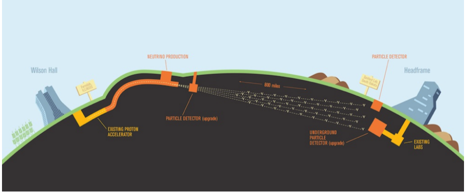
Neutrino Physics:
Now and at Future Accelerators

Vedran Brdar

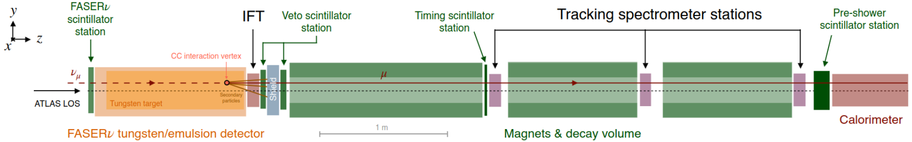
Neutrinos & Accelerators

- Accelerator Neutrinos (MiniBooNE, NOvA, DUNE...)



DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

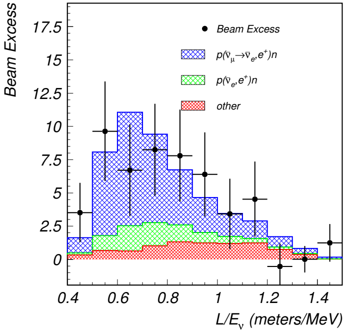
- LHC Neutrinos
- Neutrinophilic BSM searches at Colliders

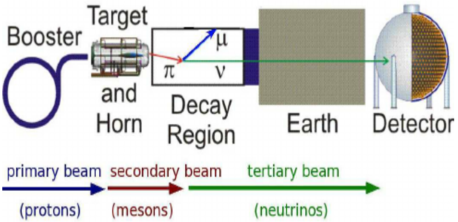


Outline

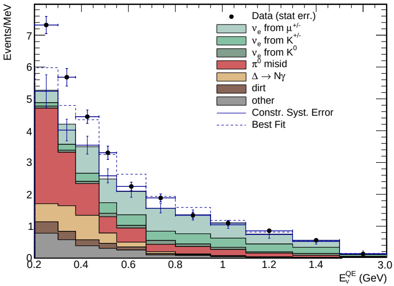
- MiniBooNE Anomaly
- New Physics Searches at DUNE
- Resonances in $\bar{\nu}_e - e^-$ scattering at FPF
- Neutrino Magnetic Moment and Future Colliders

Anomalies: LSND and MiniBooNE





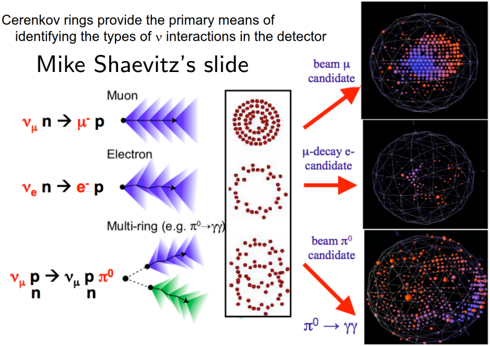
- LSND: $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam from stopped pion source ($> 3\sigma$) at $L/E \sim 1\mathrm{km\,GeV}^{-1}$
- MiniBooNE: reports electron-like event excess (4.8σ)
- in combination with LSND 6.1σ



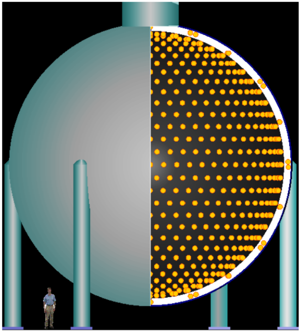
Main Channels for MiniBooNE

- shower events can be produced by e, γ, collimated e^+e^- and $\gamma\gamma$
- in SM, majority of events relevant for MiniBooNE excess arise from

1) CC ν_e events, 2) NC π^0 production, 3) NC γ from e.g. $\Delta(1232)$



Mike Shaevitz's slide



Employed MC Generators

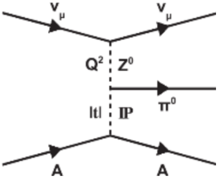
Generator	Tune	Ref.	Comments
NUANCE	–	[40]	the generator used by MiniBooNE
GiBUU	–	[42]	theory-driven generator
NuWro	–	[41]	
GENIE	G18_01a_02_11a	[39, 44]	GENIE baseline tune; see [44] for naming conventions
	G18_01b_02_11a		different FSI implementation compared to G18_01a_02_11a
	G18_02a_02_11a		updated res./coh. scattering models compared to G18_01a_02_11a
	G18_02b_02_11a		updated res./coh. scattering models and different FSI
	G18_10a_02_11a		theory-driven configuration; similar to G18_02a
	G18_10b_02_11a		theory-driven configuration; similar to G18_02b

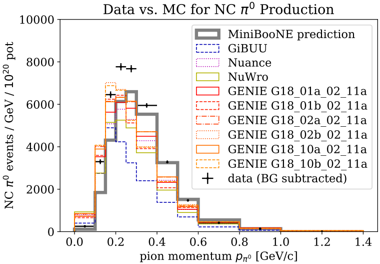
Strategy

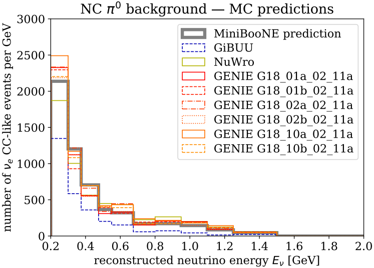
1. Make a prediction using NUANCE
2. Compare with the prediction obtained by the MiniBooNE collaboration; the differences are compensated by bin-by-bin tuning
3. Predict the event sample using GiBUU, NuWro and GENIE using the same cuts as for NUANCE; apply the tuning factors

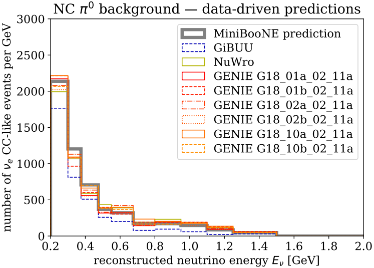
Neutral Current π^0 Production

$$\nu + N \to \nu + N + \pi^0(\gamma\gamma)$$





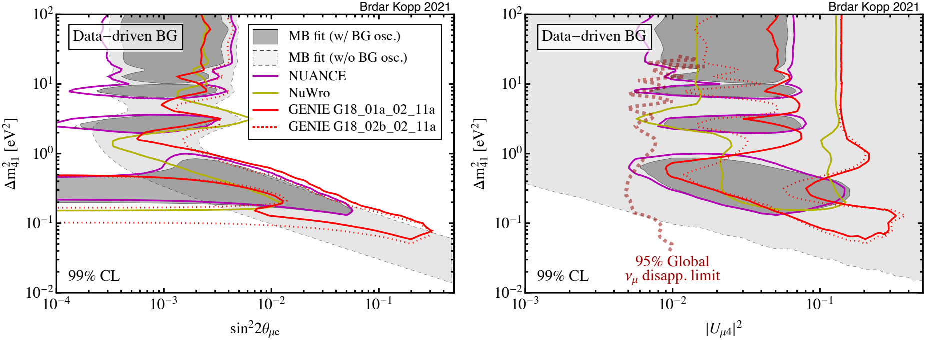




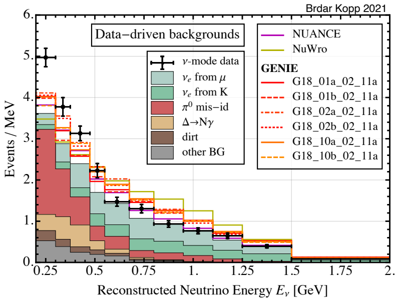
3+1 Model with eV-scale Sterile Neutrino

$$U^{4\text{flavor}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \color{red}{U_{e4}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \color{red}{U_{\mu 4}} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$



Results: Data-driven backgrounds



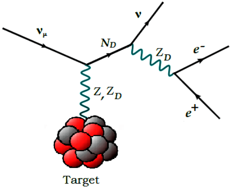
Generator	Tune	Δm^2_{41} [eV^2]	$\sin^2 2\theta_{\mu e}$	Significance
MB official		0.25	0.01	4.0σ
NUANCE	–	0.32	0.0079	4.0σ
NuWro	–	3.2	0.0016	3.1σ
GENIE	G18_01a_02_11a	0.79	0.00020	4.4σ
	G18_01b_02_11a	0.79	0.0001	3.5σ
	G18_02a_02_11a	0.13	0.063	4.0σ
	G18_02b_02_11a	0.13	0.050	3.7σ
	G18_10a_02_11a	0.25	0.016	3.5σ
	G18_10b_02_11a	0.40	0.013	4.0σ

Non-oscillatory Explanations of MiniBooNE Anomaly

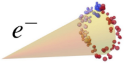
slide from MicroBooNE presentations

Evolving Theory Landscape

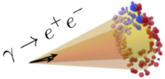
- Decay of O(keV) Sterile Neutrinos to active neutrinos
  - [13] Dentler, Esteban, Kopp, Machado Phys. Rev. D 101, 115013 (2020)
  - [14] de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141
- New resonance matter effects
  - [5] Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)
- Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay
  - [7] Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470
- Decay of heavy sterile neutrinos produced in beam
  - [4] Gninenko, Phys.Rev.D83:015015,2011
  - [12] Alvarez-Ruso, Saul-Sala, Phys. Rev. D 101, 075045 (2020)
  - [15] Magill, Plestid, Pospelov, Tsai Phys. Rev. D 98, 115015 (2018)
  - [11] Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)
- Decay of upscattered heavy sterile neutrinos or new scalars mediated by Z' or more complex higgs sectors
  - [1] Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)
  - [2] Abdullahi, Hostert, Pascoli, Phys.Lett.B 820 (2021) 136531
  - [3] Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)
  - [10] Dutta, Ghosh, Li, PRD 102, 055017 (2020)
  - [6] Abdallah, Gandhi, Roy, Phys. Rev. D 104, 055028 (2021)
- Decay of axion-like particles
  - [8] Chang, Chen, Ho, Tseng, Phys. Rev. D 104, 015030 (2021)
- A model-independent approach to any new particle
  - [9] Brdar, Fischer, Smirnov, PRD 103, 075008 (2021)



Produces true electrons

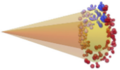


Produces true photons



Produces e^+e^- pairs

Overlapping e^+e^-

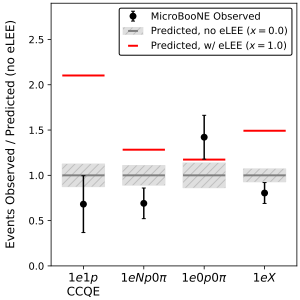


Leverage the power of LArTPC technology to distinguish between models based on exclusive final state topologies!

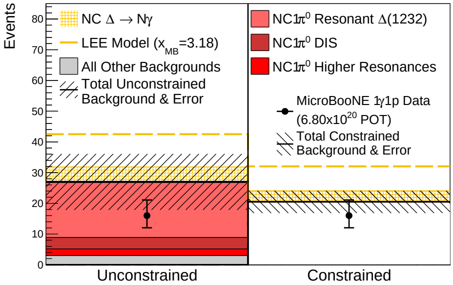
88

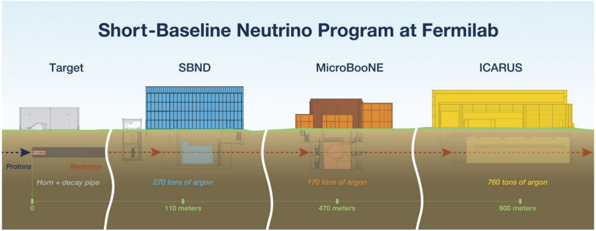
First Results from Short-Baseline Neutrino Program

2110.14054



PRL 2022

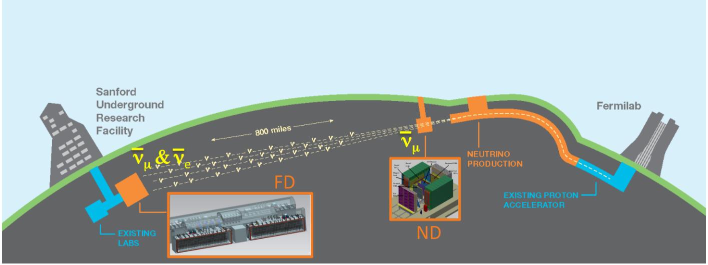


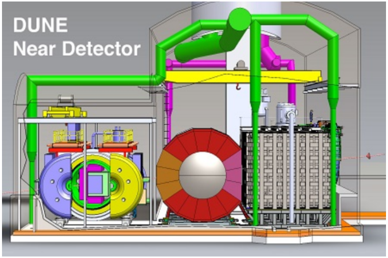


Outline

- MiniBooNE Anomaly
- New Physics Searches at DUNE
- Resonances in $\bar{\nu}_e - e^-$ scattering at FPF
- Neutrino Magnetic Moment and Future Colliders

DUNE

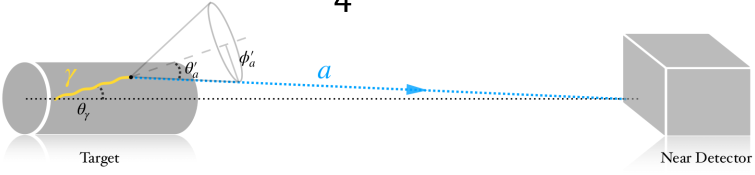




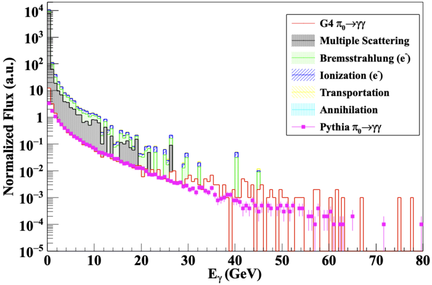
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

BSM at DUNE: Axion-like Particles (ALPs)

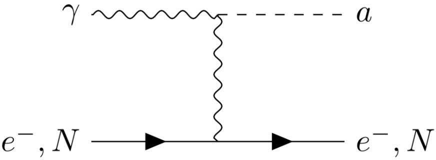
$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



production of photons

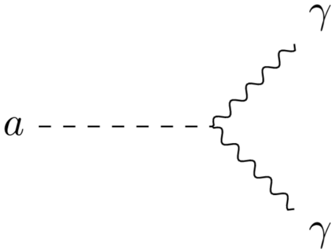


production of ALPs

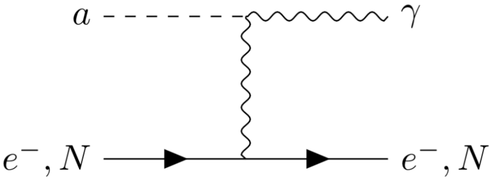


Detection of ALPs

Decay

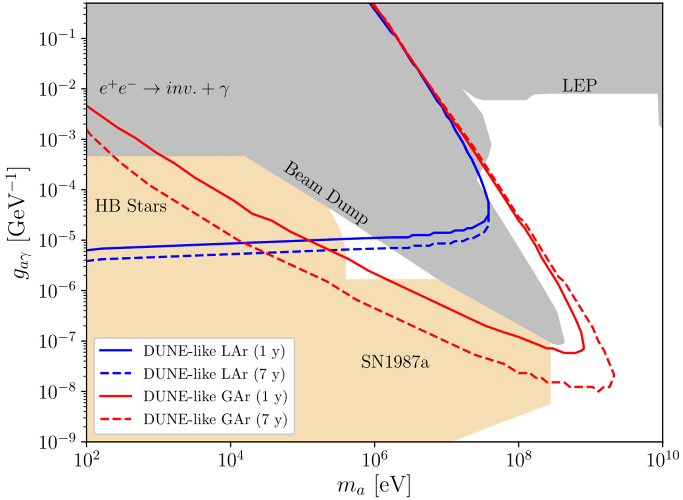


Scattering

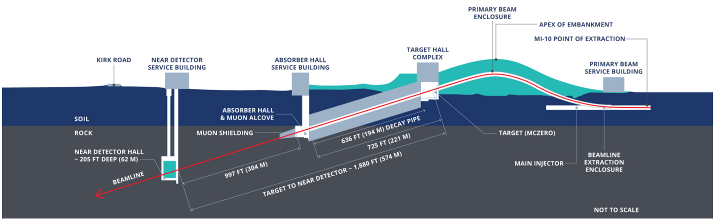


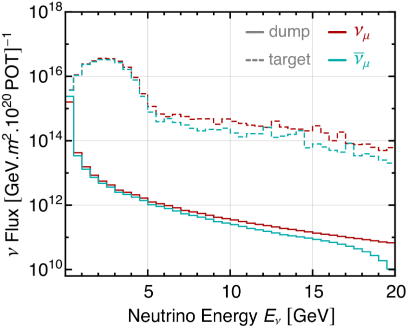
Sensitivity

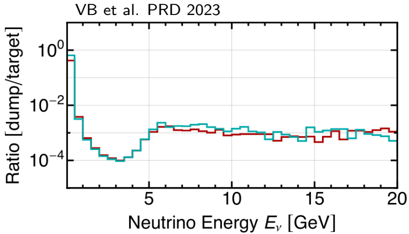
VB et al. PRL 2021



Target-less DUNE

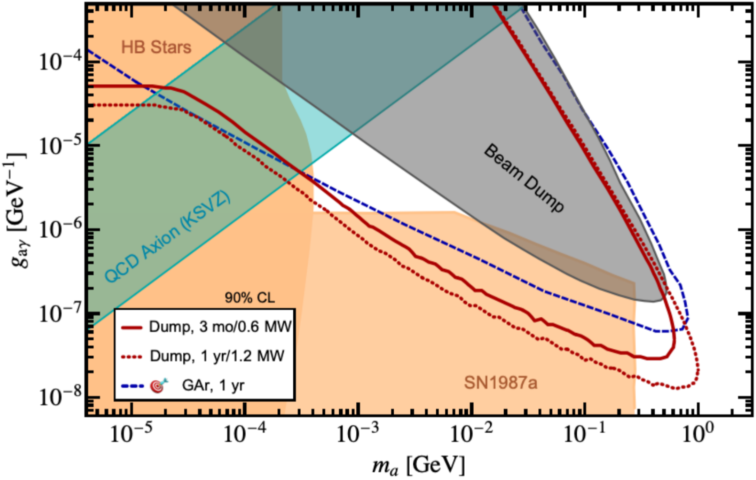






Sensitivity

VB et al. PRD 2023



Further BSM Scenarios

adopted from Jae Yu

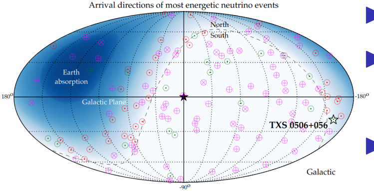
Process	Signatures	Background
ALP	Scattering: γ+e/ γ+N (n) Decay in flight : $\gamma\gamma$	ν coherent, NC w/ π^0, ν_e CC w/ π^0, etc
LDM	$\chi e^- \rightarrow \chi e^-$, $\chi N \rightarrow N'n$	NC w/ $\pi^{0,}$ ν_e CC, QE, RES
mCP	Multiple e^- scatterings	ν_e CC w/ π^0
Dark Photon	$A \rightarrow e^-e^+$, $\mu^-\mu^+$	ν CC + mis-ID π, Accidental overlap of CC
HNL	$N \to \nu e^- e^+$, $\nu\mu^-\mu^+$, $\nu e\mu$, $\nu\pi^0$, $e\pi$, $\mu\pi$	ν CC + mis-ID π, ν_e CC w/ π^0
ν trident	$\nu \rightarrow \nu e^- e^+$, $\nu\mu^-\mu^+$, $\nu e\mu$	$\nu_\mu N \rightarrow \nu_\mu \pi N$□ ($\nu$ CC)
BDM/ iBDM	$\chi N \rightarrow e^- N$	ν coherent, NC w/ π^0, ν_e CC

Outline

- MiniBooNE Anomaly
- New Physics Searches at DUNE
- Resonances in $\bar{\nu}_e - e^-$ scattering at FPF
- Neutrino Magnetic Moment and Future Colliders

First Glashow Resonance Event at IceCube

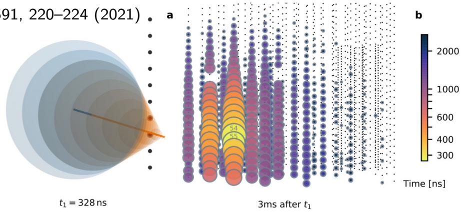
Bull. Am. Astron. Soc. 51, 185 (2019)



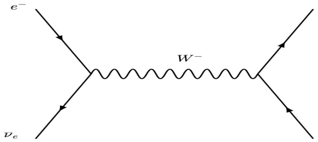
- $\mathcal{O}(100)$ upgoing tracks and HESE events
- Glashow resonance: cross section enhancement from on-shell W^- production
- $\sigma \propto \frac{1}{(E-E_0)^2+\Gamma^2}$, $E_0 = \frac{M_W^2}{2m_e} \approx$ 6.3 PeV

- $\bar{\nu}_e$ in the astrophysical flux $\Longrightarrow$ way to distinguish ν from $\bar{\nu}$
- PeV partially contained events: shower with energy of 6.05 ± 0.72 PeV
- $\mathcal{O}$(PeV) cosmic muon as BKG yields 10^{-7} events $\Longrightarrow$ rejected at 5σ

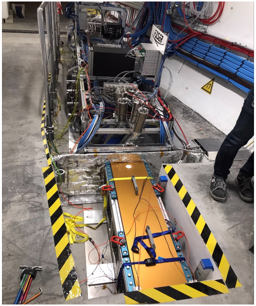
Nature 591, 220–224 (2021)



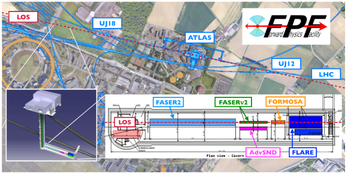
S. Glashow, Phys. Rev. 118, 316



Collider Neutrinos

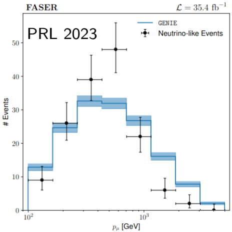


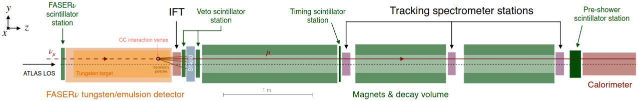
- FASERν is a 1.2 tonne detector located 480 m from the ATLAS interaction point containing emulsion films and tungsten plates



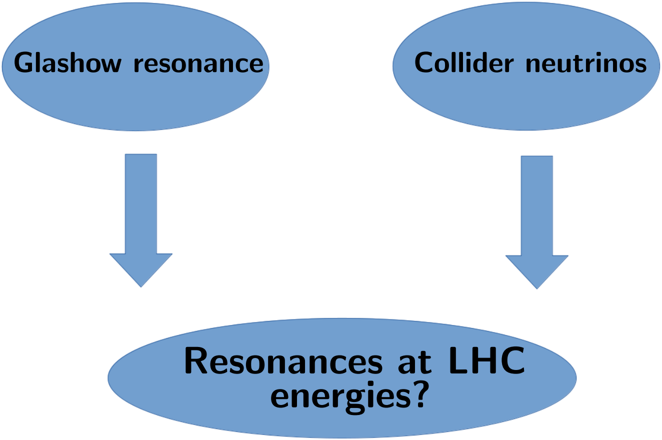
- FASERν2 and FLArE (LAr) at FPF

- 153 ν_μ charged-current interactions at FASER $\implies$ first direct observation of ν interactions at a particle collider experiment





"Glashow-like" Events at Low Energies?



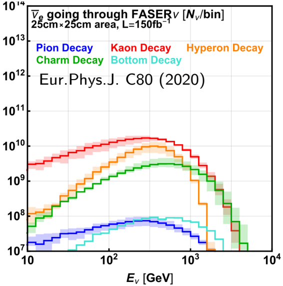
$$\bar{\nu}_e e^- \to R^-$$

- electrically charged
- no baryon number
- no lepton number

→ W^- works but mesons as well!

$$s = 2E_\nu m_e \sim \text{GeV}^2$$

- there are many GeV-scale charged mesons



“Glashow-like” Events at Low Energies?

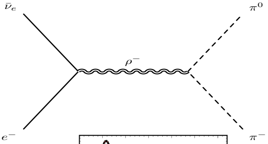
$$\bar{\nu}_e e^- \rightarrow \text{meson} \rightarrow \text{anything}$$

Breit-Wigner: $\sigma_{\rm res} = (2J+1) 8\pi\, \Gamma^2\, \mathrm{Br_{in}}\, \mathrm{Br_{fi}} \dfrac{s/M^2}{(s-M^2)^2 + M^2\Gamma^2}$

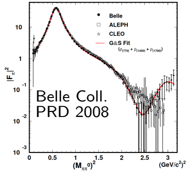
- pseudoscalar mesons: $\Gamma(\mathfrak{m} \to \bar{\nu}_e e^-) = \frac{G_F^2}{8\pi} f^2 m_{lep}^2 M \left(1 - \frac{m_{lep}^2}{M^2}\right) |V_{\rm CKM}|^2$
- vector mesons: $\Gamma(\mathfrak{m} \to \bar{\nu}_e e^-) = \frac{G_F^2}{12\pi} f^2 M^3 |V_{\rm CKM}|^2$

$$\bar{\nu}_e e^- \rightarrow \rho^- \rightarrow \pi^0 \pi^-$$

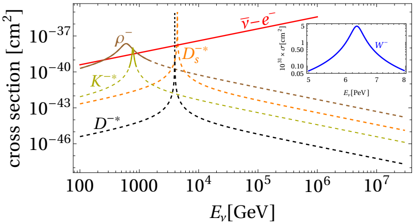
$$E_\nu^{res}(\rho^-) = \frac{(770\text{MeV})^2}{2m_e} \approx 580 \text{ GeV}$$
$$E_\nu^{res}(K^{-*}) \approx 780 \text{ GeV}$$



- alternative calculation using $\langle \pi^-(k_1)\pi^0(k_2)|V_\mu|0\rangle = (k_1 - k_2)_\mu F(q^2)$



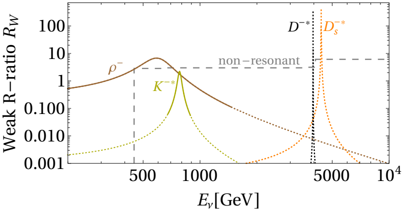
Event Rates

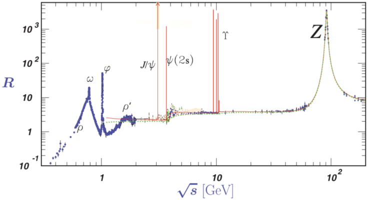


Experiment	ρ^-, $\pm\Gamma/2$	ρ^-, $\pm 2\Gamma$	K^{-*}, $\pm\Gamma/2$	K^{-*}, $\pm 2\Gamma$
FASERν	0.3	0.5	–	–
FASERν2	23	37	0.7	3
FLArE-10	11	19	0.3	2
FLArE-100	63	103	2	8
DeepCore	3 (1)	5 (2)	–	–
IceCube	8 (40)	17 (83)	–	–

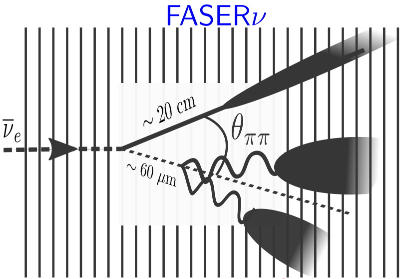
$$R_W = \frac{\sigma(\bar{\nu}_e e^- \to \text{hadrons})}{\sigma(\bar{\nu}_e e^- \to \bar{\nu}_\mu \mu^-)}$$

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$





Signature of ρ^- Resonance



S:B $\approx 1:5000 \Rightarrow$ S:B > 1

- cut on $E_{\pi^-} + E_{\pi^0}$ to lie near 580 GeV
- $\theta_{\nu N} \sim 1/\gamma_{\rm cm} \sim 28\ {\rm mrad} \times \sqrt{600\ {\rm GeV/E_\nu}}$ for deep inelastic scattering
- $\theta_{\pi\pi} = 28\ {\rm mrad}\sqrt{m_e/m_N} \times \sqrt{600\ {\rm GeV/E_\nu}} = 0.7\ {\rm mrad} \times \sqrt{600\ {\rm GeV/E_\nu}}$ for $\bar{\nu} - e$ scattering
- cut on charged track and photon multiplicity
- reconstruct the invariant mass of the $\pi^0\pi^-$ pair, $m^2_{\pi\pi} = m^2_{\pi^0} + m^2_{\pi^-} + E_{\pi^0}E_{\pi^-}\theta^2_{\pi\pi}$, and require it to lie within $\Gamma_\rho \sim 150$ MeV of $m_\rho \approx 770$ MeV

- Sweeper Magnet for FASERν2

IceCube:

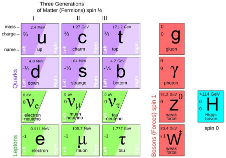
- large background and difficult to identify $\pi^-\pi^0$ topology
- $S:B \approx 1:100$

Outline

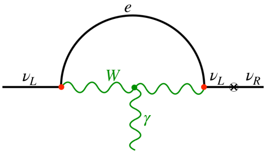
- MiniBooNE Anomaly
- New Physics Searches at DUNE
- Resonances in $\bar{\nu}_e - e^-$ scattering at FPF
- Neutrino Magnetic Moment and Future Colliders

Magnetic Moment for Massive Neutrinos

$$\mathcal{L} \supset \frac{1}{2}\mu_\nu^{\alpha\beta}\,\bar{\nu}_L^\alpha \sigma^{\mu\nu} \nu_R^\beta F_{\mu\nu}$$



- neutrinos are massless in the Standard Model $\Longrightarrow \mu_\nu^{\alpha\beta} = 0$
- adding ν_R to the Standard Model generates Dirac mass $m_\nu \bar{\nu}_L \nu_R$ which generates nonzero μ_ν



$$\mu_\nu^{\text{diag}} = \frac{3eG_F m_\nu}{8\sqrt{2}\pi^2} \approx 3\times 10^{-20}\mu_B \left(\frac{m_\nu}{0.1\,\text{eV}}\right)$$

- for Majorana neutrinos, only non-diagonal elements are nonzero

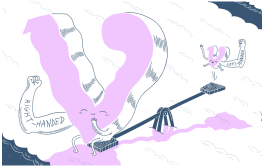
$$\mu_\nu^{ij} = -\frac{3eG_F(m_i+m_j)}{16\sqrt{2}\pi^2}\sum_k \text{Im}\left[U_{ki}^* U_{kj}\right]\frac{m_k^2}{m_W^2} \lesssim 10^{-23}\mu_B \qquad \mu_B = \frac{e}{2m_e}$$

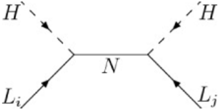
- not testable $\Rightarrow$ more BSM physics required

Sterile Neutrinos

Type-I Seesaw

Minkowski, Mohapatra, Senjanović,
Gell-Mann, Ramond, Slansky, Yanagida





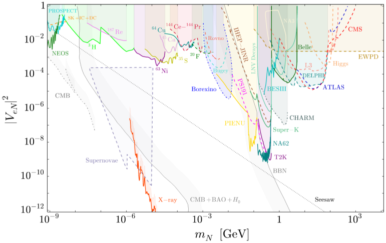
$$\mathcal{M} = \begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix}$$

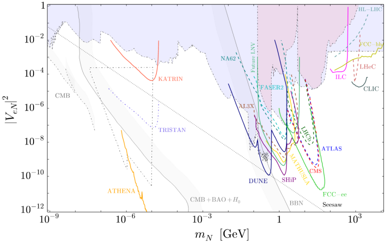
$$m_\nu = -M_D {\color{red}M_R^{-1}} M_D^T$$

$$\theta = M_D / M_R$$

$$\mathcal{L} \supset \frac{1}{2}\overline{N^c} M_R N + \bar{L} Y_\nu \tilde{H} N + \text{h.c.}$$

Bolton et al., JHEP 2020

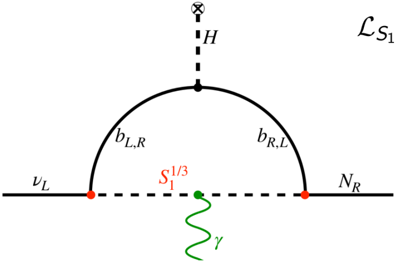




Active-to-Sterile Neutrino Transition Magnetic Moment

$$\mathcal{L} \supset \frac{1}{2}\mu_N \, \bar{\nu}_L^{\alpha} \sigma^{\mu\nu} N_R F_{\mu\nu}$$

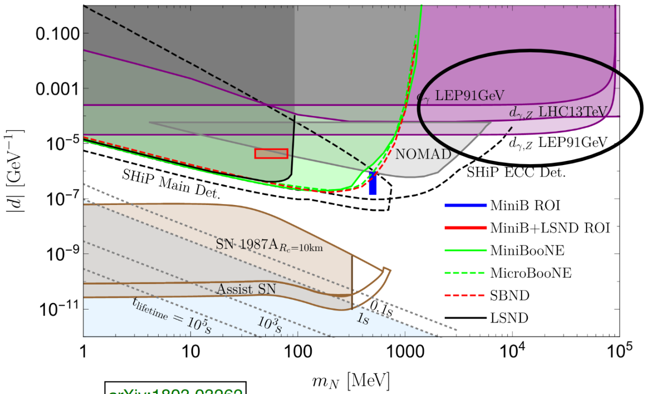
Example for a model generating transition magnetic moment:



$$\mathcal{L}_{S_1} \supset y_1 \, \overline{b_R^{\,c}} N_R \, S_1 + y_2 \, \overline{Q_L^3} L_L^{i\,c} \, S_1^{\dagger} + \text{h.c.}$$

$$\mu_N \approx \frac{e \, y_1 y_2}{8\pi^2 m_{LQ}^2} \, m_b \log \frac{m_b^2}{m_{LQ}^2}$$

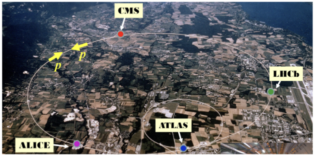
Collider Probes



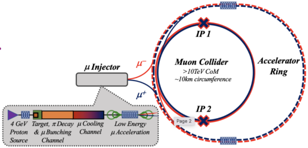
arXiv:1803.03262

Future Colliders

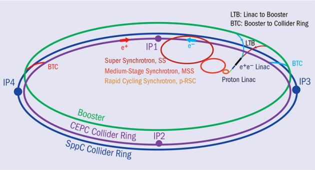
High Lumi LHC
$\sqrt{s} = 14$ TeV,
$\mathcal{L} = 3\ ab^{-1}$
Operational by 2029



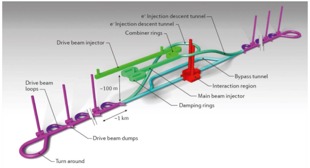
Muon Collider
$\sqrt{s} = 10$ TeV,
$\mathcal{L} = 10\ ab^{-1}$



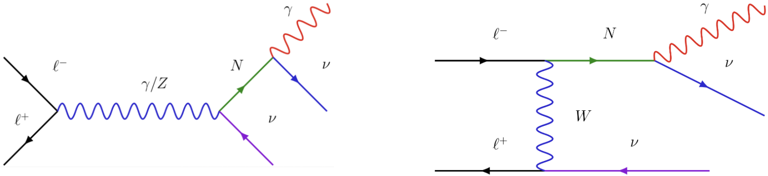
Circular e^-e^+ Collider (CEPC)
$\sqrt{s} = 240$ GeV,
$\mathcal{L} = 20\ ab^{-1}$

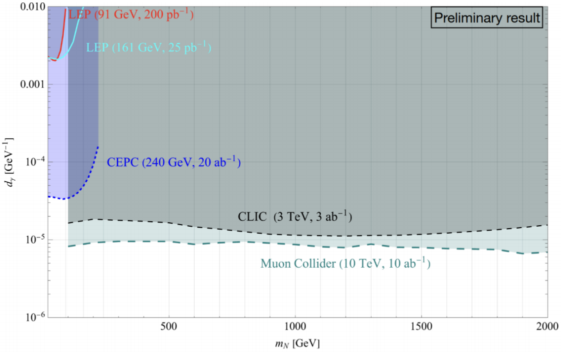


Compact Linear Collider (CLIC)
$\sqrt{s} = 3$ TeV,
$\mathcal{L} = 3\ ab^{-1}$



Collider Probes of Neutrino Transition Magnetic Moment





Summary

- Accelerators and colliders are invaluable for the present success and future progress of ν physics

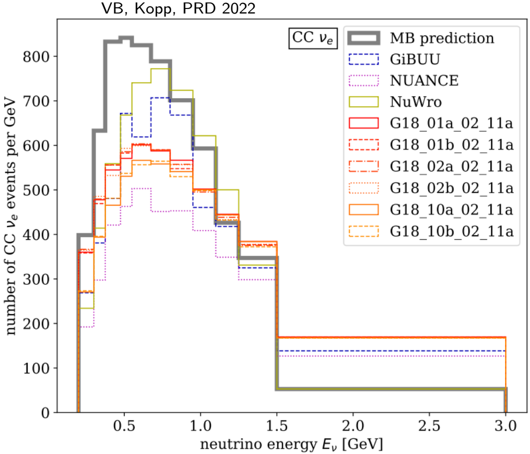
Some examples....

- Exciting prospects for new physics at near-future experiments such as DUNE (e.g., probing ALPs)
- The MiniBooNE anomaly, scrutinized from both the SM and BSM sides, is being tested at the Short-Baseline Neutrino Program at Fermilab
- $\mathcal{O}(100)$ resonance events from $\bar{\nu} - e^-$ scattering are expected at proposed FPF detectors
- For neutrinophilic BSM models (e.g., neutrino magnetic moment), unconstrained regions in the parameter space can be tested at future colliders

BACKUP

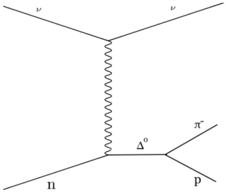
Charged Current Events

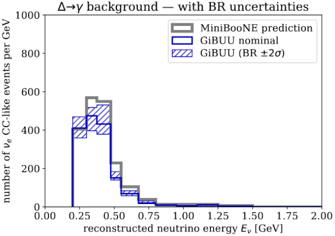
$\nu_e + n \to e^- + p$

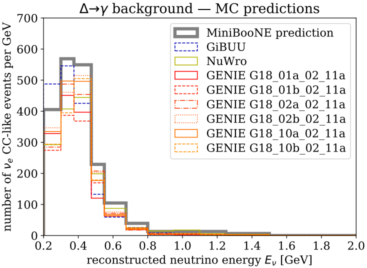


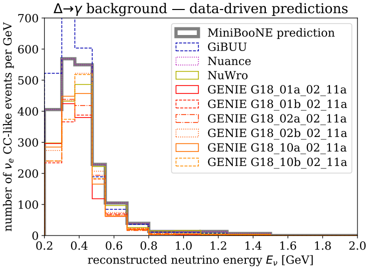
Neutral Current Single γ Production

$\Delta \to N\gamma$

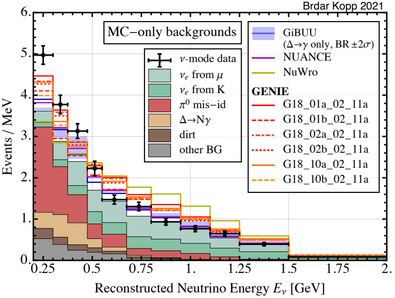








Results: Monte Carlo-only predictions



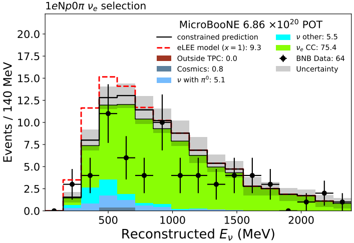
Generator	Tune	Δm^2_{41} [eV^2]	$\sin^2 2\theta_{\mu e}$	Significance
MB official		0.25	0.01	4.0σ
GiBUU	default	0.25	0.01	4.6σ
	$\mathrm{BR}(\Delta \to \gamma) - 2\sigma$	0.32	0.0063	4.9σ
	$\mathrm{BR}(\Delta \to \gamma) + 2\sigma$	0.32	0.0050	4.2σ
NUANCE	–	0.32	0.0079	4.0σ
NuWro	–	3.2	0.0020	3.5σ
GENIE	G18_01a_02_11a	0.13	0.079	4.3σ
	G18_01b_02_11a	0.79	0.0001	3.6σ
	G18_02a_02_11a	0.13	0.050	3.5σ
	G18_02b_02_11a	0.13	0.050	3.5σ
	G18_10a_02_11a	0.25	0.016	2.9σ
	G18_10b_02_11a	0.40	0.013	3.8σ

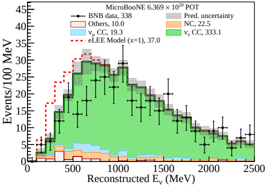
First Results from MicroBooNE

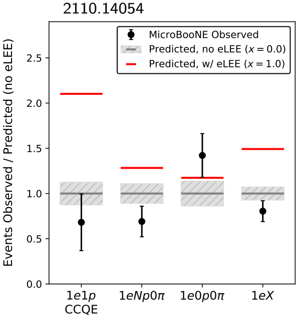
two-body ν_e CCQE scattering (1e1p)

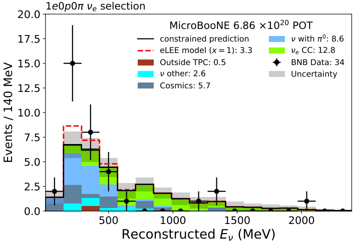
pionless ν_e scattering ($1eNp0\pi$, $1e0p0\pi$)

inclusive ν_e scattering ($1eX$)









First Results from MicroBooNE

arXiv:2110.00409

$1\gamma 1p$

$1\gamma 0p$

	$1\gamma 1p$	$1\gamma 0p$
Unconstr. bkgd.	27.0 ± 8.1	165.4 ± 31.7
Constr. bkgd.	20.5 ± 3.6	145.1 ± 13.8
NC $\Delta \rightarrow N\gamma$	4.88	6.55
LEE ($x_{\rm MB} = 3.18$)	15.5	20.1
Data	16	153

Process	$1\gamma 1p$	$1\gamma 0p$
NC $1\pi^0$ Non-Coherent	24.0	68.1
NC $1\pi^0$ Coherent	0.0	7.6
CC ν_μ $1\pi^0$	0.5	14.0
CC ν_e and $\bar{\nu}_e$	0.4	11.1
BNB Other	2.1	18.1
Dirt (outside TPC)	0.0	36.4
Cosmic Ray Data	0.0	10.0
Total Background (Unconstr.)	27.0	165.4
NC $\Delta \rightarrow N\gamma$	4.88	6.55