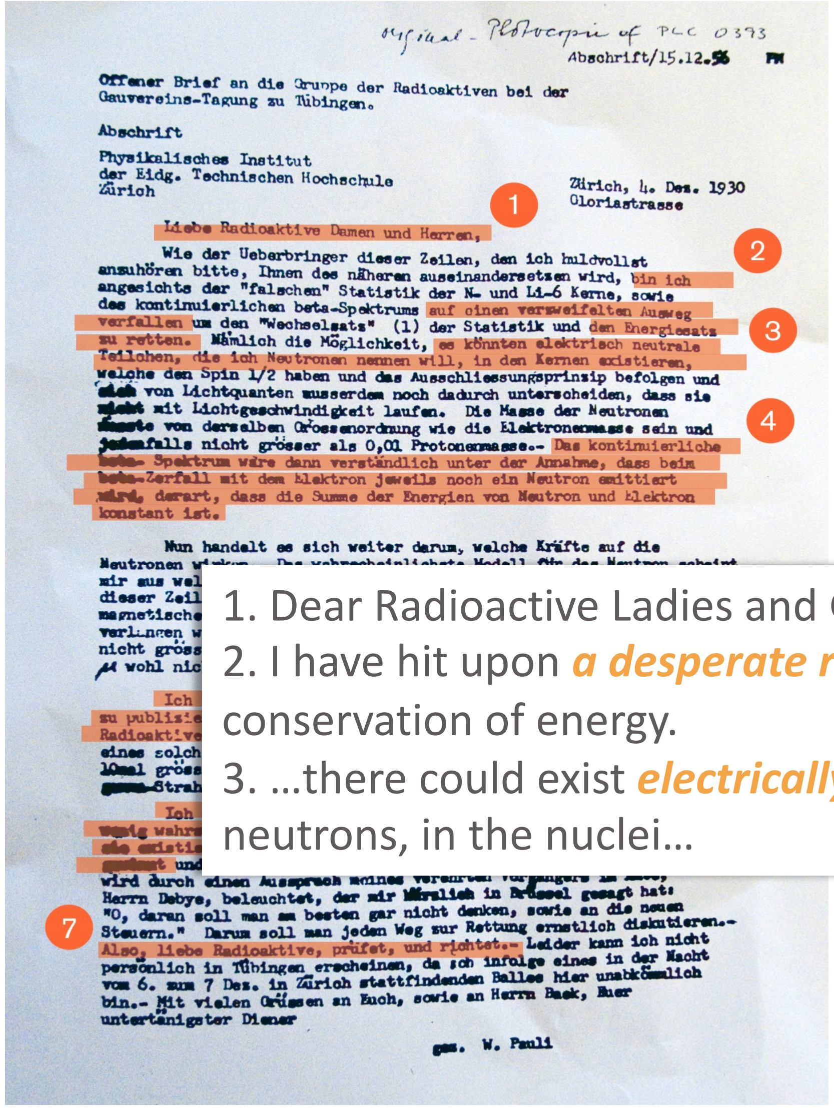
Recent Result from MicroBooNE: Hunting for new piece of Neutrino Puzzle with LArTPCs

Maya Wospakrik

Fermilab Neutrino Seminar

3rd February 2022

Neutrino: the “missing energy” puzzle



Original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

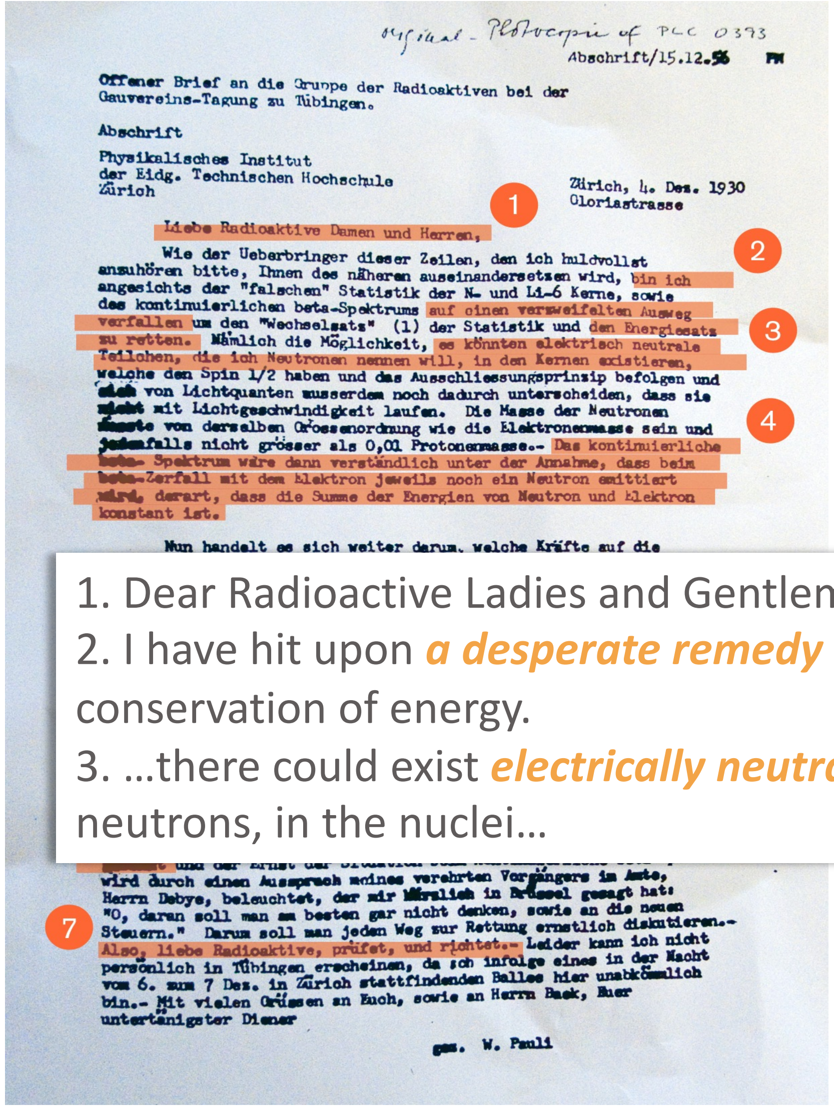
Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. ...

... wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

1. Dear Radioactive Ladies and Gentlemen!
2. I have hit upon ***a desperate remedy*** to save…the law of conservation of energy.
3. …there could exist ***electrically neutral particles***, which I will call neutrons, in the nuclei…

From “Desperate Remedy” to Standard Model



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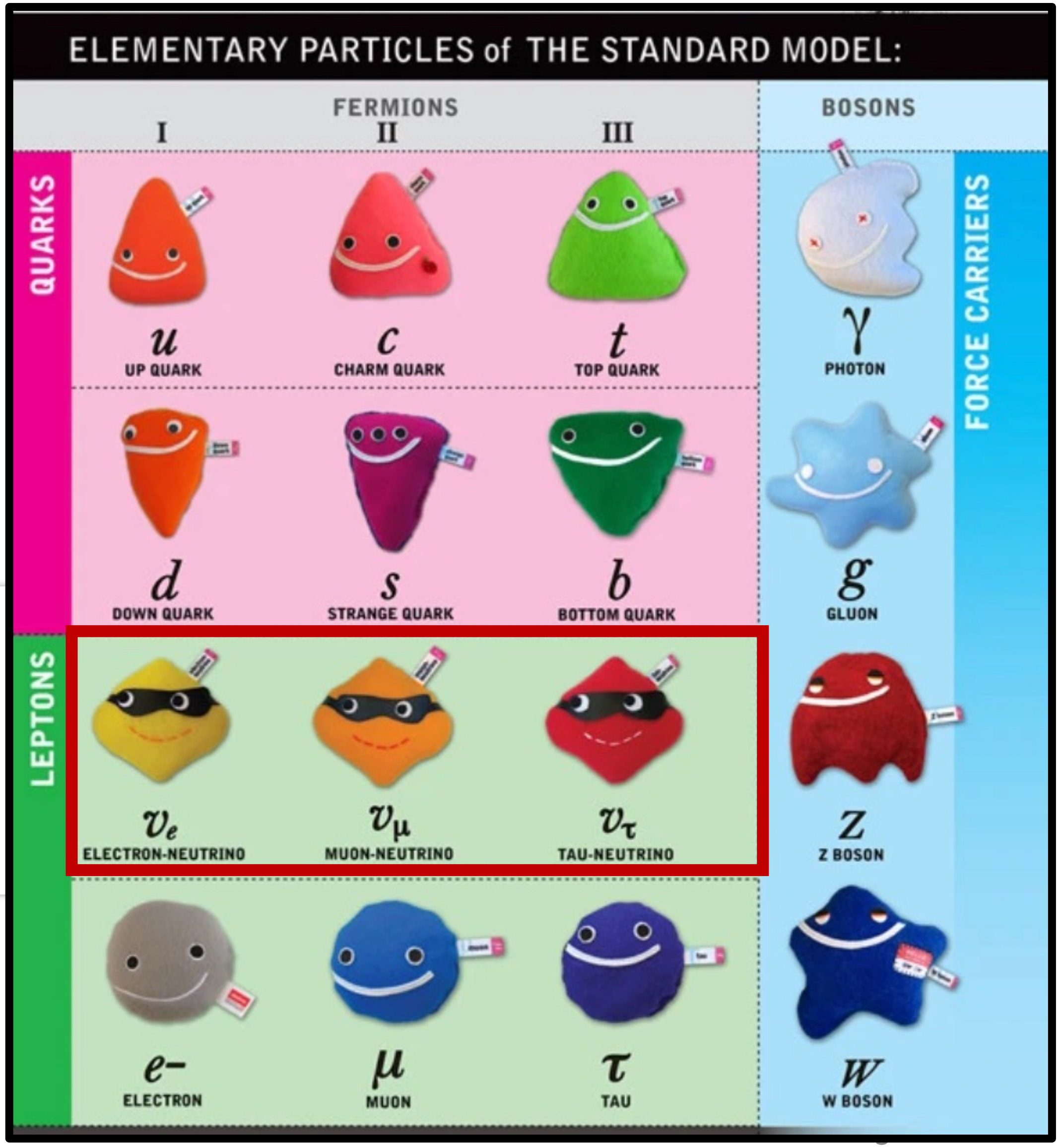


Solar neutrino puzzles

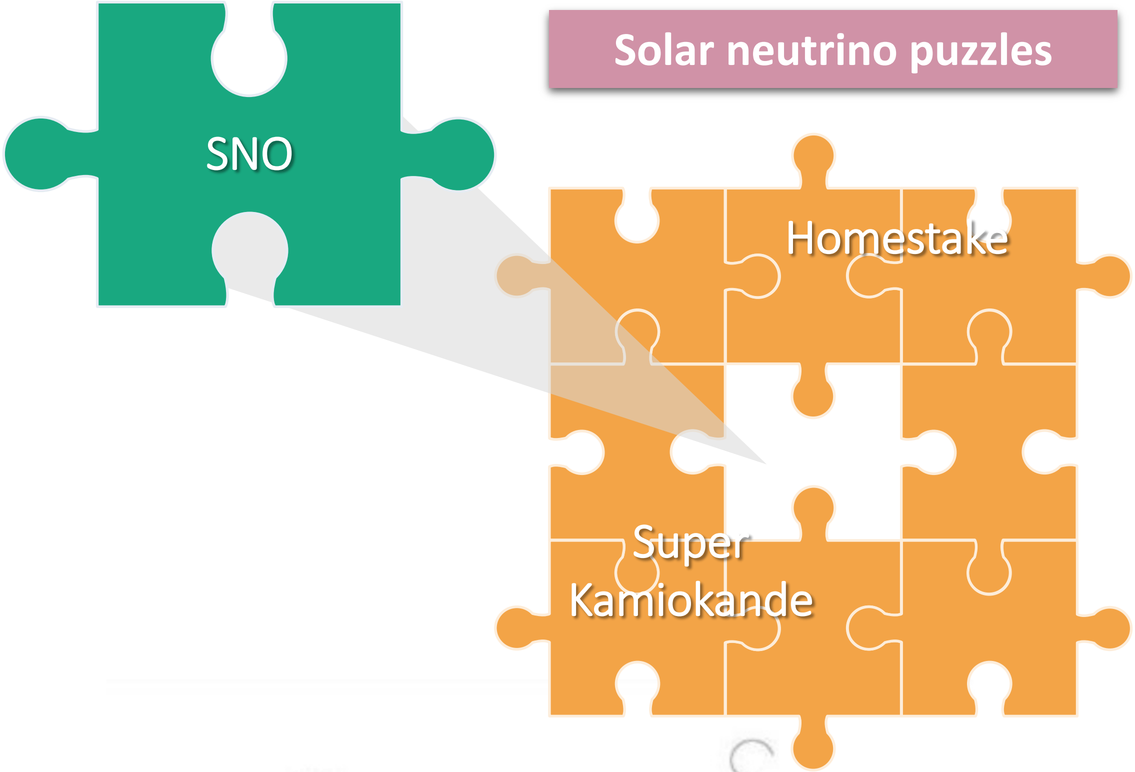


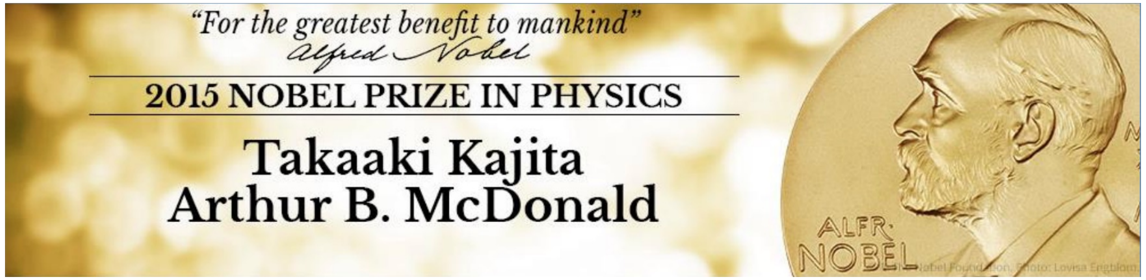
Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

They Solved the Neutrino Puzzle

Takaaki Kajita and Arthur B. McDonald solved the neutrino puzzle and opened a new realm in particle physics. They were key scientists of two large research groups, Super-Kamiokande and Sudbury Neutrino Observatory, which discovered the neutrinos mid-flight metamorphosis.

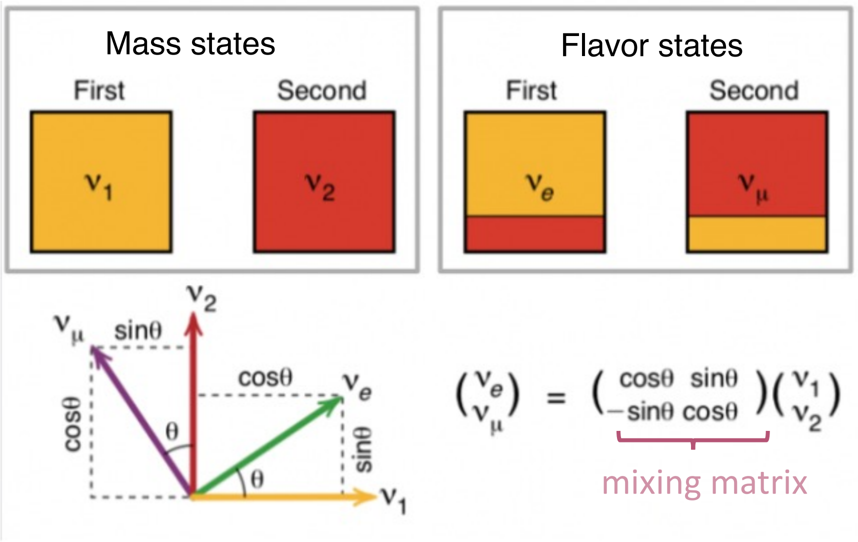
To discovery of Neutrino Oscillation

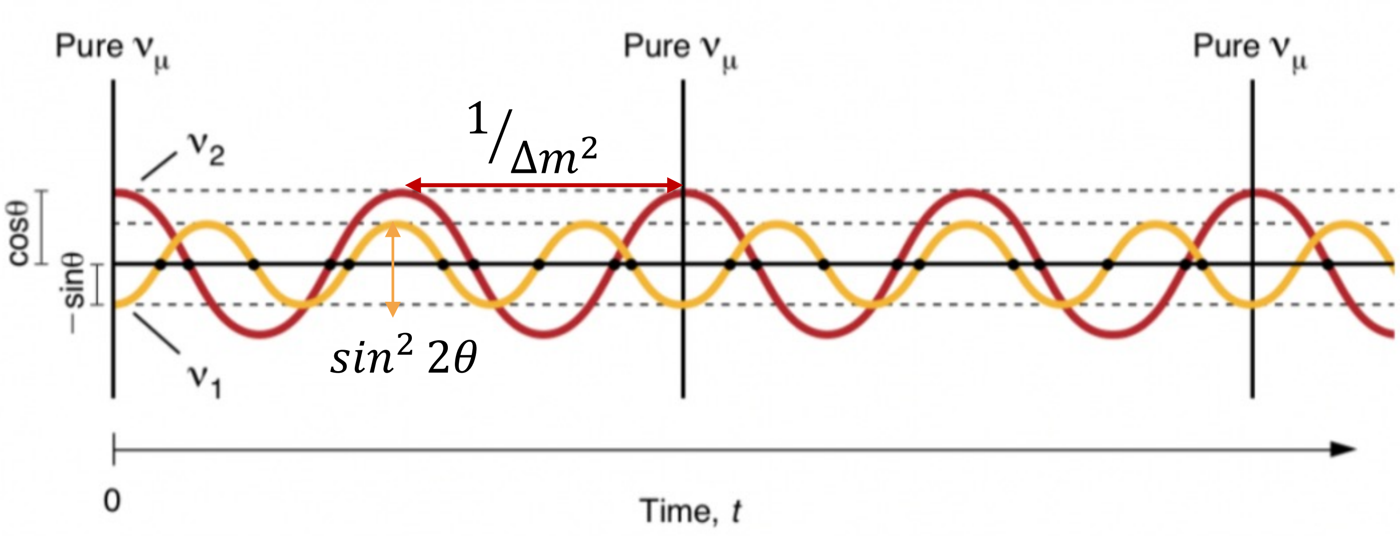
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}^{\text{Neutrino mixing matrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



2 Neutrino Oscillation

Image credit: "Celebrating Neutrinos", Los Alamos Science, 25 (1997).





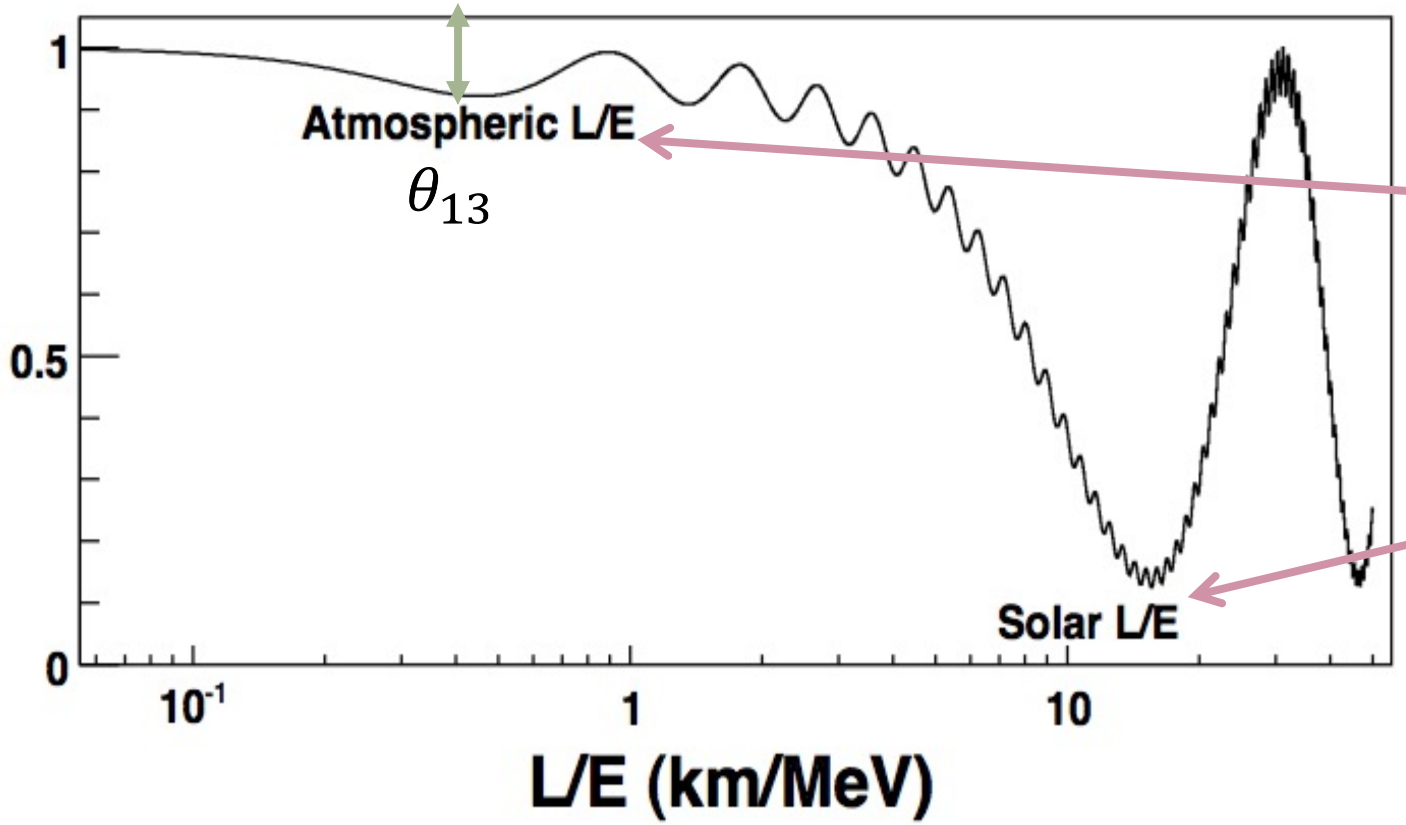
Two neutrino model:

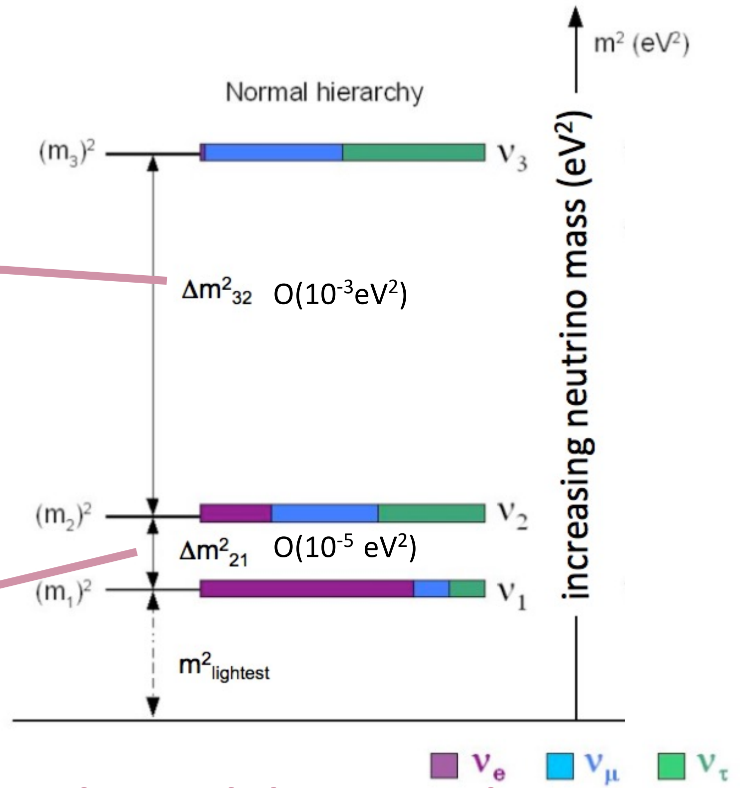
$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2[eV]^2.L\ [km]}{E_\nu[GeV]}\right)$$

$\sin^2(2\theta)$: amplitude of oscillation
"large" : easy to detect

Δm^2: frequency of oscillation
Choose L, E appropriate for Δm^2

3 Flavor Neutrino Oscillation





Neutrino mixing matrix

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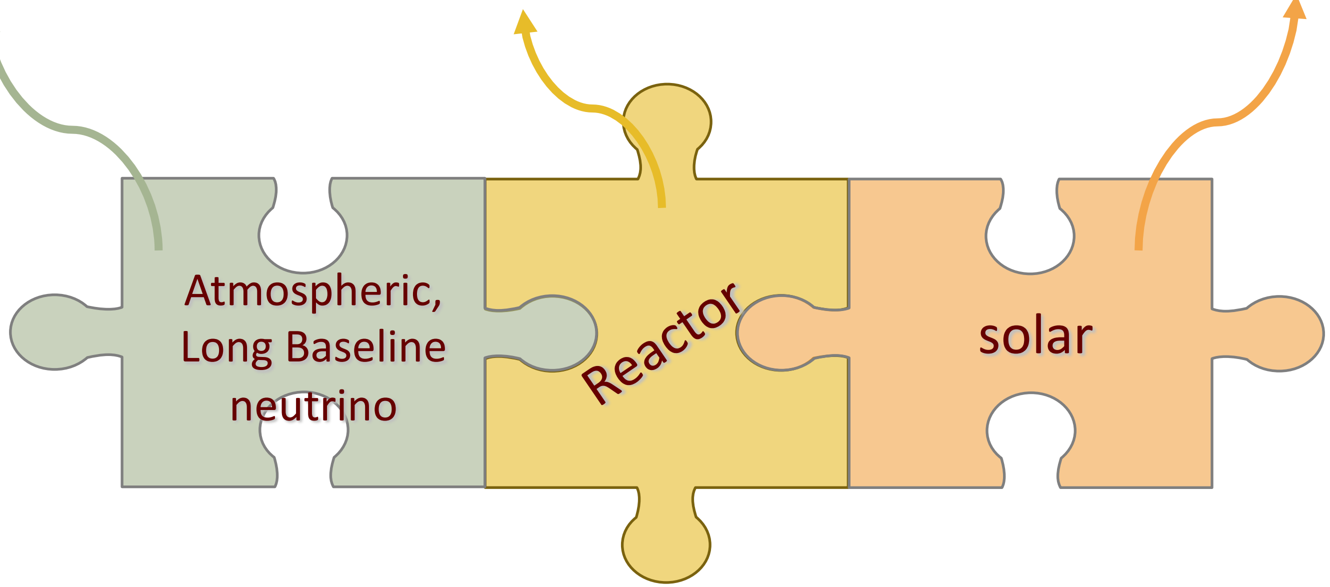
The difference between masses and the mixing of 3 neutrinos are one of the questions that can be answered by experiments looking at neutrino oscillation at different beamline

What we know so far

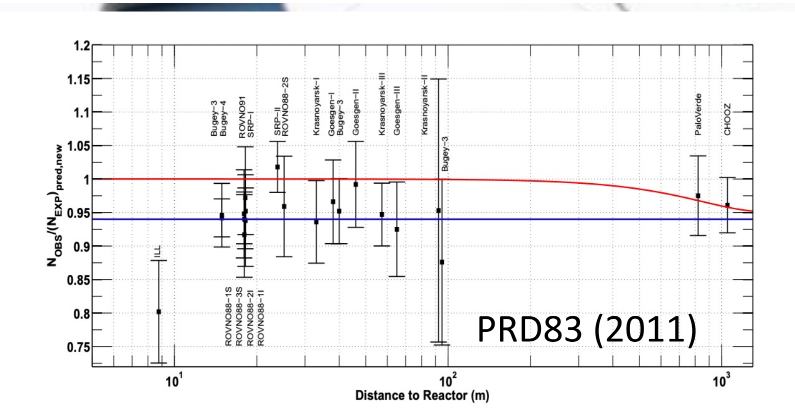
PMNS mixing matrix: a unitary matrix with three mixing angles $(\theta_{13}, \theta_{12}, \theta_{23})$ and CP violating phase (δ_{CP}).

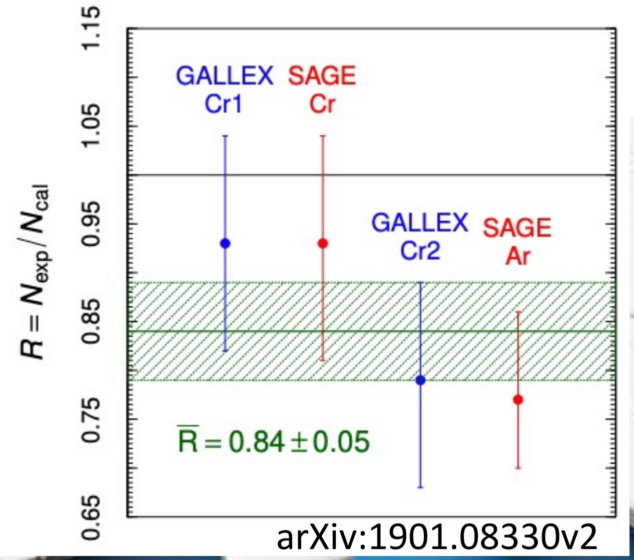
$$\mathrm{U}_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

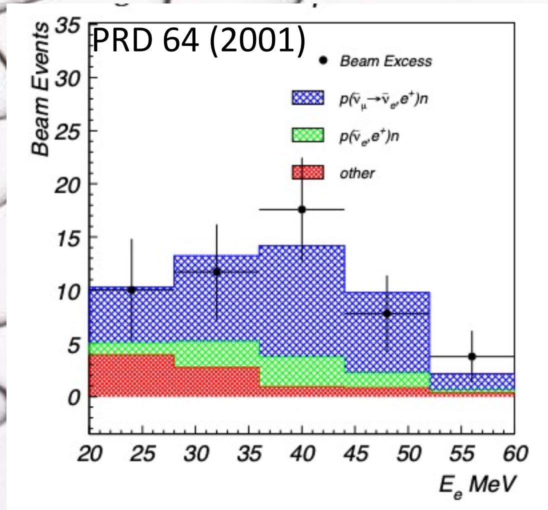


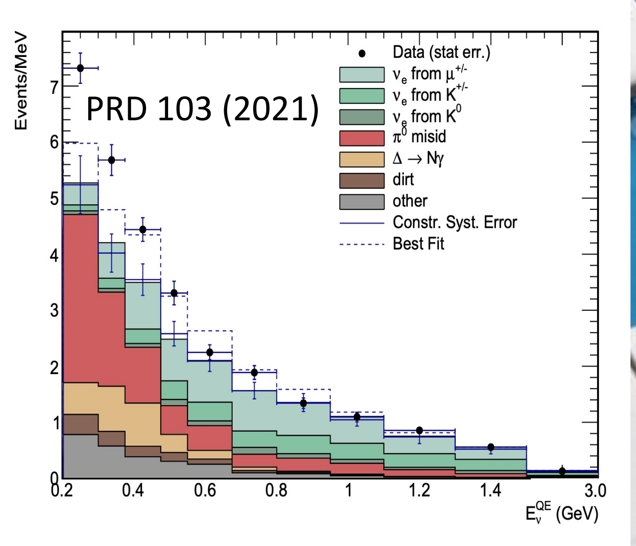
Not the full picture?

Series of short baseline neutrino oscillation experiments introduced puzzling results









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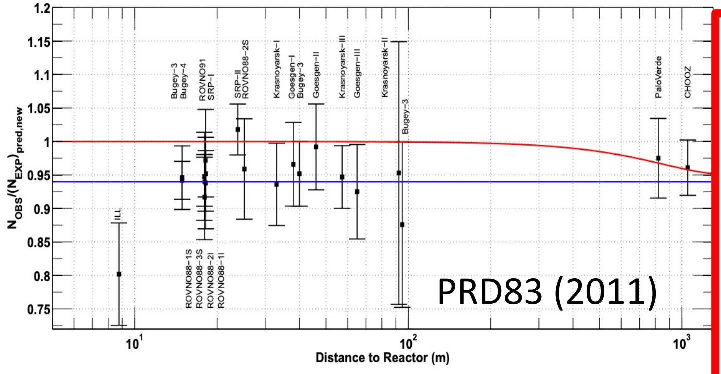
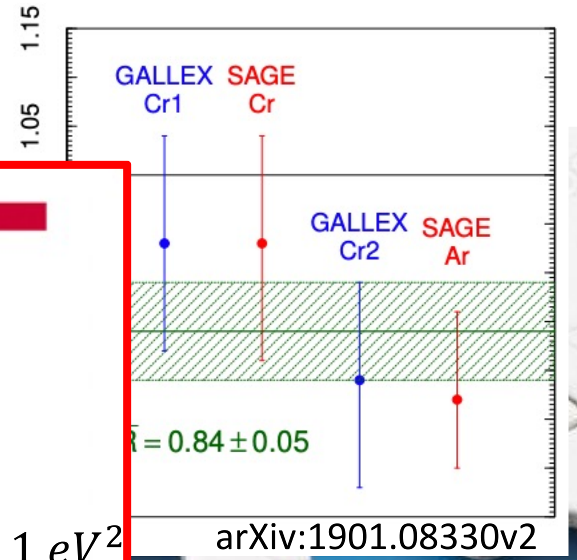
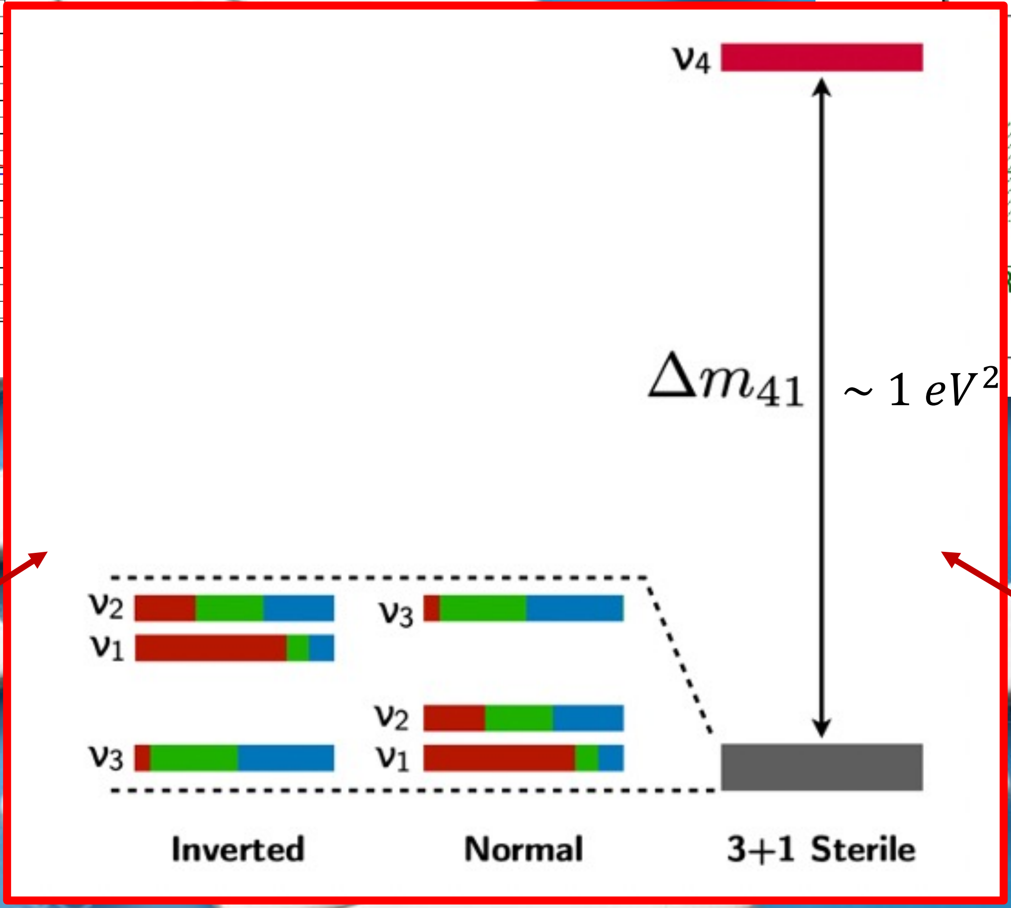
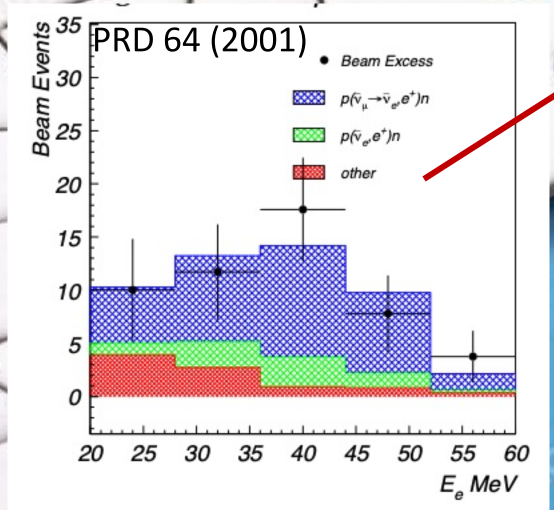
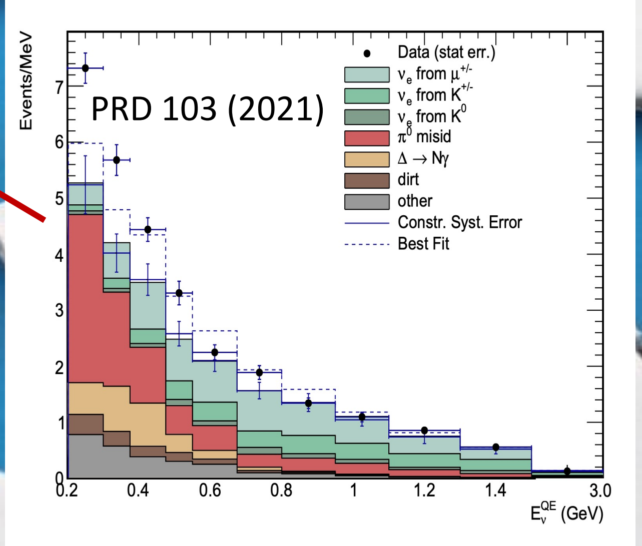




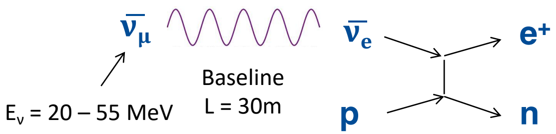




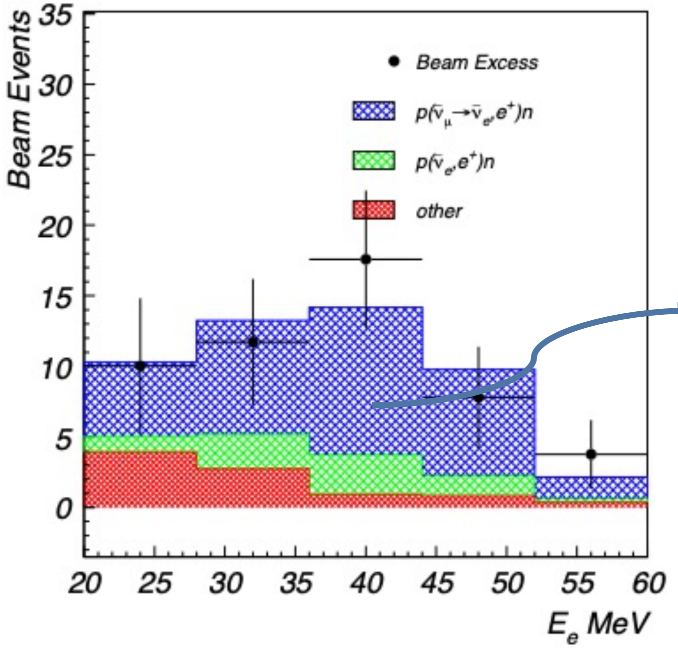


Short Baseline Anomalies: LSND and MiniBooNE

LSND



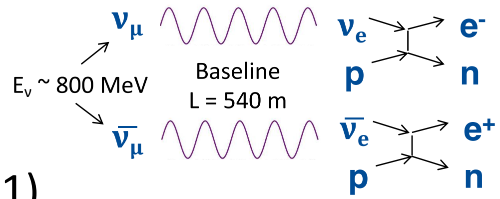
Phys. Rev. D 64 112007, 2001



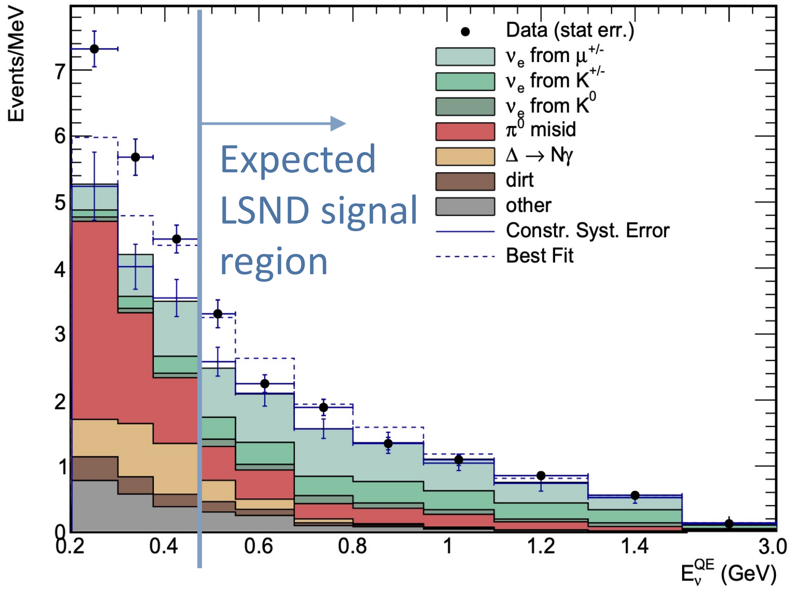
3.8σ excess

neutrino oscillations at $\Delta m^2 \sim 1\ eV^2$

MiniBooNE



Phys. Rev. D 103, 052002 (2021)



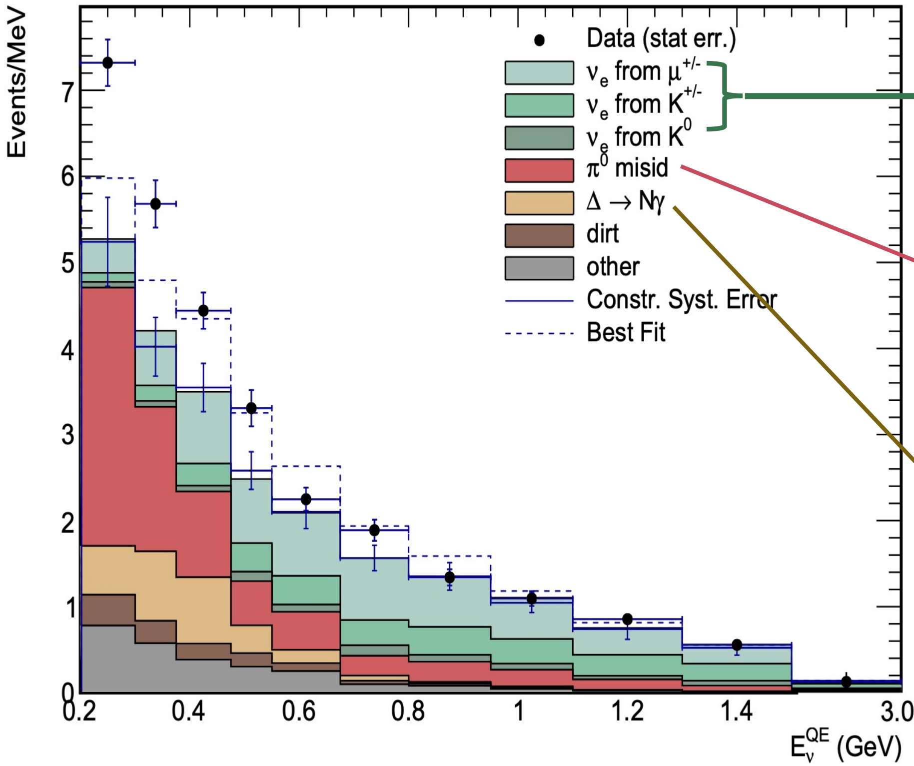
- Similar L/E oscillation
- LSND signal expected for E > 475 MeV
- New low-energy anomaly for E < 475 MeV that doesn't fit the 3+1 hypothesis

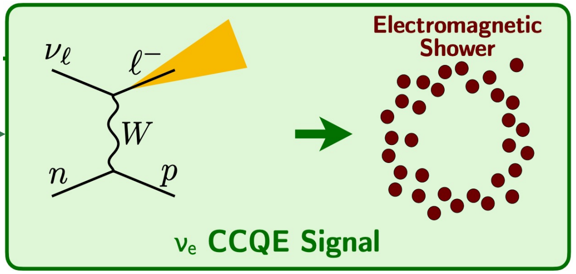
Excess of electromagnetic events on a scale of $\Delta m^2 \sim 1\ eV^2$, different with the "standard" mass splittings for 3 neutrinos

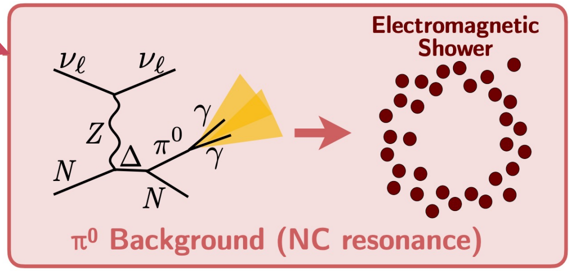
- Oscillation signal from additional sterile neutrino?
- Unmodeled background?
- New physics?

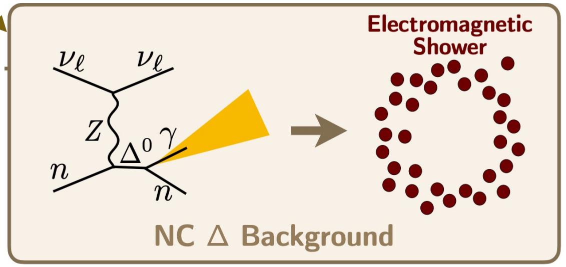
Zooming in on MiniBooNE Low Energy Excess

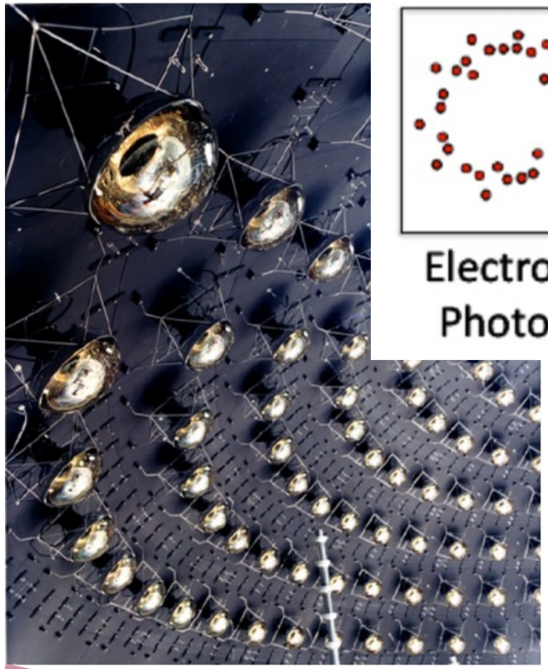
Phys. Rev. D 103, 052002 (2021)

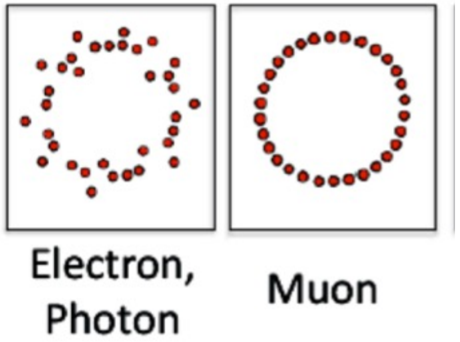


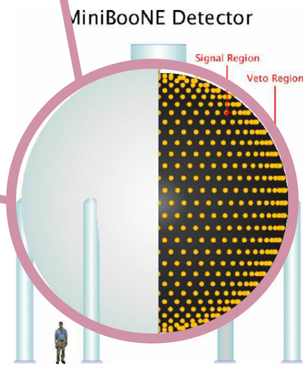










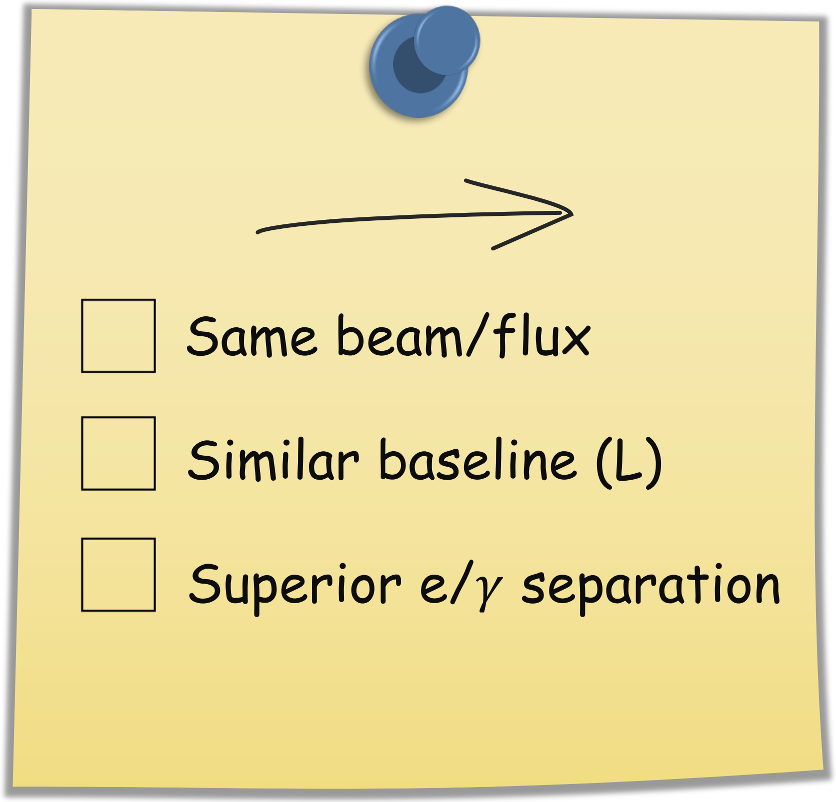


MiniBooNE is a mineral oil Cherenkov Detector

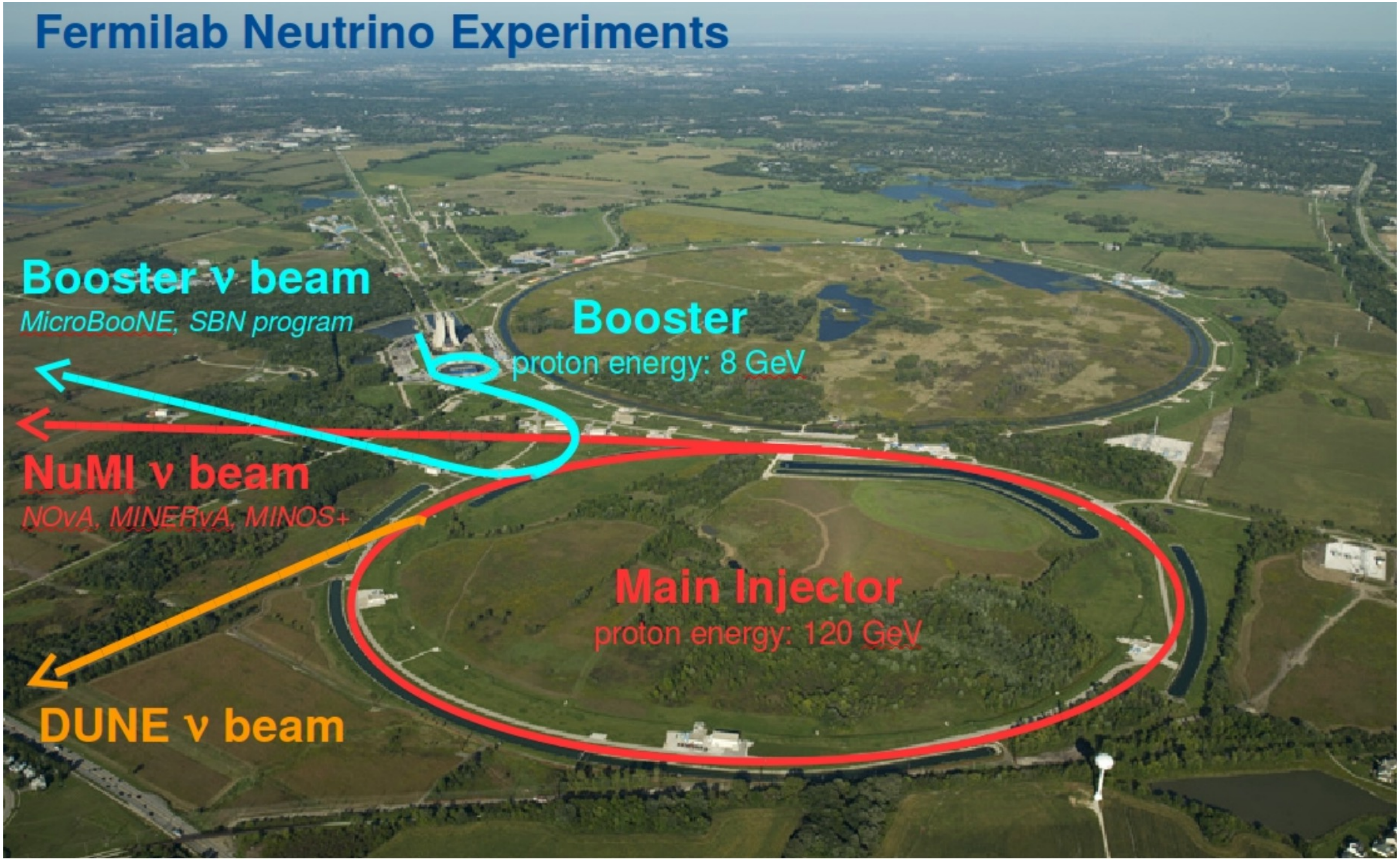
PID from the Cherenkov ring

MiniBooNE cannot distinguish electrons from γ

Experiment to test the MiniBooNE LEE



#1. MicroBooNE sees the same neutrino flux



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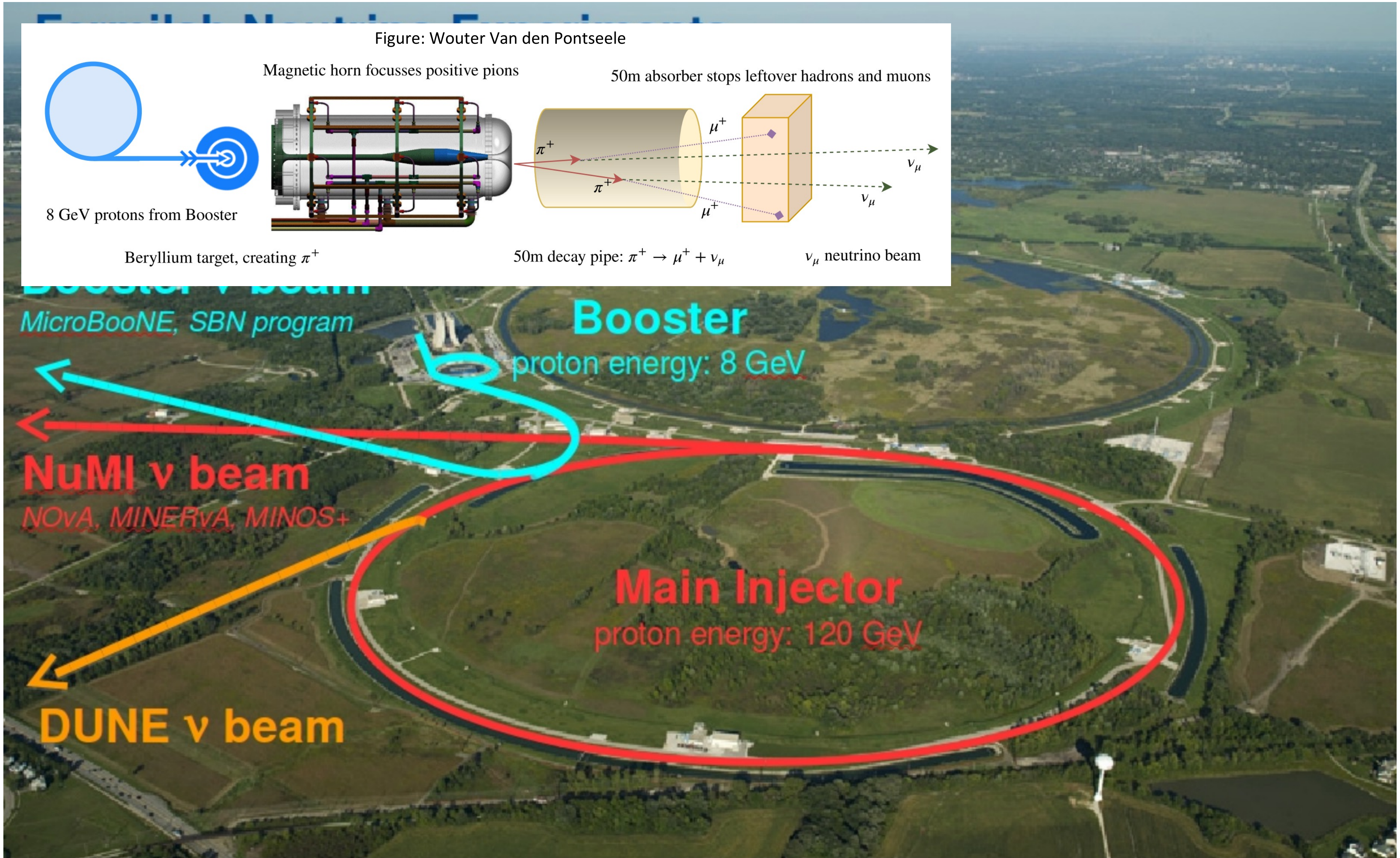

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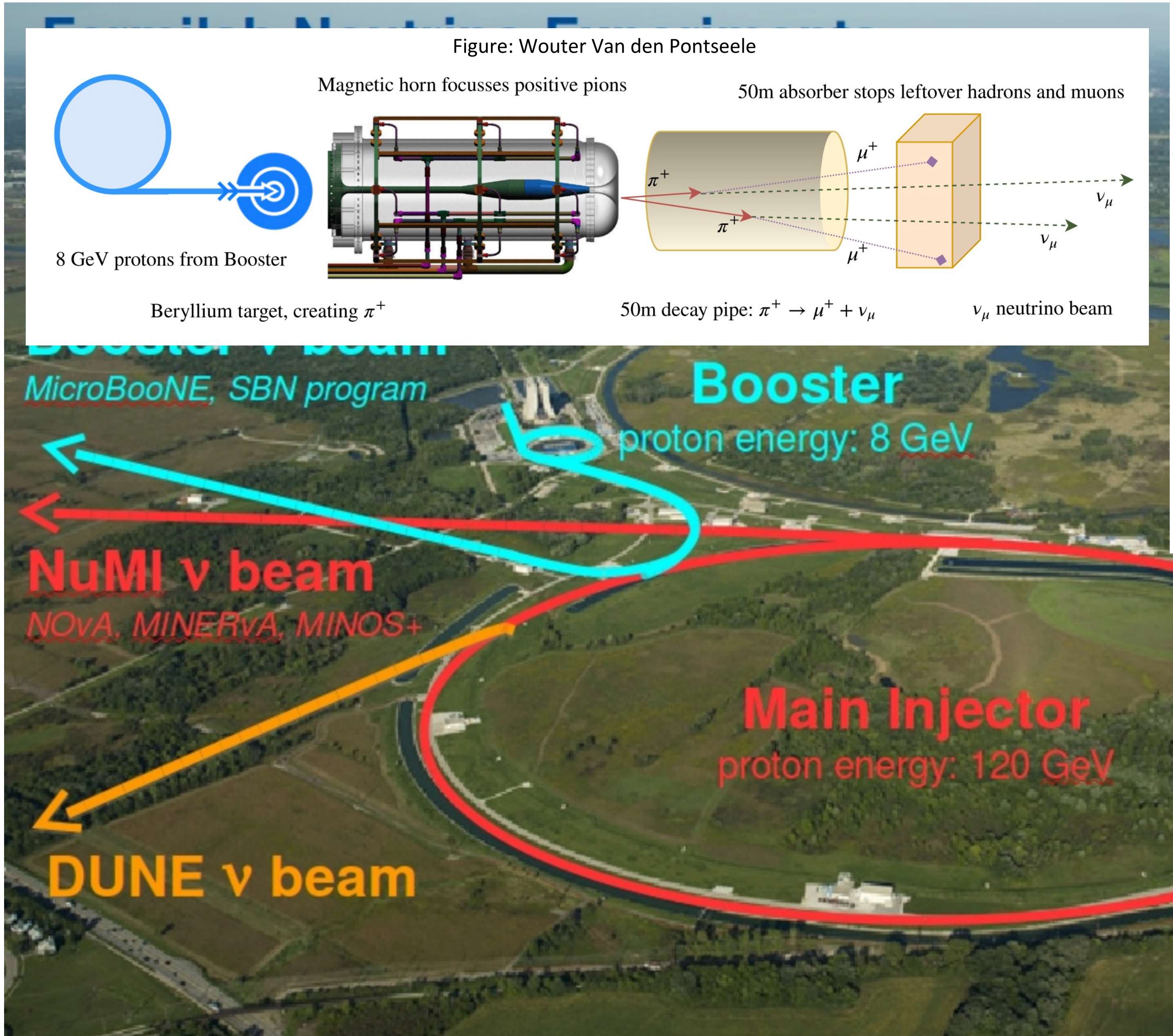

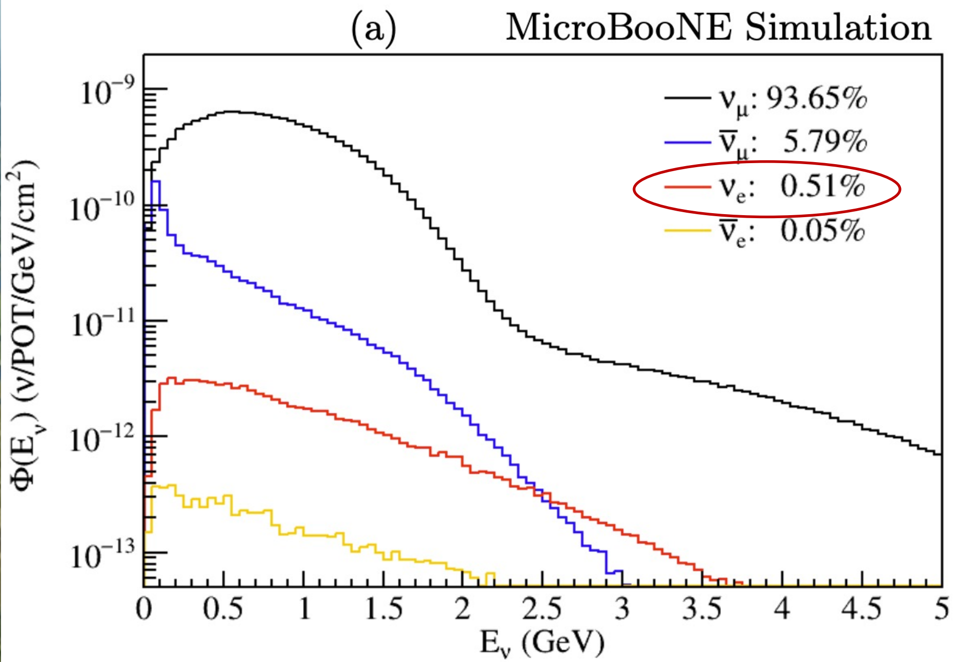

$$\pi^+ \to \mu^+ + \boxed{\nu_\mu}$$
$$\mu^+ + \bar{\nu}_\mu + \boxed{\nu_e}$$

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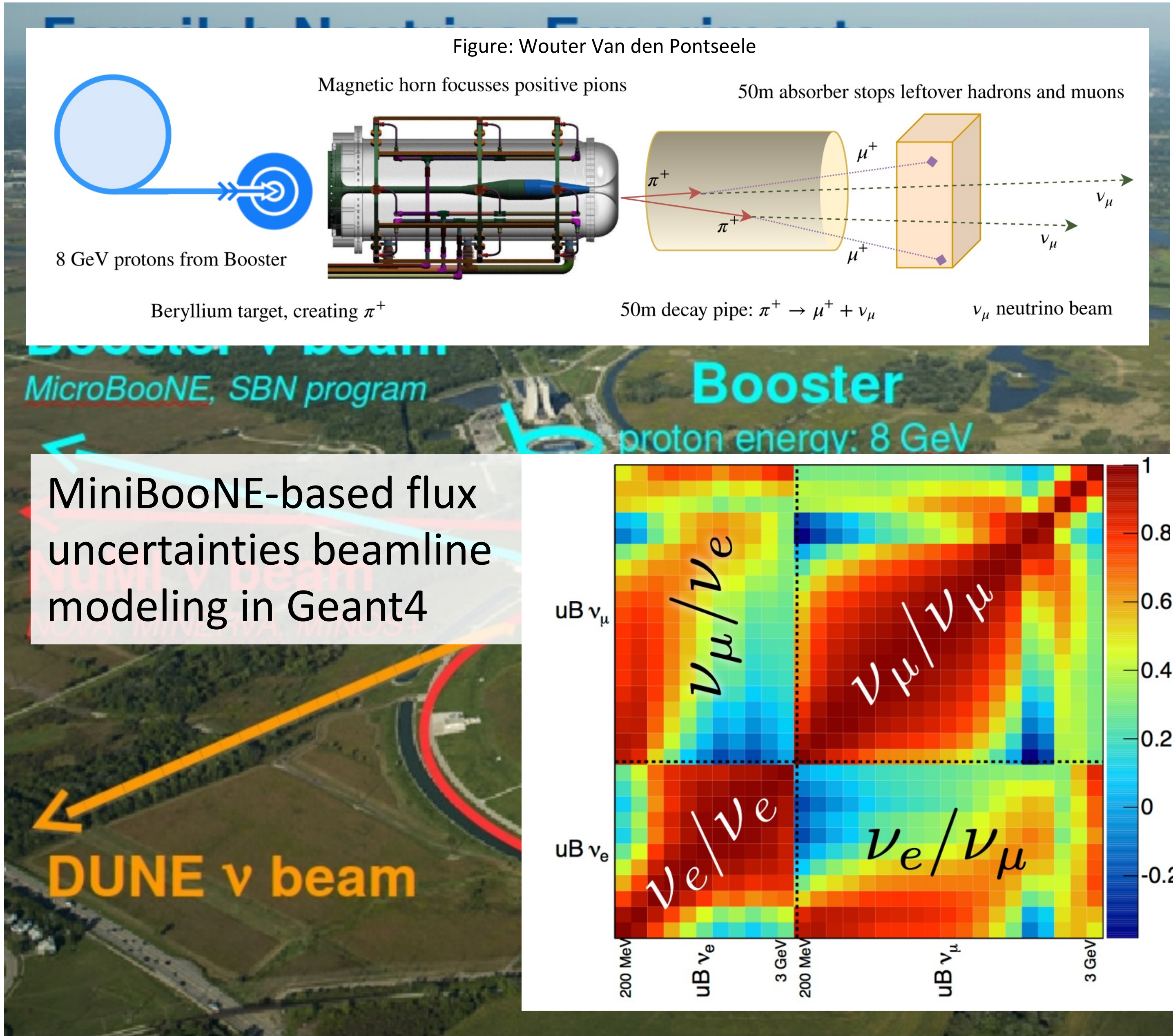
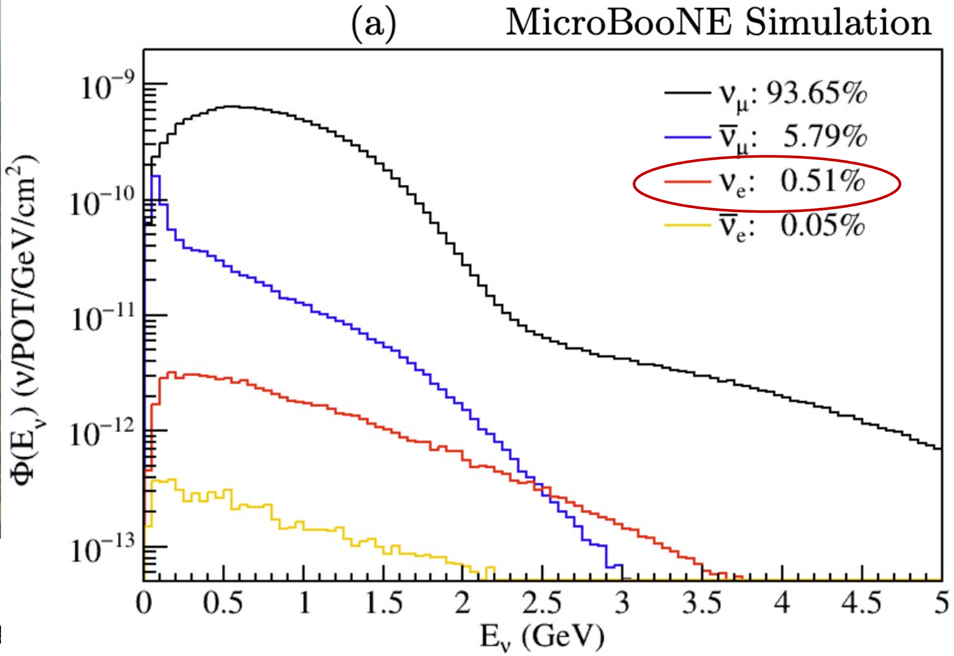




$$\pi^+ \to \mu^+ + \boxed{\nu_\mu}$$
$$\mu^+ + \bar{\nu}_\mu + \boxed{\nu_e}$$

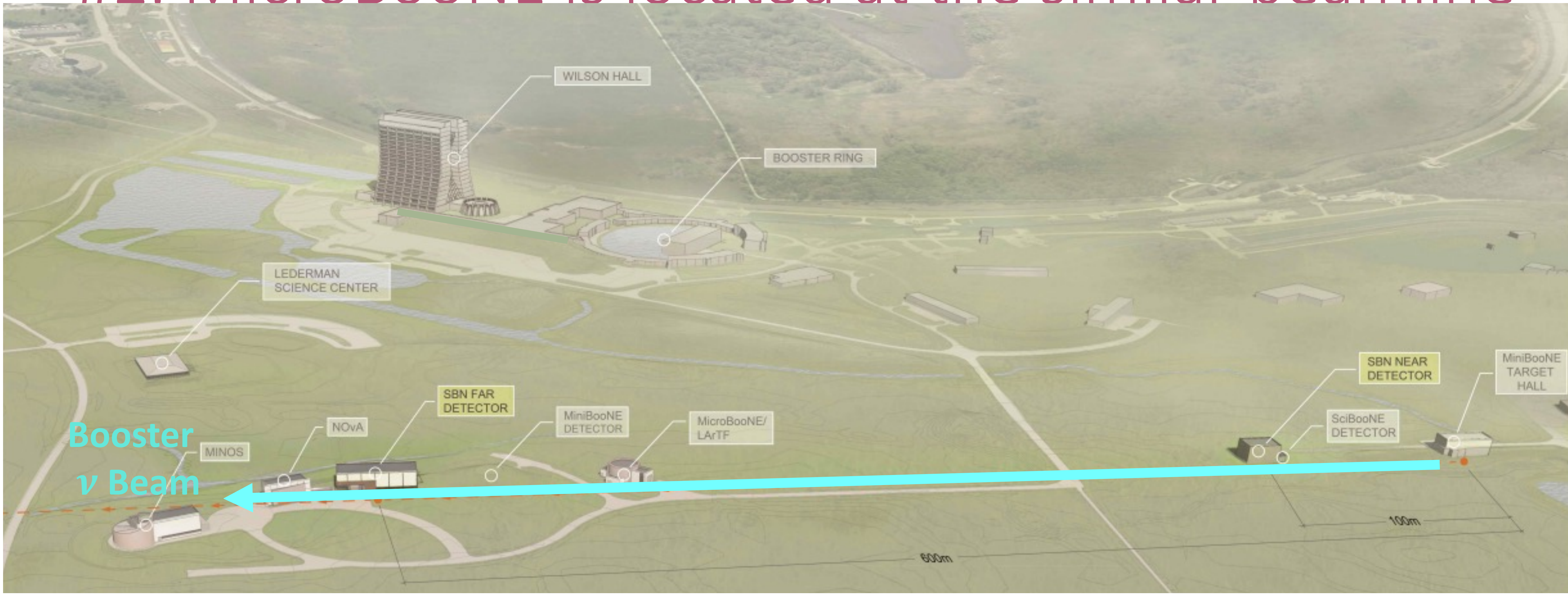
MiniBooNE-based flux uncertainties beamline modeling in Geant4

Strong ν_μ - ν_e correlations at low energy

Experiment to test the MiniBooNE LEE

- [x] Same beam/flux
- [ ] Similar baseline (L)
- [ ] Superior e/g separation

#2. MicroBooNE is located at the similar beamline



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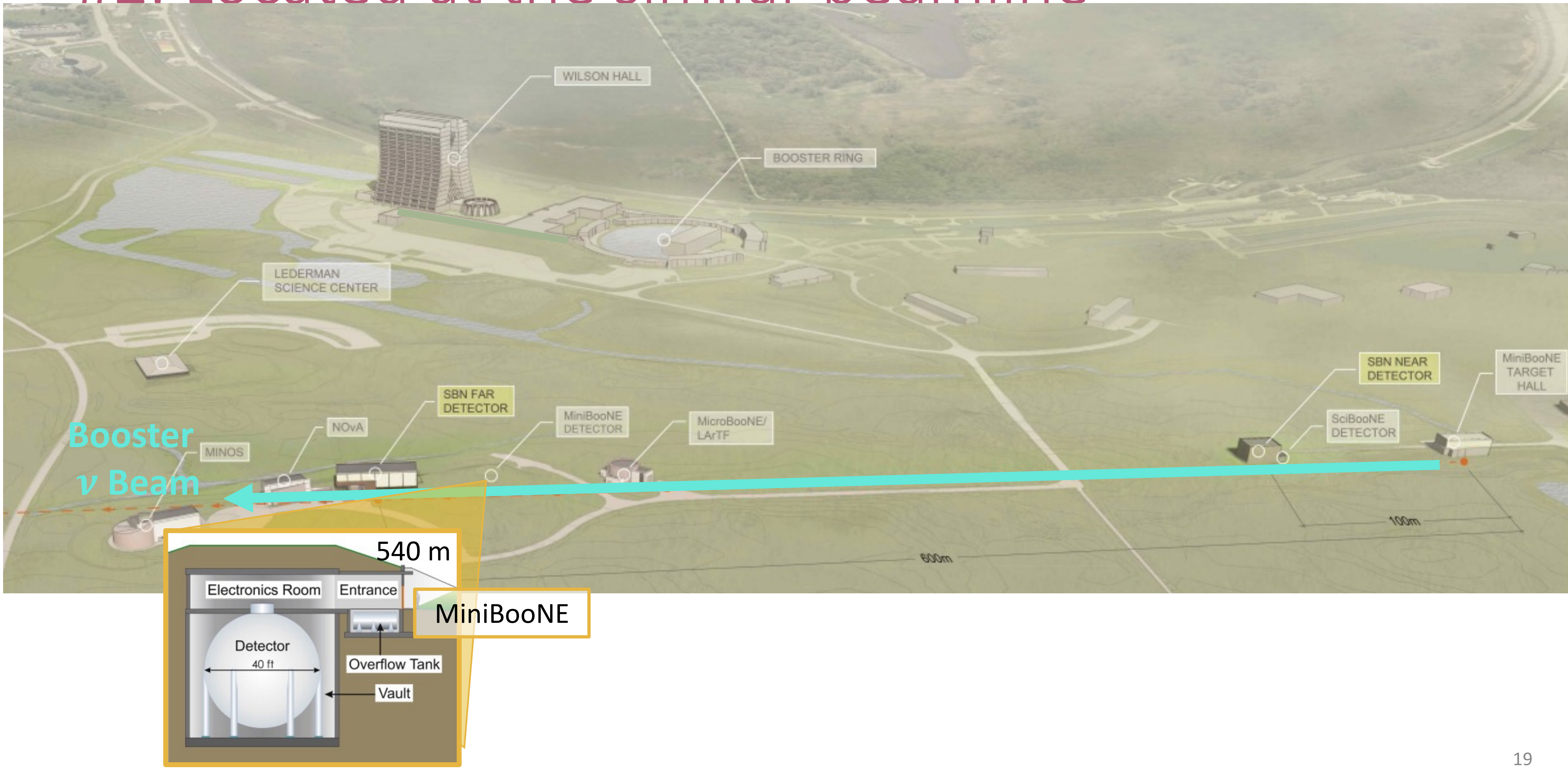

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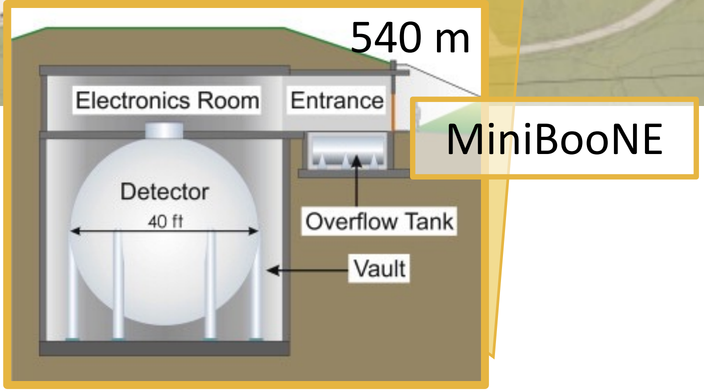
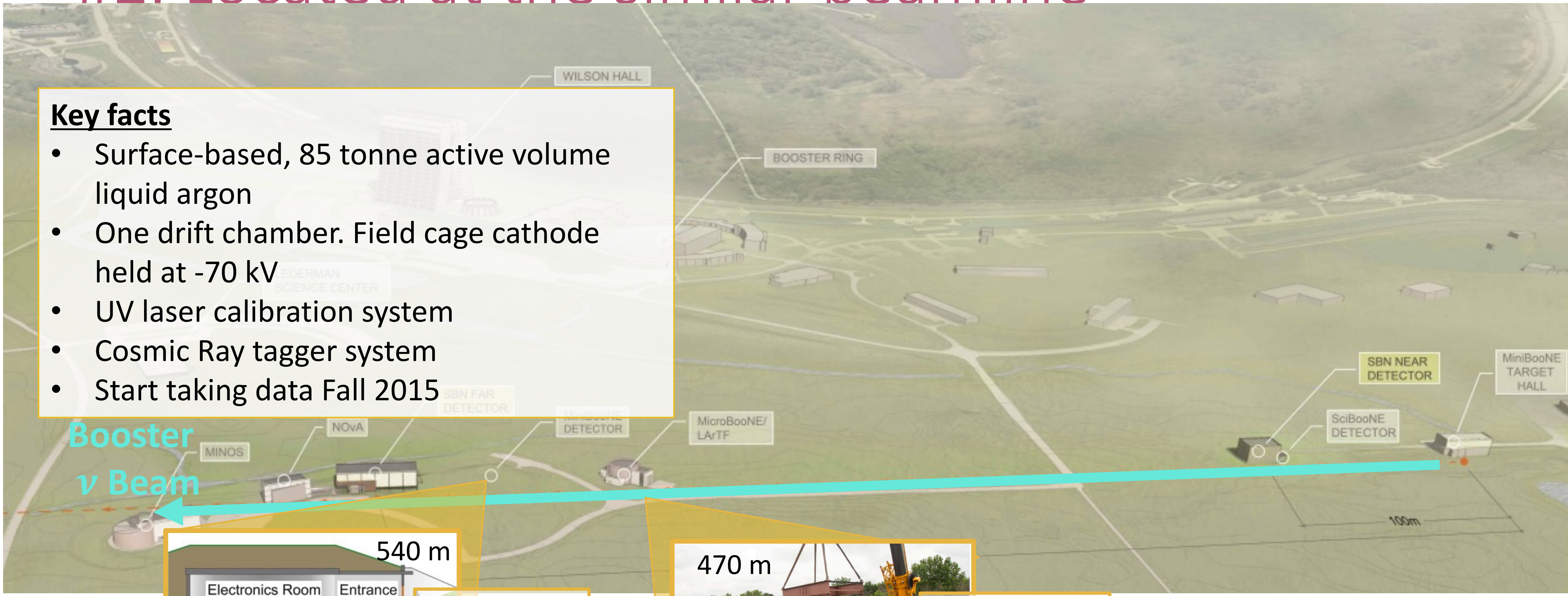
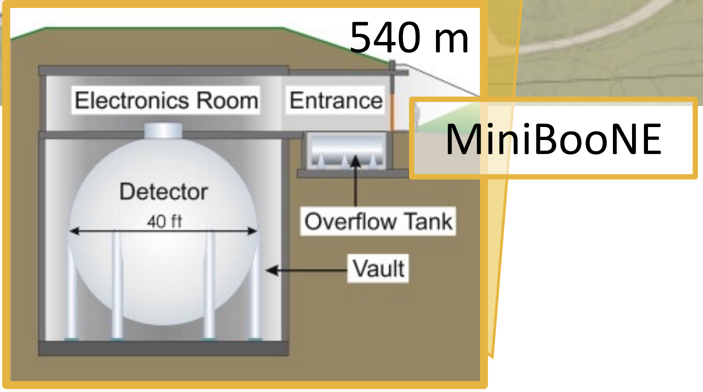


#2. Located at the similar beamline

Key facts

- Surface-based, 85 tonne active volume liquid argon
- One drift chamber. Field cage cathode held at -70 kV
- UV laser calibration system
- Cosmic Ray tagger system
- Start taking data Fall 2015





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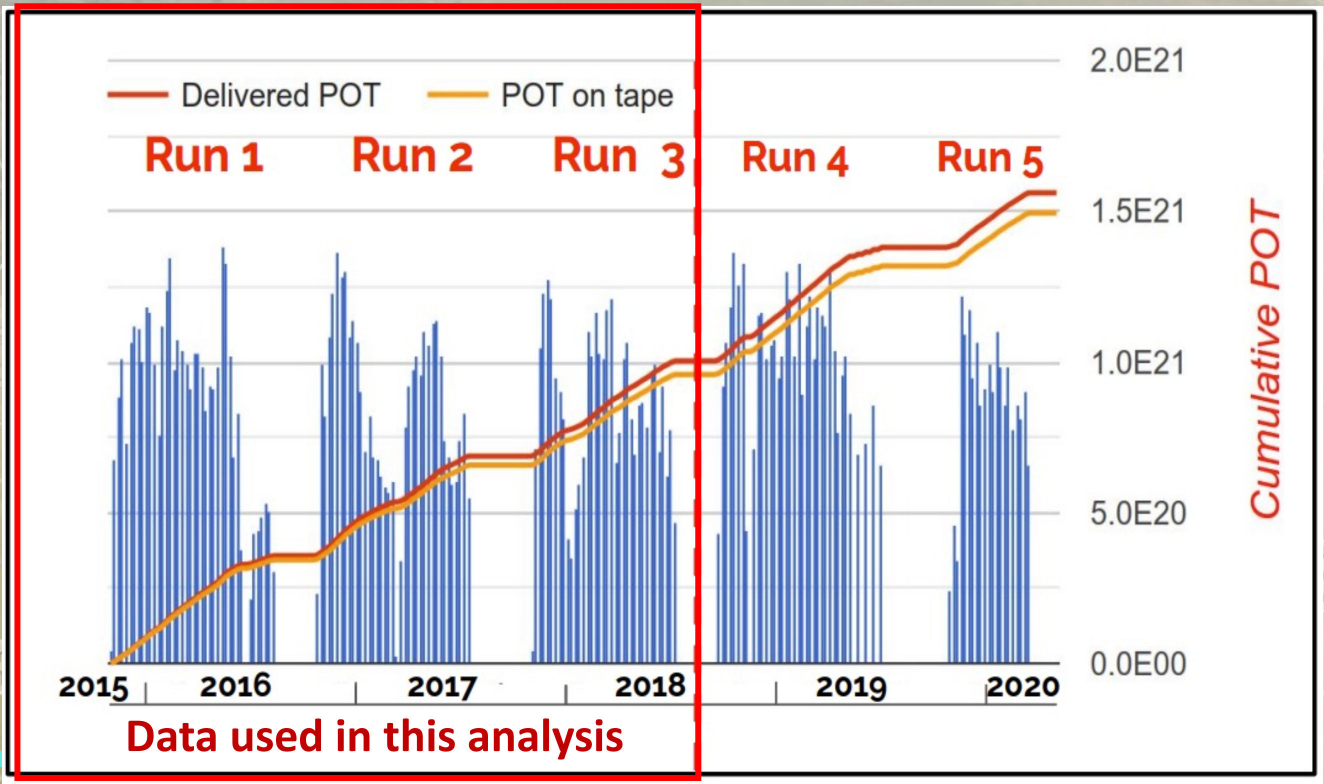
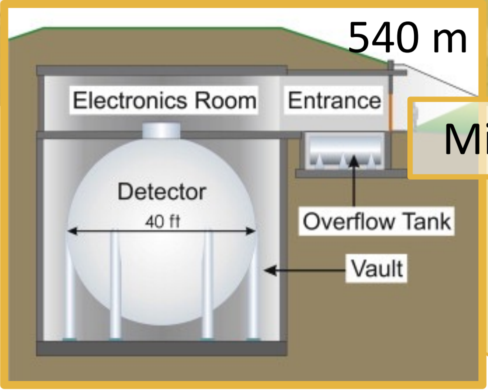


Booster ν Beam

540 m



MiniBooNE

470 m

MicroBooNE

Thanks to Fermilab Accelerator Division!

Experiment to test the MiniBooNE LEE

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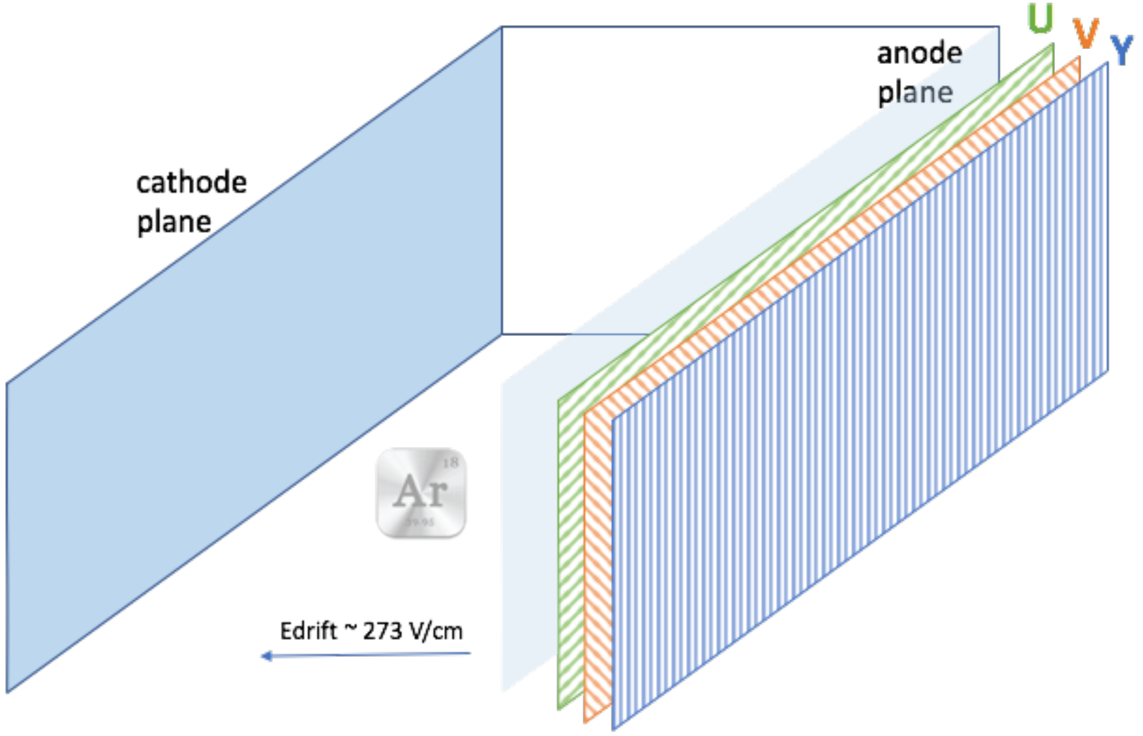
LArTPC
(Liquid Argon Time Projection Chamber)



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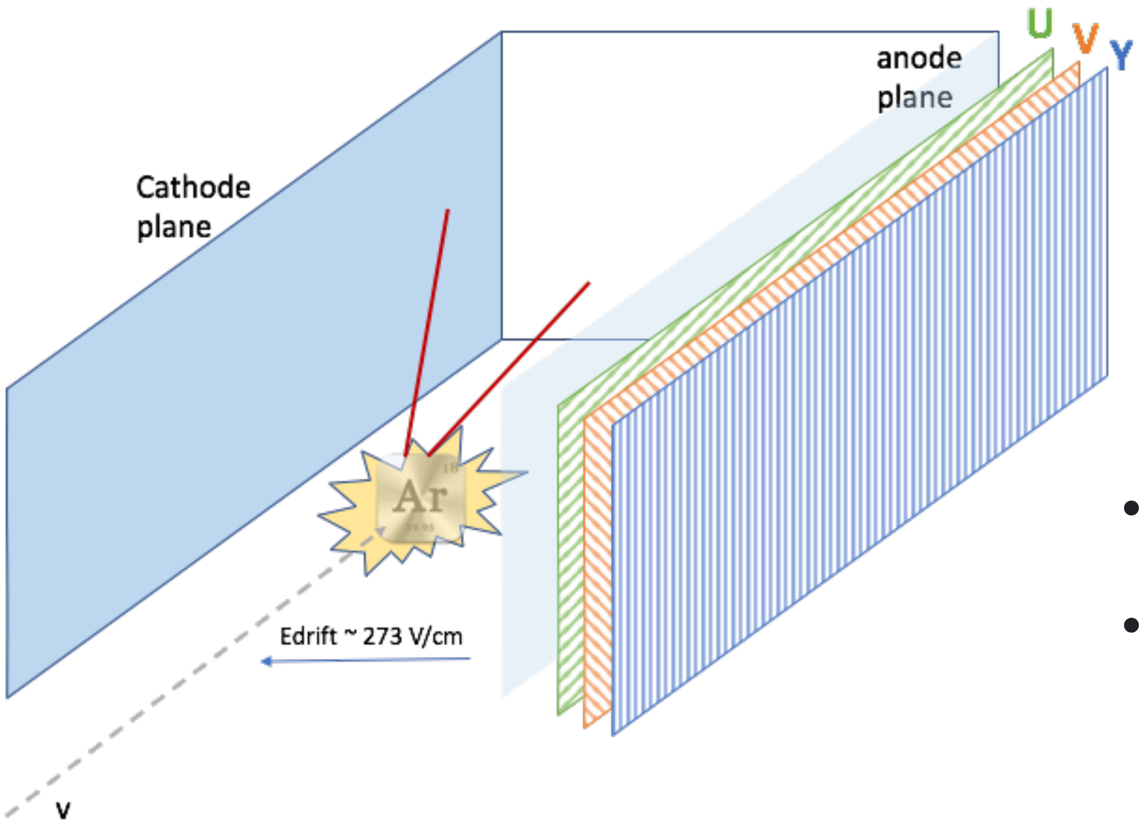

- Neutrino enters the large volume of liquid argon.
- Neutrino interacts with argon and produces charged particles

LArTPC
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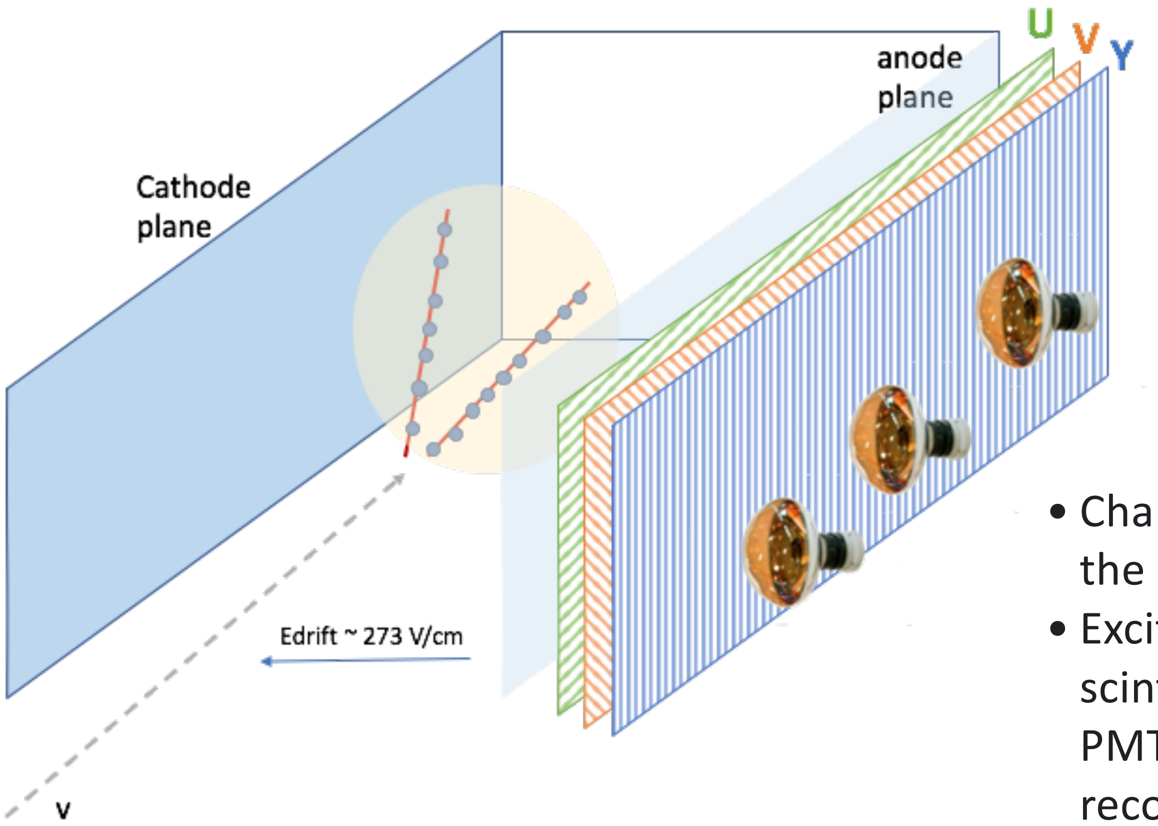
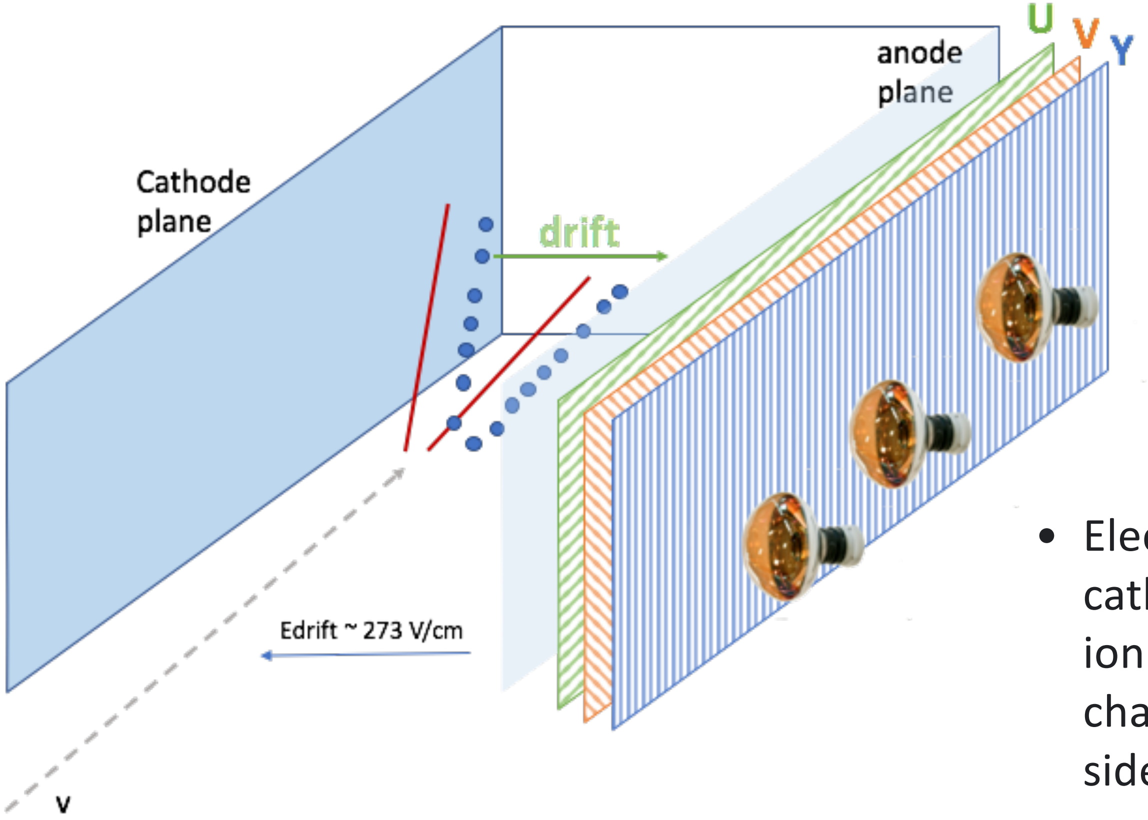


- Charged particle can ionize/excite the argons.
- Excited argons produce scintillation light and arrays of PMTs behind the wire planes recorded the lights.

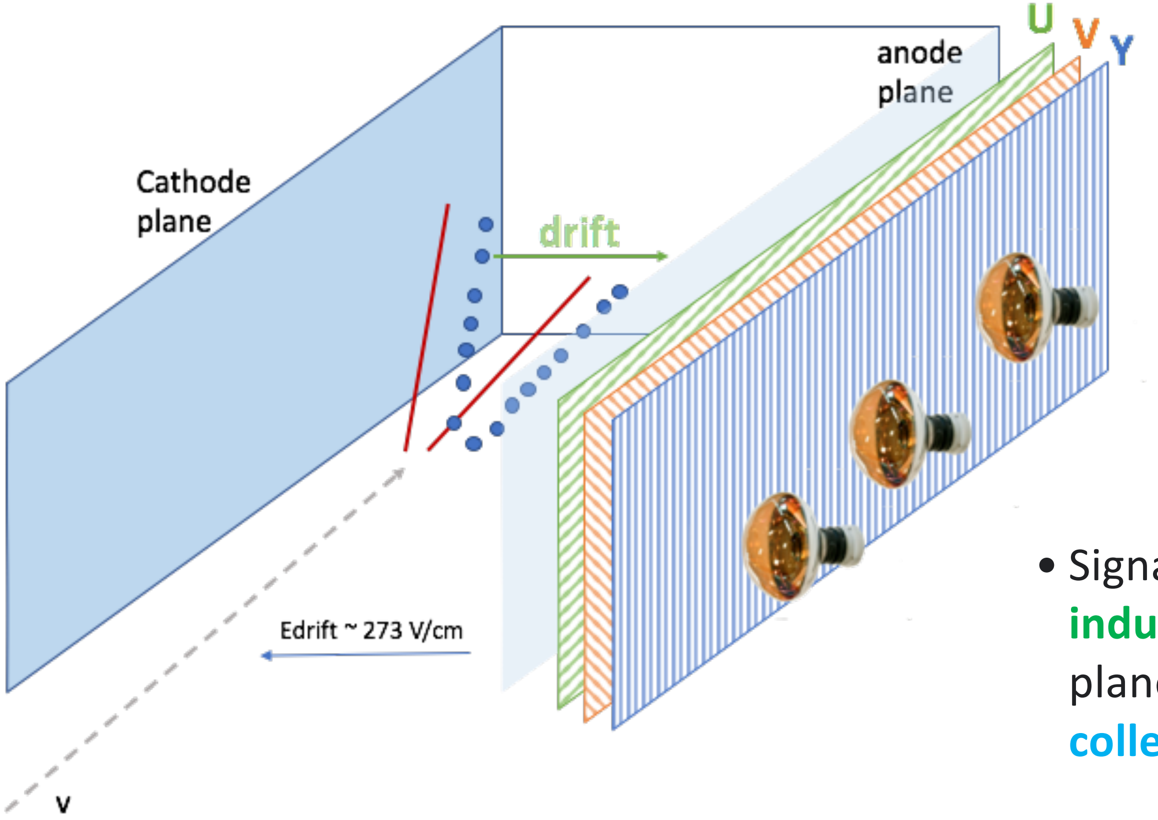
LArTPC

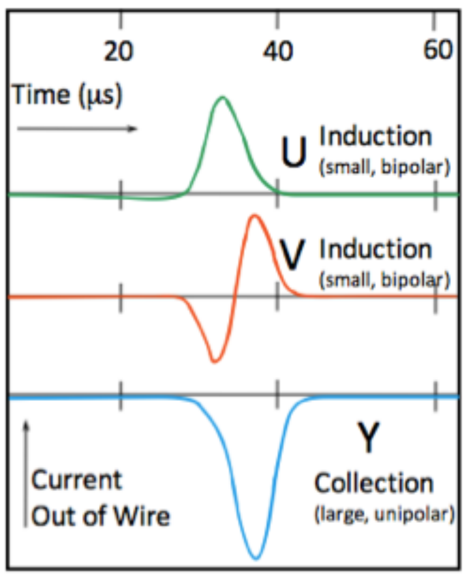
(Liquid Argon Time Projection Chamber)



- Electric field set up between the cathode and the anode drift the ionized electron to the wire chamber planes on the anode side of the detector.

LArTPC
(Liquid Argon Time Projection Chamber)

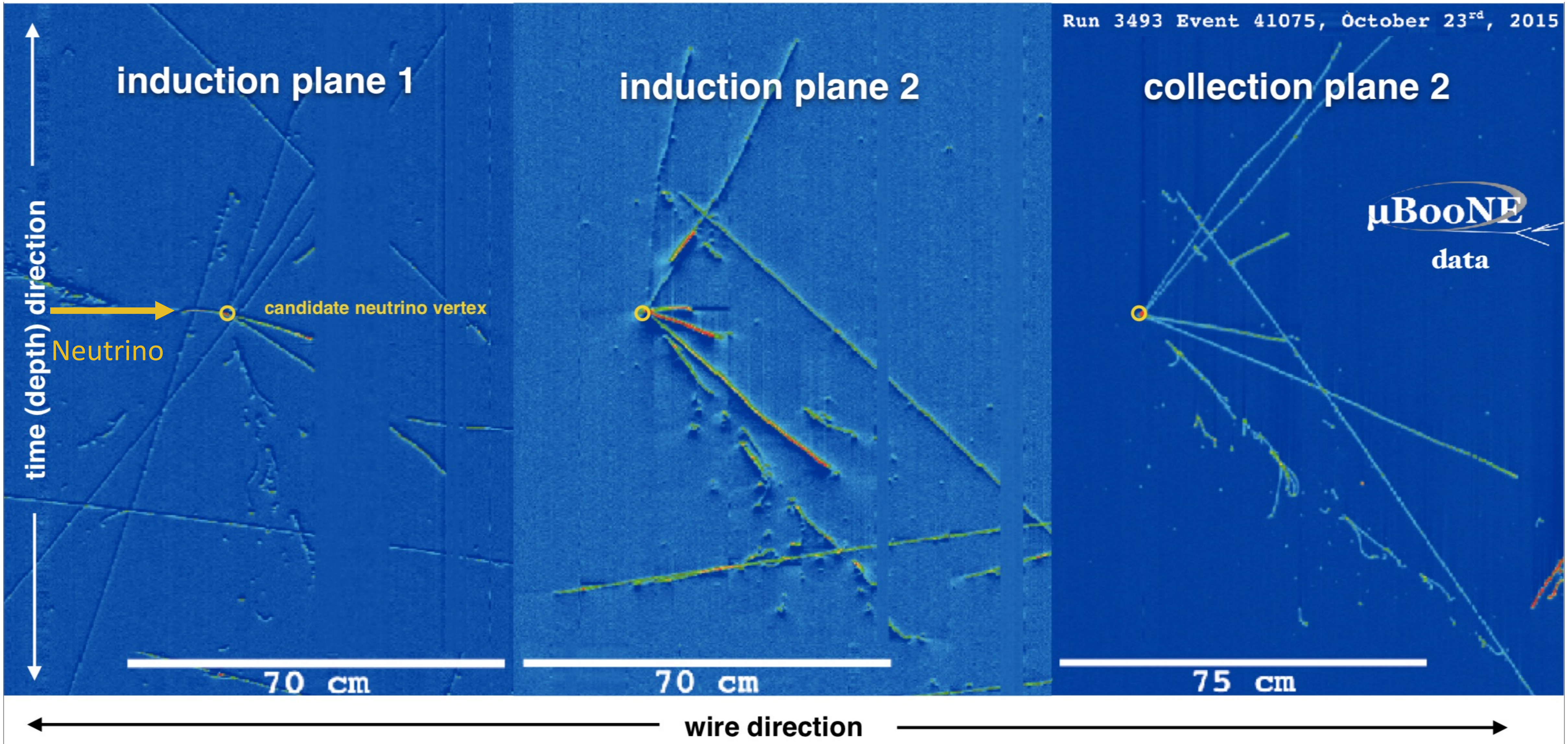




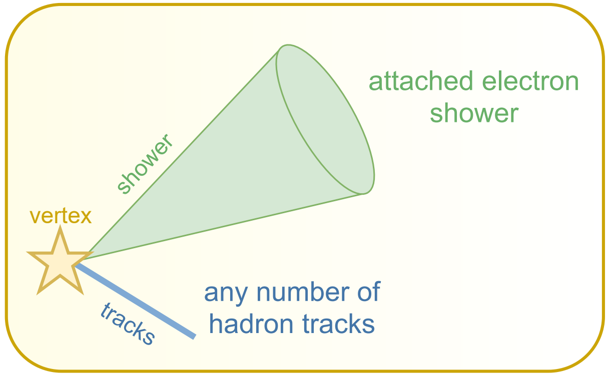
- Signals from the event are **induced** by the first two wire planes and electrons are **collected** by the last plane

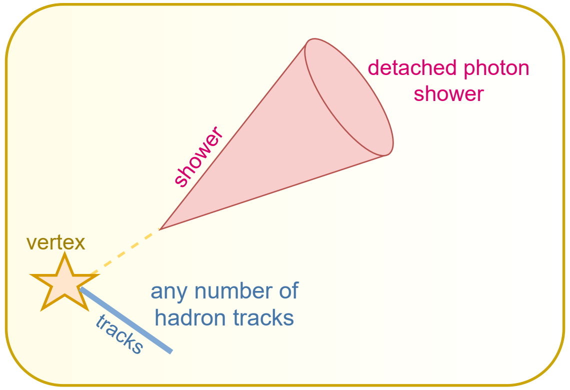
LArTPC
(Liquid Argon Time Projection Chamber)

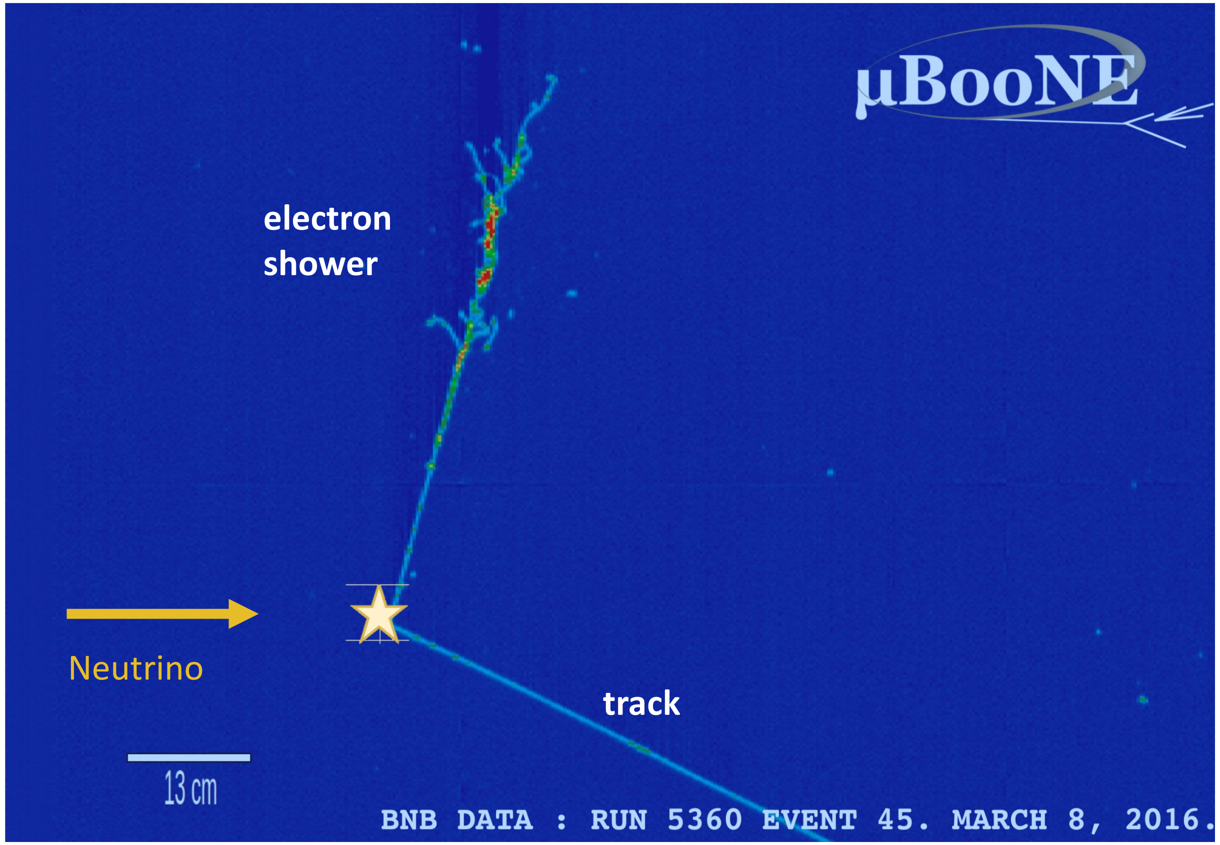
High resolution photographic-like image of neutrino interaction
Scales to large masses!

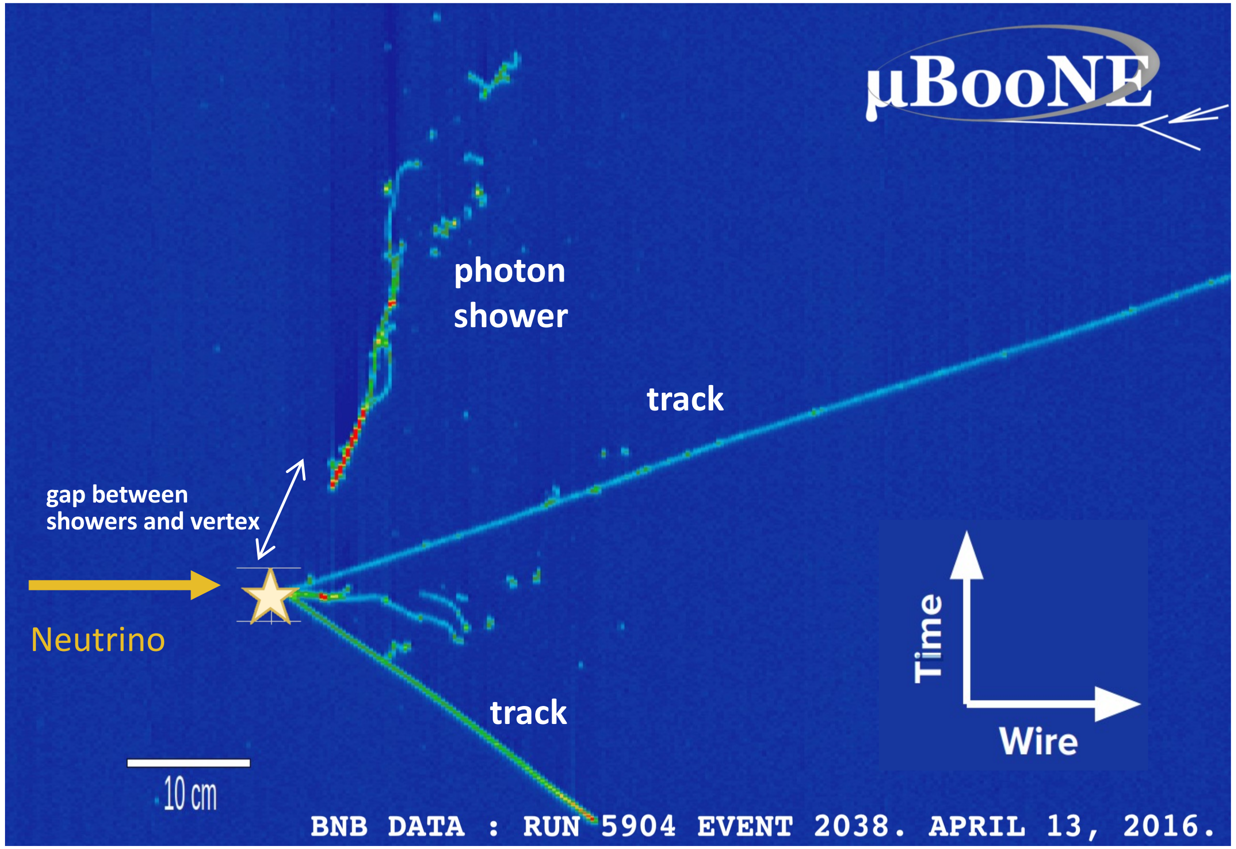


Superior e/γ separation power: topology

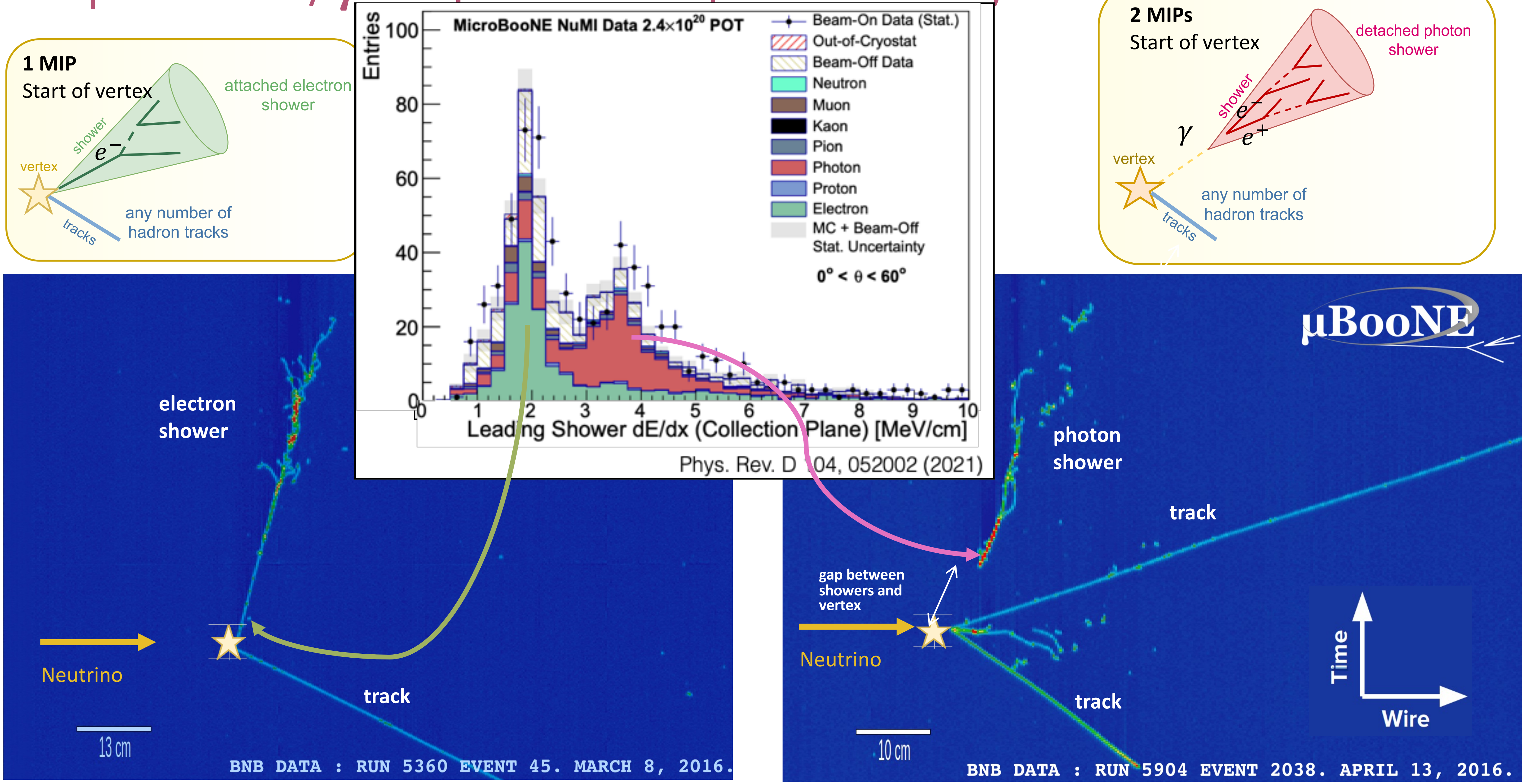




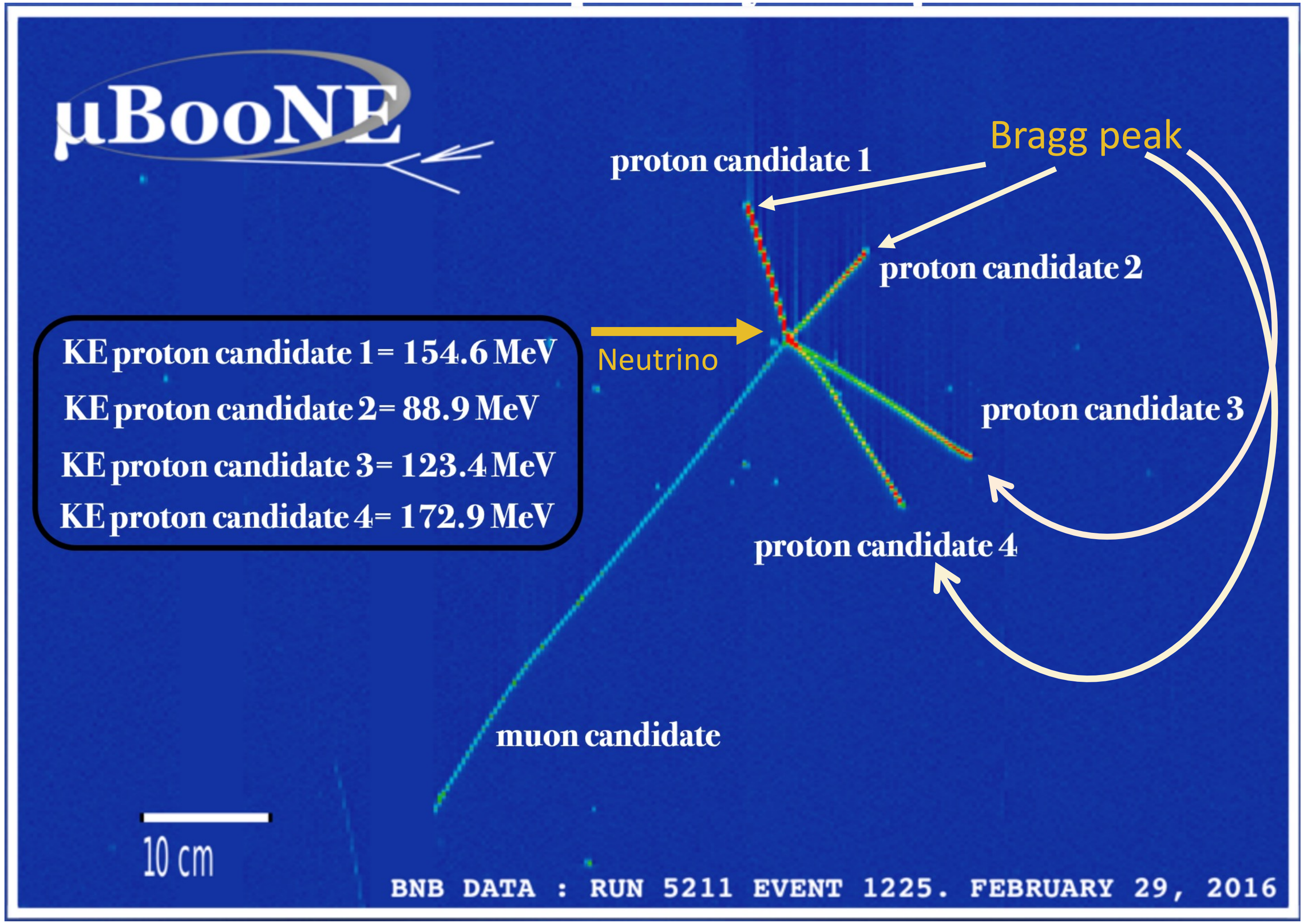




Superior e/γ separation power: dE/dx



Low protons kinematics threshold



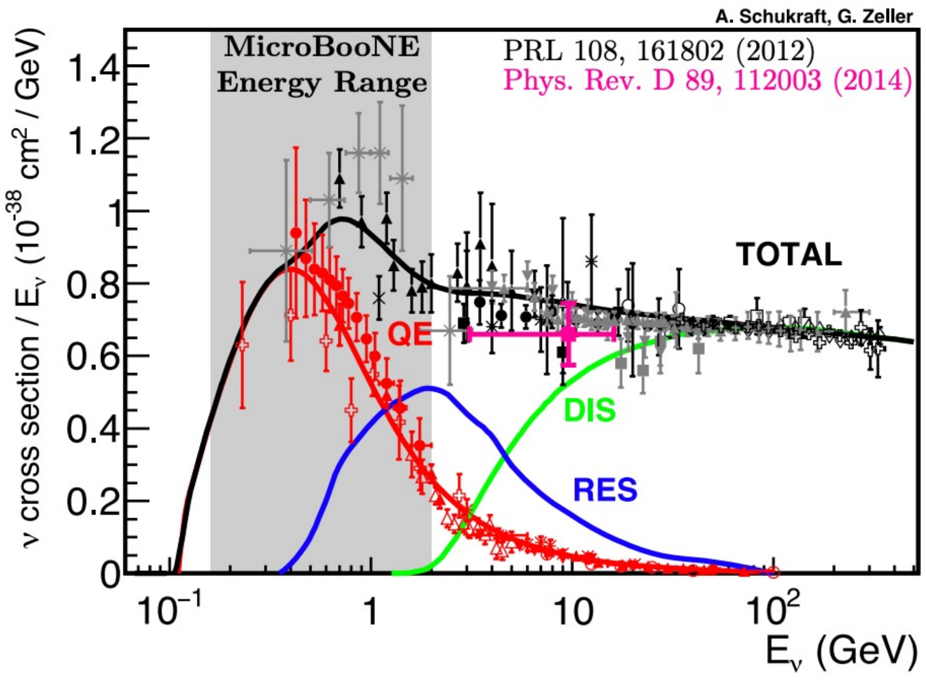
Low proton kinematic thresholds (300 MeV) → access to new information about nuclear effects, neutrino interactions.

Protons identified by Bragg peak in last 30 cm of track

Experiment to test the MiniBooNE LEE

- [x] Same beam/flux
- [x] Similar baseline (L/E)
- [x] Superior e/g separation

Neutrino Interaction in Argon



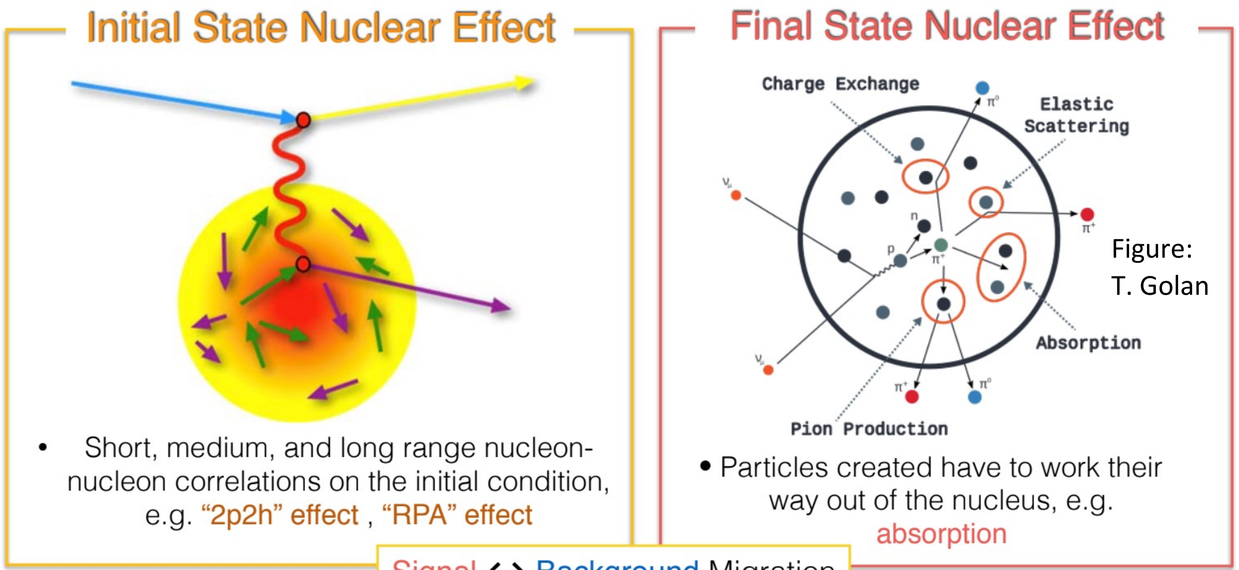


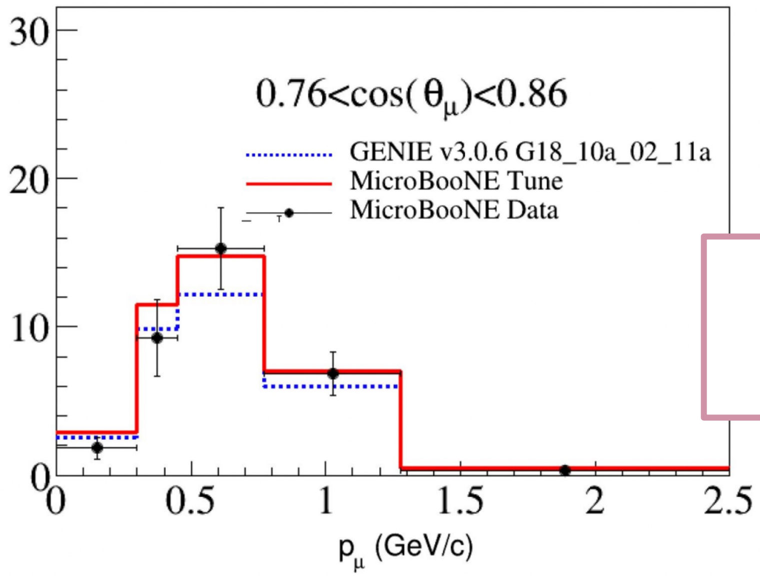
Figure: T. Golan

- Short, medium, and long range nucleon-nucleon correlations on the initial condition, e.g. "2p2h" effect , "RPA" effect
- Particles created have to work their way out of the nucleus, e.g. absorption

Signal ↔ Background Migration

Theory-driven models

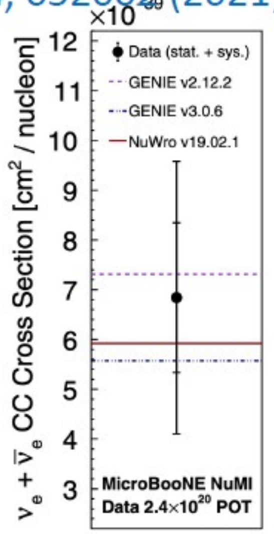
- Fit to 2016 T2K ν_μ $CC0\pi$ data taken at similar energies
- More than **50 parameters are varied** to assess interaction uncertainties



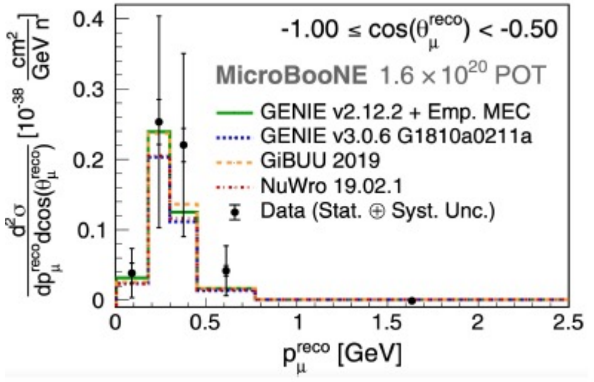
New Theory-driven GENIE Tune for MicroBooNe arXiv:2110.14028

Cross Section Measurements

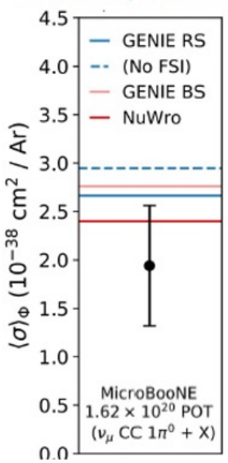
PRD **104**, 052002 (2021)



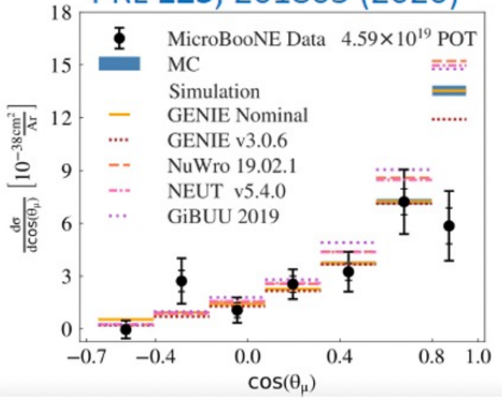
PRL **123**, 131801 (2019)



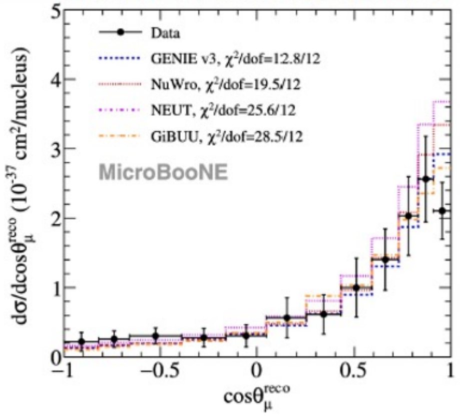
PRD **99**, 091102 (2019)



PRL **125**, 201803 (2020)



PRD **102**, 112013 (2020)



Developed high statistics ν-Ar cross-section measurements targeting **various interaction kinematics and final states** and filling in the missing pieces in the ν-Ar cross-section puzzle.

- $\nu_\mu CC\ Np0\pi$, **Phys.Rev.D 102 (2020) 11, 112013**
- ν_μ CCQE-like, **Phys.Rev.Lett 125 (2020) 20, 201803**
- ν_μ CC Inclusive, **Phys.Rev.Lett 123 (2019) 13, 131801**
- $\nu_\mu CC\ \pi^0$ **Phys.Rev.D 99 (2019) 9, 091102**
- $\nu_e\ CC$ **Inclusive Phys.Rev.D 104 (2021) 5, 052002**
- ν_e CC **arXiv:2109.06832 (2021)**
- ν_μ CC Inclusive **arXiv:2110.14023 (2021)**
- **Many more to come…**

As electron drifts…

cathode

Diffusion

electron cloud is smeared in longitudinal & transverse directions

Space charge Effect (SCE)

Slow moving ions creates distortion to the Efield

Recombination

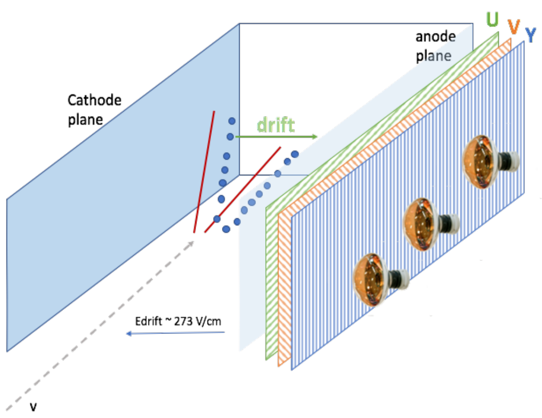
Underestimation of particle energy loss

Purity

attenuation of the signal on the TPC wires

Correlated detector effects varying the reconstructed charge signal (dQ/dx) and needs to be *disentangled and calibrated*

anode



As electron drifts…

cathode

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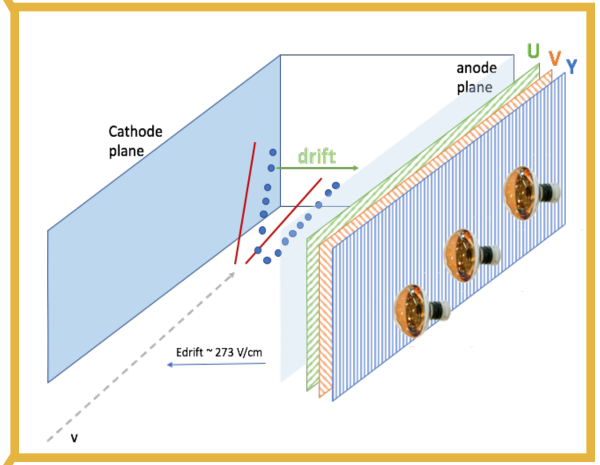
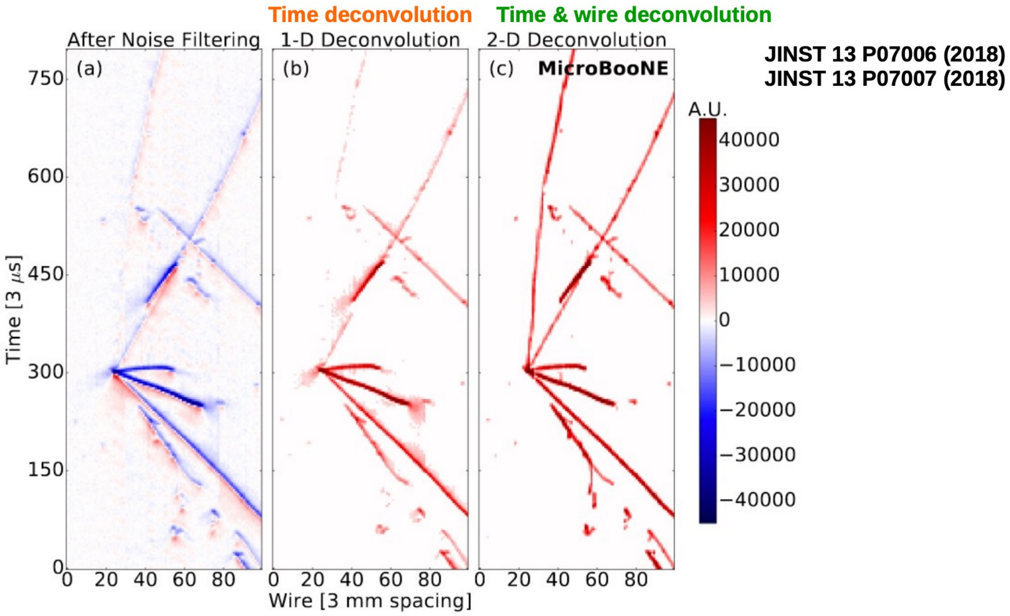
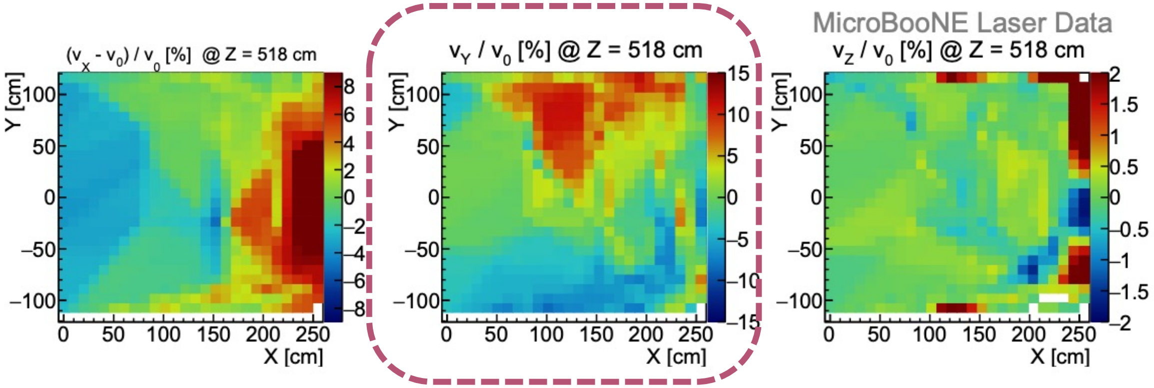


Detector Response Modeling and Calibration



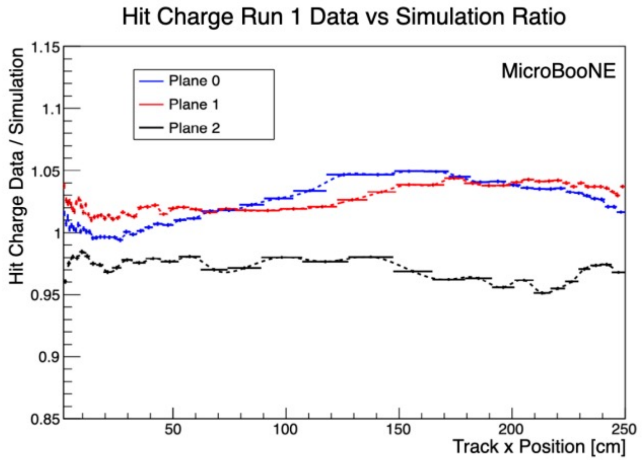


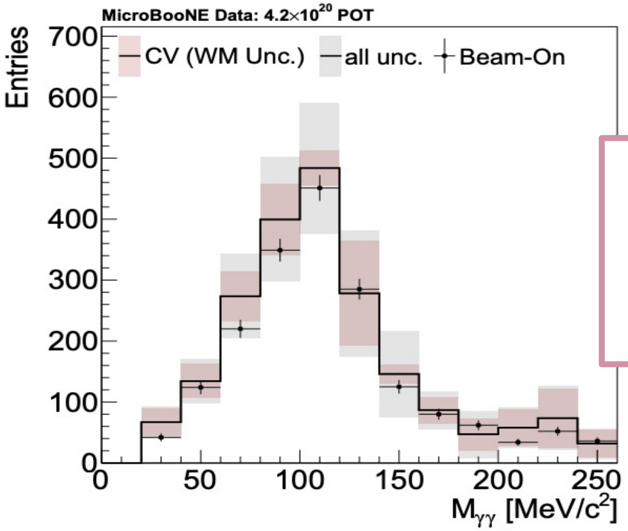
- Pioneered novel techniques for noise filtering and signal processing **JINST 13 P07006 (2018), JINST 13 P07007 (2018)**
- Leverage a strong program of low-level detector modeling:
  - data-driven E-field map calibration **JINST 15 P07010 (2020)**, space charge effects, **JINST 15 P12037 (2020)**
  - Calorimetric and EM shower calibrations, **JINST 15 P03022 (2020)**
- Measurement of the Longitudinal Diffusion of Ionization Electrons in the MicroBooNE Detector, **JINST 16 P09025 (2021)**

Good understanding of detector response and precise measurement of particle kinematics.

Data Driven Detector Systematics

- Data-driven detector simulation: simulated neutrino interaction is "overlaid" on top of cosmic only data
  - Eliminate modeling related to TPC/PMT for cosmic simulation and reduce systematics
- Evaluate data-driven systematics of space charge, recombination, optical model, GEANT4 uncertainties
- Pioneered a novel method to capture waveform-level data/MC differences as a function of positions and angular orientation of particle's trajectory as a correction and residual detector modeling systematic



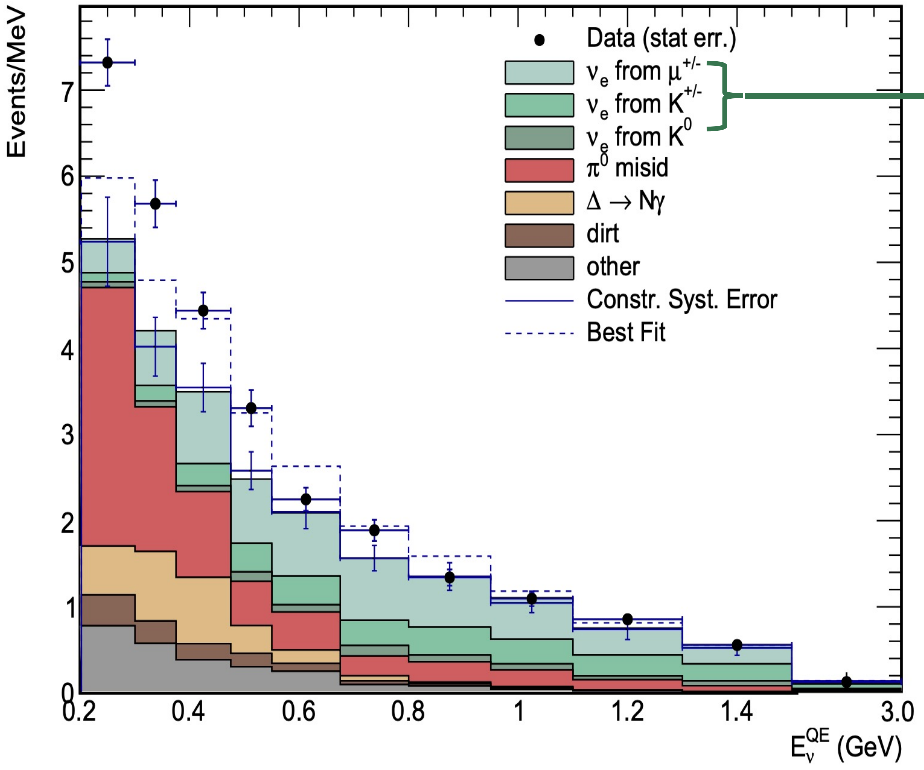


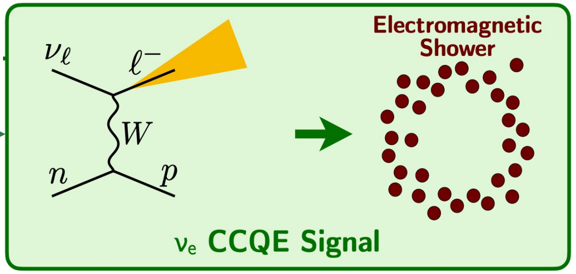
Novel Approach for Evaluating Detector-Related Uncertainties in a LArTPC Using MicroBooNE Data
arXiv:2111.03556

Strategy to investigate MicroBooNE Low Energy Excess

Zooming in on MiniBooNE Low Energy Excess

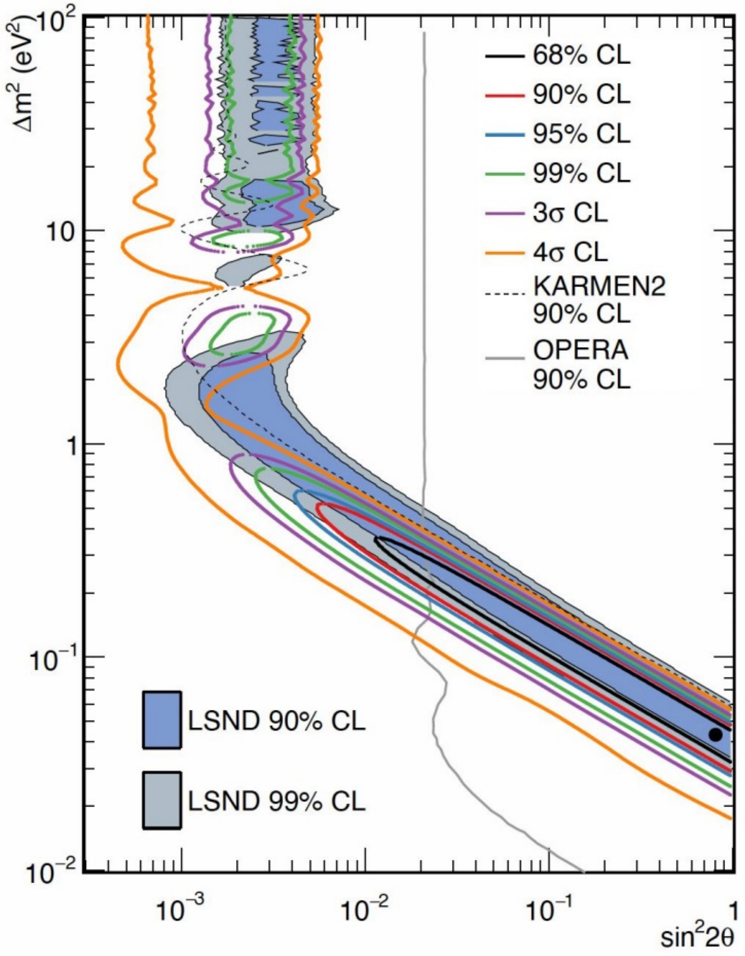
Phys. Rev. D 103, 052002 (2021)



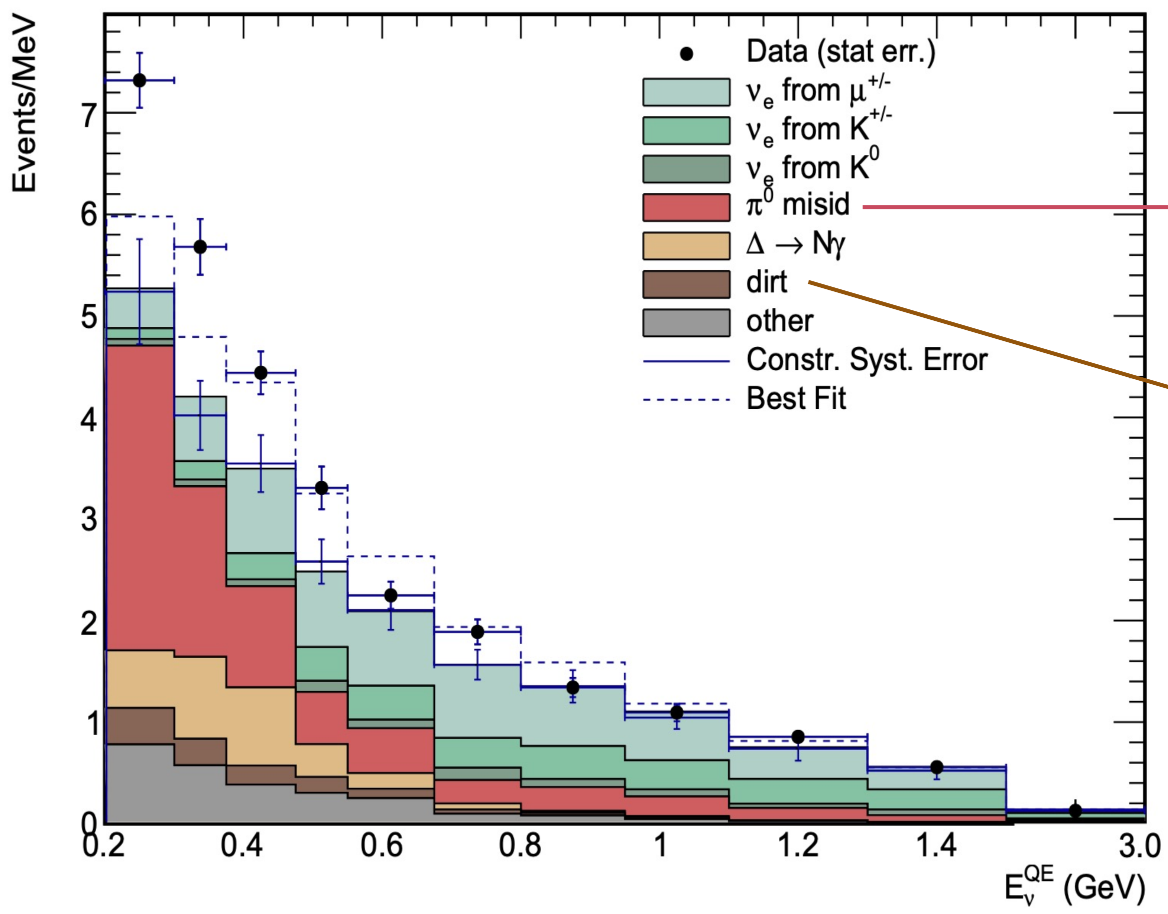


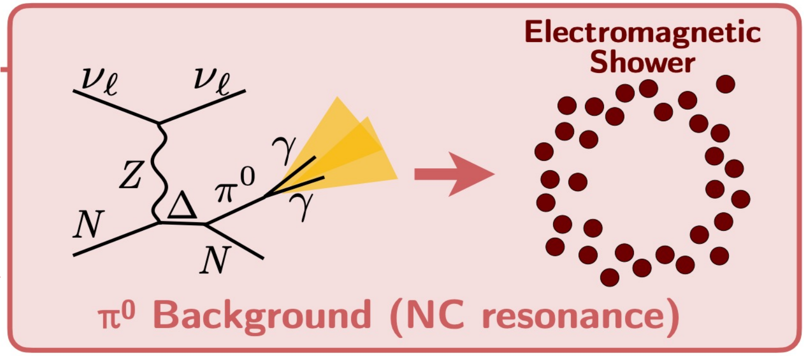
- MiniBooNE's goal is to investigate the excess seen by LSND
  - Test if the excess is due to ν_e appearance from sterile neutrino ~ 1eV^2
- MicroBooNE's goal is to see if we see an excess of electron with respect to the intrinsic neutrino beam or not

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

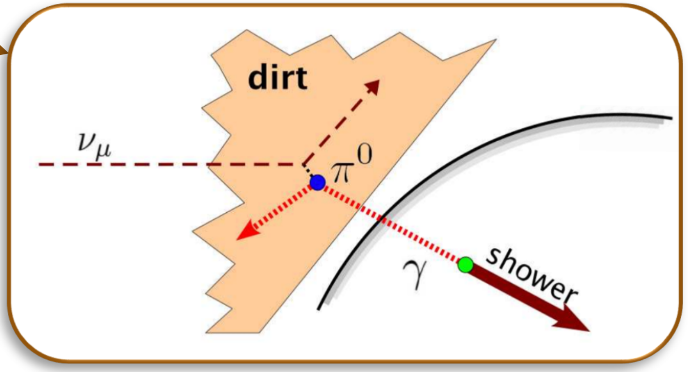


Zooming in on MiniBooNE Low Energy Excess



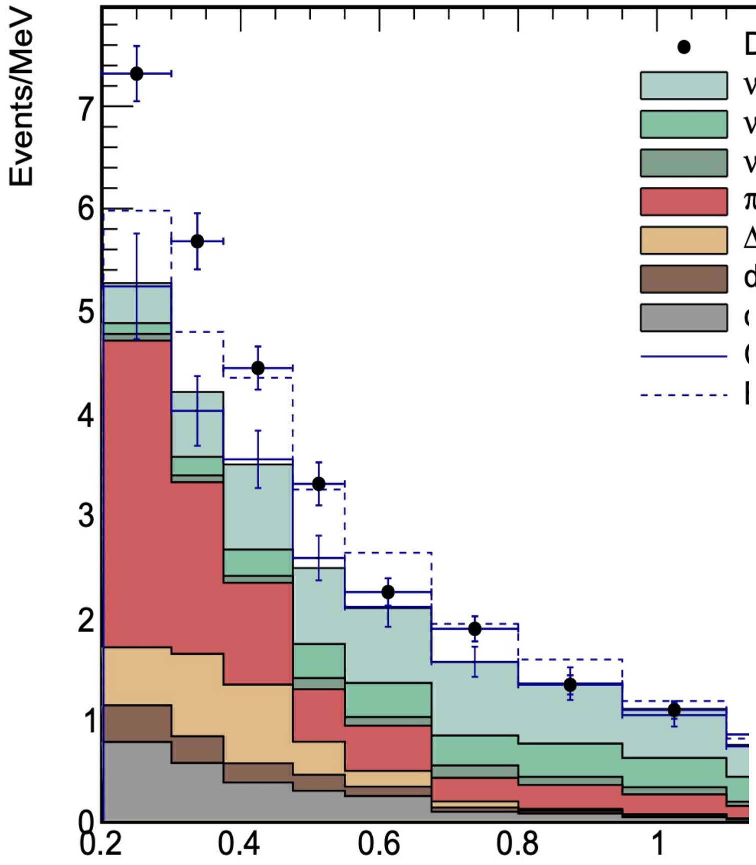


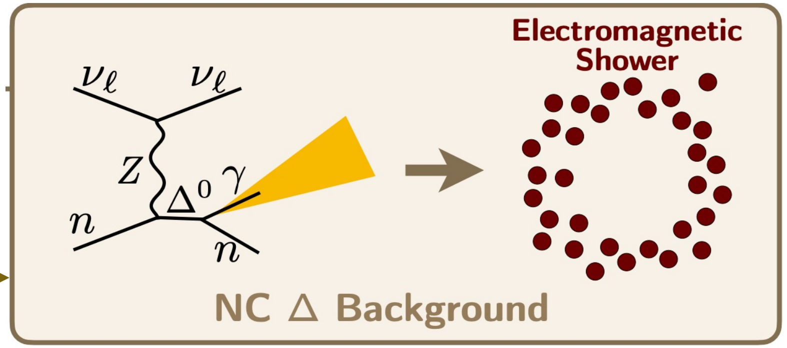
π^0 MisID constrained from in situ measurement of NC π^0 rate

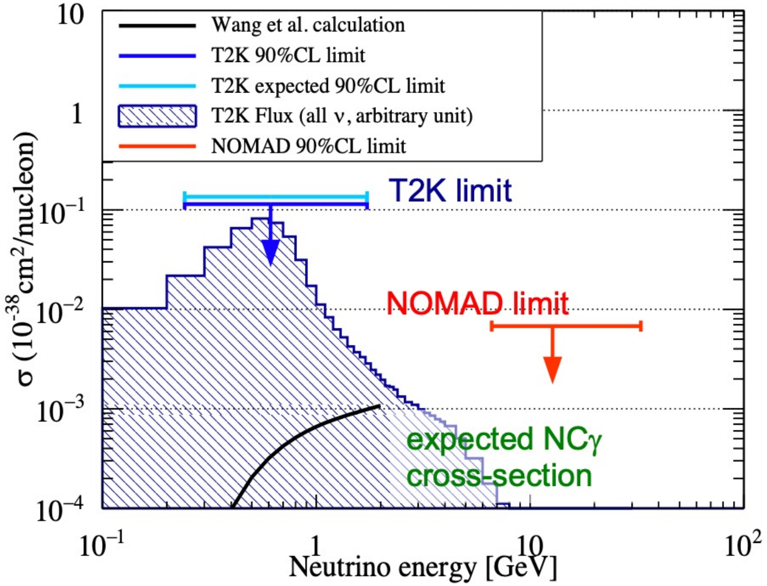


constrained from in situ dirt data sample

Zooming in on MiniBooNE Low Energy Excess







- NC Δ process is not experimentally identified.
- T2K and NOMAD set limits on this process, but x3.18 higher cross-section can explain MiniBooNE excess.

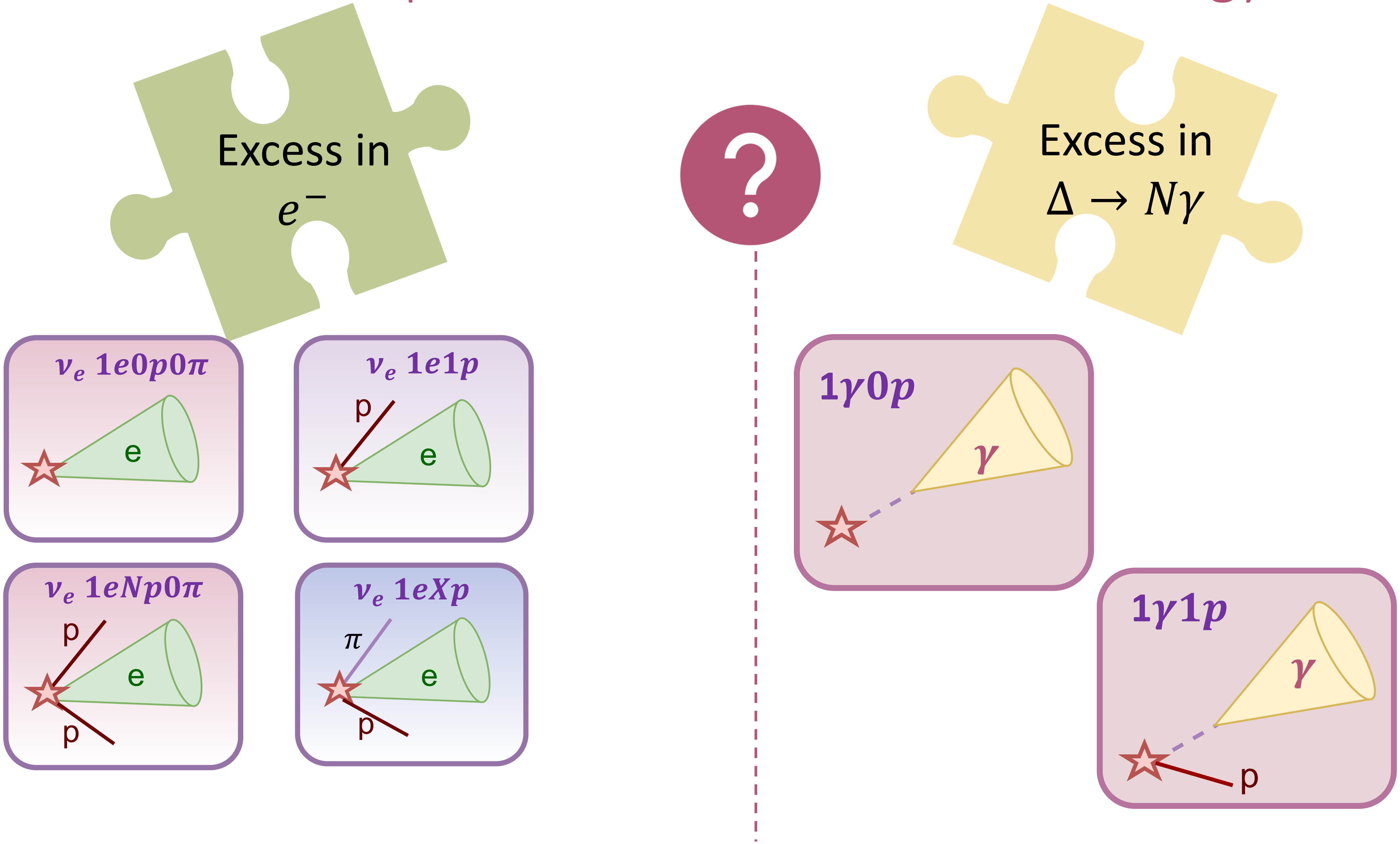
How to solve a puzzle like MiniBooNE Low Energy Excess

Excess in e^-

?

Excess in $\Delta \to N\gamma$

How to solve a puzzle like MiniBooNE Low Energy Excess

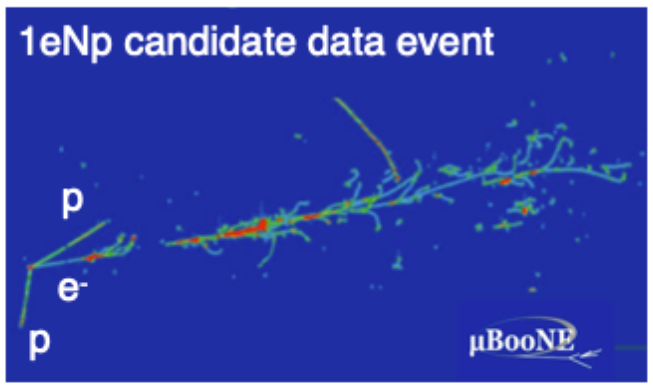


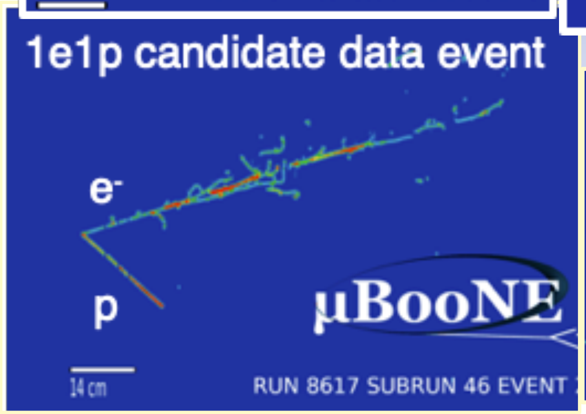
How to solve a puzzle like MiniBooNE Low Energy Excess

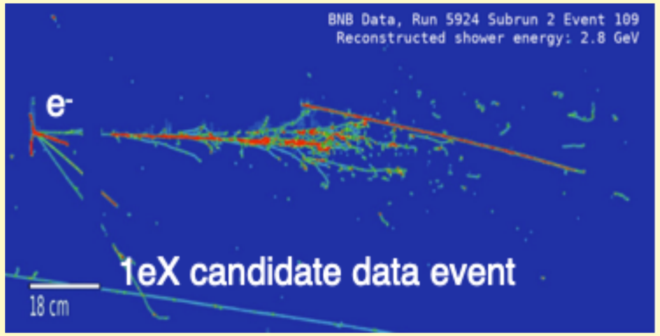
Excess in e^-

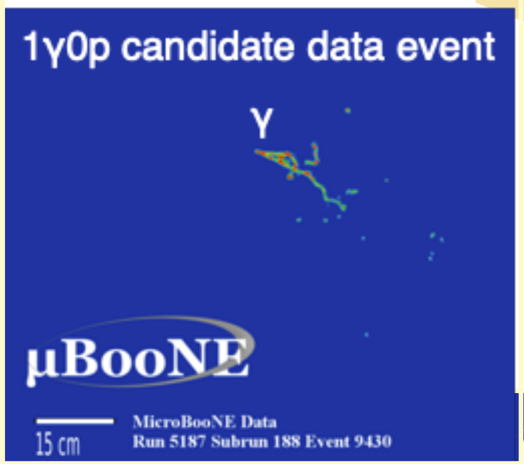
?

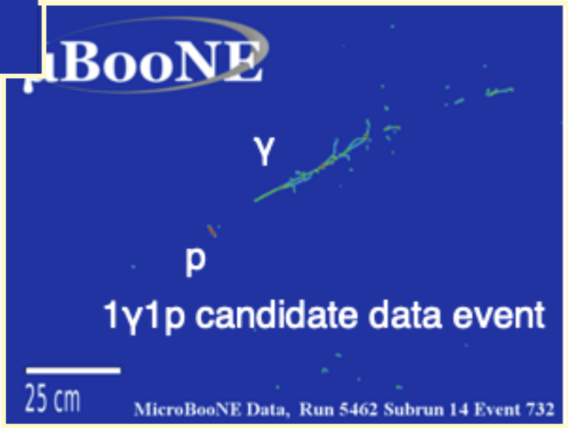
Excess in $\Delta \rightarrow N\gamma$











Modeling the Low Energy Excess

Excess in e^-

Excess in $\Delta \to N\gamma$

Modeling the Low Energy Excess

Excess in e^-

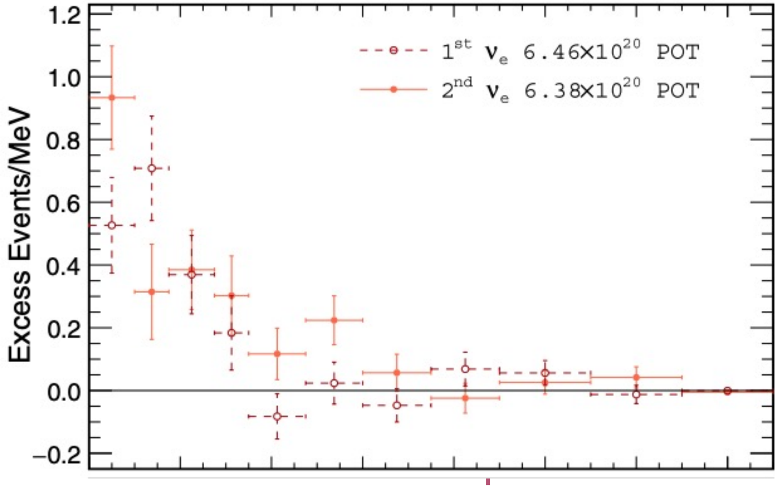
Many literatures for models to explain MiniBooNE excess

First test: use empirical LEE model in MicroBooNE

Excess in $\Delta \rightarrow N\gamma$

Modeling the Low Energy Excess

Excess in e^-

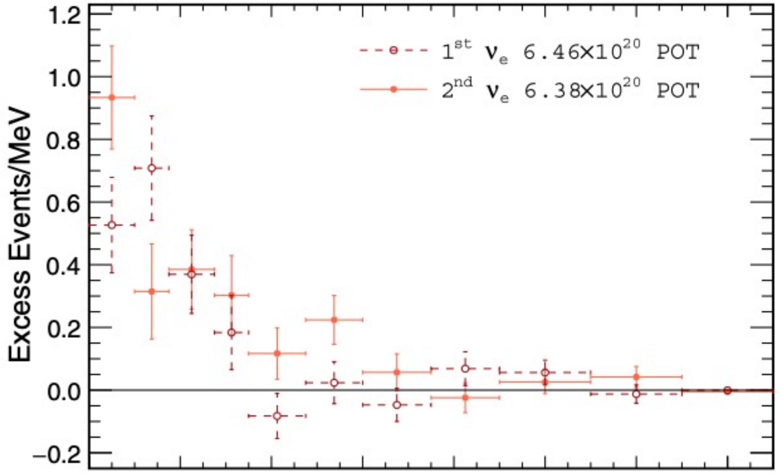


Excess in $\Delta \rightarrow N\gamma$

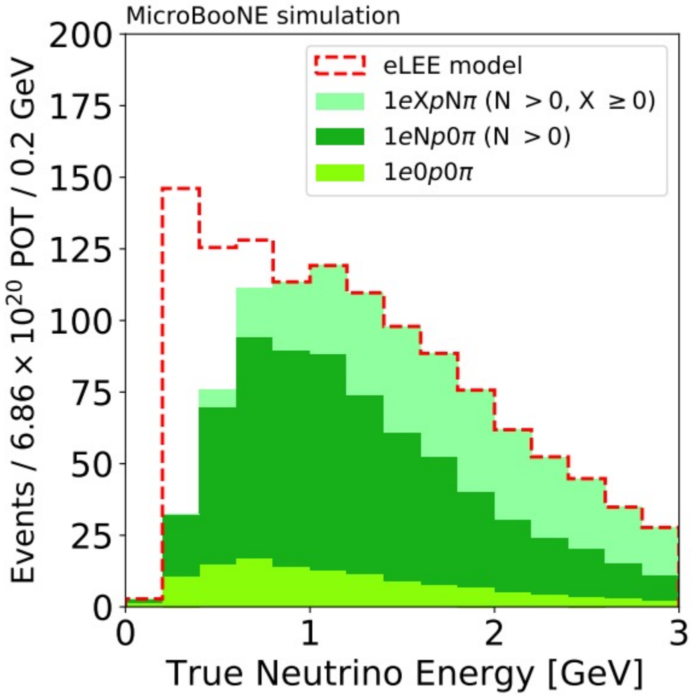
Take background subtracted excess of data events in MiniBooNE

Modeling the Low Energy Excess

Excess in e^-

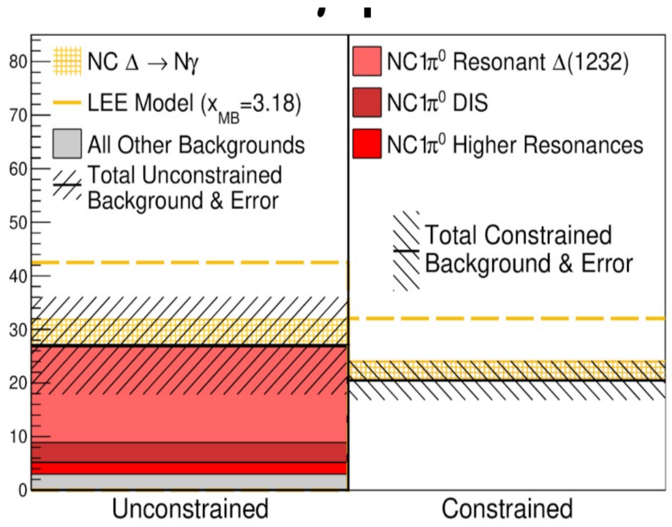


Excess in $\Delta \rightarrow N\gamma$



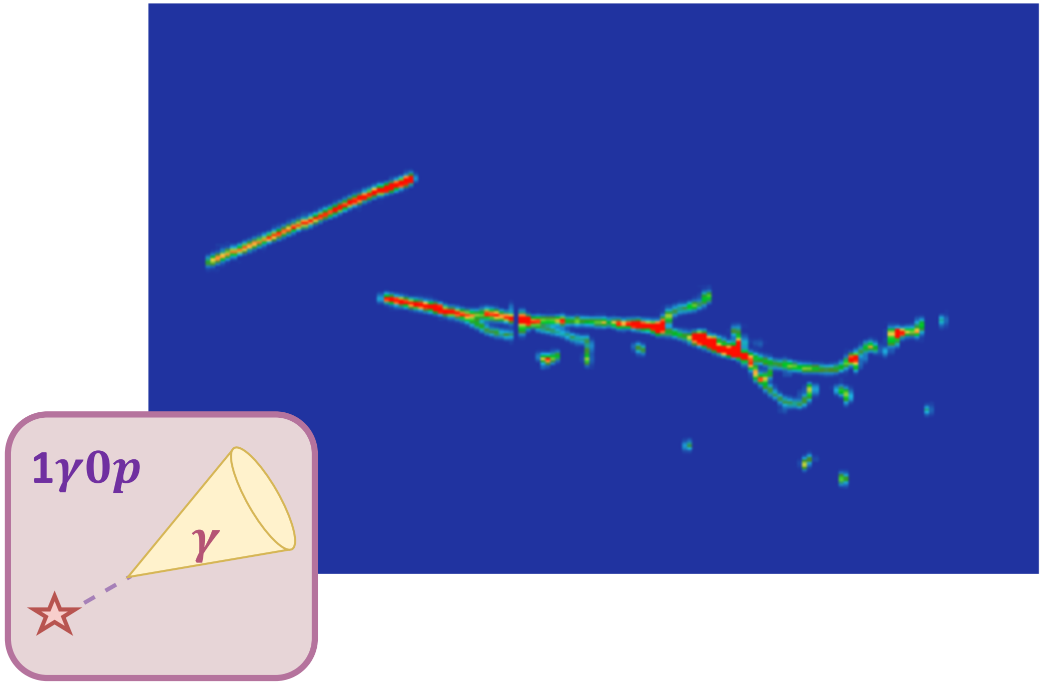
Assume excess is **intrinsic ν_e**
Unfold to true energy
Apply to MicroBooNE to benchmark the analysis wrt excess
(Scaling is allowed to float)

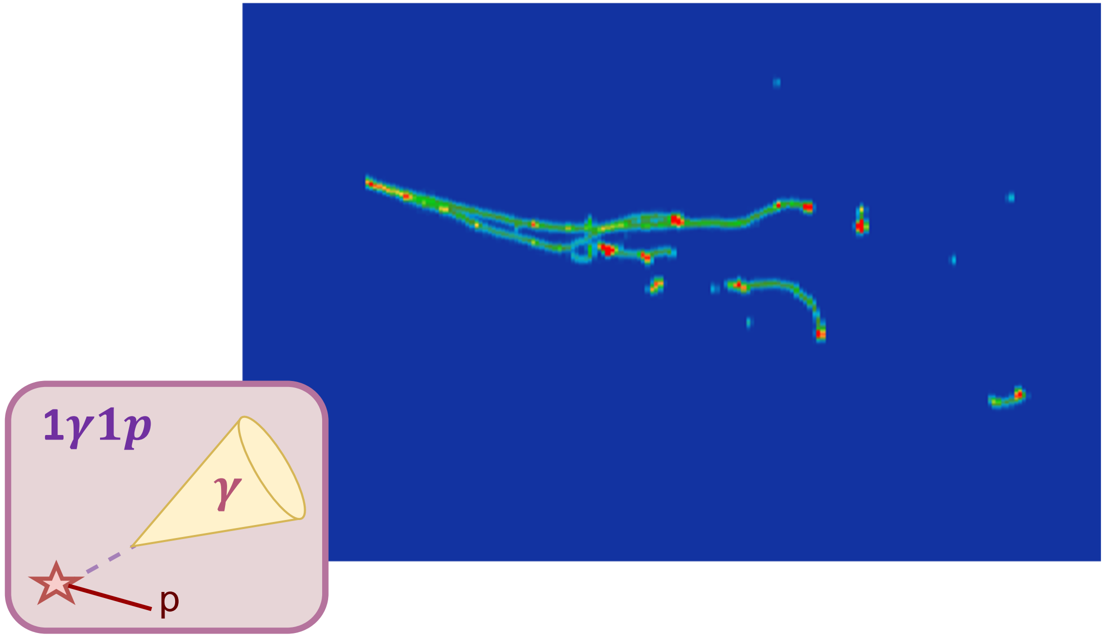
Assume excess is **$\Delta \rightarrow N\gamma$**
Unfold to true energy
Apply to MicroBooNE to benchmark the analysis wrt excess
(Scaling ~3.18)



Analysis Method for MicroBooNE Low Energy Excess Analyses

The single photon LEE search



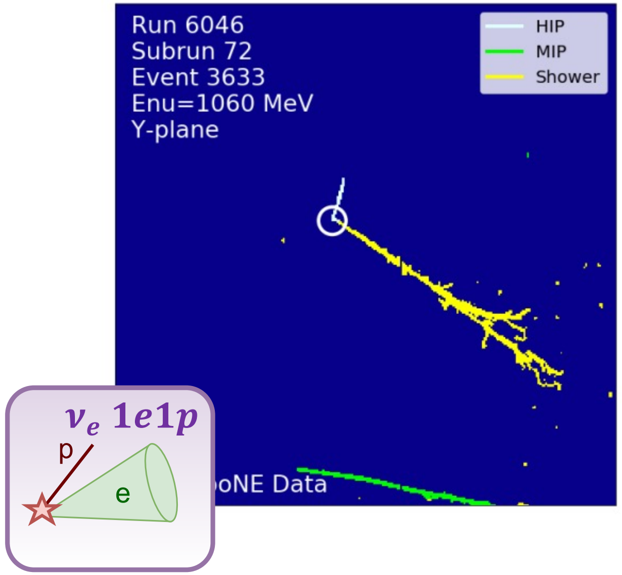


Pandora reconstruction

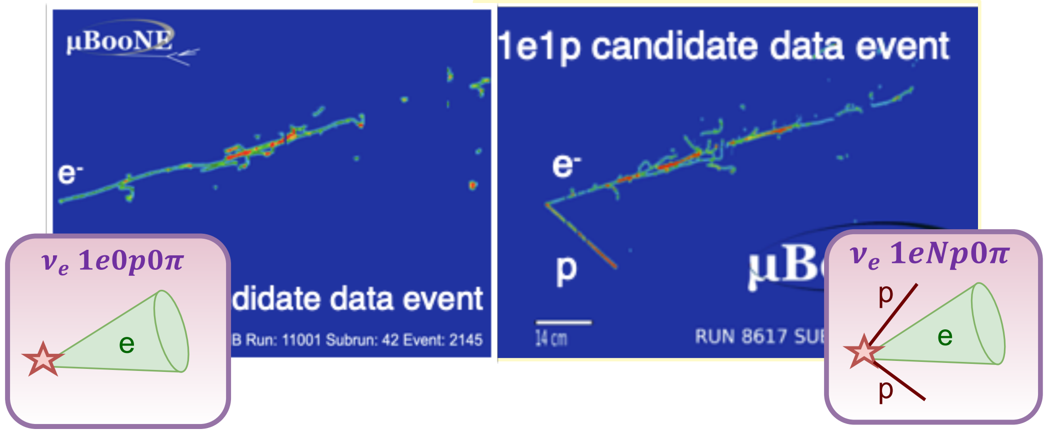
- $\Delta \rightarrow N\gamma$ search utilizes $1\gamma 1p$ and $1\gamma 0p$ which are fit simultaneously to maximize signal statistics
- Major challenge is understanding and rejecting NC π^0 backgrounds
- In situ measurement used to constrain the background

The electron channel LEE search

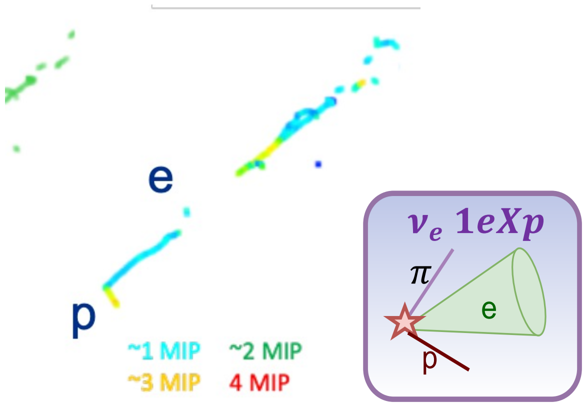
Three complementary analyses using 3 fully automated reconstruction probing different final states



Deep Learning
JINST 12, P03011 (2017)



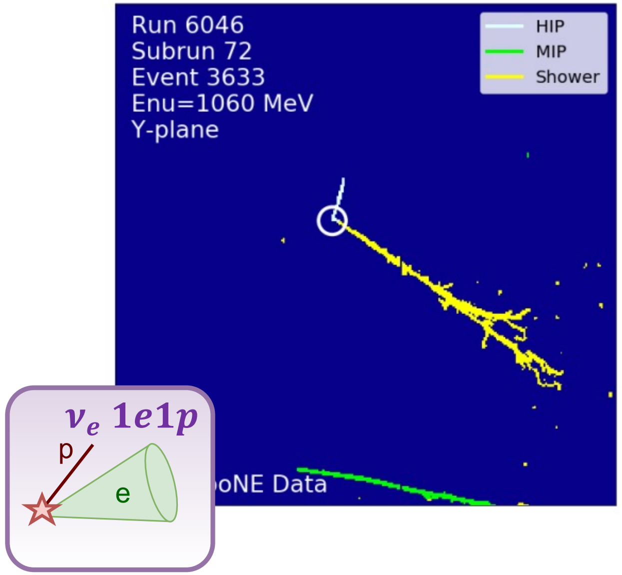
Pandora reconstruction
Eur.Phys.J.C 78 (2018) 1, 82



Wirecell reconstruction
JINST 16, P06043 (2021)

The electron channel LEE search

Three complementary analyses using 3 fully automated reconstruction probing different final states



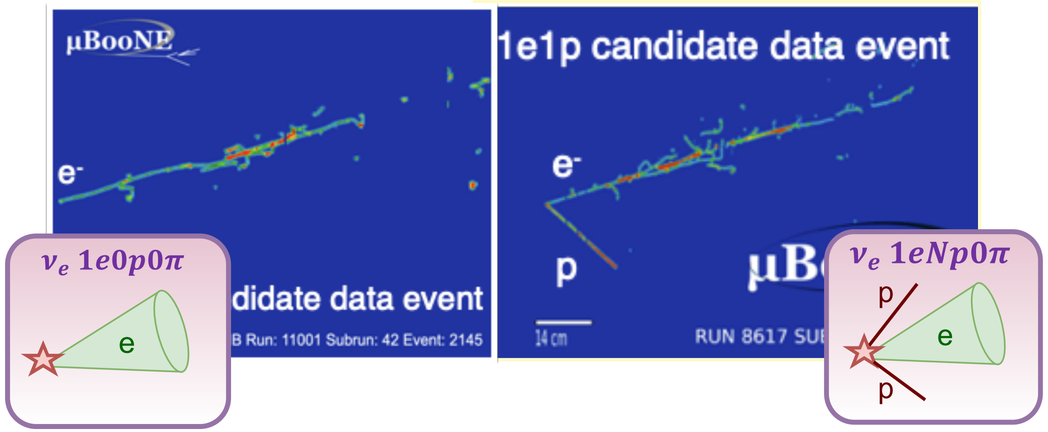
Deep Learning.

Use Convolutional Neural Net to label tracks and showers from input pixel image

Aim for high purity of CCQE signal selection (oscillation signal)

The electron channel LEE search

Three complimentary analyses using 3 fully automated reconstruction probing different final states



Pandora reconstruction

Use patterns recognition in 2D to build 3D reconstruction of interaction

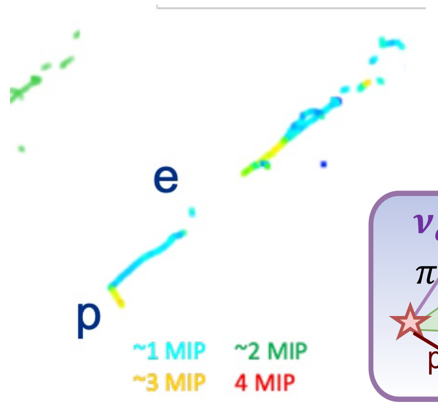
Semi-inclusive pion-less final states

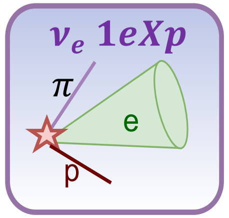
1eNp: more sensitive to empirical model of MiniBooNE result

1e0p: Mitigate uncertainties related to proton multiplicity, kinematics, and reconstruction

The electron channel LEE search

Three complementary analyses using 3 fully automated reconstruction probing different final states



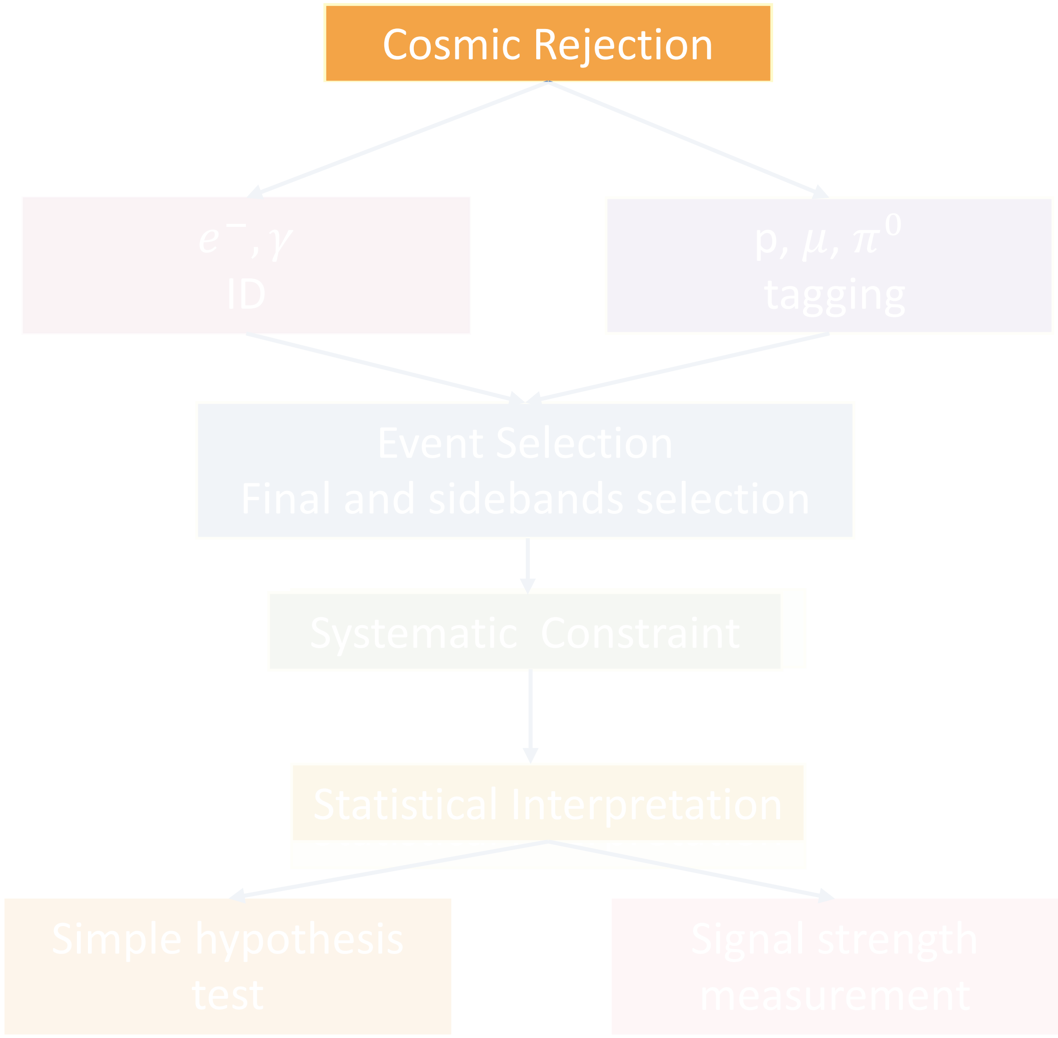


Wirecell reconstruction

Use tomographic image to turn 2D charge information to 3D charge.

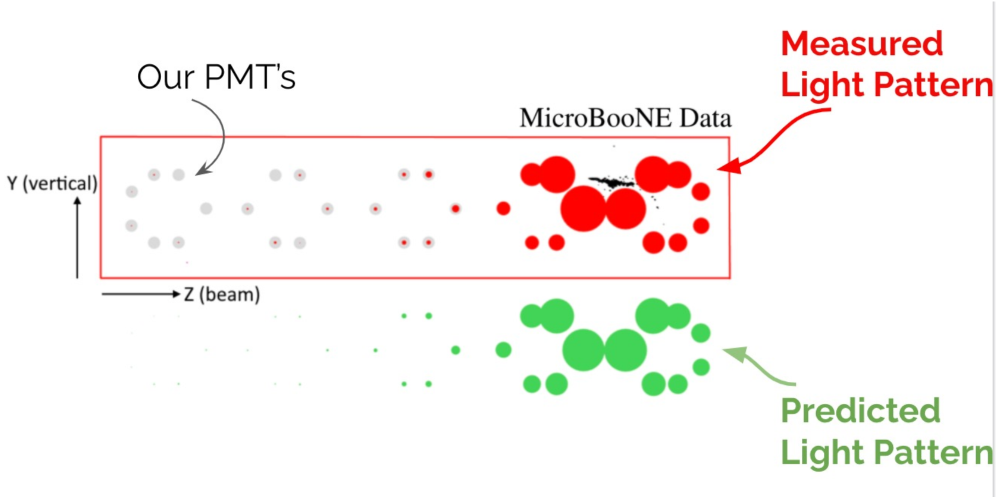
- Fully inclusive selection
- Least sensitive to the cross-section models

Common Strategy



MicroBooNE is a surface detector:

- 97% of triggered events have only cosmic activity
- Events with a neutrino typically contain 20 cosmic muons
- Matching with PMT flashes is used to identify the true beam neutrinos



JINST 16 P06043 (2021)

Cosmic rejection > 99.7%

Common Strategy

Cosmic Rejection

e^-, γ ID

p, μ, π^0 tagging

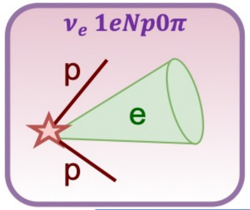
Event Selection
Final and sidebands selection

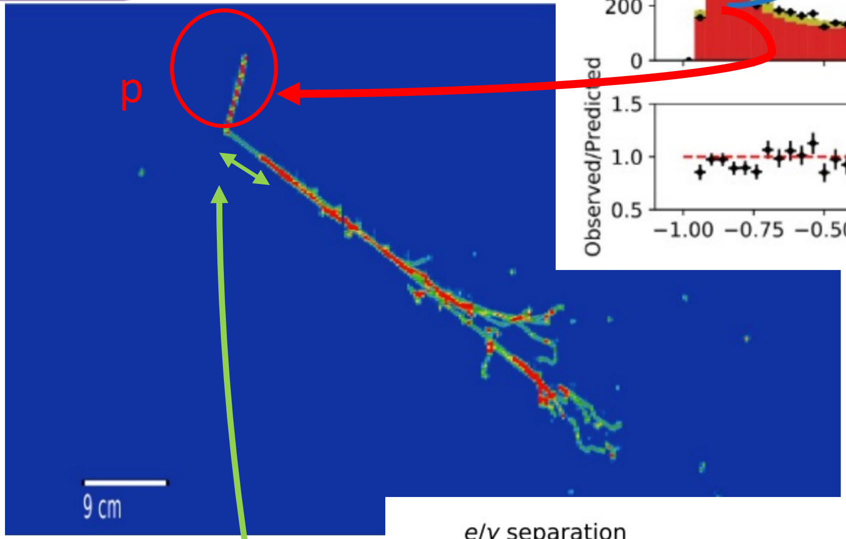
Systematic Constraint

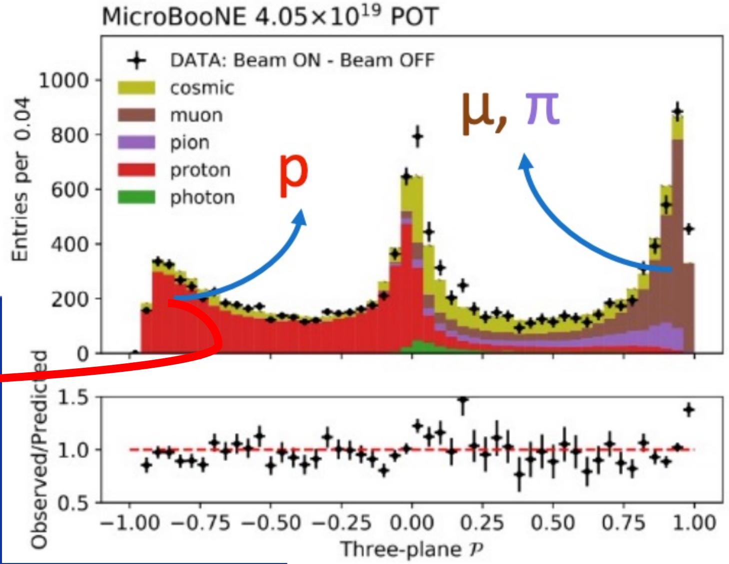
Statistical Interpretation

Simple hypothesis test

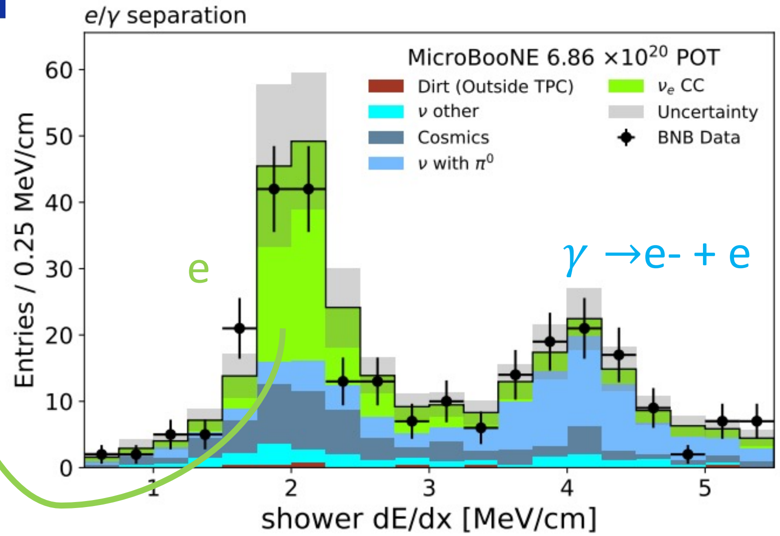
Signal strength measurement



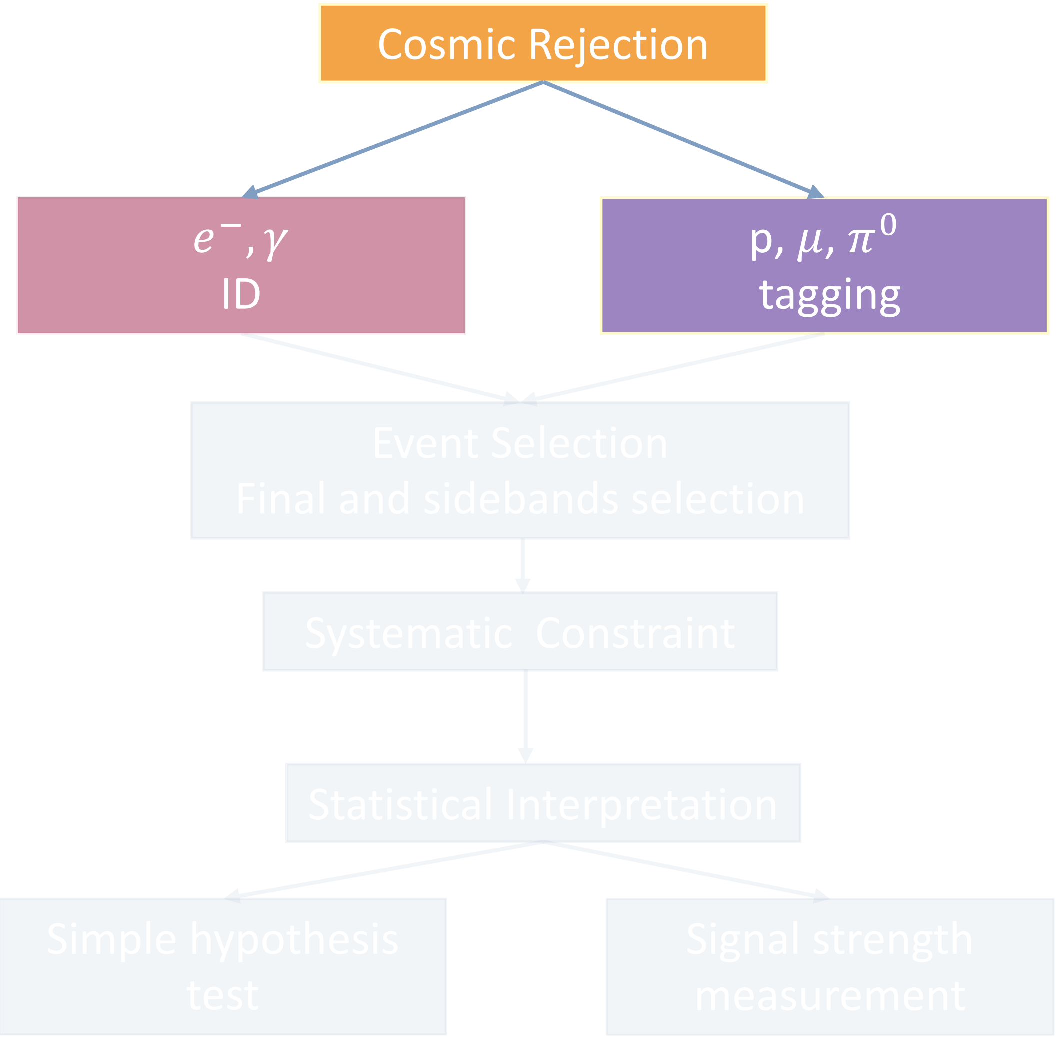


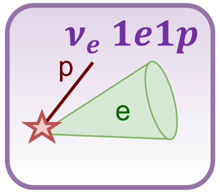


J. High Energ. Phys. 153 (2021)

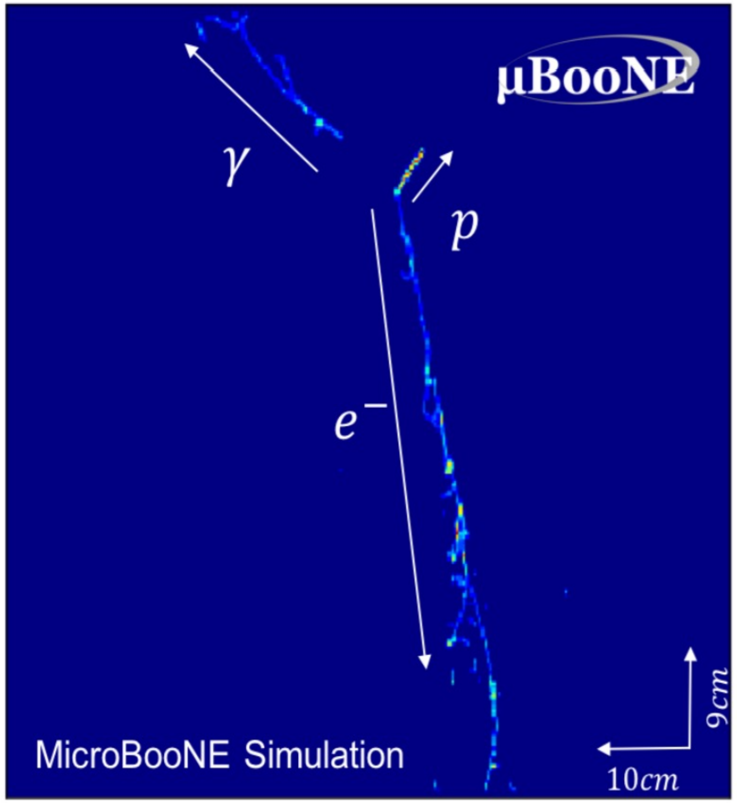


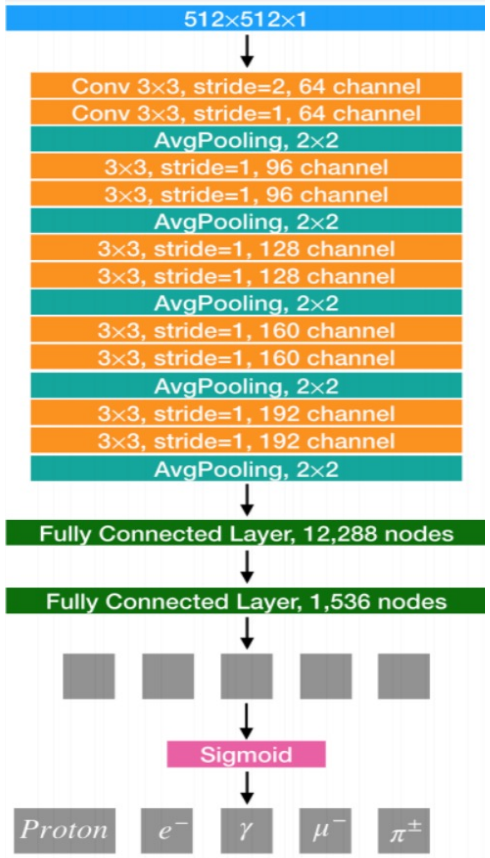
Common Strategy





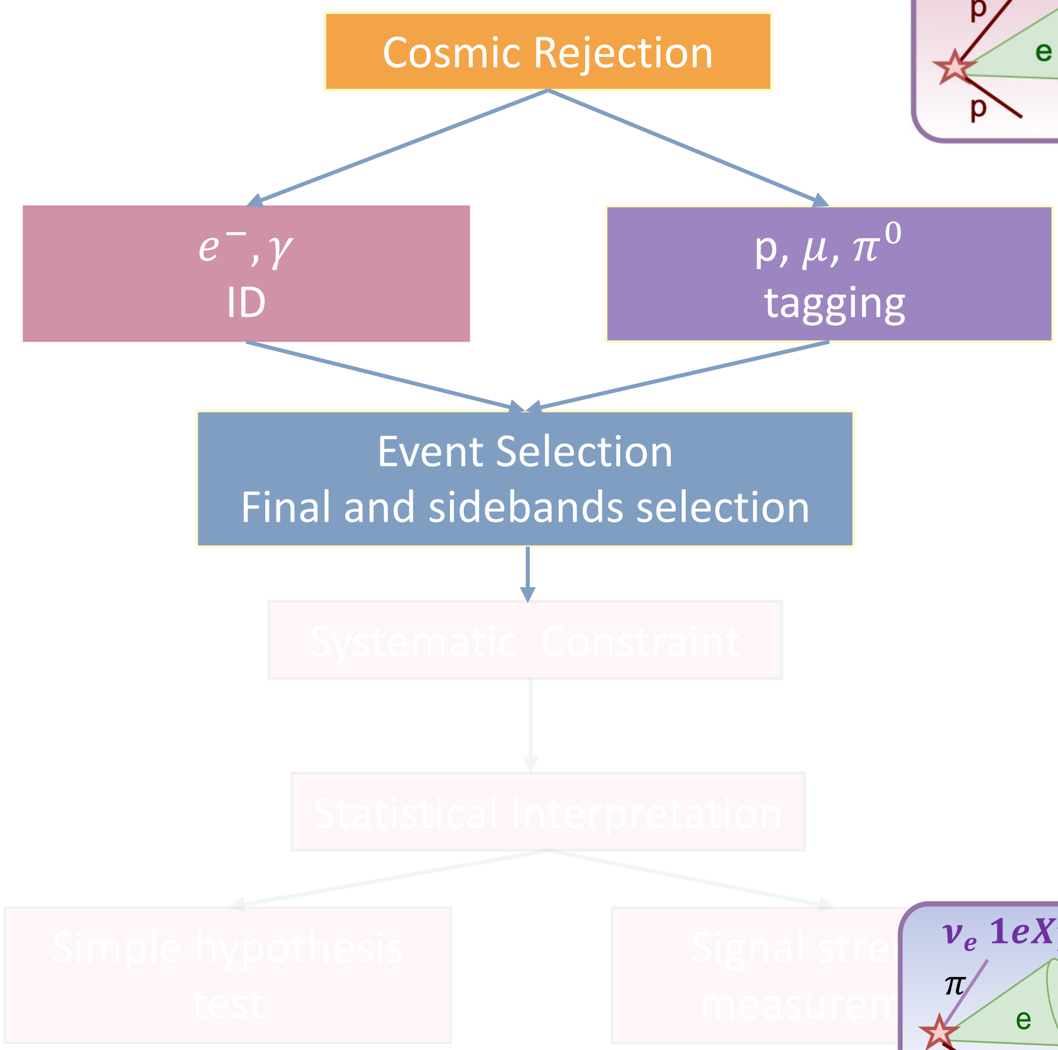
Convolutional neural network for multiple particle identification in the MicroBooNE liquid argon time projection chamber
Phys.Rev.D 103, 092003 (2021)

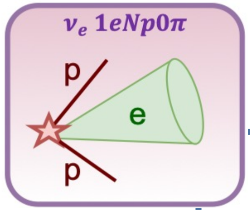




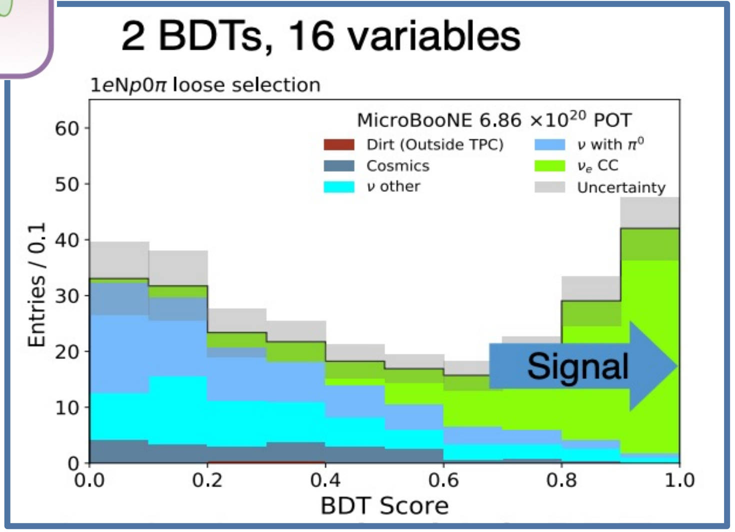
	p	e^-	γ	μ^-	$\pi^\pm$
MPID Score	0.89	0.95	0.85	0.06	0.17

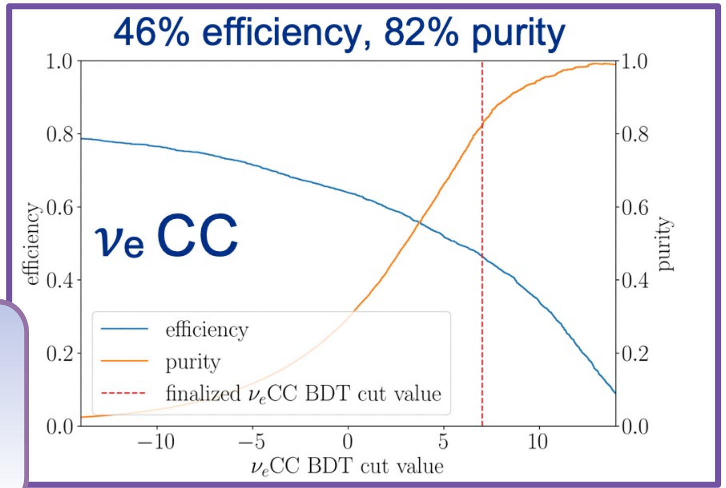
Common Strategy: BDTs

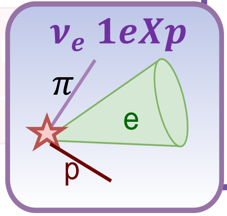


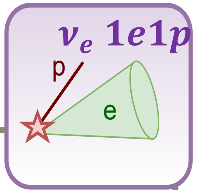


Boosted decision tree (BDT): common tool used to separate signal from background.

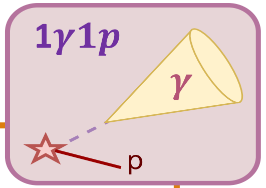








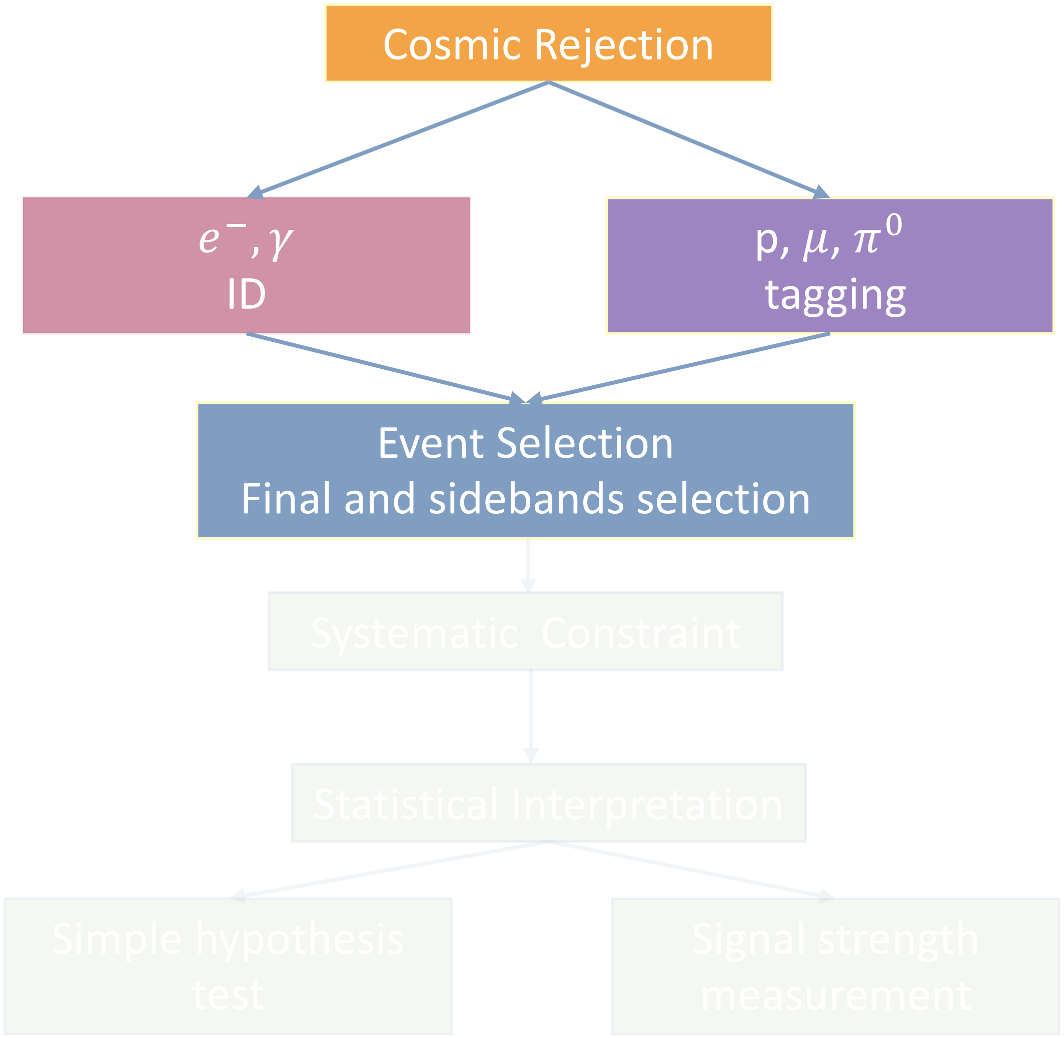
1e1p
- 19 kinematic variables (e.g., QE consistency)
- 4 ionization variables (e.g., shower labeled pixel fraction)

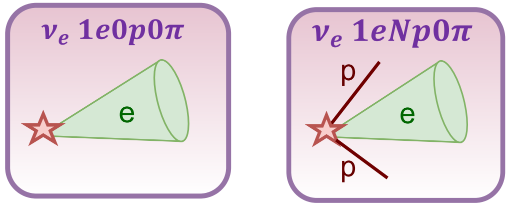


1γ1p

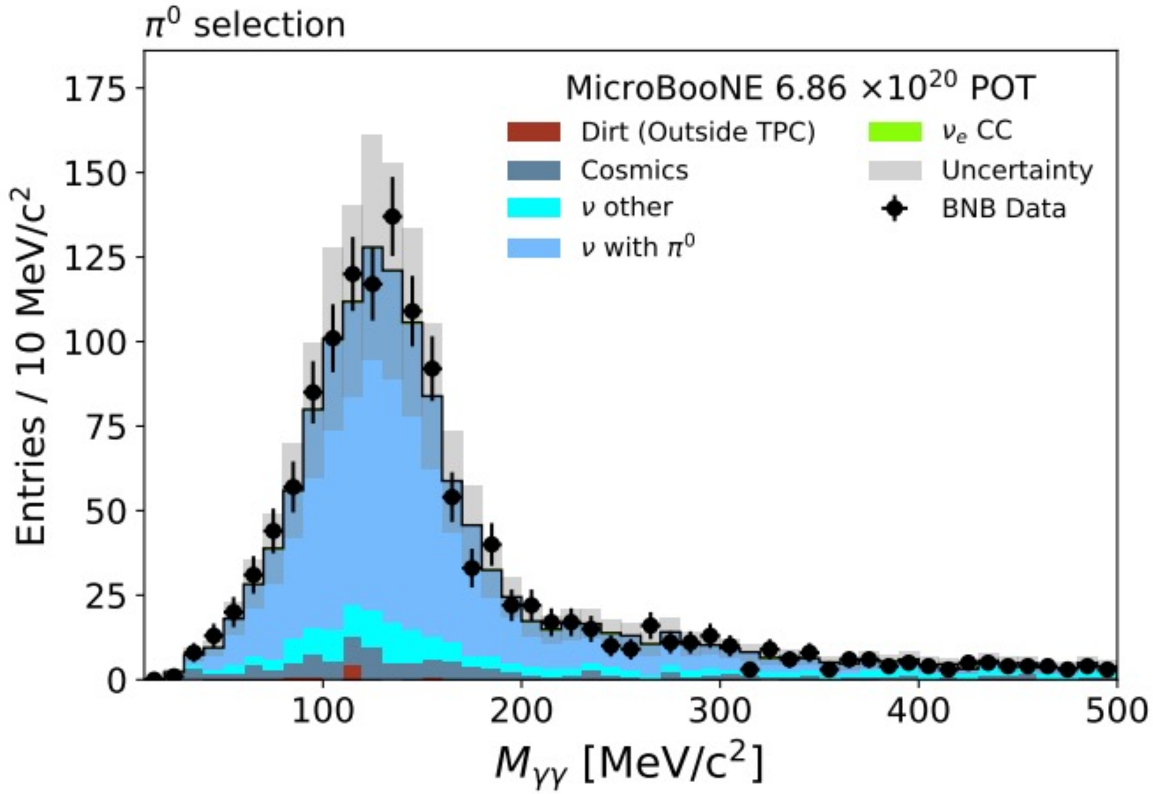
5 boosted decision trees to reject backgrounds from 1γ1p topology

Common Strategy

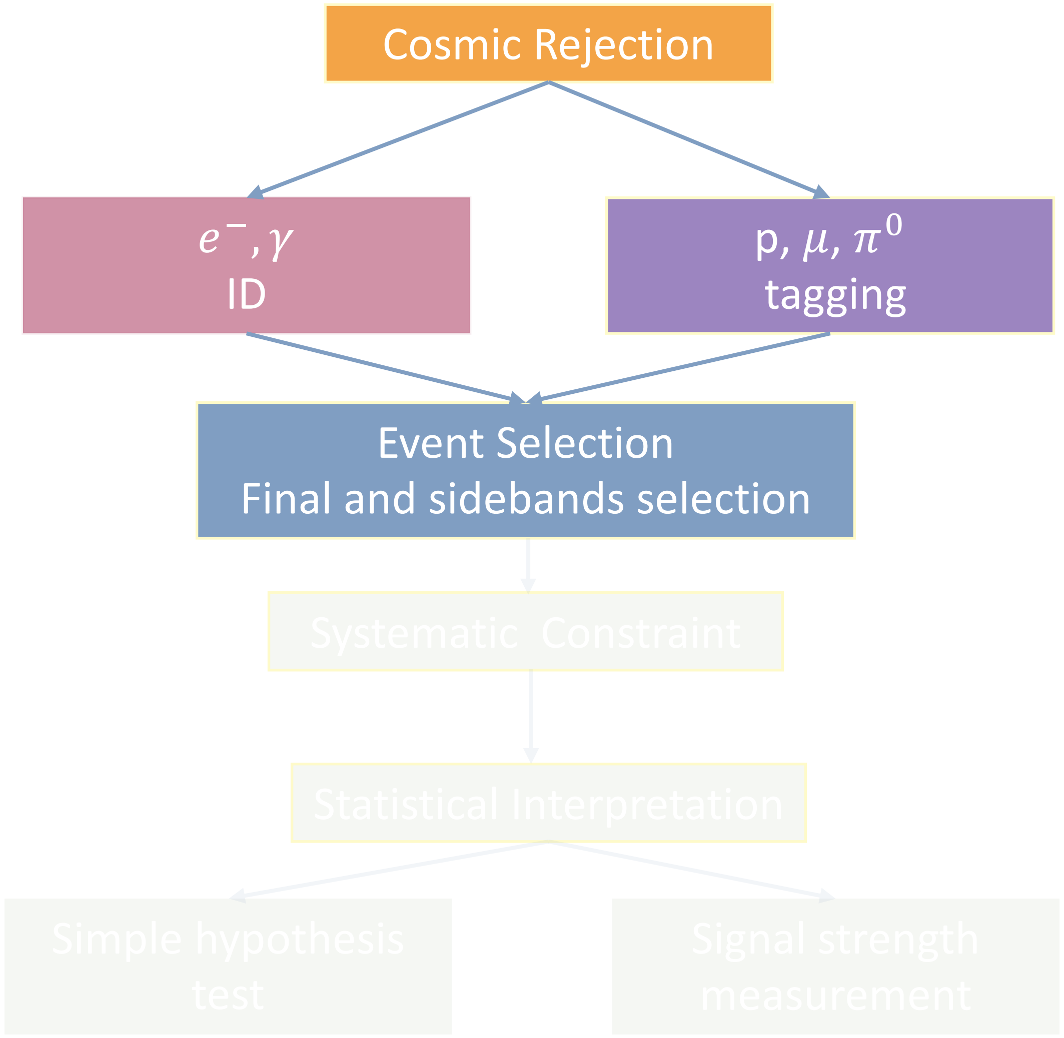


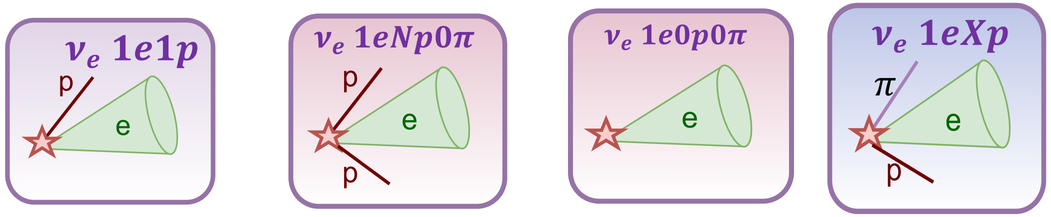


- Reconstructed π^0 mass within 5% of 135 MeV/c2
- Used to calibrate the shower



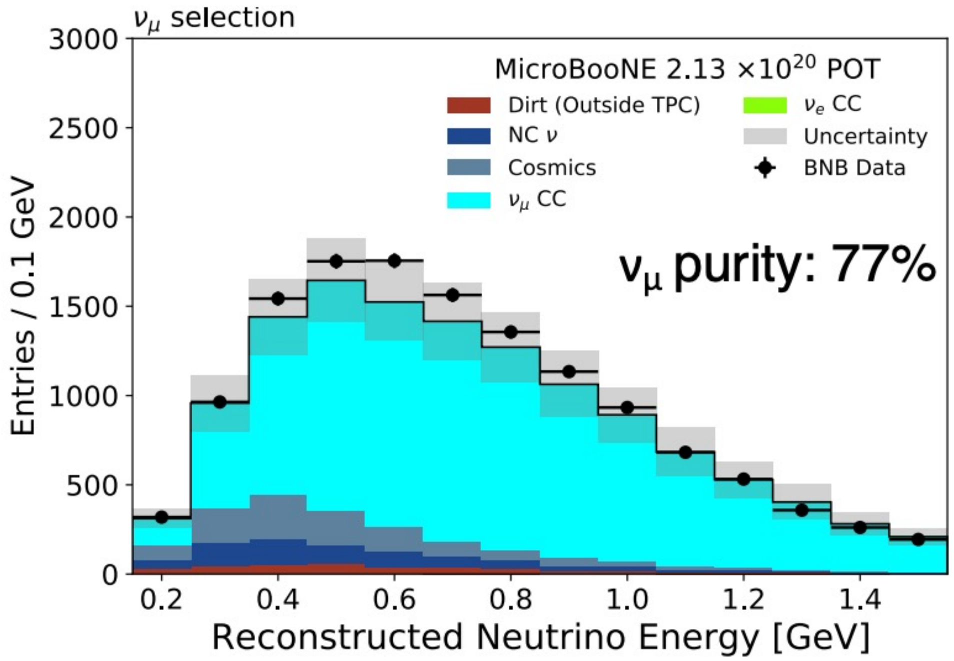
Common Strategy



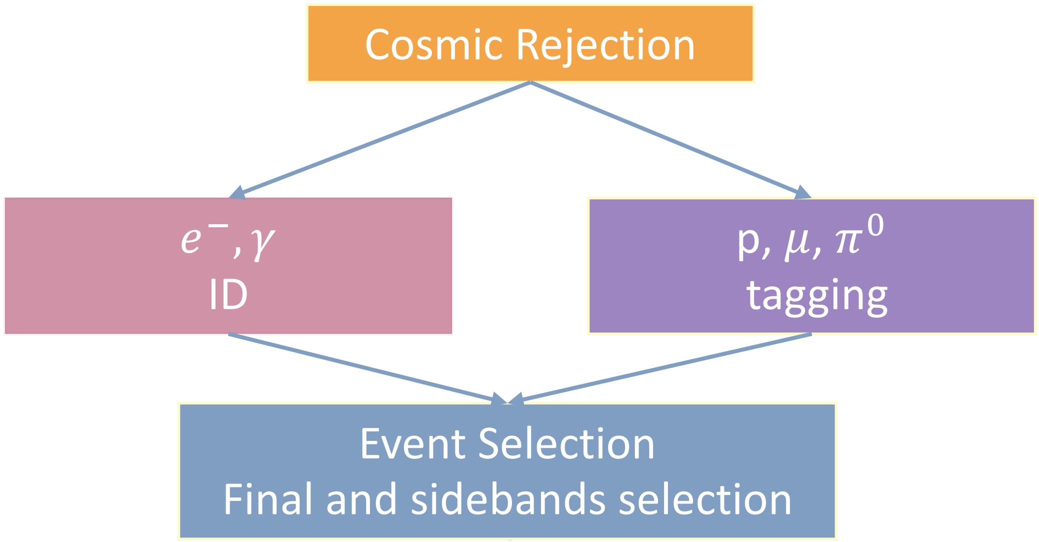


High statistic inclusive contained ν_μ selection to constrain ν_e systematics

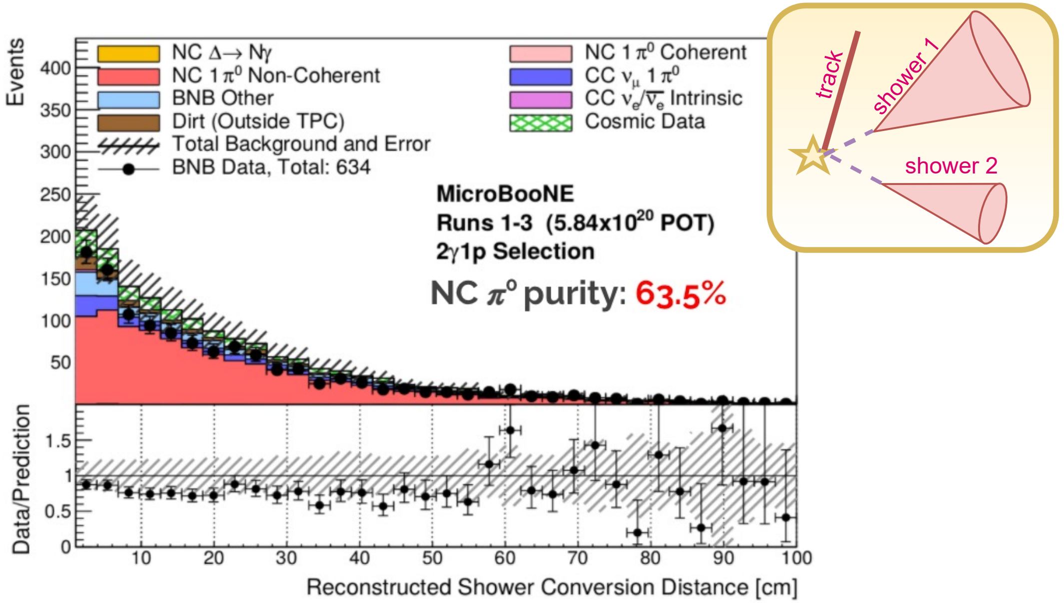
- Flux: both νe and νμ come from the same beamline, and hadrons
- Cross section: Both interact in argon

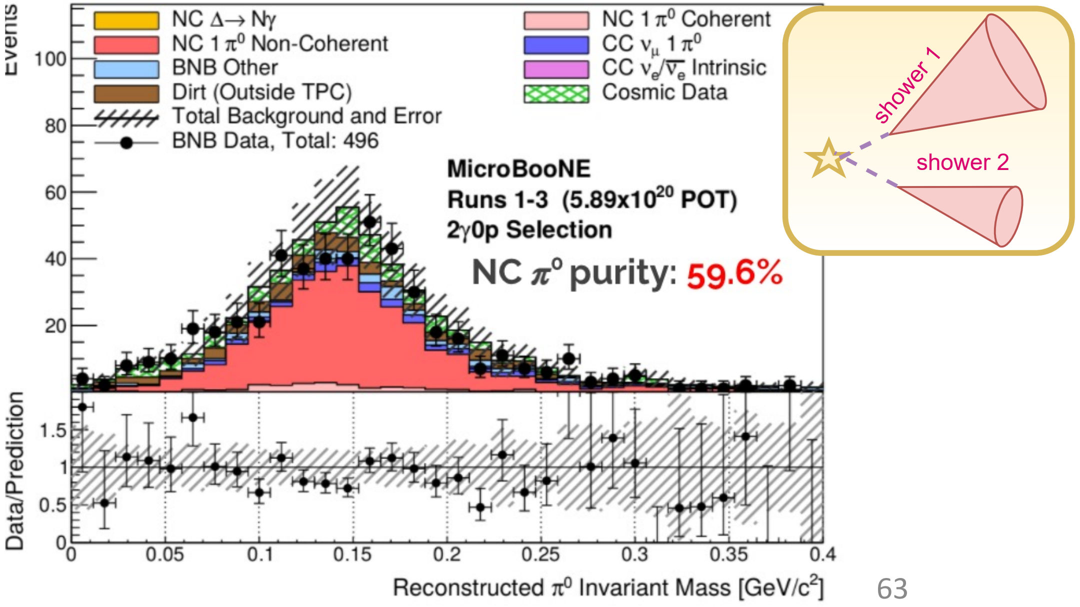


Common Strategy

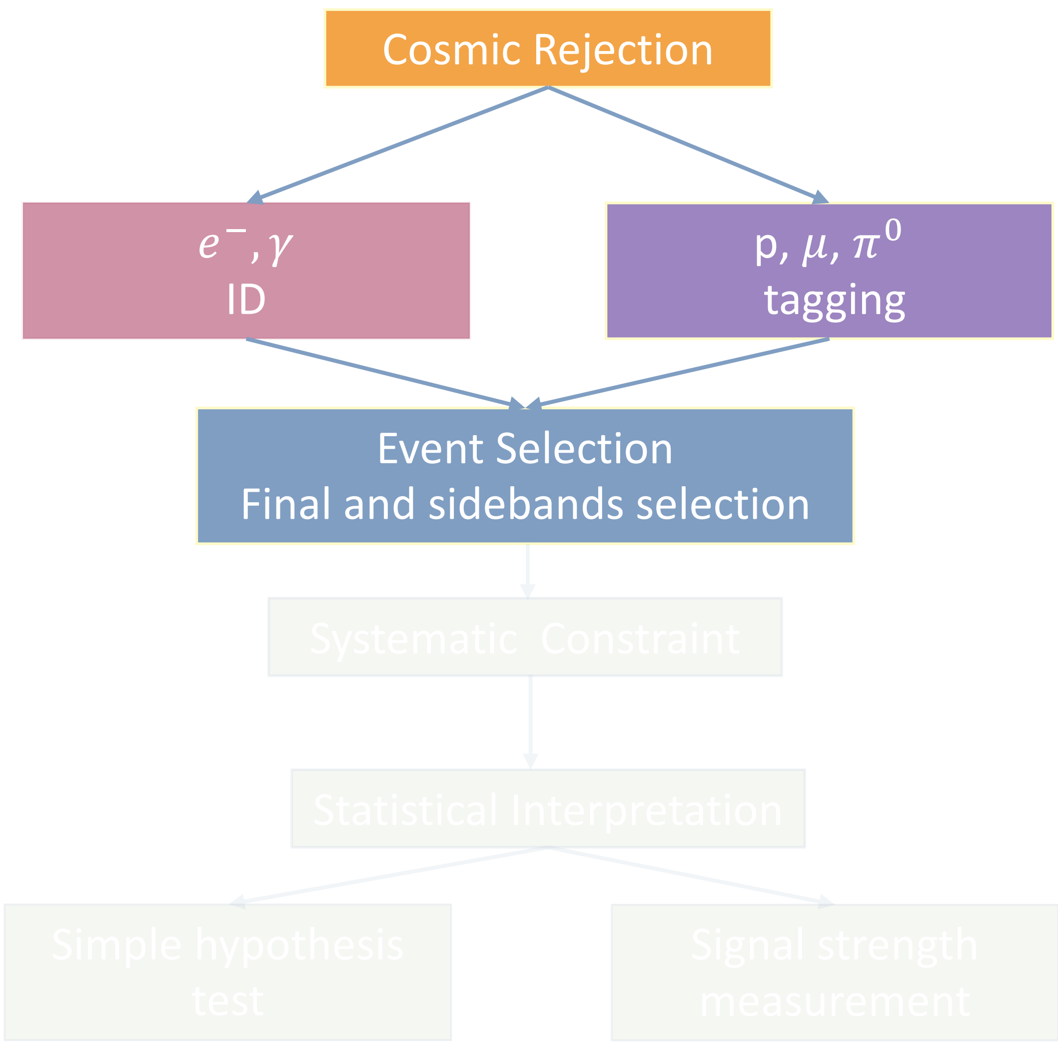


- High statistics π^0 interactions
- Used to constrain the π^0 backgrounds in the $\Delta \to N\gamma$ signal samples
  - validate shower reconstruction and energy measurement

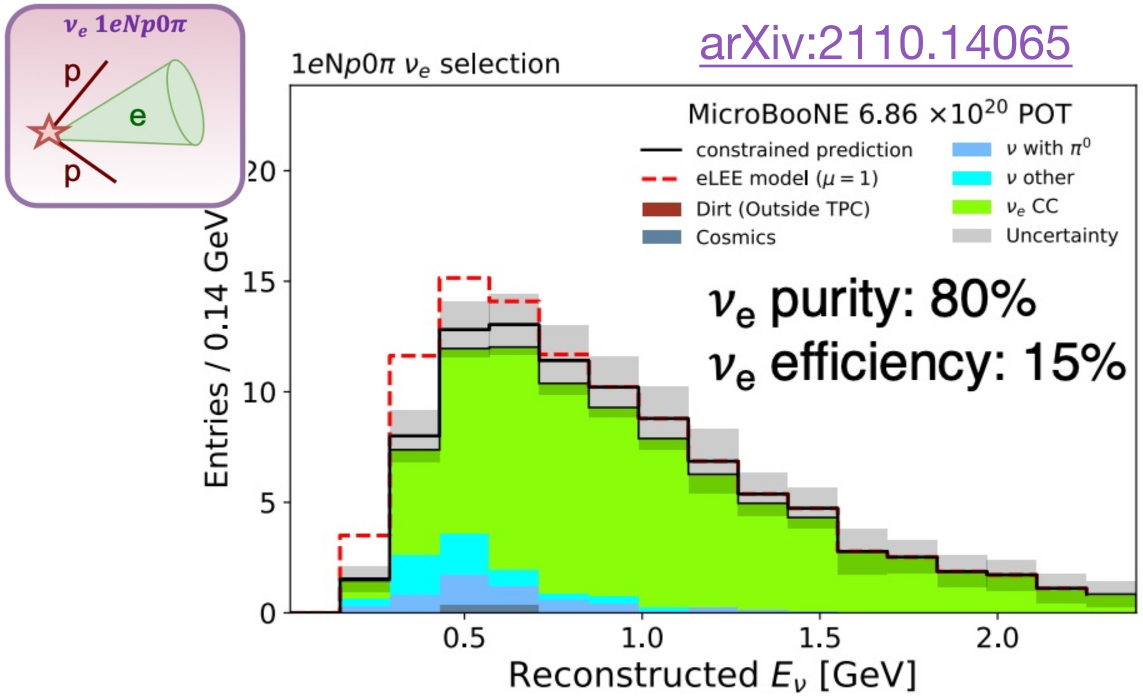




Common Strategy



arXiv:2110.14065



- Reject over 99.7% of background events from cosmic muons or π^0
- Select ν_e with high purity despite large backgrounds

Common Strategy

Cosmic Rejection

e^-, γ ID

p, μ, π^0 tagging

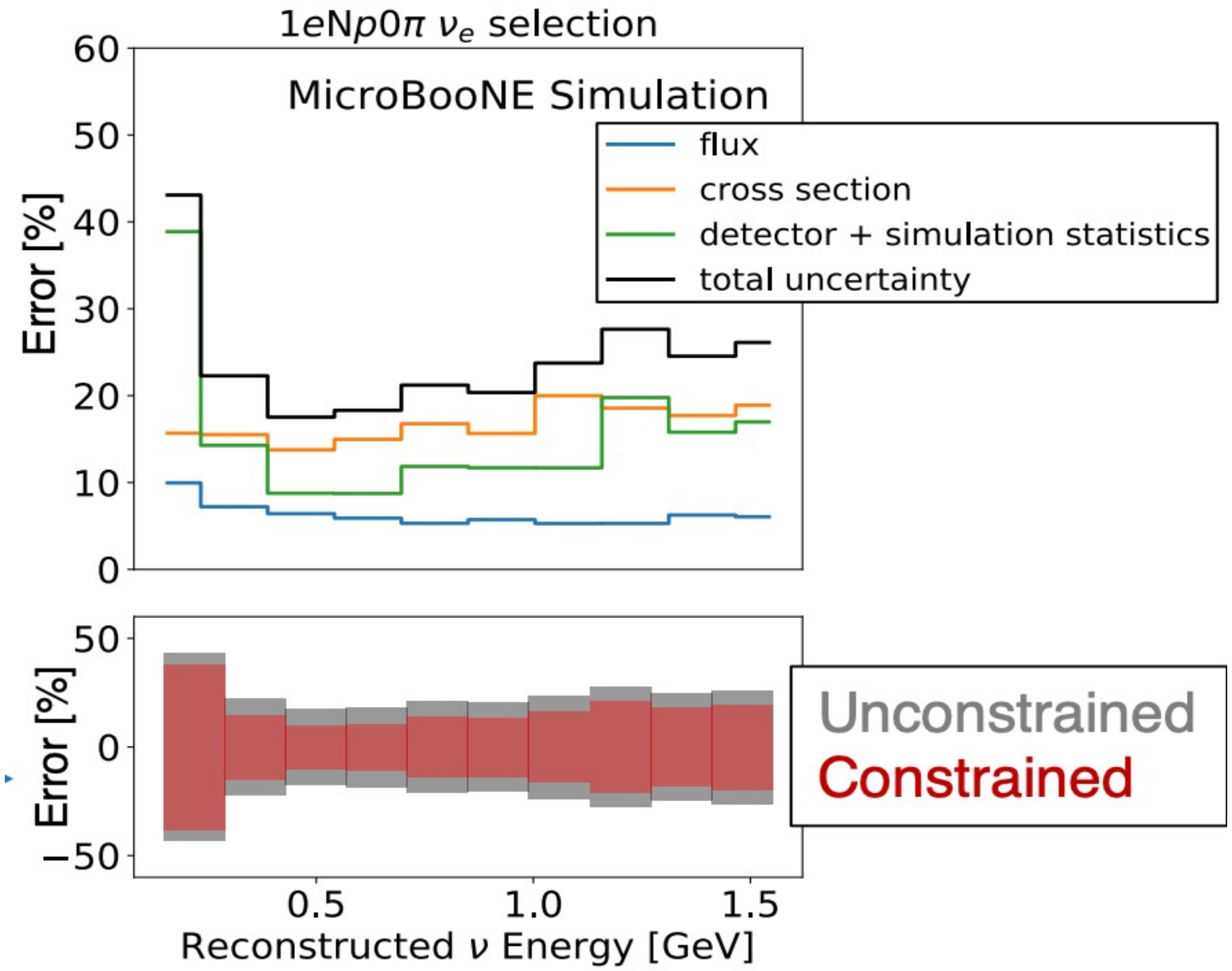
Event Selection
Final and sidebands selection

Systematic Constraint

Statistical Interpretation

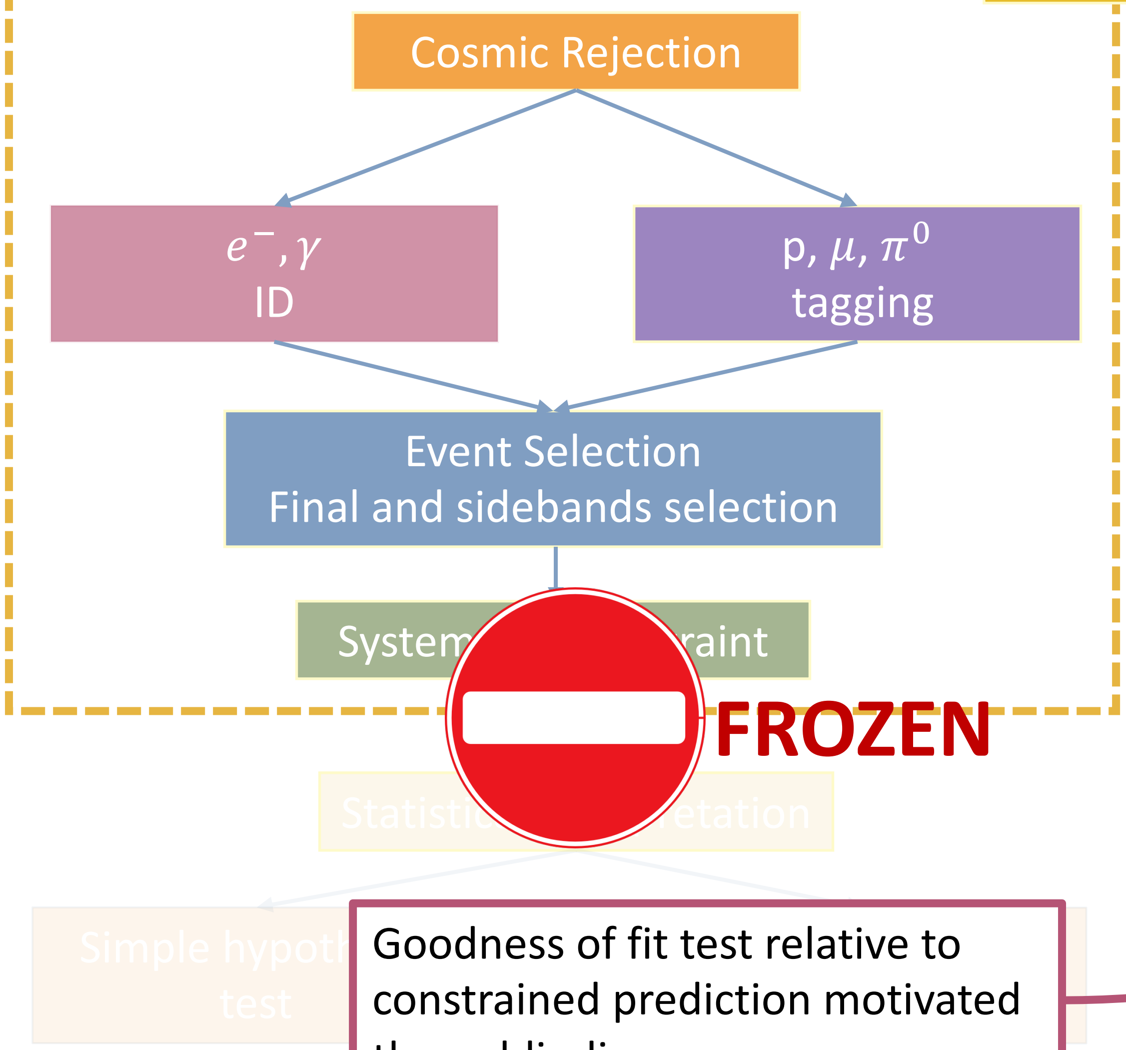
Simple hypothesis test

Signal strength measurement

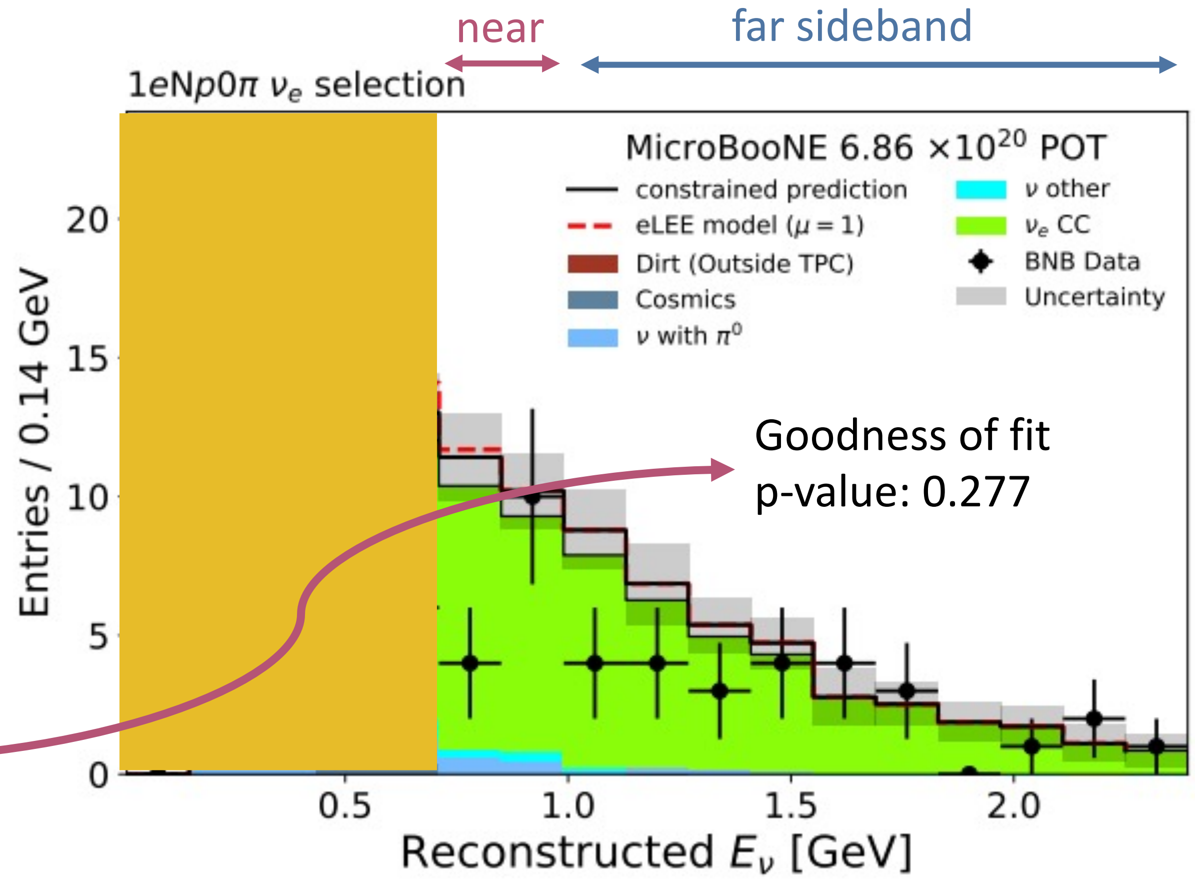


Blind analysis

STAGED UNBLINDING

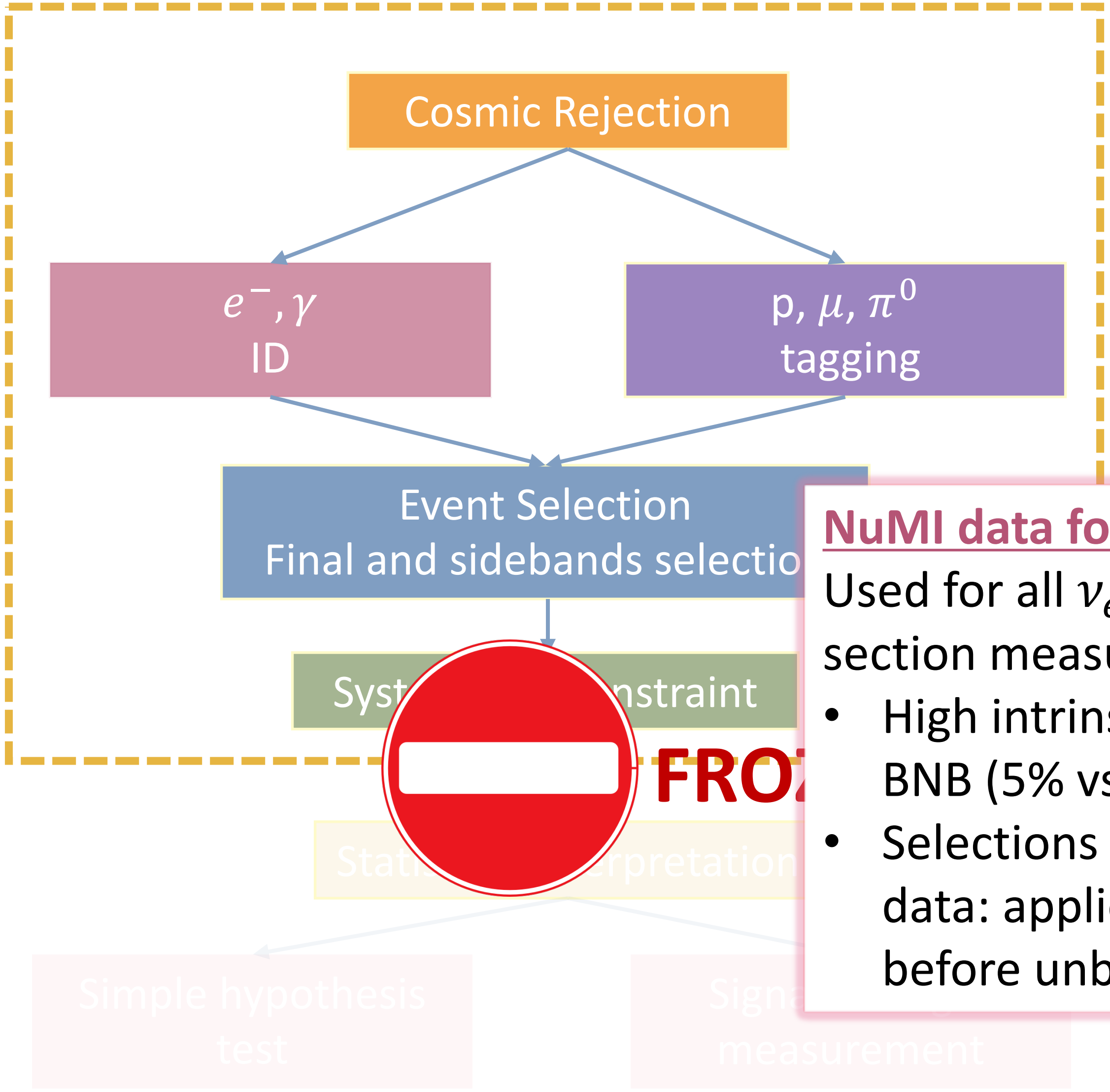


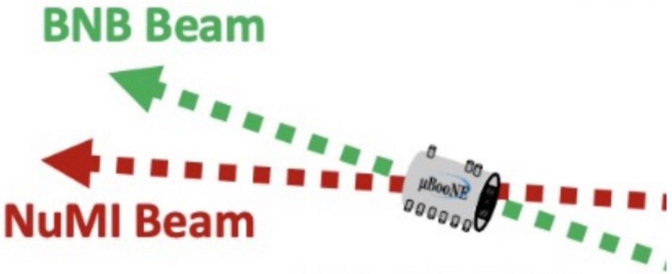
- Data in **non-signal region** used to validate analysis strategy and modeling.
- Selection is frozen before looking at **sideband** data.
- The **energy threshold is lowered gradually** towards full unblinding.

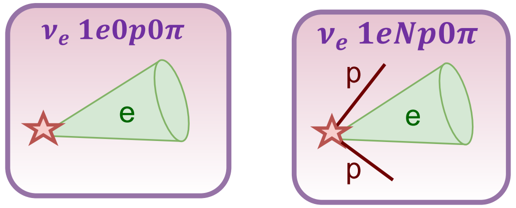


Goodness of fit test relative to constrained prediction motivated the unblinding

Blind Analysis



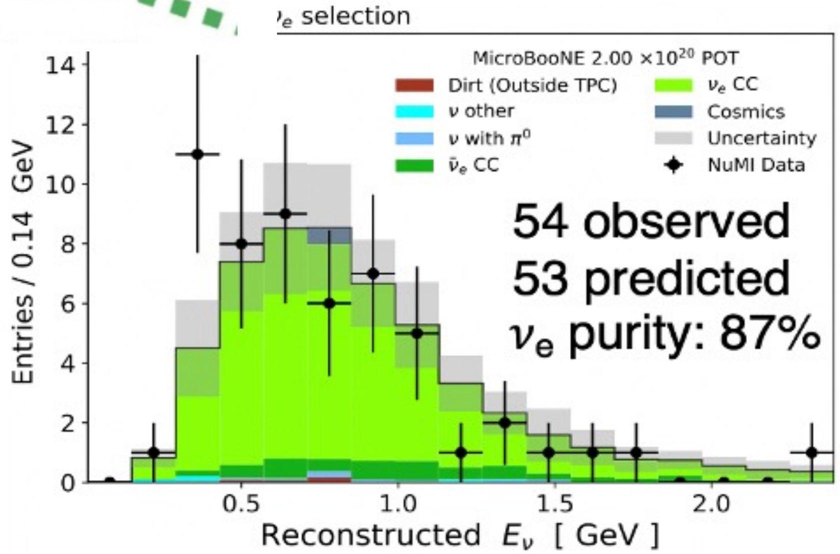


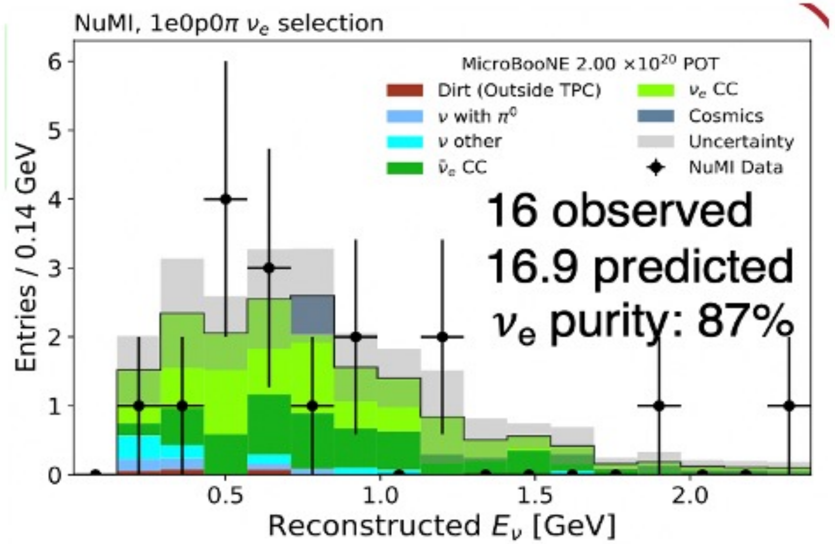


NuMI data for validation

Used for all ν_e-argon cross section measurements to date.

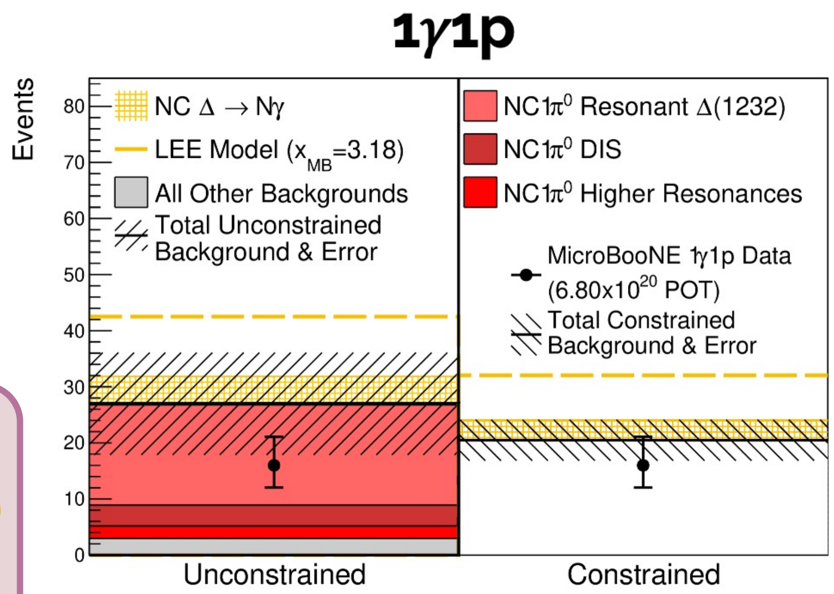
- High intrinsic ν_e relative to BNB (5% vs 0.5%)
- Selections not tuned on NuMI data: applied after frozen, before unblinding BNB data

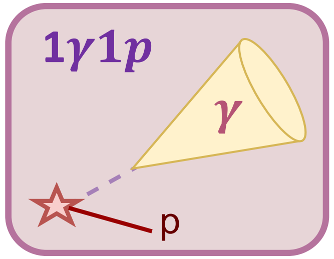




Results

Photon Results



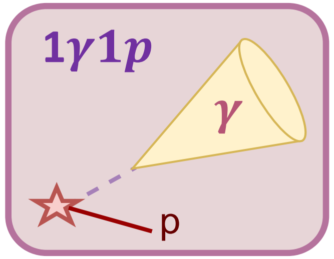


1γ1p

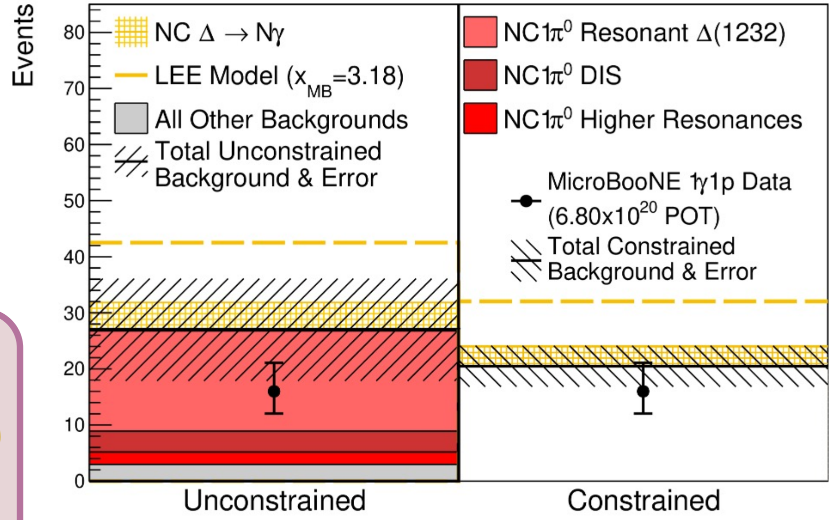
Unconstr. bkgd.	27.0 ± 8.1
Constr. bkgd.	20.5 ± 3.6
NC $\Delta \to N\gamma$	$+4.88$
LEE ($x_{\rm MB} = 3.18$)	$+15.5$

16
Data Events Observed

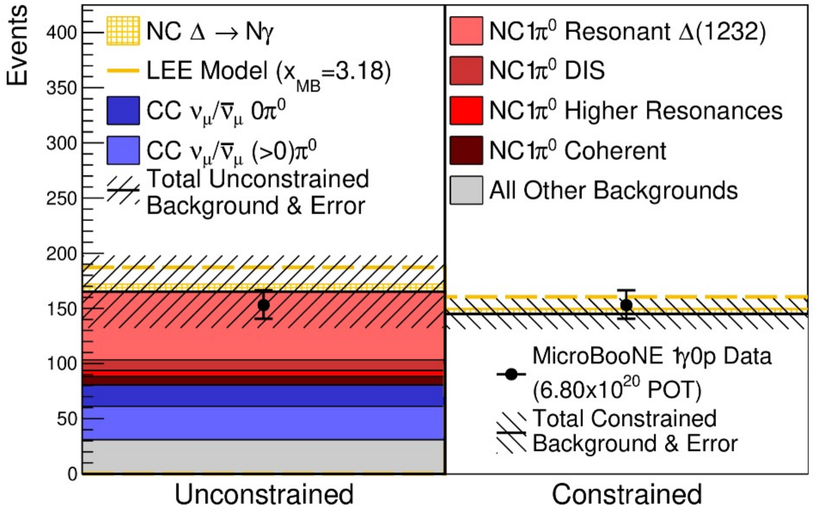
Photon Results

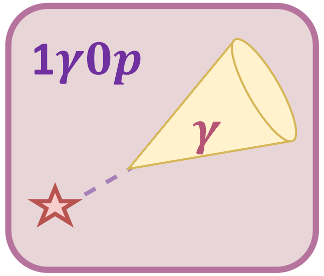


1γ1p



1γ0p





1γ1p

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

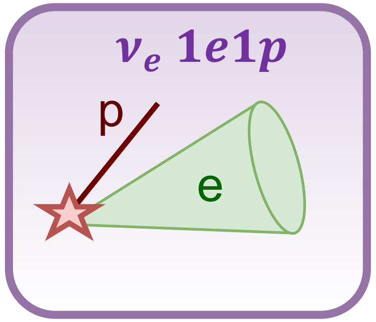
16
Data Events Observed

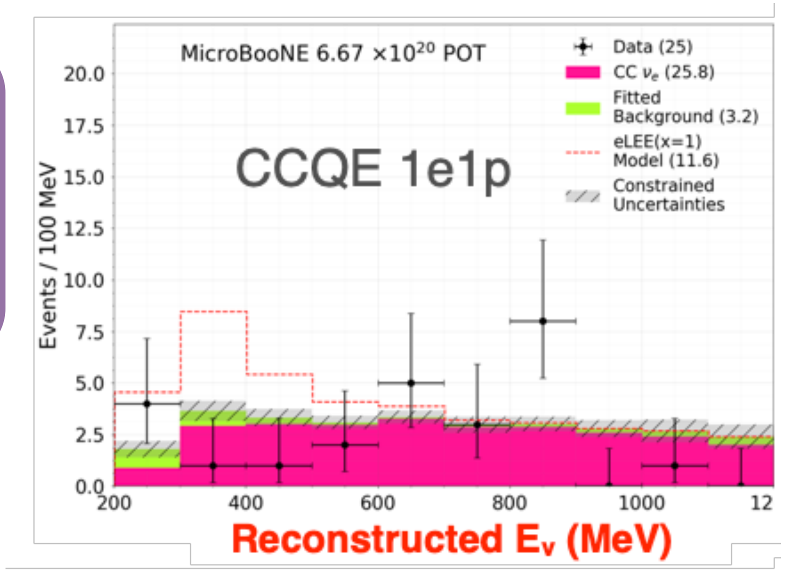
1γ0p

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

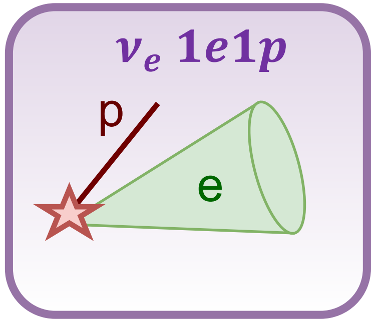
153
Data Events Observed

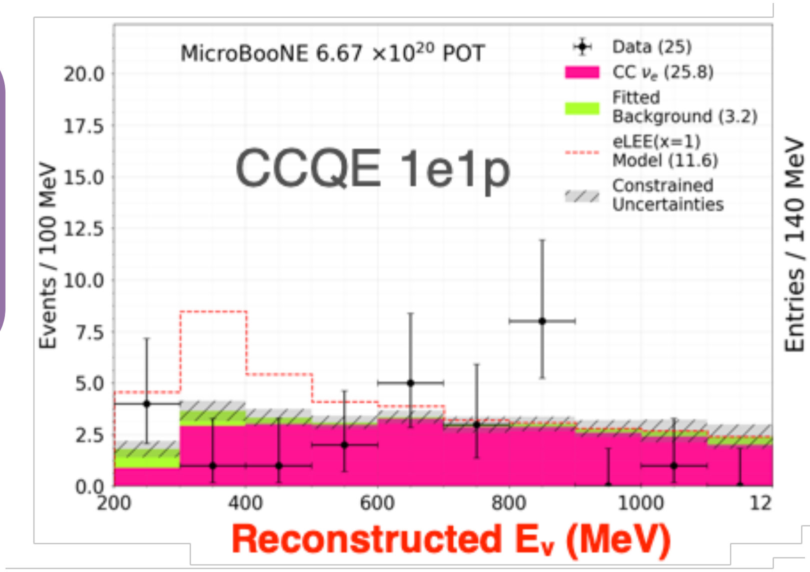
Electron Results

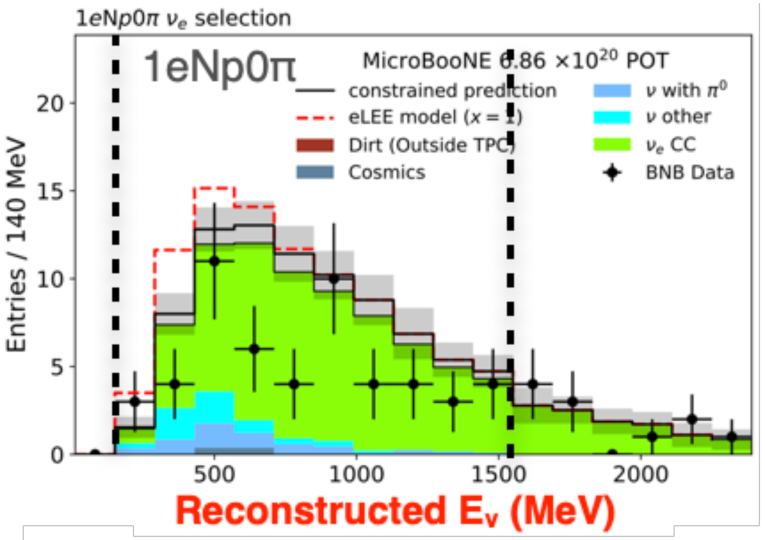


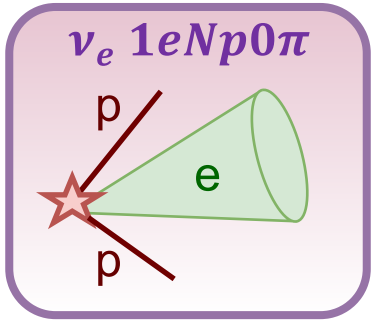


Electron Results

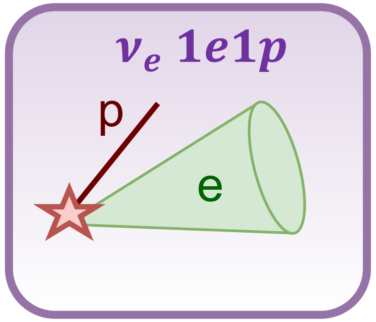


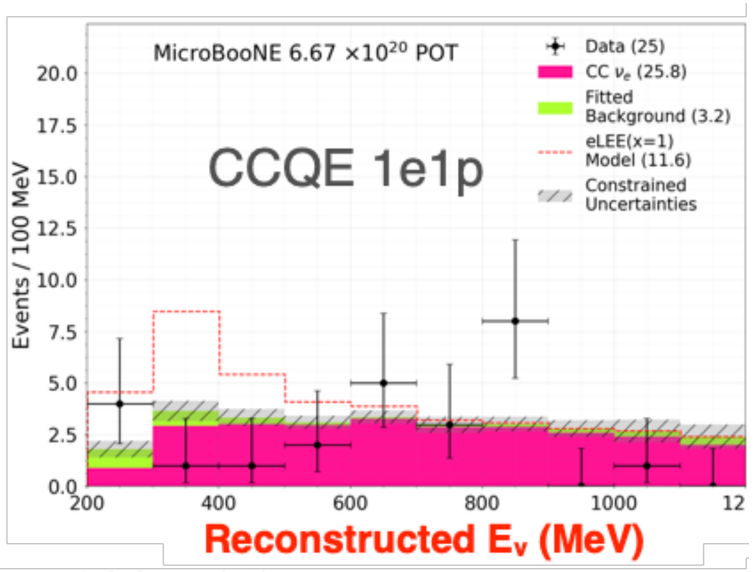


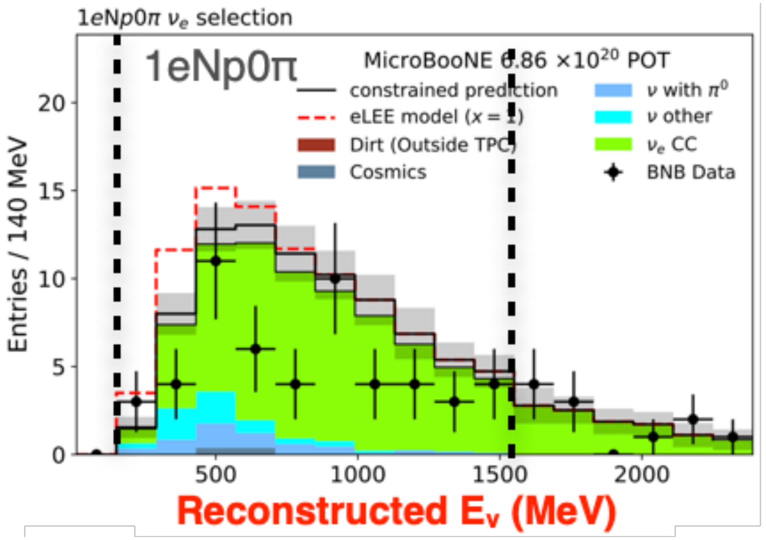


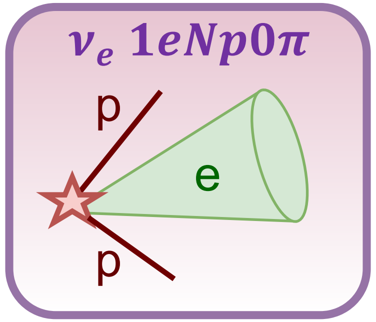


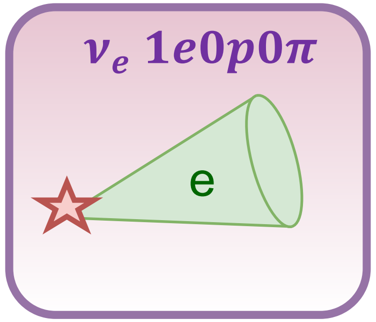
Electron Results

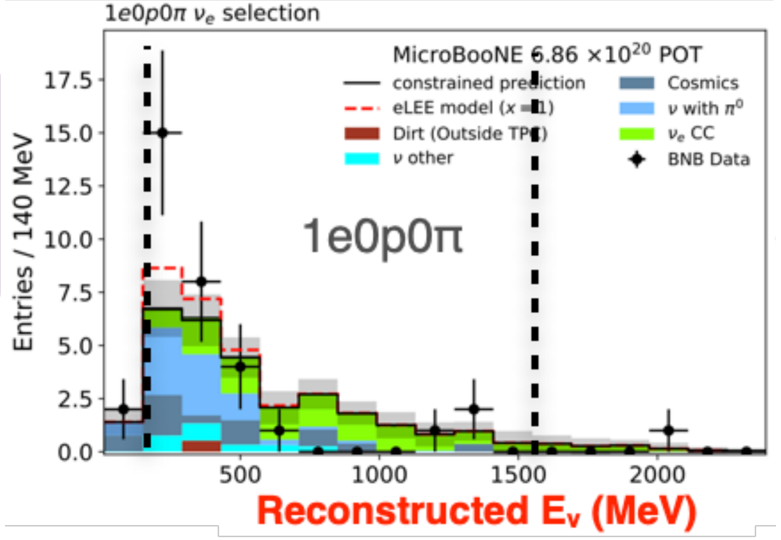




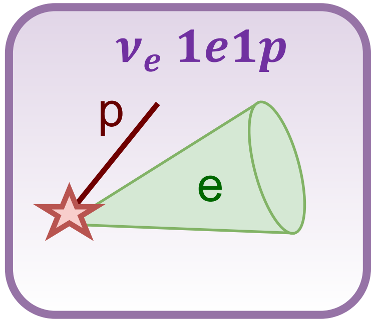


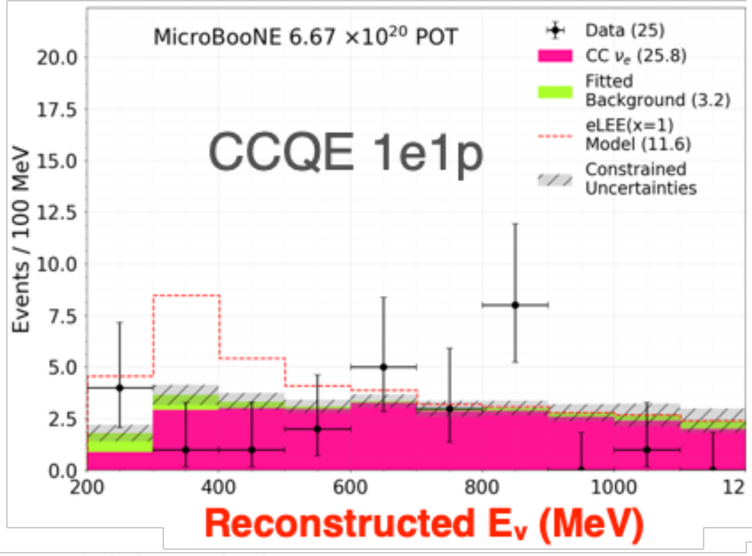


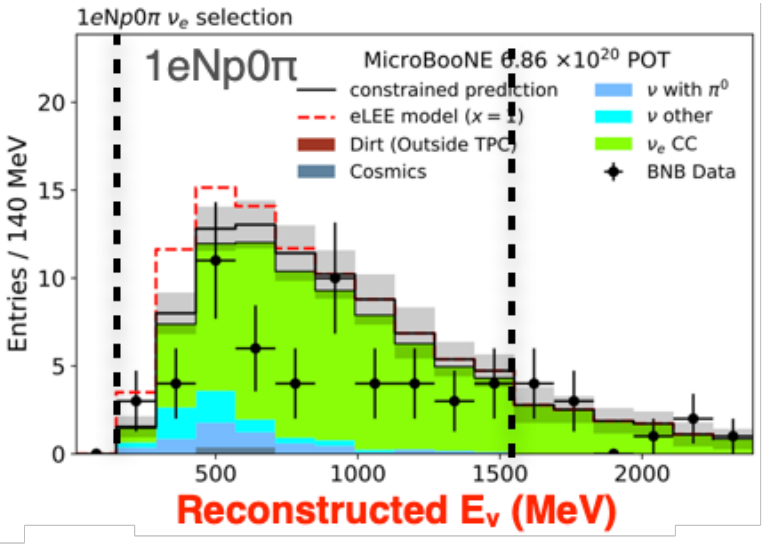


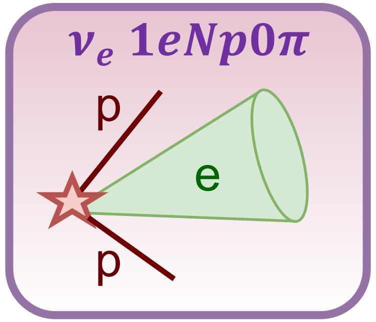


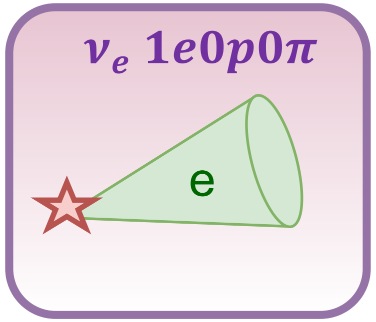
Electron Results

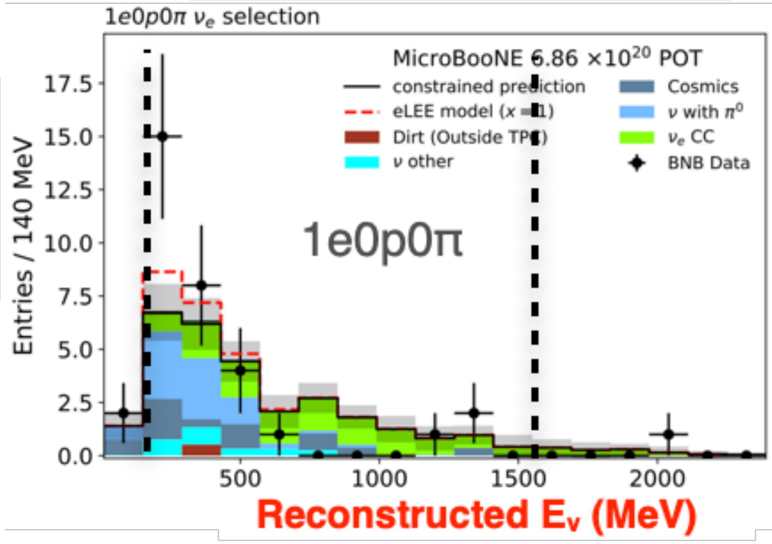


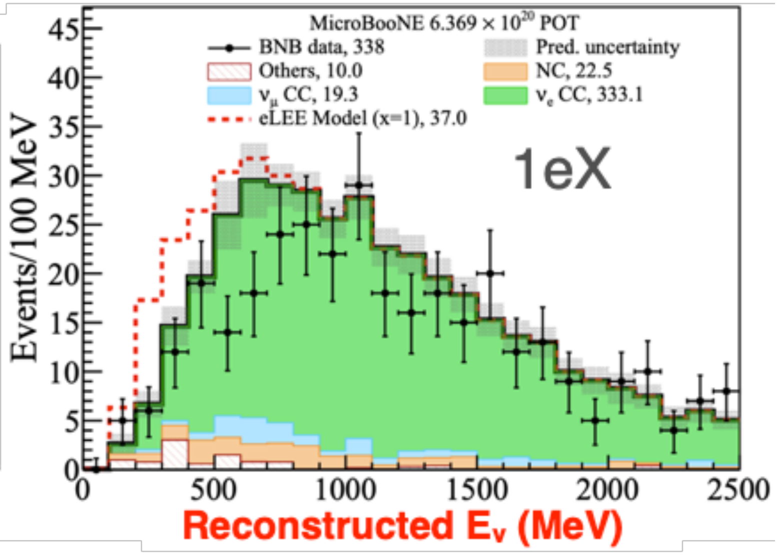


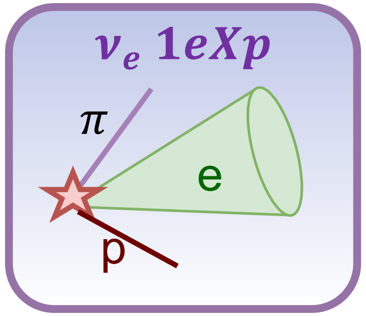






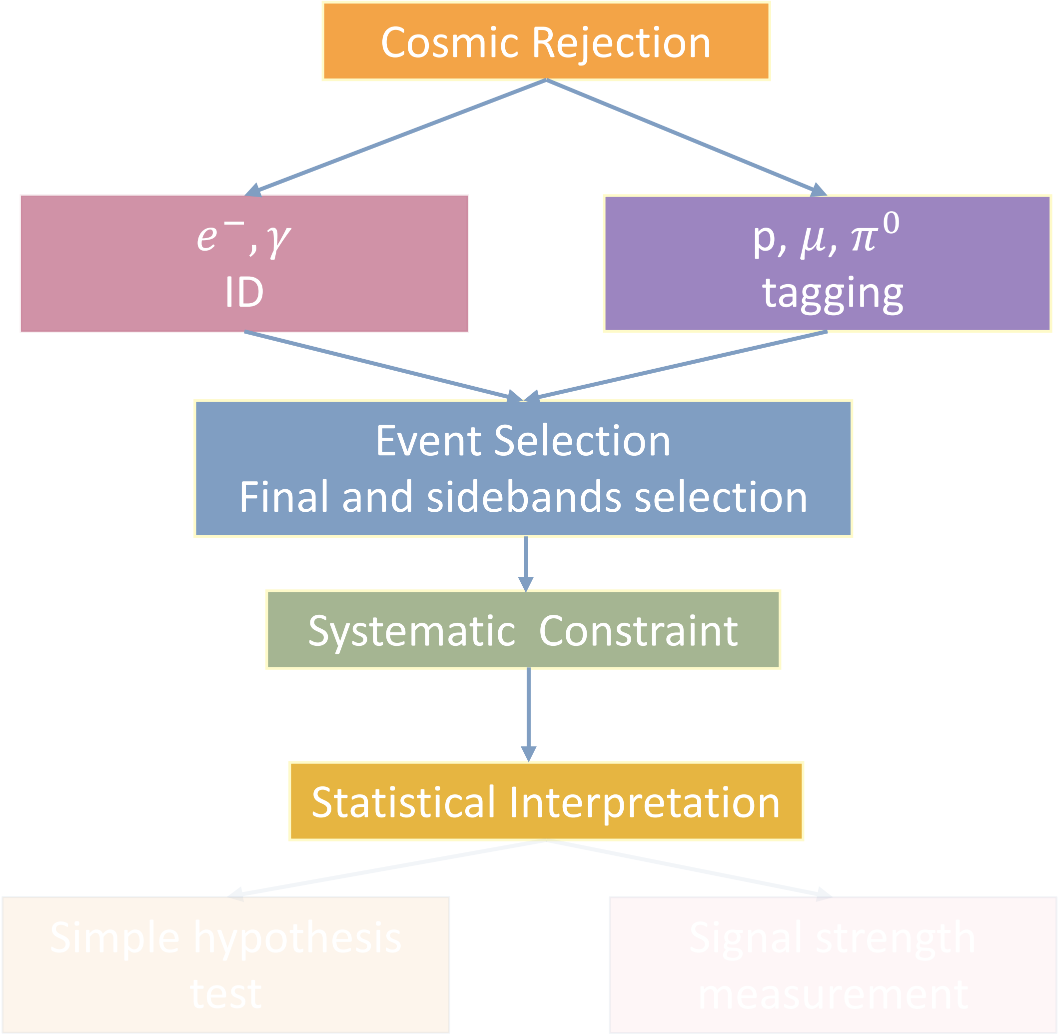




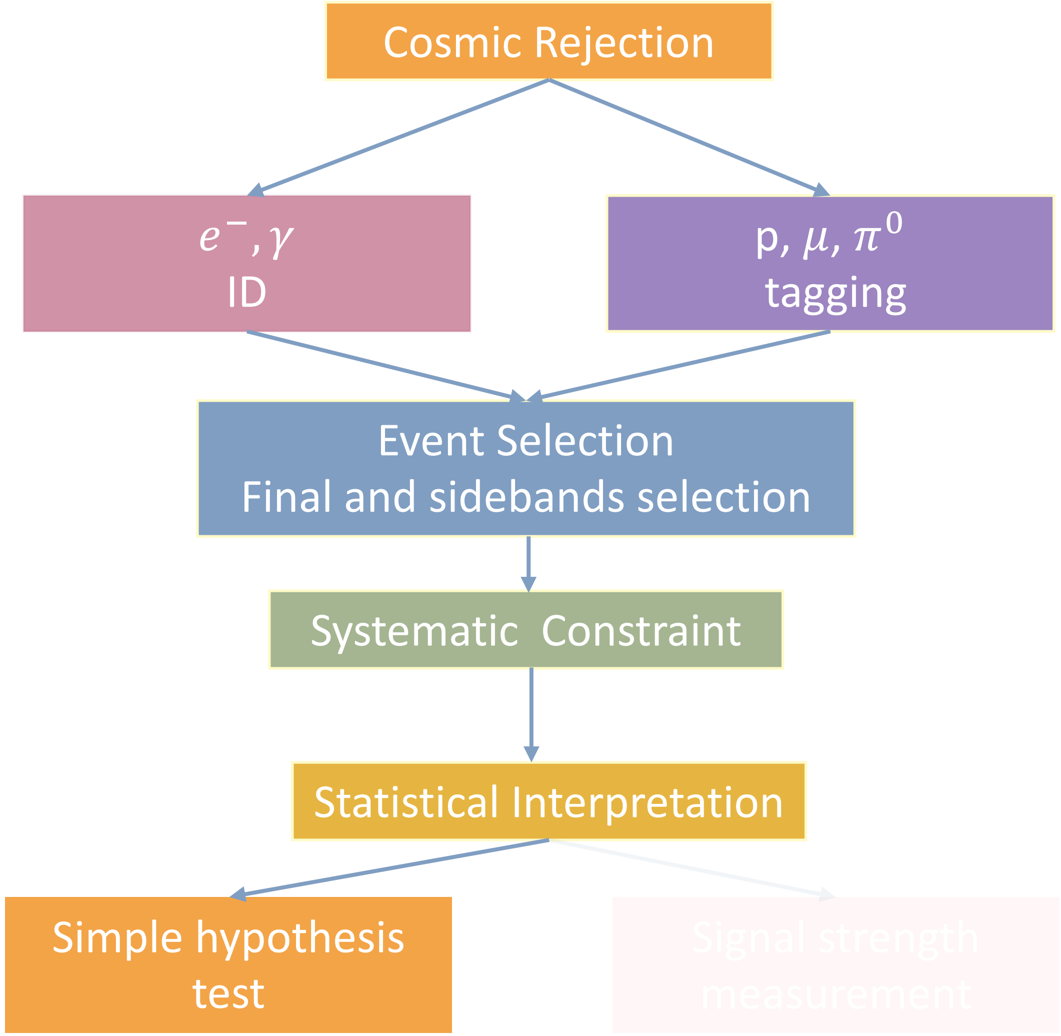


Interpretation

Common Strategy



Common Strategy

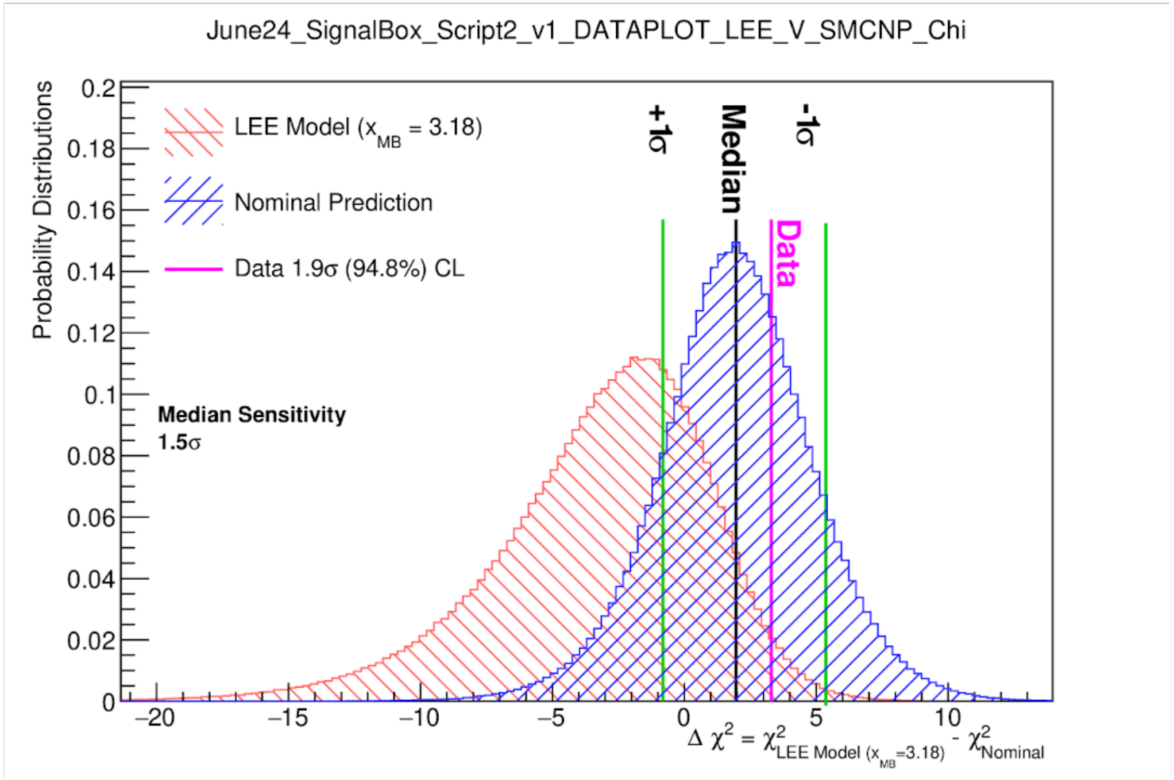


Interpretation: Simple Hypothesis Test

Probability of the data rejecting one hypothesis assuming the other is true, using a $\Delta\chi^2$ formalism.

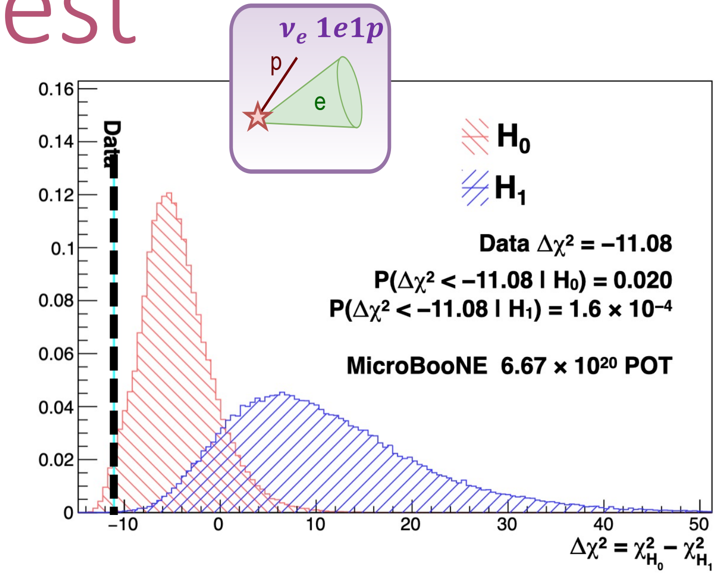
Observed data is **consistent with the nominal NC $\Delta \rightarrow \gamma$N prediction** well within expected 1σ of experiments.

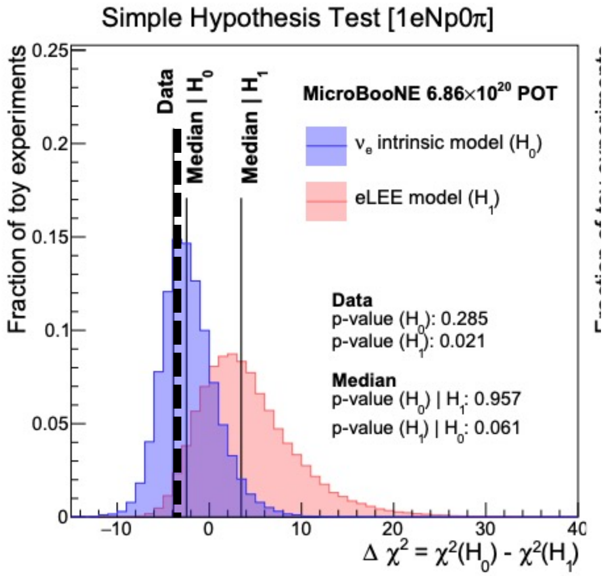
The data rejects the LEE model hypothesis in favor of the nominal prediction at 94.8% CL



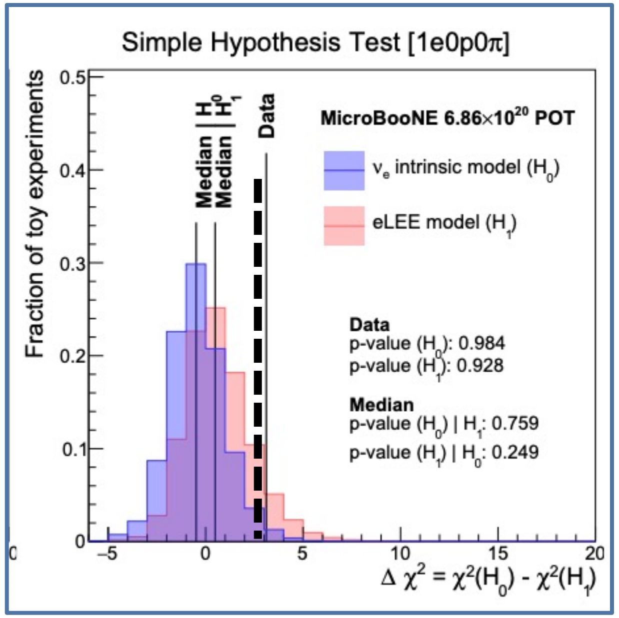
Simple Hypothesis Test

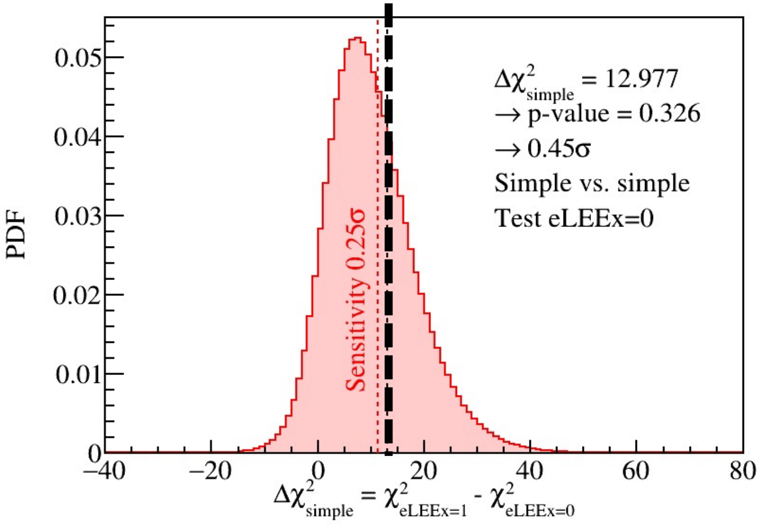
Result indicates no observation of ν_e excess in data



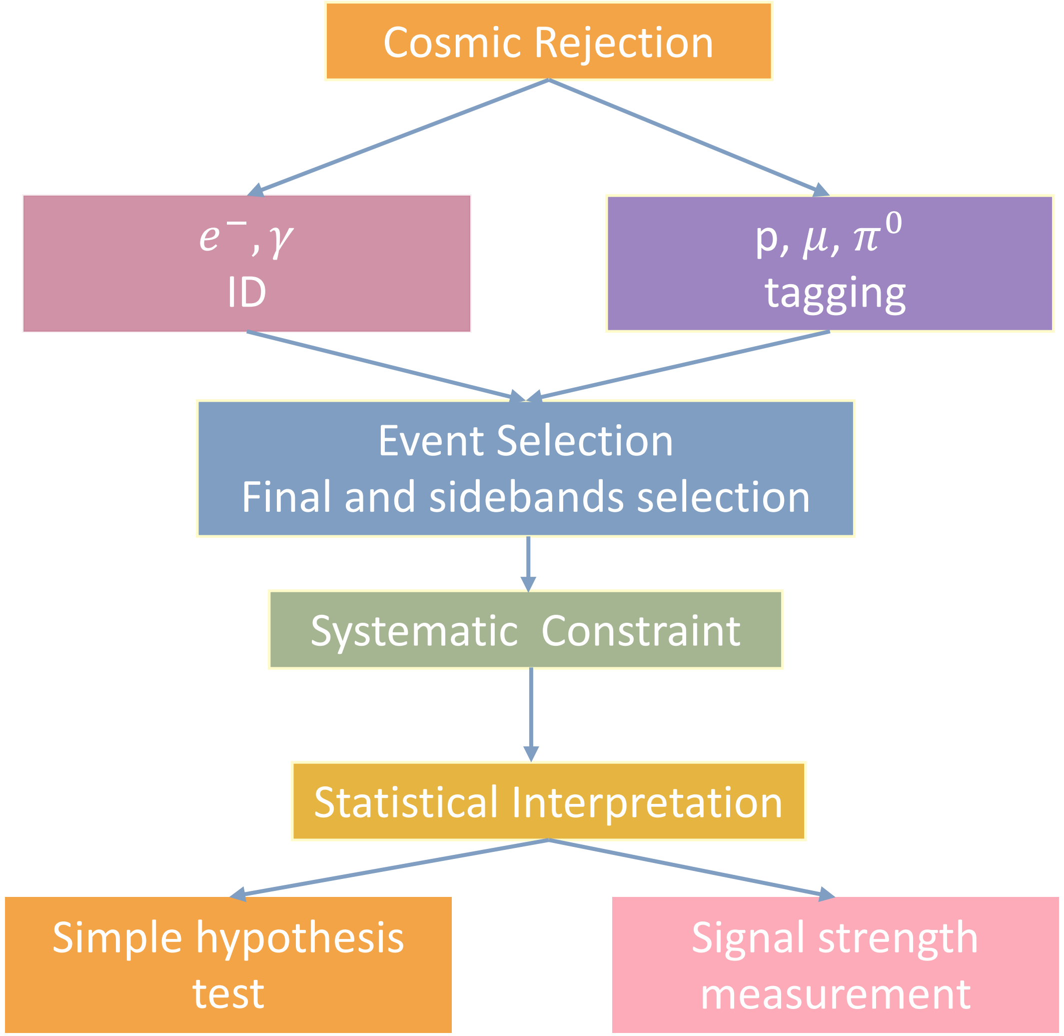


Low sensitivity, prefers eLEE model over nominal νe model





Common Strategy



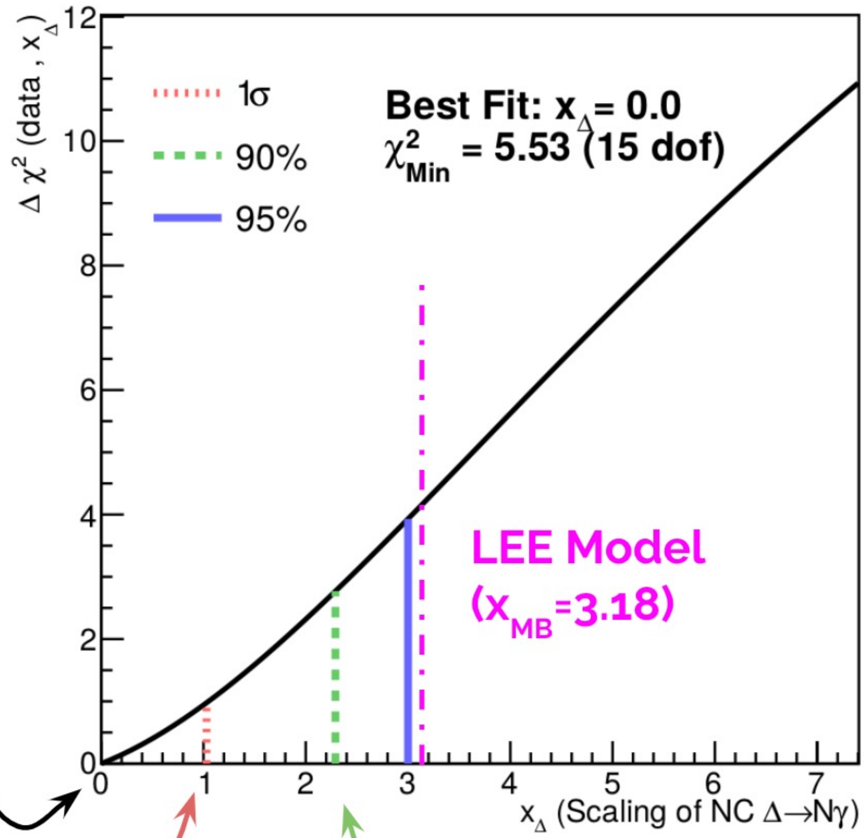
Interpretation: Signal Strength Comparisons

No evidence for an enhanced rate of single photons from NC Δ→Nγ decay above nominal GENIE expectations

x3.18 scaling disfavoured at 94.8% C.L.

One-sided bound on the normalisation of NC Δ→Nγ events of $\mathbf{x_\Delta < 2.3}$ (90% C.L.)

> 50 times better than the world's previous limit



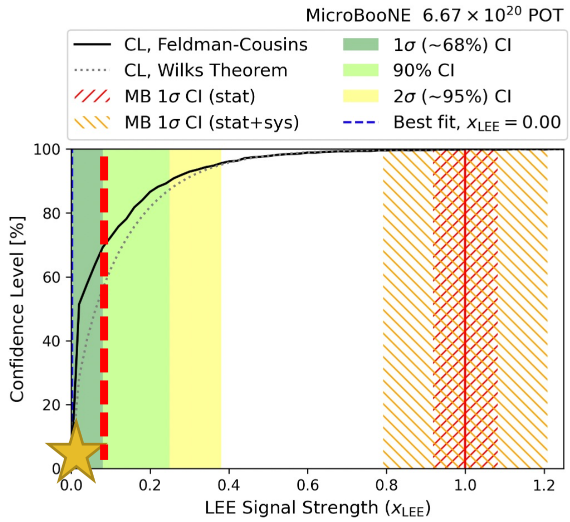
Best Fit: x_Δ = 0

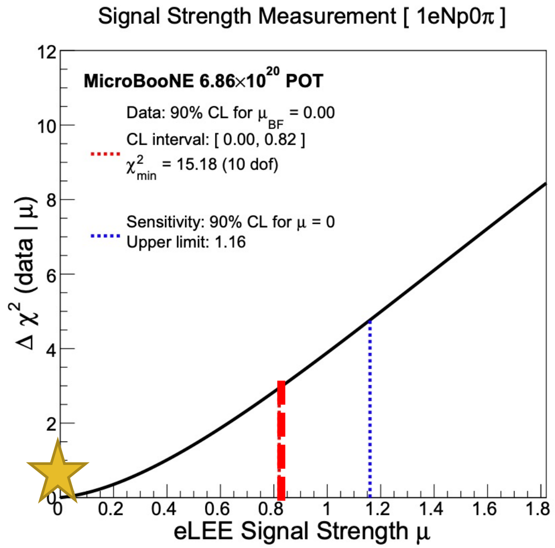
Nominal GENIE NC **Δ**→Nγ rate (x_Δ = 1) within 1σ

x_Δ **< 2.3** at the **90% CL**

Interpretation: Signal Strength Comparisons

Use Feldman-Cousins procedure to measure best fit signal strength (μ), assuming a flat scaling of the eLEE model



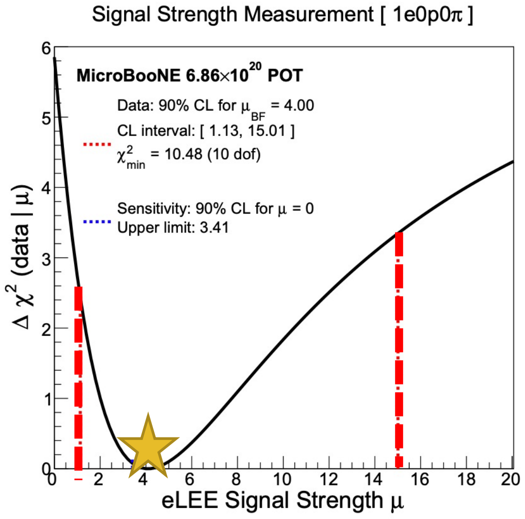


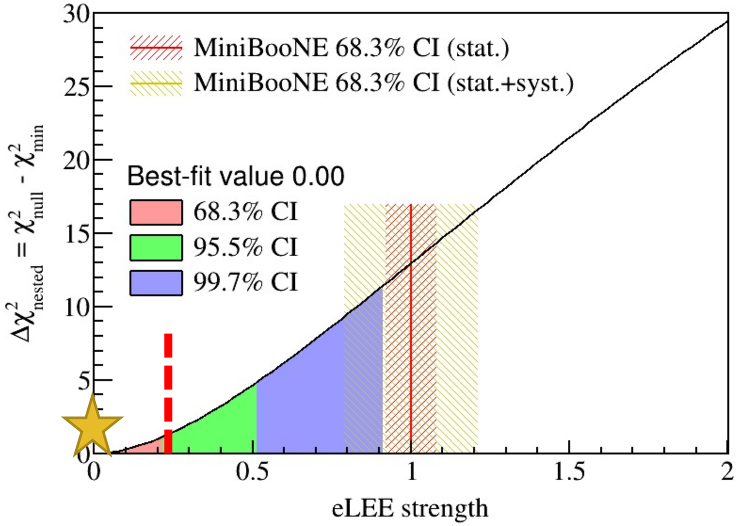
Best-fit

$1\sigma(68\%\ CL)$

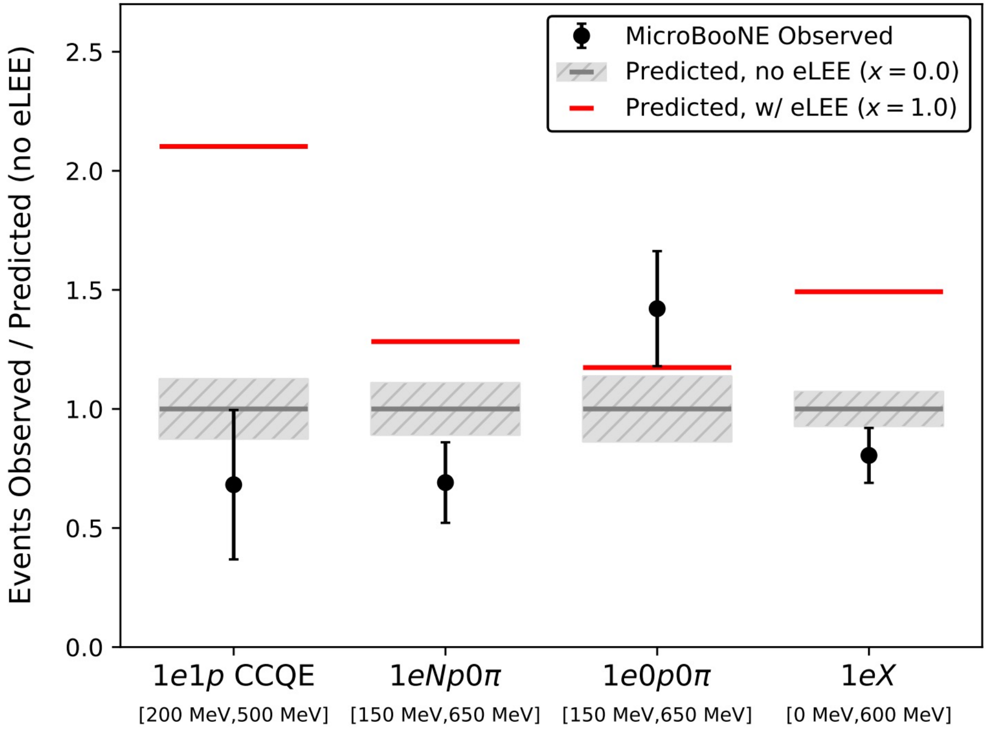
Energy-dependent scaling of ν_e beam content as in eLEE model is not favored

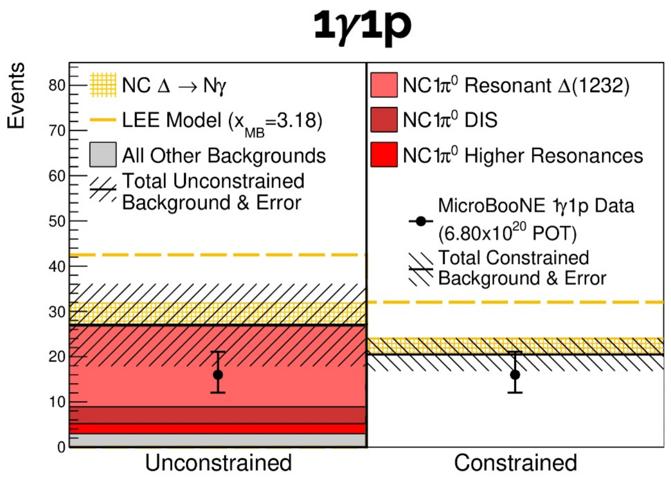
Low sensitivity, wide range of signal strength

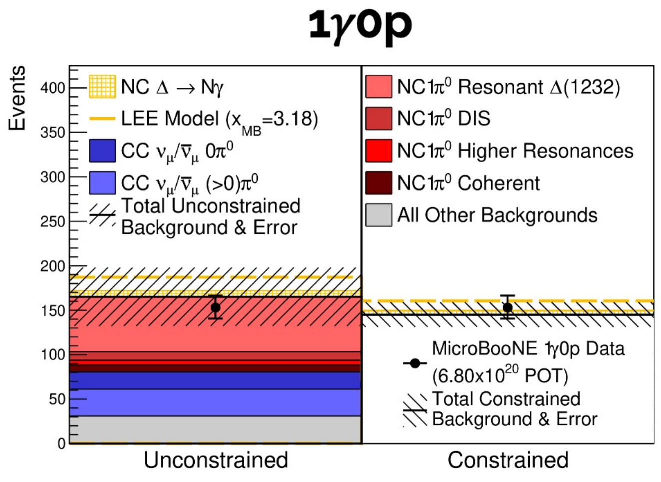




Summary of Electron and Single Photon Results







- Investigated two hypotheses to see if the MiniBooNE excess originate from of ν_e or NC $\Delta \rightarrow N\gamma$
- No evidence for excesses relative to prediction in both selection: 95% CL to 3σ

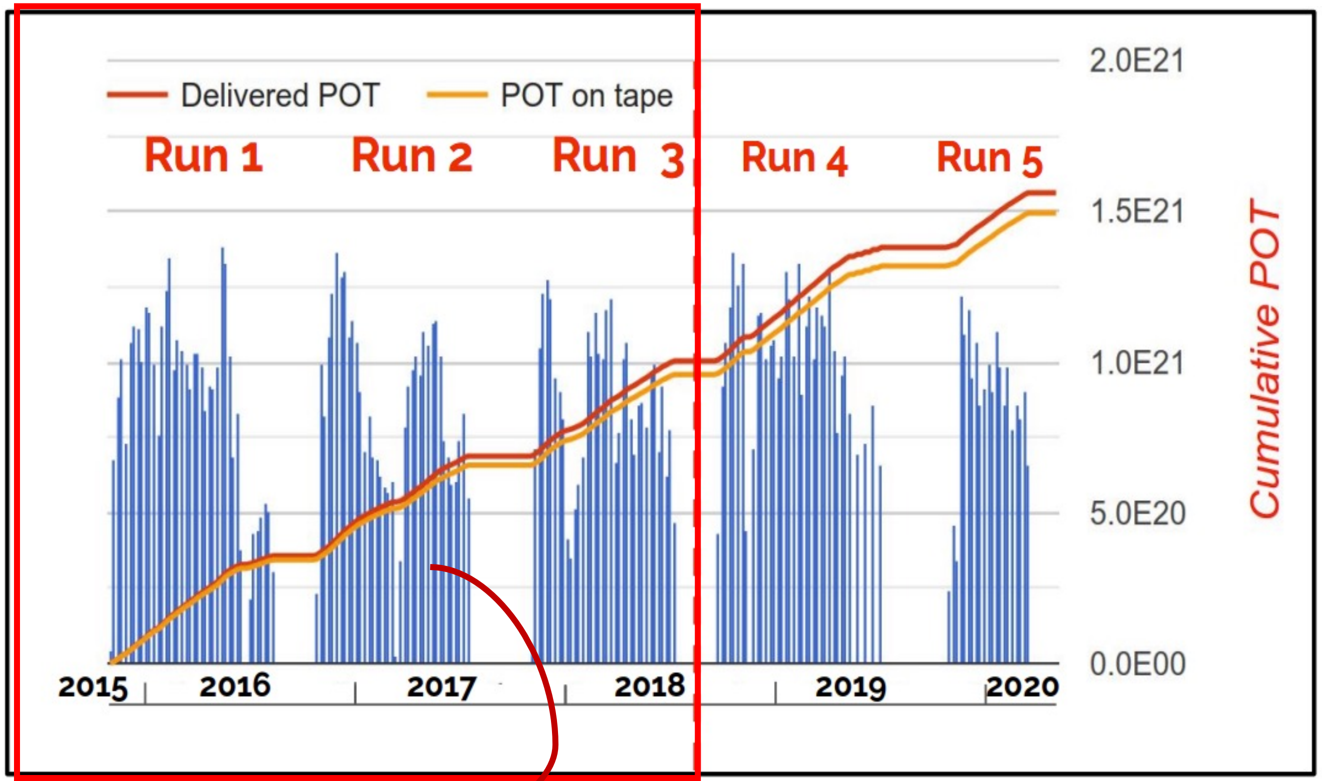
Summary of Electron and Single Photon Results

Publication References

- electron neutrino:
  - MicroBooNE collaboration, “Search for an Excess of Electron Neutrino Interactions in MicroBooNE Using **Multiple Final State Topologies**“, arXiv:2110.14054, submitted to PRL
  - MicroBooNE collaboration, “Search for an Anomalous Excess of **Inclusive** Charged Current Electron Neutrino Interactions in the MicroBooNE Experiment Using Wire-Cell Reconstruction”, arXiv:2110.13978, submitted to PRD
  - MicroBooNE collaboration, “Search for an Anomalous Excess of Charged Current Electron Neutrino Interactions **Without Pions** in the Final State with the MicroBooNE Experiment”, arXiv:2110.14065, submitted to PRD
  - MicroBooNE collaboration, “Search for an Anomalous Excess of Charged Current **Quasi-Elastic** Electron Neutrino Interactions with the MicroBooNE Experiment Using Deep-Learning-Based Reconstruction”, arXiv:2110.14080, submitted to PRD
- single photon:
  - MicroBooNE collaboration, “Search for Neutrino-Induced Neutral Current **Delta Radiative Decay** in MicroBooNE and a First Test of the MiniBooNE Low Energy Excess Under a Single Photon Hypothesis”, arXiv:2110.00409, submitted to PRL

What’s Next

More Statistics



Analyses are stats-limited. Full datasets will give fuller pictures

Data used for this analysis

More statistics to come. Increasing the statistics by 2-folds

Evolving Theory Landscape

Already started probing with first LEE results

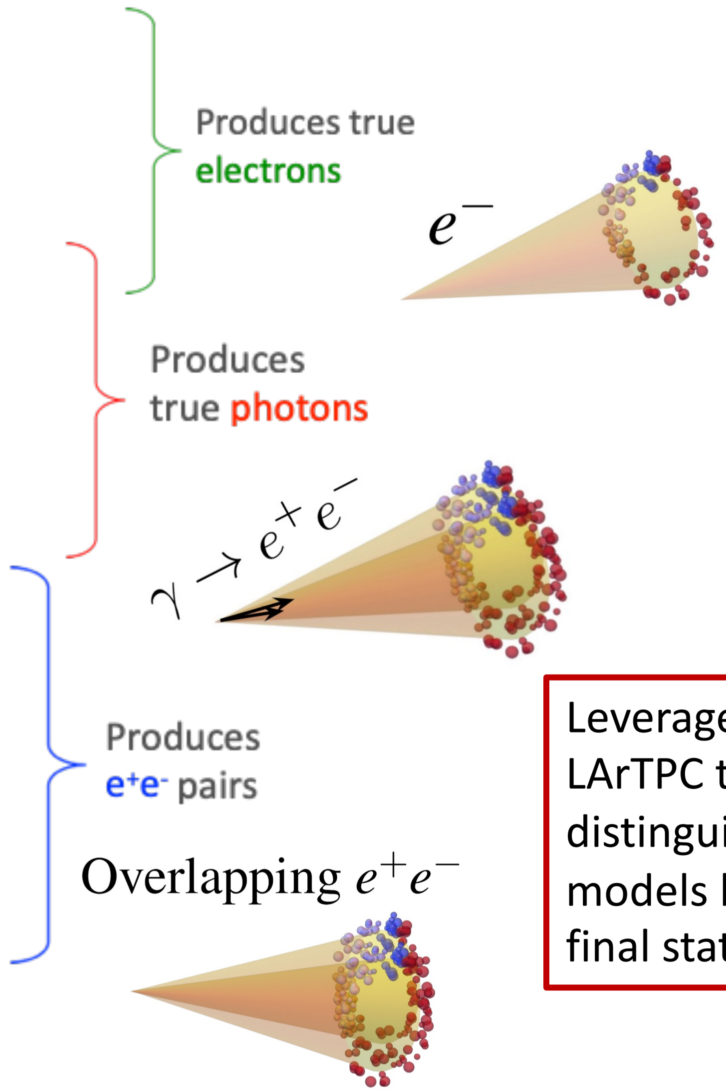
Already in the works

Models \ Reco topology	1e0p	1e1p	1eNp	1eX	e^+e^- + nothing	e^+e^-X	$1\gamma 0p$	$1\gamma 1p$	$1\gamma X$
eV Sterile ν Osc	✔	✔	✔	✔					
Mixed Osc + Sterile ν	✔ [7]	✔ [7]	✔ [7]	✔ [7]			✔ [7]		
Sterile ν Decay	✔ [13,14]	✔ [13,14]	✔ [13.14]	✔ [13,14]			✔ [4,11,12,15]	✔ [4]	✔ [4]
Dark Sector & Z' *	✔ [2,3]				✔ [2,3]	✔ [2,3]	✔ [1,2,3]	✔ [1,2,3]	✔ [1,2,3]
More complex higgs *					✔ [10]	✔ [10]	✔ [6,10]	✔ [6,10]	✔ [6,10]
Axion-like particle *					✔ [8]		✔ [8]		
Res matter effects	✔ [5]	✔ [5]	✔ [5]	✔ [5]					
SM γ production							✔	✔	✔

*Requires heavy sterile/other new particles also

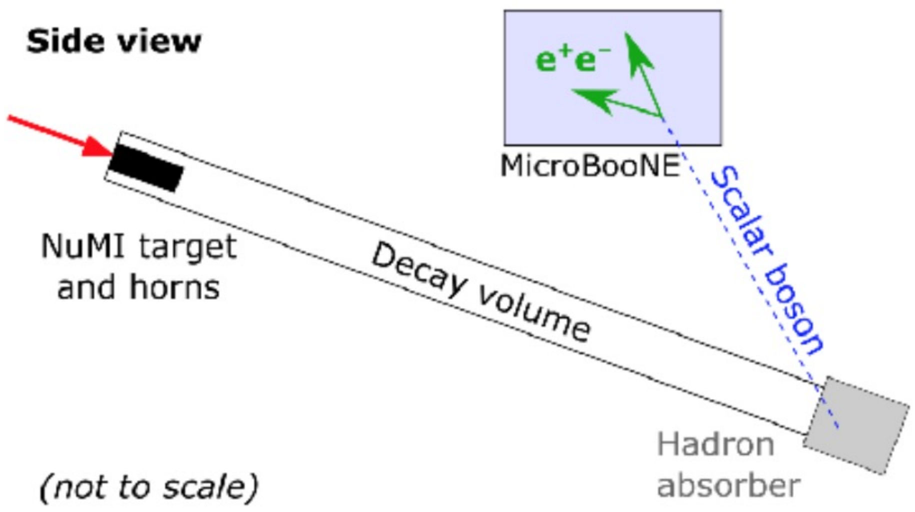
Evolving Theory Landscape

- Decay of O(keV) Sterile Neutrinos to active neutrinos
  - [13] Dentler, Esteban, Kopp, Machado Phys. Rev. D 101, 115013 (2020)
  - [14] de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141
- New resonance matter effects
  - [5] Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)
- Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay
  - [7] Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470
- Decay of heavy sterile neutrinos produced in beam
  - [4] Gninenko, Phys.Rev.D83:015015,2011
  - [12] Alvarez-Ruso, Saul-Sala, Phys. Rev. D 101, 075045 (2020)
  - [15] Magill, Plestid, Pospelov, Tsai Phys. Rev. D 98, 115015 (2018)
  - [11] Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)
- Decay of upscattered heavy sterile neutrinos or new scalars mediated by Z' or more complex higgs sectors
  - [1] Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)
  - [2] Abdullahi, Hostert, Pascoli, Phys.Lett.B 820 (2021) 136531
  - [3] Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)
  - [10] Dutta, Ghosh, Li, PRD 102, 055017 (2020)
  - [6] Abdallah, Gandhi, Roy, Phys. Rev. D 104, 055028 (2021)
- Decay of axion-like particles
  - [8] Chang, Chen, Ho, Tseng, Phys. Rev. D 104, 015030 (2021)
- A model-independent approach to any new particle
  - [9] Brdar, Fischer, Smirnov, PRD 103, 075008 (2021)

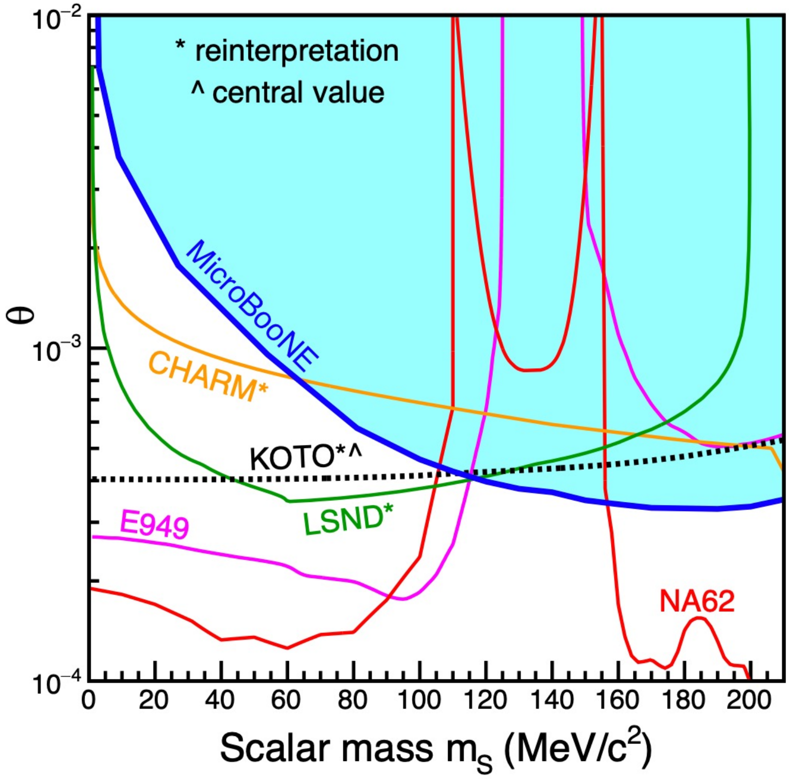


Leverage the power of LArTPC technology to distinguish between models based on exclusive final state topologies!

MicroBooNE Higgs Portal Scalar Search



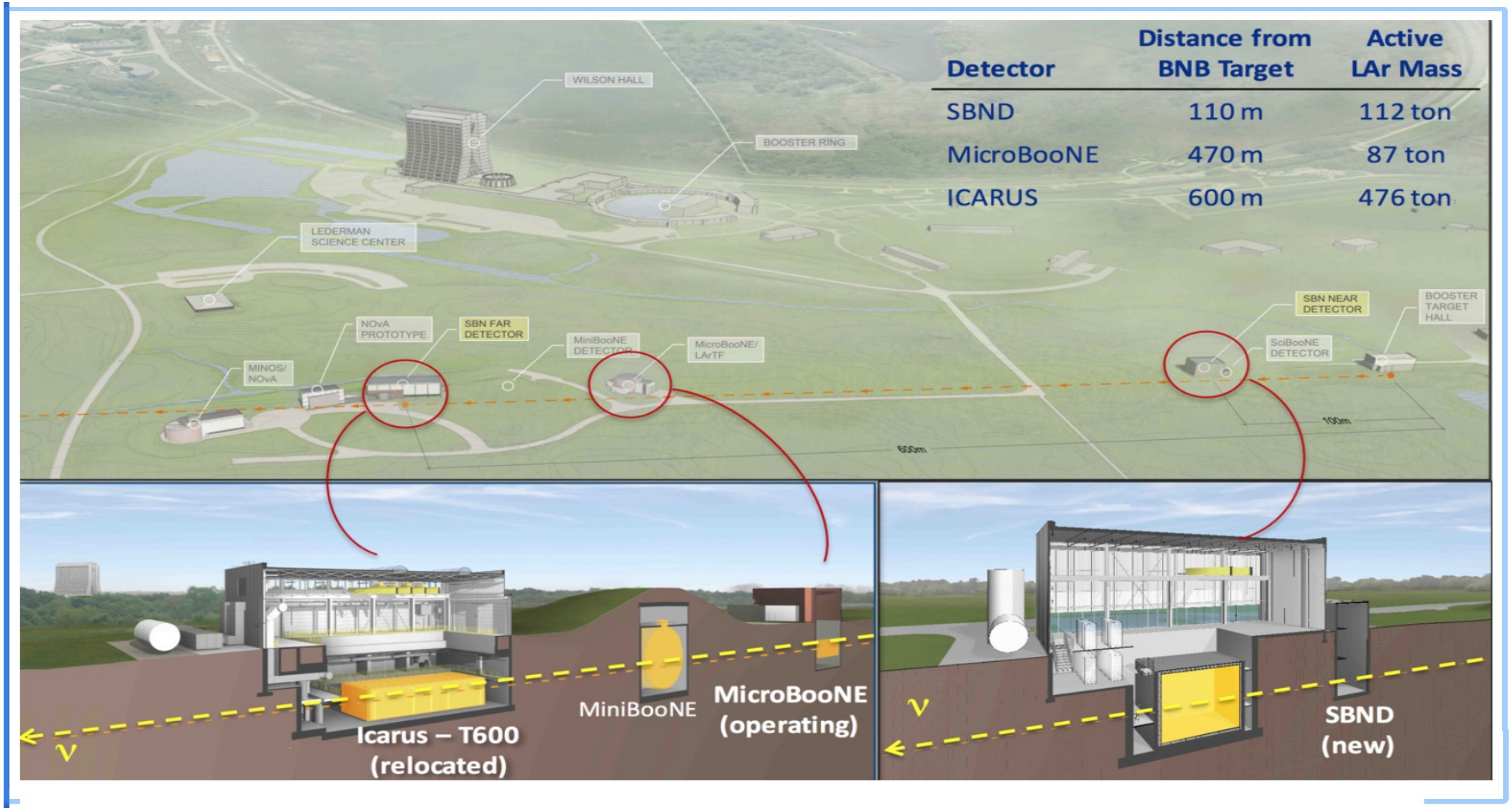
- Search for **e+e- decays** from scalars coming from NuMI hadron absorber
- 1 event observed → 95% C.L. excludes KOTO central value



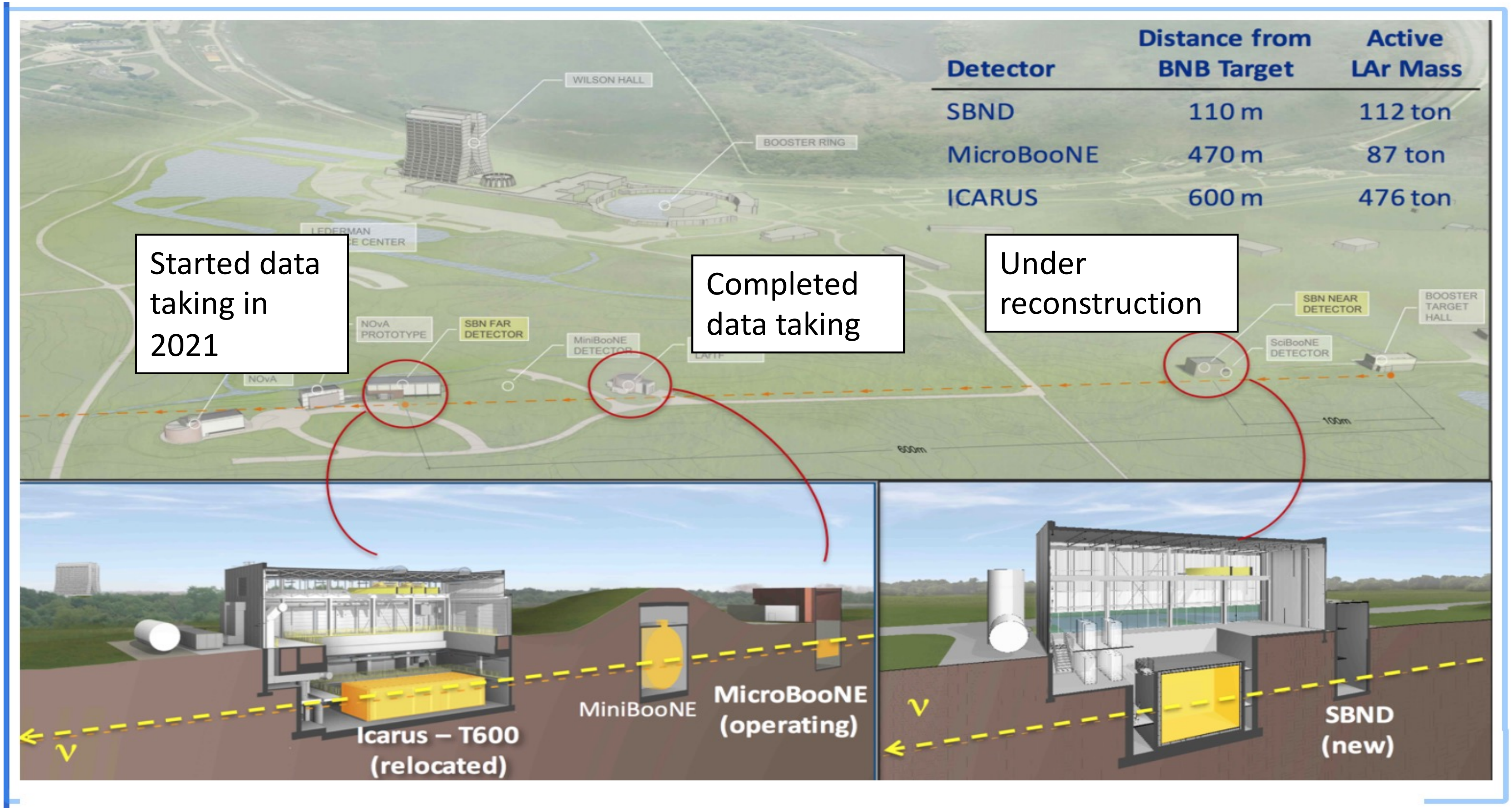
PhysRevLett.127.151803

Search for a Higgs Portal Scalar Decaying to Electron-Positron Pairs in the MicroBooNE Detector

SBN Program: Definitive Test of Short-Baseline Oscillations



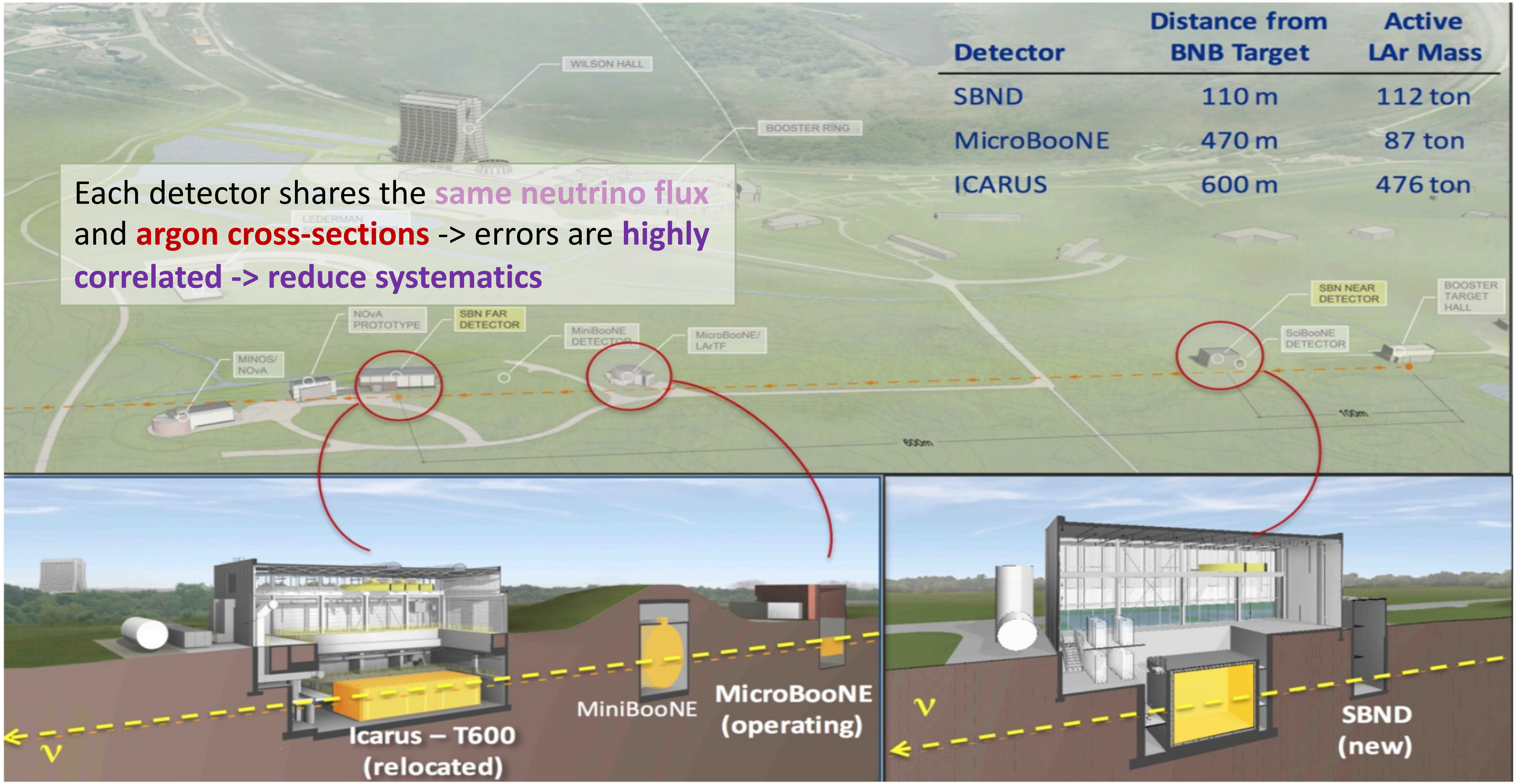
SBN Program: Definitive Test of Short-Baseline Oscillations



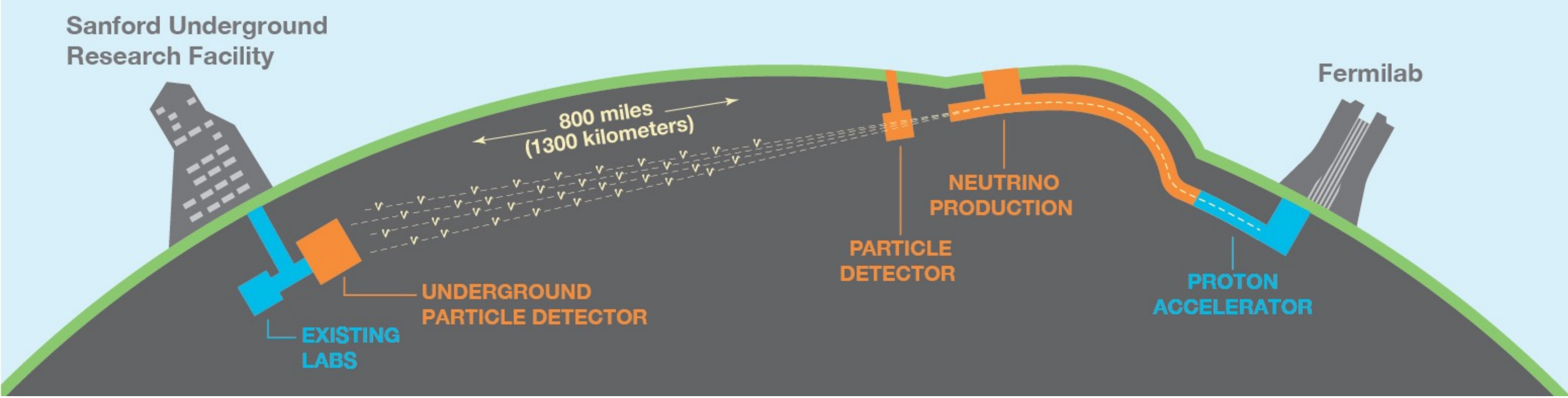
SBN Program: Definitive Test of Short-Baseline Oscillations

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

Each detector shares the same neutrino flux and argon cross-sections -> errors are highly correlated -> reduce systematics



Onwards to DUNE



- MicroBooNE demonstrated the power of LArTPC technology for precision neutrino analyses and rare signal searches
    - Performed end-to-end excess searches, cross-section measurements, BSM searches
- Lay out the foundation for precision oscillation measurements and other searches at DUNE through physics measurements and detector R&D.

Conclusion

- MicroBooNE has concluded its first search into the long-standing MiniBooNE LEE puzzle by searching for excesses in electron-neutrino interactions and $\Delta \rightarrow N\gamma$ single photon production.
- MicroBooNE's investigation of the MiniBooNE anomaly shows no evidence for anomaly in electron or $\Delta \rightarrow N\gamma$ single photon samples
- MicroBooNE has demonstrated the excellent power of LArTPCs as the tool for precision measurement
    - Pioneering high statistics ν-Ar cross-sections measurements, and BSM searches
    - Published detailed detector performance results to be used by new and upcoming LArTPCs, such as DUNE and SBN program
- More statistics to come and more analyses planned for probing into different channels and more BSM searches

Thank You!