# BSM Physics at (Short-Baseline) Neutrino Experiments

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CERN
Neutrino Platform Week

16th March 2023





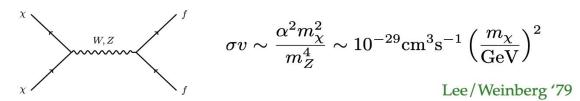
### Why Light Dark Sectors?

#### Light dark sectors are potentially within reach of current experimental programs

#### LDM requires light new forces

slide from G. Krnjaic, 2018

Overproduced without comparably light, neutral "mediators"



Annihilation through renormalizable interactions

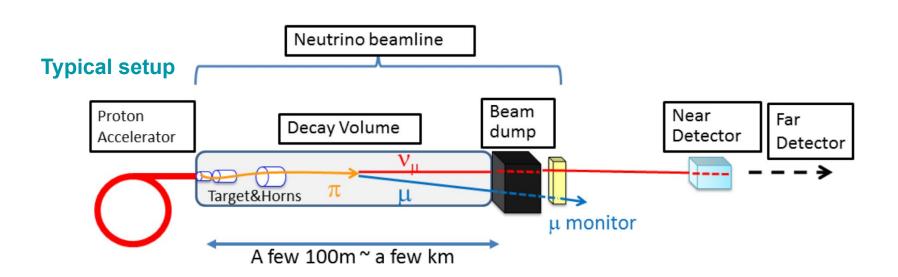
Higher dimension operators have same problem as electroweak mediators

Light mediators are not optional; they're essential

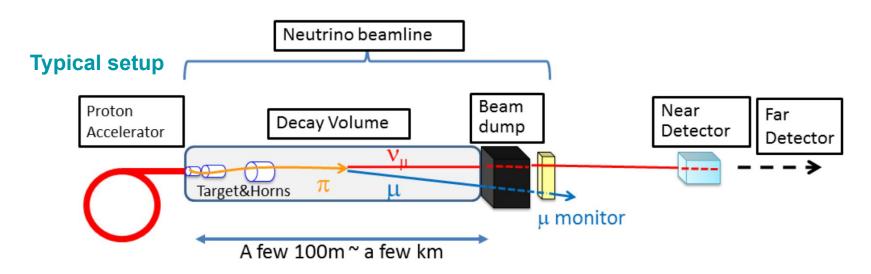
Light mediators from "portal" interactions, e.g. scalar-Higgs mixing, dark photons

### **Neutrino Experiments**

If the dark sector is populated by light fermions and mediators, how can neutrino experiments help us?



### **Neutrino Experiments**

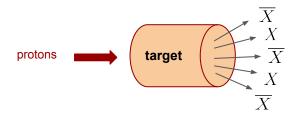


#### Possible search strategies

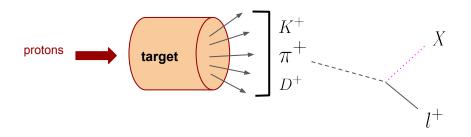
- 1. <u>Direct production of new particles and mediators</u> → THIS TALK
- 2. Indirect effects on e.g. neutrino oscillation

### **Direct Production of New Particles**

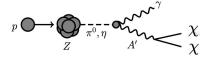
1. Drell-Yan/Bremsstrahlung in the proton target

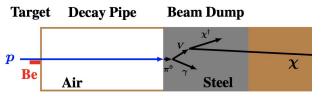


2. Meson decay-in-flight

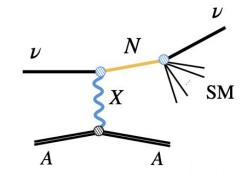


3. Beam dump mode





4. In-detector neutrino scattering



### **Advantages of Neutrino Experiments**

- → High POT (~1e21)
  - → large flux of charged and neutral mesons
  - → Potentially sizeable flux of BSM particles
- → Large detector masses ~ O(1e2) tonnes
  - → Potentially larger interaction cross-sections
- → Good PID (p, μ, e, γ reconstructed) and calorimetry
- → High cosmic rejection
  - → necessary for cosmic neutrino bkg reduction
- Parasitic
  - → shared cost with neutrino projects

See talk by Richard Van de Water, U.S. Cosmic Visions 2017

"Future possibilities at Proton fixed target experiments"

# Message

There is more new physics to be explored at neutrino experiments than

just sterile neutrinos

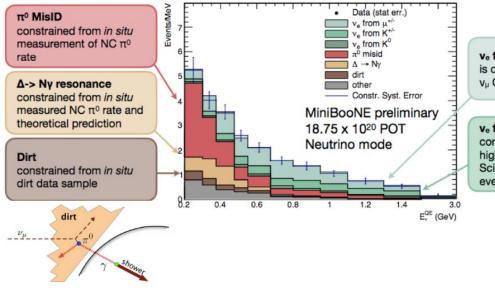


#### MiniBooNE Excess

Among the SBN physics goals is elucidating the origin of the MiniBooNE

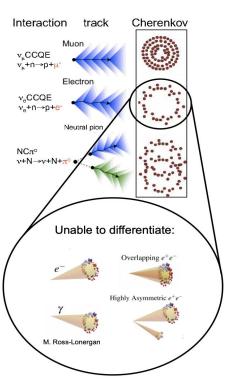
electron/photon-like excess  $\rightarrow$  distinguishing e<sup>-</sup> and  $\gamma$ 

Hourlier, Adrien, MiniBooNE Coll. Neutrino2020



v<sub>e</sub> from μ decay is constrained by *in situ* v<sub>u</sub> CCQE measurement

 $v_e$  from K decay constrained from in situ high energy events + SciBooNE high energy  $v_\mu$  event rate



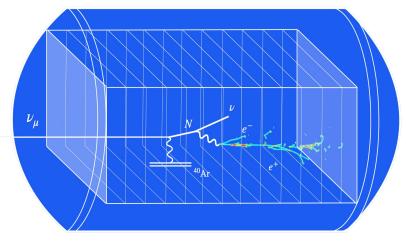
### **LArTPC Detectors**

#### Newer neutrino detectors utilising LArTPC technology

Improved hadronic vertex ID

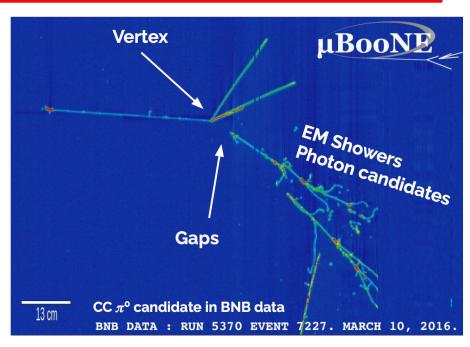
**Better spatial resolution** 

**Improved calorimetry** 



Schematic of MicroBooNE TPC and cryotank (HNL upscattering)

LArTPCs are like a digital bubble chamber allowing for 3D images of the neutrino interaction



Mark Ross-Lonergan, NeuTel 2021

### **LArTPC Detectors**

#### LArTPCs make these final states distinguishable

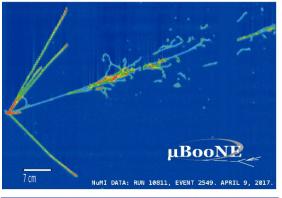
**Spatial resolution** 

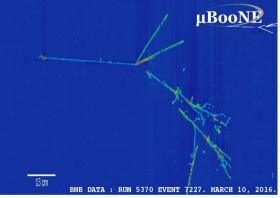
b.

electrons begin to shower at vertex

before pair converting

Similar Different photons travel ~15cm in Argon Wouter Van De Pontseele



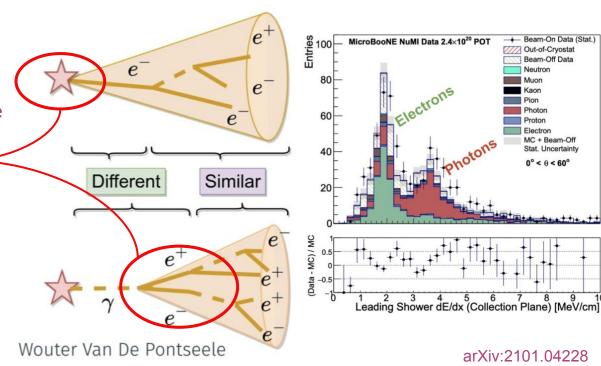


### **LArTPC Detectors**

#### LArTPCs make these final states distinguishable

#### **Calorimetry**

Photons deposit twice the energy per unit length as single electron



Beam-On Data (Stat.)

Out-of-Cryostat

Beam-Off Data Neutron Muon

Photon Proton

Electron MC + Beam-Off Stat. Uncertainty

0° < 0 < 60°

# QUESTIONS

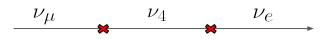
How can we utilise these detectors to search for new physics?

MicroBooNE already searching for SM and BSM LEE explanations and could be sensitive to BSM models that predict photon (and electron)-like final states



talk from Matheus Hostert, Community Summer Study Snowmass 2022

#### Sterile neutrino models

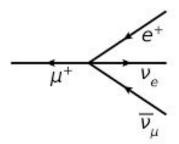


oscillation to light eV-scale sterile

C .	Maria	C: .	Anomalies					
Category	Model	Signature	LSND	MiniBooNE	Reactors	Sources	References	
	(3+1) oscillations	oscillations	1	1	1	1	Reviews and	
	(0   1) 000		-		-		global fits [93,	
							103, 105, 106]	
Flavor transitions	(3+1) w/ invisible	oscillations w/ $ u_4$	/	1	/	/	[151, 155]	
Secs. 3.1.1-3.1.3,	sterile decay	invisible decay			200		1	
3.1.5	(3+1) w/ sterile decay	$ u_4  o \phi \nu_e $	1	/	1	1	77 77 77	
							[159-162, 270]	
	(3+1) w/ anomalous	$ u_{\mu}  ightarrow  u_{e}$ via	/	/	X	X	[143, 147,	
	matter effects	matter effects					271-273]	
Matter effects	(3+1) w/ quasi-sterile	$\nu_{\mu} \rightarrow \nu_{e} \; \mathbf{w} /$	/	1	1	1	[148]	
Secs. 3.1.4, 3.1.7	neutrinos	resonant $ u_s$						
		matter effects						
	Lepton-flavor-violating	$\mu^+ \to e^+ \nu_\alpha \overline{\nu_e}$	1	X	Х	Х	[174, 175, 274]	
	$\mu$ decays							
Flavor violation	neutrino-flavor-	$\nu_{\mu}A \to e\phi A$	1	1	X	X	[275]	
Sec. 3.1.6	changing							
	bremsstrahlung							
	Transition magnetic	$N \to \nu \gamma$	×	1	X	X	[207]	
Decays in flight	mom., heavy $ u$ decay							
Sec. 3.2.3	Dark sector heavy	$N \to \nu(X \to$	X	1	X	X	[208]	
	neutrino decay	$e^+e^-)$ or						
		$N \to \nu(X \to \gamma\gamma)$						
Neutrino	neutrino-induced	$\nu A \to NA$ ,	1	1	X	X	[205, 206,	
Scattering	upscattering	$N  ightarrow  u e^+ e^-$ or					209216]	
Secs. 3.2.1, 3.2.2		$N \rightarrow \nu \gamma \gamma$		,	V		[40 105 107	
5003. 5.2.1, 5.2.2	neutrino dipole	$ \nu A \to NA, \\ N \to \nu \gamma $	V	~	X	×	[40, 185, 187, 188, 190, 193,	
	upscattering	$IV \rightarrow \nu\gamma$					233, 276	
	deals weakful a finds and		· ·		V		-	
Dark Matter	dark particle-induced	$\gamma$ or $e^+e^-$	X	1	X	×	[217]	
Scattering	upscattering dark particle-induced	2/		/	X	X	[217]	
Sec. 3.2.4	inverse Primakoff	γ	V	~	^	^	[211]	
	mverse Filmakoli							

talk from Matheus Hostert, Community Summer Study Snowmass 2022

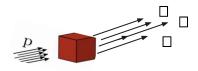
### Flavour violation models



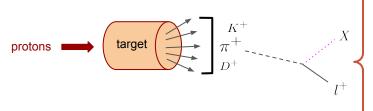
Another source of electrons is from models in which flavour is violated

				Anomali	es		
Category	Model	Signature	LSND	MiniBooNE	Reactors	Sources	References
	(3+1) oscillations	oscillations				1	Reviews and
	(O   I) OSCINACIONS	OSCIII del Olis	•				global fits [93,
							103, 105, 106]
Flavor transitions	(3+1) w/invisible	oscillations w/ $\nu_4$		/	1		[151, 155]
Secs. 3.1.1-3.1.3,	sterile decay	invisible decay	•				[131,133]
3.1.5	(3+1) w/ sterile decay	$ u_4 \rightarrow \phi \nu_e $		/	/	/	
	(5   1) W/ Sterile decay	ν4 / ψνε	•				[159-162, 270]
	(3+1) w/ anomalous	$ u_{\mu} \rightarrow \nu_{e} \text{ via} $		/	X	X	[143, 147,
	matter effects	$\nu_{\mu} \rightarrow \nu_{e}$ via matter effects	•	•			271-273]
Matter effects	(3+1) w/ quasi-sterile	$\nu_{\mu} \rightarrow \nu_{e} \text{ w/}$		/	/	/	[148]
Secs. 3.1.4, 3.1.7	neutrinos	resonant $\nu_s$					[140]
	Heutillos	matter effects					
	Lepton-flavor-violating	$\mu^+ \to e^+ \nu_{\alpha} \overline{\nu_e}$	/	X	X	X	[174,175,274
	, ,	$\mu^+ \rightarrow e^+ \nu_{\alpha} \nu_e$	•	^	^	^	[174,175,274
Flavor violation	$\mu$ decays neutrino-flavor-			/	X	X	[275]
Sec. 3.1.6	changing	$ u_{\mu}A \to e\phi A$	•	•	^	^	[275]
Sec. 5.1.0	bremsstrahlung						
		3.7	.,			.,	food
D : (I: L:	Transition magnetic	$N  o  u \gamma$	X	1	X	X	[207]
Decays in flight	mom., heavy $\nu$ decay	37 . (37					[000]
Sec. 3.2.3	Dark sector heavy	$N \to \nu(X \to -)$	X	-	X	X	[208]
	neutrino decay	$e^+e^-)$ or					
		$N \to \nu(X \to \gamma\gamma)$					
Neutrino	neutrino-induced	$\nu A \to NA$ ,	1	1	X	X	[205, 206,
Scattering	upscattering	$N  ightarrow  u e^+ e^-$ or					209216]
Secs. [3.2.1] [3.2.2]		$N \rightarrow \nu \gamma \gamma$			.,	.,	[40 405 407
Secs. S.Z.1, S.Z.Z	neutrino dipole	$\nu A \to NA$ ,	1	1	X	X	[40, 185, 187
	upscattering	$N \to \nu \gamma$					188, 190, 193,
							233, 276]
Dark Matter	dark particle-induced	$\gamma$ or $e^+e^-$	X	1	X	X	[217]
Scattering	upscattering						
Sec. 3.2.4	dark particle-induced	$\gamma$	1	1	X	X	[217]
JCC. J.Z.4	inverse Primakoff						

#### New particle production



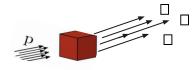
#### e.g. meson decay-in-flight



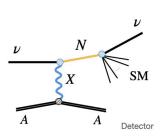
Catagory	Model	Signature		Anomali	es	References	
Category		Signature	LSND	MiniBooNE	Reactors	Sources	References
	(3+1) oscillations	oscillations	<b>√</b>	/	1	1	Reviews and global fits [93]
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3.1.5	(3+1) w/ sterile decay	$\nu_4 \to \phi \nu_e$	1	/	/	1	[159-162, 27
	(3+1) w/ anomalous matter effects	$ u_{\mu}  ightarrow  u_{e}$ via matter effects	<b>√</b>	<b>V</b>	X	X	[143, 147, 271-273]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ quasi-sterile neutrinos	$ u_{\mu}  ightarrow  u_{e}  ext{ w/} $ resonant $ u_{s}$ matter effects	<b>√</b>	/	√	X X X X X	[148]
	Lepton-flavor-violating $\mu$ decays	$\mu^+ \to e^+ \nu_\alpha \overline{\nu_e}$	<b>√</b>	×	X	X	[174, 175, 27
Flavor violation Sec. 3.1.6	$\begin{array}{ccc} \mu \text{ decays} & & \\ \text{neutrino-flavor-} & & \nu_{\mu}A \rightarrow e\alpha \\ \text{changing} & & \\ \text{bremsstrahlung} & & \end{array}$	$\nu_{\mu}A \to e\phi A$	<b>√</b>	/	X	X	[275]
Decays in flight	Transition magnetic mom., heavy $\nu$ decay	$N  o  u \gamma$	X	1	×	×	[207]
Sec. 3.2.3	Dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-) \text{ or } \\ N \to \nu(X \to \gamma\gamma)$	X	1	×	×	[208]
Neutrino Scattering	neutrino-induced upscattering	$ uA  o NA, \\ N  o  u e^+ e^-  ext{ or } \\ N  o  u\gamma\gamma $	✓	/	×		[205, 206, 209216]
Secs. 3.2.1, 3.2.2	neutrino dipole upscattering	$ \begin{array}{c} \nu A \to NA, \\ N \to \nu \gamma \end{array} $	/	1	×	×	[40, 185, 18 188, 190, 19 233, 276]
Dark Matter	dark particle-induced upscattering	$\gamma$ or $e^+e^-$	X	1	X		[217]
Scattering Sec. 3.2.4	dark particle-induced inverse Primakoff	γ	1	1	X	X	[217]

talk from Matheus Hostert, Community Summer Study Snowmass 2022

#### New particle production



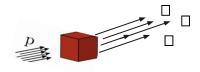
e.g. neutrino scattering



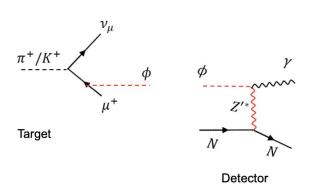
		C.	Anomalies				D (
Category	Model	Signature	LSND	MiniBooNE	Reactors	Sources	References
FI	(3+1) oscillations	oscillations	<b>√</b>	1	1	1	Reviews and global fits [93, 103, 105, 106]
Flavor transitions Secs. 3.1.1-3.1.3,	(3+1) w/ invisible sterile decay	oscillations w/ $\nu_4$ invisible decay	/	1	/	1	[151, 155]
3.1.5	(3+1) w/ sterile decay	$\nu_4 \to \phi \nu_e$	1	1	1	1	[159-162, 270]
	(3+1) w/ anomalous matter effects	$ u_{\mu}  ightarrow  u_{e}$ via matter effects	<b>√</b>	1	X	×	[143, 147, 271-273]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ quasi-sterile neutrinos	$ u_{\mu}  ightarrow  u_{e}  ext{ w}/ $ resonant $ u_{s}$ matter effects	/	/	X X X X X X X X X X X X X X X X X X X	1	[148]
	Lepton-flavor-violating $\mu$ decays	$\mu^+ \to e^+ \nu_\alpha \overline{\nu_e}$	<b>√</b>	×	X	X	[174,175,274]
Flavor violation Sec. 3.1.6	neutrino-flavor- changing bremsstrahlung	$\nu_{\mu}A \to e\phi A$	/	/	X	X	[275]
Decays in flight	Transition magnetic mom., heavy $\nu$ decay	$N  o  u \gamma$	X	1	X	X	[207]
Sec. 3.2.3	Dark sector heavy neutrino decay	$\begin{array}{c} N \rightarrow \nu(X \rightarrow \\ e^+e^-) \text{ or } \\ N \rightarrow \nu(X \rightarrow \gamma\gamma) \end{array}$	X	1	×	×	[208]
Neutrino Scattering	neutrino-induced upscattering	$ uA  o NA, \\ N  o  u e^+ e^-  ext{ or } \\ N  o  u\gamma\gamma $	/	1	X	×	[205, 206, 209–216]
Secs. 3.2.1, 3.2.2	neutrino dipole upscattering	$ \begin{array}{c} \nu A \to NA, \\ N \to \nu \gamma \end{array} $	<b>✓</b>	1	×	×	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter	dark particle-induced upscattering	$\gamma$ or $e^+e^-$	Х	/	X		[217]
Scattering Sec. 3.2.4	dark particle-induced inverse Primakoff	γ	/	/	×	×	[217]

talk from Matheus Hostert, Community Summer Study Snowmass 2022

#### New particle production



#### e.g. dark particle scattering



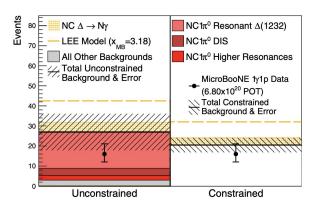
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3.1.5	(3+1) w/ sterile decay	$\nu_4  o \phi \nu_e$	1	1	1		[159-162, 270]
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Flavor violation Sec. 3.1.6	Lepton-flavor-violating $\mu$ decays	$\mu^+ \to e^+ \nu_\alpha \overline{\nu_e}$	<b>√</b>	X	X	X	[174,175,274]
	neutrino-flavor- changing bremsstrahlung	$\nu_{\mu}A \to e\phi A$	<b>√</b>	/	X	×	[275]
Decays in flight	Transition magnetic mom., heavy $\nu$ decay	$N  o  u \gamma$	X	1	X	X	[207]
Sec. 3.2.3	Dark sector heavy neutrino decay	$N  o  u(X  o e^+e^-) \text{ or } N  o  u(X  o \gamma \gamma)$	×	<b>/</b>	×	×	[208]
Neutrino Scattering	neutrino-induced upscattering	$ uA  o NA, \\ N  o  u e^+ e^- \text{ or } \\ N  o  u\gamma\gamma $	1	/	X	×	[205, 206, 209-216]
Secs. 3.2.1 3.2.2	neutrino dipole upscattering	$ \begin{array}{c} \nu A \to NA, \\ N \to \nu \gamma \end{array} $	<b>√</b>	1	×	×	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter	dark particle-induced upscattering	$\gamma$ or $e^+e^-$	×	1	×	×	[217]
Scattering Sec. 3.2.4	dark particle-induced inverse Primakoff	γ	1	1	X	X	[217]



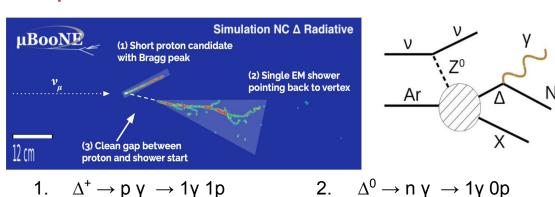
### MicroBooNE Single γ Searches

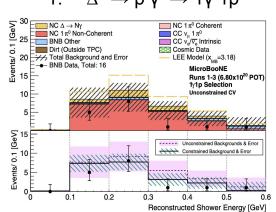
#### Search for photon-like LEE has already been performed

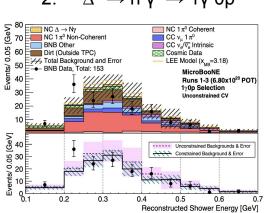
**SM NC**  $\Delta \rightarrow$  **Ny** (PRL 128, 111801 2022)



With no excess observed compatible with MiniBooNE!







# QUESTIONS

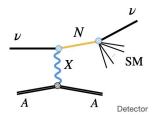
Why do we care about

NC ∆-radiative decays?



### **Neutrino Upscattering**

### Neutrino Scattering detector



Attractive BSM search avenue is through neutrino scattering signatures

Category	Model	Signature	Anomalies				References
Category	Signature	Signature	LSND	MiniBooNE	Reactors	Sources	References
	(3+1) oscillations	oscillations	1	/	/	/	Reviews and
	(-,-)						global fits [93,
							103, 105, 106]
Flavor transitions	(3+1) w/ invisible	oscillations w/ $ u_4$		/	/		[151, 155]
Secs. 3.1.1-3.1.3,	sterile decay	invisible decay					[101, 100]
3.1.5	(3+1) w/ sterile decay	$\nu_4 \rightarrow \phi \nu_e$		/	/	1	
	(0   1) W/ Sterne decay	7 4 7 4 6					[159-162, 270]
	(2 + 1) /				X	V	
	(3+1) w/ anomalous matter effects	$ u_{\mu}  ightarrow  u_{e}$ via matter effects		1	^	X	[143, 147, 271-273]
Matter effects				,			
Secs. 3.1.4, 3.1.7	(3+1) w/ quasi-sterile	$\nu_{\mu} \rightarrow \nu_{e} \text{ w}/$	1	/	1	1	[148]
Jecs. J.I.T, J.I.1	neutrinos	resonant $\nu_s$					
		matter effects					
	Lepton-flavor-violating	$\mu^+ \to e^+ \nu_\alpha \overline{\nu_e}$	1	×	X	Х	[174, 175, 274]
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Sec. 3.1.6	changing						
	bremsstrahlung						
	Transition magnetic	$N  o \nu \gamma$	X	/	X	X	[207]
Decays in flight	mom., heavy $\nu$ decay						
Sec. 3.2.3	Dark sector heavy	$N \to \nu(X \to$	X	1	Х	Х	[208]
	neutrino decay	$e^+e^-)$ or					
		$N \to \nu(X \to \gamma \gamma)$					
	neutrino-induced	$\nu A \rightarrow NA$ ,	1	1	Х	Х	[205, 206,
Neutrino	upscattering	$N  ightarrow  u e^+ e^-$ or			1.2		209216]
Scattering	, ,	$N  o  u \gamma \gamma$					
Secs. 3.2.1, 3.2.2	neutrino dipole	$\nu A \rightarrow NA$ ,	/	/	X	X	[40, 185, 187,
	upscattering	$N  o  u \gamma$		1000			188, 190, 193,
		,					233, 276]
5	dark particle-induced	$\gamma$ or $e^+e^-$	Х	/	Х	Х	[217]
Dark Matter	upscattering						1
Scattering	dark particle-induced	γ	/	/	Х	Х	[217]
Sec. 3.2.4	inverse Primakoff	1					-

### MicroBooNE Search for e<sup>+</sup>e<sup>-</sup> LEE (plug... sorry)

### Our group is currently working on performing a *dedicated search* for an e<sup>+</sup>e<sup>-</sup> LEE at MicroBooNE



Jaime Hoefken Zink Uni. of Bologna



Matheus Hostert Perimeter & UMN



Georgia Karagiorgi Columbia Uni



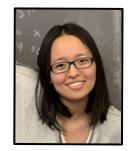
Daniele Massaro Uni. of Bologna



Silvia Pascoli Uni. of Bologna



Mark Ross-Lonergan LANL



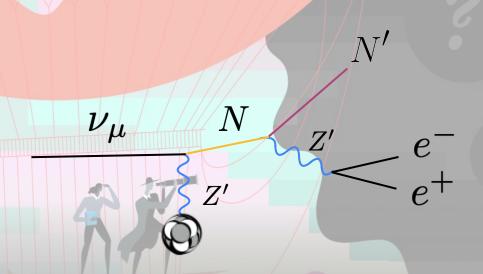
Guanqun Ge Columbia Uni.

**COMING SOON!** 

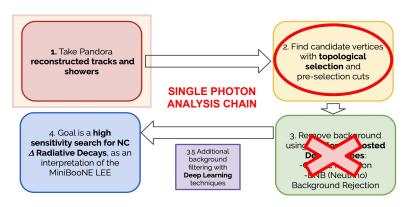
(This Autumn?... Maybe)

## **CASE-STUDY:**

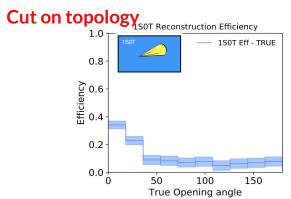
# Light Dark Photon Model with HNL



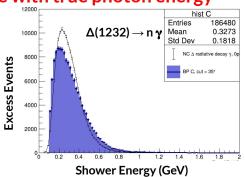
### 1γ Op (Pseudo-) Analysis in One slide



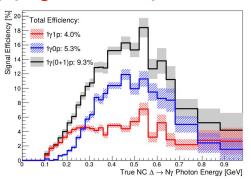
Estimate selection efficiency using prior studies  $e^+e^-$  reconstruction and comparisons with NC  $\Delta$ -decays







#### **Apply signal efficiency**

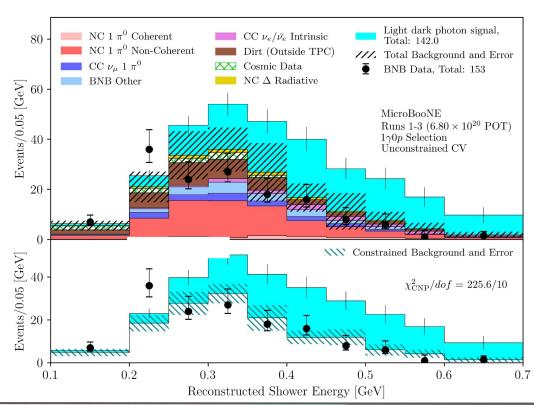


### Case-Study: Light Dark Photon + HNLs

#### 142 predicted signal events (on top of 153 total events)

#### **Benchmark**

 $m_i = 150 \text{ MeV}, m_j = 107$ MeV,  $m_{7'} = 30 \text{ MeV}$ 



### Main Takeaways

Neutrino experiments are an excellent place to search for new physics

→ large flux of charged and neutral mesons

Searches for SM and BSM LEE interpretations sensitive to photon-like BSM signatures

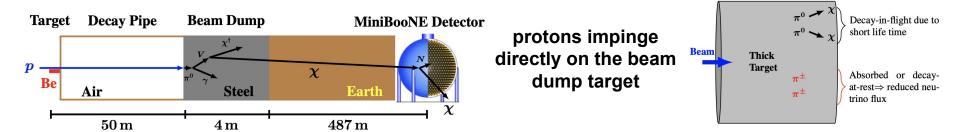
First constraints using the **gLEE** ∆-radiative decay search can *already* provide limits





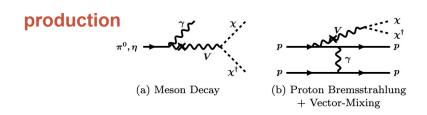
### **Fixed Targets for Dark Matter**

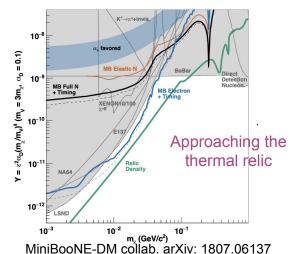
Neutrino experiments can act as DM detector by running in beam dump mode



charged pions absorbed or DAR  $\rightarrow$  neutrino flux suppressed

MiniBooNE experiment performed search with beam dump strongly constraining MeV vector-portal LDM

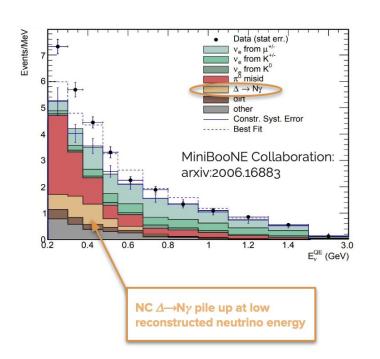




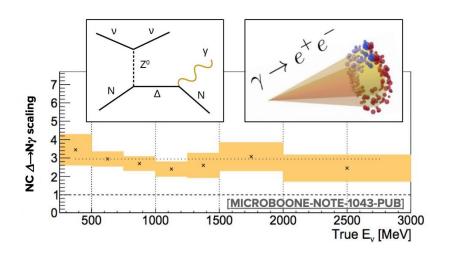
### NC Δ-radiative decays: context

Mark Ross-Lonergan, NeuTel 2021

The shape of the  $\Delta$ -radiative decay events agree extremely well with MiniBooNE excess



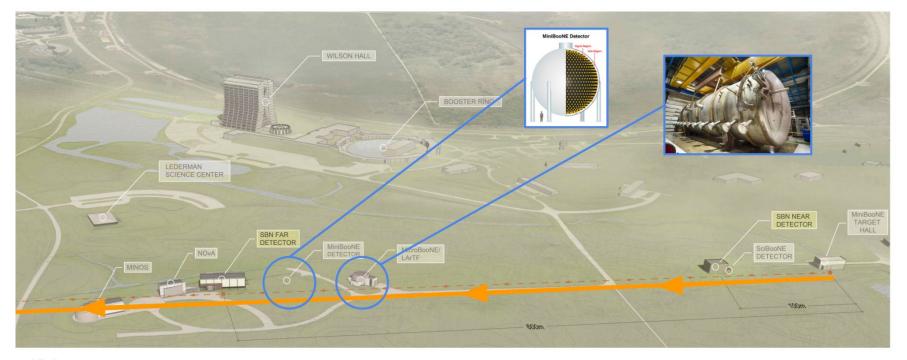
A ~3x flat scaling to NC  $\triangle \rightarrow N\gamma$  can explain the observed MiniBooNE excess. Use this as a  $\gamma$ LEE signal template for  $\mu$ BooNE



### Fermilab SBN Program

Three LArTPC detectors on the Booster Neutrino Beamline (BNB)

→ SBND (near detector), MicroBooNE, Icarus (far detector)



arXiv/1503.01520

### **DarkNews**

#### Signal events generated by DarkNews

(A. Abdullahi, J. Hoefken, M. Hostert, D. Massaro, S. Pascoli)

**DarkNews** is a light-weight Python generator for neutrino-nucleus upscattering to heavy neutrinos.

- Supports up to 3 (Dirac or Majorana) HNLs
- Scalar, vector, or transition magnetic moment contributions.
- Event output weighted (fast) or unweighted (slower).
- Pandas or numpy, as well as HepEvt, HepMC2 and 3.
- Simple detector geometry for MiniBooNE and MicroBooNE.
- Several neutrino fluxes implemented.

#### **Public and documented!**

Paper: <a href="mailto:arxiv.org/abs/2207.04137">arxiv.org/abs/2207.04137</a>

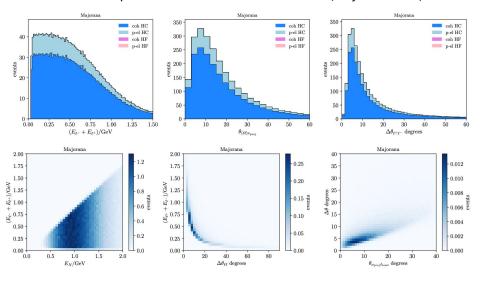
GitHub: github.com/mhostert/DarkNews-generator

PyPI: <a href="mailto:pypi.org/project/DarkNews/">pypi.org/project/DarkNews/</a>



pip install DarkNews

#### Example of e<sup>+</sup>e<sup>-</sup> kinematics at MiniBooNE (Majorana HNL)



### Single Photon pseudo-selection

2. Find candidate vertices with **topological selection** and pre-selection cuts

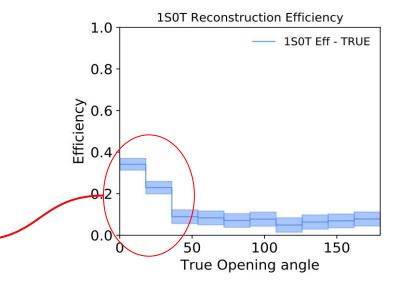
#### **Topological selection**

1γ Op selection requires exactly one shower to be reconstructed alongside the neutrino vertex

...recall that for

1S0T

Efficiency highest to reconstruct a single shower for e<sup>+</sup>e<sup>-</sup> separation angle < 35 deg.



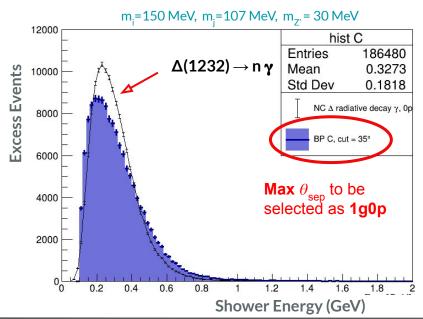
### Single Photon pseudo-selection

2. Find candidate vertices with **topological selection** and pre-selection cuts

#### **Pre-selection cuts**

- 1. Reconstructed shower energy
- 2. Shower start position from SCE

Taking light dark photon model as an example, energy distribution of the  $e^+e^-$  approaches that of NC  $\Delta$  photon for > 20°



### Single Photon pseudo-selection

2. Find candidate vertices with **topological selection** and pre-selection cuts

#### **Pre-selection cuts**

1. Reconstructed shower energy → Apply signal efficiency

Note: 5.3% is doubled to 10.6% as generated events 2.Find candidate contain only Op events vertices with topological selection Signal Efficiency [% Total Efficiency: <del>||||</del> 1γ1 p: 4.0% 1γ(0+1)p: 9.3% 170p is more difficult, but provides a secondary dataset for comparison and verification **54.7%** of true 1γ events 9% reconstruction efficiency with 0 track and 1 shower requirement and 0.2 0.3 pre-selection cuts True NC  $\Delta \rightarrow Ny$  Photon Energy [GeV]