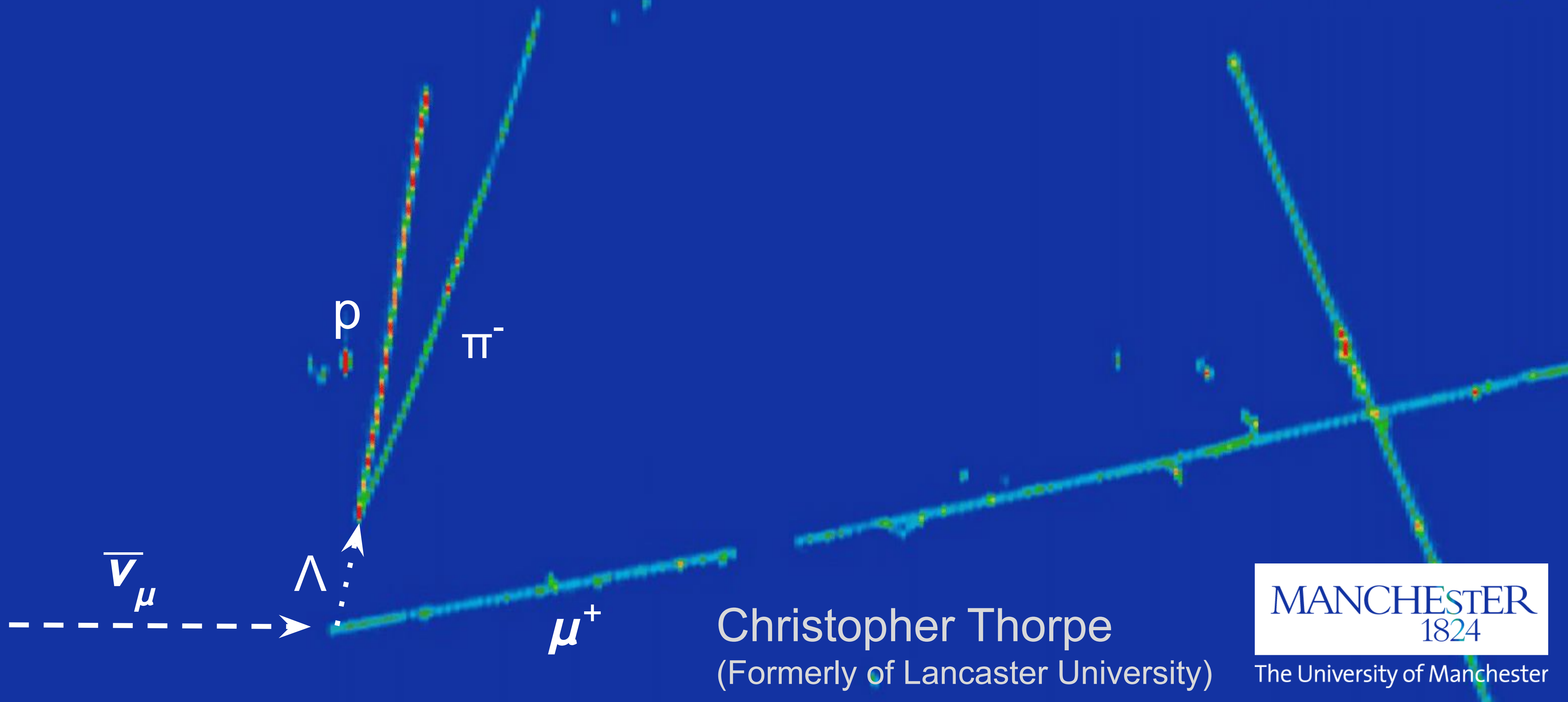
Rare Neutrino Interactions in MicroBooNE



Christopher Thorpe
(Formerly of Lancaster University)

MANCHESTER 1824
The University of Manchester

The Importance of Cross Sections

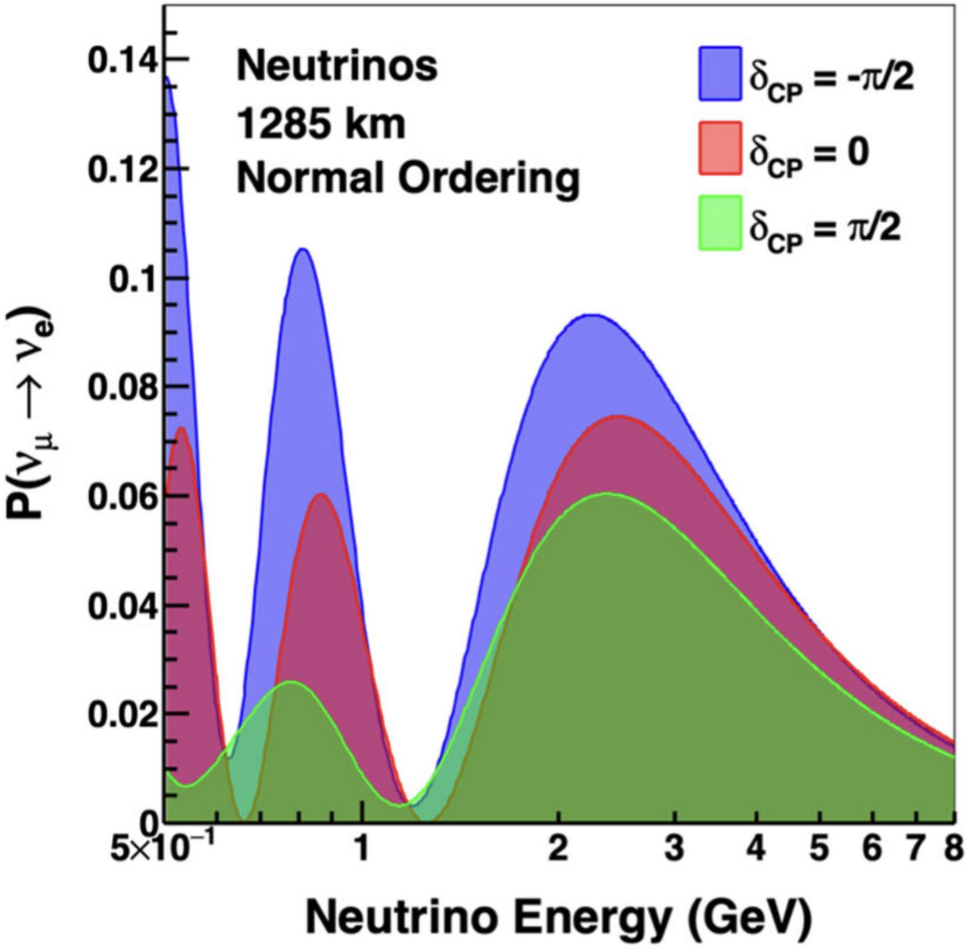


Figure from Eur.Phys.J.C 80 (2020) 10, 978.

- Neutrino oscillation ↔ the observed flavour content of a neutrino beam changes with distance from the source.
- So we just measure the flux….?

The Importance of Cross Sections

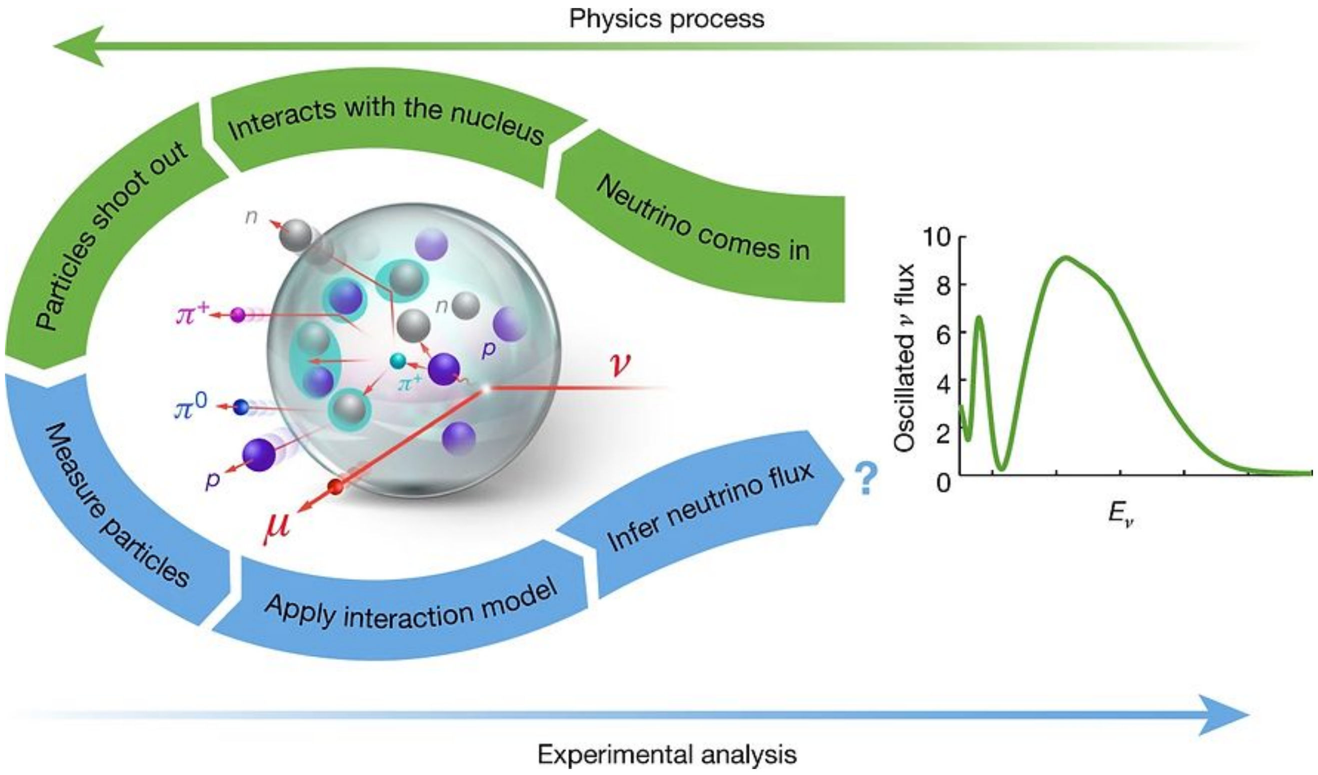
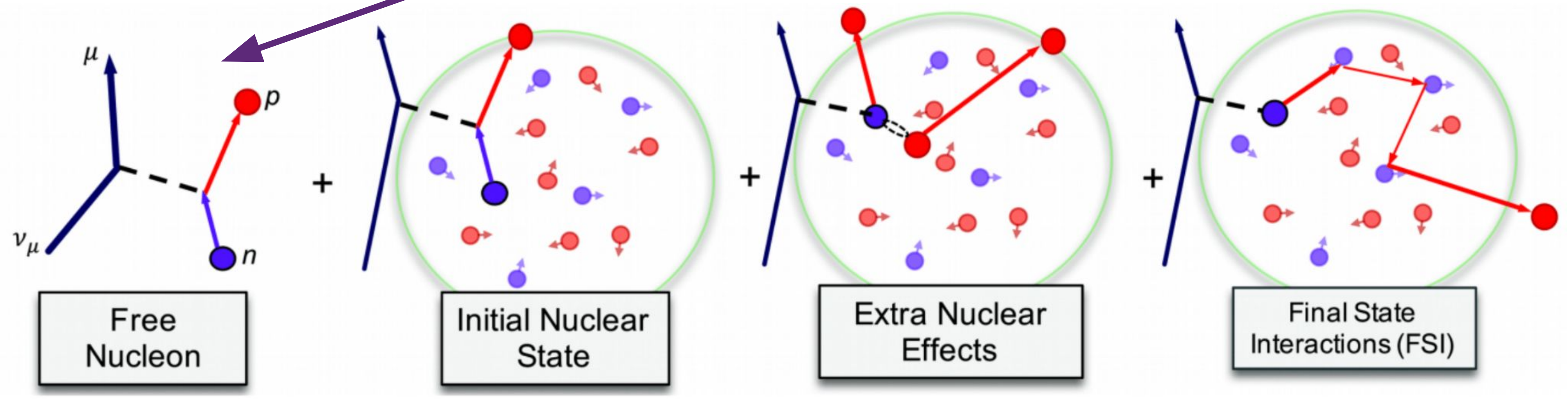


Figure from [*Nature* 599, 565–570 (2021).]

- This is not straightforward:
  - No monoenergetic beams.
  - Can't observe the neutrino energy directly, estimate from other quantities.

Neutrino-Nucleus Interactions

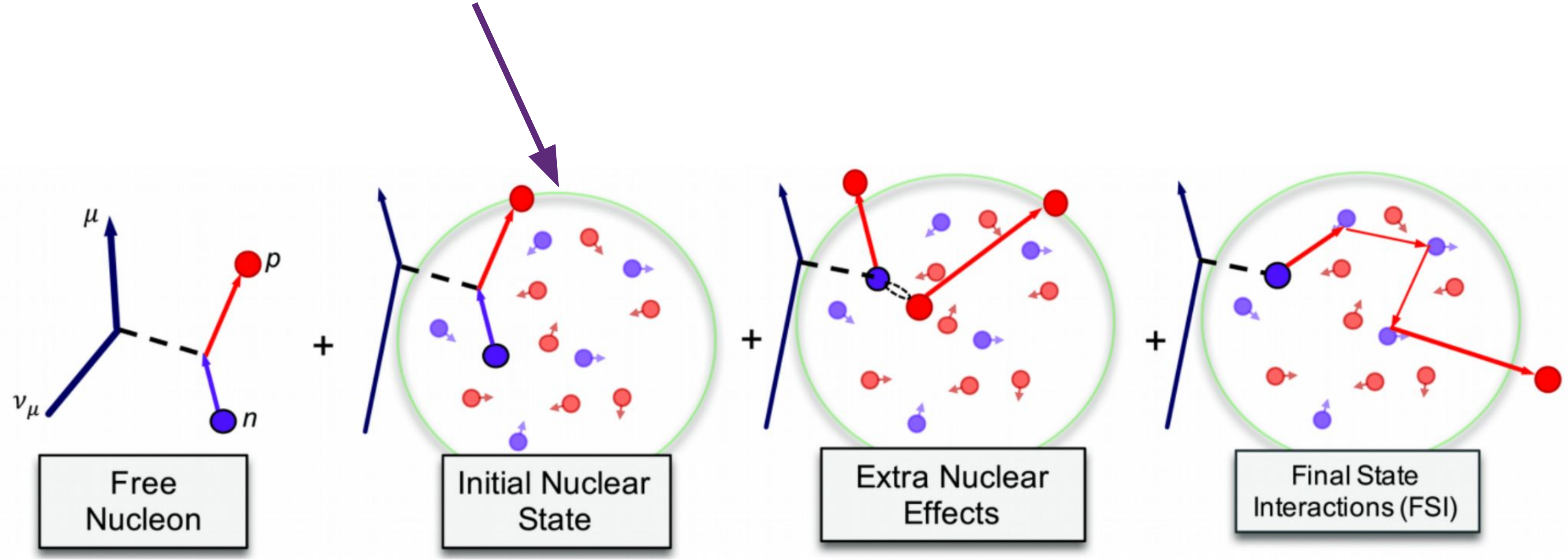
- In principle, if a neutrino interacts with a single, stationary nucleon, the neutrino energy may be calculated from the kinematics of the final state.



From talk by C Wilkinson at NNN 2017.

Neutrino-Nucleus Interactions

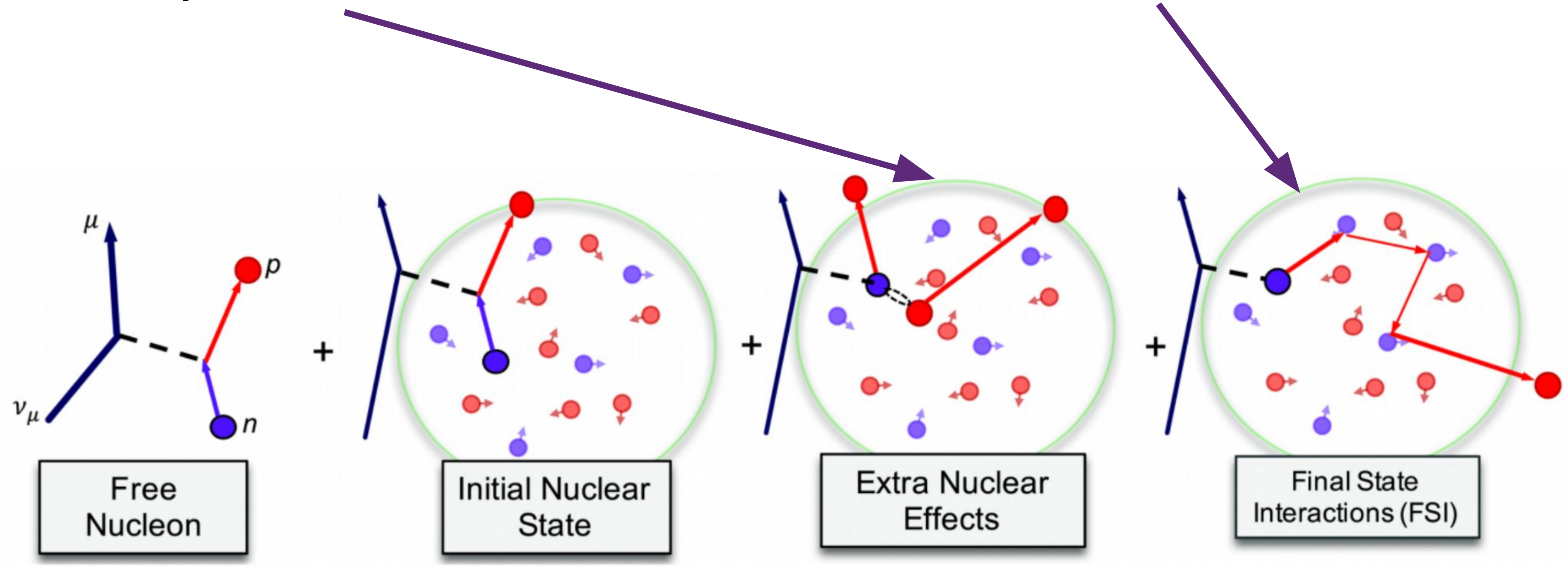
- However, the nucleon isn't stationary, it lives inside a nucleus, and has some initial momentum.



From talk by C Wilkinson at NNN 2017.

Neutrino-Nucleus Interactions

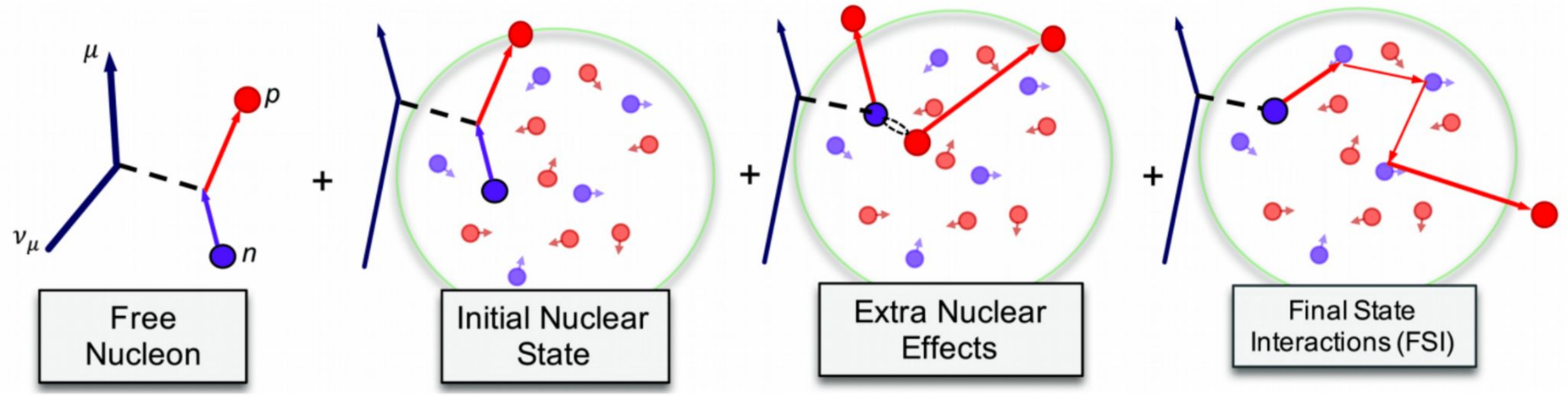
- Furthermore, the neutrino can interact with multiple nucleons, and additional processes can occur inside the nucleus.



From talk by C Wilkinson at NNN 2017.

Neutrino-Nucleus Interactions

- All of these effects modify the relationship between the neutrino energy and observable quantities, often in very complex ways.
- You detector can’t always see all final state particles either!

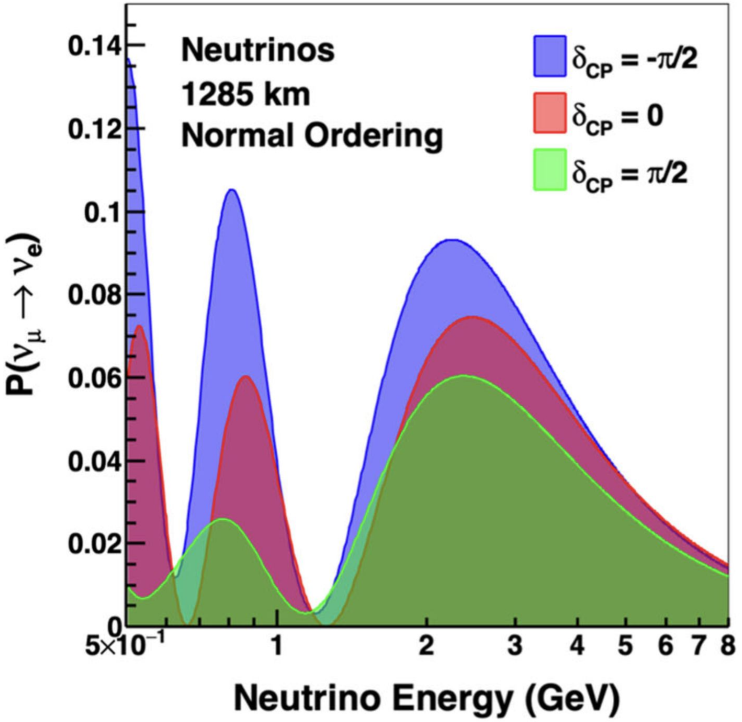


From talk by C Wilkinson at NNN 2017.

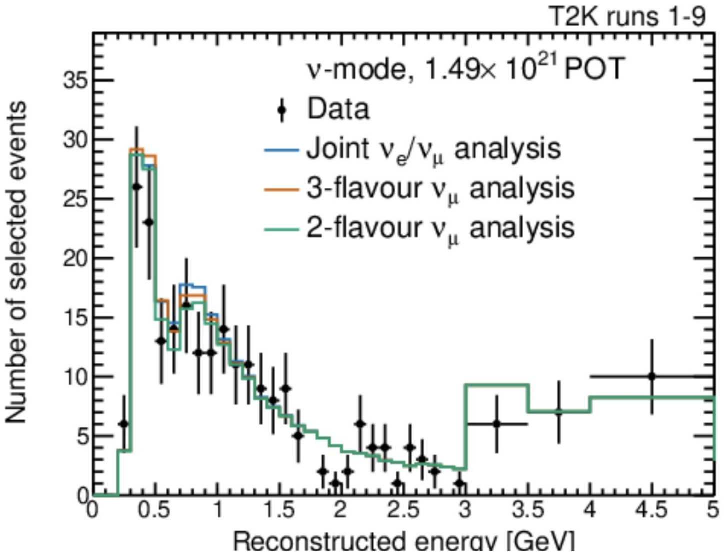
Neutrino-Nucleus Interactions

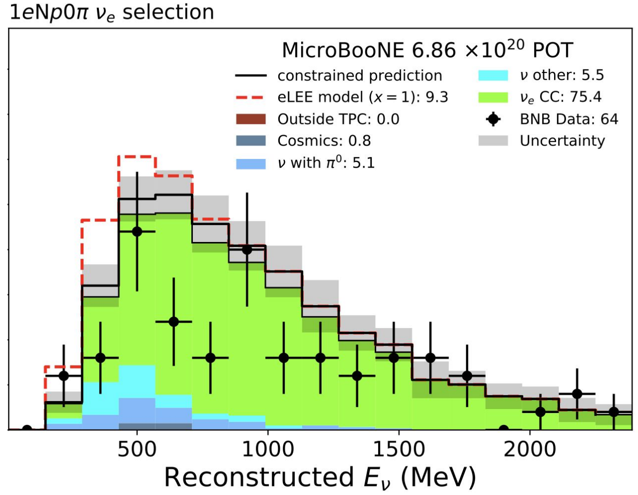
- Cross sections are the bridge between neutrino energy and observable quantities!

Figures from Phys. Rev. D 103, L011101 and Phys. Rev. Lett. 128 (2022) 24, 241801.



Neutrino flux



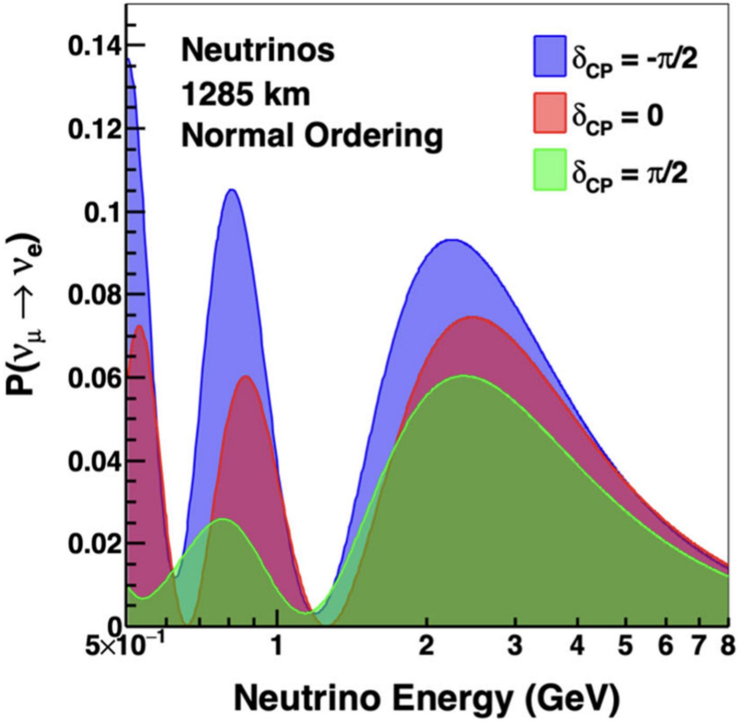


Observable Quantities

Neutrino-Nucleus Interactions

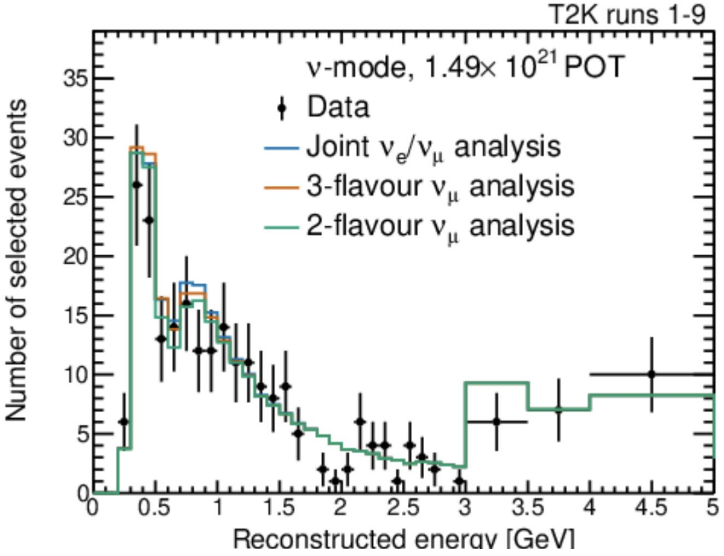
- Cross sections are the bridge between neutrino energy and observable quantities!

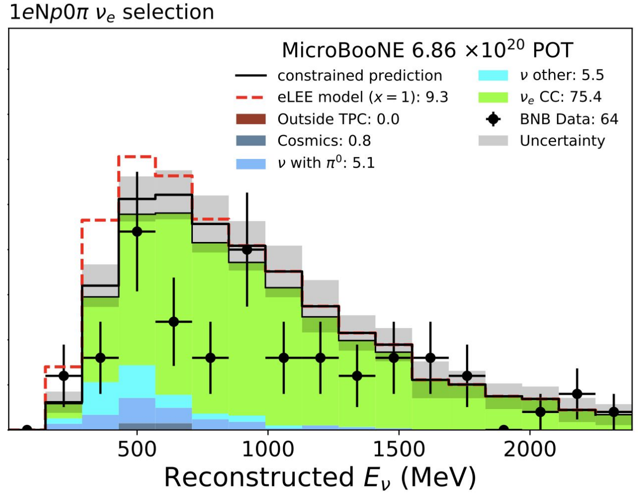
Figures from Phys. Rev. D 103, L011101 and Phys. Rev. Lett. 128 (2022) 24, 241801.



Neutrino flux

Our understanding of cross sections is far from complete!





Observable Quantities

MicroBooNE's Cross Section Program

CC inclusive

- 1D ν_μ CC inclusive @ BNB
  Phys. Rev. Lett. 123, 131801 (2019)
- 1D ν_μ CC E_ν @ BNB
  Phys. Rev. Lett. 128, 151801 (2022)
- 3D CC E_ν @ BNB
  arXiv:2307.06413 , submitted to PRL
- 1D ν_e CC inclusive @ NuMI
  Phys. Rev. D105, L051102 (2022)
  Phys. Rev. D104, 052002 (2021)

Pion production

- ν_μ NCπ^0 @ BNB
  Phys. Rev. D 107, 012004 (2023)

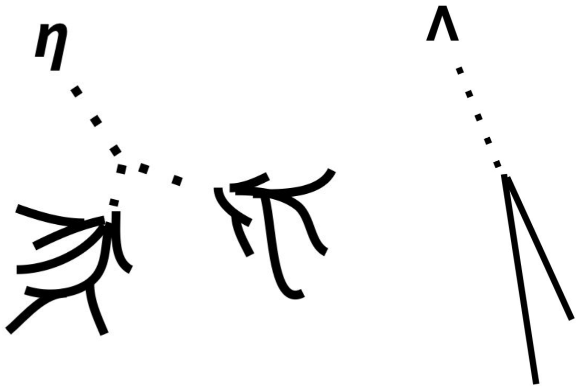
CC0π

- 1D ν_e CCNp0π @ BNB
  Phys. Rev. D 106, L051102 (2022)
- 1D & 2D ν_μ CC1p0π Transverse Imbalance @ BNB
  Phys. Rev. Lett. 131, 101802 (2023)
  Phys. Rev. D 108, 053002 (2023)
- 1D & 2D ν_μ CC1p0π Generalized Imbalance @ BNB
  arXiv:2310.06082, submitted to PRD
- 1D ν_μ CC1p0π @ BNB
  Phys. Rev. Lett. 125, 201803 (2020)
- 1D ν_μ CC2p @ BNB
  arXiv:2211.03734
- 1D ν_μ CCNp0π @ BNB
  Phys. Rev. D102, 112013 (2020)

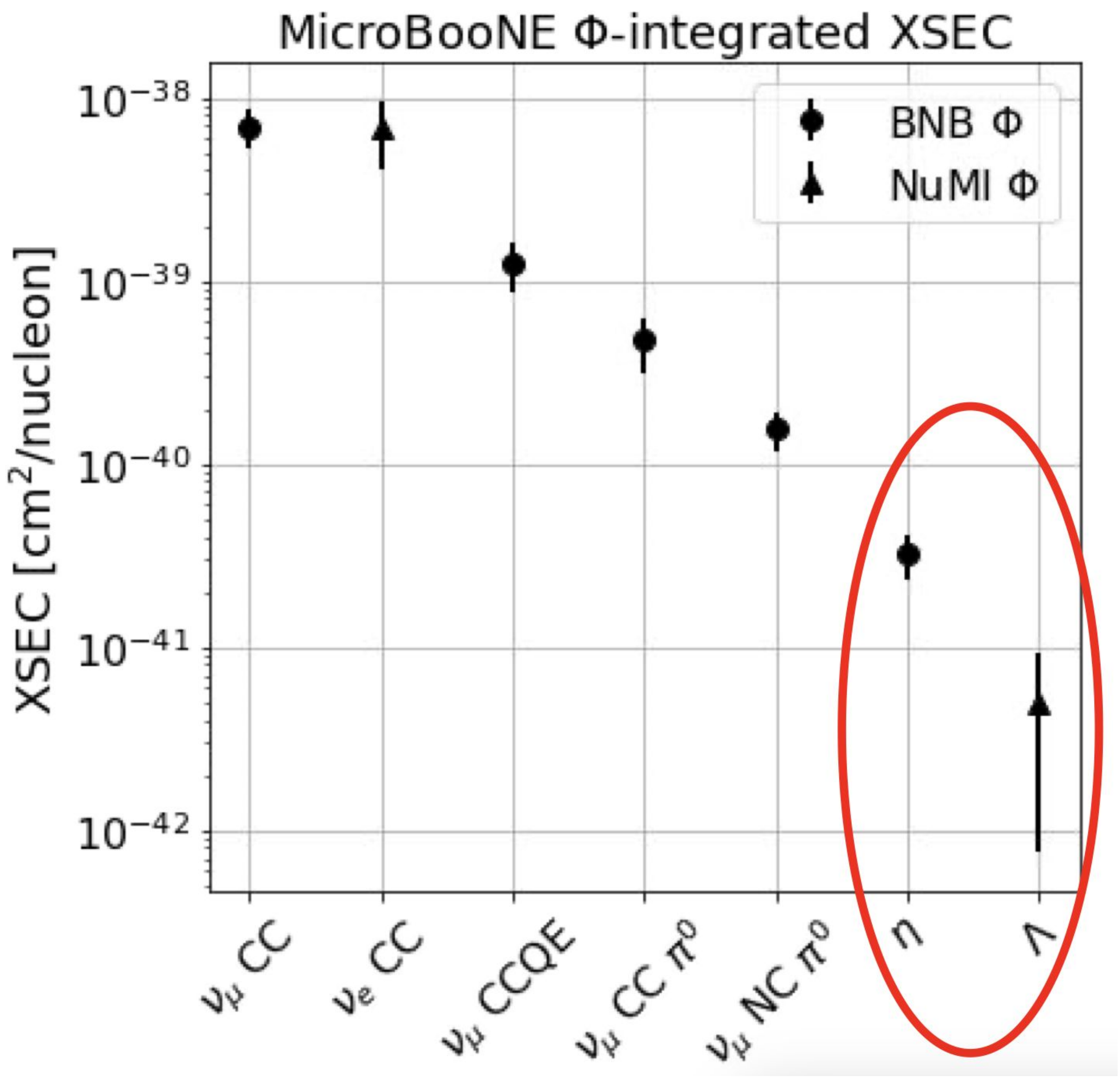
Rare Event Searches

- The topics of this talk are two recent measurements that exploit MicroBooNE's large dataset:

1. **η meson production.**
2. **Λ baryon production.**

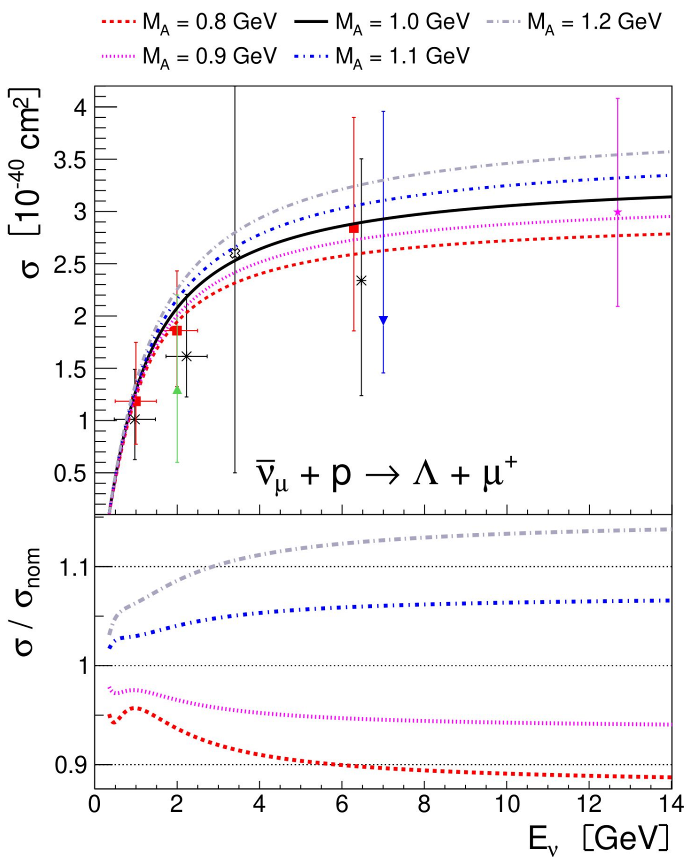


Look out for the logos!



Λ Production - Why?

Neutrino-nucleon cross section physics!



The Hyperon Puzzle!

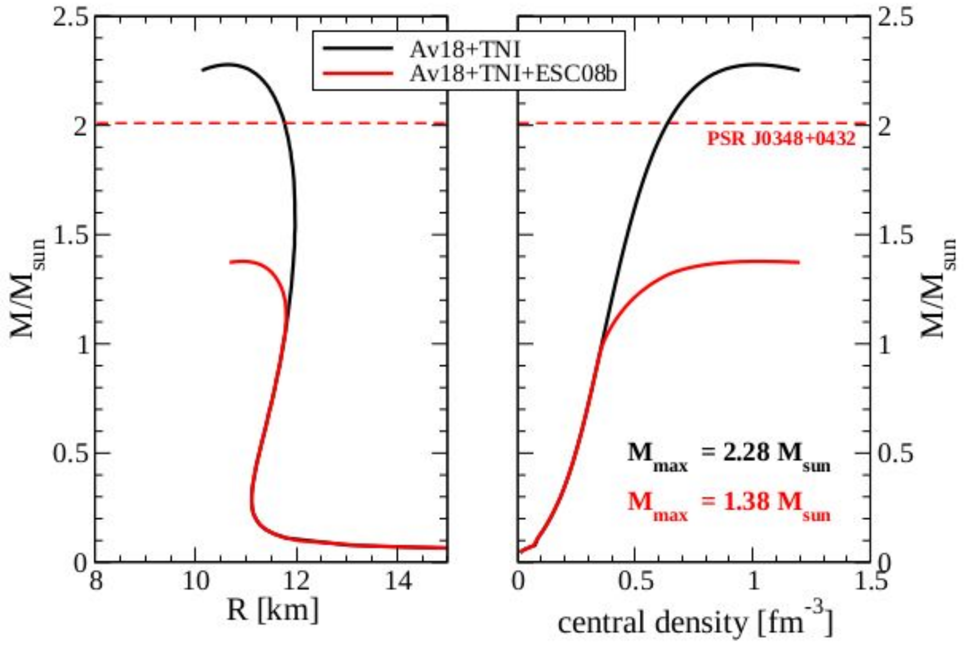
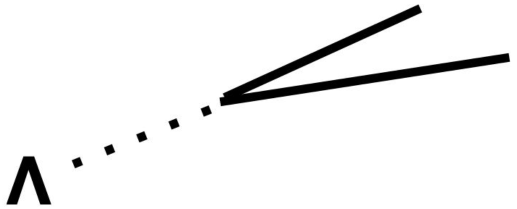
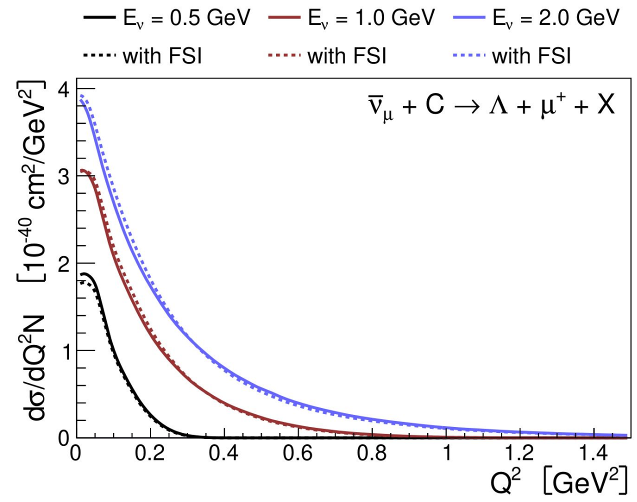
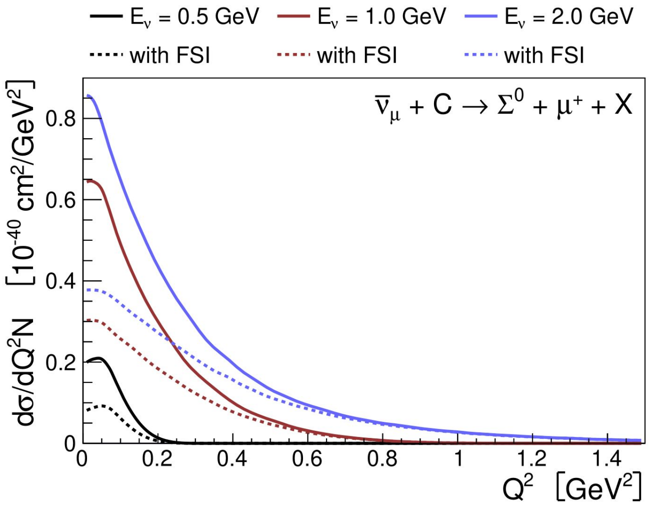


Figure from [EPJ Web Conf .271(2022), p. 09001]().



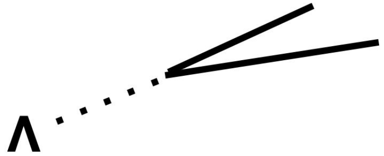
Unique Nuclear Effects!



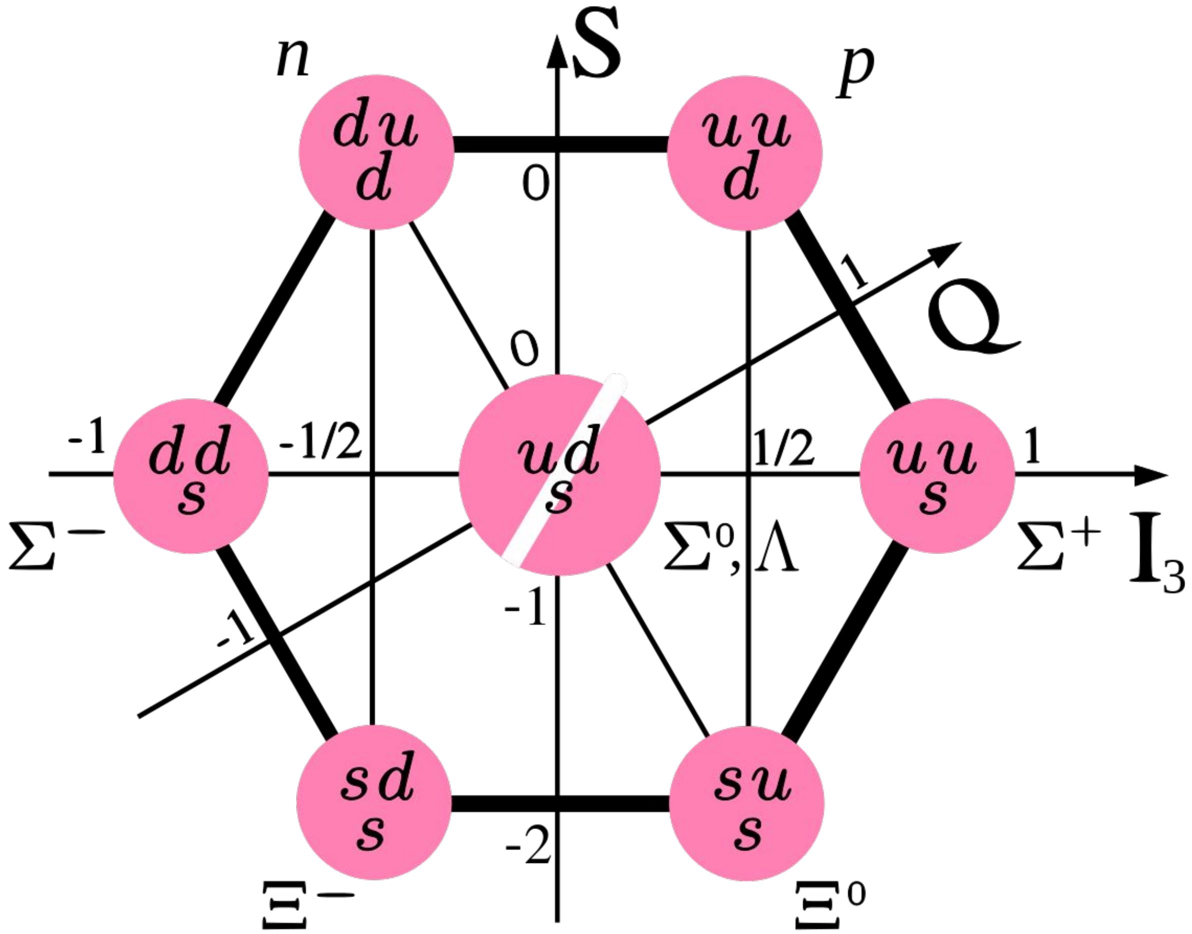


Figures from [Phys.Rev.C 104 (2021) 3, 035502]()

Hyperons



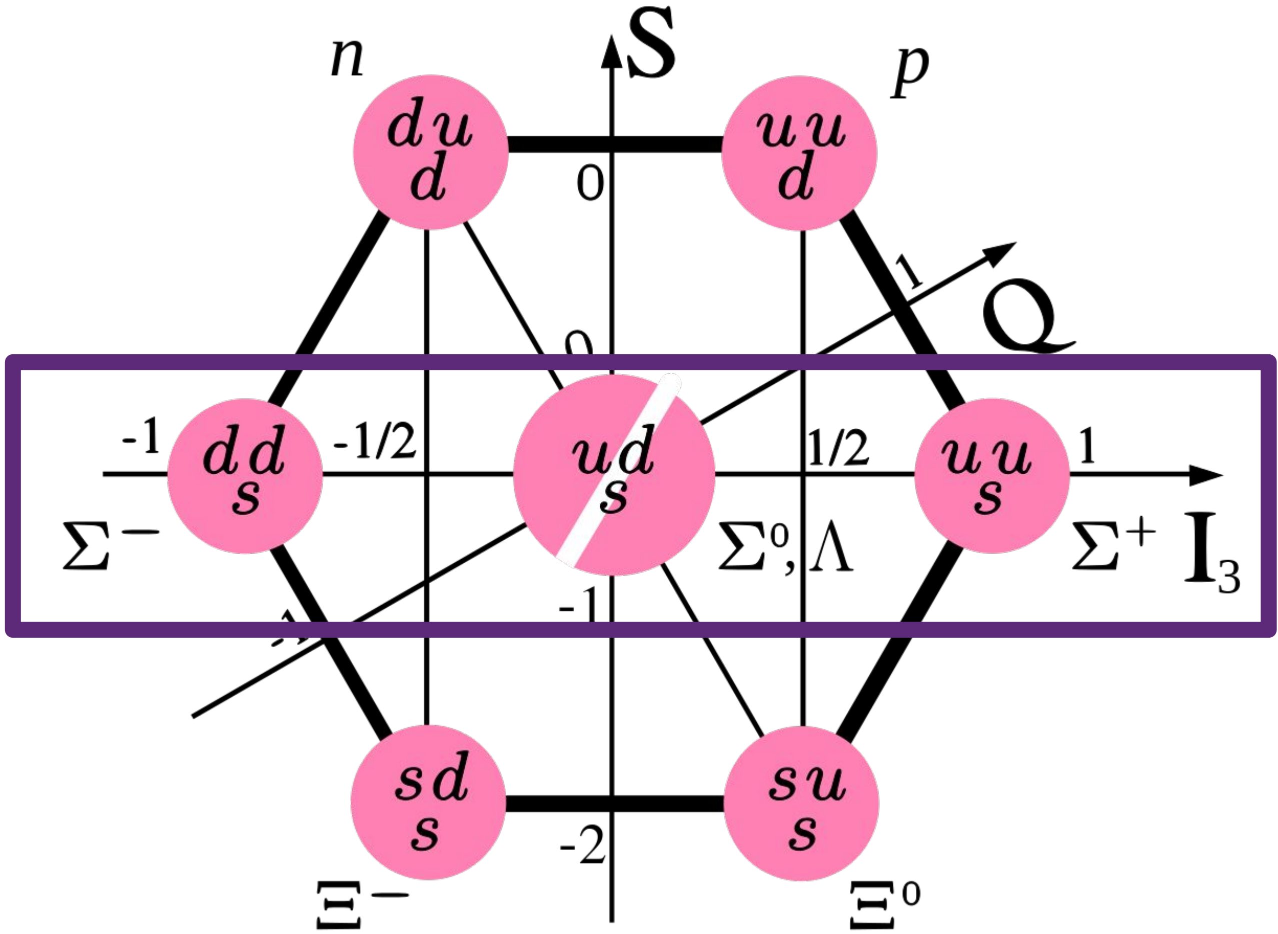
- The Λ^0 baryon is a hyperon - a baryon containing a strange quark*.



*Sometimes this term means multiply strange baryons and charmed baryons. Here we just care about the Λ and Σ baryons.

Hyperons

- The Λ^0 baryon is a hyperon - a baryon containing a strange quark*.
- The lightest hyperons are the spin ½ Λ and Σ baryons, with masses around 1.1-1.2 GeV.

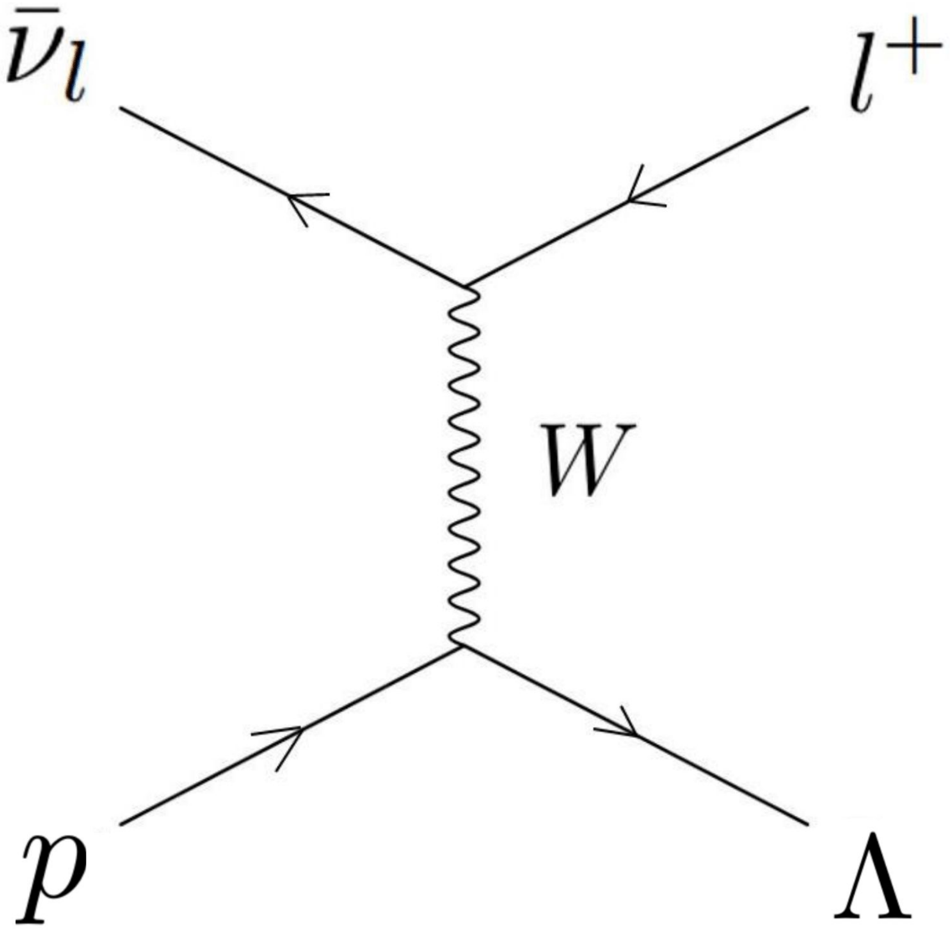


*Sometimes this term means multiply strange baryons and charmed baryons. Here we just care about the Λ and Σ baryons.

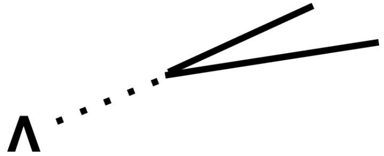
CCQE-like Hyperon Production

- **Cabibbo suppressed** counterpart of CCQE.
- Hyperons are heavier than nucleons.
- Only available to anti-neutrinos.

- All make this a rare interaction!

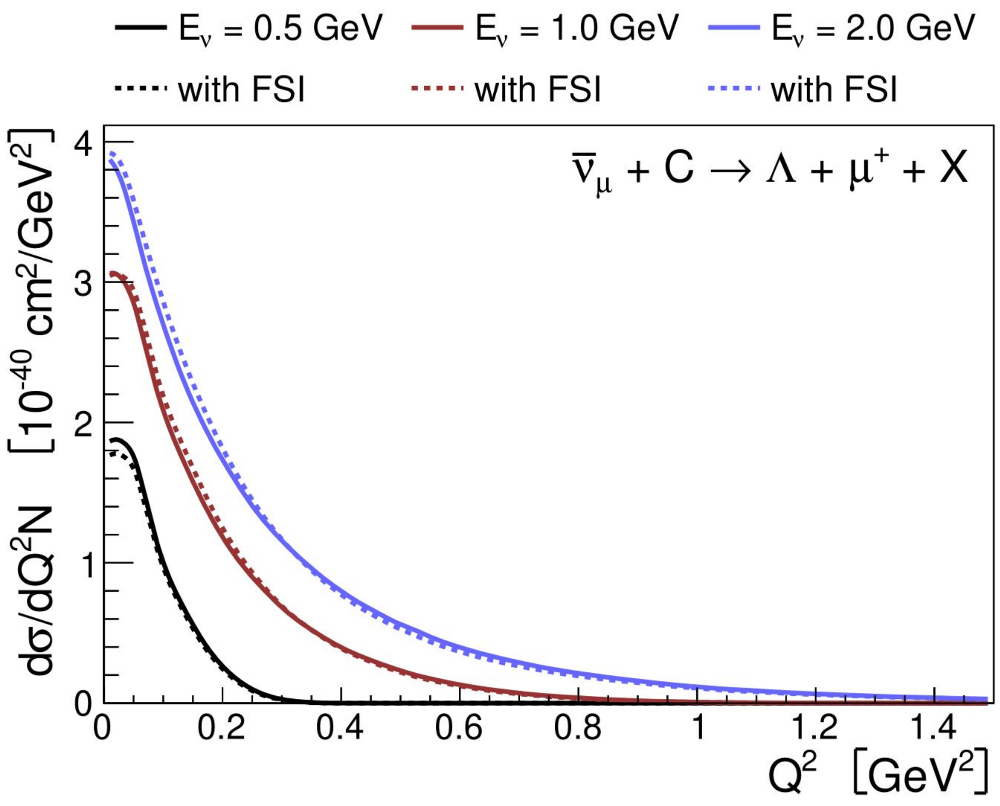


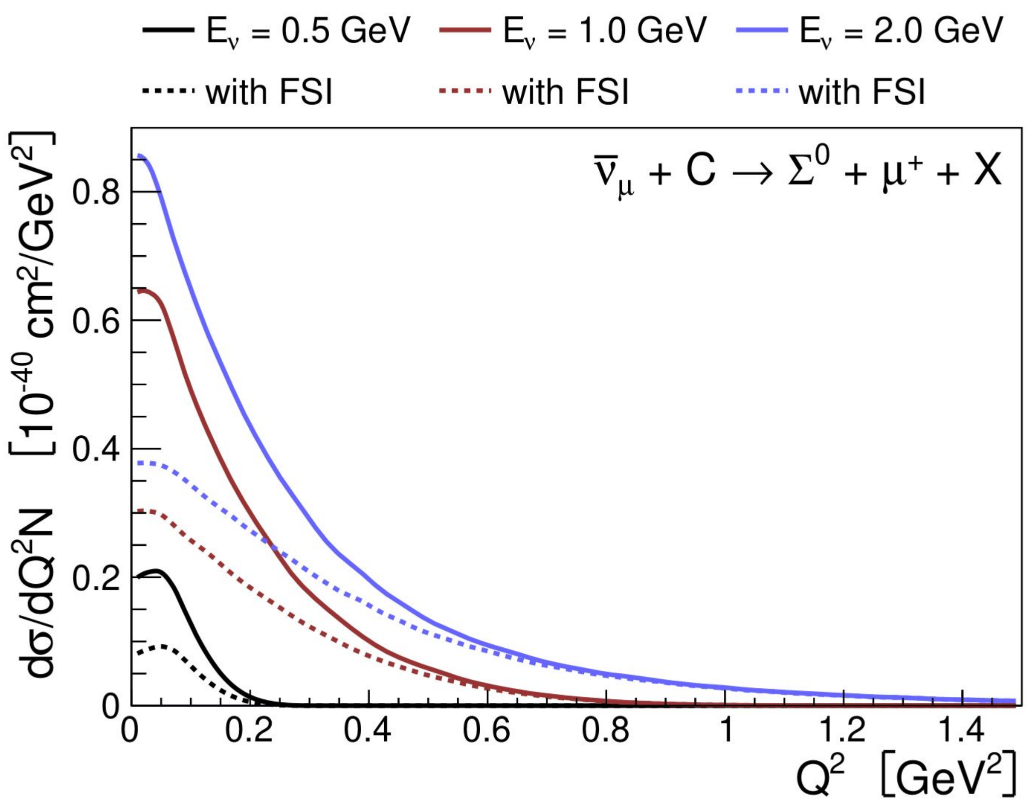
CCQE-like Hyperon Production



- Cross sections of Σ production channels are predicted to be very sensitive to FSI.

Figures from [Phys.Rev.C 104 (2021) 3, 035502]



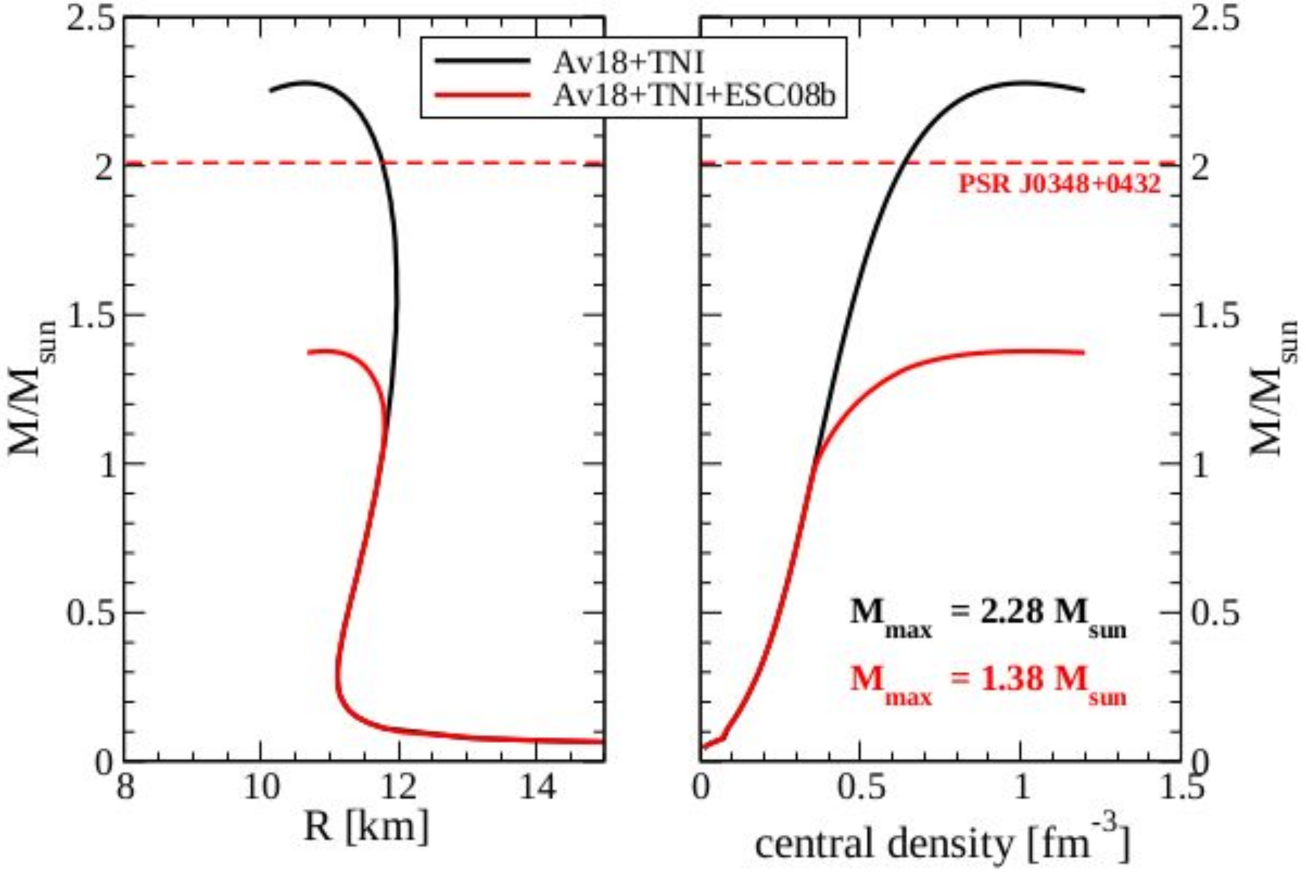


- Measure multiple channels - disambiguate FSI from other effects!

The Hyperon Puzzle

- Creation of hyperons in dense neutron stars not well understood.
- Long range interactions between hyperons and nucleons are a factor - we can study these through hyperon production in neutrino scattering.

Figure from [EPJ Web Conf .271(2022), p. 09001].



Mass limits of neutron stars, **with** and **without** including hyperons in the EOS. Conflict with observation (horizontal line).

CCQE-like Λ Baryon Production - Measurements

- Only a handful of low-statistics bubble chamber measurements, all several decades old at this point.

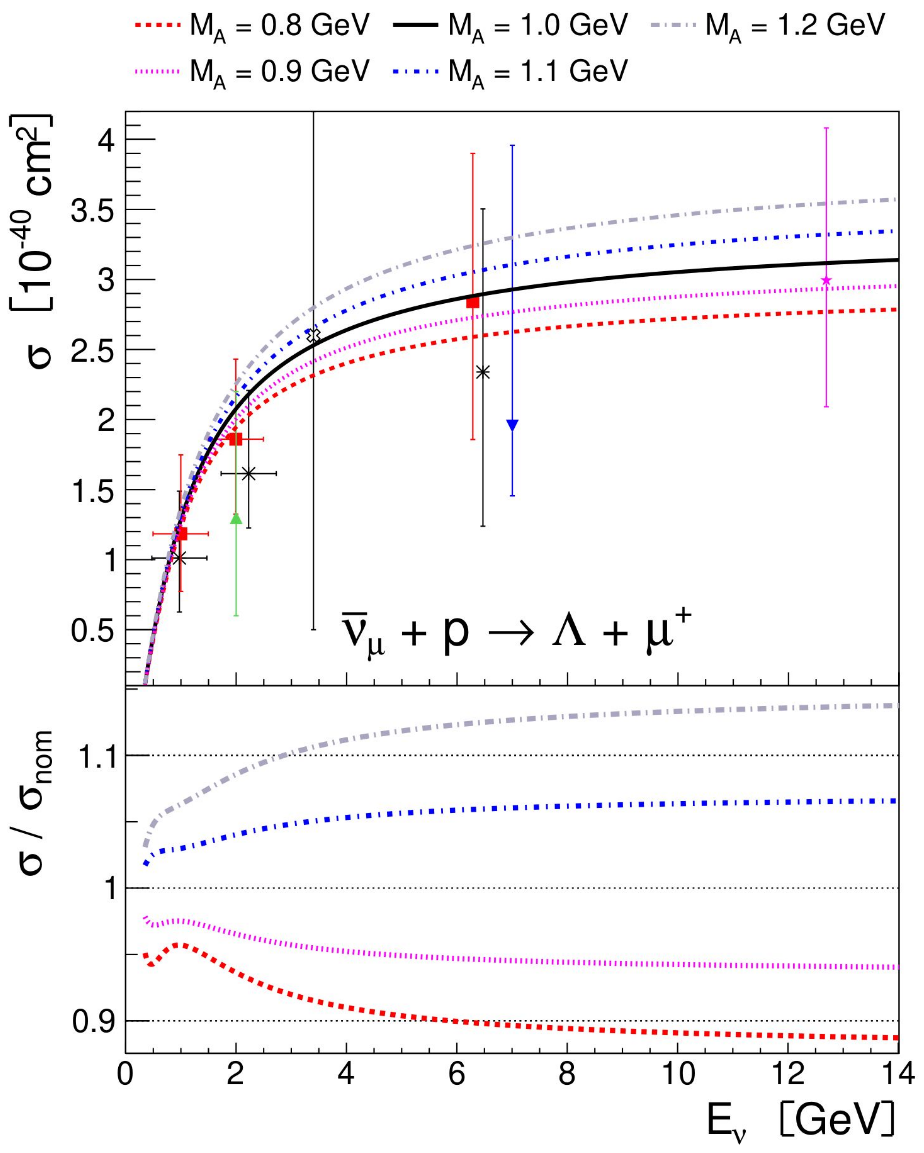
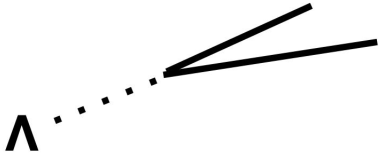
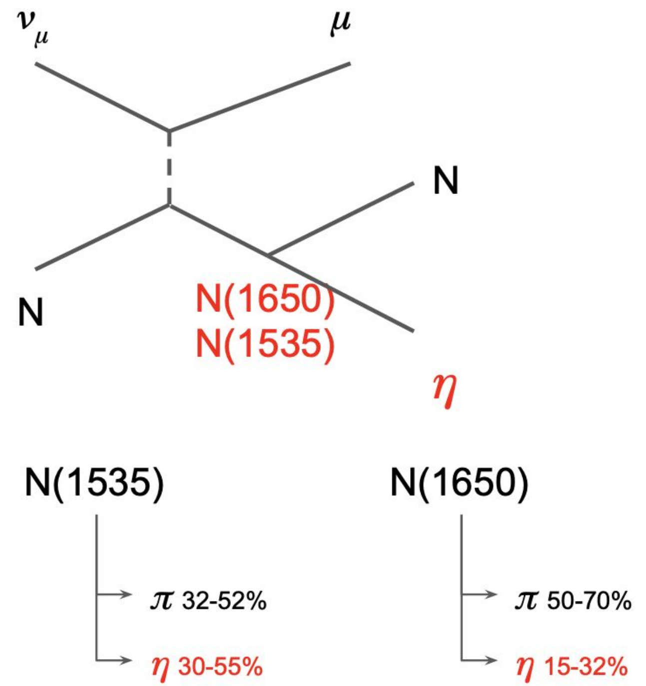


Figure from [Phys.Rev.C 104 (2021) 3, 035502]



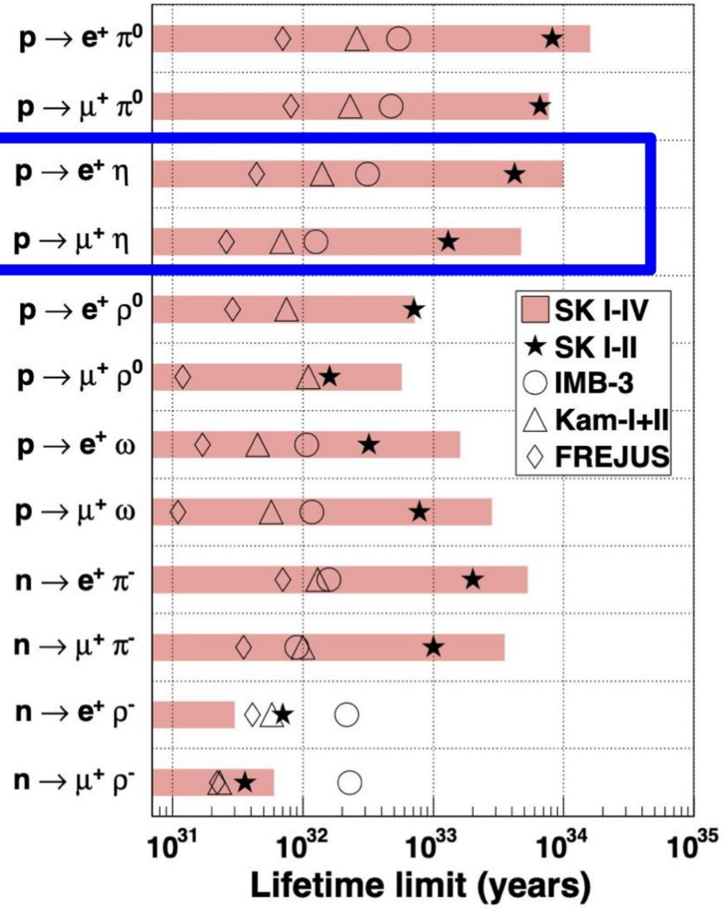
η Meson Production - Why?

Neutrino-nucleon cross section physics!



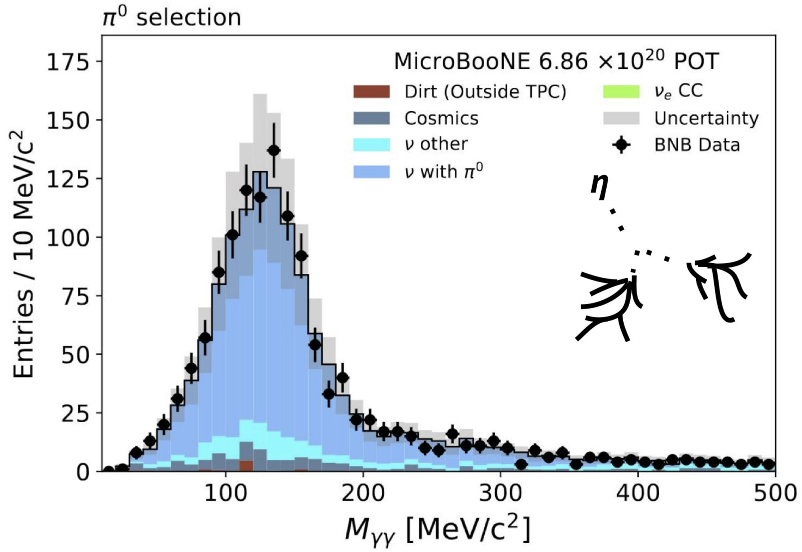
Proton decay!

Super-K PRD 96, 012003



Super-K Limits

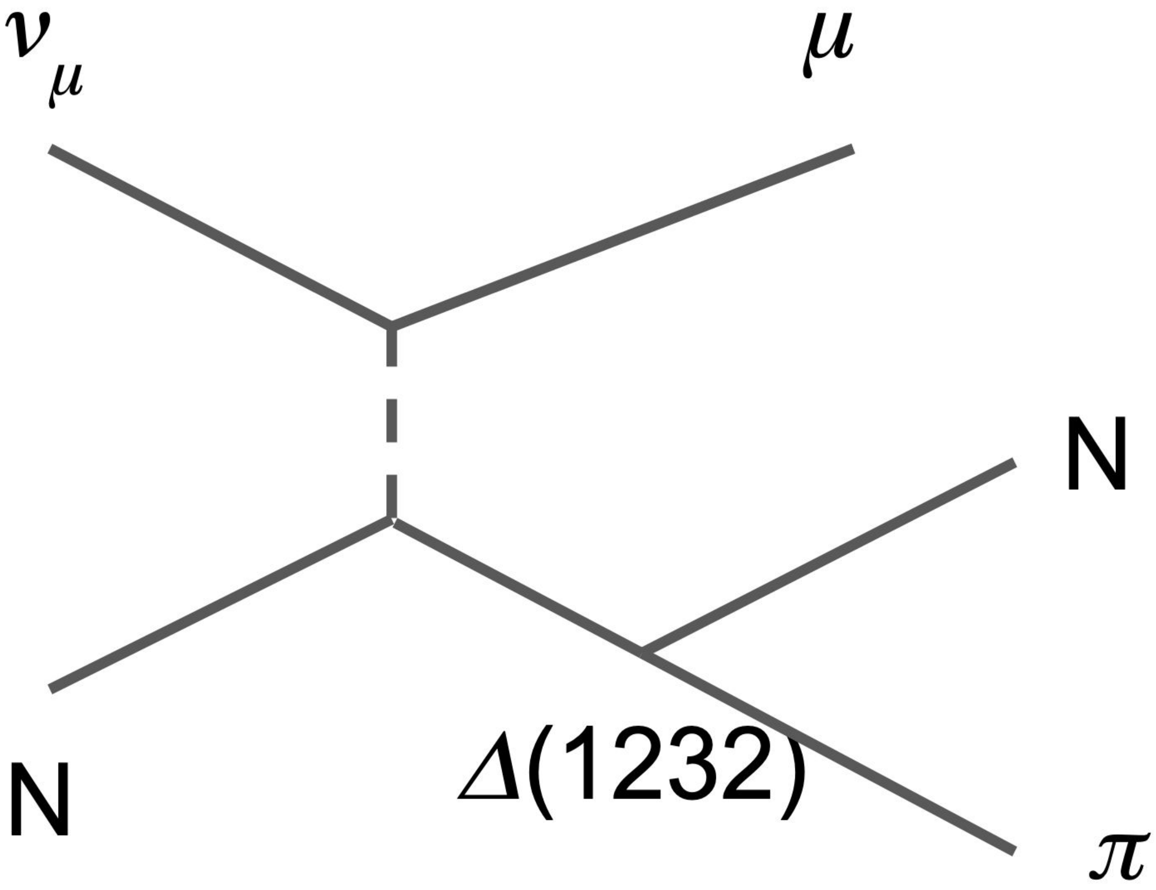
LArTPC Calibration!



η Mesons and Resonance Structure

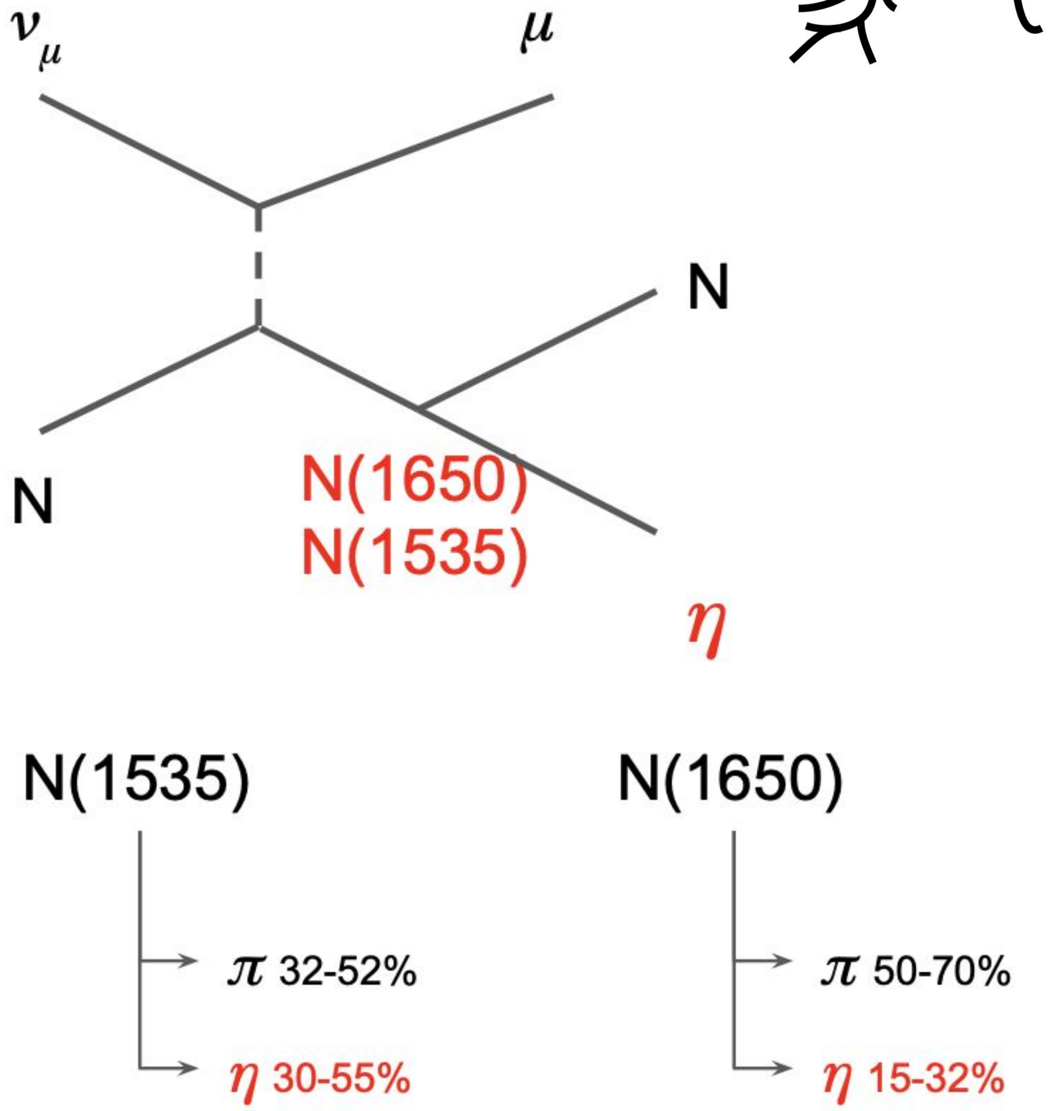
- The most common resonance in neutrino interactions is the Δ (1232).

- Creation of higher resonances above this in neutrino interactions very poorly understood.



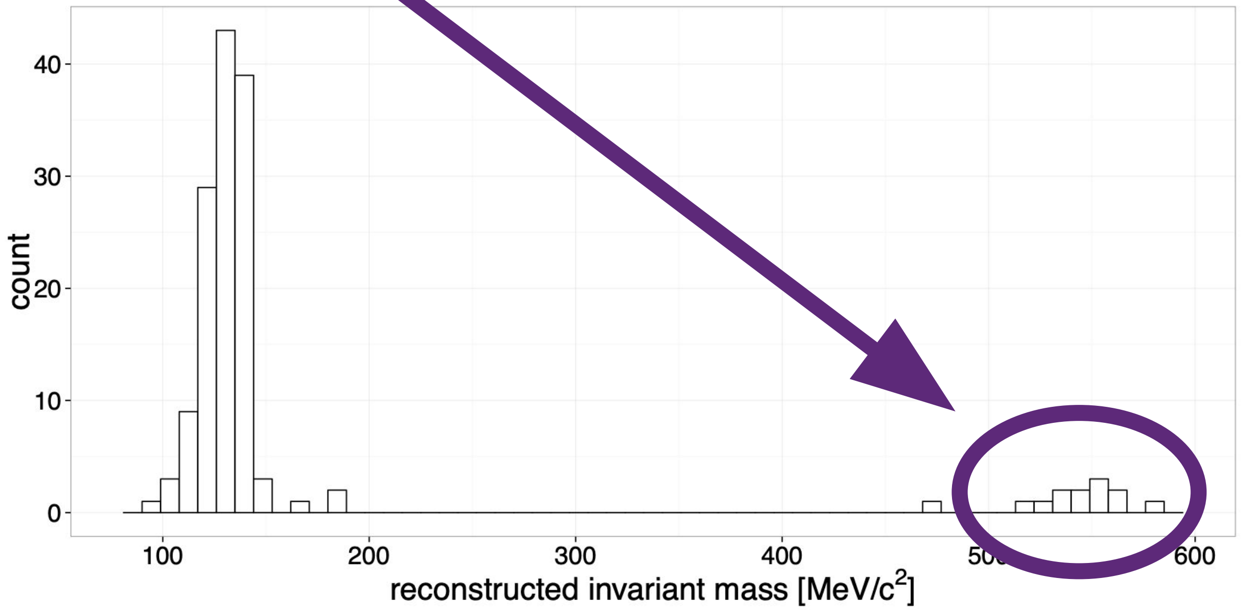
η Mesons and Resonance Structure

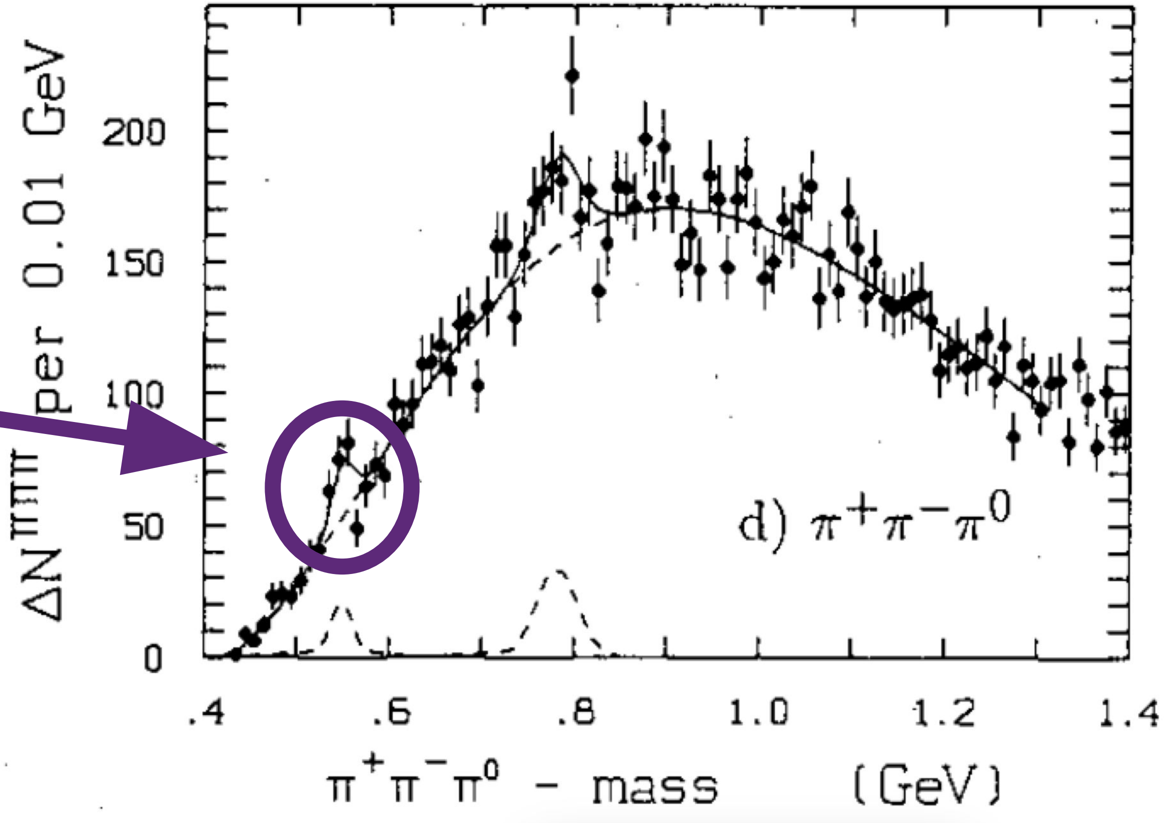
- Creation of higher resonances above this in neutrino interactions very poorly understood.
- η cannot be produced in Δ (1232) decays, equip us with less ambiguous handle to study higher resonances.



η Production Measurements

- “Bumps” in invariant mass plots observed by BEBC WA49 and ICARUS collaborations.

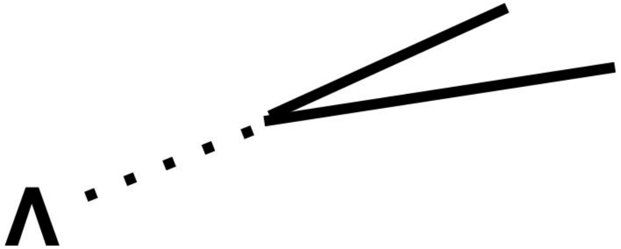




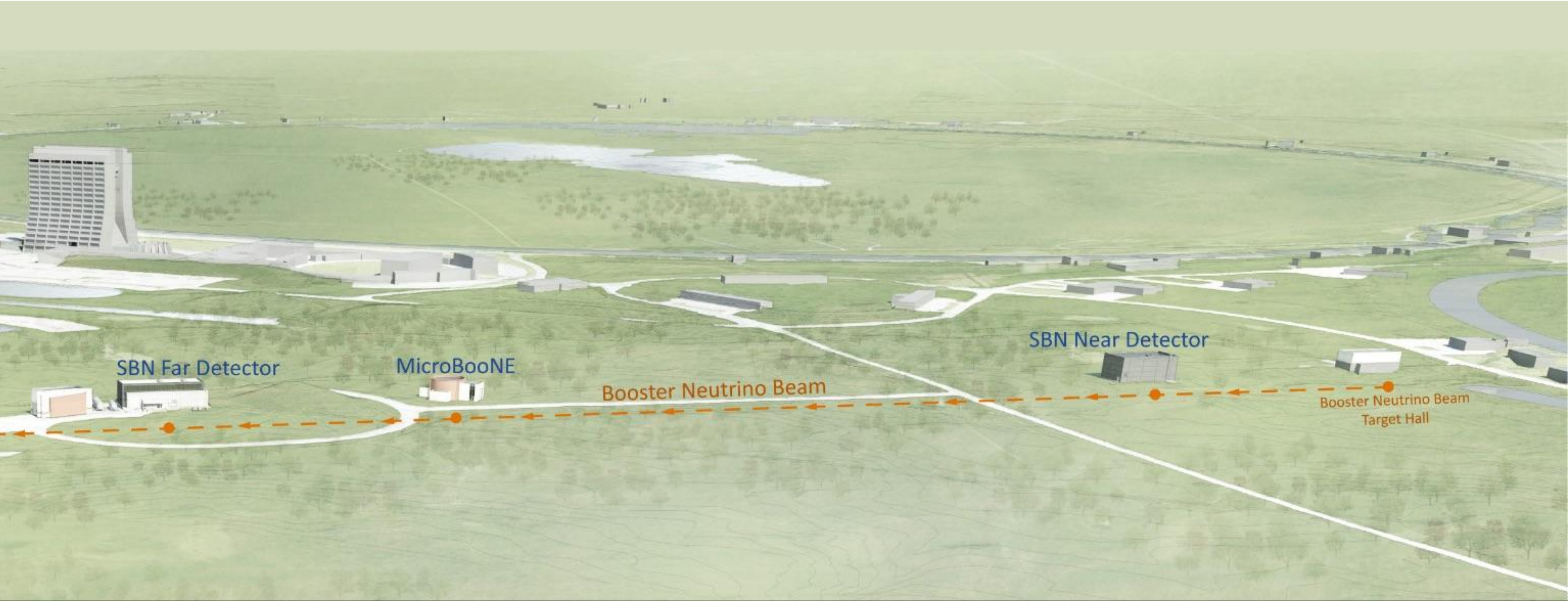
[BEBC WA59]

[I. Kochanek PhD Thesis (Silesia University)]

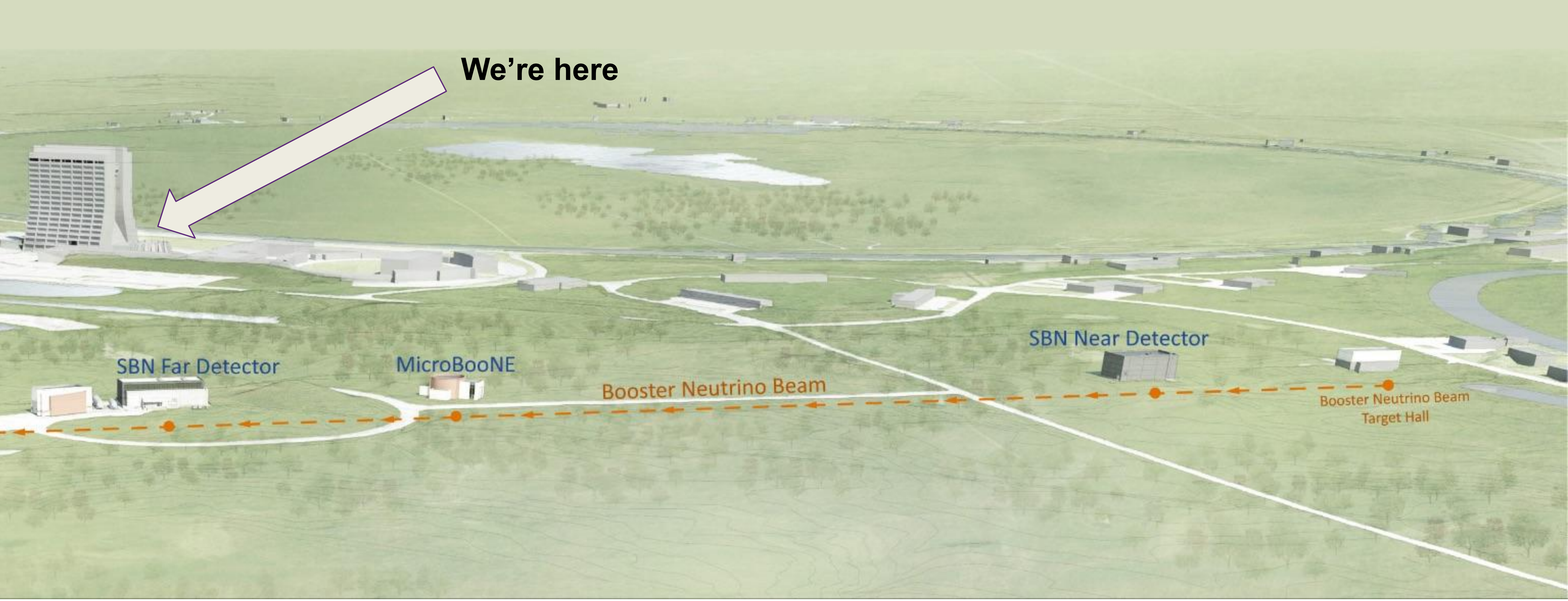
So Can We Measure Them?



The Micro-Booster-Neutrino-Experiment

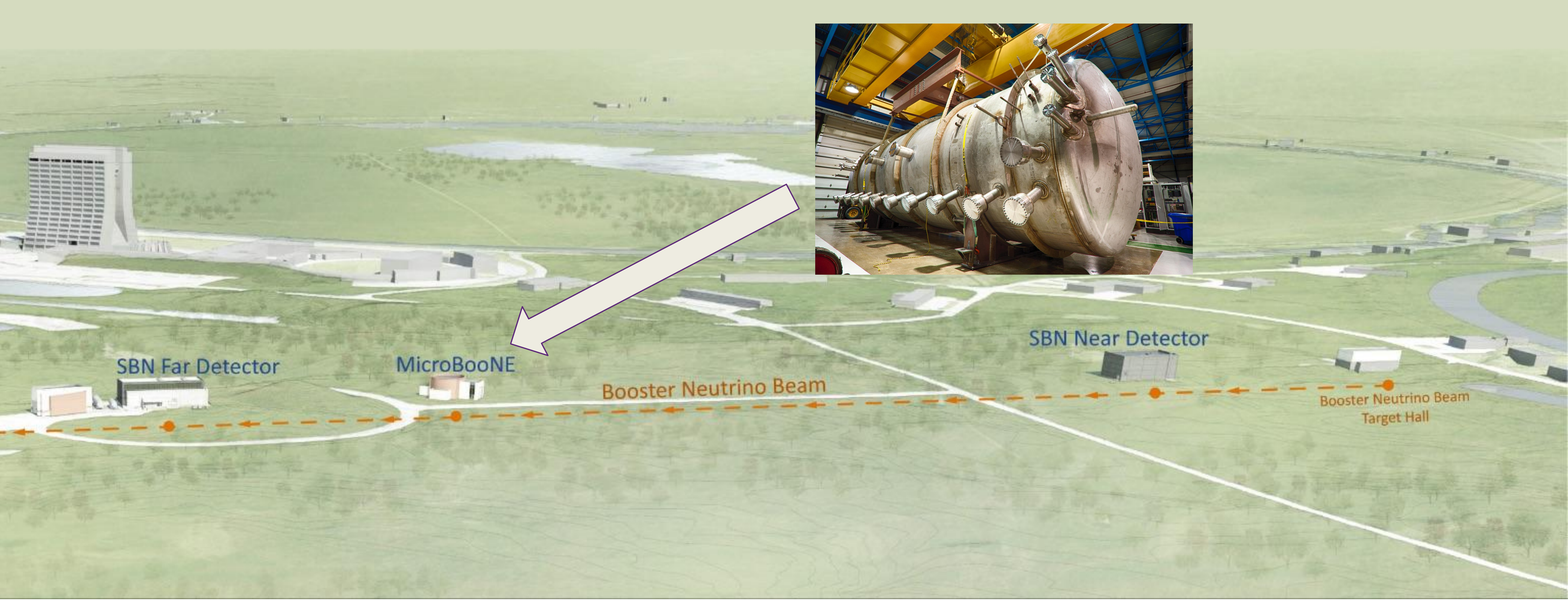


The Micro-Booster-Neutrino-Experiment



Alas, the bison pen does not fit onto this slide…

The Micro-Booster-Neutrino-Experiment



Alas, the bison pen does not fit onto this slide…

The Liquid Argon Time Projection Chamber

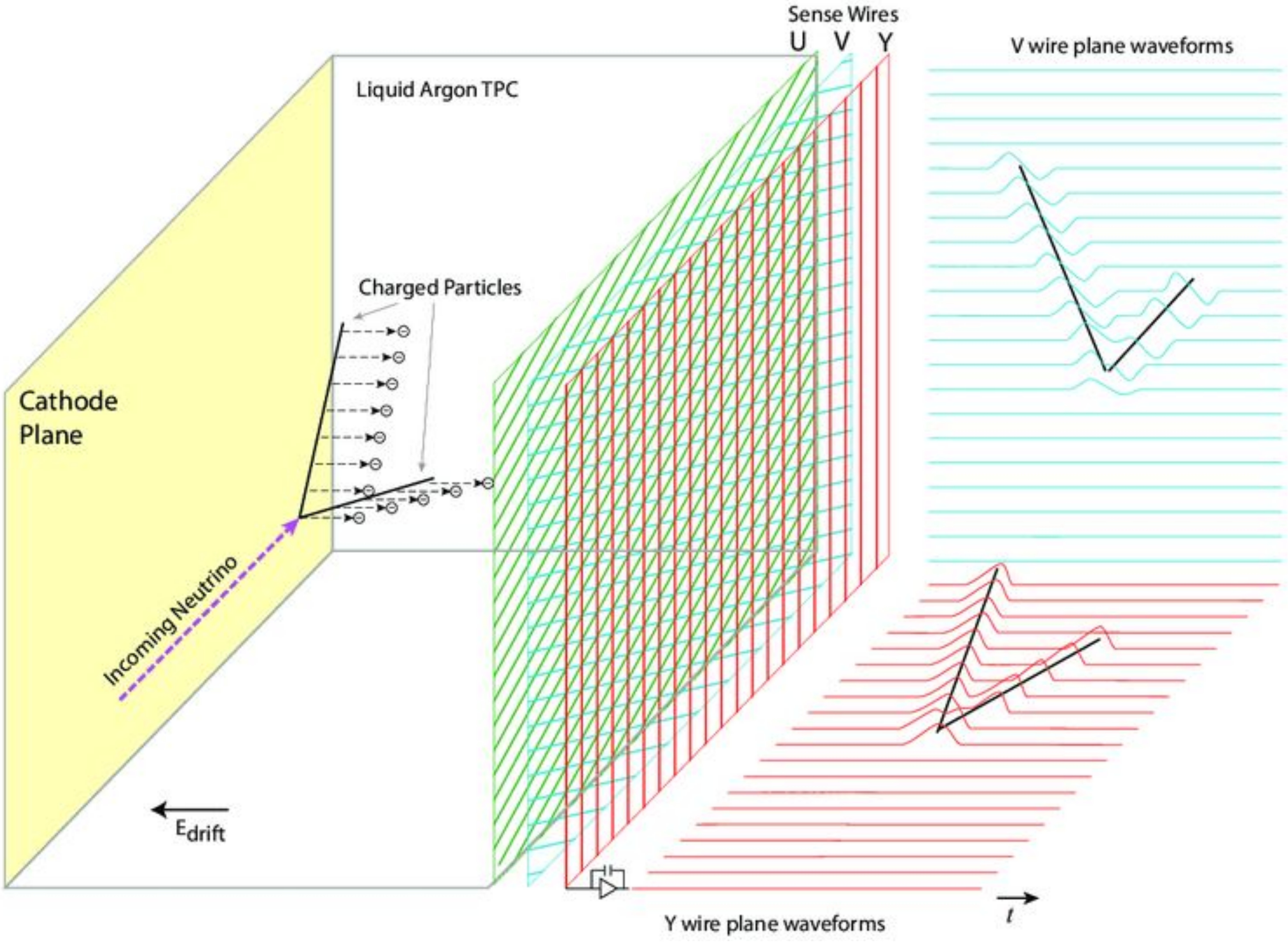


Figure from JINST 12.02 (2017), P02017.

The LArTPC - Tracking

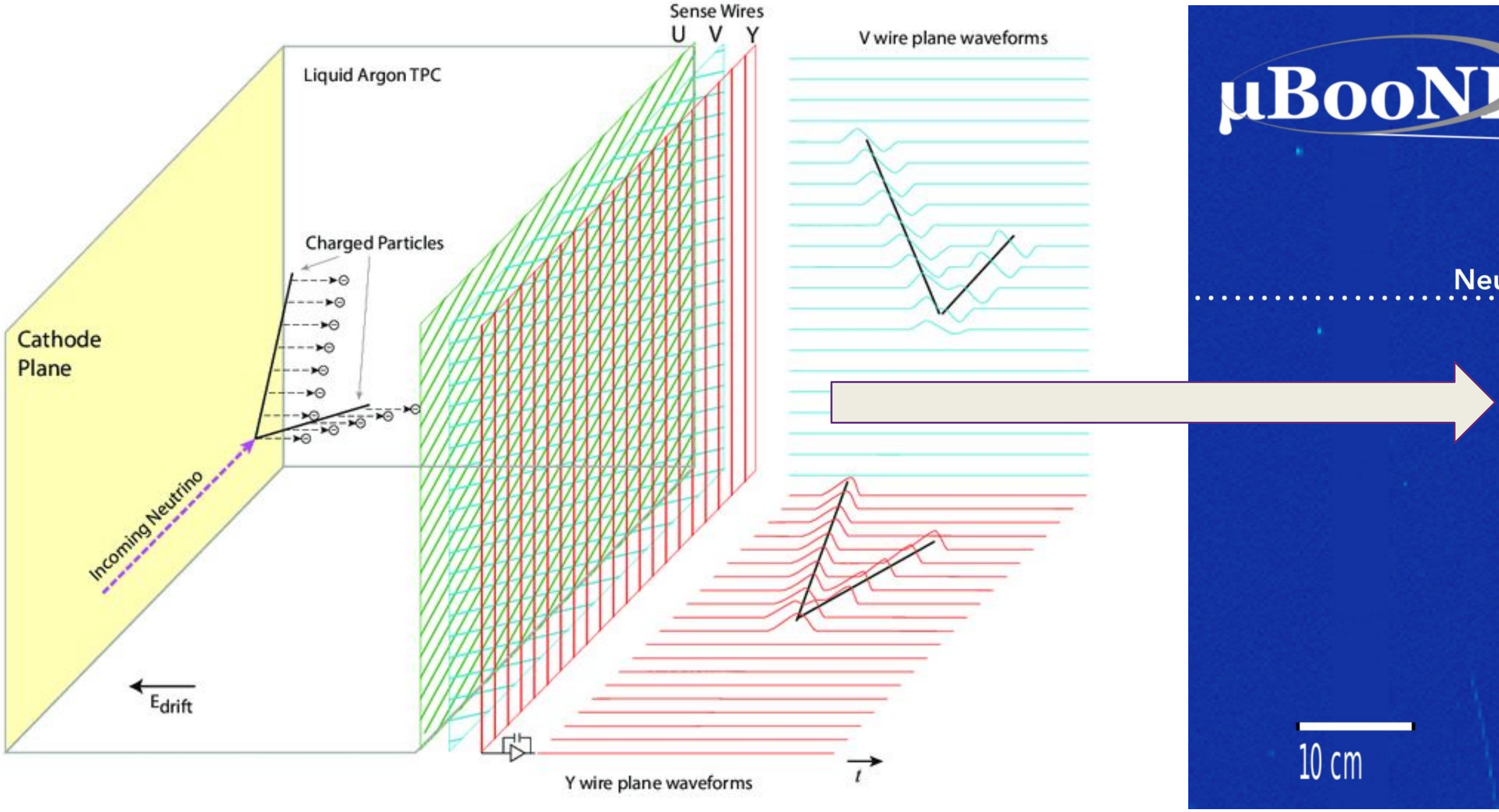
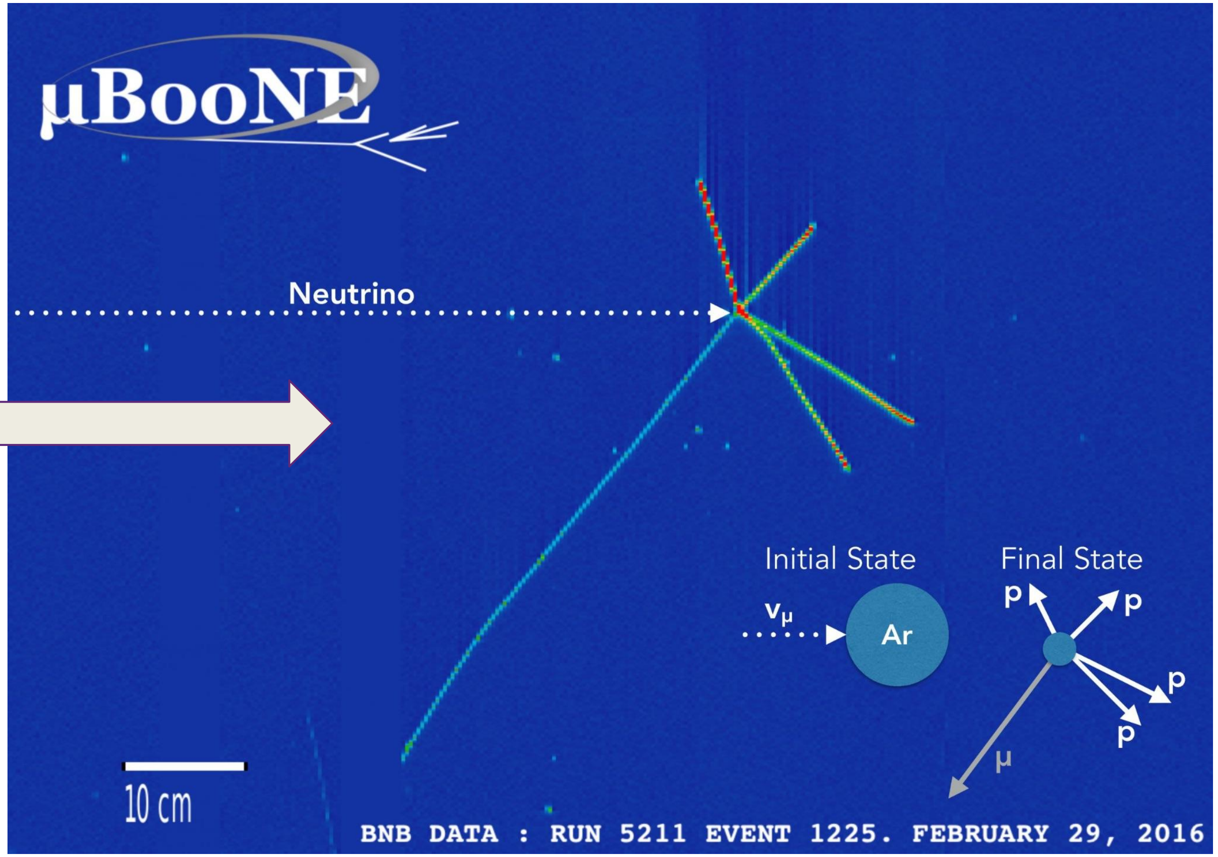


Figure from JINST 12.02 (2017), P02017.



\+ 2 other images from different angles

LArTPC - Calorimetry

- Measure intensity of energy loss in the detector - main ingredient in particle ID.

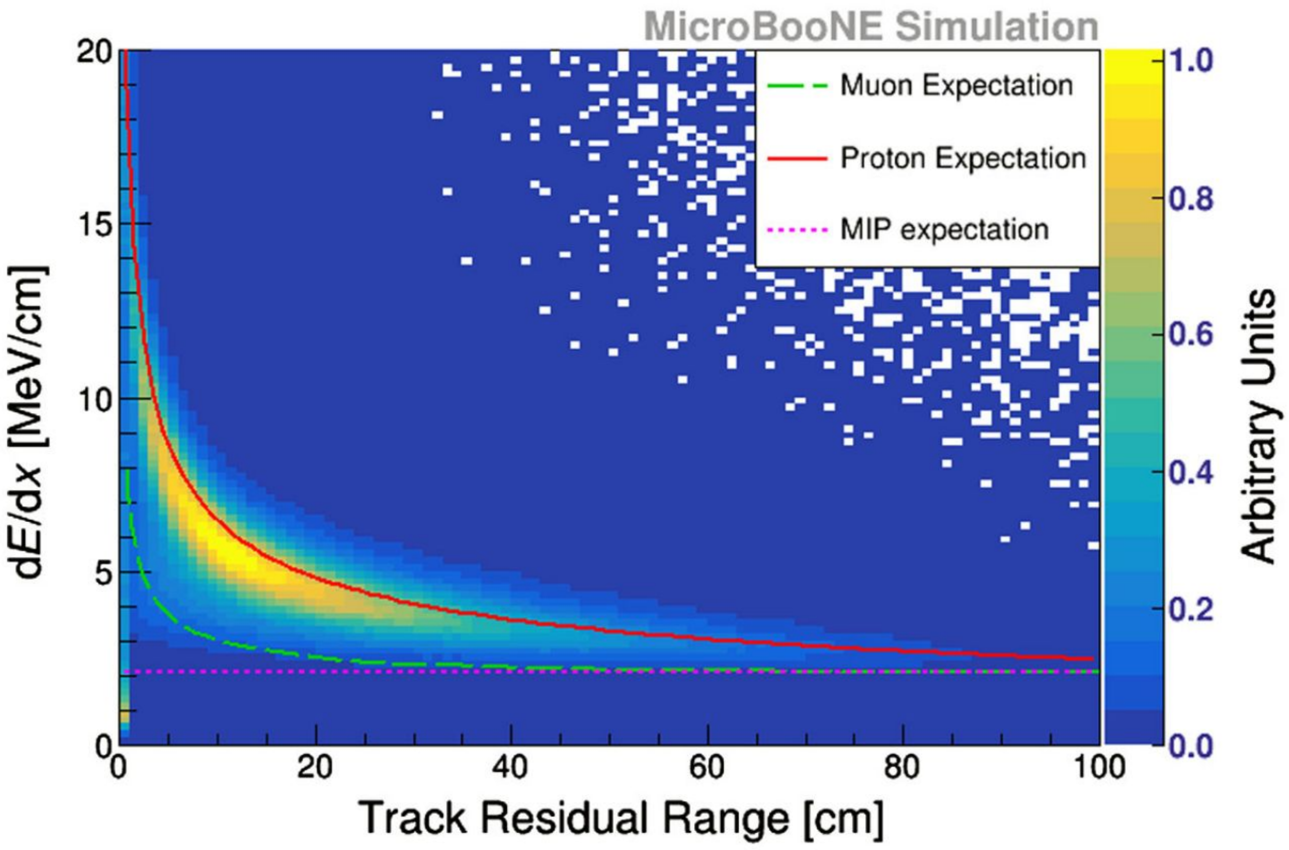


Figure from Phys. Rev. D 102, 112013.

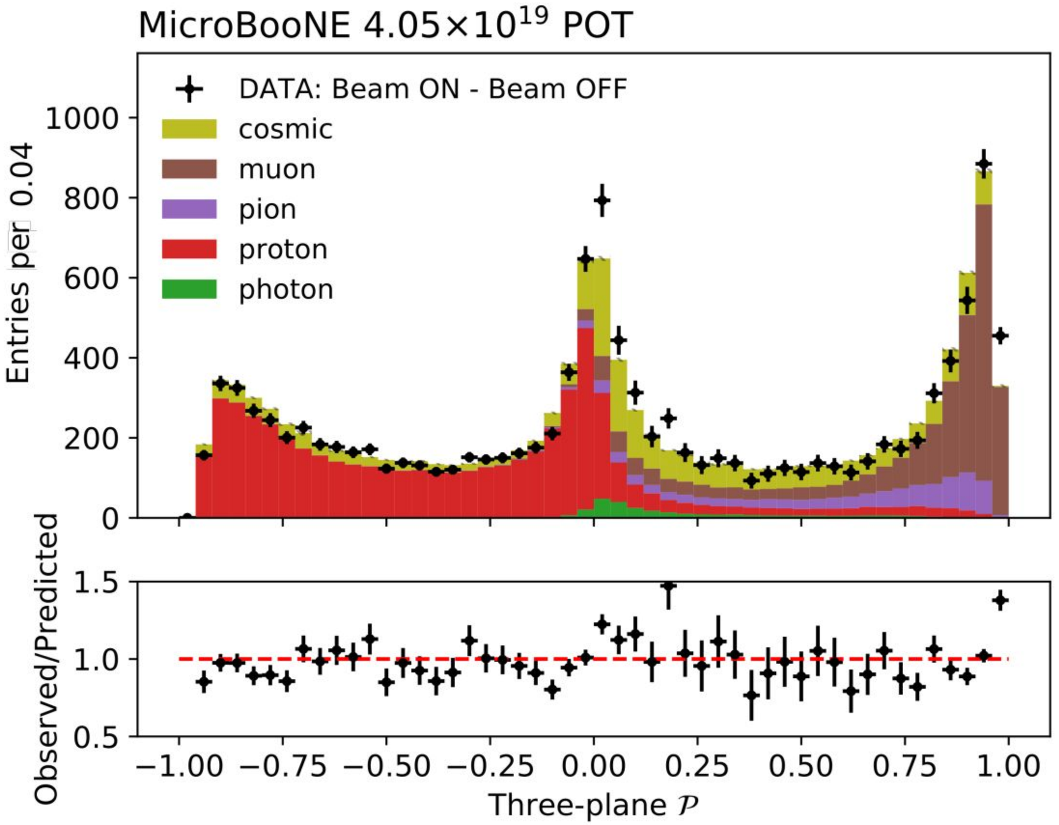


Figure from JHEP 12 (2021) 153.

MicroBooNE Reconstruction

- For both analyses, we employ the Pandora reconstruction framework.
- This classifies reconstructed particles as either tracks or showers:

Track-like	Shower-like
p, μ, $\pi^{\pm}$, $K^{\pm}$	e, γ

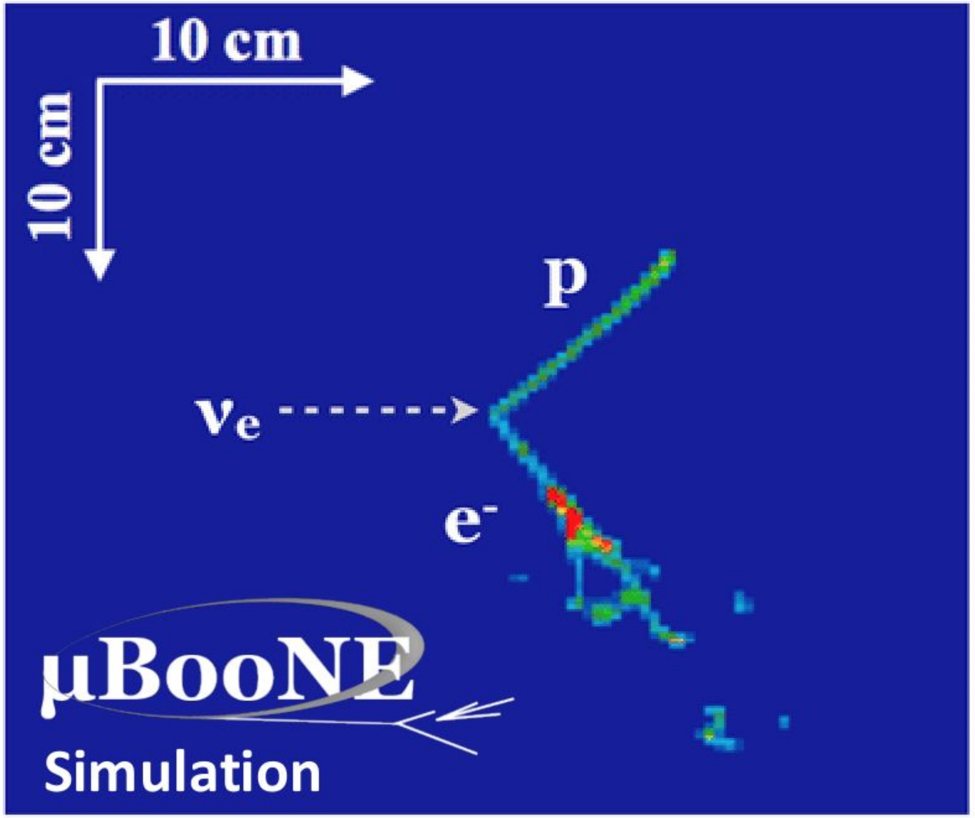
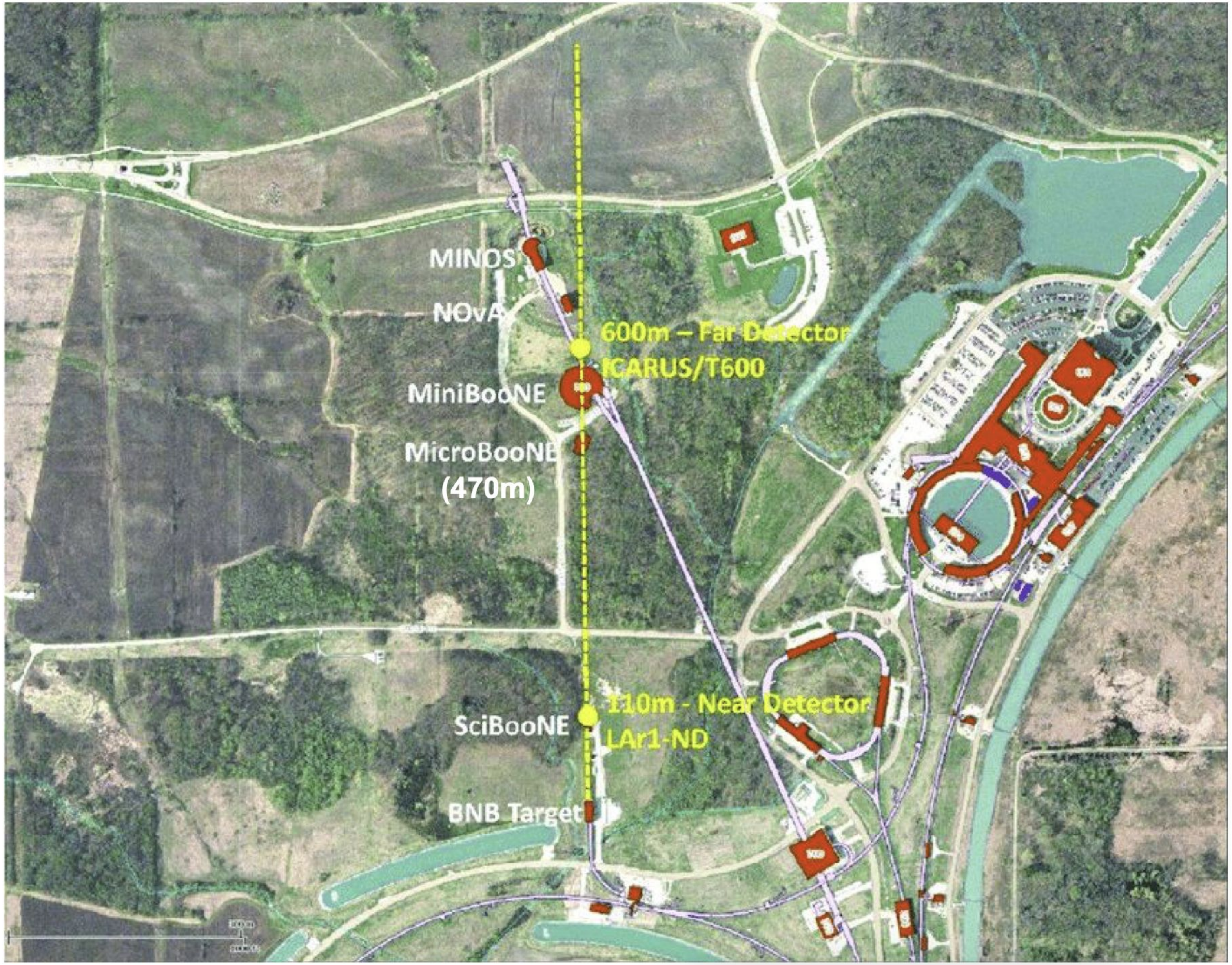


Figure from Phys. Rev. D 99, 092001.

The Beams

Figure from arXiv:1503.01520.



The Beams

The BNB:
On-axis.
Neutrino mode only.

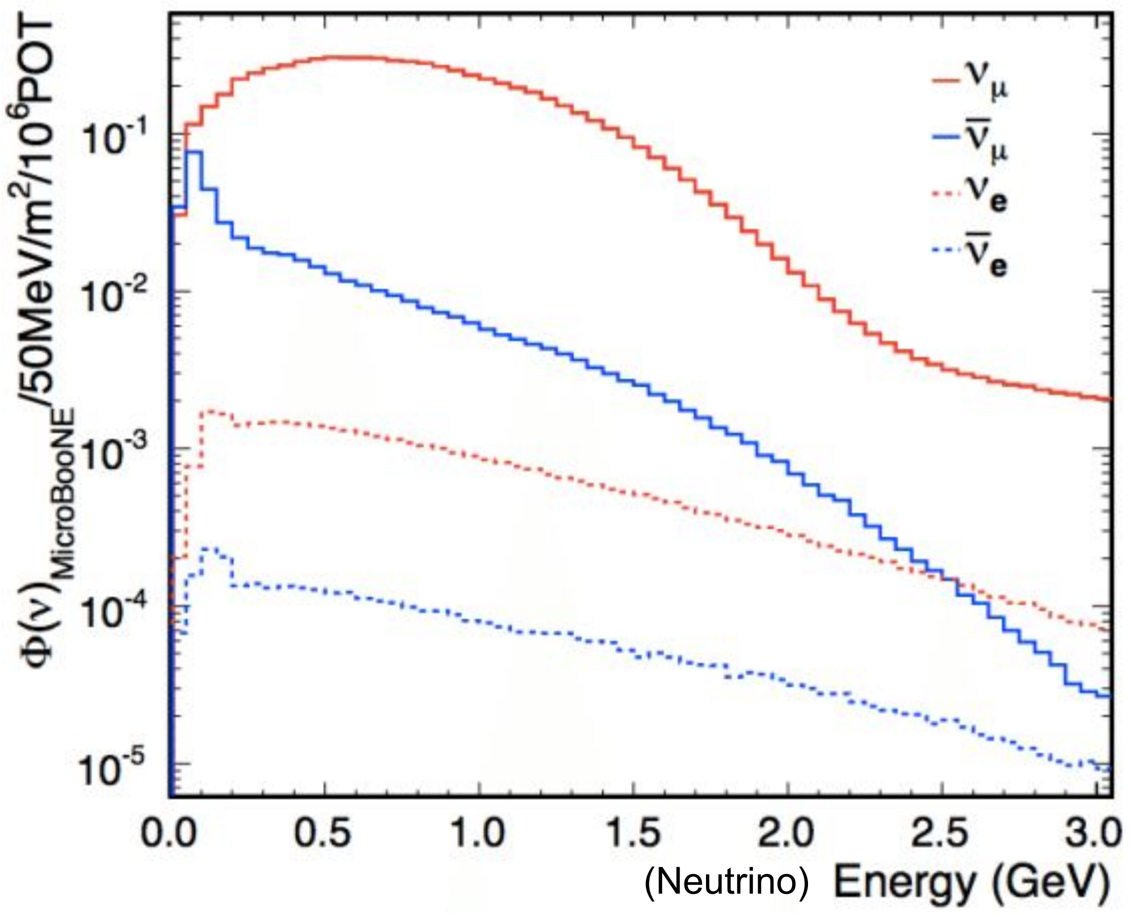


Figure from arXiv:1709.00146.

NuMI:
Off-axis.
Mixture of both modes.

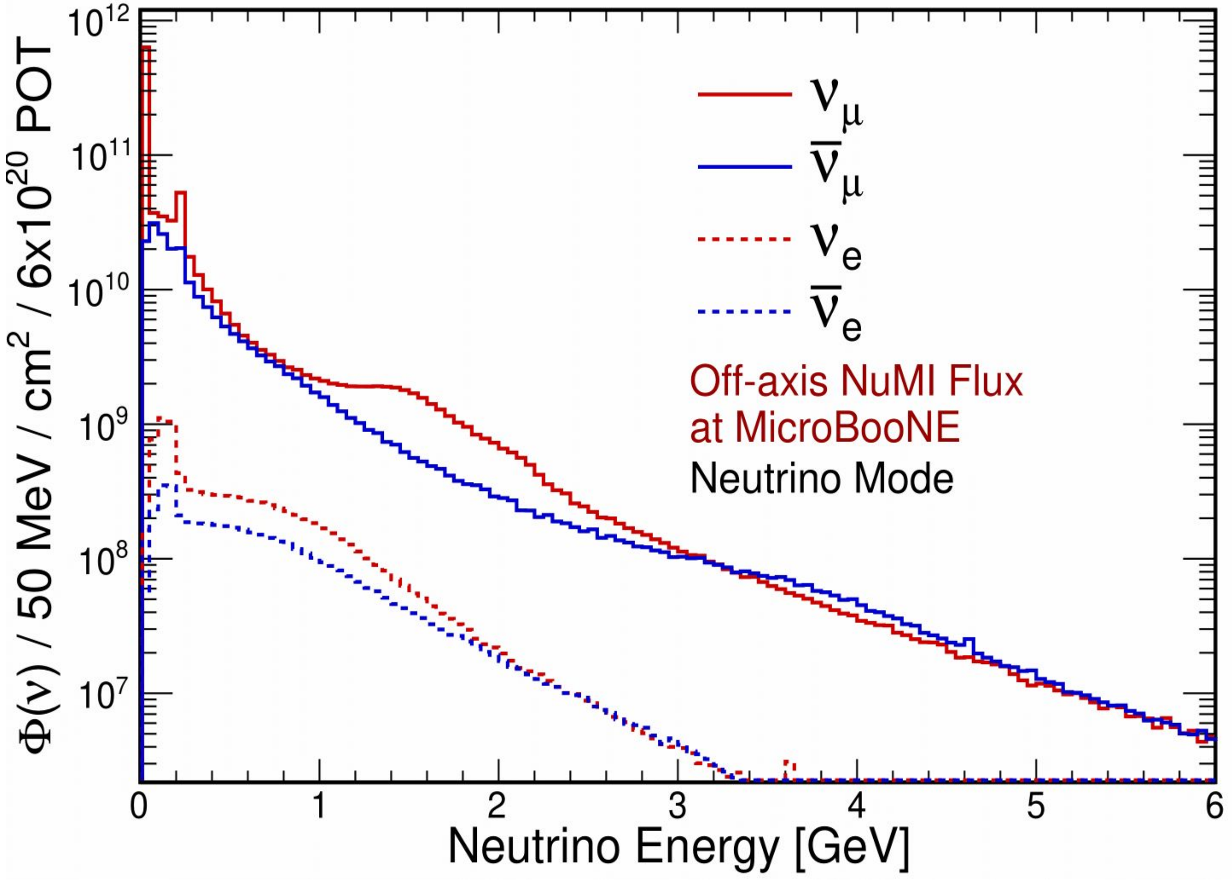


Figure source.

The Beams

MicroBooNE's off axis location significantly enhances wrong sign component.

The BNB:
On-axis.
Neutrino mode only.

NuMI:
Off-axis.
Mixture of both modes.

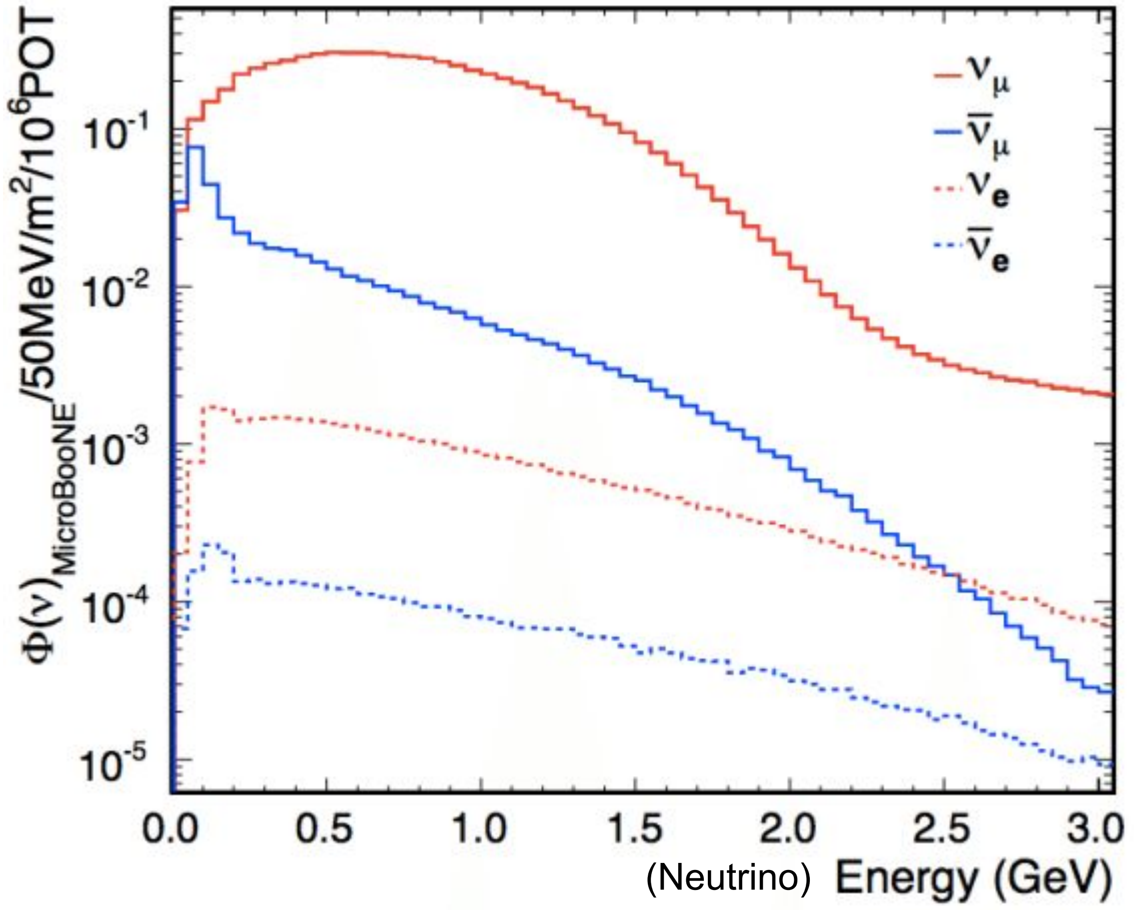


Figure from arXiv:1709.00146.

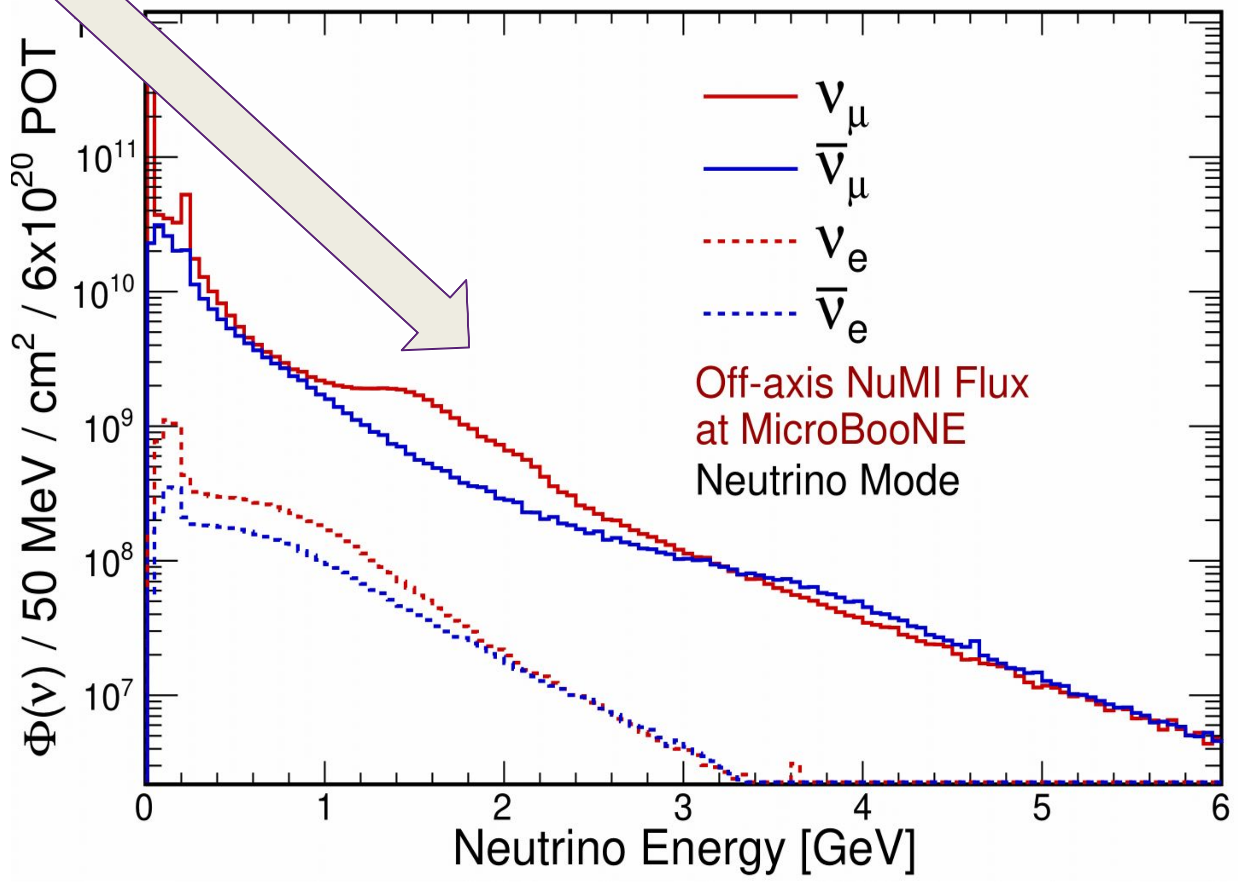


Figure source.

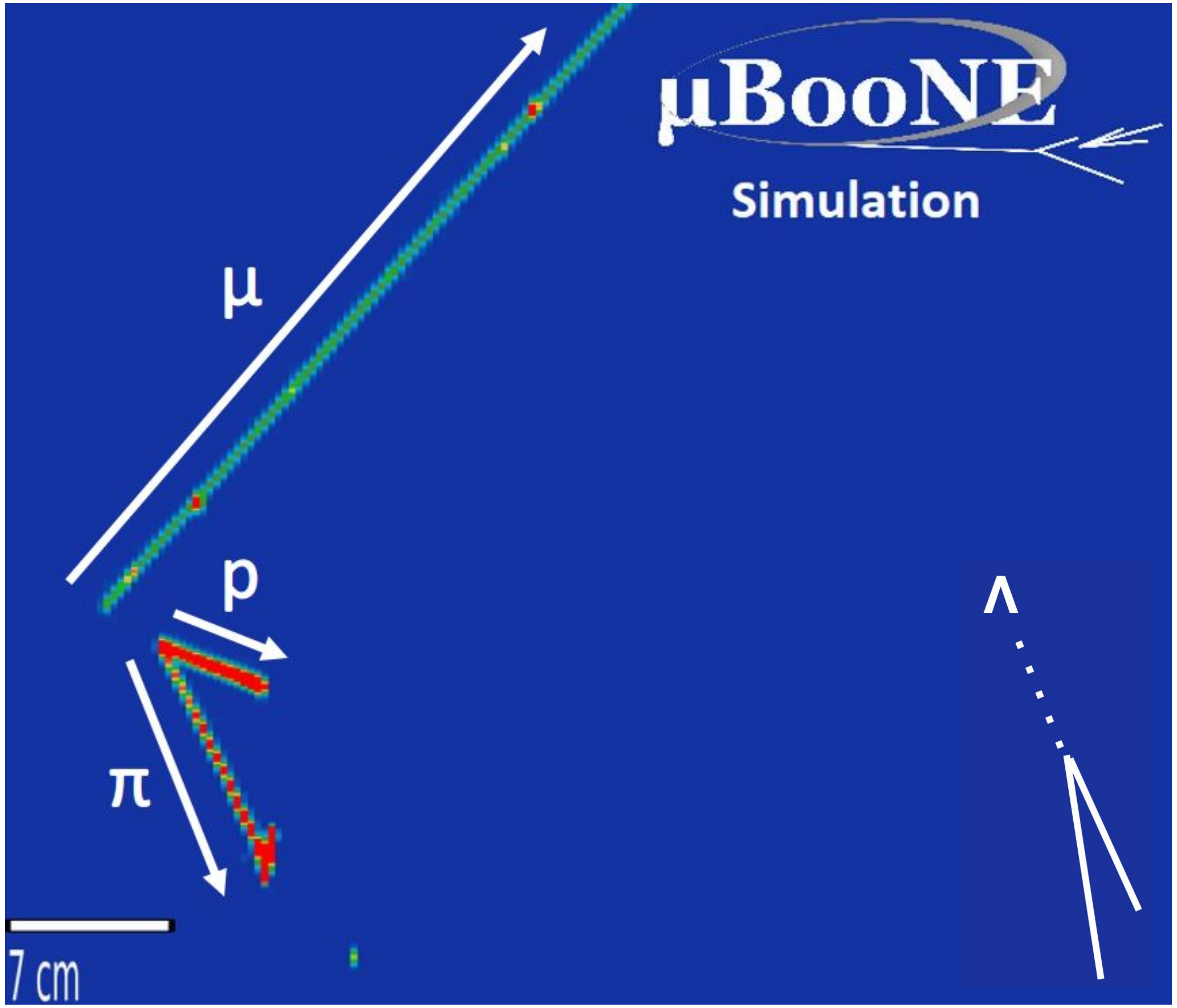
Analysis #1 - Single Λ Production

- CCQE-like hyperon production is anti-neutrinos only - use data taken with NuMI flux.
- Single Λ with no other strange final state particles:

$$\bar{\nu}_\mu + \mathrm{Ar} \rightarrow \mu^+ + \Lambda + X$$

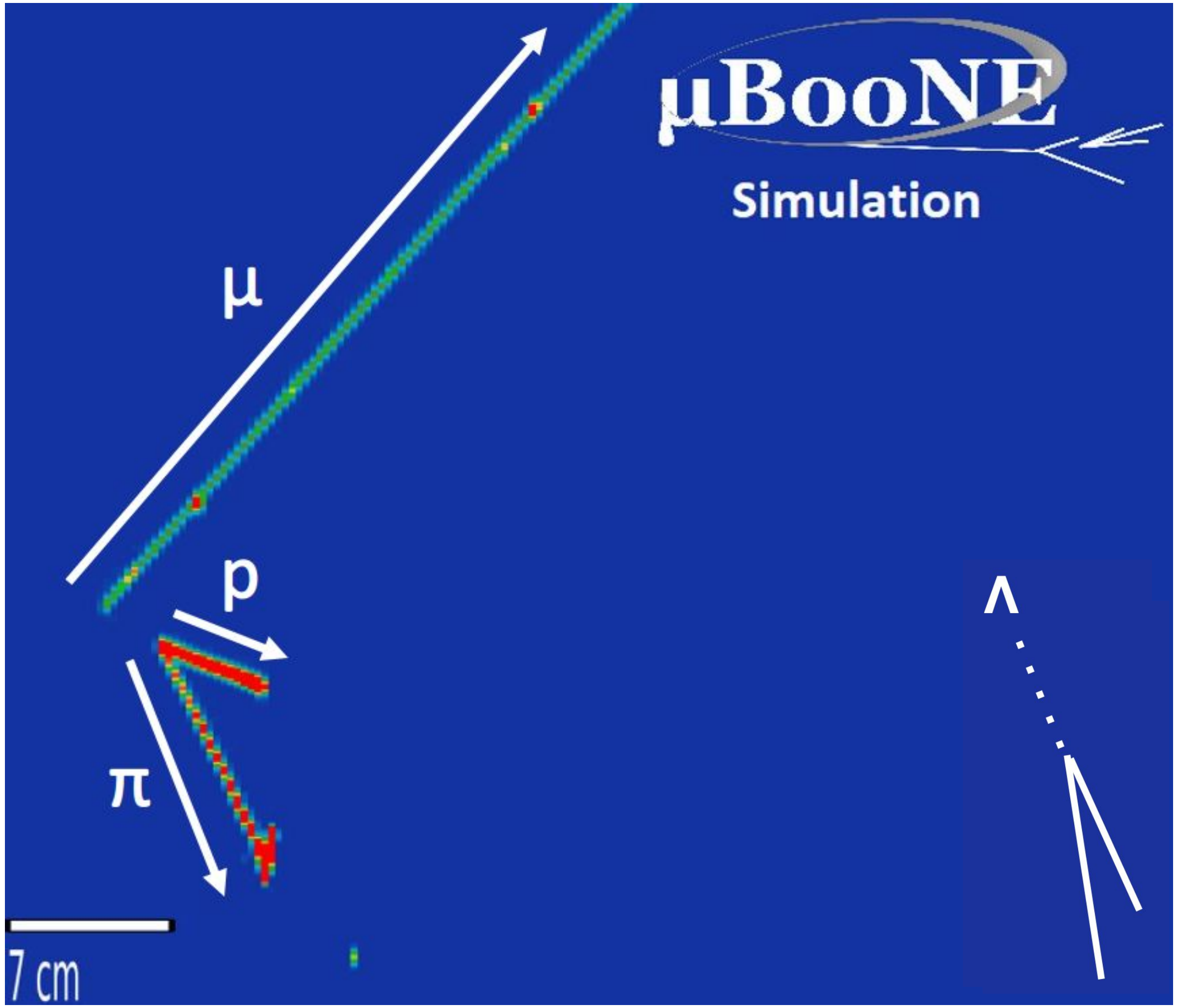
- Search for dominant decay mode, $\Lambda \rightarrow p + \pi^-$.

(Branching fraction = 68%)

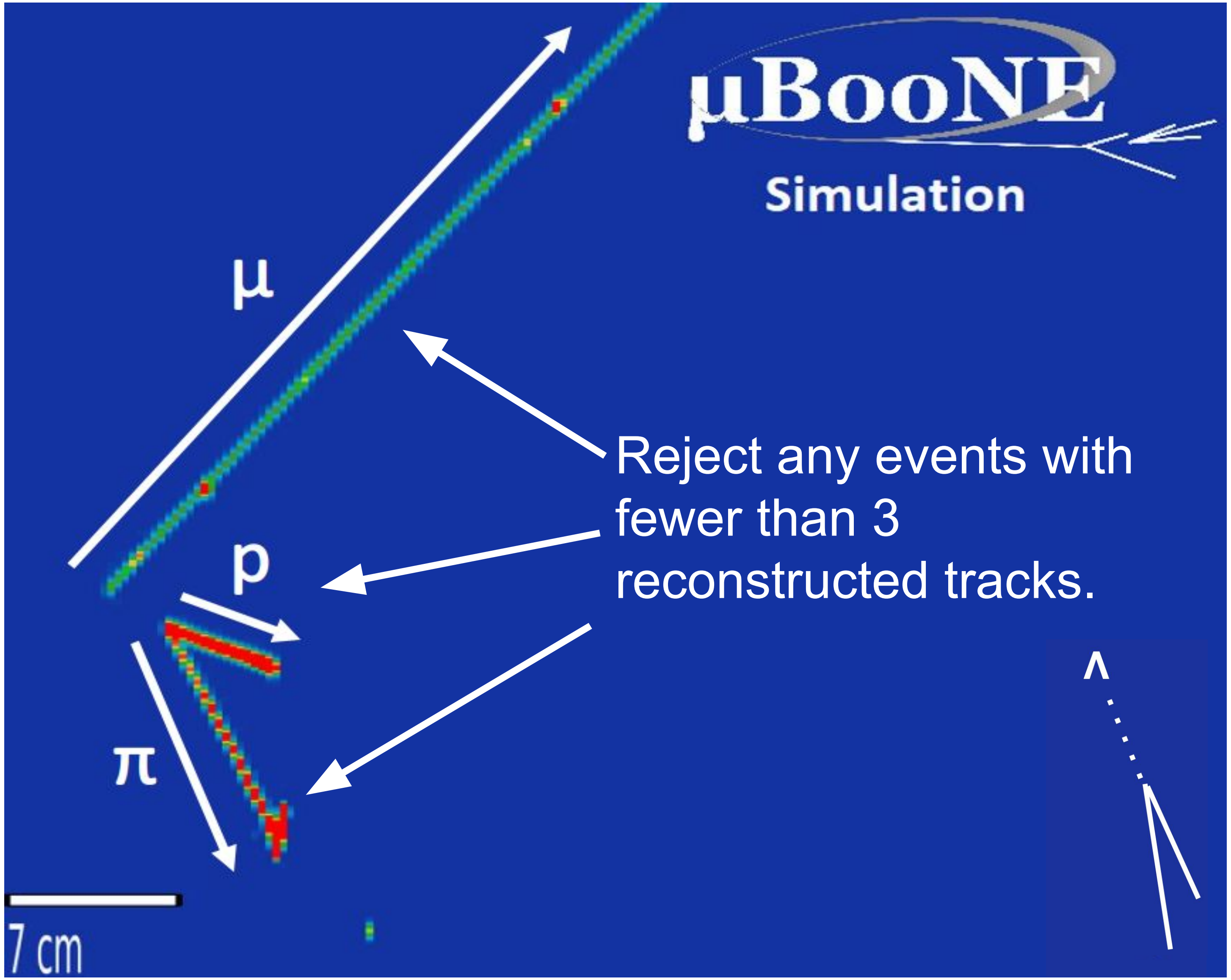


Analysis #1 - Single Λ Event Selection

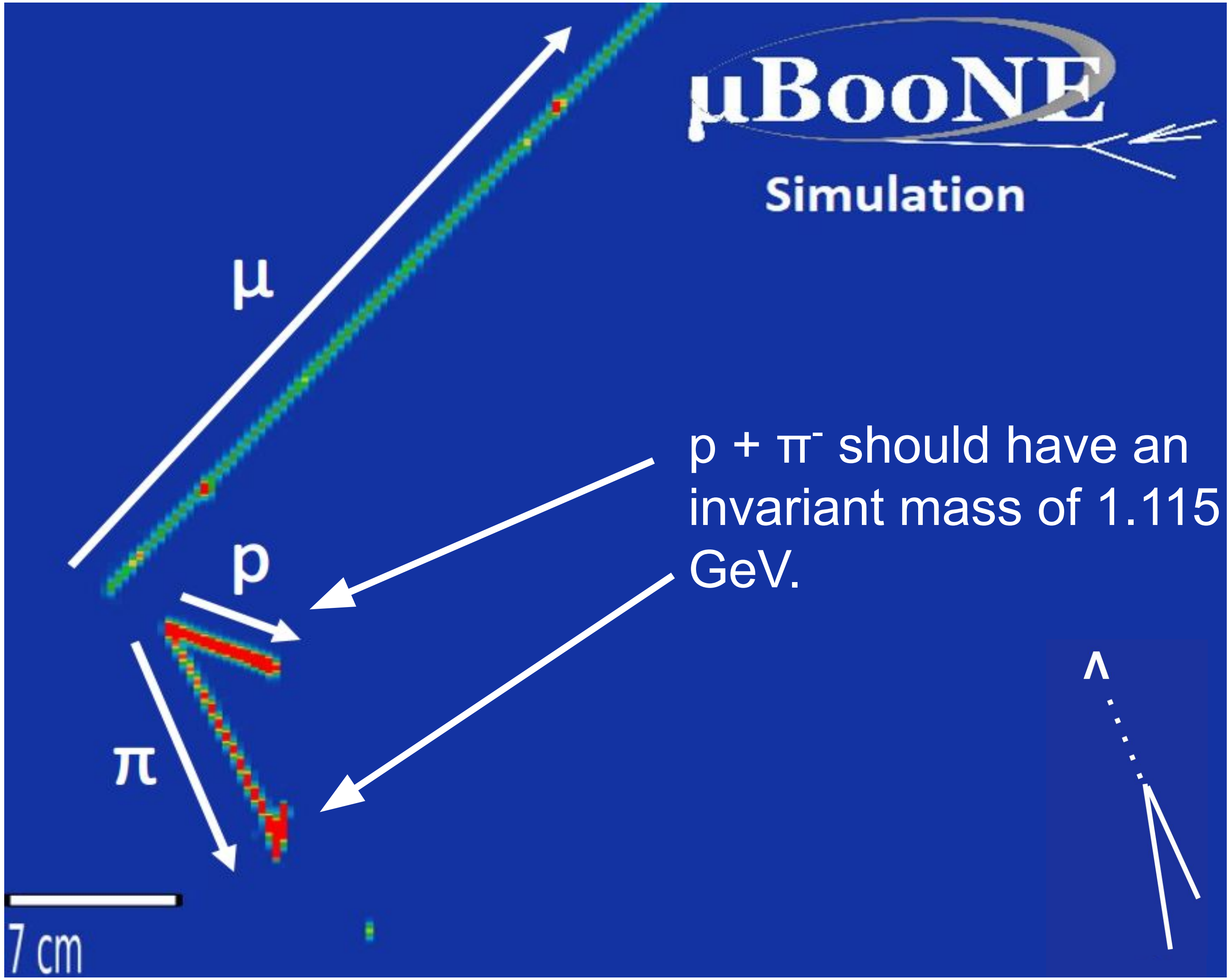
- Rare process search - lots of background to contend with.
- Prior to selection, **expected signal of 34 events, BG of 1.6M events**.
- Three main elements to the selection: topological cuts,kinematic cuts and island finding.



Λ Selection - Topological Criteria

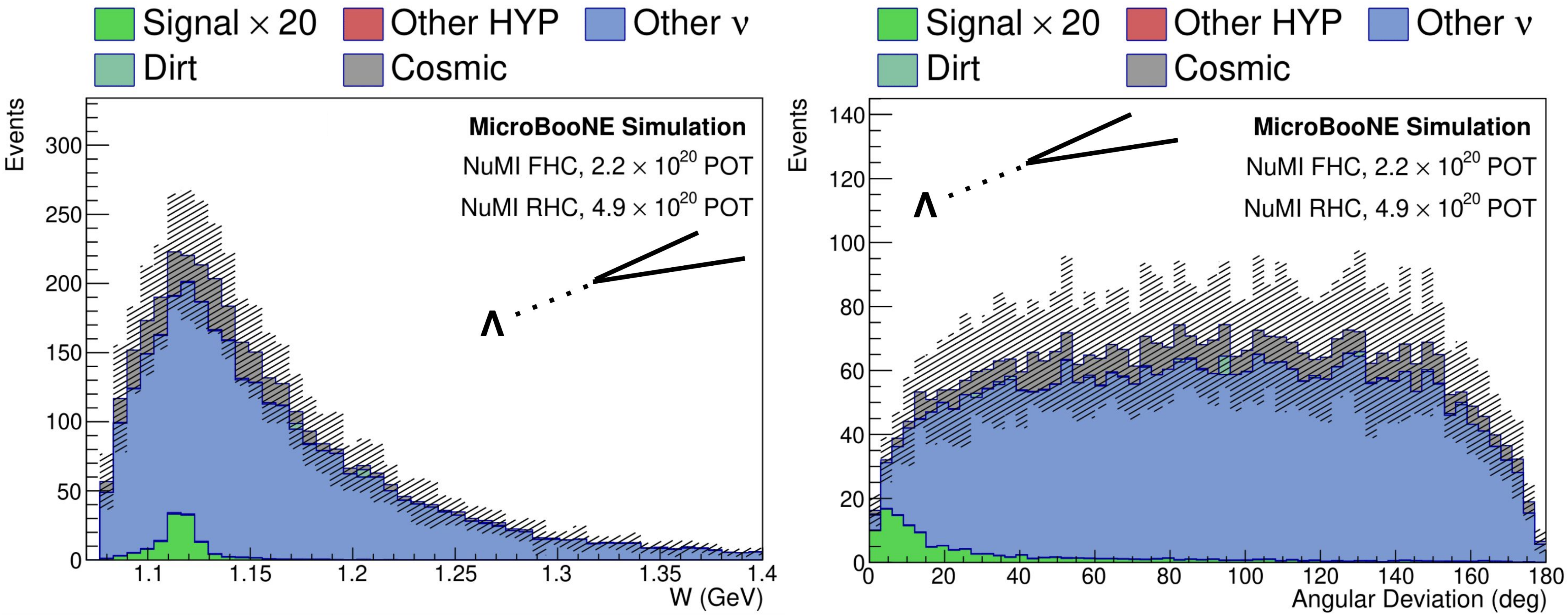


Λ Selection - Kinematic Criteria



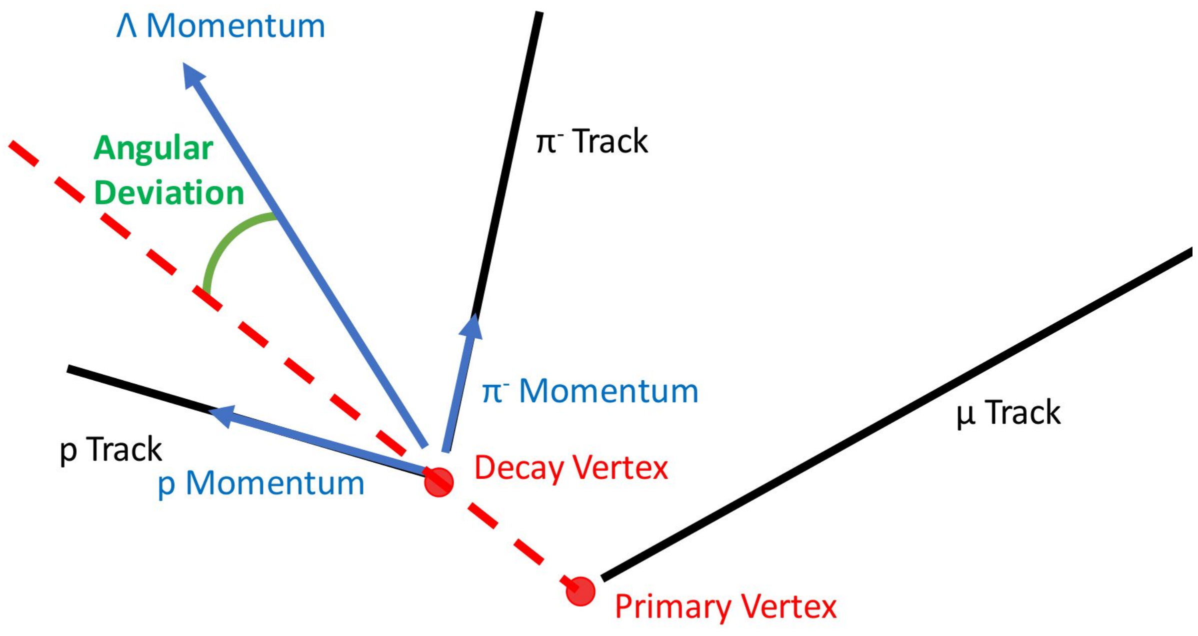
Λ Selection - Kinematic Cuts

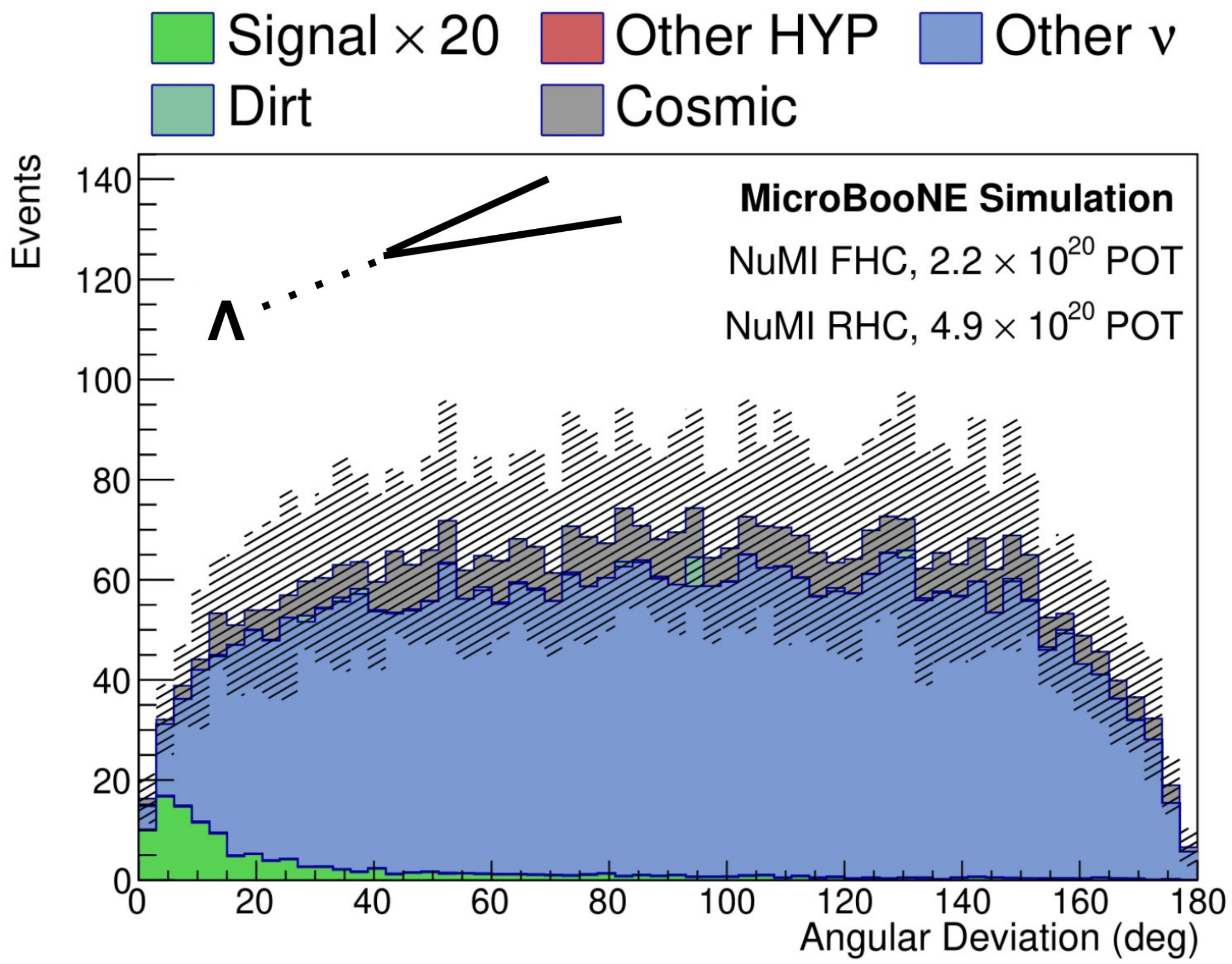
- Estimate momenta of proton and pion from their range.



From supplemental material of [Phys. Rev. Lett. 130, 231802](https://doi.org/10.1103/PhysRevLett.130.231802).

Λ Selection - Kinematic Cuts

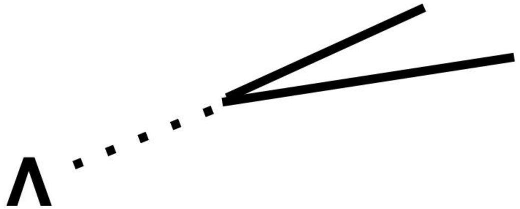


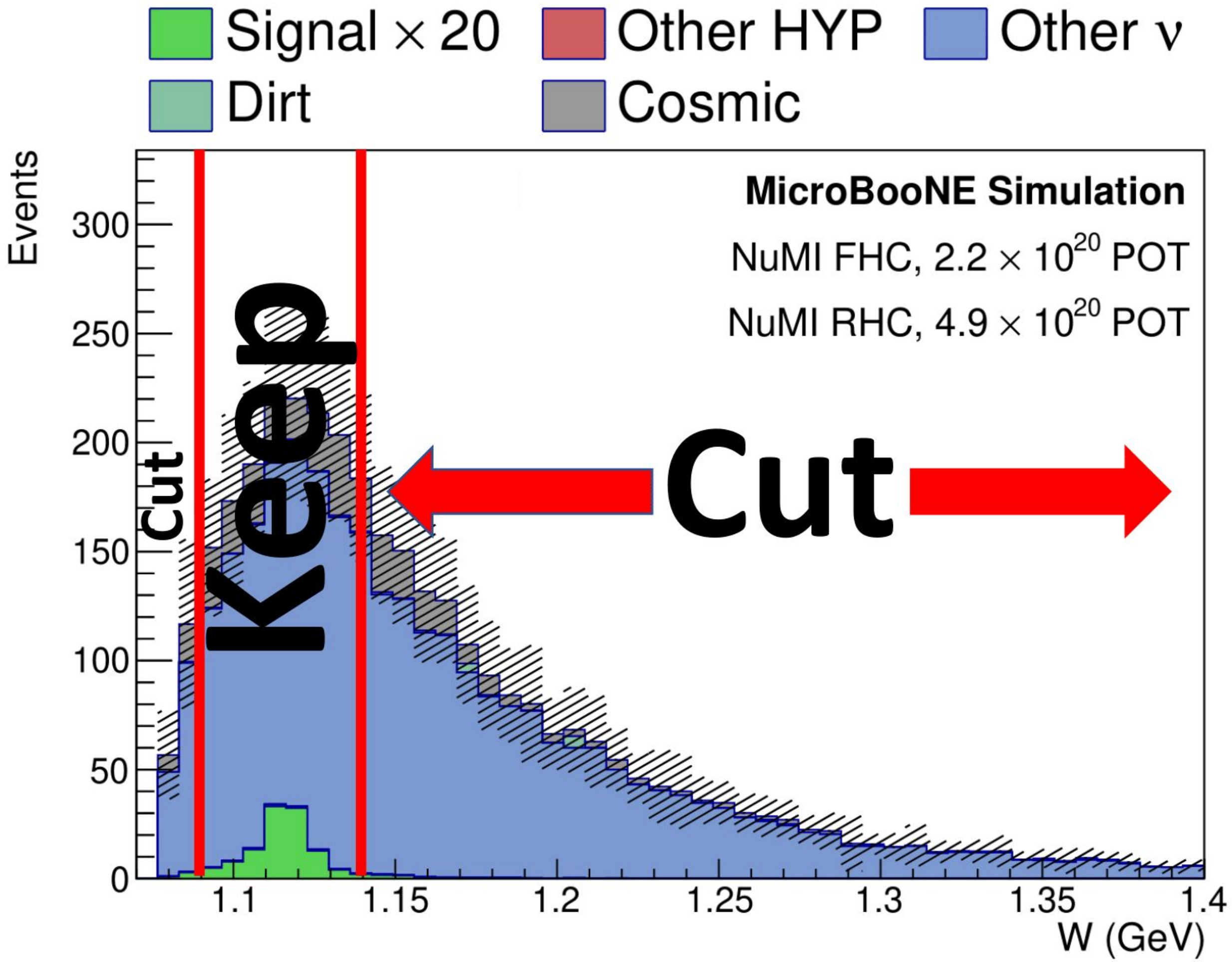


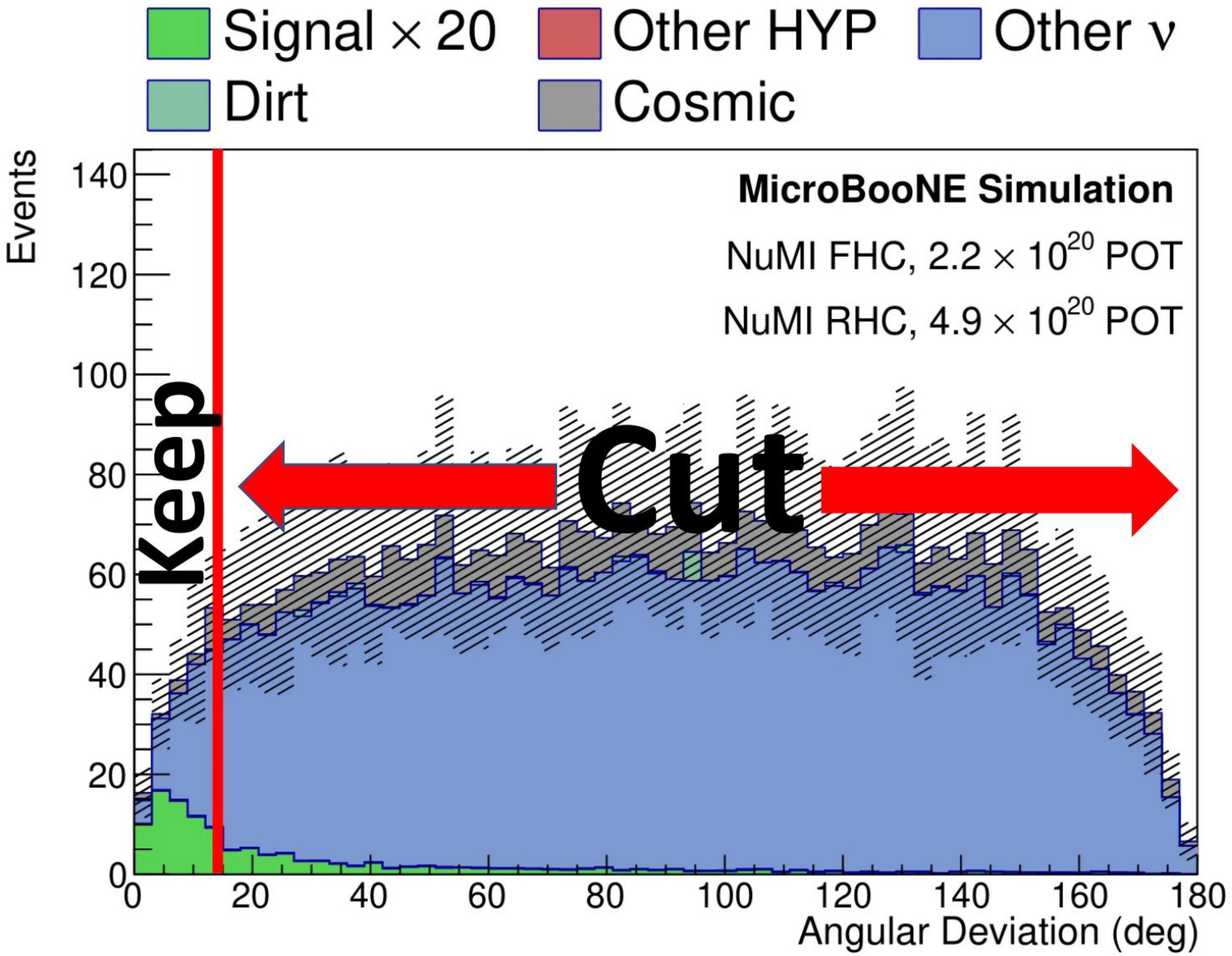
If we assume Λ travels in a straight line before decaying, combined momentum vector of proton and pion should be parallel to line joining vertices.

From supplemental material of Phys. Rev. Lett. 130, 231802.

Λ Selection - Kinematic Cuts

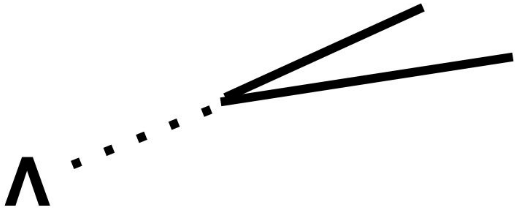






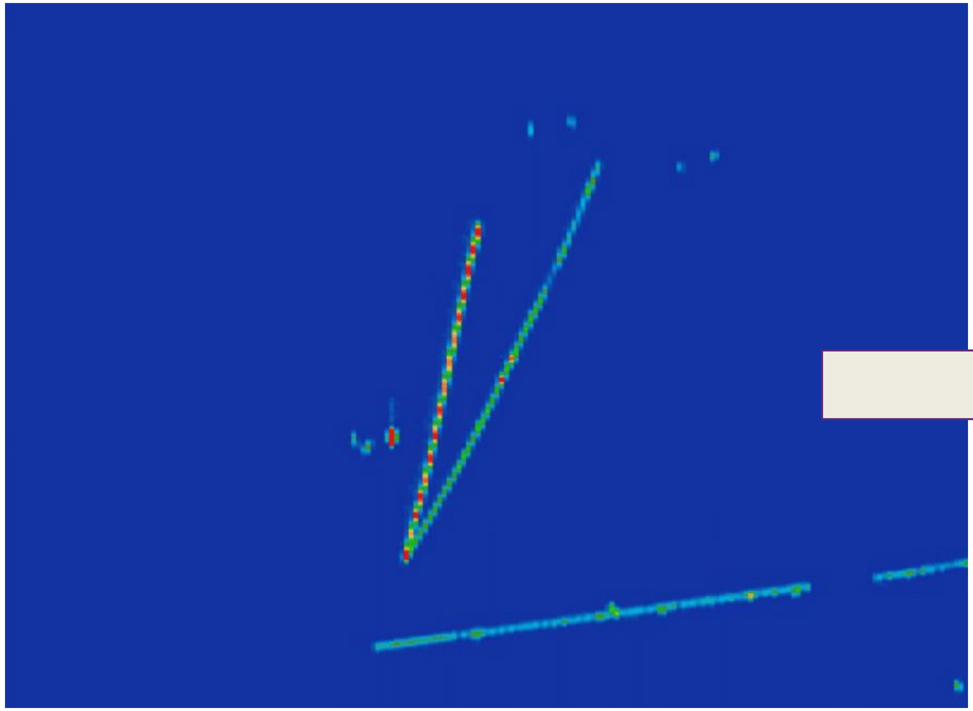
From supplemental material of Phys. Rev. Lett. 130, 231802.

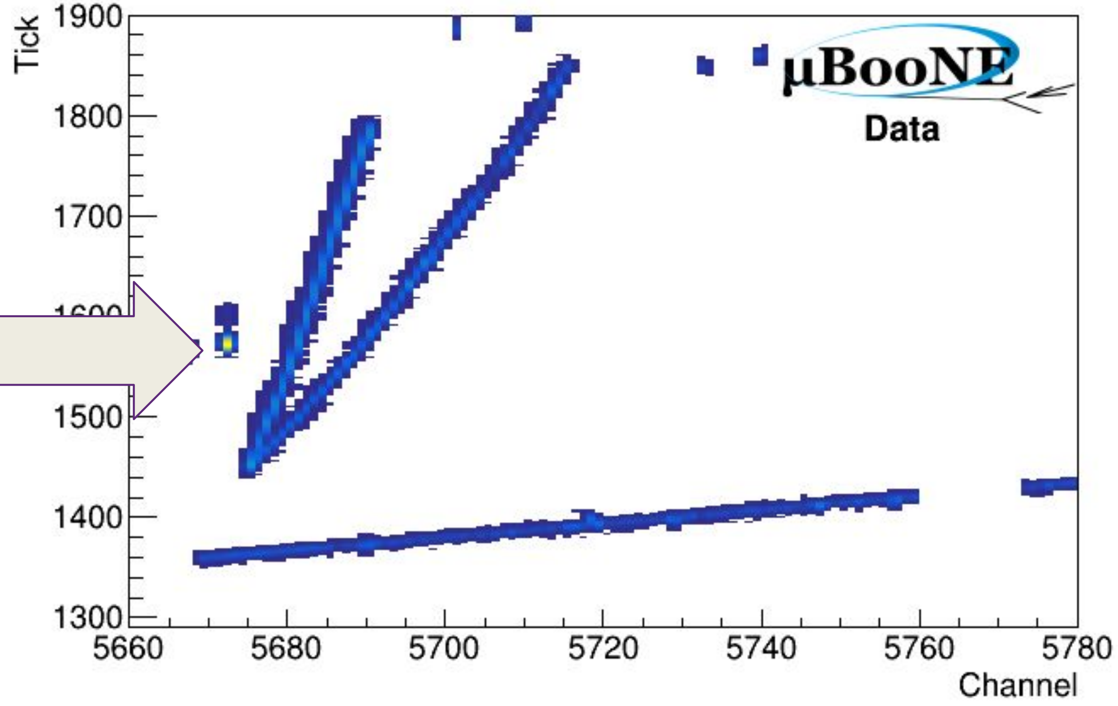
Λ Selection - Island Finding



- Convert wire responses from each plane into a 2D histogram:

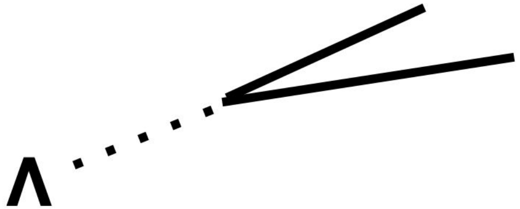
From supplemental material of [Phys. Rev. Lett. 130, 231802](#).





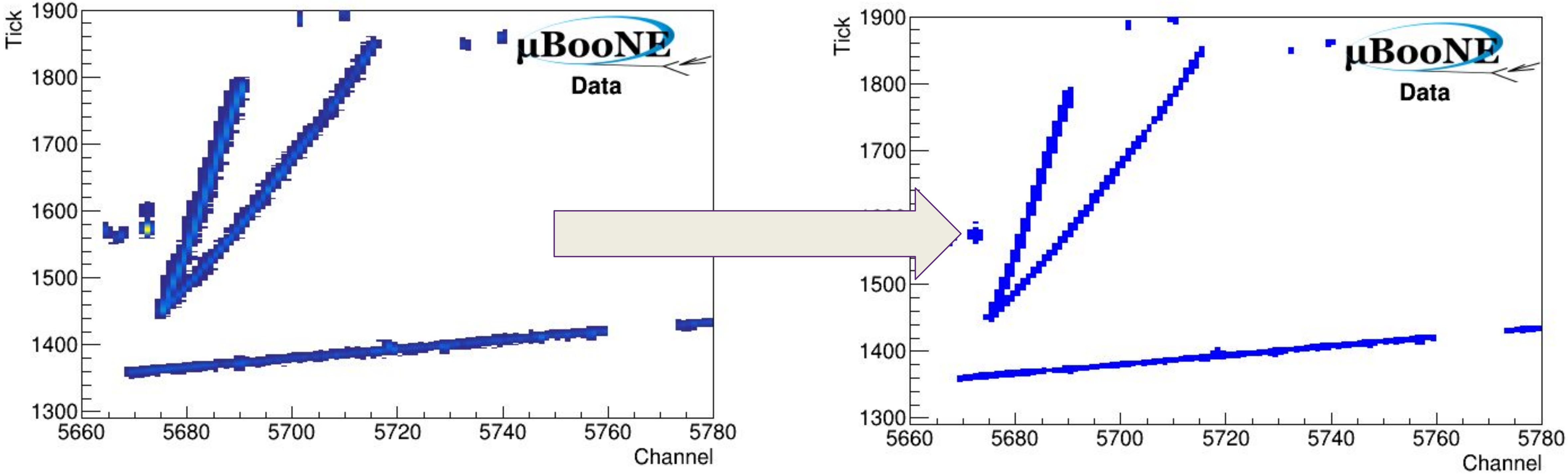
x axis is the wire number, y axis is drift time.

Λ Selection - Island Finding



- Remove all cells with less than a given amount of activity.

From supplemental material of Phys. Rev. Lett. 130, 231802.

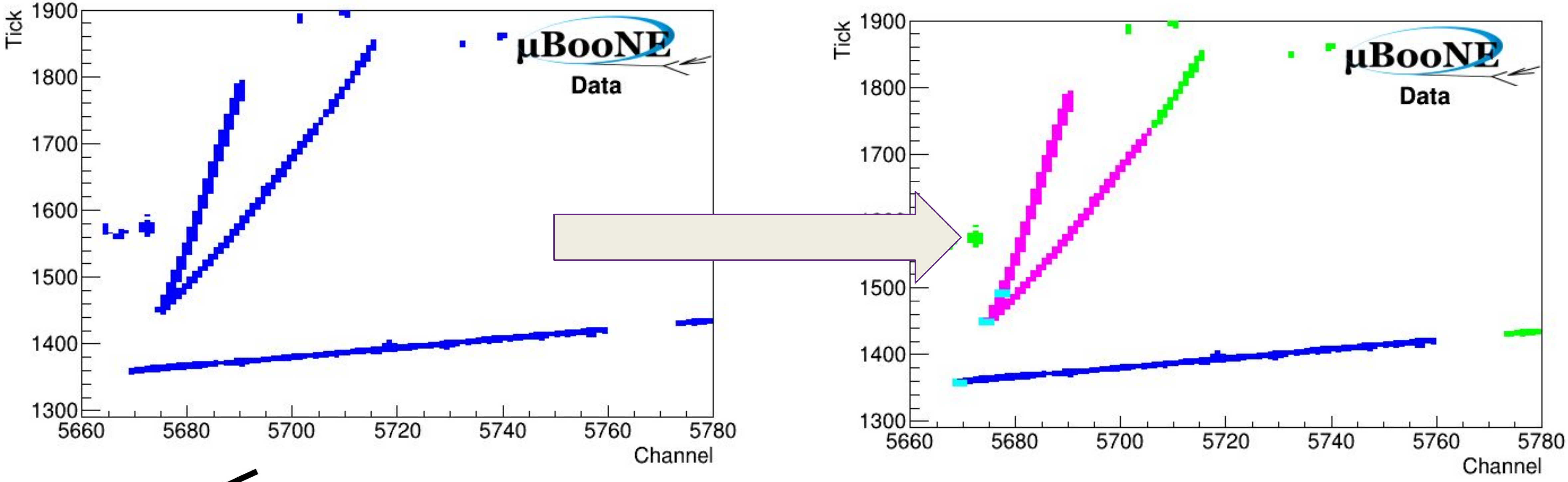


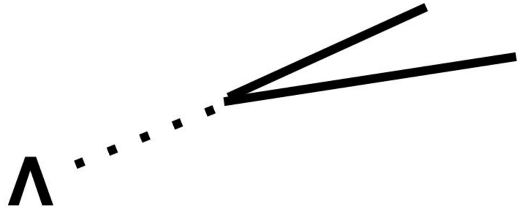
x axis is the wire number, y axis is drift time.

Λ Selection - Island Finding

- Project the start points of the 3D reconstructed tracks back into 2D.
- Identify the contiguous regions activity they belong to.

From supplemental material of Phys. Rev. Lett. 130, 231802.





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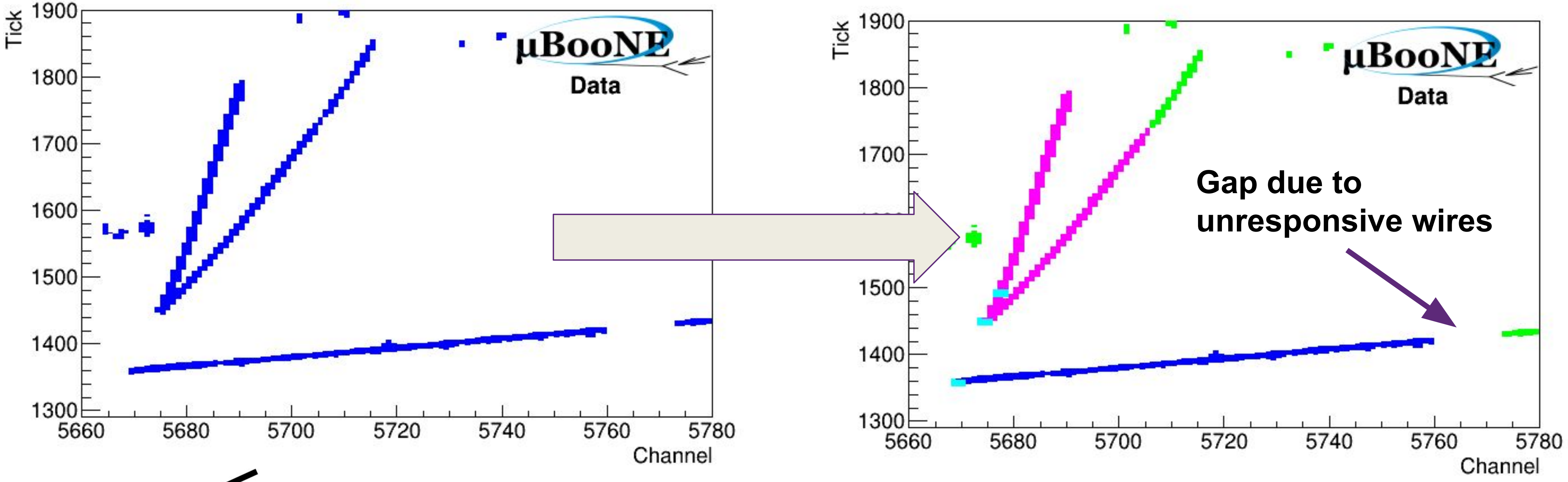

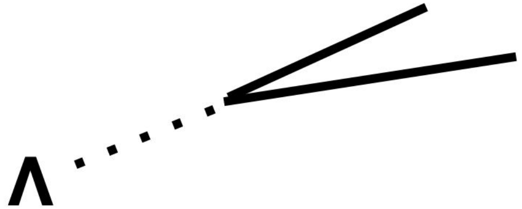

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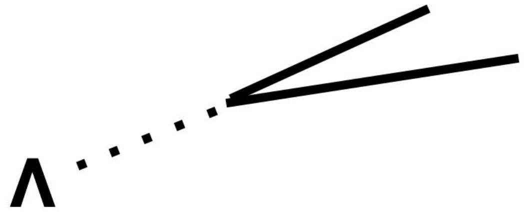
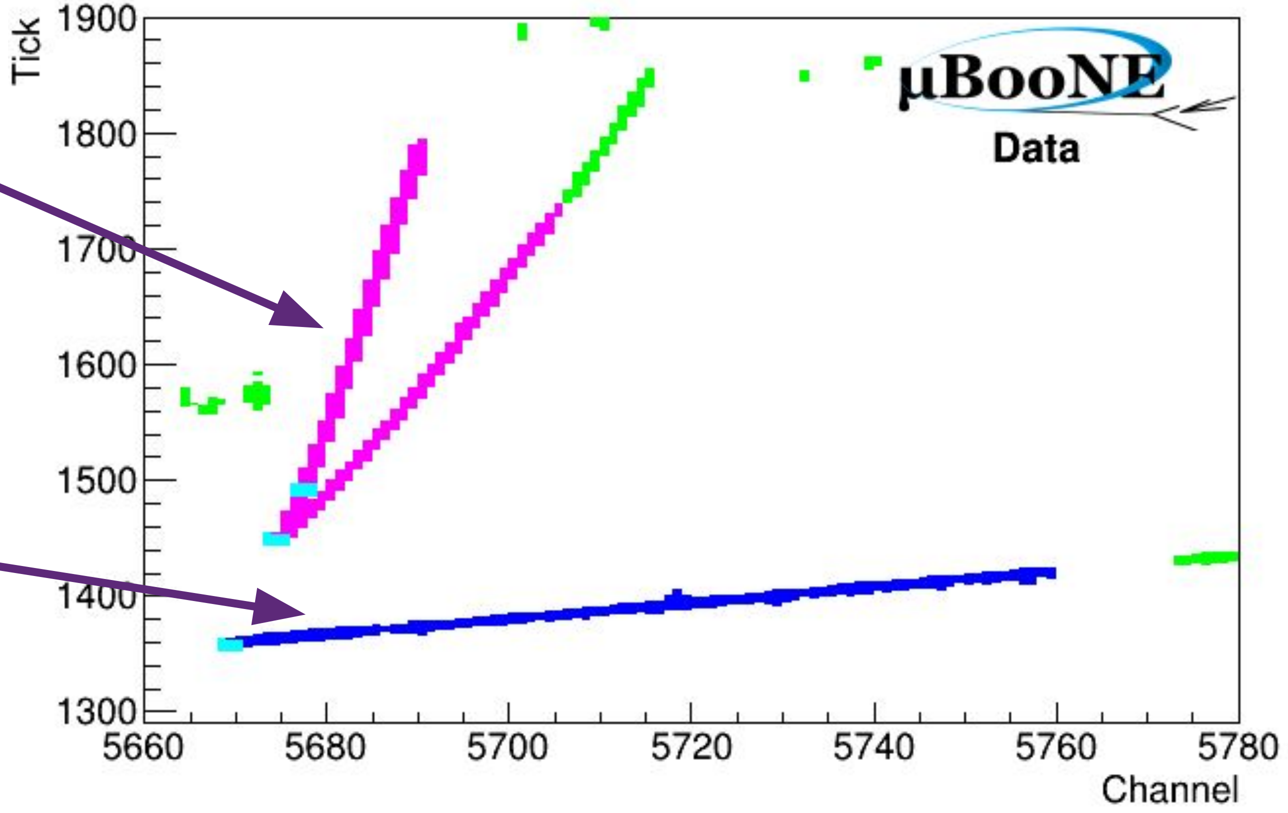
Λ Selection - Island Finding



- Record if the proton and pion lie on one “island”, while the muon belongs to a belongs to a separate “island”.
- Do this separately for each plane.



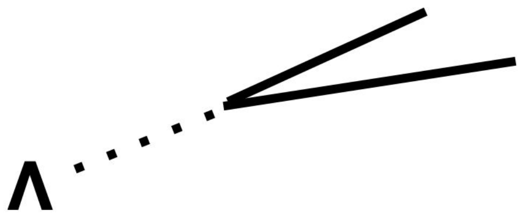
x axis is the wire number, y axis is drift time.

From supplemental material of [Phys. Rev. Lett. 130, 231802].

Λ Selection - Background Sources

- After applying the event selection, we obtain the following predictions for the data from our simulation:

Category	Predicted Events
Signal	2.5
Other Λ	0.7
Other hyperons	1.0
Neutrons	0.3
Mis-reconstruction	0.9



- Final purity is approximately 50%. Background reduction of ~ 10^6.

Analysis #2 - η Meson Production

- Selection inclusively targets CC and NC interactions:

$$\nu + \mathrm{Ar} \rightarrow \eta + X$$

- Only restriction on other FS particles is there must be no π^0.

- Search for dominant decay mode, $\eta \rightarrow \gamma\gamma$ (BF = 40%).

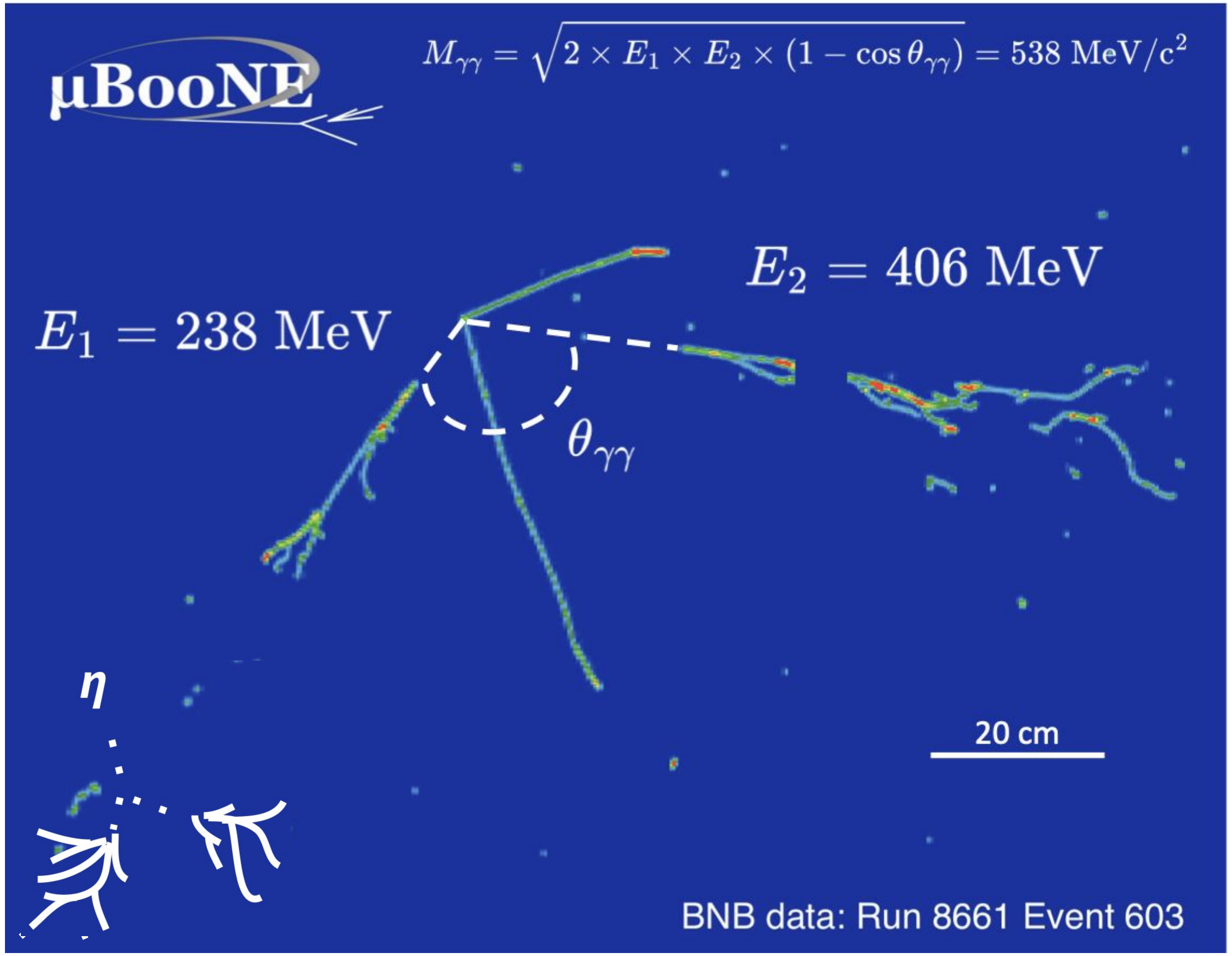
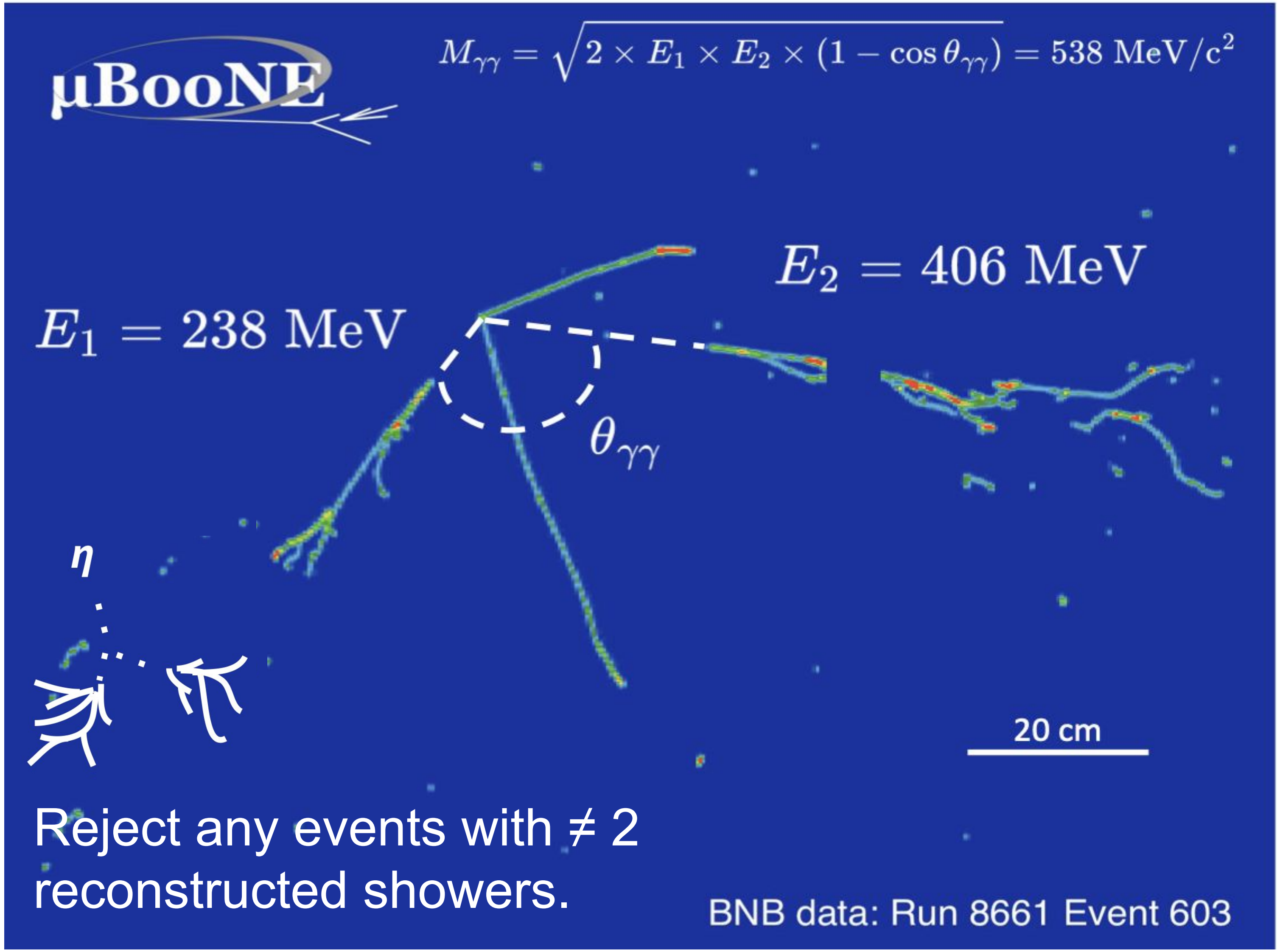


Figure from arXiv:2305.16249.

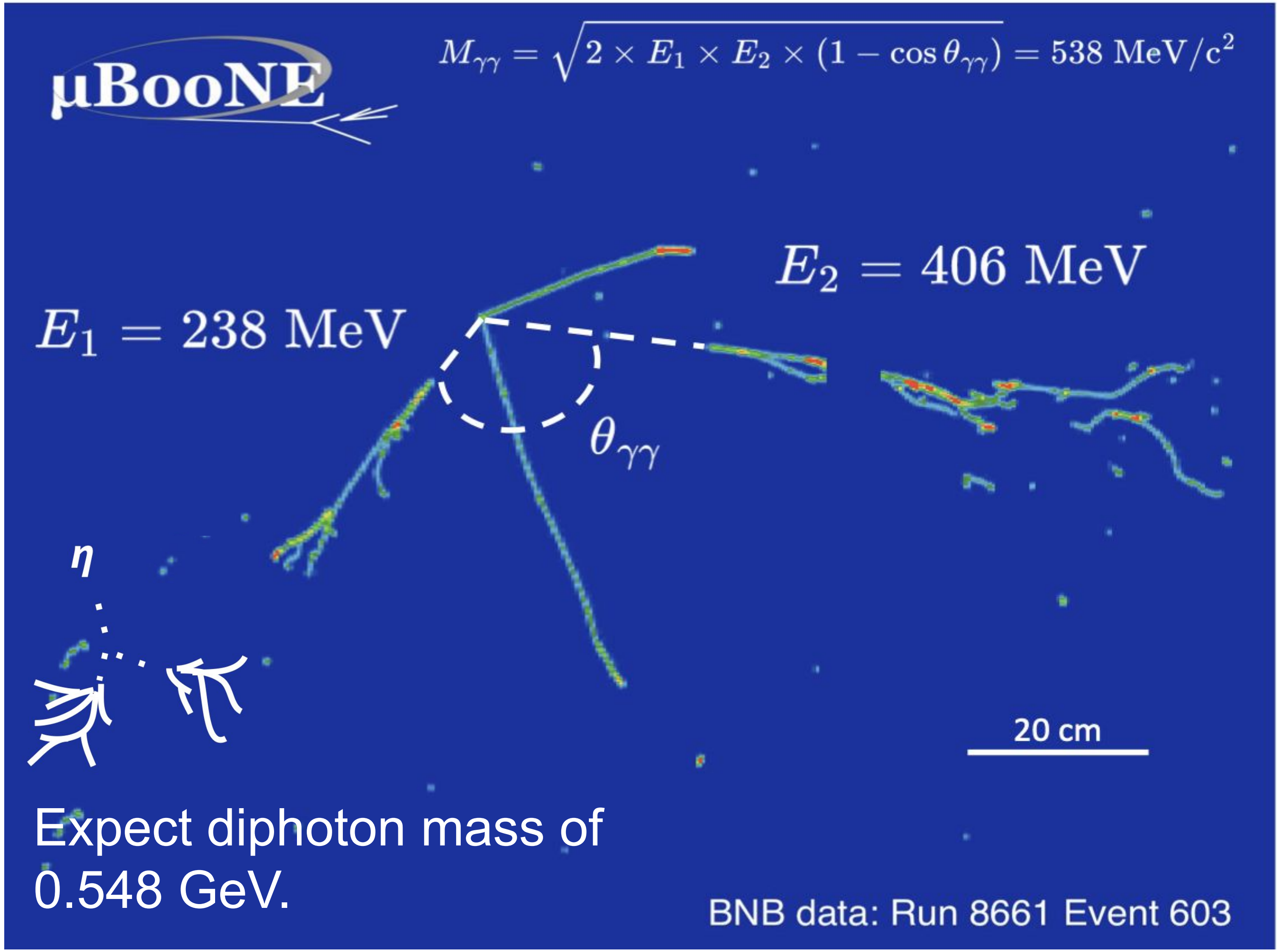
η Selection - Topological Criteria

Figure from arXiv:2305.16249.



η Selection - Kinematics

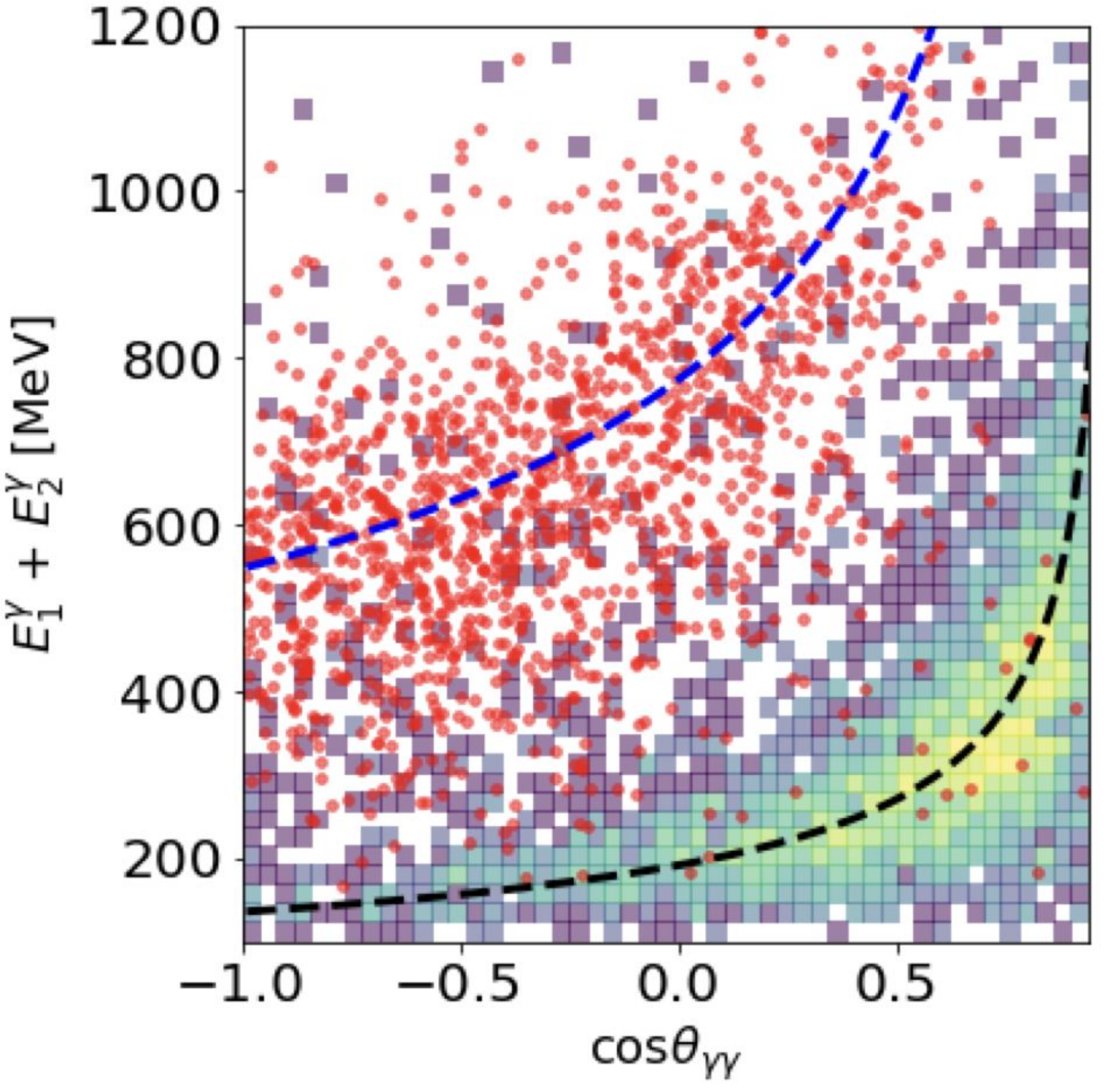
Figure from arXiv:2305.16249.



η Selection - Kinematics

Blue curve - expectation for η decays.

Black curve - expectation for π^0 decays.



Red points - reco η decays.

Tiles - reco π^0 decays.

η Selection - Kinematics

Blue curve - expectation for η decays.

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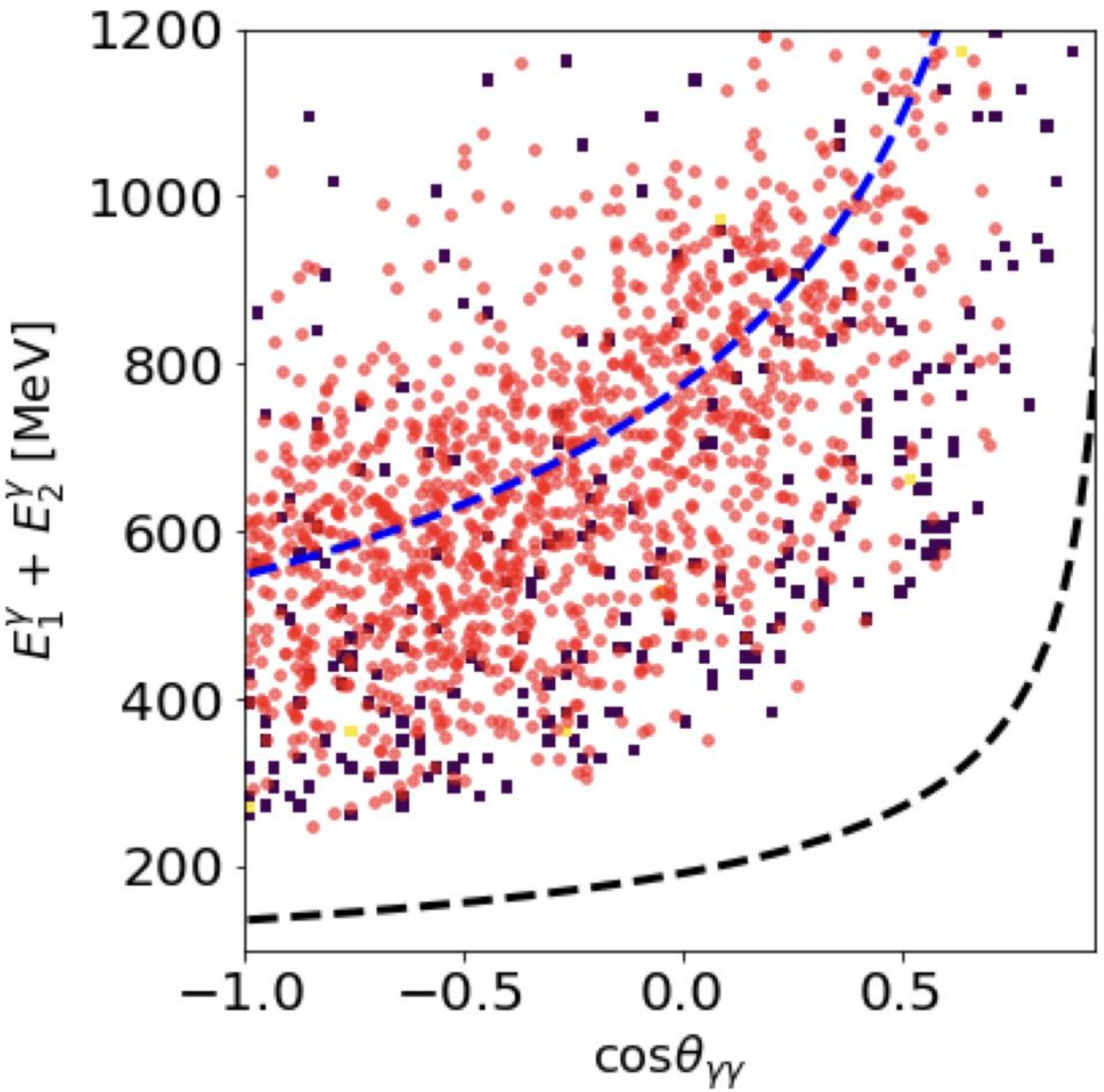


Red points - reco η decays.

Tiles - reco π^0 decays.

After cutting events with diphoton mass < 250 MeV.

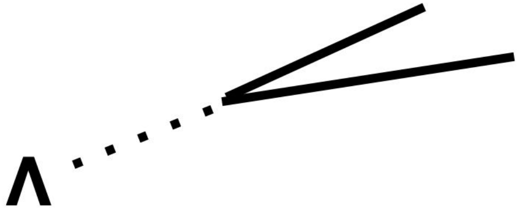
Selected Backgrounds

- After applying the event selection, we obtain the following predictions for the data from our simulation:

Category	Prediction Events
Signal	56.1
Other η	0.8
1 π^0	13.2
2 π^0	24.6
Other ν Interaction	6.8
Other	11.0

- Final purity is approximately 50%.

Selected Backgrounds



Category	Prediction
Signal	2.5
Other Λ	0.7
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Neutrons	0.3
Mis-reconstruction	0.9

Mis-reconstruction background really problematic. Solution explained in a moment.

Category	Prediction
Signal	56.1
Other η	0.8
1 π^0	13.2
2 π^0	24.6
Other ν Interaction	6.8
Other	11.0

Pion backgrounds addressed through constraint.

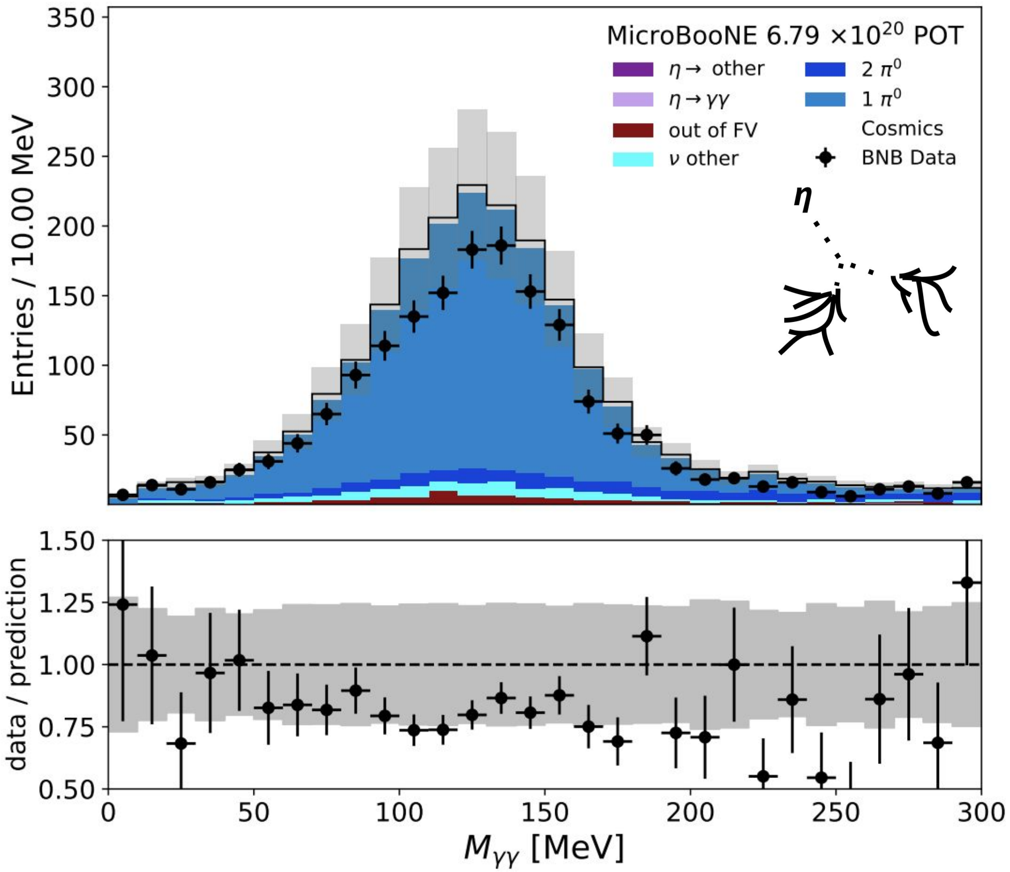
Systematics

- In most MicroBooNE cross section analyses we consider five main sources of systematic uncertainty:

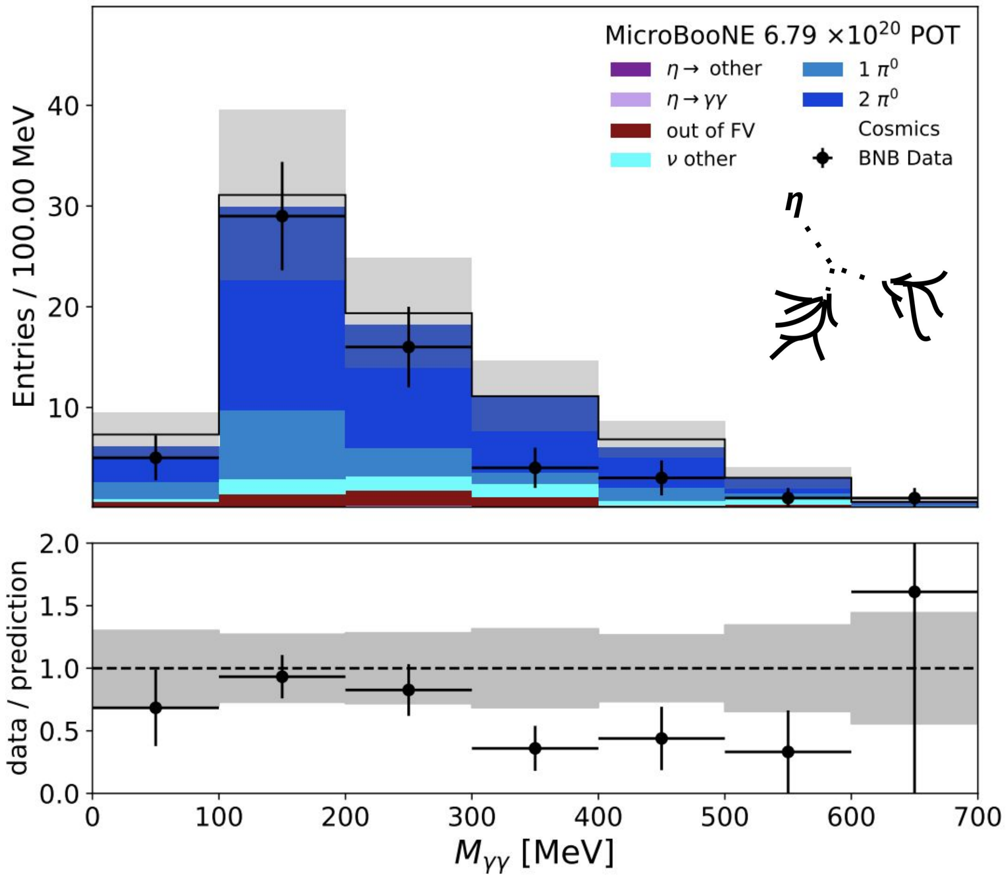
1. Neutrino flux.
2. Cross sections of background neutrino interactions.
3. Secondary interactions of hadrons outside the nucleus.
4. Detector response modelling.
5. Background from neutrino interactions outside the cryostat (“dirt” backgrounds) + **other analysis specific uncertainties**.

η Production - Background Constraint

Single π^0



2+ π^0



Reduce background uncertainty by leveraging two sidebands.

η Production - Background Constraint

- Obtain sideband-constrained background prediction and uncertainty with:

$$N_{MC}^{S,constrained} = N_{MC}^{S} + \frac{\sigma^{corr}}{\left(\sigma^{B}\right)^2} \times \left(N_{data}^{B} - N_{MC}^{B}\right),$$

$$\left(\sigma^{S,\text{ constrained}}\right)^2 = \left(\sigma^{S}\right)^2 - \frac{\left(\sigma^{corr}\right)^2}{\left(\sigma^{B}\right)^2}$$

- Reduce uncertainty in π^0 induced background by around a quarter.
- Overall uncertainty reduced form 48% to 37%.

Λ Visual Scanning (VS)

- Events contributing to mis-reconstruction background are extremely rare*, and there is no practical way to manufacture enough.
- This causes problems when trying to evaluate related systematic uncertainties, especially those related to the detector response.

- Two approaches explored to resolve this:
  - Visual inspection of event displays.
  - Invert some cuts to produce a sideband, use this to generate a data driven constraint on the size of this background.

*We have 9 MC events across all of our samples, only a subset of which can be used to evaluate detector response systematics.

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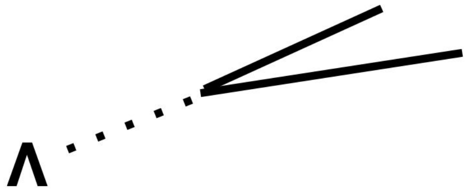
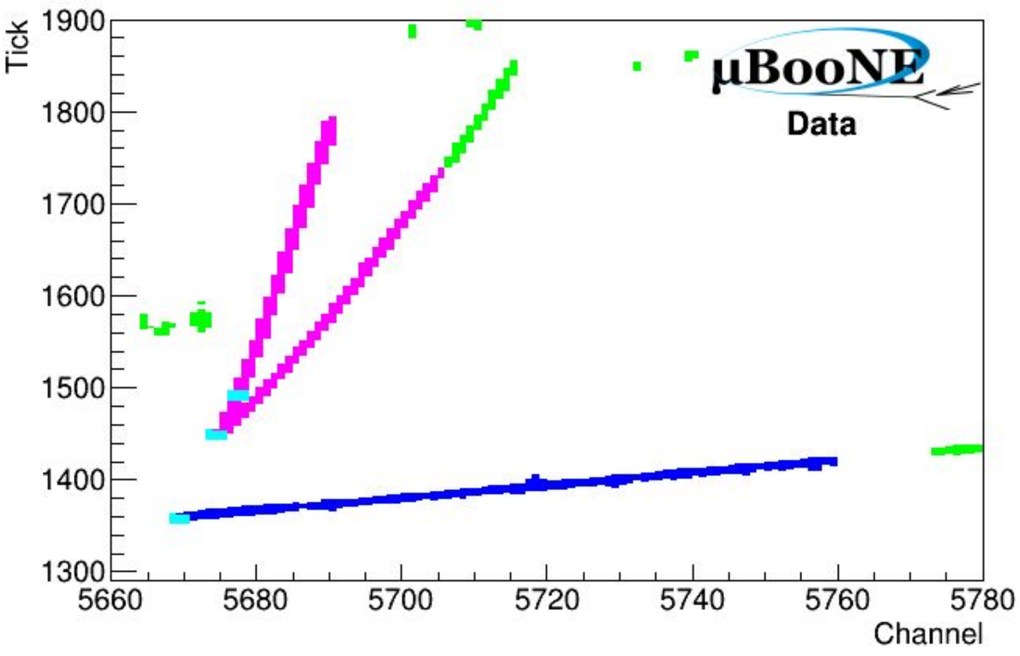
- Two approaches explored to resolve this:
  - **Visual inspection of event displays**.
  - Invert some cuts to produce a sideband, use this to generate a data driven constraint on the size of this background. → **In backup slides!**

*We have 9 MC events across all of our samples, only a subset of which can be used to evaluate detector response systematics.

Λ Visual Scanning (VS)

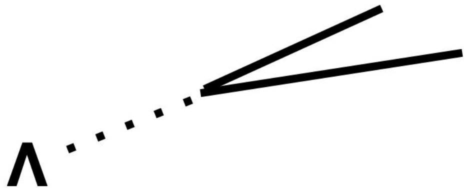


- Avoid the need for systematic uncertainties on mis-reconstruction background by removing from the data entirely through visual scanning (aka. hand scanning).
- Used blinded study with five different scanners to evaluate background rejection, efficiency, and reliability of this technique.



Ask the scanners to corroborate information from all three planes

Λ Visual Scanning (VS)



- Obtain corrected predictions after incorporating results of visual scan.
- Spread in scan results included as an additional systematic*.

Category	Prediction	Prediction after VS
Signal	2.5 ± 0.6	2.3 ± 0.6
Other Λ	0.7 ± 0.2	0.5 ± 0.3
Other hyperons	1.0 ± 0.5	0.7 ± 0.5
Neutrons	0.3 ± 0.1	0.1 ± 0.1
Mis-reconstruction	0.9 ± 0.4	0.1 ± 0.1

*Result from each scanner used as a systematic universe. Use these to calculate contribution to covariance matrix from “VS uncertainty”.

Cross Section Extraction

- Both analyses present their result in the form of a flux integrated total cross section, related to the measured data event count by:

Observed data events after selection

Predicted background

$$\sigma = \frac{N_{\text{obs}} - B}{\epsilon T \Phi}$$

Selection efficiency

Total flux

Number of Ar nuclei in fiducial volume

Uncertainties

- All of the quantities in this calculation have uncertainties.
- The η analysis can assume roughly Gaussian statistics, for the Λ measurement the process is a little more unorthodox.

Observed data events after selection

Predicted background

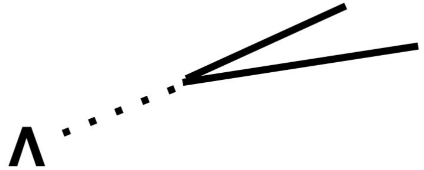
$$\sigma = \frac{N_{\text{obs}} - B}{\epsilon T \Phi}$$

Selection efficiency

Total flux

Number of Ar nuclei in fiducial volume

Λ Statistical Uncertainties



- To capture the entire shape of the statistical uncertainties, we employ **Bayesian posterior probability distributions**.

$$P(N|N_{\text{obs}})$$

$$P(B|B_{\text{MC}})$$

$$\sigma = \frac{N - B}{\epsilon T \Phi}$$

$$P(\epsilon|\epsilon_{\text{MC}})$$

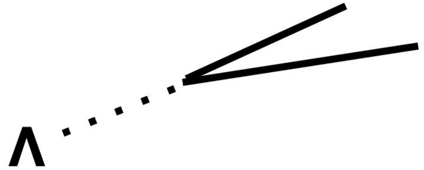
Λ MC Statistics

- If a Beta distribution is used as a prior of ε, it can be shown that the posterior distribution of ε for an ensemble of weighted binomial trials is also a Beta distribution:

$$P(\epsilon|\epsilon_{\mathrm{MC}}) \sim \mathrm{Beta}(\epsilon; a, b)$$

- Same treatment to obtain the posterior of the selected background.
- Both use uniform priors.

Λ Data Statistics



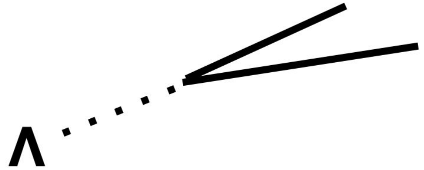
- The number of data events we see in the signal region N_{obs}, is a single observation of a Poissonian random variable.
- **This variable has a true mean N**.

- The Bayesian posterior probability this true mean value is N is:

$$P(N|N_{\mathrm{obs}}) \sim \mathrm{Poiss}(N_{\mathrm{obs}}; N)P(N)$$

P(N) = Bayesian prior = uniform distribution over [0,20] events.

Λ Cross Section Extraction - Systematics



- Calculate the covariance matrix of the selection efficiency ϵ, integrated muon anti-neutrino flux Φ, and selected background B.
- Construct 3D Gaussian distribution:

$$P(\alpha_\epsilon, \alpha_\Phi, \alpha_B) \sim \mathrm{Gaus}(\alpha_\epsilon, \alpha_\Phi, \alpha_B; \mathrm{Cov}(\epsilon, \Phi, B))$$

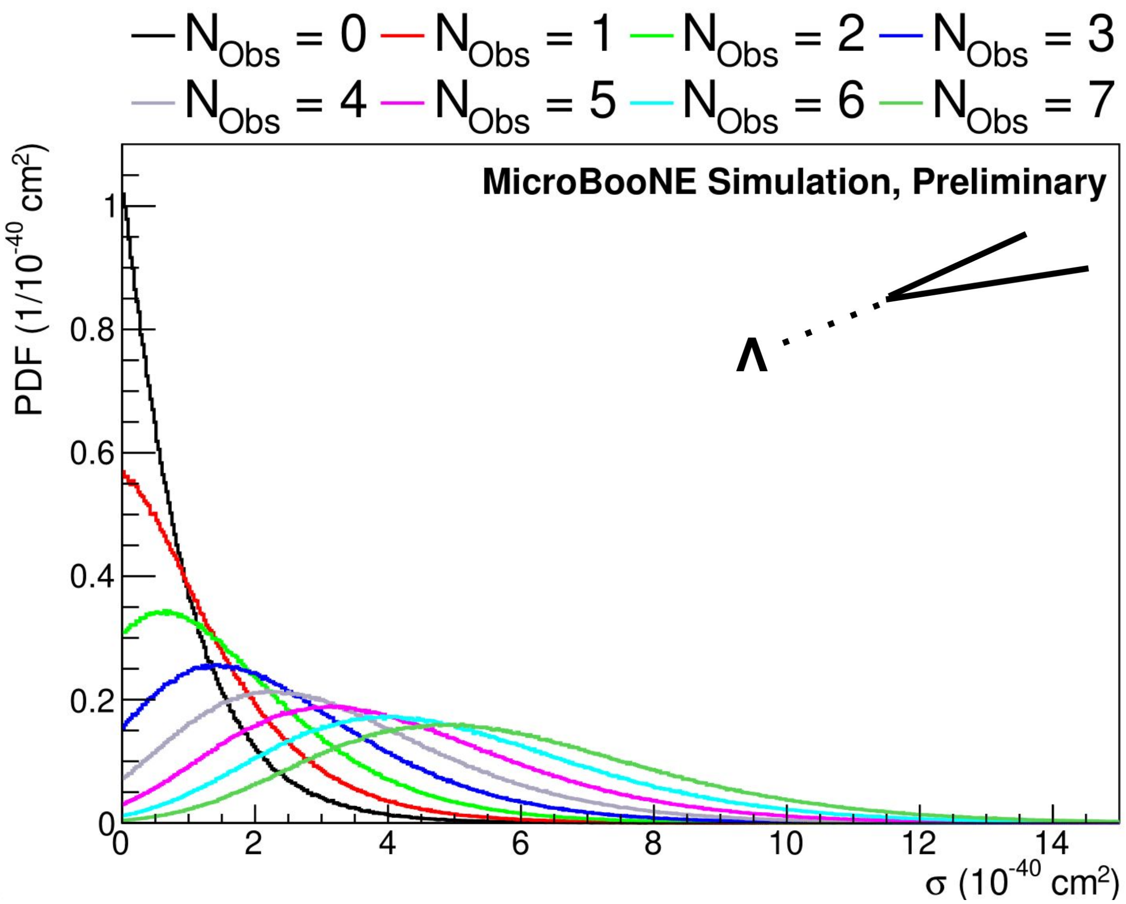
- Gives the probability of ϵ, Φ, and B deviating away from their default values by α_ϵ, α_Φ, and α_B.

Λ Cross Section Extraction - Putting it Together

- Construct pseudo-experiments:
  - Sample a values of ϵ, B and N from their distributions.
  - Sample values of α_ϵ, α_Φ, and α_B from their joint distribution.
- Calculate the cross section with:

$$\sigma_* = \frac{N - (B + \alpha_B)}{(\Phi + \alpha_\Phi)(\epsilon + \alpha_\epsilon)\Gamma T}$$

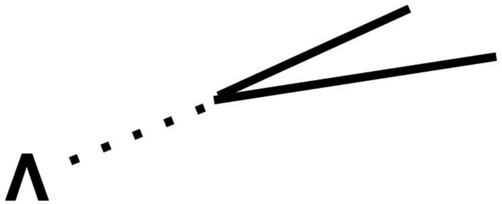
$\Gamma = 0.64 = BF(\Lambda \rightarrow p + \pi^-)$



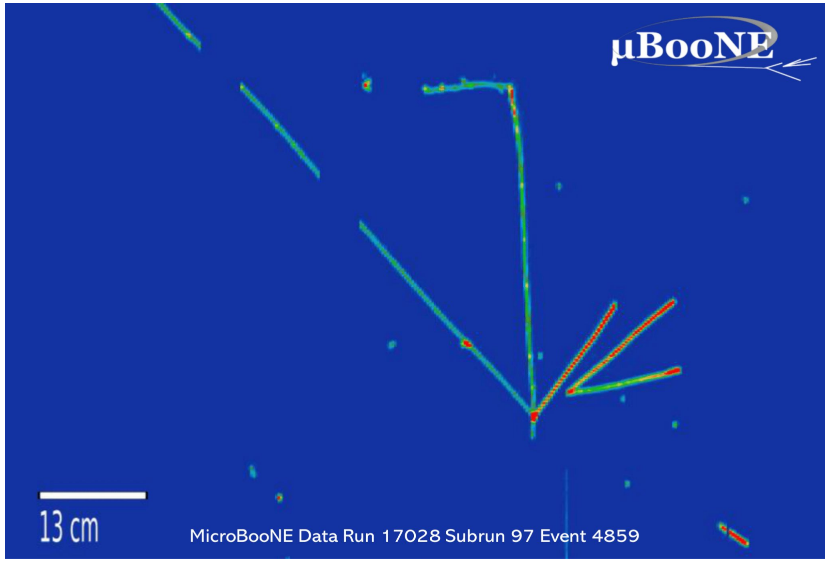
Repeat, and plot the distribution of the values. This is the Bayesian posterior on σ.

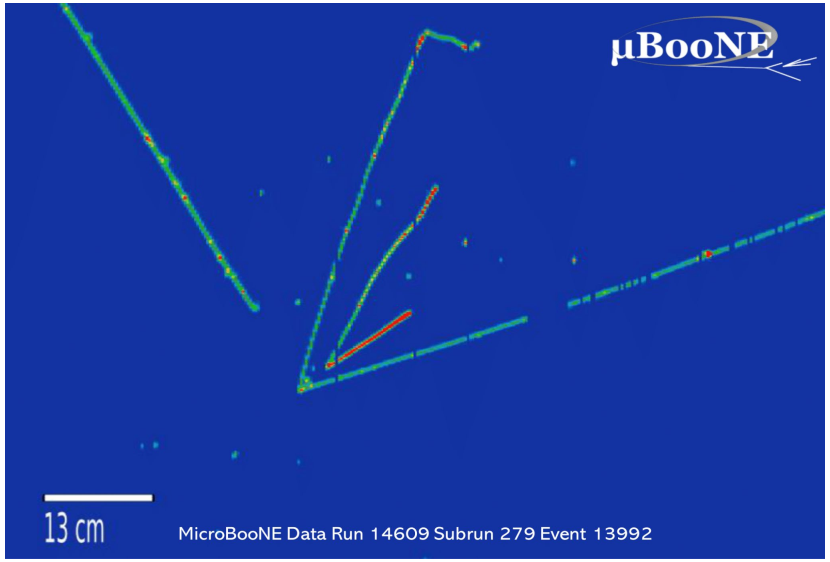
Figure from Phys.Sci.Forum 8 (2023) 1, 16.

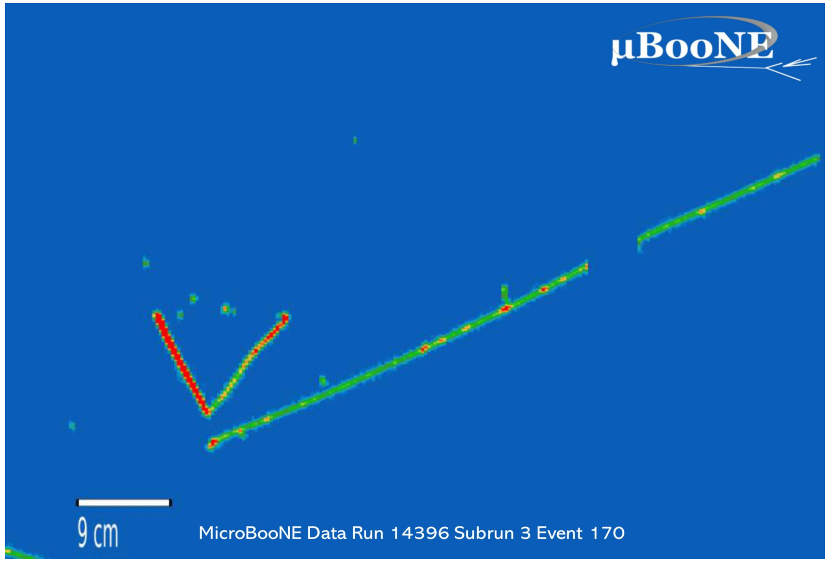
We Found Five Λ Candidates!

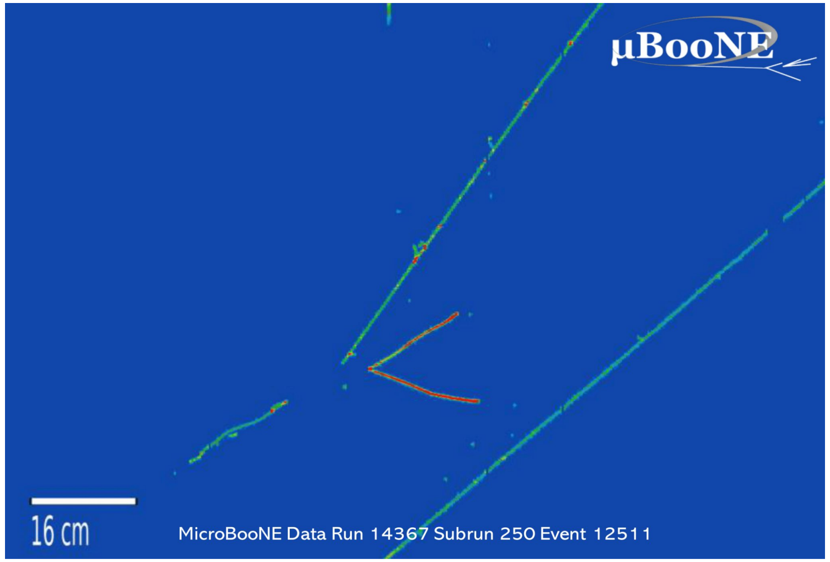


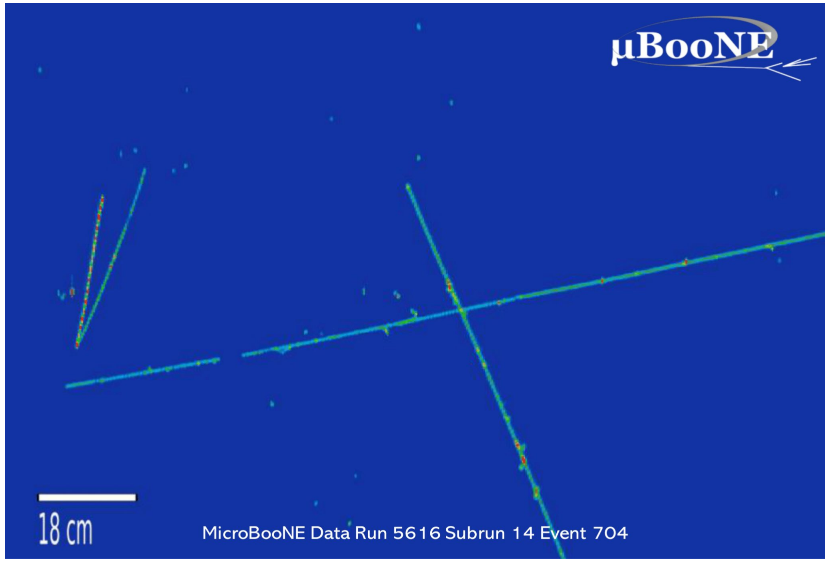
From supplemental material of Phys. Rev. Lett. 130, 231802.











Λ Measured Cross Section

- Final cross section presented as a Bayesian posterior distribution.
- Measured cross section:

$$\sigma_R = 2.0^{+2.2}_{-1.7} \times 10^{-40}\ \mathrm{cm}^2/\mathrm{Ar}$$

- Consistent with generator predictions (for now).

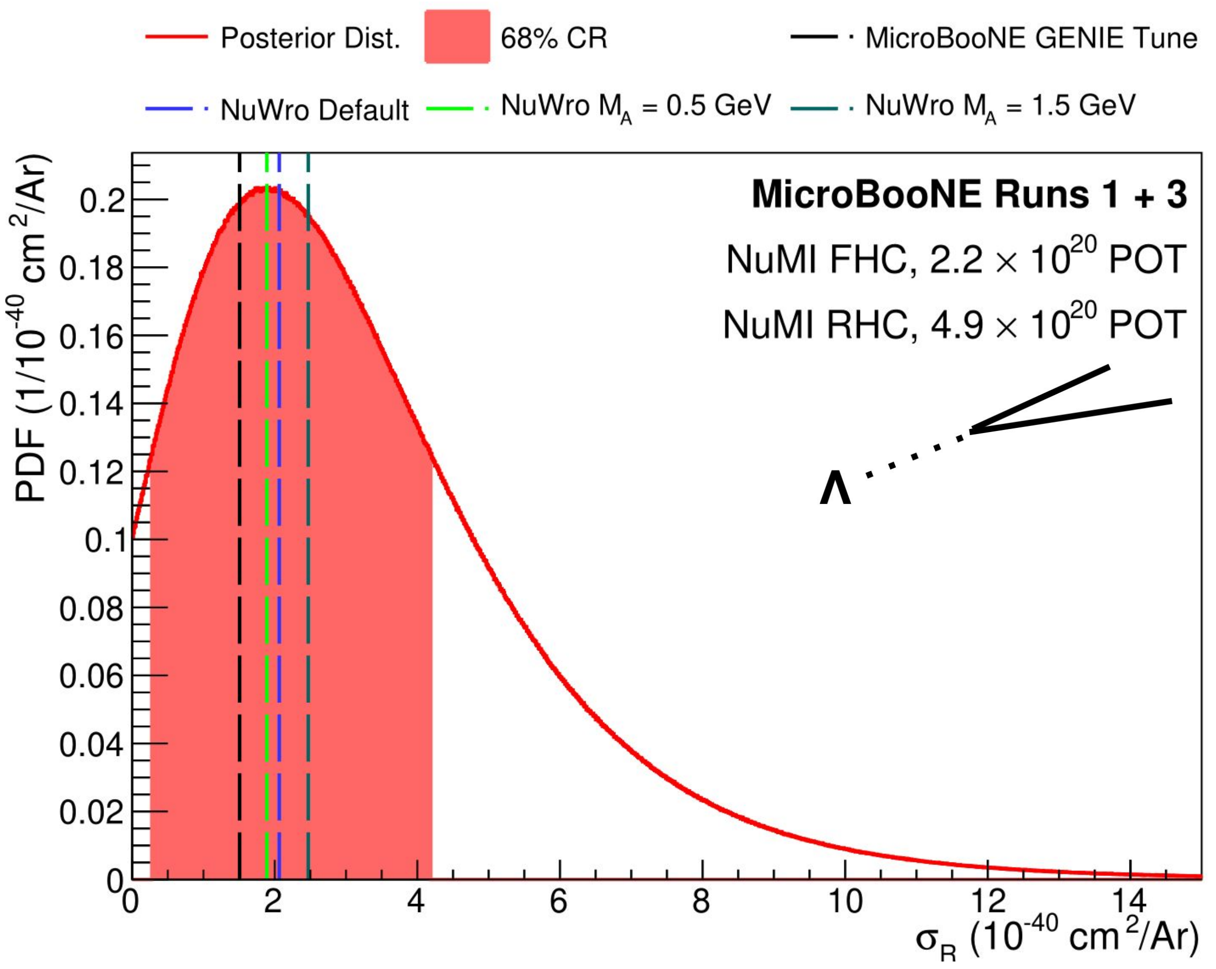
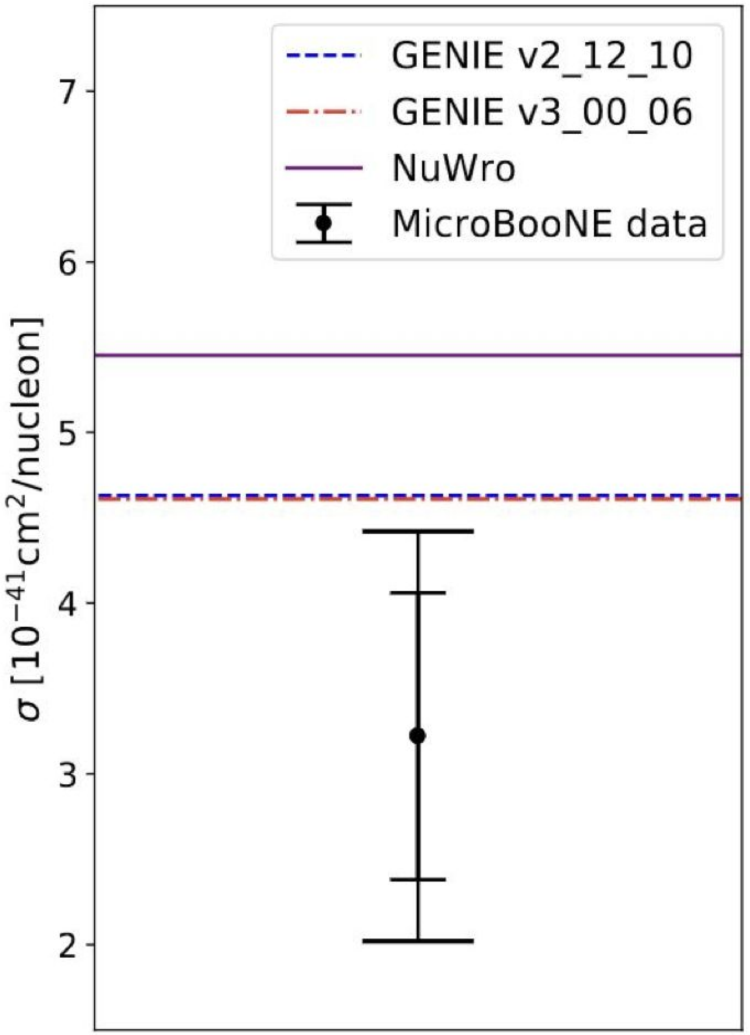


Figure from Phys. Rev. Lett. 130, 231802.

η Measured Cross Section



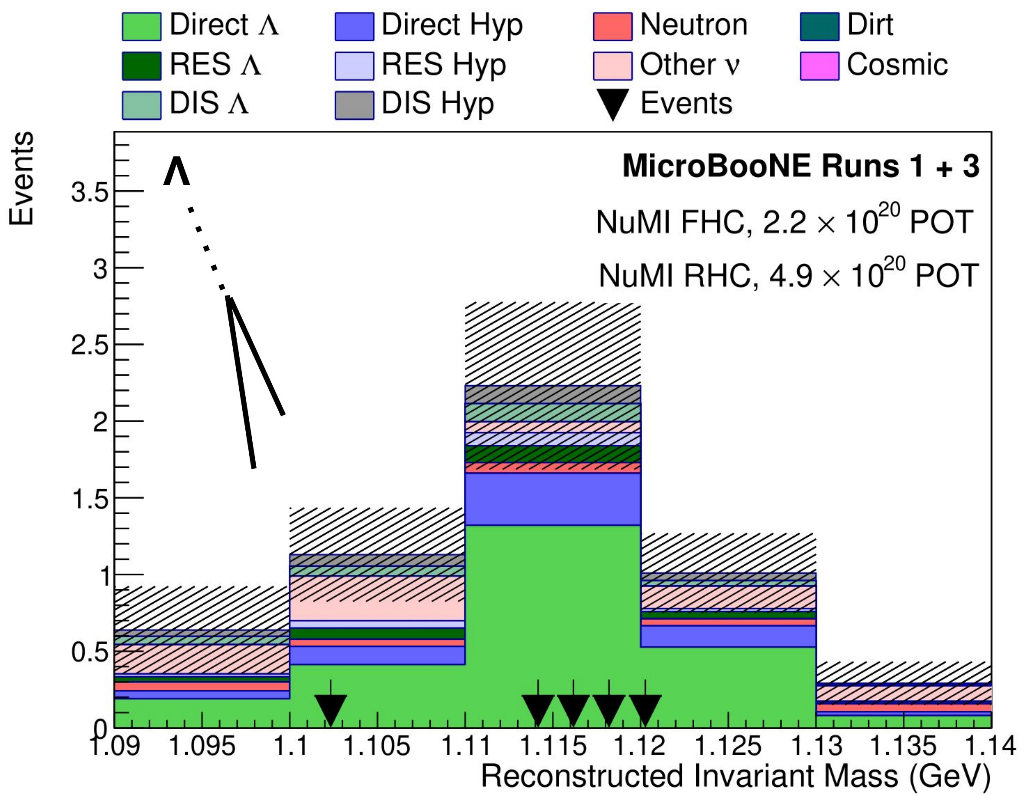
- After unblinding we selected 93 η meson candidates! Predicted background was 55.4 events.
- Final measured cross section:

$$3.22 \pm 0.84 \ (\text{stat.}) \pm 0.86 \ (\text{syst.}) \ 10^{-41}\text{cm}^2/\text{nucleon}$$

Invariant Mass Spectra

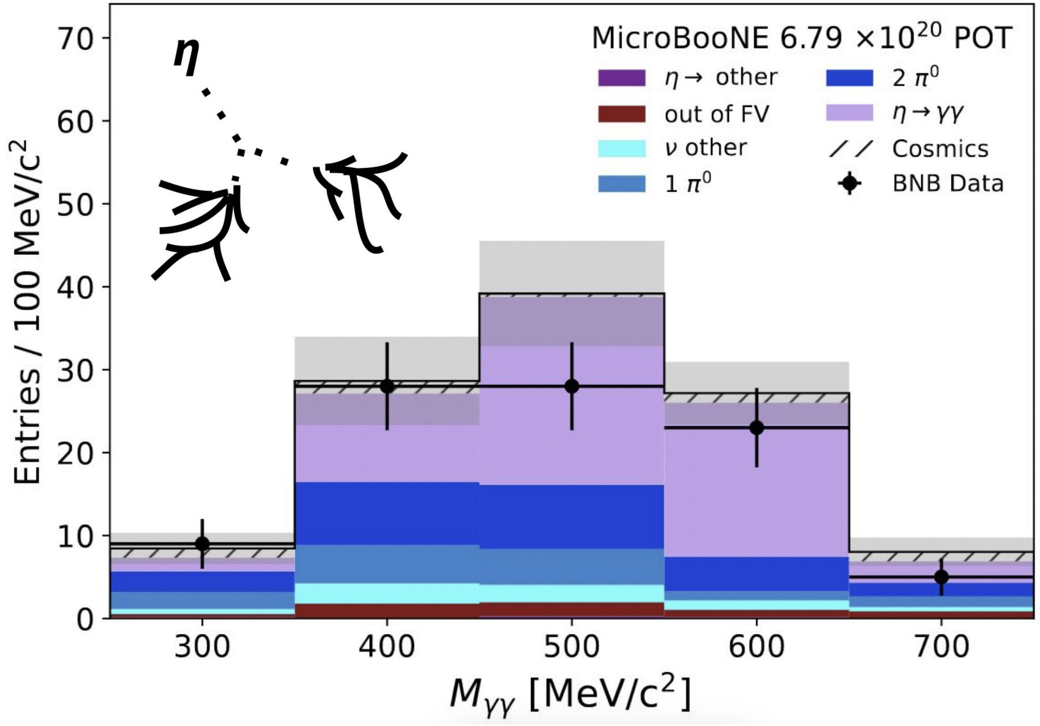
- A nice check is the look at the invariant masses of our selected Λ and η candidates.

Figure from Phys. Rev. Lett. 130, 231802.



Lots of Λs around the true mass!

Figure from arXiv:2305.16249.



η Hadronic Invariant Mass

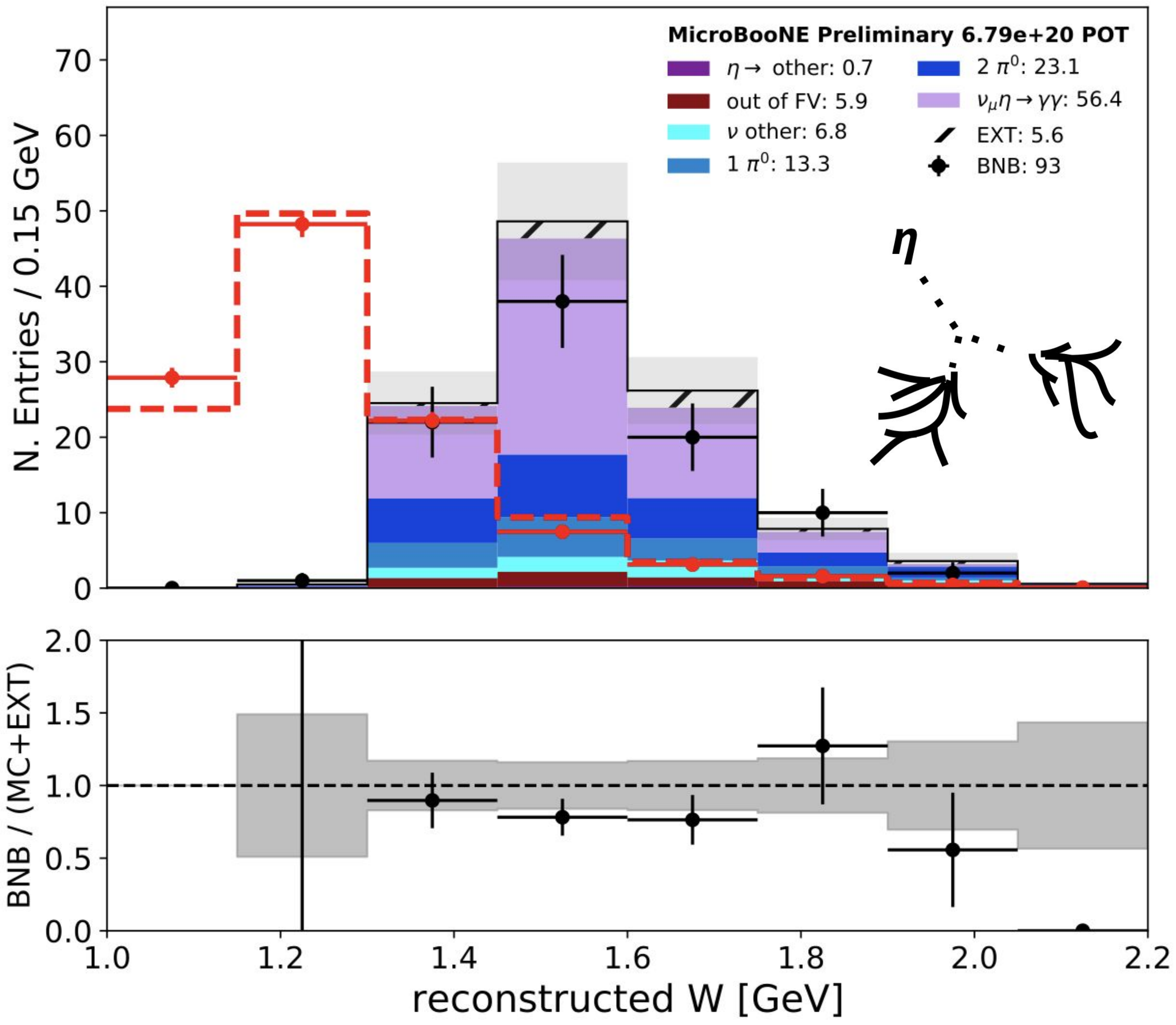


Figure from arXiv:2305.16249.

- Superimpose invariant mass spectra of hadronic final states from η selection and π^0 selection.
- Two distinct peaks! - first at about 1.2 GeV (around the Δ resonance), the second at 1.5 GeV (the N(1535) resonance).

Summary

- MicroBooNE has the largest neutrino-Ar scattering dataset yet recorded.
- We've successfully exploited this to start measuring rare neutrino interaction cross sections.
- Λ analysis first of its type in over 30 years, and the first ever with fully automated reconstruction/selection.
- First ever measurement of η production on argon!

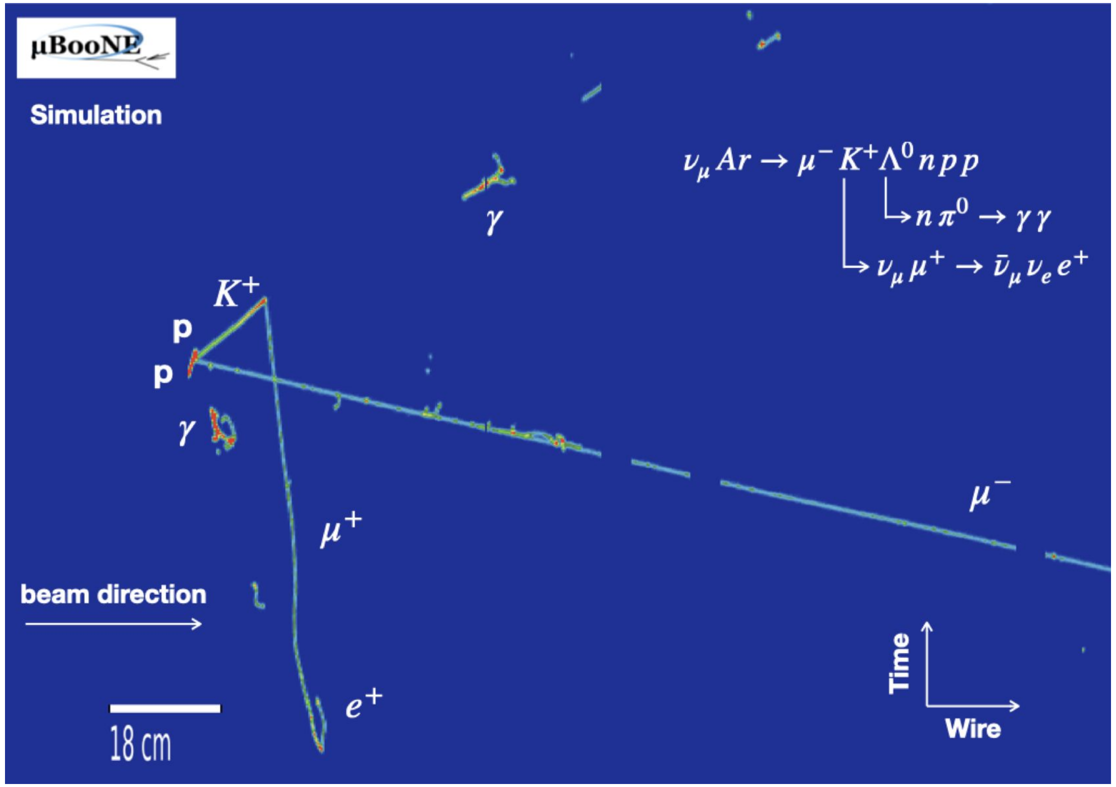
Outlook

- These analysis only utilise a portion of MicroBooNE's dataset.
- Expect fourfold increase in statistics with the full dataset in the Λ analysis.
- η analysis will have twice the statistics with the full dataset.

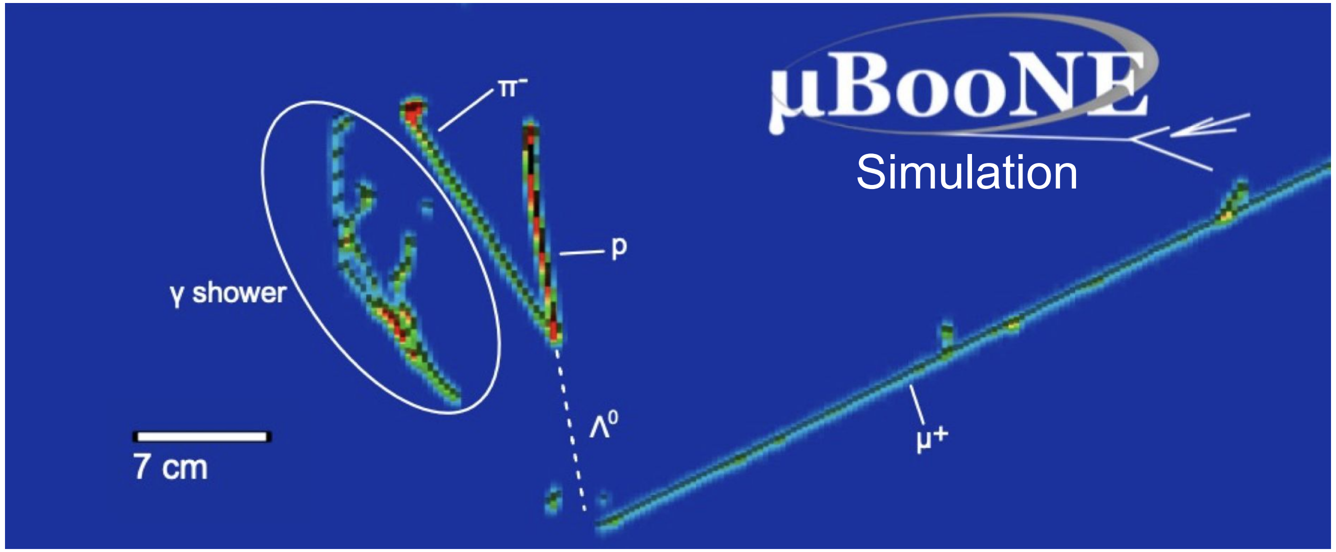
- All of the analysis techniques described here will translate into other SBN experiments and DUNE, which will obtain far larger datasets.

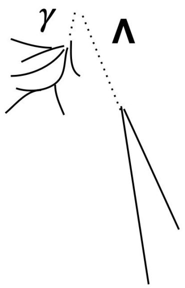
Other Rare Event Searches

[MICROBOONE-NOTE-1071-PUB]



Charged kaons!
(Two ongoing analyses)





Σ^0 Baryons!

Further Reading

- Our Λ production paper: Phys. Rev. Lett. 130 (2023) 23, 231802.
- Much more detailed description of Λ measurement: C Thorpe PhD Thesis (Lancaster University).
- Theory comparisons to our measurement: arXiv:2305.17004.

- Preprint on our η production measurement: arXiv:2305.16249.
- Theory predictions for η production: Phys.Rev.D 108 (2023) 5, 053009.

Thank You!

Backup Slides

MicroBooNE's BSM Program

Published Results

- Long-lived Heavy Neutral Leptons and Higgs Portal Scalars
  Phys. Rev. D 106 9, 092006 (2022).
- Higgs Portal Scalar Decaying to e^+e^-
  Phys. Rev. Lett. 127 15, 151803 (2021).

Submitted

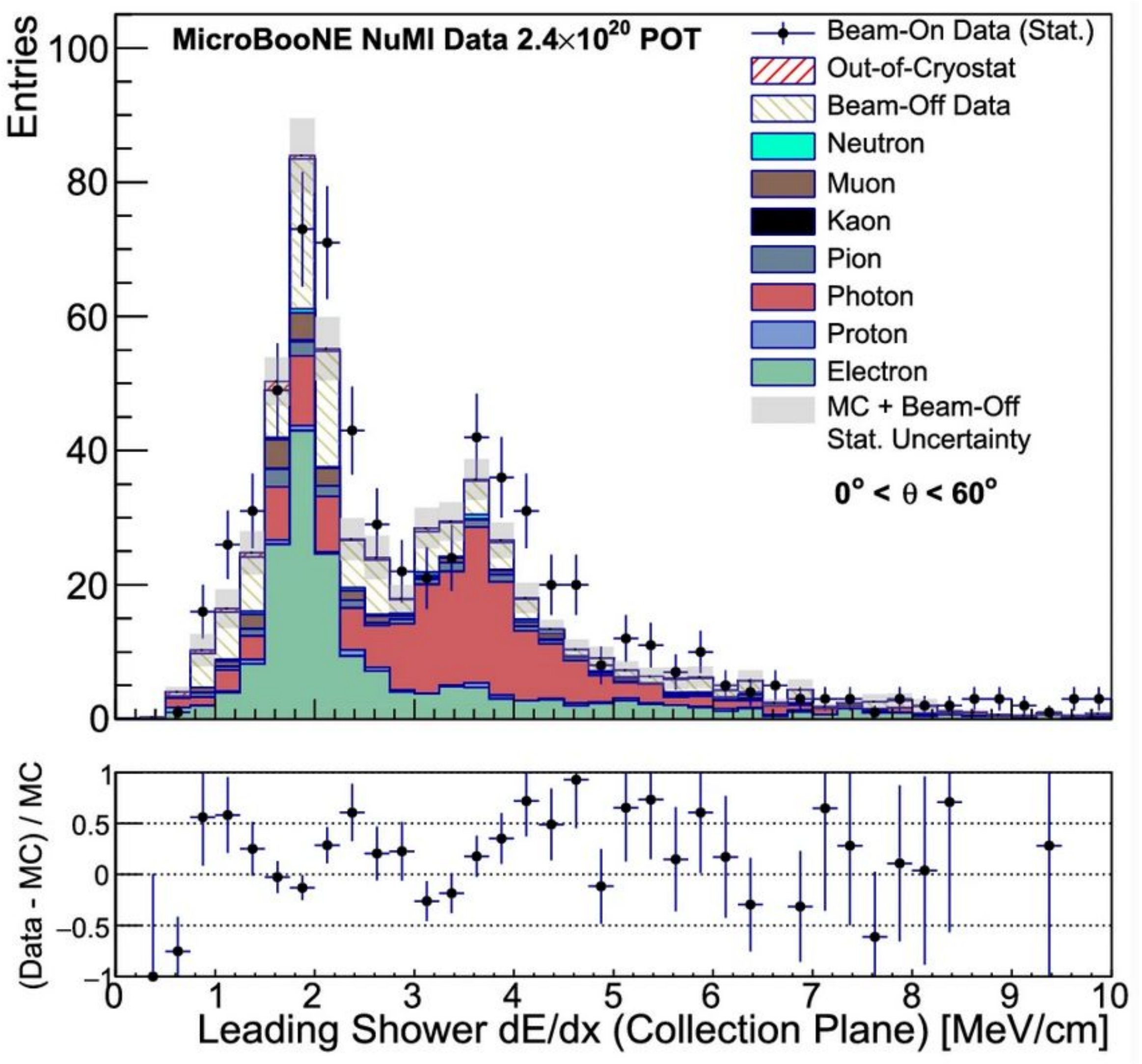
- Heavy Neutral Leptons in e^+e^- and π^0 Final States
  arxiv:2310.07660.
- Neutron-antineutron Oscillation arxiv:2308.03924.

Ongoing

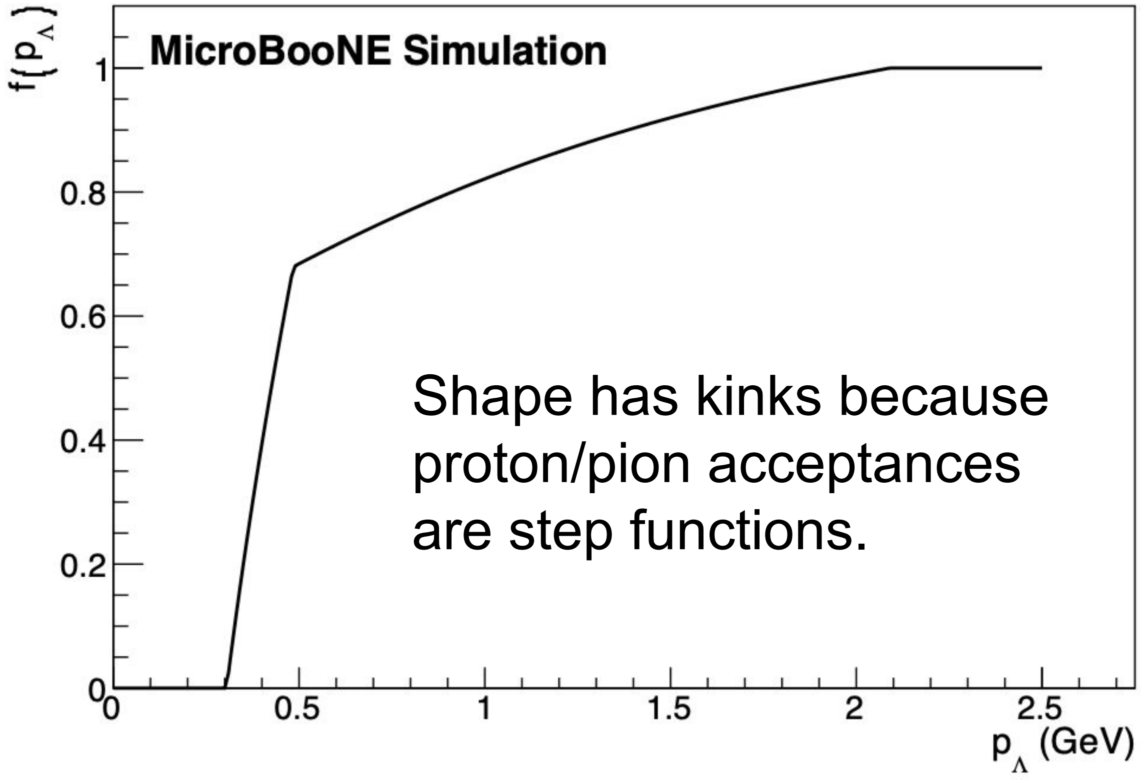
- Higgs Portal Scalars in NuMI.
- Dark Tridents.
- Millicharged Particles.
- Heavy Axions.

Electron/Photon Discrimination

- Study the dE/dx profile near the start of the shower.
- Photon pair produces - two electrons depositing energy at the start of the shower → dE/dx 2x larger than that of an electron.



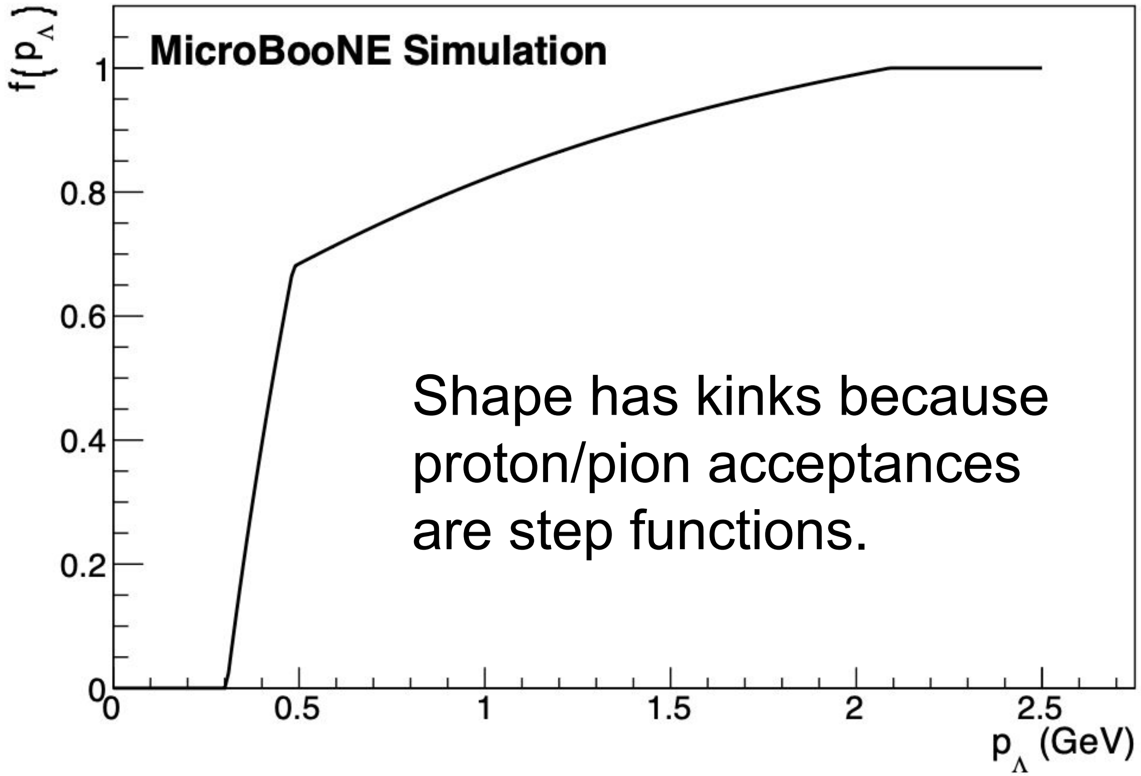
Λ Partial Phase Space Definition



From supplemental material of Phys. Rev. Lett. 130, 231802.

- MicroBooNE is insensitive to protons and charged pion of momenta < 0.3 GeV and < 0.1 GeV respectively.
- Calculate what fraction of Λ baryons that will produce decay products above those thresholds.

Λ Partial Phase Space Definition



Shape has kinks because proton/pion acceptances are step functions.

$$f(p_\Lambda) = \begin{cases} 0 & \text{if } A > B \\ \frac{B-A}{2} & \text{Otherwise} \end{cases},$$

$$A = \max\left(\frac{\sqrt{M_p^2 + |p_p^{\text{thresh}}|^2} - \gamma E_p}{\beta\gamma p}, -1\right),$$

$$B = \min\left(\frac{-\sqrt{M_\pi^2 + |p_\pi^{\text{thresh}}|^2} + \gamma E_\pi}{\beta\gamma p}, 1\right),$$

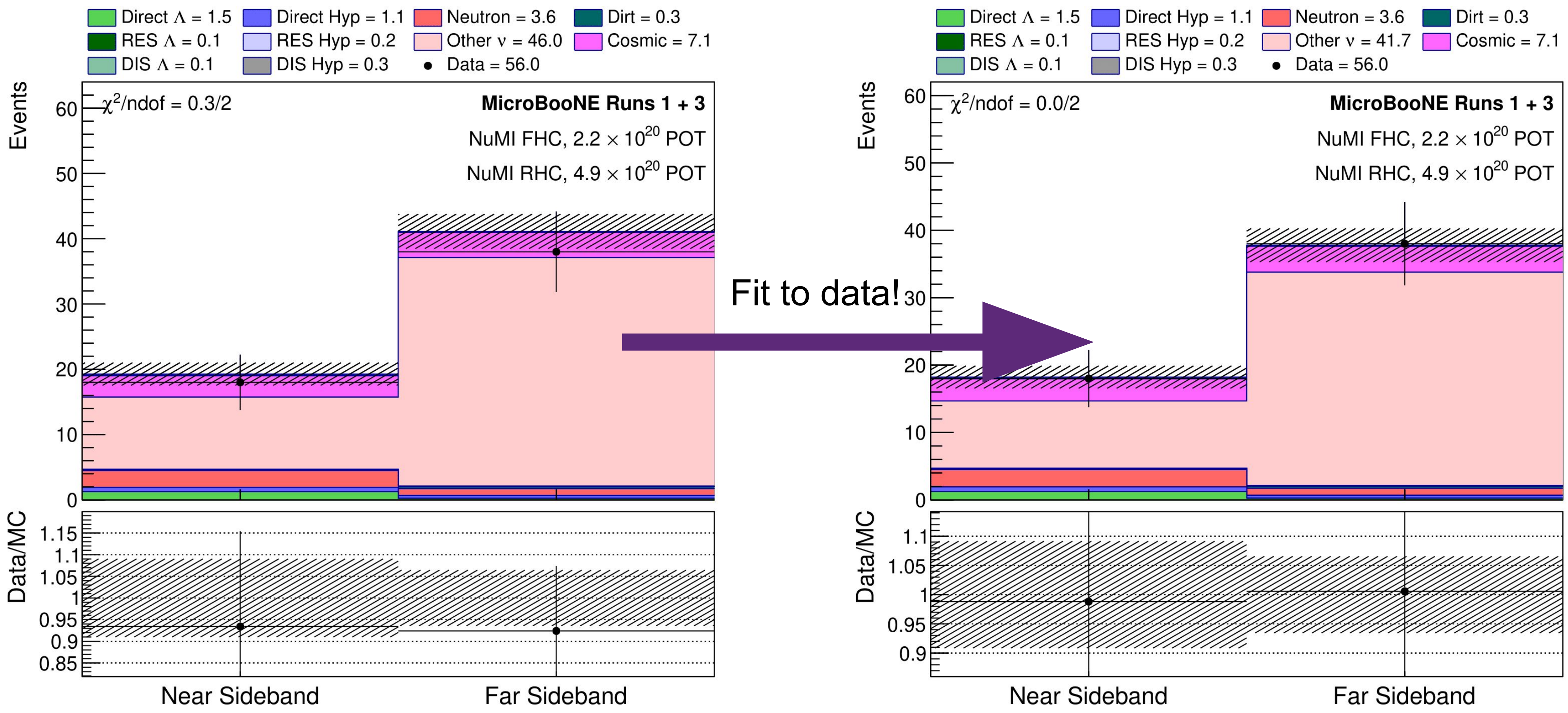
$$E_p = \sqrt{M_p^2 + p^2},$$

$$E_\pi = \sqrt{M_\pi^2 + p^2}.$$

From supplemental material of Phys. Rev. Lett. 130, 231802.

Λ Sideband Constraint

- Invert cuts on invariant mass and angular deviation. Split data into two regions. Rescale pale-pink prediction.



Λ Sideband Constraint

- Get the MC prediction for sideband bin b, rescale the mis-reco component by k:

$$R_b(k) = S_b + B_b^{\mathrm{Hyperon}} + B_b^{\mathrm{Neutron}} + B_b^{\mathrm{Out-of-cryo}} + B_b^{\mathrm{Cosmic}} + kB_b^{\mathrm{Mis-reco}}$$

- Minimise χ^2 score. Use data/MC statistical uncertainties only:

$$\chi^2(k) = \sum_{b=1,2} \frac{(R_b(k) - D_b)^2}{\sigma_b^2},$$

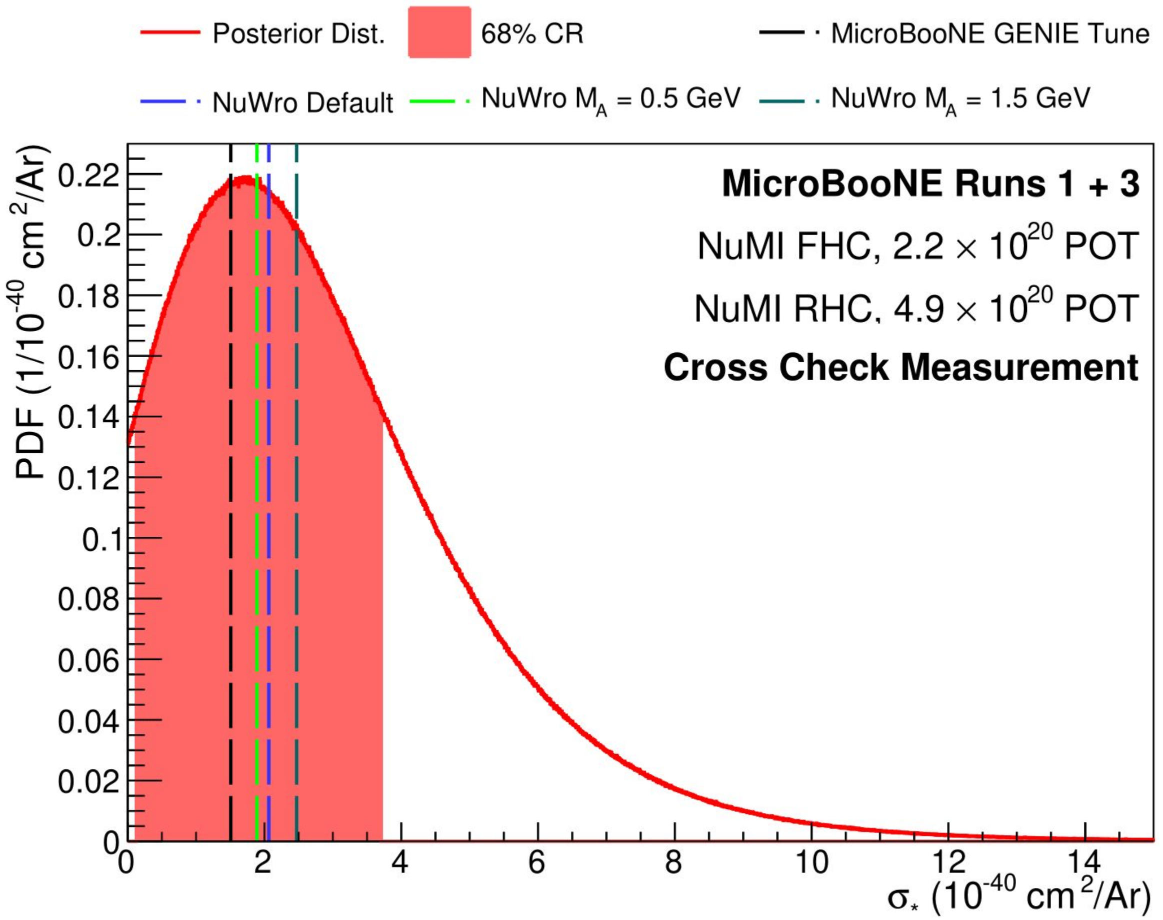
- Fitted value of k used to correct mis-reco prediction in signal region.
- Systematics: fit k for each universe. Correct the CV prediction in the signal region to obtain alt universe prediction.

Λ Sideband Constraint - Result

- Final cross section result:

$$\sigma_*^{SC} = 1.8^{+2.0}_{-1.6} \times 10^{-40}\ \mathrm{cm}^2/\mathrm{Ar}$$

- Consistent with the value obtained through the visual scan method.



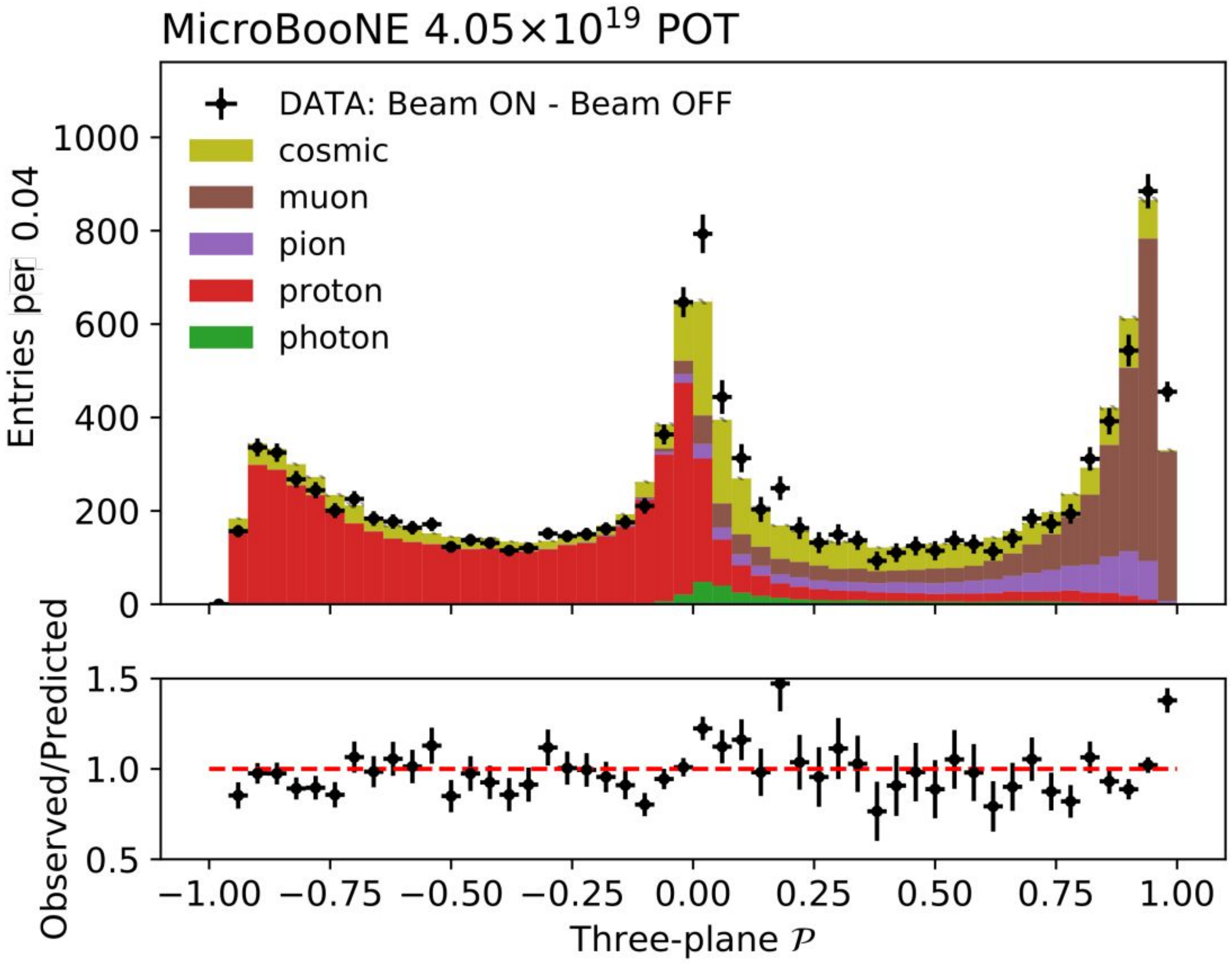
From supplemental material of Phys. Rev. Lett. 130, 231802.

Proton/MIP Discrimination

- MIPs = minimally ionising particles = muons and charged pions.
- Compare dE/dx profiles along tracks, with corrections for non-isotropy of detector.
- Calculate likelihood ratio:

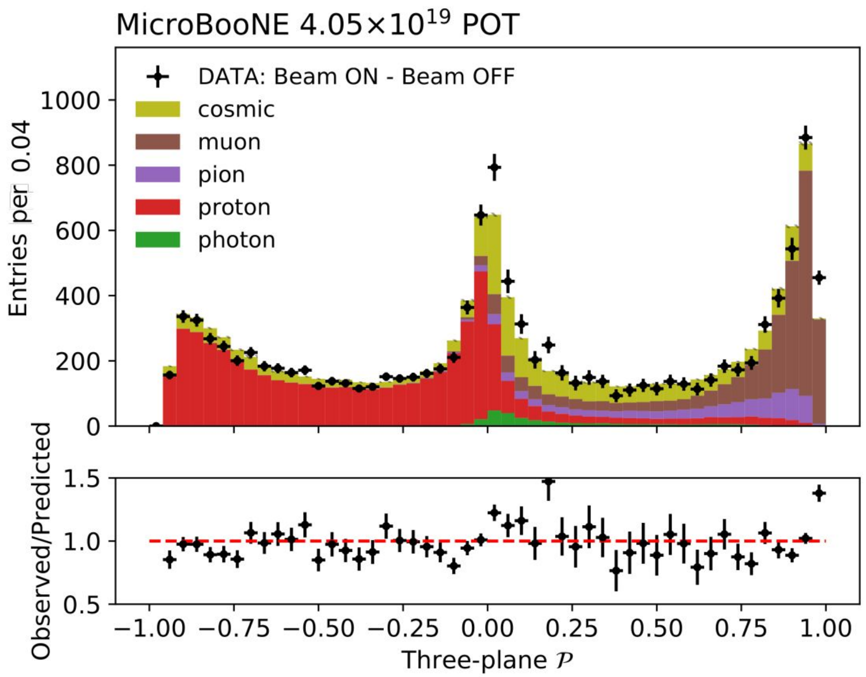
$$\text{LLR PID} = \frac{2}{\pi}\arctan\left(\ln\frac{\mathcal{L}\left(\mu|dE/dx, r, \theta\right)}{\mathcal{L}\left(p|dE/dx, r, \theta\right)}\right)$$

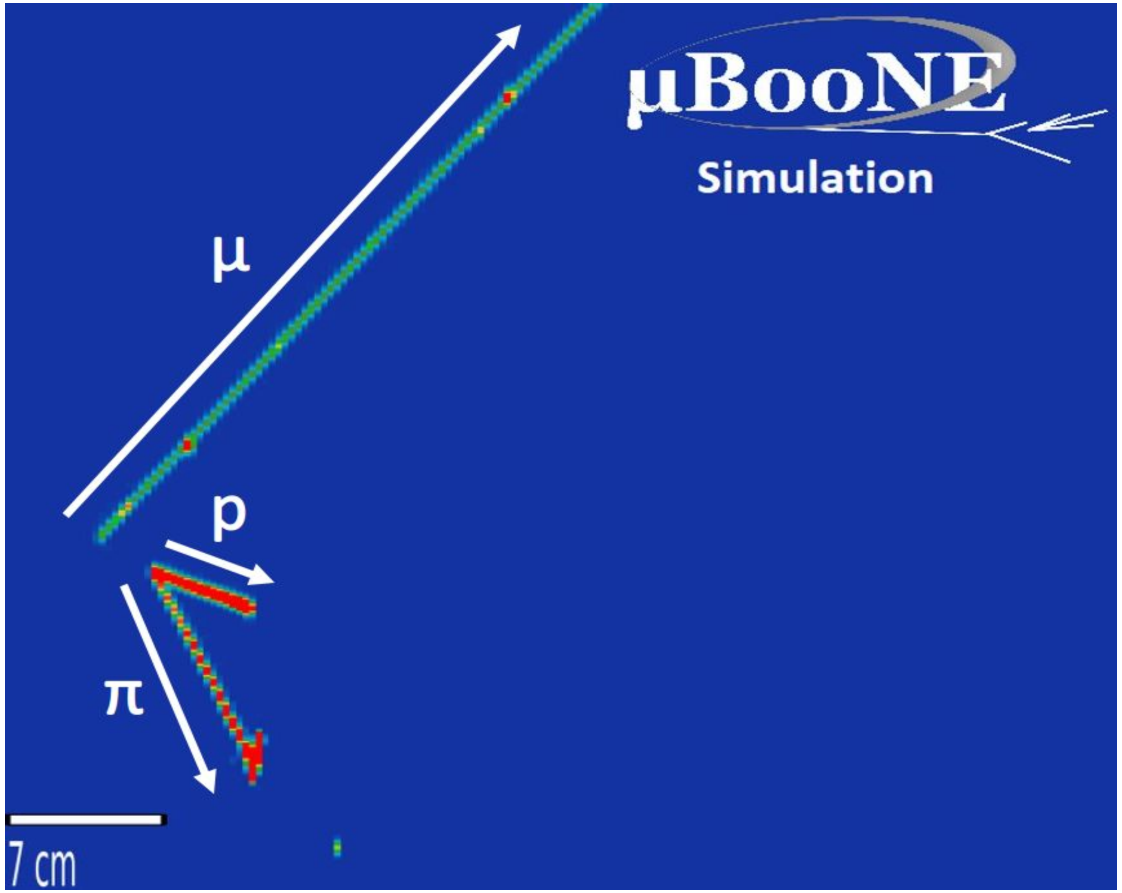
Figure from JHEP 12 (2021) 153.



Λ Proton, Pion, Muon - Which is Which?

- Muon identification is relatively easy - we select the longest track that has a PID score consistent with that of a muon.

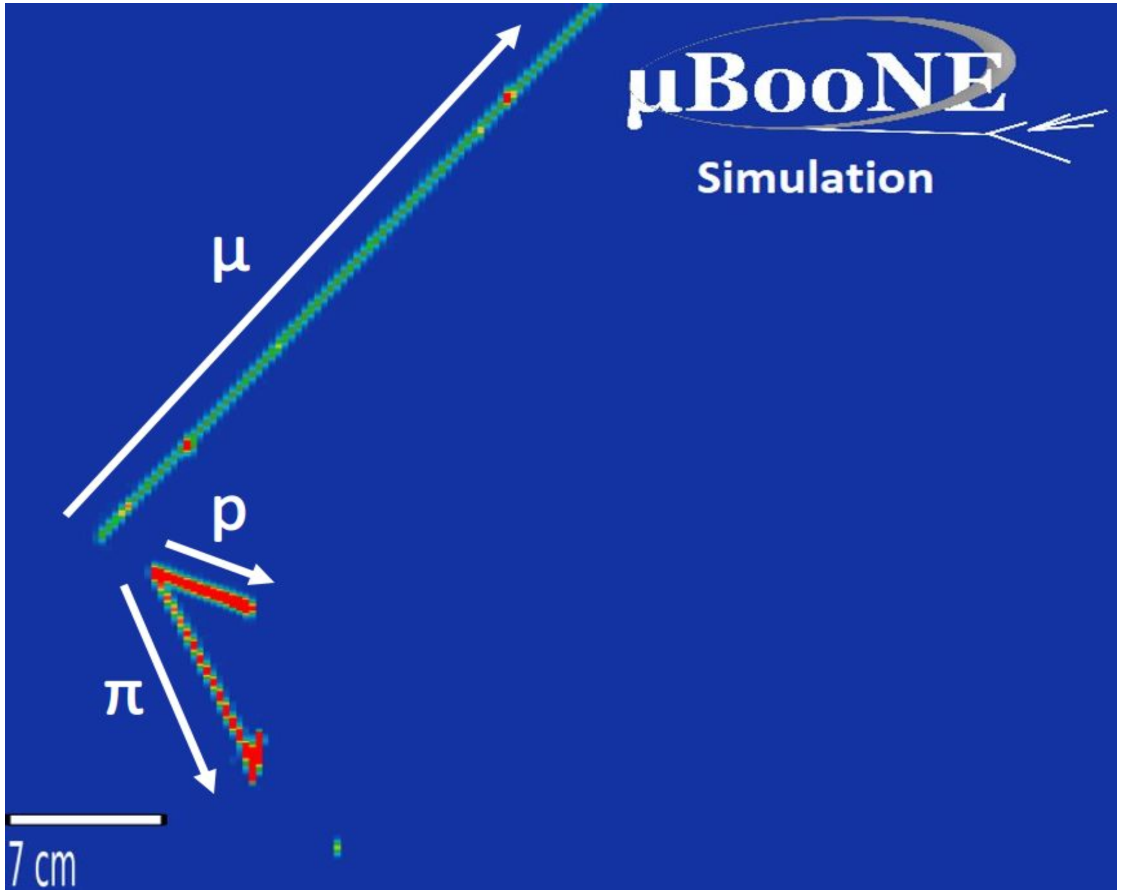




Use LLR PID score to separate muons from protons.

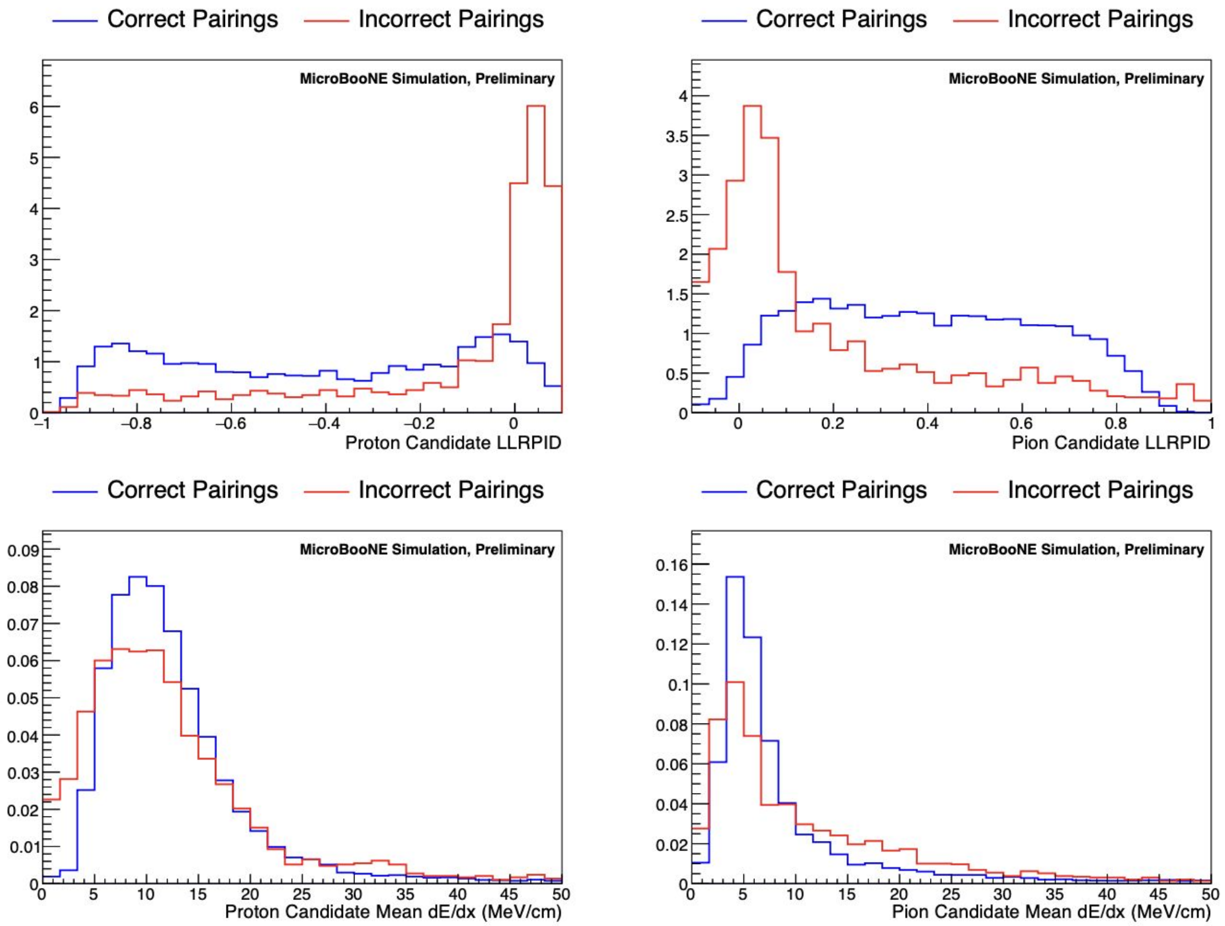
Λ Proton, Pion, Muon - Which is Which?

- Proton and pion selection is more complicated. There can be a few tracks to choose from, and crucially, we have to assign the proton/pion labels the right way round.



Λ Proton, Pion, Muon - Which is Which?

1. Select two tracks, assign the proton label to one, and the pion label to the other.
2. Calculate seven useful variables assuming these hypotheses.
3. Feed this information into an array of BDTs, get response score.
4. Select the combination with the best response.



When we assign the p/п labels to the correct tracks.
When we assign the p/п labels to two other tracks/the wrong way round.

Systematics

- In most MicroBooNE cross section analyses we consider five main sources of systematic uncertainty:

1. Neutrino flux.
2. Cross sections of background neutrino interactions.
3. Secondary interactions of hadrons outside the nucleus.
4. Detector response modelling.
5. Background from neutrino interactions outside the cryostat (“dirt” backgrounds) + **other analysis specific uncertainties**.

Systematics

1. Neutrino flux:

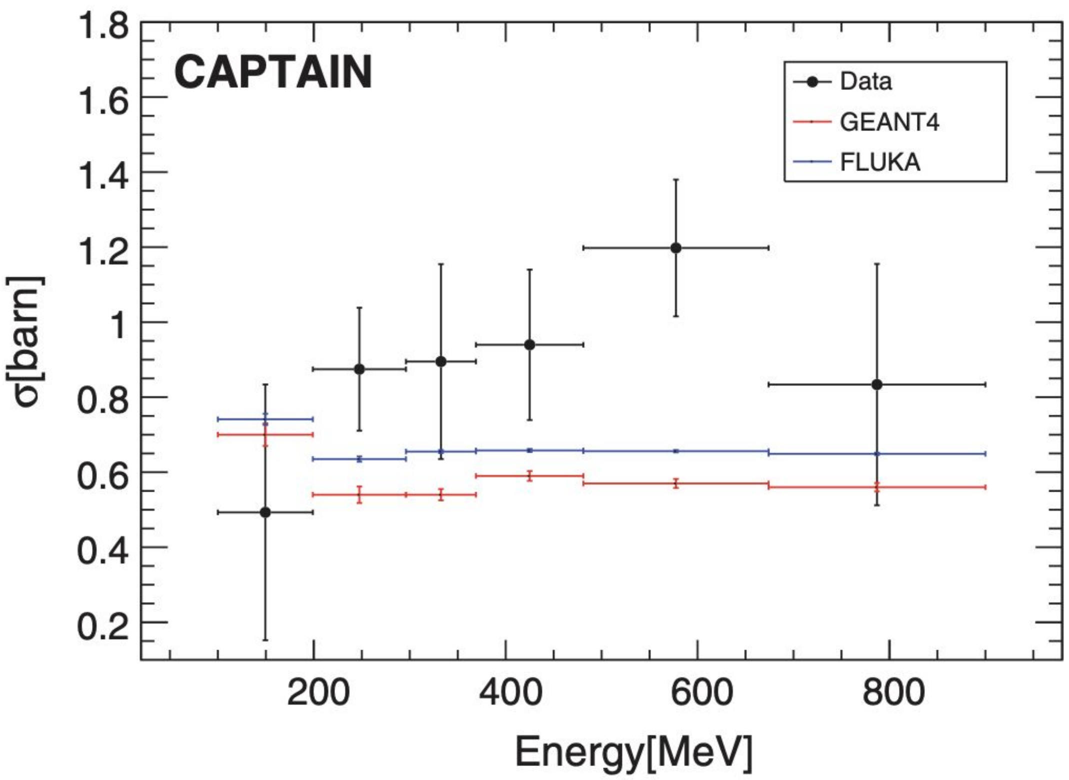
- η analysis: we use the MiniBooNE flux with its uncertainties, updated for MicroBooNE's baseline.
- Λ analysis we employ the Package to Predict Flux (PPFX). Considers hadron production and beamline geometry uncertainties. Hadron production dominates.

Systematics

2. Background neutrino interactions. Both analyses employ uncertainties from our GENIE tune. This is based on T2K and MINERvA data.
    - η leverages sideband constraint described earlier.
    - Λ assumes 100% uncertainty on irreducible Σ^0 background.

Systematics

3. Secondary interactions outside the Ar nucleus. MicroBooNE uses Geant4Reweight, combined with fits to pion data. Apply uncertainties to protons, charged pions and Λ baryons.



The Λ analysis also includes an uncertainty on the neutron-Ar cross section, tuned to data from the CAPTAIN experiment.

Systematics

4. Detector response. Nine variations compared to default model:

- Light yield, three variations: 25% reduction, alternative attenuation and rescattering models (very small for both analyses).
- Wire Response: four data driven variations based on fits to size and shapes of wire signals from MicroBooneE cosmic data.
- Space Charge: alternative correction map based off measurements using cosmic rays and a laser.
- Alternative recombination model.

Systematics

5. Neutrino interactions outside the cryostat:

- Fit to dirt rich sideband - obtain uncertainty of ±71%.
- No dirt uncertainty included in the η analysis.

Bayesian Efficiency Uncertainty

- Posterior probability of selection efficiency ϵ given weighted events w_i.

$$P(\epsilon) = \mathrm{Beta}(\epsilon; a, b)$$

$$a = \alpha + k \qquad b = \beta + n - k$$

$$k = \hat{\epsilon}\hat{N}, \qquad \hat{\epsilon} = \frac{\sum_{\mathrm{sel}} w_i}{\sum_{\mathrm{all}} w_i} \qquad \hat{N} = \frac{(\sum_{\mathrm{all}} w_i)^2}{\sum_{\mathrm{all}} w_i^2} \qquad n = \hat{N}.$$

- See root documentation for derivation.