Searching for anomalous photon and dark-sector e+e- pairs in the MicroBooNE detector

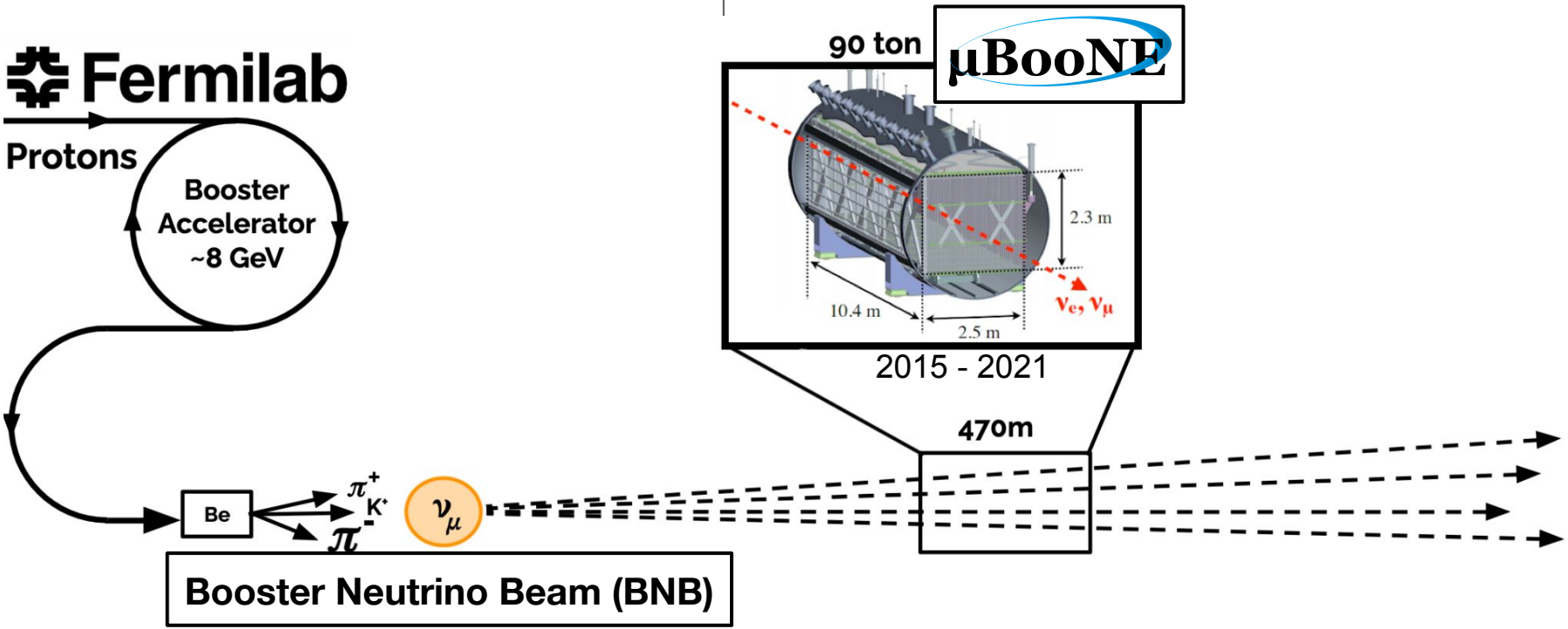
Erin Yandel
On behalf of the MicroBooNE Collaboration

NuFact 2024
September 16, 2024

MicroBooNE

Surface-level Liquid Argon time Projection Chamber (LArTPC) neutrino experiment

Amassed ~0.5M neutrino events - the largest sample of neutrino interactions on argon in the world



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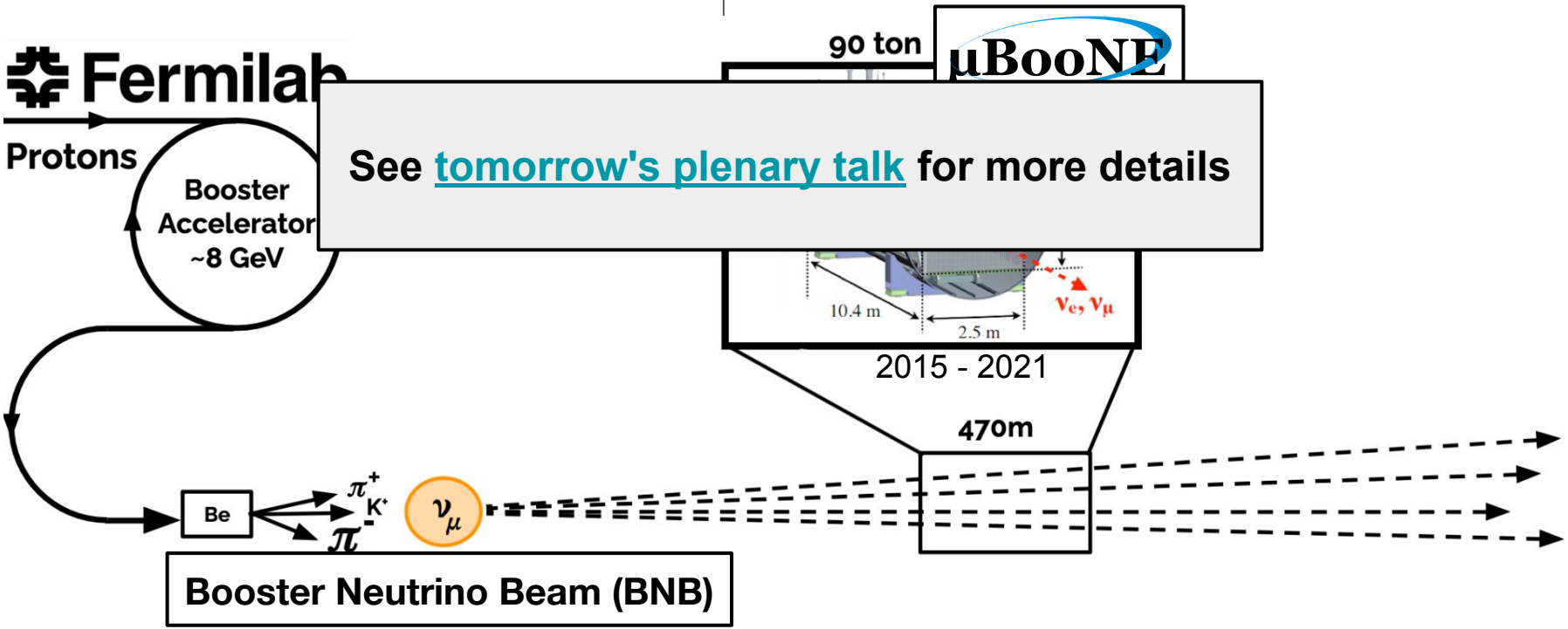
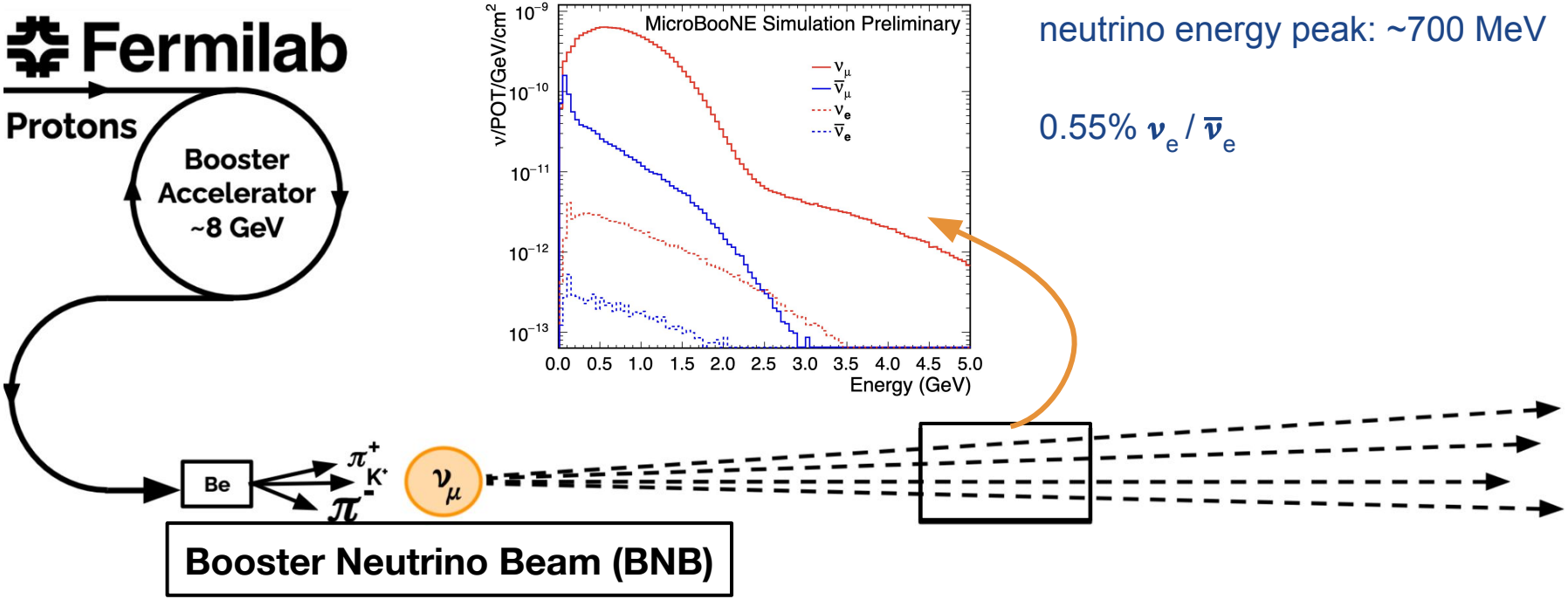


See tomorrow's plenary talk for more details

MicroBooNE on the BNB

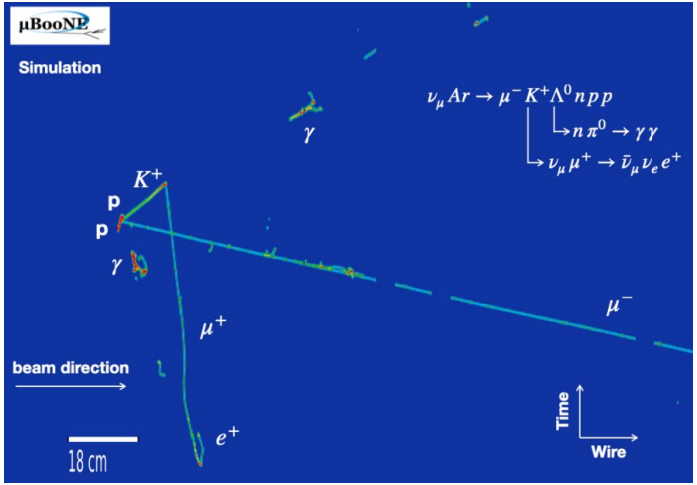


neutrino energy peak: ~700 MeV

0.55% ν_e / $\bar{\nu}_e$

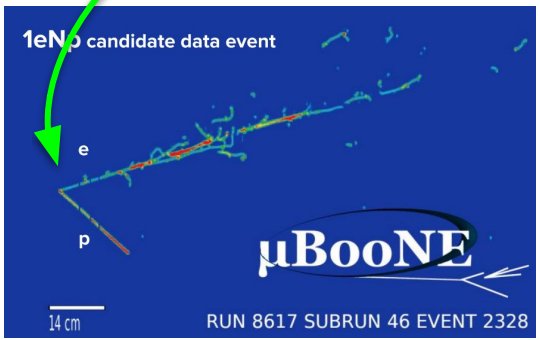
LArTPC

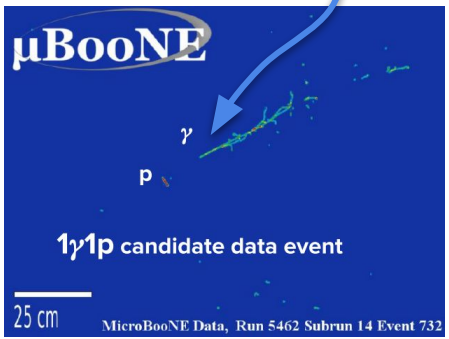
Very effective at **particle identification**
- can see and distinguish complicated topologies



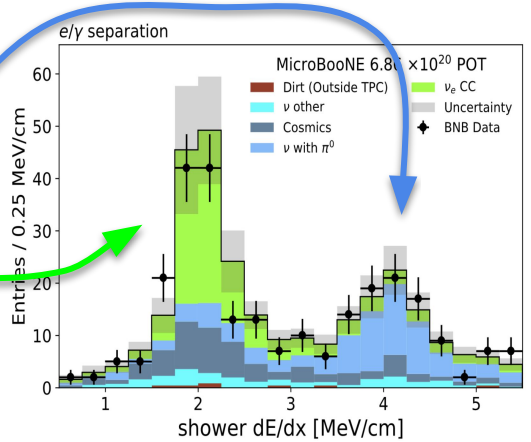
Excellent **electron** / **photon** **separation**

Millimeter spatial resolution (gap)



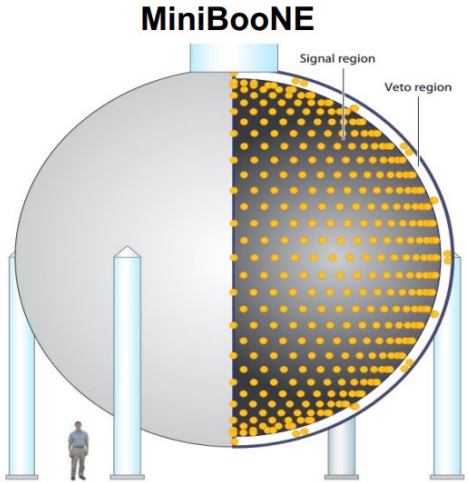


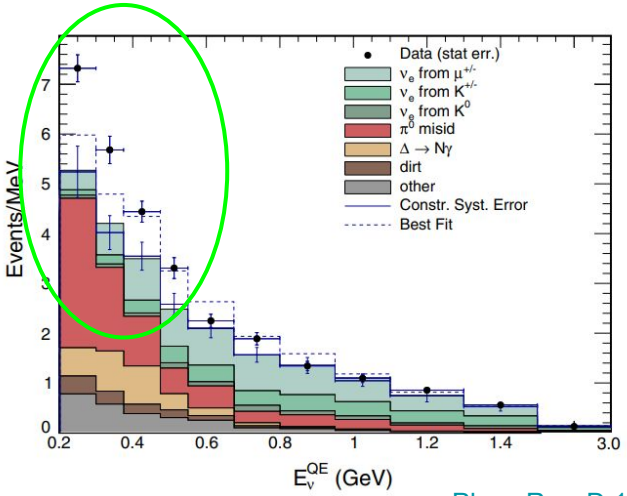
Calorimetry

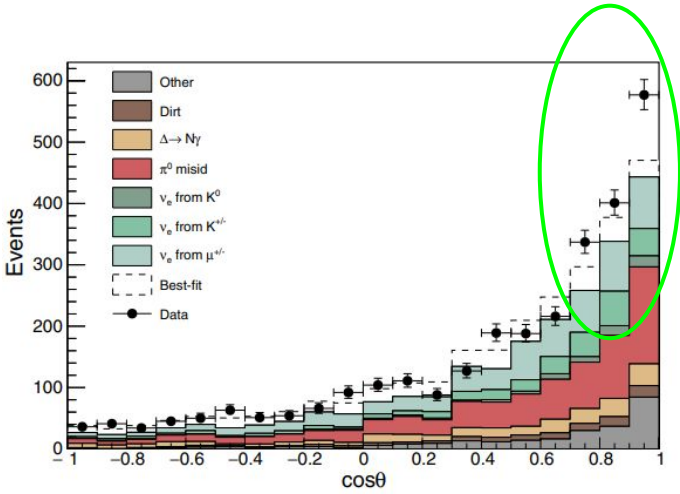


MiniBooNE Low Energy Excess (LEE) Anomaly

- Spherical Mineral Oil (CH2) Cherenkov Detector at Fermilab
  - On the Booster Neutrino Beam (BNB) (~99% ν_μ)
- L/E~1 meter/MeV
- With data collected from 2002 to 2019, sees a **4.8σ** excess of ν_e candidate events
  - neutrino energies of about 200-800 MeV
  - forward-going angles







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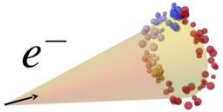
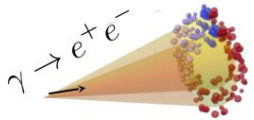
Sterile Neutrinos?



- MiniBooNE interpreted it as $\nu_\mu \rightarrow \nu_e$ oscillations
- But it's short-baseline → No standard oscillations
- Requires the existence of a **4th (sterile) neutrino** with $\Delta m^2 \sim O(1eV^2)$
  - "sterile" = no weak interactions

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Or Something Else?

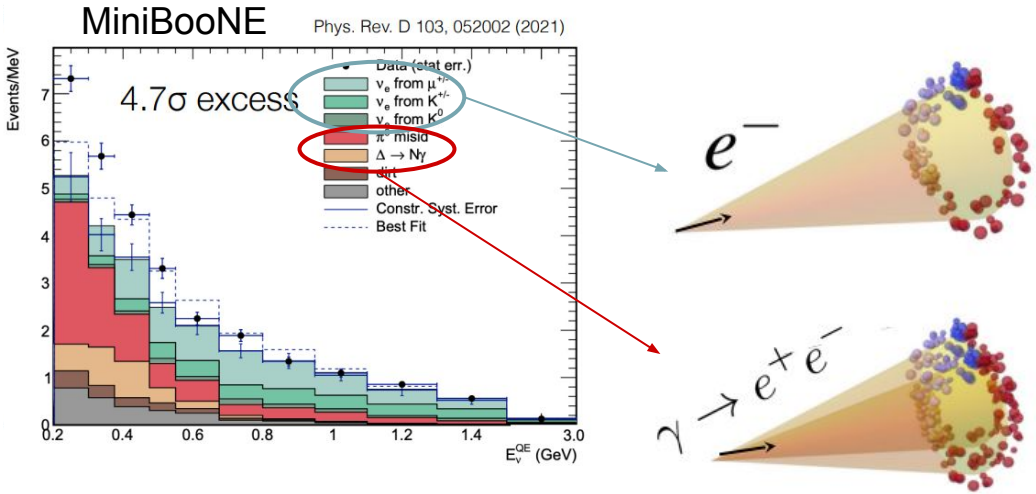


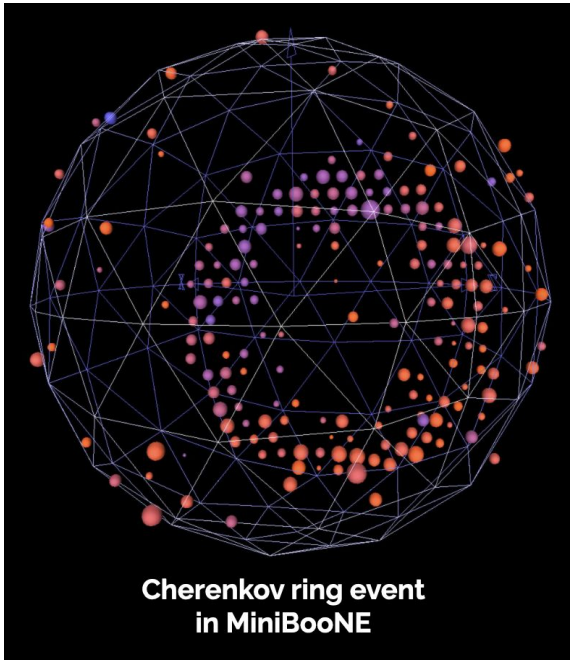
- But MiniBooNE doesn't know for sure it's electrons
- Various results from other experiments increasingly exclude sterile neutrinos in this range

Testing the MiniBooNE LEE with MicroBooNE

- MiniBooNE, as a cherenkov detector, can not distinguish between e^- and γ

MiniBooNE

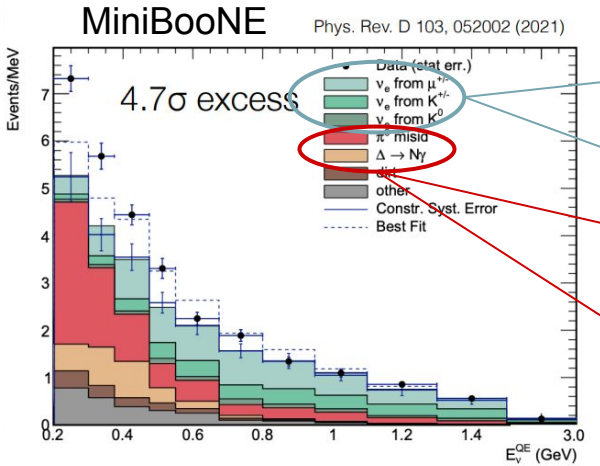


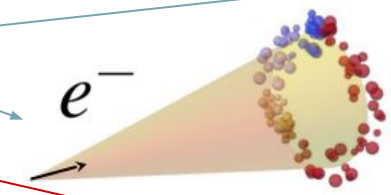


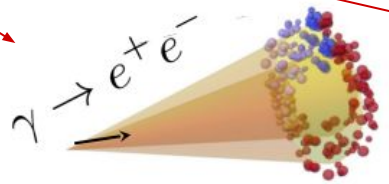
Testing the MiniBooNE LEE with MicroBooNE

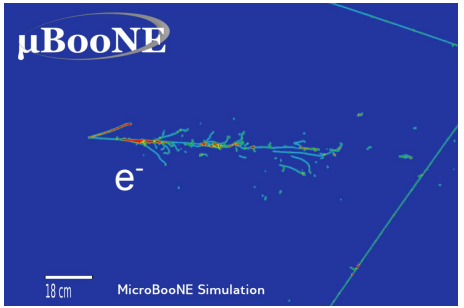
- MiniBooNE, as a cherenkov detector, **can not distinguish between e^- and γ**
- MicroBooNE **can** distinguish these, allowing us to probe into the nature of the excess.

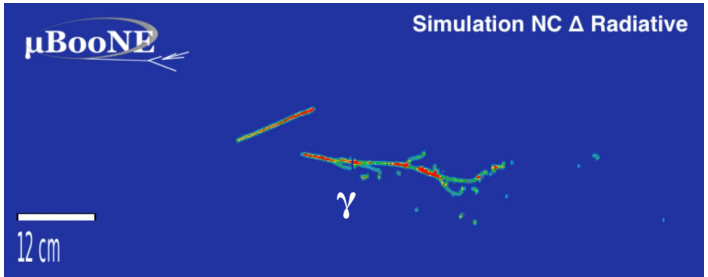
MiniBooNE **MicroBooNE**



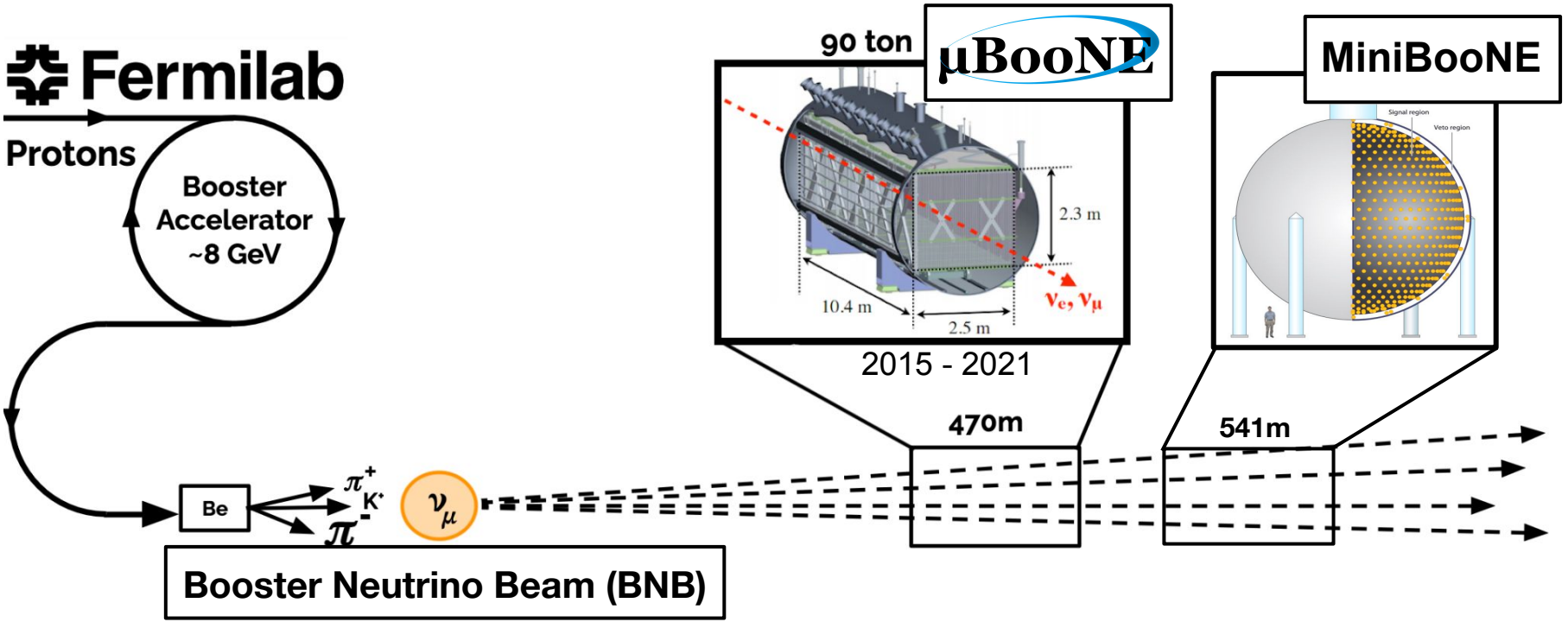






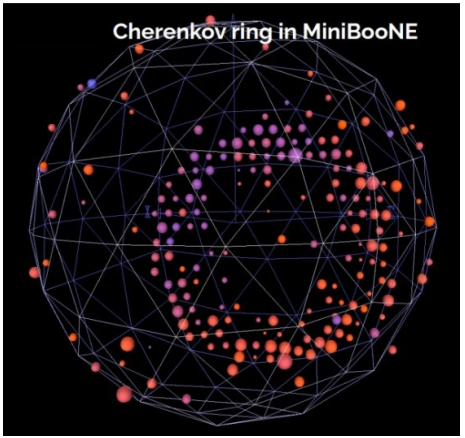


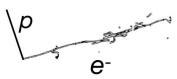
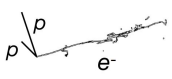
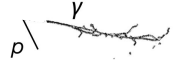
MicroBooNE and MiniBooNE



Possible Anomaly Channels

First series of results (½ the MicroBooNE data set)

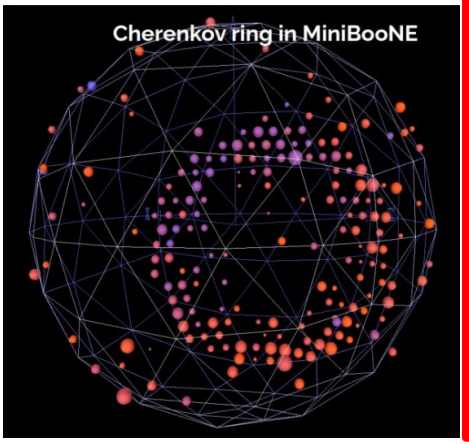


1e0p	1e1p	1eNp	1eX	1γ0p	1γ1p	1γX
						

Possible Anomaly Channels

See Fan Gao's talk on Thursday

set)



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	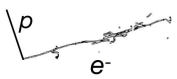	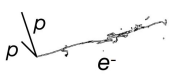			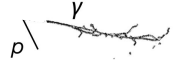	

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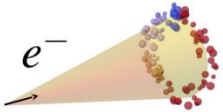

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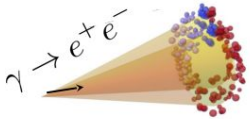

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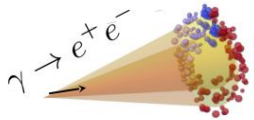
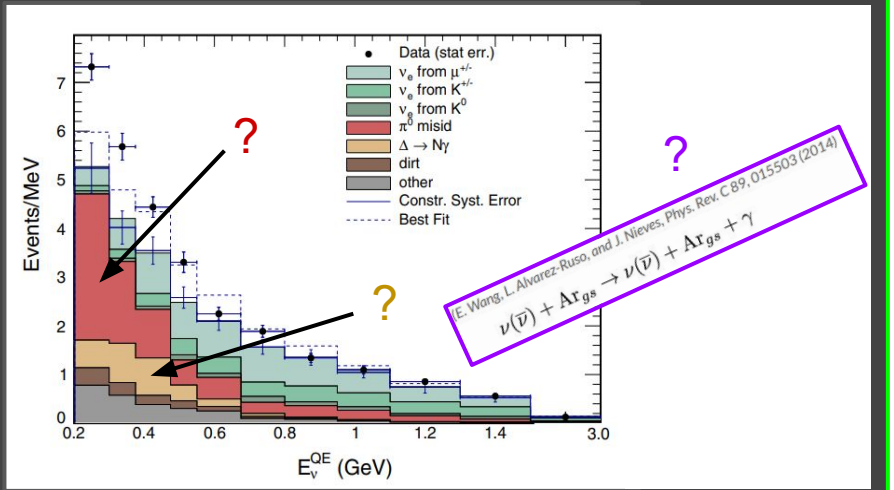
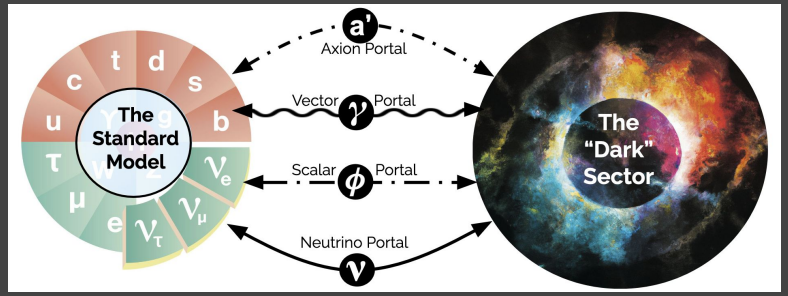


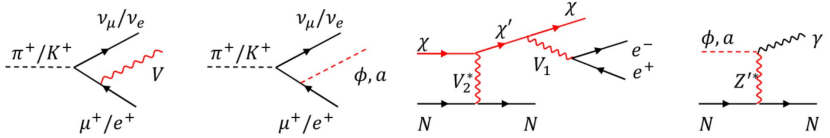
Mismodeled or missing SM backgrounds?



Signs of new physics?



Phys. Rev. Lett. **129**, 111803 (2022)



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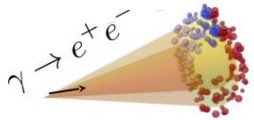

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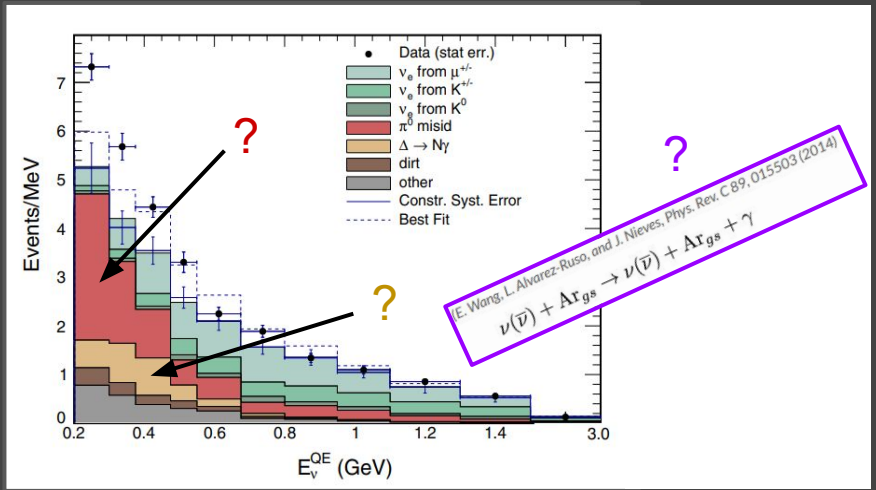

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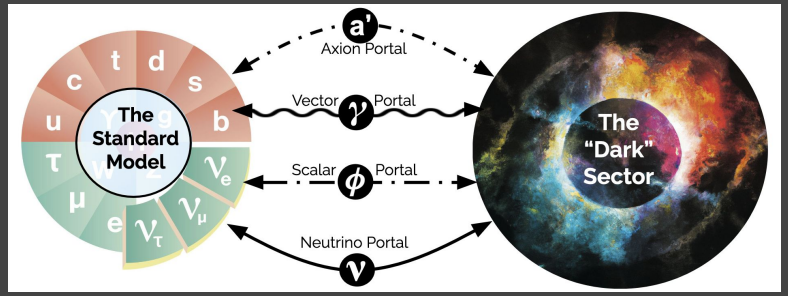

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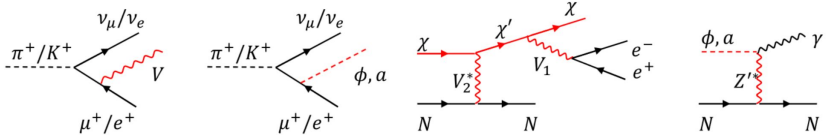

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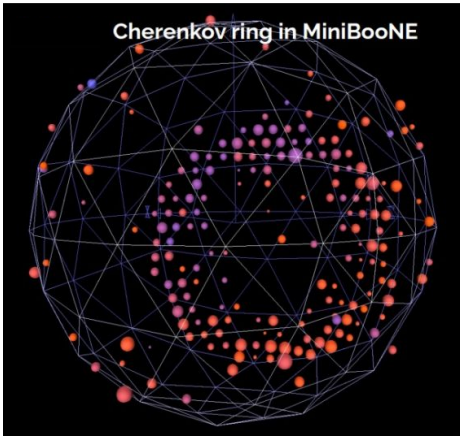

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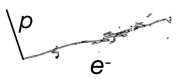
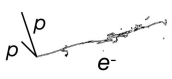
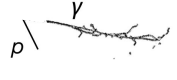
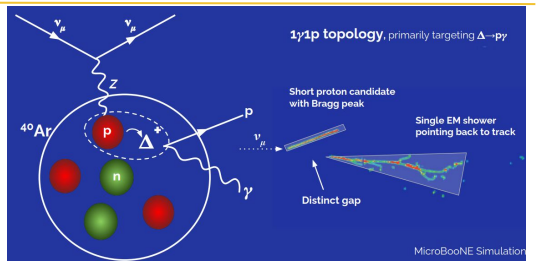
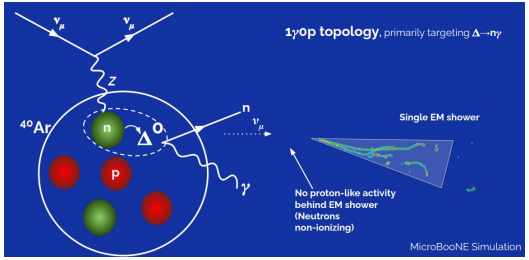
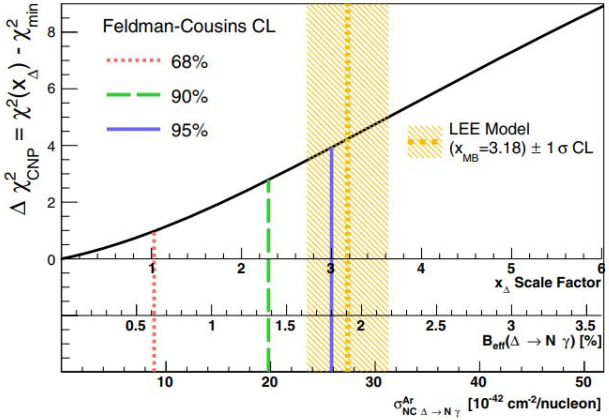
						

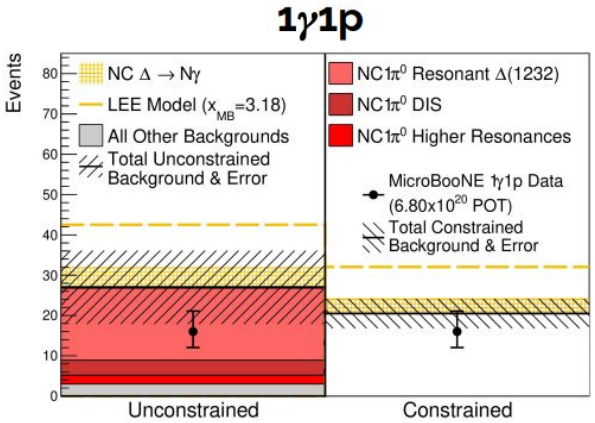
First Results: NC Δ → Nγ

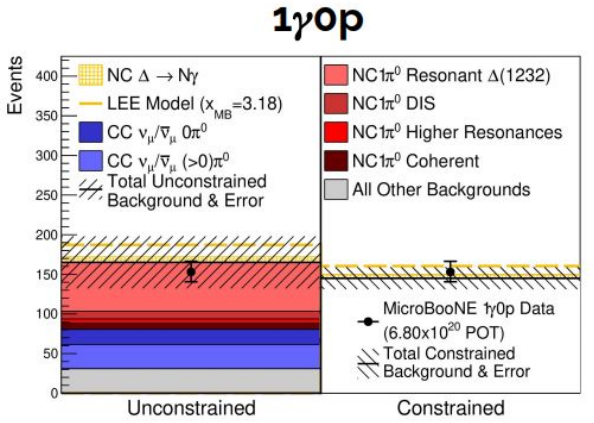
- Single photon search for **NC Δ → Nγ radiative decay**
  - 1γ0p, 1γ1p
- **Rules out photons from NC Δ → Nγ** as the cause of the LEE at 94.8% C.L.
- Higher purity/more sensitive **1γ1p** channel dominates





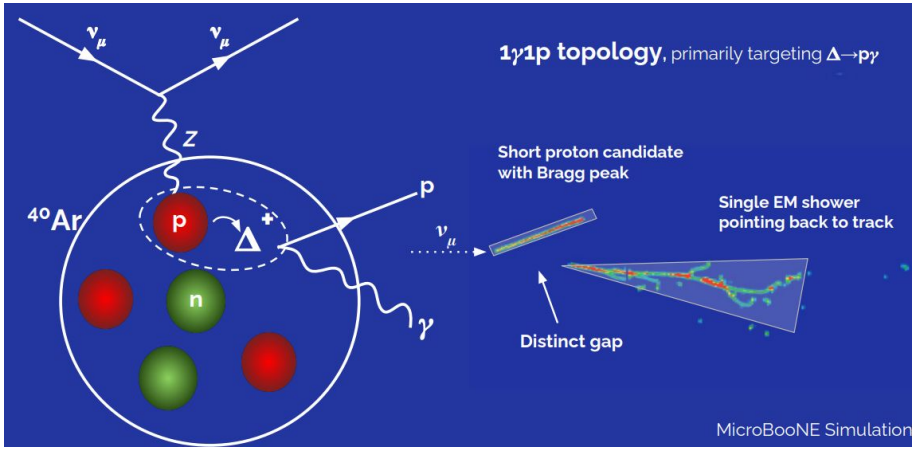






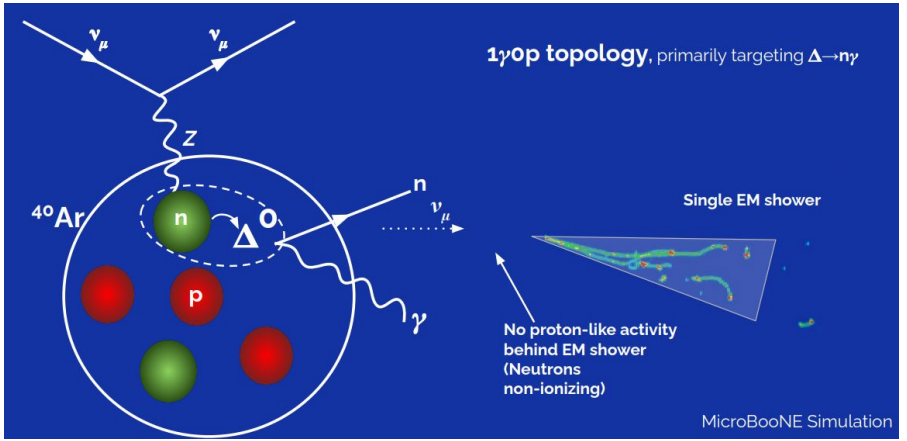
First Results: NC Δ → Nγ

X



Heavily constrained

✓

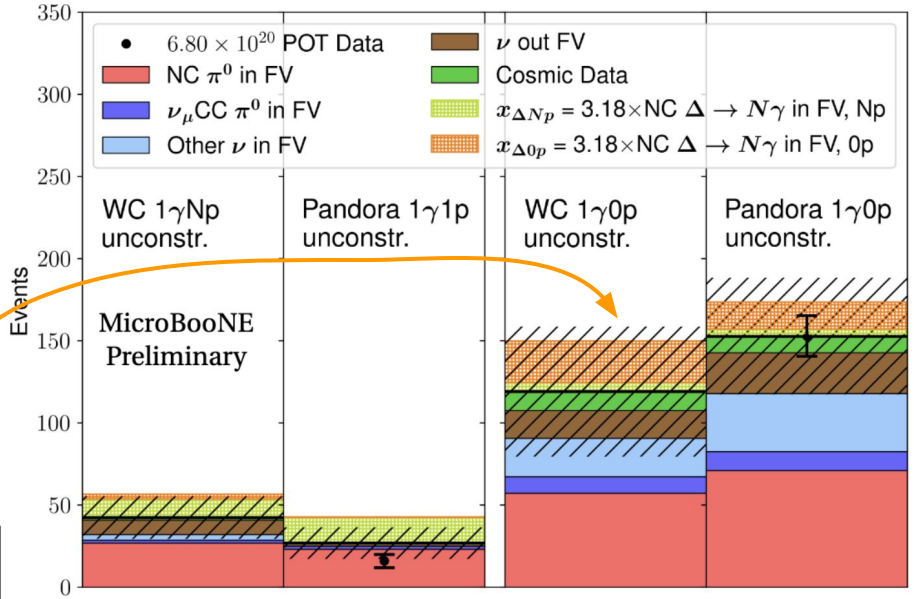


Currently Allowed!

Need further probes.

Expanding Results: NC $\Delta \rightarrow N\gamma$

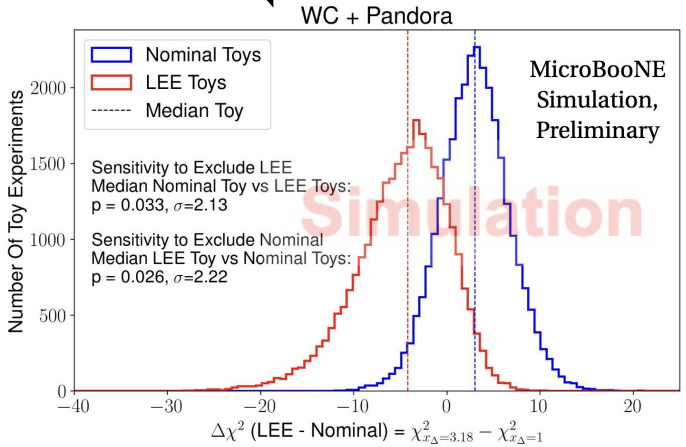
- Expanded NC $\Delta \rightarrow N\gamma$ search
- Incorporates Wire-Cell reconstruction in addition to previous Pandora-based results
  - largely orthogonal -> almost doubles statistics
- In particular, additional $1\gamma 0p$ selection has more sensitivity

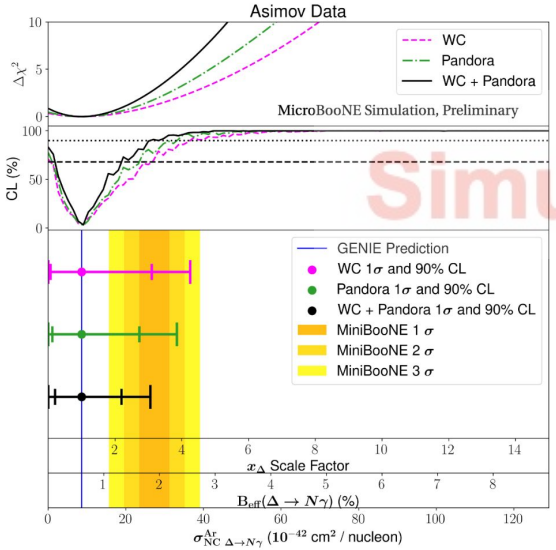


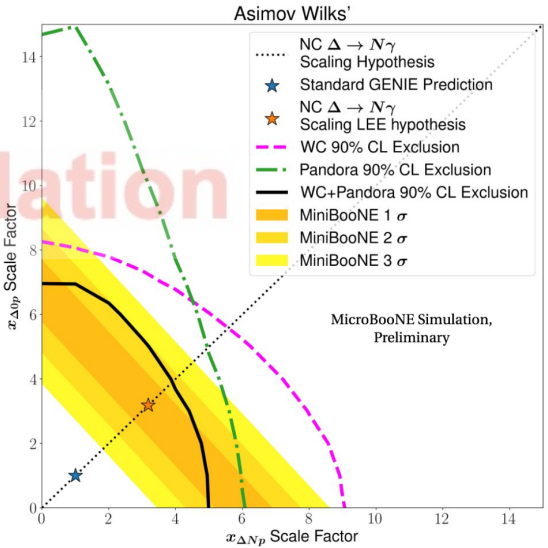
	Wire-Cell $1\gamma Np$	Pandora $1\gamma 1p$	Wire-Cell $1\gamma 0p$	Pandora $1\gamma 0p$
NC $\Delta \rightarrow N\gamma$ eff.	4.09%	4.31%	8.78%	5.58%
NC $\Delta \rightarrow N\gamma$ pur.	9.95%	15.1%	8.79%	4.35%

Expanding Results: NC Δ → Nγ

Increased sensitivity in probing the **1D** NC Δ → Nγ radiative decay scaling







Additional statistics and 0p sensitivity allows to probe a 2D (0p vs 1p) phase-space

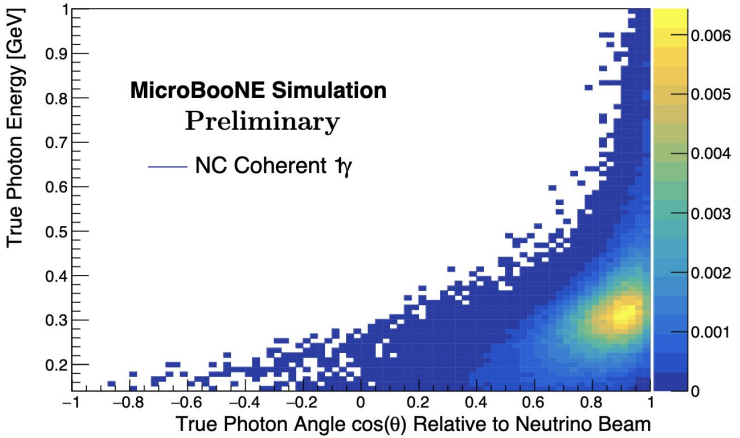
Coherent Photon

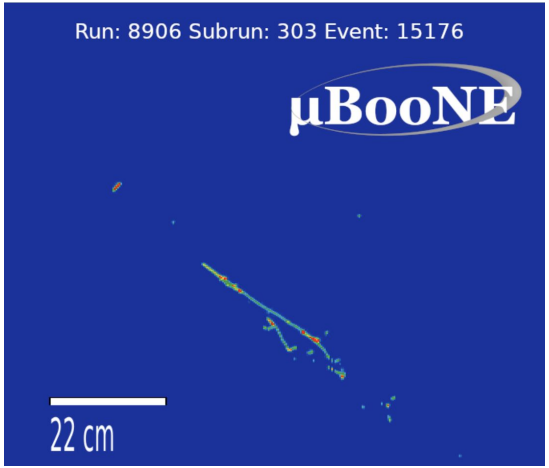
- Coherent-like single-photon production search
- building on the previous 1γ0p result
  - Subdominant NC 1γ background, never been measured experimentally
- increased sensitivity to "coherent-like" events
  - Standard Model predicted process

(E. Wang, L. Alvarez-Ruso, and J. Nieves, Phys. Rev. C 89, 015503 (2014)

$$\nu(\overline{\nu}) + \mathrm{Ar}_{gs} \rightarrow \nu(\overline{\nu}) + \mathrm{Ar}_{gs} + \gamma$$

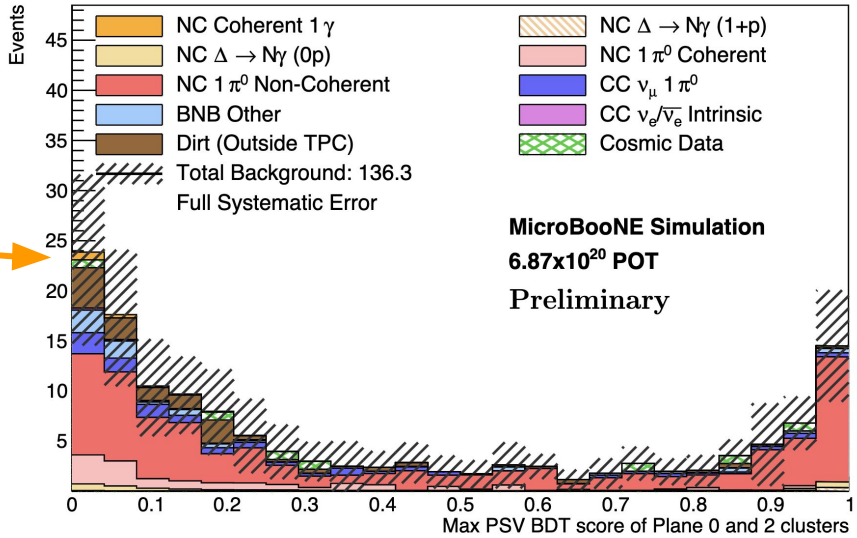
  - forward-going photons
  - no visible hadronic activity
    - improvements in proton identification for better event selection

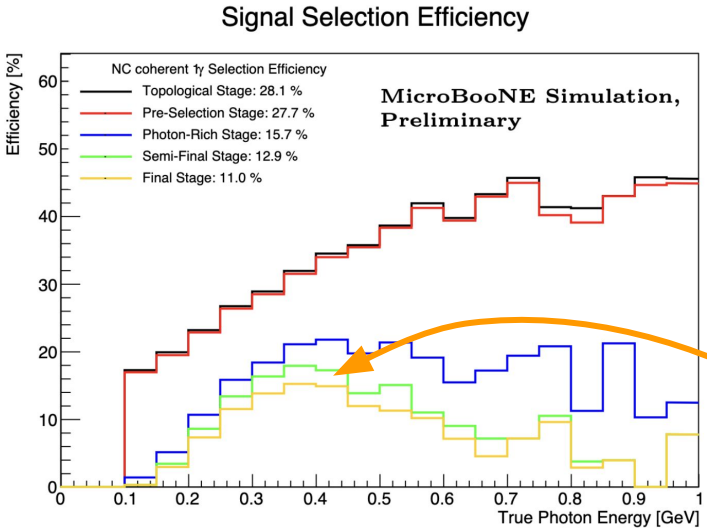




Coherent Photon

improvements in proton identification for better event selection

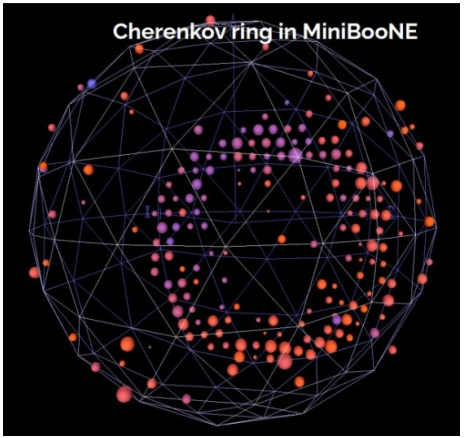


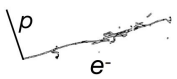
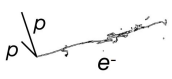
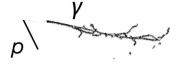


10-20% efficiency for relevant “low” energies

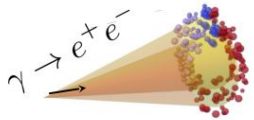
Possible Anomaly Channels

First series of results (½ the MicroBooNE data set)

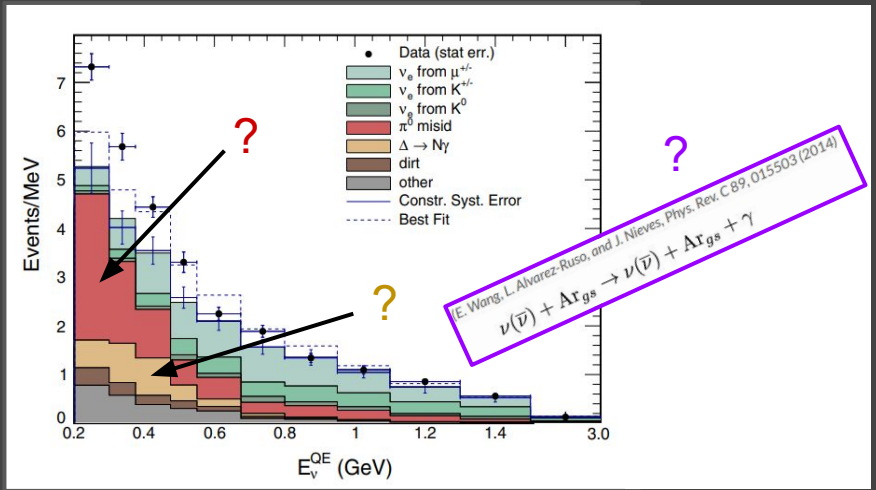


1e0p	1e1p	1eNp	1eX	1γ0p	1γ1p	1γX
						

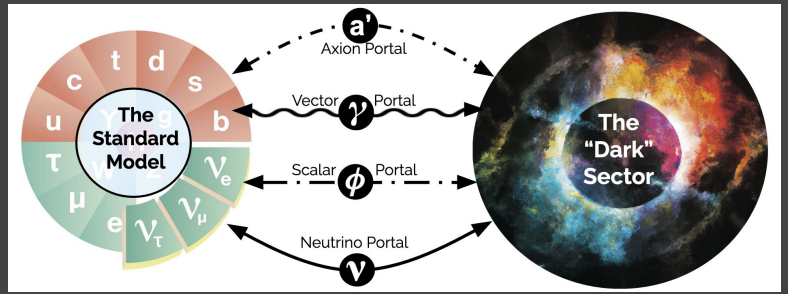
Or Something Else?



Mismodeled or missing SM backgrounds?



Signs of new physics?



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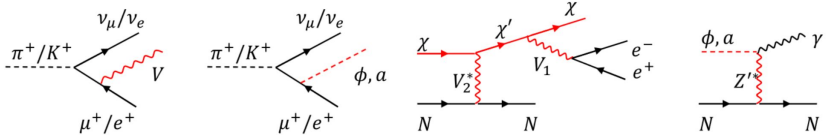
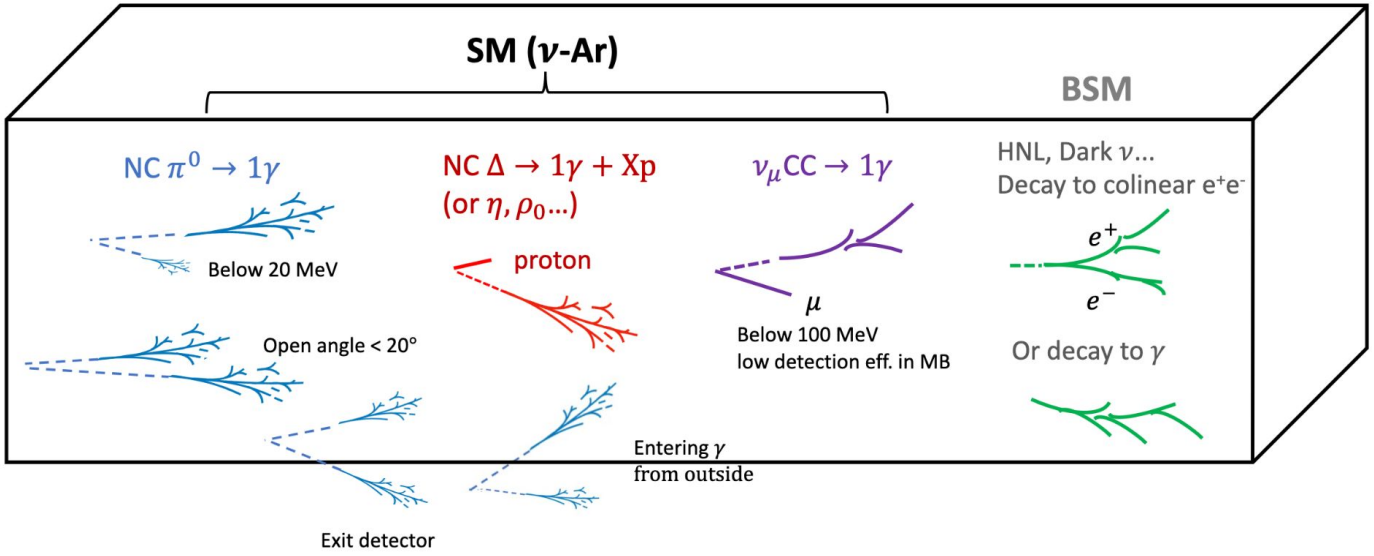


Inclusive Photon Search

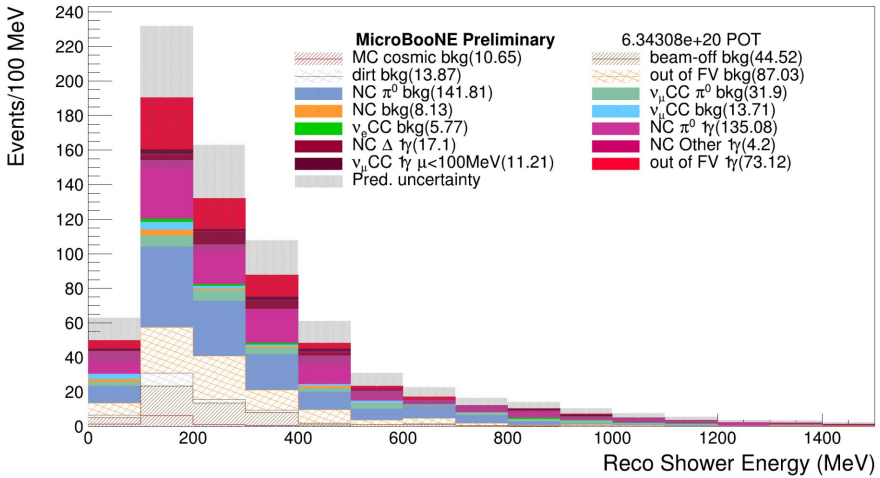
- MicroBooNE's first generation photon analysis was ***not*** **a generic or model independent result**, it was specific to **NC Δ Radiative decay**
- **New inclusive single photon selection** has been developed with the aim to **cast a wide net** that will capture any potential single photon anomaly



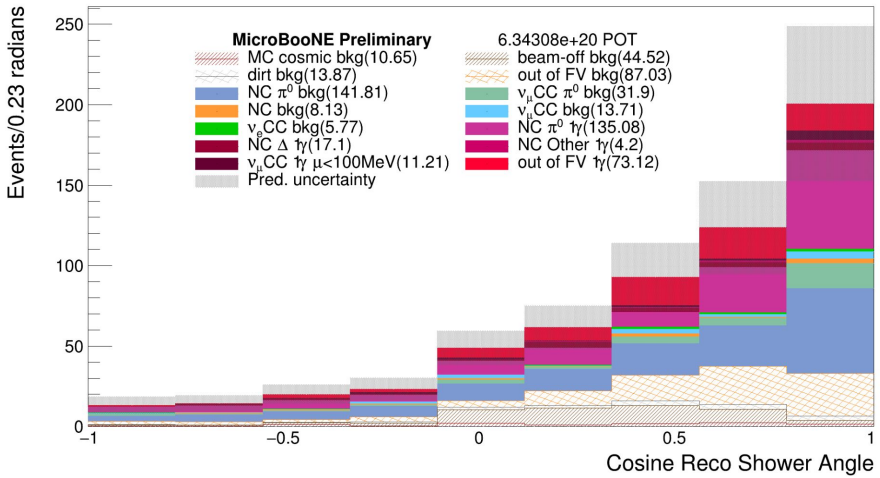
Inclusive Photon Search

Expect O(600) events in final selections, with a purity of ~40% and single-photon efficiency of 7%

Shower Energy

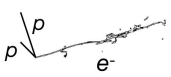
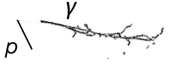
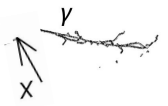
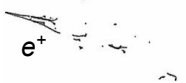
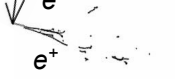


Shower Direction

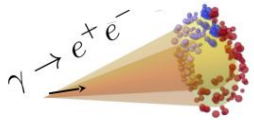


Exploring Further Channels

First series of results (½ the MicroBooNE data set)

1e0p	1e1p	1eNp	1eX	1γ0p	1γ1p	1γX	e^+e^- + nothing	e^+e^-X
								

Or Something Else?



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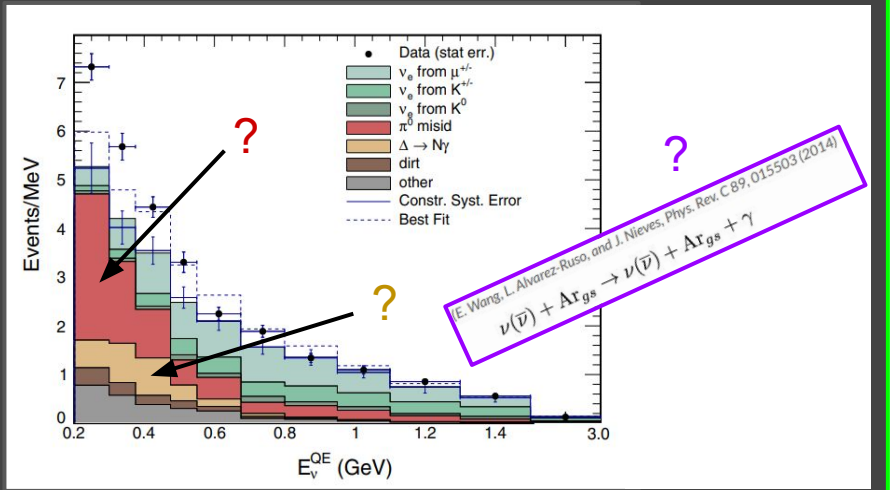
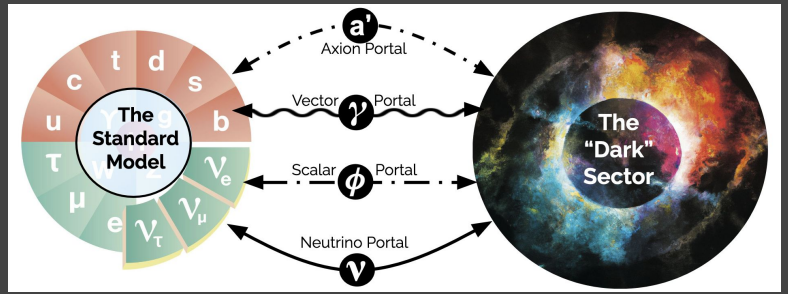


Signs of new physics?



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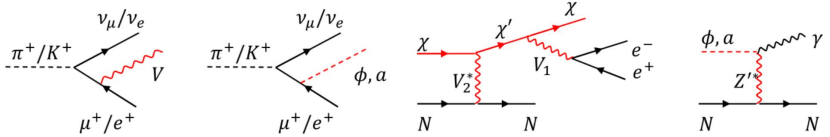
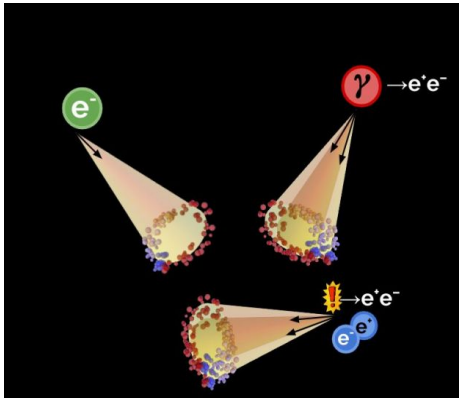
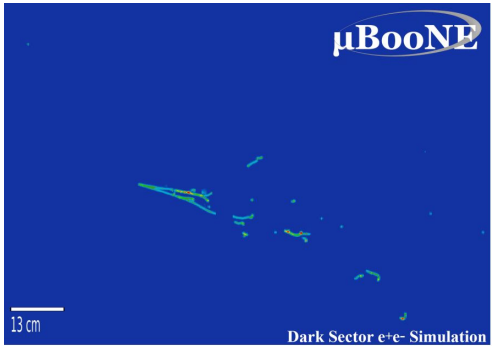
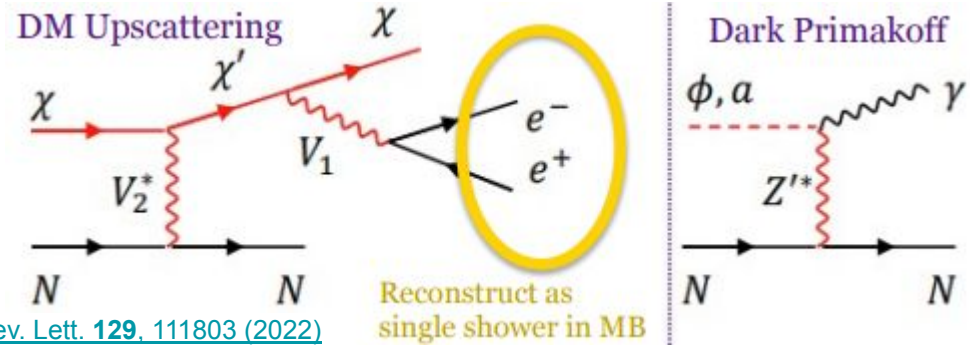


Other BSM Explanations

- A number of proposed BSM scenarios beyond sterile neutrinos
- Overlapping e^+e^- final states will mimic a single shower topology
- Models include dark neutrinos, heavy neutral leptons, new scalars, dark matter, and many more







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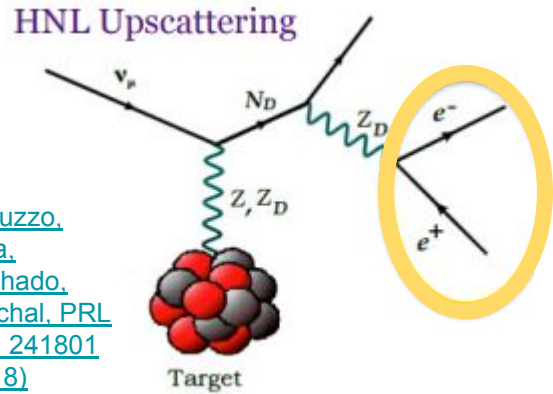
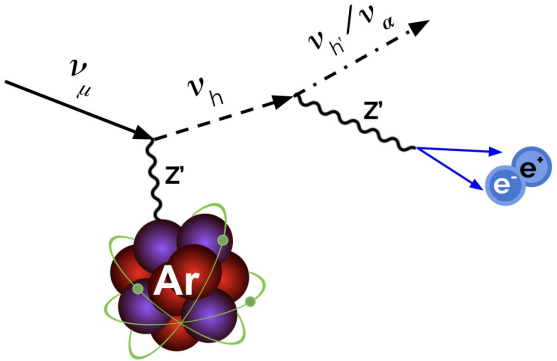


Bertuzzo, Jana, Machado, Funchal, PRL 121, 241801 (2018)

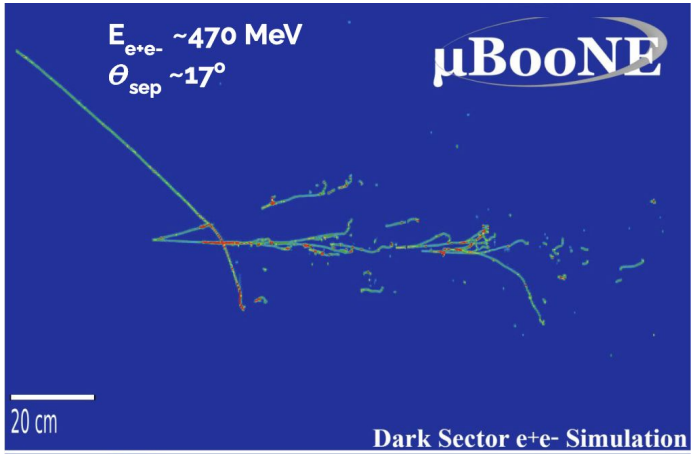
e+e- Searches

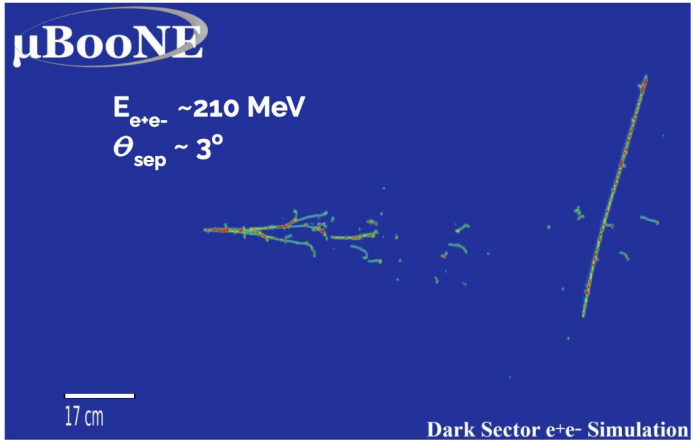
Current search for dark neutrino portal model ongoing



One or more **heavy sterile neutrinos**, charged under a new **dark U(1)'**

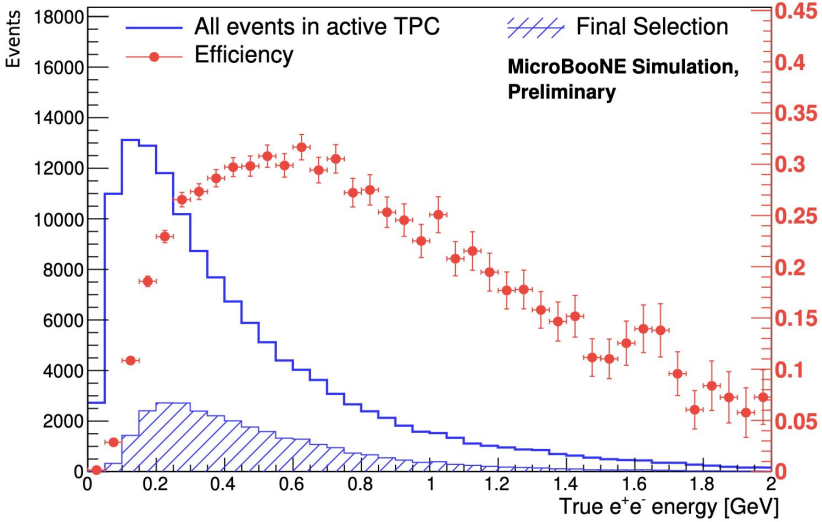
Upscattering produces ν_5 via **neutrino portal**, with scattering and **visible decay via vector portal** mediated by **dark gauge boson Z'**



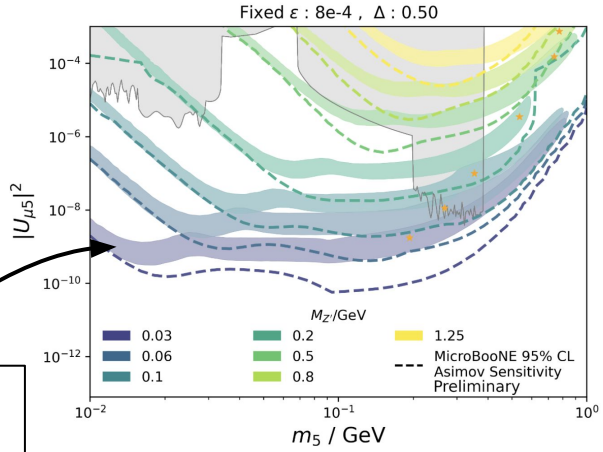


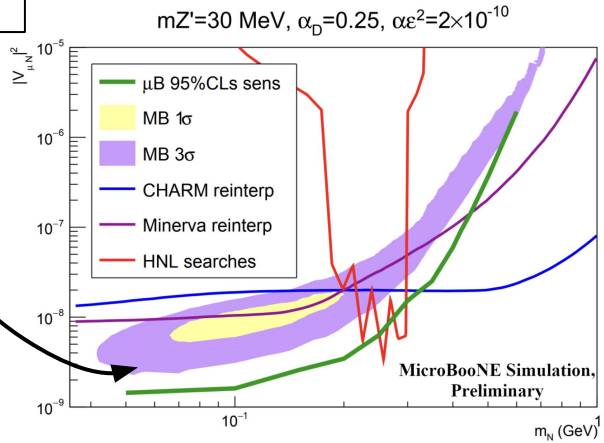
e+e- Searches

Signal efficiencies up to 30% across model phase space show significant enhancement over first generation photon results, ~O(5%)



MiniBooNE allowed region





Summary

- The MicroBooNE experiment was designed to test the nature of the excess of single electromagnetic shower events seen by MiniBooNE
- The anomaly could be coming from electrons or photons
  - MicroBooNE has a number of analysis dedicated to searching in both channels
- On the photon side, the current set of published results from MicroBooNE **disfavor photon from NC $\Delta \rightarrow N\gamma$ decay** as an explanation for the MiniBooNE LEE
- A number of new MicroBooNE photon LEE results, including **inclusive single photon** and **heavy sterile neutrino decaying to an electron-positron pair,** are coming soon

Thank You!