MicroBooNE Low-Energy-Excess Search - Photon Analyses

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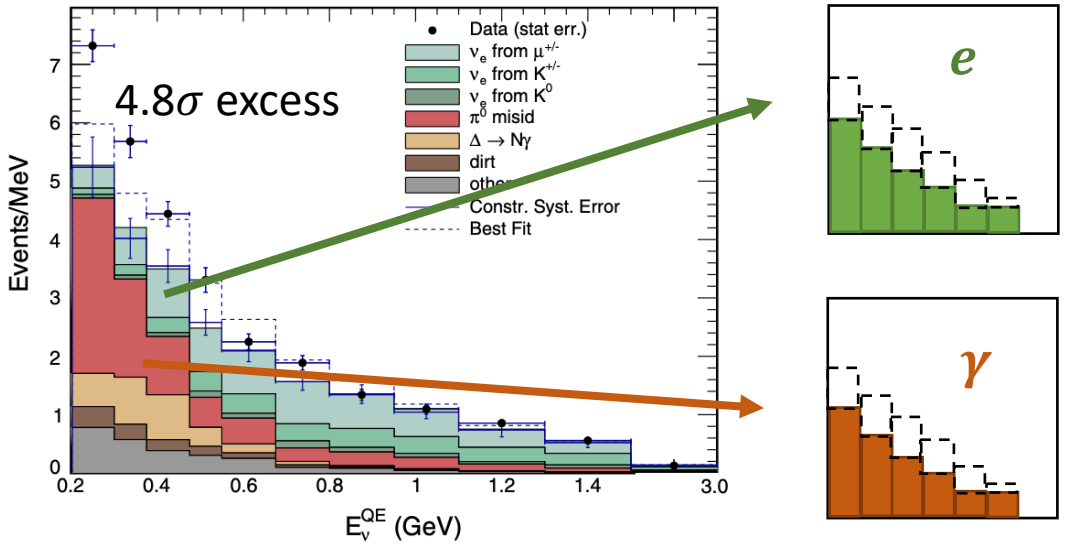
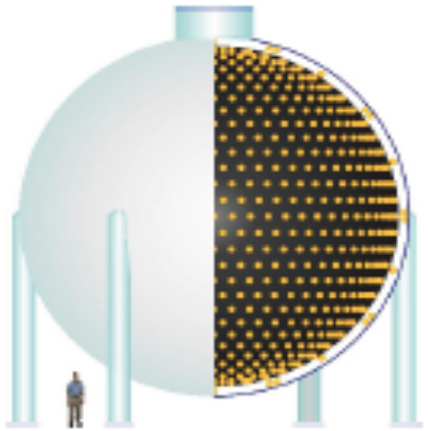
on behalf of MicroBooNE collaboration

MiniBooNE's Low-Energy-Excess (LEE) anomaly

MiniBooNE, PRD 103, 052002 (2021)



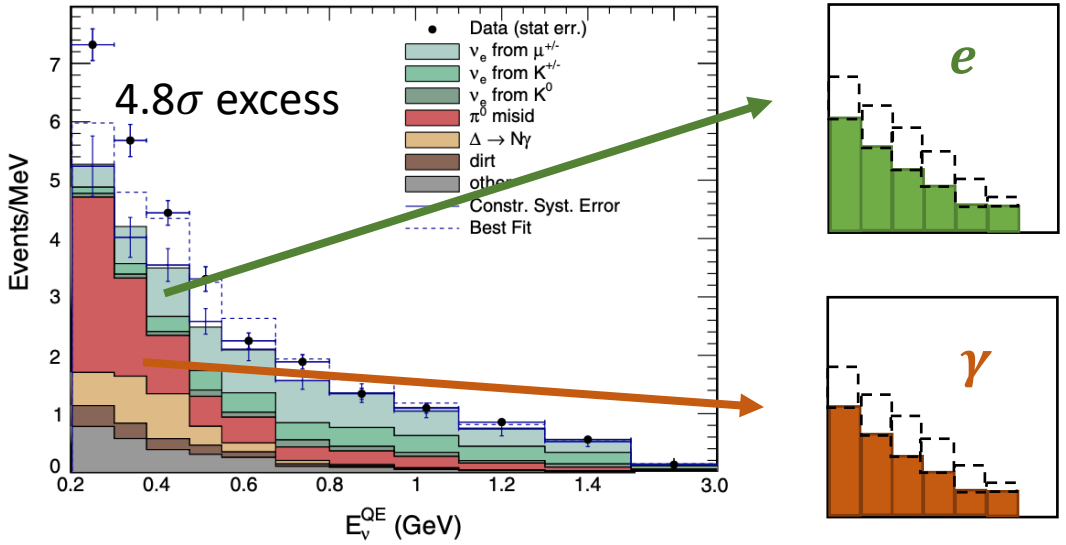


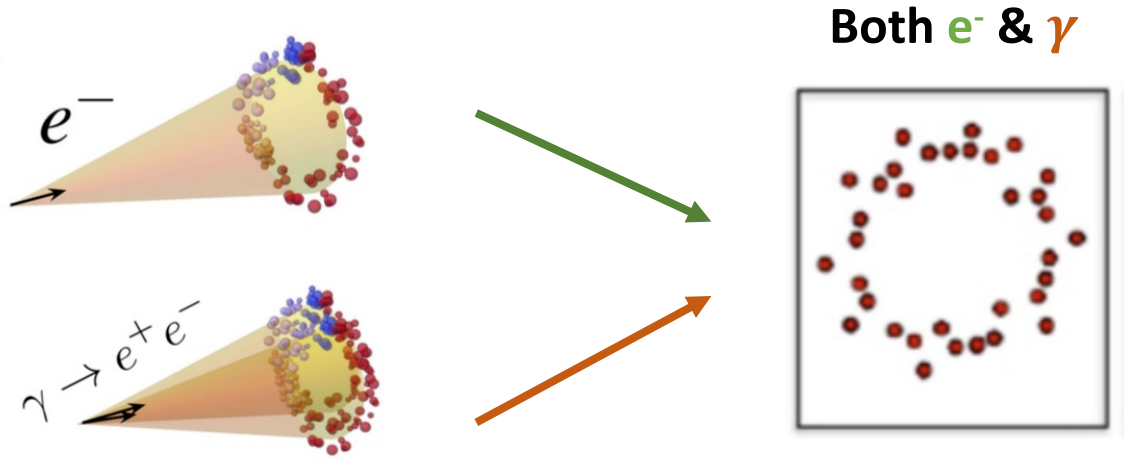
MiniBooNE

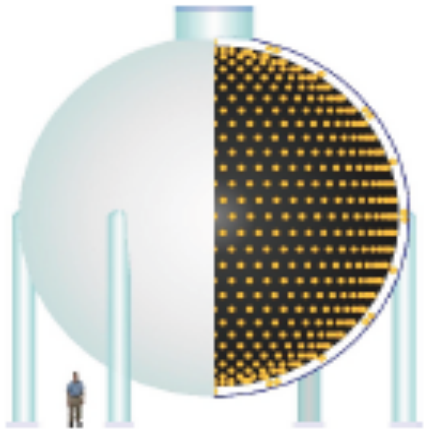
- Oil Cherenkov detector
- Located on-axis of Fermilab Booster Neutrino beam (BNB)
- with L/E ~1 m/MeV

MiniBooNE's Low-Energy-Excess (LEE) anomaly

MiniBooNE, PRD 103, 052002 (2021)







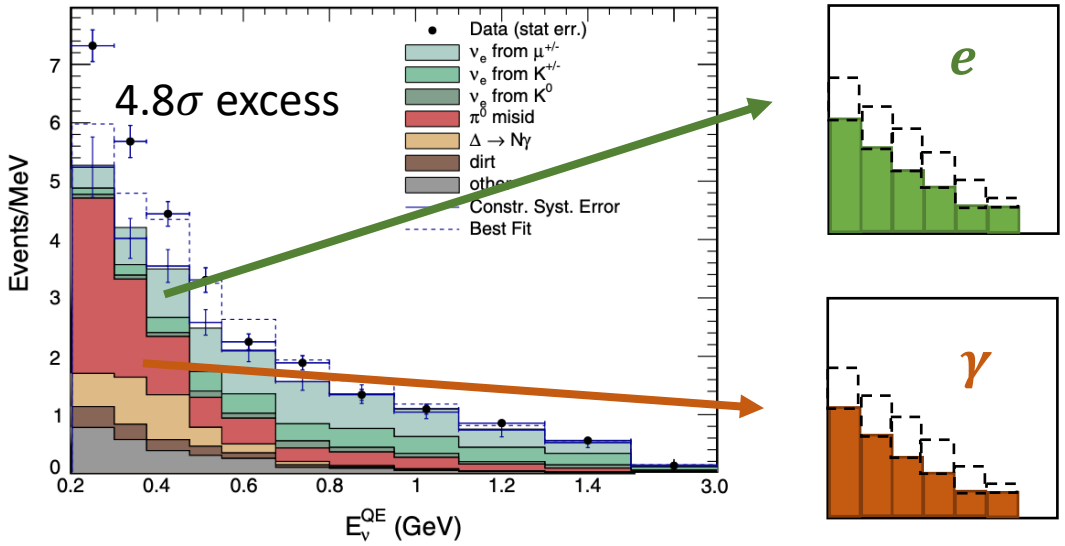
MiniBooNE

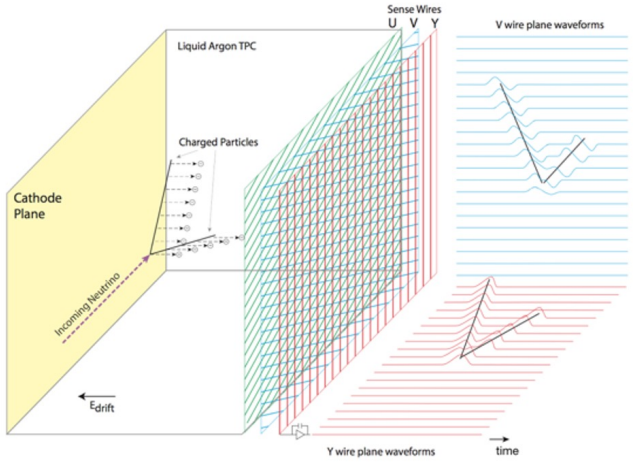
- Oil Cherenkov detector
- Located on-axis of Fermilab Booster Neutrino beam (BNB)
- with L/E ~1 m/MeV

MiniBooNE detector is not able to distinguish e^- from γ.
Need a different detector technology to understand the origin of this LEE anomaly-> MicroBooNE's primary physics goal

MicroBooNE's LArTPC going after LEE

MiniBooNE, PRD 103, 052002 (2021)



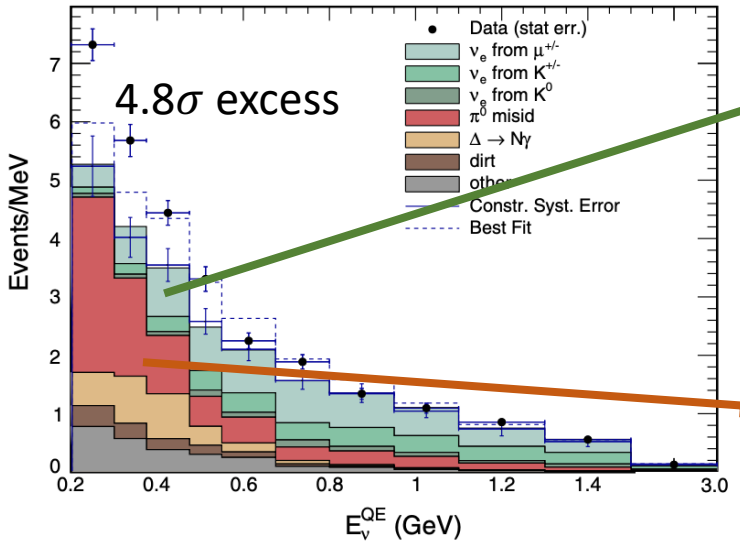


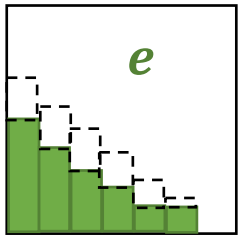
MicroBooNE

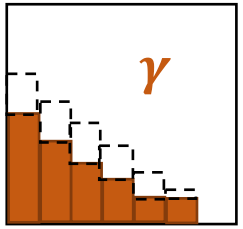
- Liquid Ar Time Projection Chamber (LArTPC)
- Located right upstream of MiniBooNE, same beamline -> same L/E as MiniBooNE

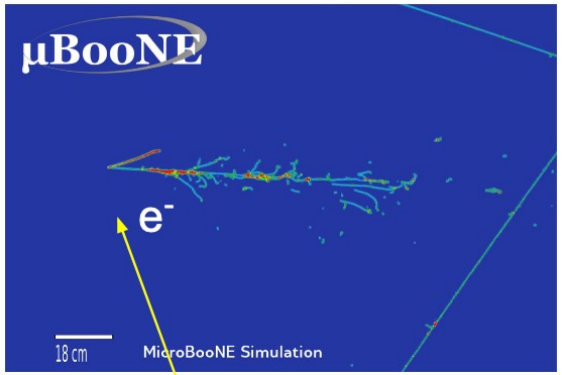
MicroBooNE's LArTPC going after LEE

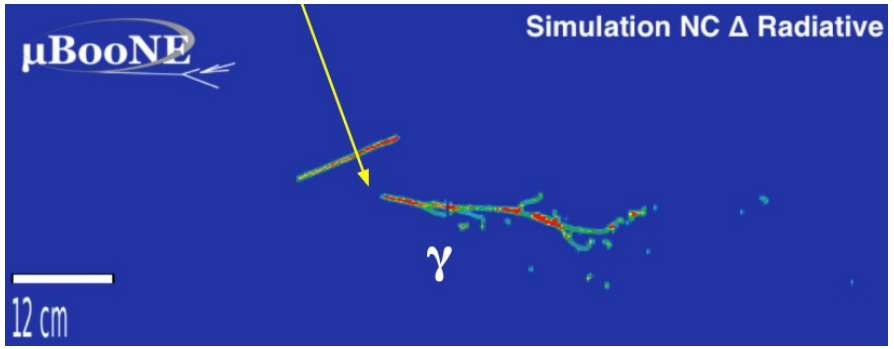
MiniBooNE, PRD 103, 052002 (2021)





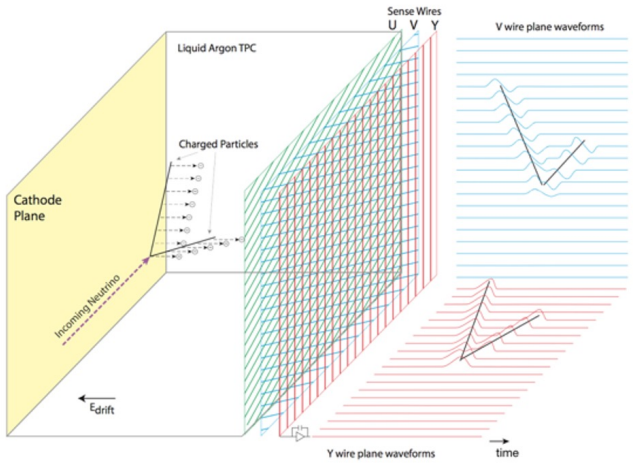






Two handles for e^- /γ separtion

- Gap between shower start and vertex
- 2MIP Vs 1 MIP for shower dE/dx



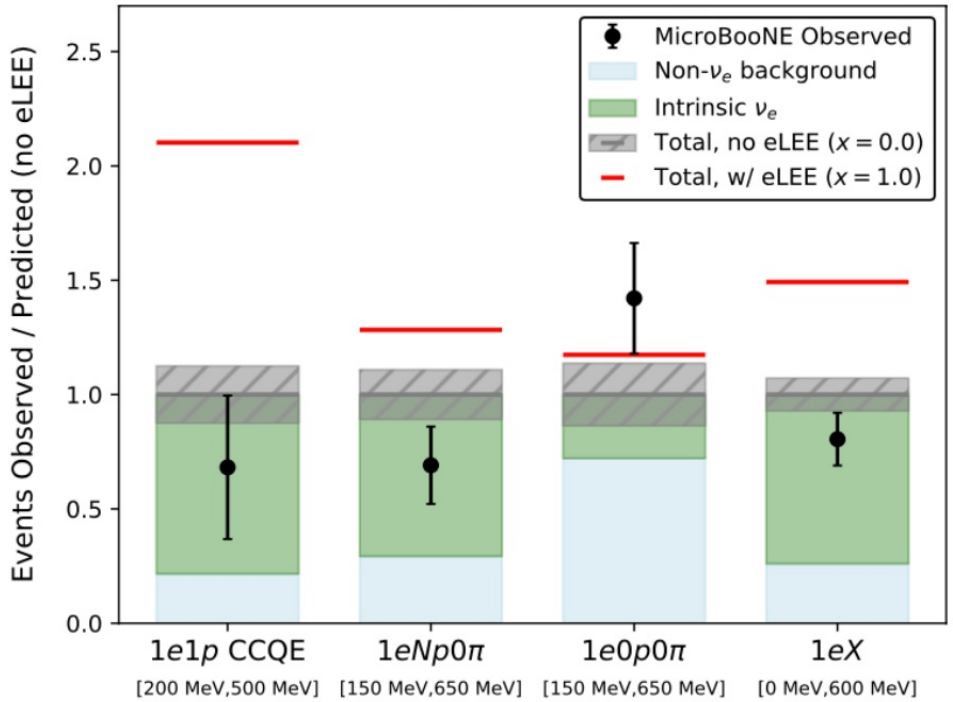
MicroBooNE

- Liquid Ar Time Projection Chamber (LArTPC)
- Located right upstream of MiniBooNE, same beamline -> same L/E as MiniBooNE

MicroBooNE's signature LEE analyses search for excess events in electron and photon channel

1st round of Electron LEE search result

Phys. Rev. Lett. 128, 241801 (2022)



No significant excess in the ν_e channel!

Observed ν_e rates are **consistent** with the predicted background in the low energy region:

- Slight data deficit overall
- 1e0p background dominated

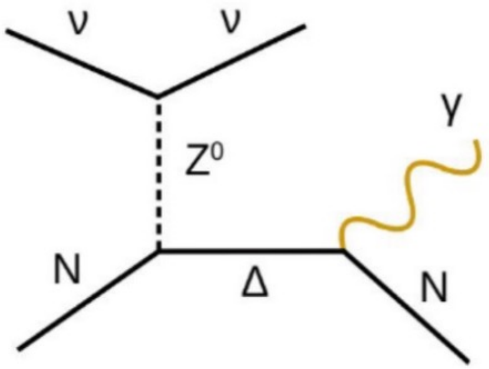
Result

ν_e alone to explain MiniBooNE-LEE is rejected at 97% C.L.;
(>3σ in the inclusive channel)

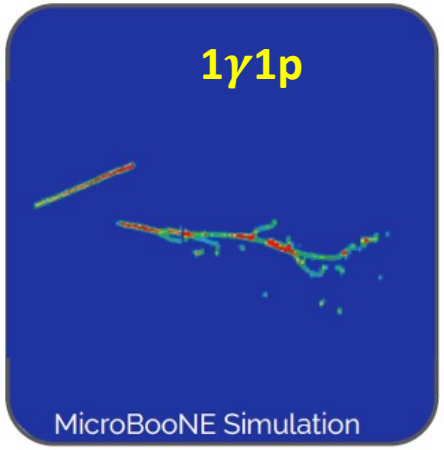
New eLEE result with **full dataset** presented by Miquel Nebot-Guinot on Thursday

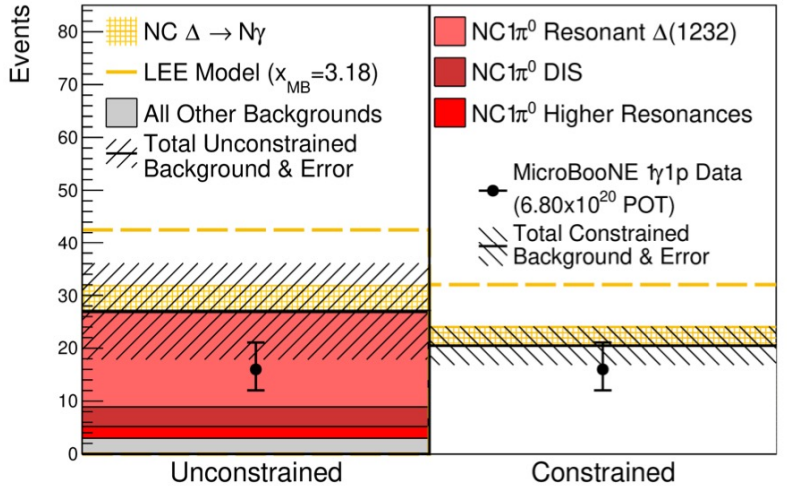
1st round of photon LEE search: $NC\ \Delta\rightarrow N\gamma$

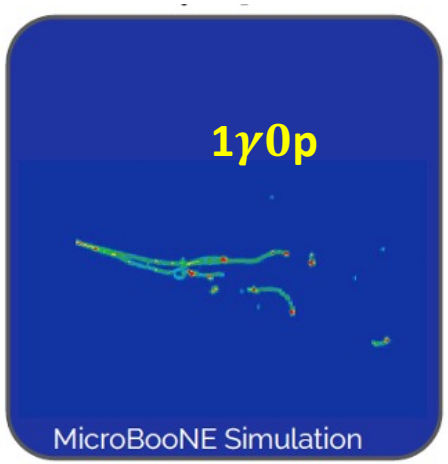
NC $\Delta\rightarrow N\gamma$

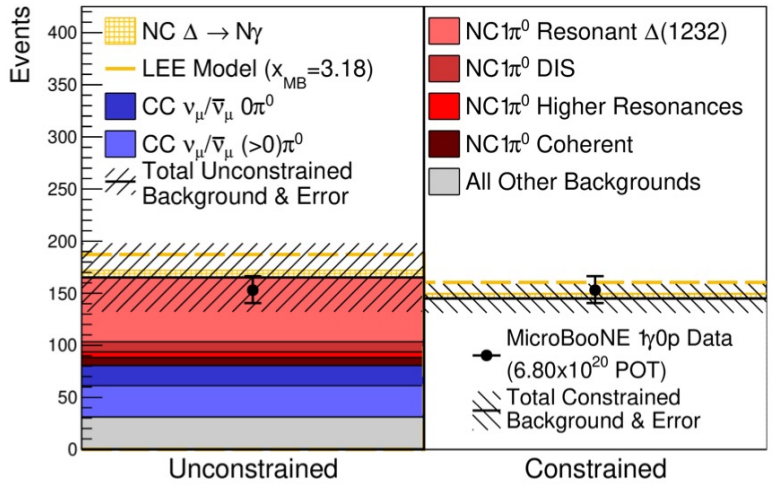


A flat ~3X enhancement of the SM rate would match the MiniBooNE LEE









Result

- Observed **no data excess** in both NC $\Delta\rightarrow N\gamma$ signal channels
- Reject 3x NC$\Delta\rightarrow N\gamma$ rate at 95% C.L.

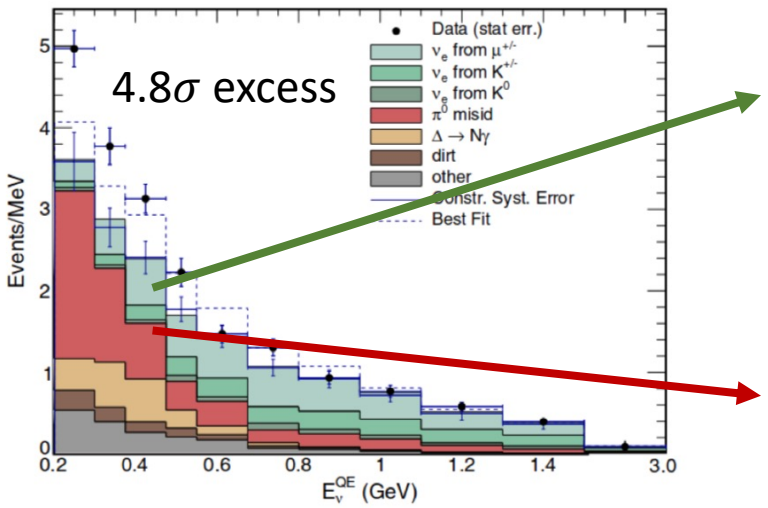
Phys. Rev. Lett. 128, 111801 (2022)

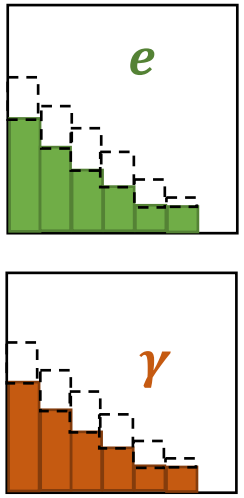
Summary of 1st round of MicroBooNE LEE results:

No excess:

- in the electron channel
- only investigated in the **NC $\Delta\rightarrow N\gamma$** channel

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





?

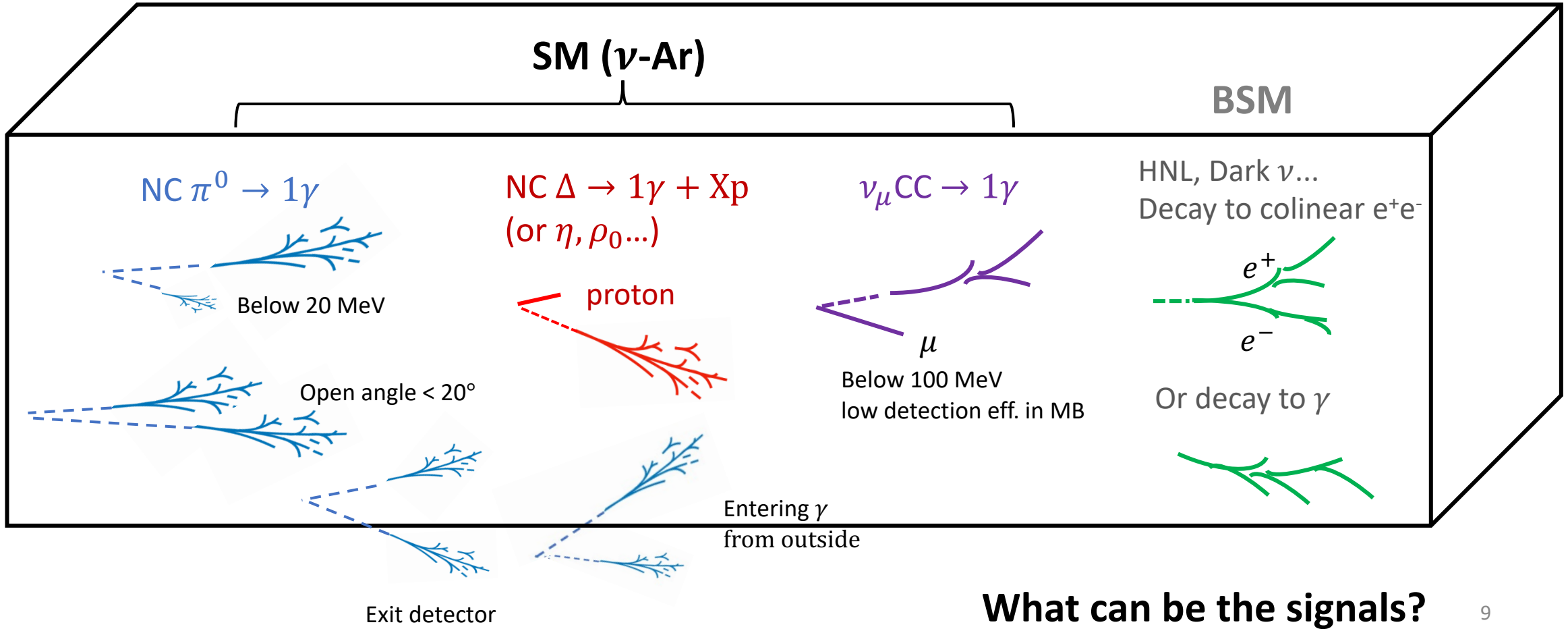
To address if MicroBooNE sees any excess in the **photon** channel

New round of Photon LEE analyses

- **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
- Exclusive channels
  - Extended NC $\Delta\rightarrow N\gamma$
  - NC Coherent
  - BSM decay to e^+e^- and γ

Inclusive photon LEE – signal definition

Model-independent approach: select an inclusive set of photon events that can enter the MiniBooNE LEE plot. -> Final states: One visible γ-like shower + anything.

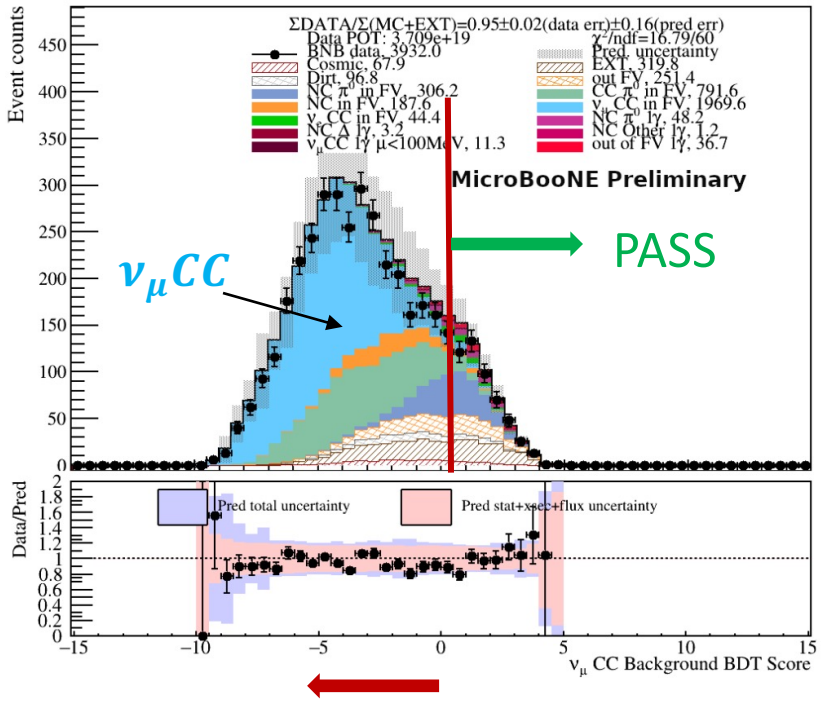


What can be the signals?

Inclusive photon LEE – signal selection

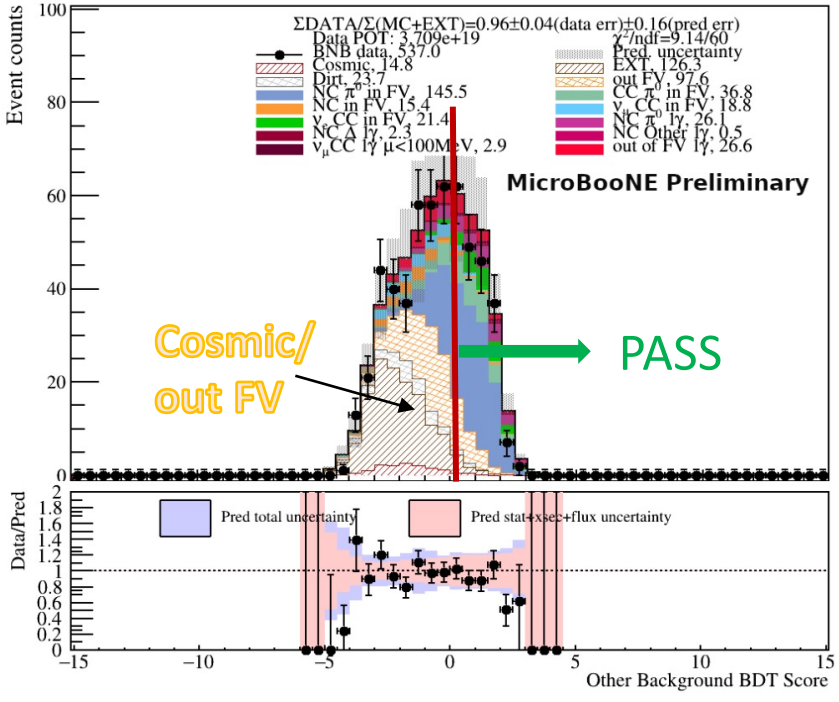
After Cosmic Rejection, S : B ~ 1 : 100 -> **BDTs targeted on background rejection**

$\nu_\mu CC$ BDT

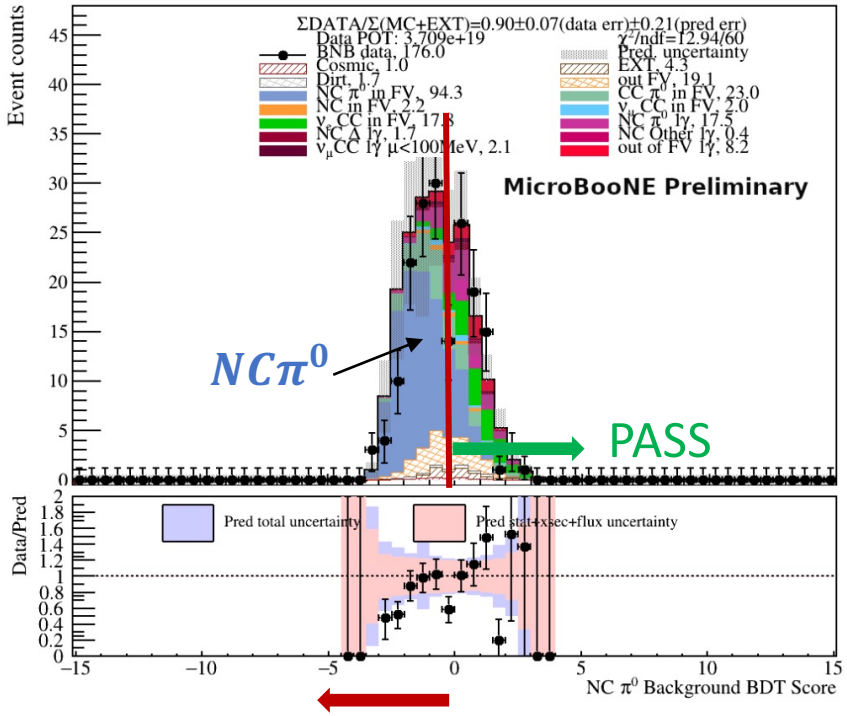


Used for Sideband Constraints

"Other" BDT

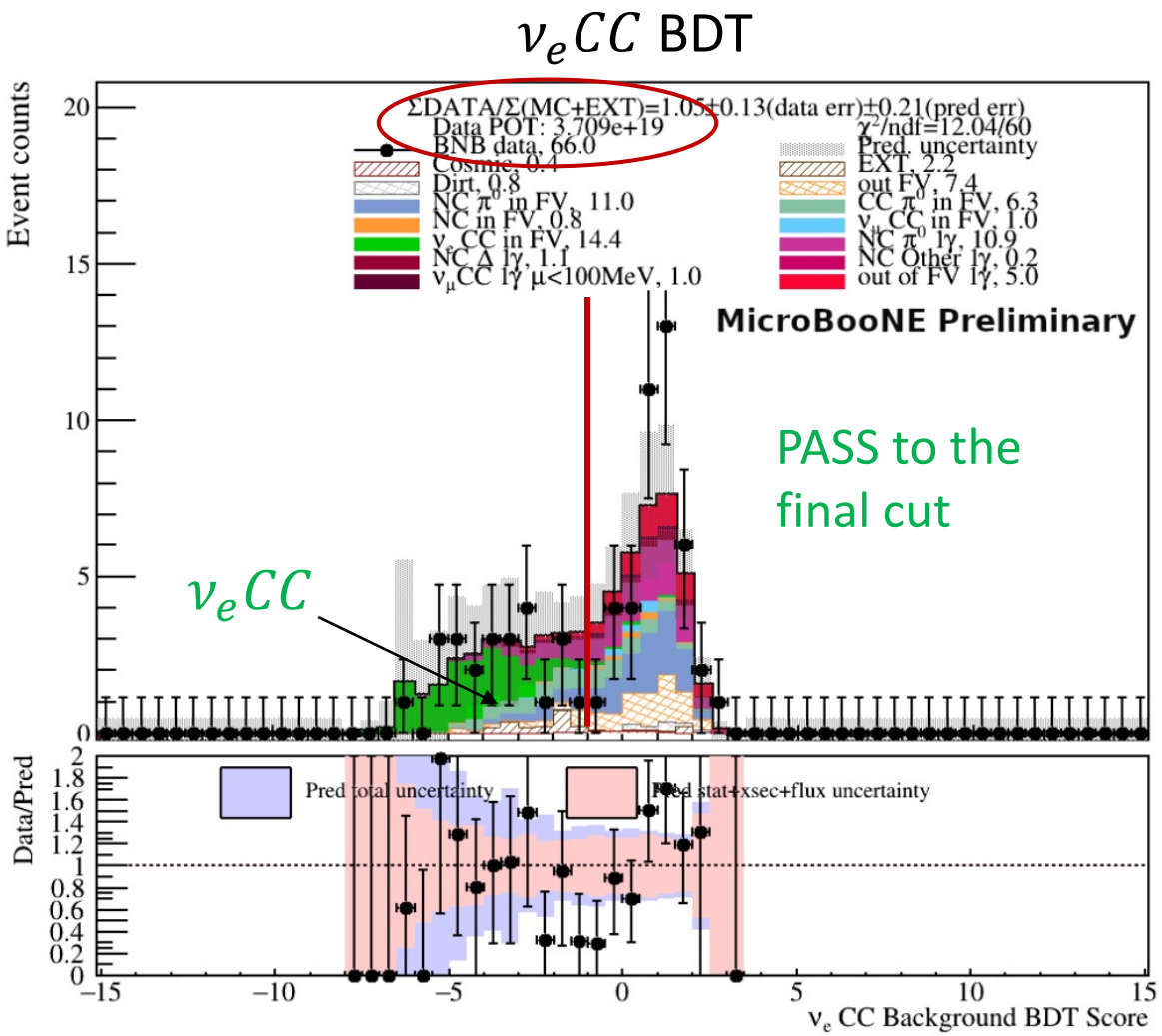


$NC\pi^0$ BDT



Used for Sideband Constraints

Inclusive photon LEE – signal selection



Last BDT: e/γ separation

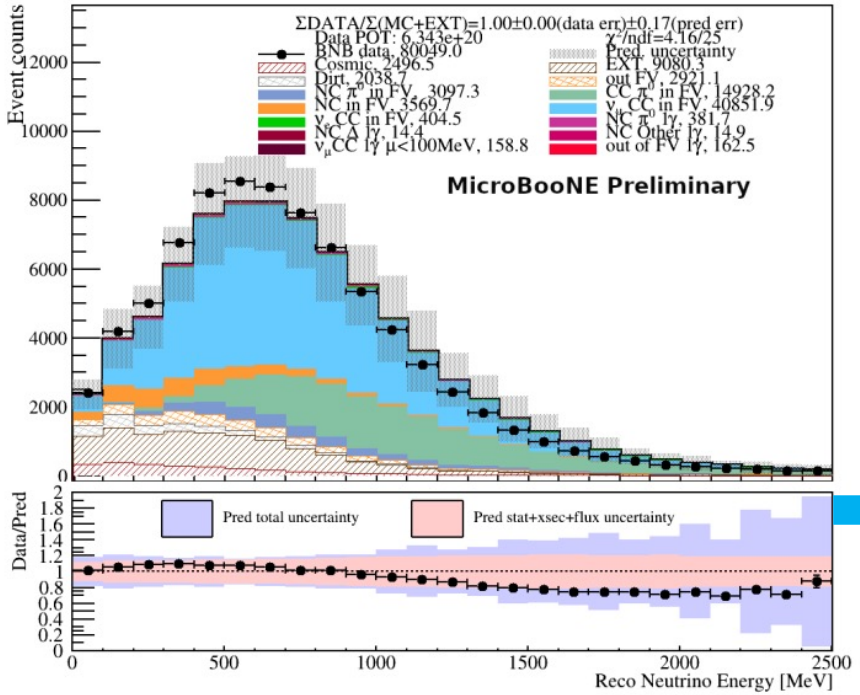
Final cut: requiring exactly 1γ reco shower

S : B ~ 1 : 1

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

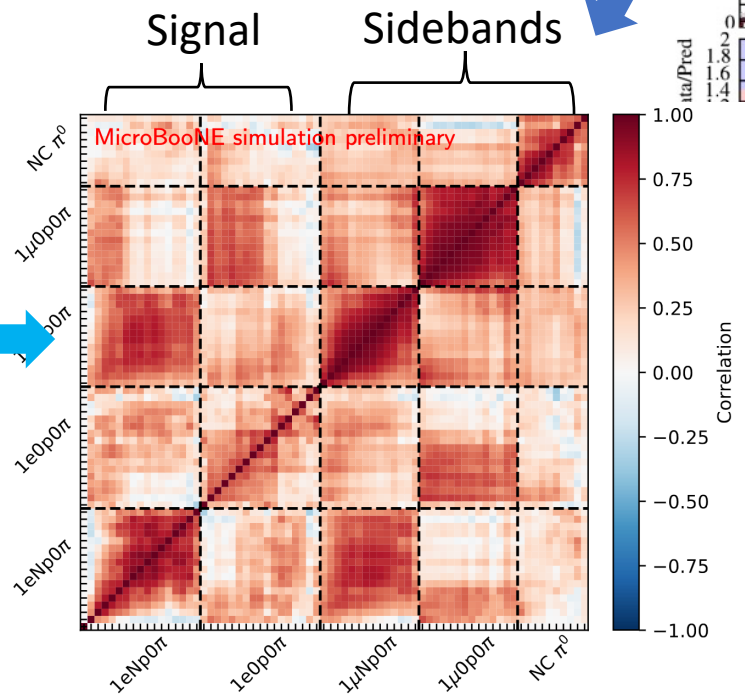
Sideband constraints

Reco. ν Energy

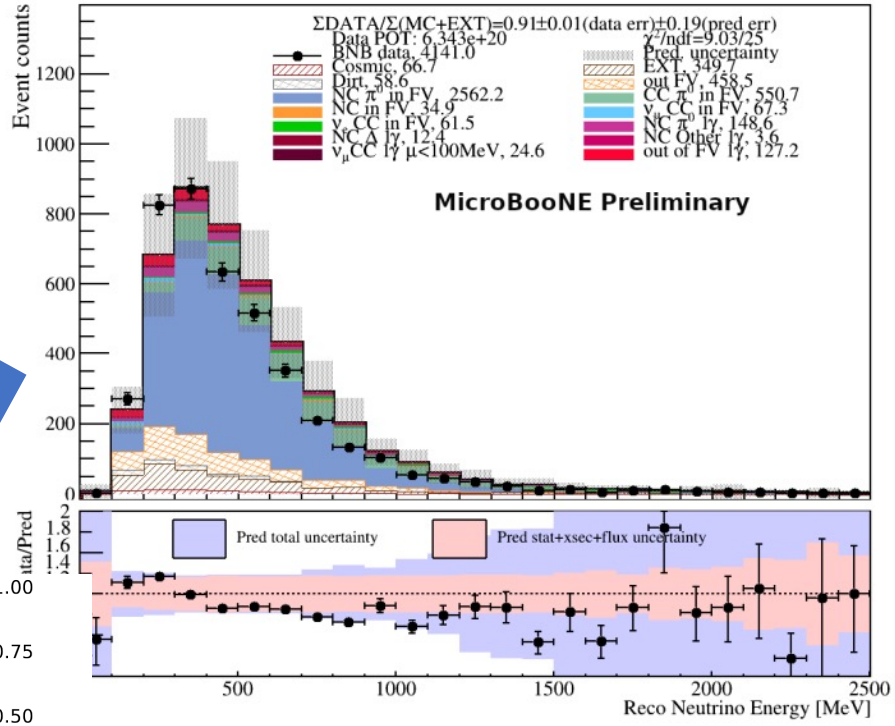


$\nu_\mu CC$ Sideband
(Left side of
$\nu_\mu CC$ BDT)

Use our own data in the sidebands to constrain the uncertainty in the signal region



Reco. ν Energy



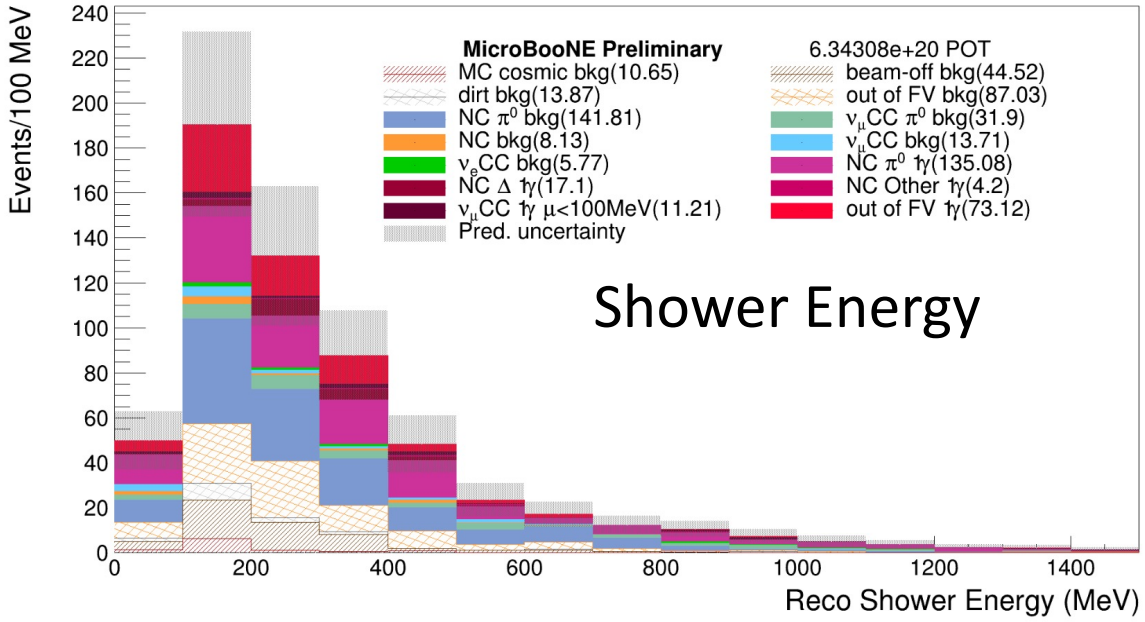
$NC\pi^0$ Sideband
(Left side of
$NC\pi^0$ BDT cut)

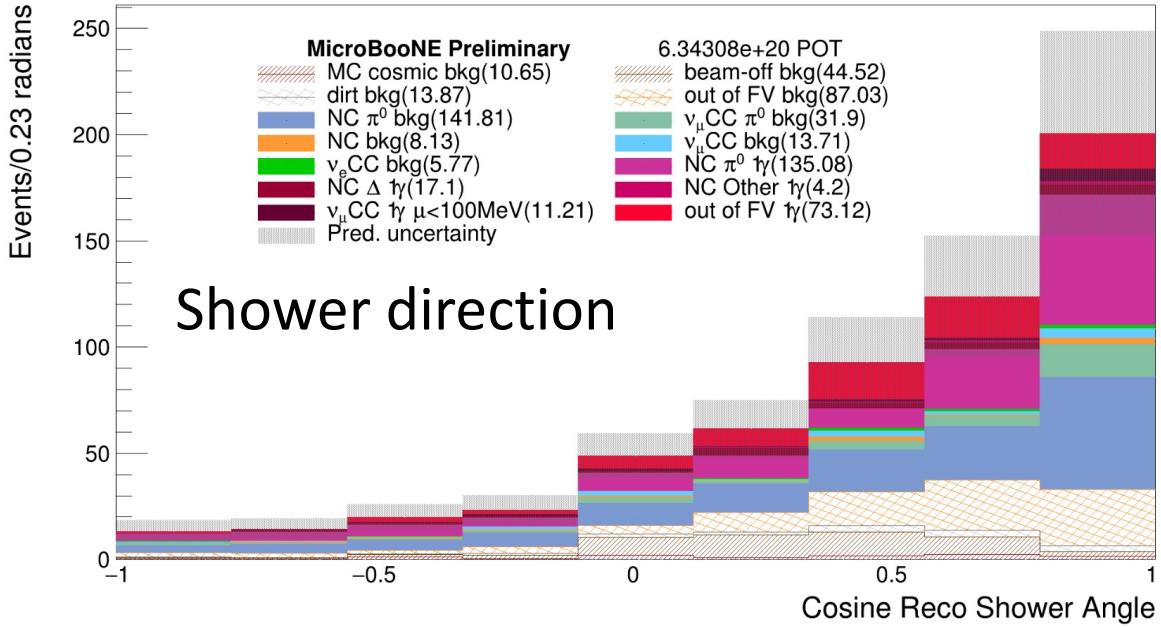
Example of the correlation matrix between sidebands and signal sample from the new eLEE analysis

Inclusive photon LEE status

MICROBOONE-NOTE-1125

Final selection: reconstructed photon shower energy and angle



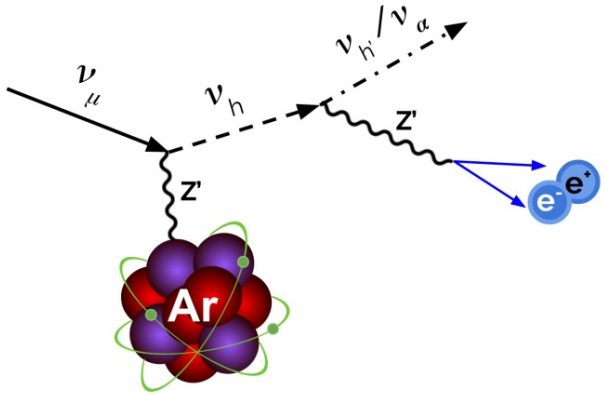


Inclusive analysis access a broad range of kinematic phases (e.g. number of protons), crucial to characterize the events in case of an excess

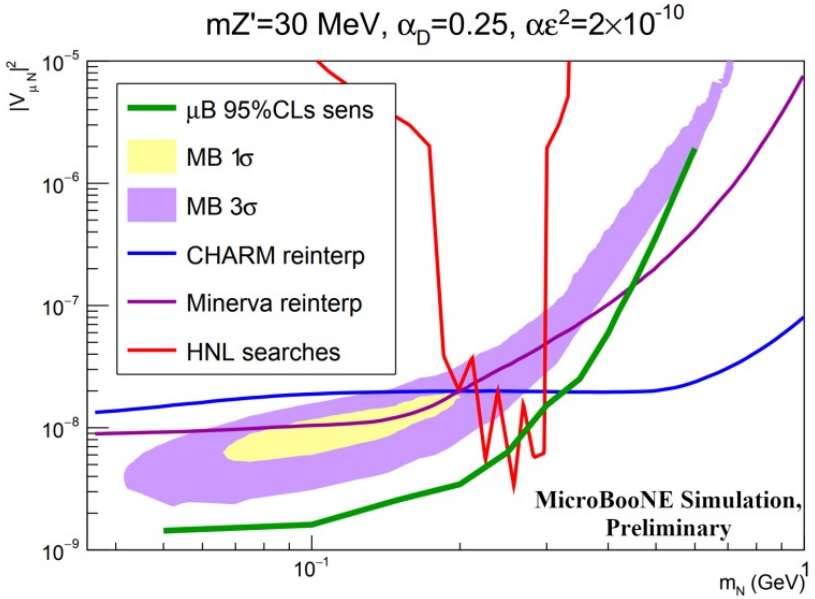
Current status: analysis development completed

Result coming soon!

Exclusive LEE analyses in γ/e^+e^-

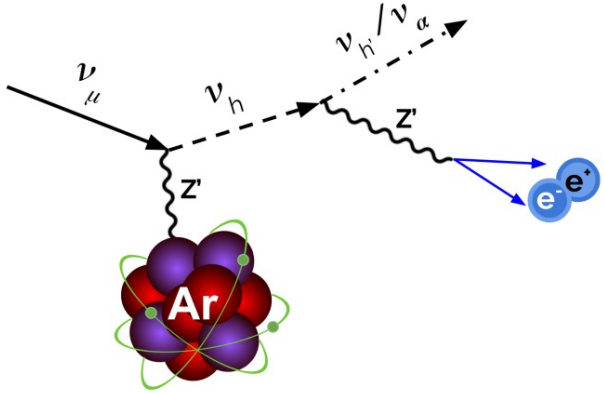


Dark ν decays to e^+e^-



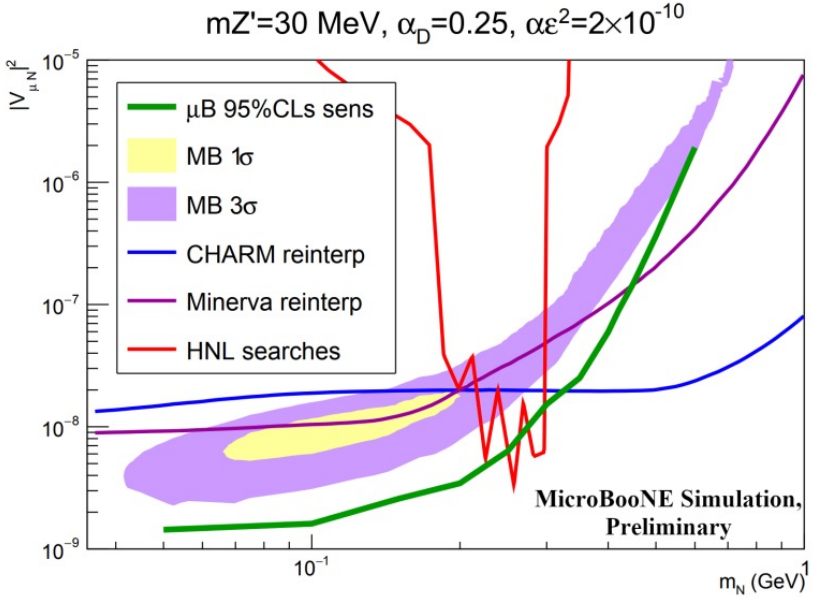
MICROBOONE-NOTE-1124

Exclusive LEE analyses in γ/e^+e^-

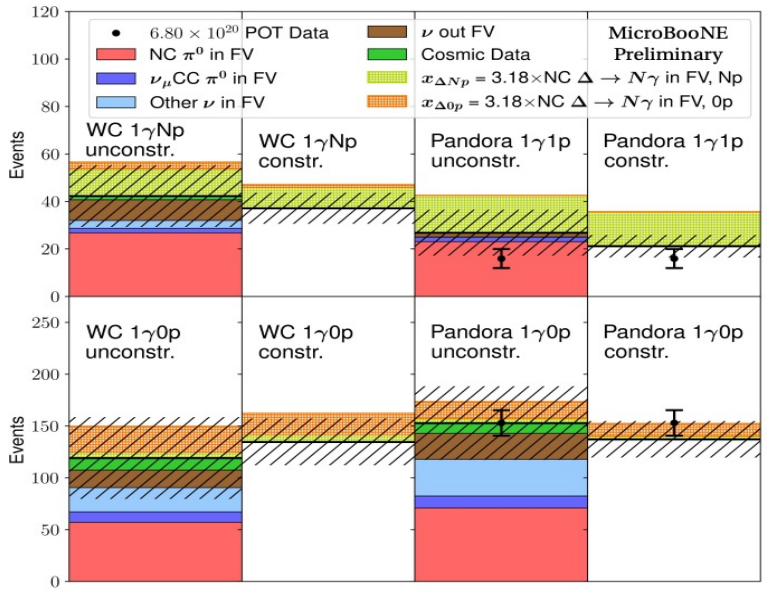


Dark ν decays to e^+e^-

Updated NC$\Delta \rightarrow 1\gamma$

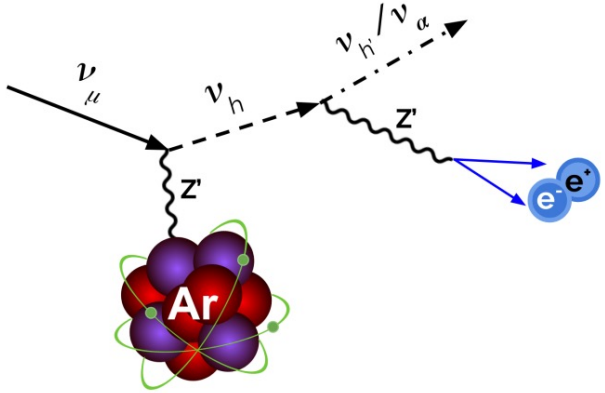


MICROBOONE-NOTE-1124



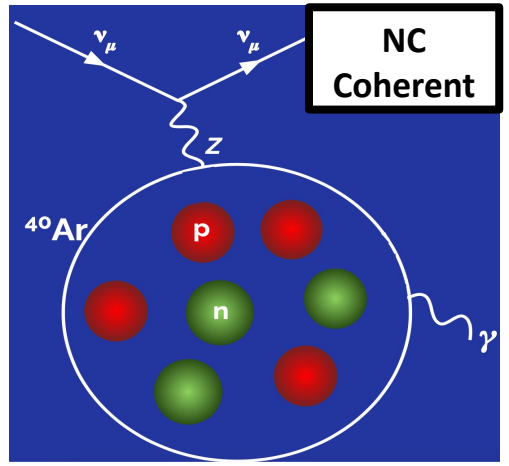
MICROBOONE-NOTE-1126

Exclusive LEE analyses in γ/e^+e^-

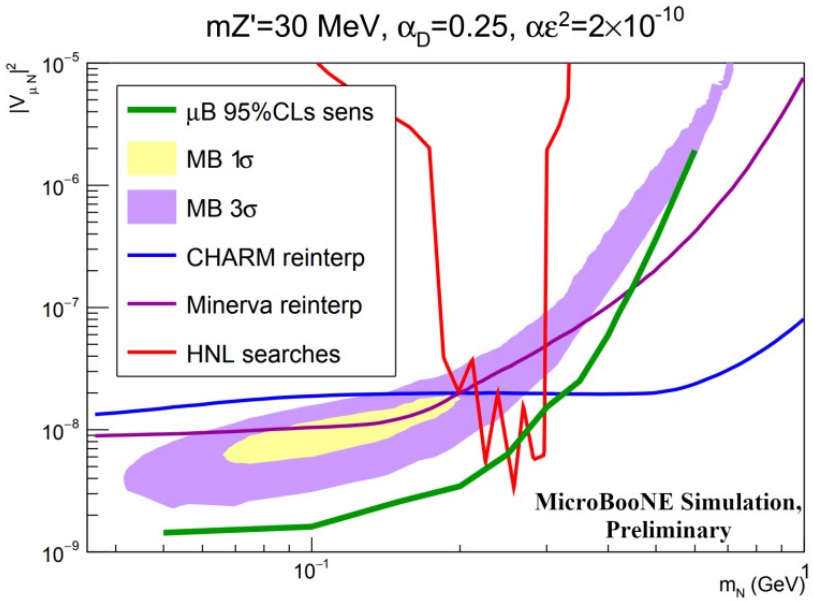


Dark ν decays to e^+e^-

NC Coherent 1γ



Updated NC$\Delta \rightarrow 1\gamma$



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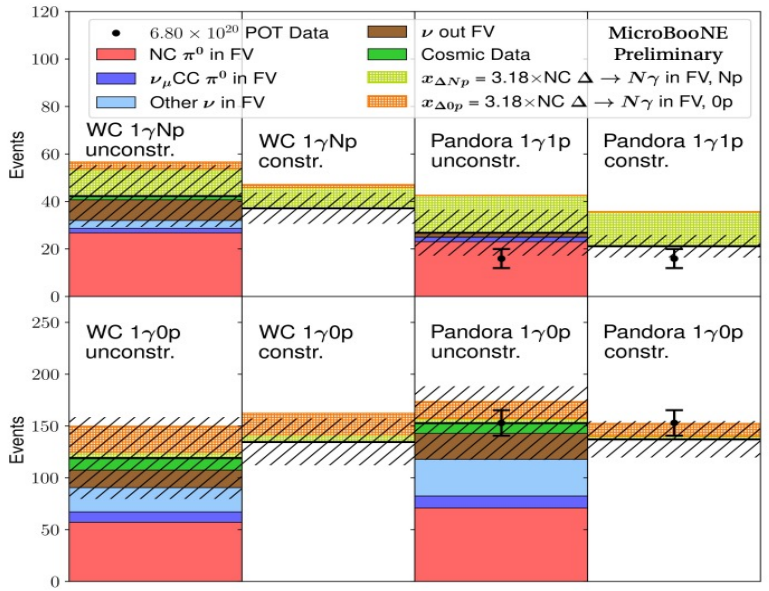

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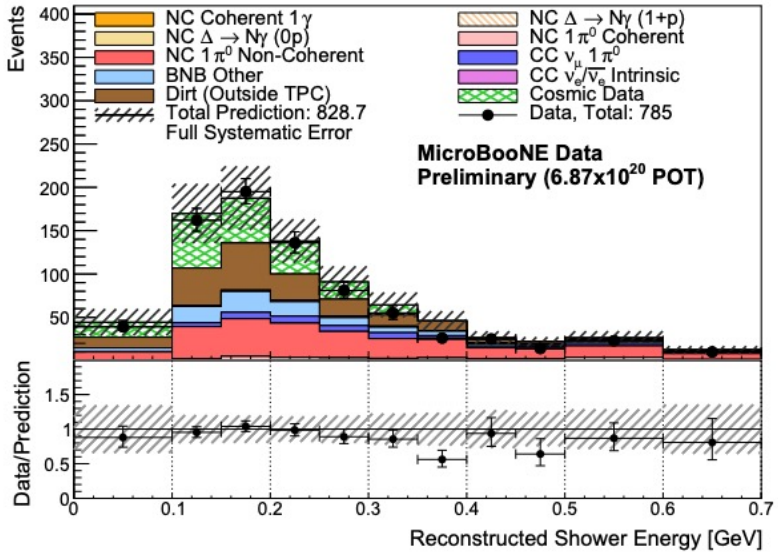


MICROBOONE-NOTE-1131

Summary

- MicroBooNE's 1st round LEE result showed no excess in the electron channel -> Need **photon LEE search**
- **Inclusive single photon** is designed to answer if MicroBooNE sees an anomaly in any γ channel.
- Several exclusive analyses are also ongoing to search for LEE in the γ/e^+e^- channel
- Stay tuned for new round of MicroBooNE results featuring LEE search in these channels!

Thank you!

Backup

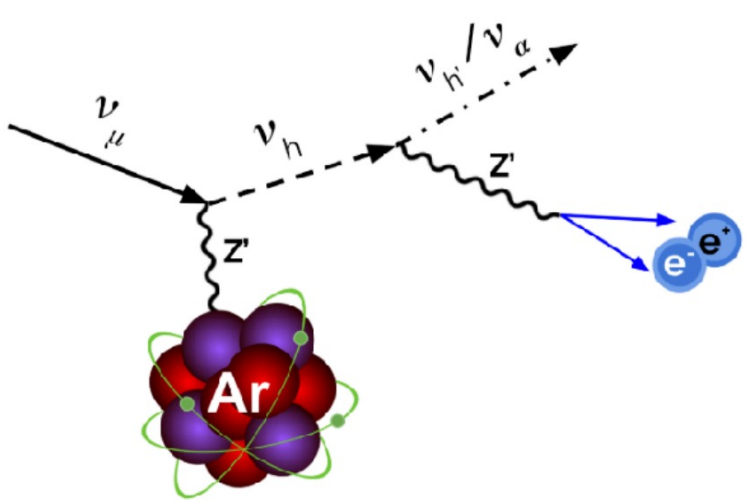
LEE search: e^+e^- from Dark neutrinos

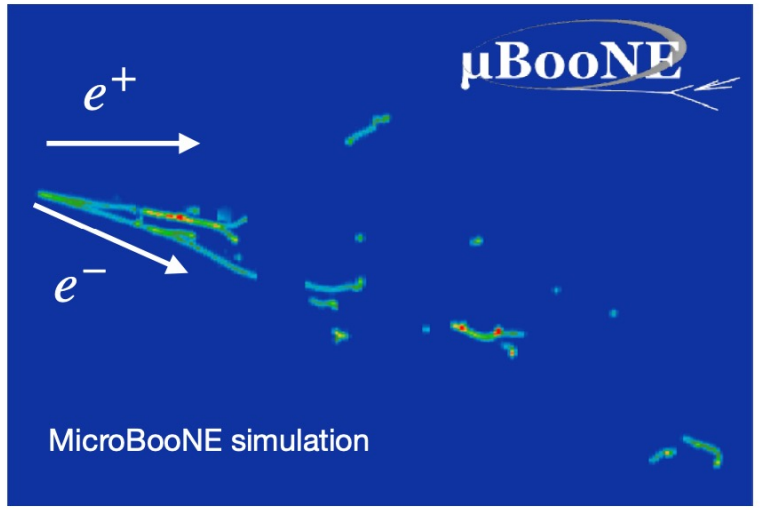
Dark neutrino decays to e+e-

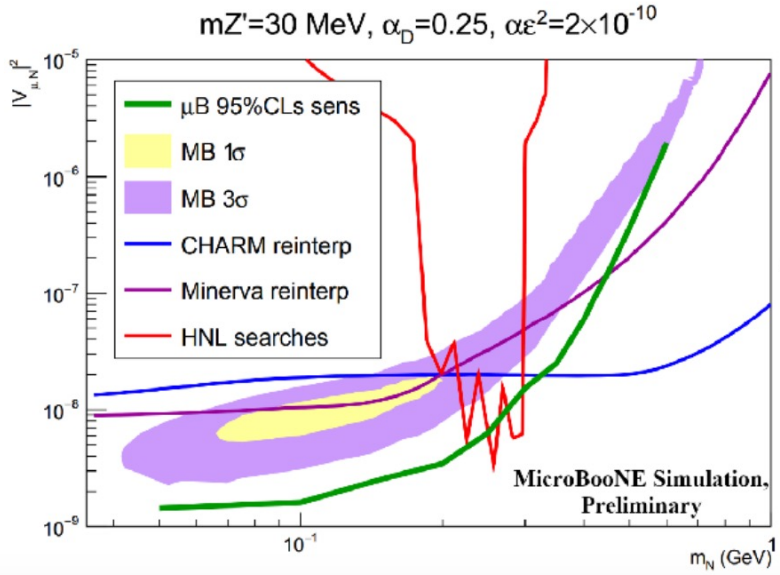
Ballet, Pascoli, Ross-Lonergan PRD 99 (2019) 071701

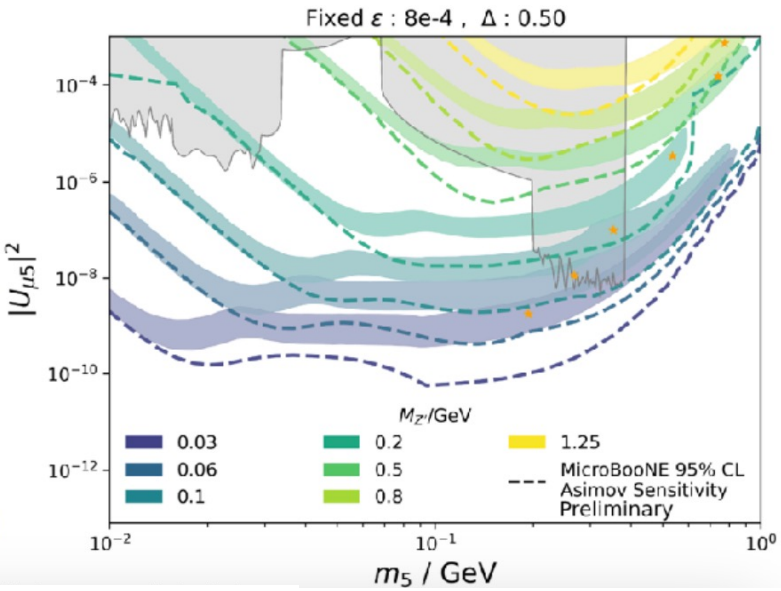
Bertuzzo, Jana, Machado, Zukanovich Funchal PRL 121 (2018) 24, 241801

Sensitive to MiniBooNE allowed region for these models at > 95% CL More details at: MICROBOONE-NOTE-1124-PUB





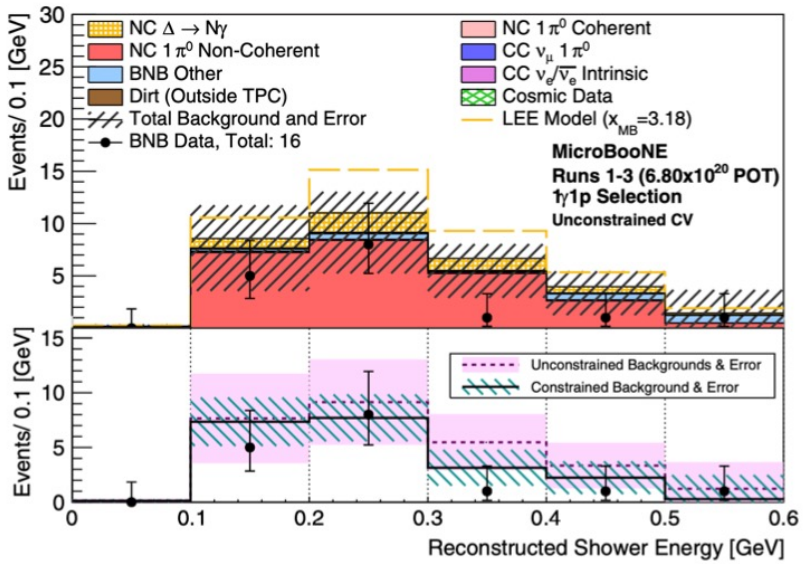


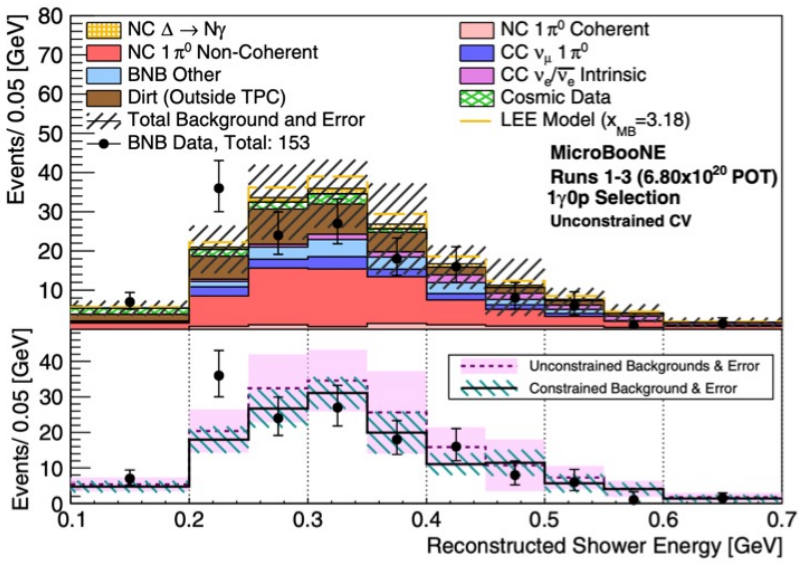


MicroBooNE Sensitivities

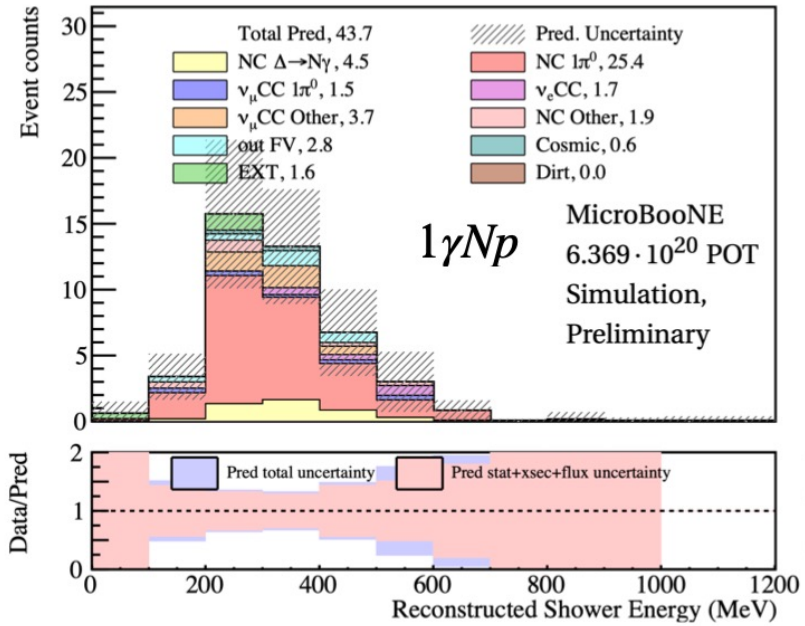
Exclusive photon LEE analysis: expanding NC$\Delta \rightarrow 1\gamma$

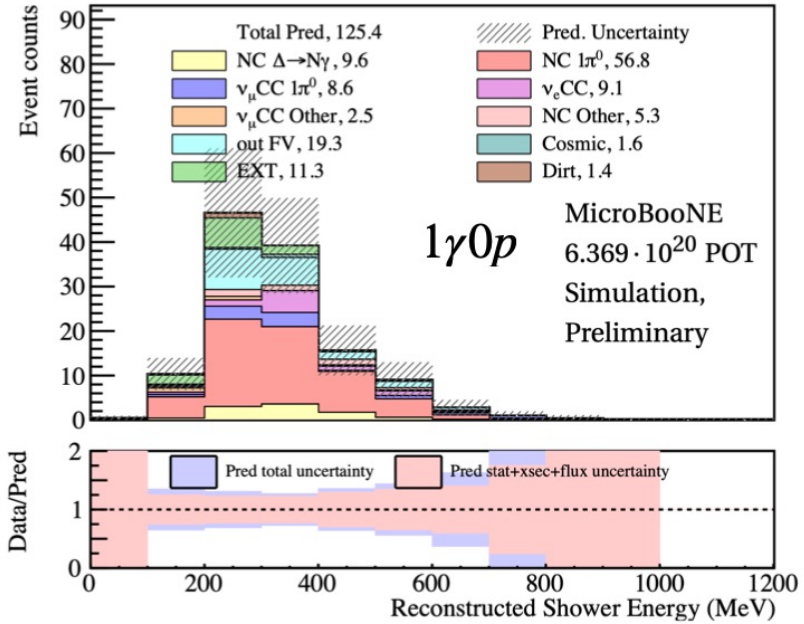
Selection from 1st round analysis





New Analysis





Different event reconstruction:
- Pandora 2D (old)
- Wirecell 3D (new)

Orthogonal selection:
- nearly double statistics.
- Expands 1γ1p to 1 γNp

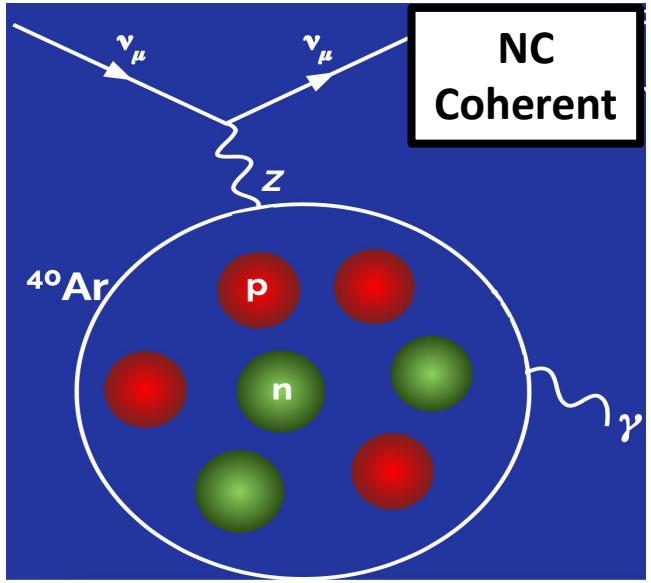
New analysis improves efficiency and purity in 1γ0p channel

Target two-dimensional search in 0p / Np topologies.

Result coming soon!
MicroBooNE Public Note 1104

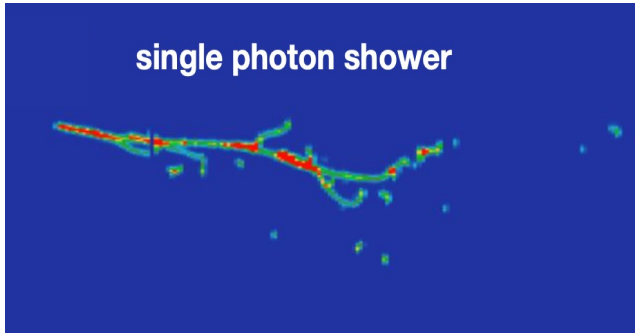
Exclusive photon LEE analysis: NC Coherent

[MicroBooNE Public Note 1103]

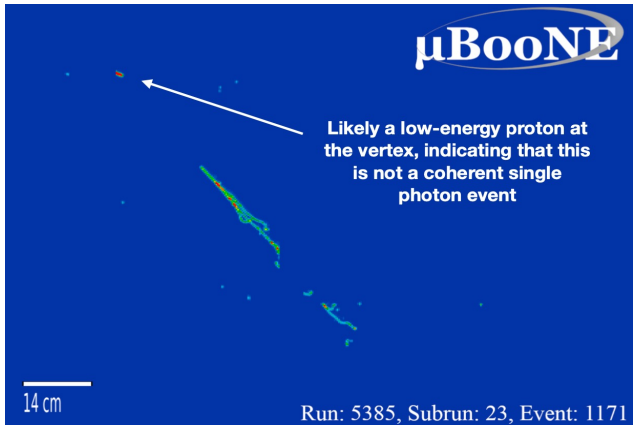


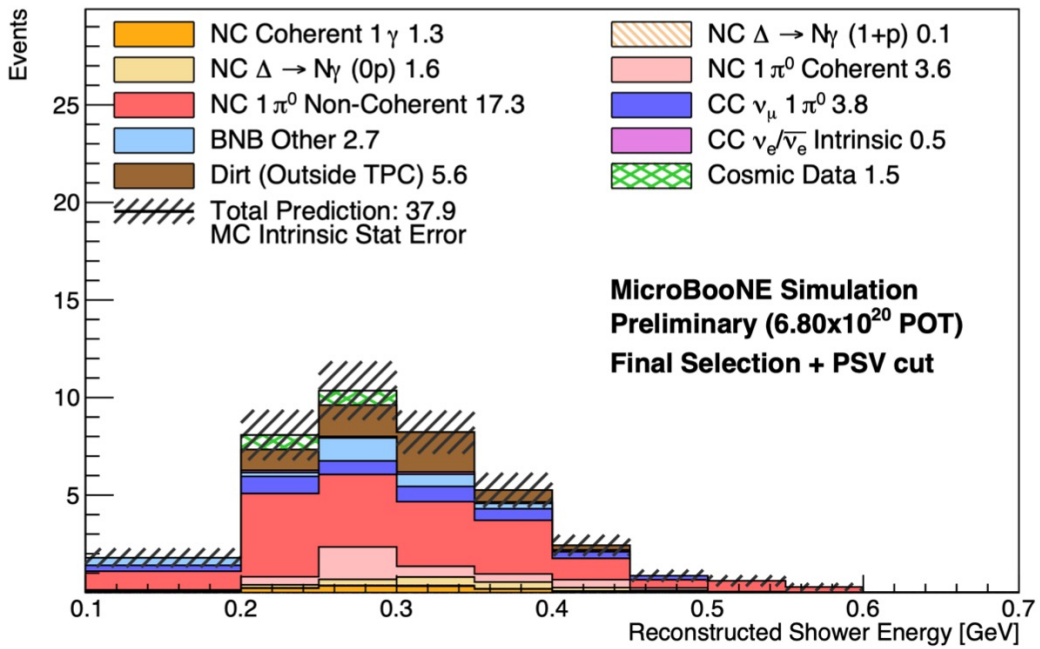
A very rare SM process
1/40 branching ratio
compared to NC $\Delta \rightarrow 1\gamma$

Event signature:
One low energy, forward going (beam direction) photon shower



Use published NC $\Delta 1\gamma$ selection
+ new tools to reject proton





Status: sideband study and mock-data test.

SM signature beyond sensitivity reach

Probe coherent LEE explanations more generally

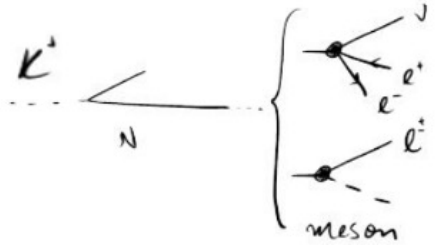
Result coming soon...

Exclusive photon LEE analyses – e^+e^- from BSM

Numerous BSM particles decay to e+e-. The predicted colinear electron pair can look like single photon, entering MiniBooNE's LEE

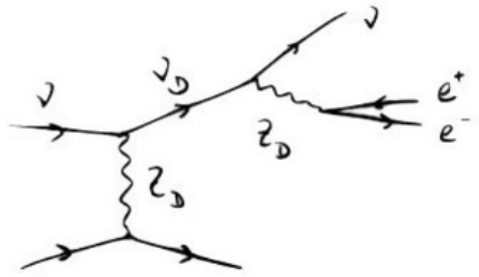
Inclusive photon LEE selection can be used as the pre-selection for this exclusive final state.

Heavy Neutral Leptons



Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021

Dark Neutrinos



Bertuzzo Jana Machado Zukanovich PRL 2018, PLB 2019
Arguelles Hostert Tsai PRL 2019
Ballett Pascoli Ross-Lonergan PRD 2019
Ballett Hostert Pascoli PRD 2020

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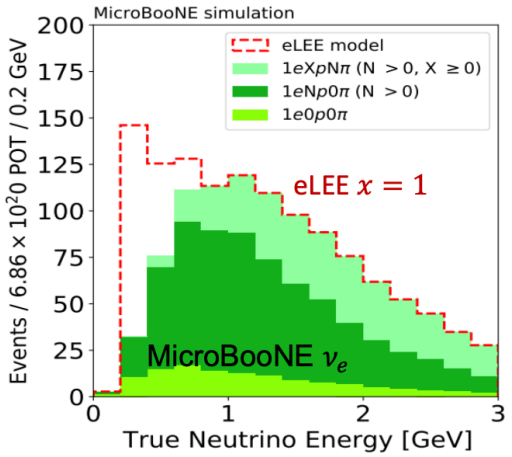
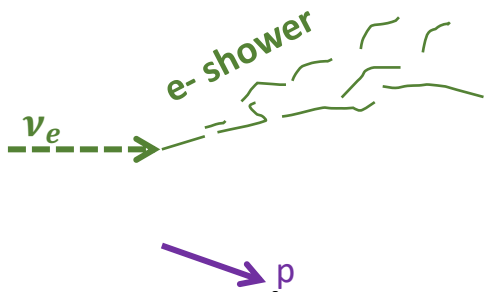
1st round of electron LEE search

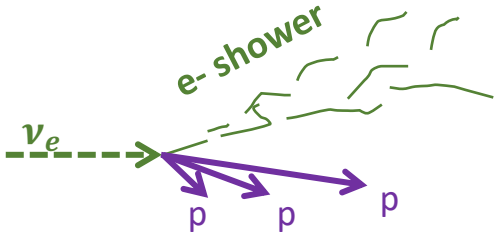
Phys. Rev. Lett. 128, 241801 (2022)

Empirical eLEE model derived from MiniBooNE

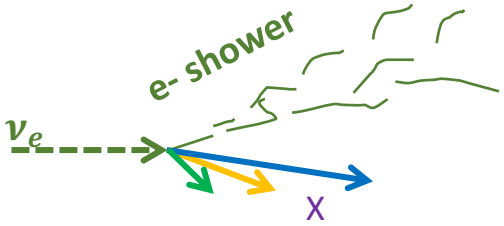




Deep Learning
Simple topology
Simpler E_ν reco (CCQE)
Lower backgrounds



Pandora
Larger signal stat.
Less model dependency
MiniBooNE topology

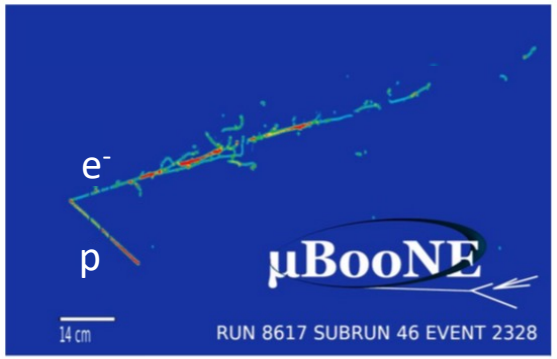


Wirecell
Inclusive -> sensitive
Less model dependency
Most useful for DUNE

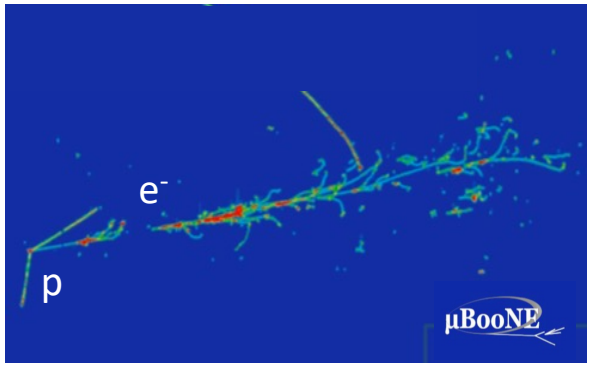
Search for excess events from intrinsic beam ν_e

Three separate analyses focusing on different final state topologies

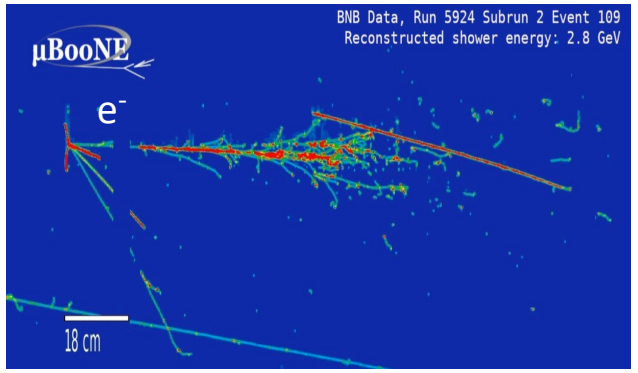
1e1p candidate



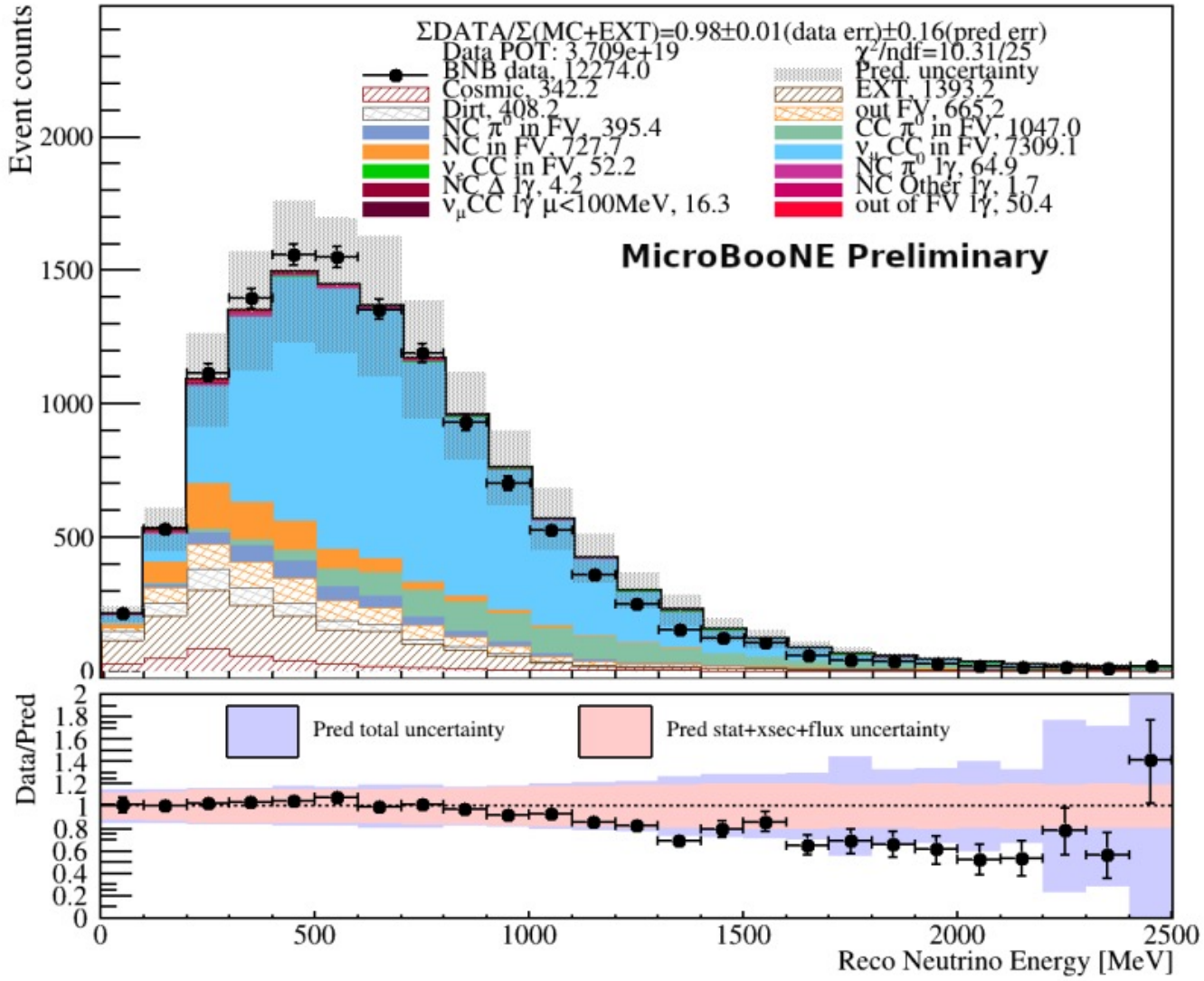
1eNp candidate



1eX candidate



Inclusive photon LEE – event selection



MicroBooNE is a surface detector

First Step: Cosmic Rejection

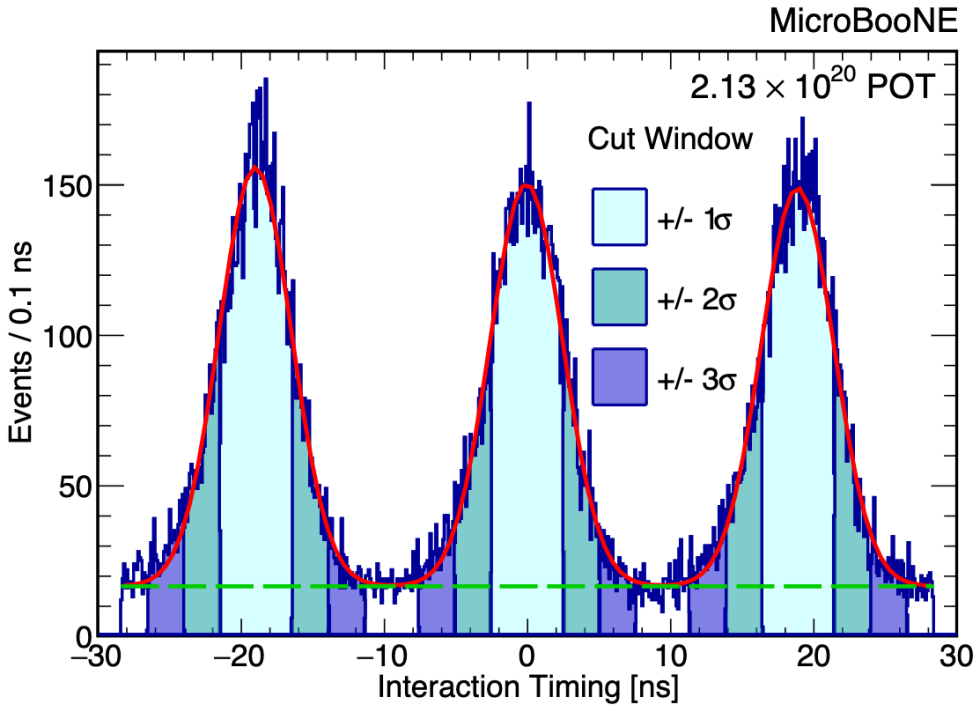
After cosmic rejection:

S : B ~ 1 : 100

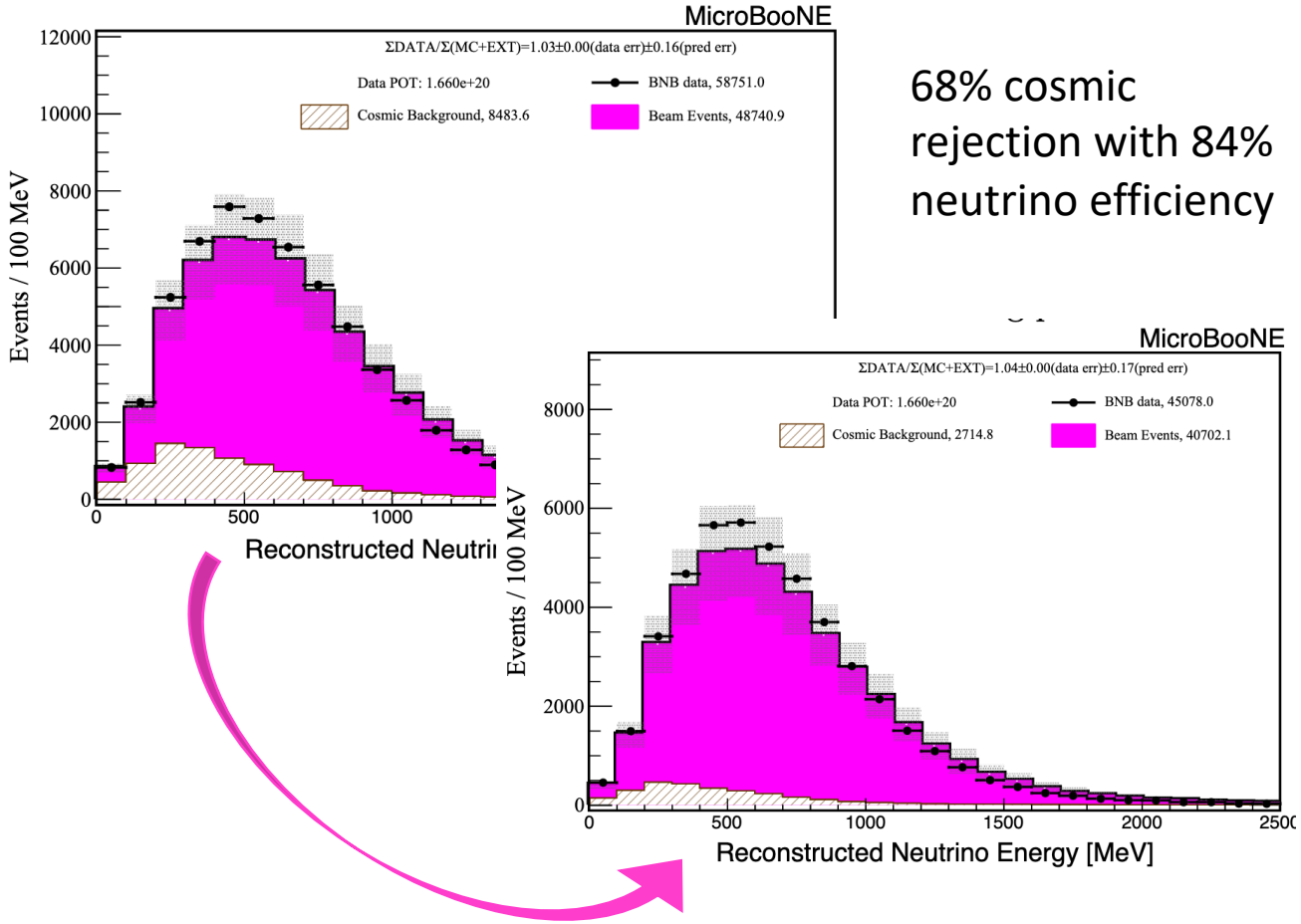
Inclusive photon LEE – event selection

[Phys. Rev. D 108, 052010]

First step is **cosmic rejection**: Innovative use of O(1 ns) timing for cosmic rejection. (First-time application in any MicroBooNE physics analysis!)

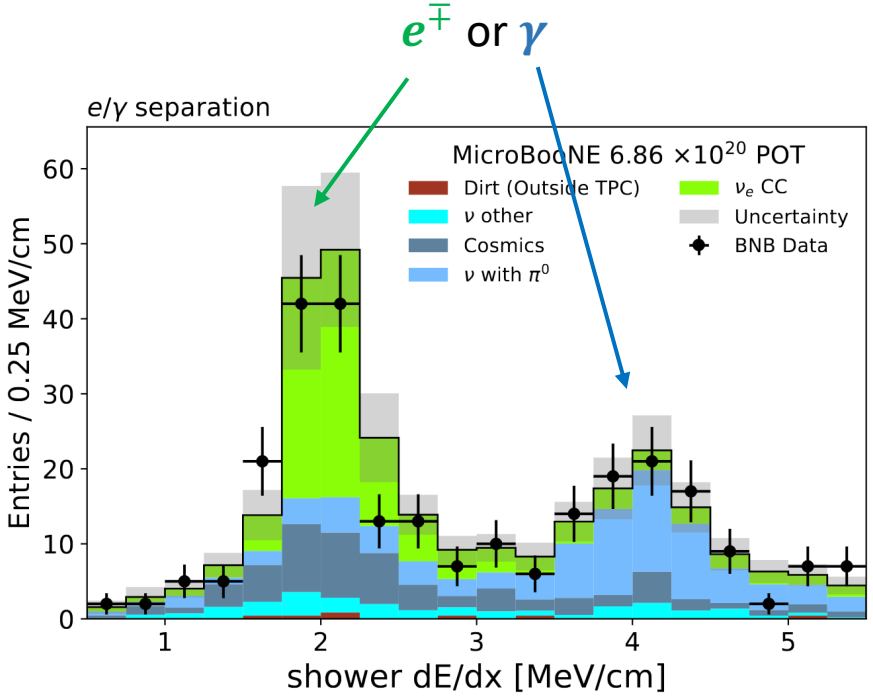


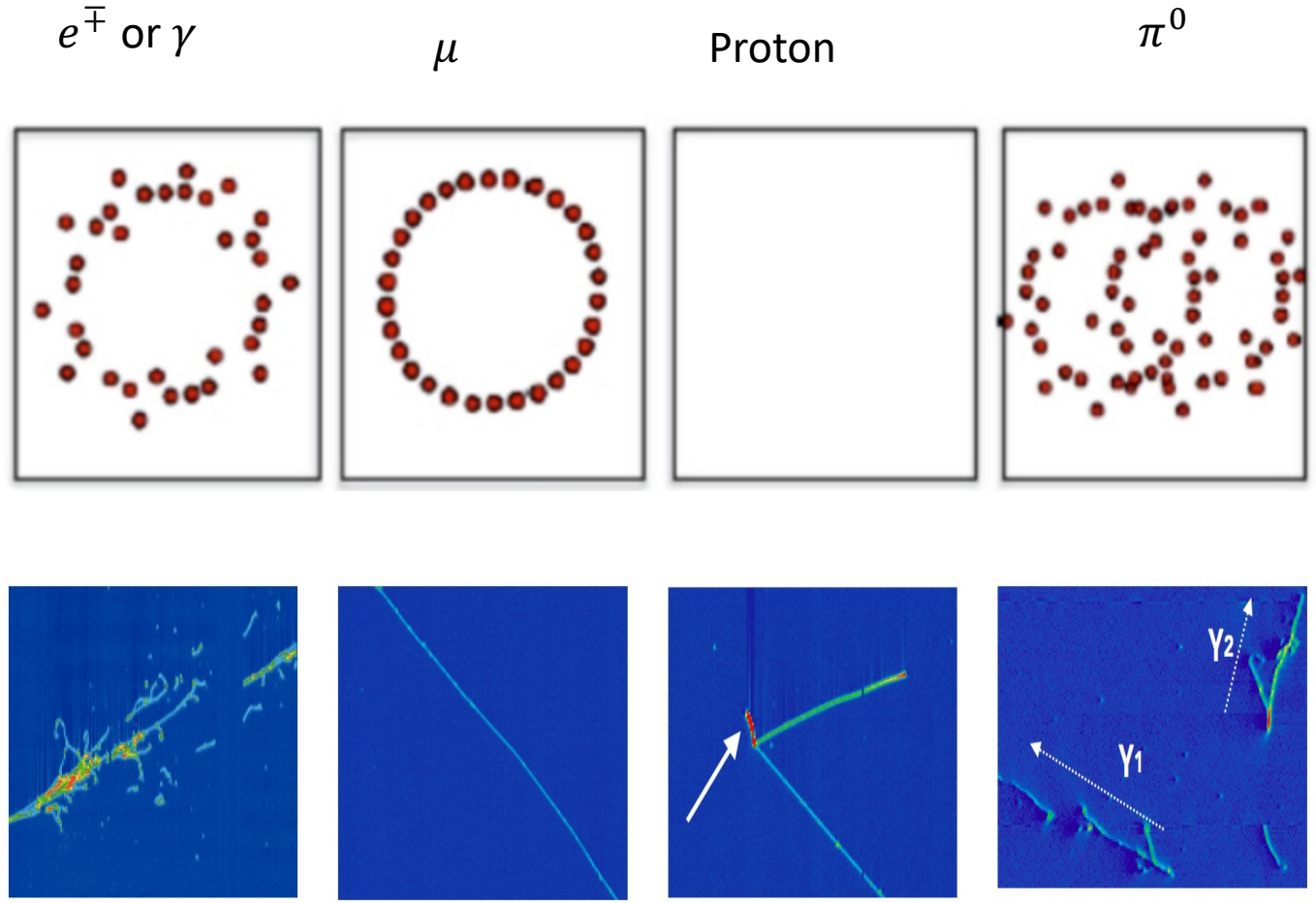
Neutrinos “bunches” while cosmic uniform in time
Cut on interaction timing to remove cosmic.



68% cosmic rejection with 84% neutrino efficiency

MicroBooNE's powerful PID with LArTPC





Inclusive photon LEE – event selection

More challenging backgrounds than electron LEE

BDTS

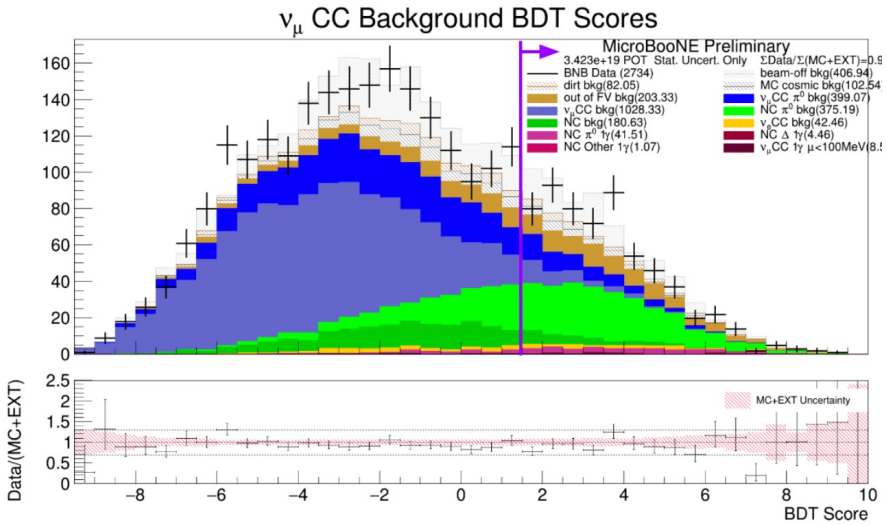
NumuCC
remove remaining numuCC non-signal (high energy muon, 0 or >1γ) events

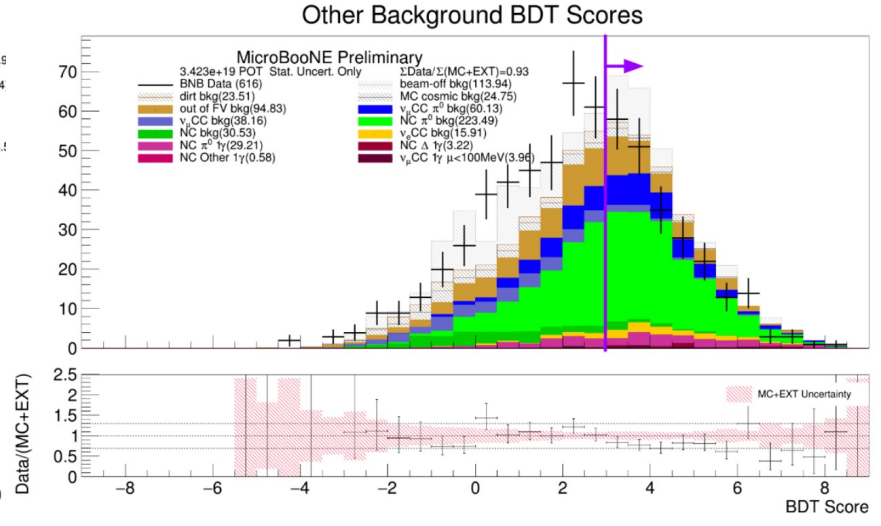
Other
remove remaining smaller/less problematic backgrounds

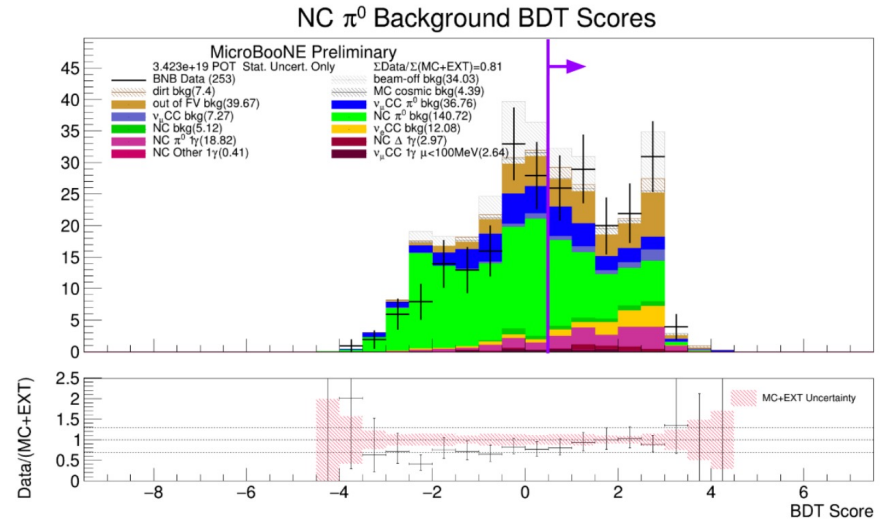
NC Pi0
remove NC Pi0 non-signal (2γ) events

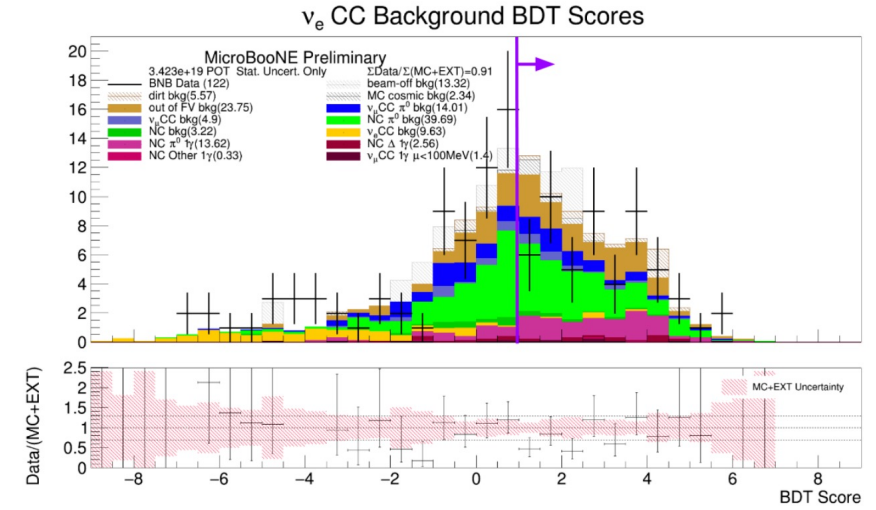
NueCC
remove nueCC events

BDT- based selection focusing on background rejection





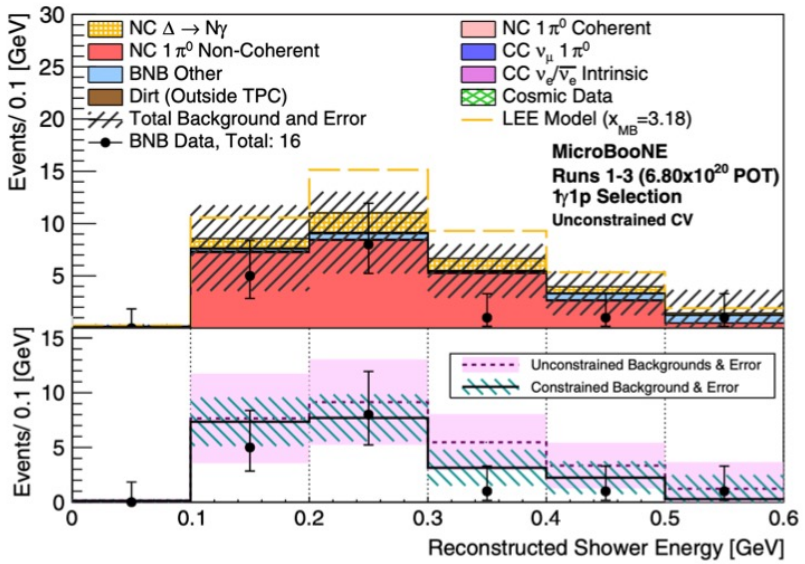


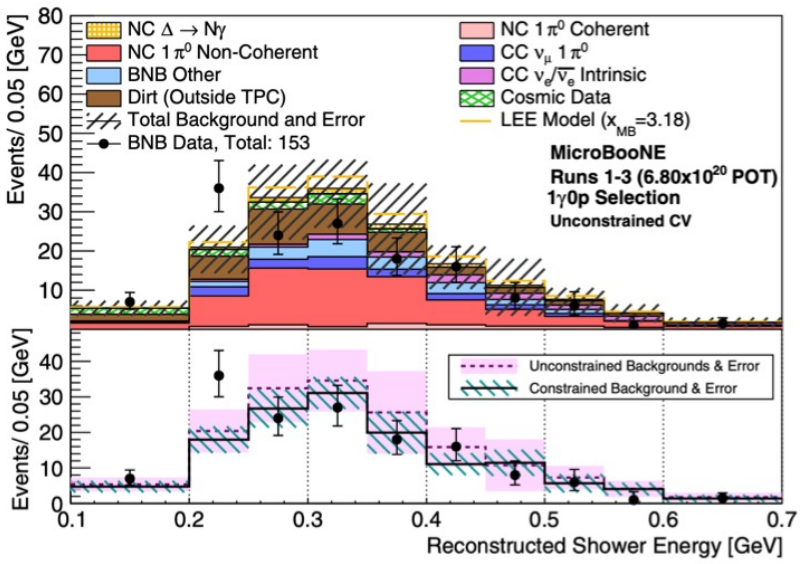


[MicroBooNE Pubic NOTE - 1102]

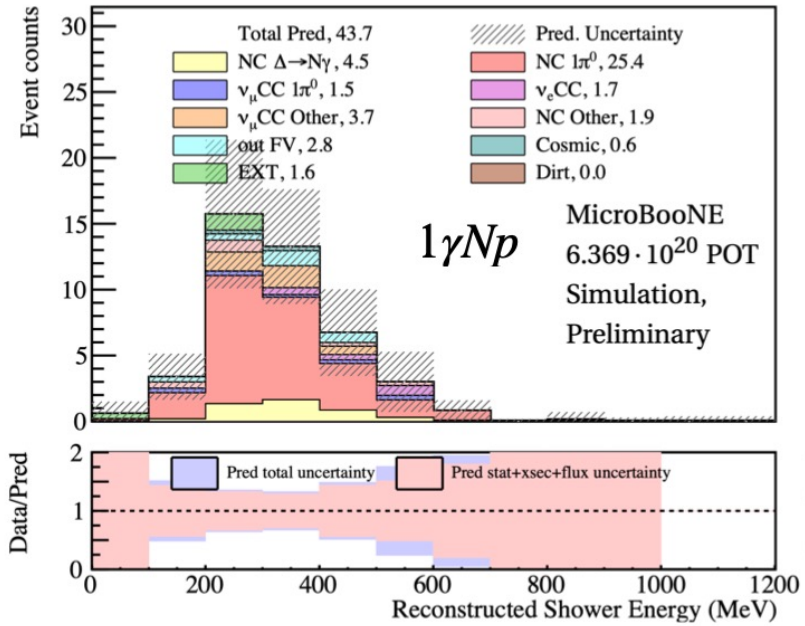
Exclusive photon LEE analysis: expanding NC$\Delta \rightarrow 1\gamma$

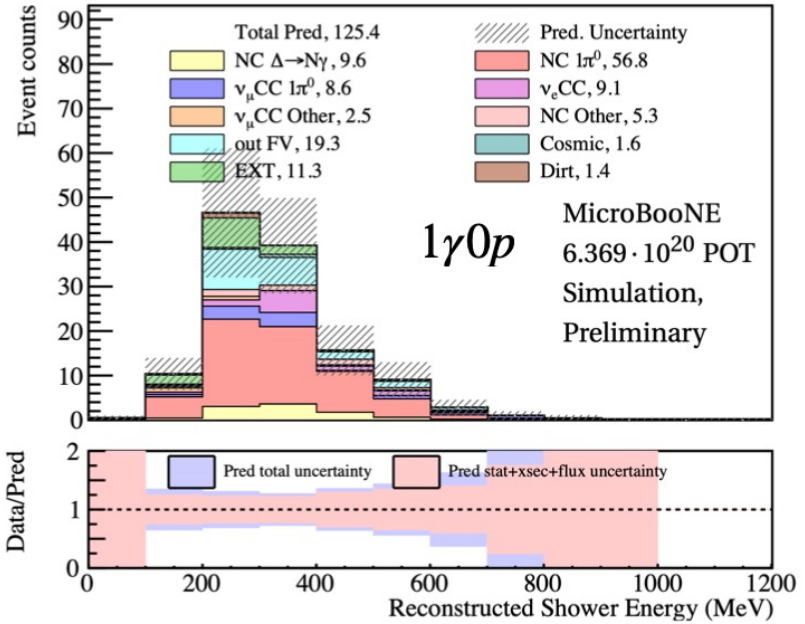
Selection from 1st round analysis





New Analysis





Different event reconstruction:
- Pandora 2D (old)
- Wirecell 3D (new)

Orthogonal selection:
- nearly double statistics.
- Expands 1γ1p to 1 γNp

New analysis improves efficiency and purity in 1γ0p channel

Target two-dimensional search in 0p / Np topologies.

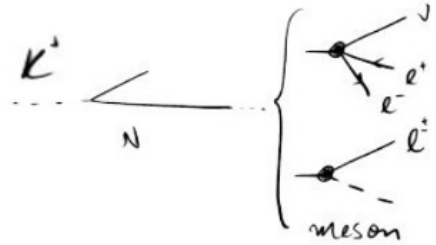
Result coming soon!
MicroBooNE Public Note 1104

Exclusive photon LEE analyses – e^+e^- from BSM

Numerous BSM particles decay to e+e-. The predicted colinear electron pair can look like single photon, entering MiniBooNE's LEE

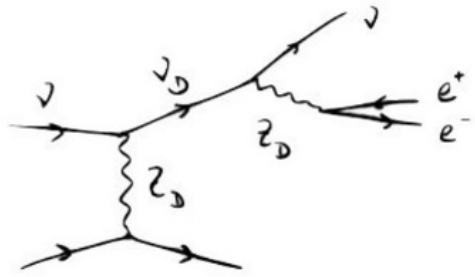
Inclusive photon LEE selection can be used as the pre-selection for this exclusive final state.

Heavy Neutral Leptons



Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021

Dark Neutrinos



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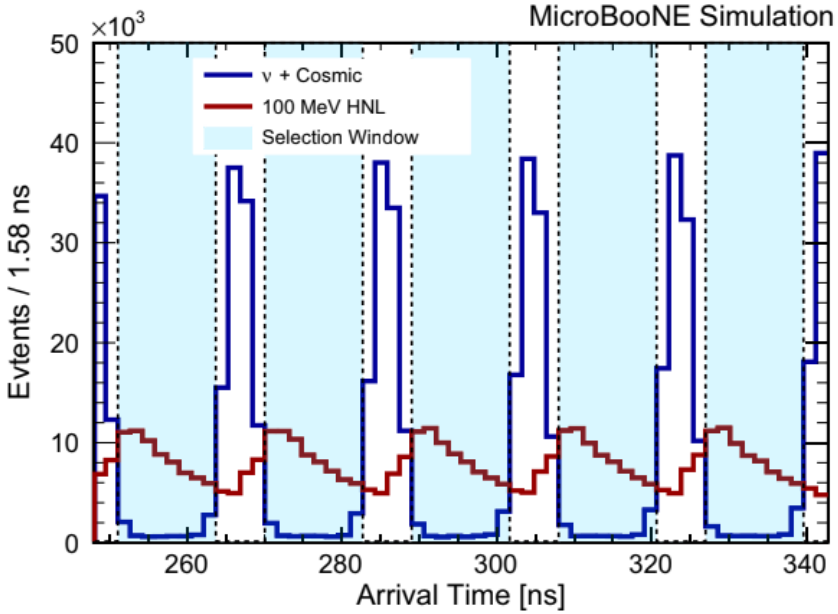
Phys. Rev. D 108, 052010



Delayed arrival of heavy BSM particle Vs. prompt neutrinos.

Time-of-flight offers a powerful handle for **rejecting SM neutrino background**.

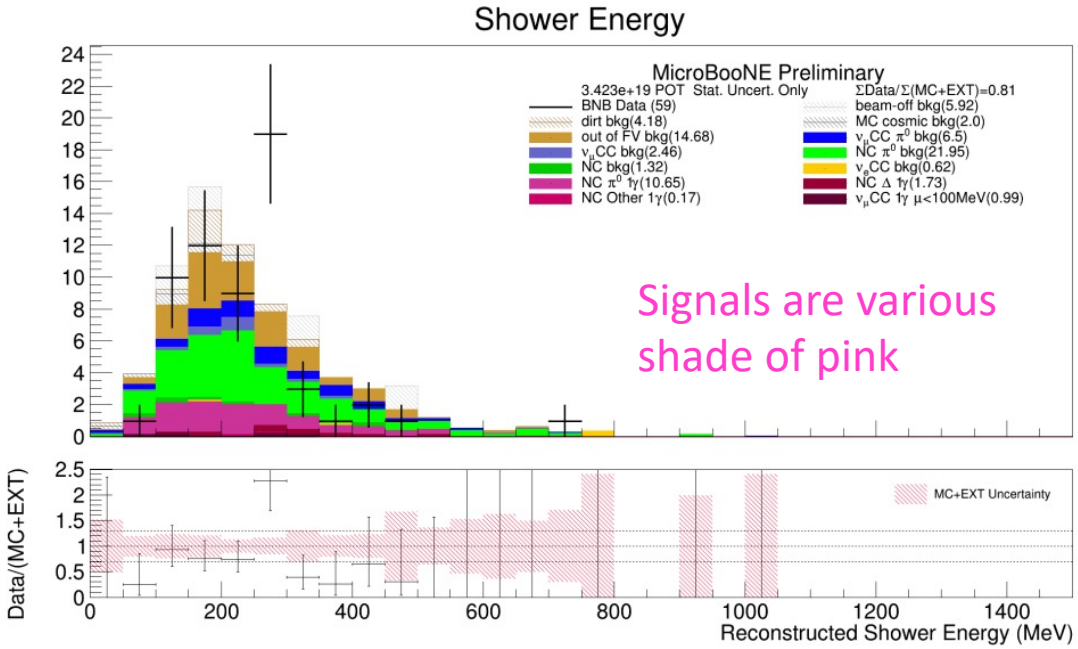
Details see Dante Totani's talk on Tuesday afternoon session

Several ongoing BSM searches in MicroBooNE focus on e^+e^- final states. e.g arxiv:2310.07660

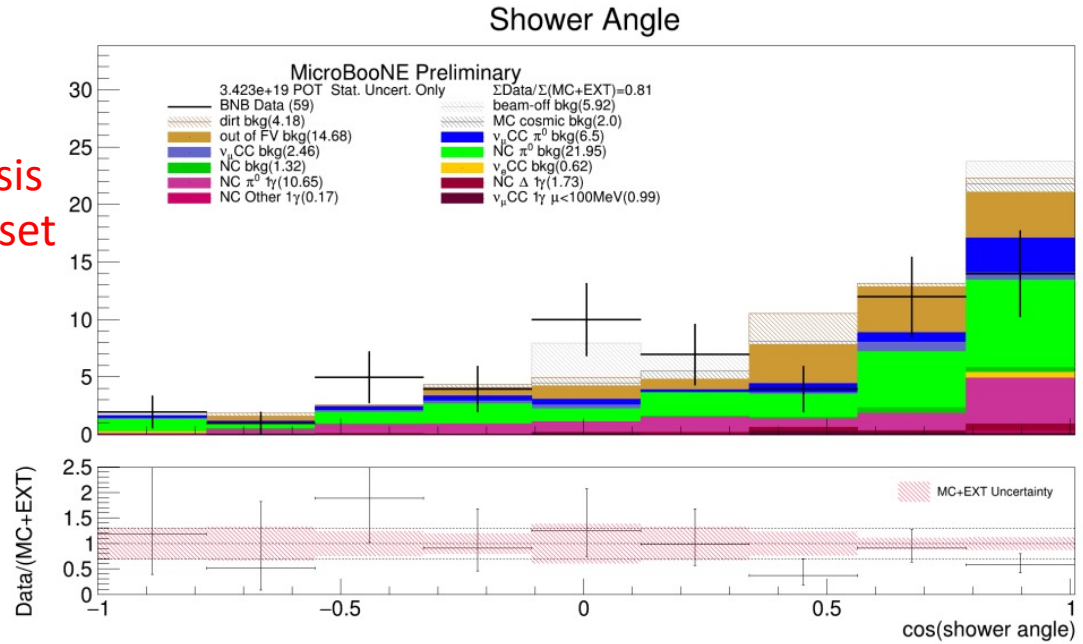
These analyses will also help provide constraints to photon LEE analysis

Inclusive photon LEE status

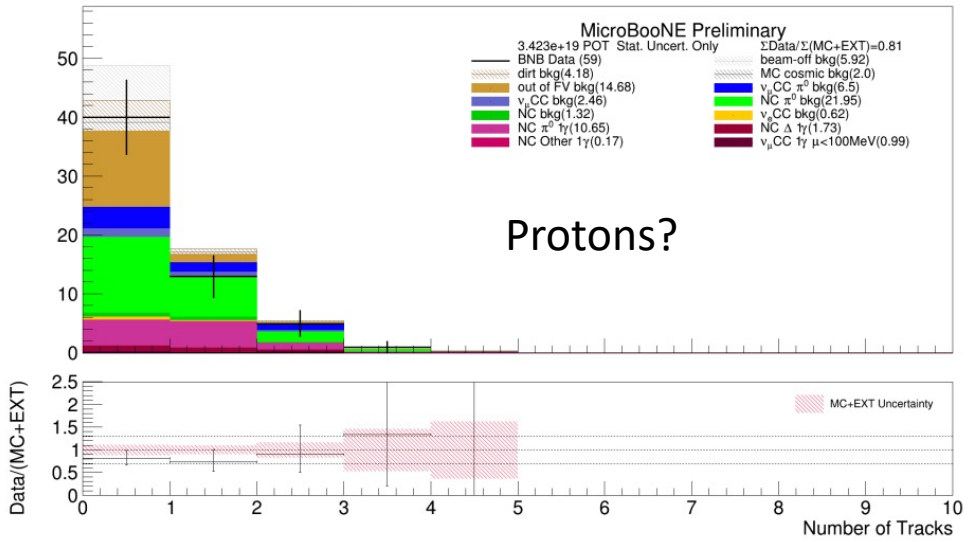
[MicroBooNE Pubic NOTE - 1102]



Blinded analysis
2% of full dataset
no syst. uncertainty



Number of tracks



Besides shower energy and angle, MicroBooNE has the advantage of seeing **proton tracks**, providing more insight in case of excess in the photon channel.

Current status: Finalizing sideband validation and mock-data study. **Result coming soon!**