Neutrinos from the LHC: Neutral Current Measurements and Electromagnetic Properties at the FPF

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FPF - Forward Physics Facility [1]

> **Introduction** In planning for the coming decades in particle physics, it is critically important to maximize the physics potential of the High-Luminosity LHC (HL-LHC). For decades, the focus at the energy frontier has been on high-p_T physics and the production of heavy particles through processes with fb to nb cross sections. The total pp interaction cross section at the LHC is 75 mb [1, 2], however, and most of the events, and most of the highest-energy particles created, are in the far-forward region at low p_T. These low-p_T events escape down the beampipe of the LHC's large detectors, and it is important to understand now if interesting physics opportunities are currently being missed in this "wasted" cross section.
>
> In recent years, it has become clear that this is in fact the case, and there is a rich physics program that is largely unexplored in the far-forward region at the LHC. In this Letter of Interest, we consider the possibility of creating a Forward Physics Facility (FPF) to house a diverse set of experiments dedicated to carrying out this program in the HL-LHC era.

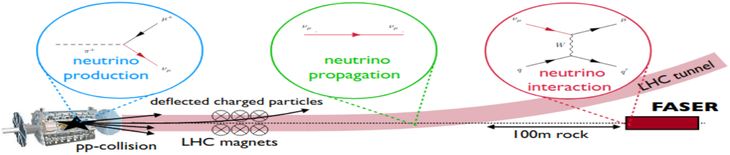
$\Theta \sim \Lambda_{\rm QCD}/\text{TeV} \sim$ mrad , most of the QCD activity is in the forward direction.

FPF will house experiments that will study neutrinos, long-lived particles, milli-charged particles, dark matter, dark sector, cosmic rays and more.

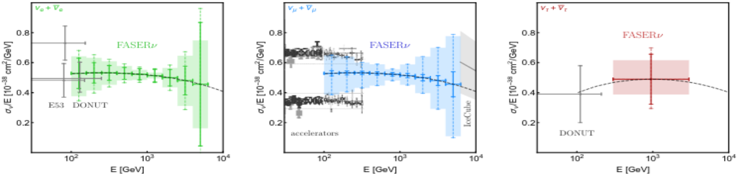
[1] SNOWMASS 2021 Letter of Interest - DOI: 10.5281/zenodo.4009641, arXiv:2109.10905, 2203.05090

Collider Neutrinos and Charged Current Events at FASERν[2]

The LHC produces many νs in the far forward (low P_T) region from meson decays in the $\sim$ [100GeV – few TeV] range.



First LHC neutrino candidate was reported in arXiv:2105.06197!!!



Charged Current (CC) cross-sections were studied in arXiv:1908.02310.

[2] LOI: 1908.02310, TP: 2001.03073

Neutral Current Cross-Section at FASERν [3]

- Here we present an analysis strategy to identify and reconstruct Neutral Current (NC) interactions and hence constrain neutral current ν cross-sections.

ν NC studies face two main obstacles at FASERν:

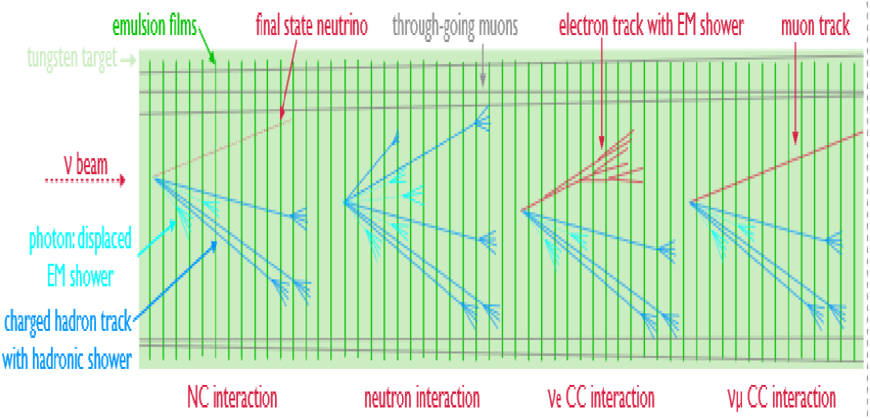
- The missing energy in the final state (carried away by the ν) makes event energy reconstruction very difficult. This is a problem shared by all ν NC studies.
- The main background for NC events at are

  - CC events (*one person's treasure is another's background*). This is a less severe problem.

  - Neutral Hadrons (NH), mainly induced by μ's.

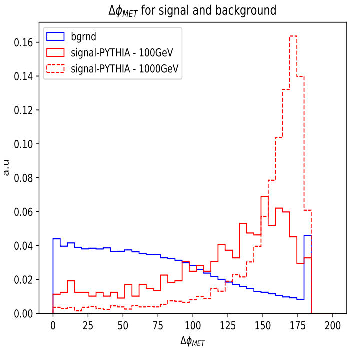
[3] Ahmed Ismail, **Roshan Mammen Abraham**, Felix Kling, *Neutral Current Neutrino Interactions at FASERν*, Phys.Rev.D 103 (2021).

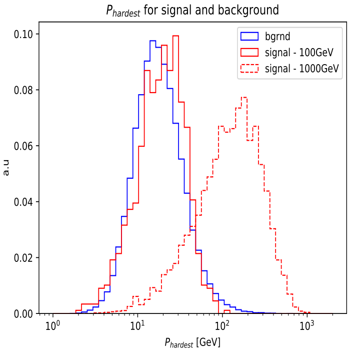
Events at FASERν



Observables - Signal vs Background

We use a total of 10 observables to characterize an event.

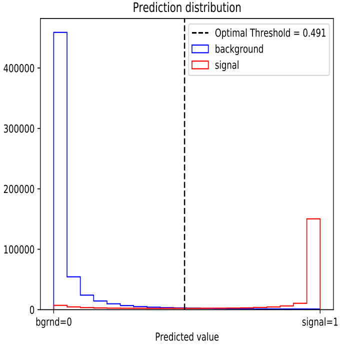


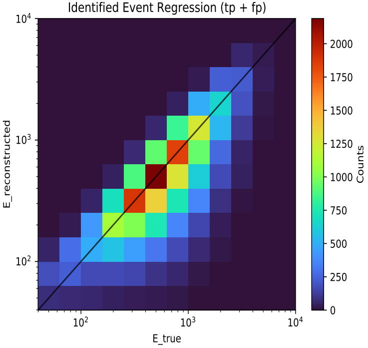


$\Delta\phi_{MET}$ = The azimuthal angle between the reconstructed missing transverse momentum and the nearest track.

Neural Network Results

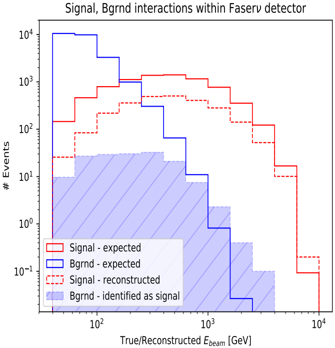
We use two neural n/w's in our study. The first classifier network separates events into signal and background. Only the events classified as signal are passed into the second regression n/w for energy estimation.

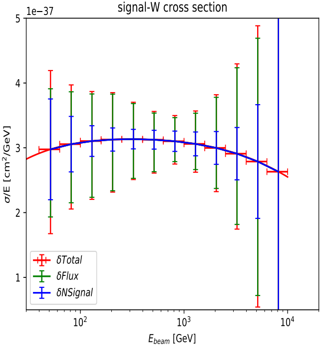




Cross-Section Results

O/p of the NN's gives us the number of reconstructed events in each energy bin. This gives us size of statistical uncertainty on ν NC interaction cross-section. The other source of uncertainty is the one on incoming flux.

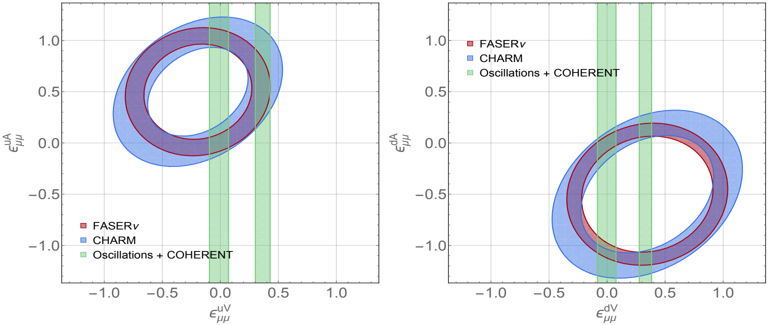




Other uncertainties: NH flux, simulation.

Constraining NSI

$$\mathcal{L} = -2\sqrt{2}G_F \sum_{f,\alpha,\beta,X} \epsilon_{\alpha,\beta}^{f,X} \left(\overline{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\overline{f}\gamma_\mu P_X f\right)$$

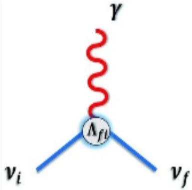


Comparison of bounds on NSI couplings from CHARM (blue) and (red) for (**left:**) up quark and (**right:**) down quark in the Vector-Axial vector coupling plane. Vertical lines are bounds from oscillations and COHERENT that constrain only vector NSI.

Neutrino Magnetic Moments

- Neutrino mixing parameters have been measured with incredible precision in recent years.
- Electromagnetic properties of neutrinos can also be used to probe new physics.
- **SM prediction for neutrino magnetic moment is exactly 0, but non-zero neutrino masses implies non-zero neutrino magnetic moment.**
- Minimally-extending the SM with right-handed neutrinos can give neutrinos a diagonal magnetic moment proportional to their mass, $\mu_\nu^D \sim 10^{-19}(\frac{m_\nu}{1\text{ev}})\mu_B$.
- Majorana neutrinos have an even smaller predicted value, $\sim 10^{-23}\mu_B$.
- These predictions are **several orders of magnitude smaller than the present experimental and astrophysical upper bounds**, motivating our study of NMM using LHC neutrinos.

Neutrino Magentic Moments - Experimental Signature



$$\mathcal{L}_{dipole} \sim \mu_\nu^{if} \bar{\nu}^i \sigma^{\mu\nu} \nu^f F_{\mu\nu}$$

A striking experimental signature of the magnetic moment operator is an **electron recoiling**. Incoming active neutrinos interact with the electrons in the target atom causing the electron to recoil. We consider two cases:

- Initial (ν_i) and final state (ν_f) neutrinos are active SM neutrinos.
- ν_f is a Heavy Neutral Lepton (HNL) a.k.a sterile neutrino, N_R.

Neutrino Magnetic Moments - Cross-Section Expression

A characteristic feature of neutrino magnetic moment interaction is an **enhancement in signal cross-section at low recoil energies,** $d\sigma/dE_{rec} \sim 1/E_{rec}$

For the scattering $\nu_\alpha e^- \longrightarrow \nu_\alpha e^-$ we have,

$$\frac{d\sigma}{dE_{rec}} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{E_{rec}} - \frac{1}{E_\nu}\right)\left(\frac{\mu_{\nu_\alpha}}{\mu_{\mathrm{B}}}\right)^2$$

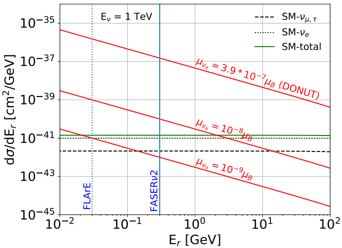
and for $\nu_\alpha e^- \longrightarrow N_R e^-$

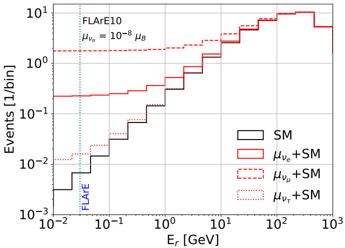
$$\frac{d\sigma}{dE_{rec}} = \alpha\left(\mu_\nu^\alpha\right)^2\left[\frac{1}{E_{rec}} - \frac{1}{E_\nu} + M_N^2\frac{E_{rec} - 2E_\nu - M_e}{4E_\nu^2 E_{rec} M_e} + M_N^4\frac{E_{rec} - M_e}{8E_\nu^2 E_{rec}^2 M_e^2}\right].$$

So if we have a **source of neutrinos and a detector with sufficiently low energy thresholds** then we can study neutrino magnetic moments. FPF!!!

Active Neutrino Magnetic Moment[4]

$$\nu_\alpha e^- \longrightarrow \nu_\alpha e^-$$





Left: The SM background has a flat distribution but the NMM contribution is enhanced at low recoil energies. **Right:** Expected number of SM and μ_{ν_α} + SM events at FLArE10.

[4] Saeid Foroughi-Abari, Felix Kling, **Roshan Mammen Abraham**, Yu-Dai Tsai, *Neutrino Magnetic Dipole Moments at the Forward Physics Facility at LHC* (in preparation)

Active Neutrino Magnetic Moment

We employ a simple cut and count analysis with *cuts* corresponding to $E_{thresh} < E_{rec} < 1$ GeV.

Detector	SM backgrounds		$\mu_{\nu_e} = 1 \cdot 10^{-8} \mu_B$		$\mu_{\nu_\mu} = 1 \cdot 10^{-8} \mu_B$		$\mu_{\nu_\tau} = 1 \cdot 10^{-8} \mu_B$	
	no cuts	cuts	no cuts	cuts	no cuts	cuts	no cuts	cuts
FASERν2	73	0.28	4.72	0.63	31.50	4.45	0.12	0.01
FLArE-10	43	0.26	3.22	1.10	24	8.80	0.13	0.04
FLArE-100	281	2.01	23.31	8.10	184	68.51	1.30	0.45

Bounds on μ_{ν_α}:

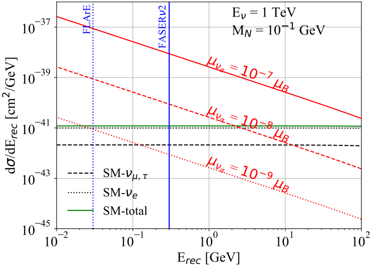
Detector	μ_{ν_e} $(10^{-9} \mu_B)$	μ_{ν_μ} $(10^{-9} \mu_B)$	μ_{ν_τ} $(10^{-8} \mu_B)$
FASERν2	11.7	4.4	7.0
FLArE-10	8.7	3.0	4.2
FLArE-100	5.3	1.8	2.2

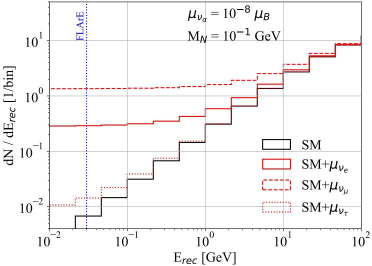
DONUT[5] bounds are at $\mu_{\nu_\tau} < 3.9 \times 10^{-7} \mu_B$. FLArE-10 can do order of magnitude better.

[5] arXiv:hep-ex/0102026

Active to Sterile Neutrino Transition Magnetic Moment[6]

$$\nu_\alpha e^- \longrightarrow N_R e^- \quad ; \quad \mathcal{L}_{dipole} \supset \frac{1}{2}\mu_\nu^\alpha \bar{\nu}_L^\alpha \sigma^{\mu\nu} N_R F_{\mu\nu}$$





Qualitatively it is the same as before so we can employ a similar cut and count analysis. But **sterile neutrinos can undergo decays**.

[6] Ahmed Ismail, Sudip Jana, **Roshan Mammen Abraham**, *Neutrino up-scattering via the dipole portal at forward LHC detectors*, Phys.Rev.D 105 (2021).

Active to Sterile Neutrino Transition Magnetic Moment

The decay length of N_R in the lab frame is given by
$l_{decay} = \frac{16\pi}{\mu_\nu^2 M_N^4}\sqrt{E_N^2 - M_N^2}$, where E_N = energy of the outgoing N_R.

l_{prompt} = minimum decay length for the decay vertex to appear displaced, and hence distinguishable from the production vertex.

- $l_{decay} > l_{detector}$: N_R decays outside the detector and the decay vertex is not observable.
- $l_{prompt} < l_{decay} < l_{detector}$: The decay vertex is sufficiently displaced from the production vertex and results in "double-bang" events.
- $l_{decay} < l_{prompt}$: The decay occurs promptly, leading to an electron and photon appearing to be produced at the same point.

Active to Sterile Neutrino Transition Magnetic Moment

Of the possible signatures above, we focus on those with a single electron track emerging from the production vertex, **with no other nearby activity in the detector**.

We discard events where the N_R decays promptly, which could have different backgrounds than the ones we consider.

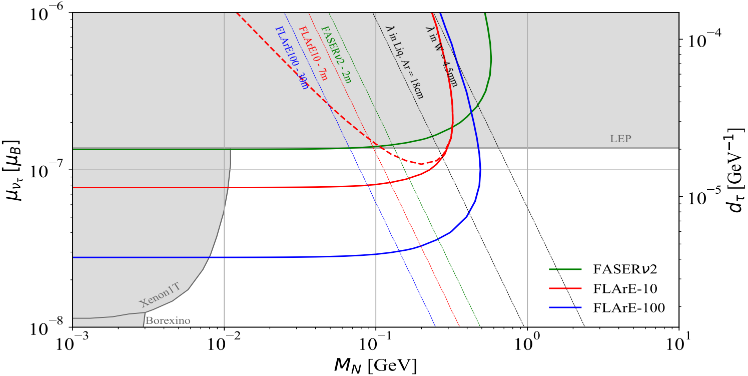
We take l_{prompt} to be the mean free path λ for pair production by the photon in the detector material: $\lambda = 4.5$ mm (18 cm) for FASERν2 (FLArE).

Loose (strong) cuts correspond to $E_{thresh} < E_{rec} < 10$ (1) GeV.

	SM backgrounds			$\mu_{\nu_e} = 10^{-7}\mu_B$			$\mu_{\nu_\mu} = 10^{-8}\mu_B$			$\mu_{\nu_\tau} = 10^{-7}\mu_B$		
Detector	no cuts	loose	strong	no cuts	loose	strong	no cuts	loose	strong	no cuts	loose	strong
FASERν2	86	2.5	0.1	480	134.1	39	30	8.6	2.5	12.7	3.6	1.0
FLArE-10	51	2	0.1	320.5	144	79.6	22.3	10.4	5.9	13.1	5.9	3.3
FLArE-100	332	15	1.0	2285	1037	575.7	165.1	78.2	44.6	126.1	57.2	31.8

Active to Sterile Neutrino Transition Magnetic Moment

$$l_{decay} \sim \frac{1}{\mu_\nu^2 M_N^4}$$



The colored dotted lines show $l_{decay} = l_{detector}$ for various detectors assuming $E_N = 100$ GeV, and the black dotted lines show $l_{decay} = \lambda$ in various detector materials. The red dashed line is from considering only double bang events at FLArE-10.

Neutrino Milli-charge

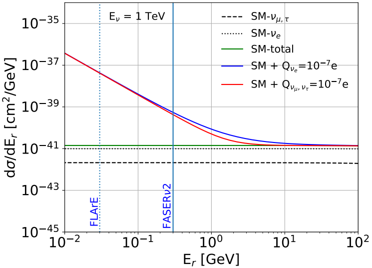
- Suppose SM neutrinos had a non-zero electric charge.
- It can couple to electrons via the photon, $\mathcal{L} \sim Q_\alpha \bar{\nu}_\alpha \gamma_\mu \nu_\alpha A^\mu$.
- This results in a differential cross section given by

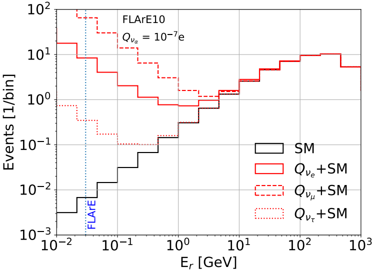
$$\frac{d\sigma(\nu_\alpha e^- \to \nu_\alpha e^-)}{dE_{rec}} = \frac{d\sigma^{SM}}{dE_{rec}} + \frac{d\sigma^{Int}}{dE_{rec}} + \frac{d\sigma^{Quad}}{dE_{rec}}$$

$$\frac{d\sigma^{Int}}{dE_{rec}} = \frac{\sqrt{8\pi} G_f \alpha}{E_\nu^2 E_{rec}} \left(\frac{Q_\alpha}{e}\right) \Big[g_V^\alpha \big(2E_\nu^2 + E_{rec}^2 - E_{rec}(2E_\nu + E_{rec}) \pm g_A^\alpha \big(E_{rec}(2E_\nu - E_{rec})\big)\big) \Big]$$

$$\frac{d\sigma^{Quad}}{dE_{rec}} = 4(\pi\alpha)^2 \left(\frac{Q_\alpha}{e}\right)^2 \left[\frac{2E_\nu^2 + E_{rec}^2 - 2E_\nu E_{rec}}{m_e E_{rec}^2 E_\nu^2} \right]$$

Neutrino Milli-charge





Bounds on Q_{ν_α}:

Detector	Q_{ν_e} $(10^{-8}e)$	Q_{ν_μ} $(10^{-8}e)$	Q_{ν_τ} $(10^{-7}e)$
FASERν2	[-9.57, 5.34]	[-2.60, 2.77]	[-4.28, 4.30]
FLArE-10	[-2.84, 1.99]	[-0.82, 0.85]	[-1.16, 1.16]
FLArE-100	[-1.94, 1.09]	[-0.48, 0.51]	[-0.61, -0.62]

Current terrestrial bounds: Q_{ν_e}[7] $\leq 10^{-12}$e ; Q_{ν_μ}[8] $\leq 10^{-8}$e

[7] reactor experiments (1302.1168, 1405.7168)
[8] COHERENT (2005.01645)

Neutrino Charge Radius

- Neutrinos have non-zero charge radii in the SM from radiative corrections[9].

$$\langle r^2_{\nu_\alpha} \rangle_{\rm SM} = \frac{G_f}{4\sqrt{2}\pi^2}\left[3 - 2\log\frac{m_l^2}{m_W^2}\right]$$

$$\left\langle r^2_{\nu_{e,\mu,\tau}} \right\rangle_{\rm SM} \simeq 4.1\times 10^{-33},\ 2.4\times 10^{-33},\ 1.5\times 10^{-33}\ \text{cm}^2$$

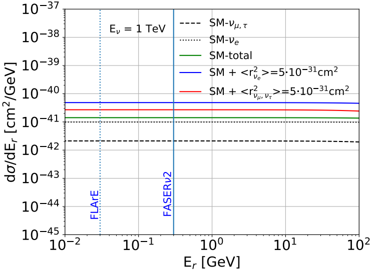
- A BSM contribution to neutrino charge radius will modify the weak interaction as[10]

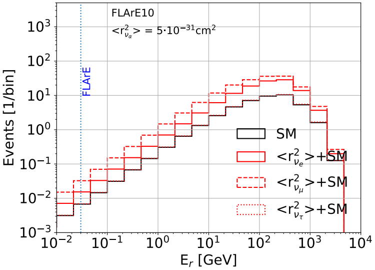
$$g_V^\alpha \to g_V^\alpha + \frac{2}{3} m_W^2 < r_\alpha^2 > S_w^2$$

[9] hep-ph/0008114, hep-ph/0210055

[10] Phys.Rev.D 39, 3378 (1989)

Neutrino Charge Radius





Bounds on $< r^2_{\nu_\alpha} >$:

Detector	$\langle r^2_{\nu_e} \rangle$ $(10^{-31} cm^2)$	$\langle r^2_{\nu_\mu} \rangle$ $(10^{-31} cm^2)$	$\langle r^2_{\nu_\tau} \rangle$ $(10^{-30} cm^2)$
FASERν2	[-1.11, 0.85]	[-0.86, 1.7]	[-1.64, 1.66]
FLArE-10	[-1.62, 1.10]	[-1.03, 1.79]	[-1.45, 1.48]
FLArE-100	[-0.54, 0.47]	[-0.56, 1.29]	[-0.78, 0.80]

Current terrestrial bounds: $< r^2_{\nu_e} >$[11] $= [-10^{-33}, 10^{-32}]cm^2$;
CCFR+CHARM-II $< r^2_{\nu_\mu} >$[12] $= [-10^{-33}, 10^{-33}]cm^2$

[11] global fit (0707.4319)
[12] hep-ph/0210137)

Summary

- There is much physics to be studied in the forward region at LHC which the FPF aims to probe.
- We present here a strategy to overcome the usual difficulties with NC studies using machine learning.
- The existence of nonzero neutrino magnetic moments is implied by neutrino masses.
- The intense beam of ν's, and detectors with low energy thresholds and timing capabilities make FPF suited for such searches.
- FPF also lends itself to the study of other electromagnetic properties of neutrinos like milli-charge, and charge radius.

Backup Slides - Event Generation and NN training

- *Event Generation:* We use Pythia to simulate ν-W and NH-W collision. Other generators were compared with Pythia and were in agreement.
- *Event Selection:* We select events with $\geq$ 5 charged tracks, each charged track has energy $\geq$ 1 GeV, and $\theta < \pi/4$.
- *Detector Simulation:*

  - Track momentum and energy smearing.

  - Identifies each visible track as electron, photon or a normal track.

  - Determines if the track interacts within the detector.
- *NN training:* We use 2 NN's:

  - Classifier N/W: Distinguishes signal(NC) and background(NH) events.

  - Regression N/W: Estimates the incoming particle energy. Only on identified signal events.

Backup Slides - Observables for NN training

- $n_{ch} \sim \log E_{\text{had}}$
- $n_{\gamma} \sim n_{\pi^0} \sim \log E_{\text{had}}$
- $\sum E_{\text{ch}} + \sum E_{\gamma} \sim E_{had}$
- $p_{\text{hard}} \sim E_{\text{had}}$
- $\sum |1/\theta_{\text{had}}| \sim E_{\text{had}}$
- $\tan \theta^{S}_{\text{cone}} = (\sum p_{T,i})/(\sum p_i) \sim H_T/E_{\text{had}}$
- $\tan \theta^{V}_{\text{cone}} = (\sum \vec{p}_{T,i})/(\sum p_i) \sim \vec{p}_T/E_{\text{had}}$
- Largest Azimuthal Gap: The largest difference in azimuthal angle between two neighbouring tracks, $\Delta\phi_{\text{max}}$.
- Track-MET-Angle: The azimuthal angle between the reconstructed missing transverse momentum, $\vec{p}_T$ and the nearest track, $\Delta\phi_{MET}$.

Backup Slides - Detectors at FPF

At the FPF we focus on the following detectors:

- FASERν2 : 0.5 m x 0.5 m x 2 m tungsten detector with a mass of 10 tonnes, and $E_{th} = 300$MeV.
- FLArE : Liquid argon detector with $E_{th} = 30$MeV and dimensions
  - 1 m x 1 m x 7 m with a mass of 10 tonnes.
  - 1.6 m x 1.6 m x 30 m with a mass of 100 tonnes.

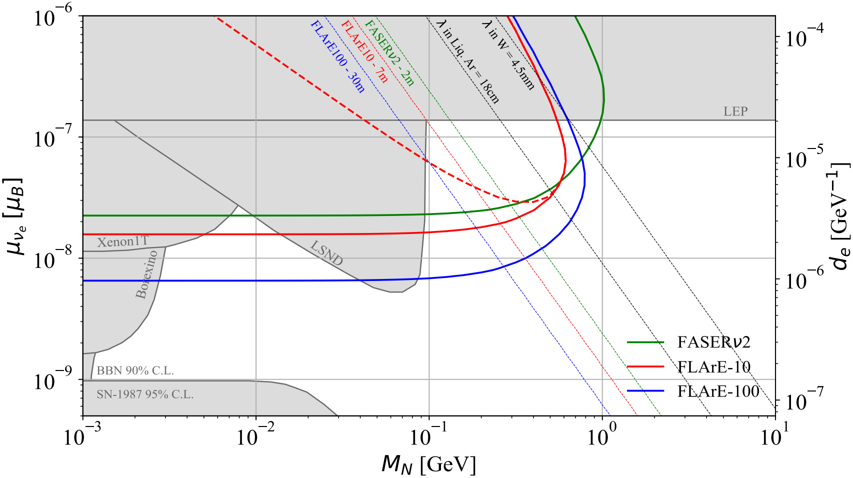
With a lower energy threshold we expect FLArE to be more sensitive.

Backup slides - Backgrounds at FPF

Before we study the prospects at FPF we have to reduce the backgrounds.

- Muon-induced backgrounds: Muons can emit photons through bremsstrahlung which subsequently undergo pair conversion. If one of the resulting $e^{\pm}$ is missed, the event would mimic our neutrino-electron scattering process. With timing, however, these events could be associated with the accompanying muon and vetoed.
- ν-induce backgrounds: The dominant background is ν interactions where only an e recoils. This is both NC interactions for all flavors, and CC interaction for ν_e only. We use differences in kinematic distributions to reduce this background.

Backup slides - μ_{ν_e}



Backup slides - μ_{ν_μ}