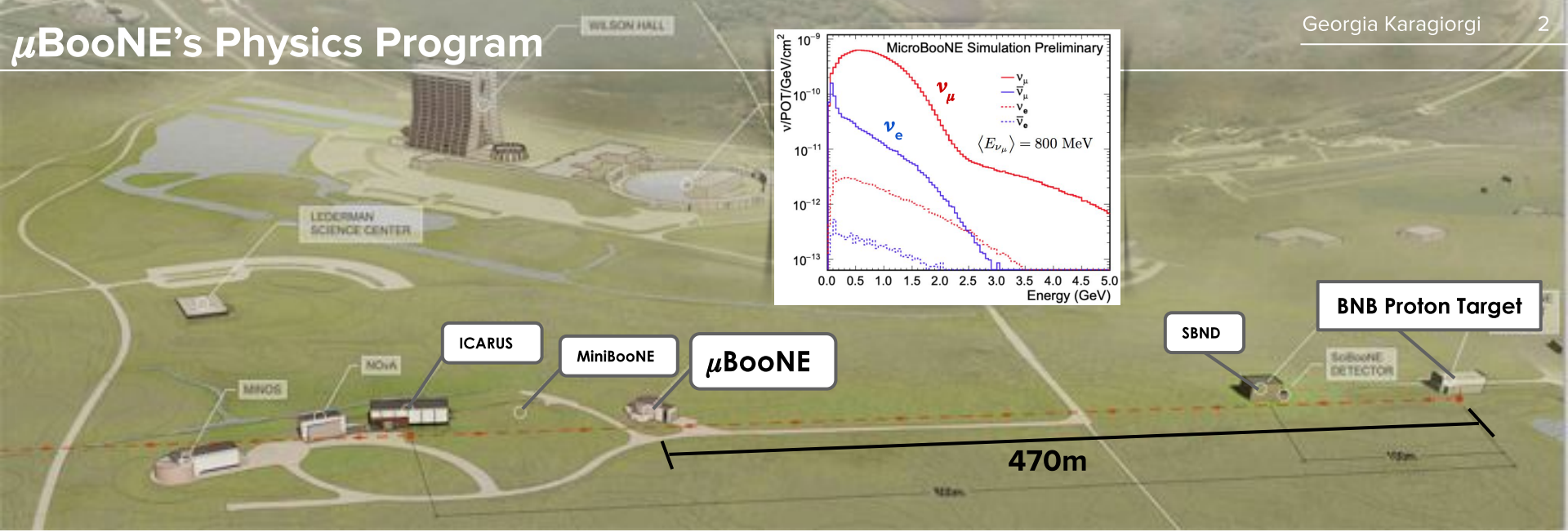
NEUTRINO 2020

Searches for New Physics with μBooNE

Georgia Karagiorgi, Columbia University
on behalf of the MicroBooNE Collaboration

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

μBooNE's Physics Program



Highest-statistics of neutrino interactions on argon enable inclusive and exclusive **cross-section** measurements

See talk by K. Duffy

Excellent tracking and calorimetric information enable tests of the previously observed **MiniBooNE anomalous low-energy excess**

This talk

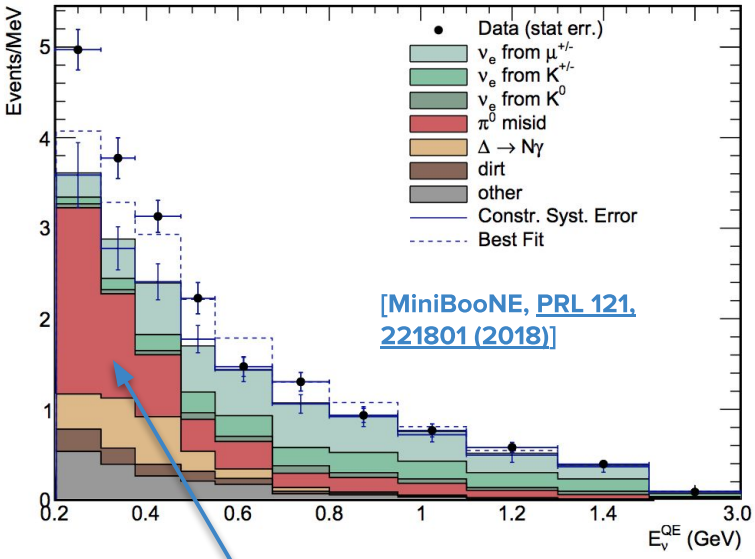
Large-scale, continuous operation of a new detector technology enables **astro-particle and exotic physics** measurements

Testing the MiniBooNE Low Energy Excess (LEE)

- MiniBooNE observed unexplained excess of ν_e CCQE-like events
- Underlying nature of excess could be:

  "electron-like" (eLEE) or **"photon-like" (γLEE)**

See talk by A. Hourlier



[MiniBooNE, PRL 121, 221801 (2018)]

At low energy, largest background in **MiniBooNE** was mis-identified NC π^0 events

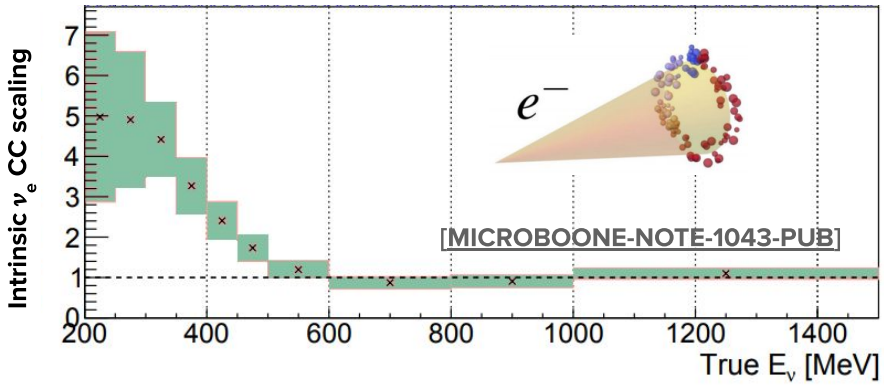
Testing the MiniBooNE Low Energy Excess (LEE)

- MiniBooNE observed unexplained excess of ν_e CCQE-like events
- Underlying nature of excess could be:

  "electron-like" (eLEE) or **"photon-like" (γLEE)**

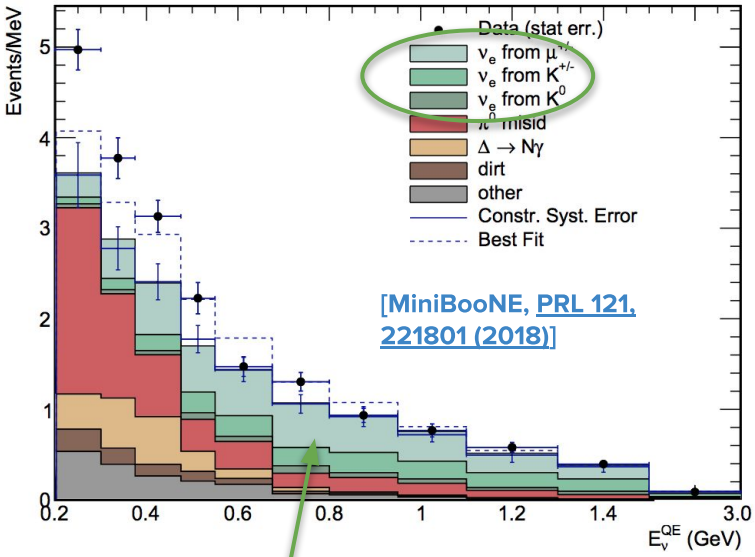
  1e + hadronic activity (below Cherenkov threshold)

See talk by A. Hourlier



Applying this scaling to intrinsic ν_e CC can explain the observed MiniBooNE excess

→ **eLEE signal template for μBooNE**



Main background in μBooNE will be from intrinsic ν_e

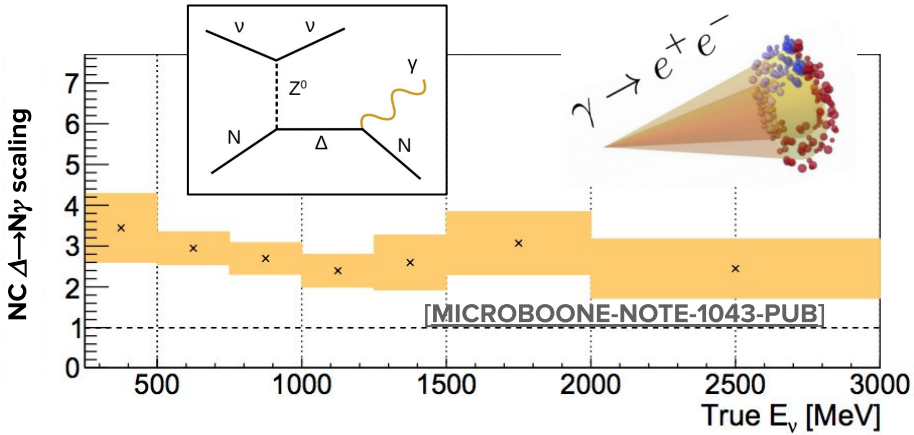
Testing the MiniBooNE Low Energy Excess (LEE)

- MiniBooNE observed unexplained excess of ν_e CCQE-like events
- Underlying nature of excess could be:

  "electron-like" (eLEE) or **"photon-like" (γLEE)**

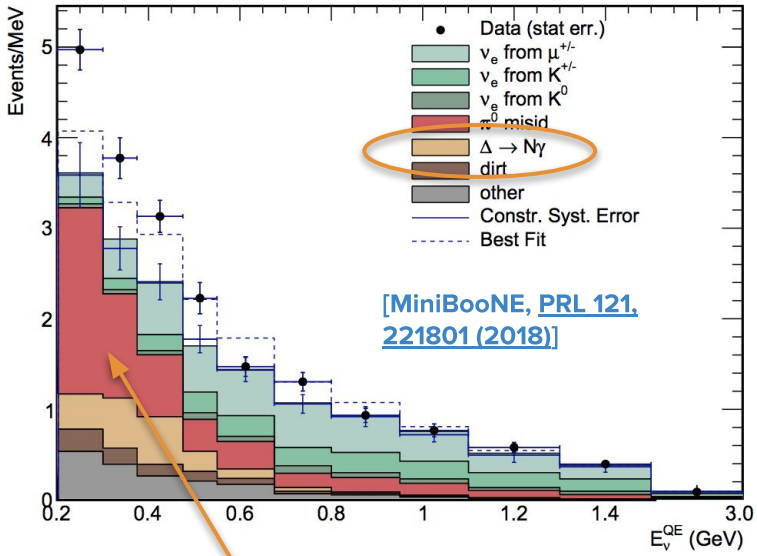
  1γ + hadronic activity (below Cherenkov threshold)

See talk by A. Hourlier



Applying a ~3x flat scaling to NC $\Delta \rightarrow N\gamma$ can explain the observed MiniBooNE excess

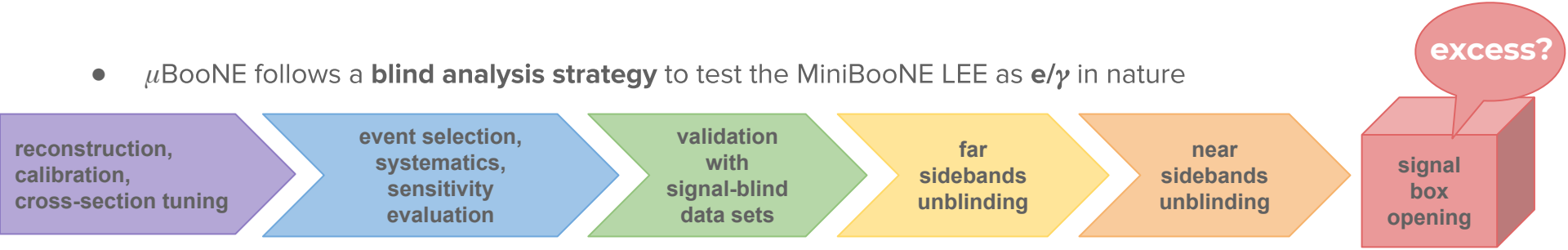
→ **γLEE signal template for μBooNE**



Main background in μBooNE will be from mis-identified NC π^0

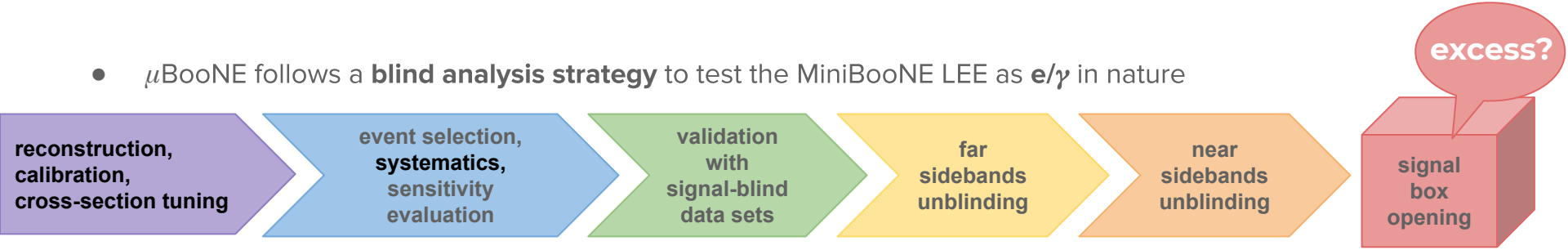
μBooNE LEE Searches

- μBooNE follows a **blind analysis strategy** to test the MiniBooNE LEE as **e/γ** in nature



μBooNE LEE Searches

- μBooNE follows a **blind analysis strategy** to test the MiniBooNE LEE as **e/γ** in nature



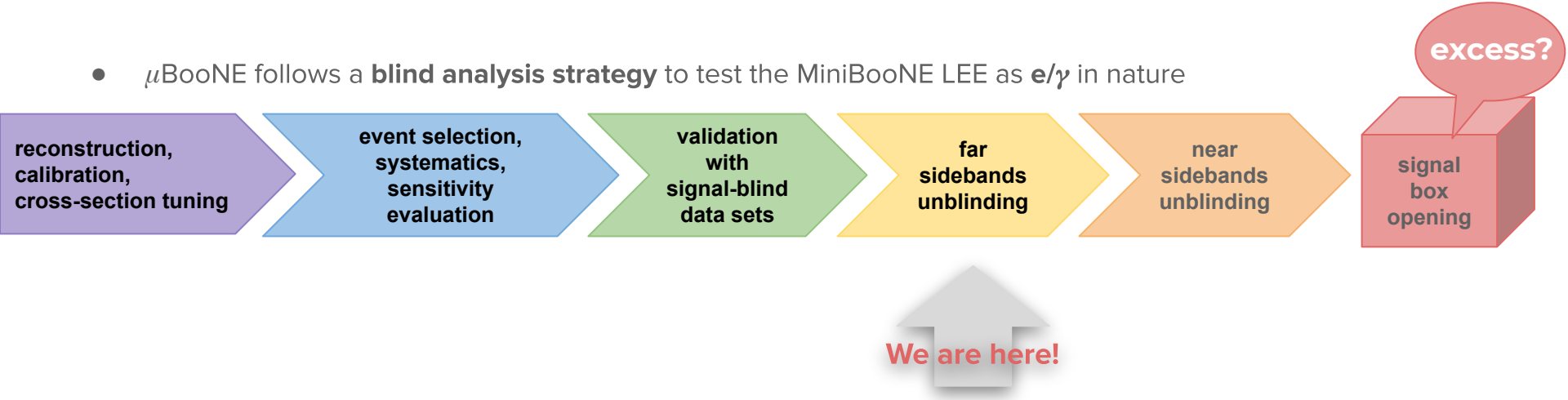
- Enormous body of **pioneering work**, **enabling science** with this new detector technology:
  - Application of **2D deconvolution** for signal processing [JINST 13, P07006 (2018), JINST 13, P07007 (2018)]
  - Application of **Machine Learning** and **tomography** techniques for reconstruction [Phys. Rev. D99, 092001 (2019), arXiv:2002.09375]
  - Understanding and tuning of **neutrino-argon cross-sections** [Eur. Phys. J. C79, 248 (2019), Phys. Rev. D99, 091102(R) (2019), Phys. Rev. Lett. 123, 131801 (2019), arXiv:2006.00108] including a dedicated **GENIE tune** [MICROBOONE-NOTE-1074-PUB]
  - Detector **calibration** and understanding of **detector effects and performance** [JINST 15, P03022 (2020), arXiv:1910.01430, JINST 15, P02007 (2020), MICROBOONE-NOTE-1018-PUB, MICROBOONE-NOTE-1050-PUB]
  - **Detector systematic uncertainty** assessment [L. Yates Poster #176, MICROBOONE-NOTE-1075-PUB]

See talk by K. Duffy

Full list of μBooNE publications

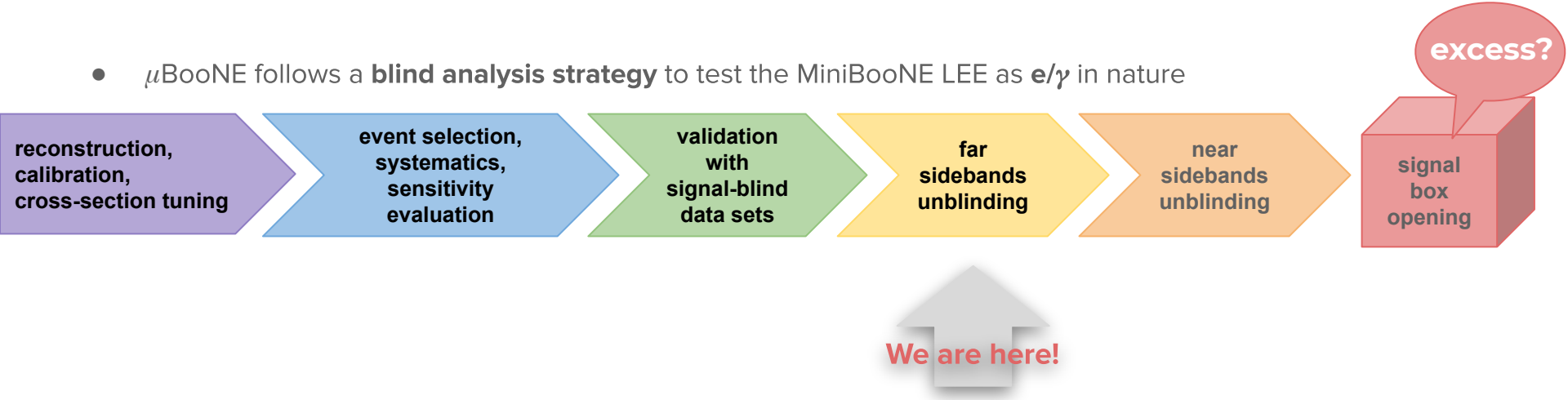
μBooNE LEE Searches: On the Cusp of Unblinding!

- μBooNE follows a **blind analysis strategy** to test the MiniBooNE LEE as **e/γ** in nature



μBooNE LEE Searches: On the Cusp of Unblinding!

- μBooNE follows a **blind analysis strategy** to test the MiniBooNE LEE as **e/γ** in nature



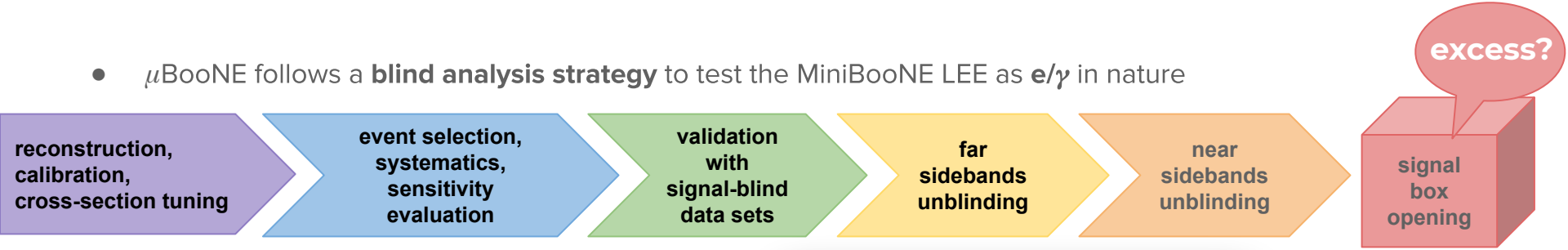
Brand-new, preliminary results shown today span data sets from this period (6.9x10^{20} POT)

Run 1, 1.7x10^{20} POT	Run 2, 2.7x10^{20} POT	Run 3, 2.6x10^{20} POT	Run 4, 3.2x10^{20} POT	Run 5, 2.2x10^{20} POT

Over its 5-year run, μBooNE has collected data corresponding to 12.25x10^{20} POT (past quality cuts)

μBooNE LEE Searches: On the Cusp of Unblinding!

- μBooNE follows a **blind analysis strategy** to test the MiniBooNE LEE as **e/γ** in nature



- **Unbiased distributions with "5%" of full data set**
- **"Signal-blind" distributions with Run 1-3 data set**

Brand-new, preliminary results shown today span data sets from this period (6.9x10^{20} POT)

- **Sensitivity projections for Run 1-5 data set**

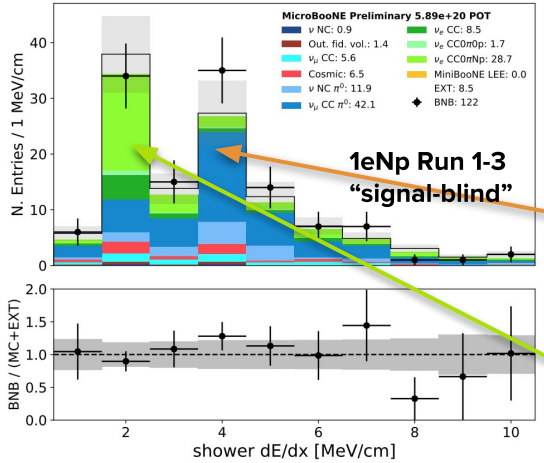
Run 1, 1.7x10^{20} POT	Run 2, 2.7x10^{20} POT	Run 3, 2.6x10^{20} POT	Run 4, 3.2x10^{20} POT	Run 5, 2.2x10^{20} POT

Over its 5-year run, μBooNE has collected data corresponding to 12.25x10^{20} POT (past quality cuts)

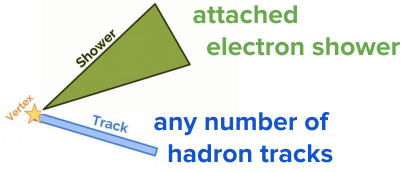
Testing e vs. γ LEE Hypotheses in μBooNE

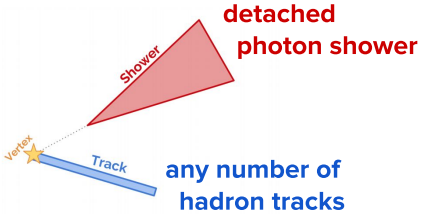
μBooNE uses the excellent properties and resolution of its LArTPC to select both **eLEE** and **γLEE** signals with high purity

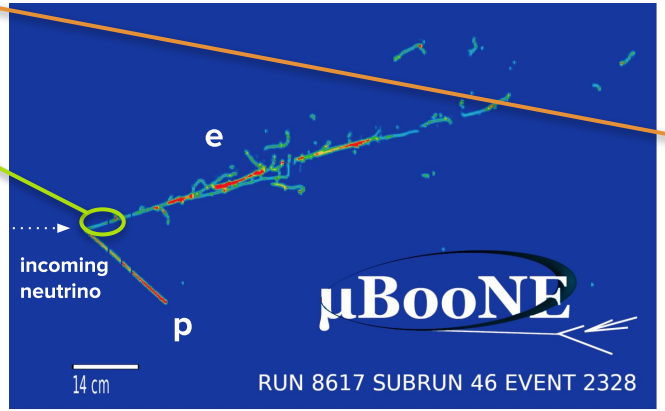
...using ionization dE/dx

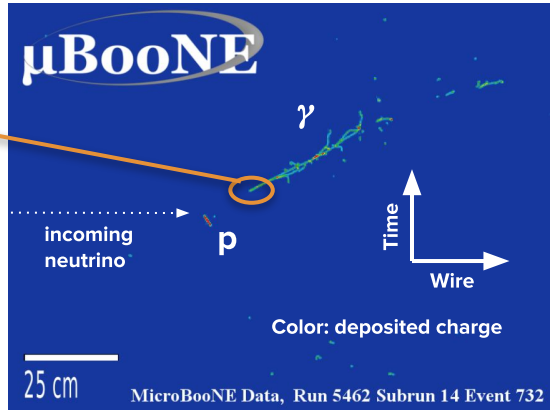


...and topology information









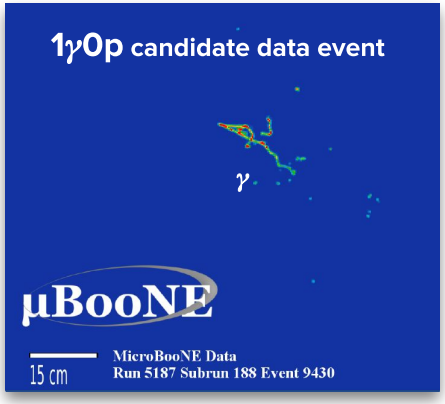
μBooNE's γLEE Search

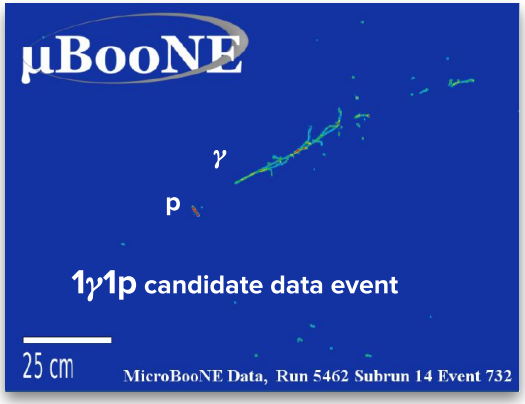
μBooNE's γLEE Search

[MICROBOONE-NOTE-1087-PUB]

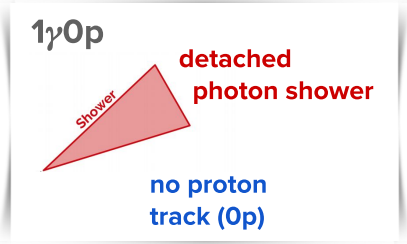
Targets **1γ0p** and **1γ1p** topologies consistent with **NC $\Delta \rightarrow N\gamma$**

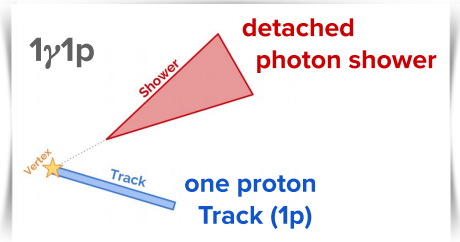
Pandora [Eur. Phys. J. C78, 1, 82 (2018)] **reconstruction, and tailored BDT-based selection**



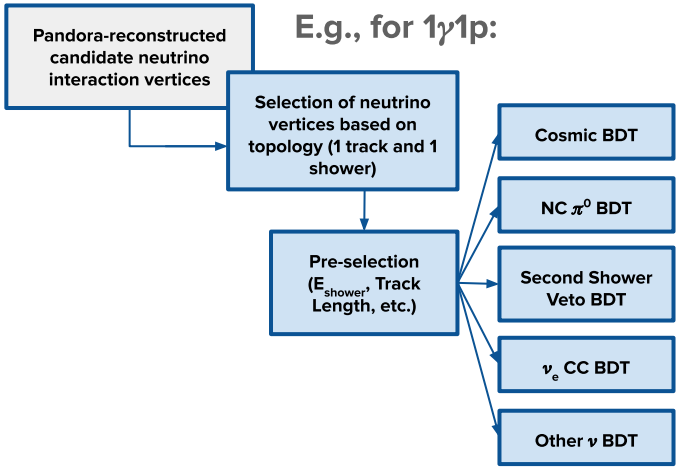


[K. Sutton Poster #121, K. Lin Poster #91]





E.g., for 1γ1p:

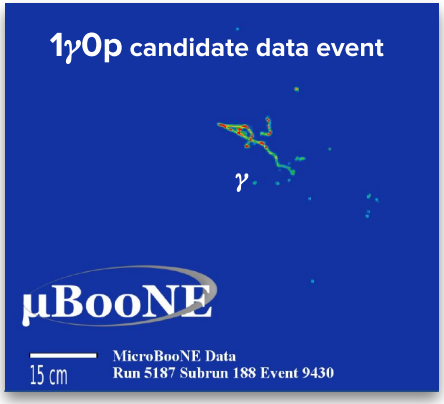


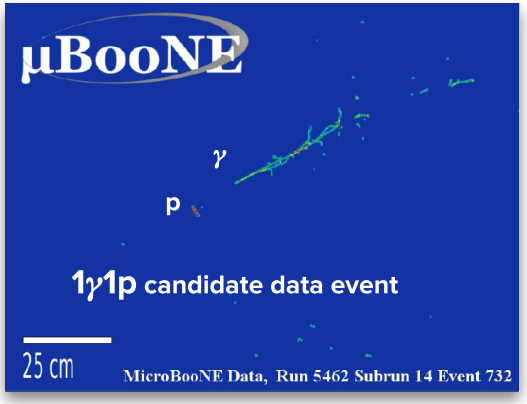
μBooNE's γLEE Search

[MICROBOONE-NOTE-1087-PUB]

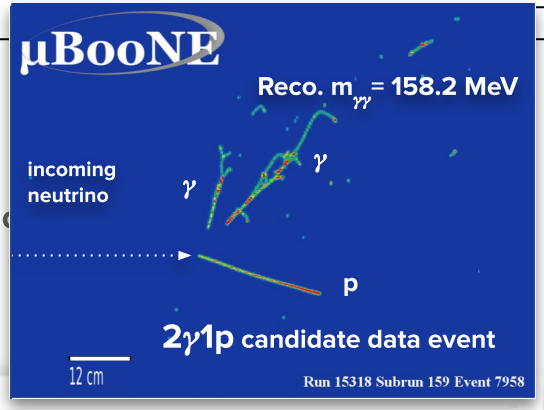
Targets **1γ0p** and **1γ1p** topologies consistent with **NC $\Delta \rightarrow N\gamma$**

Pandora [Eur. Phys. J. C78, 1, 82 (2018)] **reconstruction, and tailored BDT-based selecti**



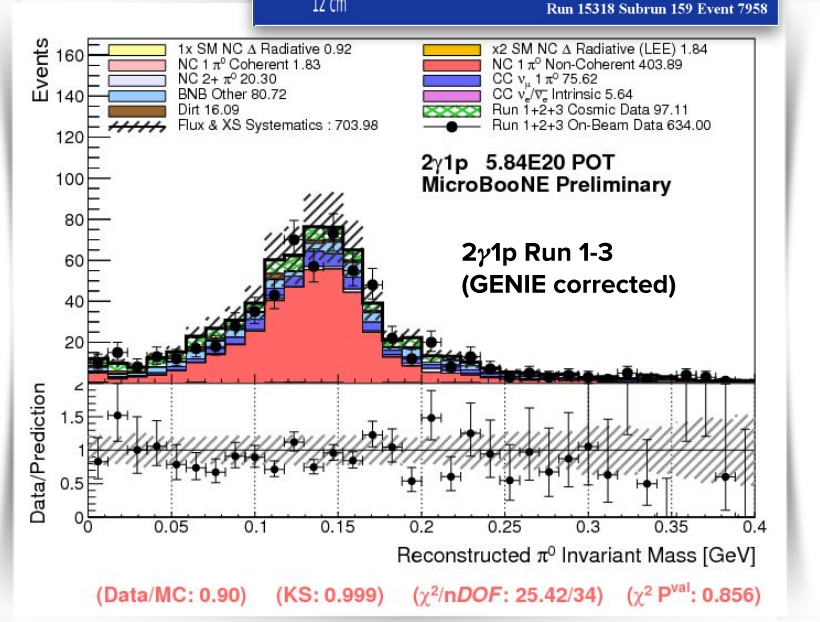


[K. Sutton Poster #121, K. Lin Poster #91]



Complementary **2γ0p** and **2γ1p** selections provide a pure sample of **NC π^0** events (main background to 1γ selection) → correction to the GENIE-predicted coherent and non-coherent NC 1π^0 production rate normalizations

[A. Mogan Poster #122]

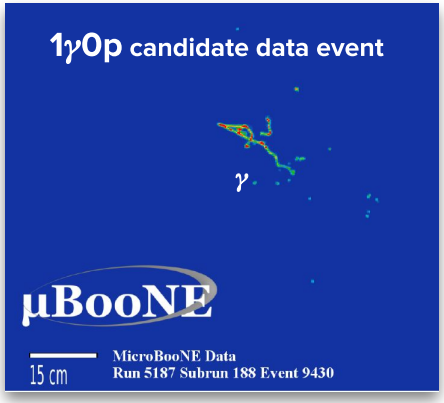


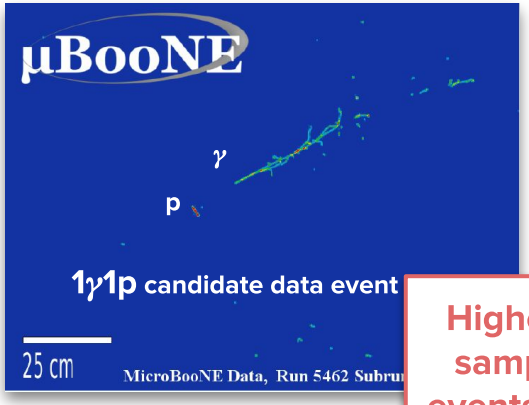
μBooNE's γLEE Search

[MICROBOONE-NOTE-1087-PUB]

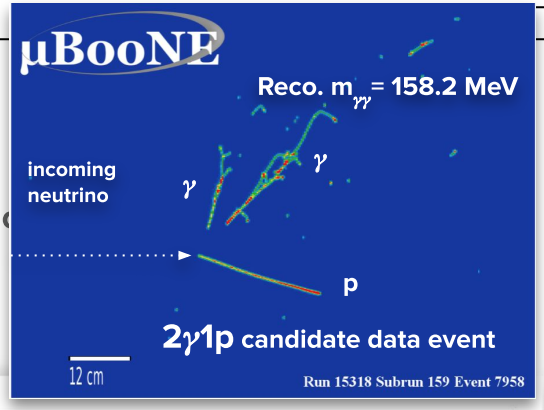
Targets **1γ0p** and **1γ1p** topologies consistent with **NC $\Delta \rightarrow N\gamma$**

Pandora [Eur. Phys. J. C78, 1, 82 (2018)] **reconstruction, and tailored BDT-based selecti**





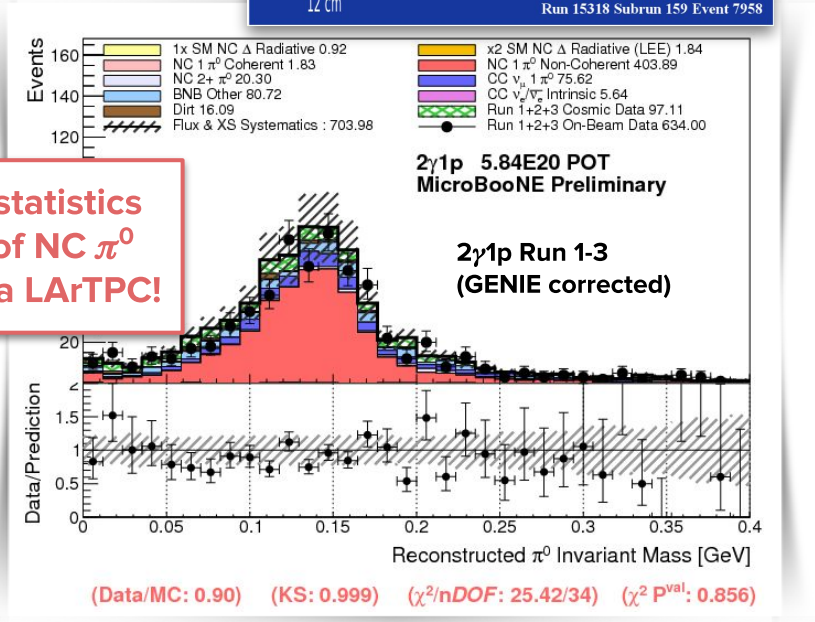
[K. Sutton Poster #121, K. Lin Poster #91]



Highest-statistics sample of NC π^0 events in a LArTPC!

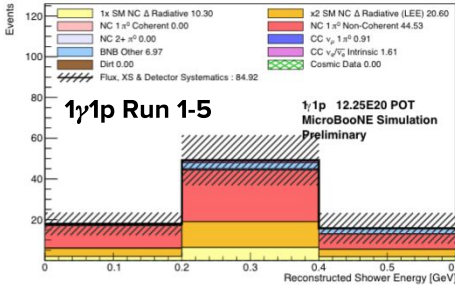
Complementary **2γ0p** and **2γ1p** selections provide a pure sample of **NC π^0** events (main background to 1γ selection) → correction to the GENIE-predicted coherent and non-coherent NC 1π^0 production rate normalizations

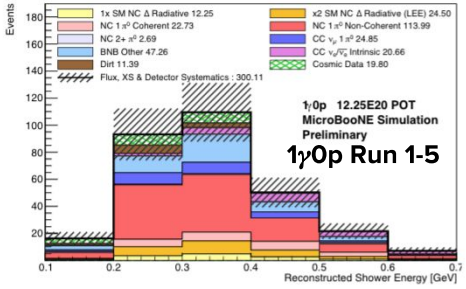
[A. Mogan Poster #122]

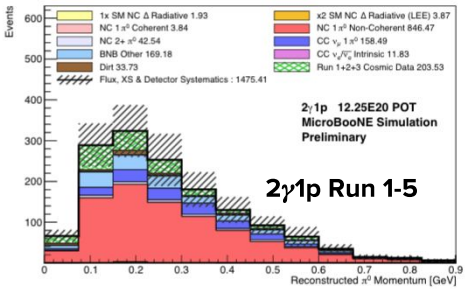


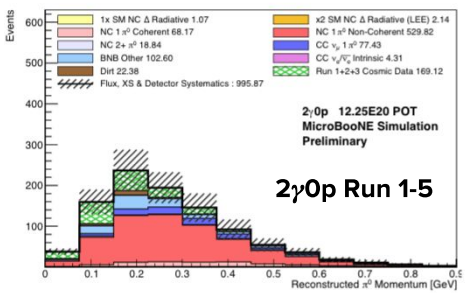
μBooNE's γLEE Search

[MICROBOONE-NOTE-1087-PUB]





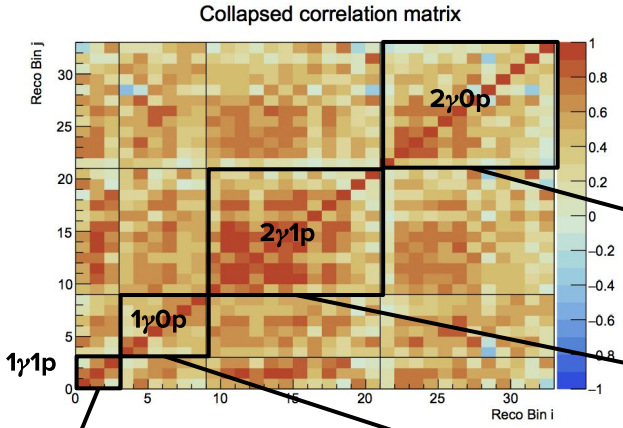




μBooNE's γLEE Search

[MICROBOONE-NOTE-1087-PUB]

Side-by-side fit to 1γ and 2γ selections indirectly constrains NC π^0 background

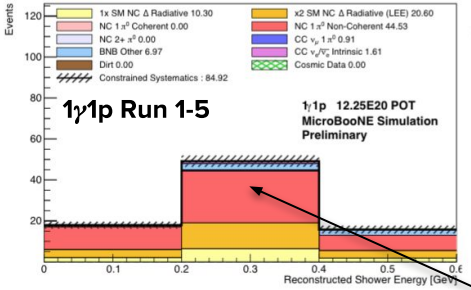


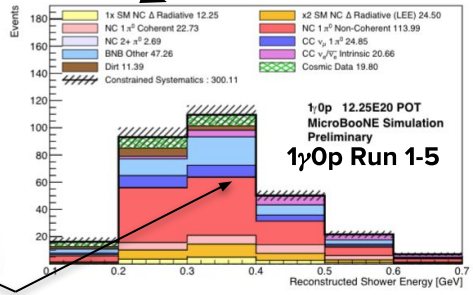
Covariance matrix captures detector and (highly correlated) flux and cross-section systematic uncertainties

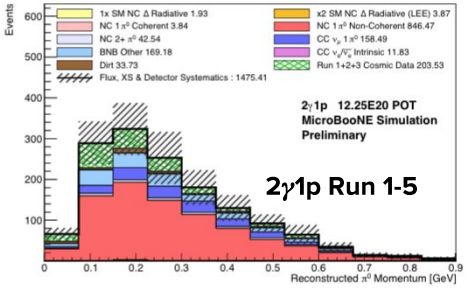
Effectively x2 reduction in $1\gamma1p$ and $1\gamma0p$ systematic uncertainties!

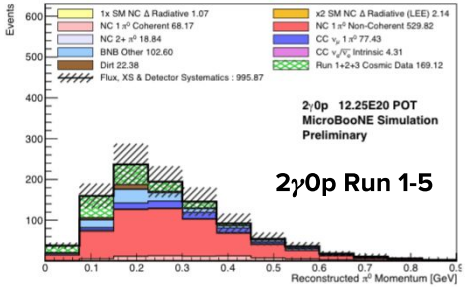
Selection Topology	Total Uncertainty	After Constraint
$1\gamma1p$	35.4%	17.1%
$1\gamma0p$	19.1%	10.8%
$2\gamma1p$	21.2%	-
$2\gamma0p$	18.0%	-

[G. Yarborough Poster #407, W. Tang Poster #388]







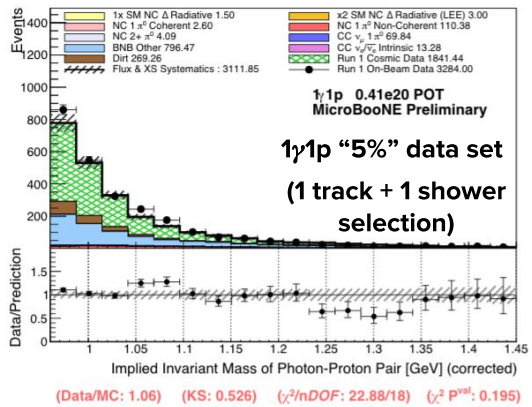


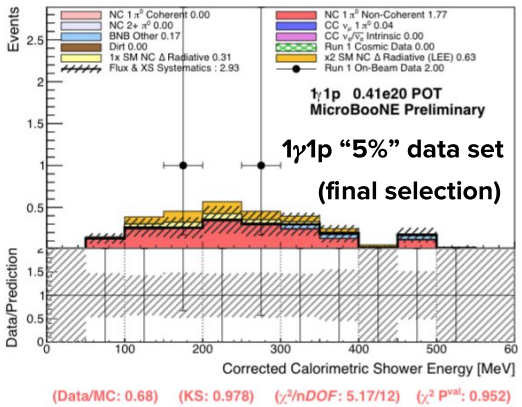
Effective systematic uncertainty reduction before/after constraint!

μBooNE's γLEE Search: Status and Projections

[MICROBOONE-NOTE-1087-PUB]

Analysis is **frozen;** 1γ selections have been **validated with "5%" data sets**, and analysis of **Run 1-3 sidebands is ongoing**. Stay tuned!





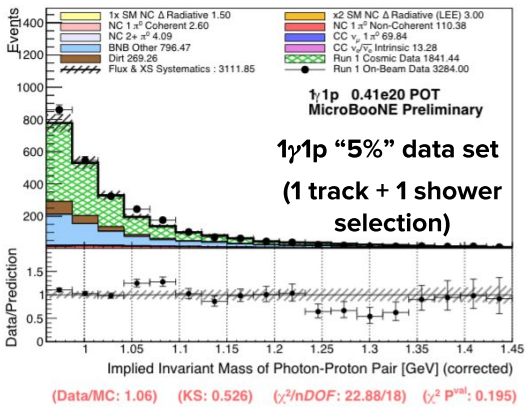
1:1000 (1 shower + 1 track selection) → 1:5 (final selection) signal-to-background improvement!

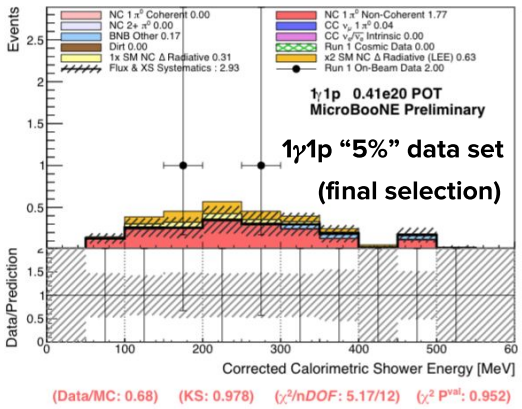
[K. Sutton Poster #121]

μBooNE's γLEE Search: Status and Projections

[MICROBOONE-NOTE-1087-PUB]

Analysis is **frozen;** 1γ selections have been **validated with "5%" data sets**, and analysis of **Run 1-3 sidebands is ongoing**. Stay tuned!

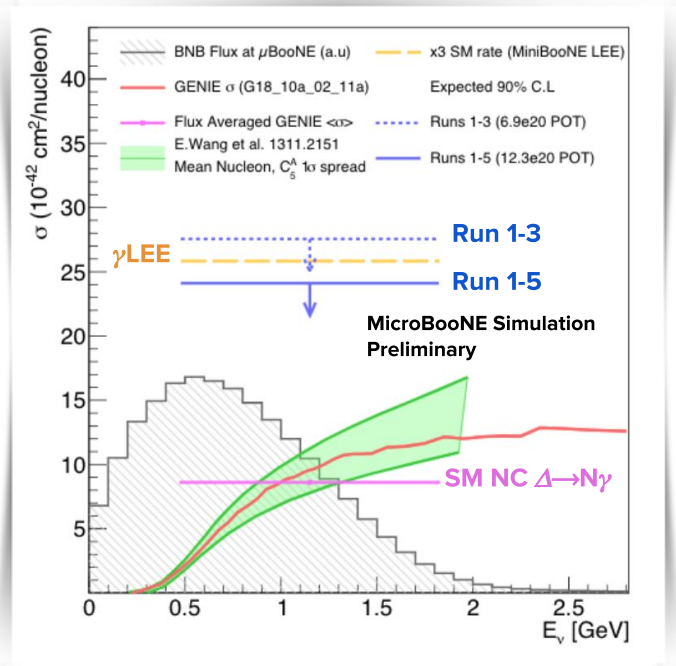




[K. Sutton Poster #121]

Projected sensitivity to NC $\Delta \rightarrow N\gamma$:

- **30x more sensitive** measurement of the SM NC $\Delta \rightarrow N\gamma$ rate than current T2K limit [J. Phys. G: Nucl. Part. Phys. 46 08LT01]
- Would be able to **exclude the γLEE** interpretation in favor of the Standard Model **at > 95% C.L.**



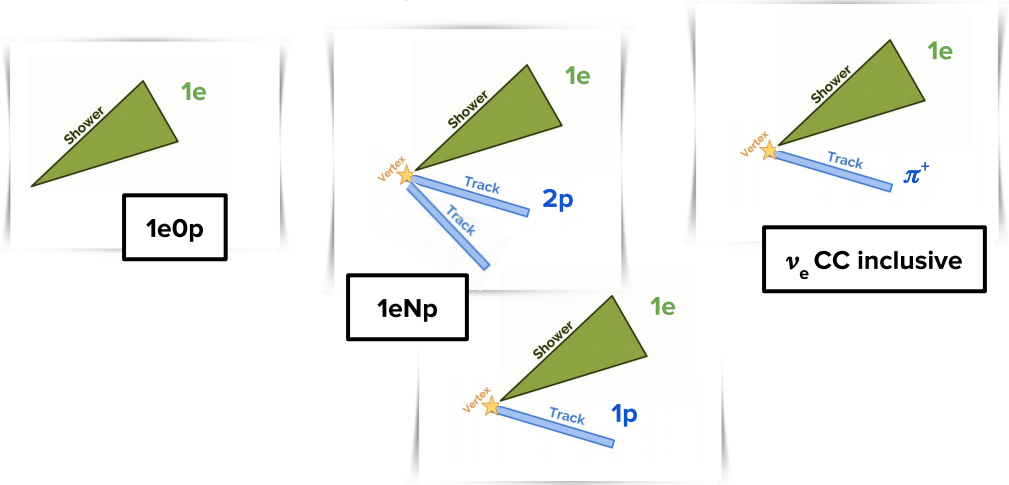
Three (3) μBooNE eLEE Analyses

Three independent, complementary analyses are underway, targeting different topologies (**1e** and **0p, Np, or CC inclusive**) and using different end-to-end reconstruction, particle identification, and selection methods:

(1) Pandora Based

(2) Deep Learning Based

(3) Wire Cell + Pandora Based (Hybrid)



Strategy shared among all eLEE analyses:

- ✓ **Reduction of cosmogenic background**
- ✓ **Reduction of π^0 background** and **validation** through NC/CC π^0 sidebands
- ✓ **Constraint of intrinsic ν_e CC background** through ν_μ CC sidebands

$$\pi^+ \rightarrow \mu^+ + \boxed{\nu_\mu}$$

$$e^+ + \bar{\nu}_\mu + \boxed{\nu_e}$$

primary ν_μ flux

ν_e background

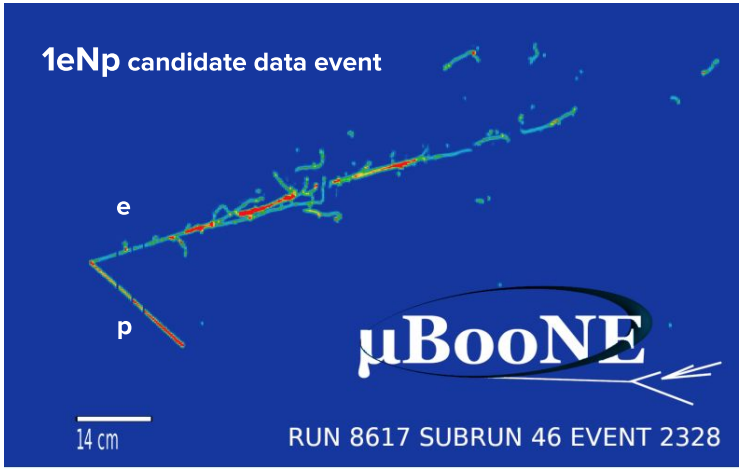
(1) Pandora Based eLEE Search

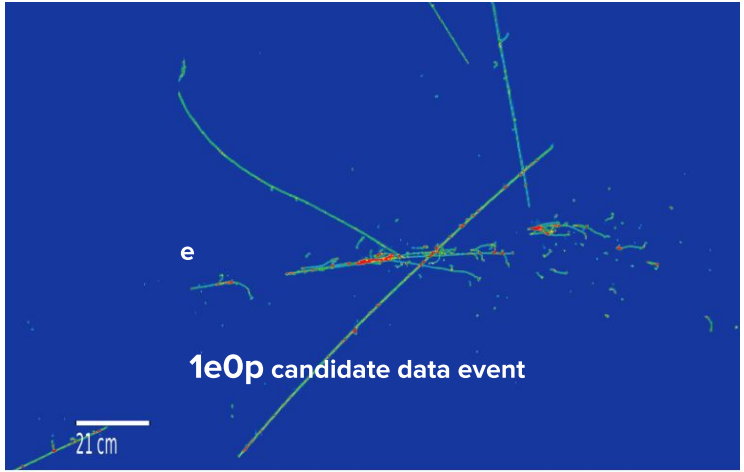
Pandora reconstruction with **additional and improved topology- and calorimetry-based** PID tools, for kinematics-agnostic selection.

[MICROBOONE-NOTE-1085-PUB]

Multi-channel selection targets:

1e0p and 1eNp LEE topologies to search for an excess of ν_e CC events at low energy





[N. Foppiani Poster #126]

[I. Caro Poster #112]

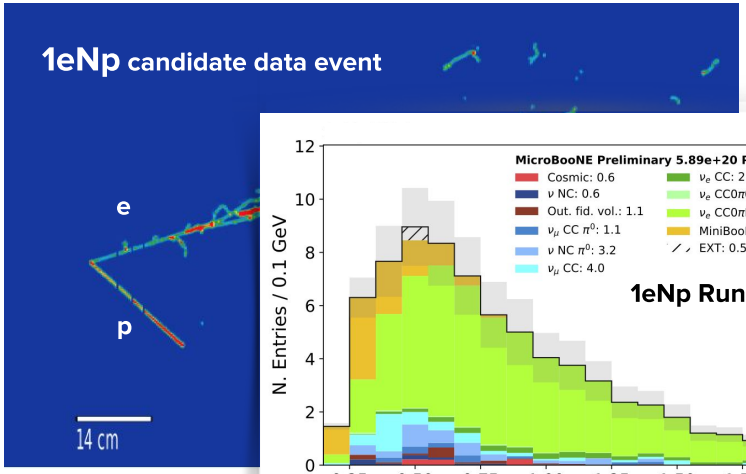
(1) Pandora Based eLEE Search

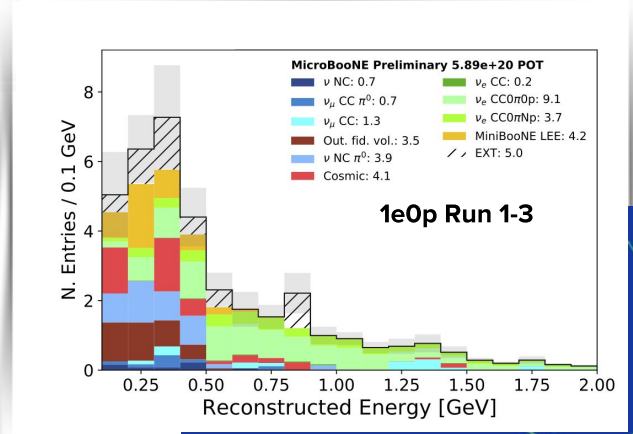
Pandora reconstruction with **additional and improved topology- and calorimetry-based** PID tools, for kinematics-agnostic selection.

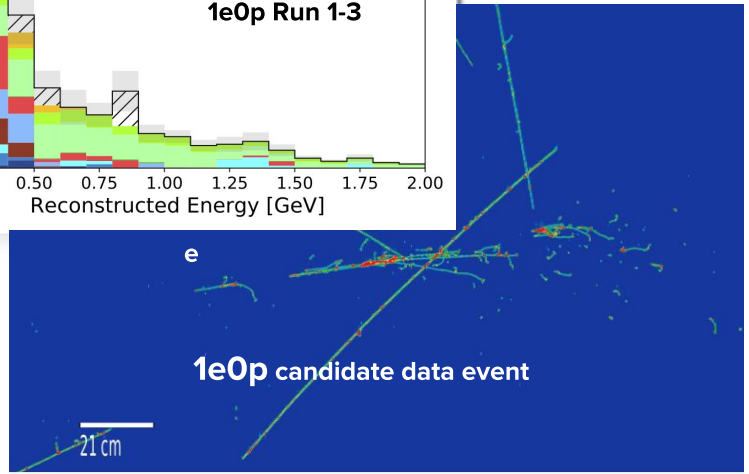
[MICROBOONE-NOTE-1085-PUB]

Multi-channel selection targets:

1e0p and 1eNp LEE topologies to search for an excess of ν_e CC events at low energy







Very pure ν_e CC selection achieved, down to low energy!
Note: very little NC/CC π^0 background

[N. Foppiani Poster #126]

[I. Caro Poster #112]

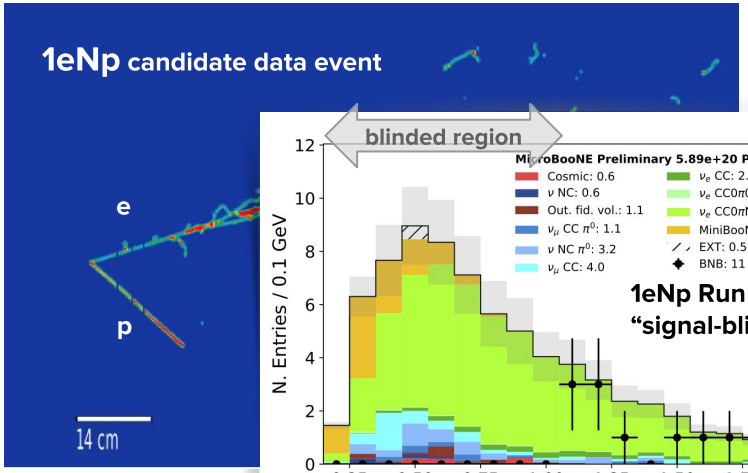
(1) Pandora Based eLEE Search

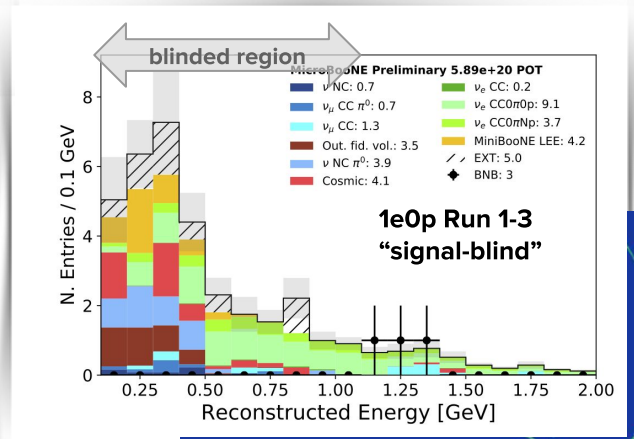
Pandora reconstruction with **additional and improved topology- and calorimetry-based** PID tools, for kinematics-agnostic selection.

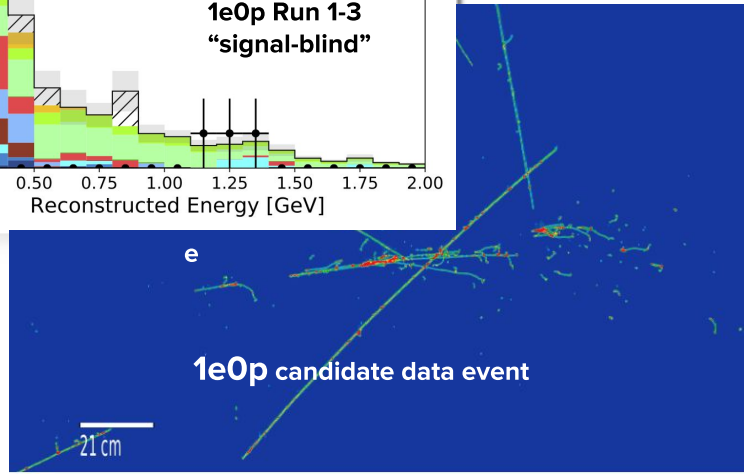
[MICROBOONE-NOTE-1085-PUB]

Multi-channel selection targets:

1e0p and 1eNp LEE topologies to search for an excess of ν_e CC events at low energy







Open Run 1-3 high-energy sidebands show reasonable data to Monte Carlo agreement!

[N. Foppiani Poster #126]

[I. Caro Poster #112]

(1) Pandora Based eLEE Search

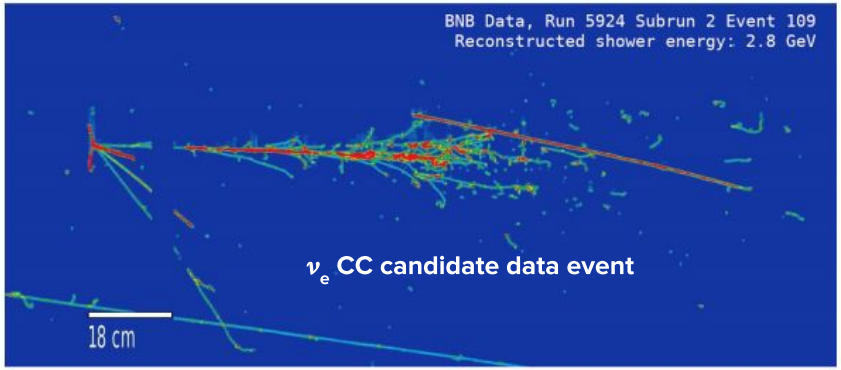
Pandora reconstruction with **additional and improved topology- and calorimetry-based** PID tools, for kinematics-agnostic selection.

[MICROBOONE-NOTE-1085-PUB]

Multi-channel selection targets:

1e0p and 1eNp LEE topologies to search for an excess of ν_e CC events at low energy

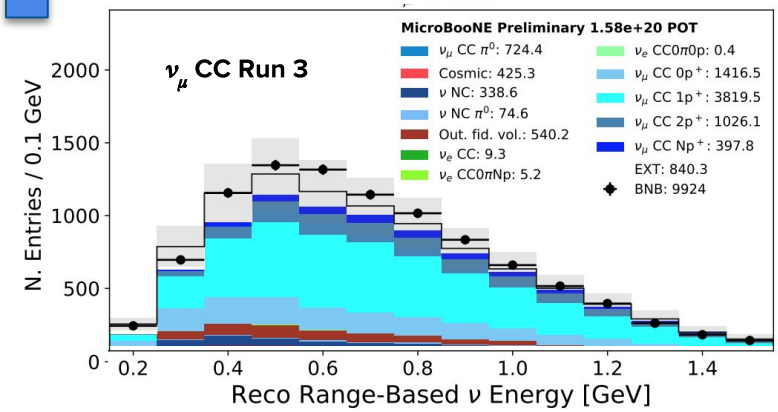
ν_e **CC inclusive sideband** for probing ν_e across a wider range of energy



[W. Van de Pontseele Poster #116]

ν_μ **CC inclusive sideband** for validating flux and cross-section modeling and constraining ν_e CC backgrounds

[S. Berkman Poster #410]



(1) Pandora eLEE Search: Status and Projections

[MICROBOONE-NOTE-1085-PUB]

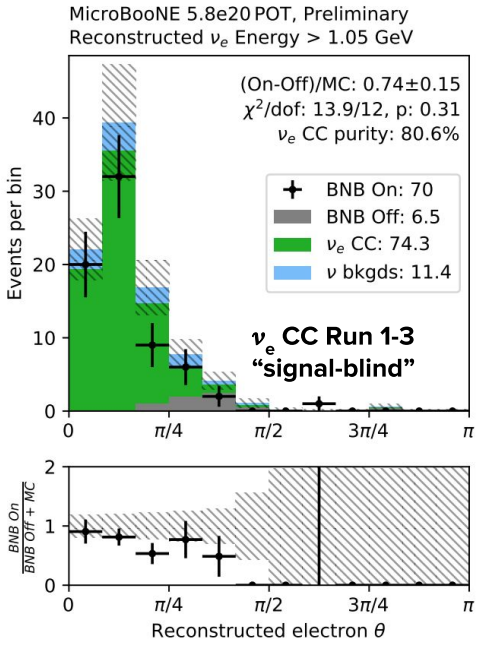
Sideband studies ongoing to validate analysis before proceeding to box opening. Stay tuned!

ν_μ **CC** shows data-MC agreement in multiple kinematic distributions

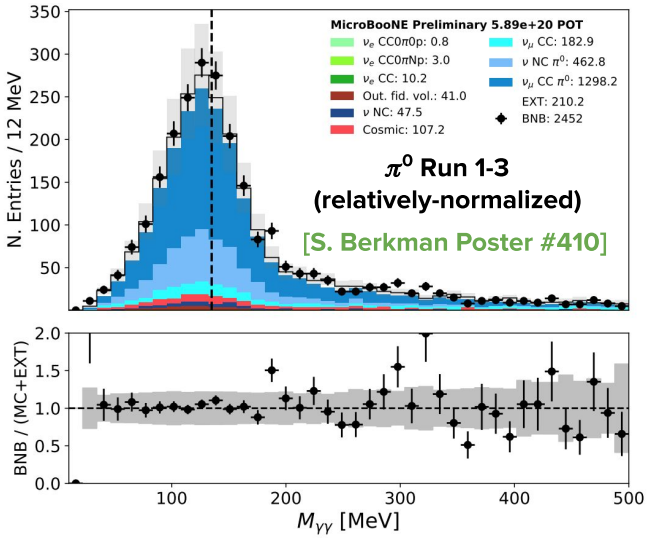
[S. Berkman Poster #410]

Signal-blind 1e0p and 1eNp (high-energy) regions and ν_e **CC** show data-MC agreement in kinematic and calorimetric distributions (see also slide 11)

[W. Van de Pontseele Poster #116]



Shower reconstruction and calorimetry validated with dedicated π^0 **selection**

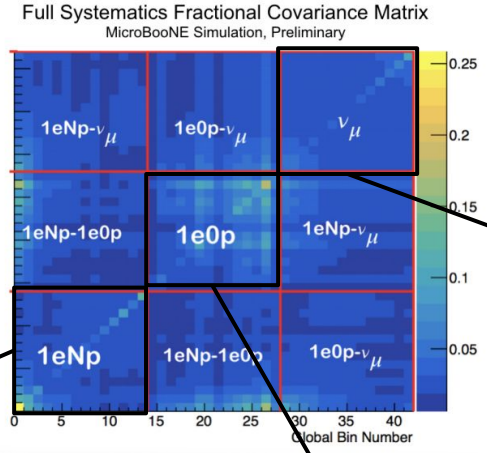


[S. Berkman Poster #410]

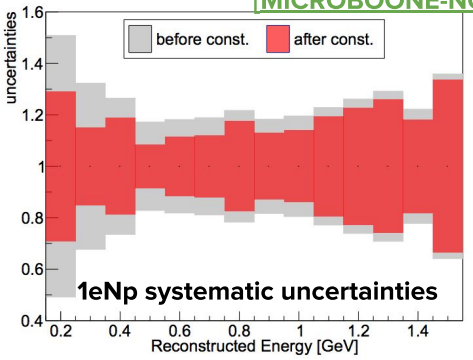
(1) Pandora eLEE Search: Status and Projections

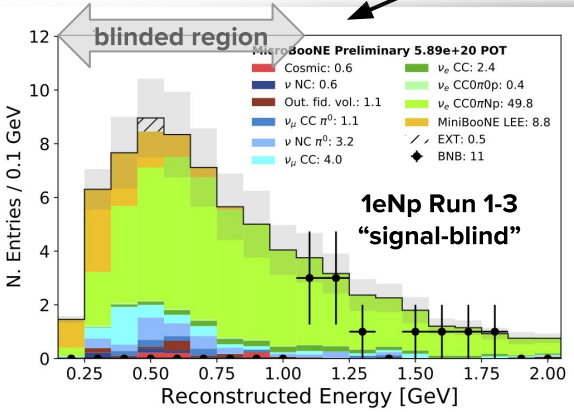
A side-by-side fit to 1eNp, 1e0p and ν_μ CC selections indirectly constrains 1eNp and 1e0p background predictions

[M. Wospakrik Poster #204]

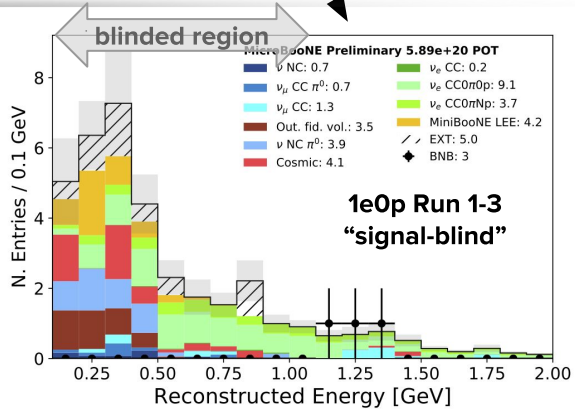


[MICROBOONE-NOTE-1085-PUB]

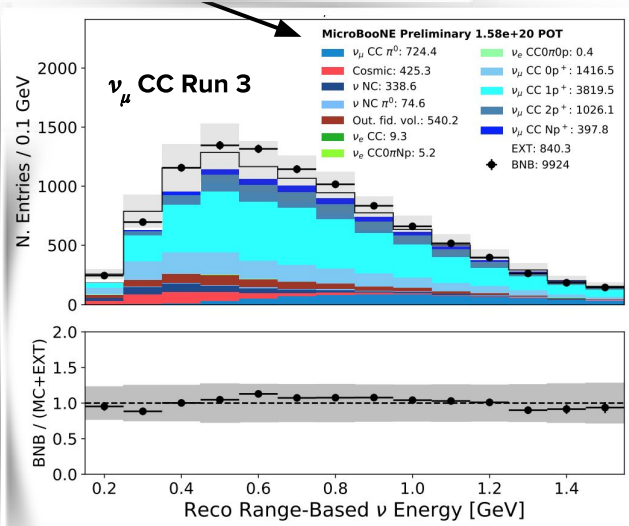




[N. Foppiani Poster #126]



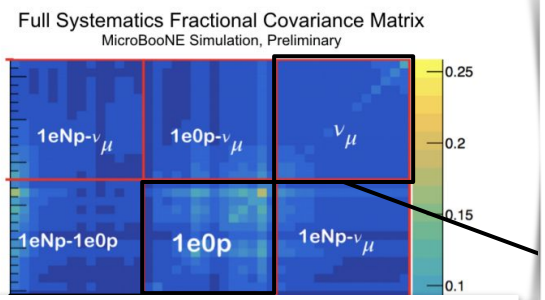
[I. Caro Poster #112]



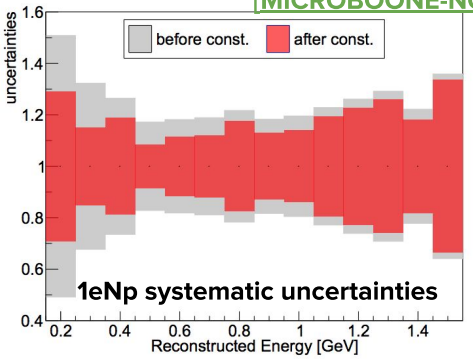
(1) Pandora eLEE Search: Status and Projections

A side-by-side fit to 1eNp, 1e0p and ν_μ CC selections indirectly constrains 1eNp and 1e0p background predictions

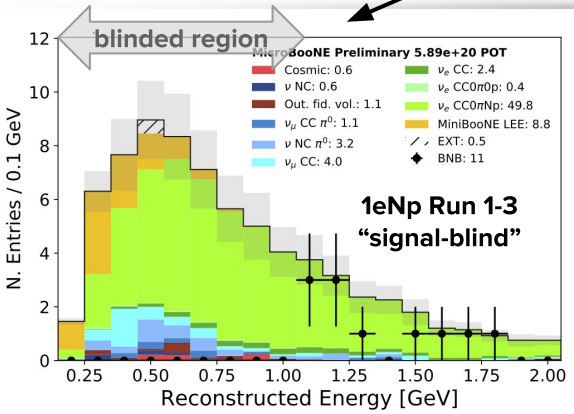
[M. Wospakrik Poster #204]



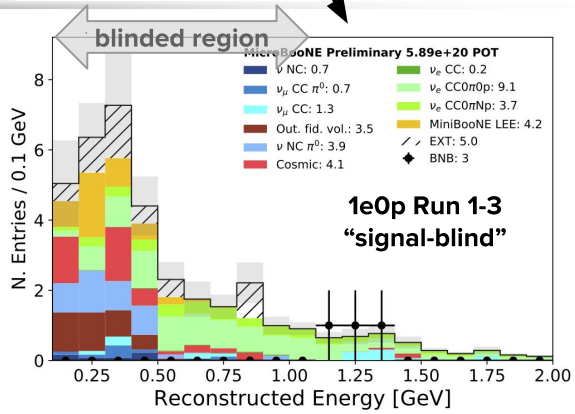
[MICROBOONE-NOTE-1085-PUB]



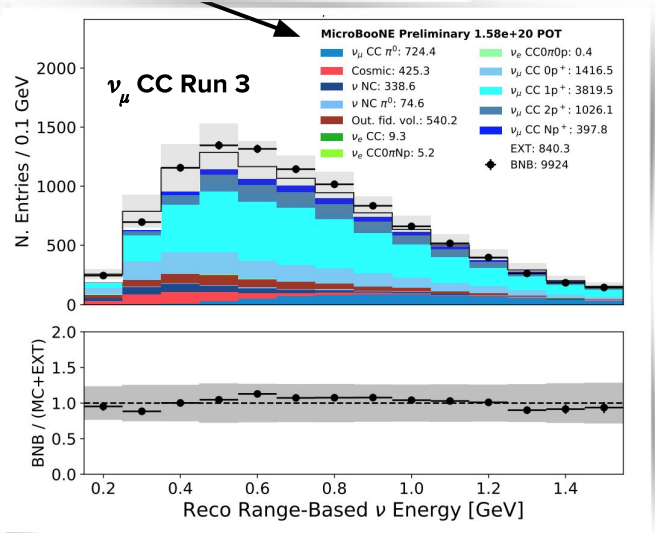
Projected sensitivity:
Would be able to exclude the SM hypothesis in favor of eLEE at 3.0σ with Run 1-5



[N. Foppiani Poster #126]

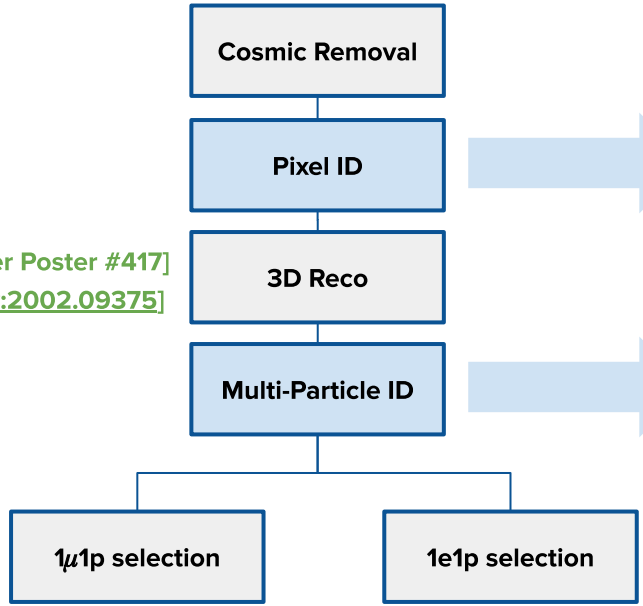


[I. Caro Poster #112]



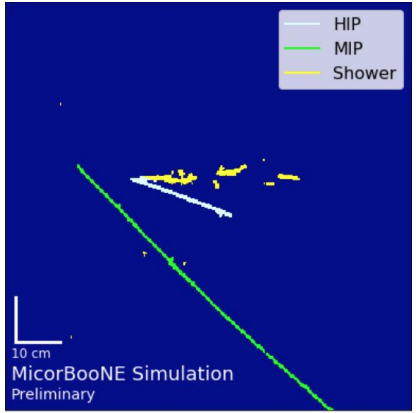
(2) Deep Learning Based eLEE Search

[MICROBOONE-NOTE-1086-PUB]



[A Hourlier Poster #417]
[arXiv:2002.09375]

End-to-end reconstruction and selection using image analysis techniques

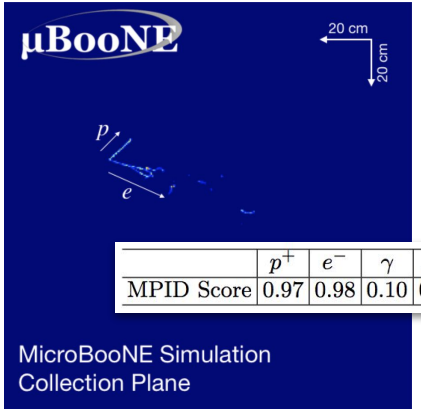


Pixel-level identification as highly ionizing track (HIP), minimum ionizing track (MIP) or shower, using **semantic segmentation**

[R. Itay Poster #282]
[MICROBOONE-NOTE-1091-PUB]

Multi-particle identification in a single image using a **convolutional neural network**

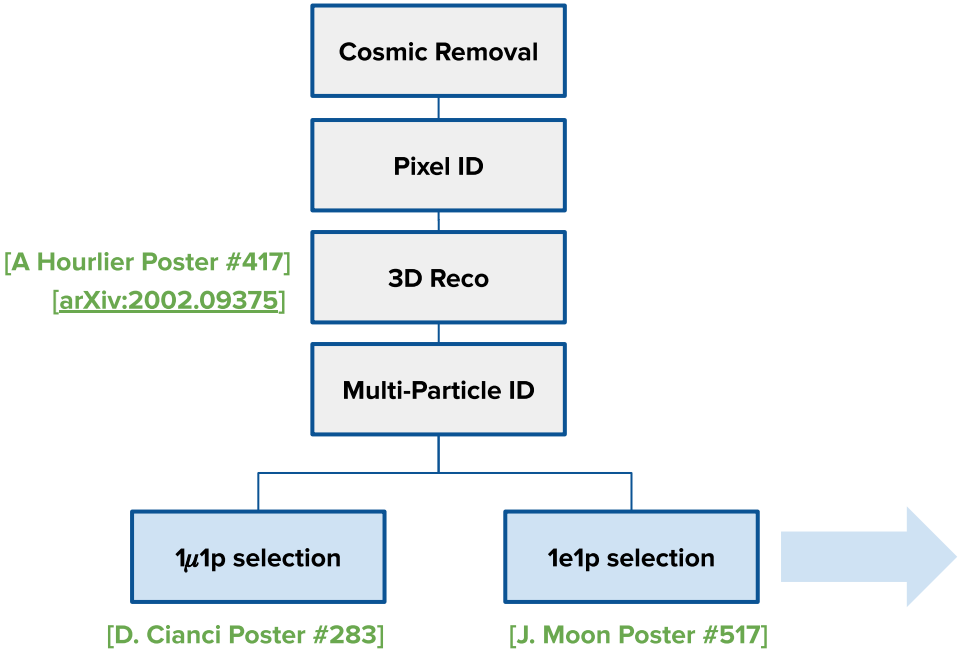
[R. An Poster #187]
[MICROBOONE-NOTE-1080-PUB]



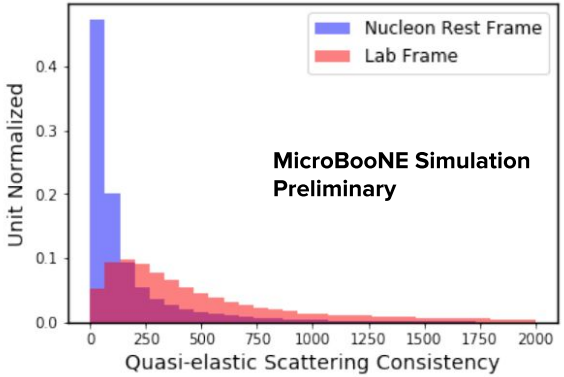
	p^+	e^-	γ	μ^-	$\pi^\pm$
MPID Score	0.97	0.98	0.10	0.02	0.03

(2) Deep Learning Based eLEE Search

[MICROBOONE-NOTE-1086-PUB]



Exclusively targets CCQE-like interactions, utilizing CCQE-consistent kinematics in the neutron rest frame to select pure and highly correlated 1e1p and 1μ1p samples; significantly reduces effects of Fermi motion



$$\sqrt{(E_\nu^{QE-p} - E_\nu^{QE-\ell})^2 + (E_\nu^{QE-p} - E_\nu^{range})^2 + (E_\nu^{QE-\ell} - E_\nu^{range})^2}$$

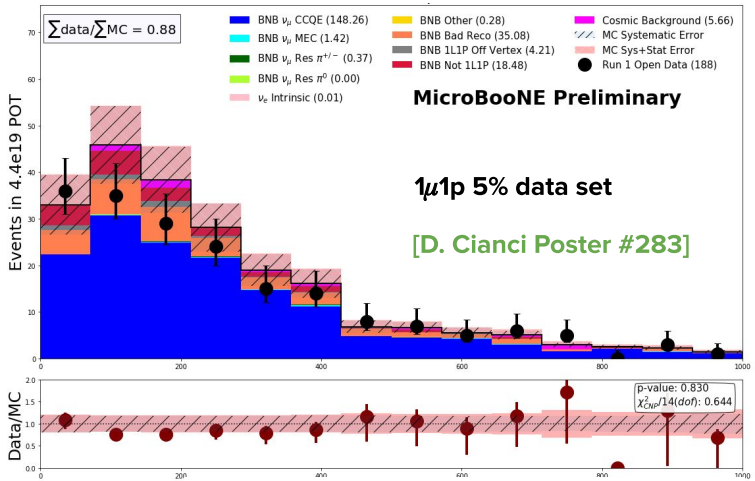
Completely independent from and complementary to other eLEE searches!

(2) Deep Learning eLEE Search: Status and Projections

[MICROBOONE-NOTE-1086-PUB]

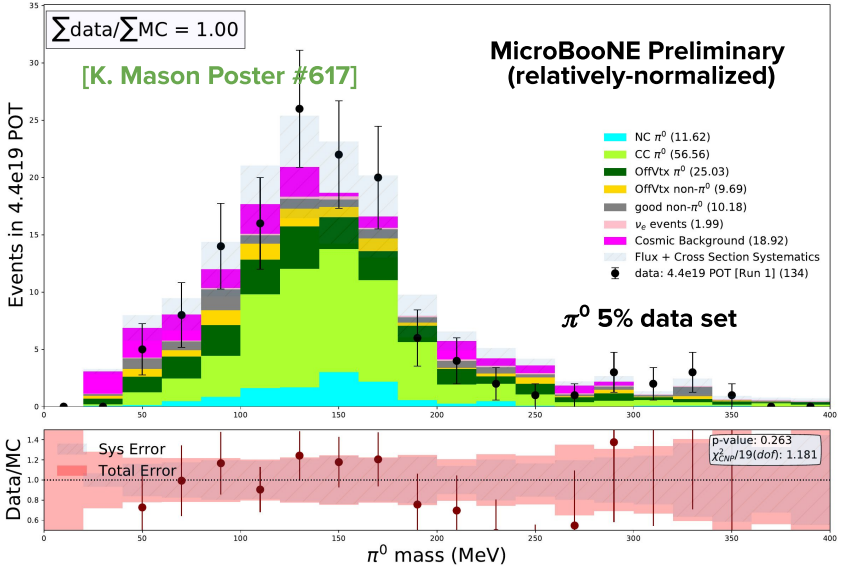
Sideband studies ongoing to validate analysis before proceeding to box opening. Stay tuned!

Excellent data-MC agreement with 1μ1p selection. Important cross-check also for μBooNE- specific GENIE cross-section tuning [MICROBOONE-NOTE-1074-PUB]



Quasi-elastic Scattering Consistency

Shower reconstruction and identification and energy reconstruction are validated with a dedicated π^0 selection [MICROBOONE-NOTE-1090-PUB]

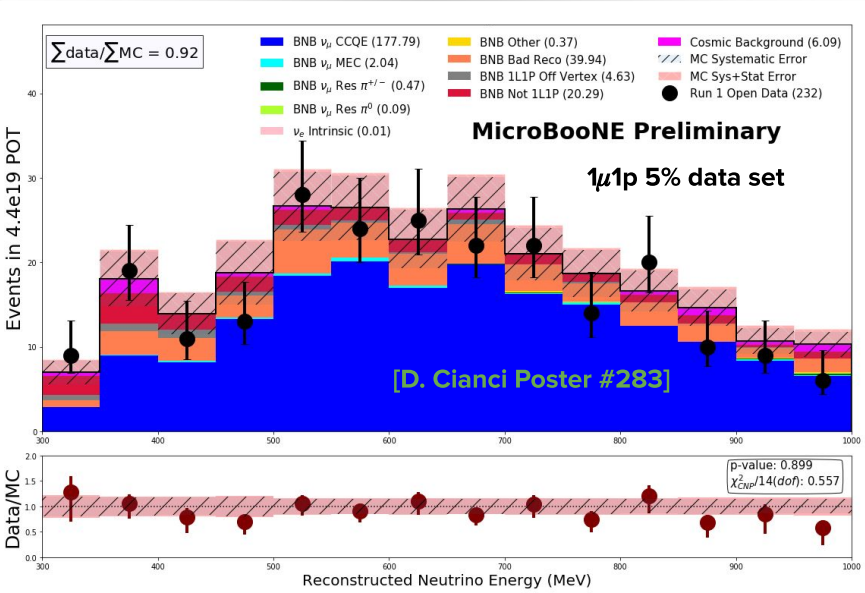


(2) Deep Learning eLEE Search: Status and Projections

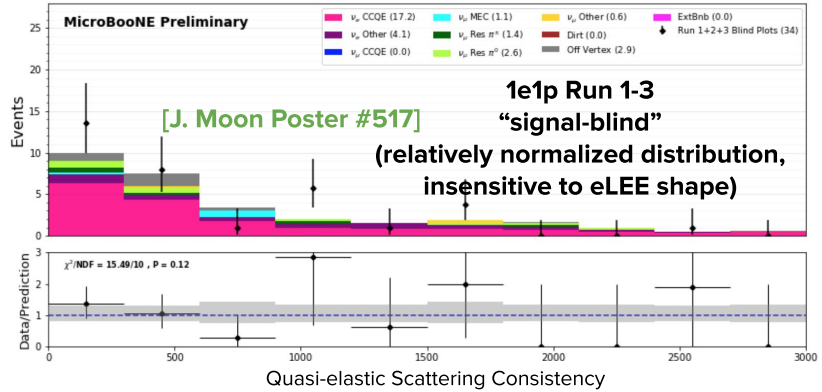
[MICROBOONE-NOTE-1086-PUB]

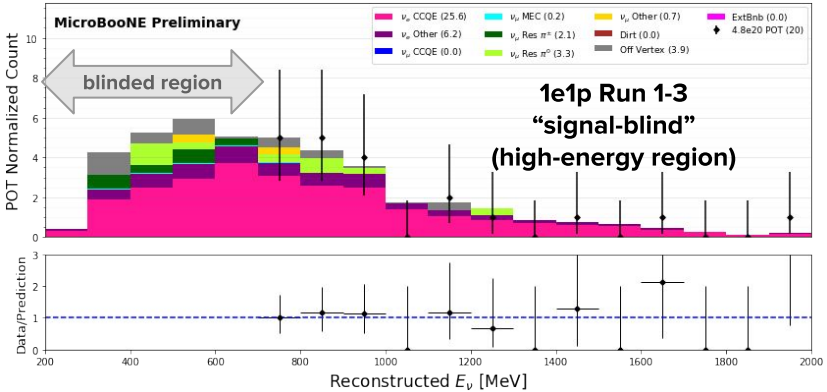
Sideband studies ongoing to validate analysis before proceeding to box opening. Stay tuned!

A simultaneous fit to very pure samples of (flux and cross-section correlated) 1e1p and 1μ1p events is projected to provide a **powerful test of the MiniBooNE eLEE!**



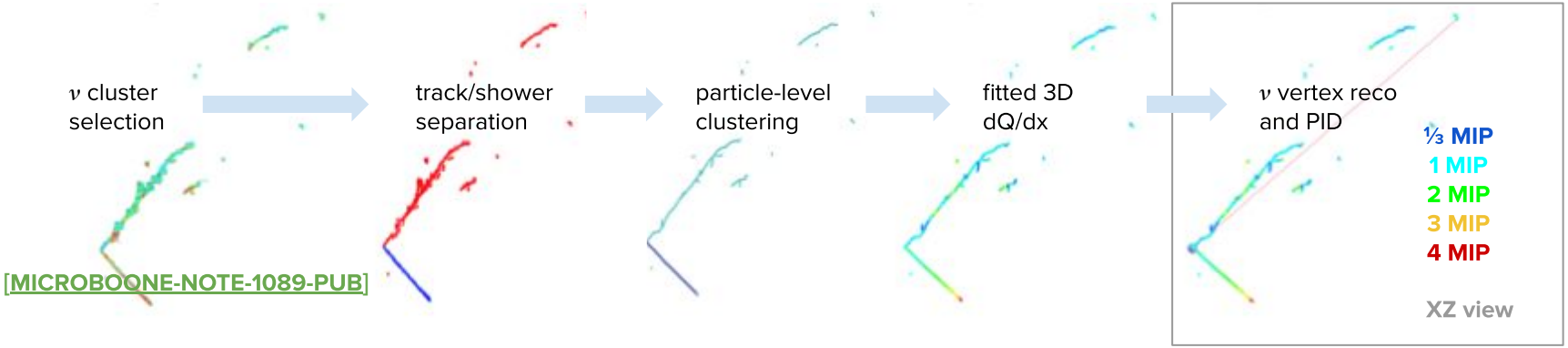
Excellent data-MC agreement for 1e1p with signal-blind data sets (in all of 23 kinematic variables)!





(3) Wire Cell + Pandora Based (Hybrid) eLEE Search

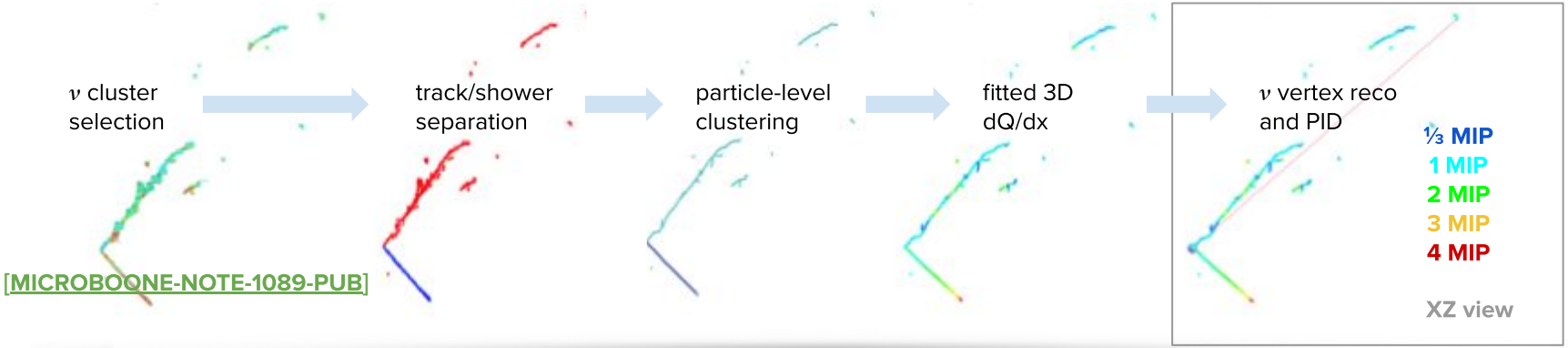
Employs **tomography** techniques to achieve highly efficient cosmic background removal, and assist Pandora-based neutrino interaction reconstruction



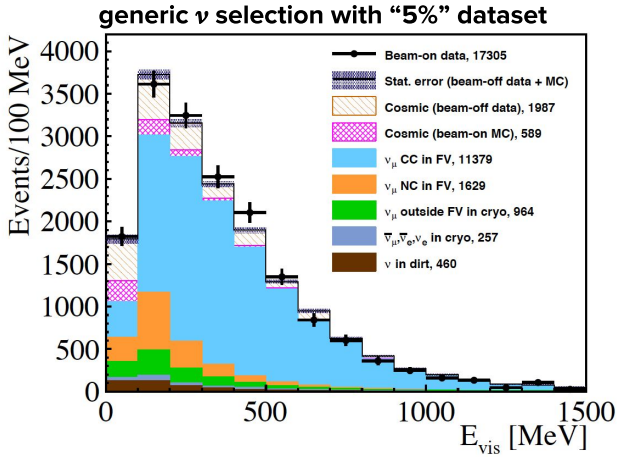
[MICROBOONE-NOTE-1089-PUB]

(3) Promise of Wire Cell Demonstrated with Generic ν Selection

Employs **tomography** techniques to achieve highly efficient cosmic background removal, and assist Pandora-based neutrino interaction reconstruction



[MICROBOONE-NOTE-1089-PUB]



Excellent performance demonstrated for Wire Cell generic neutrino selection, promising for a ν_e CC LEE search!

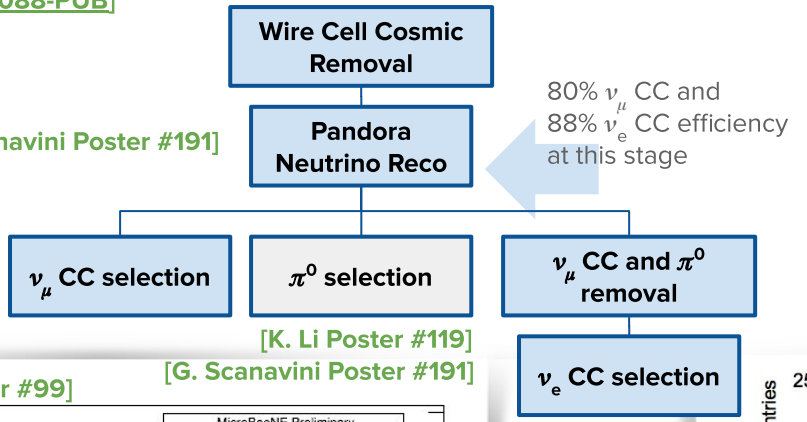
<15% cosmic contamination over all visible energy
x8 improvement relative to [EPJ C 79, 673 (2019)]

[H. Wei Poster #264,
L. Cooper-Troendle Poster #147]

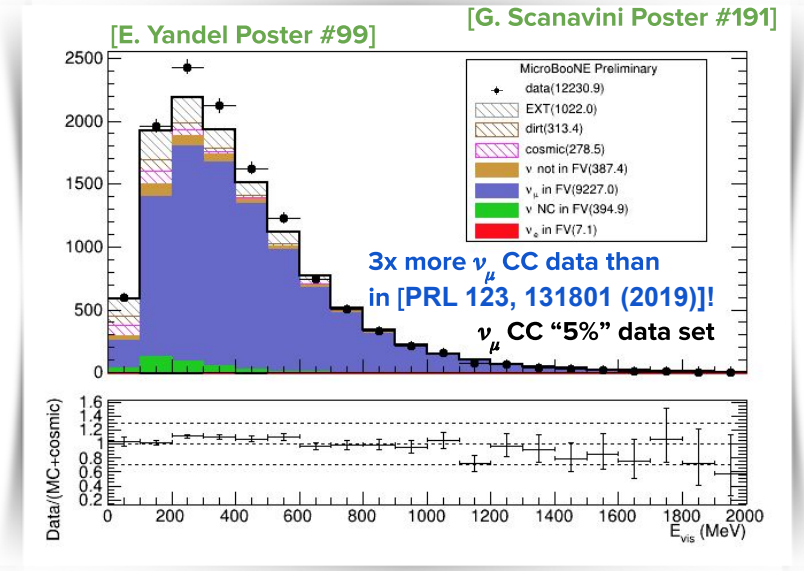
[MICROBOONE-NOTE-1083-PUB,
MICROBOONE-NOTE-1084-PUB]

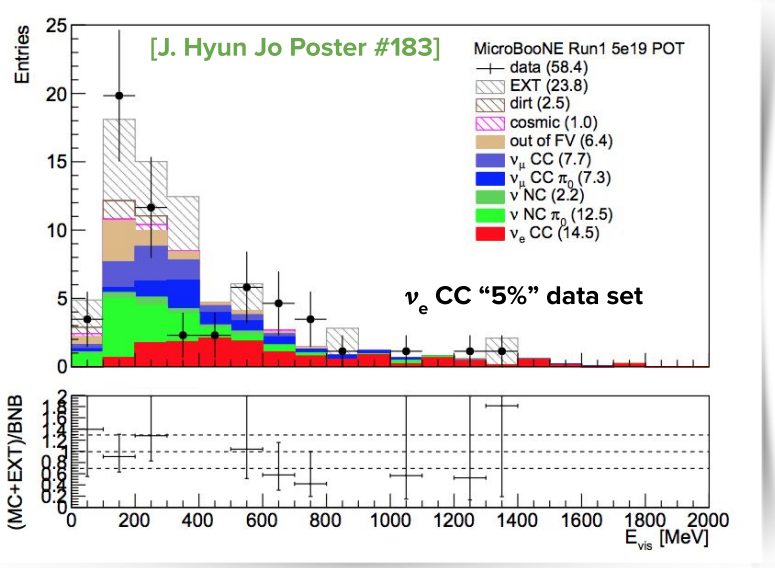
(3) Status of Wire Cell + Pandora Based (Hybrid) eLEE Search

[MICROBOONE-NOTE-1088-PUB]



Ongoing developments for Wire Cell pattern recognition and PID are targeting improved ν_e CC performance... stay tuned!



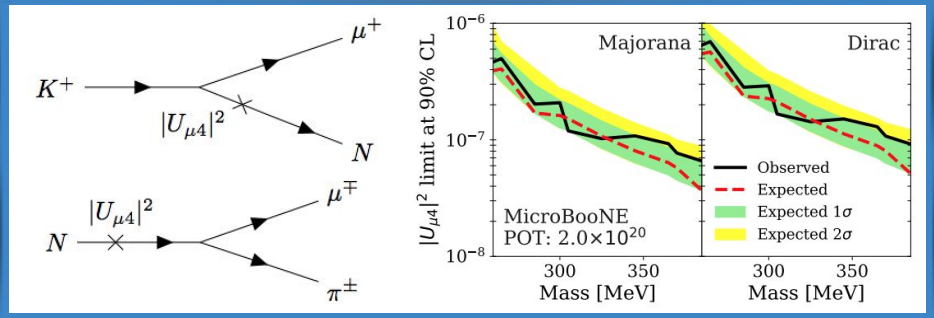


Other Searches: Astro-particle and Exotic Physics

Large-scale, continuous operation of a new detector technology enables **astro-particle and exotic physics** measurements:

- **Heavy neutral lepton search**
  [Phys. Rev. D101, 052001 (2020)]
- **KOTO experimental anomaly**
  [PRL 122, 2, 021802 (2019), KAON2019 Conference]
  follow-up
- **Baryon number-violating neutron-antineutron oscillation search**
- **Search for supernova neutrinos**
  [J. Crespo Poster #141, MICROBOONE-NOTE-1030-PUB]
  and MeV scale physics [A. Bhat Poster #4, MICROBOONE-NOTE-1076-PUB]

First heavy neutral lepton search in a LArTPC!



[Phys. Rev. D101, 052001 (2020)]

Summary

μBooNE is leading the way in mastering the **challenging but powerful LArTPC detector technology** through the development of **novel reconstruction and data analysis techniques**

and paving the way for the future **Short Baseline Neutrino program** [see talk by M. Betancourt] and **Deep Underground Neutrino Experiment** [see talk by M. Mooney].

Exploiting the unique capabilities of LArTPC technology, μBooNE has developed **full, end-to-end analyses** searching for beyond-Standard Model physics with the **highest-statistics of neutrino interactions on argon** ever collected and analyzed!

Multiple independent and complementary low-energy excess analyses, with **high purity selections** at low energy for both electron and single-photon events, are **on the cusp of unblinding!**

- **Word-leading constraint on the SM NC $\Delta \longrightarrow N\gamma$ process**, never directly measured in neutrinos before!
- **Powerful tests of the MiniBooNE excess** as an enhancement of ν_e CC events at low energy!

Backup slides

MicroBooNE Run Periods

Start of MicroBooNE running, October 2015

Software trigger at start of Run 1

Partial CRT during Run 2

Full CRT during Run 3 and onward

Lower e lifetime during Run 4

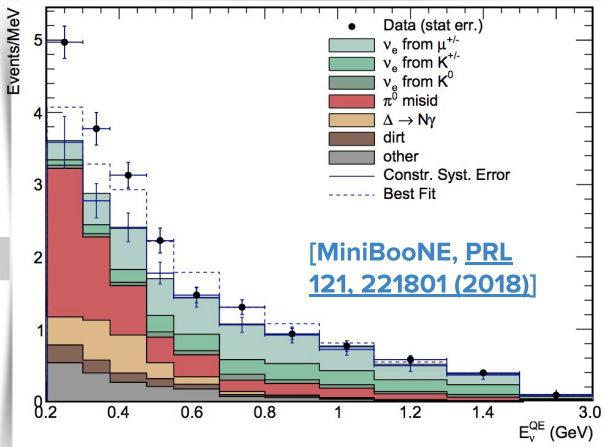
Brand-new, preliminary results shown today span data sets from this period (6.9x10^{20} POT)

Run 1, 1.7x10^{20} POT	Run 2, 2.7x10^{20} POT	Run 3, 2.6x10^{20} POT	Run 4, 3.2x10^{20} POT	Run 5, 2.2x10^{20} POT

Over its 5-year run, μBooNE has collected data corresponding to 12.25x10^{20} POT (past quality cuts)

MiniBooNE LEE unfolding

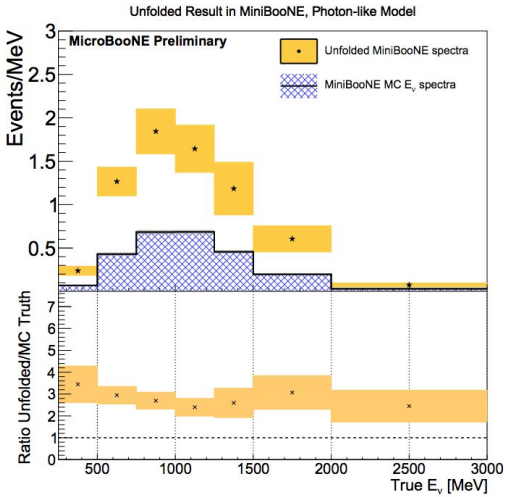
Use the MiniBooNE MC simulations to form a response matrix, and given an underlying signal hypothesis, use **D'Agostini's iterative method** and SVD unfolding to map to true underlying spectra.
[MICROBOONE-NOTE-1043-PUB]

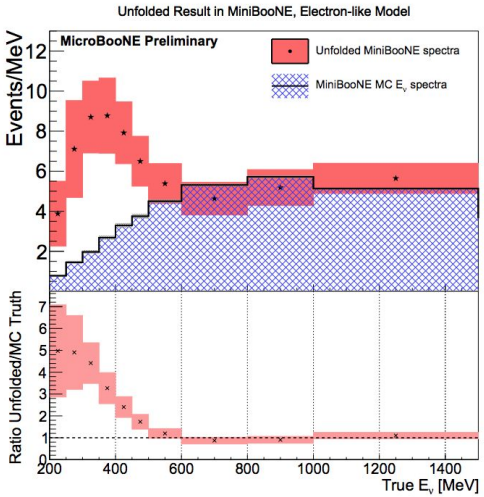


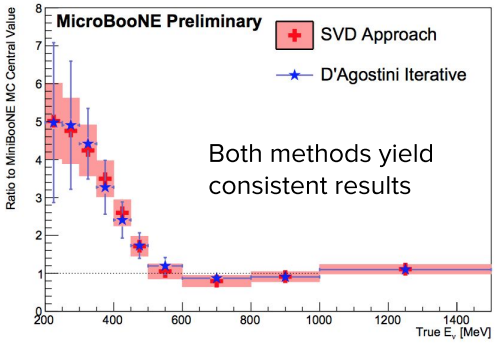
[MiniBooNE, PRL 121, 221801 (2018)]

Remove Detector Smearing, Reconstruction Effects, Analysis Selection Efficiencies, etc.

unfolding



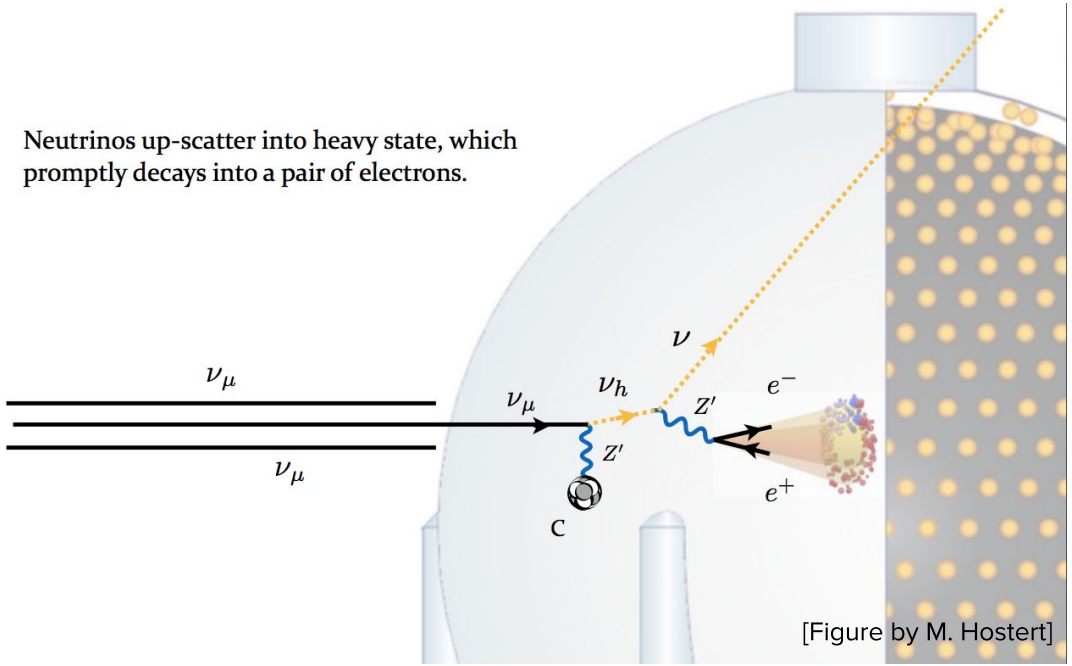




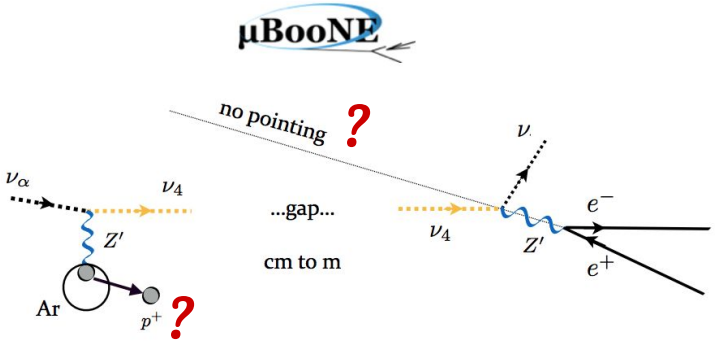
Both methods yield consistent results

Alternative LEE models

E.g., Z' mediated heavy neutrino production and decay into e+e- pair
[Phys.Rev.D 99 (2019) 071701, Phys.Rev.D 101 (2020) 11, 115025]



[Figure by M. Hostert]

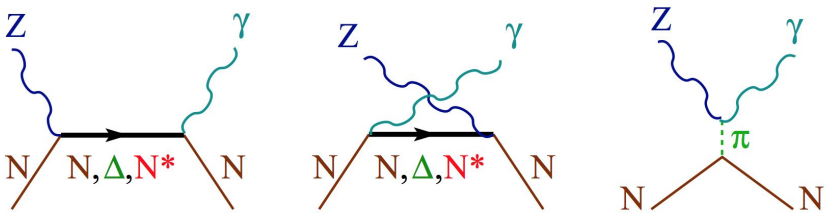


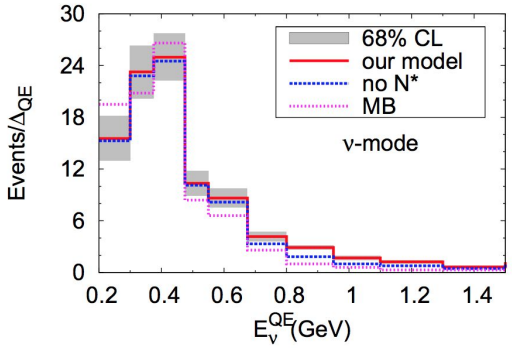
Presence of hadronic activity and pointing or forwardness/opening angle of e+e- shower(s) can help resolve between different models and model parameters

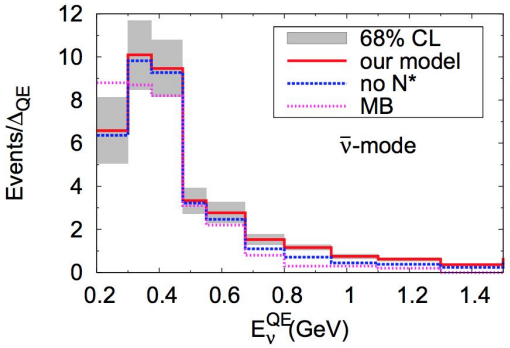
Single Photon Production - Theoretical Predictions

[Phys.Lett.B 740 (2015)]

Feynman diagrams for hadronic current of $\nu + N \longrightarrow \nu + N + \gamma$:







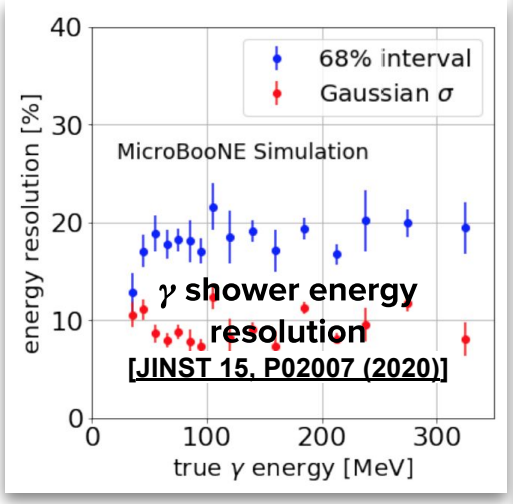
Photon emission processes from single-nucleon currents cannot explain the excess of the signal-like events observed at MiniBooNE.

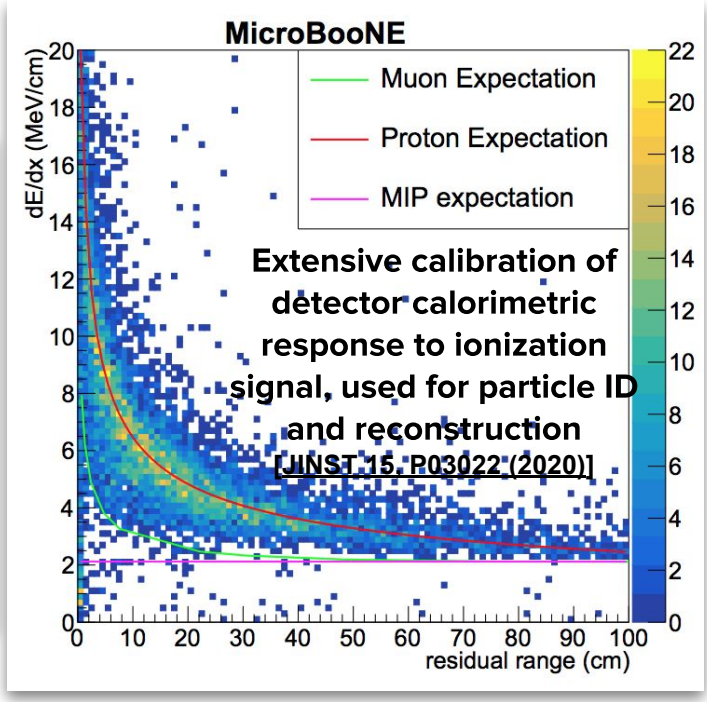
However, multinucleon mechanisms, which provide a significant amount of the CCQE-like cross section, await to be investigated for this channel.

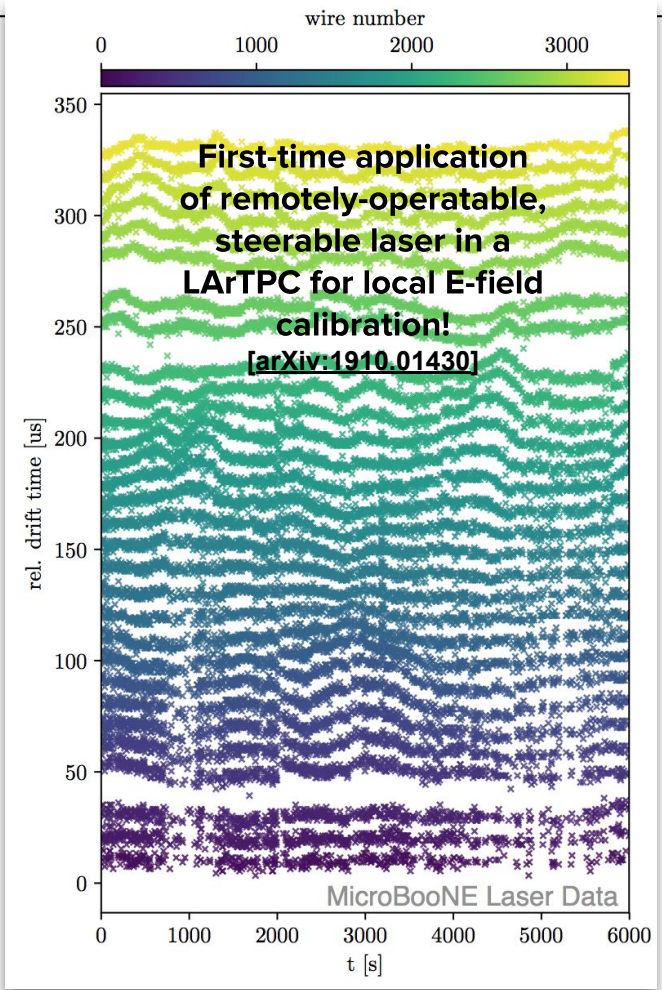
Detector calibration and performance

reconstruction,
calibration,
cross-section tuning

- Detector **calibration** and understanding of **detector effects and performance** [JINST 15, P03022 (2020), arXiv:1910.01430, JINST 15, P02007 (2020), MICROBOONE-NOTE-1018-PUB, MICROBOONE-NOTE-1050-PUB]





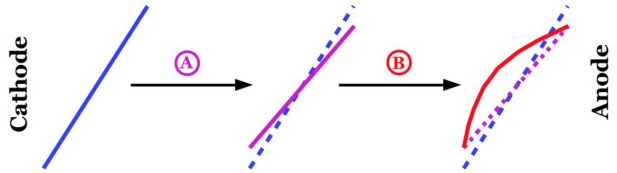


Detector calibration and performance

reconstruction,
calibration,
cross-section tuning

- Detector **calibration** and understanding of **detector effects and performance** [JINST 15, P03022 (2020), arXiv:1910.01430, JINST 15, P02007 (2020), MICROBOONE-NOTE-1018-PUB, MICROBOONE-NOTE-1050-PUB]

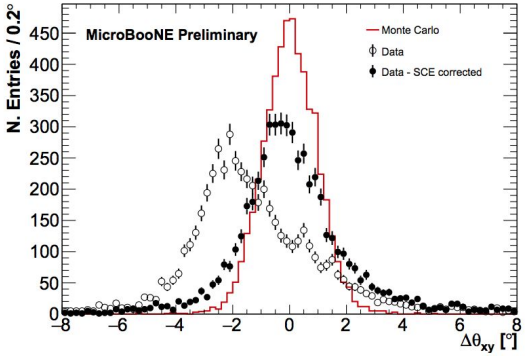
Impact of Space Charge Effect (SCE) on reconstructed tracks



A. Squeezing in the TPC transverse direction

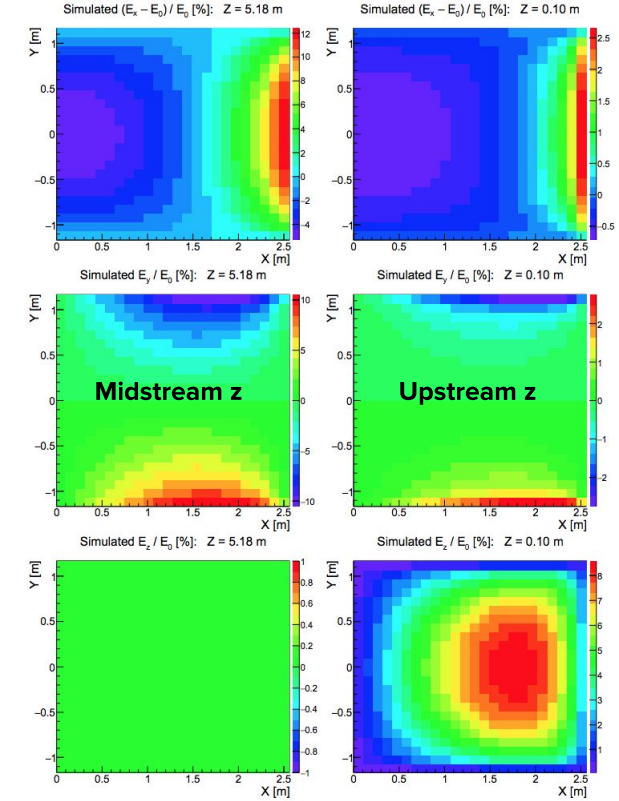
B. Bowing toward the cathode

[MICROBOONE-NOTE-1018-PUB]



(a) $\Delta\theta_{xy}$ residual distribution

Simulation of E field variation



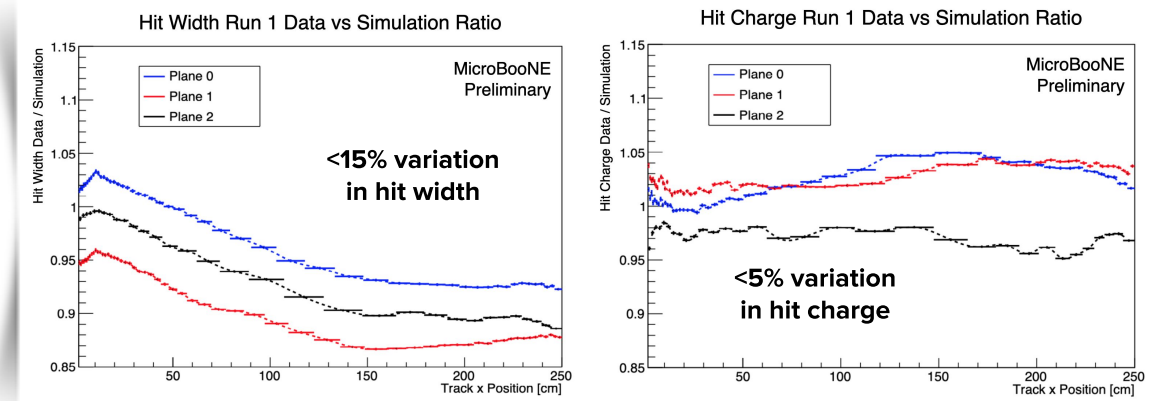
Detector Systematics

- With flux and cross-section systematic effects well understood, evaluation of **detector systematic uncertainties has ben key** for assessing our ability to test the MiniBooNE LEE
- Employed a **novel, data-driven method** for detector systematics assessment based on comparisons between data and simulated TPC waveform hits in terms of x, (y,z), θ_{yz}, θ_{xz}, and *dE/dx*
- Accommodates **model-agnostic** uncertainty evaluation for: diffusion, argon purity, space charge effects, recombination, wire response, long-range induced charge effects, signal processing, deconvolution effects

Uncertainty improvements: 16.2% → 3.3% for ν_μ CC inclusive measurement!

Novel, data-driven, model-agnostic method of evaluating detector systematic uncertainties!

[L. Yates Poster #176]
[MICROBOONE-NOTE-1075-PUB]

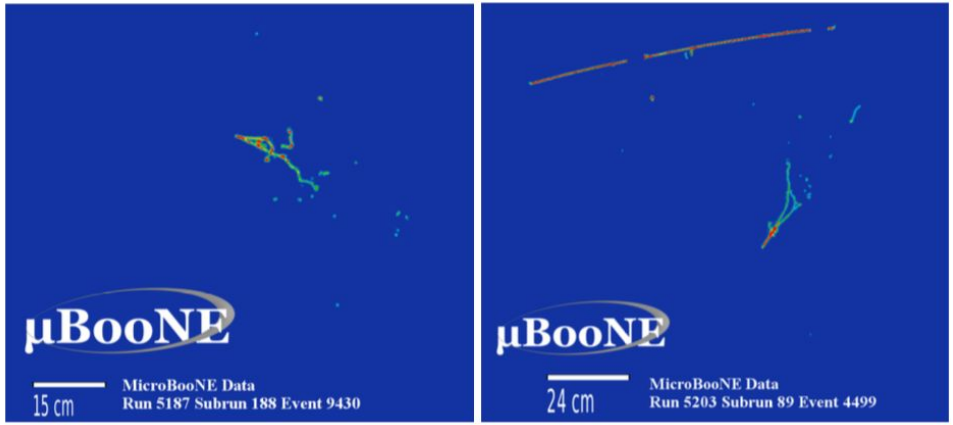


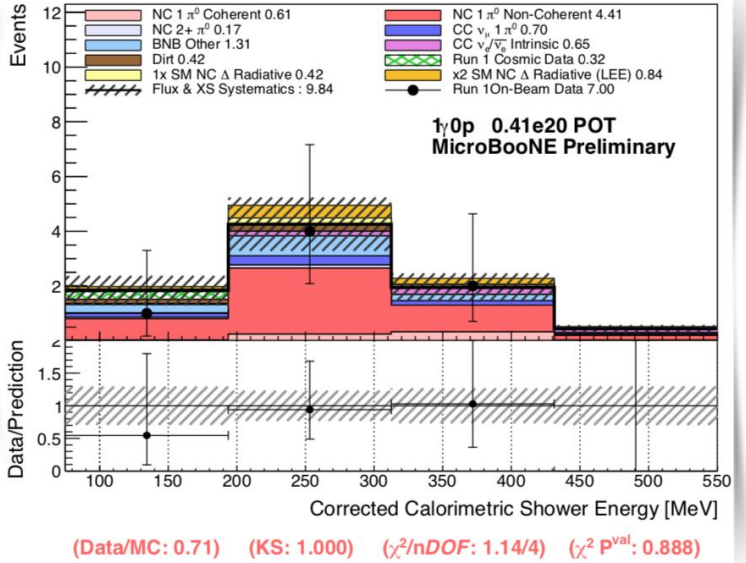
Most sophisticated understanding of LArTPC detector effects and systematics to date!

γLEE search

[MICROBOONE-NOTE-1087-PUB]

- Final selected 1γ0p sample, and example data events, “5%” data set

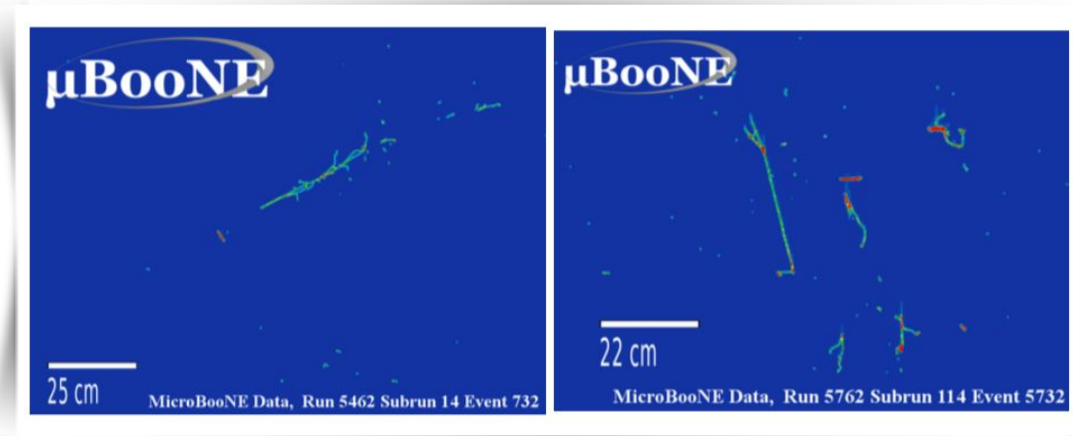


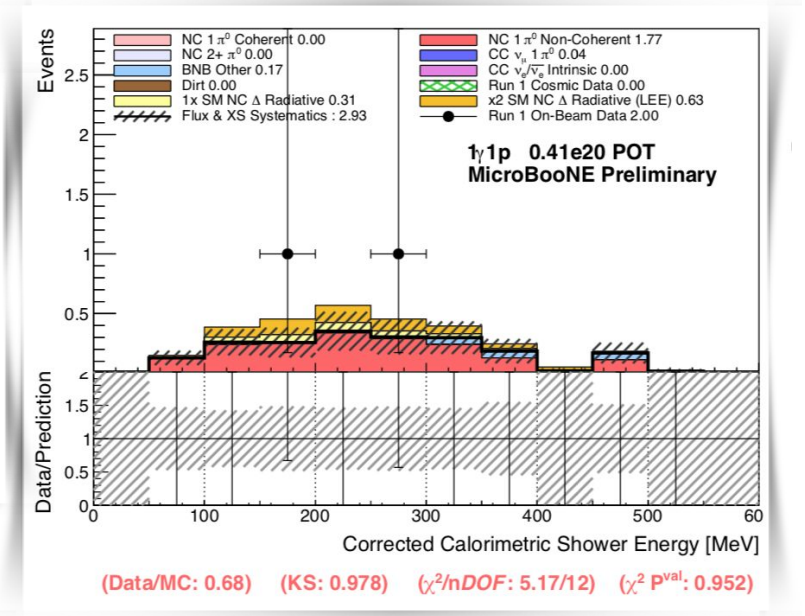


γLEE search

[MICROBOONE-NOTE-1087-PUB]

- Final selected 1γ1p sample, and selected data events, “5%” data set



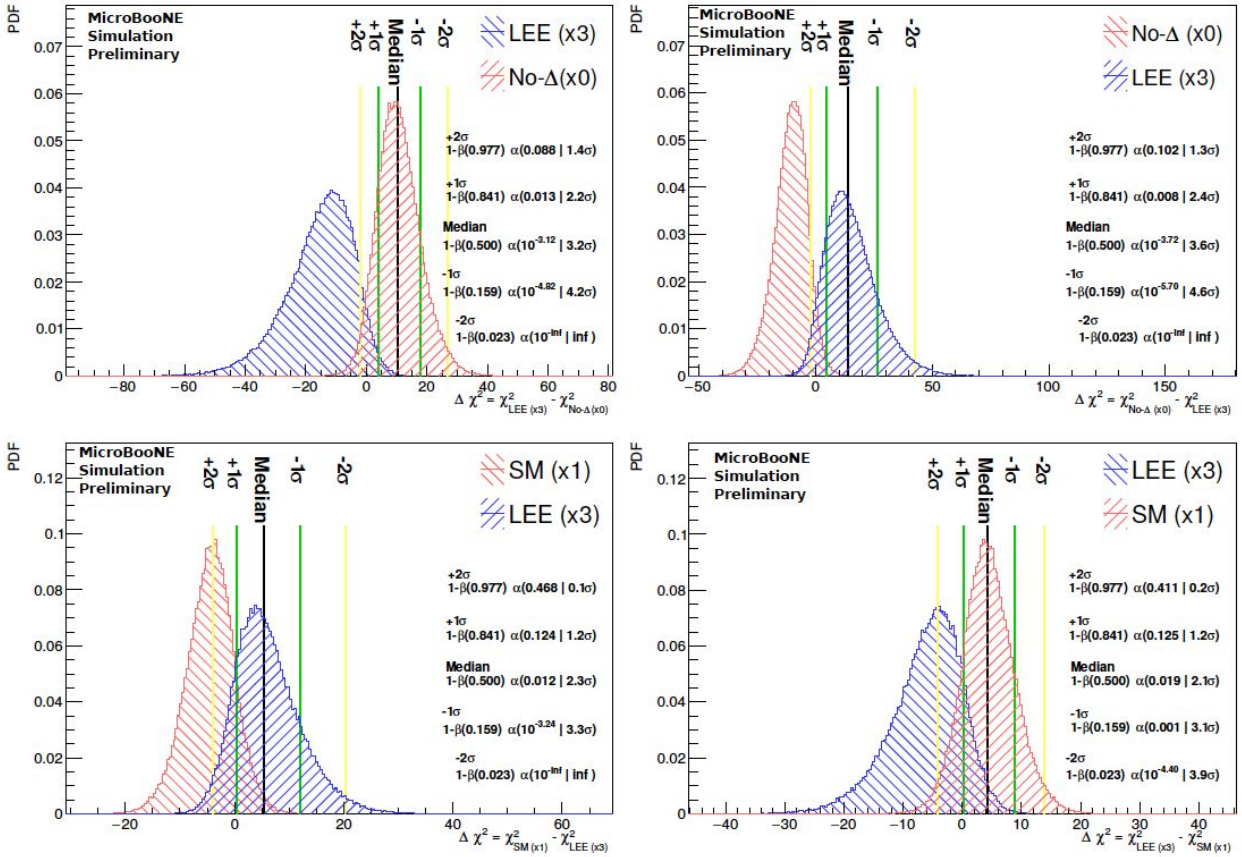


Two-hypothesis testing: γLEE

[MICROBOONE-NOTE-1087-PUB]

With **Run 1-5 data set**, MicroBooNE would be able to:

- Reject x_Δ=0 in favor of γLEE x_Δ=3, assuming γLEE is true, at **3.6σ**
- Reject SM (x_Δ=1) in favor of γLEE x_Δ=3, assuming γLEE is true, at **2.3σ**
- Reject γLEE (x_Δ=3) in favor of x_Δ=0, assuming x_Δ=0 is true, at **3.2σ**
- Reject γLEE (x_Δ=3) in favor of SM (x_Δ=1), assuming SM is true, at **2.1σ**



γLEE Systematic Uncertainties

[MICROBOONE-NOTE-1087-PUB]

- Systematic uncertainties in γLEE analysis, Run 1-5, **before constraint**

Selection Topology	Flux	GENIE cross-section	Detector	Monte Carlo Statistics	Total
$1\gamma 1p$	7.2%	23.6%	25.1%	4.6%	35.4%
$1\gamma 0p$	6.4%	15.7%	8.3%	3.7%	19.1%
$2\gamma 1p$	6.5%	18.6%	7.5%	1.6%	21.2%
$2\gamma 0p$	6.0%	15.5%	6.0%	2.0%	18.0%

- Systematic uncertainties **after constraint**

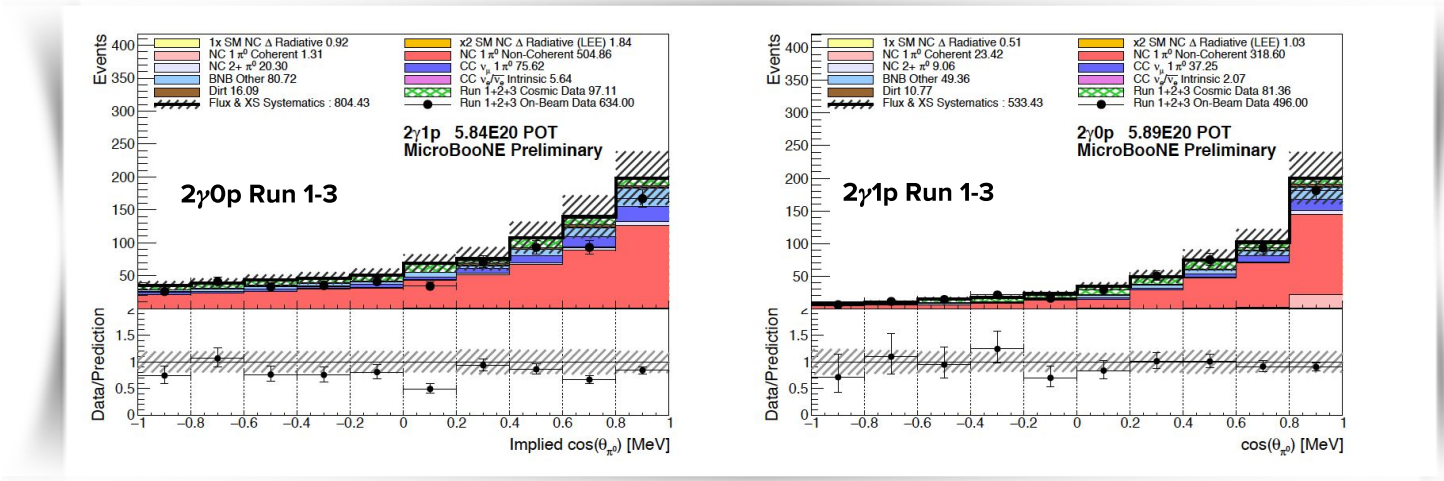
Selection Topology	Total Uncertainty	After Constraint
$1\gamma 1p$	35.4%	17.1%
$1\gamma 0p$	19.1%	10.8%
$2\gamma 1p$	21.2%	-
$2\gamma 0p$	18.0%	-

Correction to GENIE coherent and non-coherent NC π^0 rates

[MICROBOONE-NOTE-1087-PUB]

- The **2γ1p** and **2γ0p** selections for the γLEE analysis provide complementary sensitivity to coherent and non-coherent NC π^0 production.
- A simultaneous fit to 2γ1p and 2γ0p distributions enables measurement of **NCπ^0 coherent and non-coherent normalizations.**

Before correction



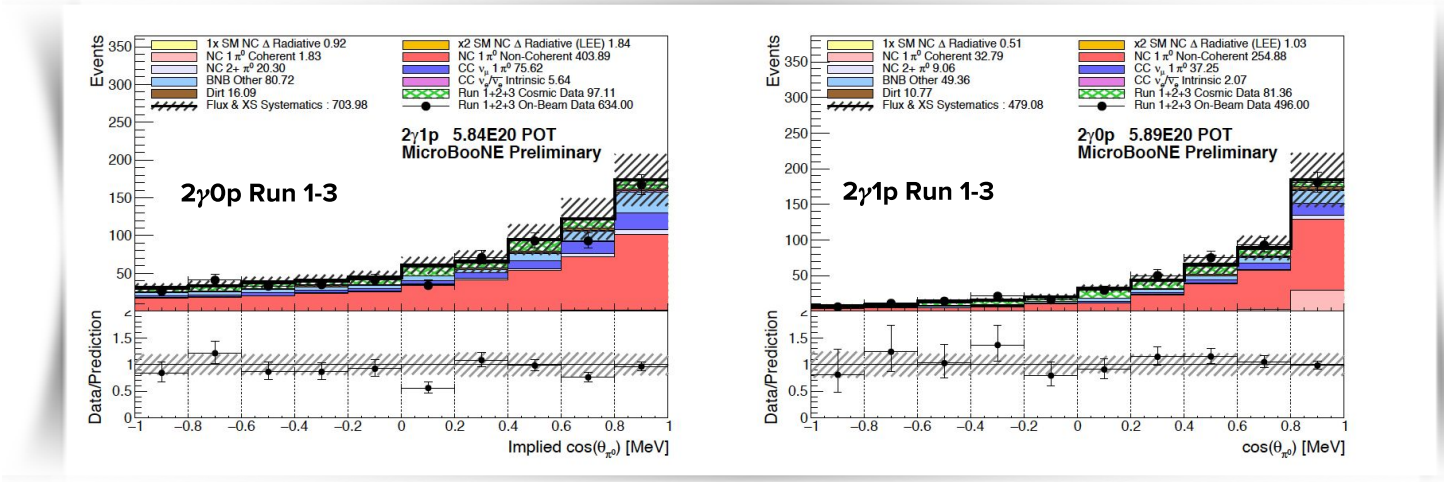
This data-driven correction is **applied to the final 1γ1p, 1γ0p, 2γ1p, and 2γ0p distributions**

Correction to GENIE coherent and non-coherent NC π^0 rates

[MICROBOONE-NOTE-1087-PUB]

- The **2γ1p** and **2γ0p** selections for the γLEE analysis provide complementary sensitivity to coherent and non-coherent NC π^0 production.
- A simultaneous fit to 2γ1p and 2γ0p distributions enables measurement of **NCπ^0 coherent and non-coherent normalizations.**

After correction

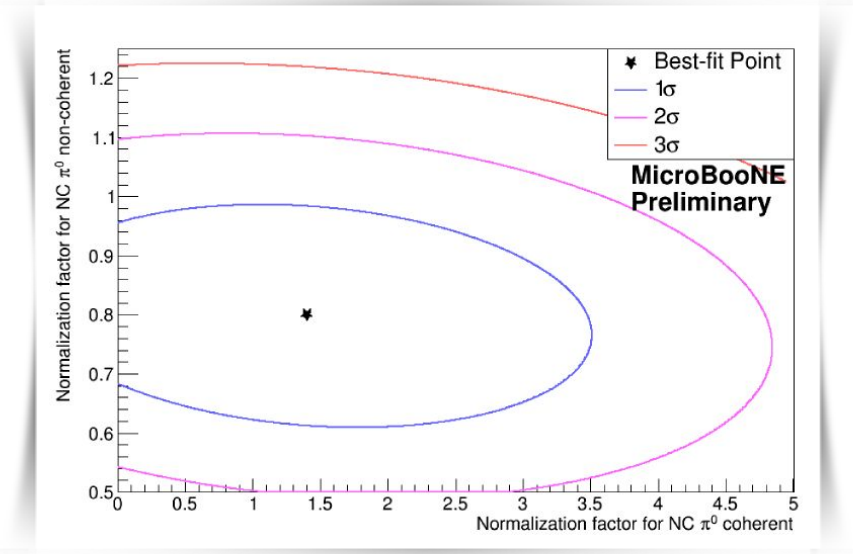


This data-driven correction is **applied to the final 1γ1p, 1γ0p, 2γ1p, and 2γ0p distributions**

Correction to GENIE coherent and non-coherent NC π^0 rates

[MICROBOONE-NOTE-1087-PUB]

- The **2γ1p** and **2γ0p** selections for the γLEE analysis provide complementary sensitivity to coherent and non-coherent NC π^0 production.
- A simultaneous fit to 2γ1p and 2γ0p distributions enables measurement of **NCπ^0 coherent and non-coherent normalizations.**

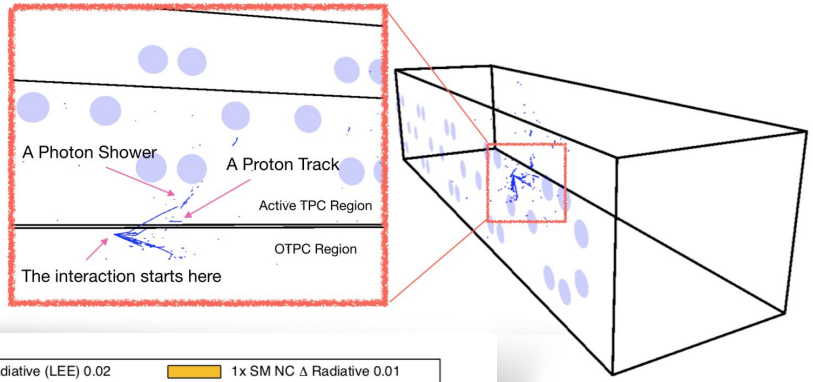


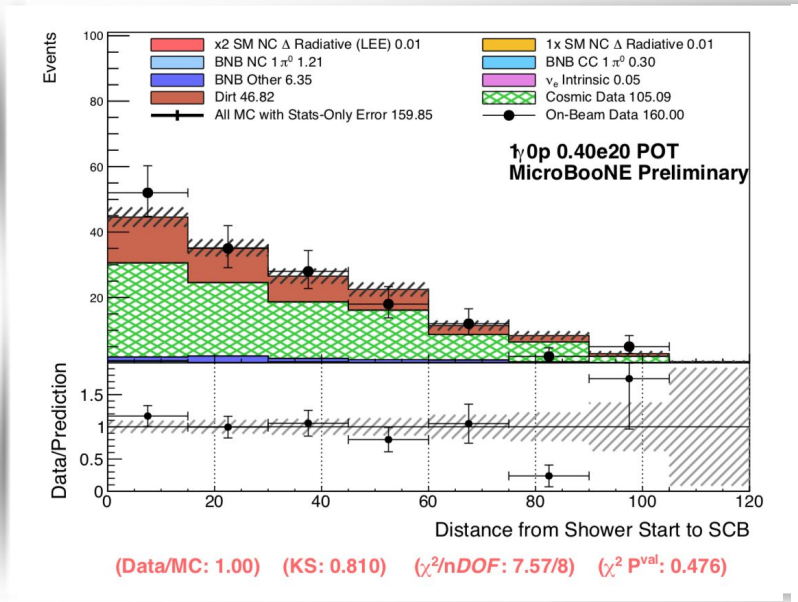
This data-driven correction is **applied to the final 1γ1p, 1γ0p, 2γ1p, and 2γ0p distributions**

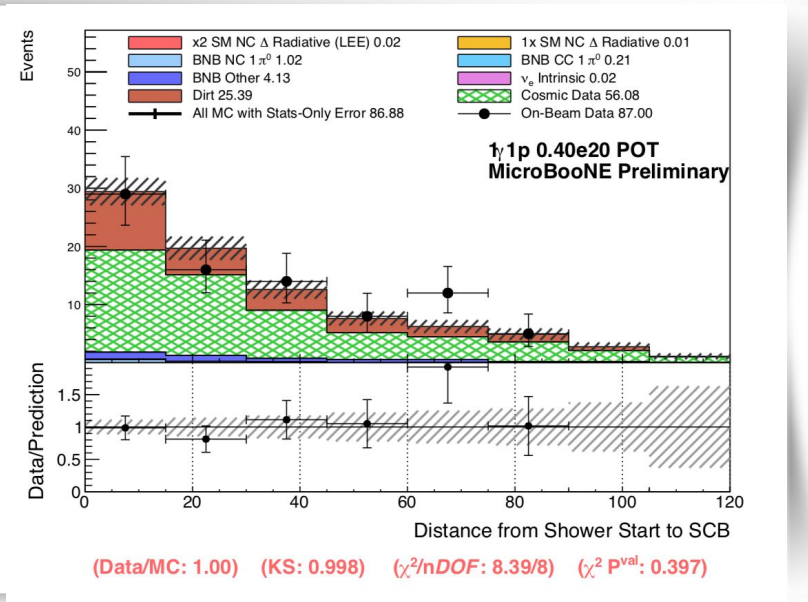
Constraining dirt backgrounds to the γLEE search

[MICROBOONE-NOTE-1087-PUB]

- Dirt-enhanced selections are used to validate **dirt background** predictions



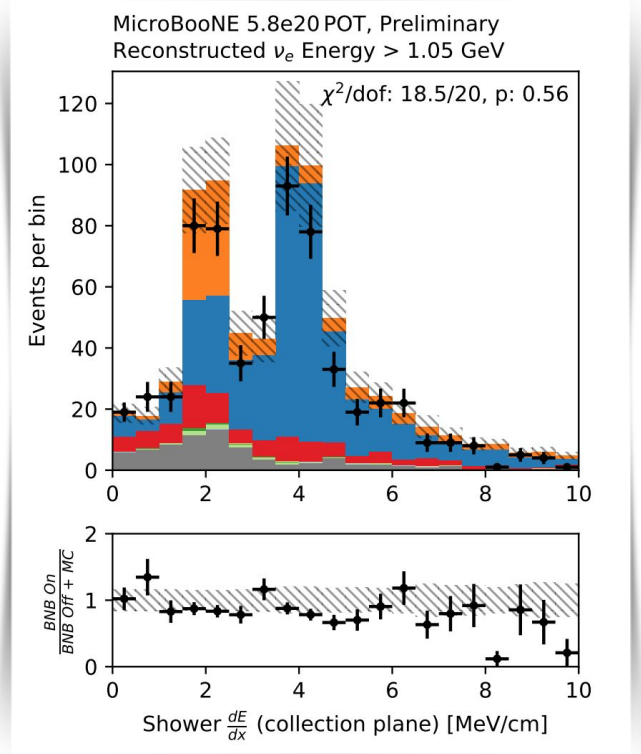


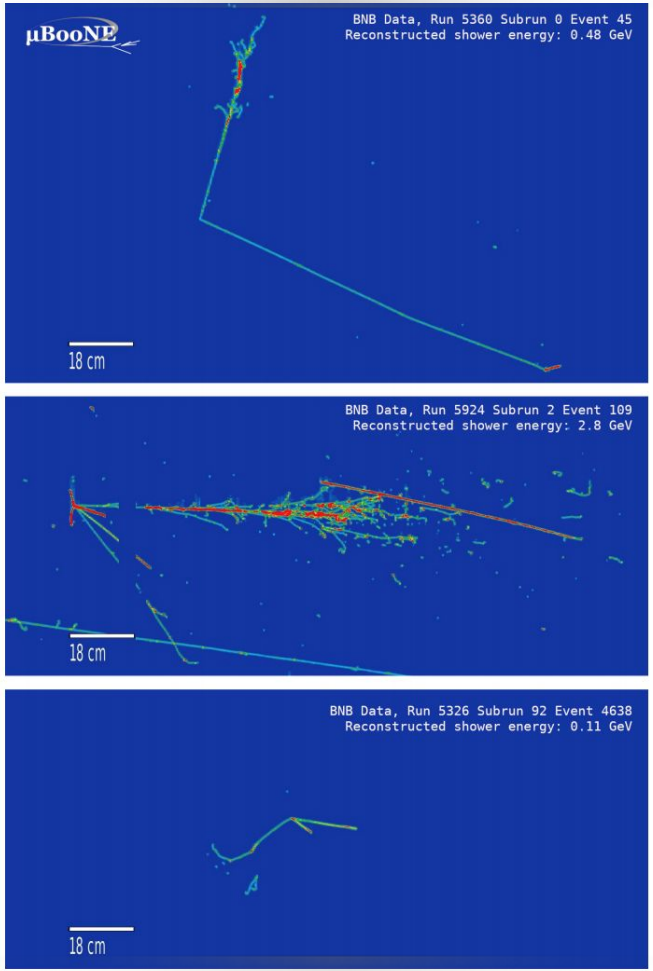


(1) Pandora eLEE search

[MICROBOONE-NOTE-1085-PUB]

- ν_e **CC** inclusive selection, data to Monte Carlo comparisons for Run 1-3

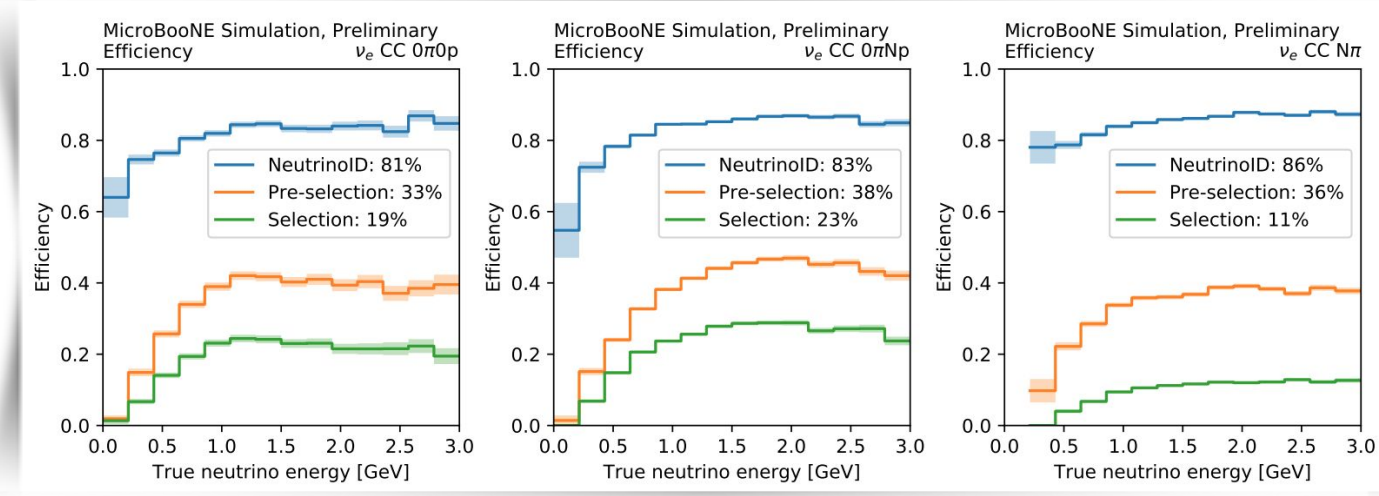




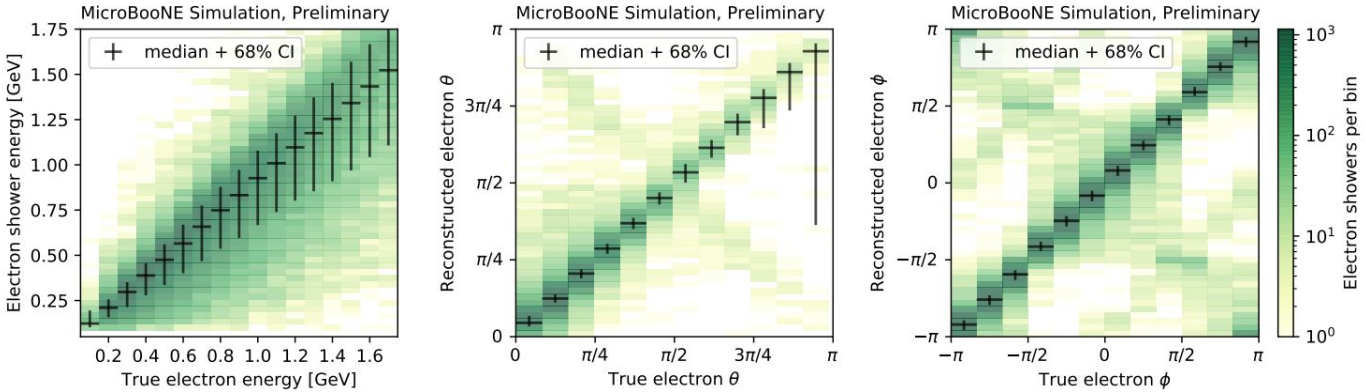
(1) Pandora eLEE search

[MICROBOONE-NOTE-1085-PUB]

1e0p, **1eNp**, and **ν_e CC** inclusive selection efficiencies



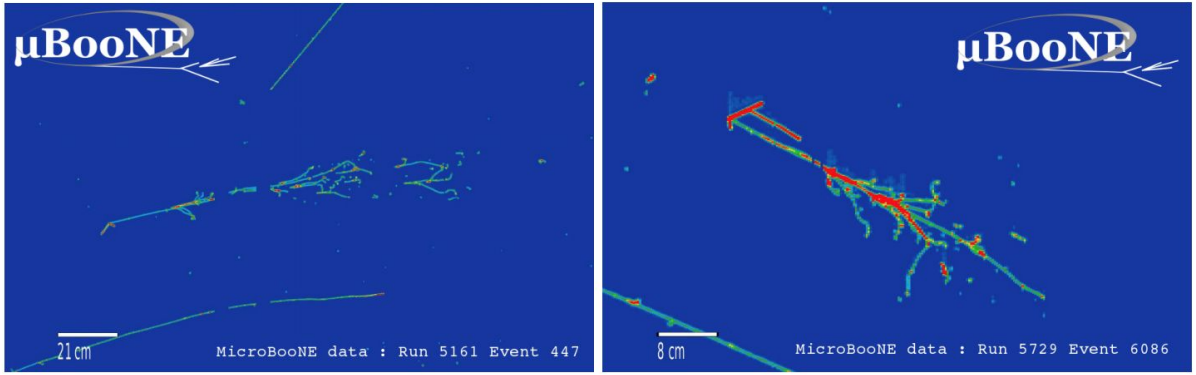
ν_e CC inclusive energy and angular resolutions



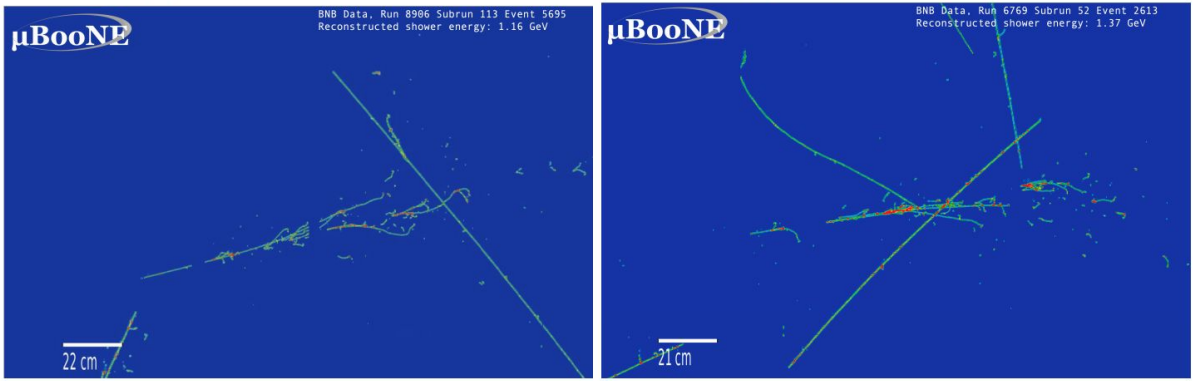
(1) Pandora eLEE search

[MICROBOONE-NOTE-1085-PUB]

Examples of **1e0p** and **1eNp** final selected (data) events



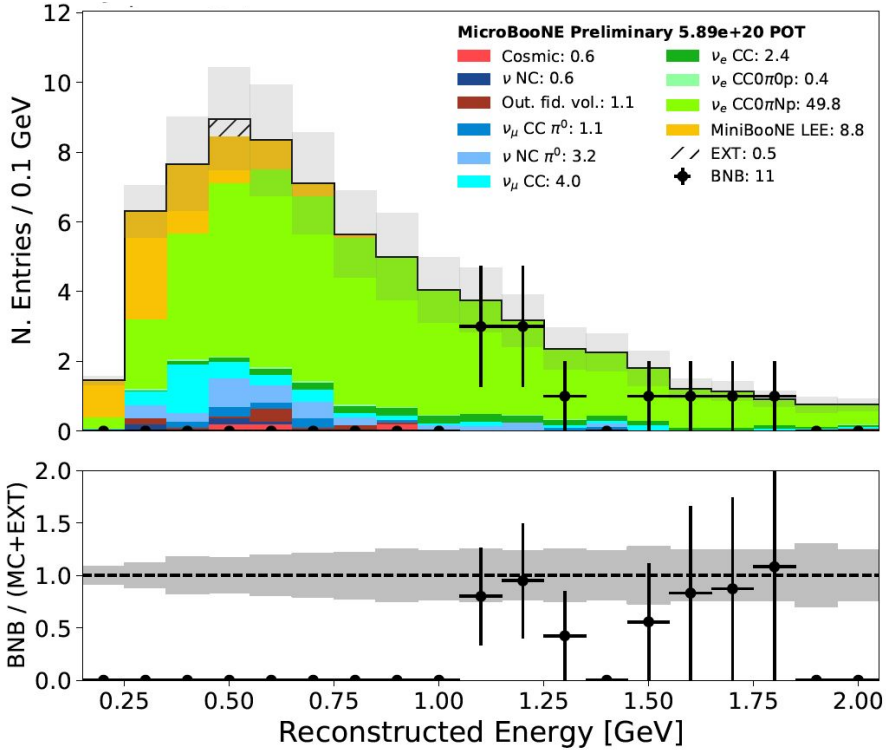
(a) 1eNp candidate event. (b) 1eNp candidate event.

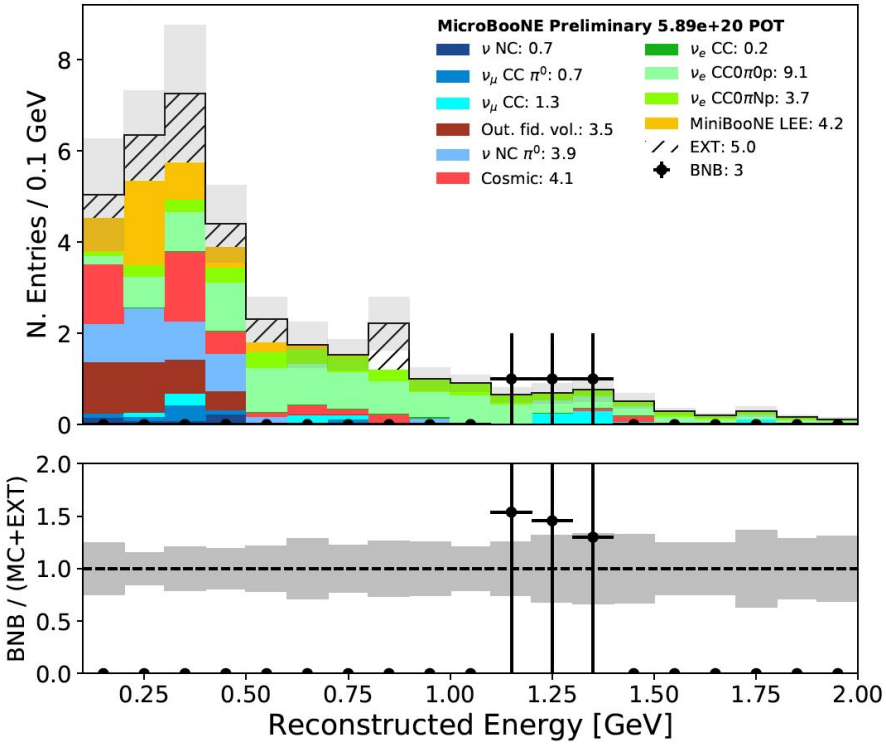


(c) 1e0p candidate event. (d) 1e0p candidate event.

(1) Pandora eLEE search

[MICROBOONE-NOTE-1085-PUB]





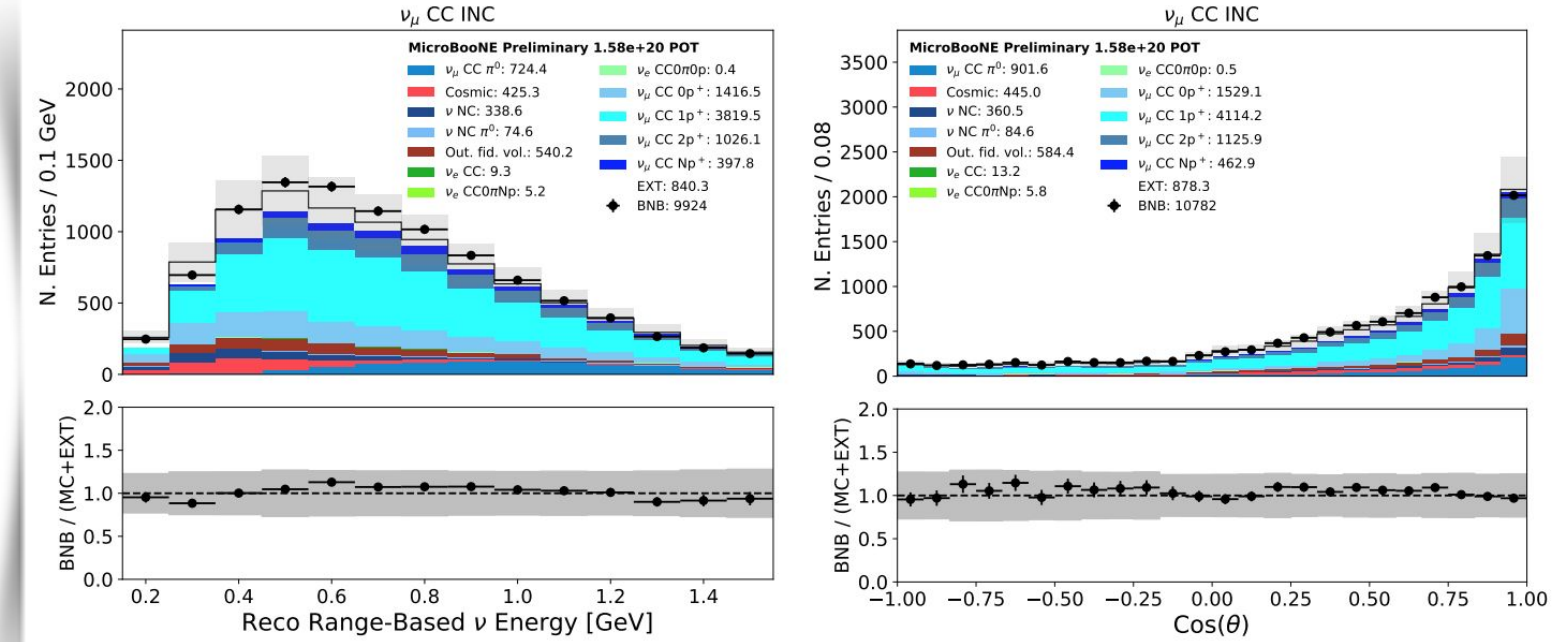
Expected: 18.2
Observed: 11

Expected: 5.5
Observed: 4

(1) Pandora eLEE search

[MICROBOONE-NOTE-1085-PUB]

- ν_μ CC inclusive selection, data to Monte Carlo comparisons for Run 3



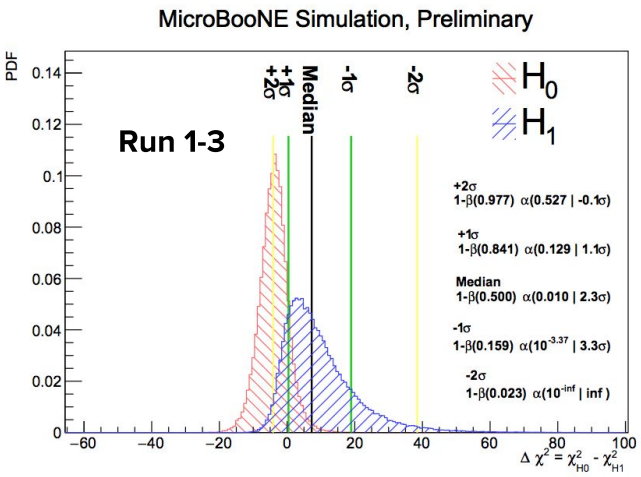
(a) ν_μ energy. (b) muon angle w.r.t. beam.

(1) Pandora eLEE search

[MICROBOONE-NOTE-1085-PUB]

With **Run 1-3 data set,** MicroBooNE would be able to:

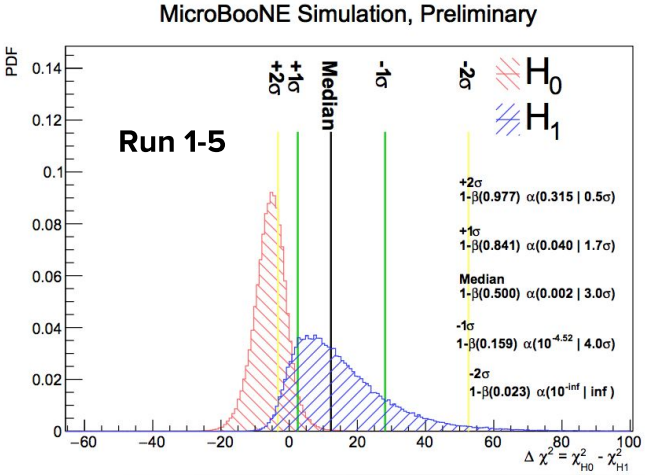
- Reject SM in favor of eLEE, assuming eLEE is true, at **2.3σ**
- Reject eLEE in favor of SM, assuming SM is true, at **1.9σ**



H_0: SM
H_1: eLEE

With **Run 1-5 data set**, MicroBooNE would be able to:

- Reject SM in favor of eLEE, assuming eLEE is true, at **3.0σ**
- Reject eLEE in favor of SM, assuming SM is true, at **2.4σ**

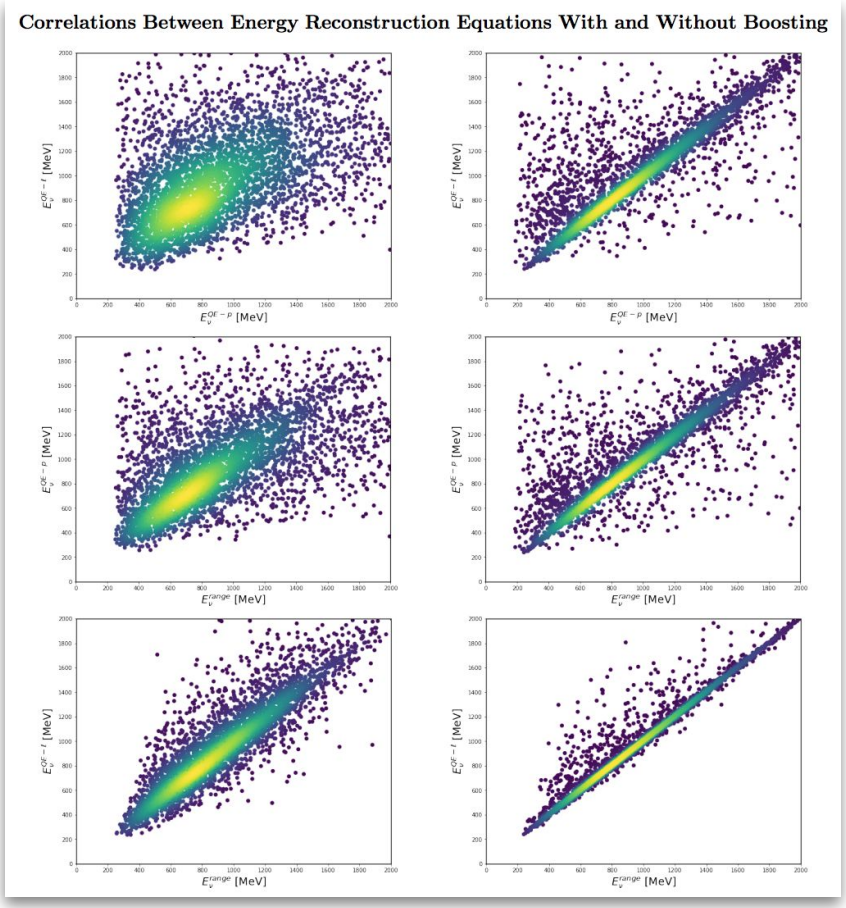


(2) Deep Learning eLEE search

[MICROBOONE-NOTE-1086-PUB]

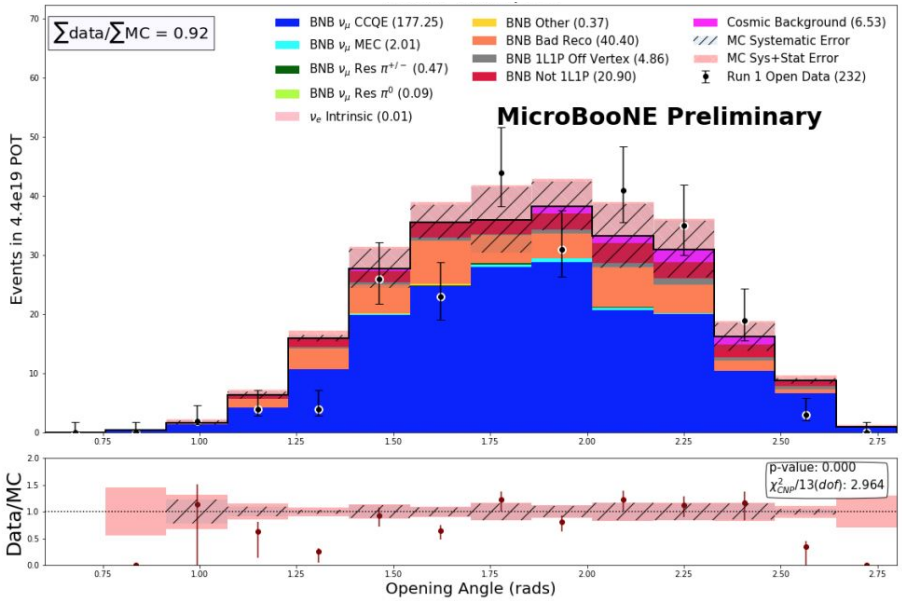
Definitions Related to Neutrino Energy	
E_ν^{range} *	$E_p + E_\ell - (m_n - E_b)$
E_ν^{QE-p}	$\dfrac{E_p(m_n - E_b) + \frac{1}{2}(m_\ell^2 - (m_n - E_b)^2 - m_p^2)}{(m_n - E_b) + \lvert\vec{p}_p\rvert cos\theta_p - E_p}$
$E_\nu^{QE-\ell}$	$\dfrac{E_\ell(m_n - E_b) + \frac{1}{2}(m_p^2 - (m_n - E_b)^2 - m_\ell^2)}{(m_n - E_b) + \lvert\vec{p}_\ell\rvert cos\theta_\ell - E_\ell}$
Δ^{QE}	$\sqrt{\left(E_\nu^{QE-p} - E_\nu^{QE-\ell}\right)^2 + \left(E_\nu^{QE-p} - E_\nu^{range}\right)^2 + \left(E_\nu^{QE-\ell} - E_\nu^{range}\right)^2}$
	* Unless explicitly noted otherwise, any reference to E_ν in this memo or histograms refer to E_ν^{range} as reconstructed in the laboratory frame.

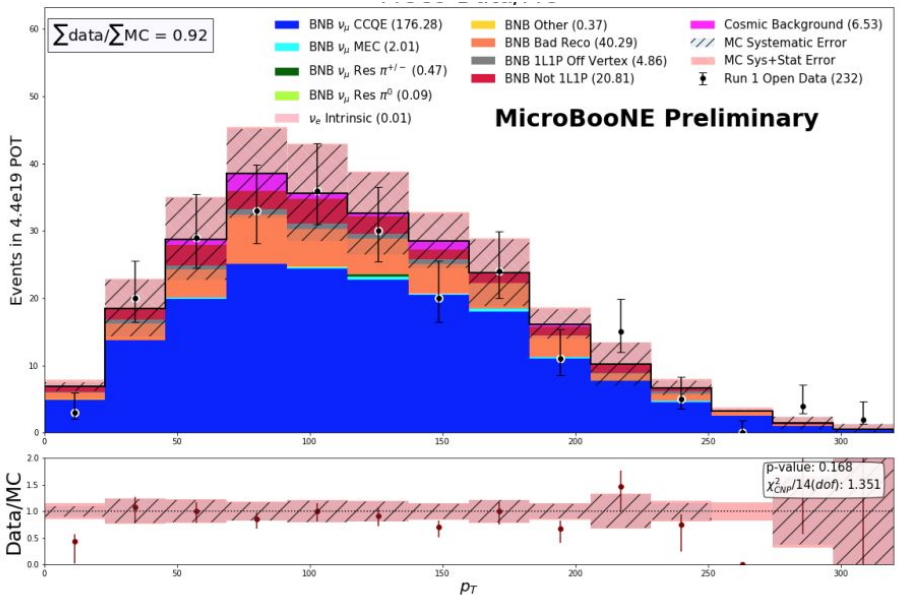
E_p → Energy of proton determined from range
E_μ → Energy of muon determined from range in detector
E_e → Energy of electron determined from deposited charge



(2) Deep Learning eLEE search

[MICROBOONE-NOTE-1086-PUB]

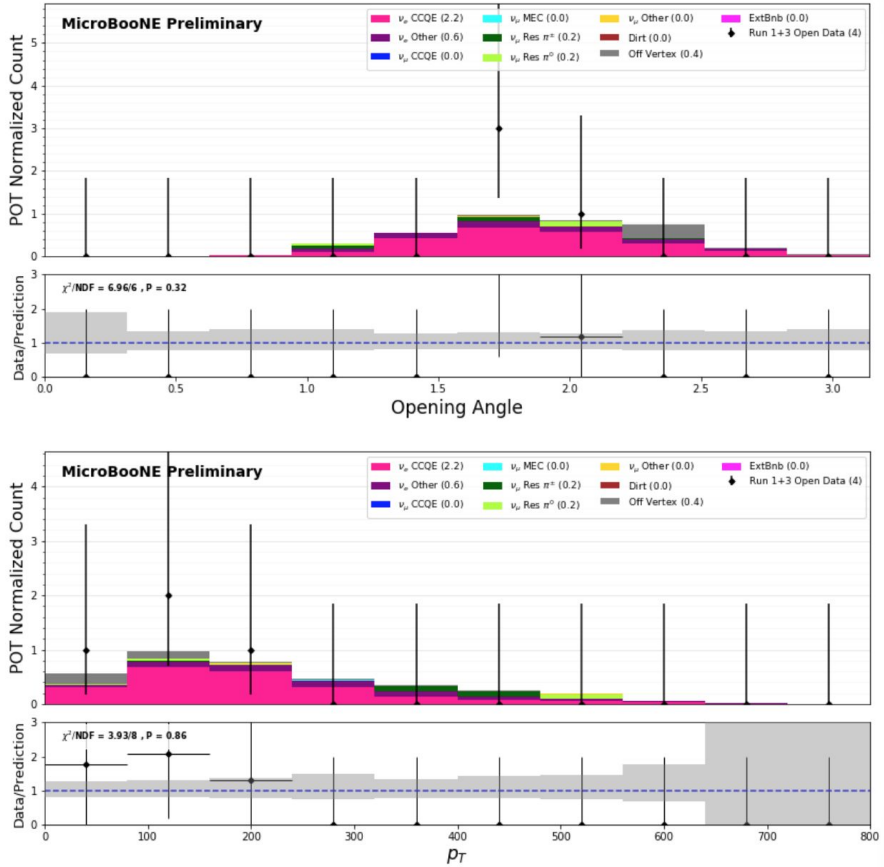


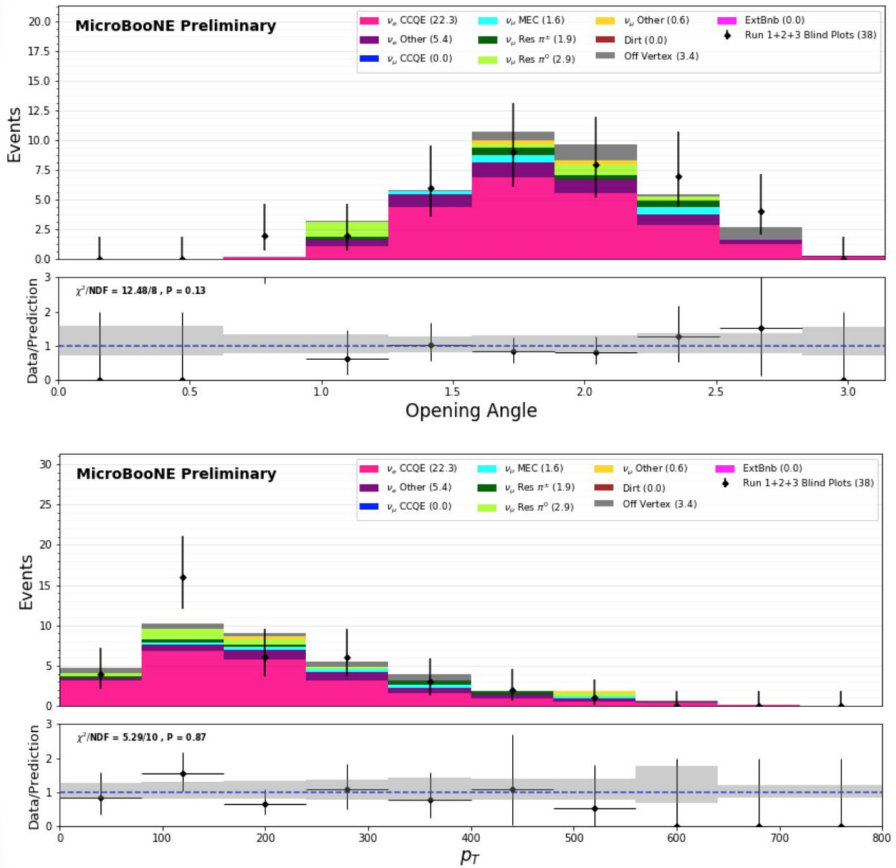


$$\chi^2_{CNP} = \sum_i \begin{cases} \dfrac{(\mu_i - M_i)^2}{\frac{3}{1/M_i + 2/\mu_i}} & \mathrm{M}_i \neq 0 \\[2ex] \dfrac{(\mu_i - M_i)^2}{\frac{\mu_i}{2}} & \mathrm{M}_i = 0 \end{cases}$$

(2) Deep Learning eLEE search

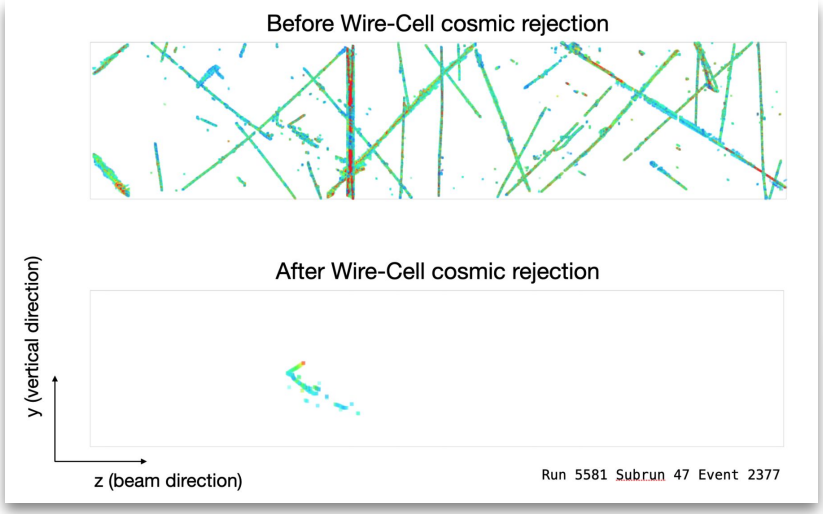
[MICROBOONE-NOTE-1086-PUB]

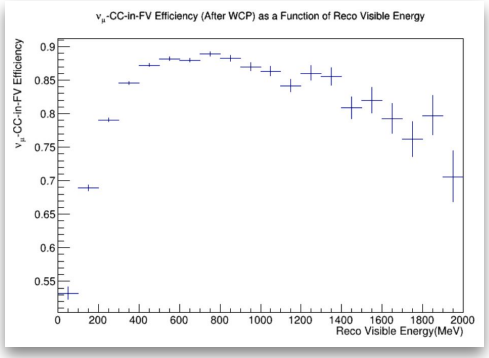


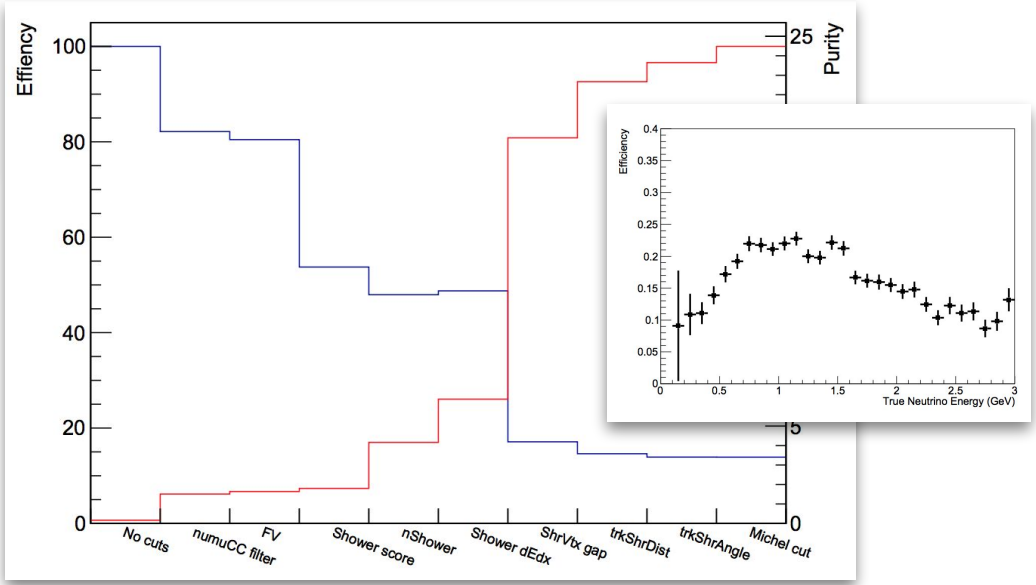


(3) Wire Cell + Pandora (Hybrid) eLEE Search

[MICROBOONE-NOTE-1088-PUB]







Cosmic Rejection Performance

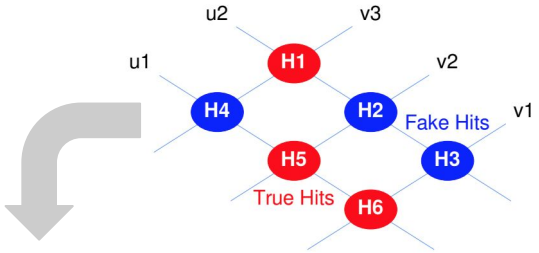
Cuts	ν : Cosmic	ν selection efficiency
Total Events	1:800	100.00%
Flash Found	1:200	98.85%
Match Found	1:5.4	98.37%
Not Light Mismatch		96.34%
Not Through-Going Muon	1.2:1	91.51%
Not Burst Event		90.65%
Not Stopped Muon	4.3:1	84.38%
Not Low Energy		81.59%
Cluster Length > 15cm	7.6:1	81.36%

(3) Wire Cell Tomographic Reconstruction

[MICROBOONE-NOTE-1040-PUB, JINST 13, P05032 (2018)]

Directly reconstruct in 3D using techniques from **Tomography**. Ambiguities in 3D reconstruction due to missing information can be mitigated by using **charge information** and the technique of **compressed sensing**,* well known in computer science and statistics fields.

(Simplified, 2D example:)



Vector of hit wires from all planes

$$\begin{pmatrix} u1 \\ u2 \\ v1 \\ v2 \\ v3 \end{pmatrix} = \begin{pmatrix} 0&0&0&1&1&1 \\ 1&1&1&0&0&0 \\ 0&0&1&0&0&1 \\ 0&1&0&0&1&0 \\ 1&0&0&1&0&0 \end{pmatrix} \cdot \begin{pmatrix} H1 \\ H2 \\ H3 \\ H4 \\ H5 \\ H6 \end{pmatrix}$$

Wire-to-Cell matrix, determined by wire geometry

Vector of hit charge