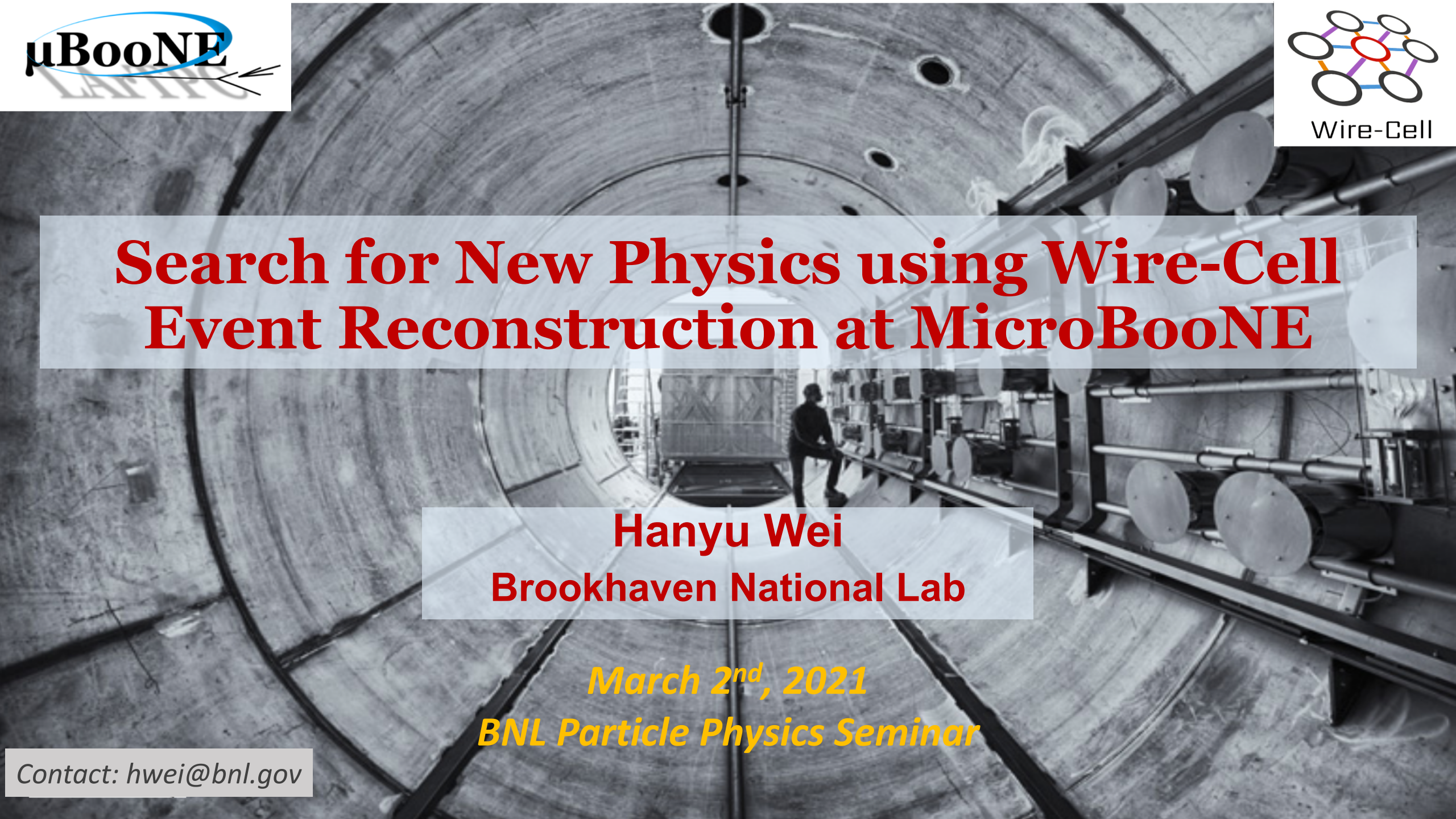


Search for New Physics using Wire-Cell Event Reconstruction at MicroBooNE

Hanyu Wei

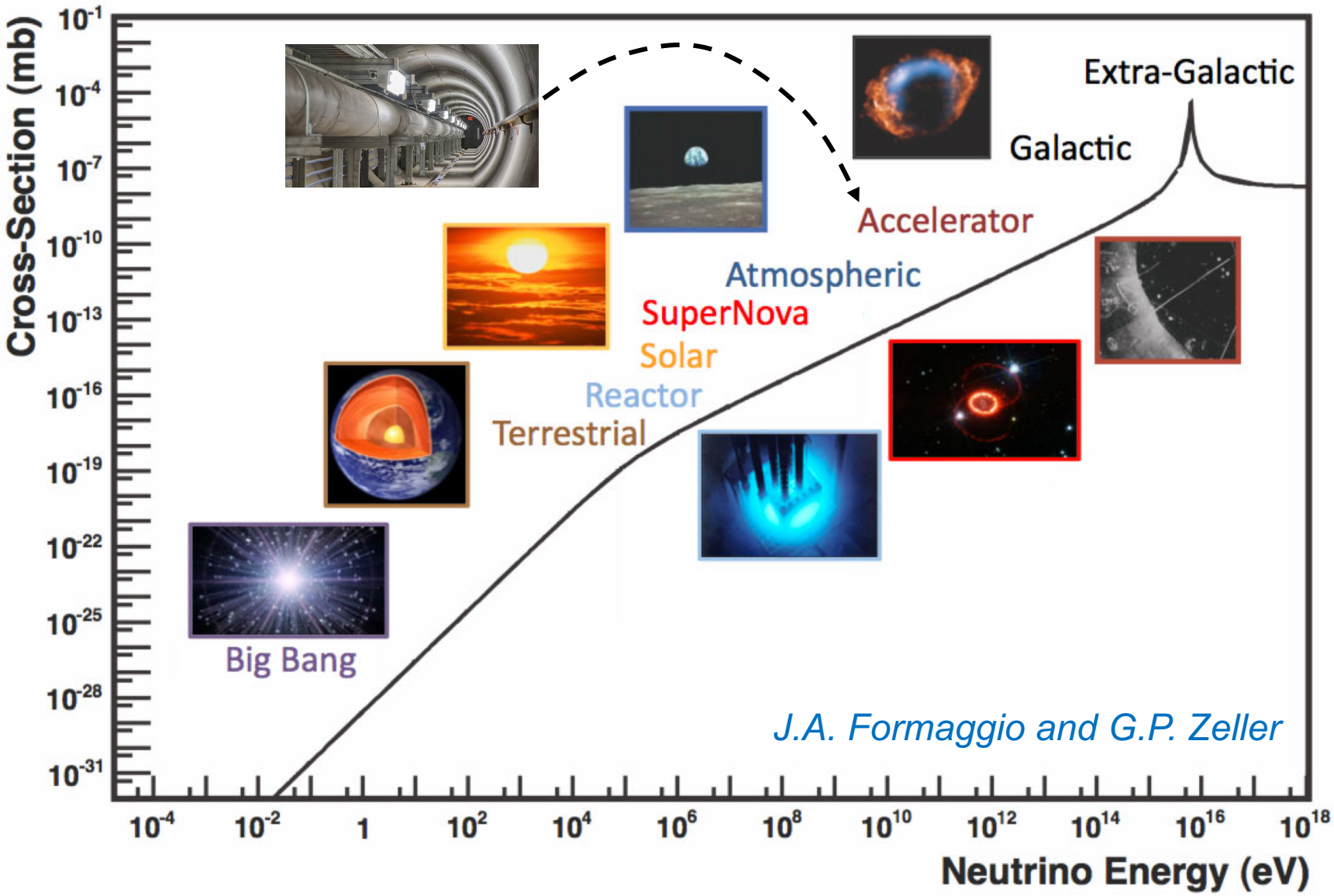
Brookhaven National Lab

March 2nd, 2021

BNL Particle Physics Seminar

Contact: hwei@bnl.gov

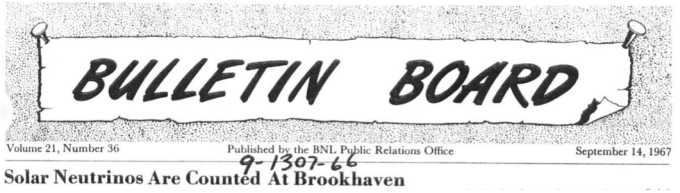
Neutrino Sources and Enriched Physics



Elusive Neutrinos



The Homestake ^{37}Cl (Chlorine) experiment
100k gallon, 4850 feet underground



BULLETIN BOARD

Volume 21, Number 36 Published by the BNL Public Relations Office September 14, 1967

9-1307-66

Solar Neutrinos Are Counted At Brookhaven



In 1967, **R. Davis** (BNL) made the first measurement of **solar neutrinos** at Homestake.
(2002 Nobel)

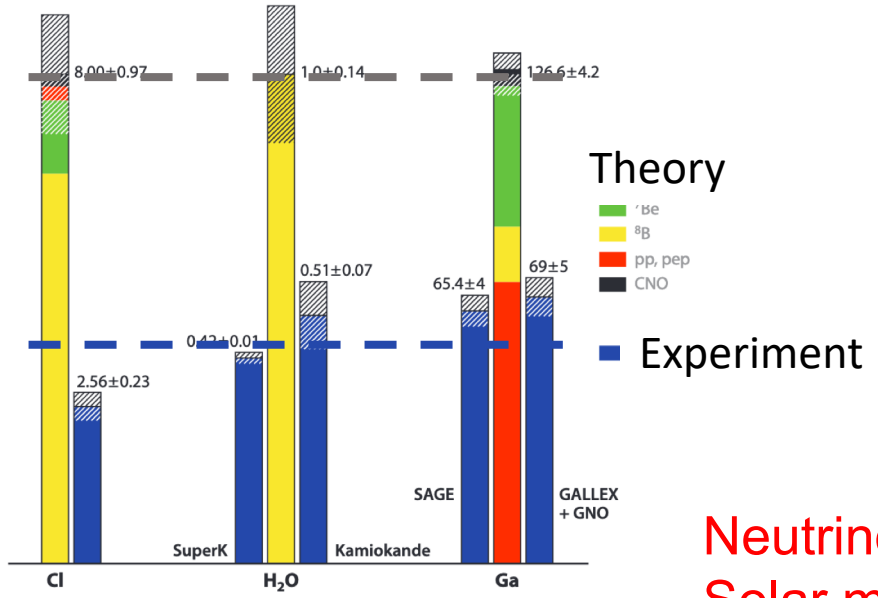
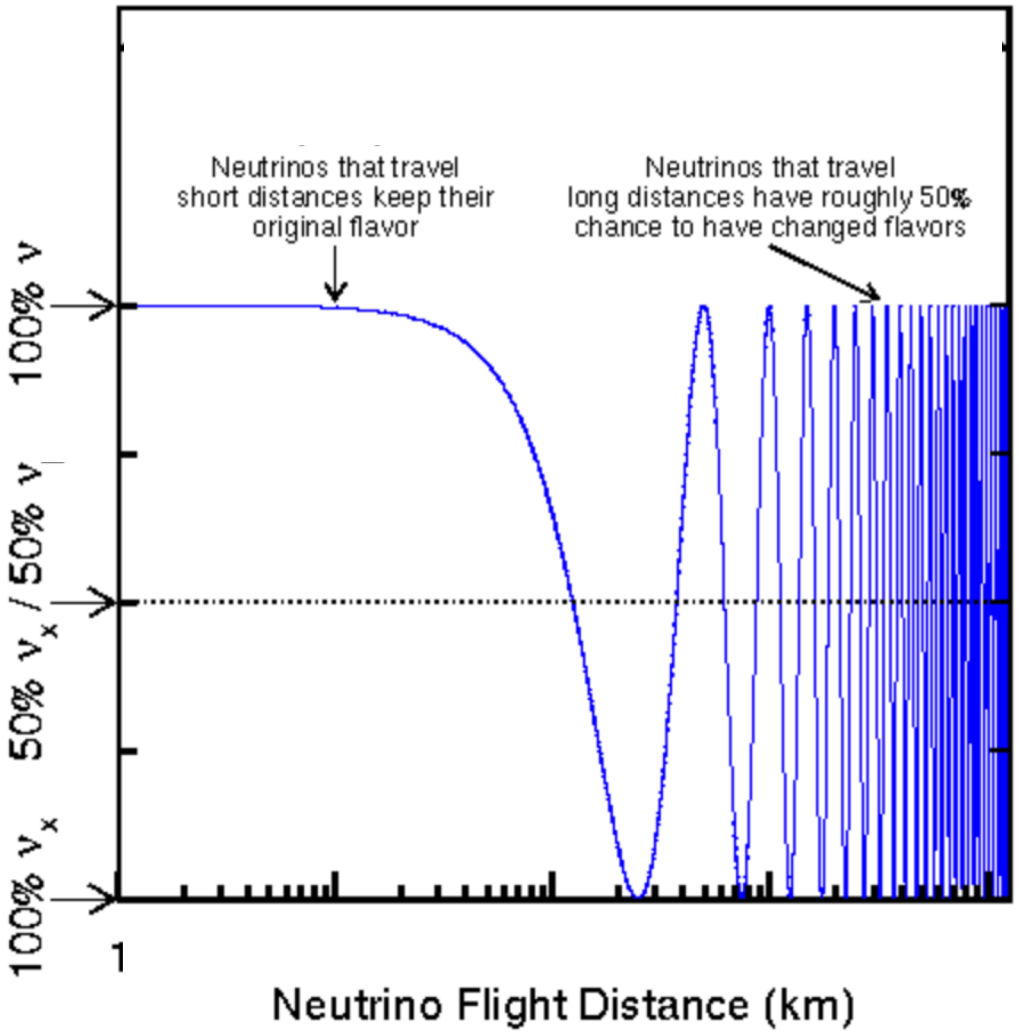


Fig. 4, Annu. Rev. Astron. Astrophys. 2013. 51:21–61

Neutrino missing?
Solar model?

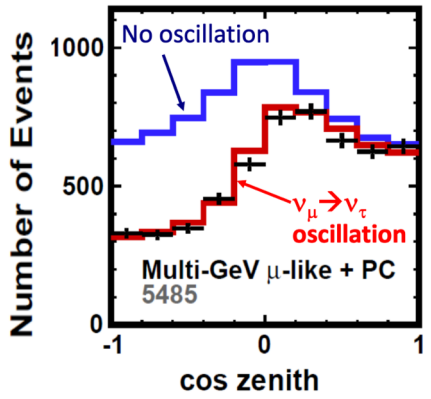
Neutrino Oscillation

In response to the solar neutrino deficit, back to a phenomenon proposed by Bruno Pontecorvo in 1957



Neutrinos convert into other types of neutrinos.

solar neutrino oscillation
+
atmospheric neutrino oscillation



The Nobel Prize in Physics 2015



© Nobel Media AB. Photo: A. Mahmoud

Takaaki Kajita

SuperK experiment



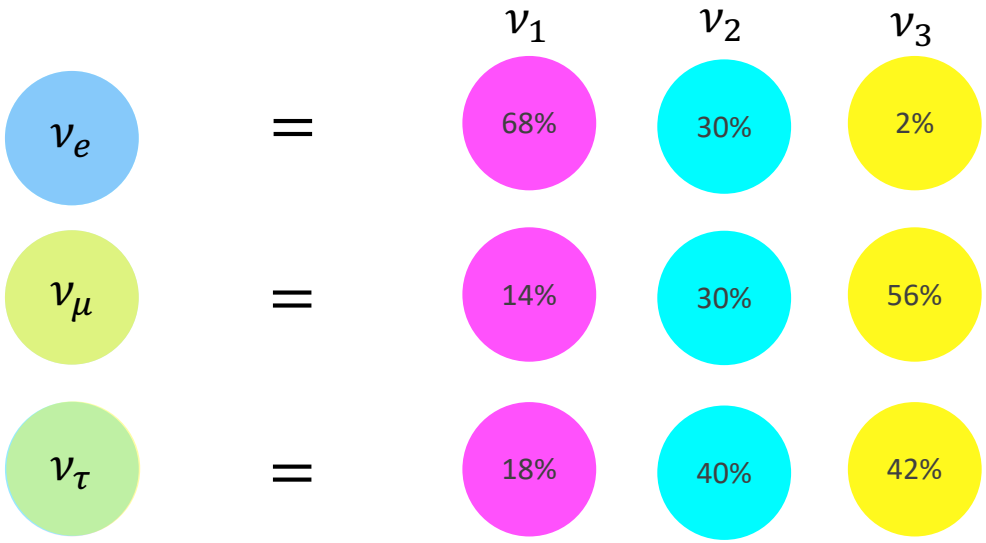
© Nobel Media AB. Photo: A. Mahmoud

Arthur B. McDonald

SNO experiment

Neutrino Mixing

Neutrino flavor = **Neutrino Mass Eigenstates**



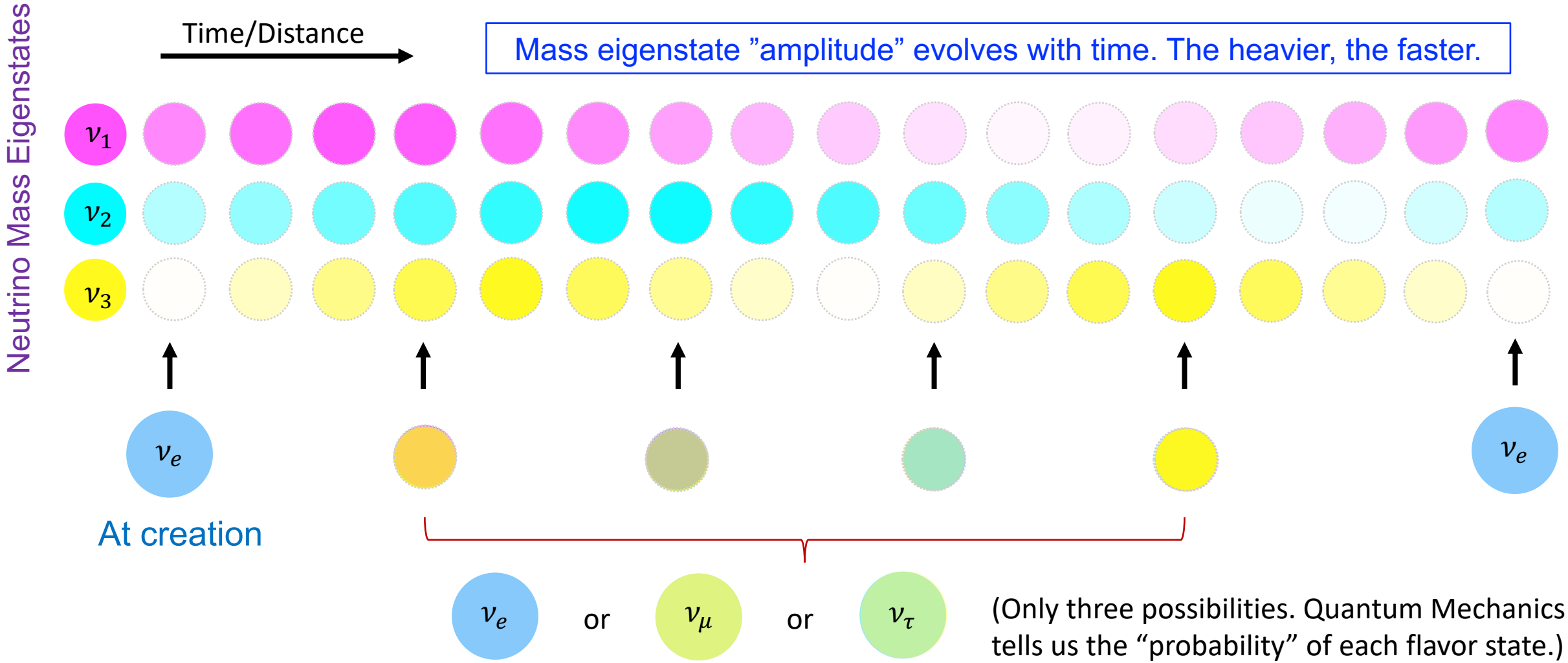
A unitary matrix to describe neutrino mixing

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Typical fractions from experimental measurements

$$\begin{bmatrix} |U_{e1}|^2 & |U_{e2}|^2 & |U_{e3}|^2 \\ |U_{\mu 1}|^2 & |U_{\mu 2}|^2 & |U_{\mu 3}|^2 \\ |U_{\tau 1}|^2 & |U_{\tau 2}|^2 & |U_{\tau 3}|^2 \end{bmatrix} = \begin{bmatrix} 0.68 & 0.30 & 0.02 \\ 0.14 & 0.30 & 0.56 \\ 0.18 & 0.40 & 0.42 \end{bmatrix} \begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix}$$
$$\nu_1 \quad \nu_2 \quad \nu_3$$

Quantum Mechanics of Neutrino Oscillation



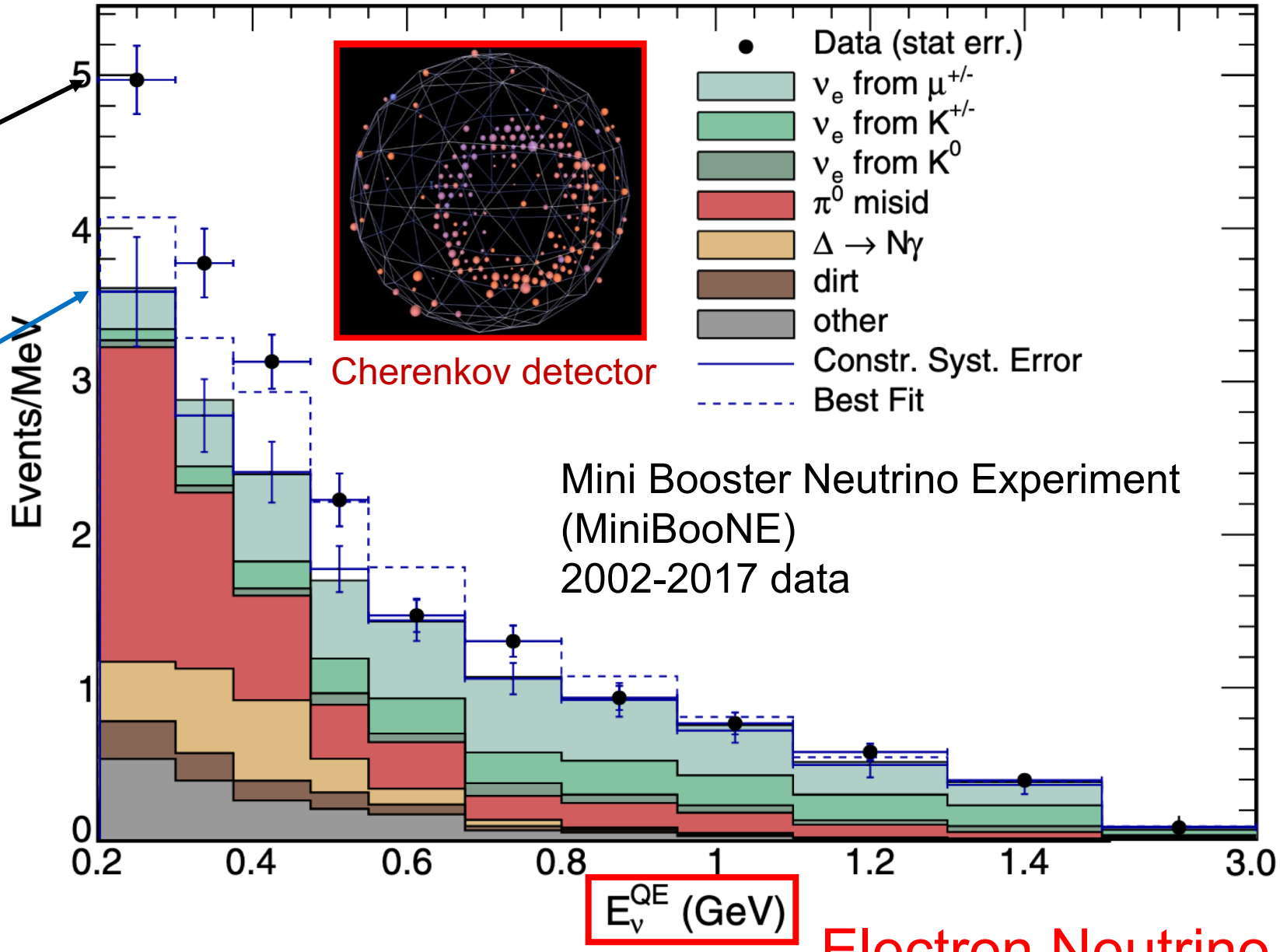
PRL **121**, 221801 (2018)

Experiment

Theory

4.7σ Low Energy Excess (LEE)

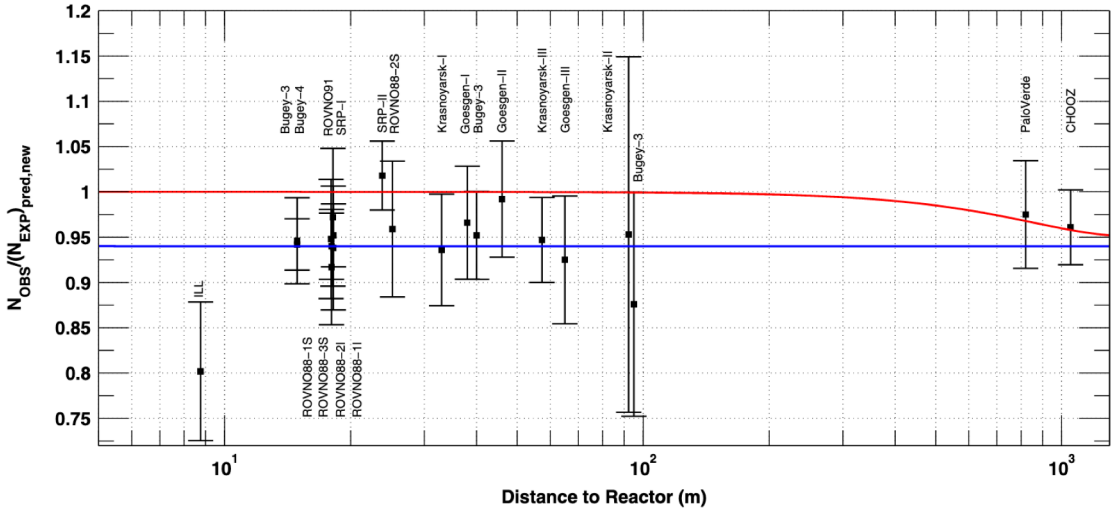
New Physics?!



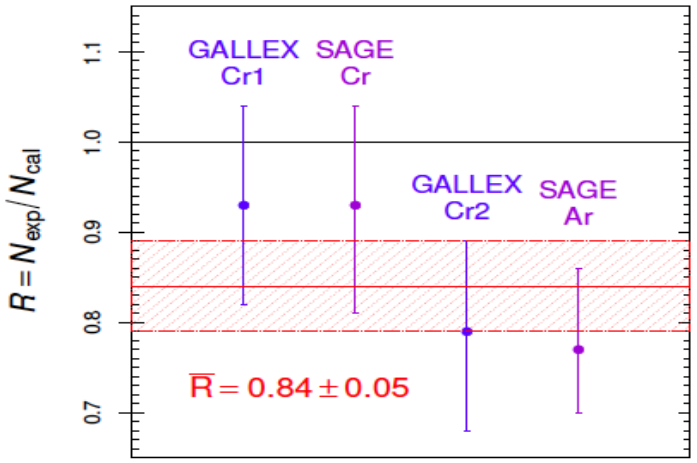
Neutrino Experiment Anomalies: hint of sterile ν

Reactor $\overline{\nu}_e$ Anomaly

PHYSICAL REVIEW D **83,** 073006 (2011)



Radioactive source ν_e Anomaly



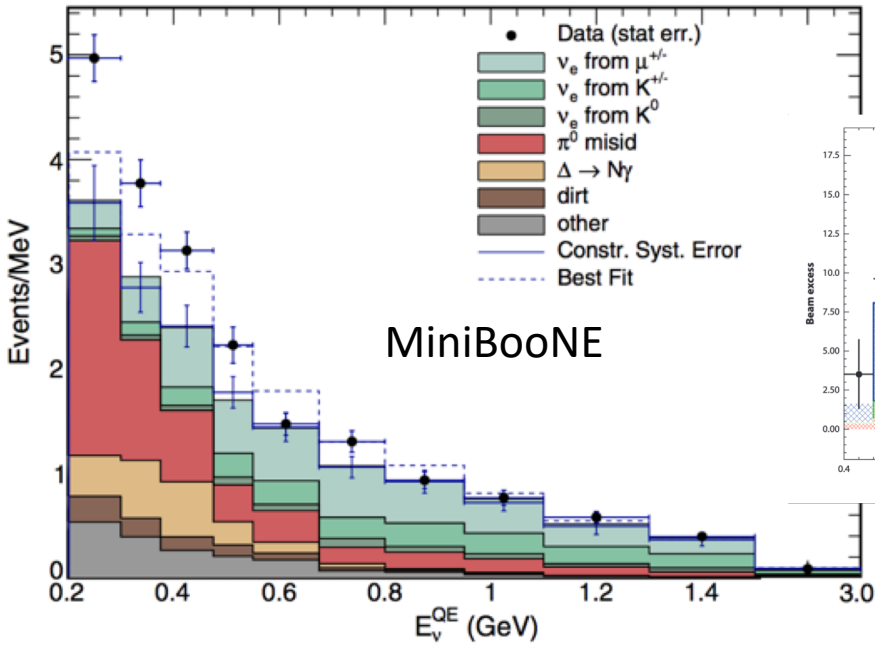
(GALLEX) PLB **342**, 440 (1995)
(GALLEX) PLB **420**, 114 (1998)
(SAGE) PRC **73**, 045805 (2006)

In a short distance, with eV-scale sterile neutrinos:

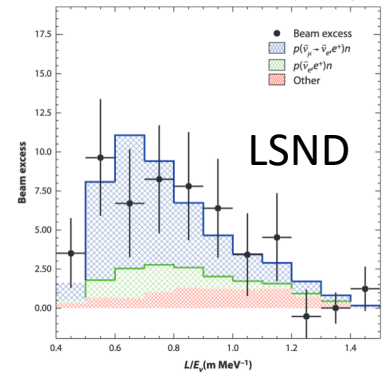
- Deficit in $\nu_e \rightarrow \nu_e$ oscillation
- Excess in $\nu_\mu \rightarrow \nu_e$ oscillation

Accelerator ν_e Anomaly

PRL **121**, 221801 (2018)

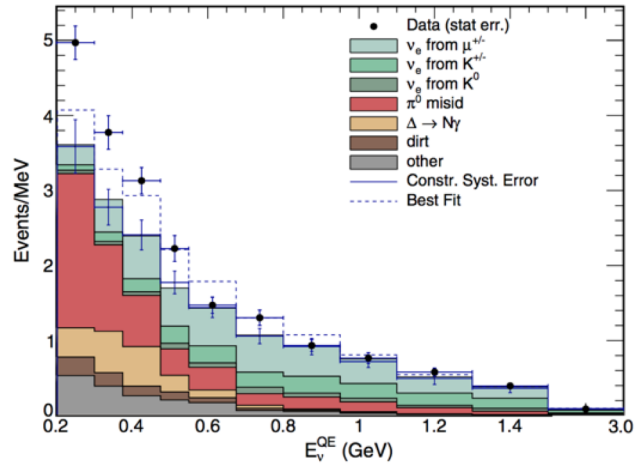


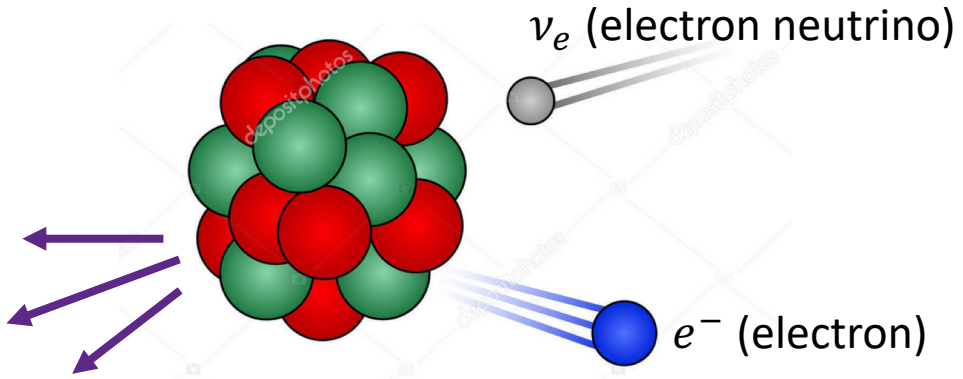
PRD 64, 112007 (2001)



New Physics?!

- **Excess ν_e from $\nu_\mu \rightarrow \nu_e$ oscillation (sterile neutrinos)**

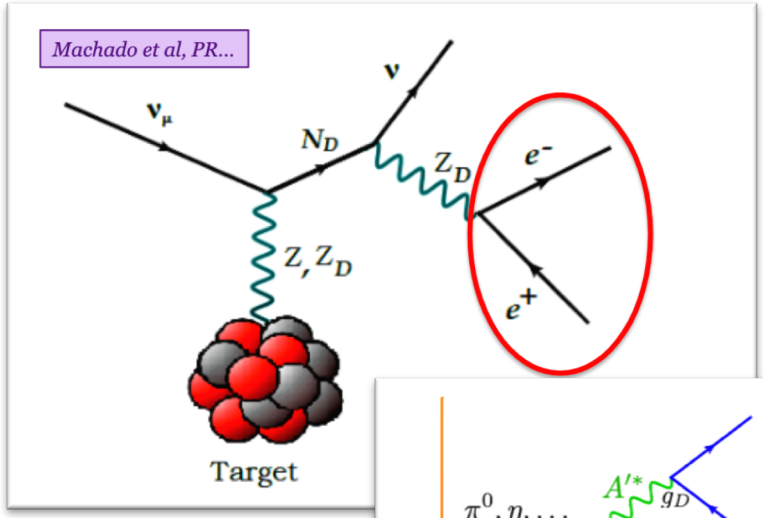


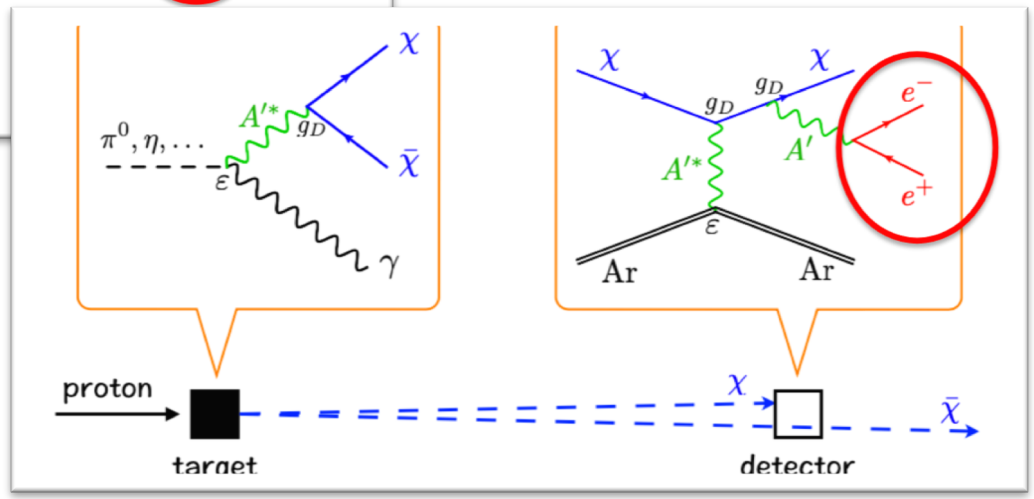


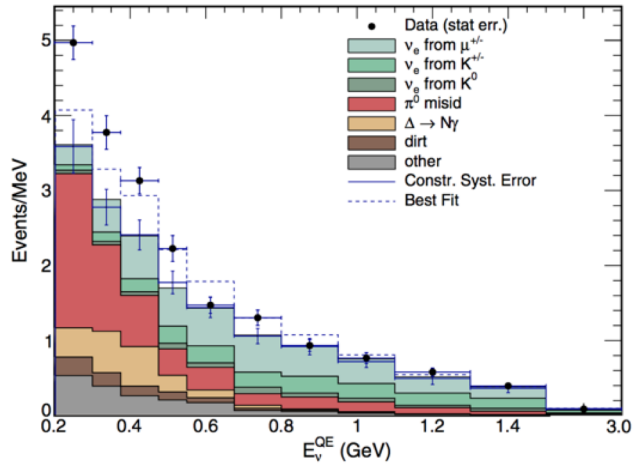
Charged-current (CC)

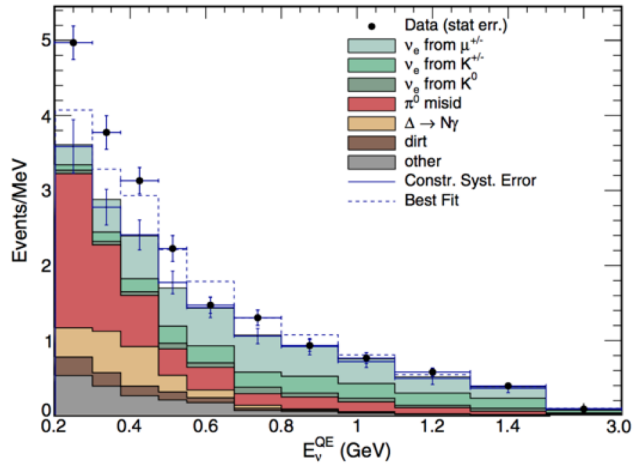
New Physics?!

- **Not neutrinos:**
  - Dark sector neutral particles decay to e^+e^-
  - …

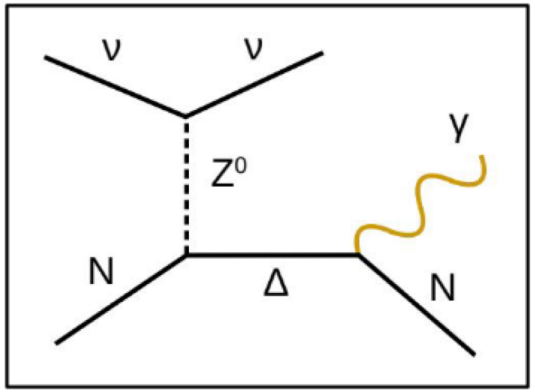




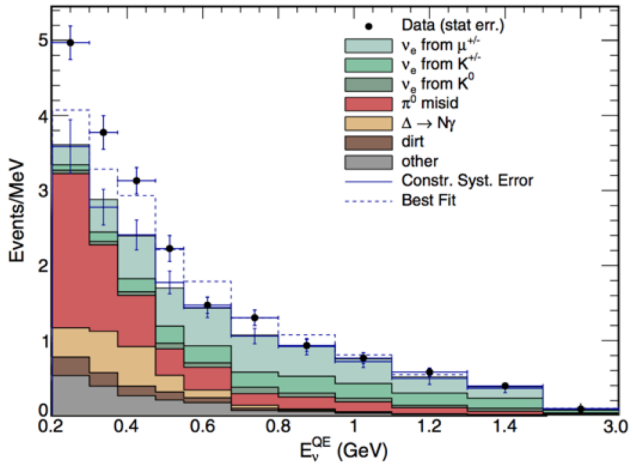




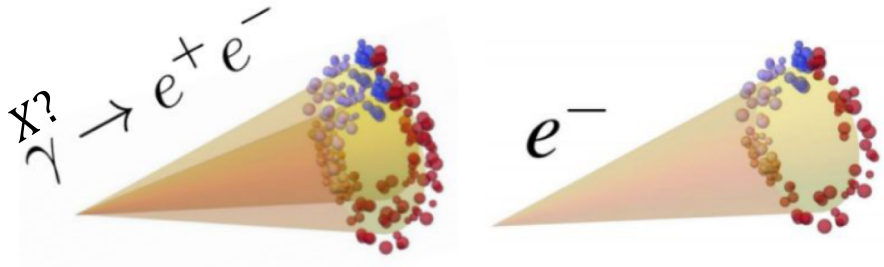
- **Not neutrinos:**
  - Dark sector neutral particles decay to e^+e^-
  - Excess $\Delta \rightarrow N\gamma$
  - …



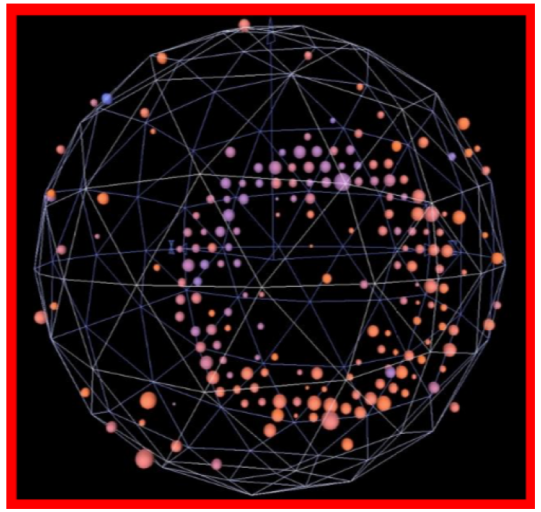
Standard Model Physics, but the rate could be higher than SM prediction



- **Not neutrinos:**
  - Dark sector neutral particles decay to e^+e^-
  - Excess $\Delta \rightarrow N\gamma$
  - Other generic photon (γ) background



Cherenkov detector



e*/*γ hard to distinguish in Cherenkov, scintillator, bubble chamber, etc.

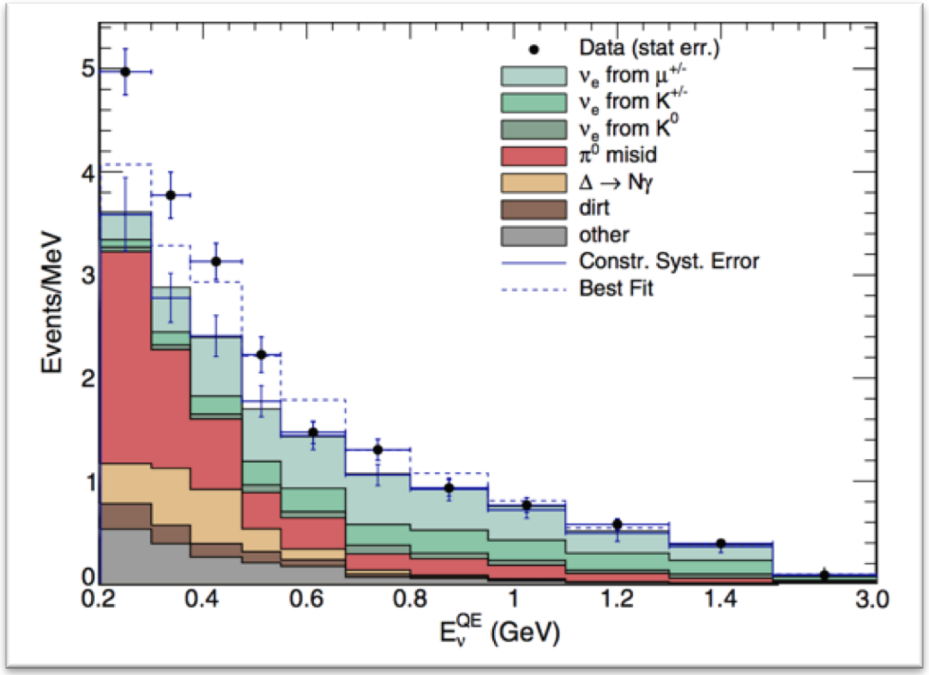
- **Excess ν_e from $\nu_\mu \rightarrow \nu_e$ oscillation (sterile neutrinos)**
- **Not neutrinos:**
  - Dark sector neutral particles decay to e^+e^-
  - Excess $\Delta \rightarrow N\gamma$
  - Other generic photon (γ) background
  - …

✓ **Need to repeat the MiniBooNE low-energy excess**

✓ **Need e/γ ($\gamma \approx e^+e^-$) separation**

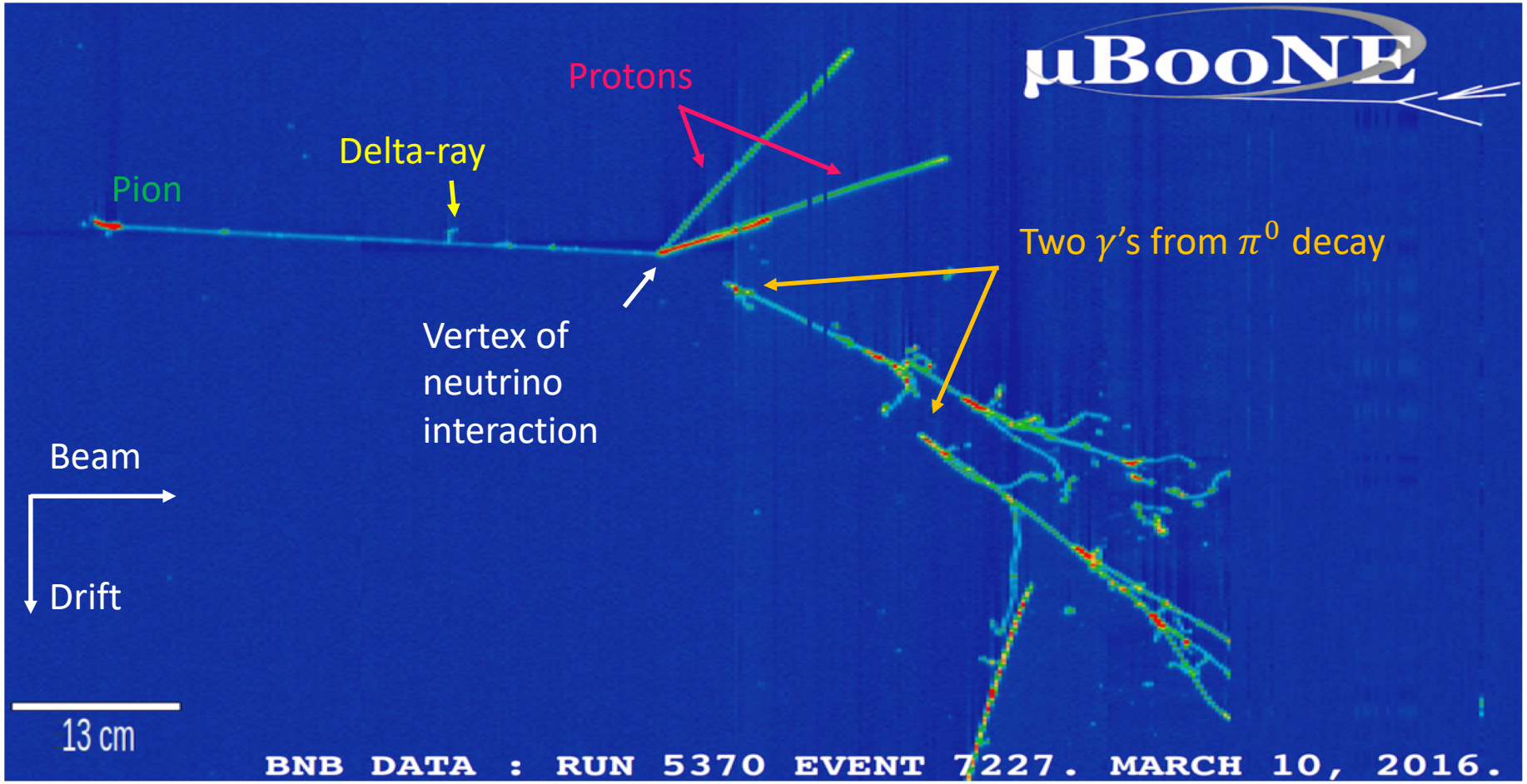
electron-like low-energy excess (eLEE) → this talk

photon-like low-energy excess (gLEE)



Liquid Argon Time Projection Chamber (LArTPC)

Large-scale + 4pi calorimetry & tracking capability



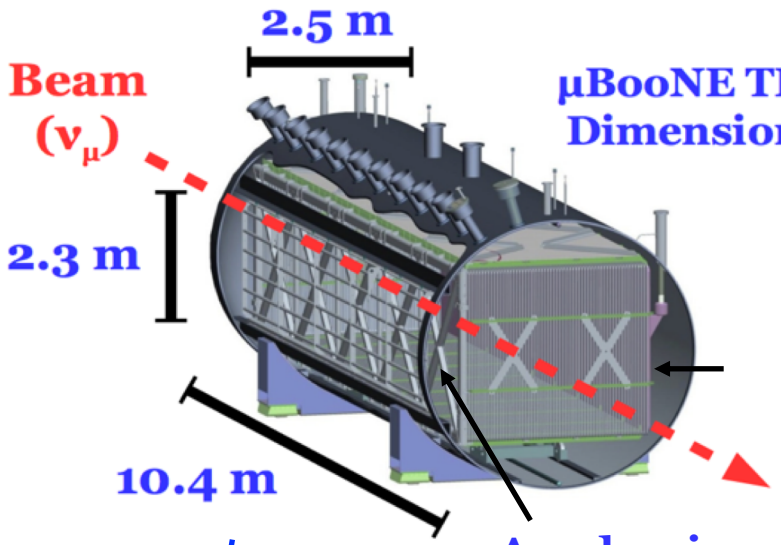
MicroBooNE (2016): neutral-current $\nu - Ar$ interaction

Micro Booster Neutrino Experiment (MicroBooNE)

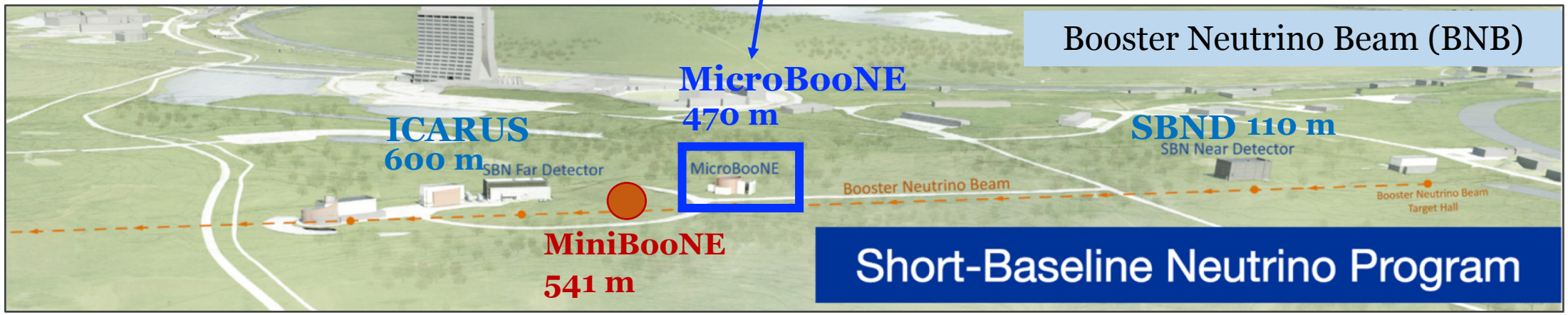


PMTs to detect scintillation light

170 (85) ton liquid argon in cryo (TPC)



- Pioneering LArTPC R&D
- $\nu - Ar$gon Cross section measurement
- **Direct test on MiniBooNE low-energy excess**

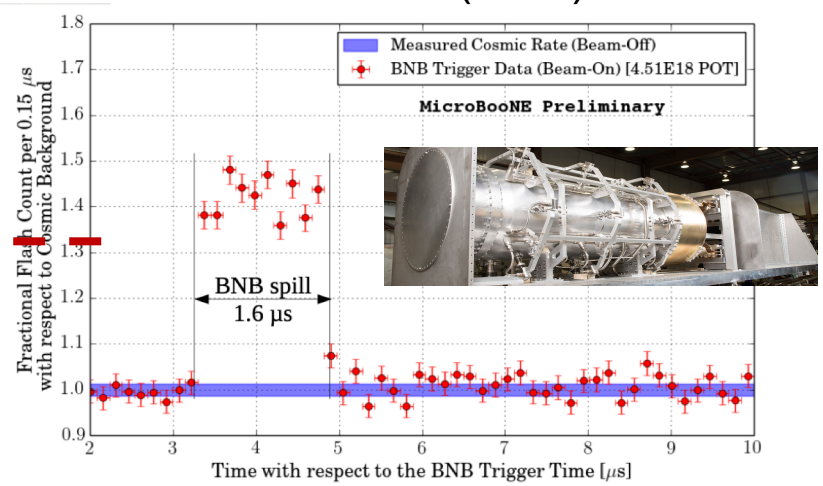


MicroBooNE detector



ν

BNB beam (4 Hz)



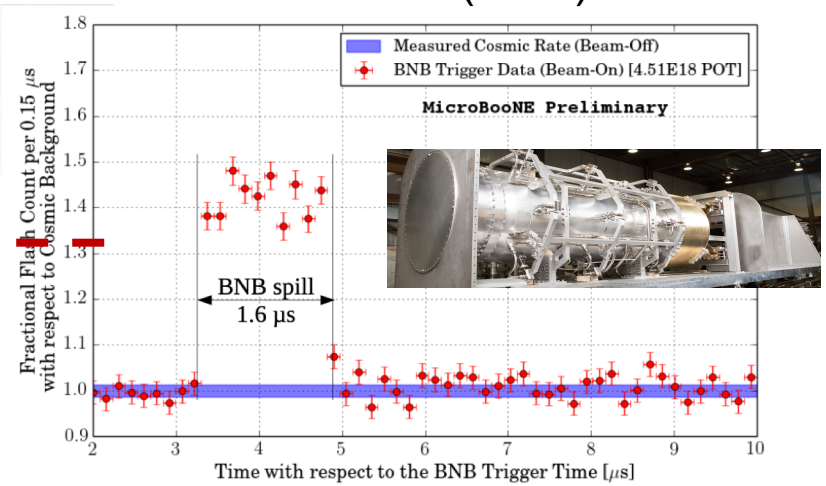
- **1** neutrino interaction in the TPC active volume per 600 beam spills

MicroBooNE detector

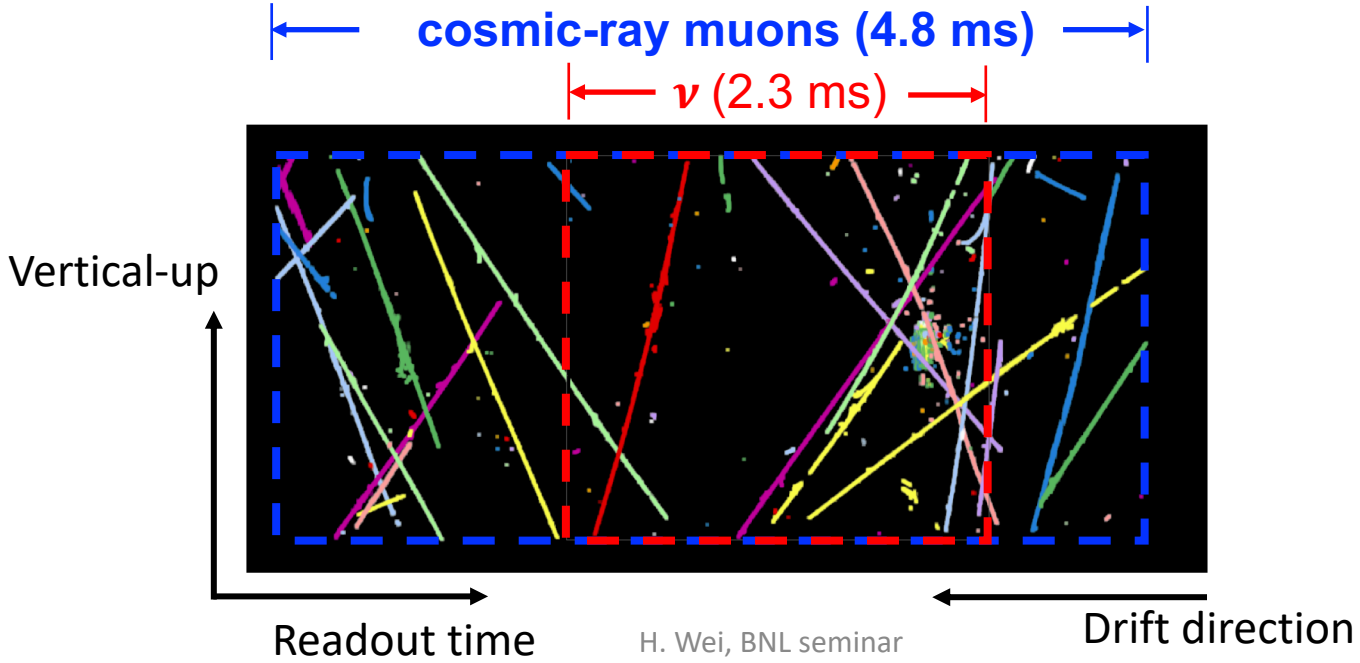


ν

BNB beam (4 Hz)



- **1** neutrino interaction in the TPC active volume per 600 beam spills
- ν : **cosmic-ray = 1 : 20k** (beam spill = 4.8 ms readout window, surface detector)

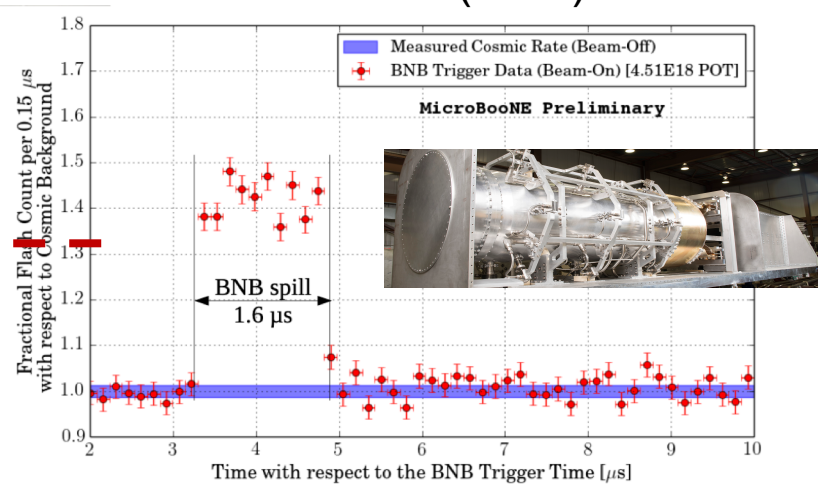


MicroBooNE detector



ν

BNB beam (4 Hz)



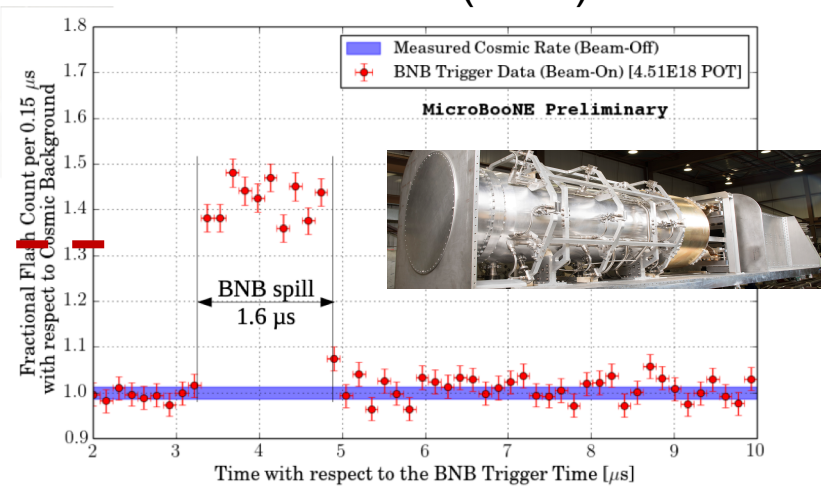
- **1** neutrino interaction in the TPC active volume per 600 beam spills
- ν : **cosmic-ray = 1 : 20k** (beam spill = 4.8 ms readout window, surface detector)
- ν : **cosmic-ray = 1 : 200** (requiring in-beam light signals)

MicroBooNE detector



ν

BNB beam (4 Hz)



- **1** neutrino interaction in the TPC active volume per 600 beam spills
- ν : **cosmic-ray = 1 : 20k** (beam spill = 4.8 ms readout window, surface detector)
- ν : **cosmic-ray = 1 : 200** (requiring in-beam light signals)
- ν_e : ν = **0.4% : 1**

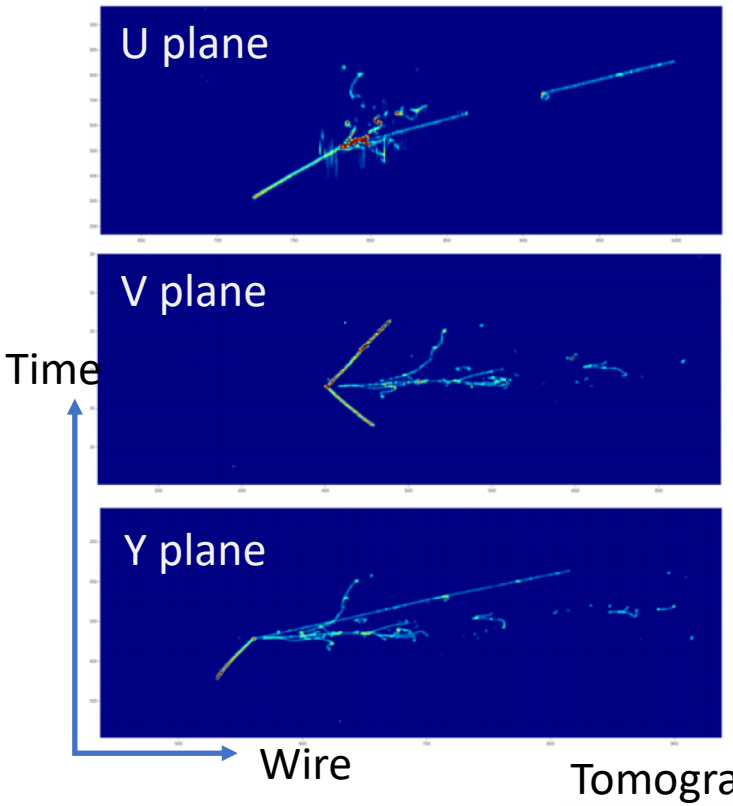
A high-performance ν_e CC selection, to search for electron-like low energy excess, requires a background rejection rate:

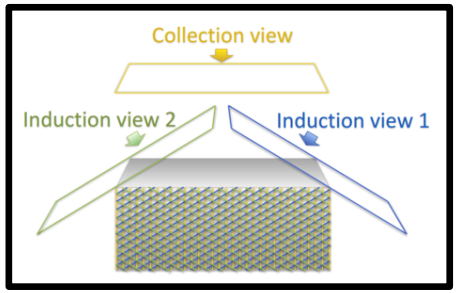
- Cosmic-ray background: **>99.99%**
- Other neutrino interactions: **>99.9%**

A brand-new end-to-end *reconstruction* and *selection* chain …

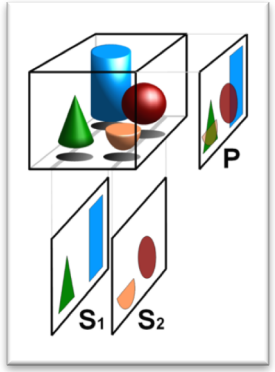
Wire-Cell 3D Reconstruction

Three time-versus-wire views



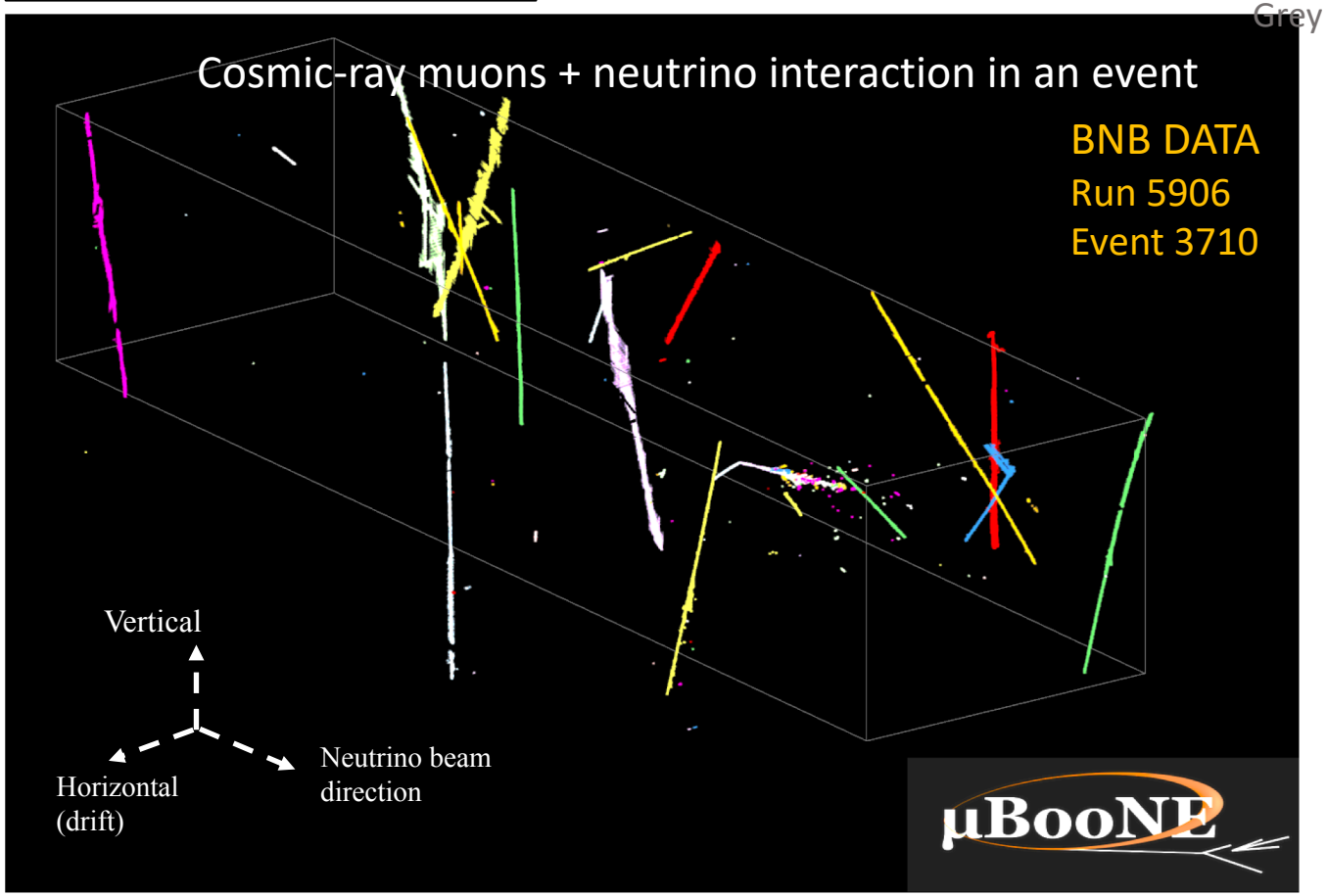


Tomography

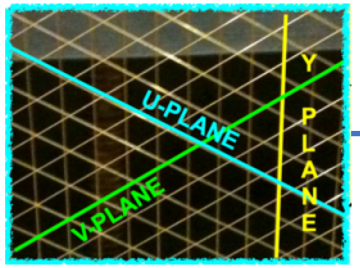


JINST 13 P05032

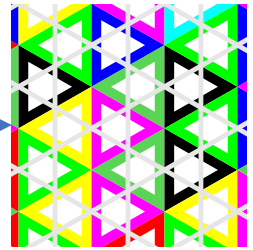
3D imaging, clustering



Wires



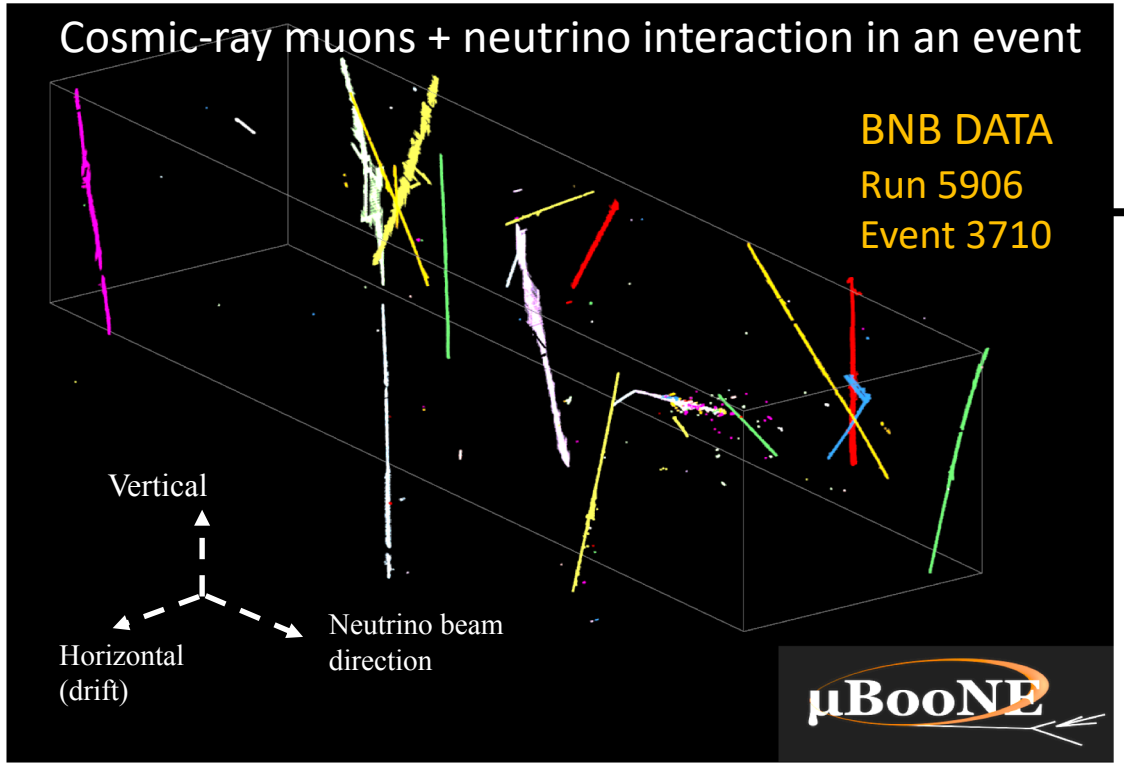
Cells



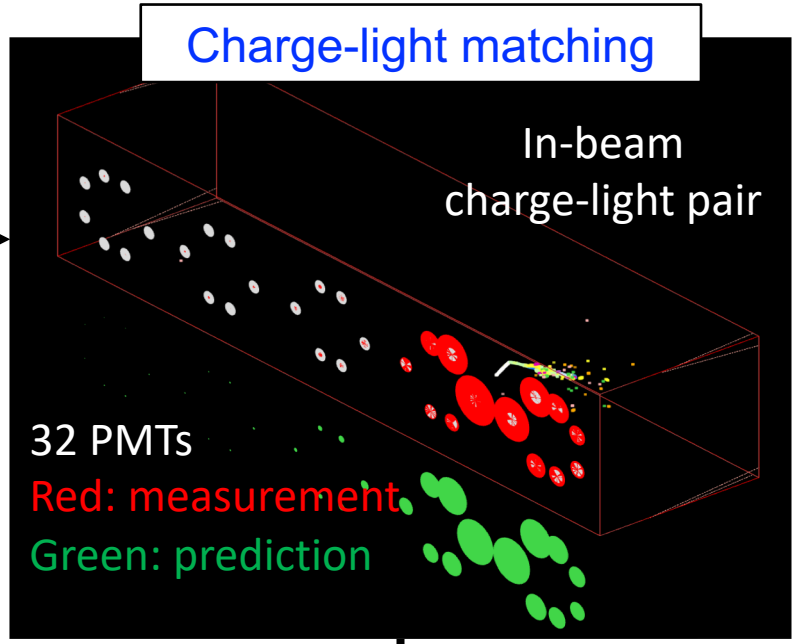
Grey lines: wires

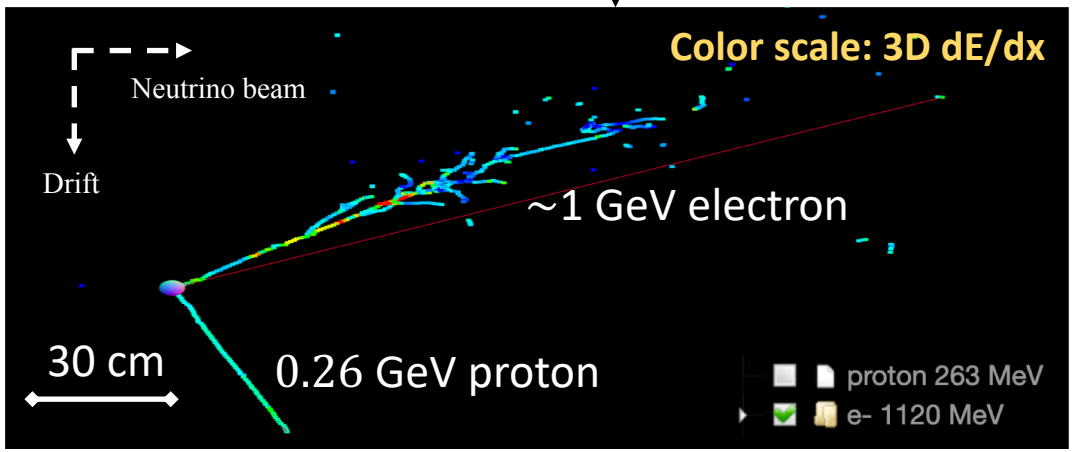
Wire-Cell Event Reconstruction

arXiv: 2011.01375



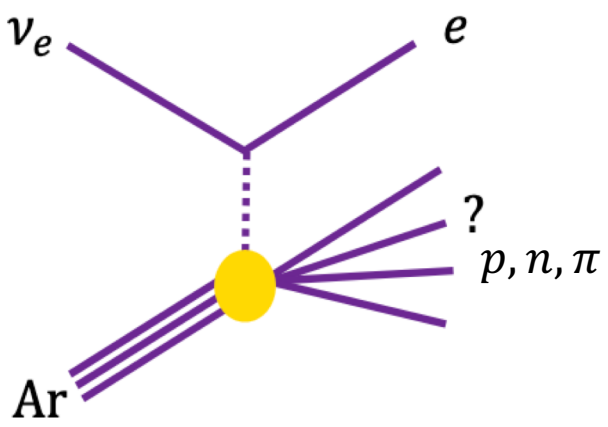
3D imaging, clustering





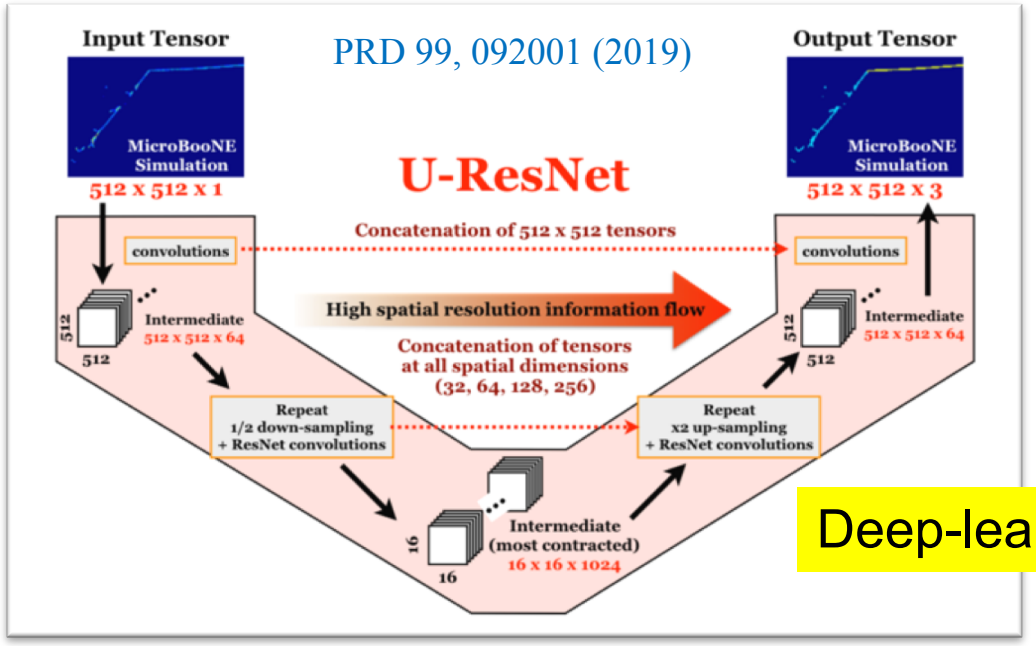
3D pattern recognition

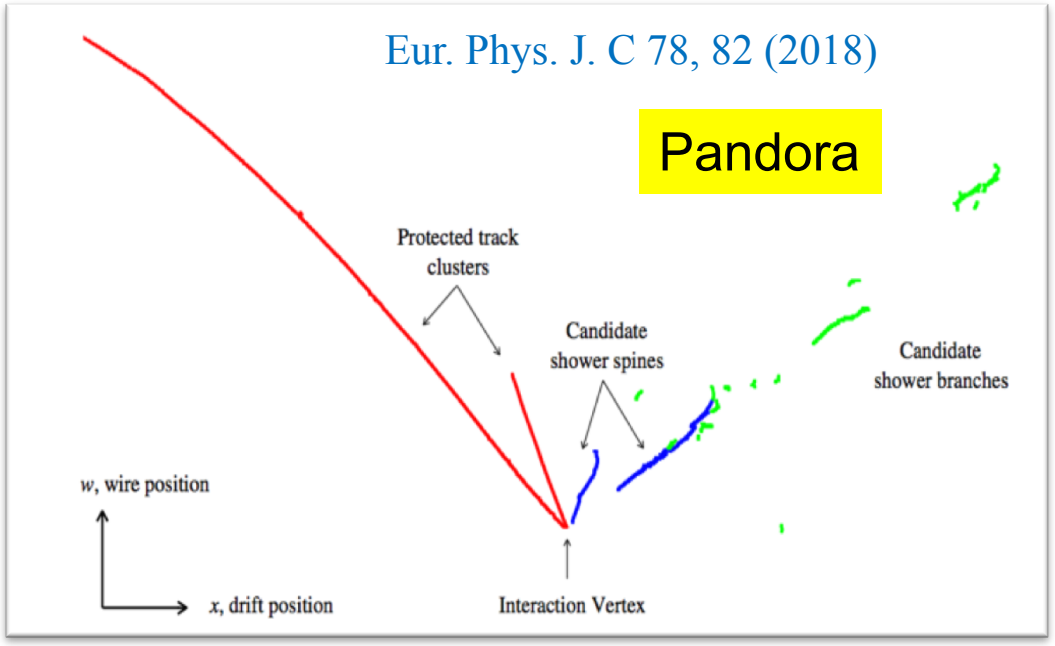
Multiple Reconstruction Methods at MicroBooNE



Various reconstruction methods looking for different final states

- Deep-learning → $1e1p0\pi$ (eLEE)
- Pandora → $1e0p0\pi$ + $1eNp0\pi$ (eLEE) or $1\gamma0p$ + $1\gamma1p$ (gLEE)
- **Wire-Cell → $1e$ + anything (inclusive eLEE, enhanced efficiency and sensitivity)**

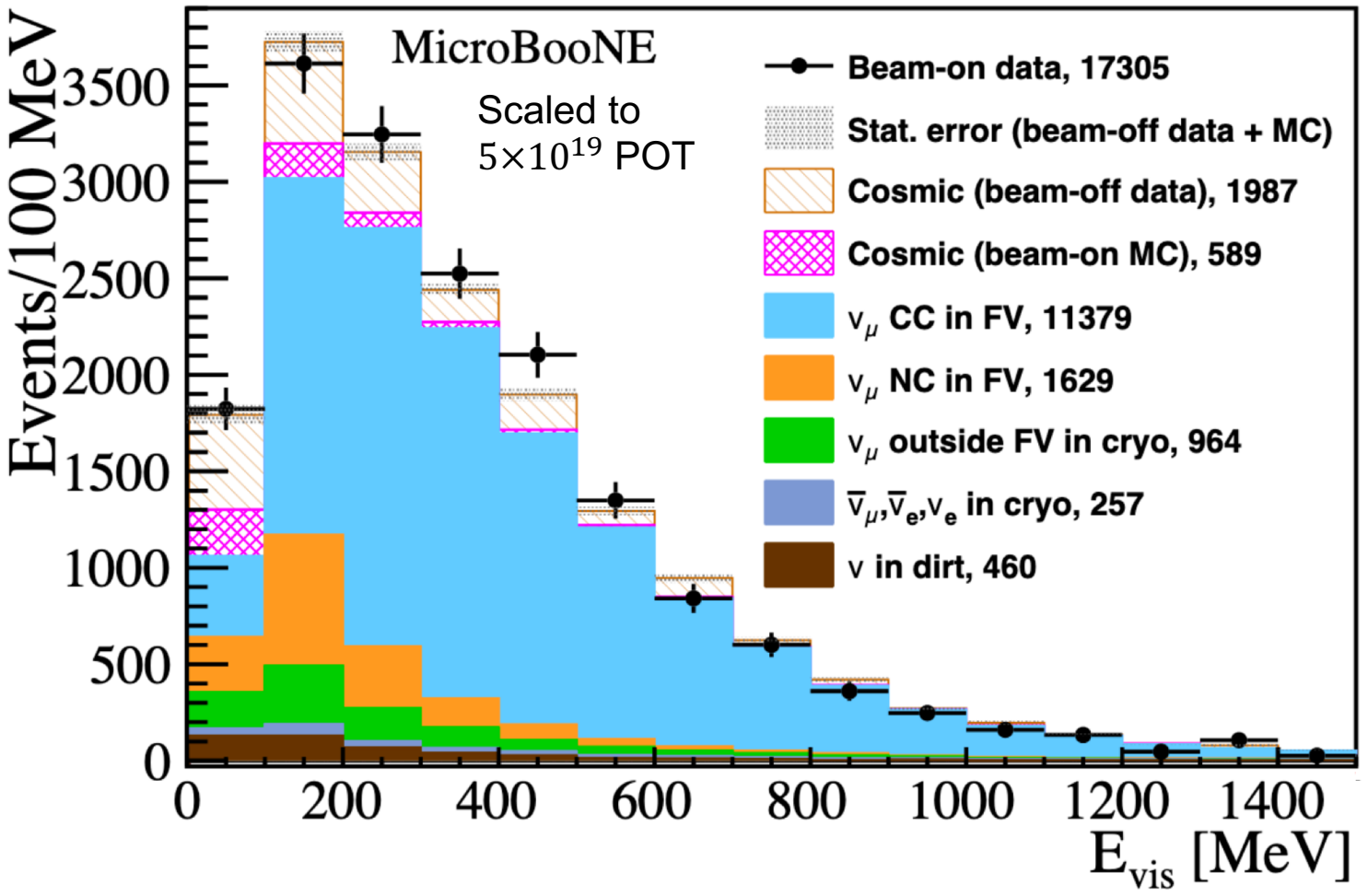




Wire-Cell generic ν selection (pre-selection)

arXiv: 2012.07928, arXiv: 2101.05076

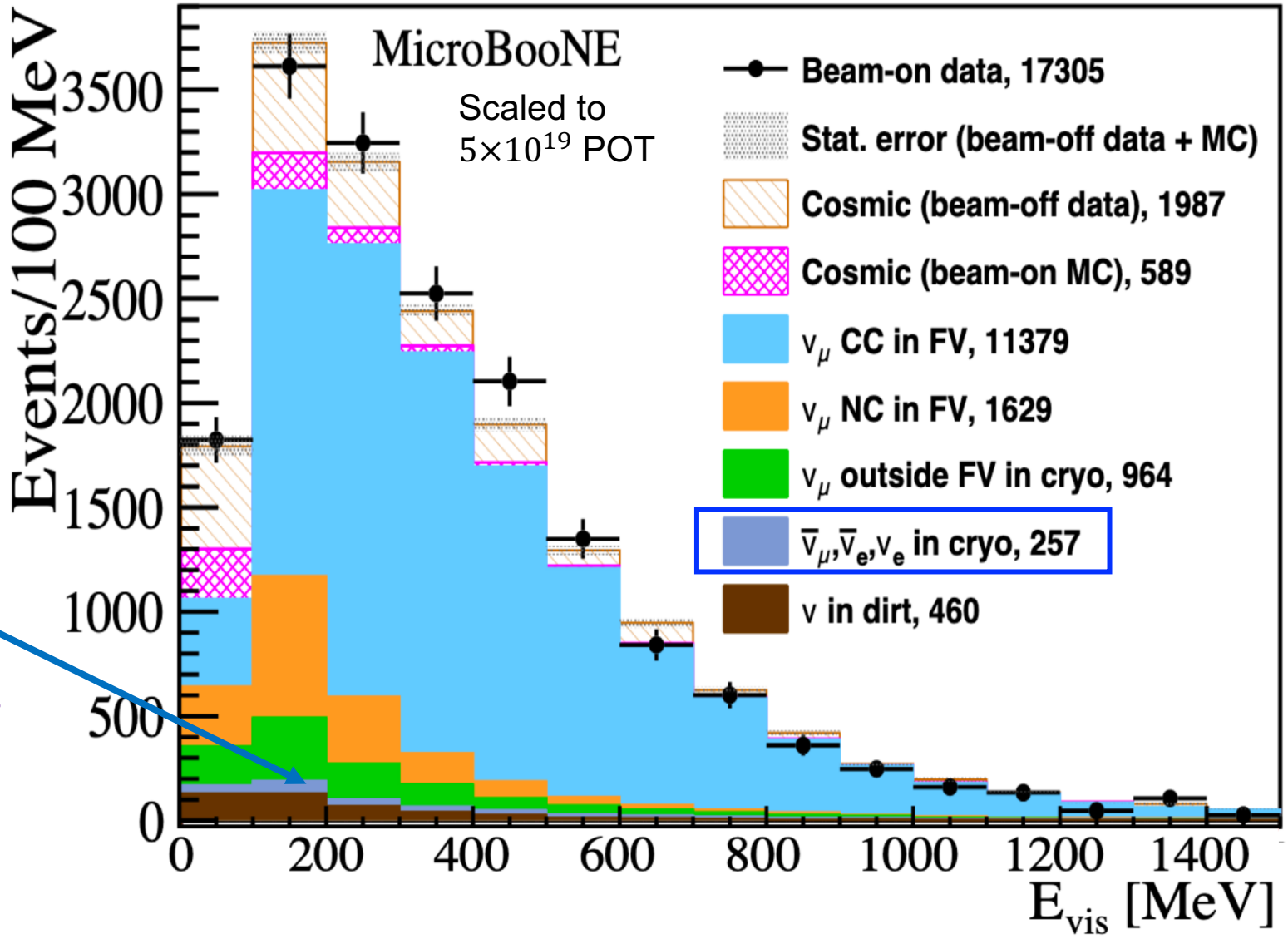
- **99.98%** in-beam-coincident cosmic-ray background is rejected (another factor of 10 in ν_e selection stage)
- ν_μ charged-current (CC) efficiency: **80%**
- ν_e CC efficiency: **90%**



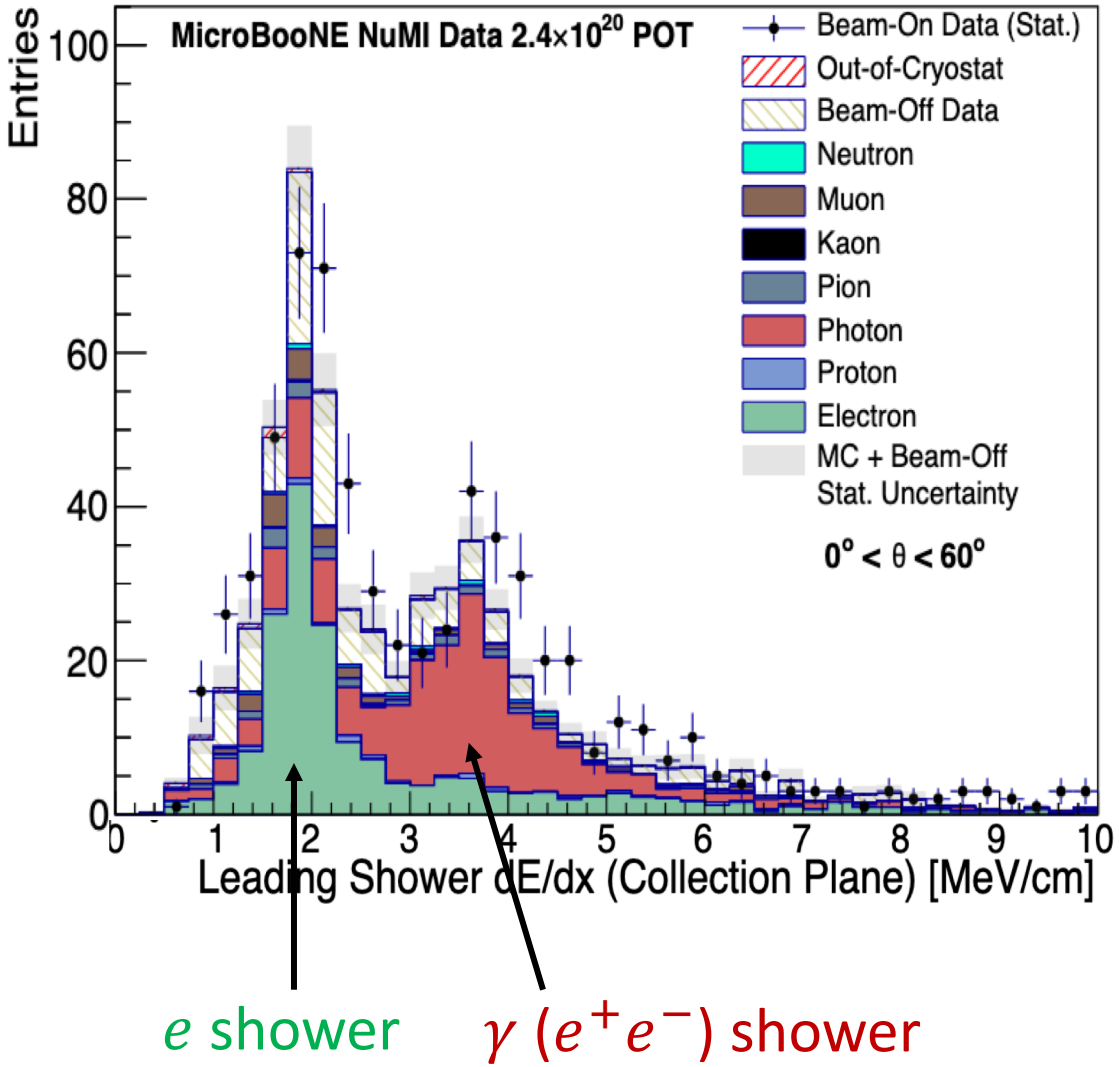
Low energy ν_e CC selection is very tough

- ν_e CC rate **~0.5%** of all neutrino interactions
- Backgrounds:
  - Cosmic-ray muons
  - Neutral-current interactions high-energy to low-energy feed-down
  - ν_μ CC interaction mis-identification

arXiv: 2012.07928, arXiv: 2101.05076



arXiv: 2101.04228



Neutrino vertex + gap identification + e/γ separation

✗ However, the extremely low signal-to-background ratio makes this story quite different

- Bad neutrino vertex
- dE/dx fluctuation
- Track overlapping with show stem
- Low energy $e/\mu(\pi)$ separation
- Asymmetric γ pair production
- π^0 decay γ escape

Rejection rate of valid (reco showers) neutrino events [MC]

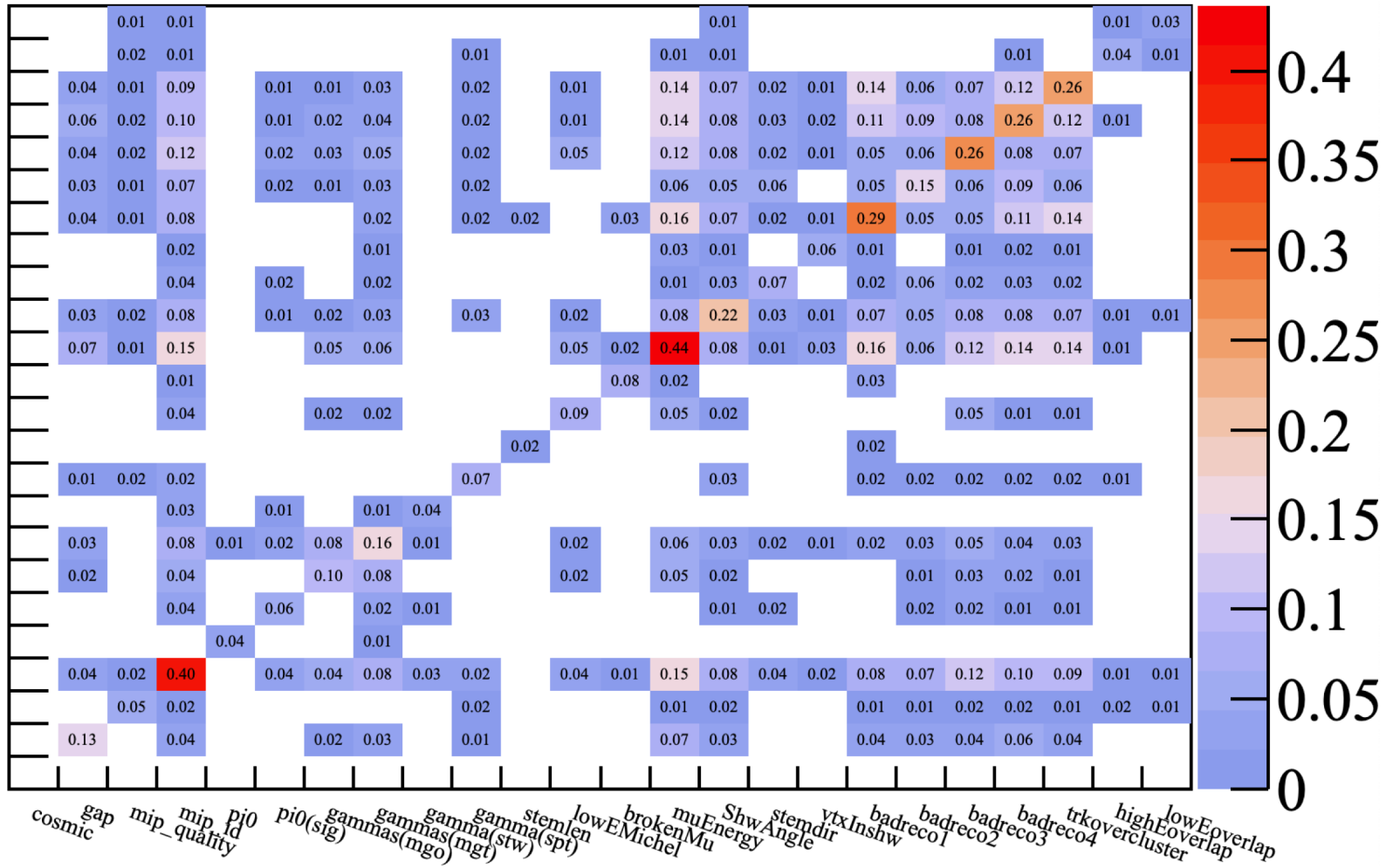
Unreliable pattern recognition

Kinematic

Muon-related misid

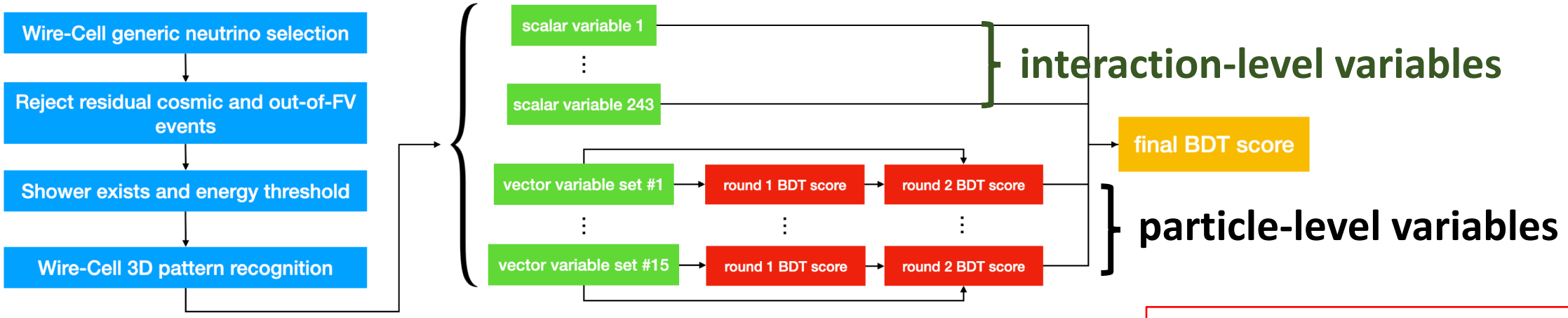
pi0 or gamma

Primary electron id



- **Analysis of various types of background through hand-scanning**

- **Capacity of hand-scan**
  - **<1000 events**
  - **1% error rate → to be 10 times lower**

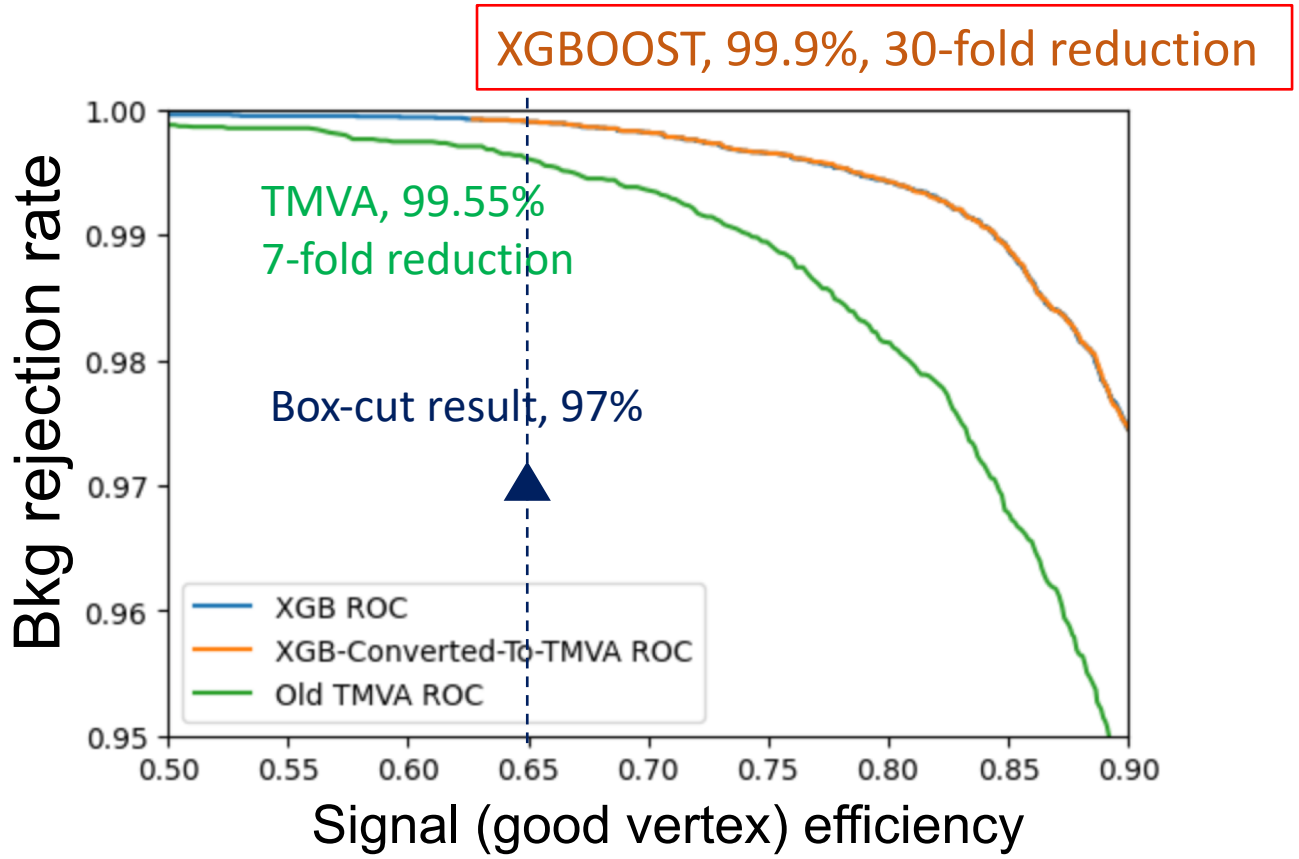


Human-engineering

↓

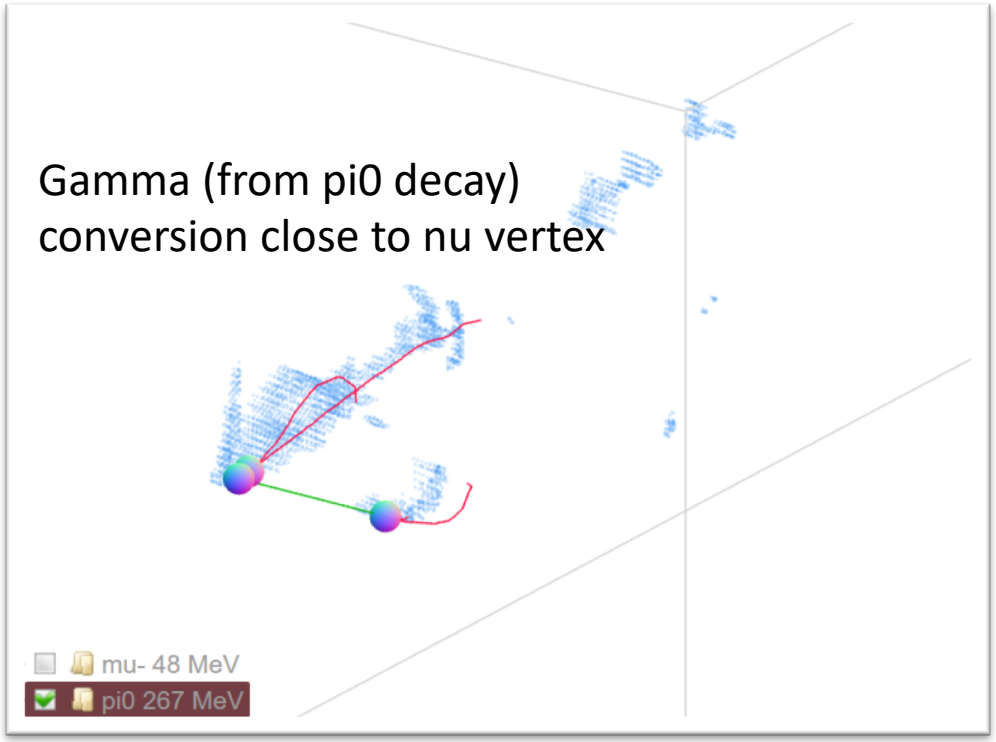
Machine-learning algorithm:

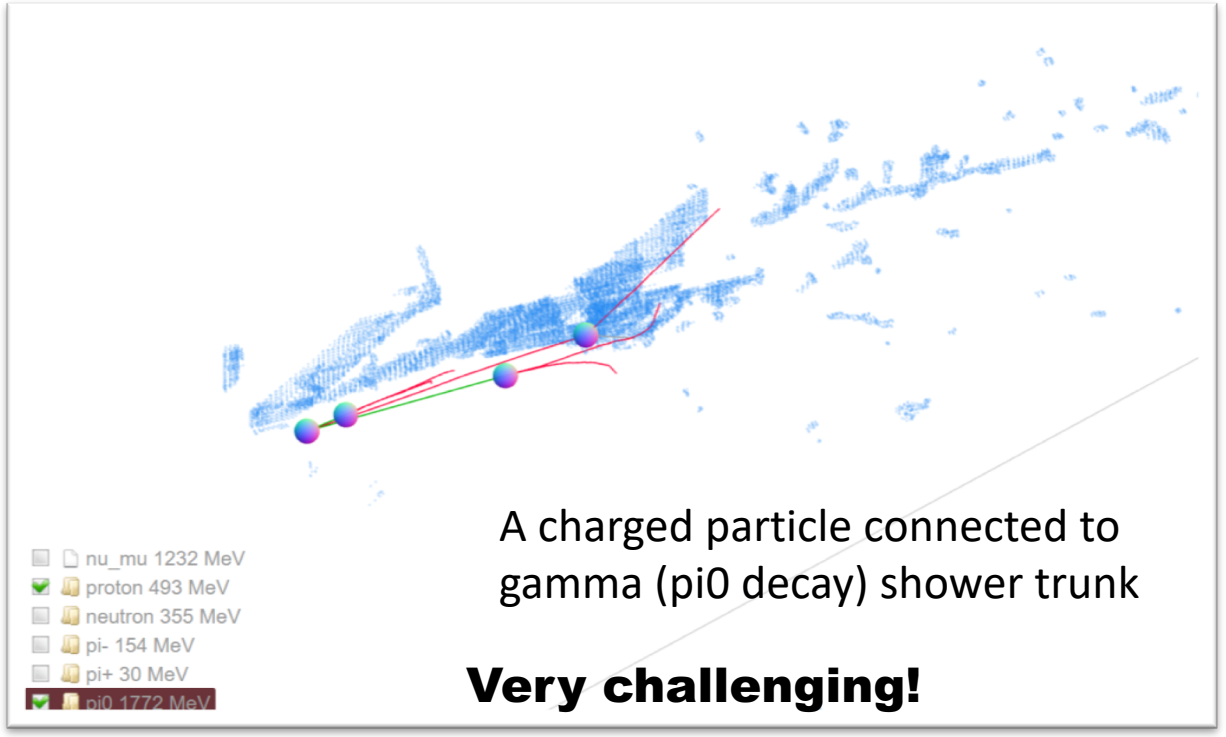
XGBOOST: e**X**treme **G**radient **B**oosting.



Remaining backgrounds

- π^0 or other gammas conversion close to the primary neutrino vertex
- Single gamma (e.g. from π^0 decay) in active volume
- Charged pion, muon, or even proton overlap gamma shower stem
- 10% NC $\nu - e$ elastic scattering

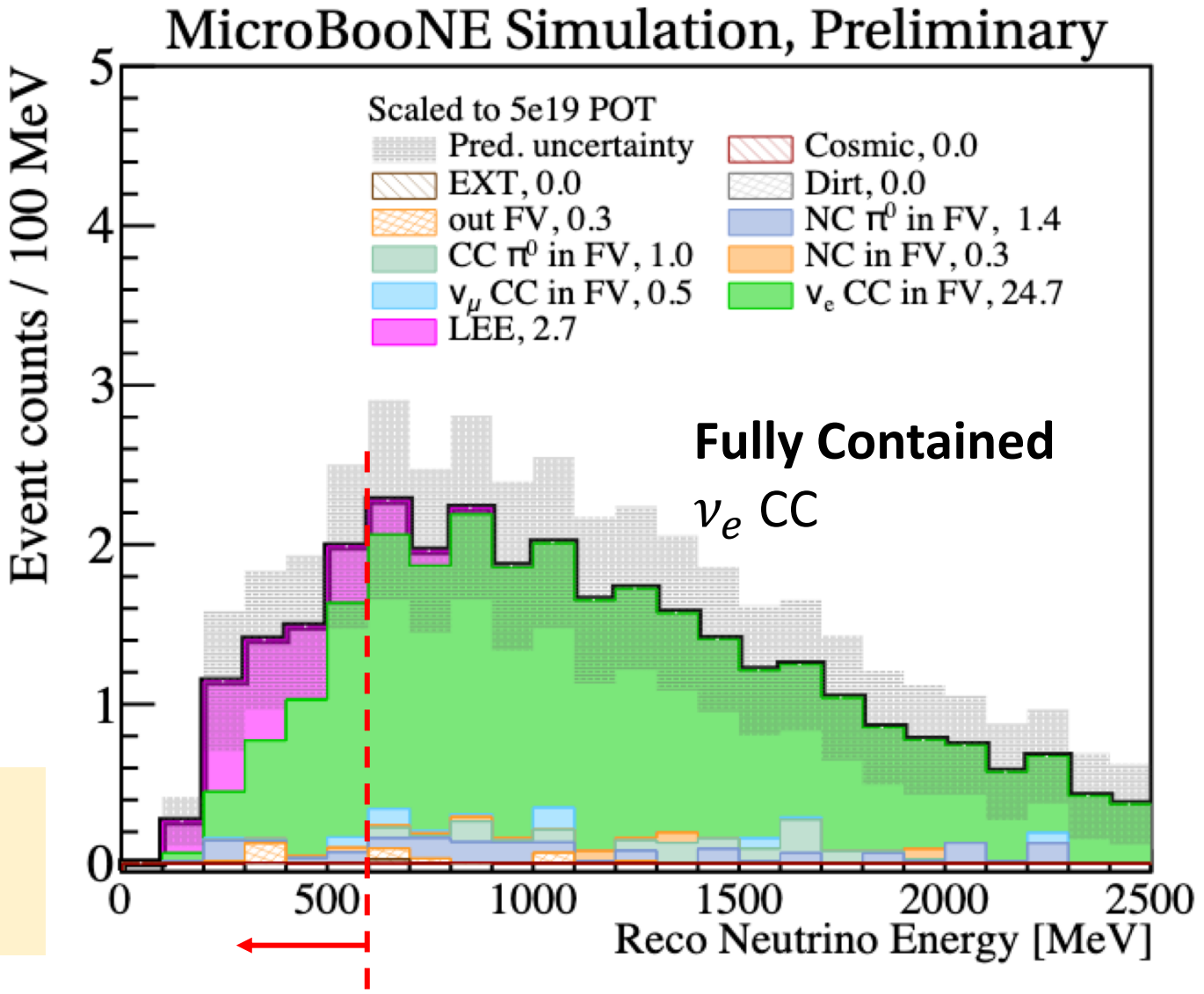




LEE-sensitive ν_e CC selection

MICROBOONE-NOTE-1095-PUB

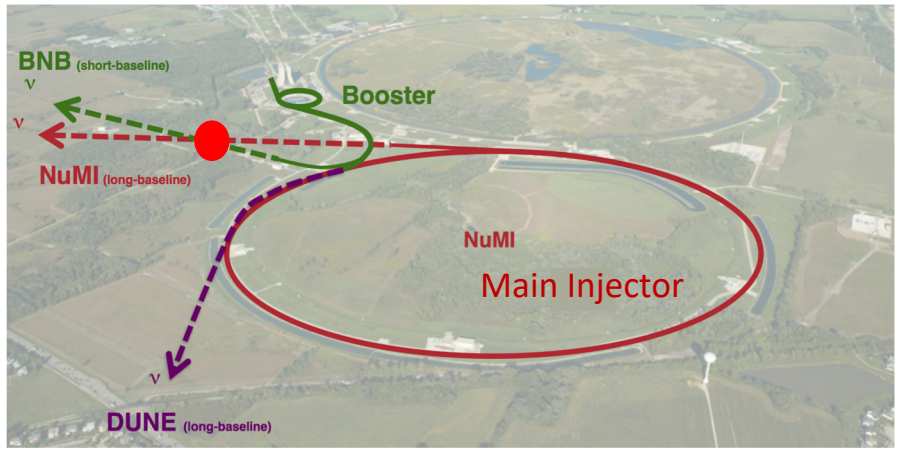
Relative to generic ν selection,
- Background rejection >99.9%
- 49% efficiency, and 84% purity



Enu < 600 MeV
LEE : intrinsic ν_eCC : others
= 0.71 : 1 : 0.15

Not public

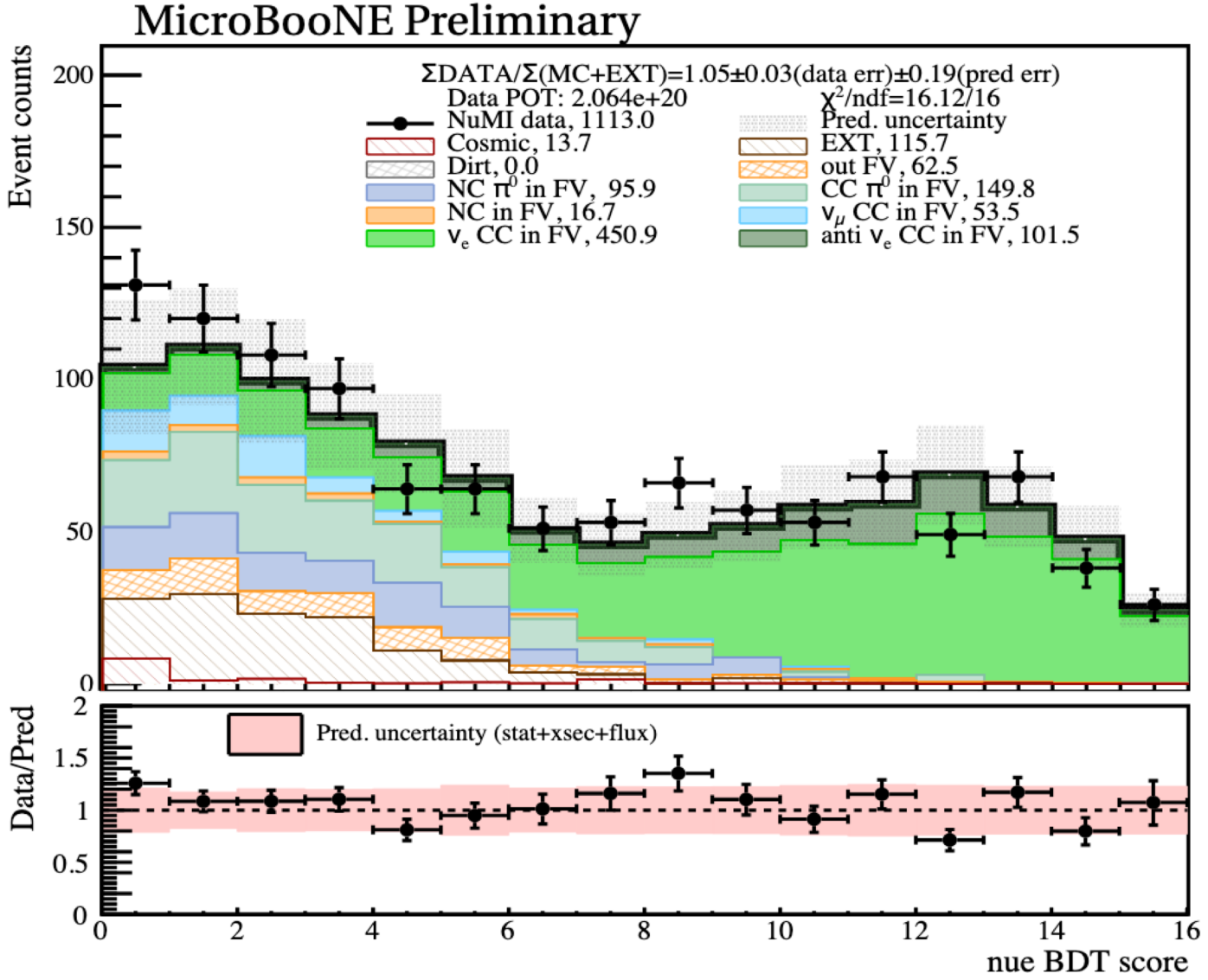
Validation of ν_e CC selection using NuMI data



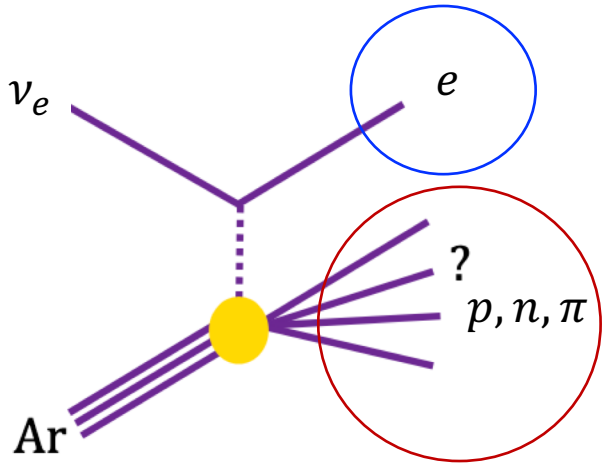
MicroBooNE ≈700m off-axis to NuMI target

No BDT retraining, no optimization of reconstruction & selection.

Good agreement between data and Monte-Carlo

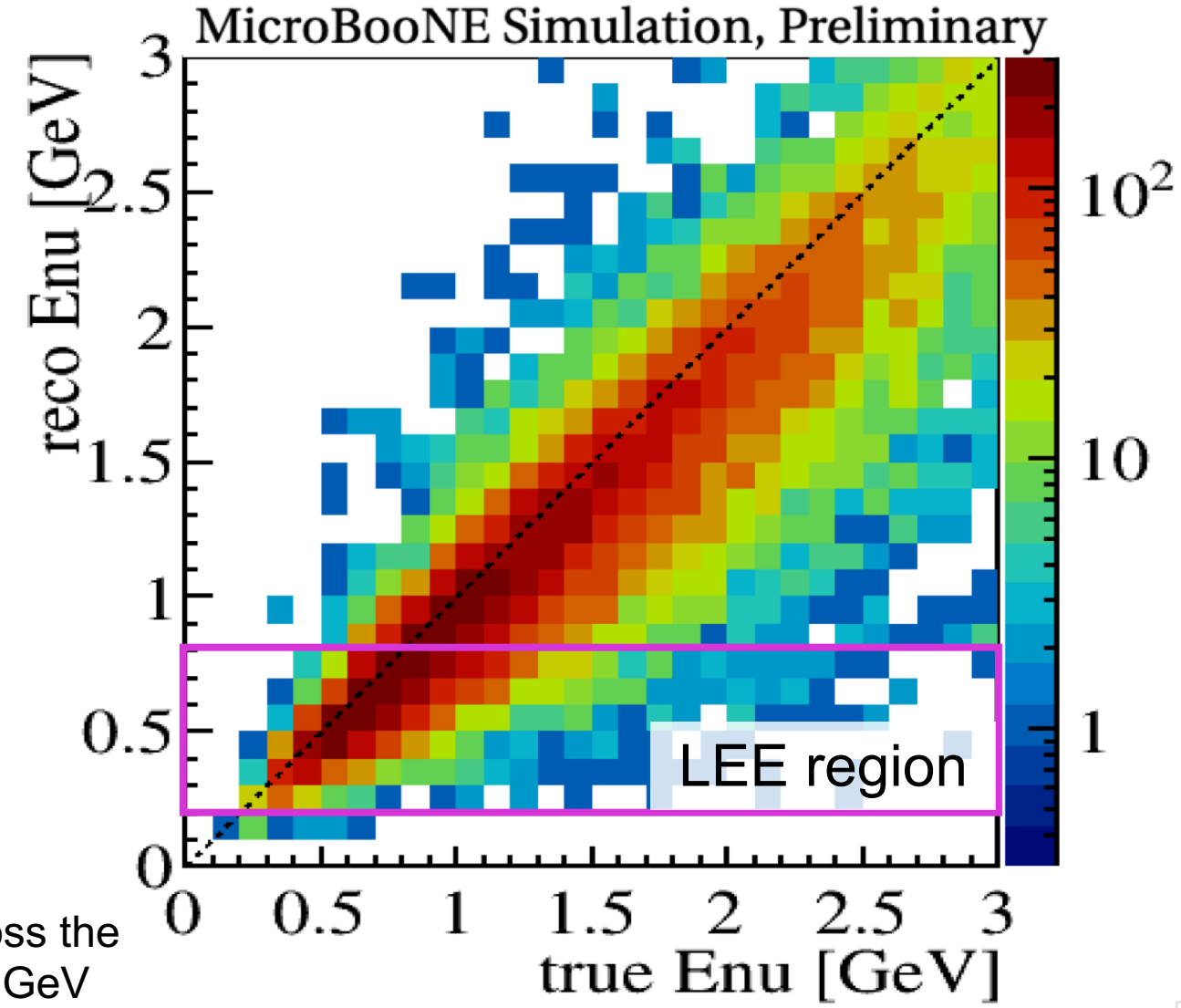


Validation of neutrino energy reconstruction



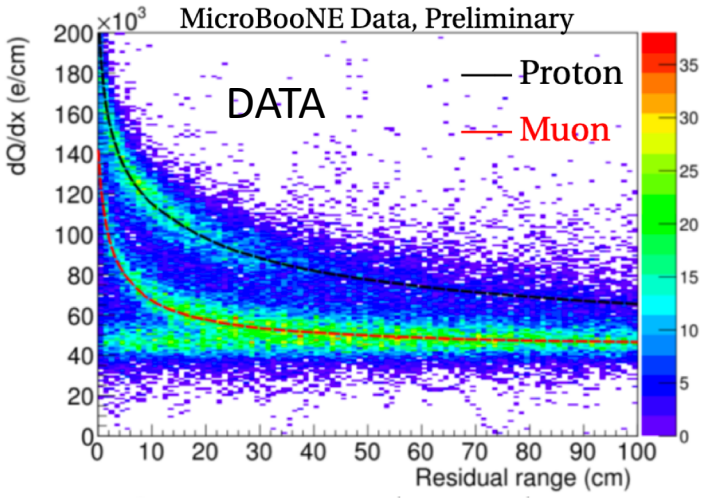
Inclusive selection

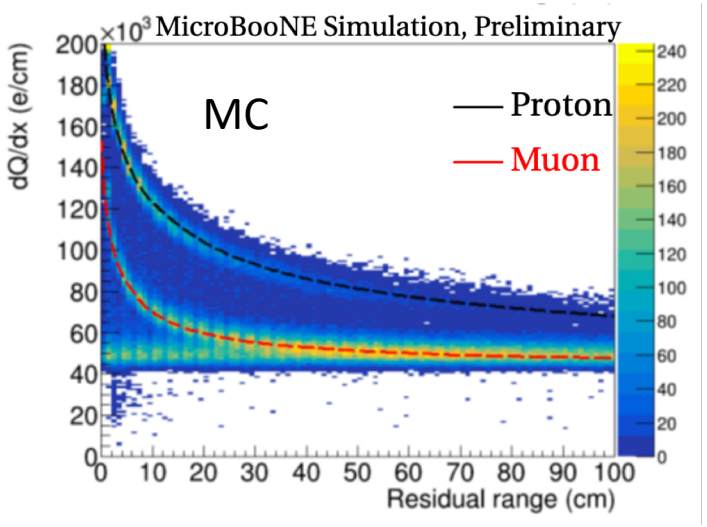
$$E_\nu^{rec} = E_{\text{lepton}}^{reco} + E_{hadron}^{reco}$$



Resolution ~15% across the energy region 0.2-2.5 GeV

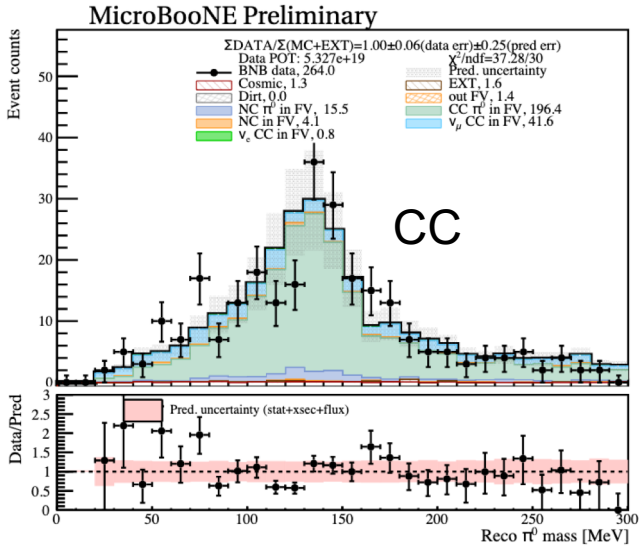
Validation of neutrino energy reconstruction

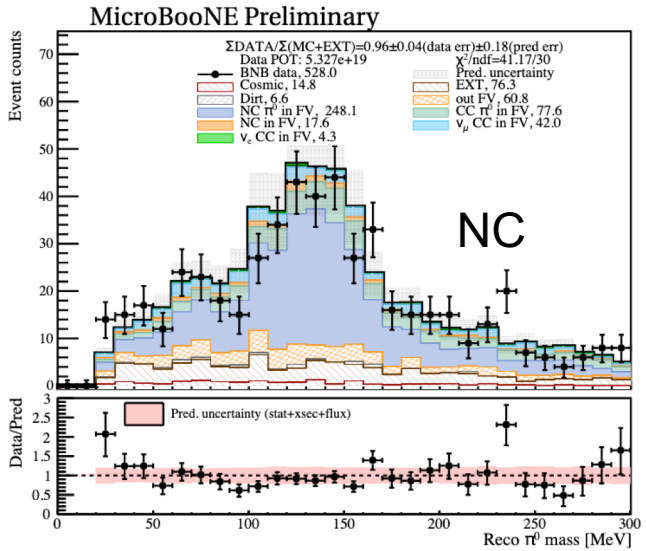




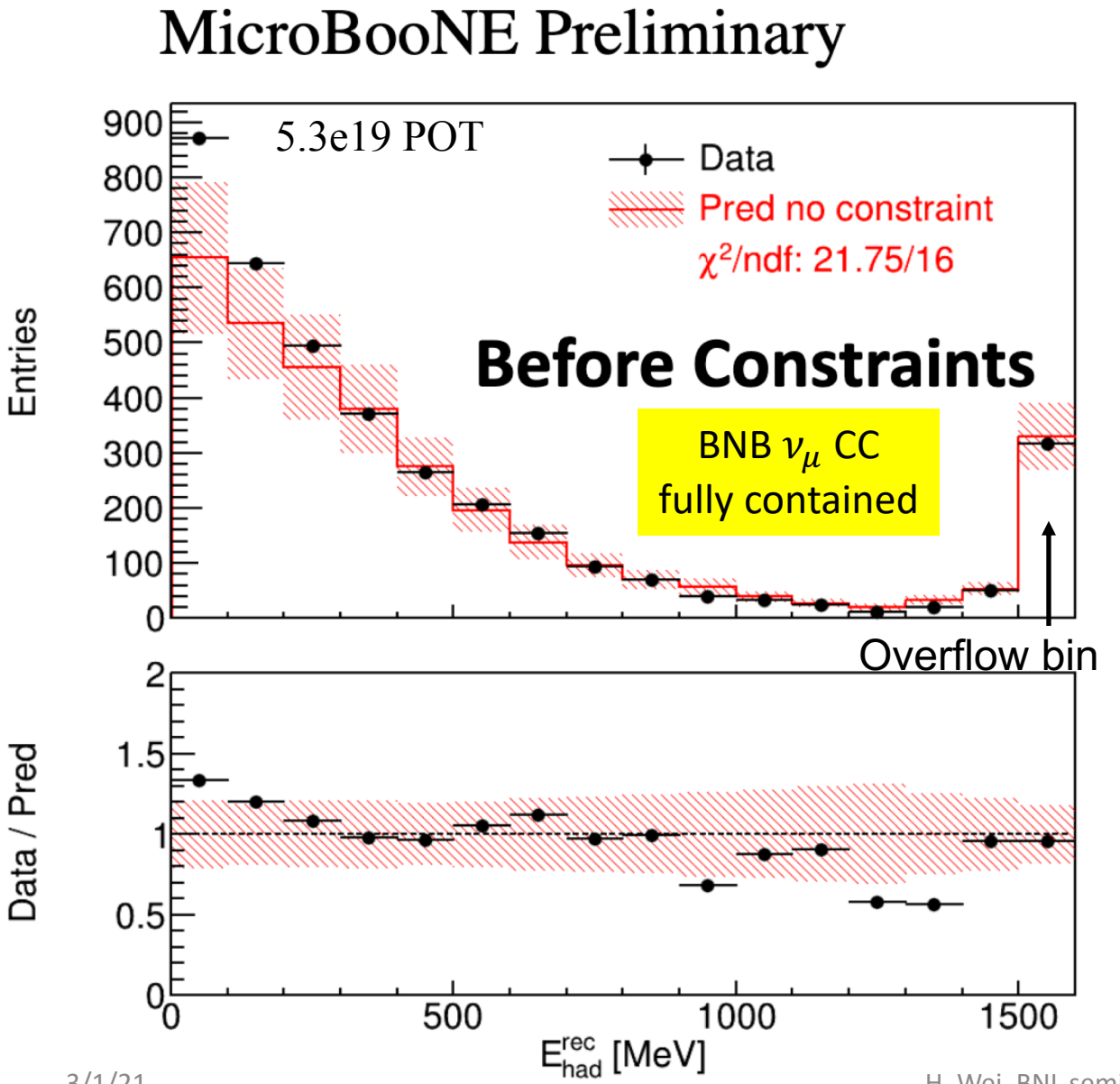
minimal/highly ionizing particle dE/dx

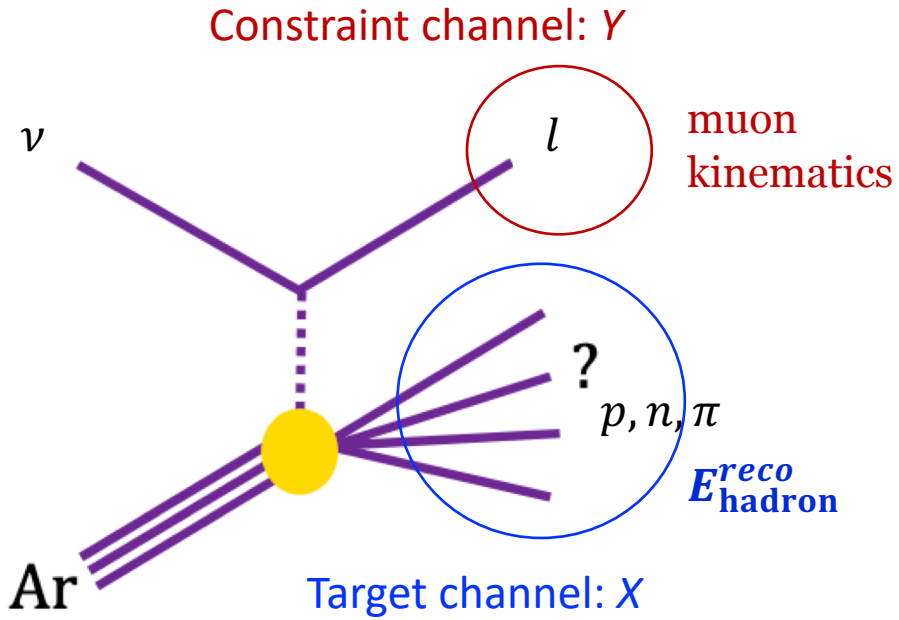
pi0 invariant mass (shower energy + open angle between the two decay γ's)





Validation of hadronic energy reconstruction

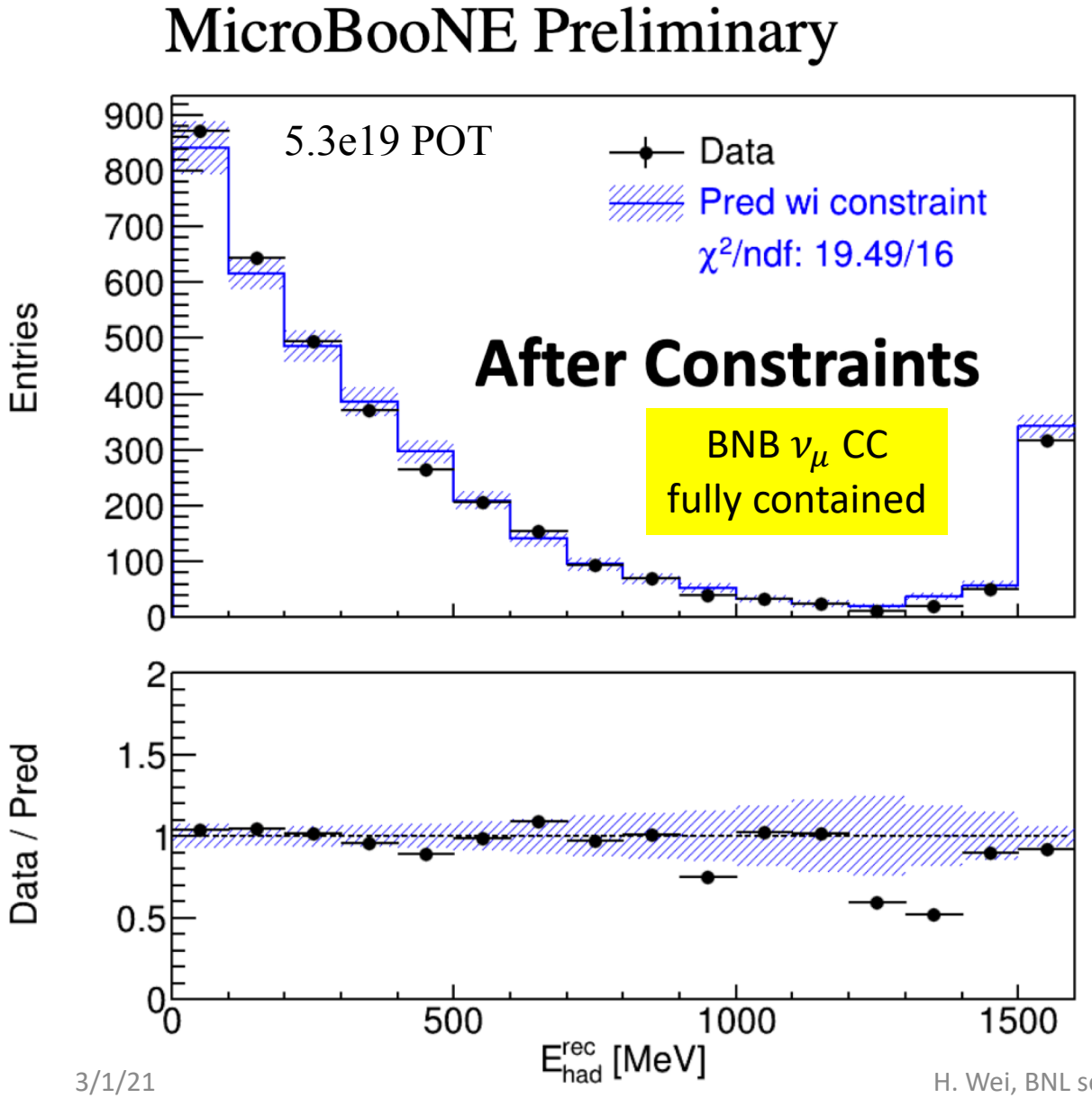




$$\mu^{X,constrained} = \mu^X + \Sigma^{XY} \cdot (\Sigma^{YY})^{-1} \cdot (n^Y - \mu^Y),$$
$$\Sigma^{XX,constrained} = \Sigma^{XX} - \Sigma^{XY} \cdot (\Sigma^{YY})^{-1} \cdot \Sigma^{YX}.$$

Data-driven correction on Monte-Carlo.

Validation of hadronic energy reconstruction



- Good agreement between data and MC within the residual systematic uncertainties after ***constraint*** from muon kinematics (E_μ and $cos\theta$)
- Hadronic energy response well modeled by Monte-Carlo

eLEE search

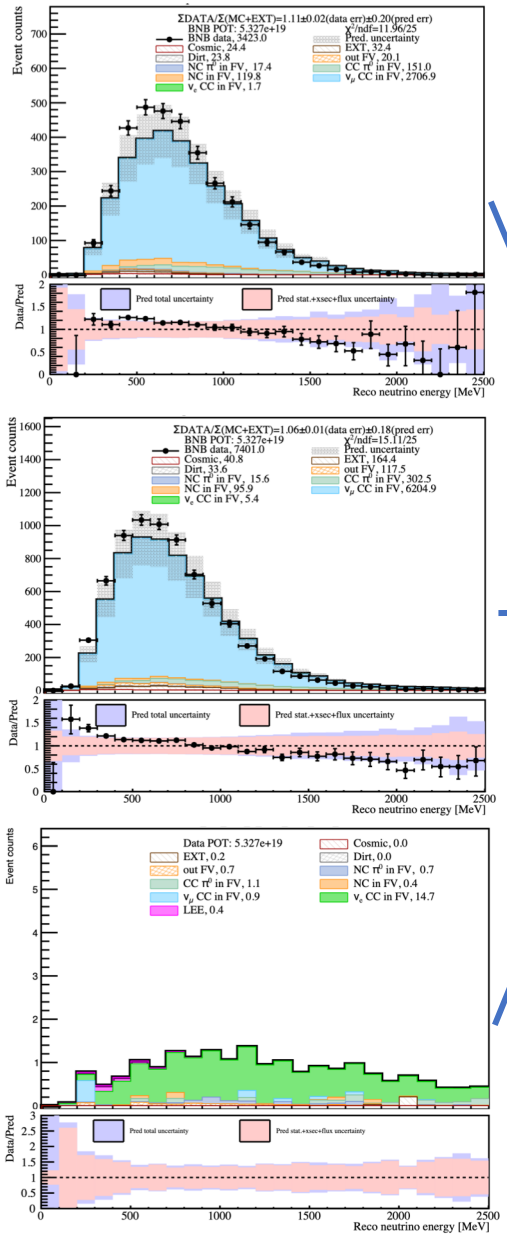
A single detector?

Signal Constraints

ν_μCC Full contained

ν_μCC Partially contained

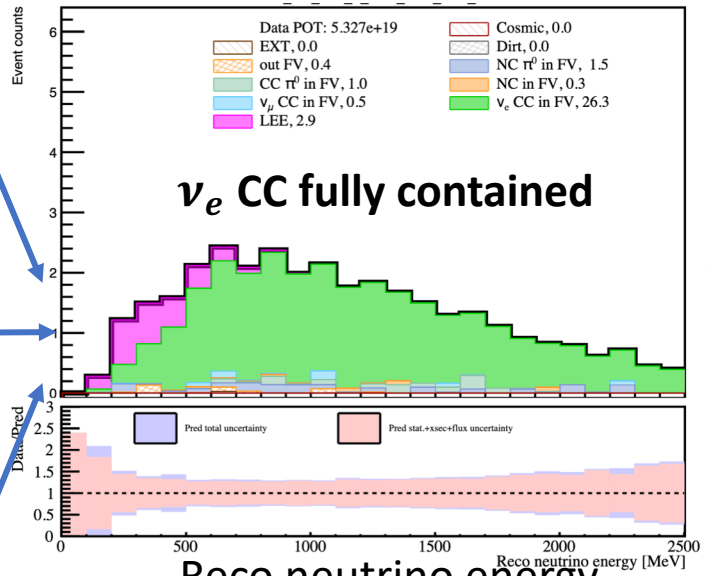
ν_eCC partially contained



Reco neutrino energy

MicroBooNE Preliminary

Search for eLEE



Reco neutrino energy

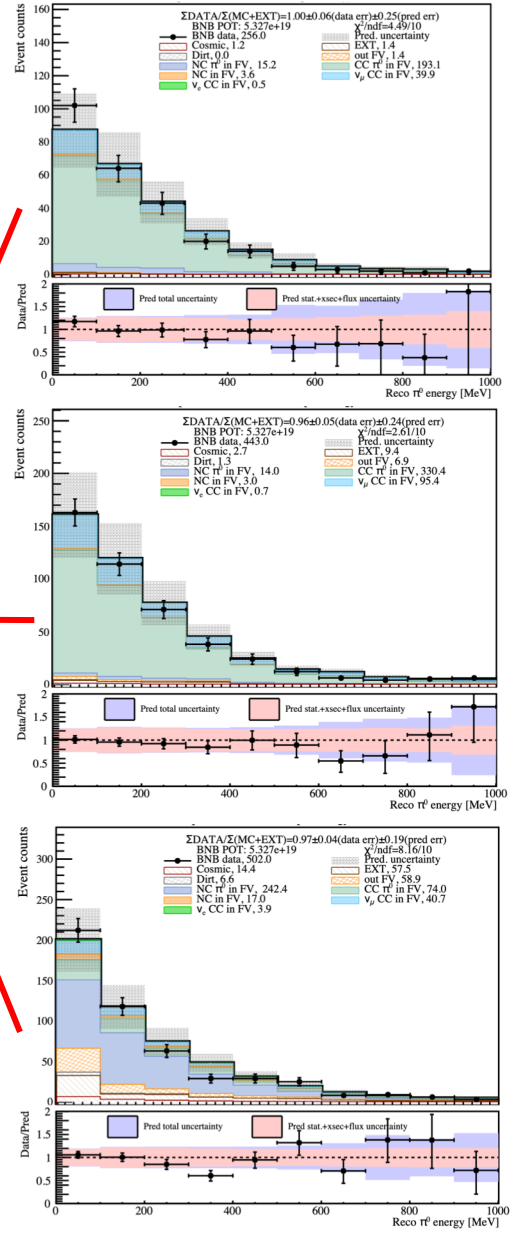
- $\nu_{\mu/e}$ CC constraint to suppress flux, xsec systematic uncertainties
- Partially contained ν_eCC not sensitive to LEE
- π^0 selection to constrain background

Background Constraints

CCπ^0 Fully contained

CCπ^0 partially contained

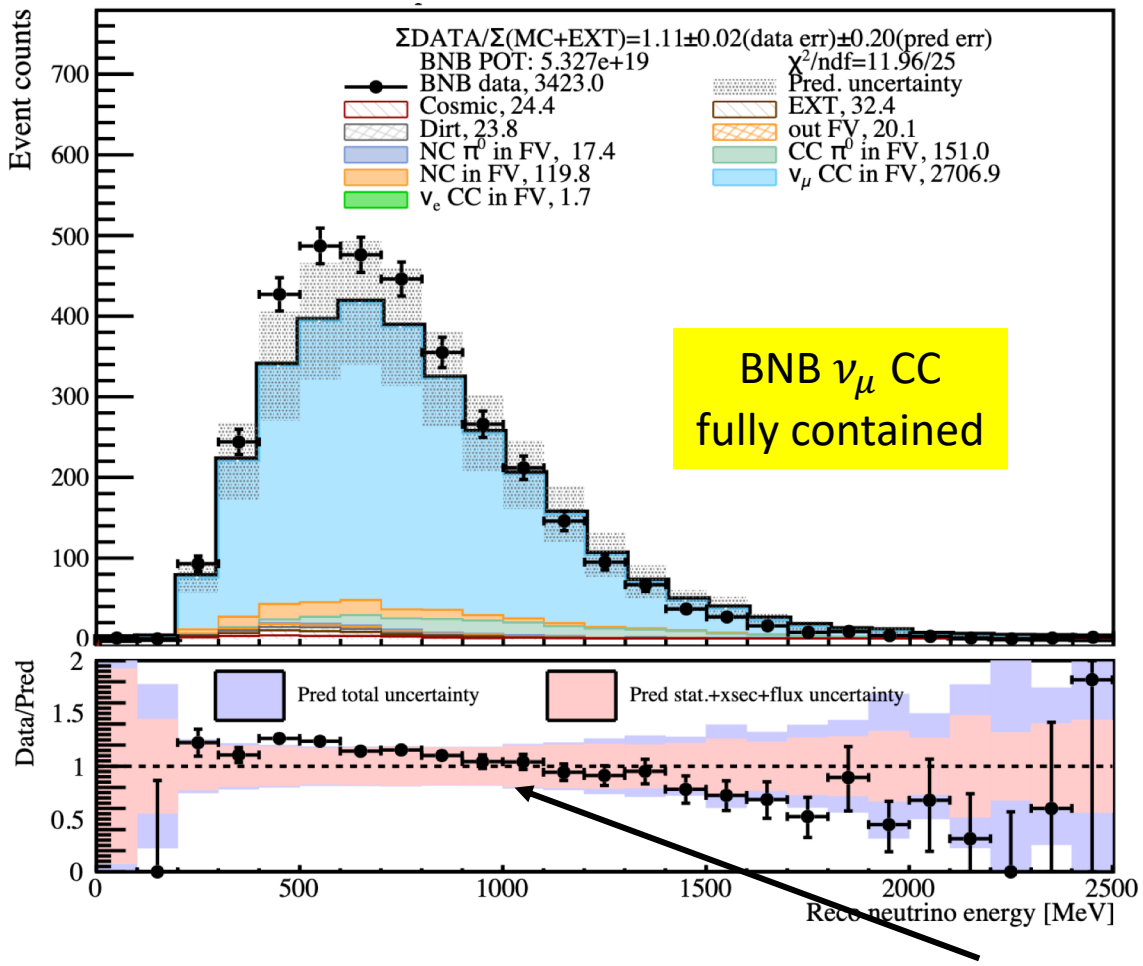
NCπ^0

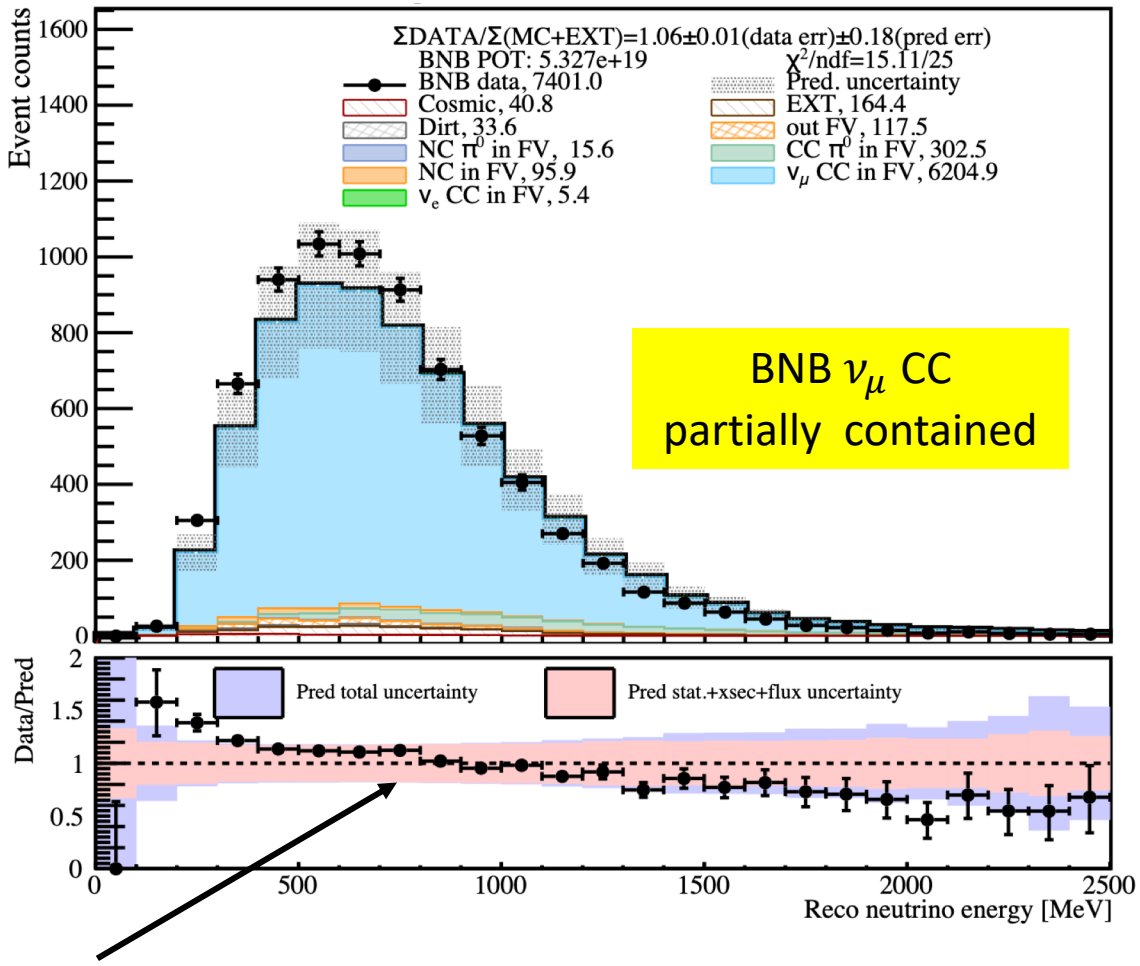


Reco pi0 energy

ν_μ CC selection (open data, 4% of full datasets)

Major constraint on cross section and flux

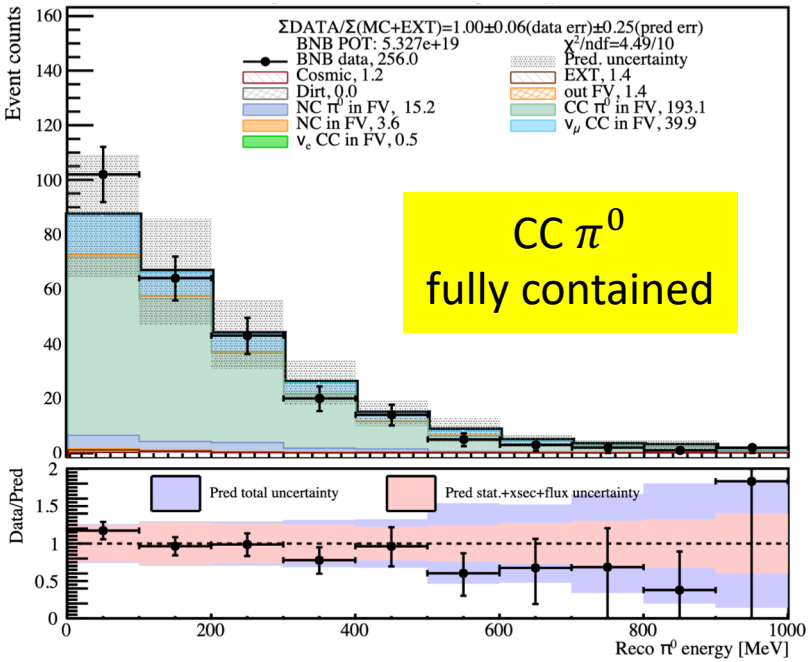


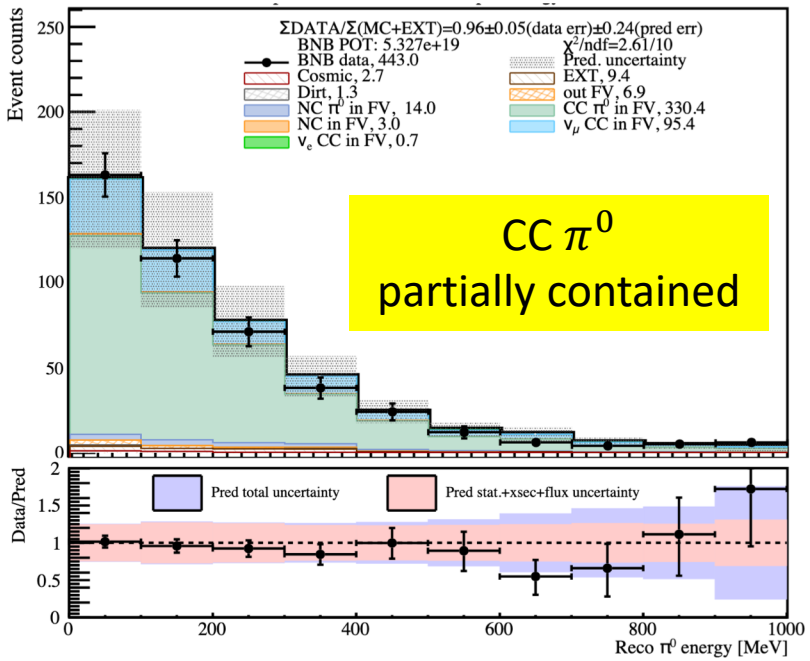


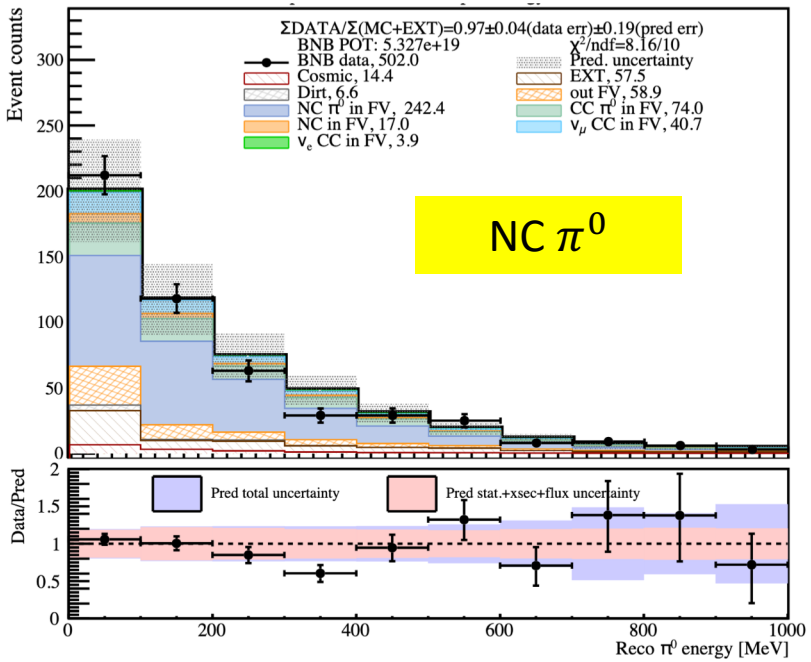
"Slope" indicates imperfect cross section model (discuss later)

π^0 selection (open data, 4% of full datasets)

Constraint on the predominant background in ν_e CC

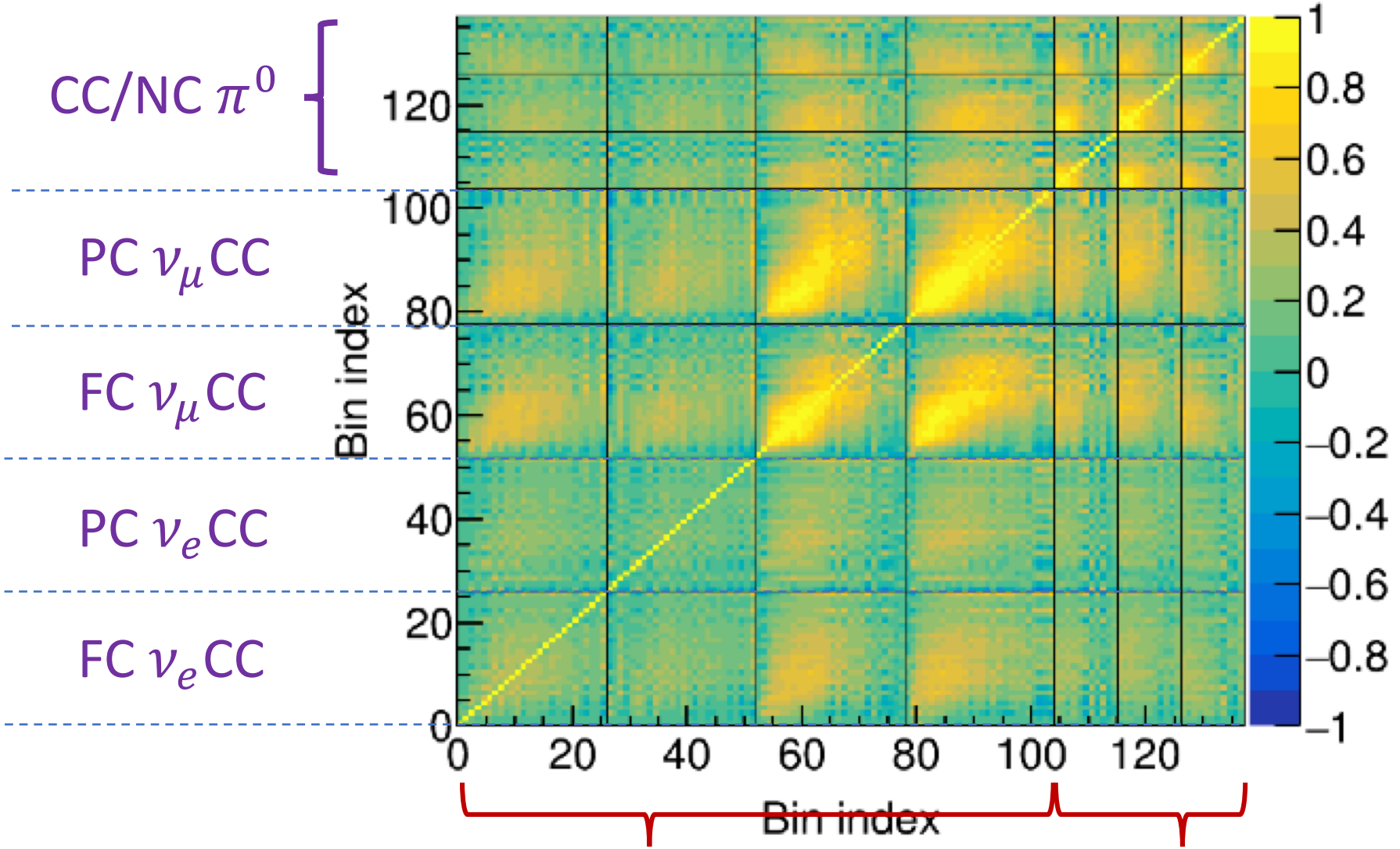






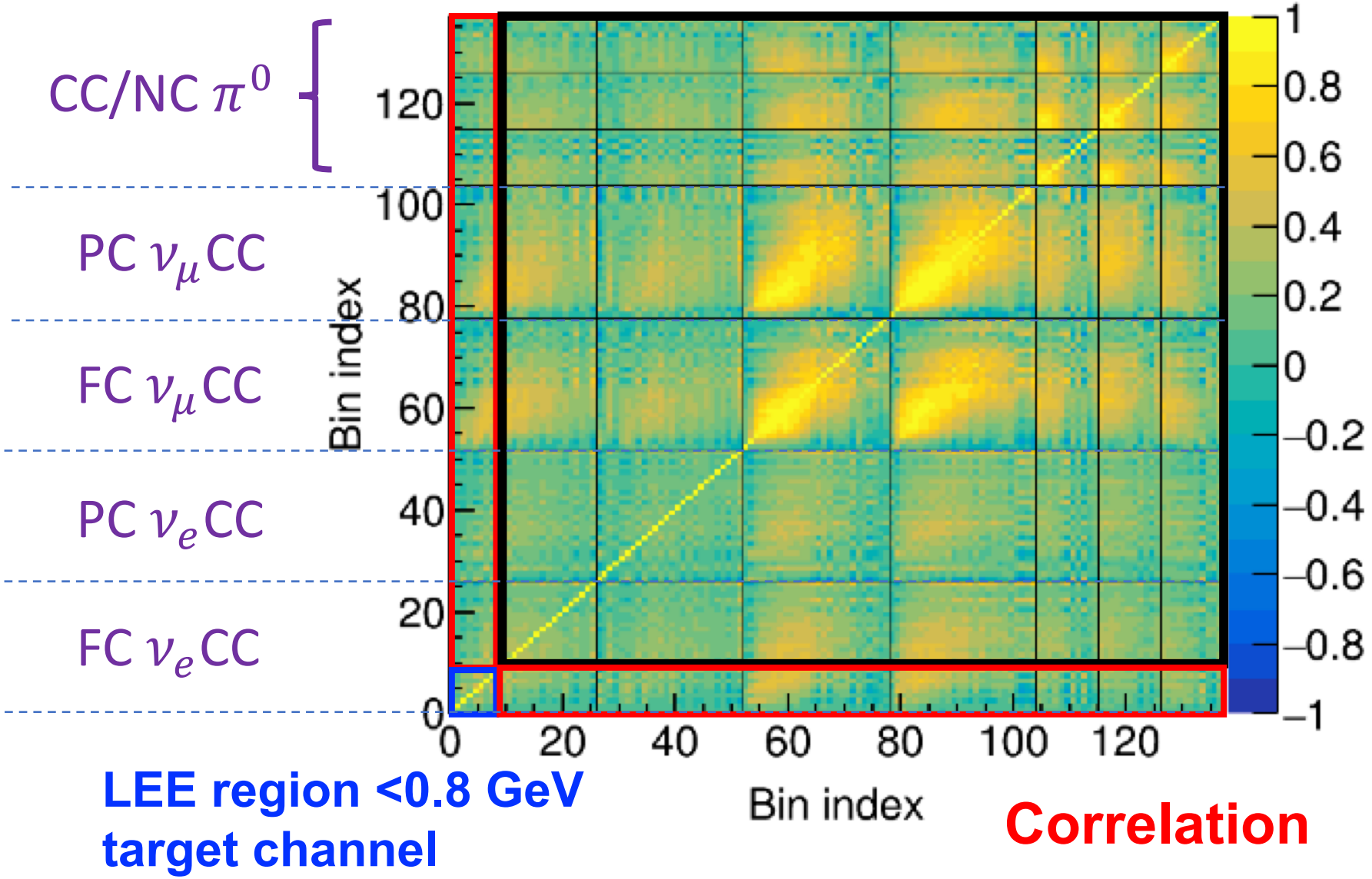
Overall a good agreement between data and Monte-Carlo

Total systematic uncertainty correlation matrix



- Key to 7-channel constraint
- Key to sensitivity calculation
- Key to final eLEE search

Total systematic uncertainty correlation matrix

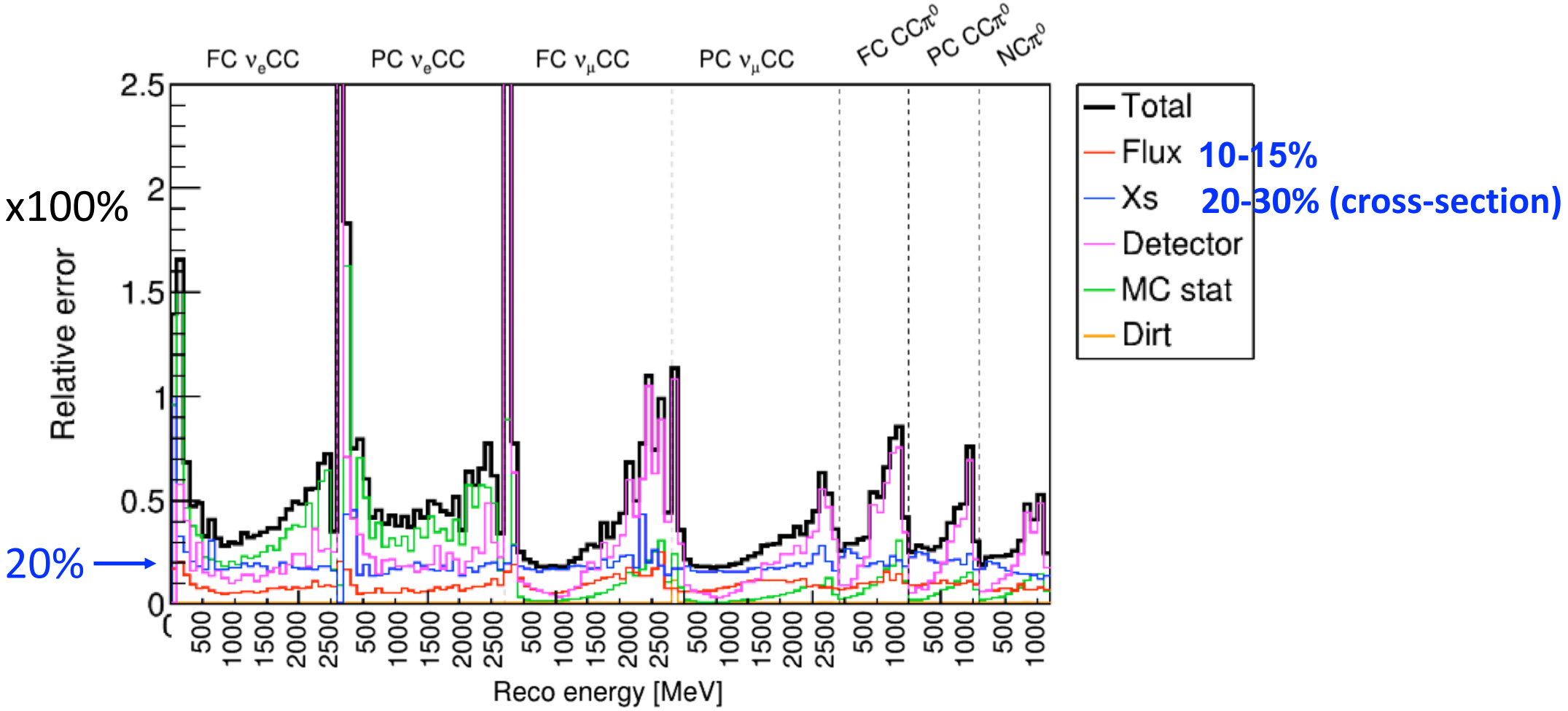


Constraint channels

LEE region <0.8 GeV target channel

Correlation

Systematic Uncertainties



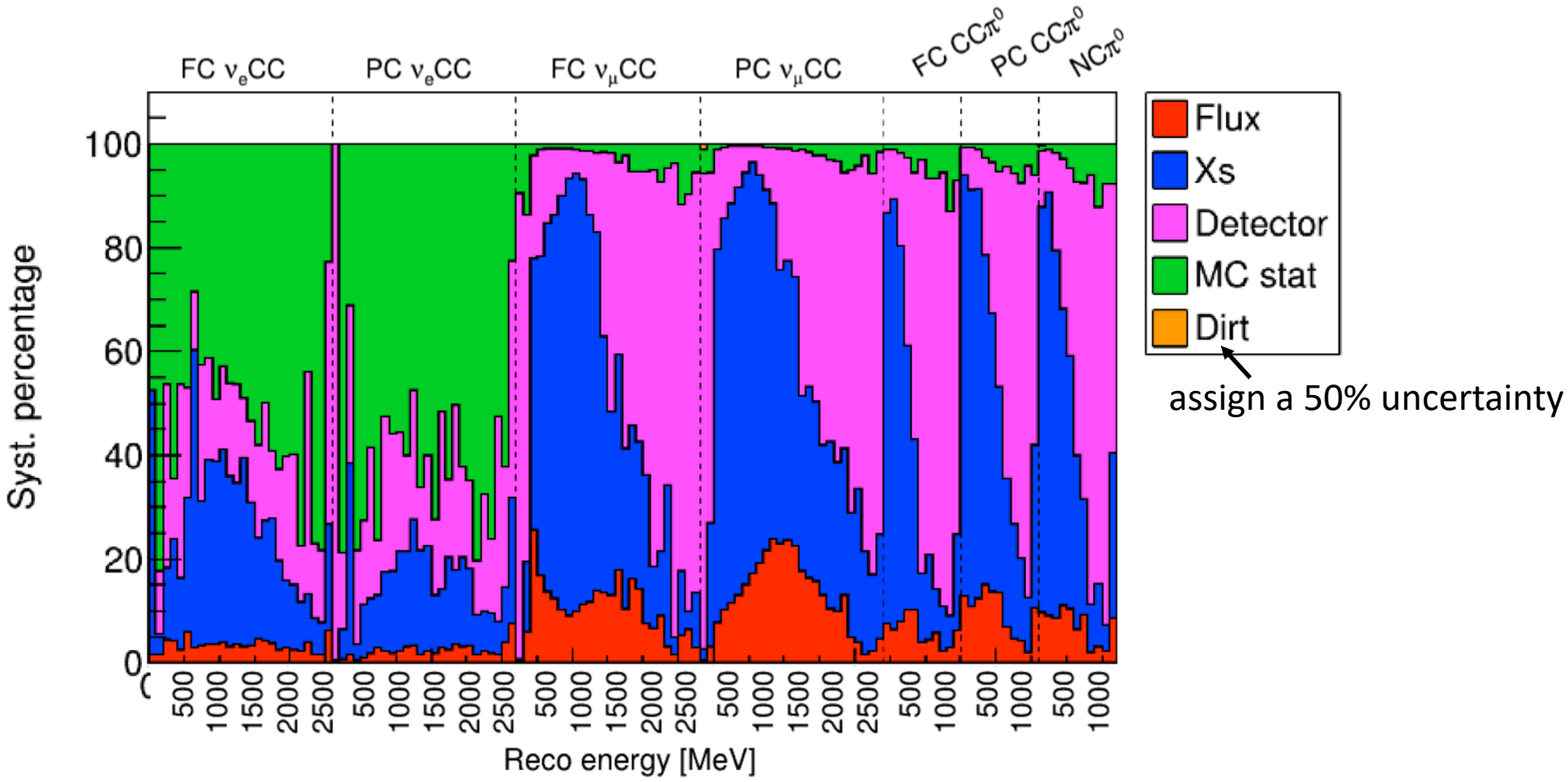
Systematic Uncertainties

Dominant systematic uncertainties:

ν_e CC: stat of MC

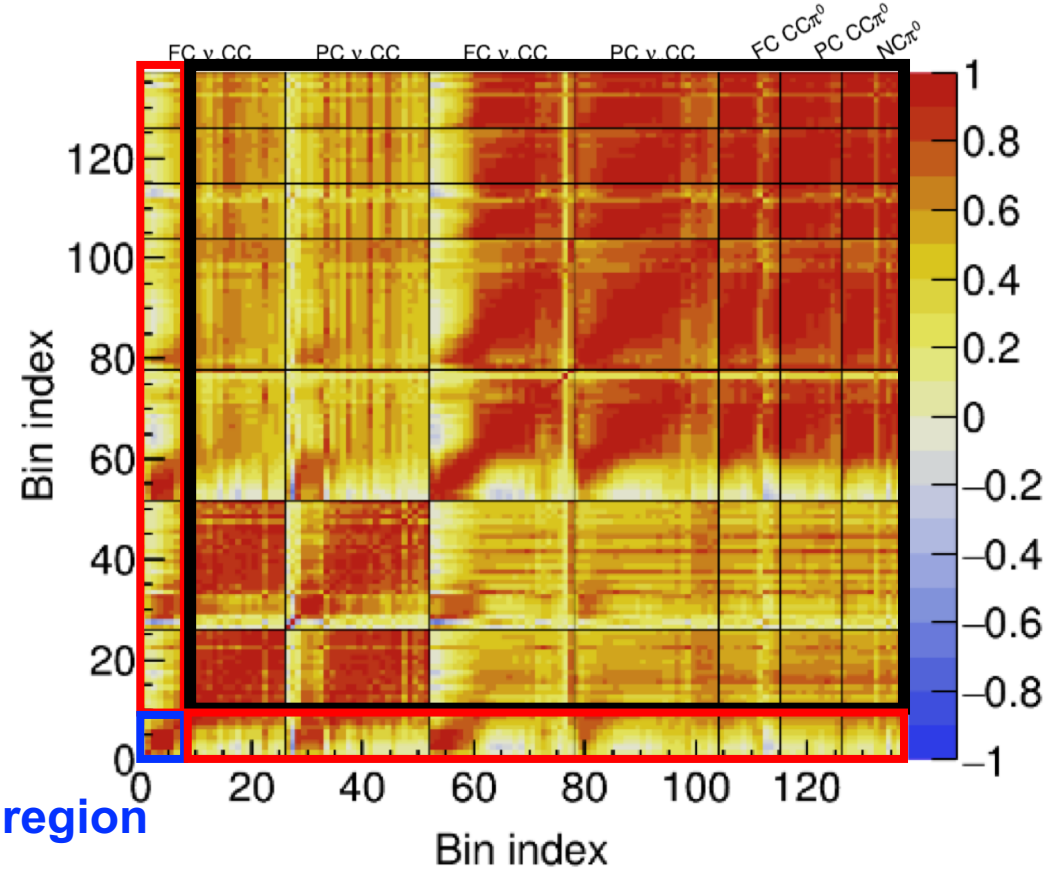
ν_μ CC:

- <1.5 GeV xsec
- >1.5 GeV detector (driven by low stat)

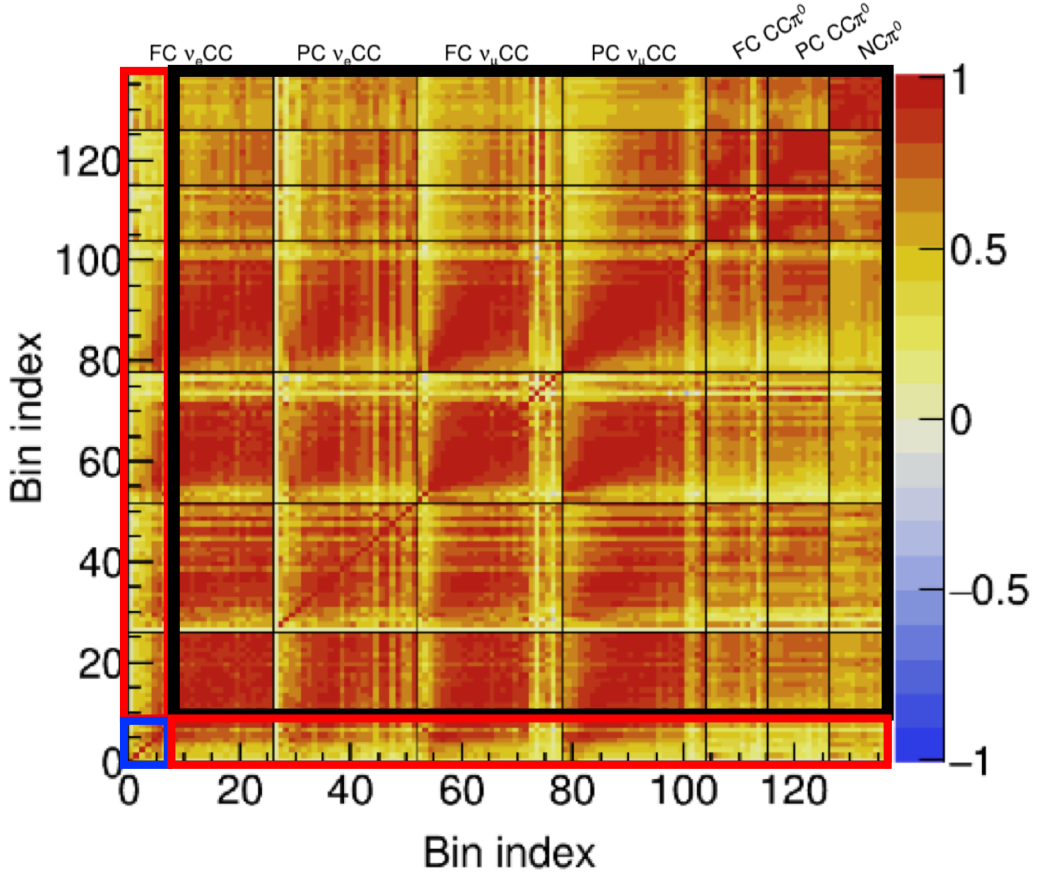


Cross section & Flux uncertainties

- Standard reweighting method using GENIE, Geant4, and flux knobs (parameters)



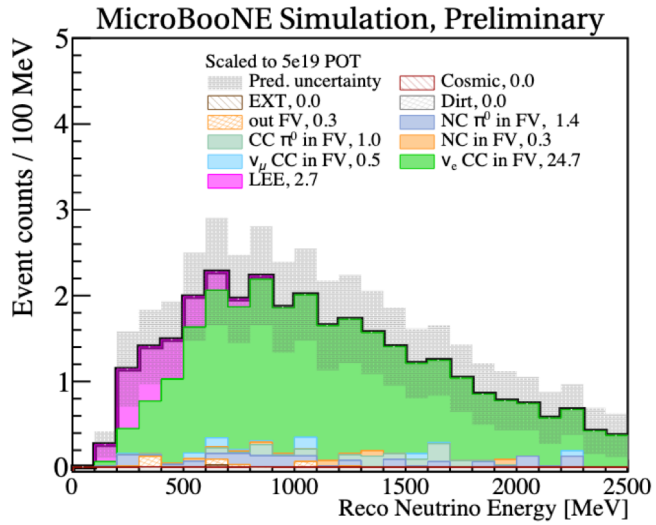
Flux uncertainty correlation matrix

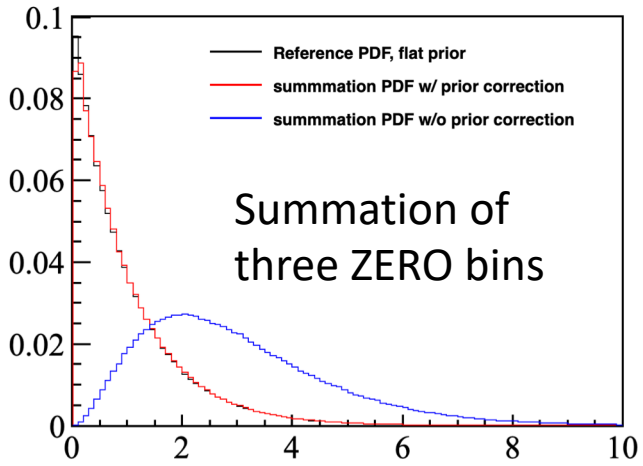


Xsec uncertainty correlation matrix

MC Bayesian statistical uncertainty

- Important “systematic” for Monte-Carlo central values
- Accurate for **low stat background** component, e.g.
  - Beam-off data (**EXT**)
  - Simulation of ν outside the cryostat (**DIRT**)
  - Other low stat background estimation from MC
- A procedure including
  - Posterior PDF calculation of compound Poisson distribution (POT scaling, event weight from GENIE)
  - Convolution of multiple components’ PDFs --> total PDF
  - Prior correction --> flat (uninformative) prior for total PDF
    - Error inflation in the summation of multiple low stat components
  - Normalization and uncertainty (68% credible interval) calculation

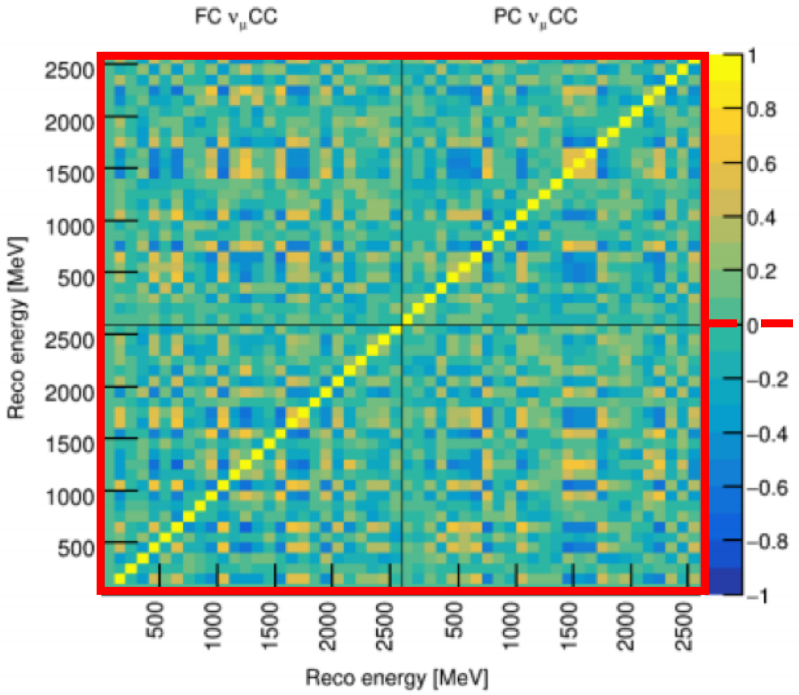




Detector systematic uncertainty

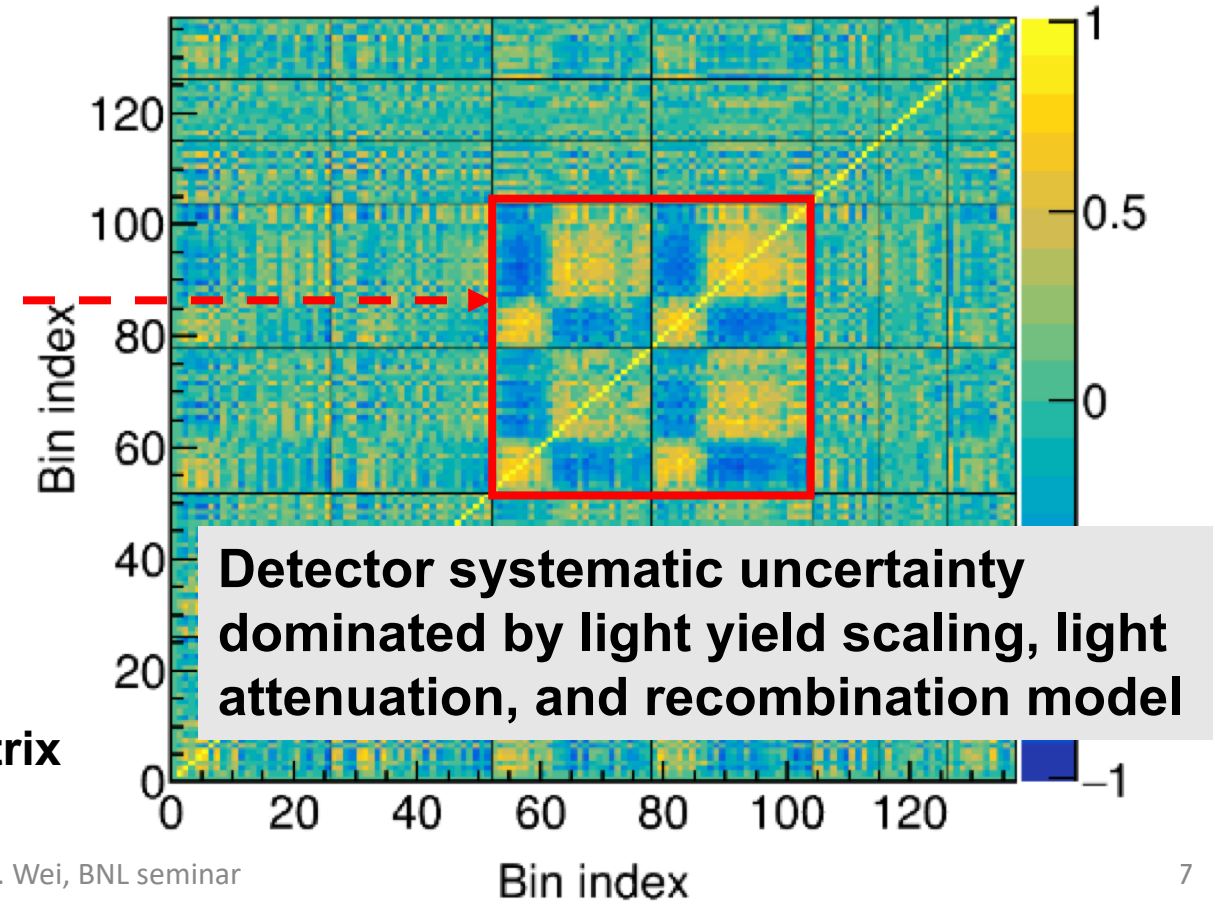
- **Bootstrapping** method to take into account the ”statistical fluctuation” in the finite statistics detector variation samples
- **Not misled by statistical effect when doing constraint**

Low-statistics detector variation samples



Detector systematic correlation matrix

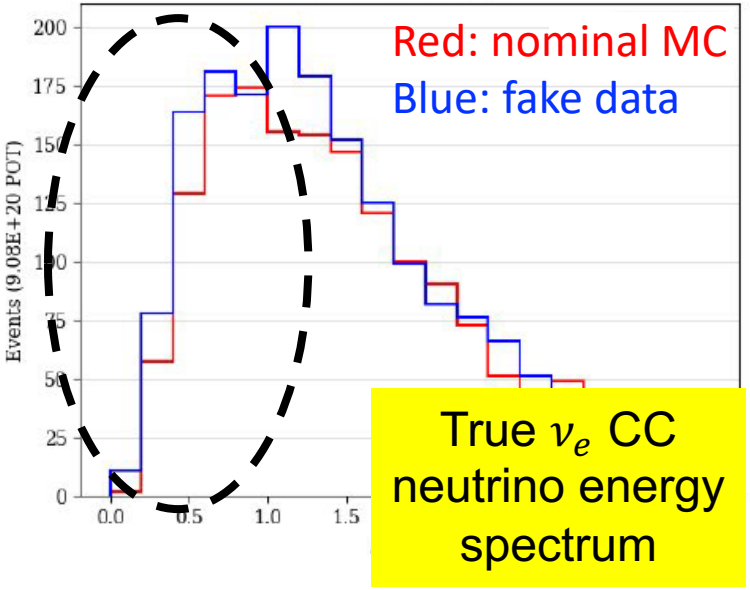
High-statistics (x10) detector variation samples



Detector systematic uncertainty dominated by light yield scaling, light attenuation, and recombination model

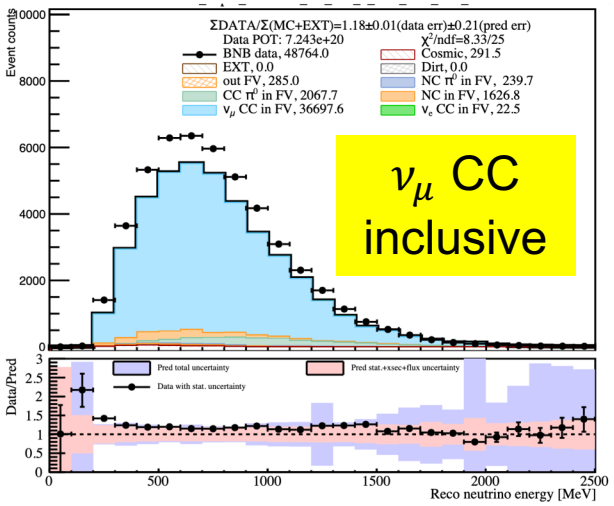
Fake data test on 7-channel eLEE search

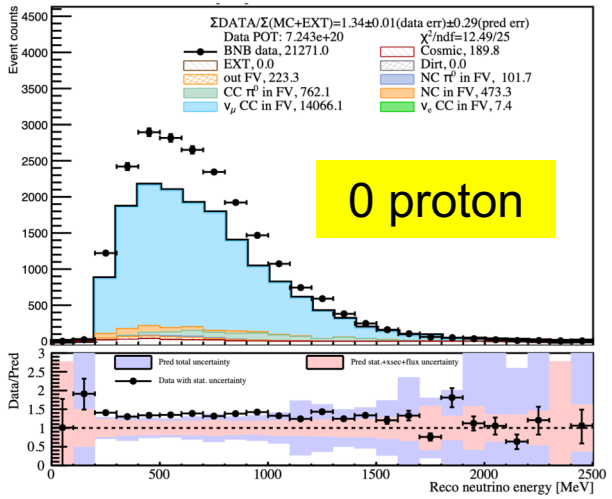
- With our full systematic uncertainty estimation and 7-channel strategy, do a LEE search in an artificially-generated "fake" dataset



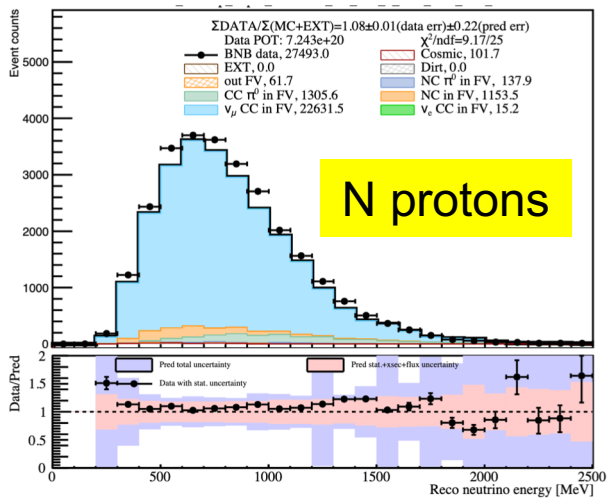
Different cross section modeling (GENIE v2):

- Enhancement of ν_μ CC for specific final-state topologies.
- Enhancement of low-energy ν_e CC
- **NO eLEE signal**

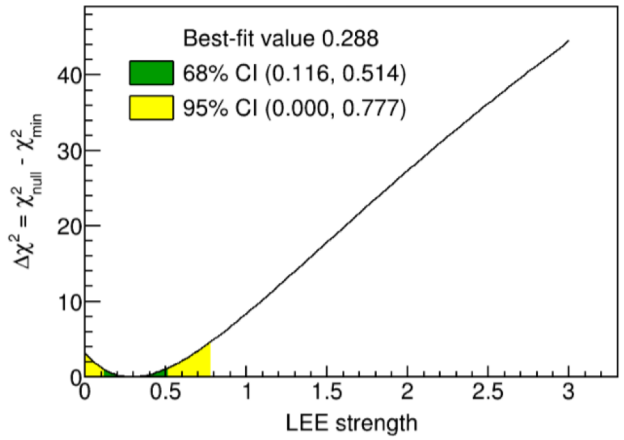


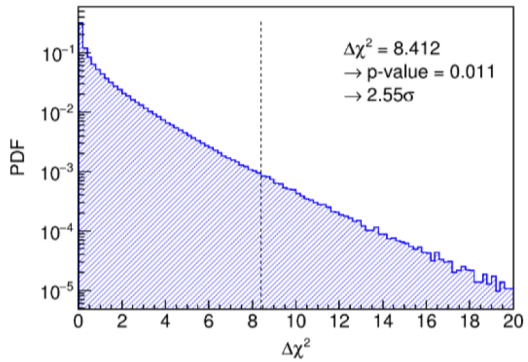


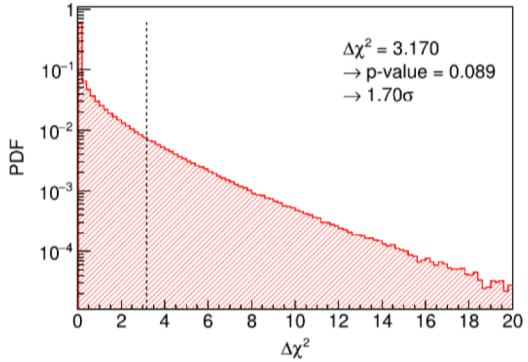
+



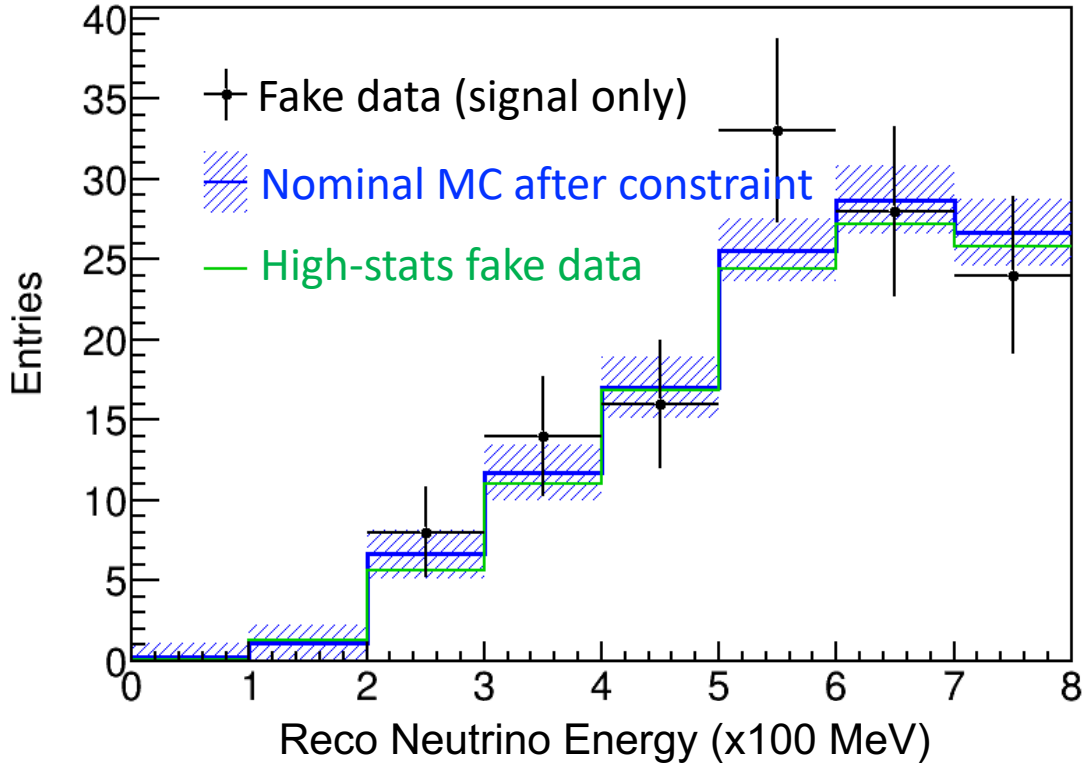
Fake data result







- **LEEx=1 (MiniBooNE LEE) is excluded at 98.9% CL.**
- Disfavor LEEx=1 at 2.6σ and favor LEEx=0 at 1.7σ



- Powerful constraint
- Unbiased ν_e CC selection (truth study)
- Other selection e.g. ν_μ CC and π^0 shows consistent results w.r.t. truth spectra

Sensitivity for eLEE

Assume the MiniBooNE LEE originates from $\nu_\mu \rightarrow \nu_e$ oscillation (sterile neutrinos), with

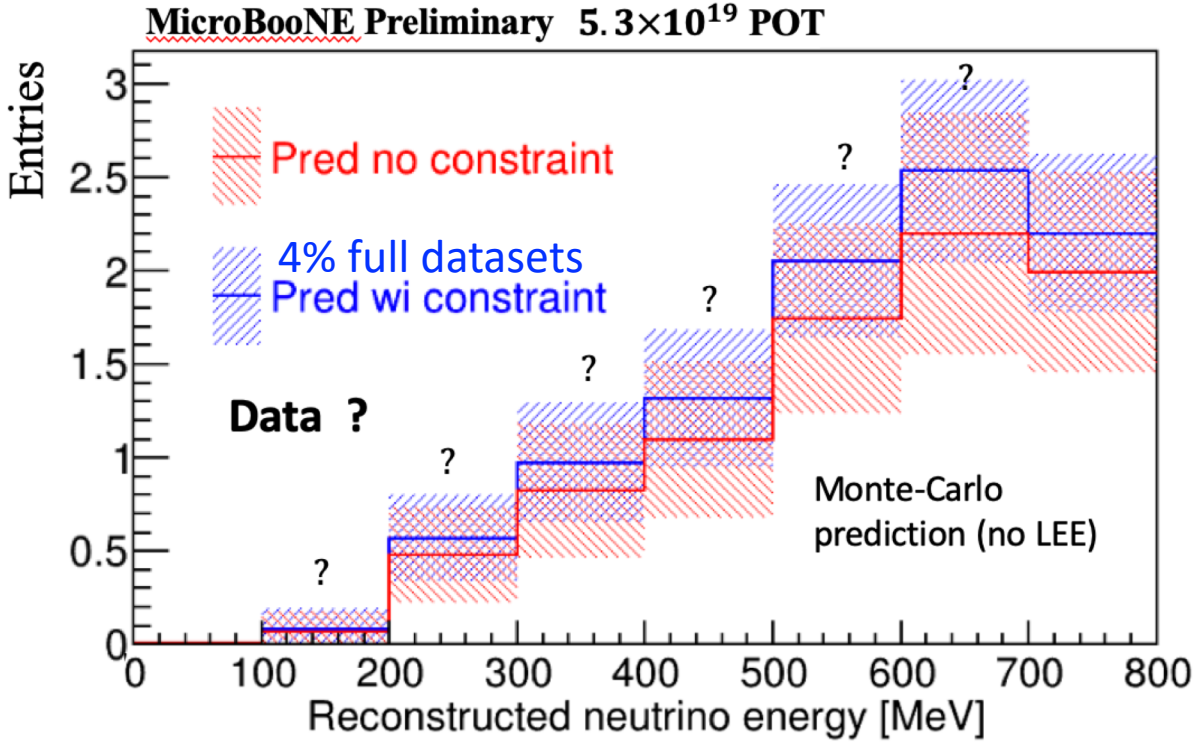
7×10^{20} POT data (three years):

41 excess ν_e events <600 MeV

66 ν_e events from the Standard Model prediction <600 MeV

Feldman-Cousins sensitivity with full systematic: not public

(to exclude LEEx=0 assuming LEEx=1)



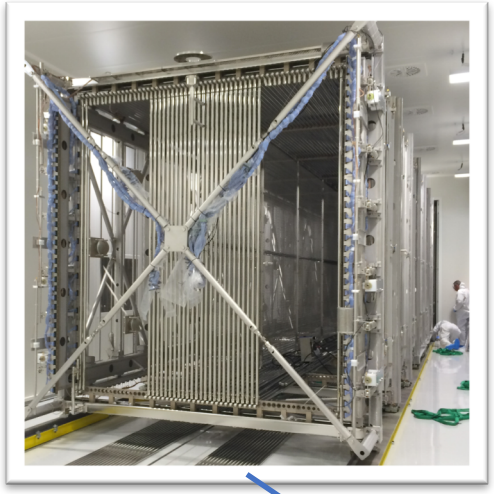
LEE-sensitive region

Fully contained ν_e CC < 800 MeV

LEE oscillation analysis

- Multiple detectors for a sensitive oscillation analysis
- Different oscillation effects

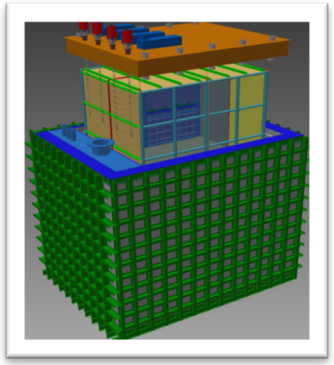
ICARUS T-600, 760 ton
moved to Fermi 2017

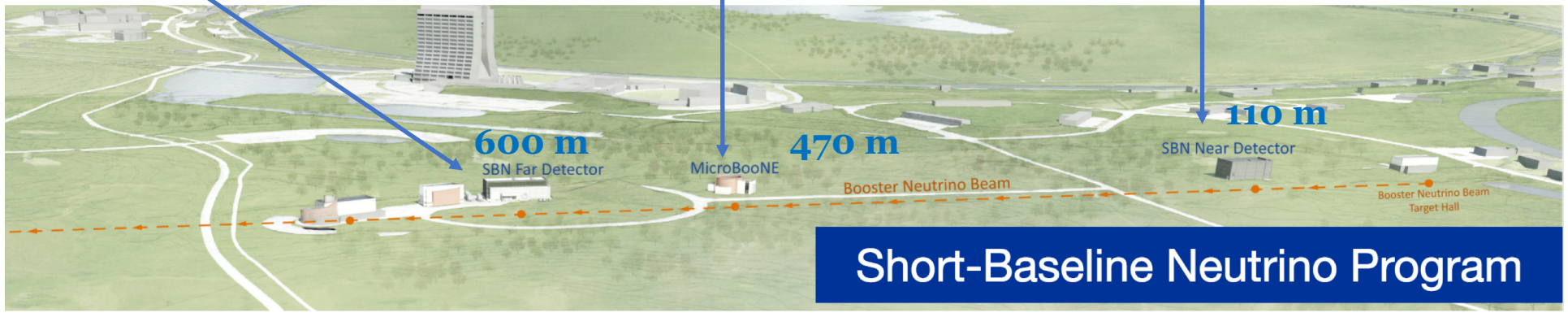


MicroBooNE 170 ton
2015-



SBND 112 ton

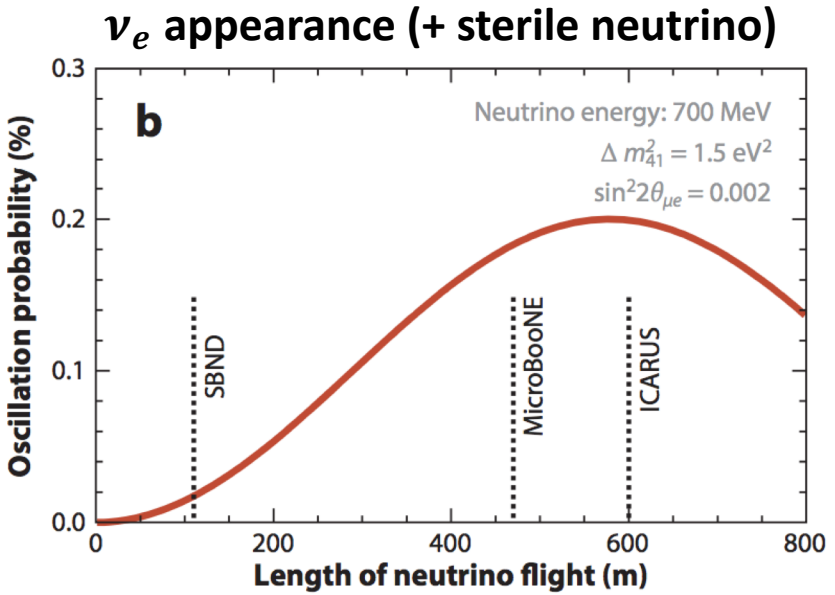


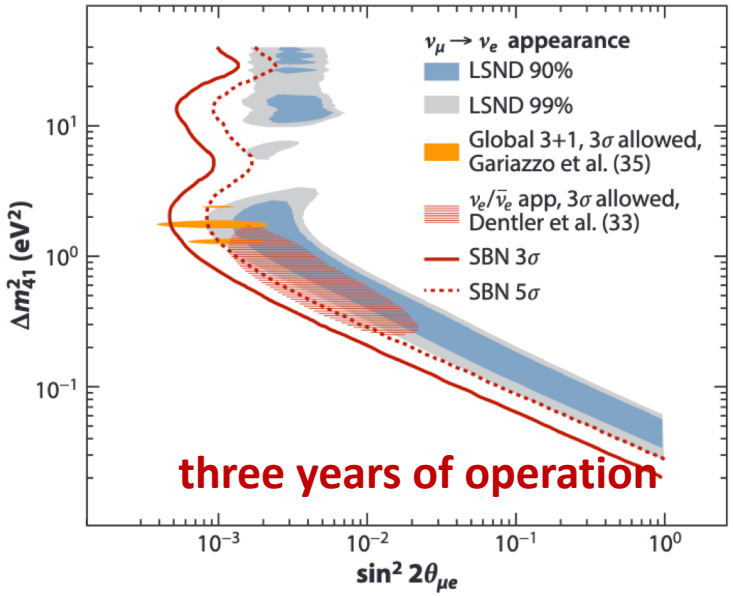


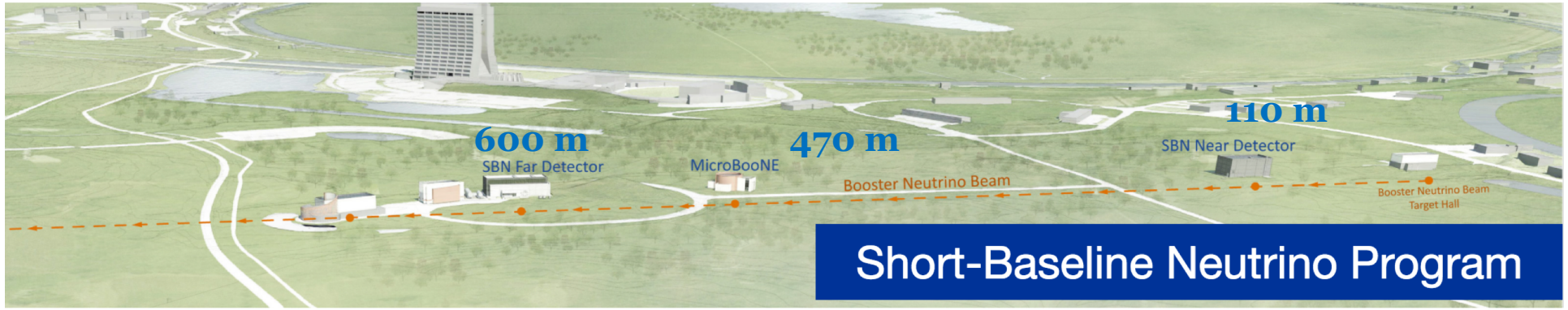
LEE oscillation analysis

- A powerful LEE oscillation analysis to provide a definite check on the existence of another flavor of neutrinos.

Annu. Rev. Nucl. Part. Sci. 2019. 69: 363-87

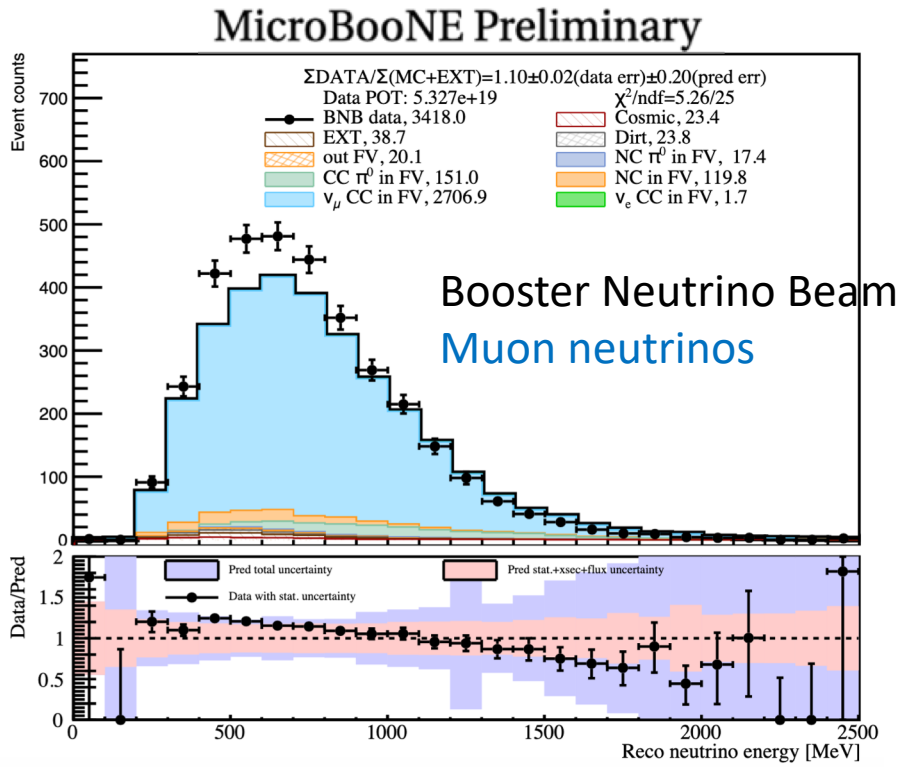






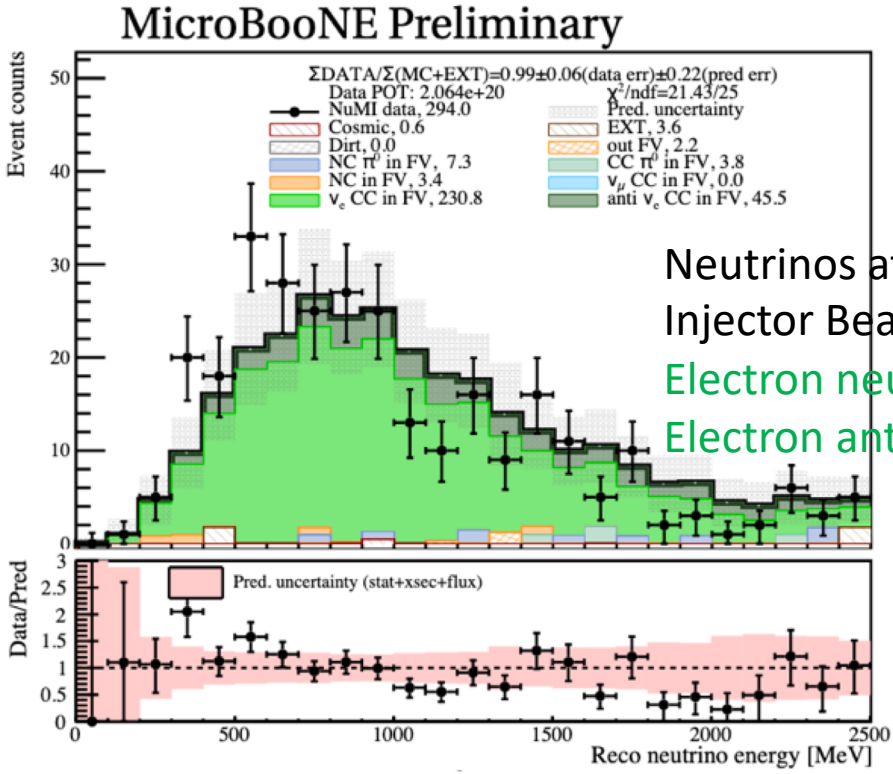
Other physics opportunities alongside the LEE analysis

Cross section measurement



Booster Neutrino Beam

Muon neutrinos



Neutrinos at the Main Injector Beam

Electron neutrinos

Electron anti-neutrinos

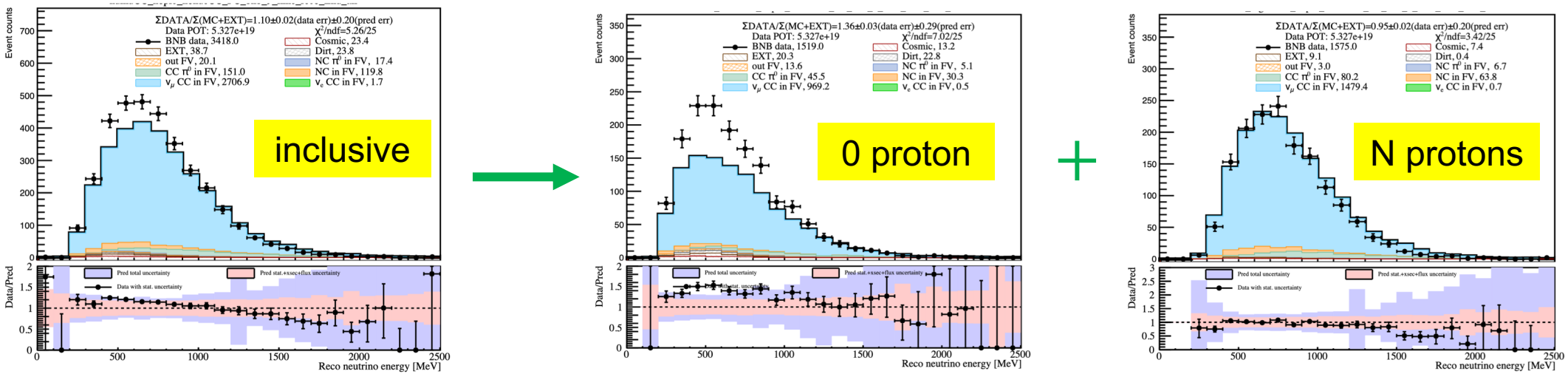
High-precision $\nu_\mu(\nu_e) - Ar$ cross section measurement

- High-statistics
- High-acceptance (fully active volume)
- Multi-dimensional (e.g. Q^2, x_{bj}, E_ν) measurement enabled by improved reconstruction

Observations from BNB ν_μ CC selection

- Not energy shift (leptonic and hadronic energy validation)
- Not flux issue
  - BNB vs NuMI (similar slope)
  - **Final states: 0 proton vs. N protons**
- **Cross section issue**
  - Similar to what we have seen in the fake dataset (GENIE v2)
  - Hints from T2K one-track and two-track ν_μ CC cross section measurement
- **Strong correlation between ν_μ CC and ν_e CC cross section modeling**

BNB open data (low-stat DetVar sample)



State-of-art Wire-Cell ν_e CC selection

PRD 102,011101(R) (2020) JHEP10 (2020) 114 L. Cremonesi, Neutrino 2020 talk

Intrinsic ν_e CC	MicroBooNE this work		ArgonNeuT	T2K near detector	NOvA near detector
Beam line	BNB @470 m	NuMI (FHC) off-axis	NuMI @1 km	J-PARC (FHC) @280 m, off-axis	NuMI @1 km, off-axis
Purity	84%	91%	79%	53%	N/A
Efficiency	42%	37%	10%	27%	N/A
# of ν_e CC /1e20 POT	84 (85 tons)	190 (85 tons)	10 (120 kg)	36 (1 ton)	1200 (300 tons)

DUNE TDR

oscillated ν_e CC	DUNE far detector
Beam line	LNBF @1285 km
Purity	90%
Efficiency	>85%
# of ν_e CC /1e20 POT	10 (10 ktons)

- Deep underground
- Enhancement (x10) of ν_e after oscillation
- 2-5 GeV
- Simulation study

Summary

- Wire-Cell end-to-end reconstruction and neutrino selection chain has been established at MicroBooNE. The inclusive ν_e CC selection has an outstanding performance with **42%** efficiency and **84%** purity.
- Will provide a definite answer to the question if the MiniBooNE low-energy excess originates from ν_e events after MicroBooNE data unblinding (this year?!)
- Expect a combined LEE oscillation analysis with other short-baseline neutrino experiments (using Wire-Cell or others), to provide a definite answer to the question if the LEE originates from sterile neutrinos.
- New physics opportunities: high-impact $\boldsymbol{\nu_\mu(\nu_e)}$ – $\boldsymbol{Ar}$ cross section measurements
- All these efforts well fit to the next-generation LArTPC experiment – DUNE.

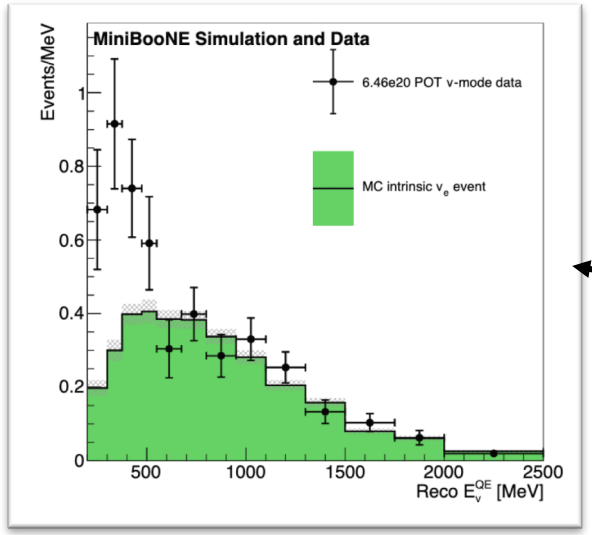
Thanks for your attention!

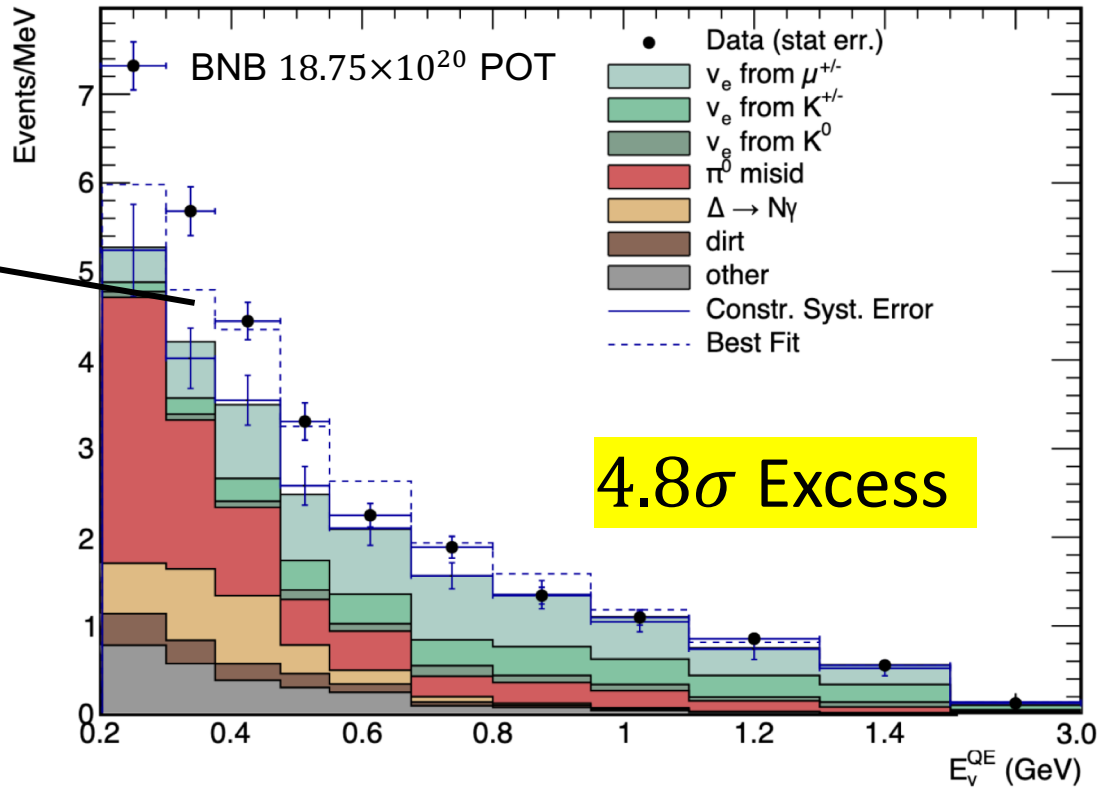
Backup slides

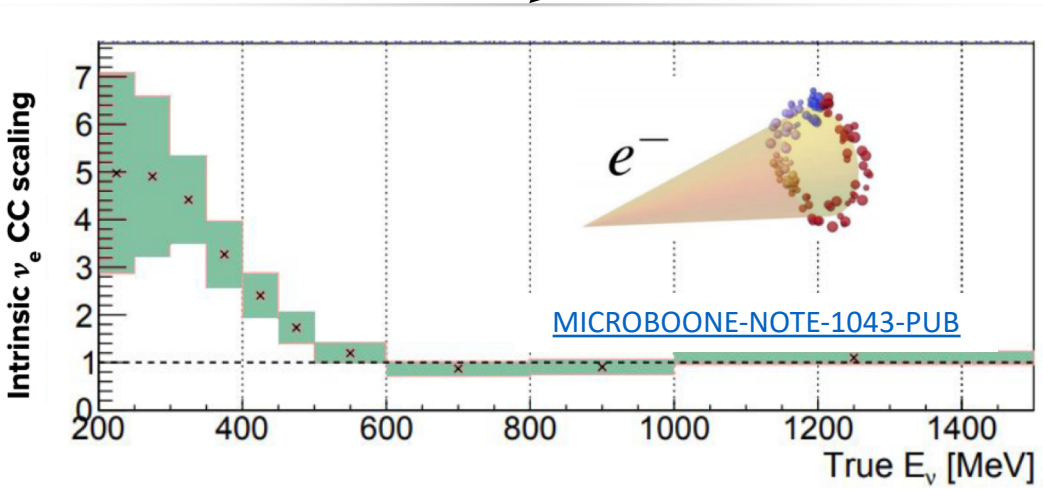
MicroBooNE electron-like LEE prediction

arXiv: 2006.16883

MiniBooNE electron-like excess unfolding

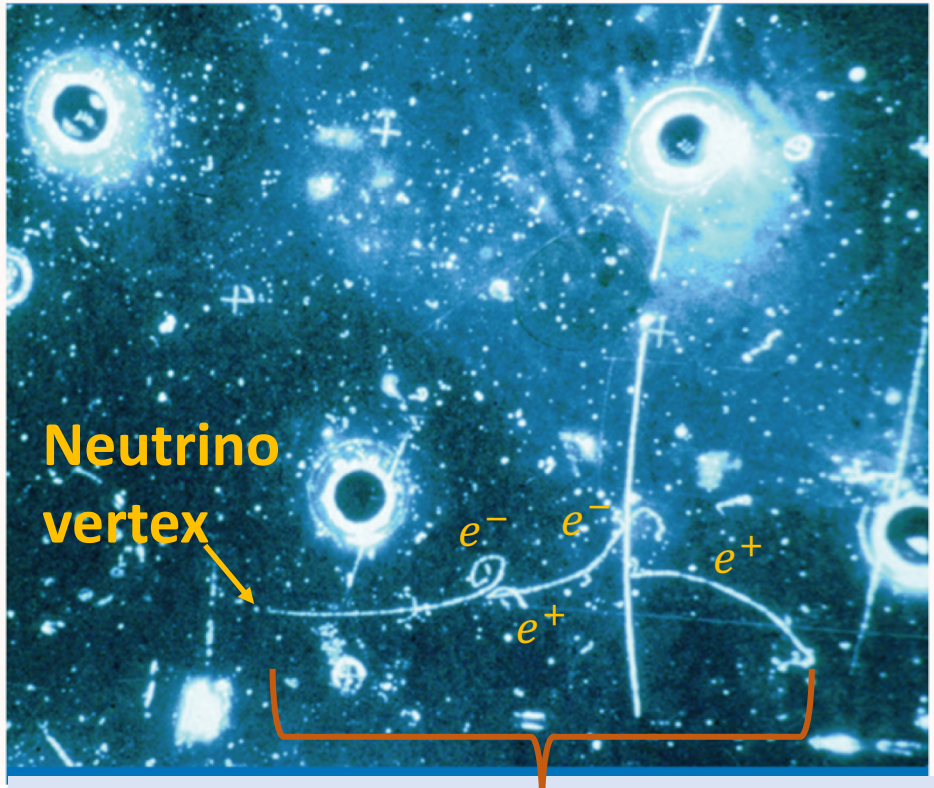






Applying this low-energy excess / beam intrinsic ν_e CC ratio to MicroBooNE → eLEE prediction

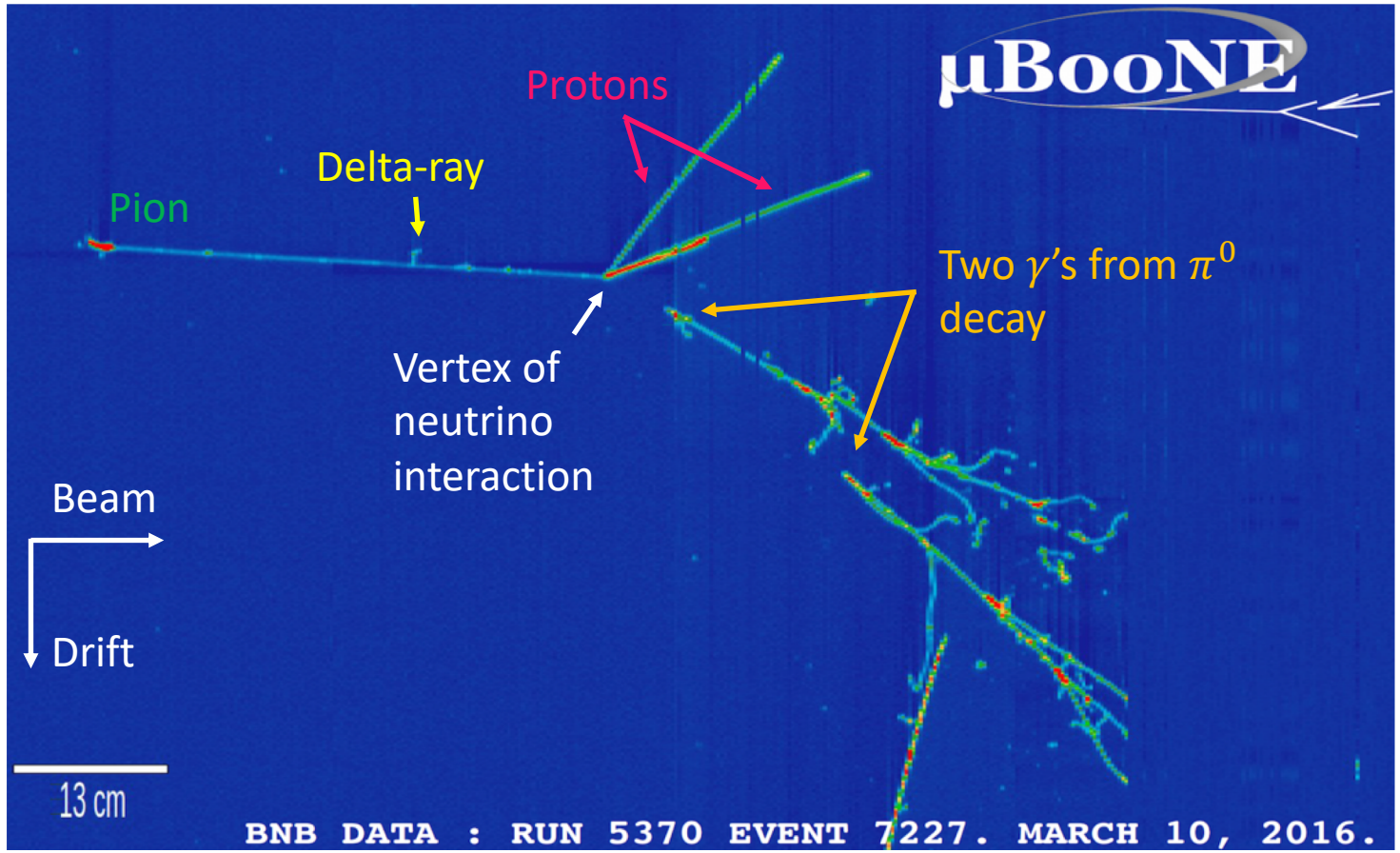
Bubble chamber



$e^- \rightarrow \mathbf{Brems.}\gamma \rightarrow e^+e^- \rightarrow \ \ldots$

Gargamelle (1973): discovery of weak neutral current [$\nu_\mu e^- \rightarrow \nu_\mu e^-$]

Liquid Argon Time Projection Chamber (LArTPC)

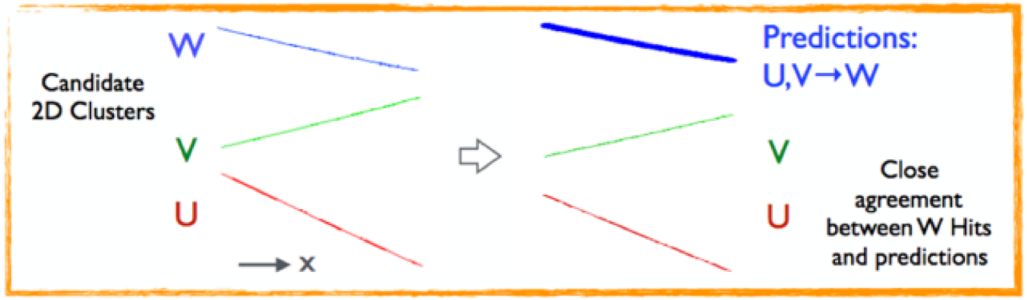


MicroBooNE (2016): neutral-current $\nu - Ar$ interaction

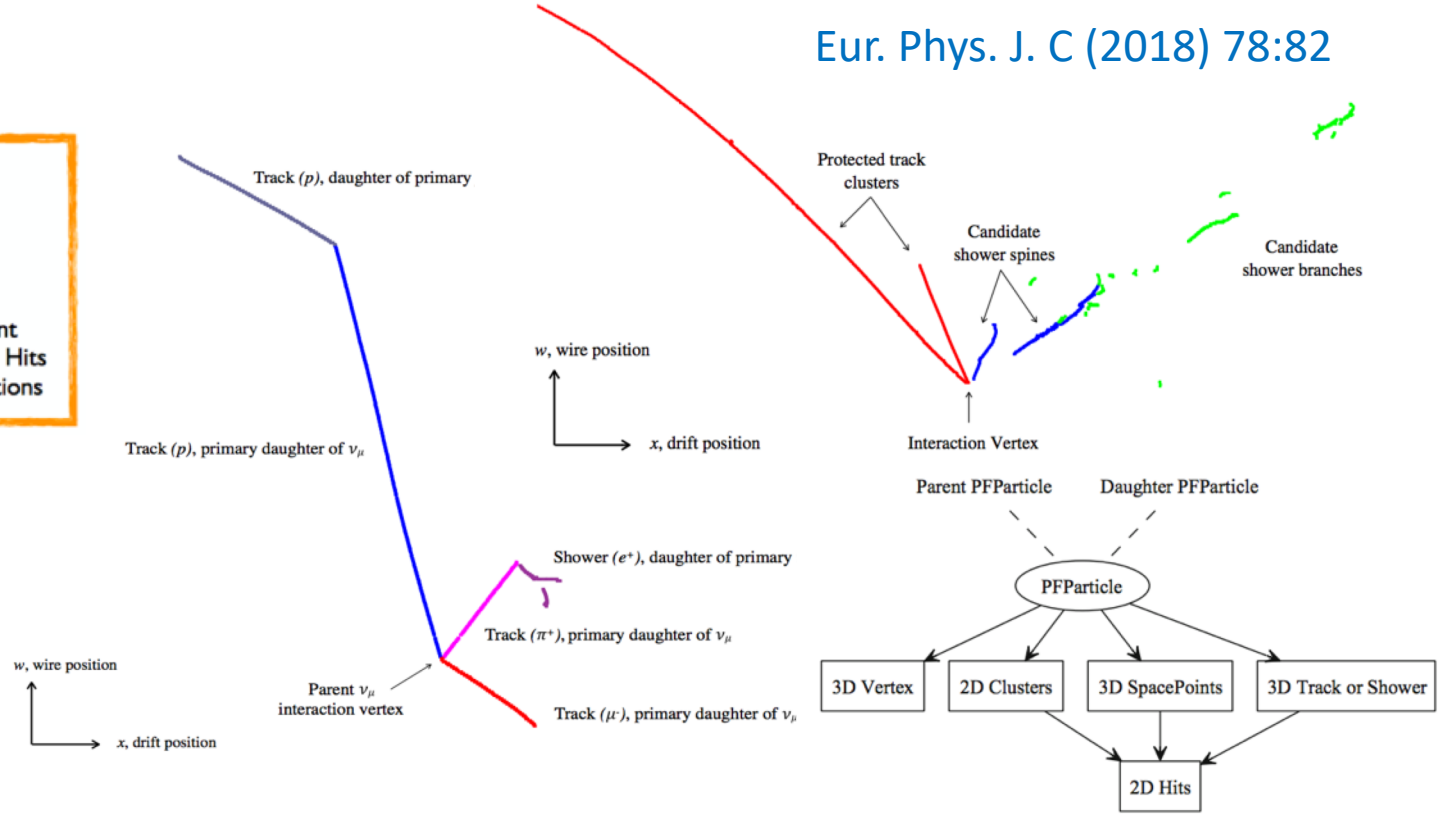
Paradigm 2: Pandora 2D Reconstruction

- **Traditional** reconstruction algorithms
- Sophisticated pattern recognition software originally developed for application of Particle Flow Calorimetry for future linear collider experiments

Matching 2D patterns into 3D



Eur. Phys. J. C (2018) 78:82

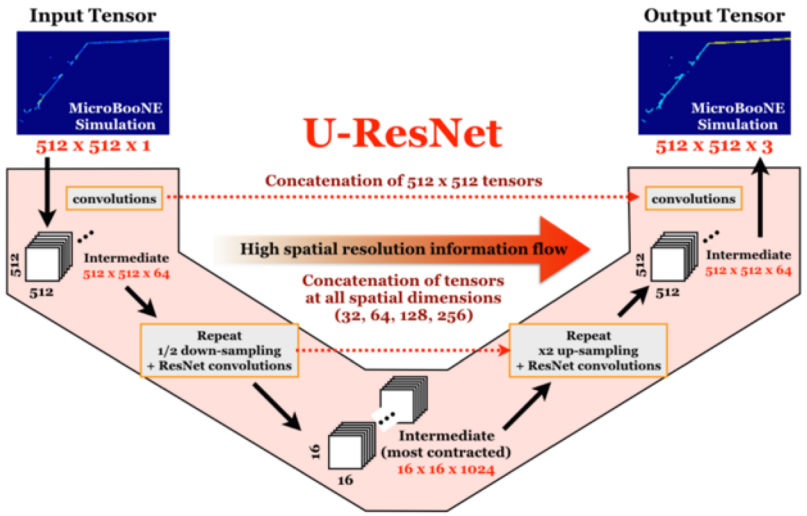


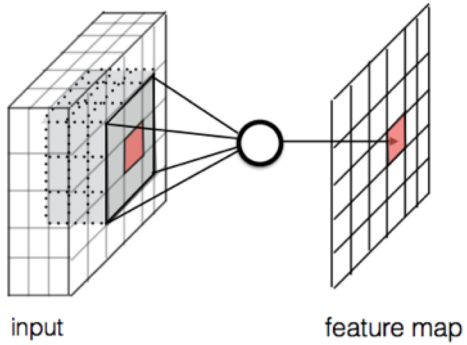
Neutrino vertex finding
Track/shower identification
Particle flow

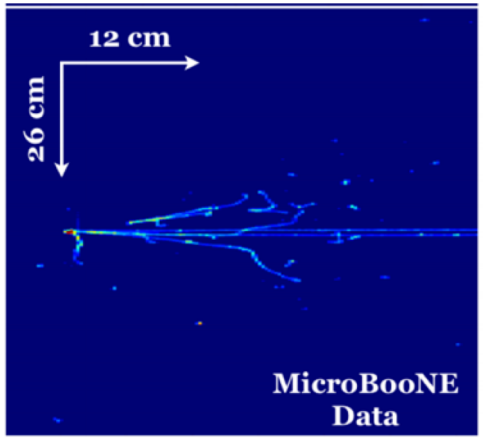
Paradigm 3: Deep Learning 2D Reconstruction

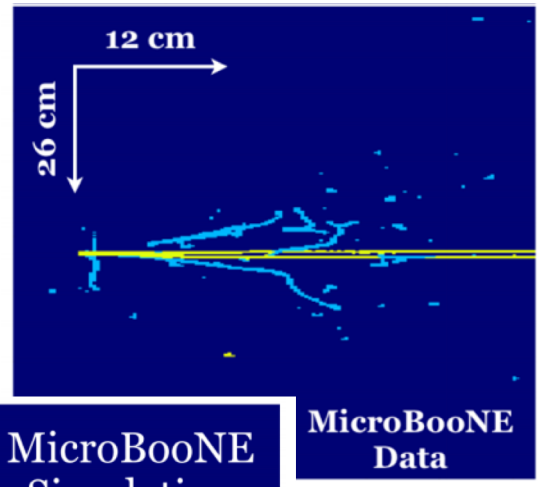
- In particular, Convolutional Neural Networks (CNNs)
- Scalable technique, generalizable to various tasks
- Superb performance on image data analysis

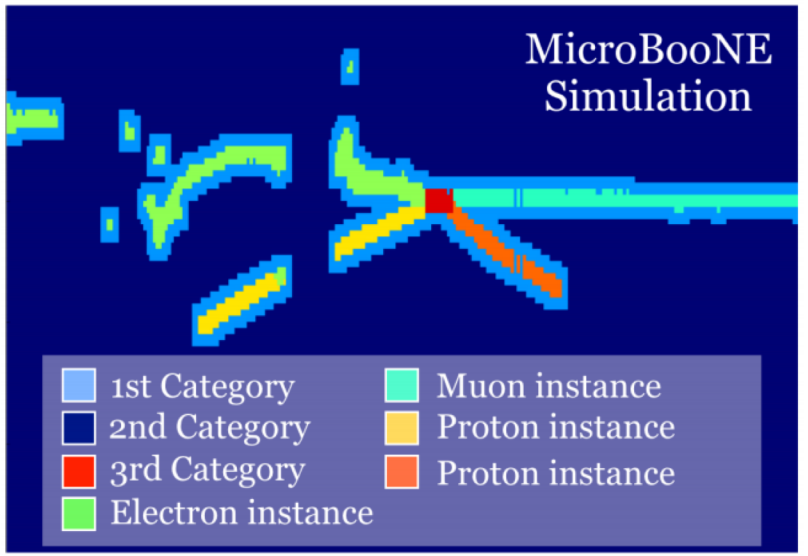
1. 2017 JINST 12 P03011
2. Phys. Rev. D 99, 092001







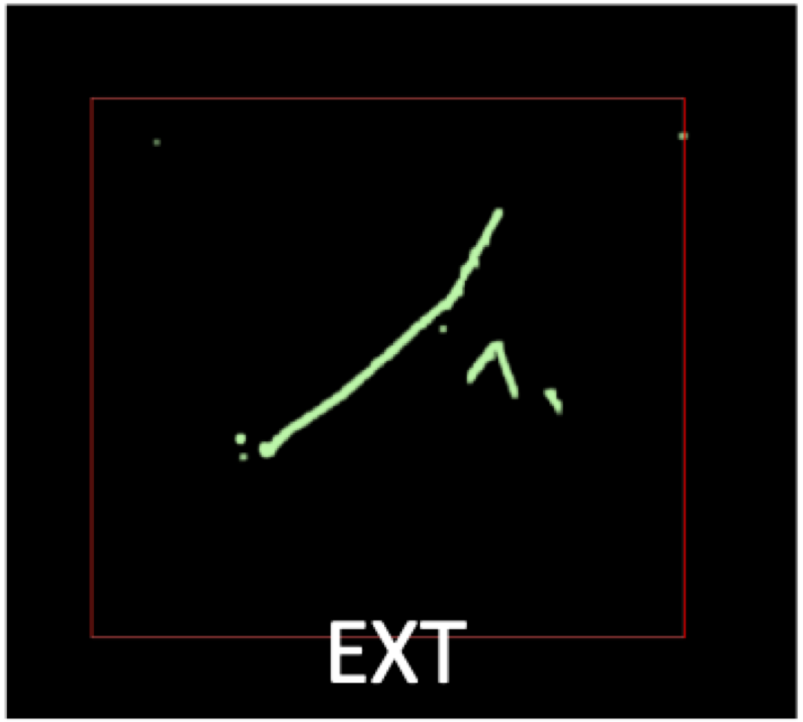


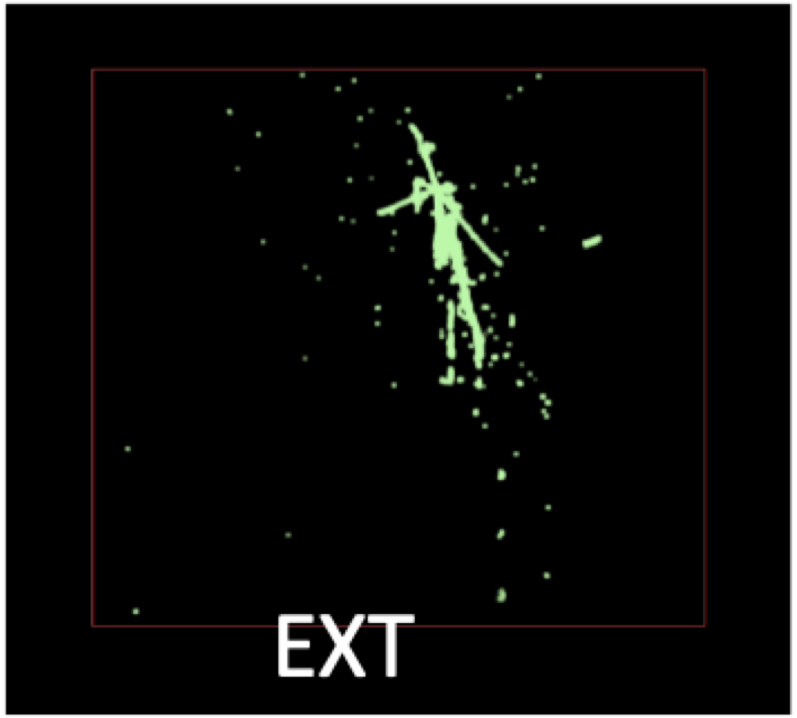


Neutrino image and particle-level segmentation
Track/shower identification
Multiple particle identification (regression)

Cosmic-ray Background After Generic ν selection

From neutrino beam-off data



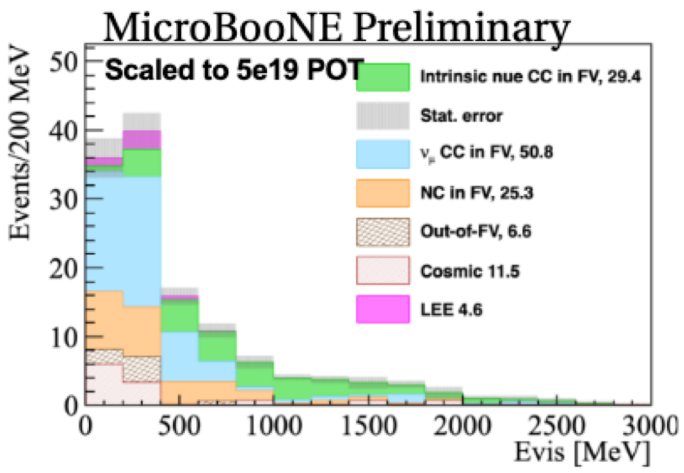


Will be reduced by a factor of 10 in neutrino selection stage

Evolution of ν_e CC selection

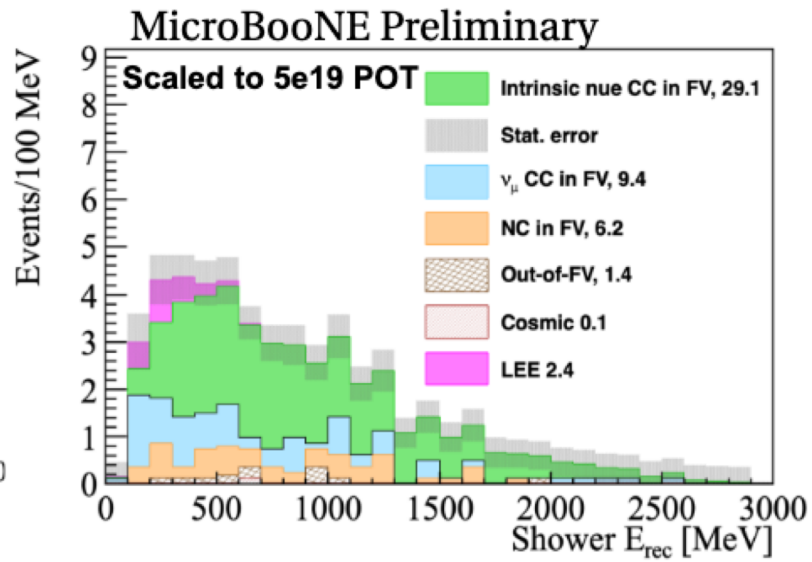
MICROBOONE-NOTE-1095-PUB

Cut-based



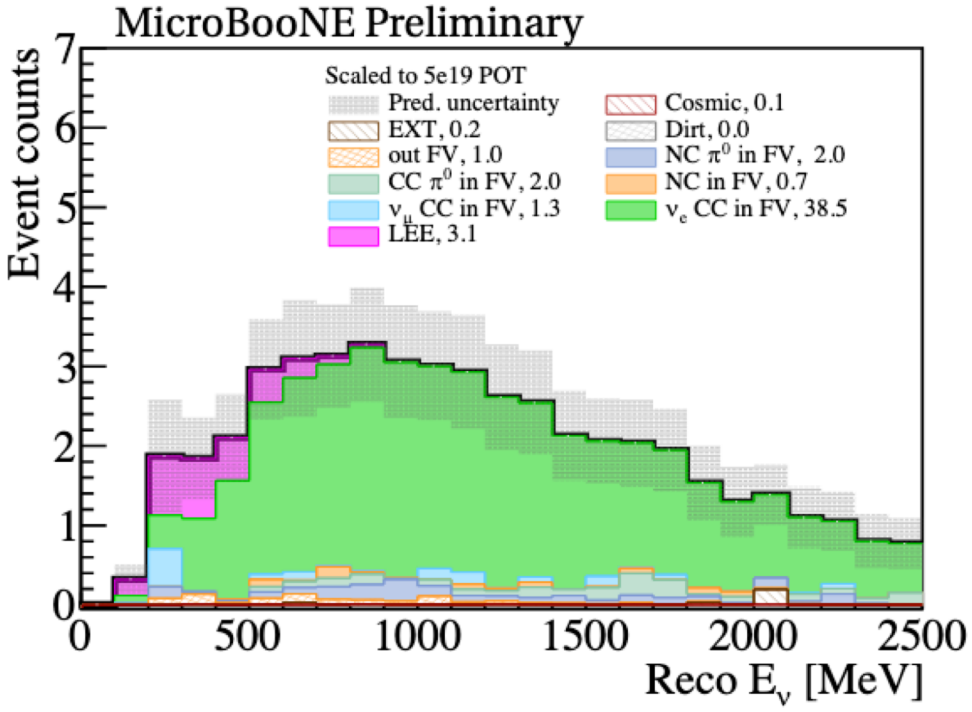
Poor purity
32% nueCC eff
4.6 LEE

TMVA BDT



63% nueCC purity
32% nueCC eff
2.4 LEE

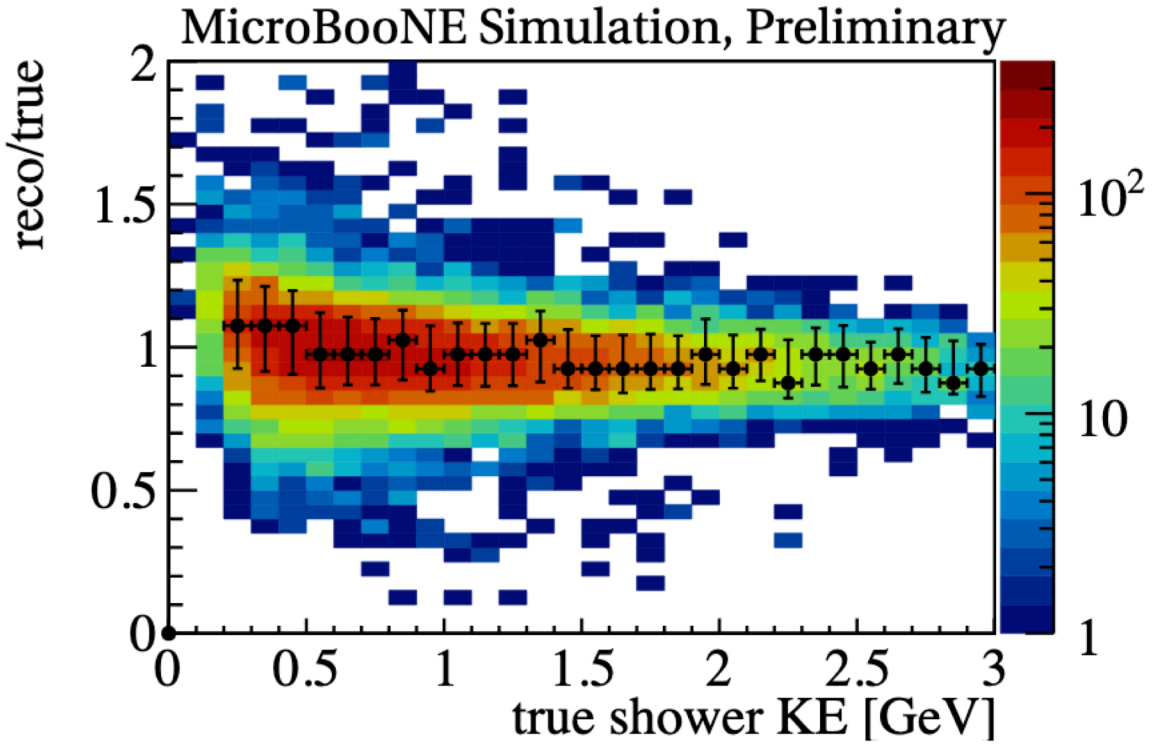
XGBOOST BDT (final)

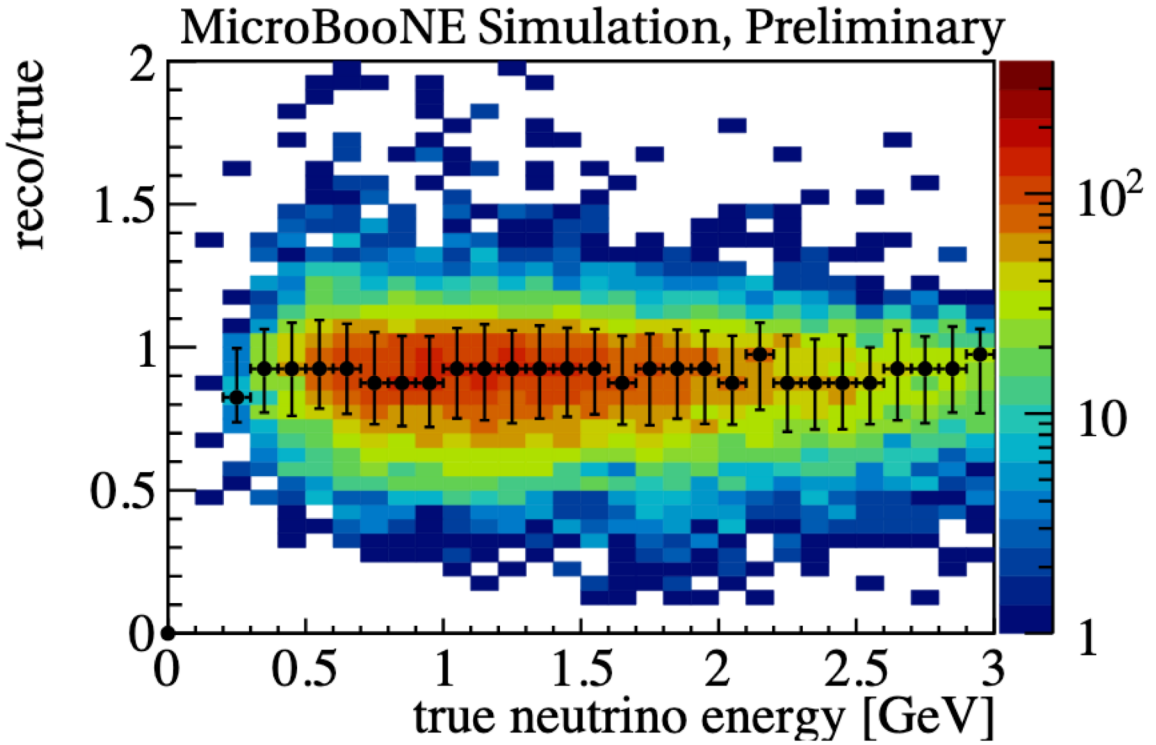


83% nueCC purity
42% nueCC eff
3.1 LEE

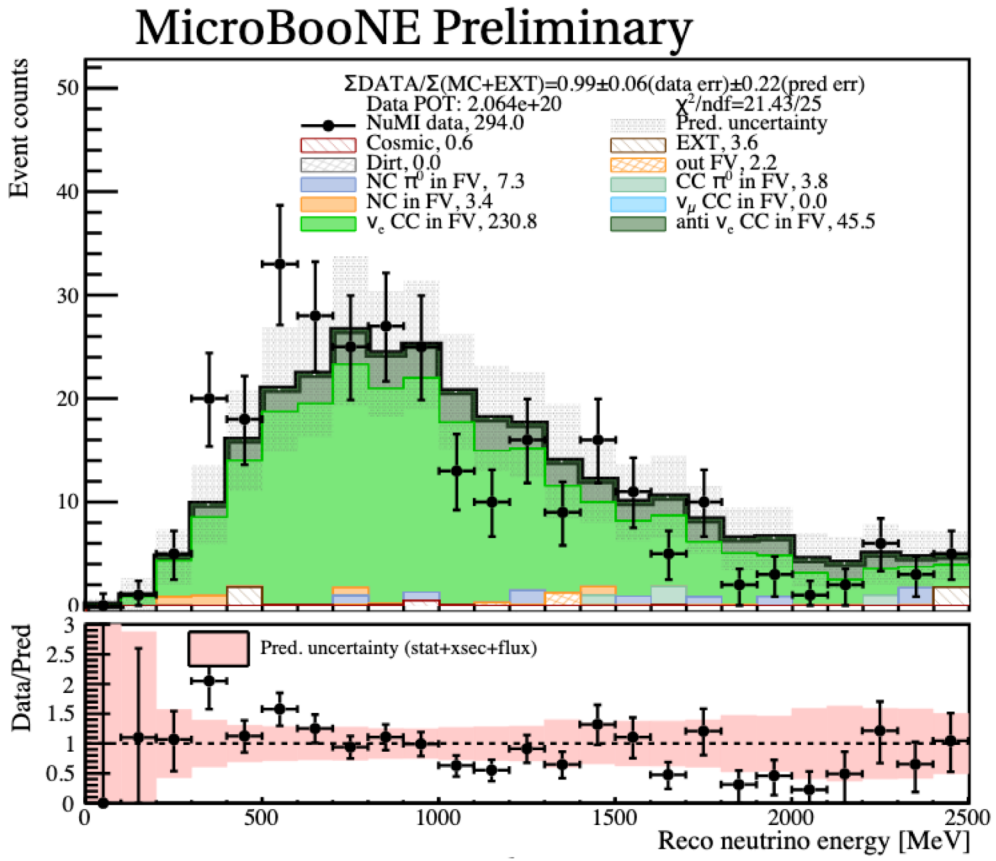
LEE: low-energy excess, unfolded from MiniBooNE low-energy excess

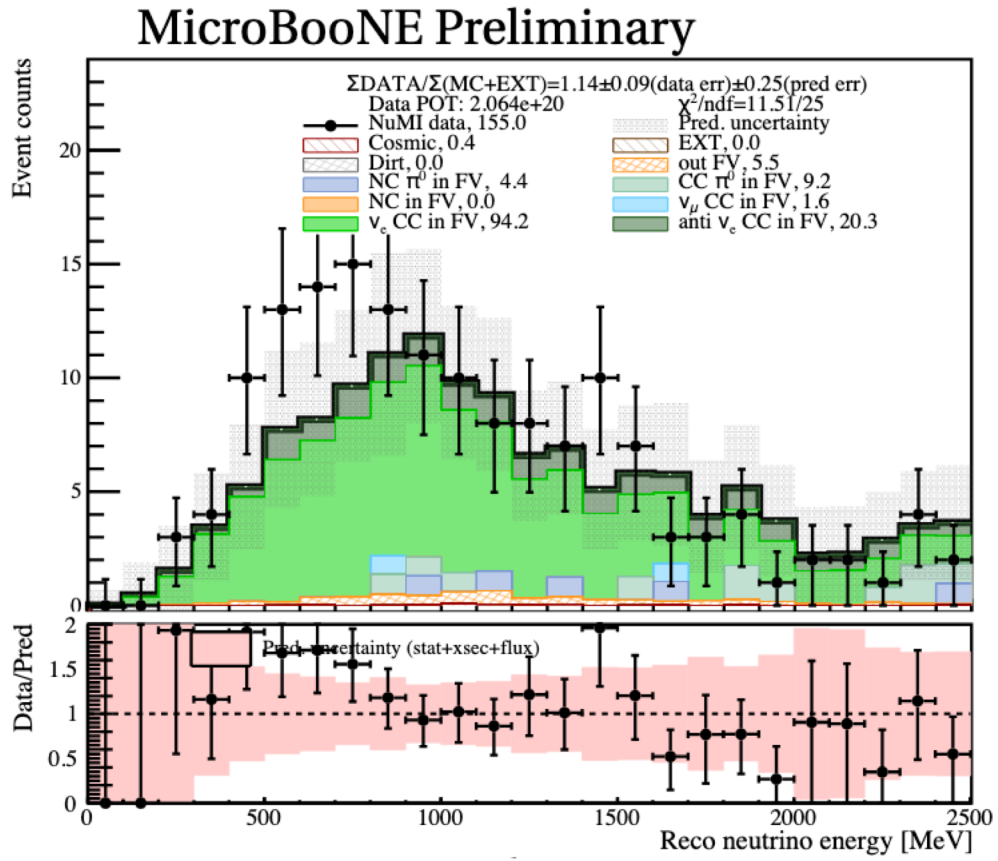
BNB ν_e CC selection: energy resolution



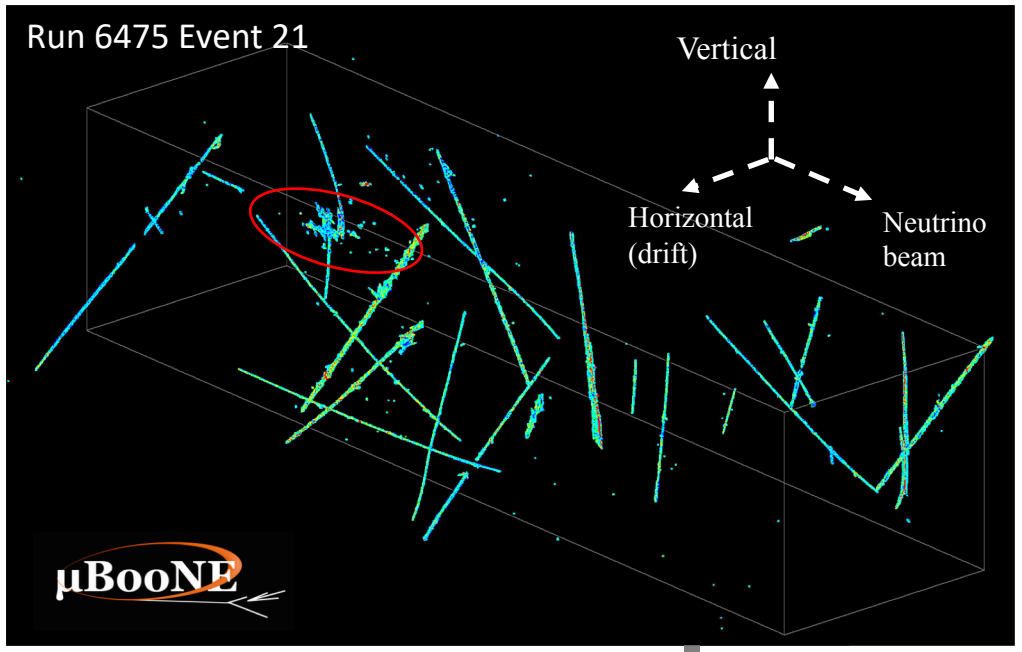


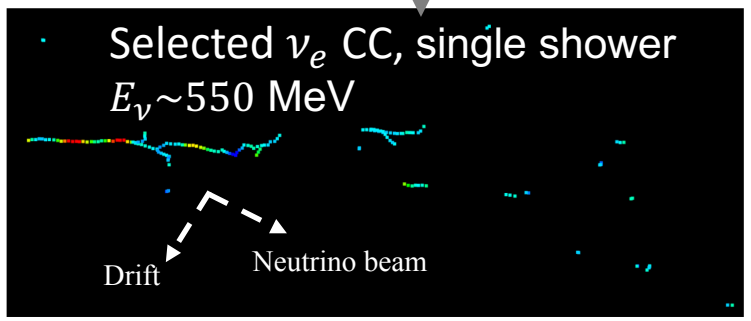
NuMI preliminary ν_e CC selection

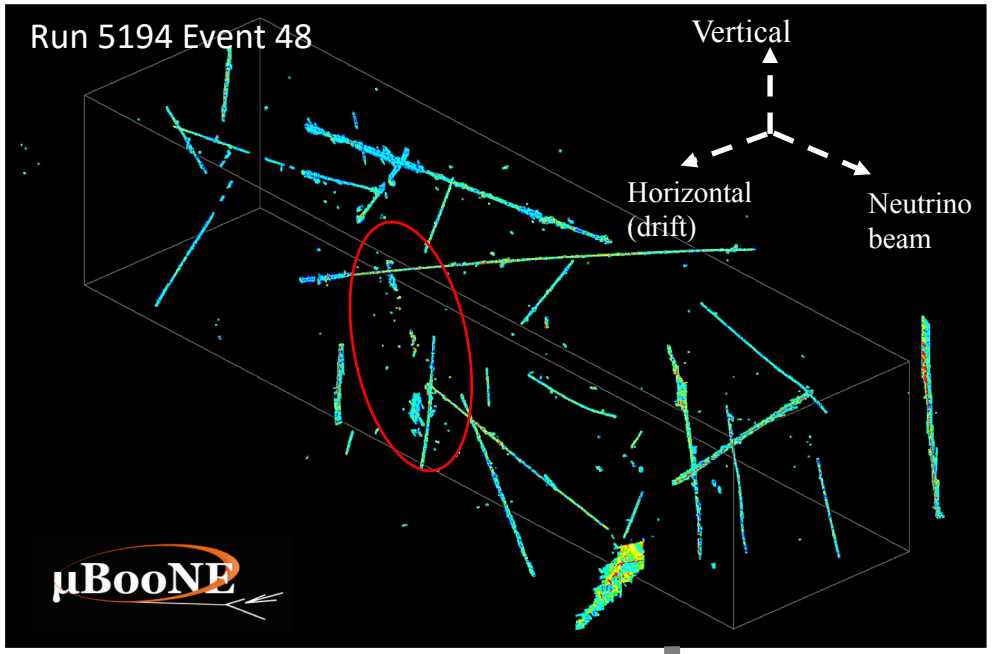


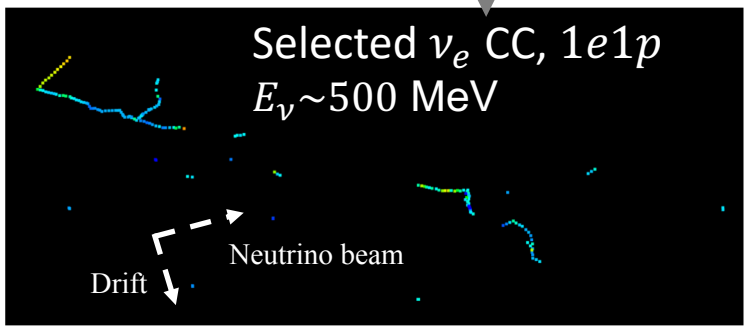


Low energy ν_e CC from NuMI data stream

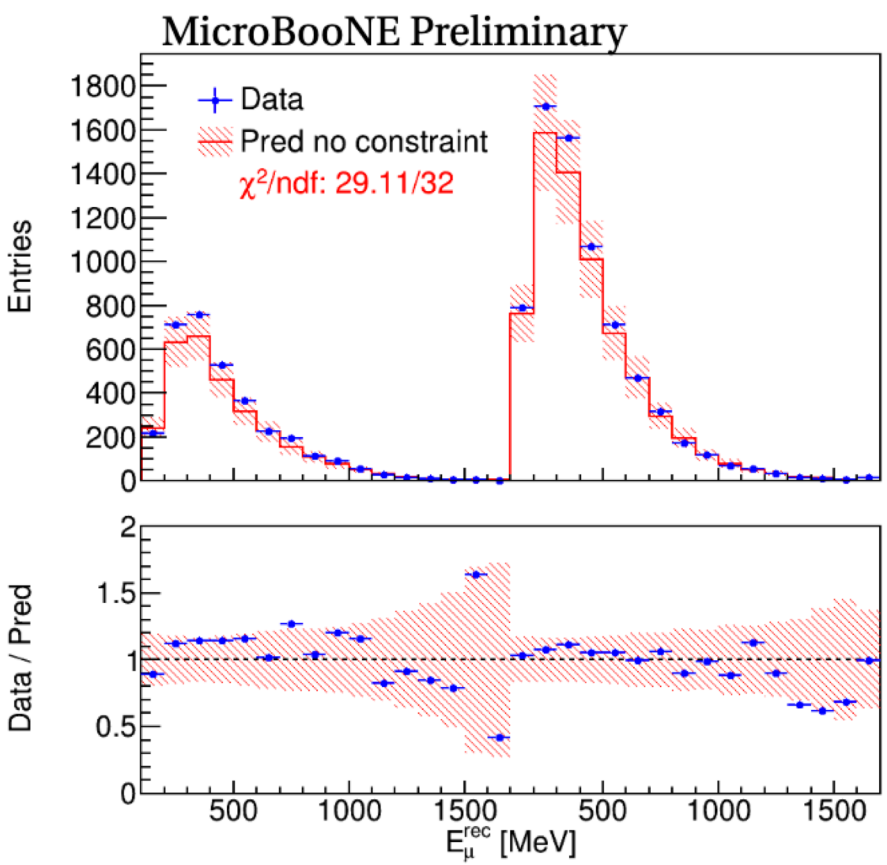


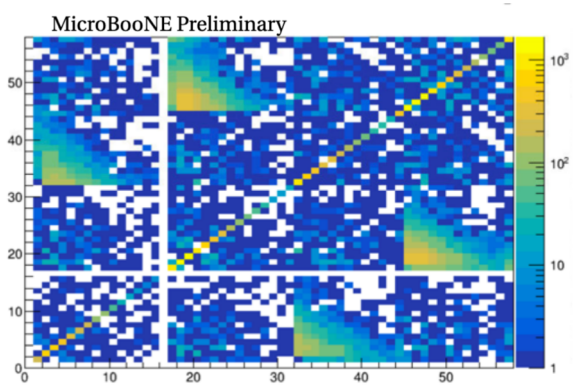




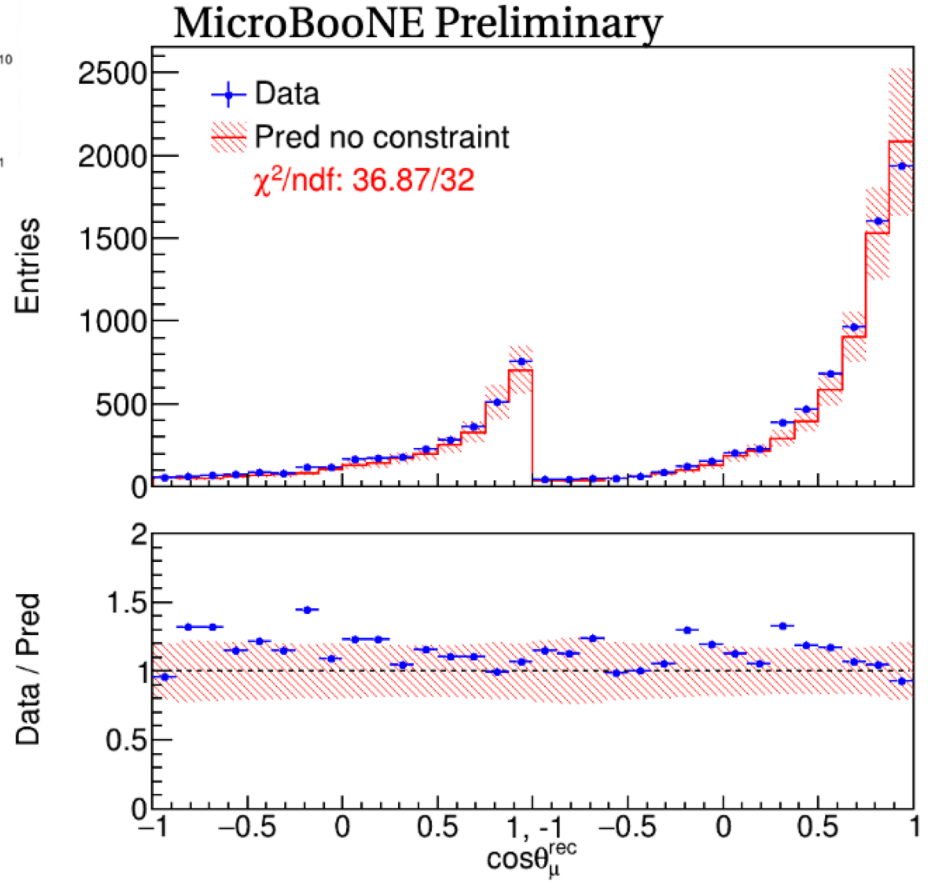


3D space point per 6 mm





Statistical correlation



M_{eff} based on $M = \sum_{i=1}^{N} \omega_i$

- Define $\sigma^2 := \sum_{i=1}^{N} \omega_i^2$ (variance of *M* actually)
- Rewrite M and σ^2
  - $M := M_{eff}\omega_{eff}$
  - $\sigma^2 := M_{eff}\omega_{eff}^2$
- $\omega_{eff} = \frac{\sigma^2}{M}, M_{eff} = \frac{M}{\omega_{eff}} = \frac{M^2}{\sigma^2}$, the expectation of M_{eff} is $\overline{M_{eff}} = \frac{\mu}{\omega_{eff}} = \frac{\mu M}{\sigma^2}$ where μ is the expectation of M (with non-uniform weights)
- Approximation: the effective likelihood function of the expectation $\overline{M_{eff}}$ follows a Poisson distribution given the measurement M_{eff} [exactly the case for uniform weights]
- So the likelihood function of μ is

$$L(\mu|M,\sigma^2) = \frac{e^{-\frac{\mu}{\omega_{eff}}}\left(\frac{\mu}{\omega_{eff}}\right)^{\frac{M}{\omega_{eff}}}}{\Gamma(\frac{M}{\omega_{eff}}+1)}$$

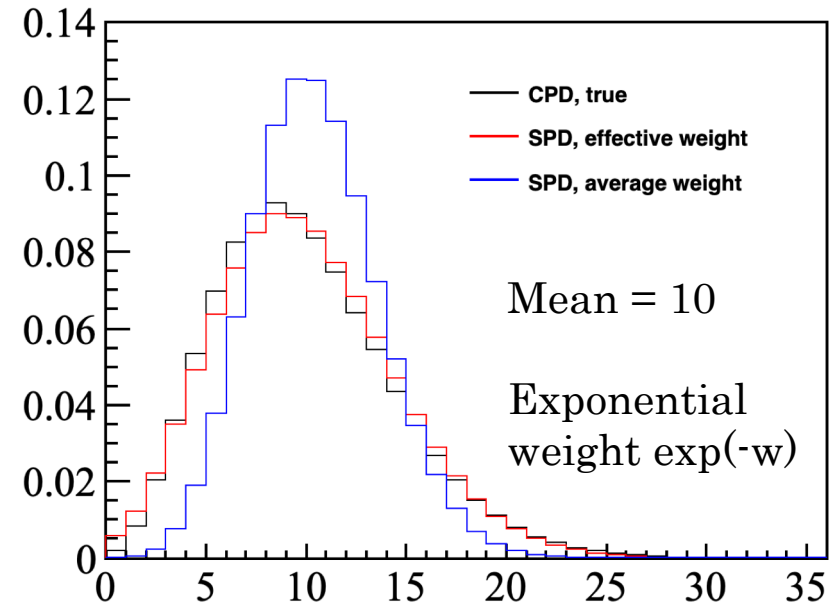
This effective likelihood accounts for both mean and variance of the measurement; remains valid for broader weight distributions than using an average weight

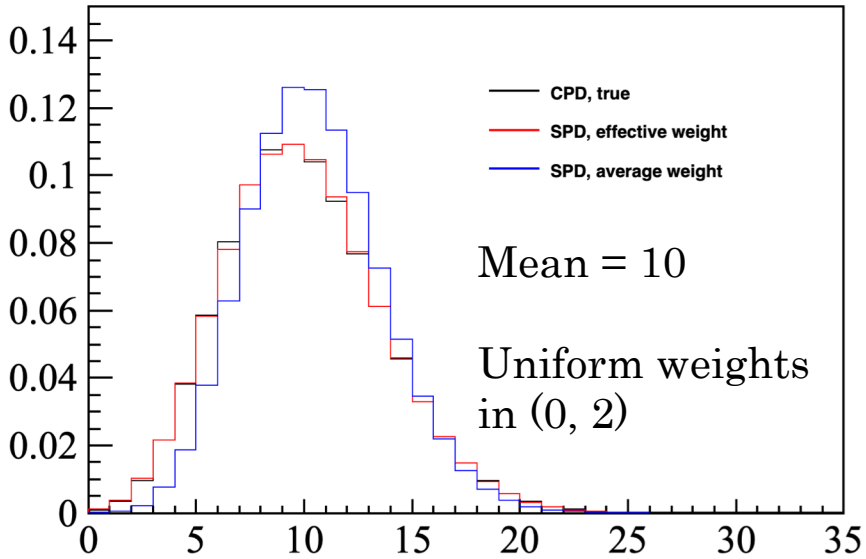
Examination of the scaled Poisson distribution (**SPD**) as a approximation of the compound Poisson distribution (**CPD**)
Event weight is an independent random variable

Likelihood: $\omega_{eff} = \frac{\sigma^2}{M}$ based on measurement

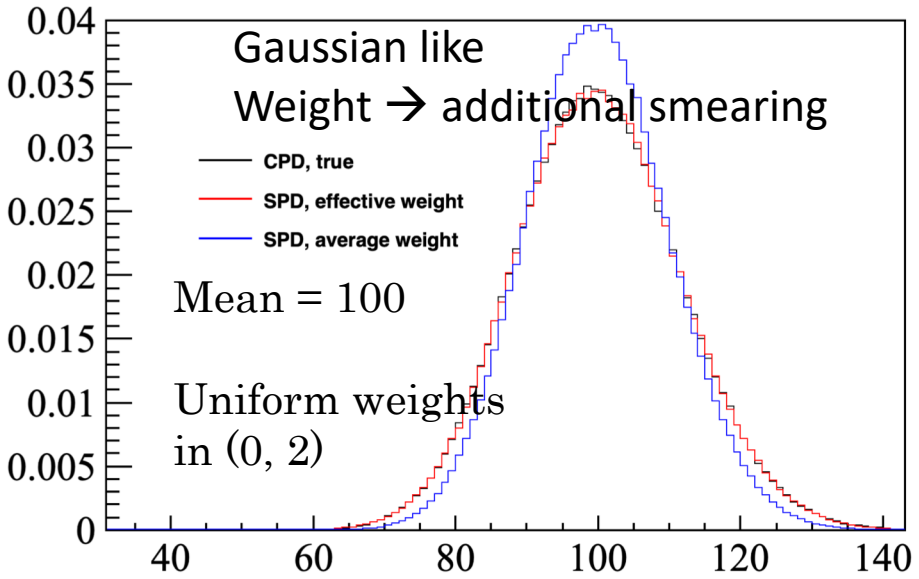
Probability: $\omega_{eff} = \frac{E[\omega^2]}{E[\omega]}$

based on the distribution of weight





The recommended SPD with effective weight is accurate especially for wider weight distribution and low statistic



More discussions can be found in Nucl. Instrum. Meth. A 748 (2014)

Final procedure of MC statistical uncertainty

1) Posterior modification taking into account non-uniform weights:

$$P(\mu|M) \propto \omega_{eff} \cdot e^{\frac{(M-\mu)}{\omega_{eff}}+\frac{M}{\omega_{eff}}\ln\left(\frac{\mu}{M}\right)}, \omega_{eff} = \frac{\sigma^2}{M}$$

2) Poisson posterior $P(\mu_i|N_i)$ of each component/sample before POT scaling → variable substitution for posterior of each component with POT scaling

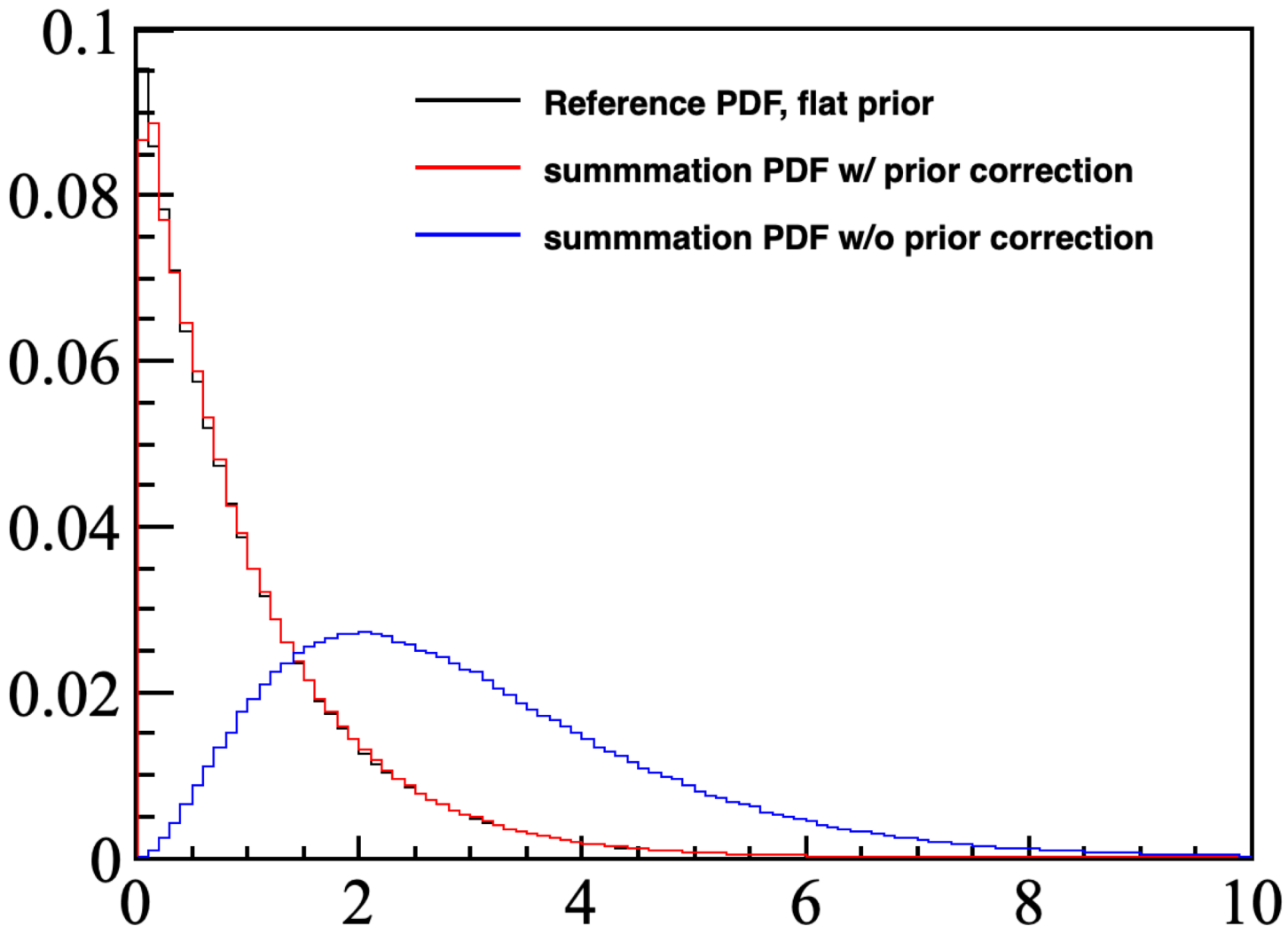
3) $P(\mu|N_{total} = \sum s_i \cdot N_i)$ convolution of PDFs of each component with POT scaling

4) Prior correction by dividing $\boldsymbol{\mu^{n-1}}$, *n* is the number of components

5) Normalize the final PDF

6) Credible interval, standard deviation, (co)variance, etc.

Example: ZERO observation for three components

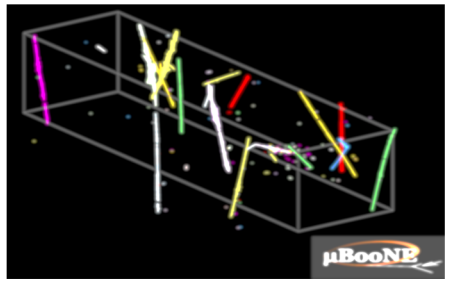


"Reference": theoretical calculation of total assuming a flat prior
"w/o prior correction": convolution of PDFs
"w/ prior correction": convolution of PDFs dividing μ^2

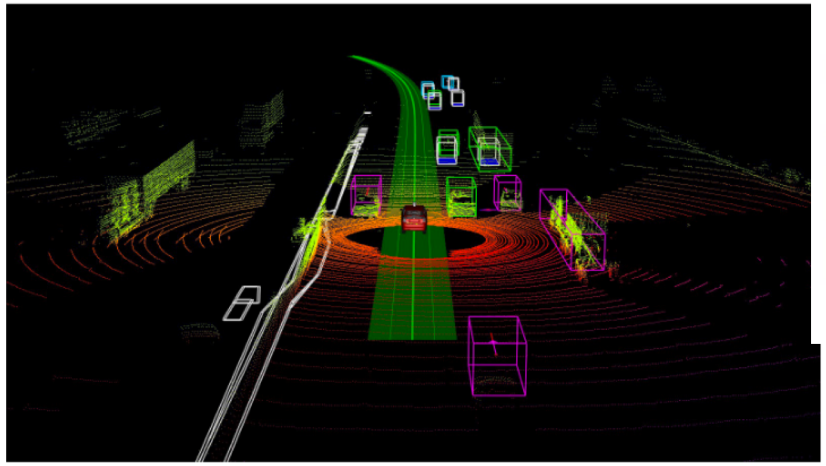
Standard Variance of these three curves:
~1.0 for reference
~1.0 for summation w/ correction
~3.0 for summation w/o correction

Improvement on Wire-Cell reconstruction

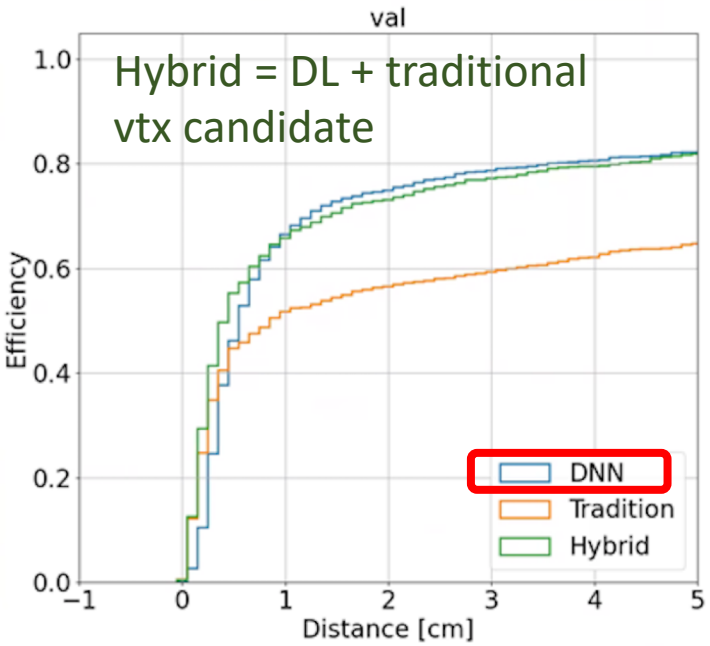
- Upgrade Wire-Cell event reconstruction with deep-learning (DL) algorithms
  - Start-up practices show impressive results



Wire-Cell 3D image (point cloud)

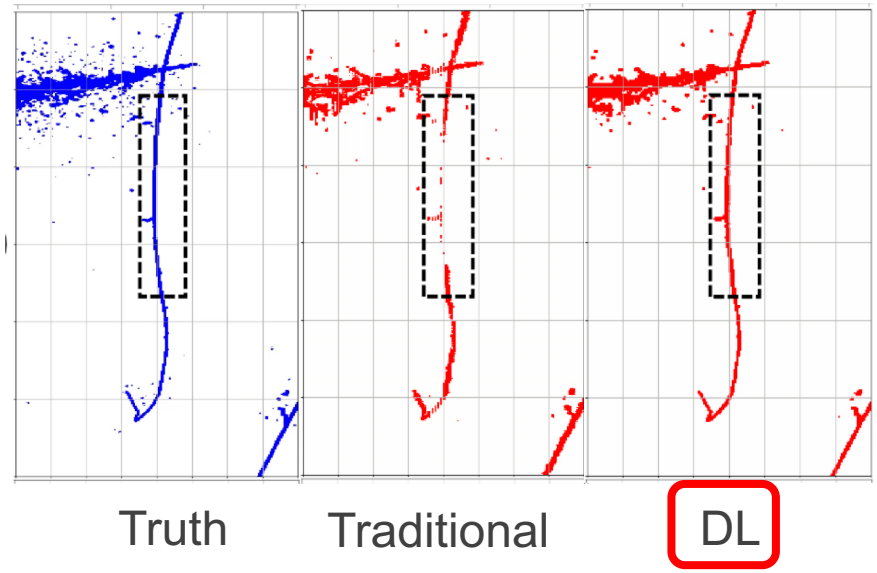


DL object detection in 3D point cloud from YOLO (arXiv:1506.02640)



NueCC vertex efficiency vs. distance to true vertex

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LArTPC time-versus-wire charge extraction