Search for anomalous single-photon production in MicroBooNE as a first test of the MiniBooNE low-energy excess

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on behalf of the MicroBooNE Collaboration

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Joint Experimental-Theoretical Physics Seminar, Fermilab

October 1st 2021

µBooNE

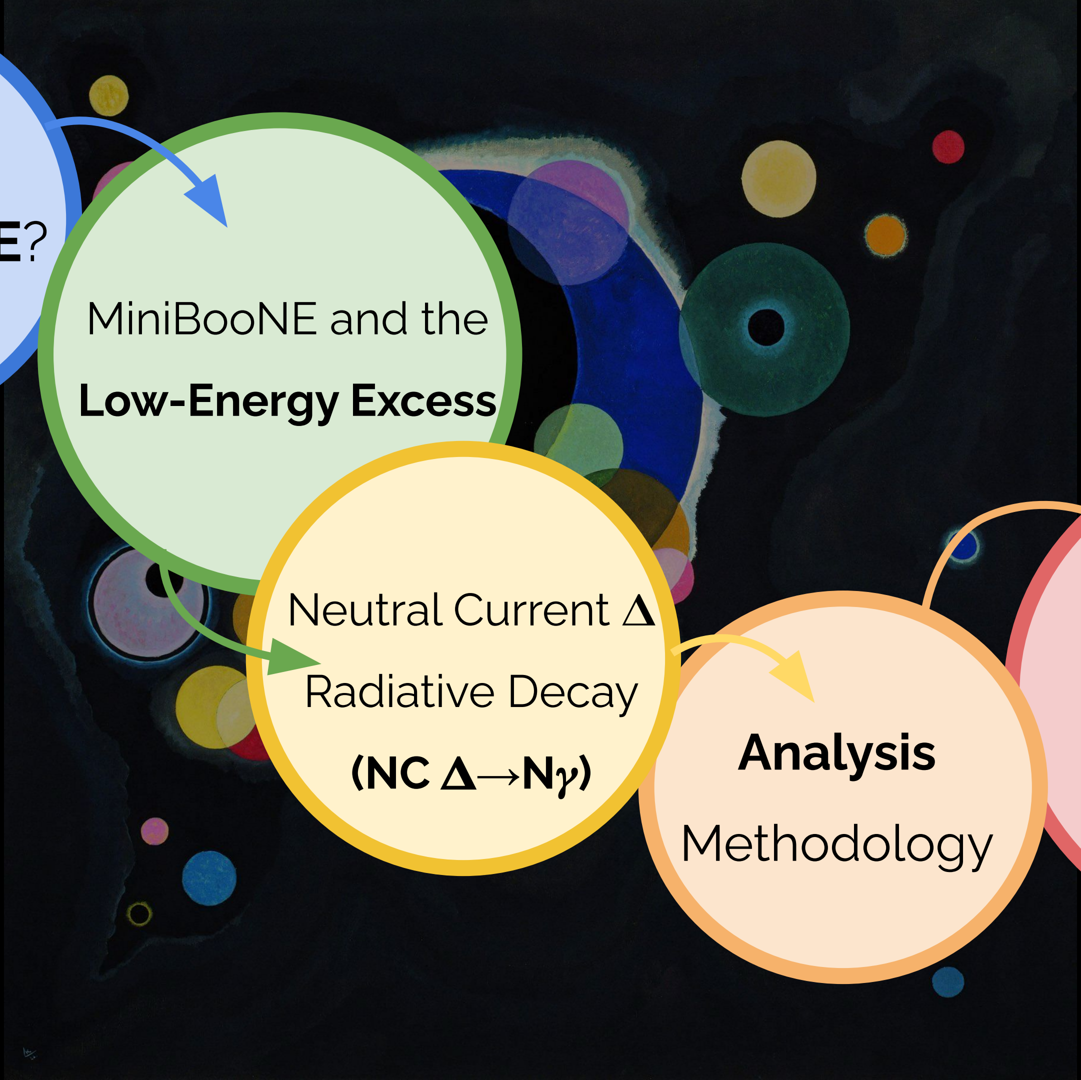
Nevis Laboratories

Fermilab

NSF

Columbia University in the City of New York

Outline



What's **MicroBooNE**?

MiniBooNE and the **Low-Energy Excess**

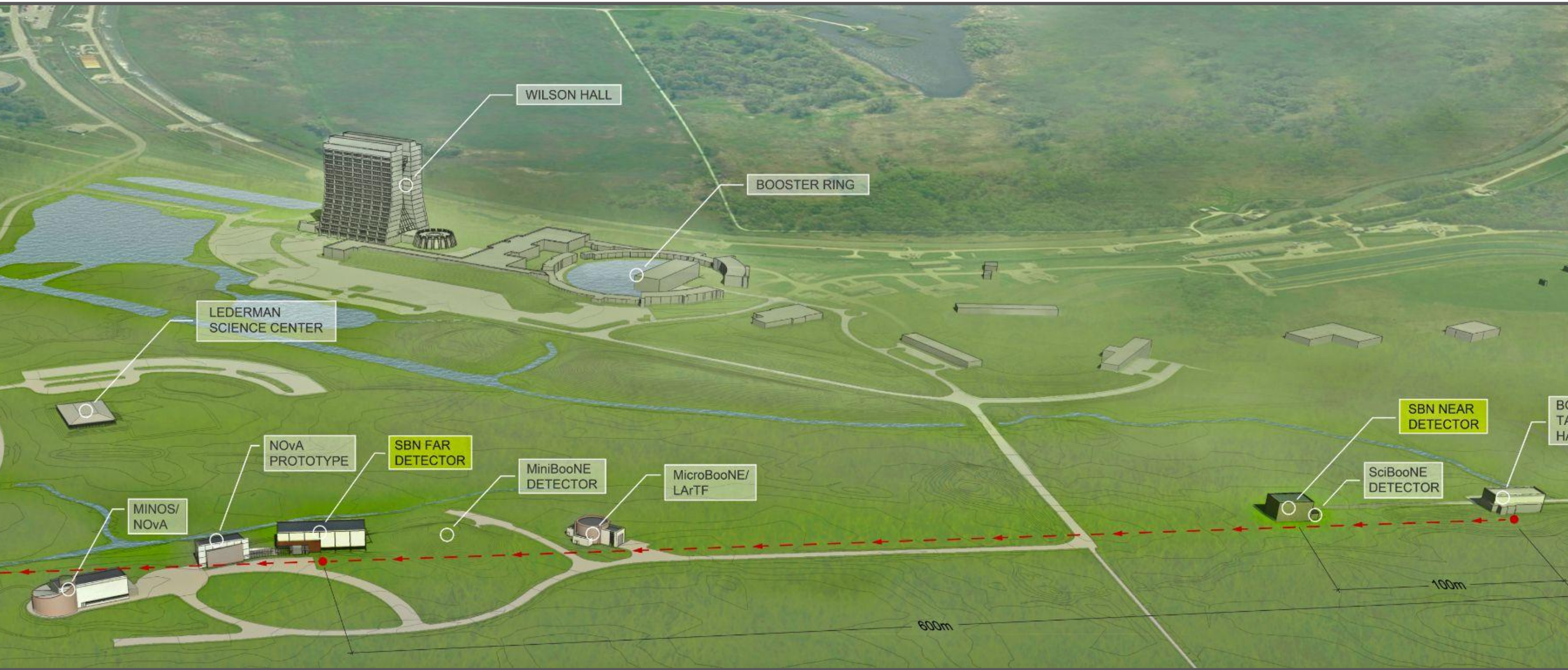
Neutral Current Δ Radiative Decay **(NC $\Delta \rightarrow N\gamma$)**

Analysis Methodology

Unblinding and **Results**!

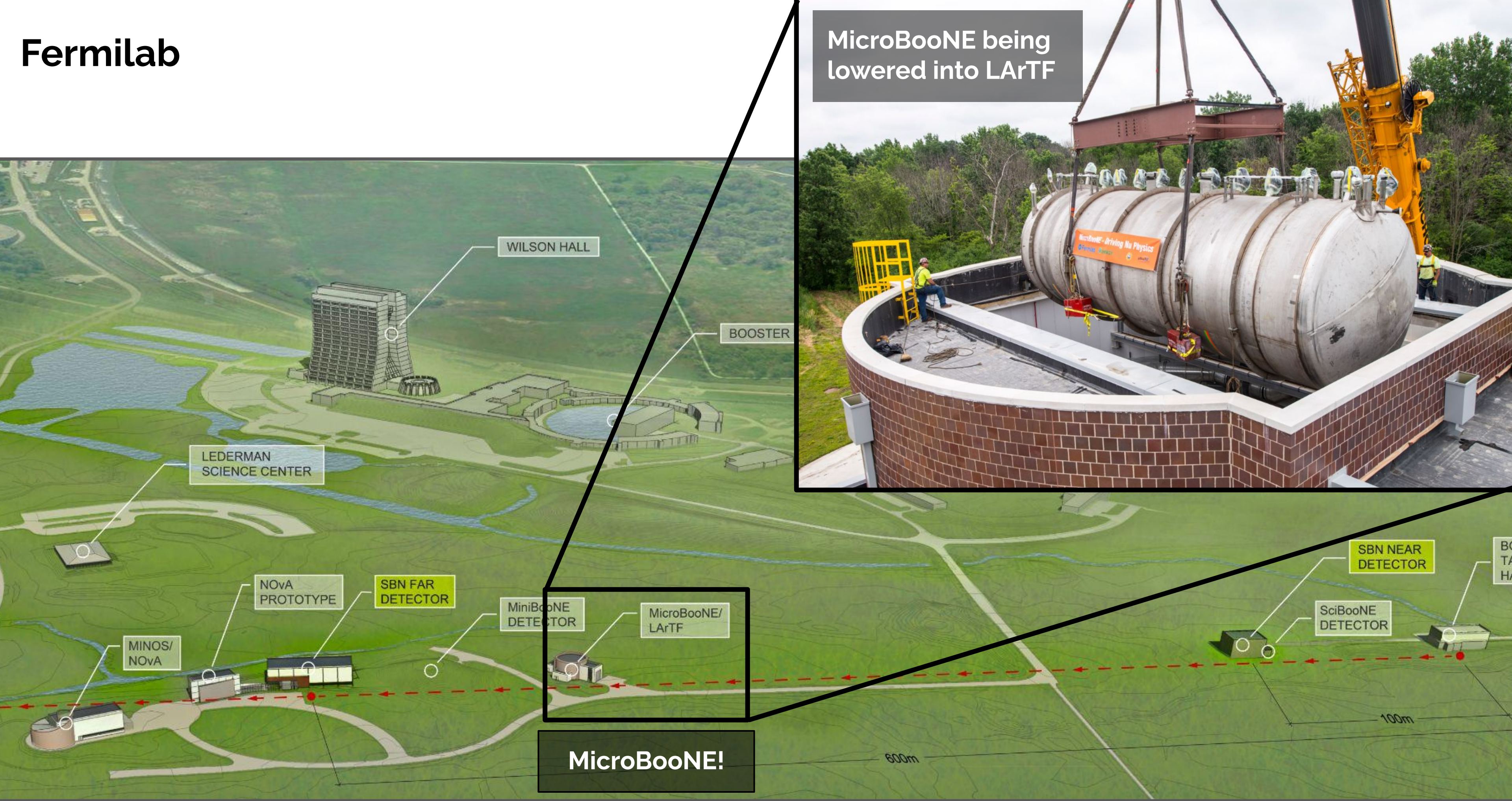
We're MicroBooNE!

Fermilab



WILSON HALL
BOOSTER RING
LEDERMAN SCIENCE CENTER
NOvA PROTOTYPE
SBN FAR DETECTOR
MiniBooNE DETECTOR
MicroBooNE/ LArTF
MINOS/ NOvA
SBN NEAR DETECTOR
SciBooNE DETECTOR
100m
600m

Fermilab


MicroBooNE being lowered into LArTF
WILSON HALL
BOOSTER
LEDERMAN SCIENCE CENTER
NOvA PROTOTYPE
SBN FAR DETECTOR
MiniBooNE DETECTOR
MicroBooNE/ LArTF
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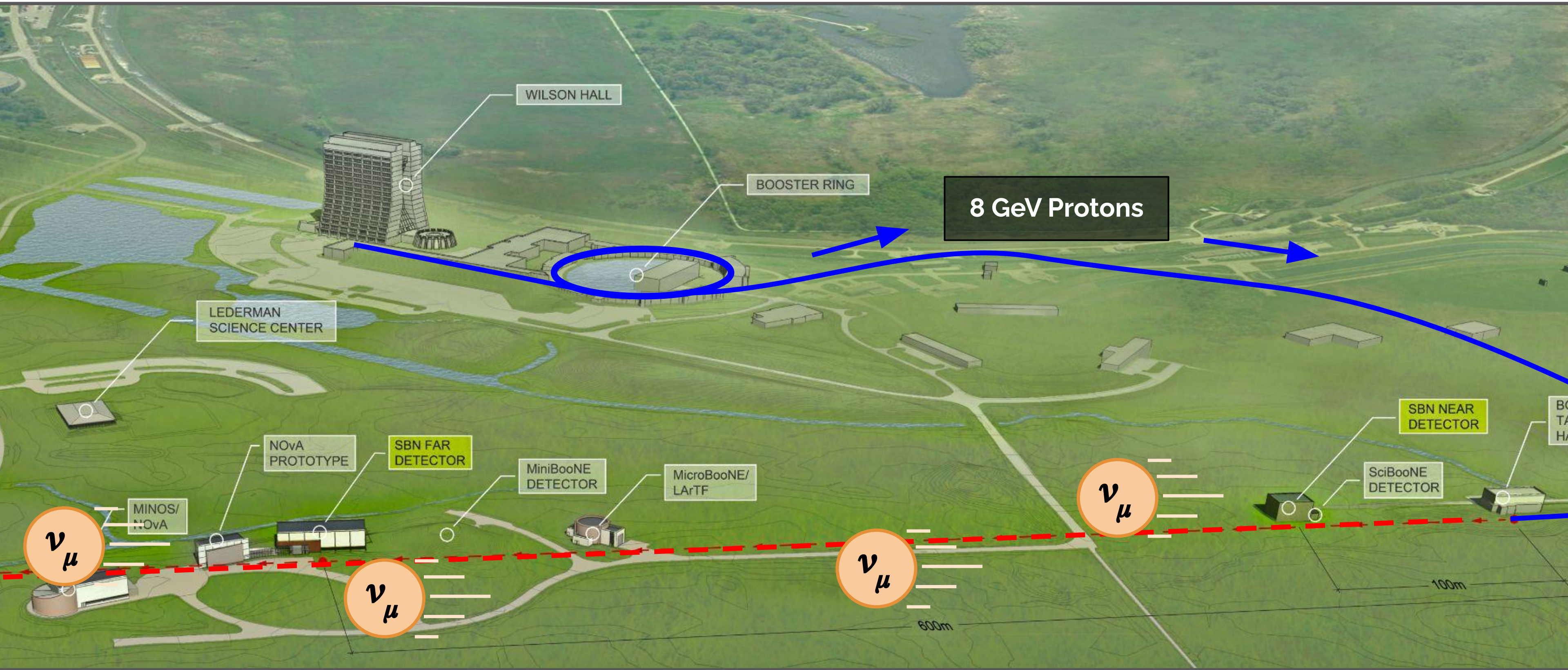
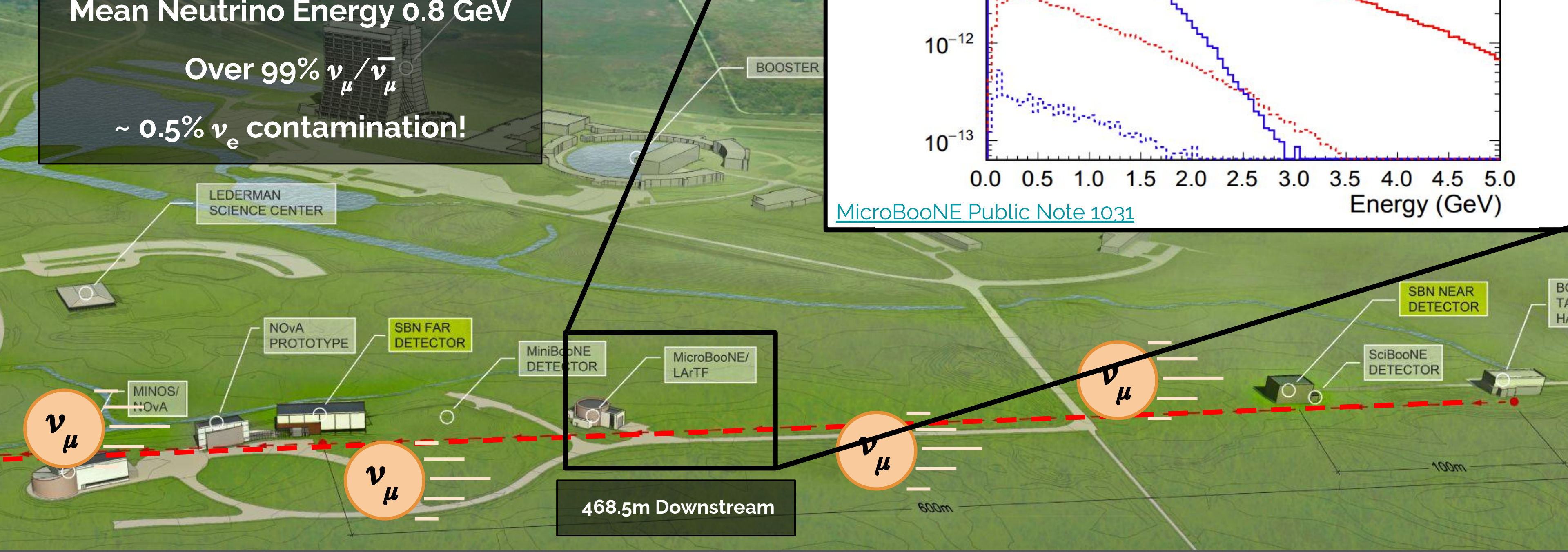
100m
600m
MicroBooNE!

Booster Neutrino Beam (BNB)



Neutrino Flux at MicroBooNE



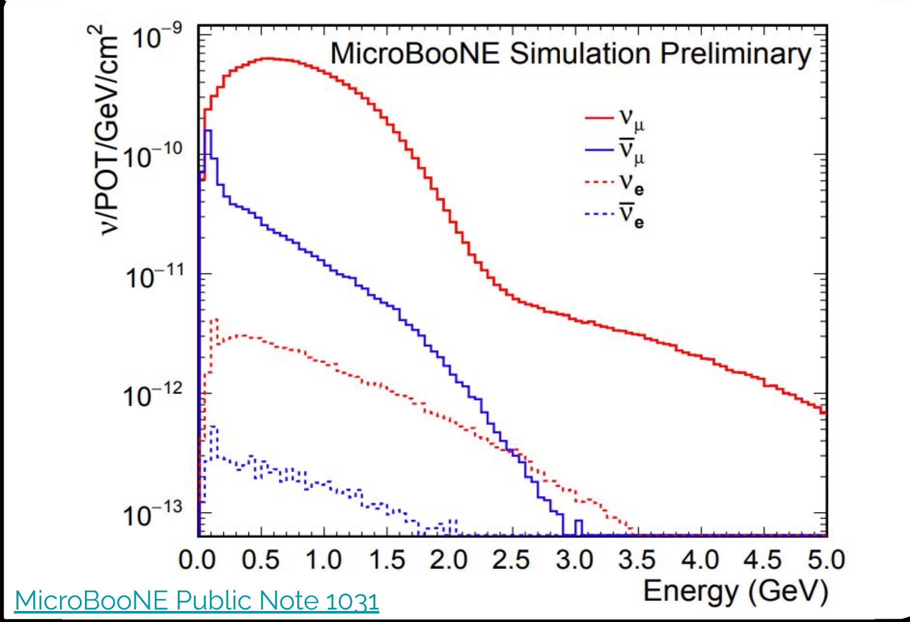
BNB @ MicroBooNE

Mean Neutrino Energy 0.8 GeV

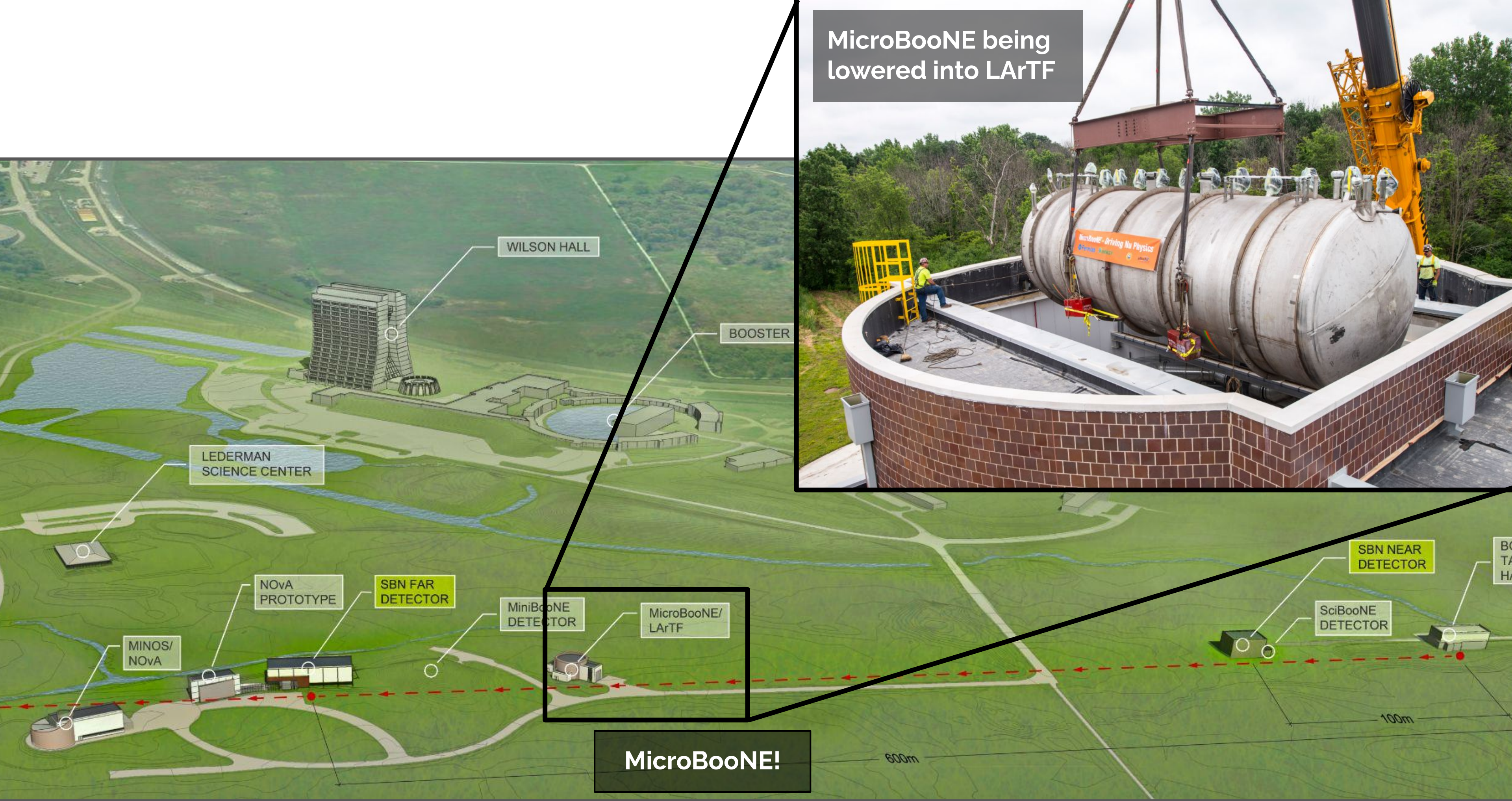
Over 99% $\nu_\mu / \bar{\nu}_\mu$

~ 0.5% ν_e contamination!

468.5m Downstream



[MicroBooNE Public Note 1031]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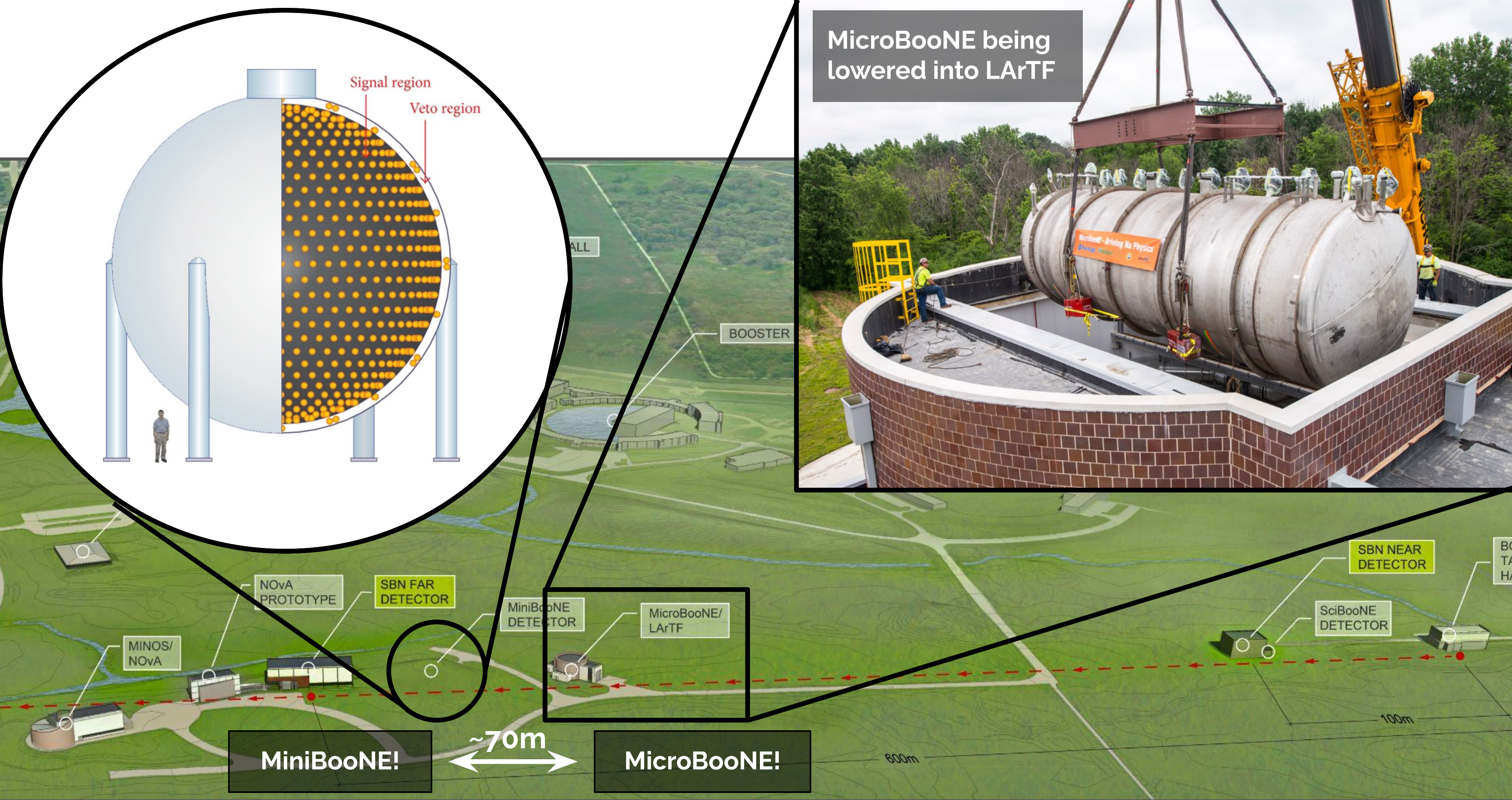
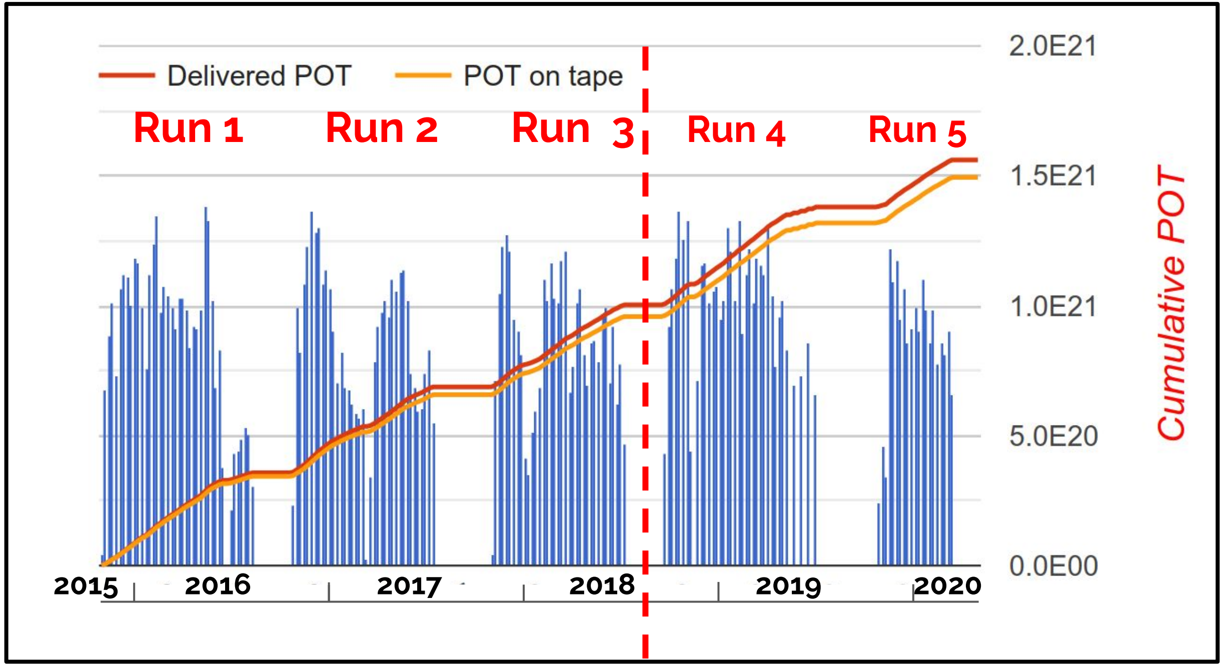
100m
600m
MicroBooNE!
MicroBooNE being lowered into LArTF



Signal region
Veto region
MicroBooNE being lowered into LArTF
MicroBooNE - Driving Nu Physics
BOOSTER
NOvA PROTOTYPE
SBN FAR DETECTOR
MiniBooNE DETECTOR
MicroBooNE/ LArTF
MINOS/ NOvA
SBN NEAR DETECTOR
SciBooNE DETECTOR
100m
600m
MiniBooNE!
~70m
MicroBooNE!

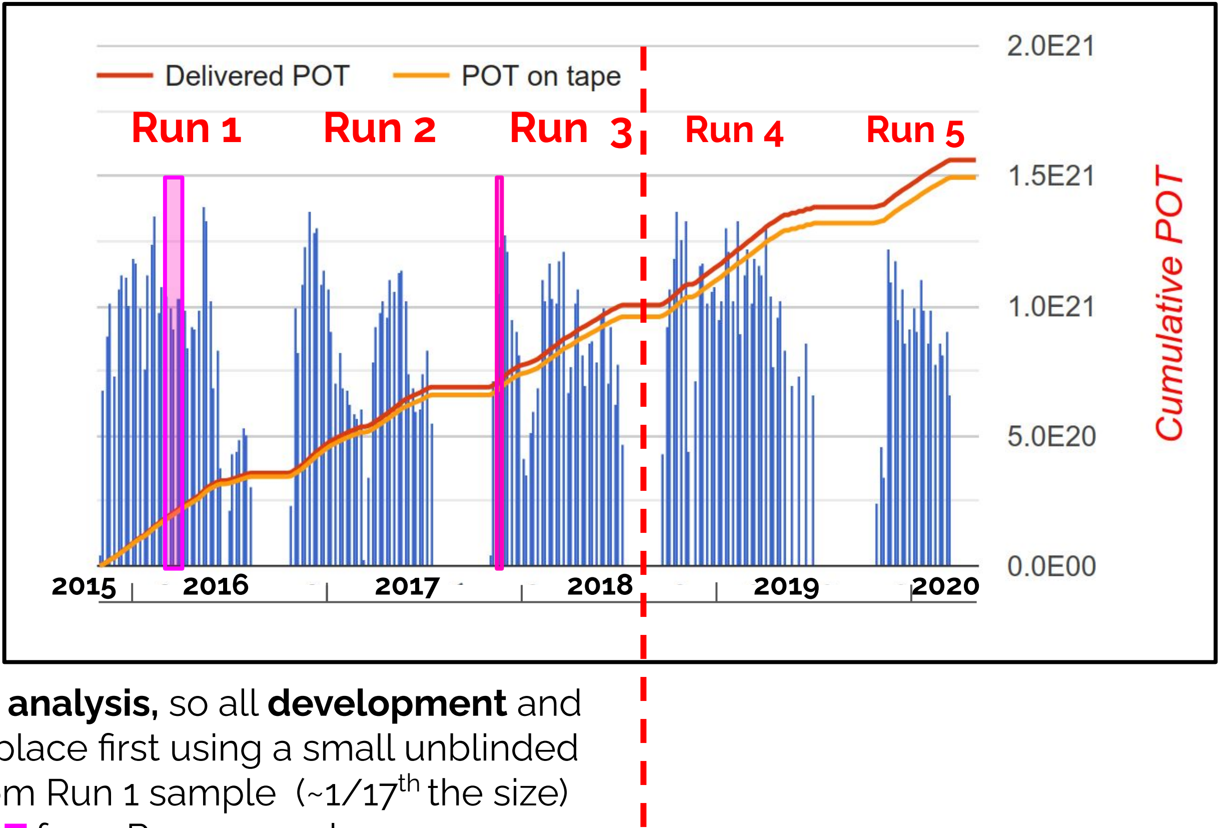
Since turning on in 2015, MicroBooNE has amassed the **largest sample of neutrino interactions on argon in the world**



In today's talk I will be presenting results based on **6.80×10^{20} protons-on-target (POT)** from **Runs 1-3**

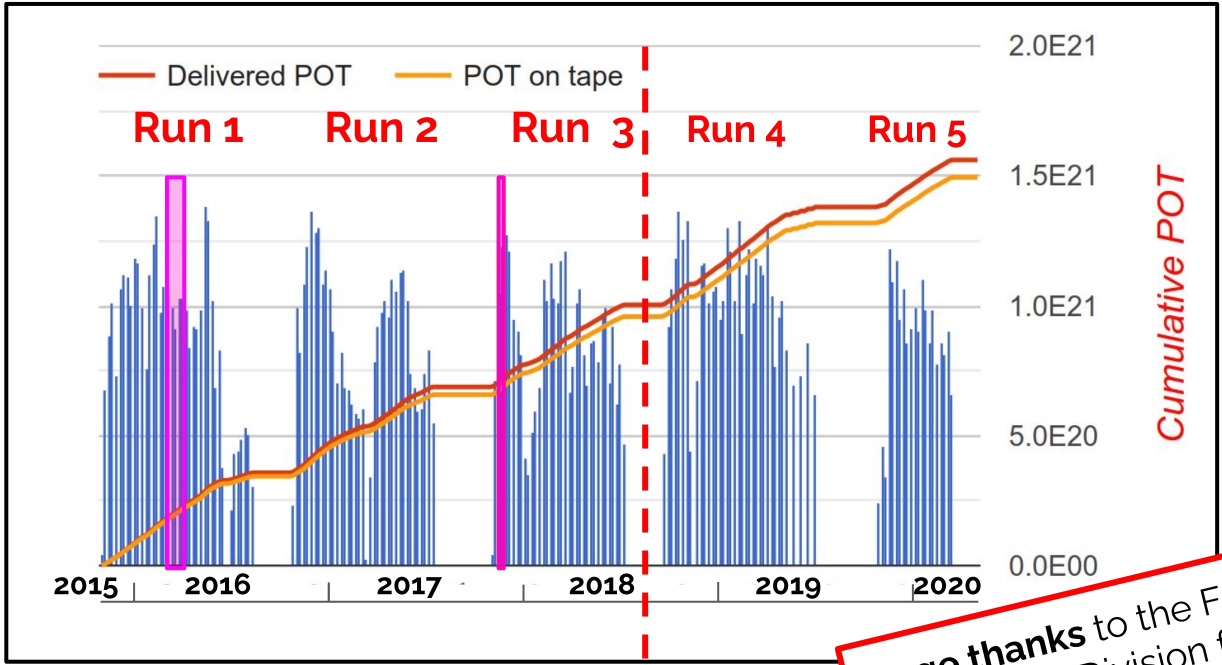
Analyzing remaining ½ of our data from Runs 4-5 is well underway!

Since turning on in 2015, MicroBooNE has amassed the **largest sample of neutrino interactions on argon in the world**



This was a **blind analysis,** so all **development** and **validation** took place first using a small unblinded 0.4×10^{20} **POT** from Run 1 sample (~1/17th the size) and 0.1×10^{20} **POT** from Run 3 sample

Since turning on in 2015, MicroBooNE has amassed the **largest sample of neutrino interactions on argon in the world**



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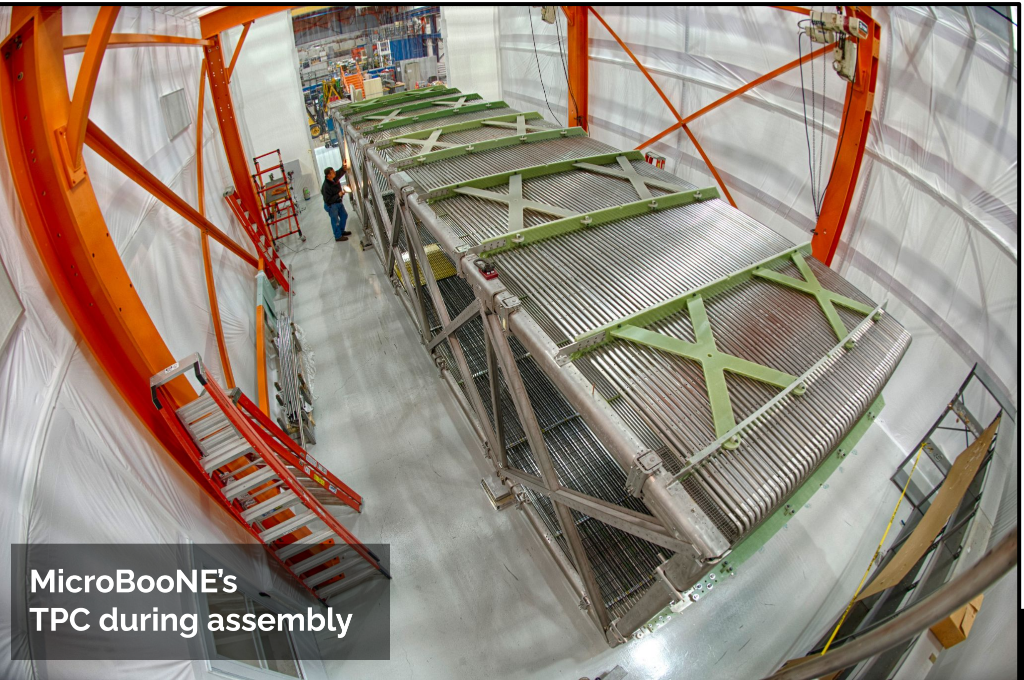
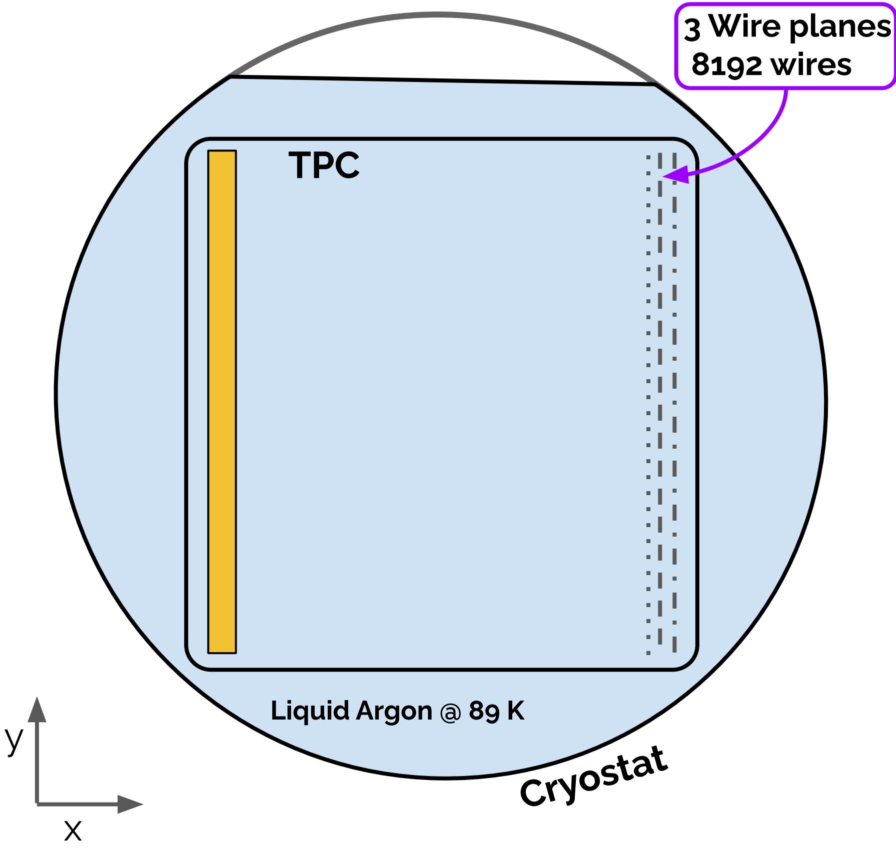
Huge thanks to the Fermilab Accelerator Division for such excellent beam delivery over all the years!

The MicroBooNE Detector

At MicroBooNE's core is an **85 metric ton** Liquid Argon Time Projection Chamber (**LArTPC**)



MicroBooNE's TPC during assembly



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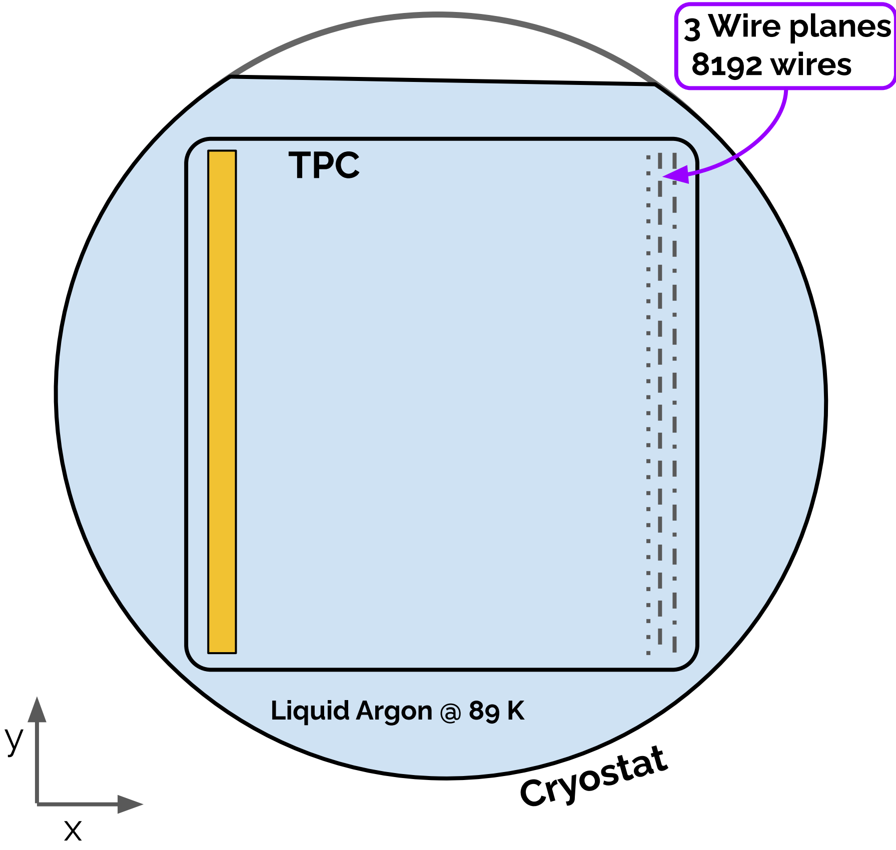
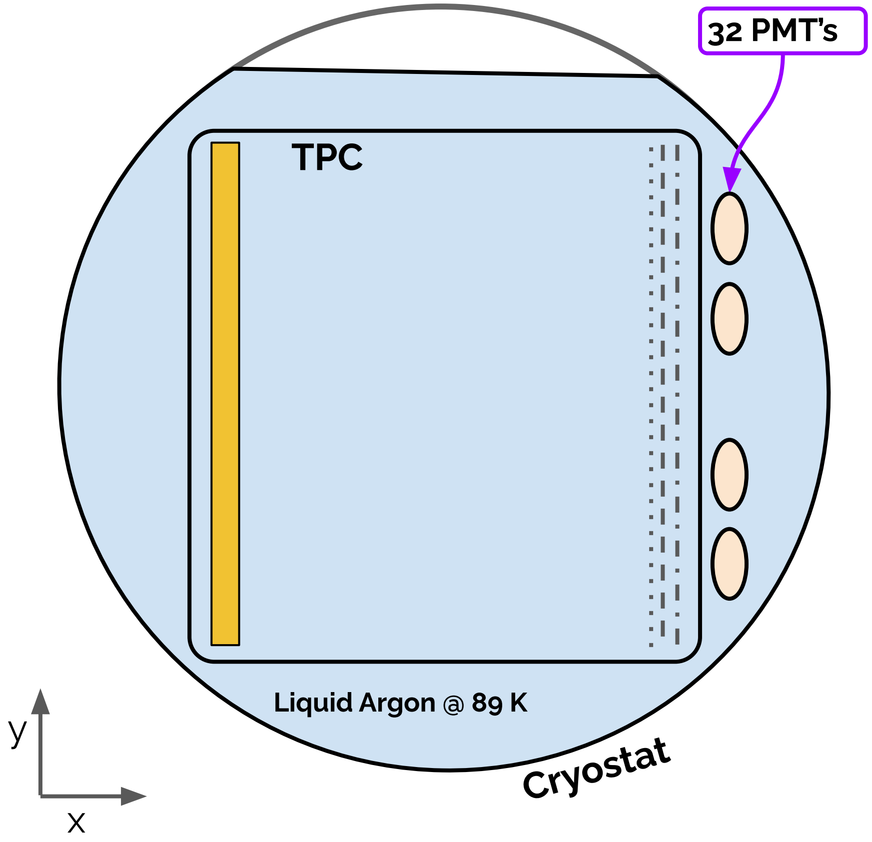
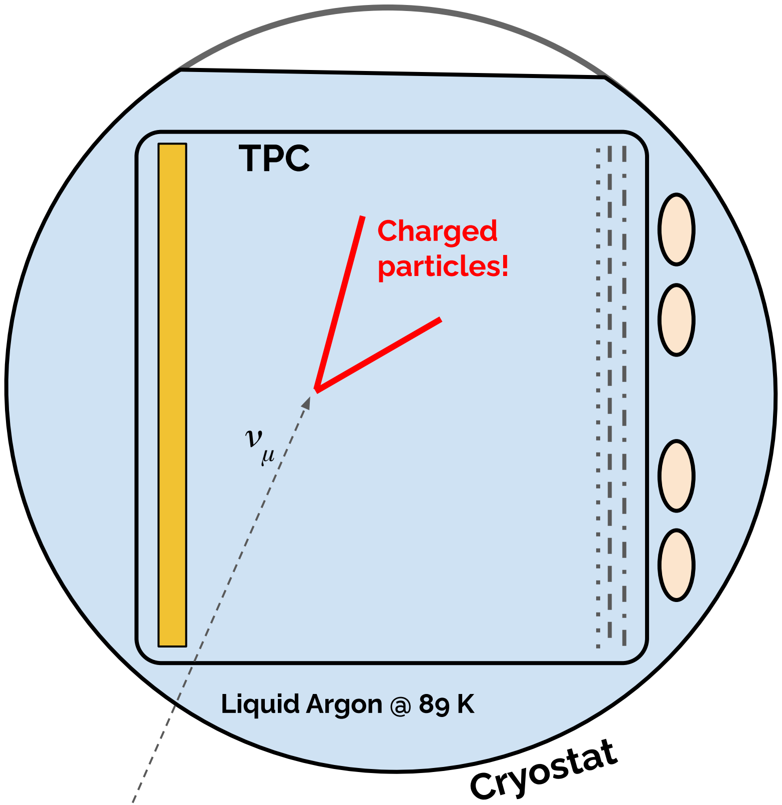


The MicroBooNE Detector

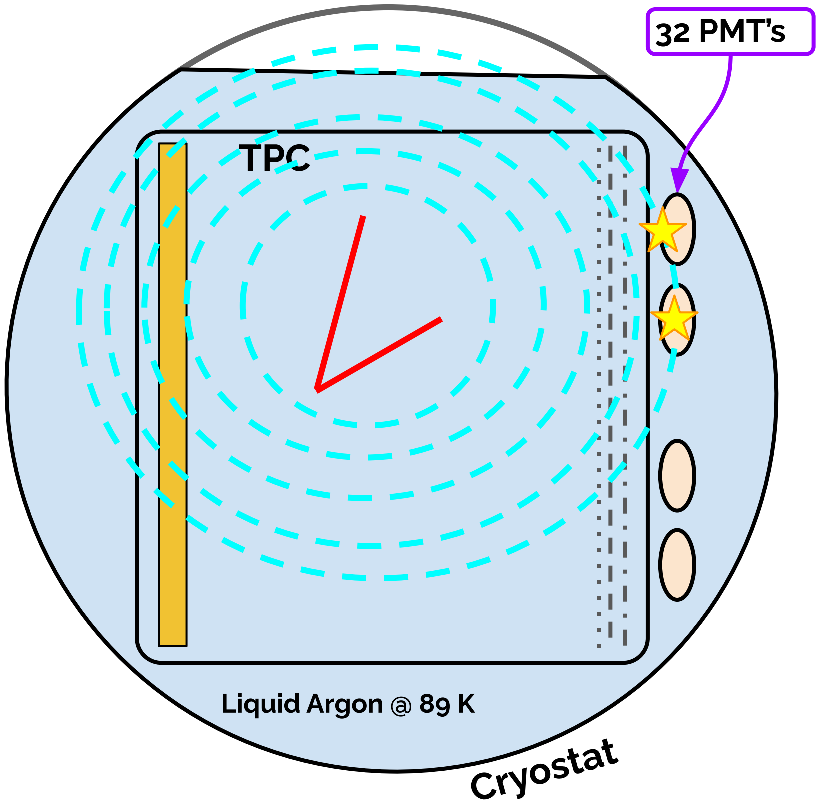
In addition we have a **Light Detection System** consisting of 32 8-inch PMT's

MicroBooNE's 8" Photomultiplier Tubes

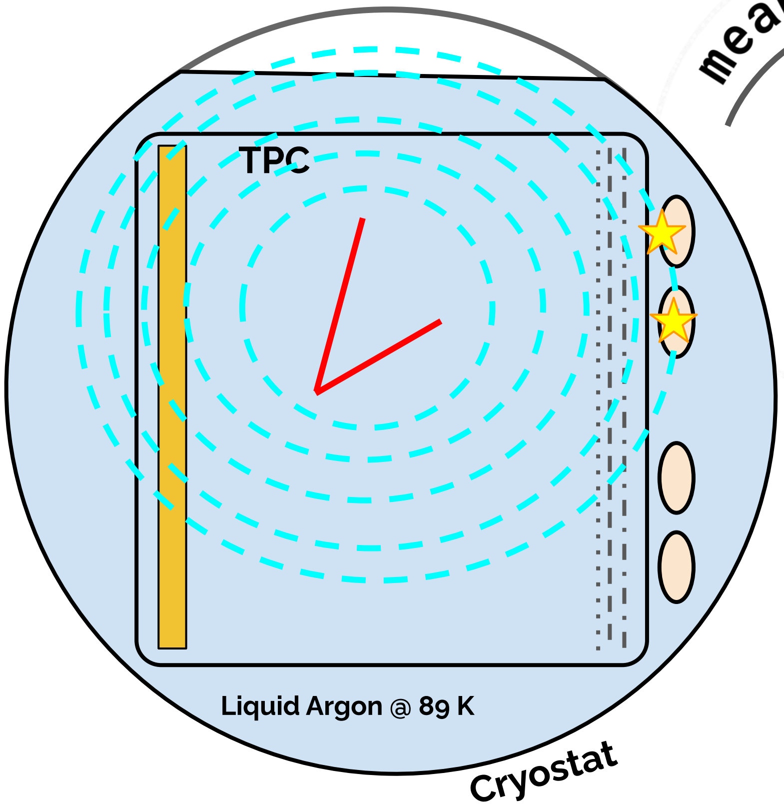



TPC
Charged
particles!
ν_μ
Liquid Argon @ 89 K
Cryostat

Scintillation light

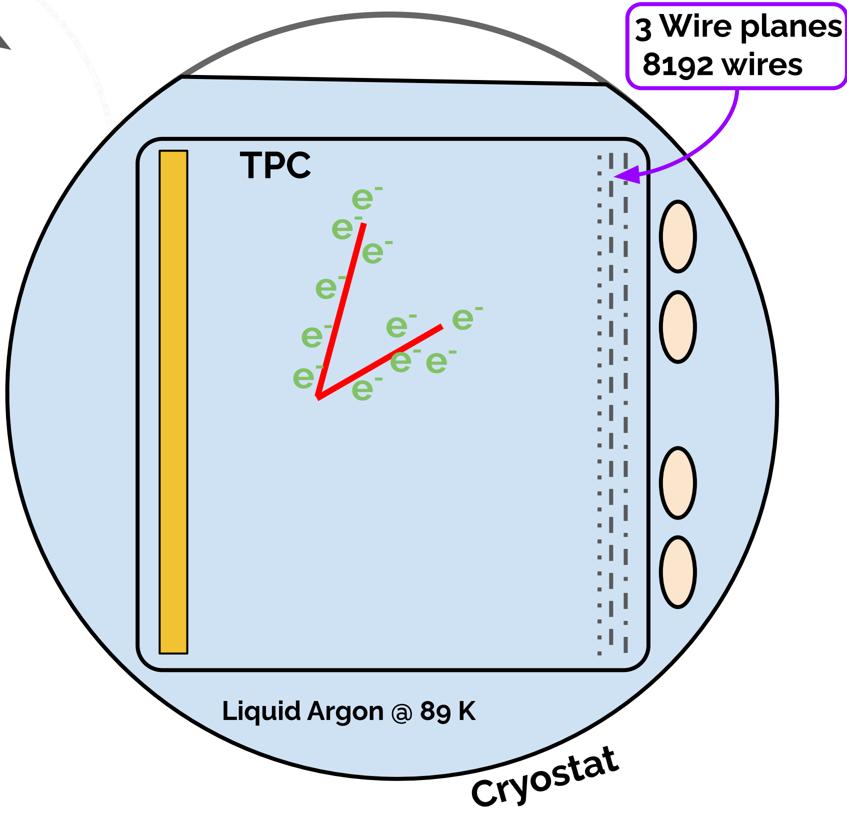


Scintillation light

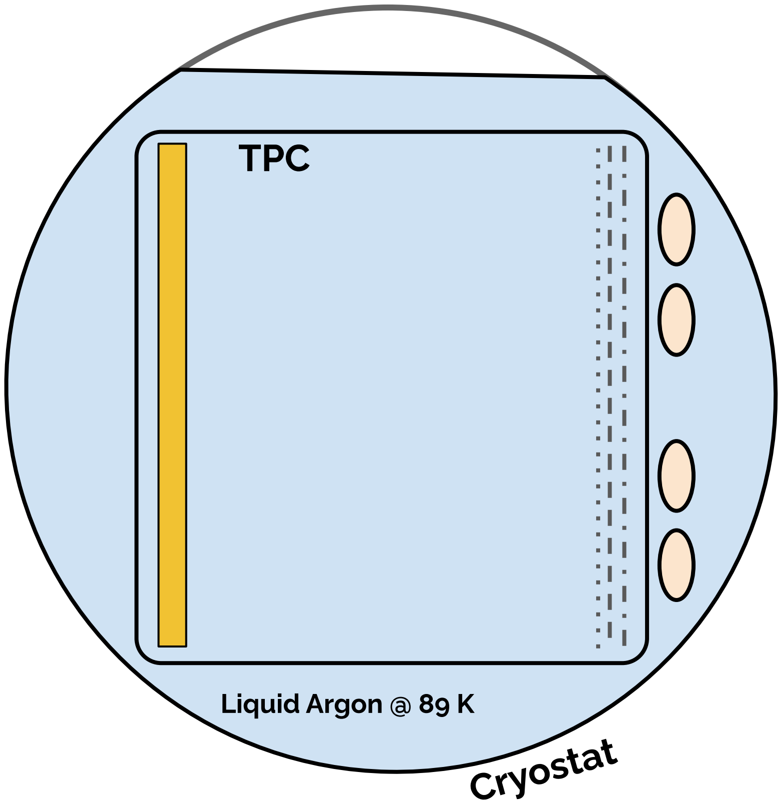


meanwhile

Ionization Charge



Scintillation light



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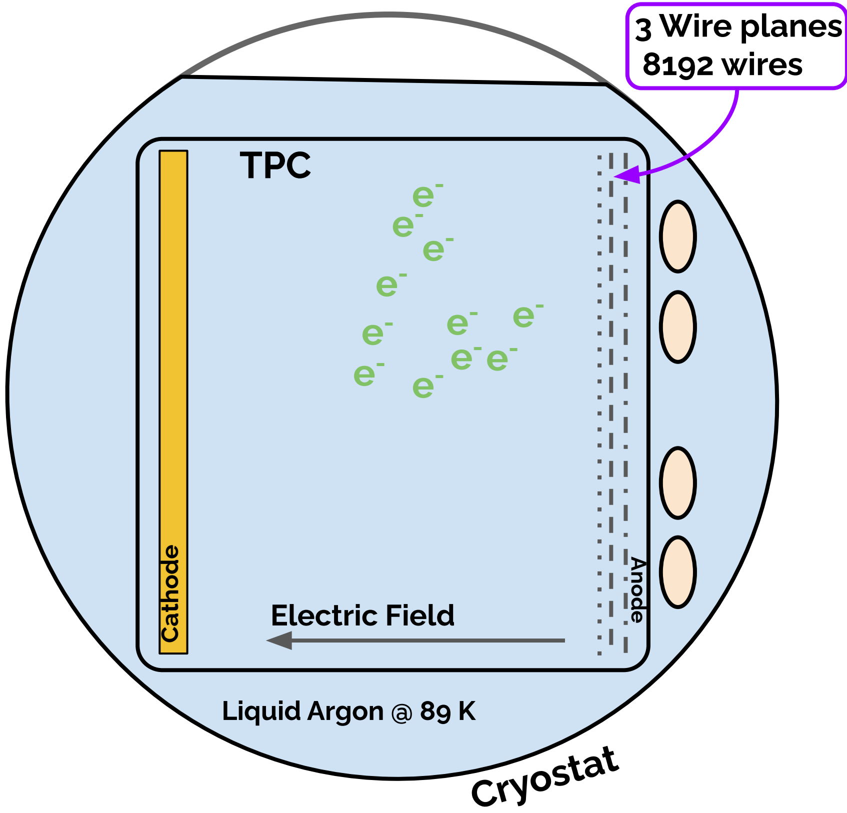

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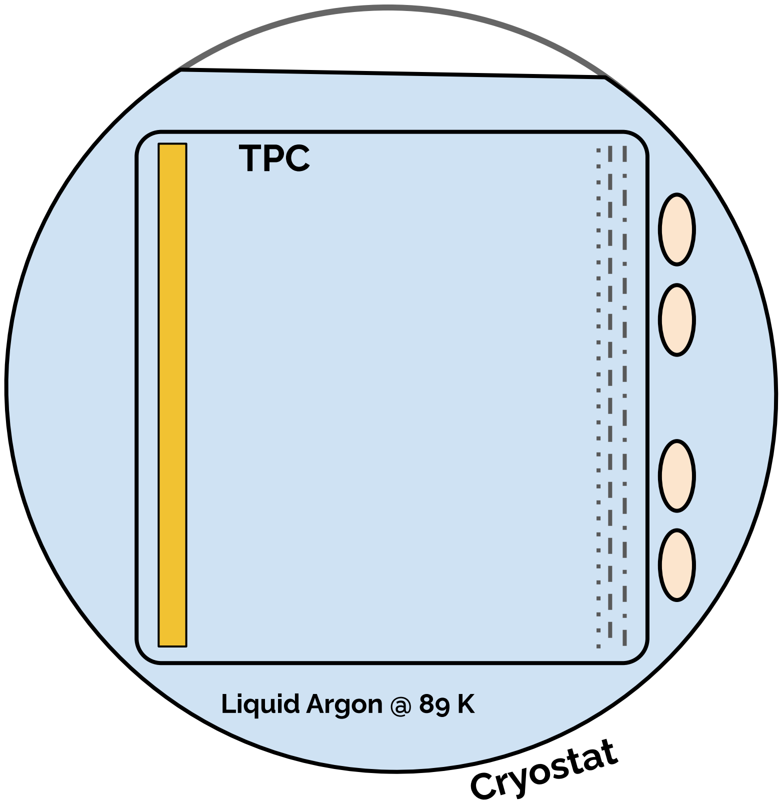
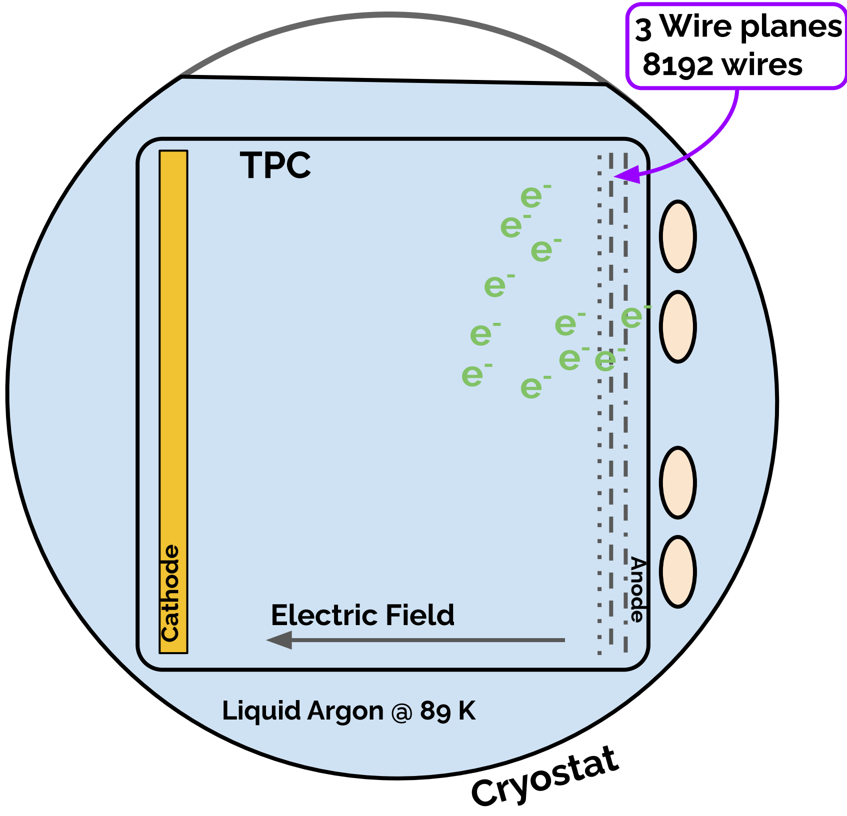
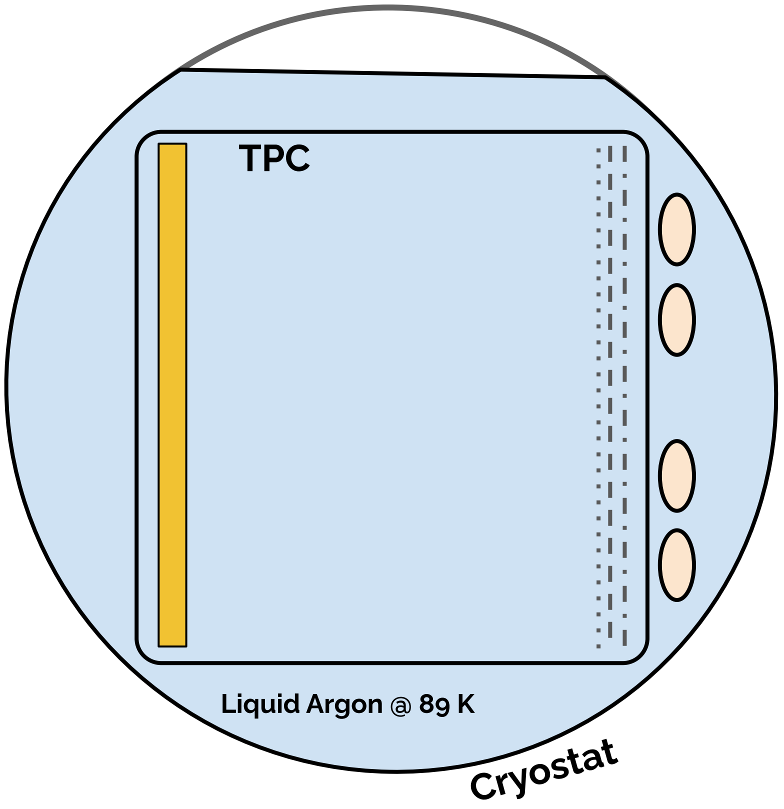


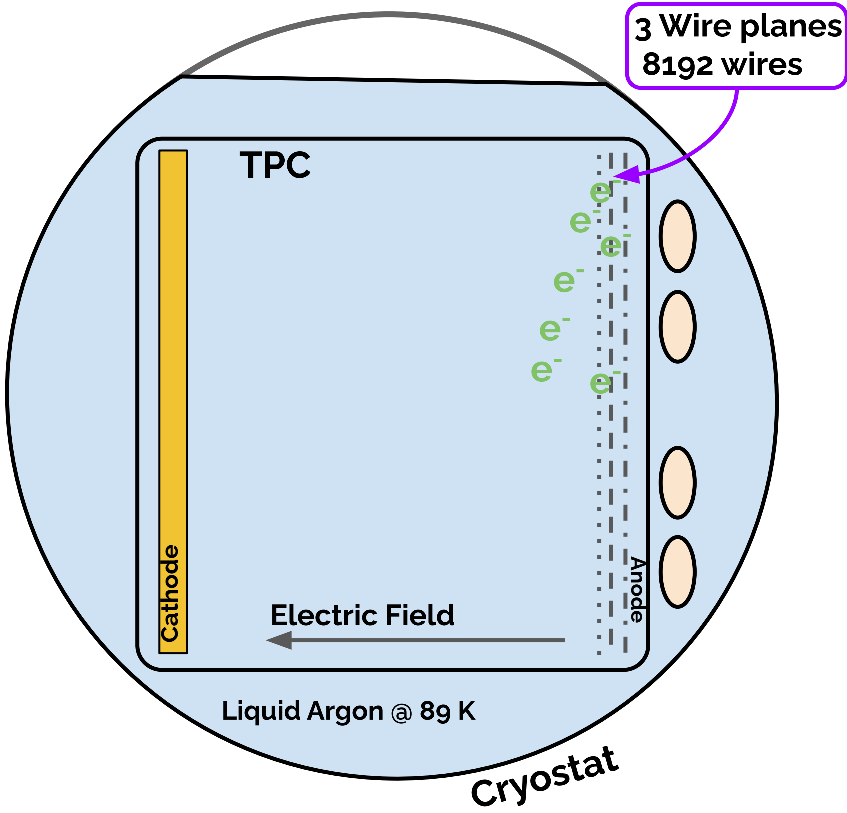
Ionization Charge



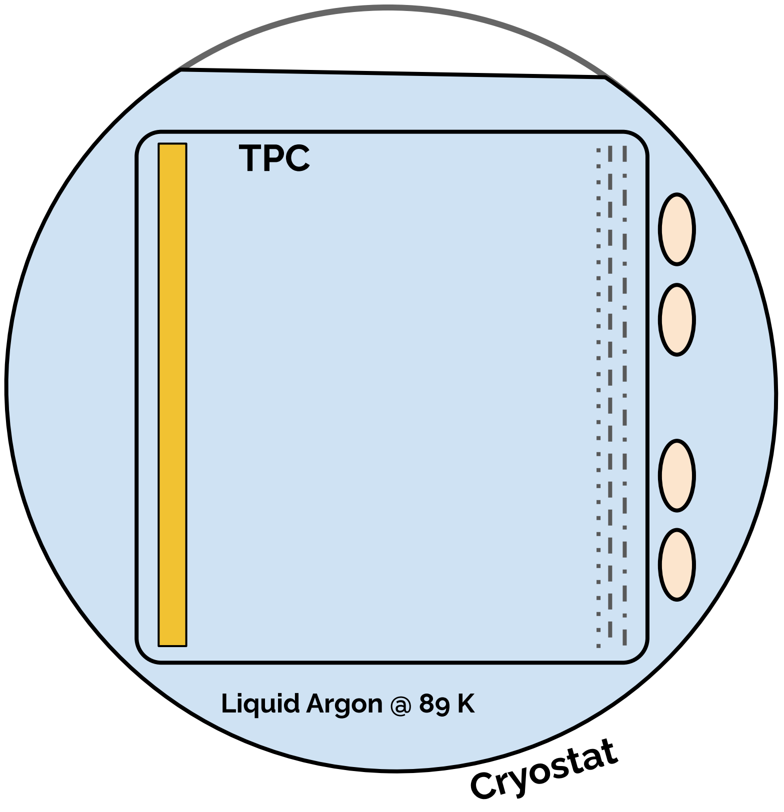
Scintillation light



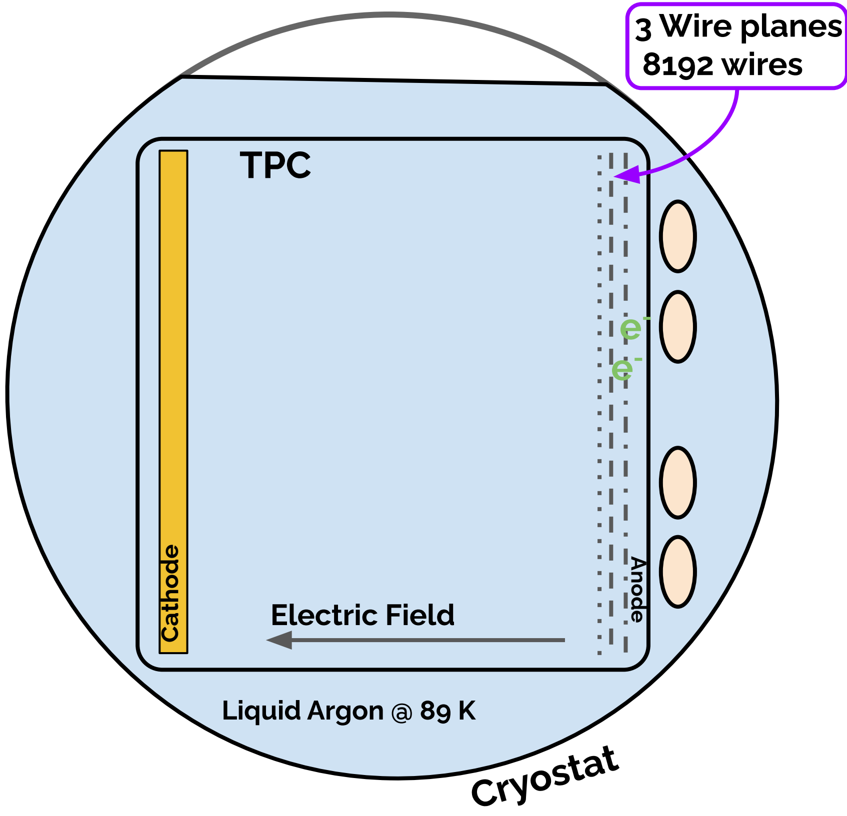
Ionization Charge



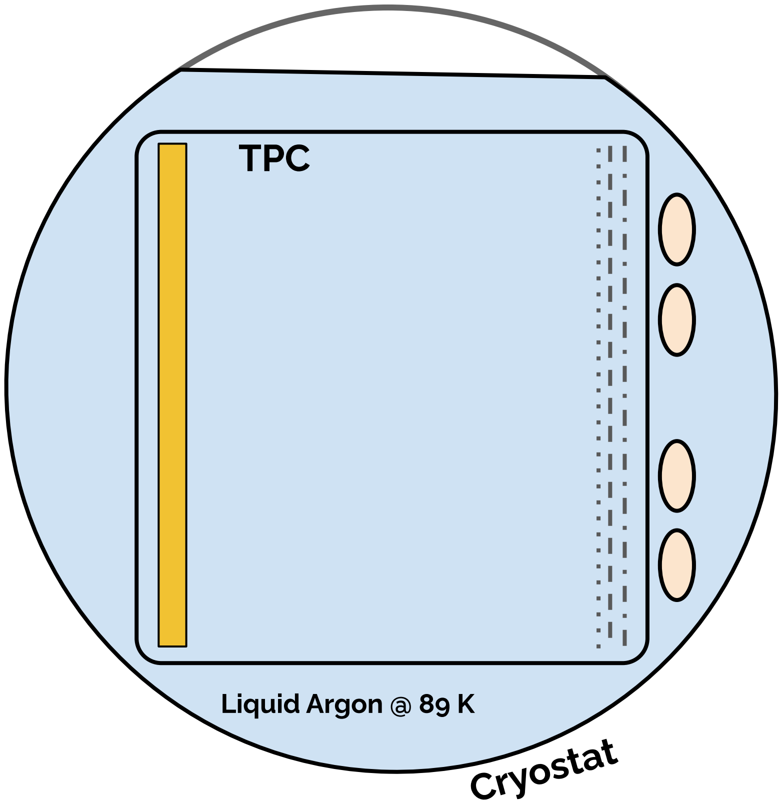
Scintillation light



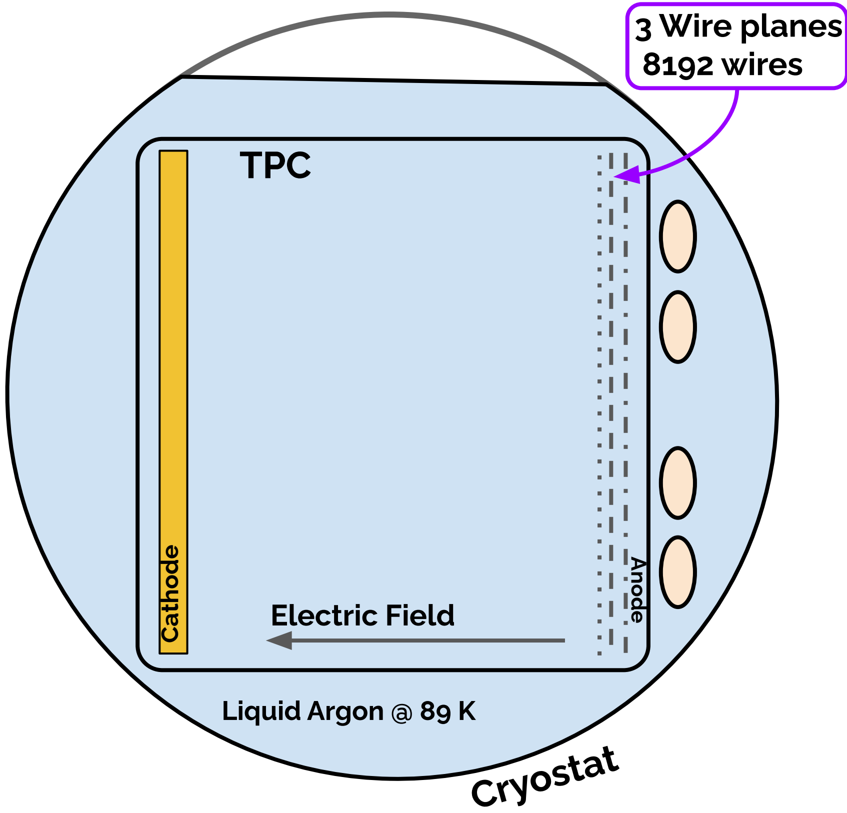
Ionization Charge



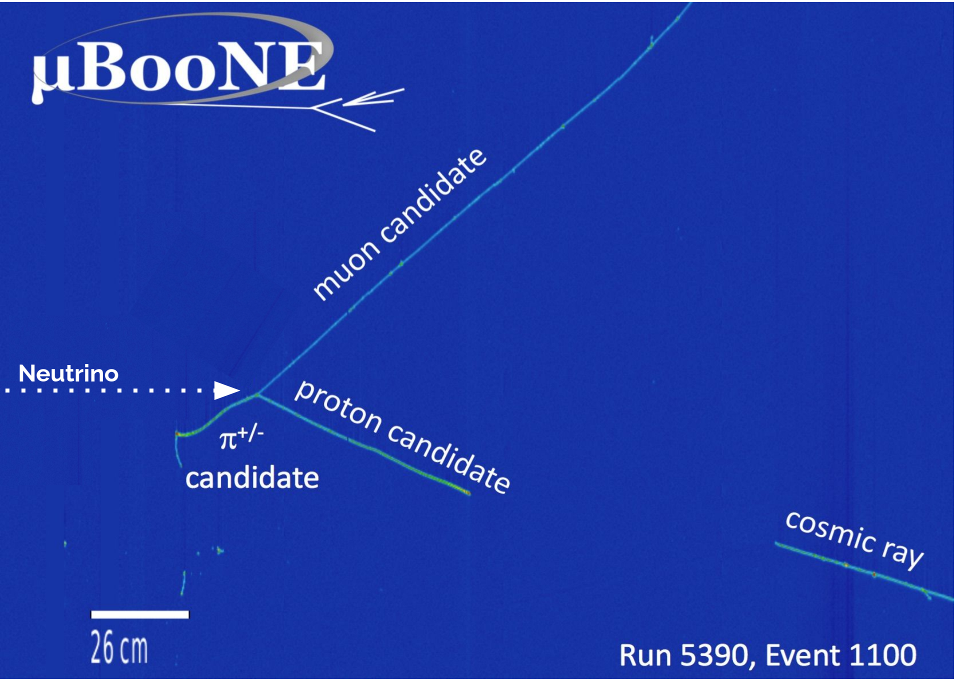
Scintillation light



Ionization Charge

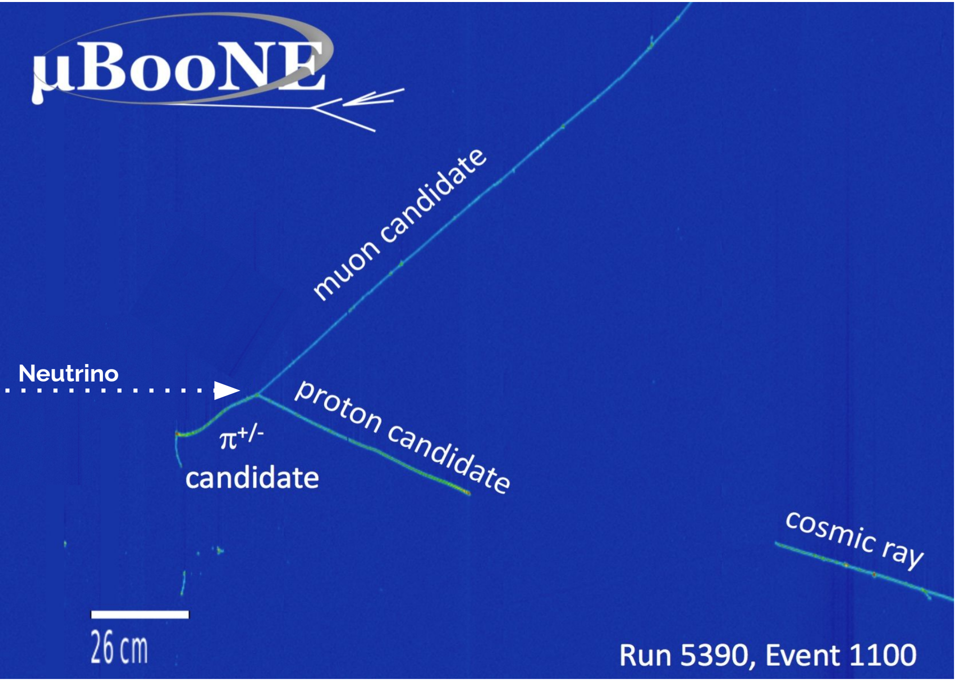


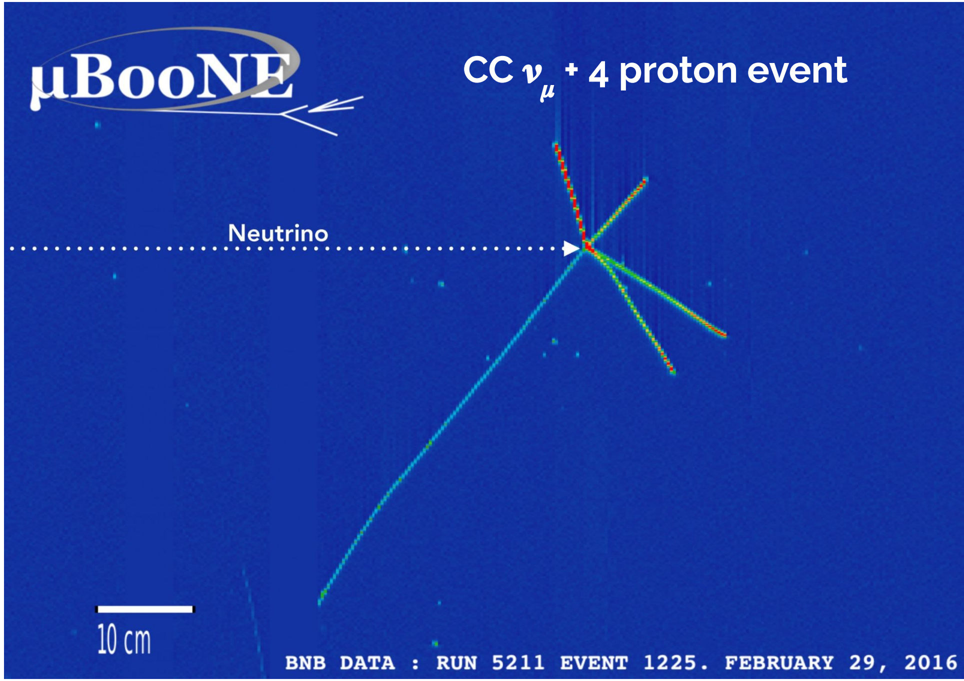
Images like a **digital bubble chamber**, but with added calorimetry: The **color scale** shows the **amount of deposited charge**



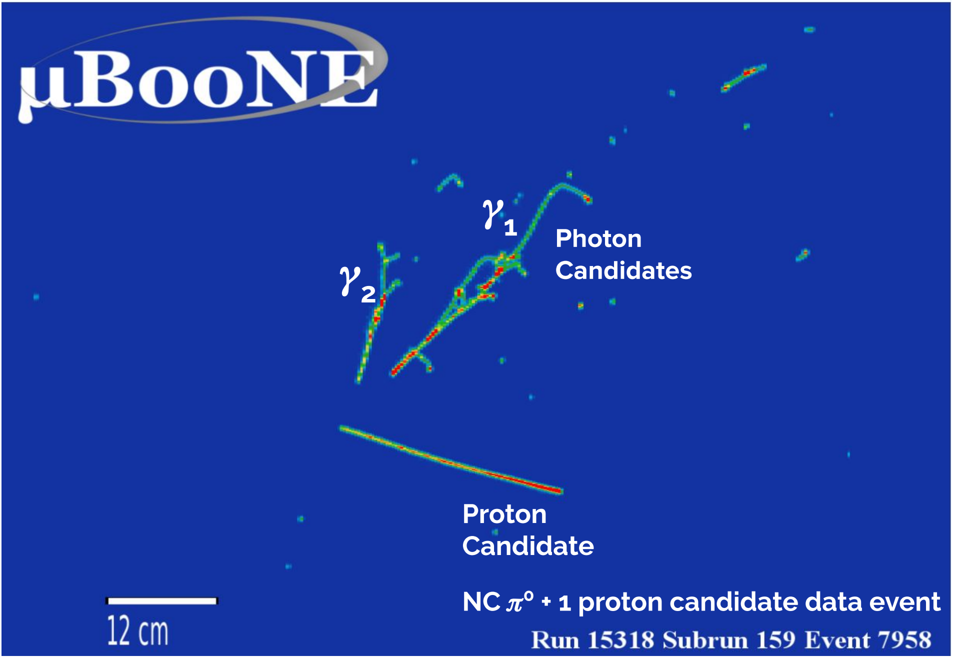
Images like a **digital bubble chamber**, but with added calorimetry: The **color scale** shows the **amount of deposited charge**

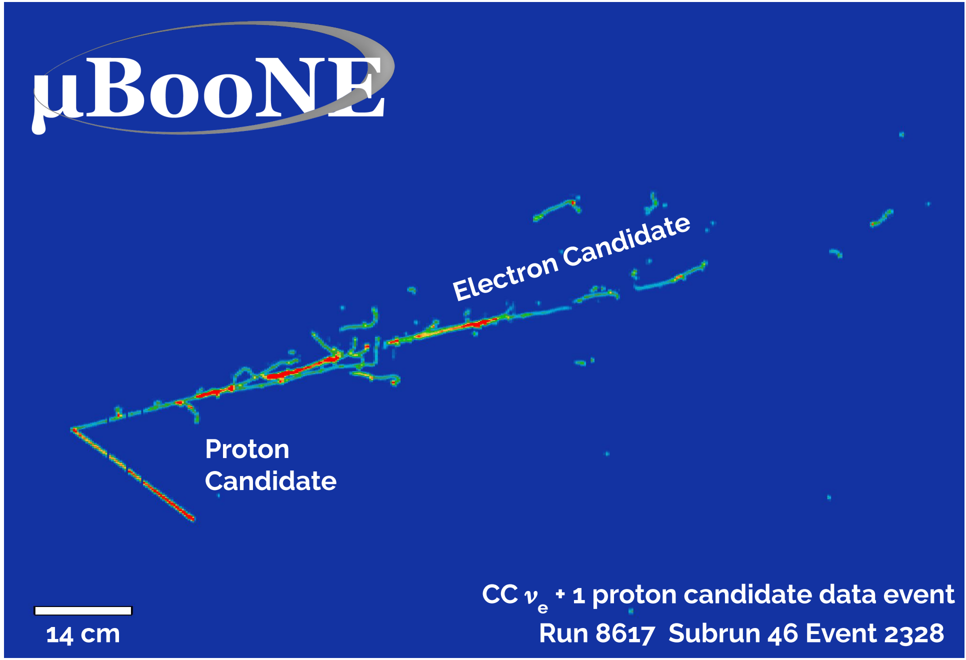
Distinguish between exclusive final-state particle multiplicities.
Ability to study precise final states to **probe nuclear models** and **test event generators** like never before





LArTPC's can separate **photons** from **electrons** due to fine spatial resolution and calorimetry





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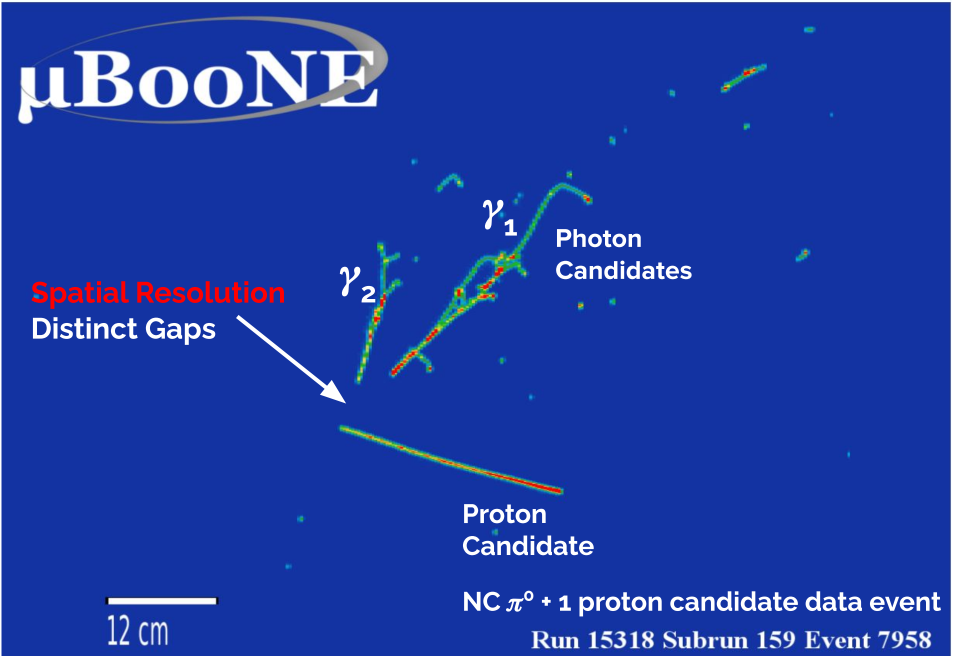
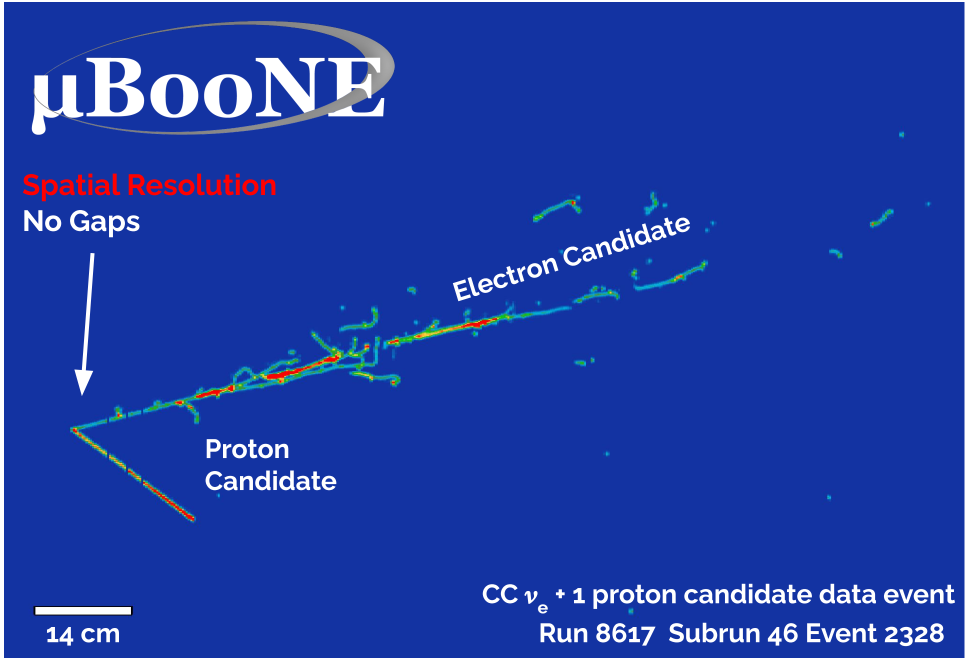
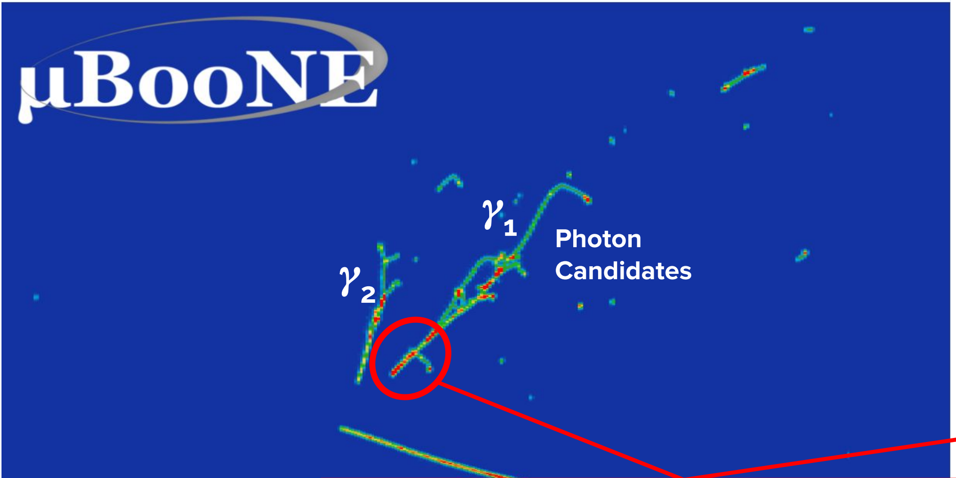
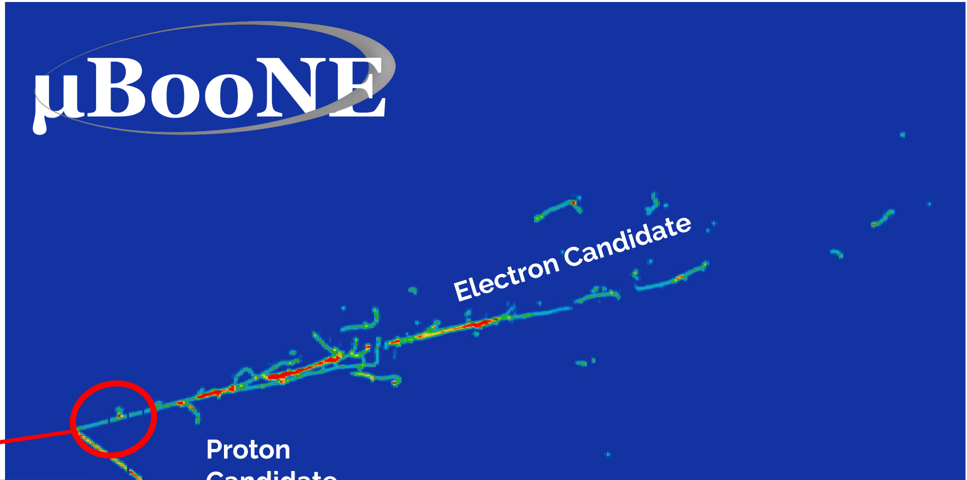




LArTPC's can separate **photons** from **electrons** due to fine spatial resolution and **calorimetry**

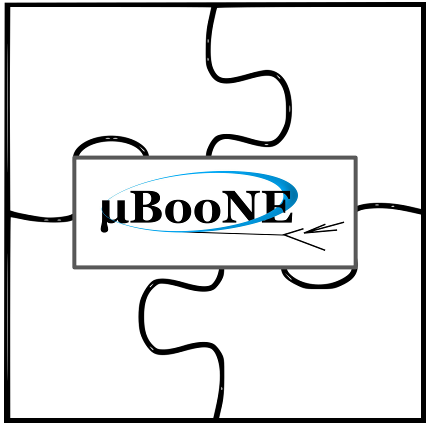




A pair producing photon quite literally has twice the number of minimally ionizing electrons, so has **twice the charge deposited at the start of the shower (dE/dx)**

Largest sample of neutrino interactions on argon **in the world**

Photon/ Electron separation



Calorimetric **Muon/Proton separation**

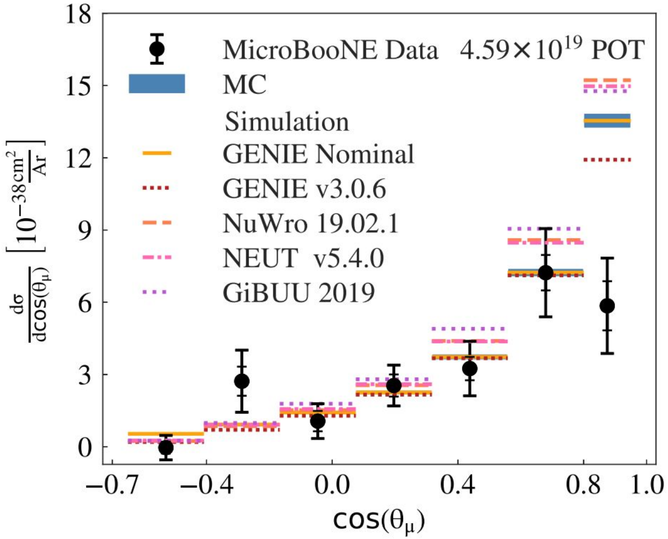
Distinguish between exclusive **final-state particle multiplicities**

What can we do when we put all of these together?!

Neutrino-Argon Cross-Sections

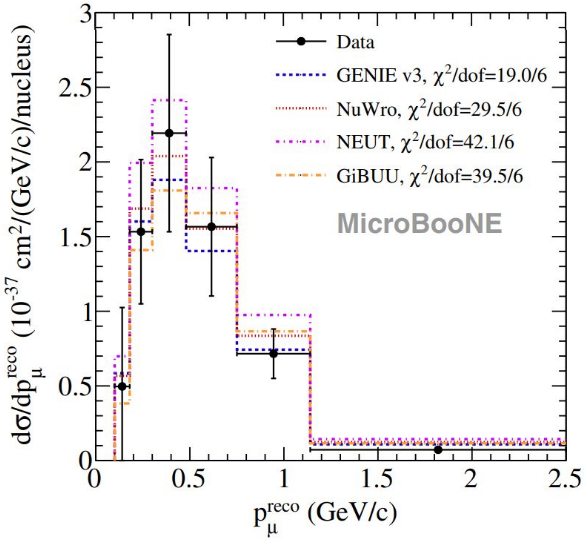
CC ν_μ 1p (ν_μ+Ar→ μ +p)

Phys. Rev. Lett. 125, 201803 (2020)



CC Np (ν_μ+Ar→ μ + any protons, no π's)

Phys. Rev. D 102, 112013 (2020)



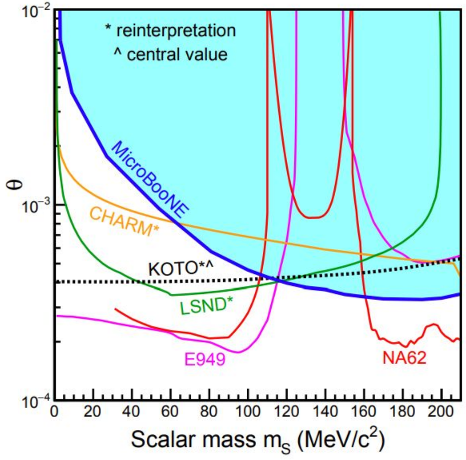
Plus many more!

- Flux-Averaged **Inclusive CC ν_e** Cross-Section using **NuMI** (Phys. Rev. D 104, 052002 (2021))
- **Inclusive CC ν_μ** Differential Cross Sections (Phys. Rev. Lett. 123, 131801 (2020))
- ν_μ–Ar **multiplicity** comparisons to GENIE model predictions (Eur. Phys. J. C 79, 248 (2019))
- First measurement of **CC $\nu_\mu \pi^0$** production on argon (Phys. Rev. D 99, 091102(R) (2019))

- Neutrino-Argon Cross-Sections

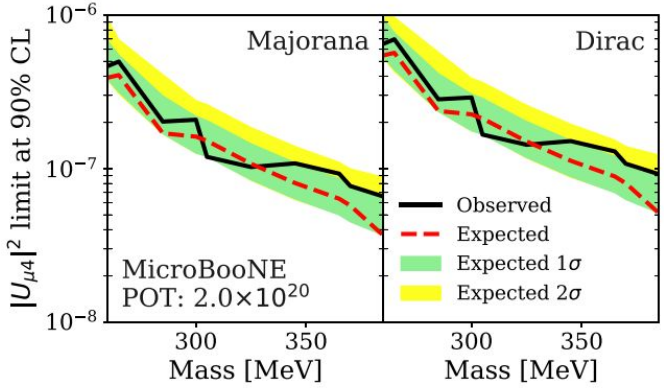
- **Beyond Standard Model Physics**

Search for a **Higgs portal scalar** decaying to **electron-positron pairs** in the MicroBooNE detector



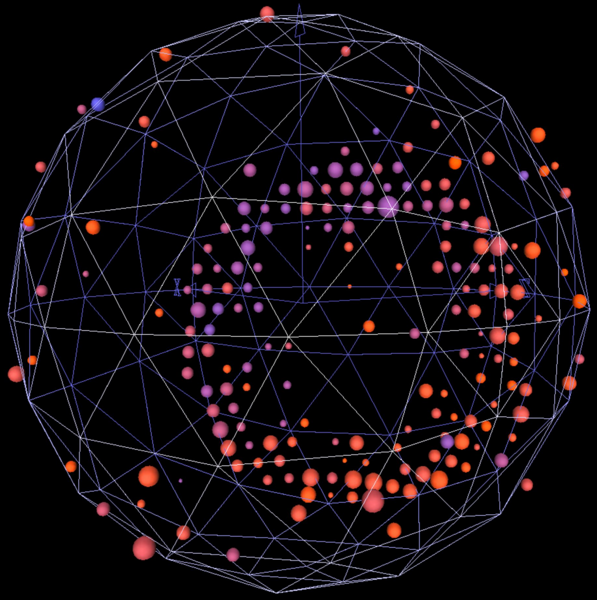
https://arxiv.org/abs/2106.00568 (Accepted to PRL)

Search for **heavy neutral leptons** decaying into **muon-pion pairs** in the MicroBooNE detector



Phys. Rev. D 101, 052001 (2020)

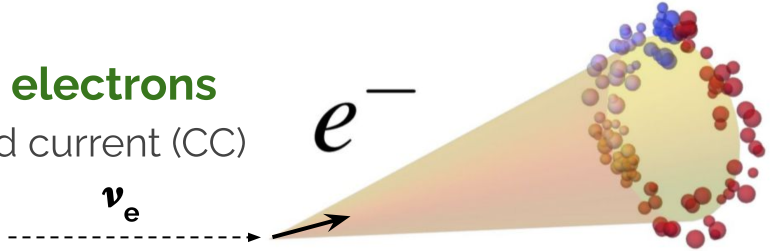
- Neutrino-Argon Cross-Sections
- Beyond Standard Model Physics
- **Search for the origin of the MiniBooNE Low-Energy Excess!**



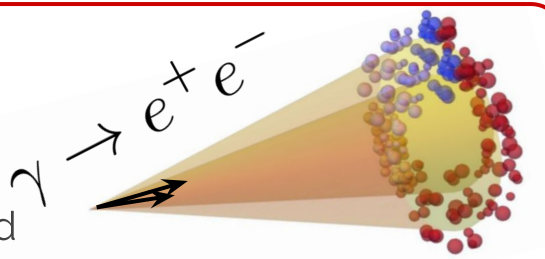
Electron Cherenkov ring event in MiniBooNE

MiniBooNE was an 800 metric ton mineral oil (CH_2) Cherenkov detector built to look for ν_e **appearance** in the primarily ν_μ Booster Neutrino Beam

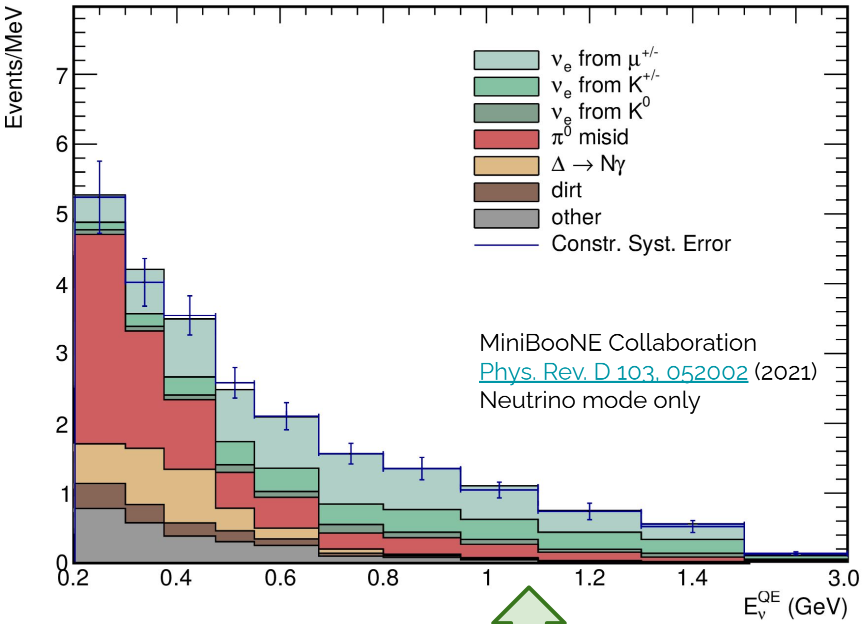
It detected ν_e by the **electrons** produced in charged current (CC) interactions.



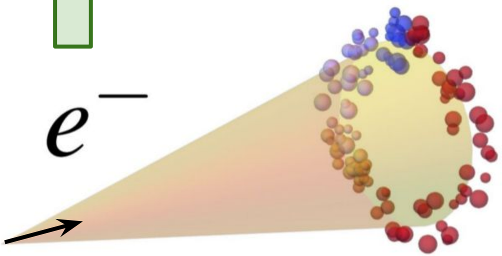
However, **photons**, that pair produce extremely collimated electron/positron pairs produced an identical Cherenkov ring



MiniBooNE Predicted Backgrounds



At **higher** reconstructed neutrino energies true **electrons** from the **intrinsic ν_e** in the beam dominate



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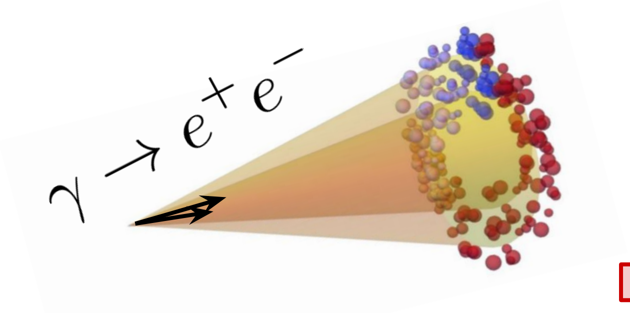
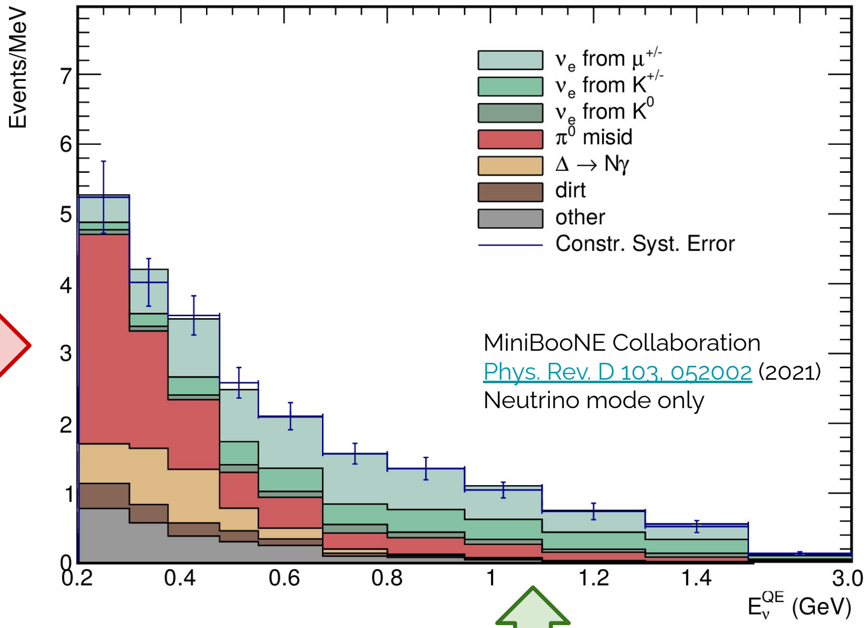
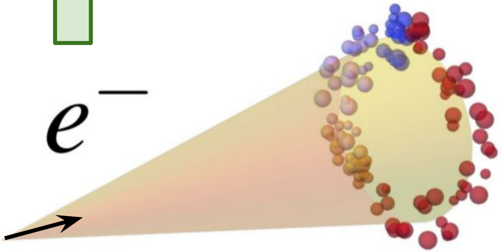




At **lower** reconstructed neutrino energies **photons** become the dominant backgrounds. These come primarily from

- **Neutral Current (NC) π^0 Mis-identification**
- **Dirt** (events scattering in from outside detector)
- **NC $\Delta \to N\gamma$**

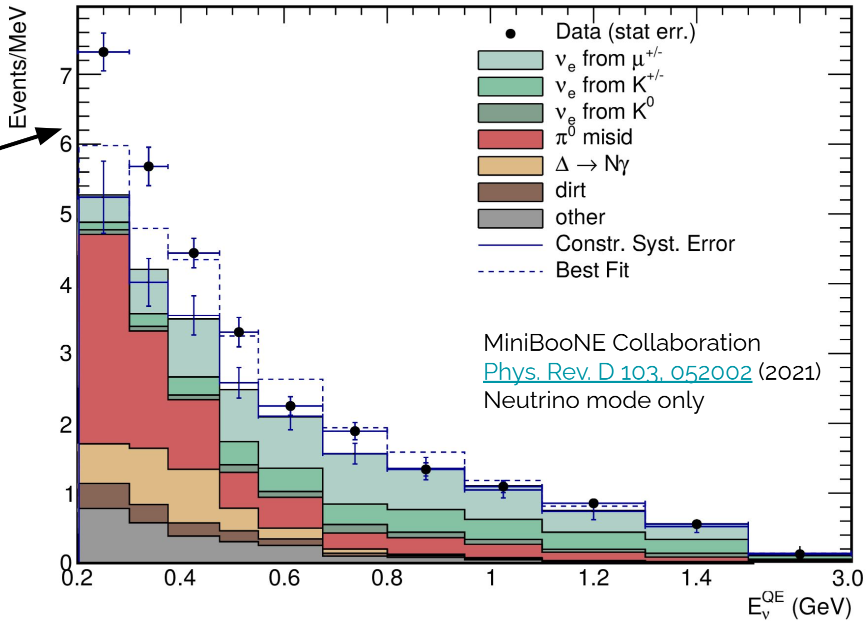
At **higher** reconstructed neutrino energies true **electrons** from the **intrinsic ν_e** in the beam dominate



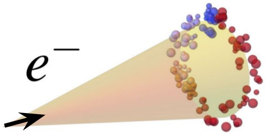
MiniBooNE Low Energy Excess (LEE)

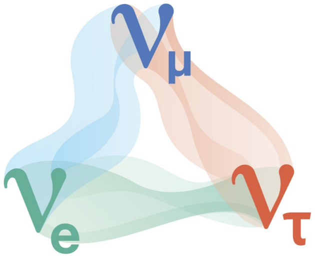
An excess of events!

After several updates, with data collected 2002-2019, its **significance** is now **4.8σ** (systematics limited) when combining all neutrino and antineutrino beam data



Electrons?

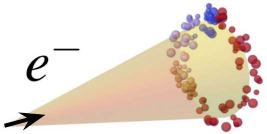


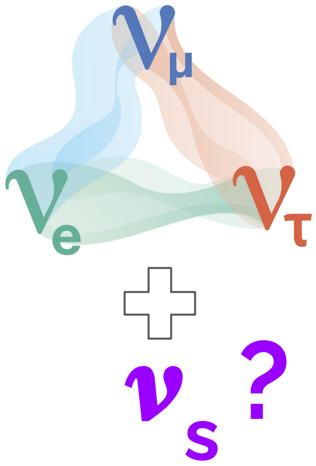


If the excess is indeed **truly electron** in origin, they need to come from somewhere.

- The BNB beam is ~0.5% ν_e (>99% $\nu_\mu/\bar{\nu}_\mu$)
- **Neutrino $\nu_\mu \rightarrow \nu_e$ oscillations?**

Electrons?





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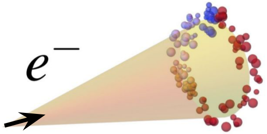
- The BNB beam is ~0.5% ν_e (>99% $\nu_\mu/\bar{\nu}_\mu$)
- **Neutrino $\nu_\mu \rightarrow \nu_e$ oscillations?**
- Oscillations at this energy and distance requires the existence of an **4^{th} (sterile) neutrino**

Electrons?



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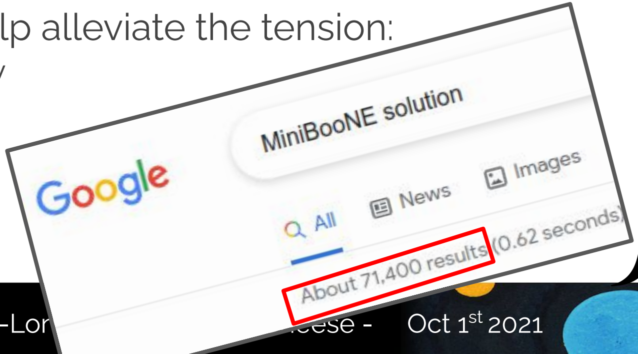
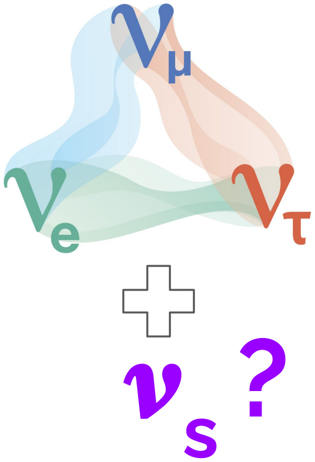
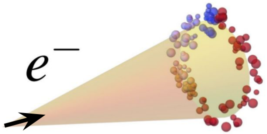
- Oscillations at this energy and distance requires the existence of an **4th (sterile) neutrino**
- Just a 4th neutrino? Difficult to explain both MiniBooNE excess and all other global data.
- More complex models can help alleviate the tension:
    - Mixed oscillations and decay
    - Resonance matter effects
    - Additional sterile neutrinos
    - Non-unitary mixing
    - … + Many more!





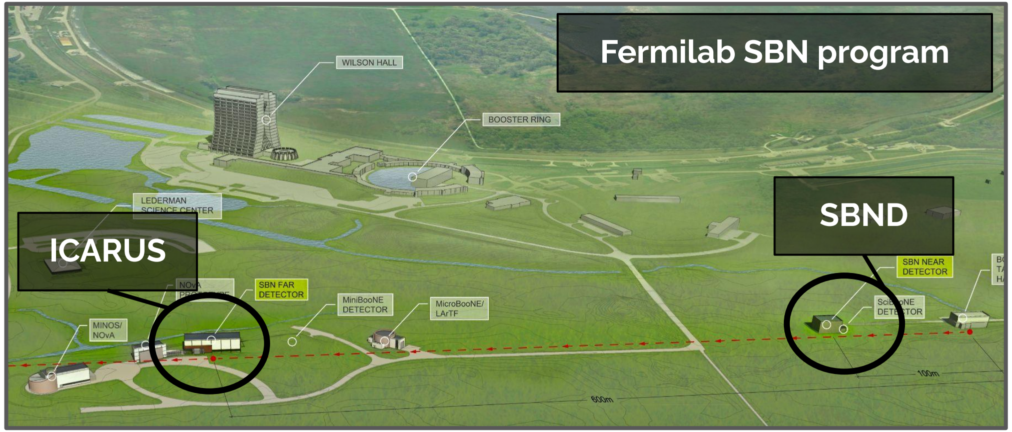
If truly electrons one generally needs to invoke **new physics associated with the neutrino sector.** Profound ramifications for all particle physics, astrophysics, and cosmology.

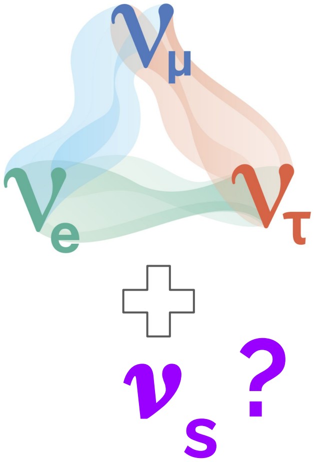
Electrons?



Both the wider evidence, and wider search, for short-baseline oscillations extends globally beyond MiniBooNE and MicroBooNE!

LSND, **Reactor** & **Gallium** anomalies all provide hints and many future experiments aim to probe this exciting direction



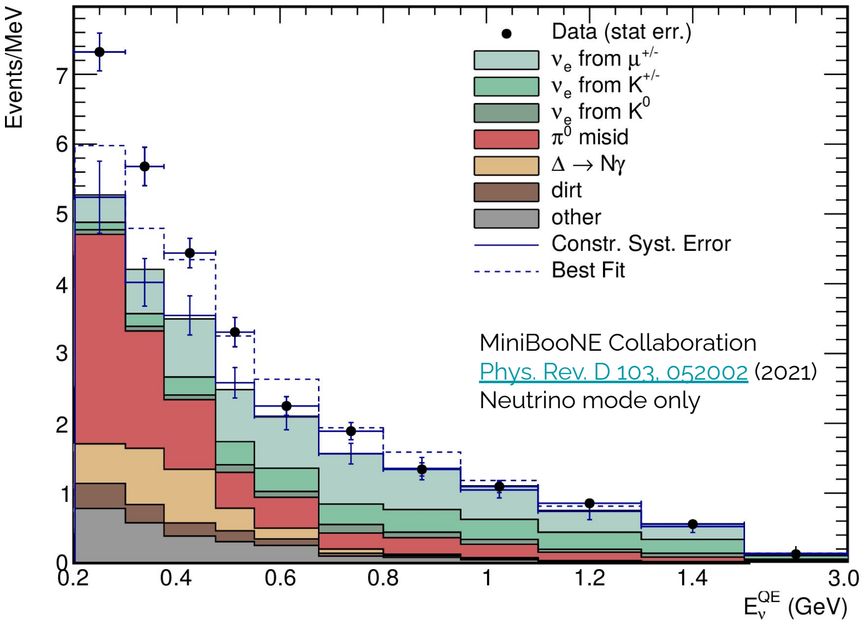


If truly electrons one generally needs to invoke **new physics associated with the neutrino sector.** Profound ramifications for all particle physics, astrophysics, and cosmology.

Electrons? Or Photons?

Several sources of photons in MiniBooNE backgrounds:

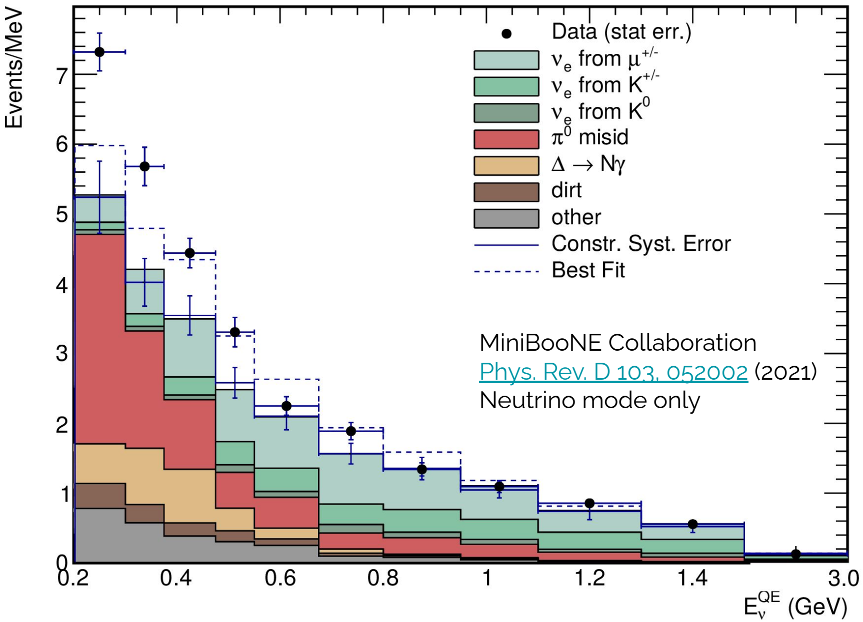
- **NC π^0 Mis-identification**
- **Dirt** (events scattering in from outside detector)
- **NC $\Delta \rightarrow N\gamma$**



Electrons? **Or Photons?**

Several sources of photons in MiniBooNE backgrounds:

- **NC π^0 Mi**… MEASURED IN-SITU
- **Dirt** (events scattering in from outside detector)
- **NC $\Delta \rightarrow N\gamma$**



MiniBooNE Collaboration
Phys. Rev. D 103, 052002 (2021)
Neutrino mode only

Electrons? Or Photons?

Several sources of photons in MiniBooNE backgrounds:

- **NC π^0 Mis** MEASURED IN-SITU
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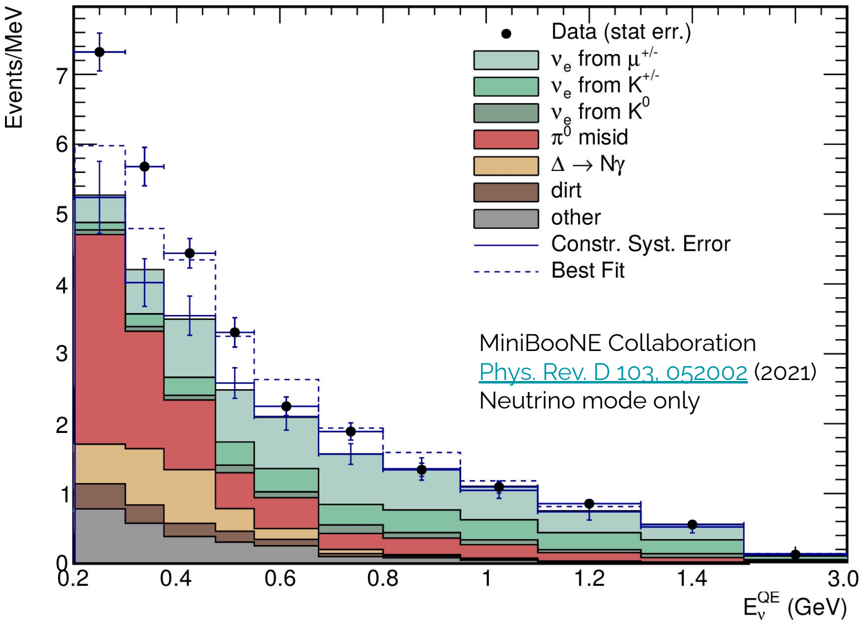
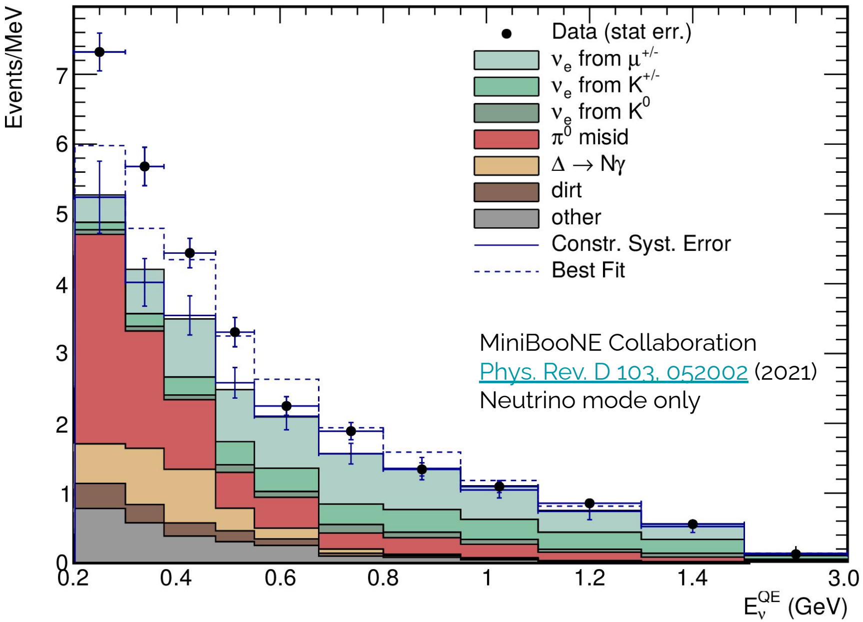


Electrons? **Or Photons?**

Several sources of photons in MiniBooNE backgrounds:

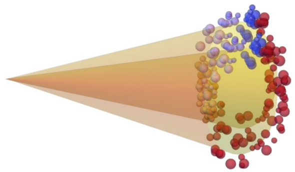
- **NC π^0 Mis**... **MEASURED IN-SITU**
- **Dirt** (events ... om outside de... **BEAM TIMING**
- **NC $\Delta \to N\gamma$** (Neutral Current Δ radiative decay)



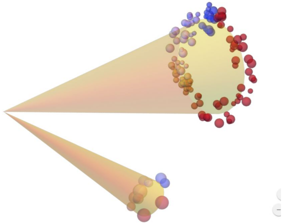
NC $\Delta \to N\gamma$ is a source of photons **not constrained directly** by the MiniBooNE experiment; rather, the rate was predicted by using the measured NC π^0 and **assuming a theoretical branching fraction** for the radiative decay.

Electrons? Or Photons? .....Or Neither?

Rich phenomenology developing in recent years around the possibility of the MiniBooNE excess being due to **e^+e^- pairs from decays of new exotic particles.**



- Decays of **new dark gauge bosons** (Z')
    - E. Bertuzzo, S. Jana, P. A.N. Machado, R.Zukanovich Funchal Phys.Rev.Lett. 121 24, 241801(2018)
    - P. Ballett, S. Pascoli, M. RL Phys. Rev. D 99, 071701 (2019)
    - A. Abdullahi, M, Hostert, S.Pascoli Phys.Lett.B 820 136531(2021)
- General **Extended higgs sectors + Decay**
    - B. Dutta, S. Ghosh, T. Li Phys. Rev. D 102, 055017 (2020)
    - W. Abdallah, R. Gandhi, S. Roy Phys. Rev. D 104, 055028 (2021)
- Decays of **leptophilic axion-like** particles
    - C. V. Chang, C, Chen, S. Ho, S. Tseng Phys. Rev. D 104, 015030 (2021)



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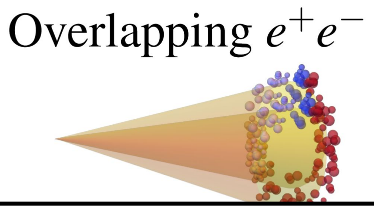
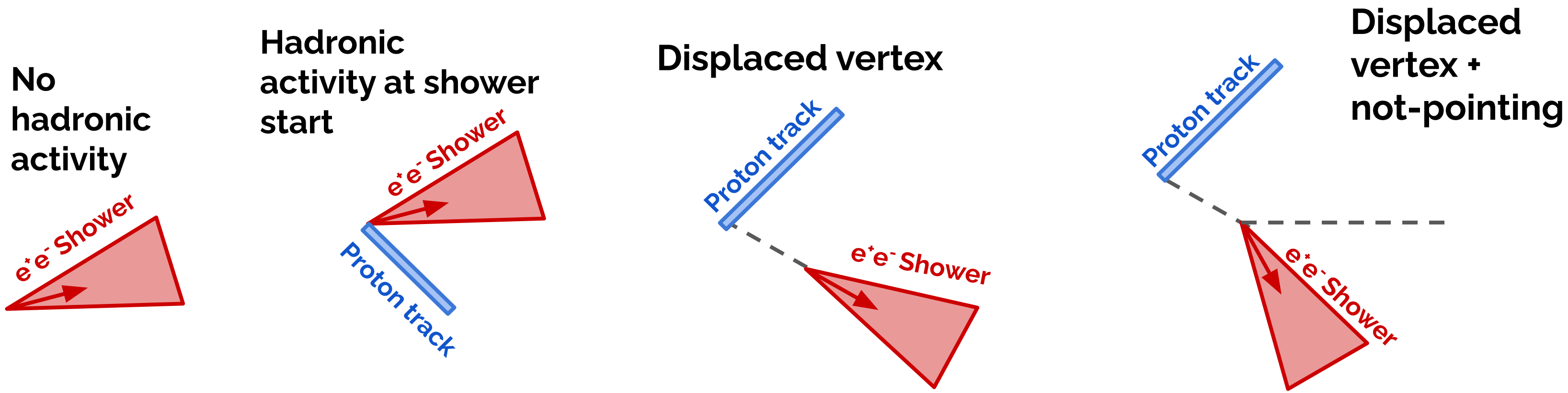
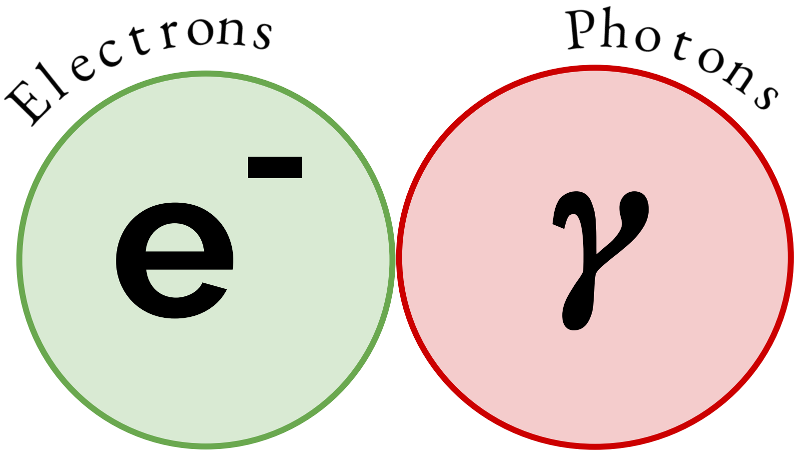
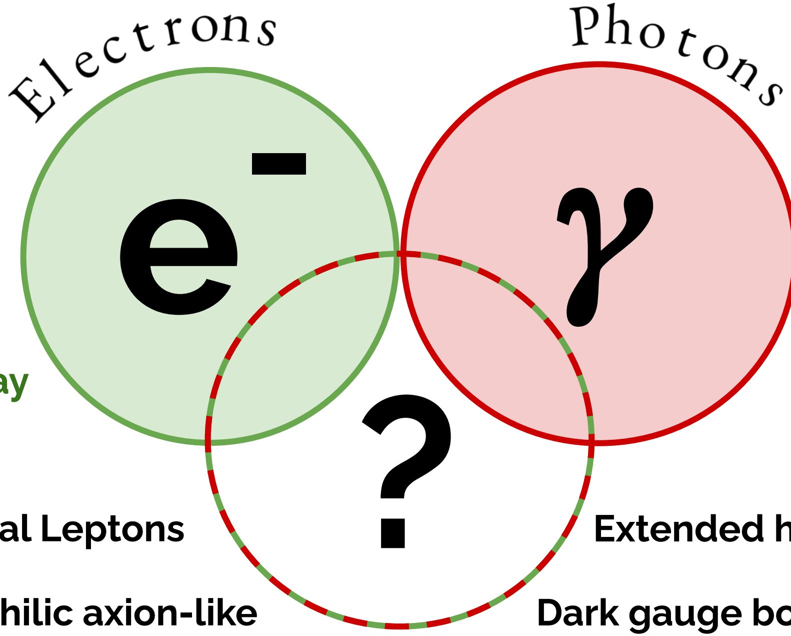


Leverage our LArTPC technology! **Not all models are the same**

Distinguish between models based on exclusive final state topologies




Electrons
e^-
Photons
γ



3+1 Oscillations

Oscillations+Decay

NC $\Delta \rightarrow N\gamma$

Coherent photon production

Heavy Neutral Leptons

leptophilic axion-like

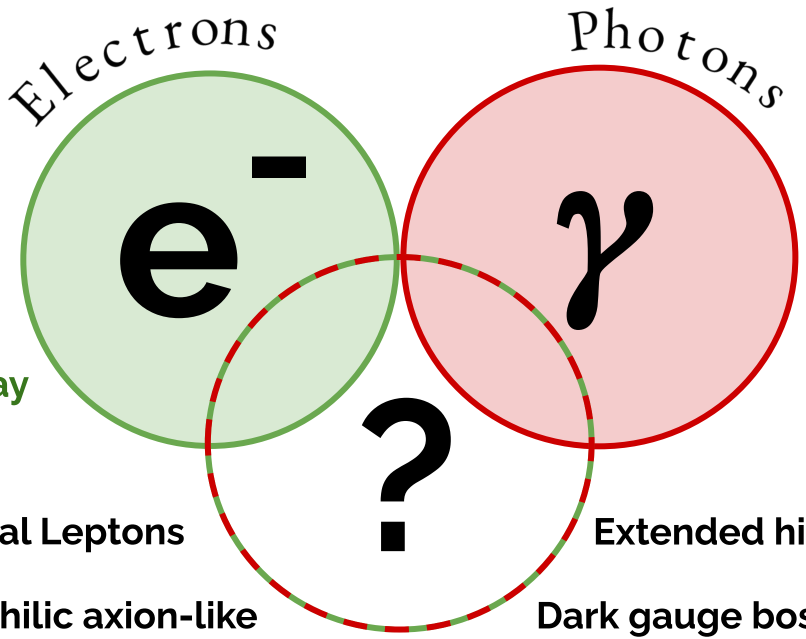
Extended higgs sectors

Dark gauge bosons (Z')

First Series of MicroBooNE Results

Three complementary electron LEE analysis targeting a variety of topologies, inclusive and exclusive, with different reconstruction paradigms (Coming soon!)

Todays Result, MicroBooNE first LEE photon search, targeting **single-photons** from neutral current **$\Delta \rightarrow N\gamma$ decays**



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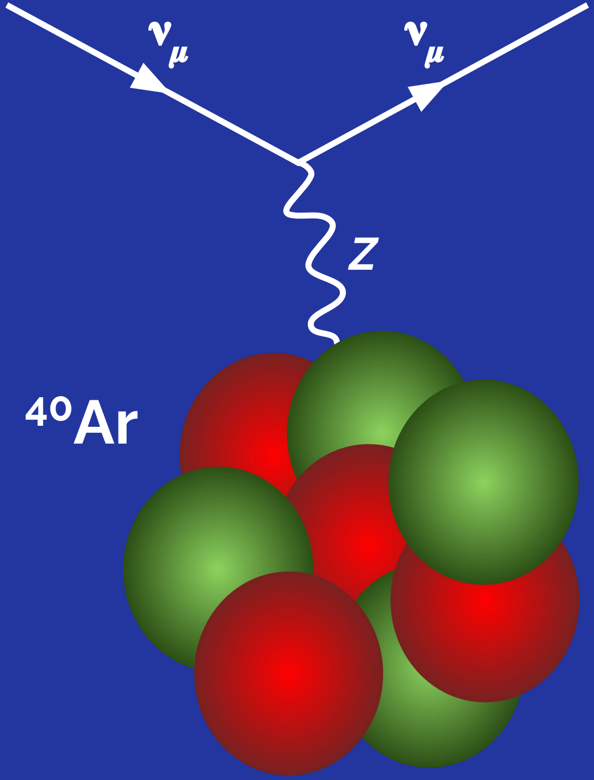
NC $\Delta \rightarrow N\gamma$ in MicroBooNE



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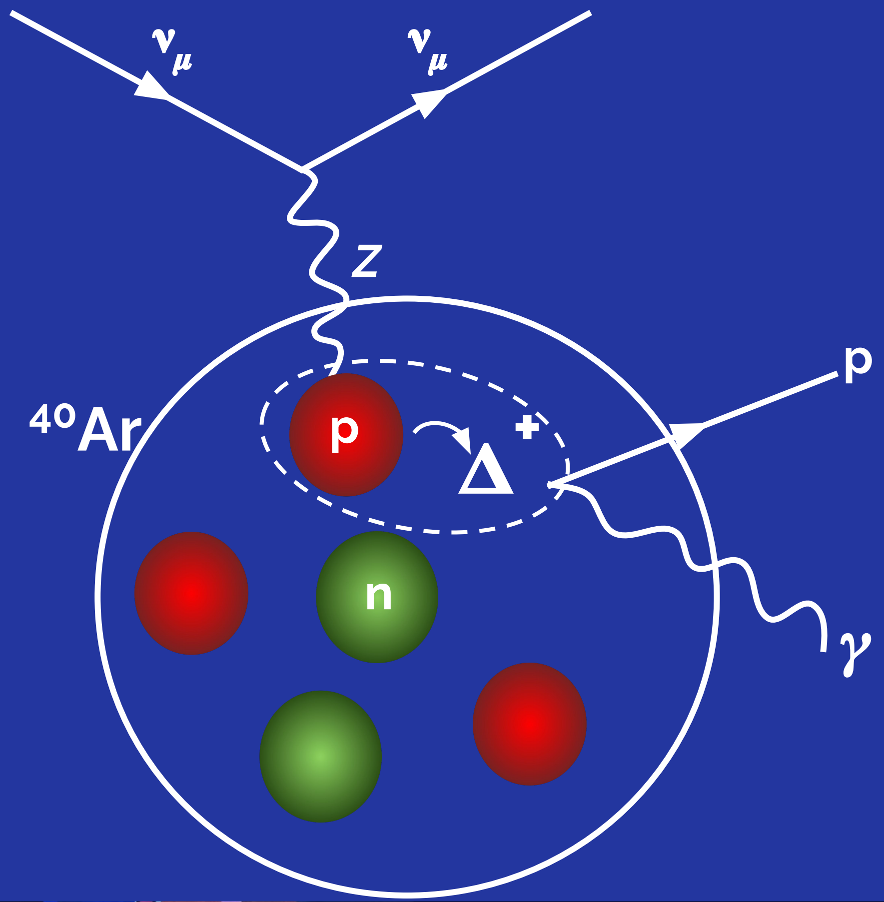

Neutral Current scattering, producing a photon which travels some distance before pair producing an e^+e^- pair

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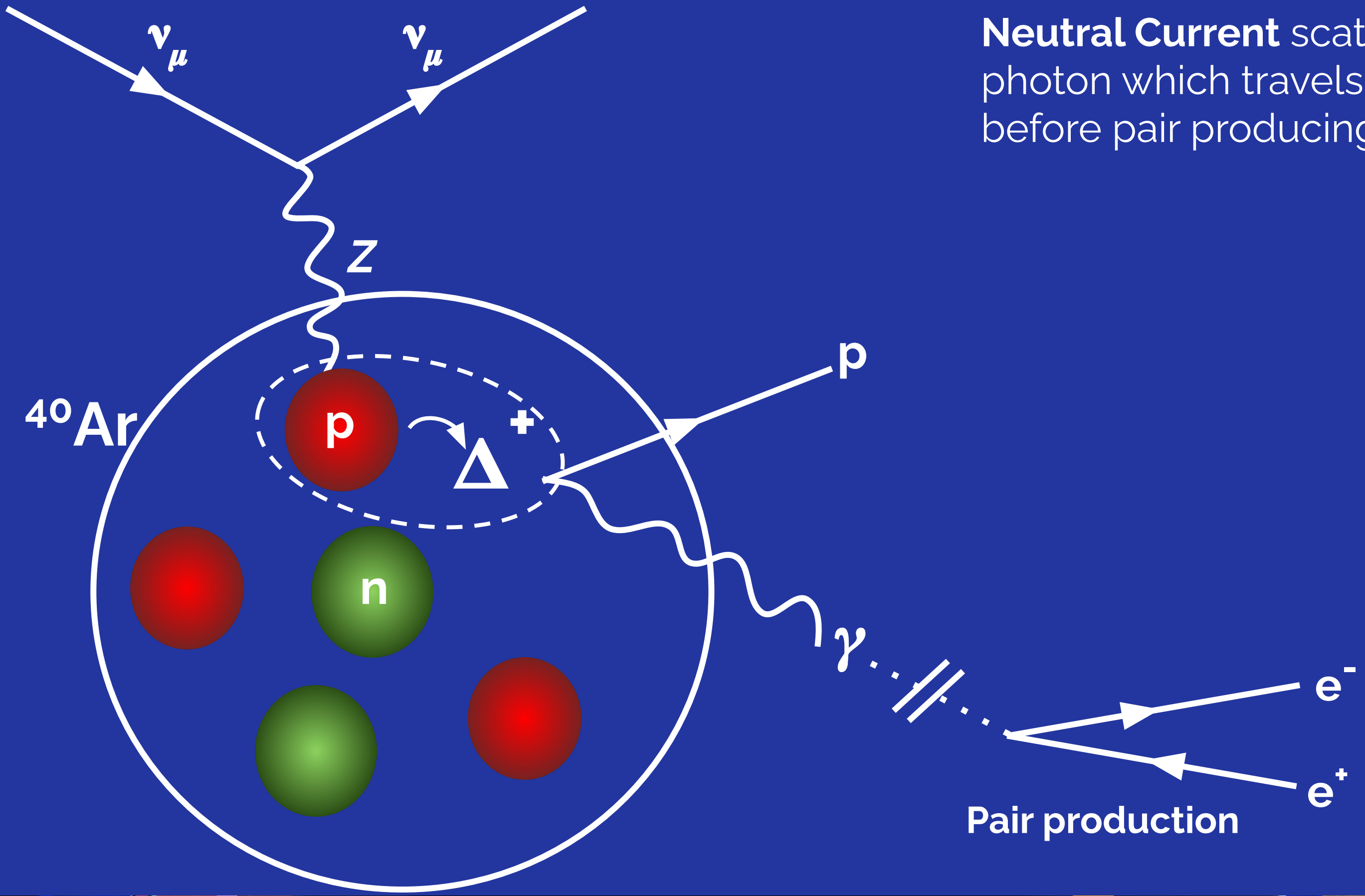

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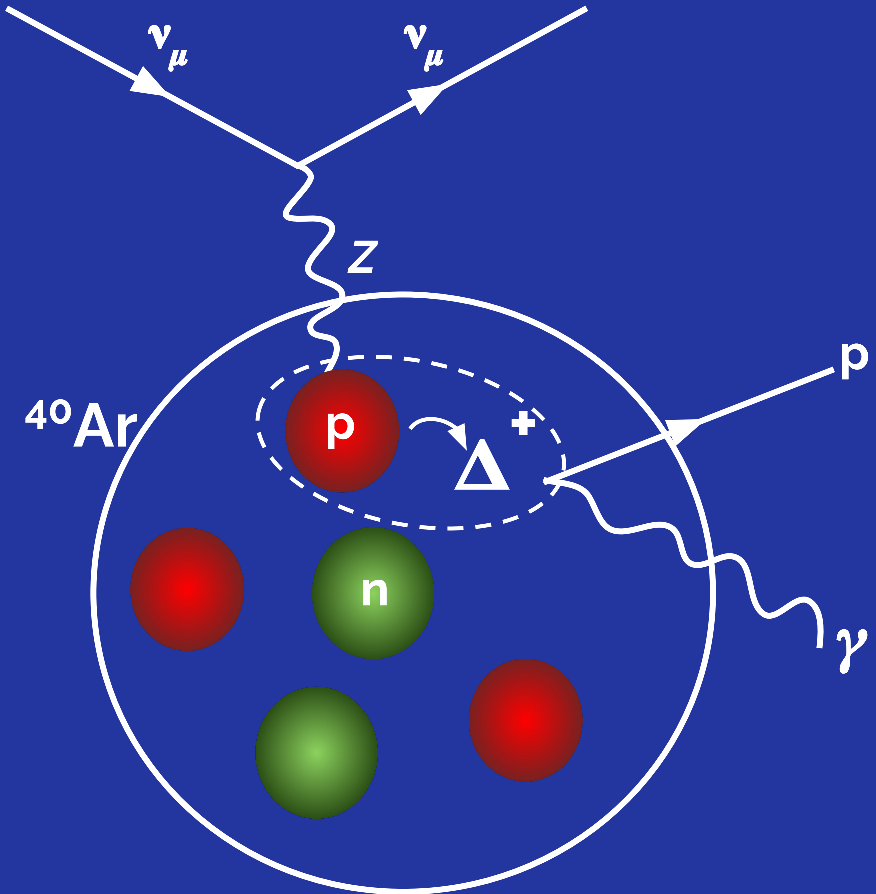
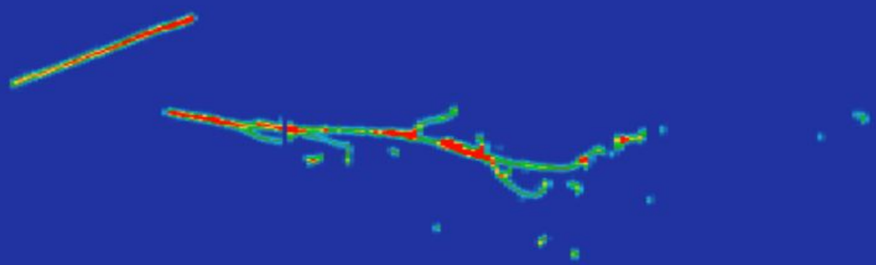
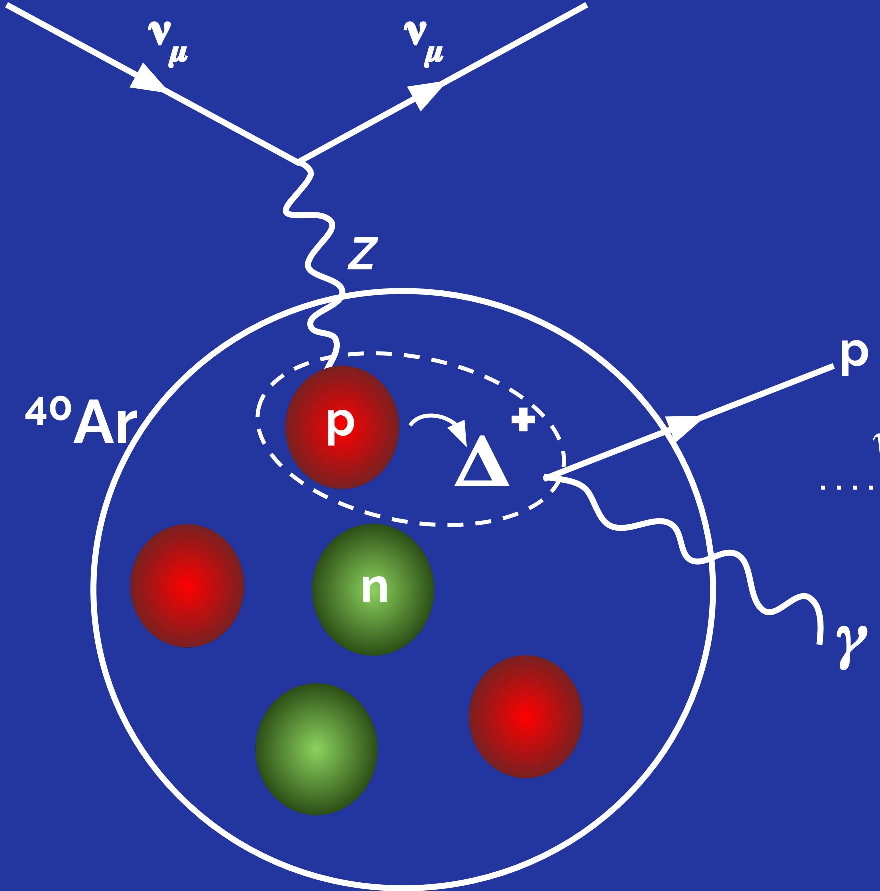


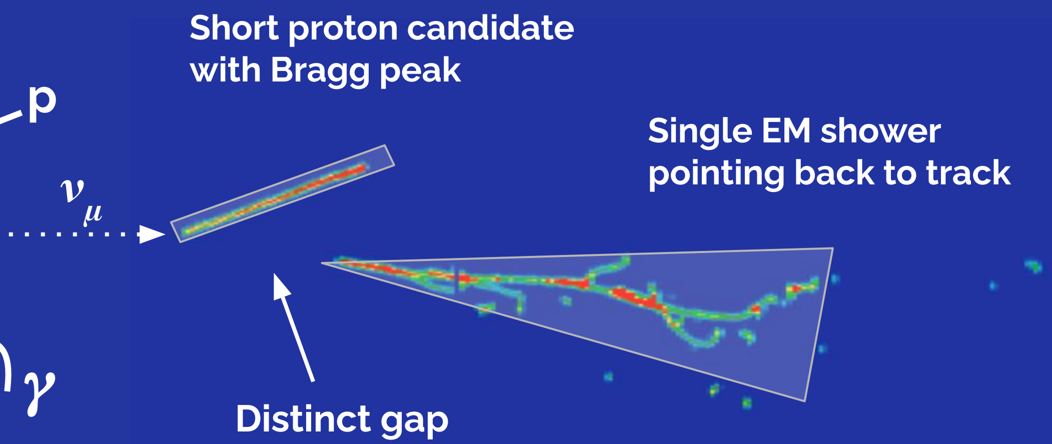


MicroBooNE Simulation

NC $\Delta \rightarrow N\gamma$ in MicroBooNE

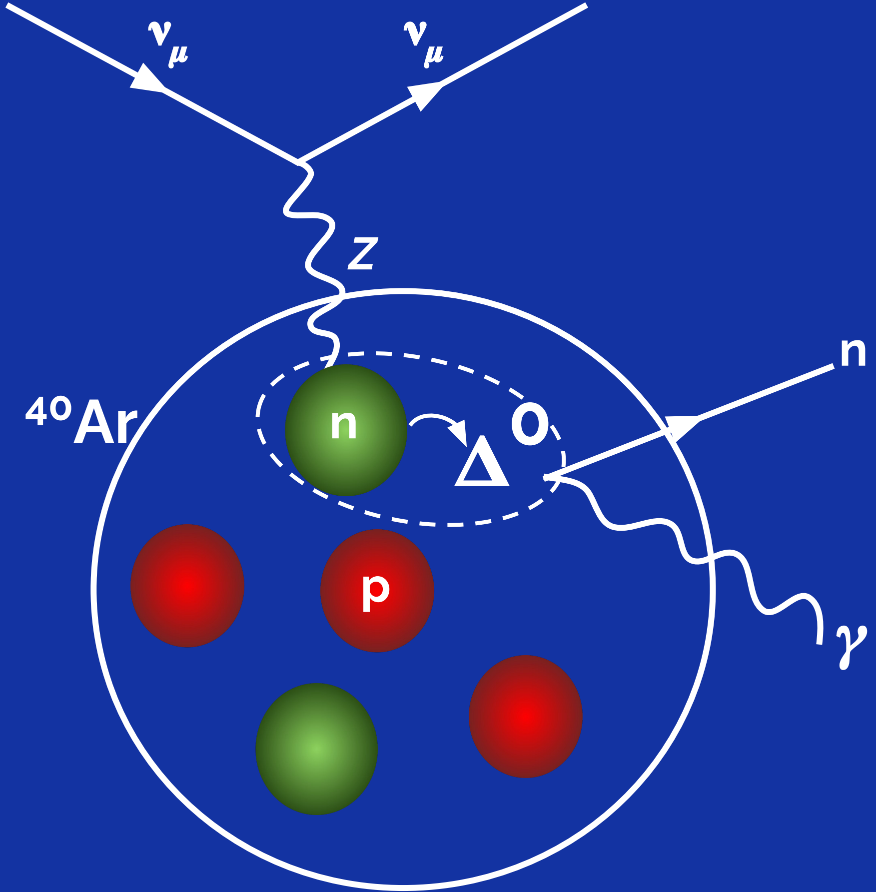


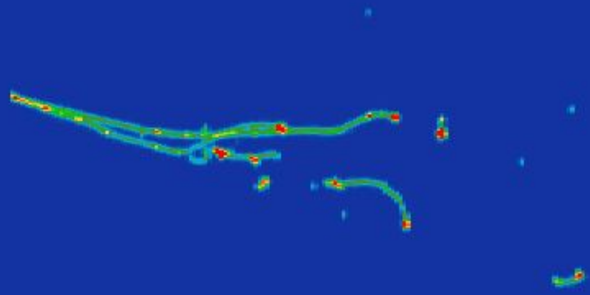
$1\gamma 1p$ topology, primarily targeting $\Delta \rightarrow p\gamma$



MicroBooNE Simulation

NC $\Delta \to N\gamma$ in MicroBooNE





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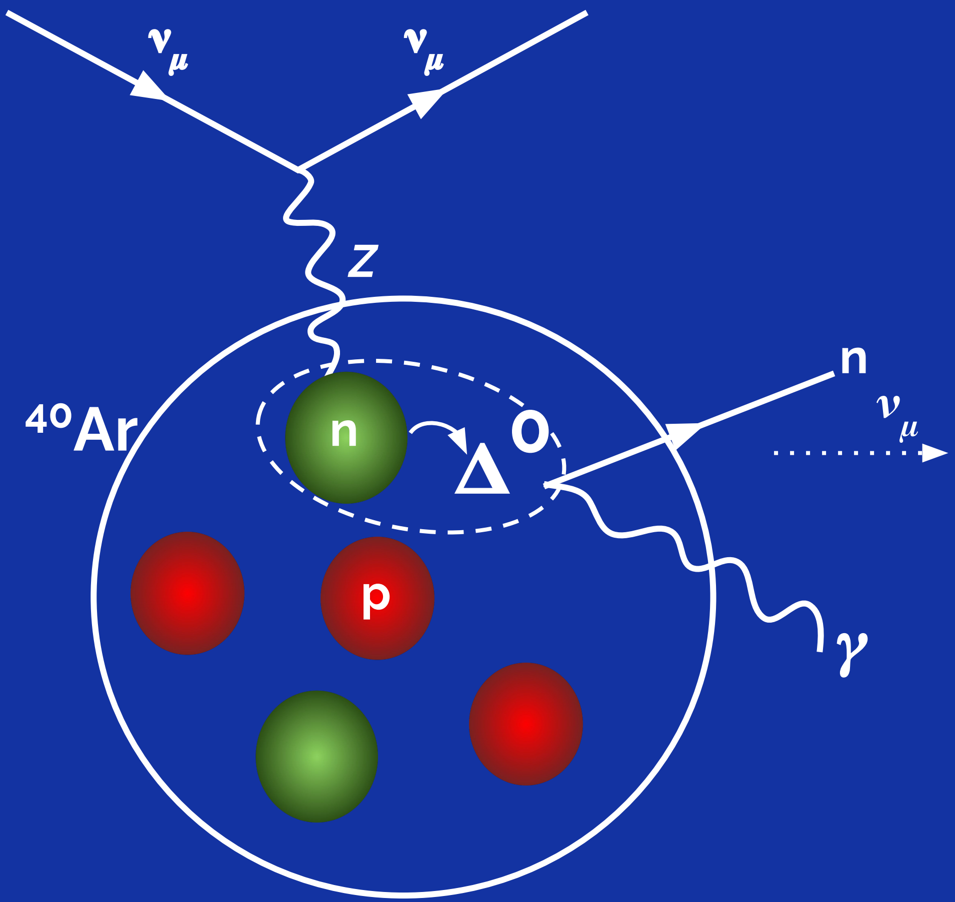
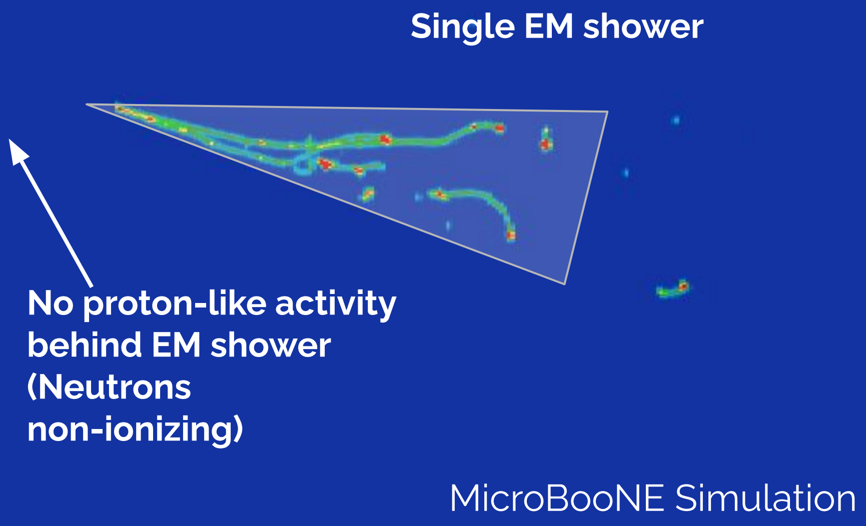


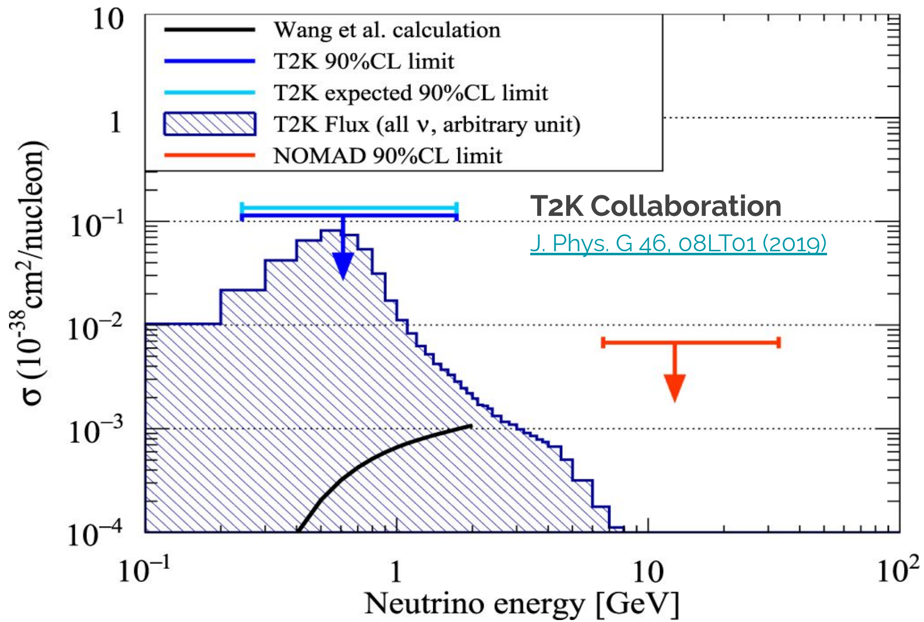
1γ0p topology, primarily targeting **Δ→nγ**



Current Experimental Limits on NC $\Delta\rightarrow N\gamma$

This radiative NC $\Delta\rightarrow N\gamma$ decay has **never been directly observed in neutrino scattering**

The Particle Data Group[1] branching fraction for $\Delta(1232)\rightarrow N\gamma$ is is 0.6% but many of these resonance decays themselves have **not been measured directly**, but are **inferred** from baryon–photon interaction amplitudes that are measured in pion- and photon–nucleon scattering experiments.



T2K Collaboration
J. Phys. G 46, 08LT01 (2019)

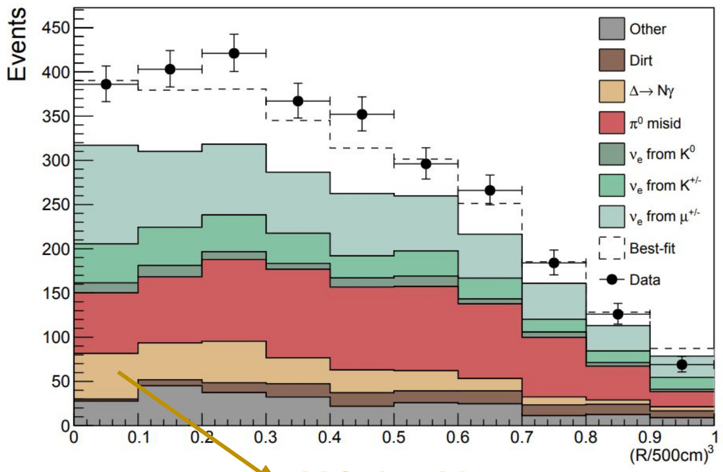
Current best experimental limits in O(1 GeV) range we are interested in are from **T2K** on carbon, but the **90% CL is over 100x that the of predicted rate[2]** of single-photon production.

[1](E. Wang, L. Alvarez-Ruso, J. Nieves 10.1103/PhysRevC.89.015503)
[2] Particle Data group *PTEP* 2020 (2020) 8, 083C01

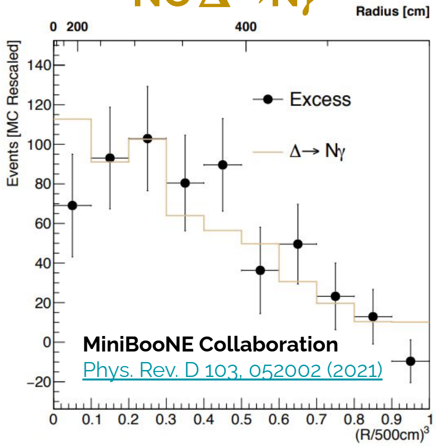
How much NC $\Delta \rightarrow N\gamma$ would we need?

Background studies by MiniBooNE showed that an enhancement of **x3.18** to their predicted NC $\Delta \rightarrow N\gamma$ rate gave excellent agreement with the observed excess in the radial distributions

MiniBooNE Collaboration Phys. Rev. D 103, 052002 (2021)



NC $\Delta \rightarrow N\gamma$



We use this to define a benchmark **directly testable LEE model**, to test whether or not our measurement is consistent with the MiniBooNE excess being entirely due to this process or not!

A multiplicative factor of x_{MB} = **3.18** enhancement to the nominal predicted NC $\Delta \rightarrow N\gamma$ rate in MicroBooNE

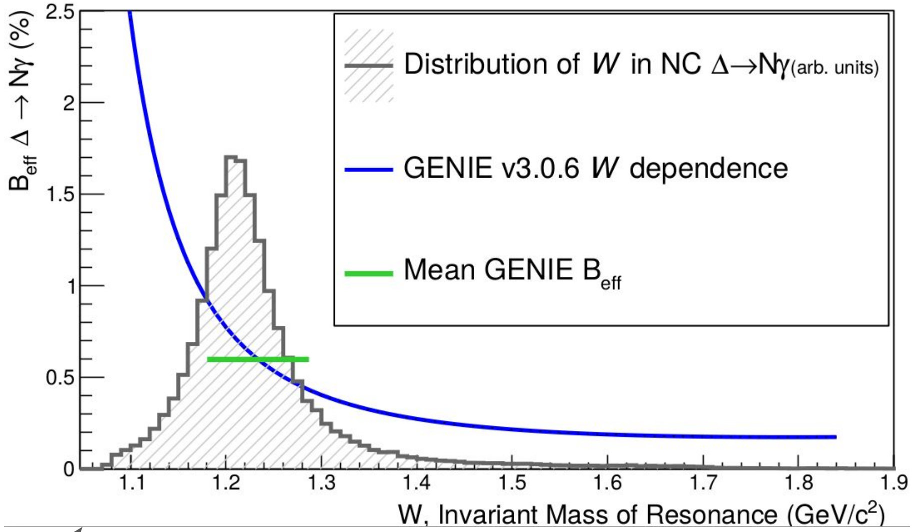
NC $\Delta \rightarrow N\gamma$ in MicroBooNE Simulations

MicroBooNE uses a custom tune of the **GENIE v3.0.6 event generator** (Nucl.Instrum.Meth.A 614 (2010) 87-104) for simulating all neutrino interactions in our detector

At BNB energies, dominant single-photon production is expected to be resonant Δ(1232) radiative decay

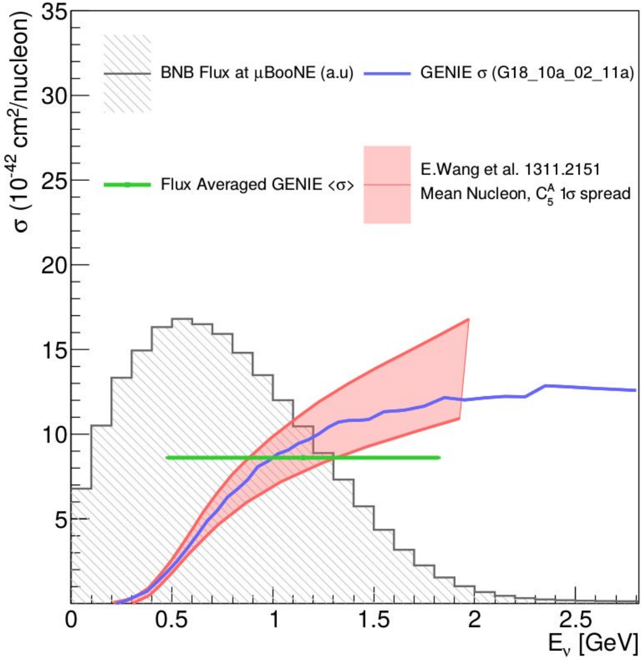
All resonances in GENIE v3 are modeled with the **Berger-Sehgal** (Phys. Rev. D 76, 113004) model

Once a Δ(1232) resonance has been simulated GENIE will then decay it to various final states based on the assumed branching fractions of $\Delta \rightarrow N\gamma$ and $\Delta \rightarrow N\pi^0$



NC $\Delta \to N\gamma$ in MicroBooNE Simulations

Neutrino-induced NC $\Delta \to N\gamma$ cross-section on argon



Resulting **GENIE cross sections** for producing NC $\Delta \to N\gamma$ on argon agree well with recent NC single photon production **theoretical predictions** for argon (E. Wang, L. Alvarez-Ruso, J. Nieves 10.1103/PhysRevC.89.015503)

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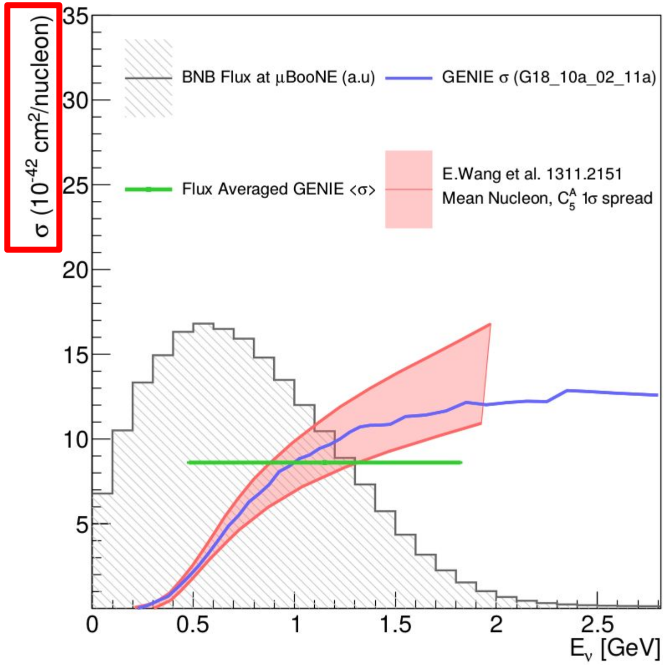

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This is a **very rare and elusive neutrino process.**

In the **first 3 years** of MicroBooNE data that I am showing you today, at truth level this is only:

124.1 NC $\Delta\rightarrow N\gamma$ events

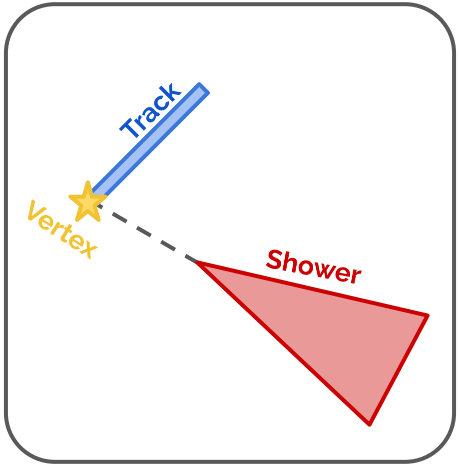
Analysis Methodology

The analysis in a nutshell

The analysis proceeds with the simultaneous side-by-side fit of **four topologically distinct samples:**

Two **NC $\Delta \rightarrow N\gamma$** rich
single-photon selections

$1\gamma1p$



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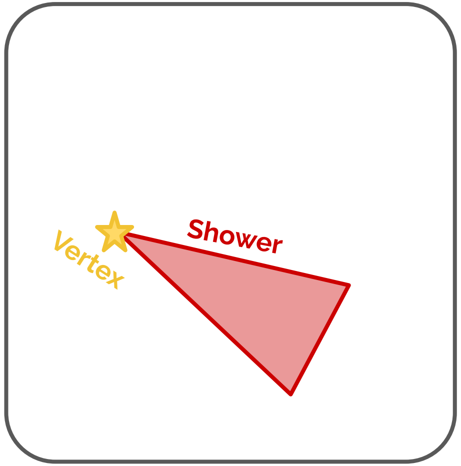

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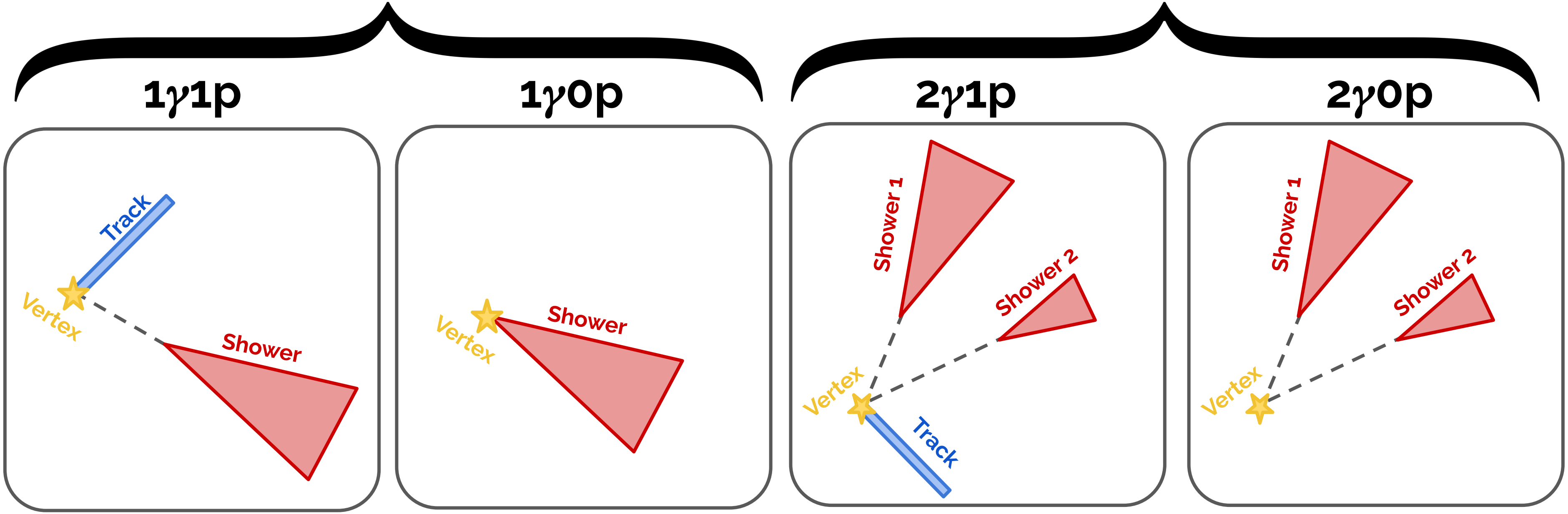
Two high-statistics **NC π^0 rich** **two-photon** selections



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➕

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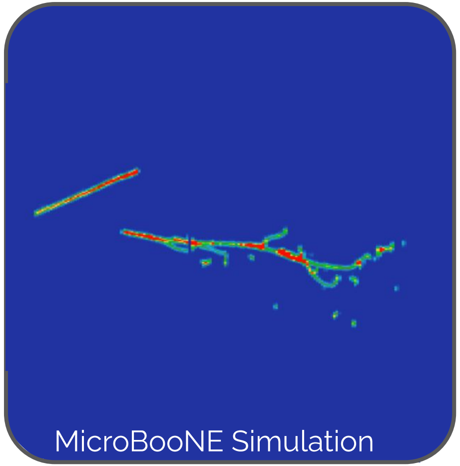

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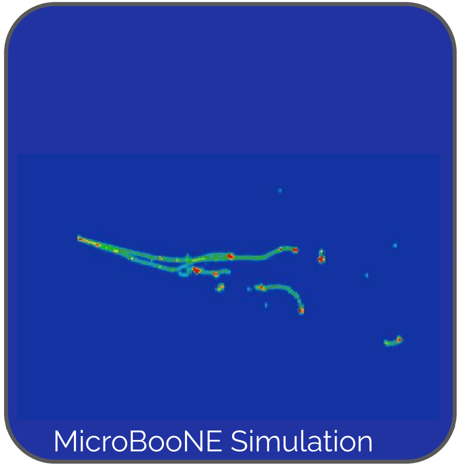
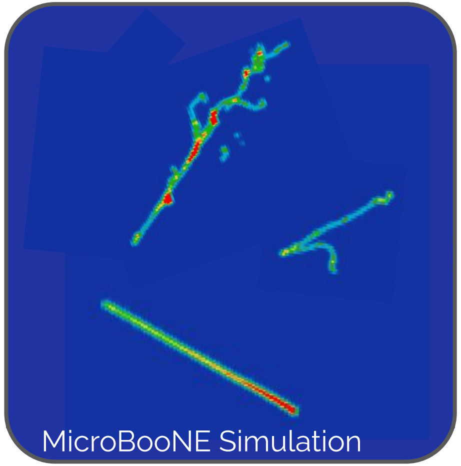
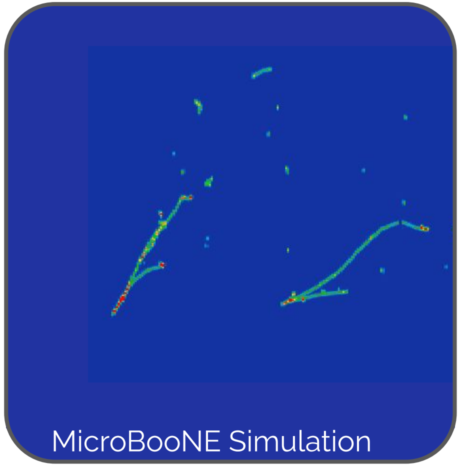


$2\gamma 1p$



$2\gamma 0p$



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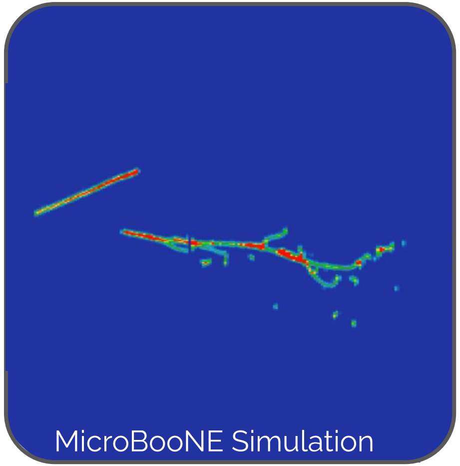

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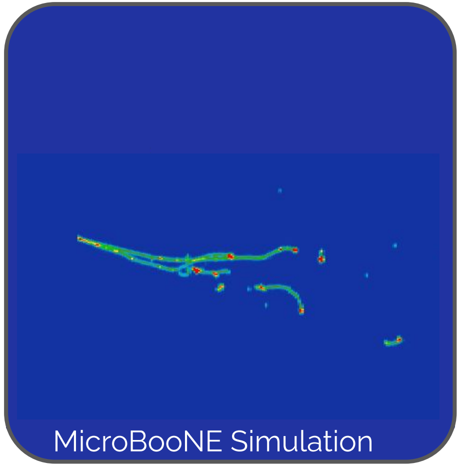

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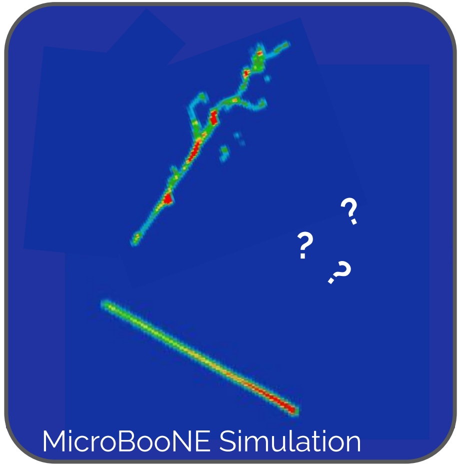

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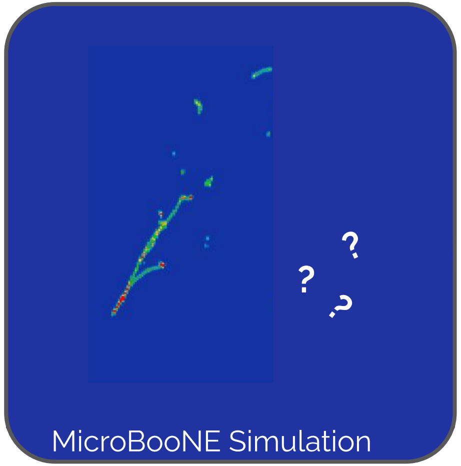
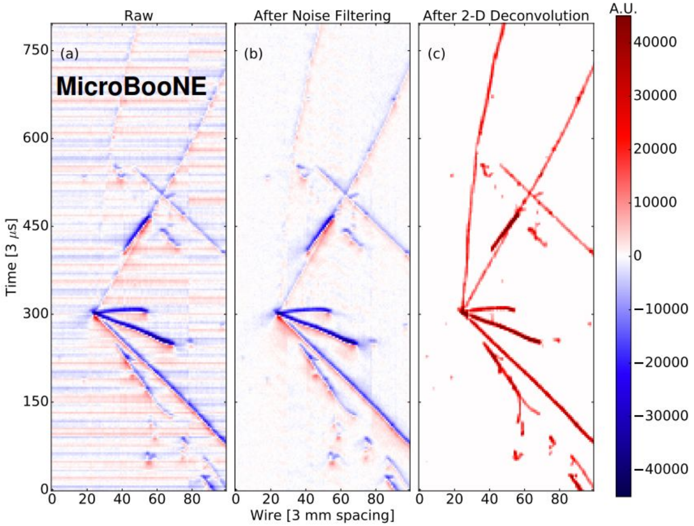


Data → Pandora Reco → Flash matching → Topological Selection → Pre-Selection Cuts → BDT Selection → Final Selections

All four samples begin the same way

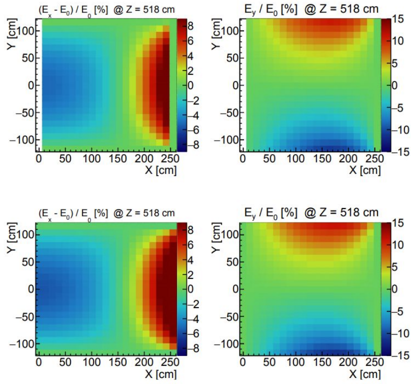
All samples start with **data**, but first need to make sure we understand it!
Leverage MicroBooNE's **extensive suite of calibrations** and **low-level detector modeling**.

Signal Processing:
From raw signals on wires to 2D reconstructed "hits"



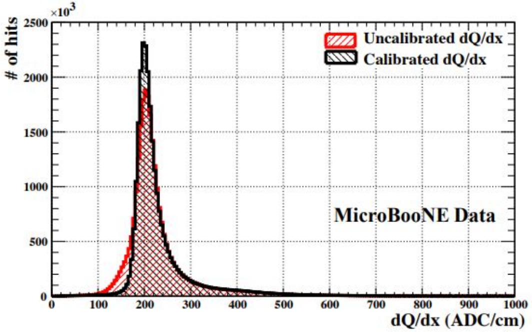
JINST 13, P07006 (2018) JINST 12 P08003 (2017)

Electric field calibration with both lasers and cosmic muons



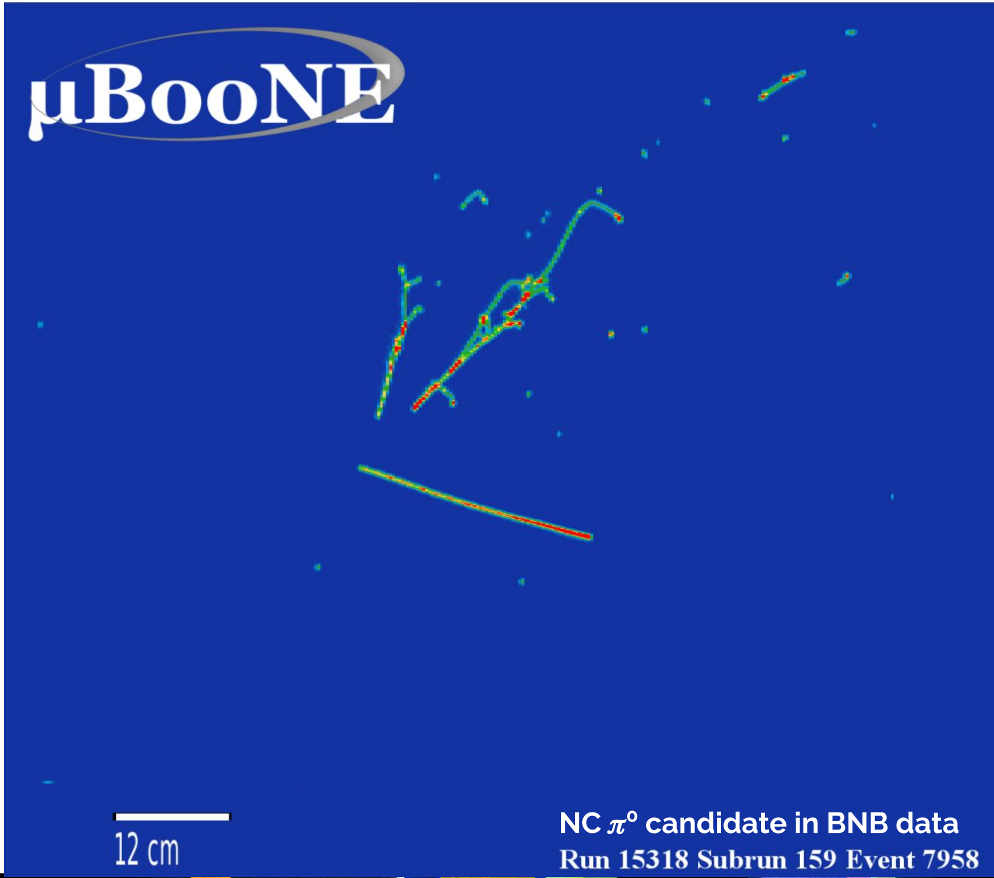
JINST 15 (2020) 07, P07010
JINST 15 (2020) P12037

Calorimetry calibration with crossing muons and π^0 samples



JINST 15 (2020) 03, P03022, *JINST* 15 (2020) 02, P02007

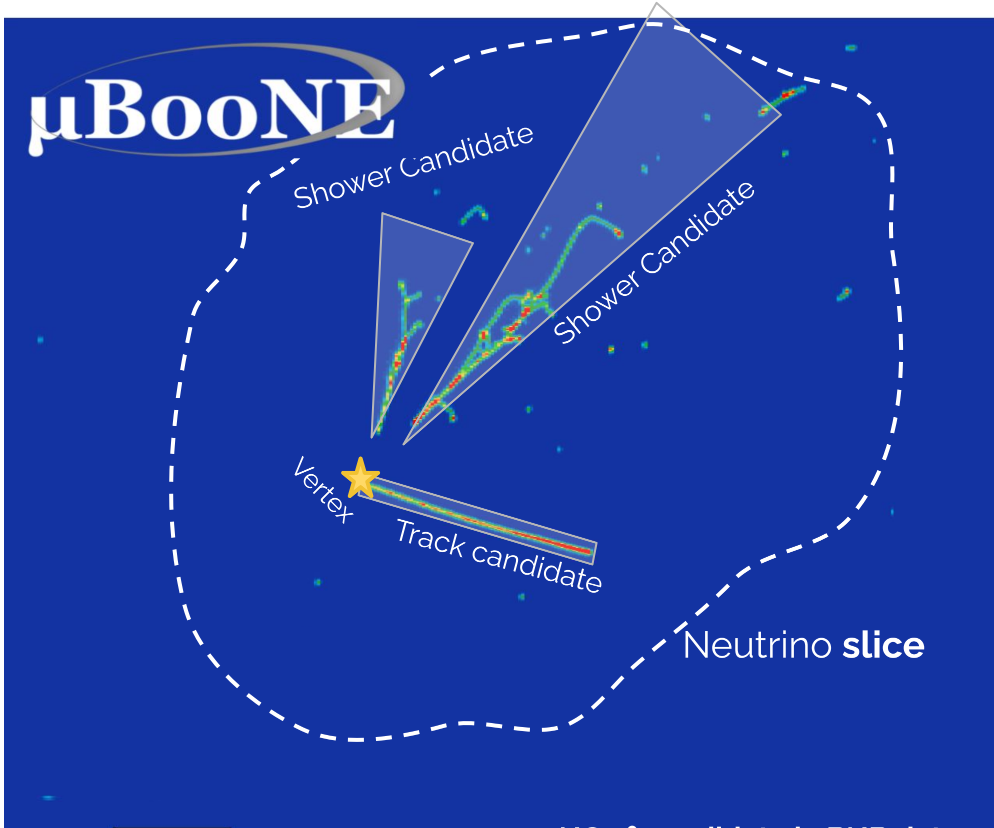
The **Pandora reconstruction framework** (Eur. Phys. J. C 78, 82 (2018)) clusters and matches these 2D hits across planes and reconstructs 3D objects.



The **Pandora reconstruction framework** (Eur. Phys. J. C 78, 82 (2018)) clusters and matches these 2D hits across planes and reconstructs 3D objects.

Objects are grouped into **slices**, and classified as **tracks** or **showers** based on a multivariate classifier score.

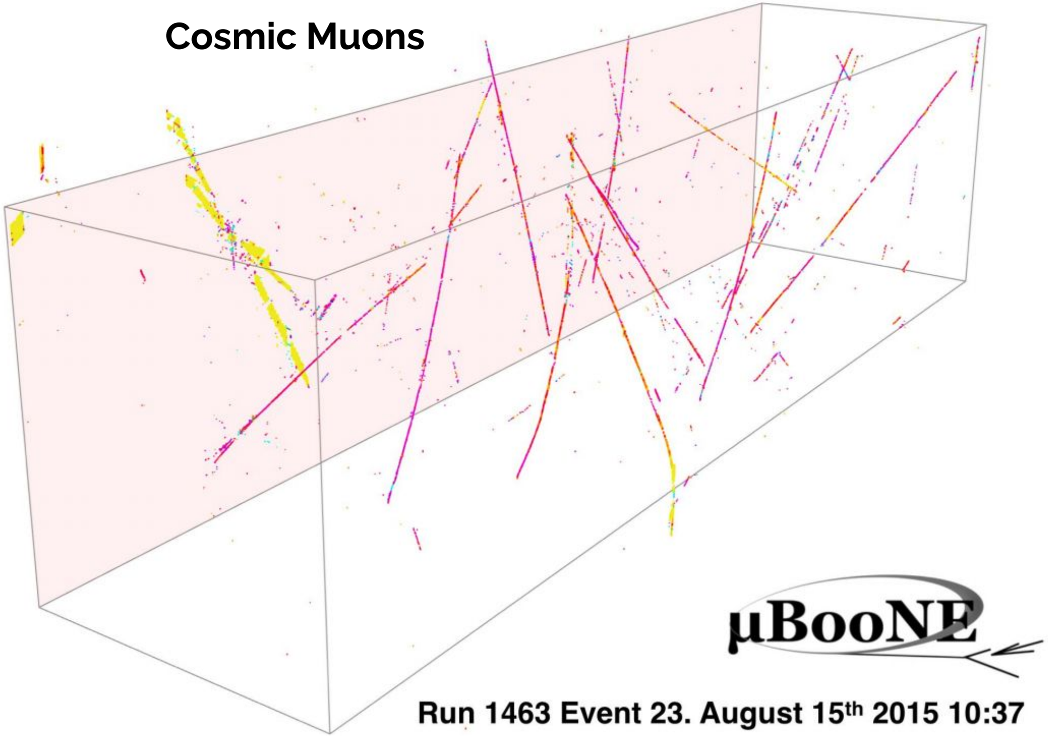
The slices are also scored on how much they look like neutrino interactions or cosmic ray in origin.



NC π^0 candidate in BNB data
Run 15318 Subrun 159 Event 7958

About **97%** of triggered events have cosmic only data

Of the remaining 3% that contain a neutrino event, they also contain **~20 cosmic rays!**

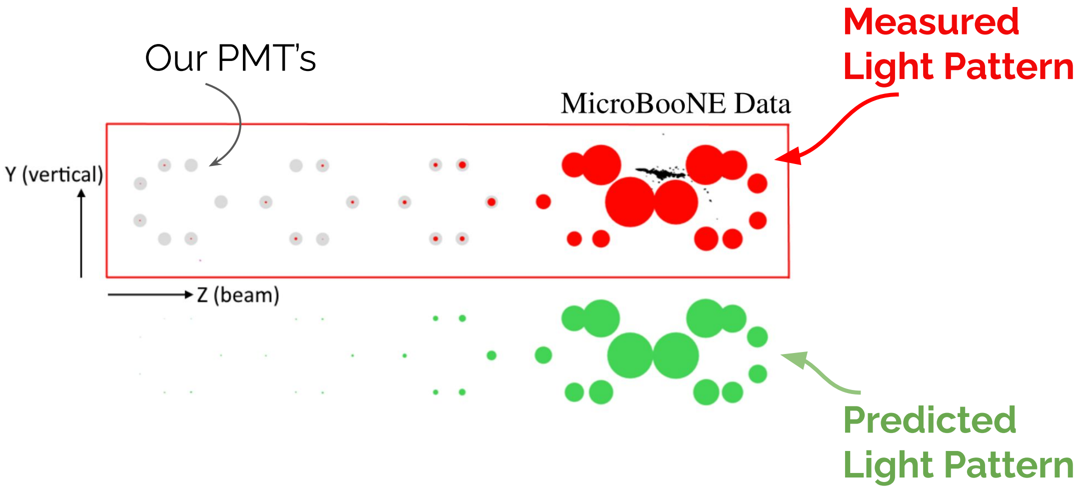


Eur. Phys.J.C 79 (2019) 8, 673

About **97%** of triggered events have cosmic only data

Of the remaining 3% that contain a neutrino event, they also contain **~20 cosmic rays!**

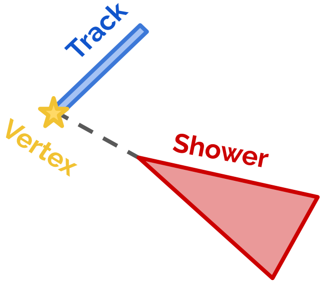
So in addition to the pandora neutrino slice selection, we also compare the **flashes observed by the PMTs** to remove events where the slice is clearly inconsistent with the beam related flash



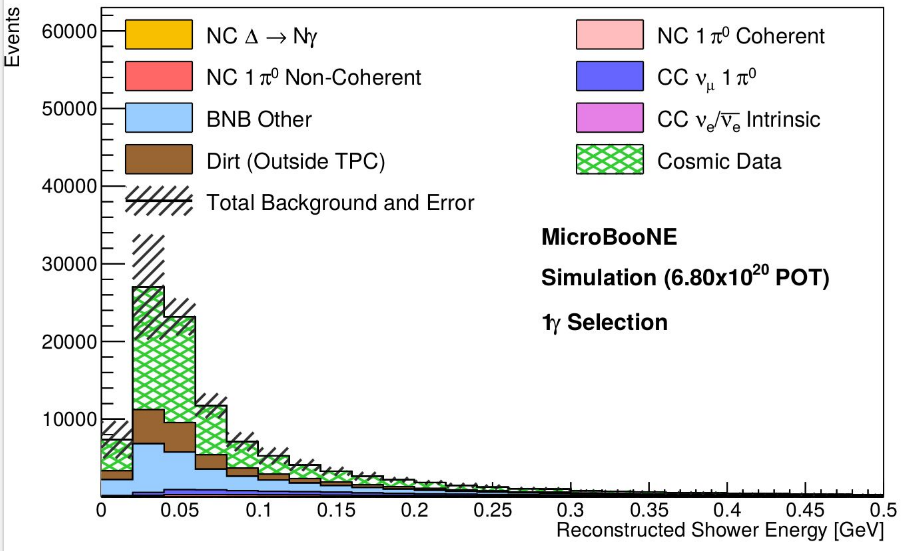
[*JINST* 16 P06043 (2021)]

All four samples begin the same way

SPLIT! →
- **$1\gamma1p$**
- $1\gamma0p$
- $2\gamma1p$
- $2\gamma0p$



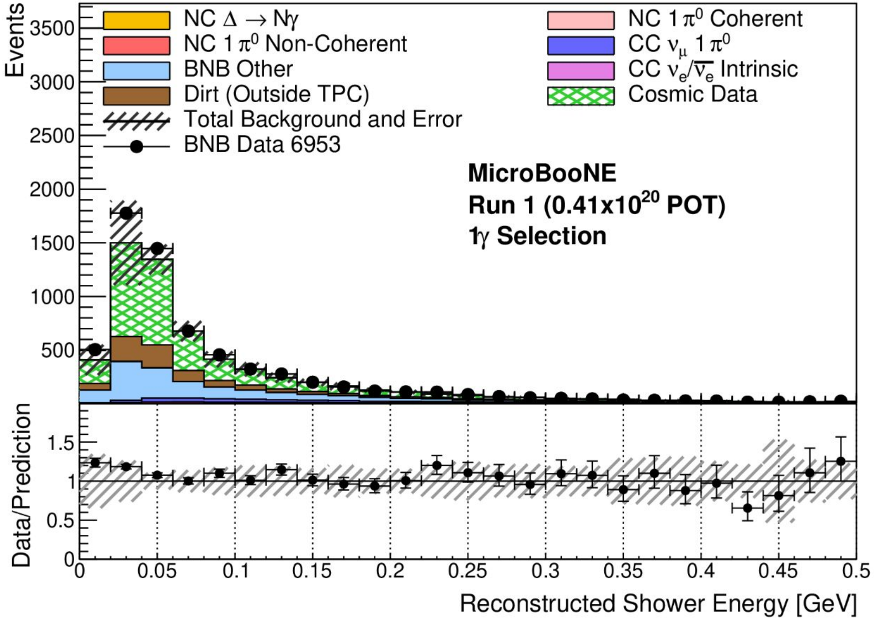
Today, focus on the primary signal channel $1\gamma1p$



First select all events with **exactly 1 shower**, and **any number of tracks.**

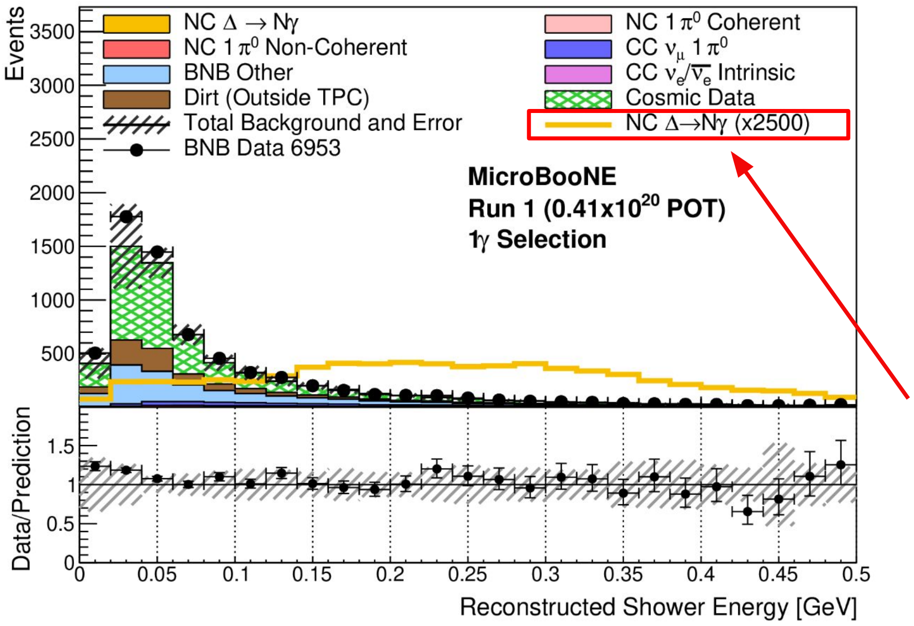
Combined Pandora + Flash-matching efficiency on NC $\Delta \rightarrow N\gamma$ of **41.4%**.

- **51.4 NC $\Delta \rightarrow N\gamma$** events
- **~110,000** Background events



Restrict ourselves to the smaller **0.41×10^{20} POT** sample

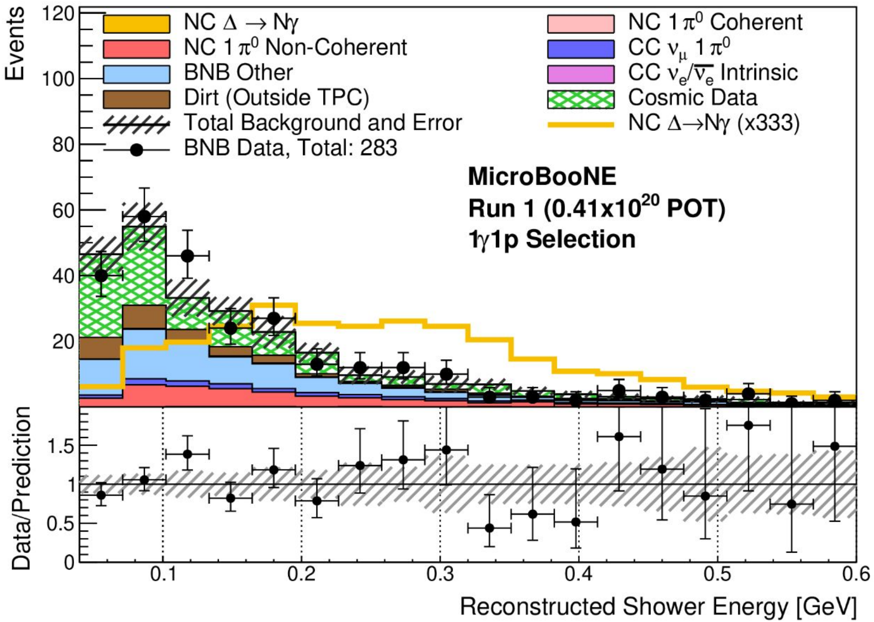
Only expect **3.1 NC $\Delta\rightarrow N\gamma$** events, hence why it was considered blind



Restrict ourselves to the smaller **0.41×10^{20} POT** sample

Only expect **3.1 NC $\Delta \rightarrow N\gamma$** events, hence why it was considered blind

Scale the NC $\Delta \rightarrow N\gamma$ rate up by **x2500** in order to start to see it above the backgrounds!

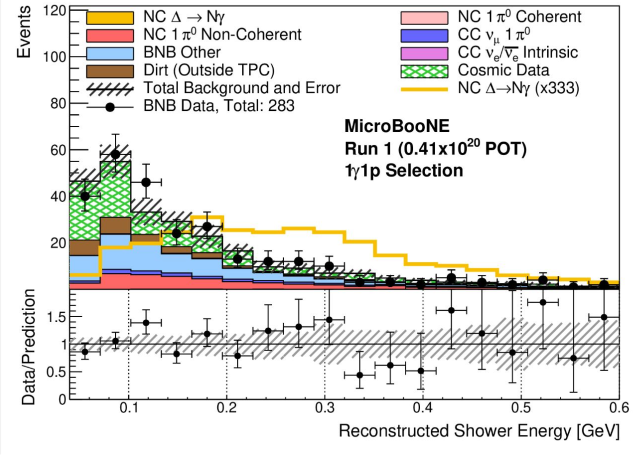


For **1γ1p** require there is a **track candidate**, as well as applying a set of simple **pre-selection cuts** we can greatly improve the situation, but still a way to go

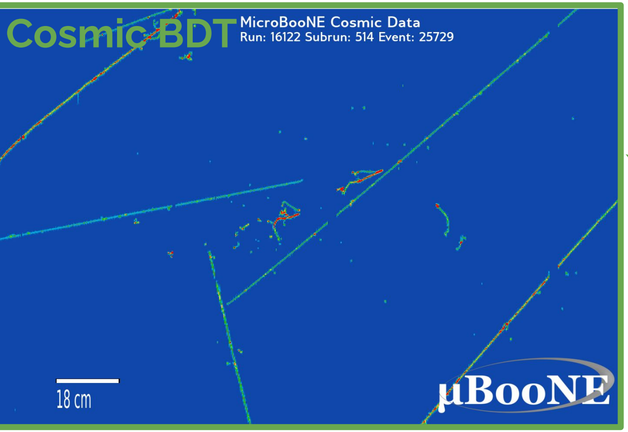
- Shower start and vertex in fiducial volume
- Minimum shower energy cut (>0.04 GeV) } Remove bulk of Michel electron showers
- Track containment in fiducial volume
- Maximum track length (<116cm)
- Minimum Track dE/dx (> 2MeV/cm)

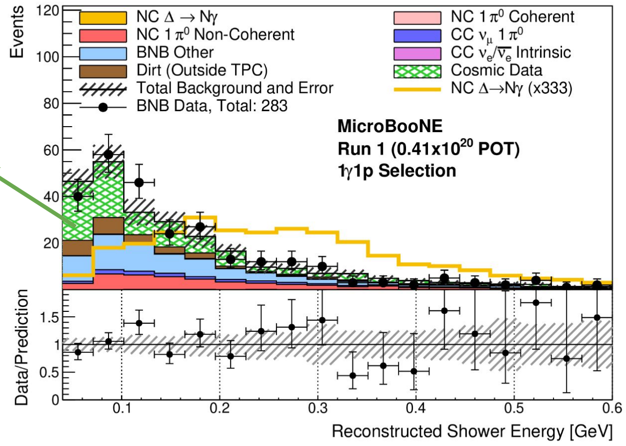
} Aim to remove more obvious muons tracks

- Remove extremely collinear track & shower

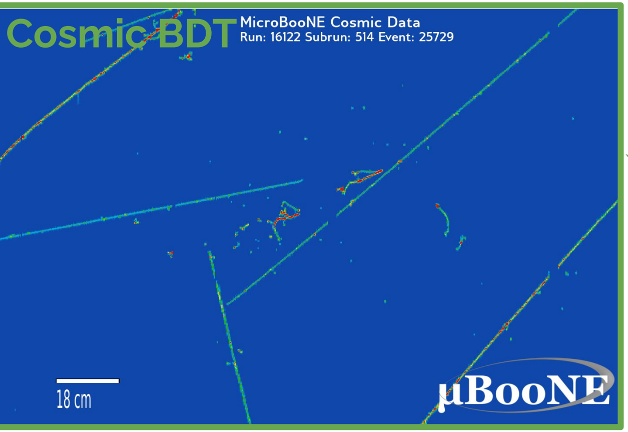


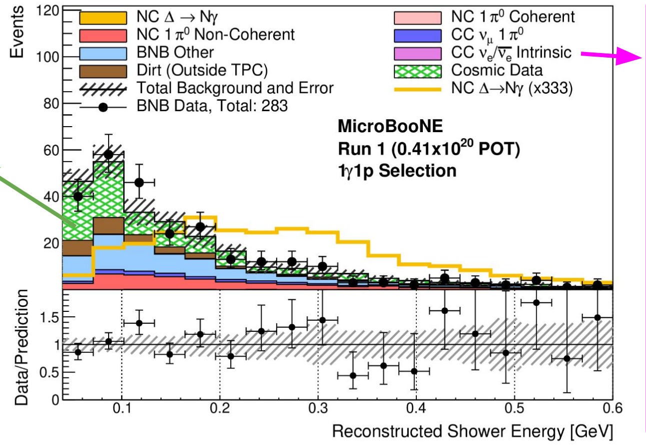
From here we developed five tailored **boosted decision trees (BDT)'s** to **target the key backgrounds** that remain to the NC $\Delta \rightarrow N\gamma$ signal

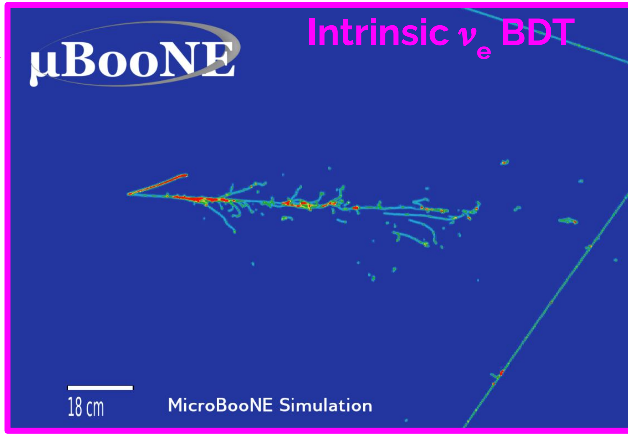

Cosmic BDT
MicroBooNE Cosmic Data
Run: 16122 Subrun: 514 Event: 25729
18 cm


NC Δ → Nγ
NC 1π⁰ Non-Coherent
BNB Other
Dirt (Outside TPC)
Total Background and Error
BNB Data, Total: 283
NC 1π⁰ Coherent
CC νμ 1π⁰
CC νe/ν̄e Intrinsic
Cosmic Data
NC Δ→Nγ (x333)
MicroBooNE
Run 1 (0.41x10^20 POT)
1γ1p Selection
Events
Data/Prediction
Reconstructed Shower Energy [GeV]

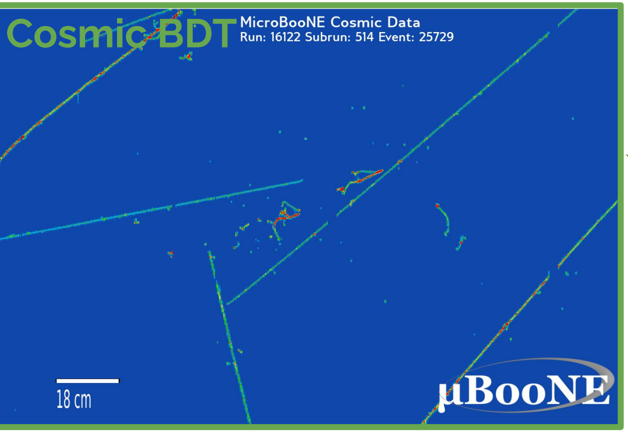
Data → Pandora Reco → Flash matching → Topological Selection → Pre-Selection Cuts → **BDT Selection** → Final Selections

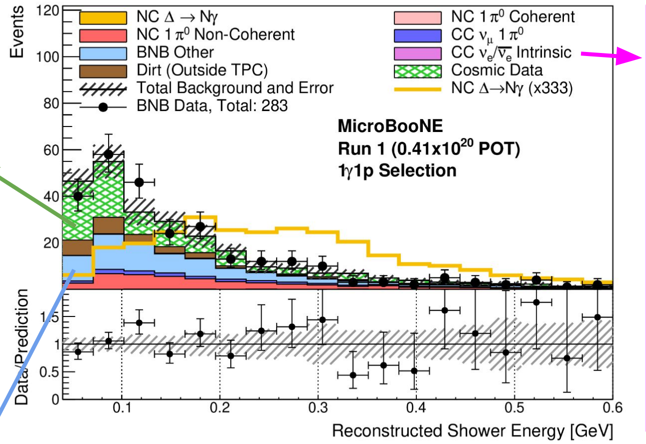


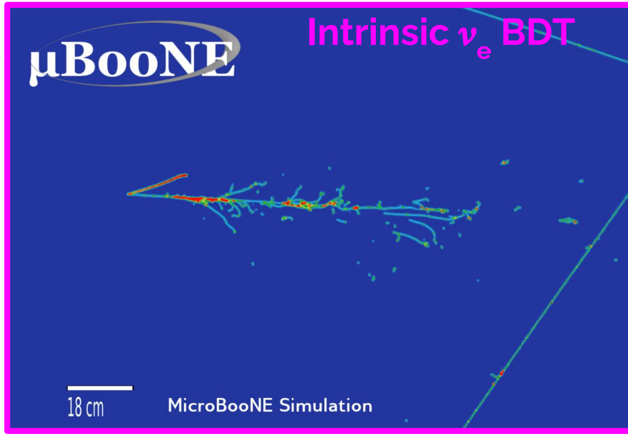


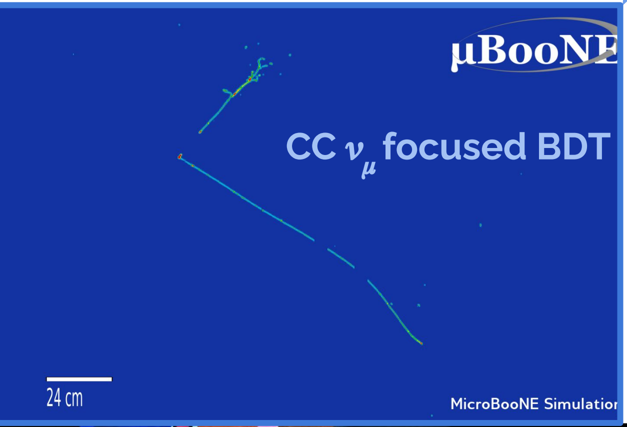


Data → Pandora Reco → Flash matching → Topological Selection → Pre-Selection Cuts → **BDT Selection** → Final Selections

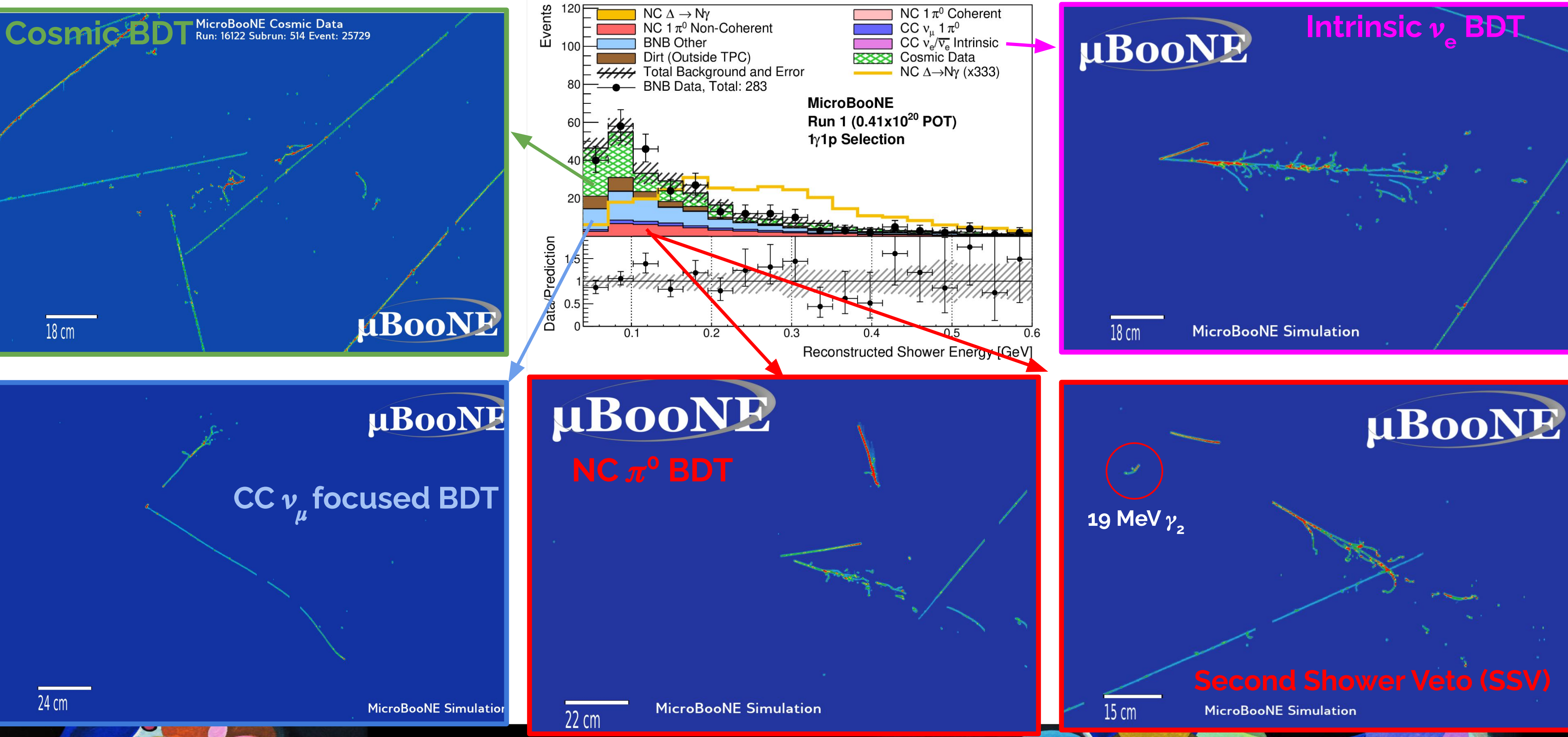








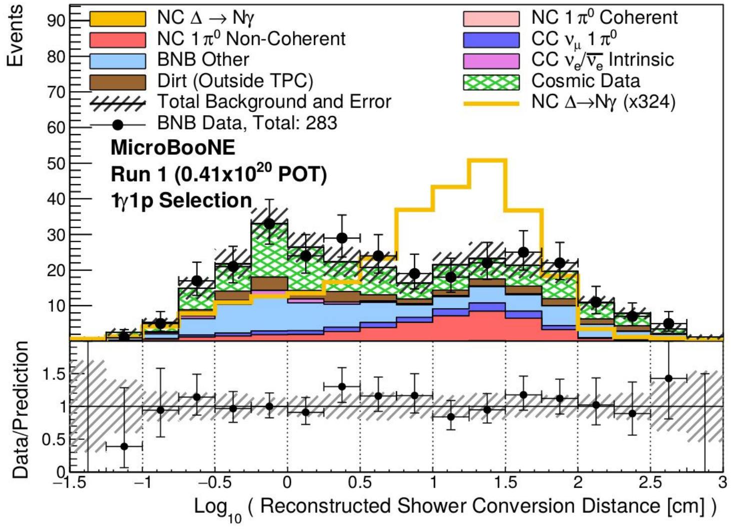
Data → Pandora Reco → Flash matching → Topological Selection → Pre-Selection Cuts → **BDT Selection** → Final Selections

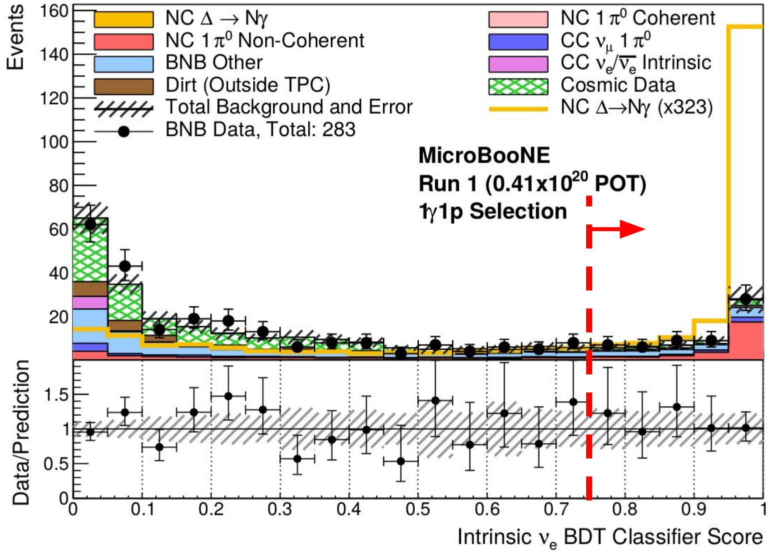


Intrinsic ν_e Rejection BDT

Important BDT variables:

- Looking for a non-zero gap between shower and vertex (**photon conversion distance)**
- Shower calorimetry (dE/dx)





Cut is placed at 0.747

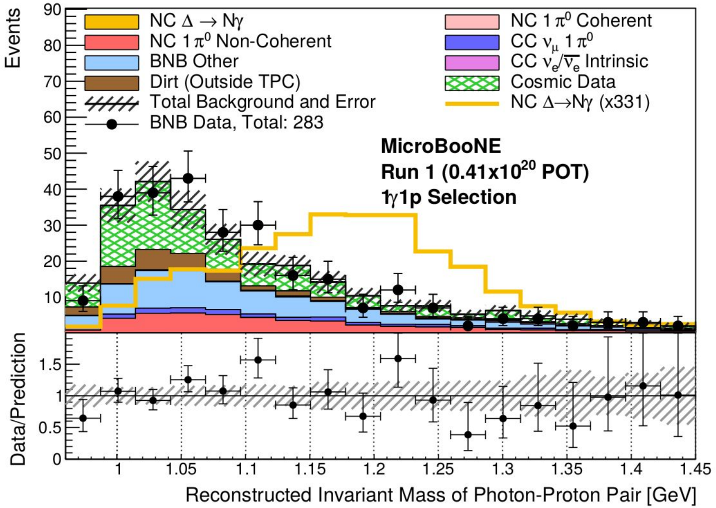
NC $\Delta \rightarrow N\gamma$ **Efficiency**: 71.4%

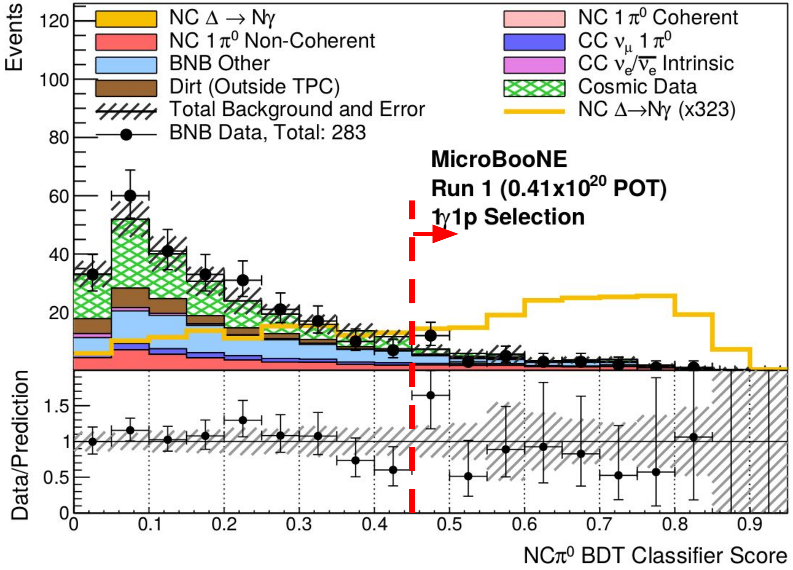
Intrinsic ν_e **Rejection**: 96.8%

NC π^0 Rejection BDT

Targeting events that are **consistent with kinematics and geometry of a π^0**. Important BDT variables:

- **Invariant mass of the reconstructed photon-proton pair** should peak at the Δ(1232) baryon mass
- Reconstructed Shower energy



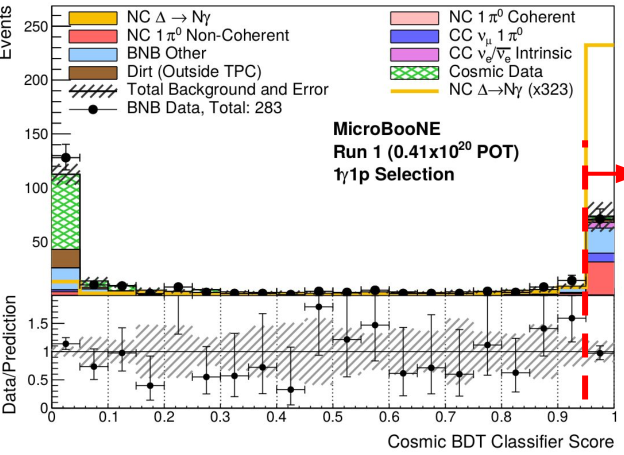


Cut is placed at 0.467

NC $\Delta \to N\gamma$ **Efficiency**:	62.1%
NC $1\pi^0$ **Rejection**:	77.9%
CC $1\pi^0$ **Rejection**:	82.9%

Data | Pandora Reco | Flash matching | Topological Selection | Pre-Selection Cuts | **BDT Selection** | Final Selections

Cosmic Rejection BDT

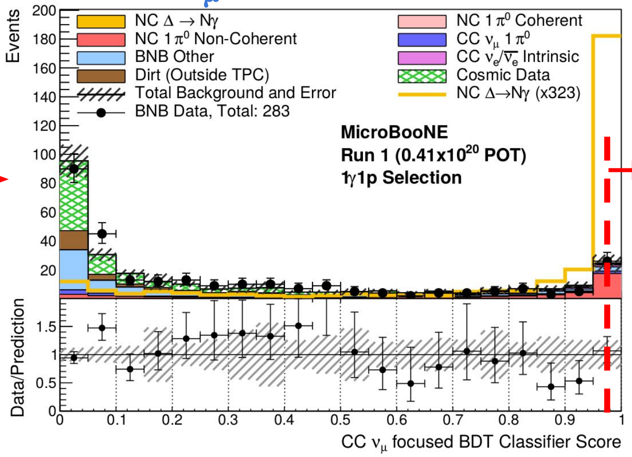


Cut is placed at 0.953

NC $\Delta \to N\gamma$ **Efficiency**: 83.6%

Cosmic Ray **Rejection**: **96.1%**

CC ν_μ focused BDT



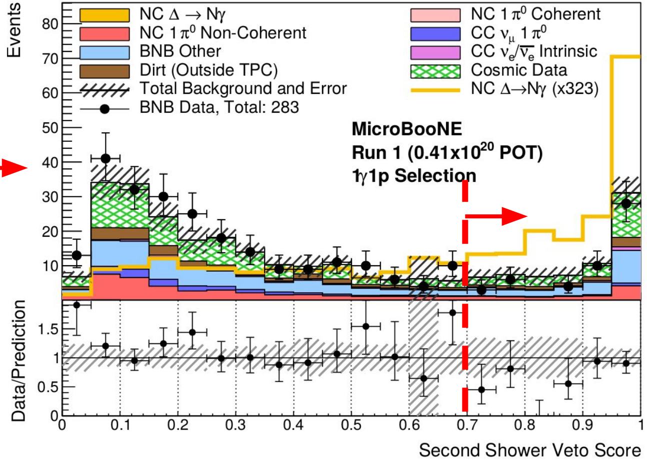
Cut is placed at 0.985

NC $\Delta \to N\gamma$ **Efficiency**: 49.0%

CC 1 π^0 **Rejection**: **96.0%**

BNB Other **Rejection**: **98.9%**

Second Shower Veto BDT



Cut is placed at 0.709

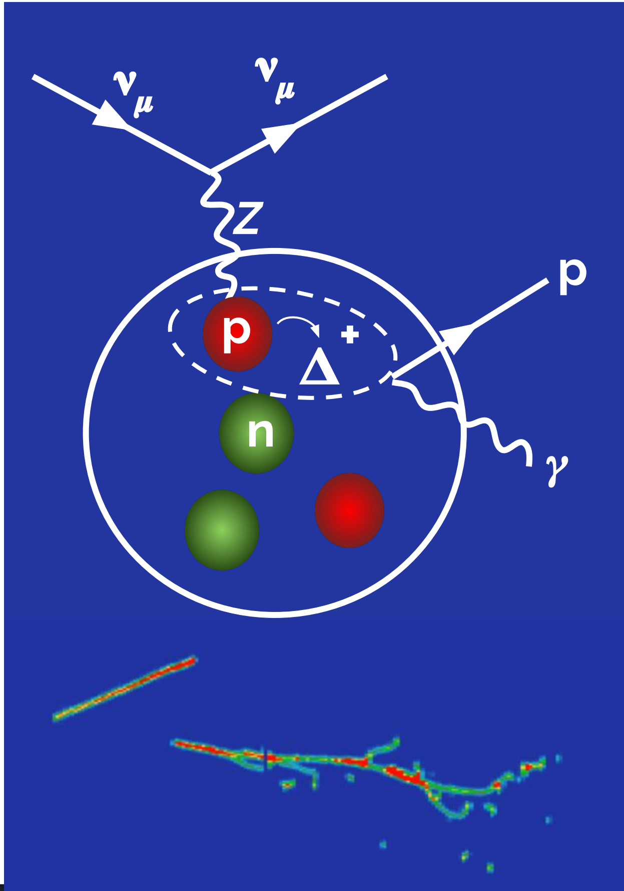
NC $\Delta \to N\gamma$ **Efficiency**: 57.7%

NC $1\pi^0$ **Rejection**: **78.0%**

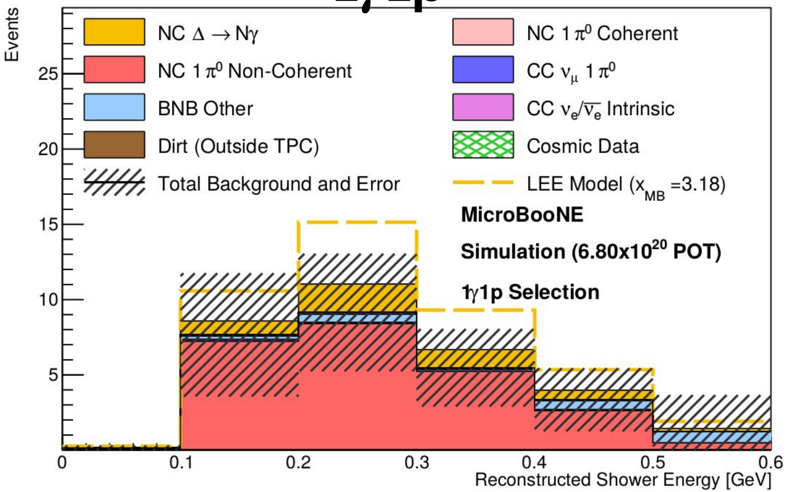
CC $1\pi^0$ **Rejection**: **86.5%**

All BDTs are trained explicitly to select well-reconstructed **NC $\Delta \rightarrow N\gamma$** events.

While **model-dependent**, this leverages the kinematics and correlations between the track and shower associated with a Δ(1232) resonance decay for **improved background rejection**



$1\gamma 1p$



Process	$1\gamma 1p$
NC $1\pi^0$ Non-Coherent	24.0
NC $1\pi^0$ Coherent	0.0
CC ν_μ $1\pi^0$	0.5
CC ν_e and $\bar{\nu}_e$	0.4
BNB Other	2.1
Dirt (outside TPC)	0.0
Cosmic Ray Data	0.0
Total Background	27.0
NC $\Delta \rightarrow N\gamma$	4.88
LEE ($x_{\text{MB}} = 3.18$)	15.5

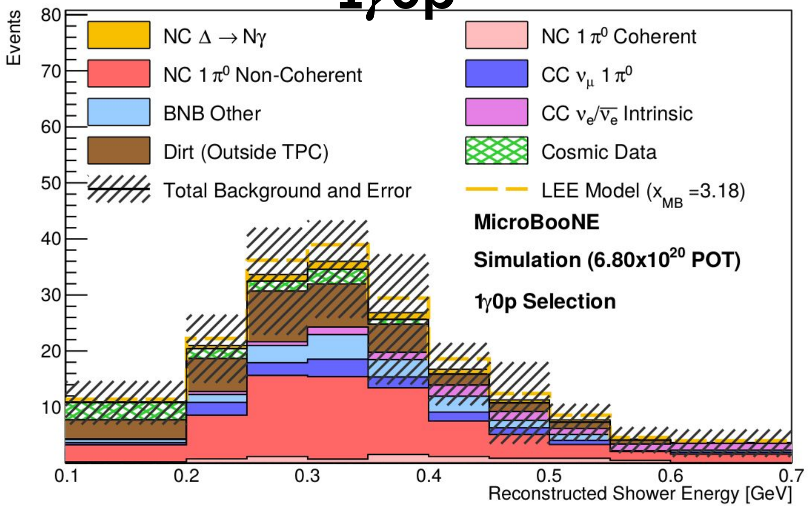
$1\gamma 1$p backgrounds are **dominated by NC π^0 (89%)**, with negligible contributions from cosmics, dirt, intrinsic ν_e and CCπ^0's.

This is a **97.2% pure photon sample** with electron rejection at **99.8%** relative to all 1 track 1 shower events.

Overall $1\gamma 1$p NC $\Delta \rightarrow N\gamma$ efficiency **3.9%**

Rejected **99.98% backgrounds**, relative to all single reconstructed shower events

$1\gamma 0p$



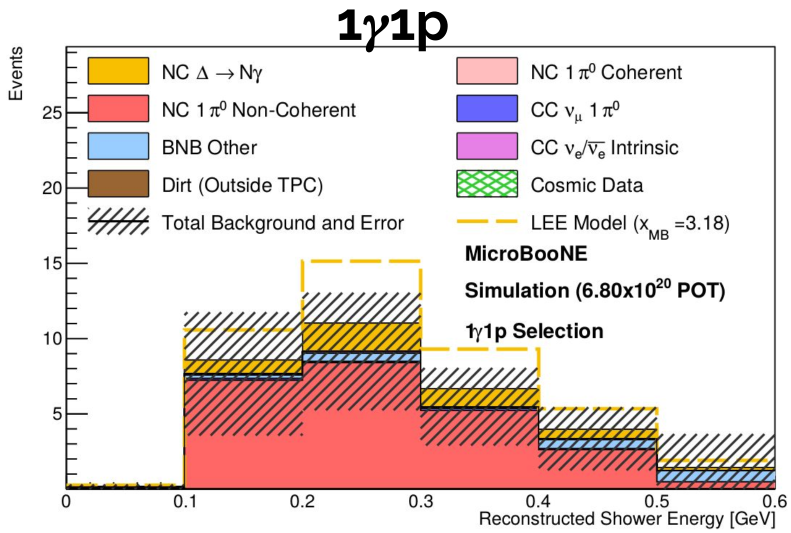
Process	$1\gamma 0p$
NC $1\pi^0$ Non-Coherent	68.1
NC $1\pi^0$ Coherent	7.6
CC ν_μ $1\pi^0$	14.0
CC ν_e and $\bar{\nu}_e$	11.1
BNB Other	18.1
Dirt (outside TPC)	36.4
Cosmic Ray Data	10.0
Total Background	165.4
NC $\Delta \rightarrow N\gamma$	6.55
LEE ($x_{\text{MB}} = 3.18$)	20.1

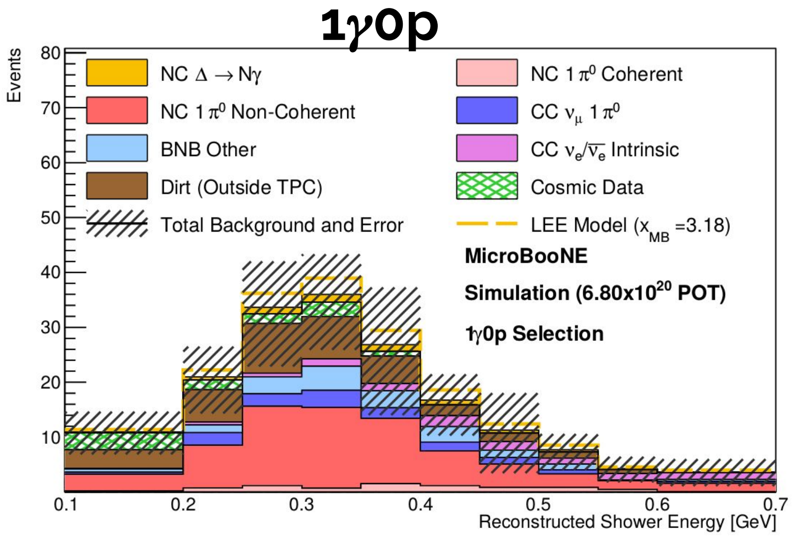
Without the proton to help tag the vertex, the $1\gamma 0p$ selection has a lower NC $\Delta \rightarrow N\gamma$ purity and a more diverse category of backgrounds (**Still very much NC π^0 dominant**).

Despite this is is still a **83.2% pure photon sample** with electron rejection is at **87.6%**

Overall $1\gamma 0p$ NC $\Delta \rightarrow N\gamma$ efficiency **5.2%**

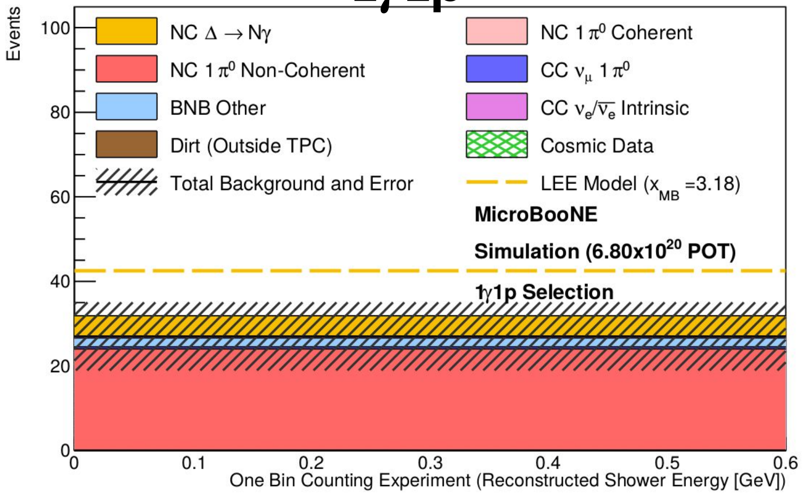
Rejected **99.8% backgrounds**, relative to all single reconstructed shower events



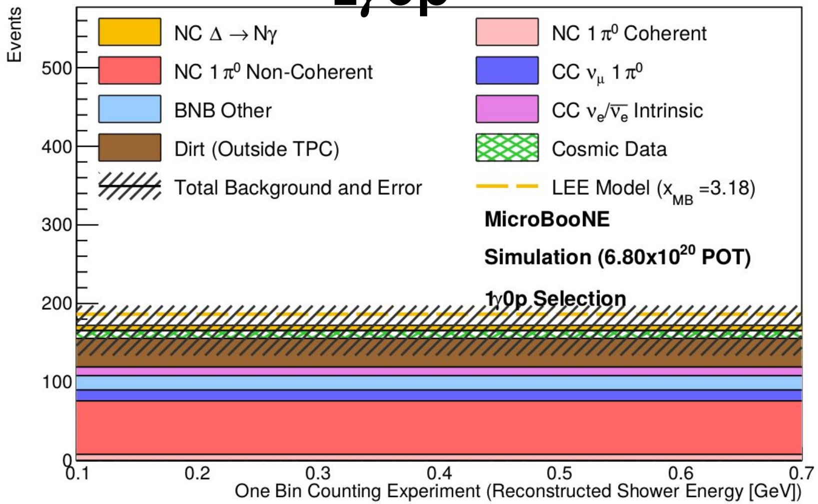


Final predicted distributions for 6.80×10^{20} POT (first 3 years data).
We are first and foremost interested in the total rate of NC $\Delta \rightarrow N\gamma$.

$1\gamma 1p$



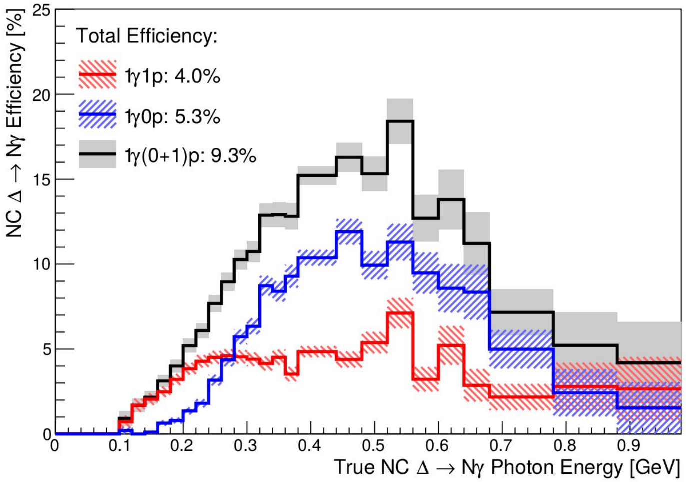
$1\gamma 0p$

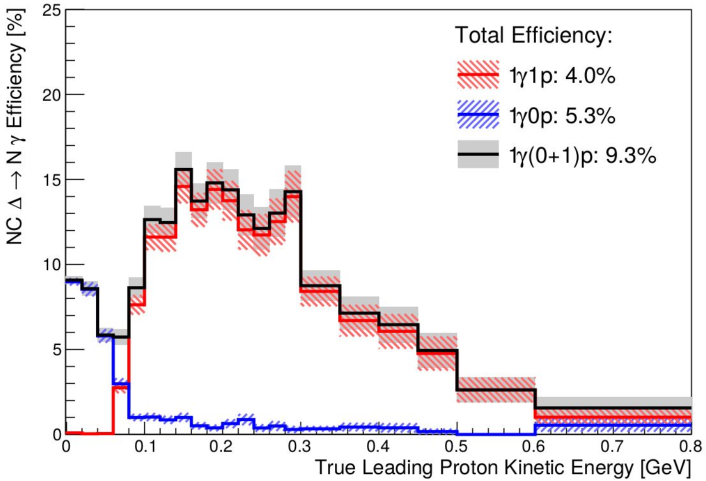


Final predicted distributions for $6.80\text{x}10^{20}$ POT (first 3 years data).
We are first and foremost interested in the total rate of NC $\Delta \rightarrow N\gamma$.

The final fits are performed with **one-bin counting experiments** for both $1\gamma 1p$ and $1\gamma 0p$ for all showers within the 0-0.6 GeV and 0.1-0.7 GeV ranges respectively.

NC Δ→Nγ efficiencies relative to all true NC Δ→Nγ in the active TPC (124.1 events).



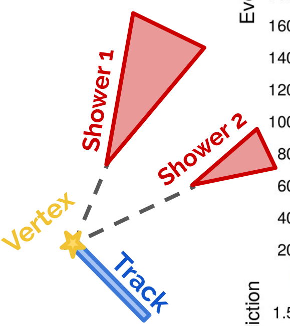


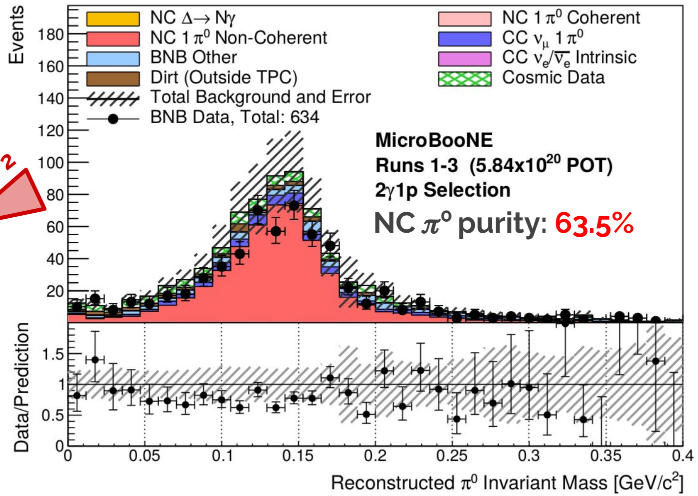
The existence of the proton track in the 1γ1p samples allows for successful reconstruction and background rejection of lower energy showers.

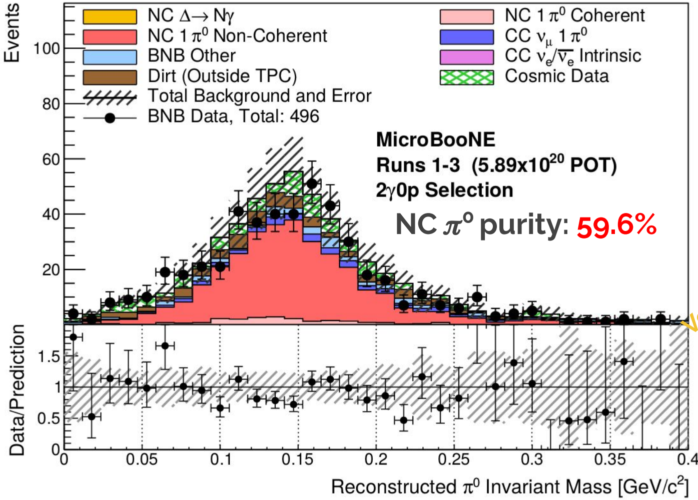
The threshold for proton kinetic energy where events start to migrate from 1γ0p to 1γ1p selections is ~60 MeV.

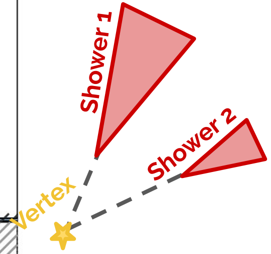
Note: These efficiencies are over whole energy range, not restricted to final selection binning.

Final 2γ - Selections





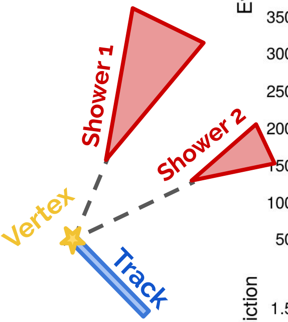


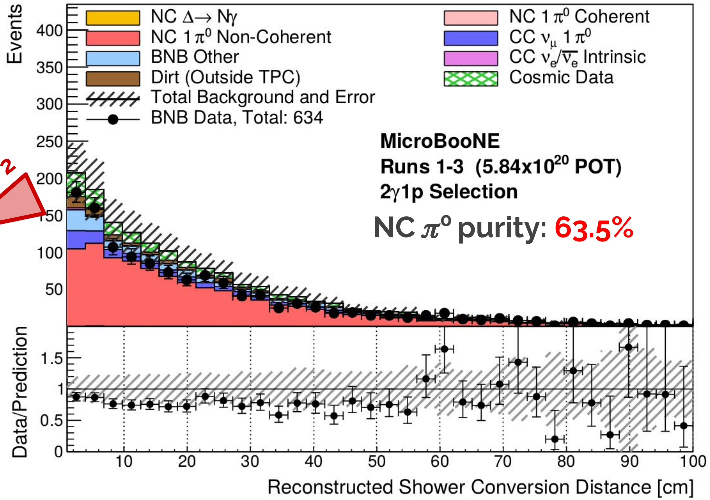


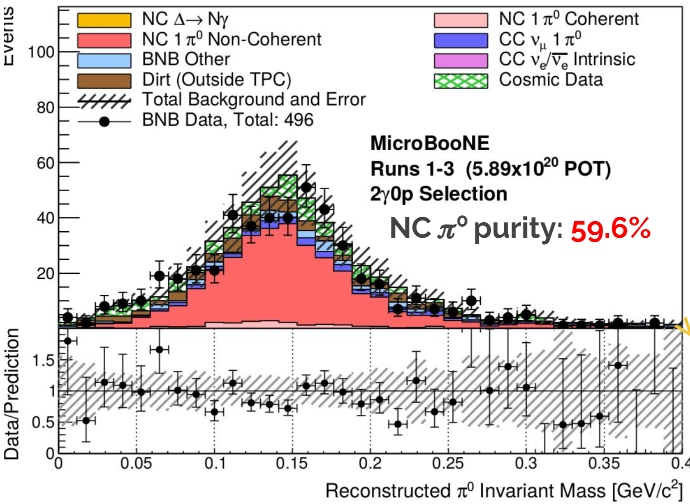
- Negligible contributions from NC $\Delta \rightarrow N\gamma$
- High statistics (1130 candidate NC π^0 data events)
- Help validate energy reconstruction and general photon shower reconstruction

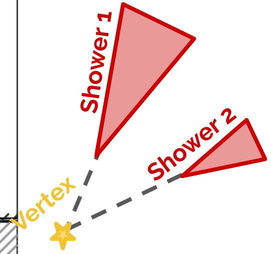
Designed to be blind to both electron and photon LEE hypothesis, so this is the full dataset shown here

Final 2γ - Selections









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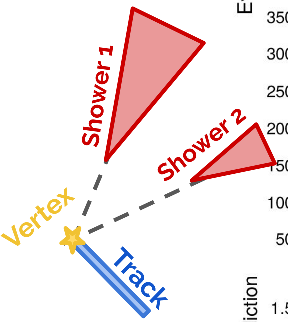
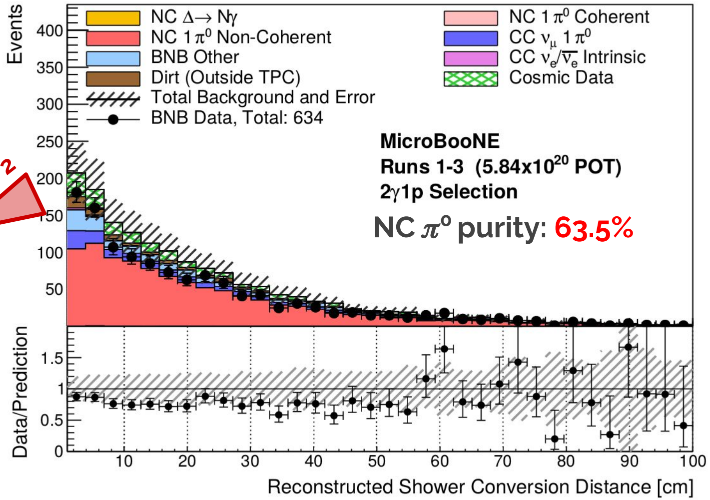
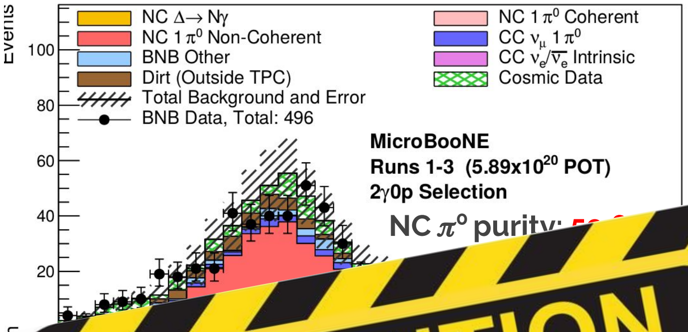
Data | Pandora Reco | Flash matching | Topological Selection | Pre-Selection Cuts | BDT Selection | **Final Selections**

Final 2γ - Selections



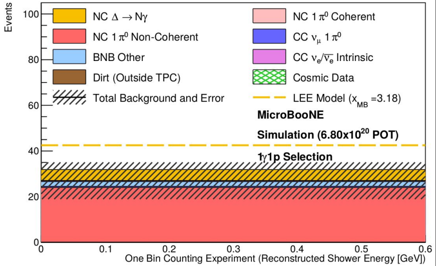




- Negligible contributions from NC $\Delta \rightarrow N\gamma$
- High statistics (1130 candidate NC π^0 data events)
- Help validate energy reconstruction and general photon shower reconstruction

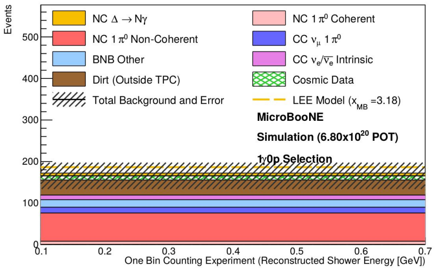
Data · Pandora Reco · Flash matching · Topological Selection · Pre-Selection Cuts · BDT Selection · **Final Selections**

1γ1p



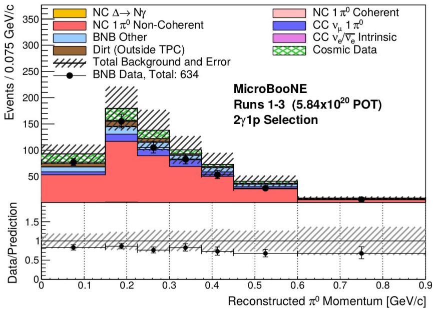
One-bin, Shower Energy from 0-0.6 GeV

1γ0p



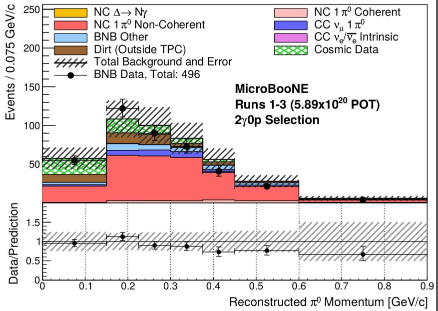
One-bin, Shower Energy from 0.1-0.7 GeV

2γ1p



7-bins, π^0 Momentum from 0-0.9 GeV/c

2γ0p



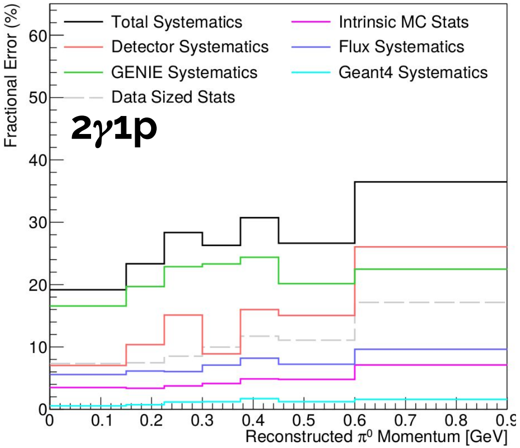
7-bins, π^0 Momentum from 0-0.9 GeV/c

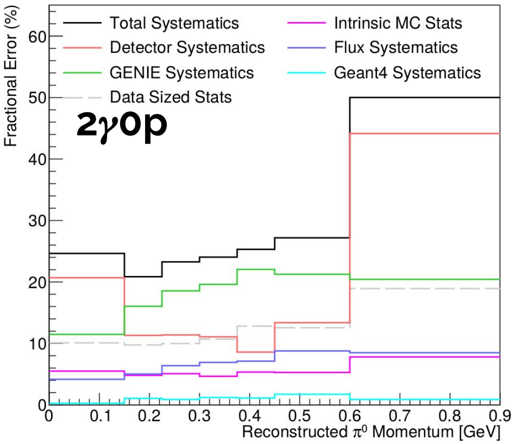
Uncertainty Estimates

A complete list of systematic uncertainties:

- **Flux** uncertainties
- **GENIE cross-section** modelling
- **Geant4 hadron-reinteraction**
- **Detector** response & modelling
- Effects of **finite background statistics**

Type of Uncertainty	$1\gamma 1p$	$1\gamma 0p$
Flux model	7.4%	6.6%
GENIE cross-section model	24.8%	16.3%
GEANT4 re-interactions	1.1%	1.3%
Detector effects	12.2%	6.4%
Finite background statistics	8.3%	4.0%
Total Uncertainty	29.8%	19.2%





Uncertainty Estimates

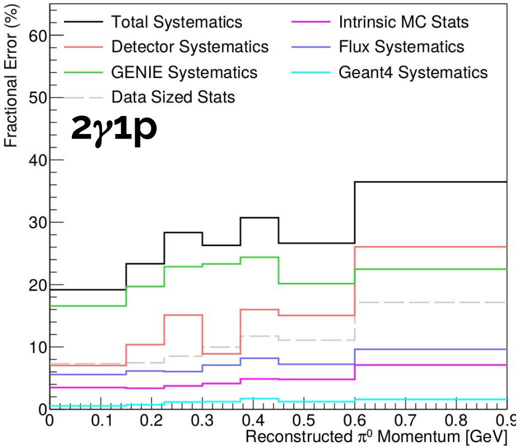
A complete list of systematic uncertainties:

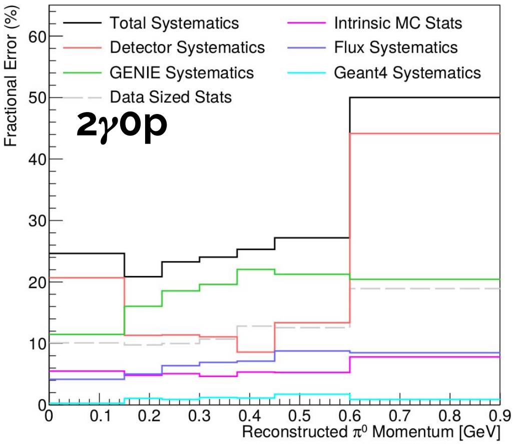
- **Flux** uncertainties
- **GENIE cross-section** modelling
- **Geant4 hadron-reinteraction**
- **Detector** response & modelling
- Effects of **finite background statistics**

Type of Uncertainty	$1\gamma 1p$	$1\gamma 0p$
Flux model	7.4%	6.6%
GENIE cross-section model	24.8%	16.3%
GEANT4 re-interactions	1.1%	1.3%
Detector effects	12.2%	6.4%
Finite background statistics	8.3%	4.0%
Total Uncertainty	29.8%	19.2%

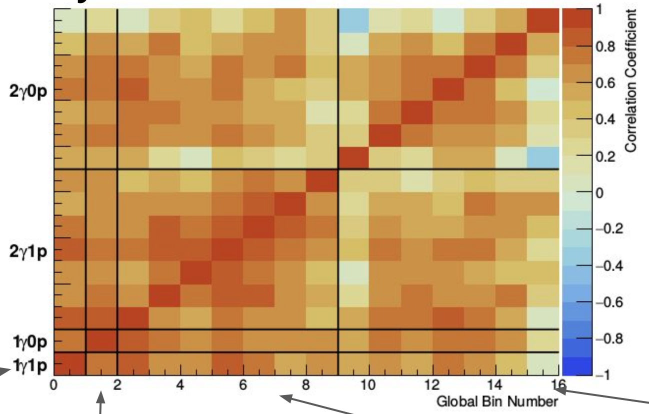
In all cases the dominant systematic uncertainty is the **GENIE cross-section and interaction** (over 50 internal parameters varied) uncertainty, followed by detector effects.

Total systematic uncertainty **20-30%** in majority of bins

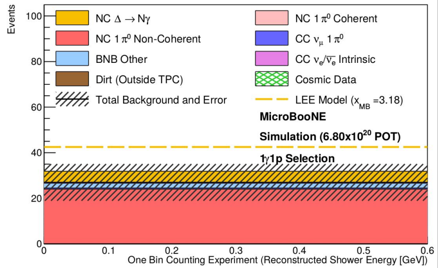




Although the NC π^0 backgrounds in the 1γ samples have large uncertainties, they are **extremely correlated** to the high statistics 2γ samples

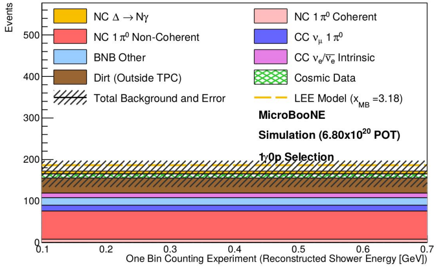


$1\gamma1p$



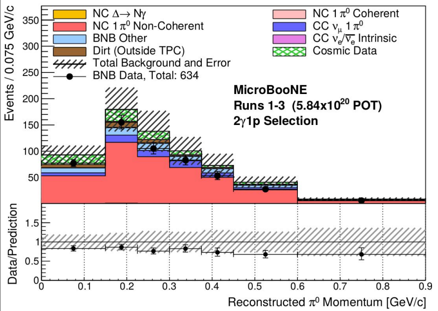
One-bin, Shower Energy from 0-0.6 GeV

$1\gamma0p$



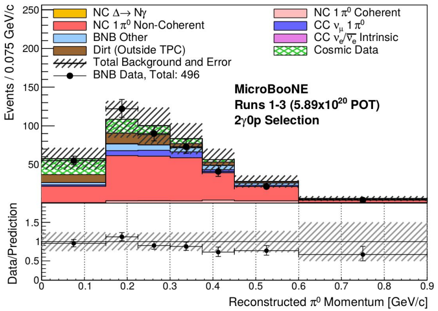
One-bin, Shower Energy from 0.1-0.7 GeV

$2\gamma1p$



7-bins, π^0 Momentum from 0-0.9 GeV/c

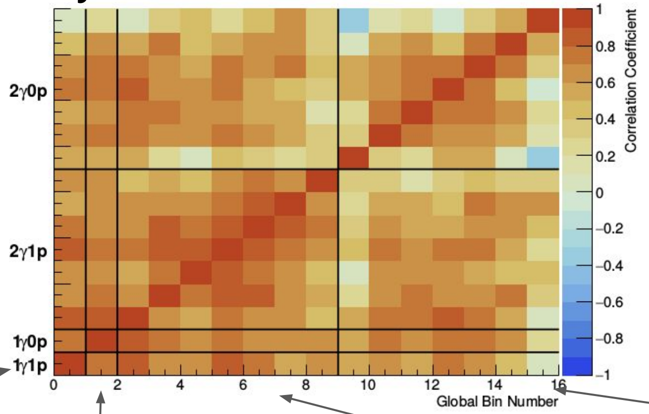
$2\gamma0p$



7-bins, π^0 Momentum from 0-0.9 GeV/c

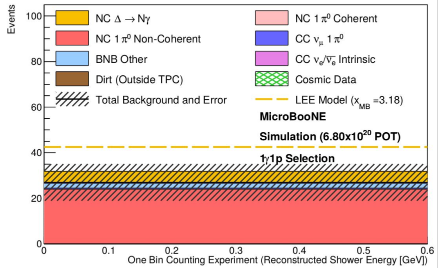
Although the NC π^0 backgrounds in the 1γ samples have large uncertainties, they are **extremely correlated** to the high statistics 2γ samples

Systematic Correlation Matrix



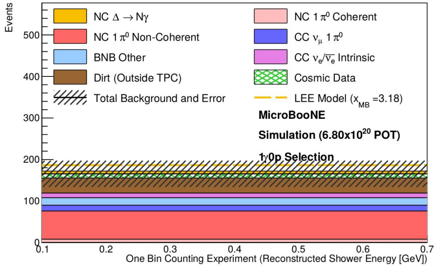
In the joint fit the high statistics 2γ samples will **constrain the background prediction and systematics** in the one-bin 1γ samples

1γ1p



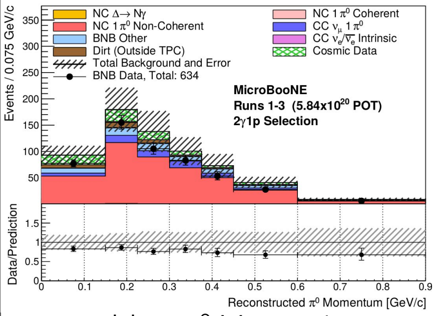
One-bin, Shower Energy from 0-0.6 GeV

1γ0p



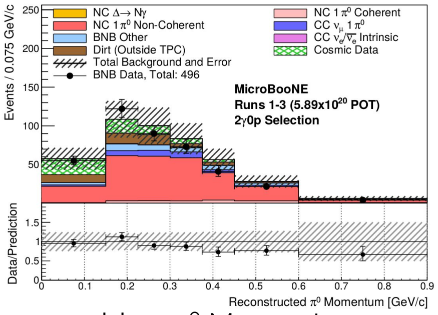
One-bin, Shower Energy from 0.1-0.7 GeV

2γ1p



7-bins, π^0 Momentum from 0-0.9 GeV/c

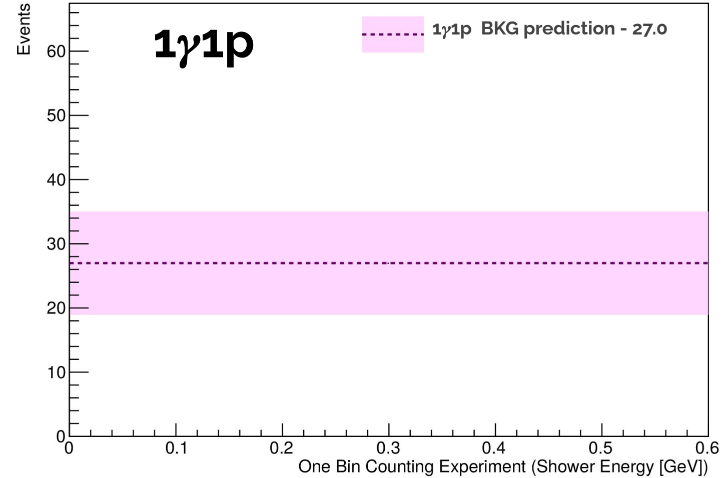
2γ0p

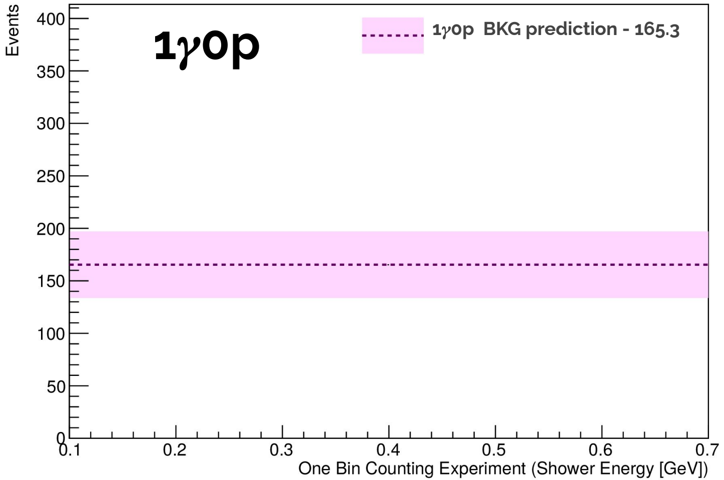


7-bins, π^0 Momentum from 0-0.9 GeV/c

Effect of the constraint

We conditionally constrain the 1γ samples by the high stats 2γ to highlight how the central value and uncertainties change:

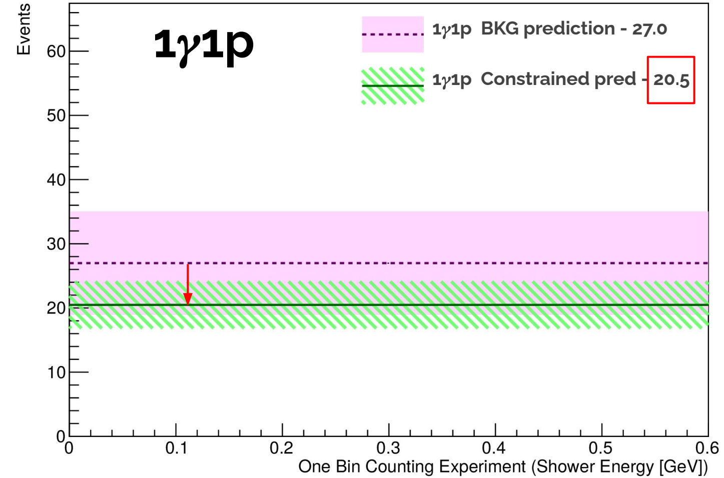


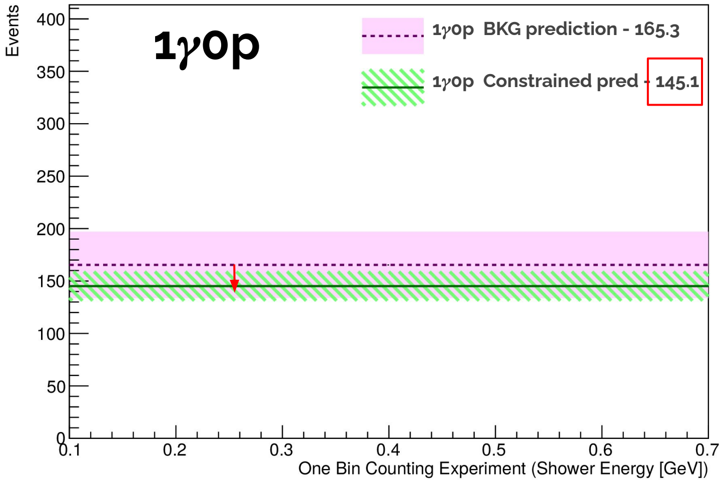


Effect of the constraint

We conditionally constrain the 1γ samples by the high stats 2γ to highlight how the central value and uncertainties change:

- Overall **drop in expected backgrounds** by **24.1%** and **12.3%**, for $1\gamma1p$ and $1\gamma0p$





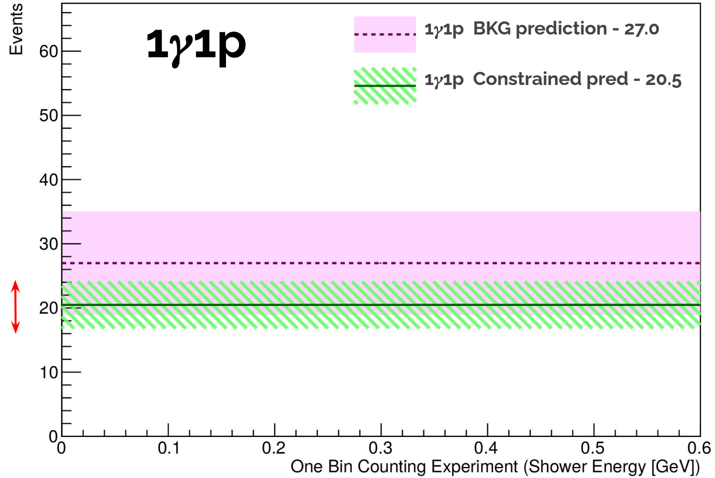
Effect of the constraint

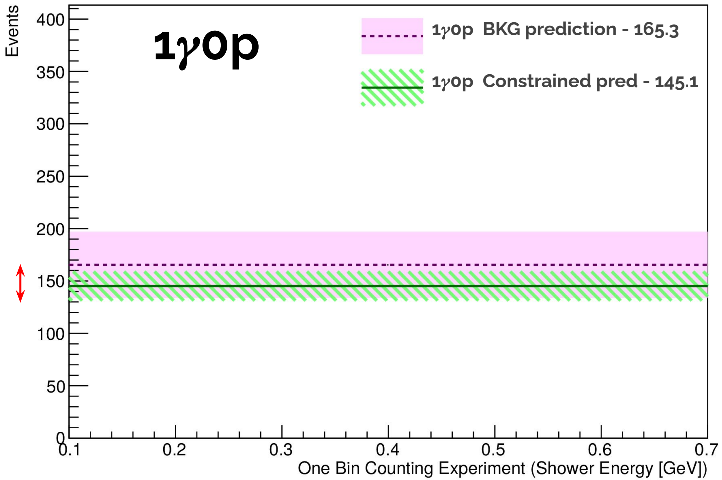
We conditionally constrain the 1γ samples by the high stats 2γ to highlight how the central value and uncertainties change:

- Overall **drop in expected backgrounds** by **24.1%** and **12.3%**, for 1γ1p and 1γ0p

- Overall **reduction in systematic uncertainty** of backgrounds by **40%** and **50%** for 1γ1p and 1γ0p

Type of Uncertainty	$1\gamma 1p$	$1\gamma 0p$
Flux model	7.4%	6.6%
GENIE cross-section model	24.8%	16.3%
GEANT4 re-interactions	1.1%	1.3%
Detector effects	12.2%	6.4%
Finite background statistics	8.3%	4.0%
Total Uncertainty (Unconstr.)	29.8%	19.2%
Total Uncertainty (Constr.)	17.8%	9.5%





Nearing signal box opening

Analysis Development

Validation on signal-blind data

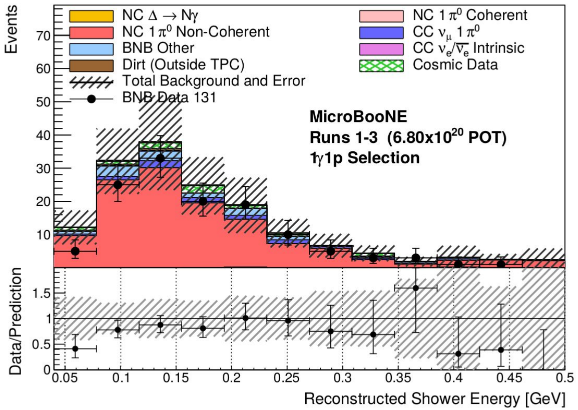
Signal Box!

- The **small unblinded 0.5 x 10^{20} POT** dataset
- **The high stat NC π^0 rich 2γ samples**.

Nearing signal box opening

Signal-blind validation samples

- **The Far Sidebands**
  - All events that fail NC π^0 BDT **OR** CC ν_μ BDT
  - Aim: **validate BDT's** on high purity single-shower proton and photon samples (~**90% true photons protons** in simulation)



Nearing signal box opening

Signal-blind validation samples

Analysis Development → **Validation on signal-blind data** → **Far Sideband** → **Near Sideband** → **Signal Box!**

- **The Far Sidebands**
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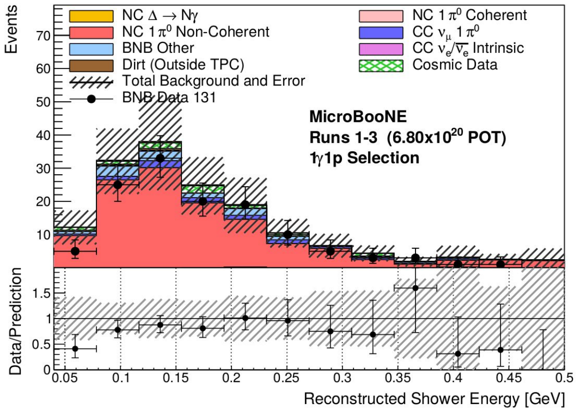
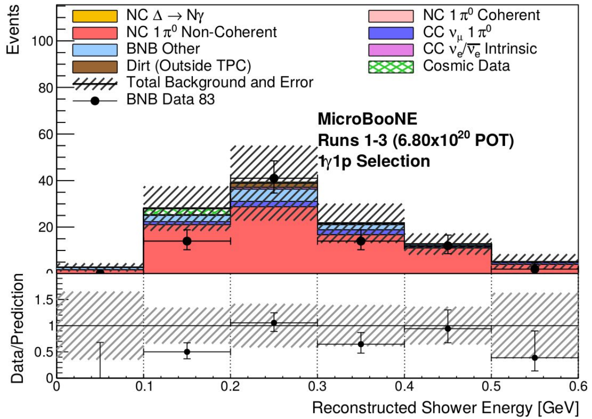
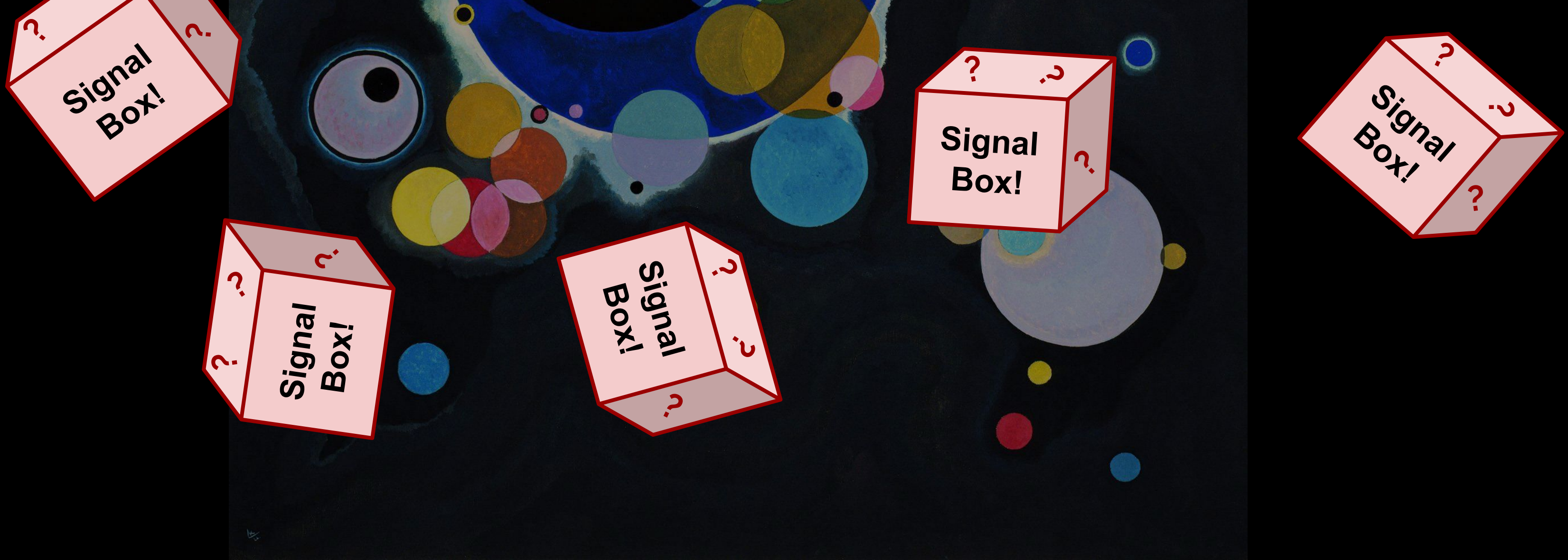


- **The Near Sidebands**
  - Designed to validate the **Second Shower Veto**.
  - Select events that look NC $\Delta \rightarrow N\gamma$ like, but have evidence of a second shower that missed 3D reco

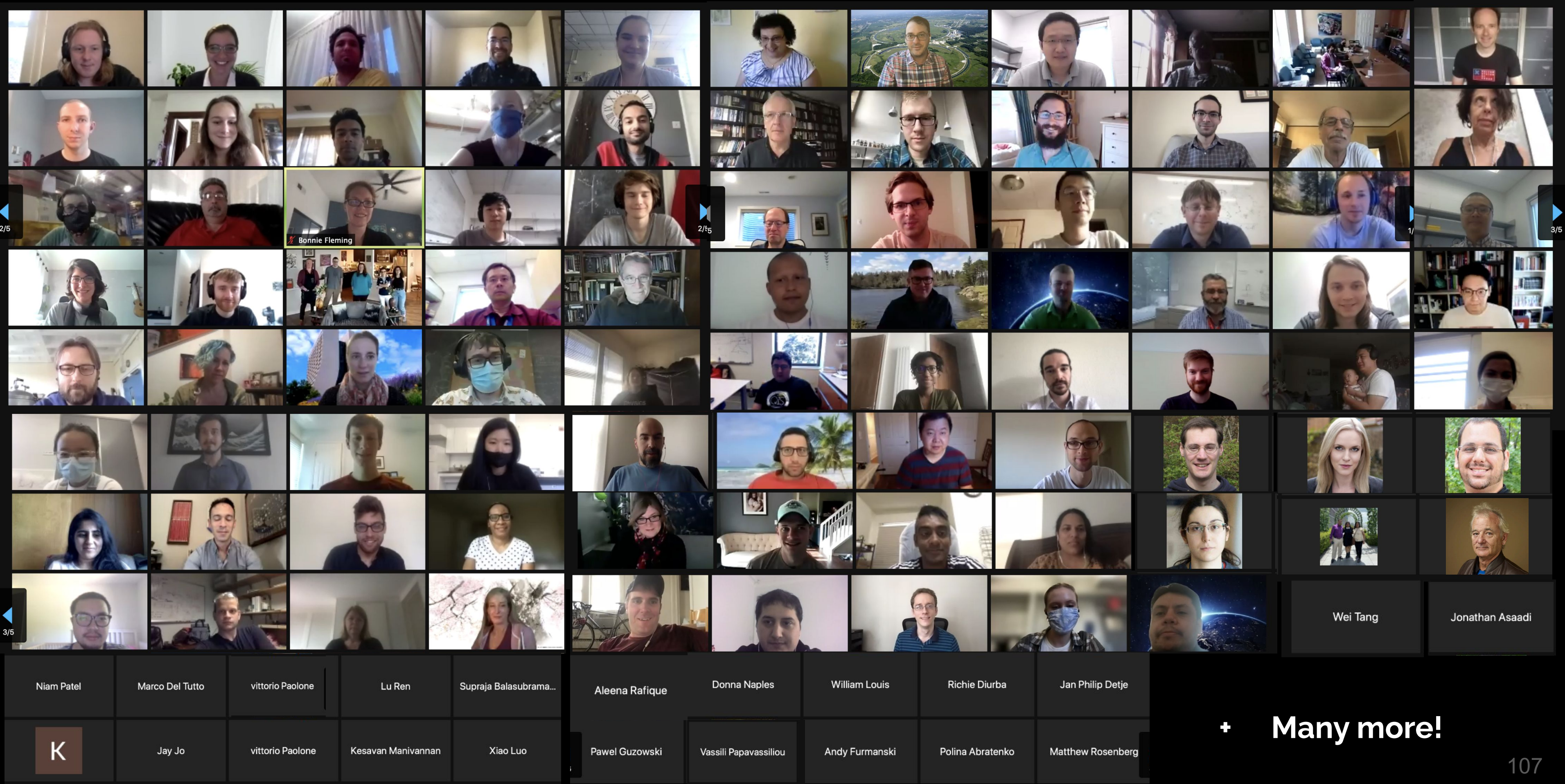


Analysis Development, Systematics and sensitivity evaluation → **Validation on signal-blind data** → **Far Sideband** → **Near Sideband** → **Signal Box!**

What's in the box?



Live (Virtual) Unblinding



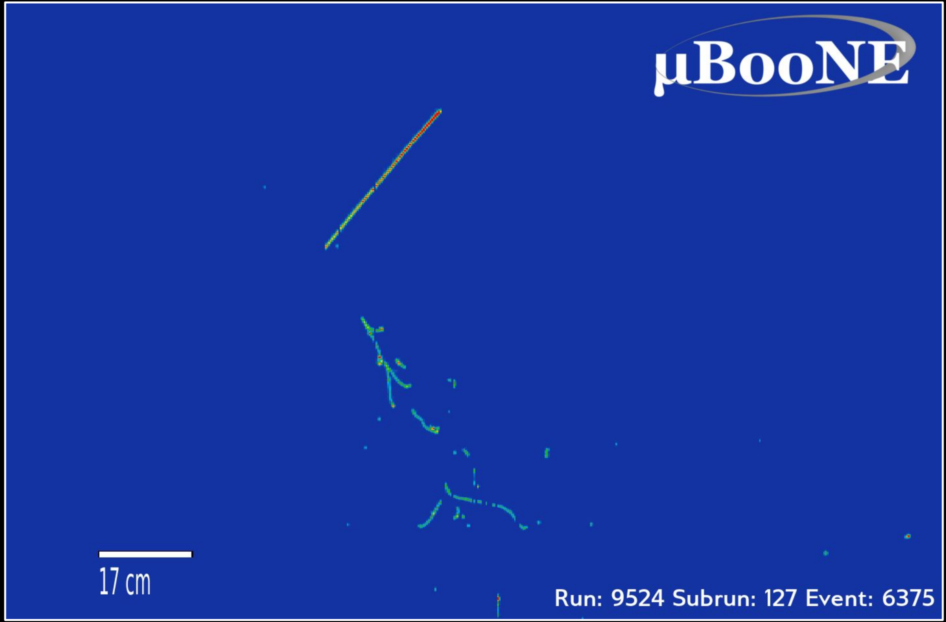
+ **Many more!**

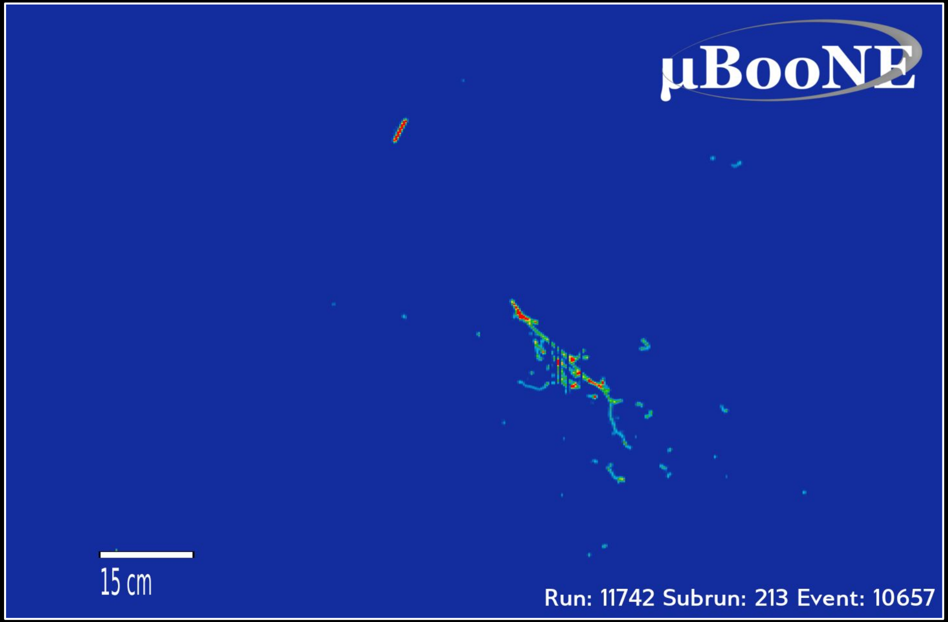
Live Unblinding

Live Unblinding

~5 seconds before box opening

Two example **1γ1p** events from our **signal search unblinded data!**

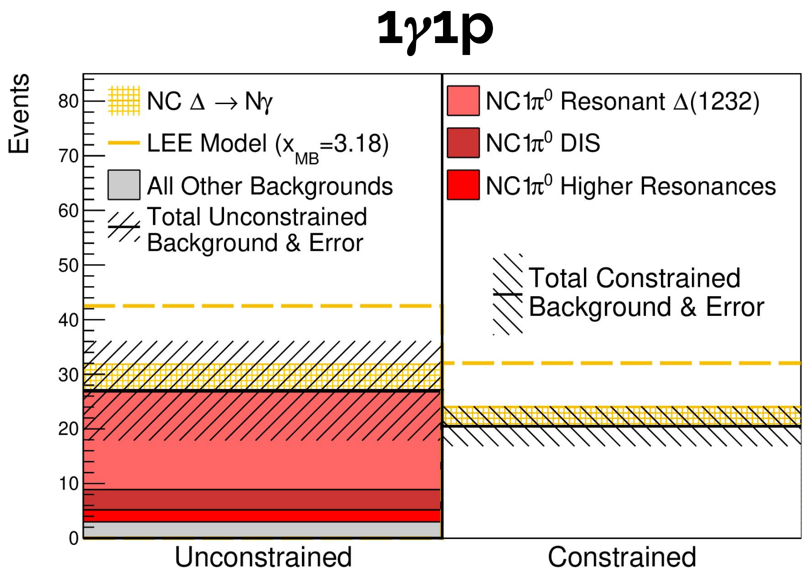




Shower energy 0.215 GeV
Track length : 35.0 cm
Proton kinetic energy: 0.238 GeV
Shower conversion distance : 13.4 cm

Shower Energy 0.469 GeV
Track length : 6.7 cm
Proton kinetic energy: 0.091 GeV
Shower conversion distance : 55.4 cm

Expectation

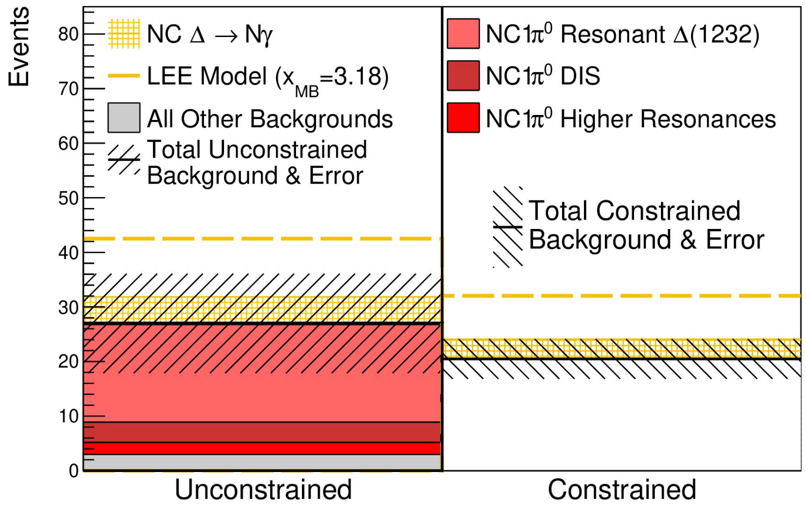


1γ1p

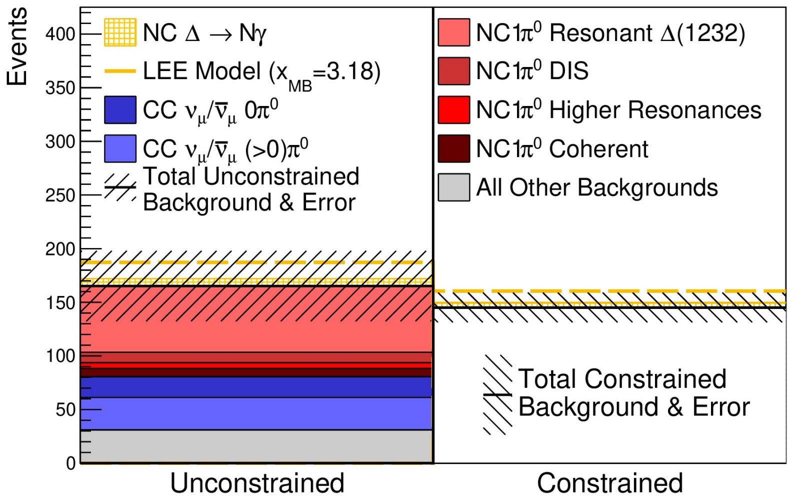
Unconstr. bkgd.	27.0 ± 8.1
Constr. bkgd.	20.5 ± 3.6
NC $\Delta \rightarrow N\gamma$	+ 4.88
LEE ($x_{\mathrm{MB}} = 3.18$)	+ 15.5

Expectation

$1\gamma 1p$



$1\gamma 0p$



$1\gamma 1p$

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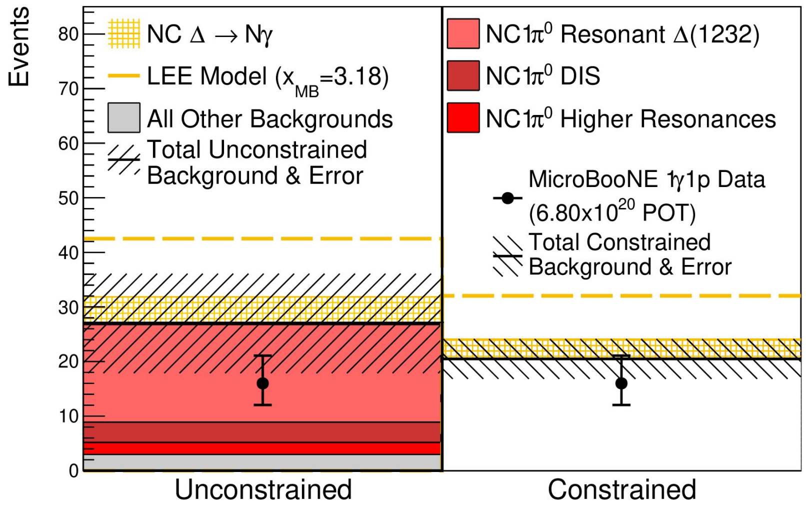
$1\gamma 0p$

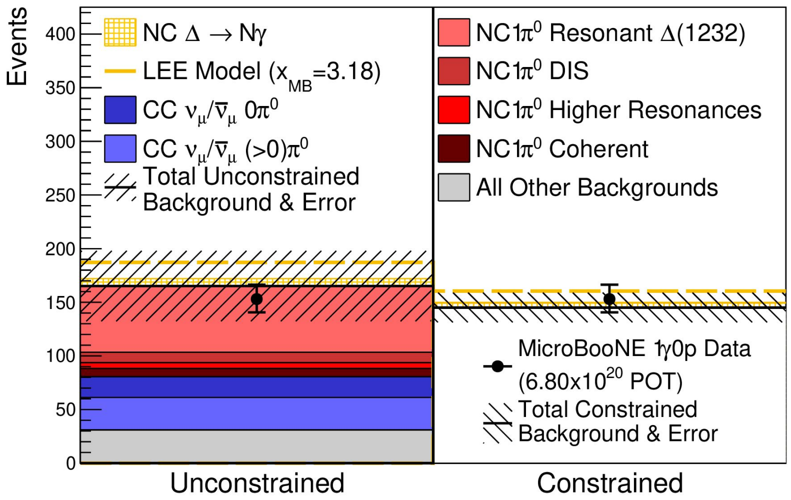
Unconstr. bkgd.	165.4 ± 31.7
Constr. bkgd.	145.1 ± 13.8
NC $\Delta \to N\gamma$	+ 6.55
LEE ($x_{\mathrm{MB}} = 3.18$)	+ 20.1

Unblinded Results

$1\gamma 1p$



$1\gamma 0p$



$1\gamma 1p$

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16
Data Events Observed

$1\gamma 0p$

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153
Data Events Observed

Testing the NC $\Delta\rightarrow\gamma$N LEE Hypothesis

In order to test the compatibility of the observed data with our **LEE model** we construct a simple two-hypothesis test between:

- **Nominal GENIE prediction** for NC $\Delta\rightarrow N\gamma$ rate
- **LEE Model (x_{MB} = 3.18)** enhancement of NC $\Delta\rightarrow N\gamma$ rate

We use the combined Neyman-Pearson† χ^2 as our metric

$$\Delta\chi^2 = \chi^2|_{\text{LEE Model}(x_{\text{MB}}=3.18)} - \chi^2|_{\text{Nominal }\Delta\rightarrow N\gamma}$$

† X. Ji et al., Nucl. Instr. and Meth. A 961, 163677 (2020).

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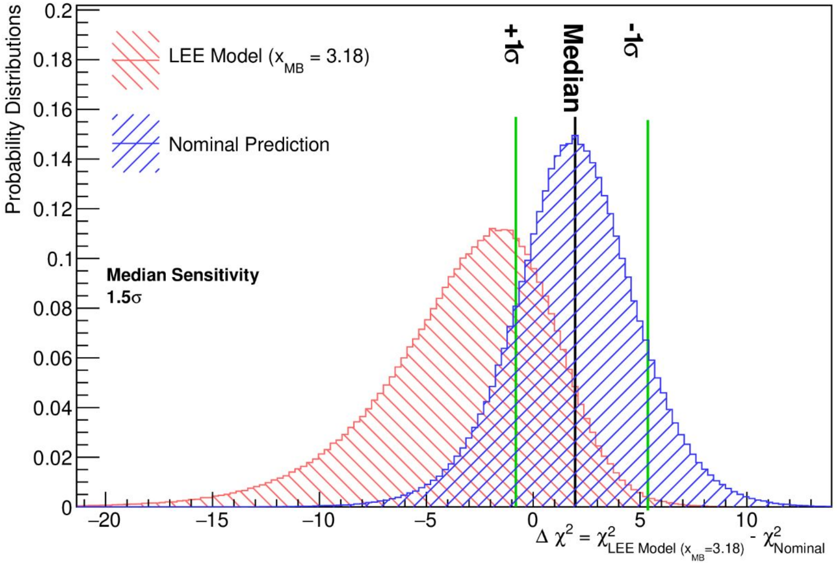

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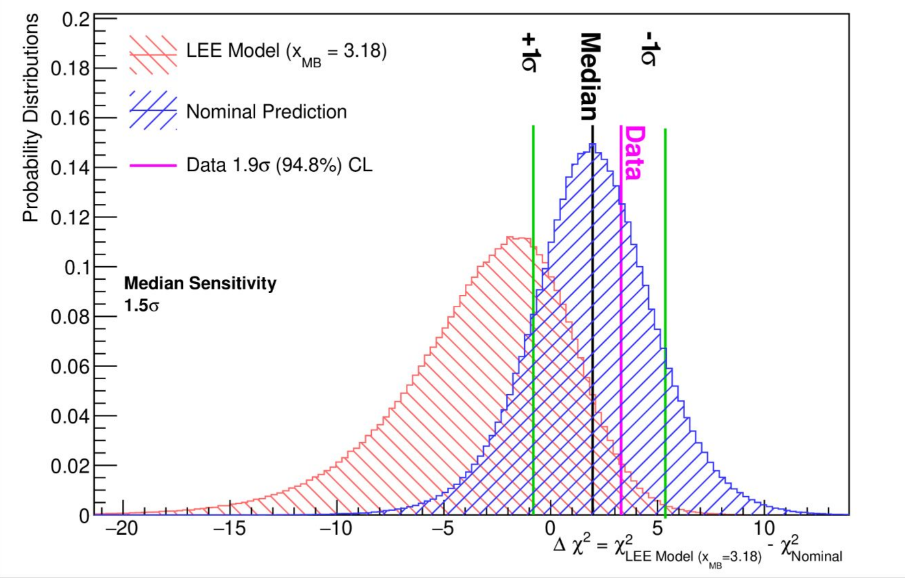
Testing the NC Δ→γN LEE Hypothesis

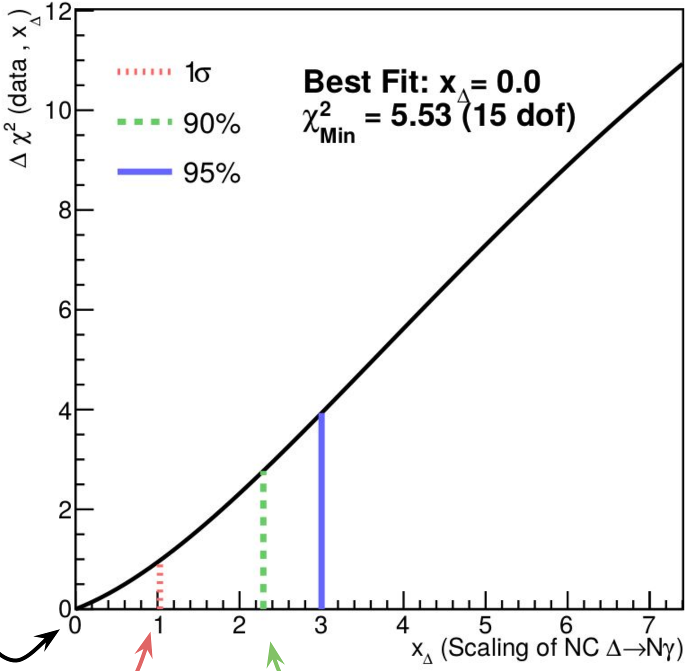
Observed data is **consistent with the nominal NC Δ→γN prediction** well within expected 1σ of experiments.

The data rejects the LEE model hypothesis in favour of the nominal prediction at 94.8% CL



A fit to NC $\Delta\rightarrow\gamma N$ Normalization

Elevate this normalization **scaling to a continuous parameter, x_Δ,** and perform a fit to extract the best fit and classical confidence intervals, via the Feldman-Cousins procedure‡



Best Fit: $x_\Delta = 0$

Nominal GENIE NC $\Delta\rightarrow N\gamma$ rate ($x_\Delta = 1$) within 1σ

$x_\Delta < 2.3$ at the **90% CL**

‡G. J. Feldman and R. D. Cousins, Phys. Rev. D 57, 3873 (1998).

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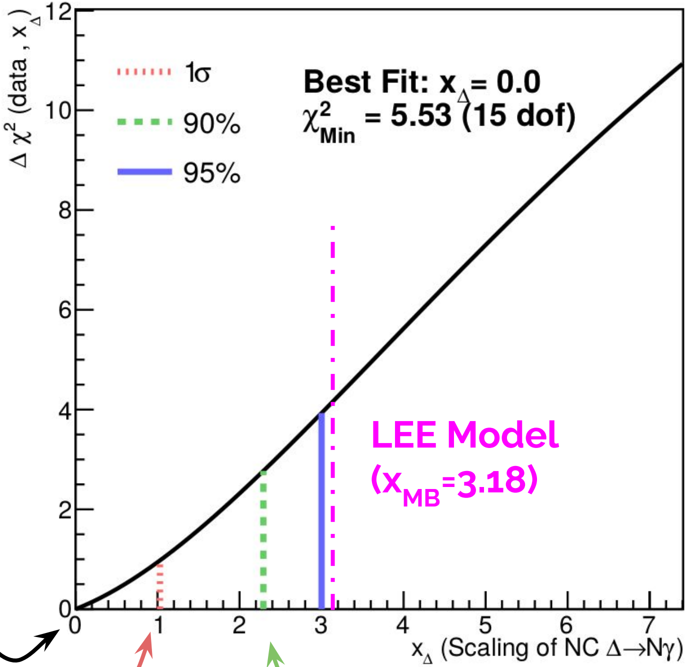

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Effective Branching Fraction of Δ→Nγ

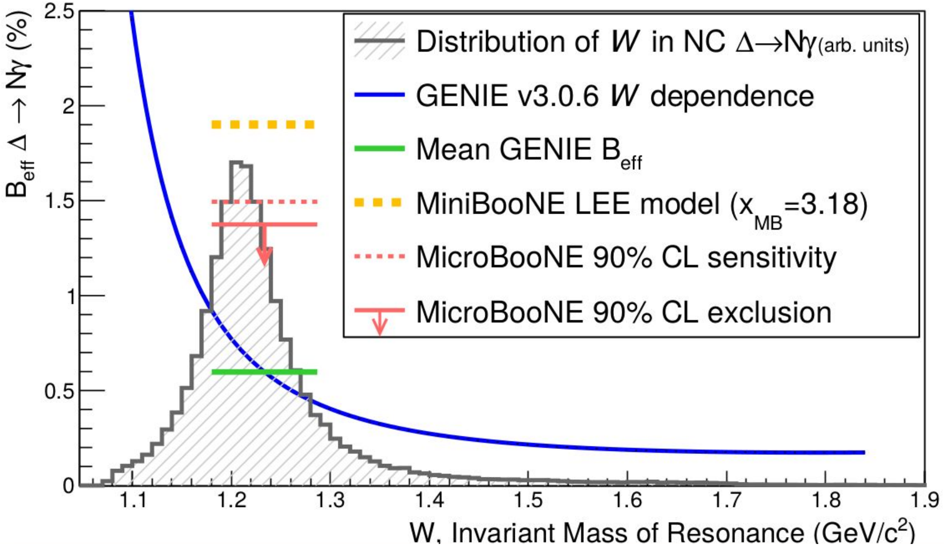
Can **reinterpret this bound** on x_Δ to a bound on the **effective branching fraction of the Δ→Nγ**:

$$\mathcal{B}_{\mathrm{eff}}(\Delta \to N\gamma) < 1.38\%$$

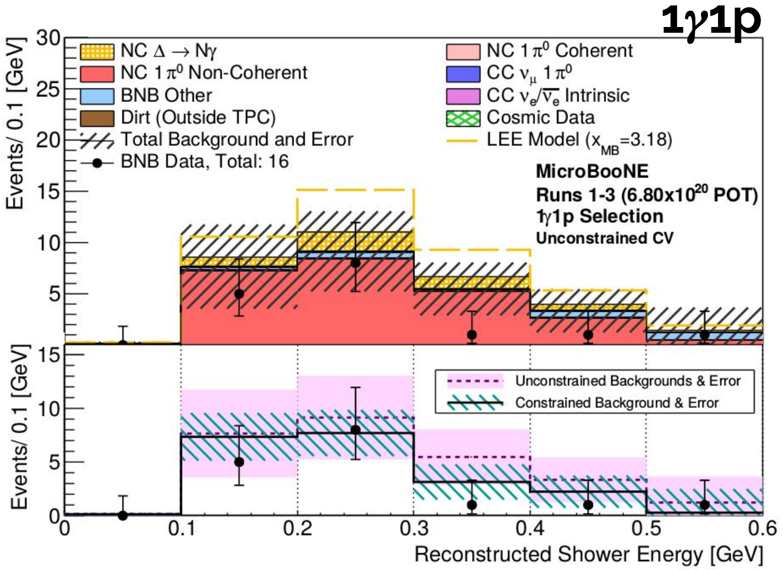
at **90% CL**. With the nominal GENIE effective branching fraction corresponding to 0.6%,

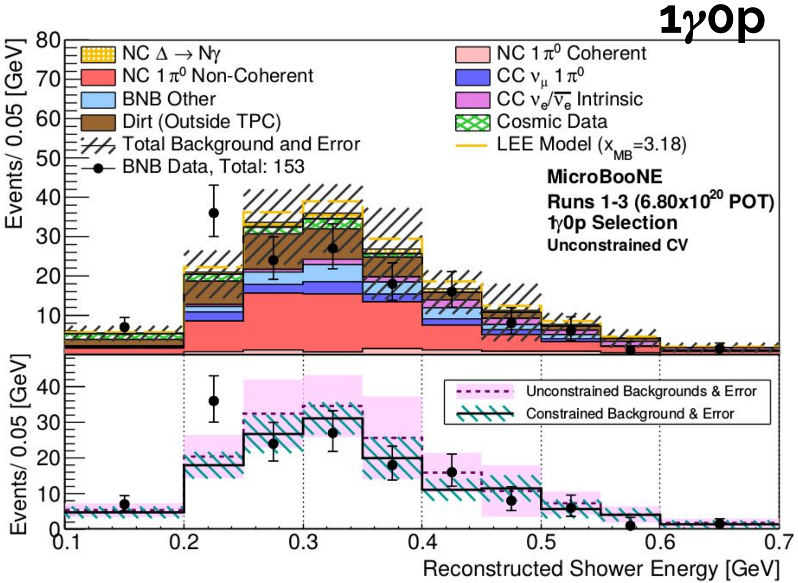
Expected sensitivity: < 1.5% 90% CL

This represents a **greater than 50-fold improvement** over the world's best limit on such neutrino-induced NC Δ→Nγ production at the O(1 GeV) scale



Reconstructed Energy Spectra

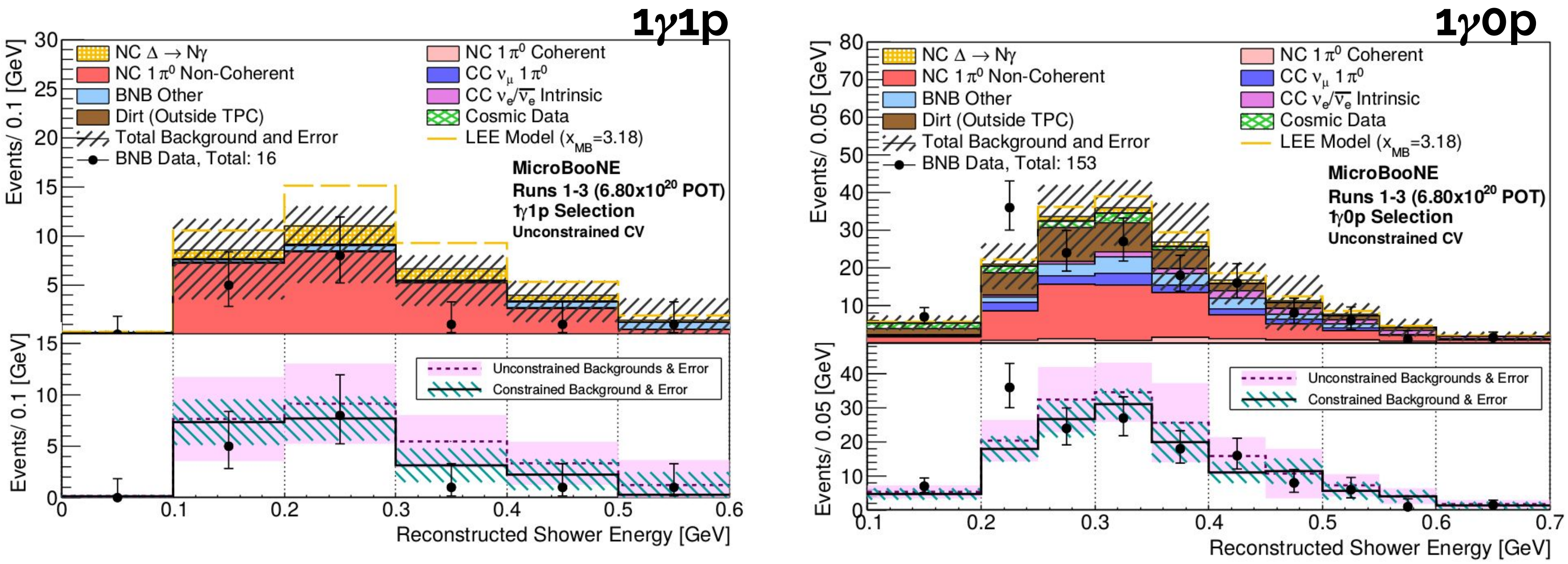




We see **good agreement** between data and background prediction when one takes into account the overall deficit observed in the 2γ NC π^0 samples.

This is highlighted by the data agreement with the constrained prediction on the bottom panels.

Reconstructed Energy Spectra



We see **good agreement** between data and background prediction when one takes into account the overall deficit observed in the 2γ NC π^0 samples.

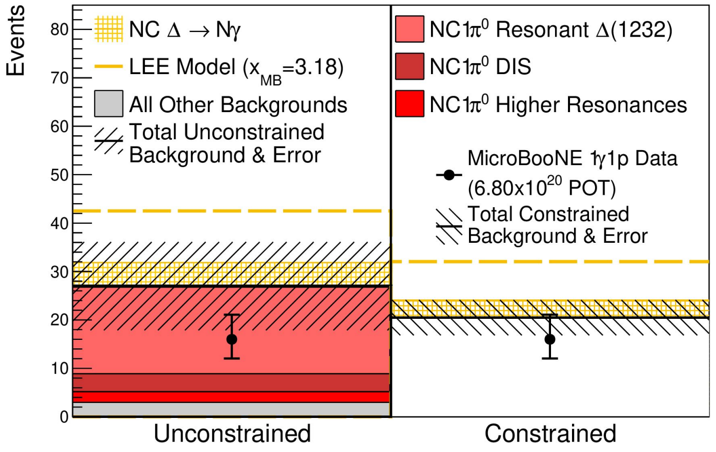
This is highlighted by the data agreement with the constrained prediction on the bottom panels.

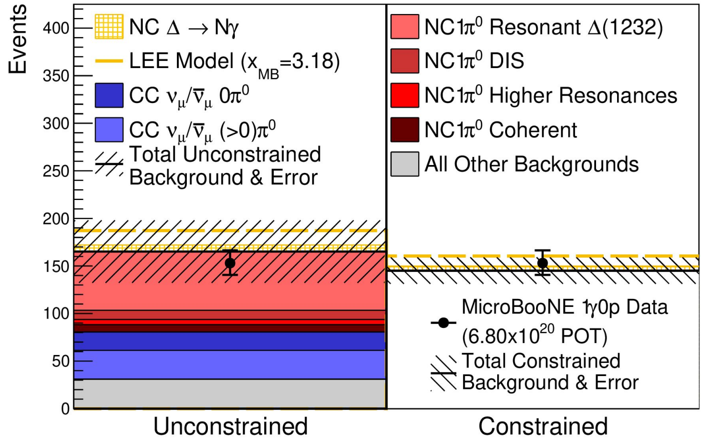
From Monte-Carlo studies, the probability of any one bin across all sixteen 1γ energy bins giving rise to a worse constrained χ^2 is 4.74%.

Summary

I have presented today MicroBooNE first analyses that investigates the origin of the low-energy excess under a **single-photon hypothesis**

- We see **no evidence** for an enhanced rate of single-photons from NC $\Delta \rightarrow N\gamma$ decay, above nominal GENIE expectations





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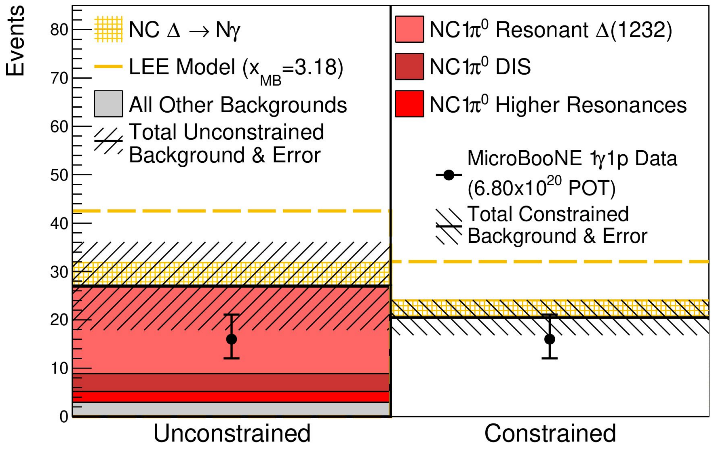
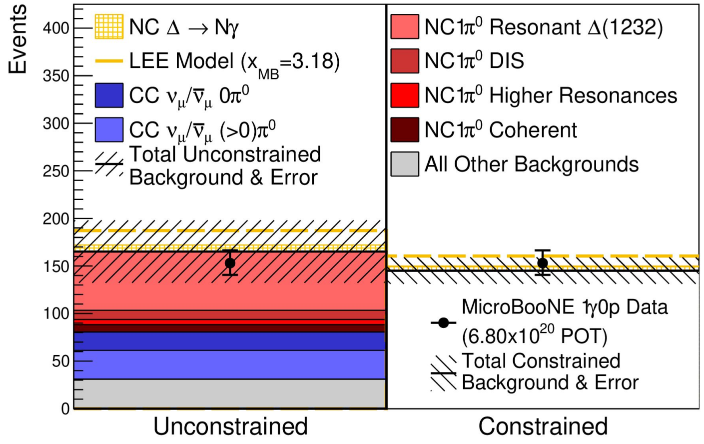
- The data places a one-sided bound on the normalization of NC $\Delta \rightarrow N\gamma$ events of $\mathbf{x_\Delta < 2.3}$, corresponding to

$$\mathcal{B}_{\text{eff}}(\Delta \rightarrow N\gamma) < 1.38\%$$

at 90% CL. This is the world's best limit on this process in neutrino sector to date!





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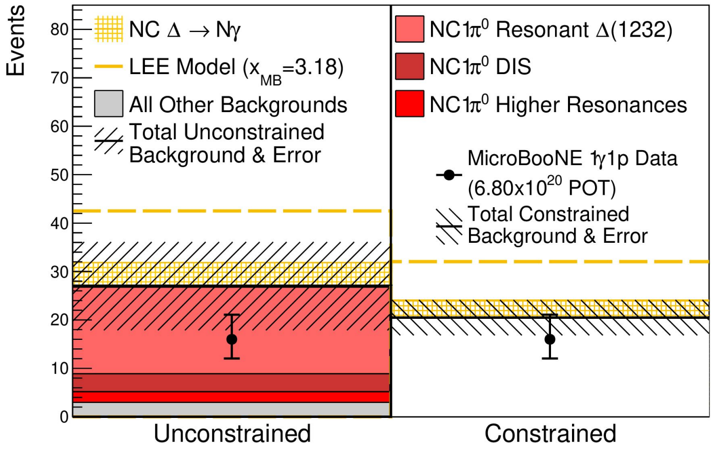
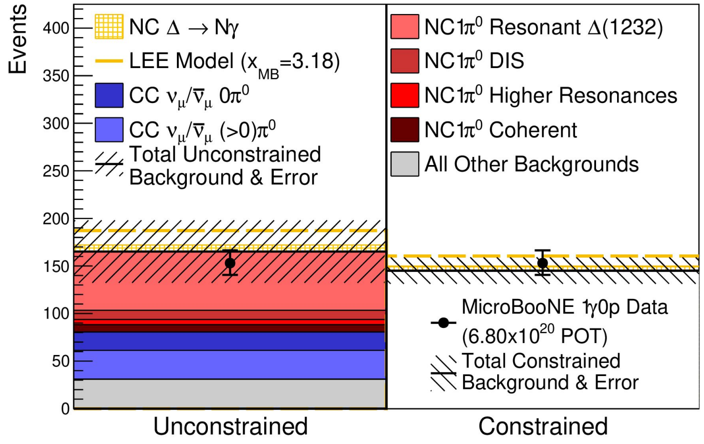
  at 90% CL. This is the world's best limit on this process in neutrino sector to date!

- Under a two-hypothesis test, the data disfavours the interpretation of the MiniBooNE anomalous excess as a factor of 3.18 enhancement to the rate NC $\Delta \rightarrow N\gamma$, in favor of the nominal prediction at **94.8% CL**



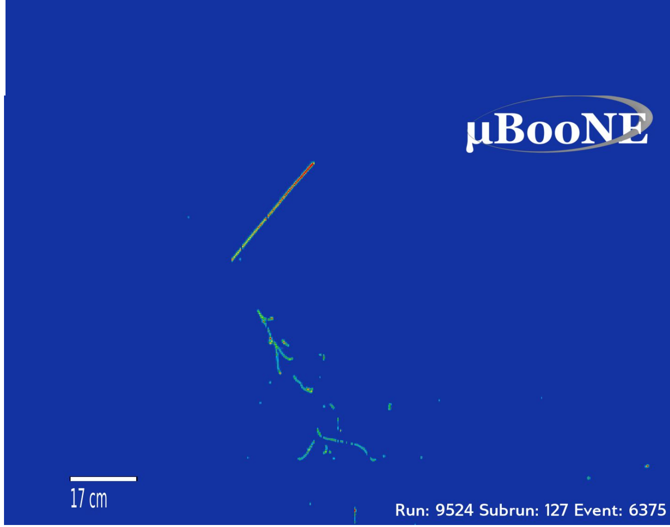


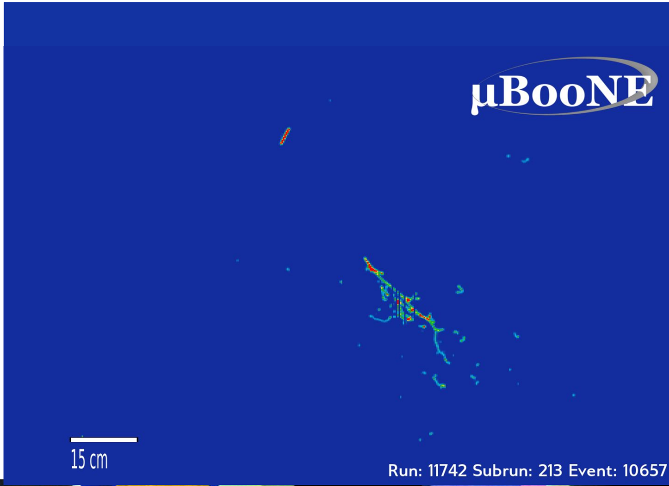
Stay tuned for more photon results!

The results I showed today featured a record number of single photon events in argon and while the data disfavours NC $\Delta \rightarrow N\gamma$ as the sole source of the MiniBooNE low-energy excess, this is still a process we want to measure regardless!

Lots to look forward to for photon-fanatics:

- **More Statistics**
    - Today's results were for **½ the MicroBooNE dataset**, processing of remainder well underway.
- **More Channels**
    - This sample may be sensitive to a wide variety of other photon and BSM photon-like models, ongoing work to quantify explicitly

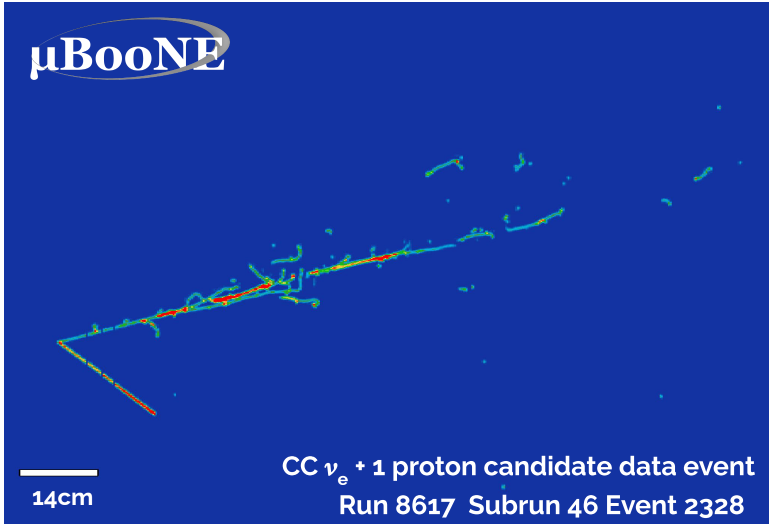




Stay tuned for upcoming electron results!

Whole other world of possibilities exist in the MicroBooNE electron analysis!

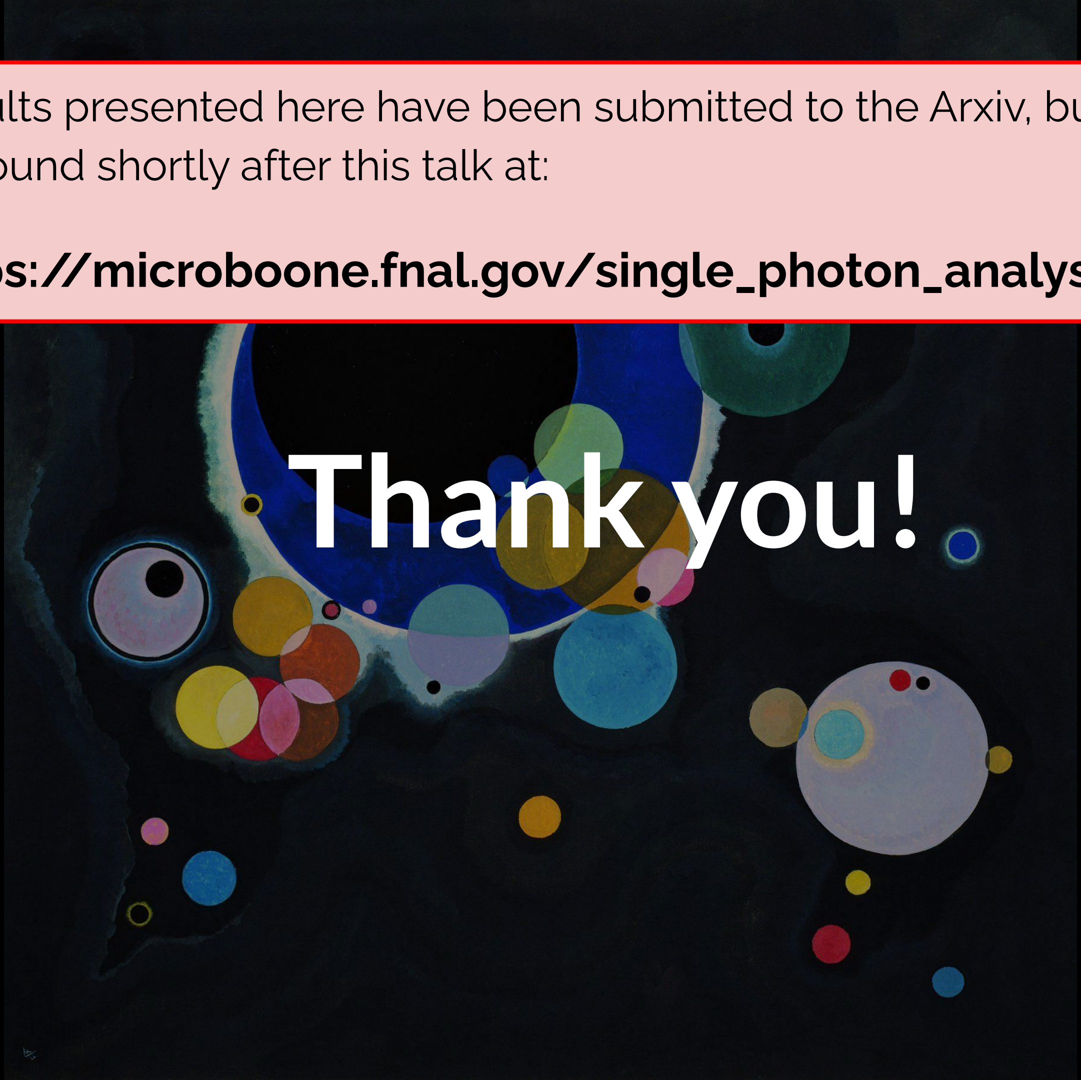
I'm pleased to announce on **October 27th** MicroBooNE will present our first **electron low-energy excess** results from three complementary analyses, targeting **multiple electron topologies**, both inclusive and exclusive, and using **three different paradigms of reconstruction!**



We hope to see you all there!

Results presented here have been submitted to the Arxiv, but can also be found shortly after this talk at:

https://microboone.fnal.gov/single_photon_analysis_2021/



Thank you!