New results from MicroBooNE's search for a Low-Energy-Excess anomaly in the $\gamma/e^{+}e^{-}$ channels

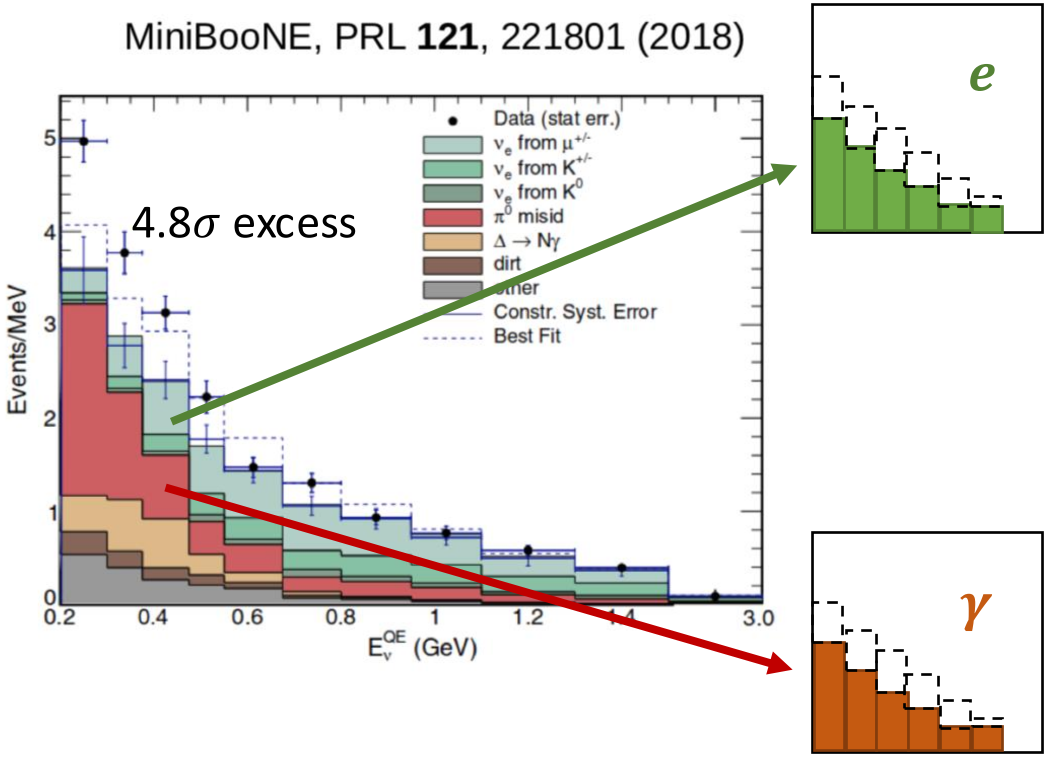
Xiao Luo, University of California Santa Barbara

On behalf of the MicroBooNE collaboration

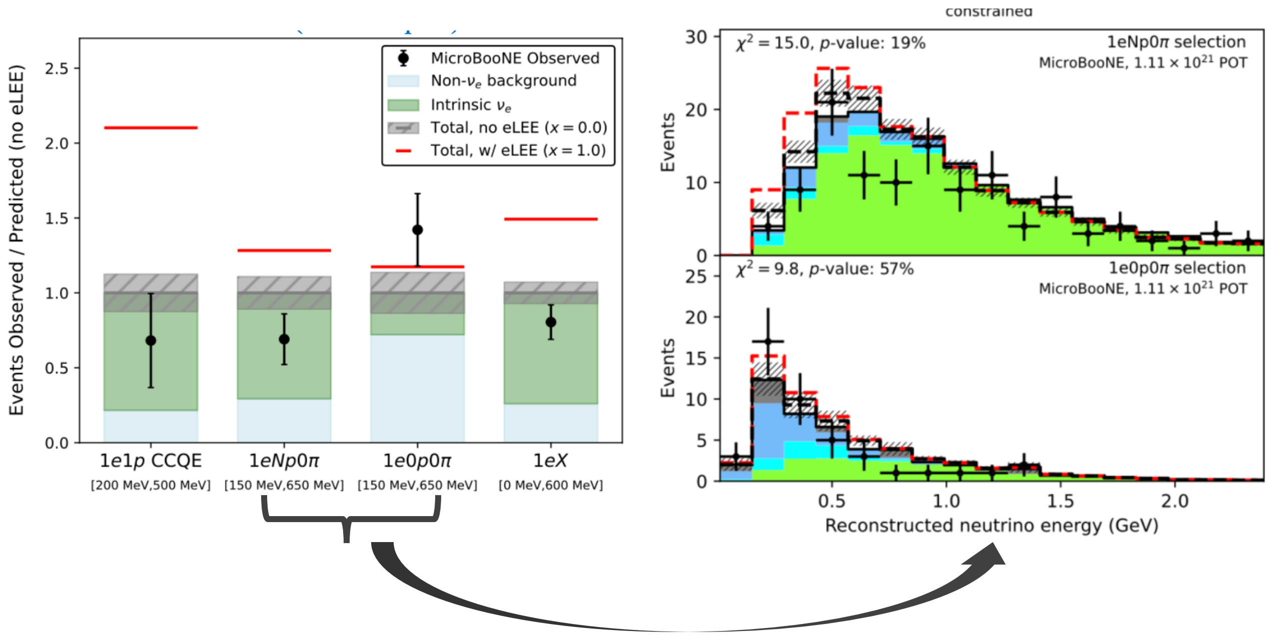
Overview of MicroBooNE LEE results:

MiniBooNE's **4.8σ** LEE anomaly

MiniBooNE, PRL **121**, 221801 (2018)



Electron LEE v1.0 (2022) / Electron LEE v2.0 (2025)



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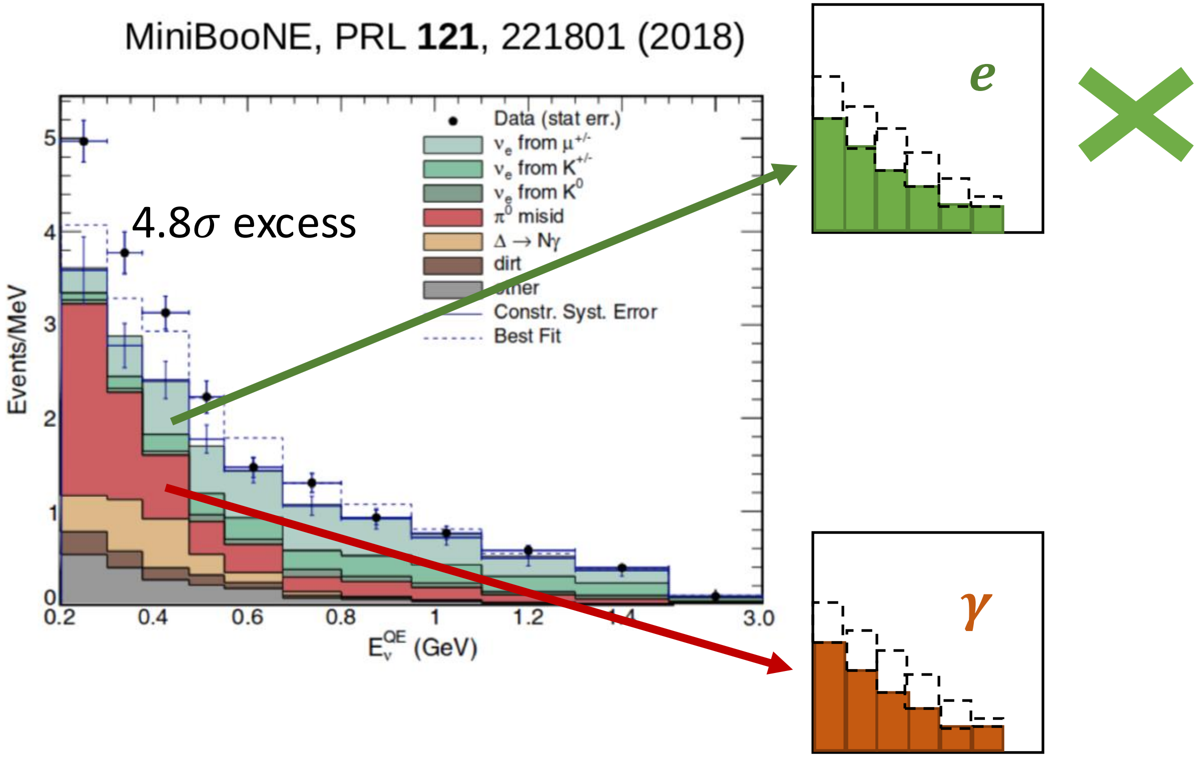

[Phys. Rev. Lett. 128, 241801 (2022)]
[Phys. Rev. D 105, 112003 (2022)]
[Phys. Rev D 105, 112004 (2022)]
[Phys. Rev. D 105, 112005 (2022)]
[Phys. Rev. Lett. 135.081802 (2025)]

No Excess in the electron channel, excluding MiniBooNE LEE as ν_e's at > 99%CL

Overview of MicroBooNE LEE results:

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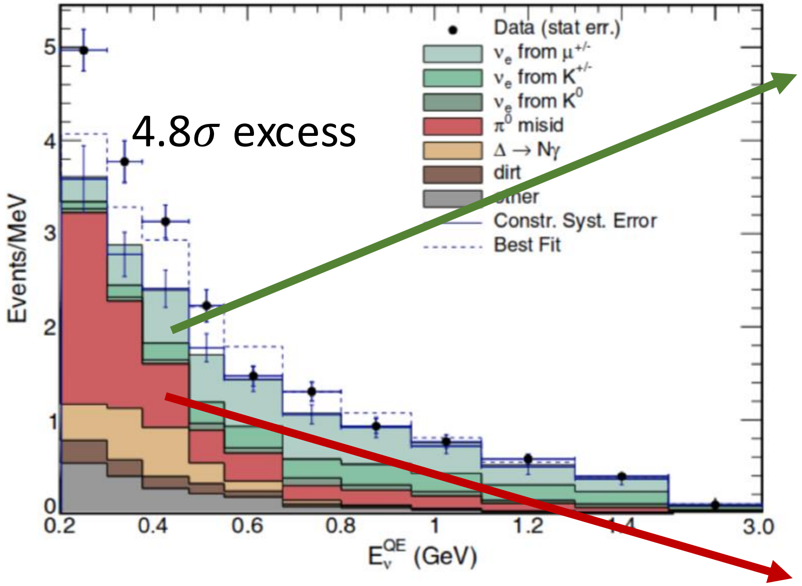
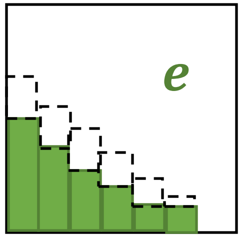
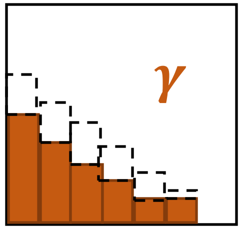
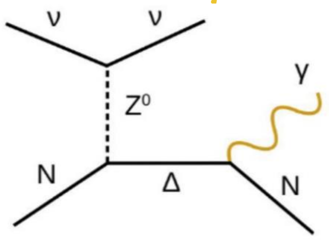
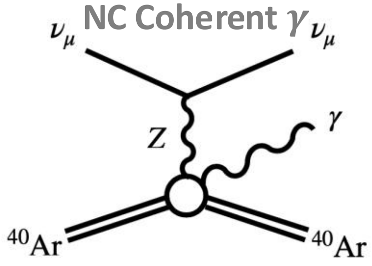




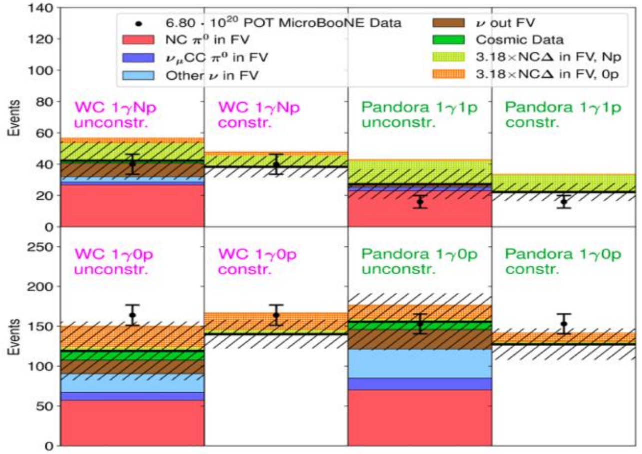


NC $\Delta \to N\gamma$

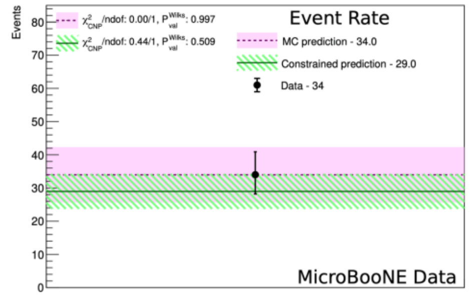




Two new results in the exclusive photon search!



No excess observed, exclusion of 3X **NC $\Delta \to N\gamma$** at 94.4% C.L. [arxiv. 2502.05750 (2025)]



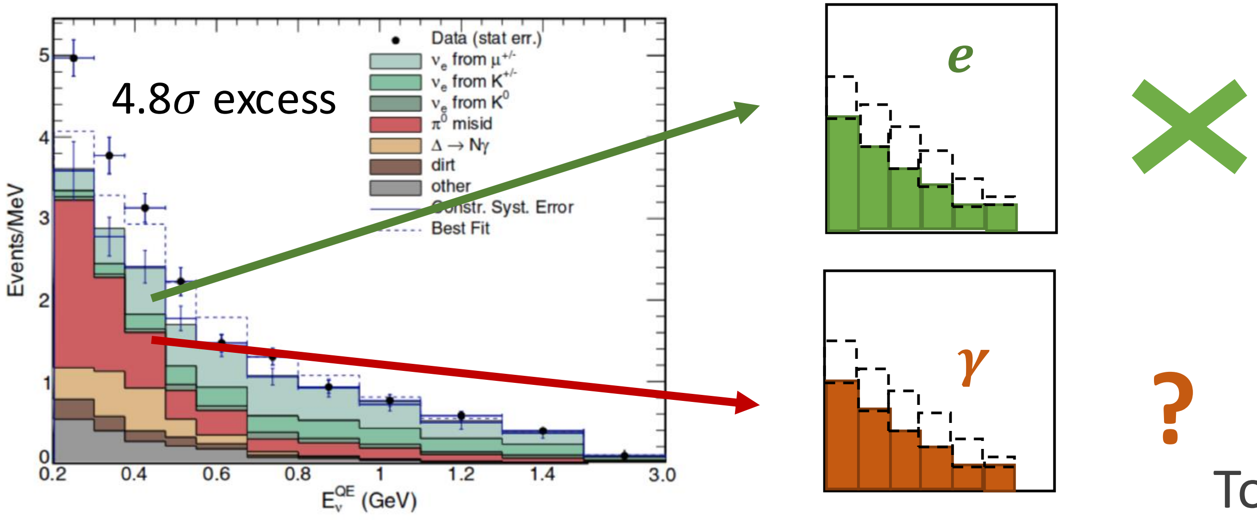
No excess observed, 1[st] world limit on NC coherent photon [arxiv.2502.06091 (2025)]

Quick summary of MicroBooNE LEE results so far:

No excess:

- in the electron channel
- in the exclusive photon channels: **NC $\Delta \rightarrow N\gamma$** and **NC Coherent**

MiniBooNE, PRL **121**, 221801 (2018)



?

To address if MicroBooNE sees any excess in the **photon** channel

Focus of this talk

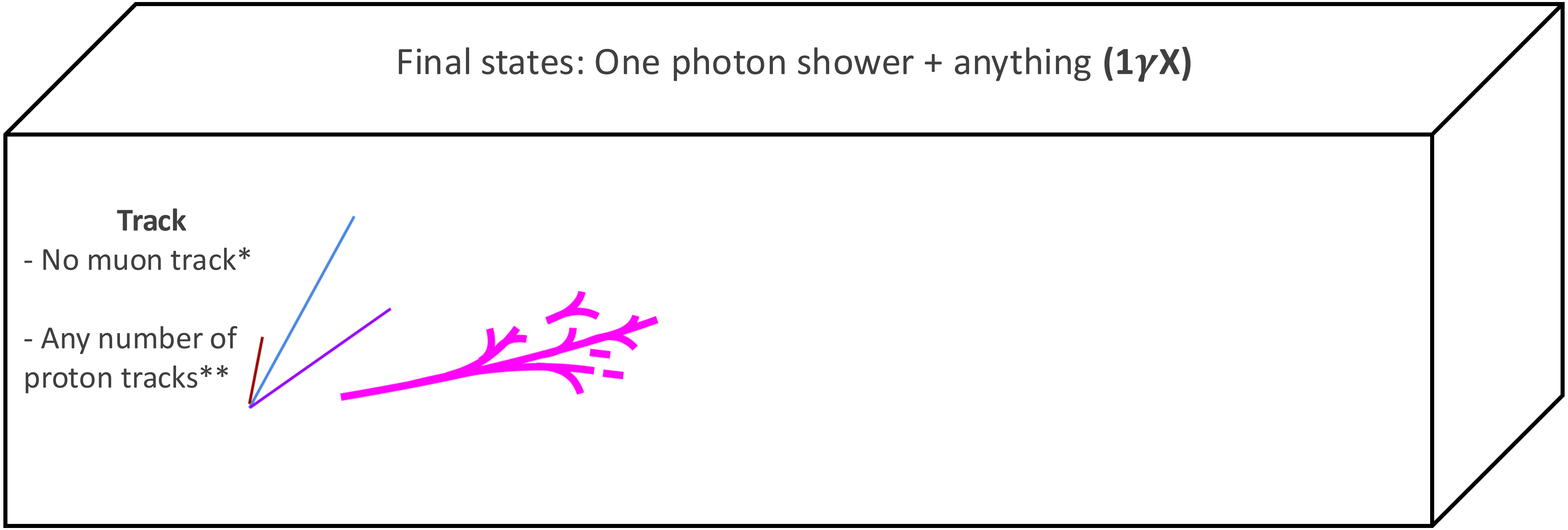
Inclusive photon - cast a wide net to search for anomaly in any process that produces a single γ, to definitively answer if MicroBooNE sees photon excess

arxiv.2502.06064

Inclusive photon LEE – signal definition

Model-independent approach:

Search for an inclusive set of **photon** events that **can enter the MiniBooNE LEE anomaly**



* MiniBooNE vetoes muon events but NOT efficient in detecting muons below 100 MeV. $\mu < 100\ MeV$ is allowed in our signal definition

** Defined as protons with true kinetic energy above 35 MeV (can be reconstructed in MicroBooNE).

Inclusive photon LEE – signal definition

Model-independent approach:

Search for an inclusive set of **photon** events that **can enter the MiniBooNE LEE anomaly**

Final states: One photon shower + anything **(1γX)**

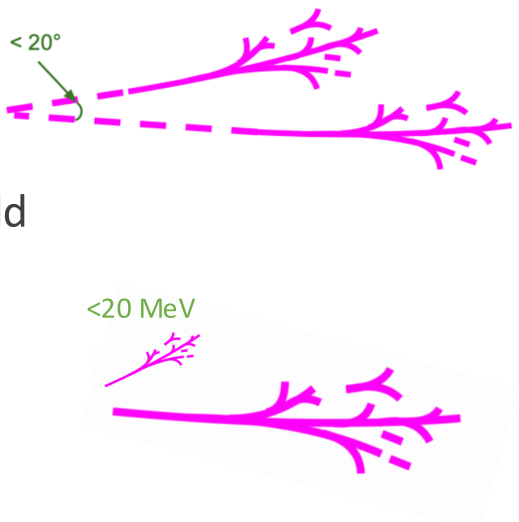
Track

- No muon track*

- Any number of proton tracks**

Shower

- 1 photon-like shower
- 20 degrees angle threshold
- 20 MeV shower energy threshold



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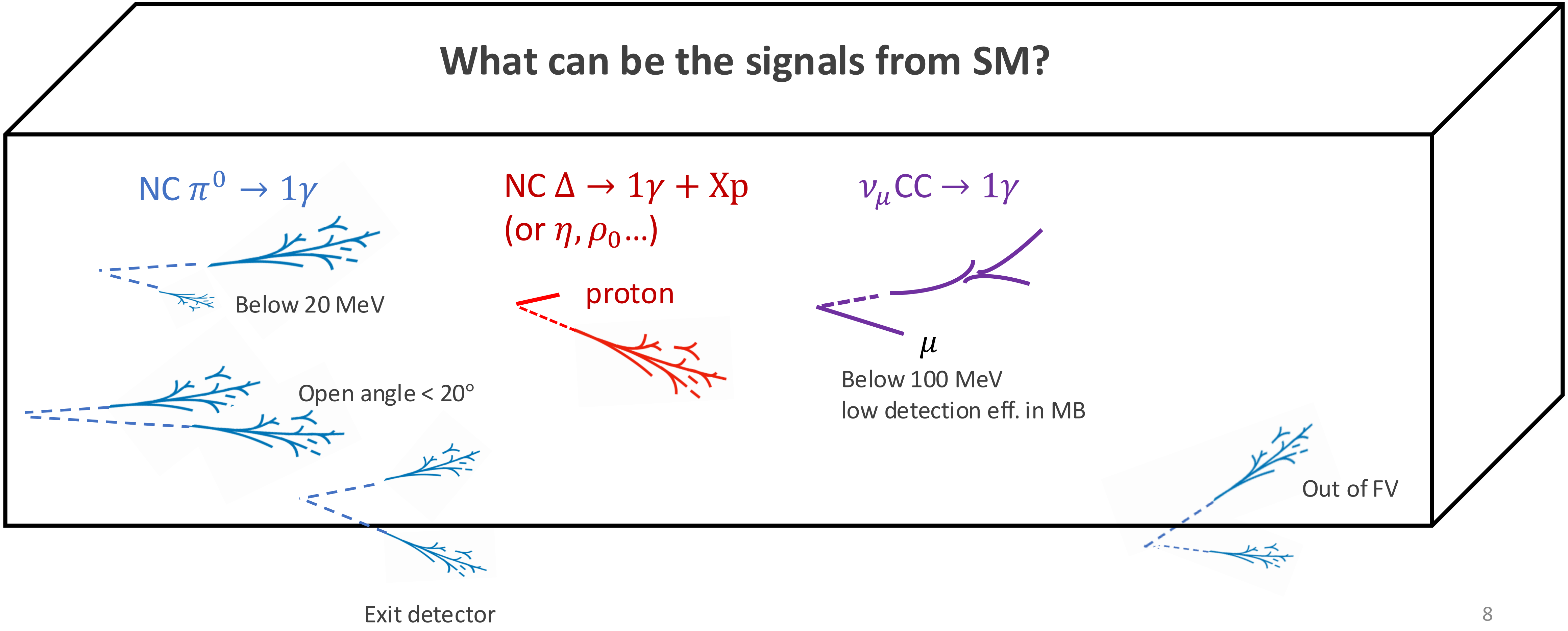
Inclusive photon LEE – signal processes

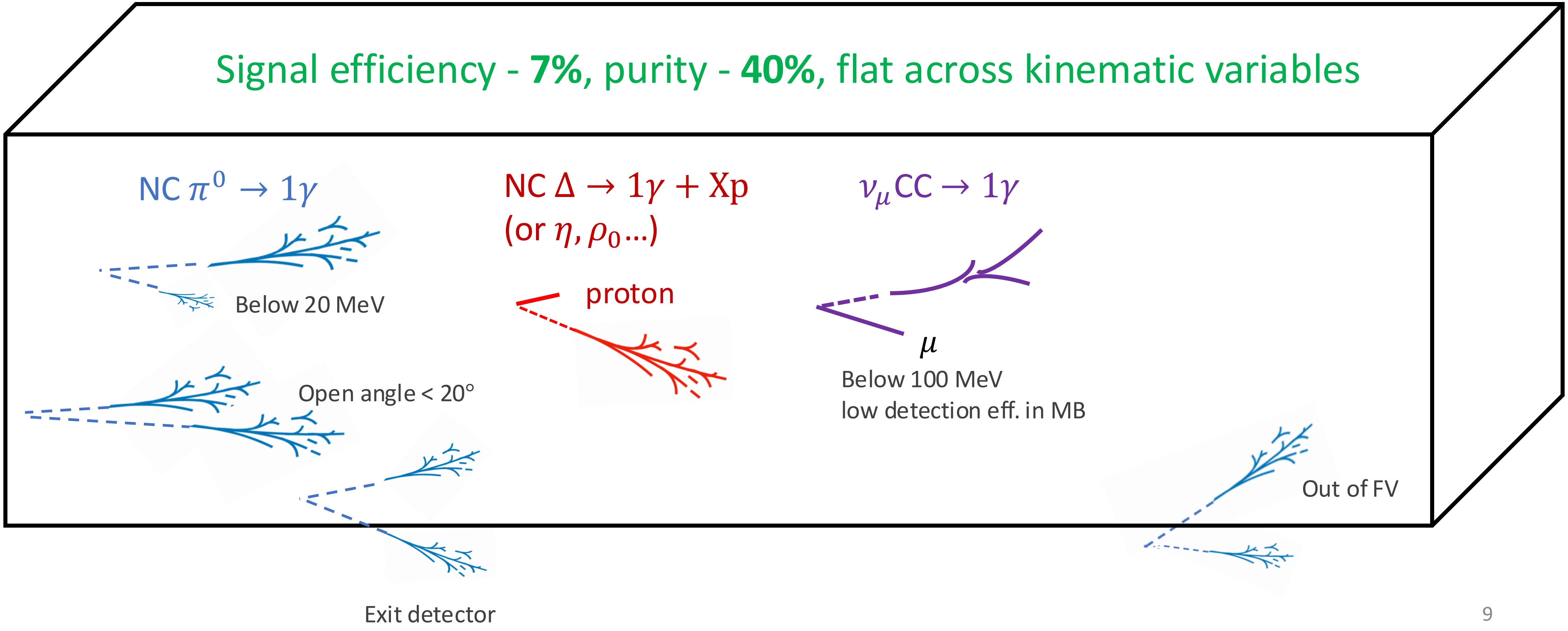
Five 1γX signal processes in SM

$NC\pi^0 1\gamma$ (40%), $NC\Delta 1\gamma$ (2%), NC Other 1γ (1%), $\nu_\mu CC$ 1γ (9%), Out of FV 1γ (46%)



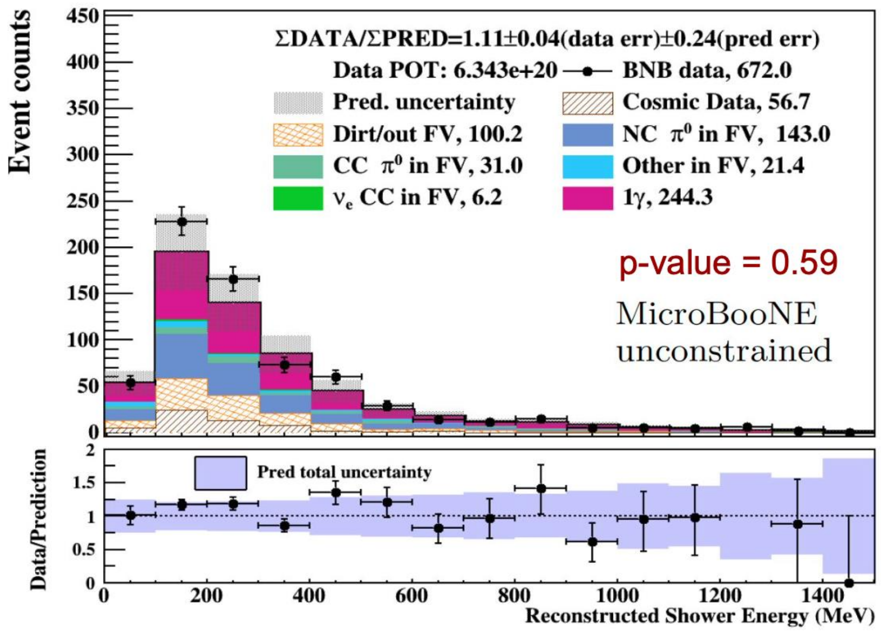
Inclusive photon LEE – signal selection

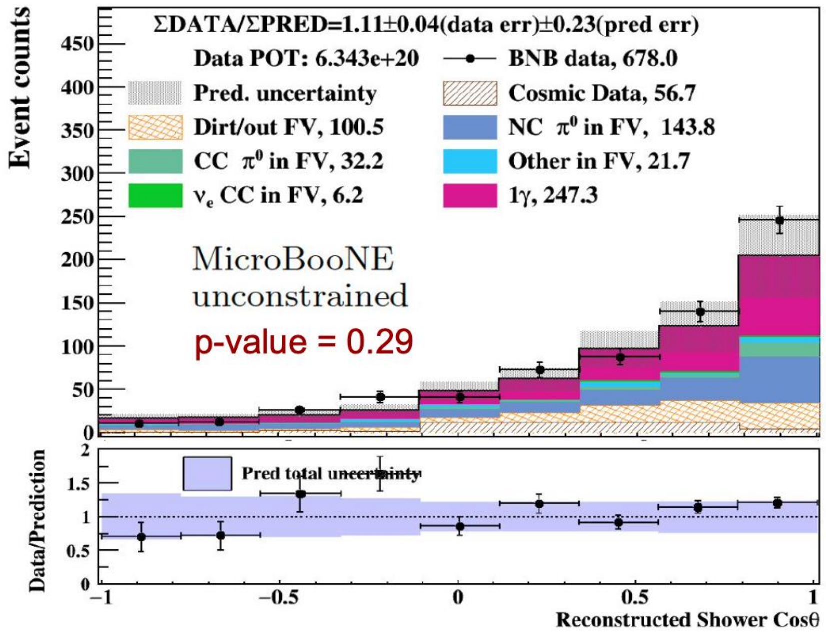
To select **SM - 1γX** signal:
Four BDTs targeted on rejecting $\nu_\mu CC$, Outside of TPC, $NC\pi^0$, $\nu_e CC$ backgrounds (details in the backup slides)



Inclusive photon LEE – final selected data

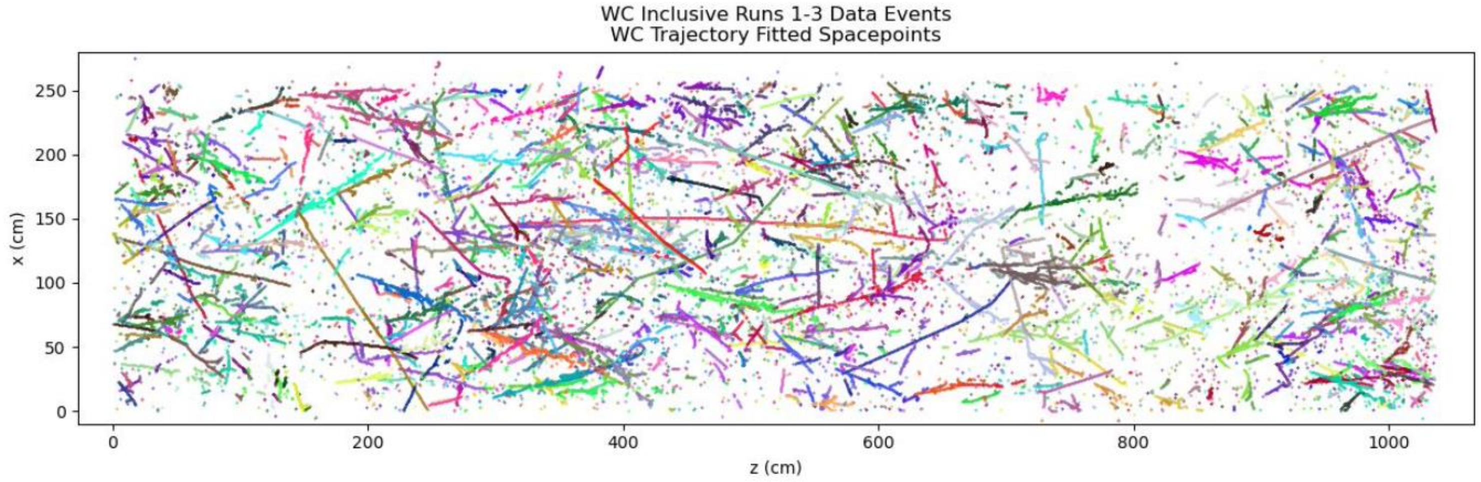
arxiv.2502.06064





After unblinding:

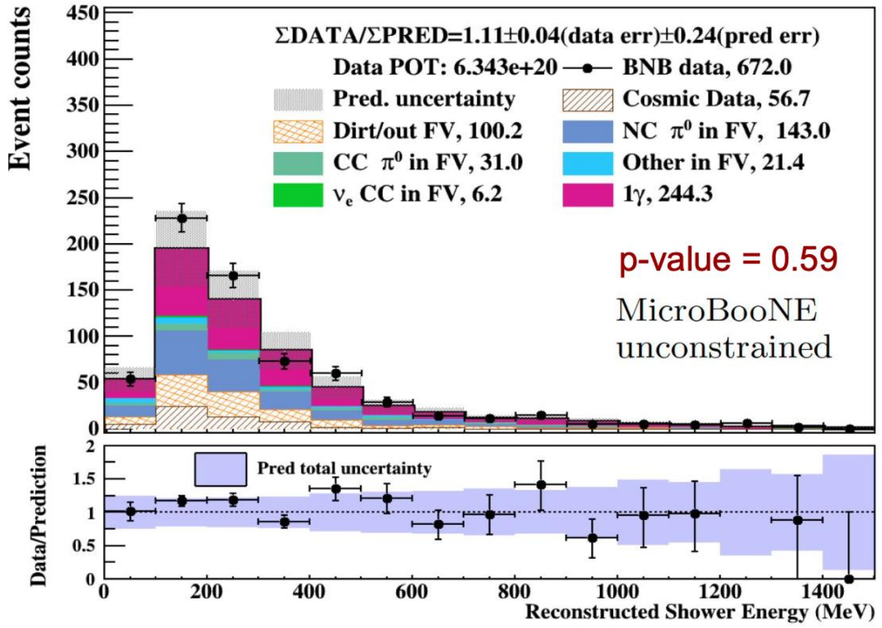
- Observed **678** data events
- Predicted **608** SM events
- Shower energy and angle show good agreement between data and prediction within error

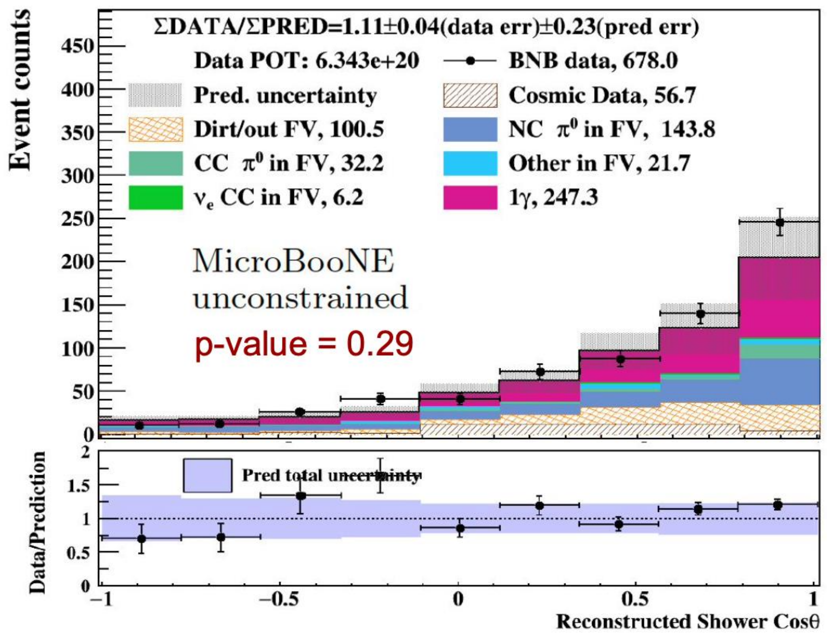


All selected 1γX data events displayed in one picture!

Inclusive photon LEE – final selected data

arxiv.2502.06064





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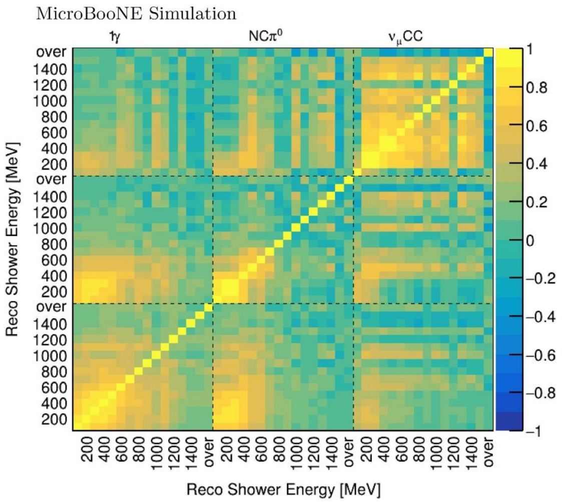


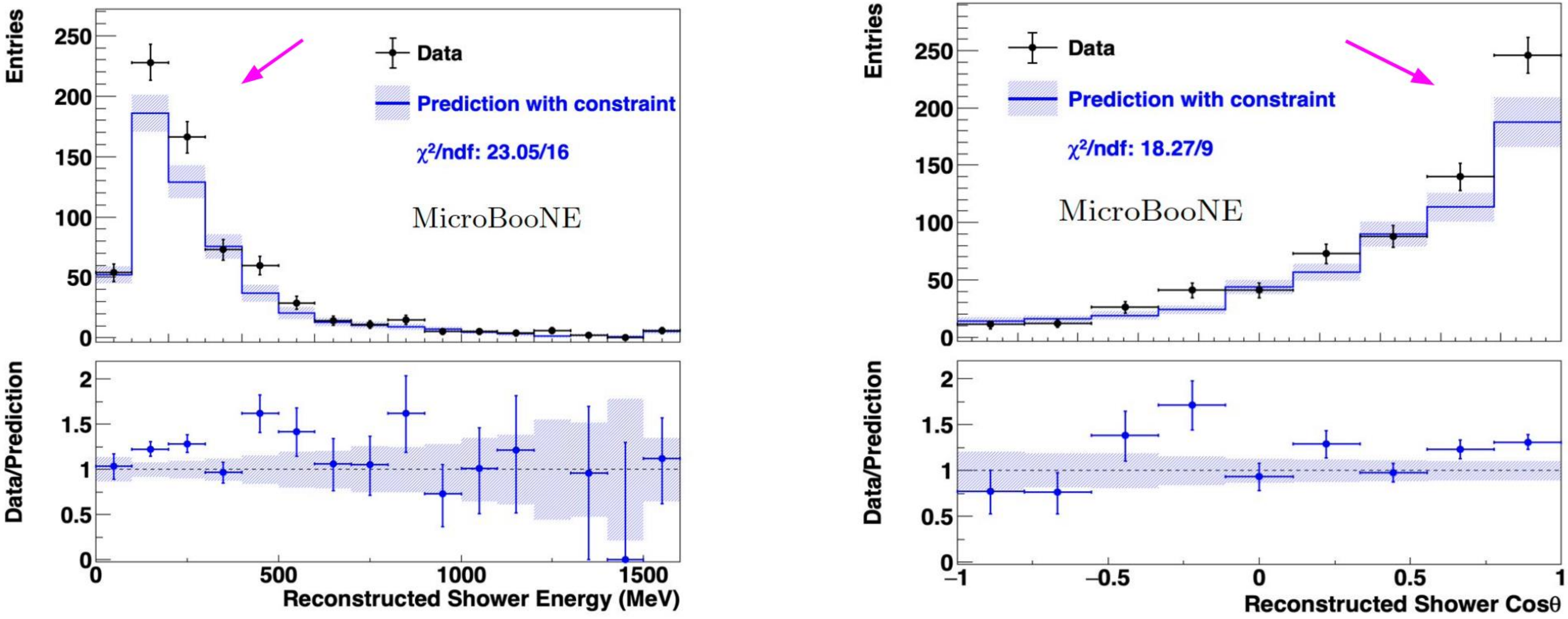
Constrain systematics

$\nu_\mu CC$ and $NC\pi^0$ sidebands to constrain systematics of signal prediction

Type of Uncertainty	Selection
Flux model	6.4%
GENIE cross section model and GEANT4 reinteractions	19.1%
Detector response	6.5%
MC statistics	2.0%
Interactions in Dirt	0.8%
Total Uncertainty (Unconstrained)	21.3%
Total Uncertainty (Constrained)	8.4%

Inclusive photon LEE – Result (constrained)

arxiv.2502.06064

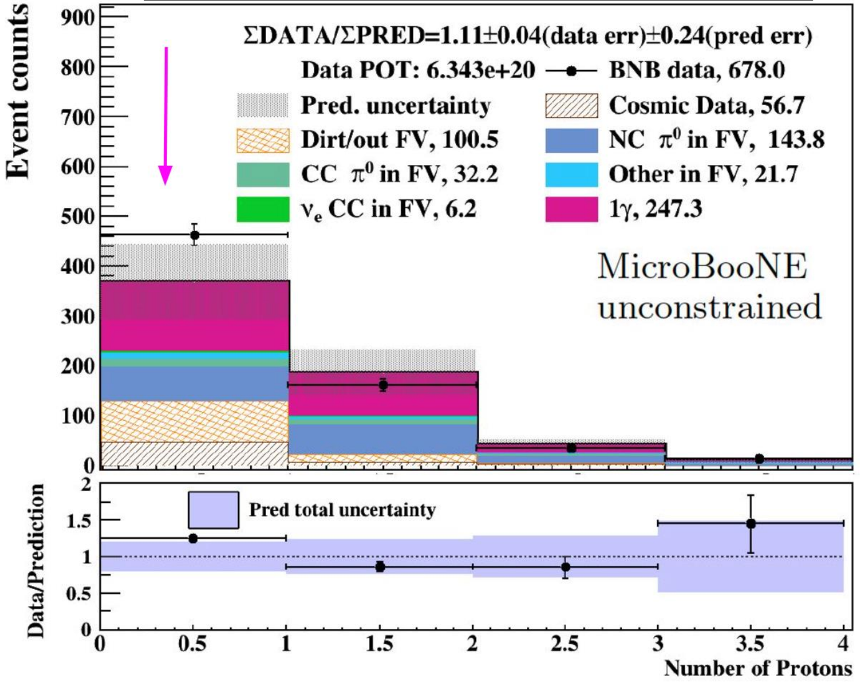


- Observed 678 data events, 114 events more than constrained prediction (564 $\pm$ 26 (stat.) $\pm$ 51 (syst.))
- Data is consistent with the constrained SM prediction to within **1.6σ**
- Excess is concentrated in low energy and forward angle

Inclusive photon LEE – Result (ROI)

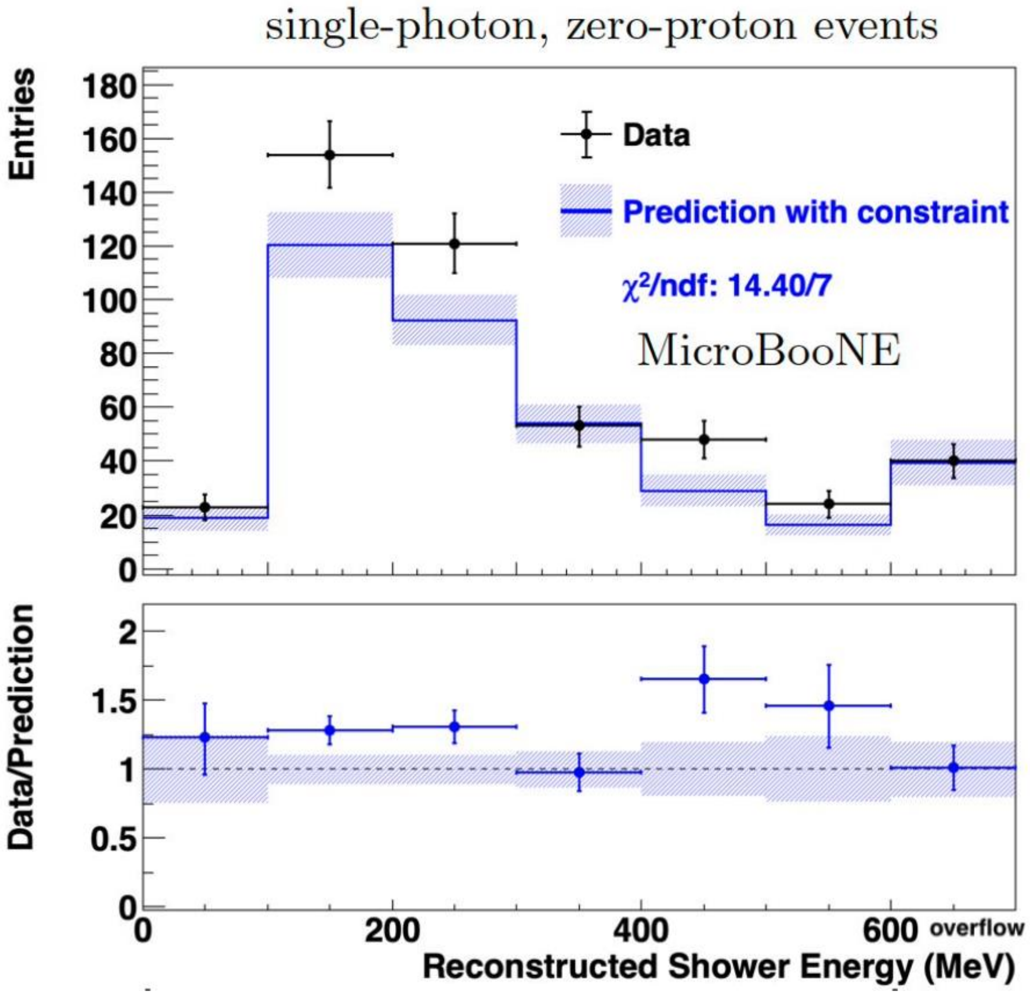
arxiv.2502.06064

Number of Proton Tracks*



ROI - 0 proton with shower energy below 600 MeV

Also use the 0p portion of the sideband events for constraints

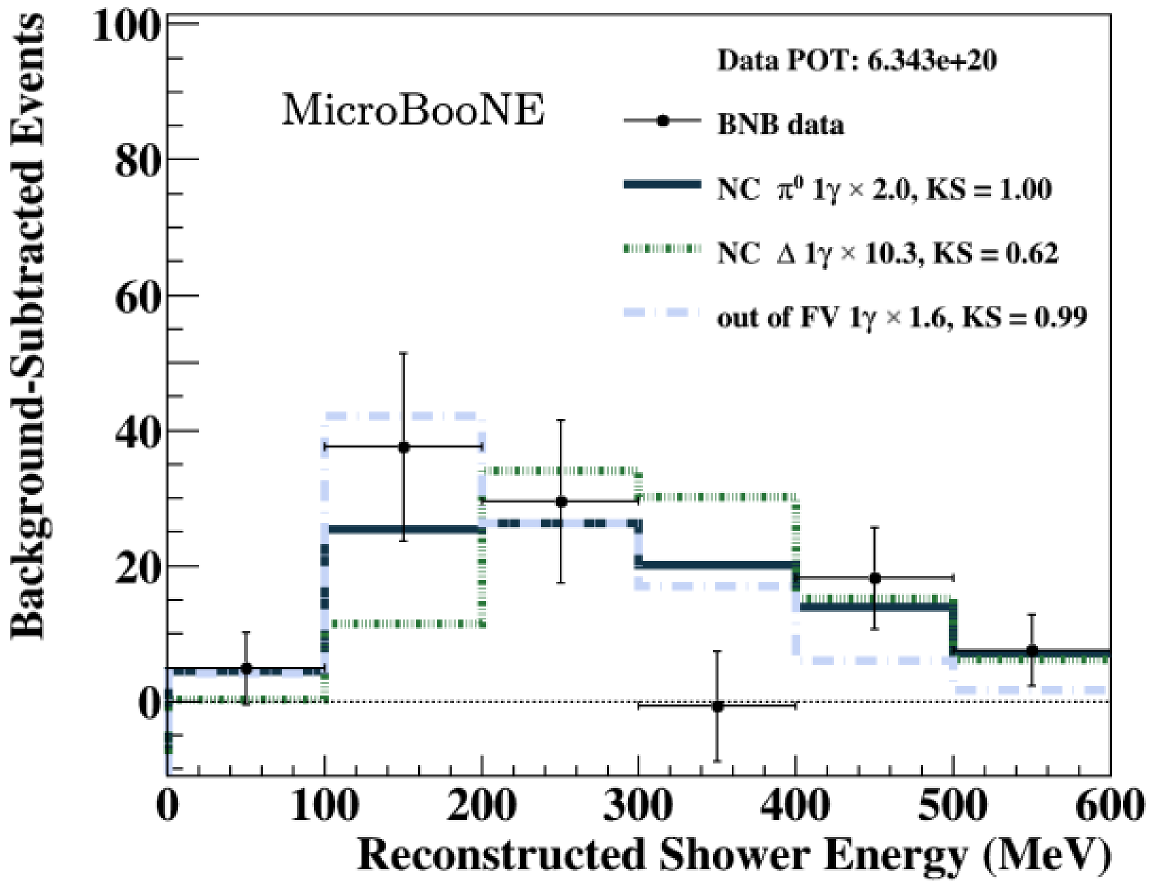


Excess only in the zero proton bin!

- Data excess of **93 $\pm 22\ (stat.) \pm 35 (syst.)$**
- **2σ** deviation from constrained prediction in ROI

*Protons is defined as above 35MeV MicroBooNE reconstruction threshold

Inclusive photon LEE – Result (excess event features)



arxiv.2502.06064

Kinematic feature of excess events:
- Without proton in the final state
- shower energy below 600 MeV
- mostly forward going

Compare shower energy of the **2σ excess** (data minus constrained prediction) to the scaled five signal processes, best agreement:

- $NC\ \pi^0 1\gamma$ X 2
- Out of FV 1γ X 1.6

As a example of unlikely source for the excess, NC Δ 1γ needs to scale up by a factor of 10, and also has a different shape in shower energy

MicroBooNE photon excess Vs. MiniBooNE LEE

arxiv.2502.06064

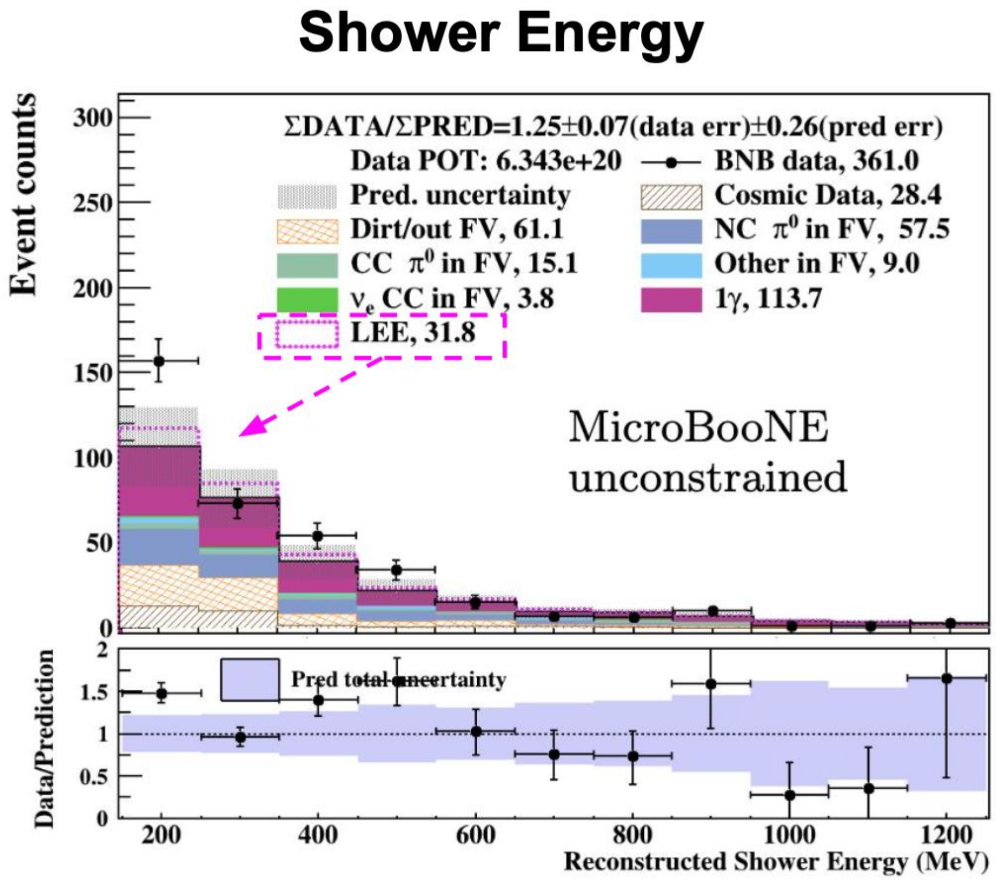
A "simple model of MiniBooNE LEE-γ"

1. Unfold MiniBooNE excess (in shower energy and angle) to true photon shower kinematics

2. Scale γ excess from MiniBooNE to MicroBooNE by **[number of nucleons]*** together with other detector differences

3. Propagate the γ excess through MicroBooNE analysis on top of the SM predictions.

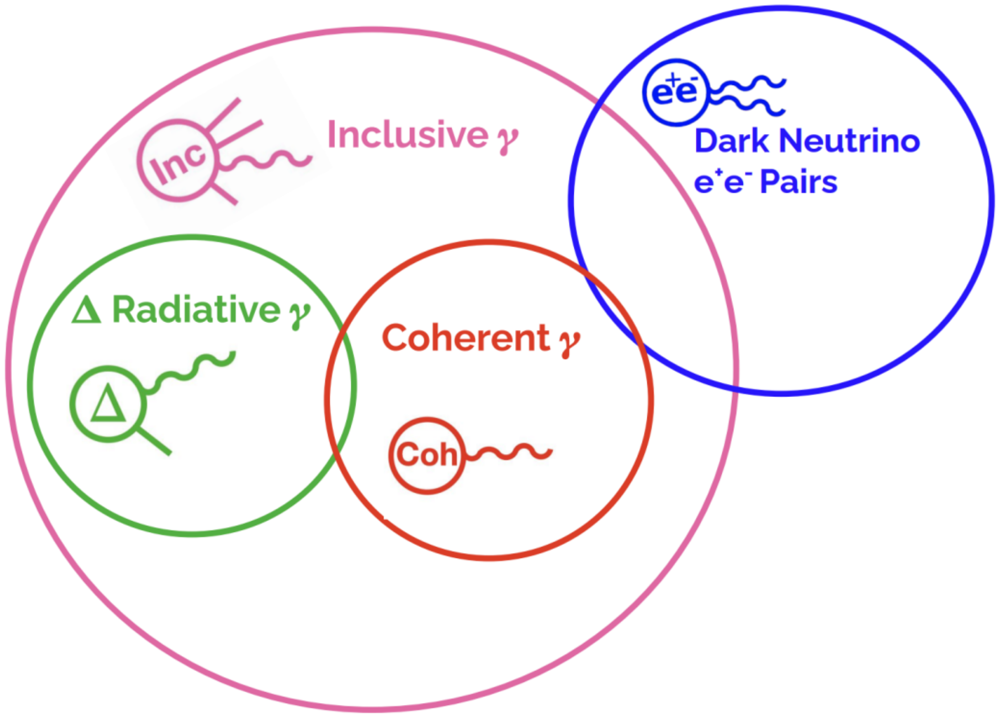
*many assumptions can go into the scaling factor when constructing the MB LEE model in uB.



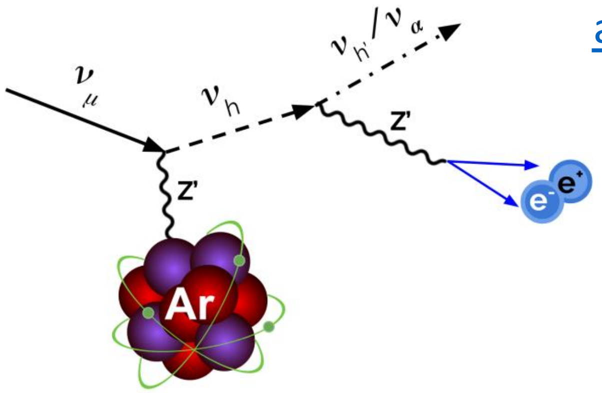
MiniBooNE LEE-γ model prediction smaller than observed excess!

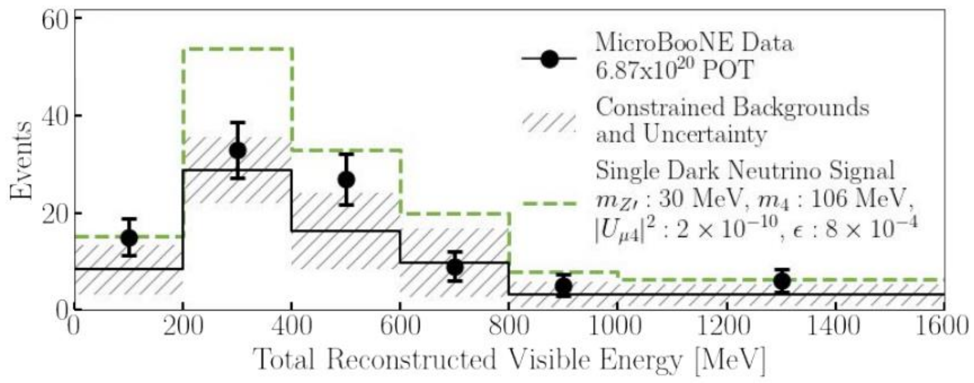
MicroBooNE photon excess – What's next?

A mild **2σ excess** in the inclusive single photon analysis narrows down the ROI at zero proton below 600 MeV shower energy.
Need deeper look at this ROI for **exclusive photon-like** search targeting on specific process, this could include BSM processes that produce single photon and e+e-



arxiv.2502.10900





Observe **no excess** of e^+e^- signal, placed world first direct bounds on the dark neutrino model and excluded the majority of the model phase space motivated by MB anomalies at **95% C.L**.

Summary of MicroBooNE's LEE search

- Observed **no excess** in the **electron** channel (exclusion at 99%CL with full dataset)

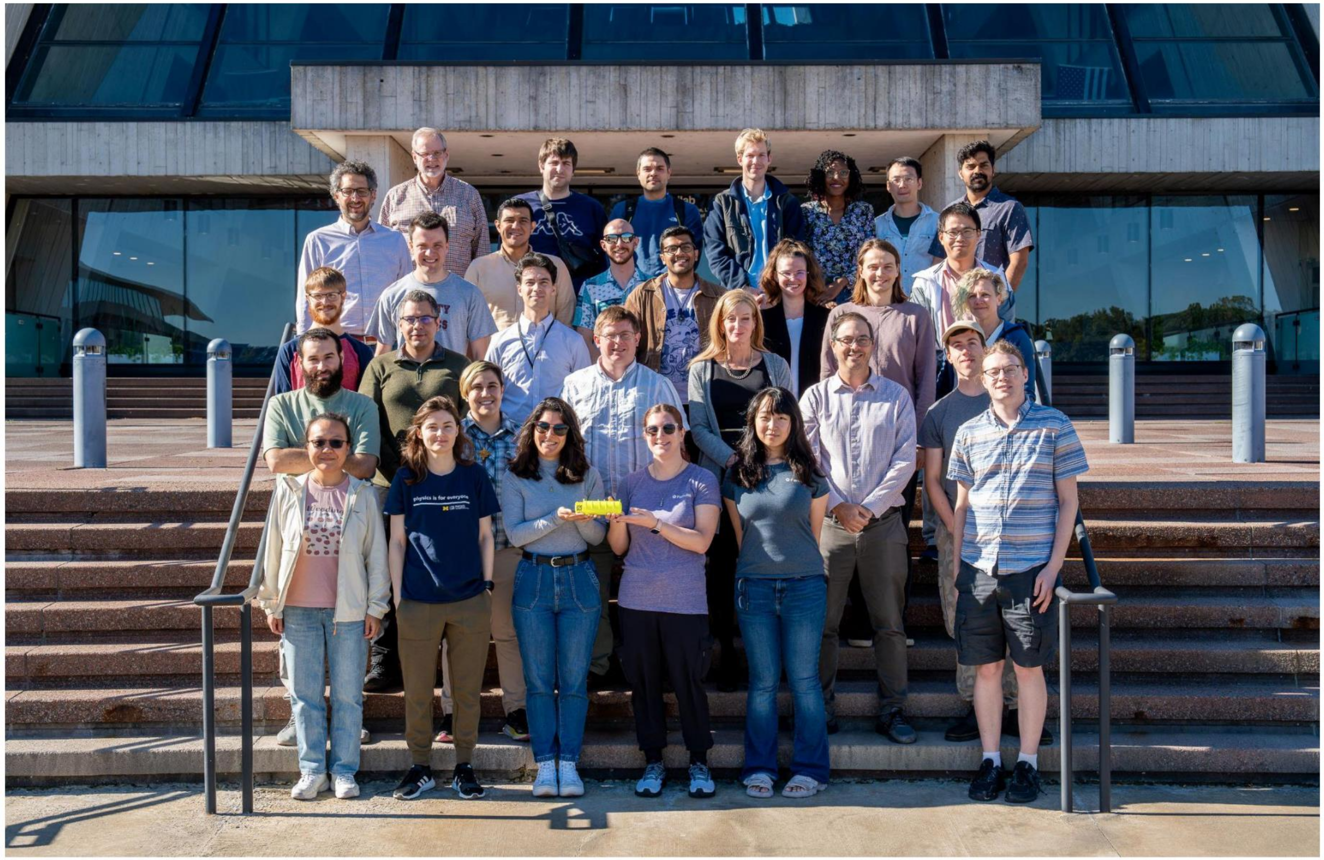
- **Inclusive photon LEE** search:
  - general agreement with SM prediction
  - **2σ** excess at ROI (zero proton & < 600MeV)
  - Excess shape similar to "NC$\pi^0 1\gamma$" (X2) or "Out-of-FV 1γ" (X1.6)

- No excess in exclusive γ/e^+e^- search investigated so far: NC $\Delta \rightarrow N\gamma$, NC Coherent, and Dark neutrino

- Four new papers featuring MicroBooNE LEE search on arXiv!

arxiv.2502.06064 arxiv. 2502.05750 arxiv.2502.06091 arxiv.2502.10900

µBooNE



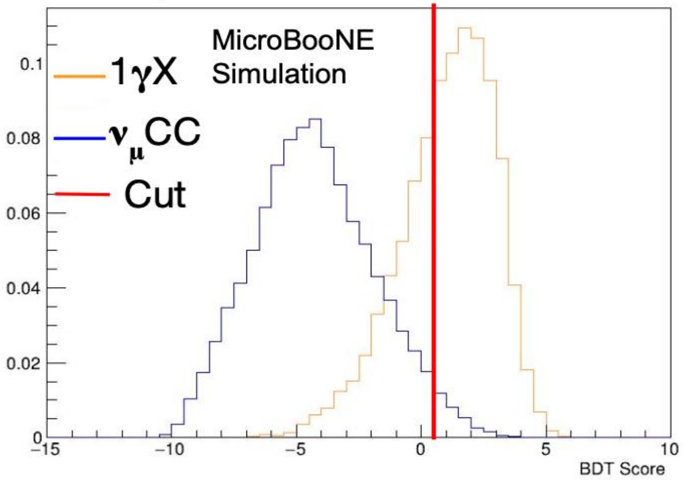
Thank you!

backup

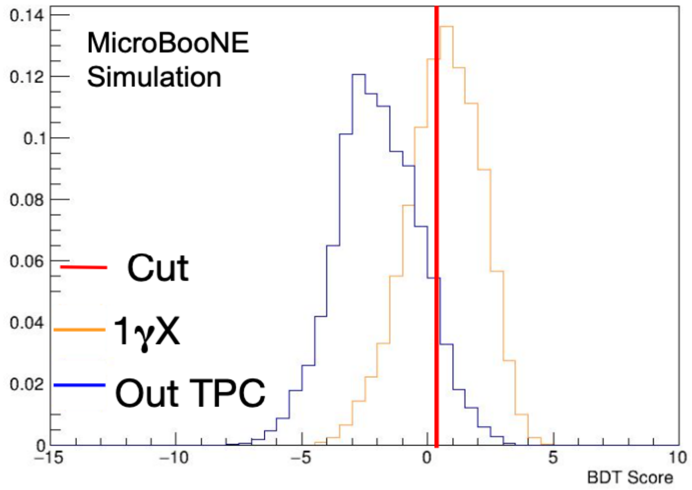
Inclusive photon LEE – signal selection

After Cosmic Rejection, S : B ~ 1 : 50 **-> Four BDTs targeted on background rejection**

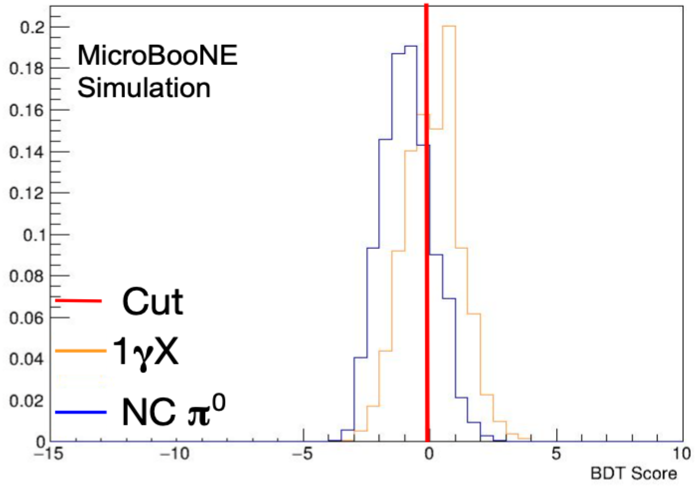
ν_μCC Removal BDT



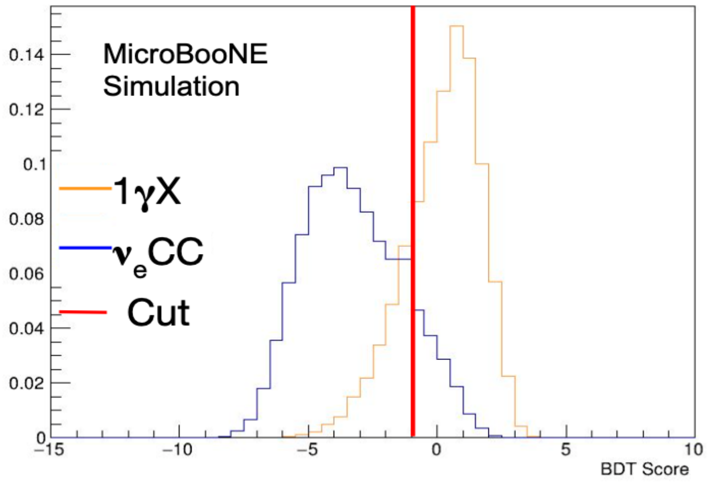
Outside TPC Removal BDT



NC π^0 Removal BDT



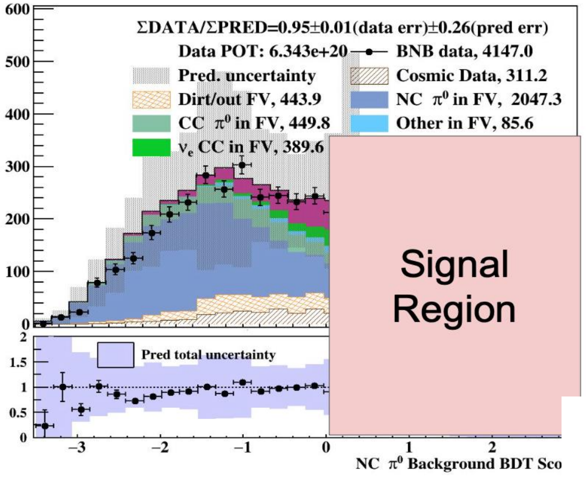
ν_eCC Removal BDT



- 1γX efficiency: 7%
- 1γX purity: 40%
- Efficiency/purity flat across kinematic variables, as designed for an inclusive photon LEE search to probe a wide phase-space.

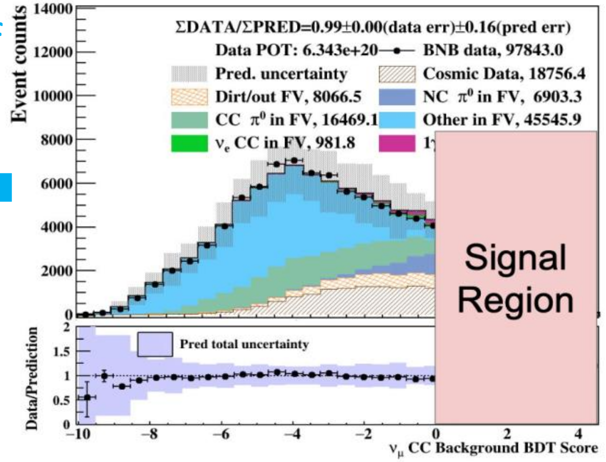
arxiv.2502.06064

Inclusive photon LEE – sideband constraints



Shower energy of $NC\pi^0$ Sideband

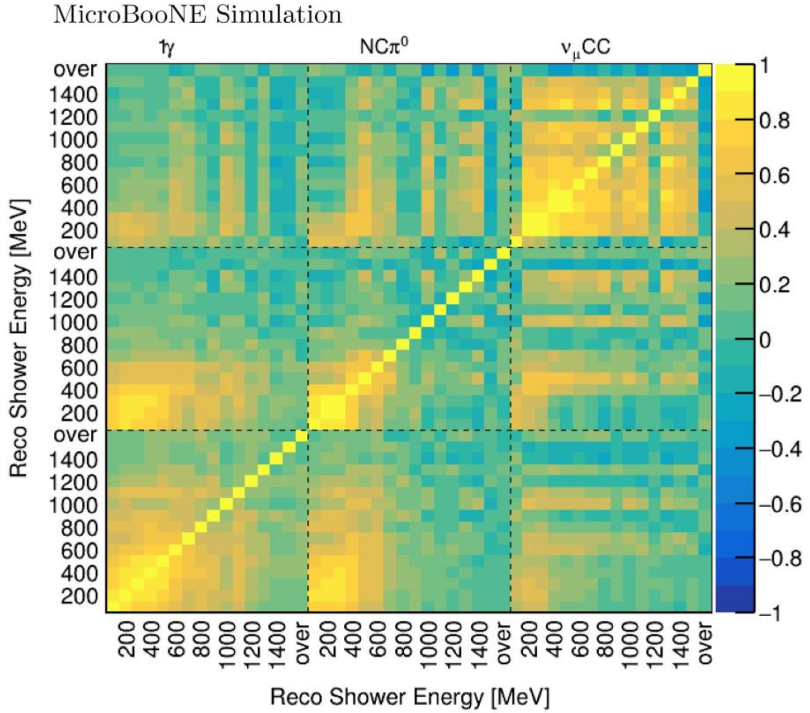
Shower energy of $\nu_\mu CC$ Sideband



Sidebands (left side of the BDT scores) used for Data/MC validation and signal constraints

Full correlation matrix:

- Flux
- Xsec
- Detector
- MC stat.
- Dirt



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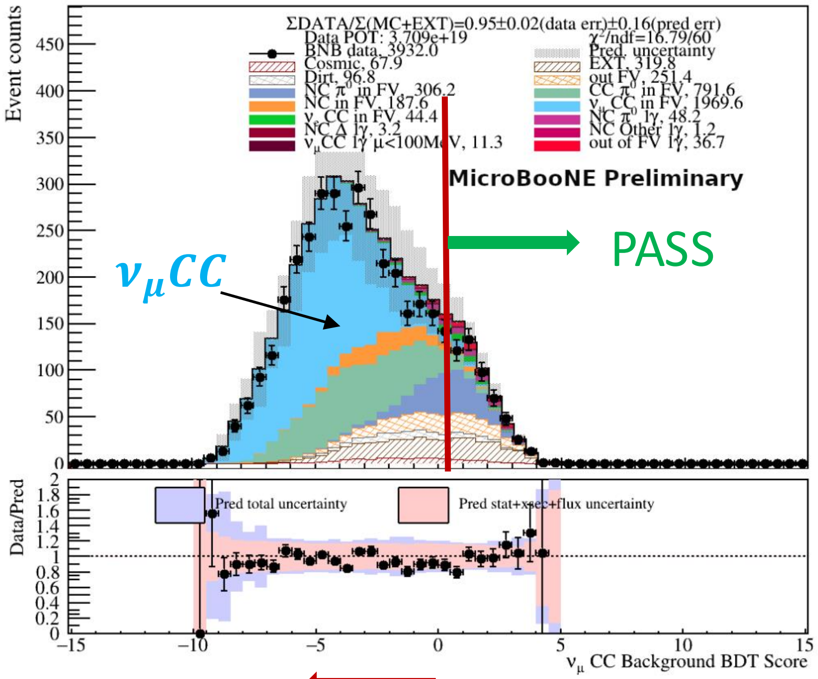
arxiv.2502.06064

Inclusive photon LEE – signal selection

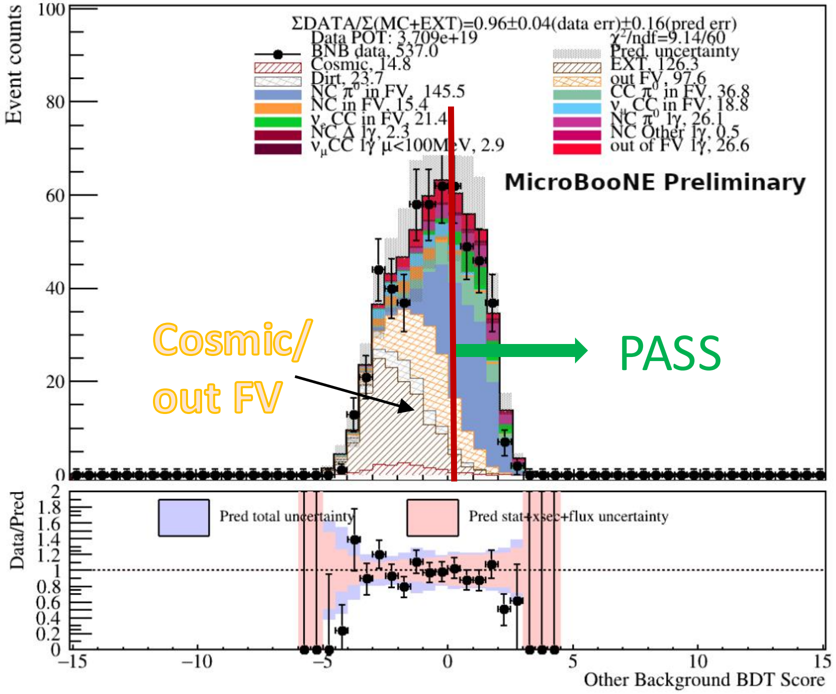
Four BDTs targeted on background rejection

$\nu_\mu CC$ BDT

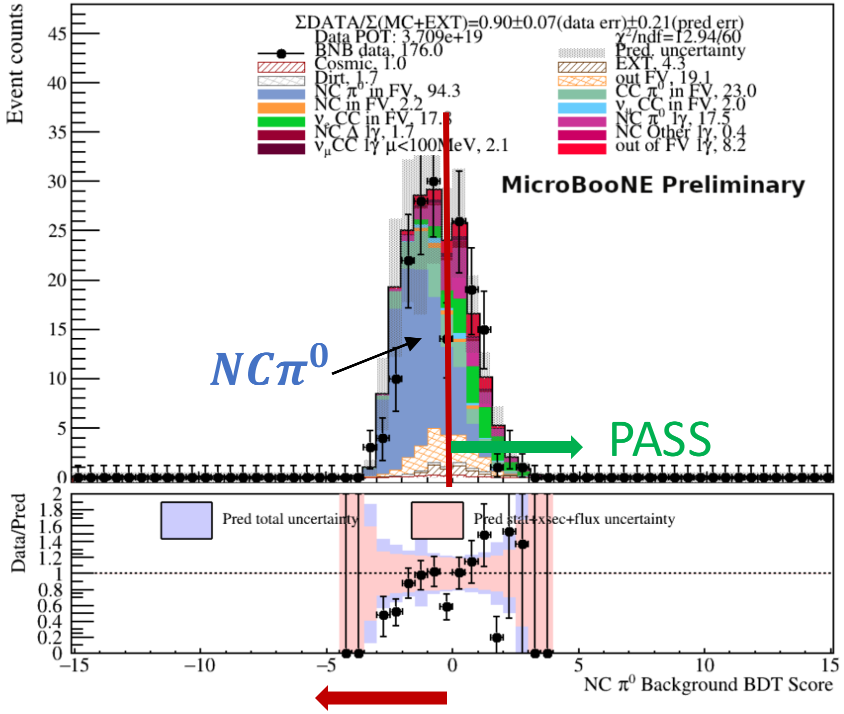


Used for Sideband Constraints

"Other" BDT

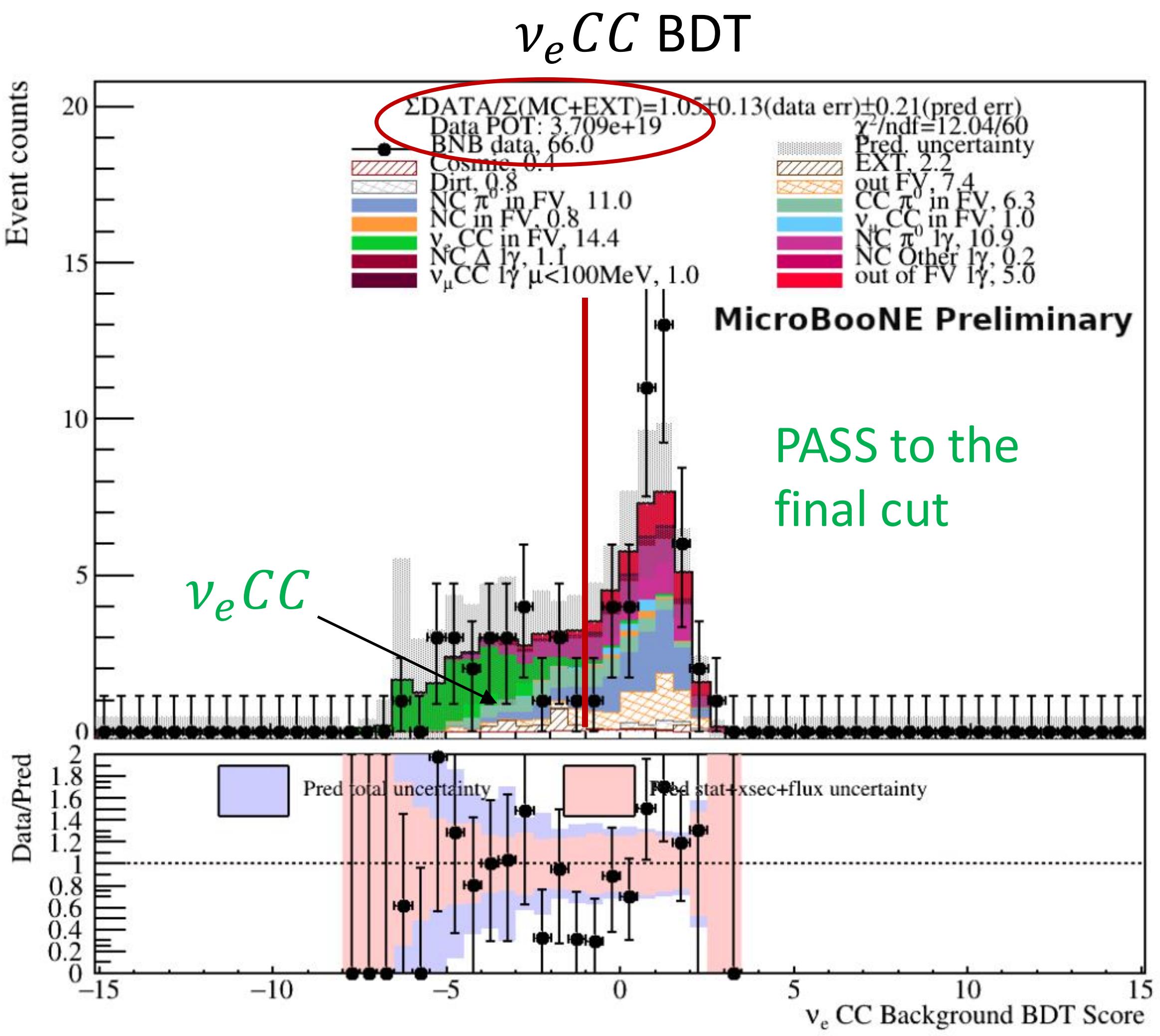


$NC\pi^0$ BDT



Used for Sideband Constraints

Inclusive photon LEE – signal selection



Last BDT: e/γ separation

Final cut: requiring exactly 1γ reco shower

S : B ~ 1 : 1

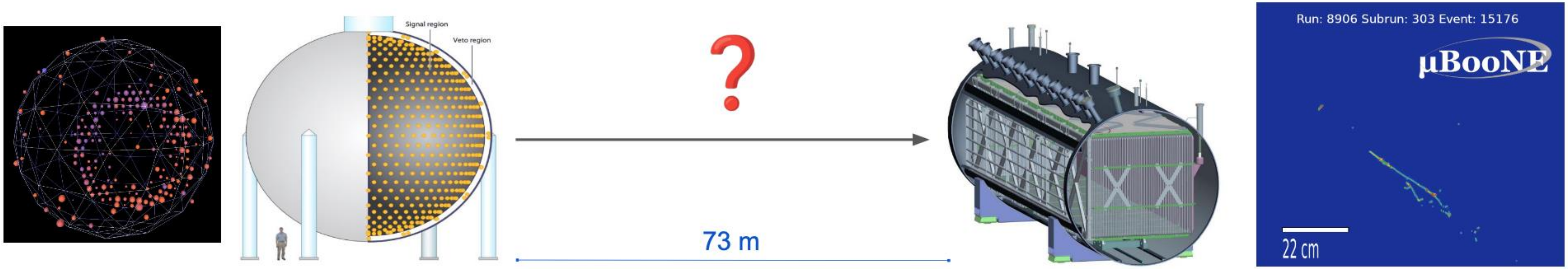
Blind analysis, this only uses ~2% of the full dataset

A MiniBooNE Excess Toy Model

$$\frac{N^{\mu\mathrm{B}}_{\mathrm{excess}}}{N^{\mathrm{MB}}_{\mathrm{excess}}} = \underbrace{\text{ratio in interaction/decay rate}}_{\text{e.g. } \frac{(M \text{ or } V)^{\mu\mathrm{B}}_{\mathrm{target}}}{(M \text{ or } V)^{\mathrm{MB}}_{\mathrm{target}}}} \times \underbrace{\text{ratio in flux}}_{\text{e.g. } \frac{POT^{\mu\mathrm{B}}}{POT^{\mathrm{MB}}} \times \frac{(L^{\mathrm{MB}}_{\mathrm{baseline}})^2}{(L^{\mu\mathrm{B}}_{\mathrm{baseline}})^2}}$$

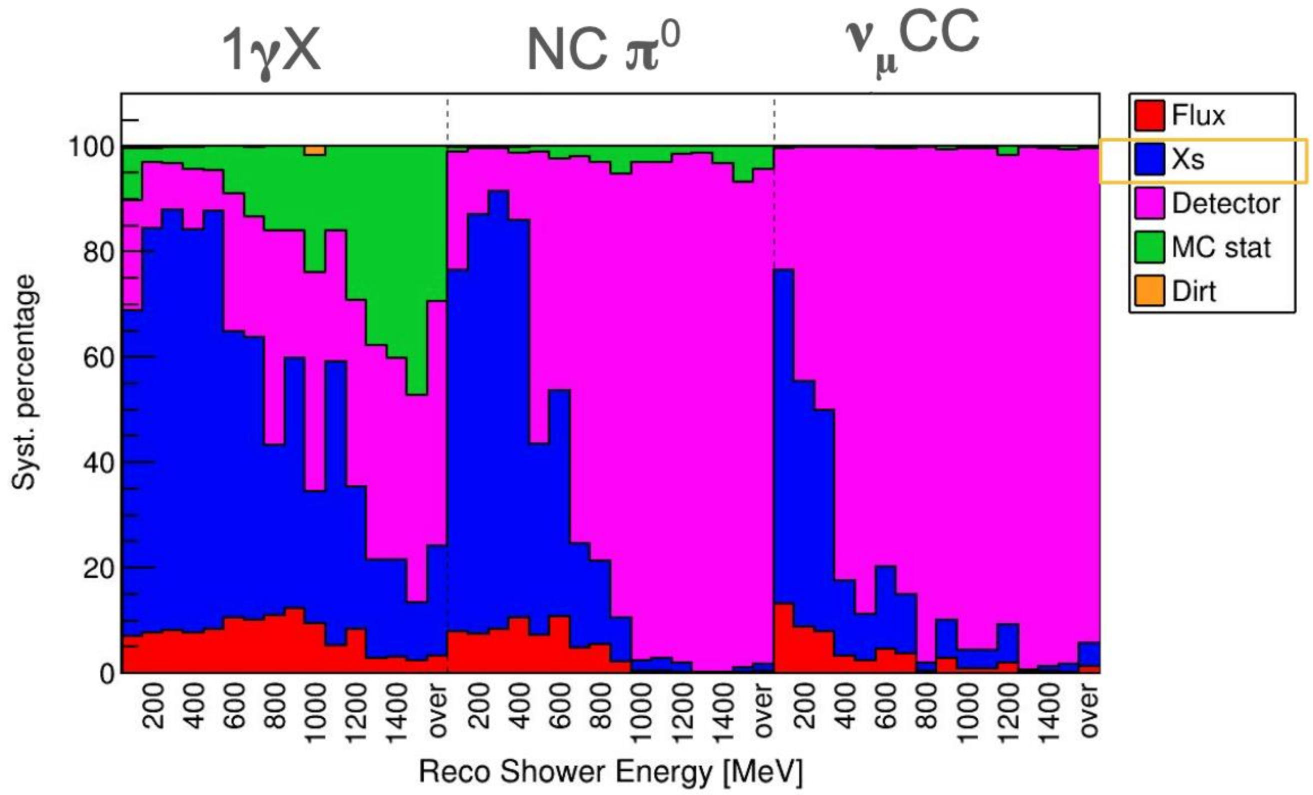
For photons, must make an assumption about the process the excess events originate from to determine overall scale factor of the excess from MiniBooNE to MicroBooNE. Some options include:

1. A neutrino interaction with target nucleons: Scale by mass (number of nucleons)
2. A coherent interaction: Scale by atom number
3. A decay-induced interaction: Scale by volume of the detector

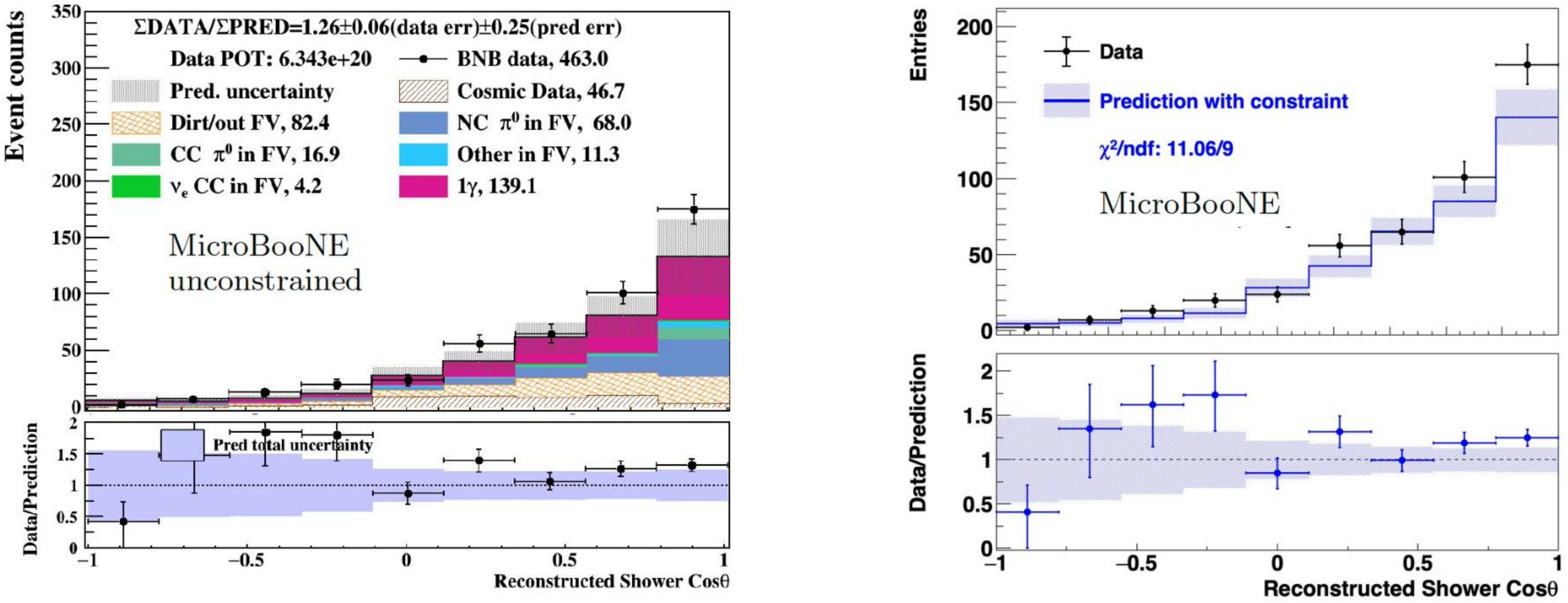


Uncertainties from the neutrino-argon cross-section based on the GENIE event generator and the hadron-argon interaction based on GEANT4

1. charged-current quasi-elastic (CCQE)
2. charged-current resonance (CCRES)
3. charged-current non-resonance
4. charged-current transition
5. charged-current deep-inelastic scattering (CCDIS)
6. neutral-current interactions
7. final-state interactions

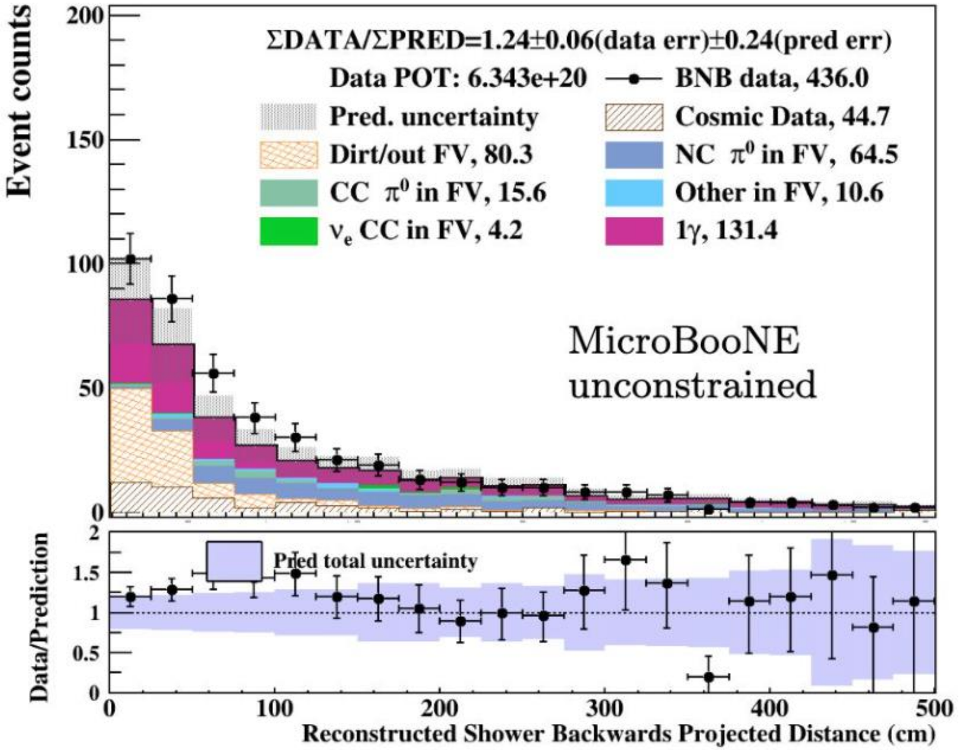


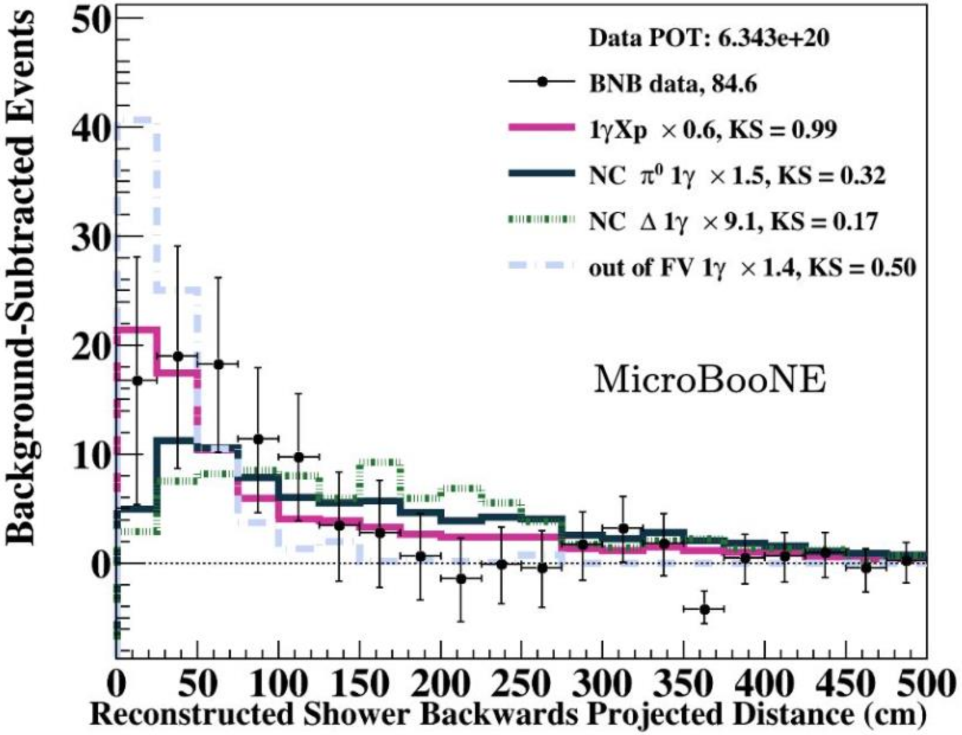
Inclusive Single-Photon, Zero-Proton Angle



Inclusive Single-Photon: Backwards Projected Distance

Single-Photon, Zero-Proton Events





What this means to theory...

My talk from CERN neutrino week in 2019!

	Models / MicroBooNE analyses	1e1p	1eNp	1eX	$1\gamma1$p	$1\gamma0$p	...
SM x-sections (NC Δγ)	NCγ Incoherent A. Ioannisian, 1909.08571	-	-	-	+	+	
	NCγ Coherent L Alvarez-Ruso et al 2018 J. Phys.: Conf. Ser. 1056 012001	-	-	-	+	+	
Dark neutrinos kinetic mixing (NC e^+e^-)	Light dark photon E. Bertuzzo et al, 1807.09877 Signature: forward boosted e^+e^- shower	-	-	+	+	+	
	Heavy dark photon P. Ballett et al, 1903.07589 Signature: showers + proton + gap	-	-	+	+	+	
Sterile Neutrinos (γ or e)	O(100MeV) Heavy sterile neutrino radiative decay Gninenko, PRL 103, 241802, L Alvarez-Ruso et al 2018 J. Phys.: Conf. Ser. 1056 012001	-	-	+	+	+	
	O(1eV) sterile neutrino oscillation (strong tension with LBL ν_μ disappearance data)	+	+	+	-	-	
	...						

Models manifest differently in event rates and kinematics. Sidebands checks are crucial to differentiate the models.
Discussion between theorists and experimentalists are very helpful to complete this table.

BSM Possibilities for the LEE

Category	Model	Signature	Anomalies LSND	MiniBooNE	Sources	References
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	osci…ns w/ ν_4 in… decay	✓	✓	✓	[151, 155]
	(3+1) w/ sterile decay	… →	✓	✓	✓	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via …atter effects	✓	✓	✗	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	… $\to \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	μ … $^+\nu_\alpha\overline{\nu_e}$	✓	✗	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to$ …	✓	✓	✗	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	…$\to \nu\gamma$	✗	✓	✗	[207]
	Dark sector heavy neutrino decay	…e^-)… N …$\nu(X \to$ …	✗	✓	✗	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	… $\to \nu$… $N \to \nu$…	✓	✓	✗	[205, 206, 209–216]
	neutrino dipole upscattering	…	✓	✓	✗	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	…^+e…	✗	✓	✗	[217]
	dark particle-induced inverse Primakoff		✓	✓	✗	[217]

- The MiniBooNE LEE has often been interpreted as an excess of e^- events, potentially from sterile neutrino short baseline $\nu_\mu \to \nu_e$ oscillations
- But there are lots of well motivated beyond-standard-model possibilities for γ and e^+e^- events as well

e⁻ Electron signals

γ Photon signals

γ γ Di-Photon signals

e⁺ e⁻ e+e- signals

Snowmass White Paper on Light Sterile Neutrinos
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