measured value is 3σ above SM value.

hep-ex/0110059

Analysis Strategy

Main experimental signatures:

- Excess events at low electron recoil energies (NMM, NMC).
- Modified NC DIS rates (NCR, $\sin^2\theta_W$)

We employ a simple cut and count analysis to place bounds.

$E_{threshold} < E_r < 1$ GeV for NMM, NMC.

$E_{threshold} < E_r$ for NCR, so count all events.

We use 30 (300) MeV for FLArE (FASERν) detector.

Systematics and Detector Requirements

Systematics:

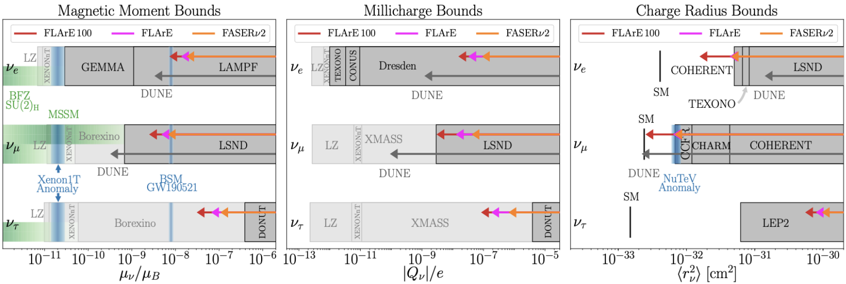
- Neutrino fluxes can be sufficiently constrained via CC measurements (more important for NCR where we assume it corresponds to stat. uncertainty of CC measurements in our work).
- Neutrino-nucleus interaction modelling.

Detector Requirements:

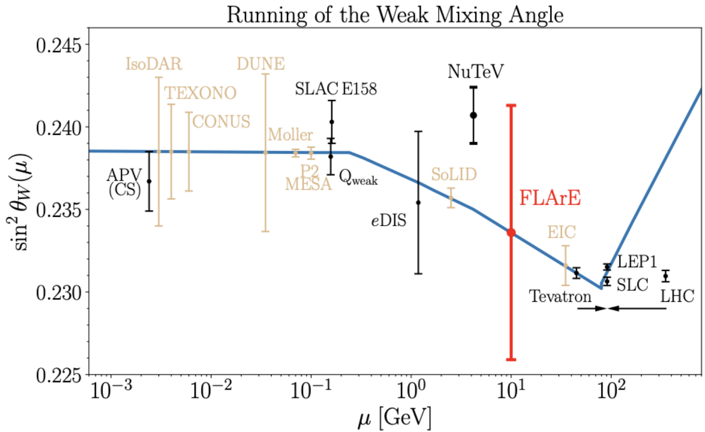
- Low electron recoil energy events can be reconstructed well.
- NC events can be sufficiently well identified and distinguished from CC events.
- All muon induced backgrounds can be vetoed with timing information.
- The low energy thresholds required can be attained in these detectors.

We assume all systematics can be made smaller than the statistical uncertainties of the measurements. How feasible is this???

Results


Magnetic Moment Bounds
Millicharge Bounds
Charge Radius Bounds
FLArE 100
FLArE
FASERν2
ν_e
ν_μ
ν_τ
LZ
XENONnT
GEMMA
LAMPF
DUNE
BFZ
SU(2)H
MSSM
Borexino
LSND
Xenon1T Anomaly
BSM GW190521
DONUT
TEXONO
CONUS
Dresden
XMASS
SM
COHERENT
CCFR
CHARM
NuTeV Anomaly
LEP2
10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6}
μ_ν/μ_B
10^{-13} 10^{-11} 10^{-9} 10^{-7} 10^{-5}
$|Q_\nu|/e$
10^{-33} 10^{-32} 10^{-31} 10^{-30}
$\langle r_\nu^2\rangle$ [cm^2]

Results



$\sin^2\theta_W$ can be measured to 3% precision at FLArE10.

Result Highlights

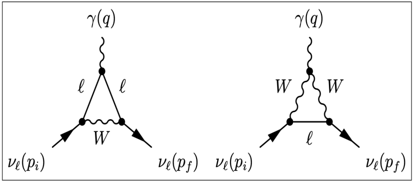
- ν_τ : Strongest laboratory-based sensitivity to the tau neutrino magnetic moment and millicharge. Order of magnitude better than DONUT.
- ν_e : Strongest experimental bounds on the electron neutrino charge radius.
- ν_μ : One of the strongest experimental bounds on the muon neutrino charge radius. Only a factor of a few from the SM value.
- Can measure weak mixing angle to 3% precision at a scale of ~ 10 GeV, important benchmark for detector considerations.

These are optimistic projections that do not consider many systematics. More detailed study is necessary.

Thank You!!!

Backup Slide - Predictions for Neutrino EM properties

- $Q_{SM} = 0$.
- Non-zero neutrino mass $\Longrightarrow$ Non-zero NMM. For Dirac neutrinos, $\mu_\nu \approx \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu \approx 3 \cdot 10^{-19} \mu_B \left(\frac{m_\nu}{1\ \mathrm{eV}}\right)$.
- NCR is generated at loop level within the SM, $\left\langle r^2_{\nu_\ell} \right\rangle_{\mathrm{SM}} = \frac{G_f}{4\sqrt{2}\pi^2}\left[3 - 2\log\frac{m_\ell^2}{m_W^2}\right]$.



  - $\left\langle r^2_{\nu_e} \right\rangle_{\mathrm{SM}} = 4.1 \times 10^{-33} \mathrm{cm}^2$
  - $\left\langle r^2_{\nu_\mu} \right\rangle_{\mathrm{SM}} = 2.4 \times 10^{-33} \mathrm{cm}^2$
  - $\left\langle r^2_{\nu_\tau} \right\rangle_{\mathrm{SM}} = 1.5 \times 10^{-33} \mathrm{cm}^2$

Backup Slide - SM Neutrino-Electron Elastic Scattering Cross-Section

$\nu_\ell e^- \longrightarrow \nu_\ell e^-$

$$\left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\mathrm{SM}} = \frac{G_F^2 m_e}{2\pi}\left[(g_V^\ell - g_A^\ell)^2\left(1 - \frac{E_r}{E_\nu}\right)^2 \right. \\ \left. + (g_V^\ell + g_A^\ell)^2 + \left((g_A^\ell)^2 - (g_V^\ell)^2\right)\frac{m_e E_r}{E_\nu^2}\right]$$

with $g_V^\ell = 2\sin^2\theta_w - \frac{1}{2} + \delta_{\ell e}$, $g_A^\ell = -\frac{1}{2} + \delta_{\ell e}$.

$E_r =$ recoil energy of the electron.

Includes Z boson exchange for $\nu_{\mu.\tau}$, and Z, W boson exchange for ν_e.

Backup Slide - Neutrino Millicharge (NMC)

- Effective Lagrangian

$$\mathcal{L} \supset Q_\nu (\bar{\nu}\gamma_\mu \nu) A^\mu$$

- Neutrino-electron elastic scattering cross-section is modified as

$$\left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\rm NMC} = \left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\rm SM} + \left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\rm Int} + \left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\rm Quad}$$

- $$\left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\rm Int} = \frac{\sqrt{8\pi}G_F\alpha}{E_\nu^2 E_r}\left(\frac{Q_{\nu_\ell}}{e}\right)\Big[g_V^\ell\big(2E_\nu^2 + E_r^2 - E_r(2E_\nu + E_r)\big) + g_A^\ell\big(E_r(2E_\nu - E_r)\big)\Big]$$

- $$\left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\rm Quad} = 4(\pi\alpha)^2\left(\frac{Q_{\nu_\ell}}{e}\right)^2\left[\frac{2E_\nu^2 + E_r^2 - 2E_\nu E_r}{m_e E_r^2 E_\nu^2}\right]$$

1703.00401, 2111.14884

Backup Slide - Neutrino Magnetic Moment (NMM)

- Effective Lagrangian for Dirac neutrinos

$$\mathcal{L} \supset \mu_\nu (\bar{\nu}\sigma_{\alpha\beta}\nu) F^{\alpha\beta}$$

- Neutrino-electron elastic scattering cross-section is modified as

$$\left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\mathrm{NMM}} = \left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\mathrm{SM}} + \frac{\pi^2}{m_e^2}\left(\frac{1}{E_r} - \frac{1}{E_\nu}\right)\left(\frac{\mu_{\nu_\ell}}{\mu_{\mathrm{B}}}\right)^2$$

- There is no interference term here, as the helicity flips in the NMM interaction but is conserved in the SM weak interaction. So the two contributions add incoherently.

hep-ph/0603036, 2007.04291

Backup Slide - Neutrino NC DIS and Neutrino Charge Radius (NCR)

- Neutral current scattering rate in the SM roughly scales proportionally to the target mass.
- If the new physics signal count decreases or doesn't increase commensurately, then moving to a heavier target will only degrade the sensitivity. This is the case for NMC, and NMM.
- NCR induces a shift in the vector coupling constant in the SM expression. Hence, we can expect higher rates of signal if we use a heavier target.
- So for NCR we consider neutrino NC DIS which gives us a higher event rate and stronger bounds.

Backup Slide - Neutrino NC DIS and NCR

- The double differential cross-section of neutral current neutrino-nucleon DIS is,

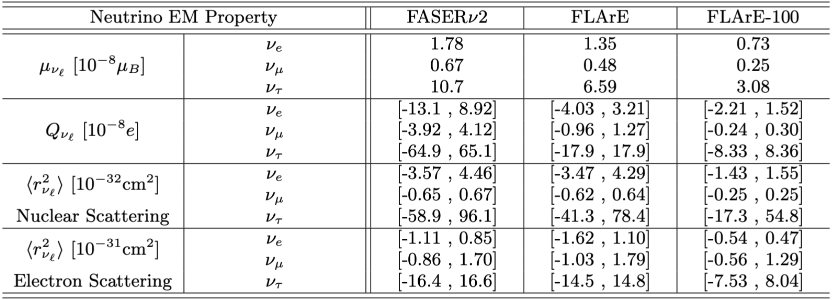
$$\frac{d\sigma(\nu N \to \nu X)}{dx\ dy} = \frac{2G_F^2 m_p E_\nu}{\pi} \frac{m_Z^4}{(Q^2 + m_Z^2)^2} \times$$
$$\sum_{q=u,d,s,c} \big[g_{q,L}^2 [x f_q(x, Q^2) + x f_{\bar{q}}(x, Q^2)(1-y)^2] +$$
$$g_{q,R}^2 [x f_q(x, Q^2)(1-y)^2 + x f_{\bar{q}}(x, Q^2)]\big]$$

  with $g_L^q, g_R^q = T^3 - Q_q \sin^2\theta_W,\ y = E_{\text{had}}/E_\nu,\ Q^2 = 2 m_p E_\nu x y$

- NCR modifies the vector coupling as, $g_V^q \to g_V^q - \frac{2}{3} Q_q m_W^2 \langle r_{\nu_\ell}^2 \rangle \sin^2\theta_w$

Vogel and Engel, 89

Backup Slide - Result Table



Neutrino EM Property		FASERν2	FLArE	FLArE-100
μ_{ν_ℓ} $[10^{-8}\mu_B]$	ν_e	1.78	1.35	0.73
	ν_μ	0.67	0.48	0.25
	ν_τ	10.7	6.59	3.08
Q_{ν_ℓ} $[10^{-8}e]$	ν_e	[-13.1 , 8.92]	[-4.03 , 3.21]	[-2.21 , 1.52]
	ν_μ	[-3.92 , 4.12]	[-0.96 , 1.27]	[-0.24 , 0.30]
	ν_τ	[-64.9 , 65.1]	[-17.9 , 17.9]	[-8.33 , 8.36]
$\langle r^2_{\nu_\ell}\rangle$ $[10^{-32}\text{cm}^2]$ Nuclear Scattering	ν_e	[-3.57 , 4.46]	[-3.47 , 4.29]	[-1.43 , 1.55]
	ν_μ	[-0.65 , 0.67]	[-0.62 , 0.64]	[-0.25 , 0.25]
	ν_τ	[-58.9 , 96.1]	[-41.3 , 78.4]	[-17.3 , 54.8]
$\langle r^2_{\nu_\ell}\rangle$ $[10^{-31}\text{cm}^2]$ Electron Scattering	ν_e	[-1.11 , 0.85]	[-1.62 , 1.10]	[-0.54 , 0.47]
	ν_μ	[-0.86 , 1.70]	[-1.03 , 1.79]	[-0.56 , 1.29]
	ν_τ	[-16.4 , 16.6]	[-14.5 , 14.8]	[-7.53 , 8.04]