Complementarity between charged and neutral current events in the search for new neutrino interactions

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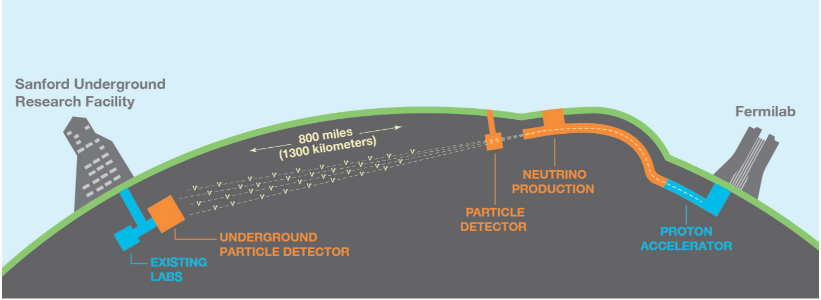
Summary

Long Baseline Neutrino Experiments

- Detection of neutrinos after macroscopic travel distances
- Accelerator experiments use artificial neutrino sources
- **Primary goal:** measure oscillation parameters via CC events

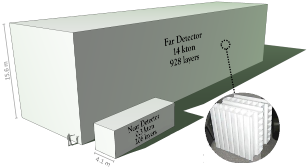


DUNE Collaboration (2020)

How Oscillation Experiments Work

The Measurement:

1. Produce ν_μ beam at source
2. Neutrinos propagate through Earth
3. Detect flavor at Far Detector
4. Compare with Near Detector (no oscillation)



Main channels:

- $\nu_\mu \to \nu_\mu$ disappearance
- $\nu_\mu \to \nu_e$ appearance

Flavor identification requires Charged Current interactions!

CC vs NC: The Traditional View

Charged Current (CC):

- $\nu_\ell + n \to \ell^- + p$
- Produces identifiable charged lepton
- **Flavor tagging:** μ^-, e^-, τ^-
- Good energy reconstruction
- $\Rightarrow$ **The signal!**

Neutral Current (NC):

- $\nu + N \to \nu + X$
- No charged lepton produced
- **Flavor-blind:** all ν_α look the same
- Poor energy reconstruction
- $\Rightarrow$ **A background!**

CC Events		**NC Events**
Oscillation physics	$\longrightarrow$	Background to reject

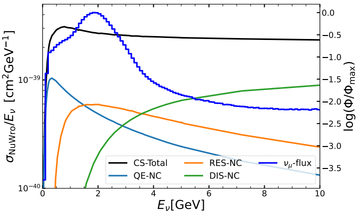
NC Events: A Dominant Background

Why NC is problematic:

- NC π^0 production mimics ν_e CC
- $\pi^0 \to \gamma\gamma$ looks like electron shower
- **Dominant background** for ν_e appearance
- Significant effort to reject/constrain

Current use of NC:

- Flux monitoring (flavor-independent)
- Systematic constraint via ND
- Otherwise... discarded



NC cross section and NOvA neutrino flux

Can we extract physics from this “background”?

Turning Background into Signal

The Insight:

NC events carry **different** information than CC events!

CC events probe NSI via:

- Matter effects during **propagation**
- Forward scattering ($q^2 \to 0$)
- Sensitive to specific combinations

NC events probe NSI via:

- **Cross section** modifications
- Finite momentum transfer
- Different parameter sensitivity!

CC: Propagation $+$ **NC: Cross section** $\longrightarrow$ **Complementarity!**

Motivations for This Work

The Problem:

- CC analyses probe NSI through matter effects
- Sensitive almost **exclusively** to isoscalar: $\varepsilon^{uV} + \varepsilon^{dV}$
- Isovector combination $\varepsilon^{uV} - \varepsilon^{dV}$ suppressed by $\sim$100$\times$

Our Solution:

- Use NC events as **signal**, not background
- NC cross sections sensitive to **both** isoscalar and isovector
- First constraints on isovector NSI from accelerator neutrinos

CC + NC complementarity $\rightarrow$ complete coverage of $(\varepsilon^{uV}, \varepsilon^{dV})$ plane

Non-Standard Interactions - The Lagrangian

The effective Lagrangian for NC-NSI with quarks:

$$\mathcal{L}_{\text{NSI}}^{\text{NC}} = -2\sqrt{2}G_F \sum_{f=u,d} \sum_{P=L,R} \varepsilon_{\alpha\beta}^{fP} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_P f)$$

Isospin Decomposition:

$$\varepsilon^{\text{isosc}} \equiv \varepsilon^{uV} + \varepsilon^{dV} \quad \text{(isoscalar)}$$
$$\varepsilon^{\text{isovec}} \equiv \varepsilon^{uV} - \varepsilon^{dV} \quad \text{(isovector)}$$

Why vector NSI?

- Arise naturally in UV-complete models (Z', leptoquarks)
- Axial NSI studied elsewhere (Abbaslu et al. 2024, 2025)
- Vector NSI affect both propagation AND scattering

CC Events: Sensitivity Through Propagation

The matter potential with NSI:

$$\varepsilon^{\text{prop}} = \varepsilon^{eV} + \frac{3(1+Y_n)}{2}\varepsilon^{\text{isosc}} + \frac{1-Y_n}{2}\varepsilon^{\text{isovec}}$$

where $Y_n \equiv N_n/N_e$ is the neutron-to-electron ratio.

For Earth matter ($Y_n \approx 1.05$):

$$\boxed{\varepsilon^{\text{prop}}_{\text{Earth}} \approx \varepsilon^{eV} + 3.08\,\varepsilon^{\text{isosc}} - 0.025\,\varepsilon^{\text{isovec}}}$$

Isovector suppressed by factor ∼100!

CC oscillation analyses are **structurally blind** to $\varepsilon^{uV} - \varepsilon^{dV}$
This is geometric, not statistical — more data won't help!

NC Events: Sensitivity Through Cross Sections

With NSI, the effective nucleon vector couplings become:

$$\tilde{g}_V^p = g_V^p + \frac{3\varepsilon^{\mathrm{isosc}} + \varepsilon^{\mathrm{isovec}}}{2}$$
$$\tilde{g}_V^n = g_V^n + \frac{3\varepsilon^{\mathrm{isosc}} - \varepsilon^{\mathrm{isovec}}}{2}$$

Main difference from propagation:

- NC cross sections depend on **both** isoscalar and isovector
- **Comparable weights** for both components
- No geometric suppression!

Observable	Isoscalar	Isovector
CC (matter effects)	✓	× (suppressed ∼100)
CEνNS	✓	× (for $N \approx Z$)
NC cross sections	✓	✓

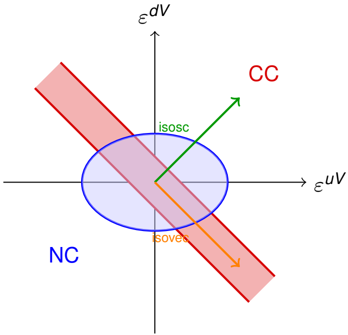
The $(\varepsilon^{uV}, \varepsilon^{dV})$ Plane

CC constraints:

- Diagonal bands along $\varepsilon^{uV} + \varepsilon^{dV} = \text{const}$
- Cannot distinguish ε^{uV} from ε^{dV}
- Same limitation for CEνNS

NC constraints:

- Probe both directions independently
- Break the CC degeneracy
- Access orthogonal parameter space



CC + NC = Complete coverage

Systematic Cancellation via FD/ND Ratio

The Challenge:

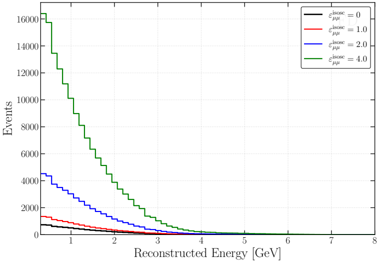
- Large uncertainties in NC cross sections (QE, RES, DIS)
- Flux normalization uncertainties

The Solution: FD/ND ratio

- ND and FD see **same** flux and cross sections
- Correlated systematics **cancel** in ratio
- Only FD-specific effects remain ($\sim$10-15%)

Parameter	NOvA	DUNE
Target	CH_2	LAr
Baseline	810 km	1300 km
FD systematic	15%	10%

Effect of NSI on Event Distributions



- NC events grow **quadratically** with NSI
- Observable: FD/ND ratio
- For large ε: ratio $\to$ 1
- BSM penalty prevents unphysical regions

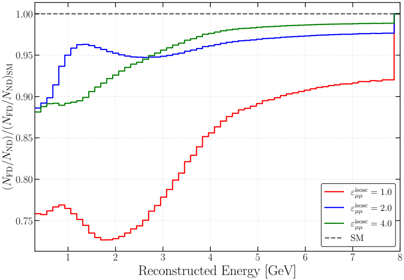
$$N_{FD} = 0.5|\nu_\mu\rangle + 0.5|\nu_\tau\rangle$$

$$N_{ND} = |\nu_\mu\rangle$$

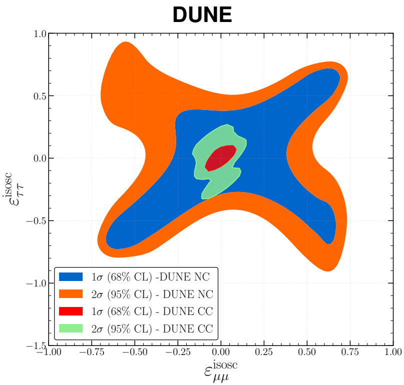
$$\frac{N_{FD}}{N_{ND}} = 1, \;\; \mathrm{SM}$$

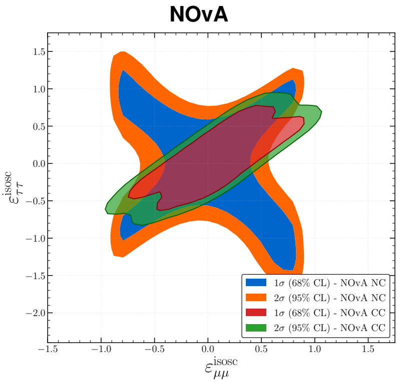
$$\frac{N_{FD}}{N_{ND}} < 1, \;\; \varepsilon_{\mu\mu}$$

$$\frac{N_{FD}}{N_{ND}} > 1, \;\; \varepsilon_{\tau\tau}$$



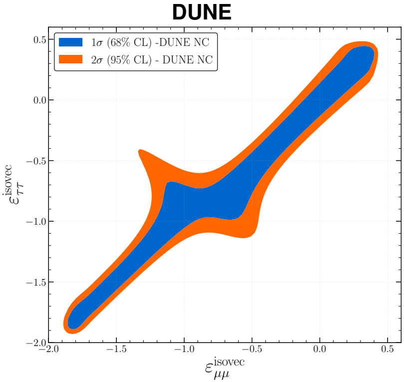
Isoscalar NSI Constraints

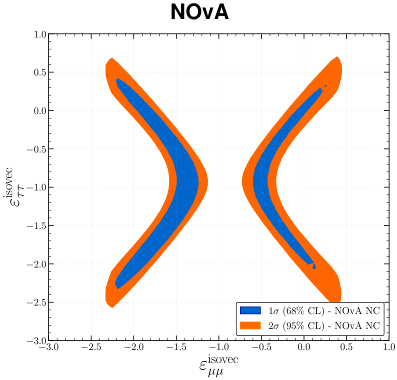




- CC (red/green): Three(Two)-island structure from oscillation degeneracies
- NC (blue/orange): Complementary sensitivity
- **DUNE**: CC dominates (longer baseline → larger matter effects)
- **NOvA**: CC and NC comparable → combination essential

Isovector NSI Constraints — NEW!

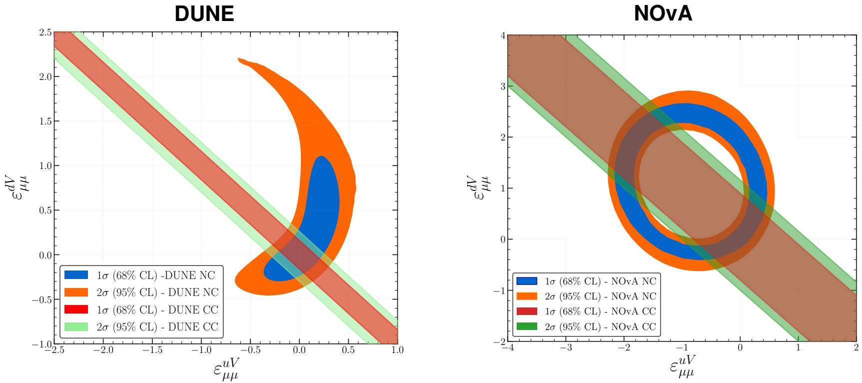




First constraints on isovector NSI from accelerator neutrinos!

- **NC events only** — CC has **zero** sensitivity here
- NOvA: Two disconnected regions (RES dominates at ∼2 GeV)
- DUNE: Connected region (DIS contribution at higher energies)
- Genuinely new parameter space, inaccessible to oscillation analyses

Constraints in the $(\varepsilon^{uV}, \varepsilon^{dV})$ Plane



- CC: Diagonal bands → blind direction along $\varepsilon^{uV} - \varepsilon^{dV}$
- NC: Elliptical regions → probe both parameters independently
- **Geometric origin of complementarity clearly visible**
- Only CC+NC combination provides complete coverage

Conclusions

Conclusions

- **Traditional view:** NC events = background to CC oscillation analysis
- **New perspective:** NC events carry **complementary** NSI information
- **CC events** $\to$ isoscalar ($\varepsilon^{uV} + \varepsilon^{dV}$)
  - Blind to isovector (suppressed $\sim$100$\times$ in Earth)
- **NC events** $\to$ isoscalar AND isovector
  - No geometric suppression
- **First constraints on isovector NSI** from LBL experiments
- **CC + NC** = complete ($\varepsilon^{uV}, \varepsilon^{dV}$) coverage
  - Parameter space hidden from oscillations + CEνNS

Thank you!

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Why Focus on Vector NSI?

Phenomenological motivation:

- Axial NSI don't affect propagation (no matter effects)
- Axial NSI studied in Abbaslu et al. (2024, 2025)
- Our work is complementary

Theoretical motivation:

- Z' models $\rightarrow$ vector couplings to quarks and neutrinos
- Leptoquark models $\rightarrow$ vector NSI at tree level
- Scalar mediators $\rightarrow$ vector after Fierz rearrangement

NC Interaction Regimes

- **Quasi-Elastic (QE):** $E_\nu < 2$ GeV
  - $\nu + N \to \nu + N$
  - Minimal energy transfer
- **Resonance (RES):** $2 < E_\nu < 10$ GeV
  - $\nu + N \to \nu + N^* \to \nu + N + \pi$
  - Dominates at NOvA energies ($\sim$2 GeV)
  - Isovector appears directly in $\Delta(1232)$ amplitude
- **Deep Inelastic (DIS):** $E_\nu > 10$ GeV
  - $\nu + N \to \nu + X$
  - Important at DUNE higher energies