# Results from MicroBooNE

**M. Weber**

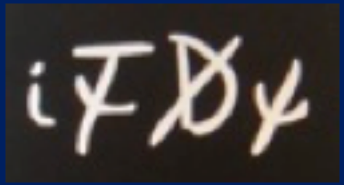
LHEP/AEC

University of Bern

MicroBooNE is a liquid argon time projection chamber that operated from 2015 to 2021 in the Booster Neutrino Beam at Fermilab. The collaboration has collected the world's largest dataset of neutrino-argon scattering events with a detector providing high-resolution imaging of neutrino interactions with a low threshold and full angular coverage. Thanks to breakthroughs in technology and event reconstruction a detailed understanding of the neutrino interactions is possible. This has let to a series of physics measurements that will be presented. Furthermore I will show how it allowed to perform an investigation of the anomalous event excess observed by previous experiments. MicroBooNE is a milestone in view of the full Short-Baseline program at Fermilab and the future Deep Underground Neutrino Experiment (DUNE).

UniZH, Oct 2022

Wolfgang Pauli



$$\frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1+\gamma^5)\nu^\lambda)$$

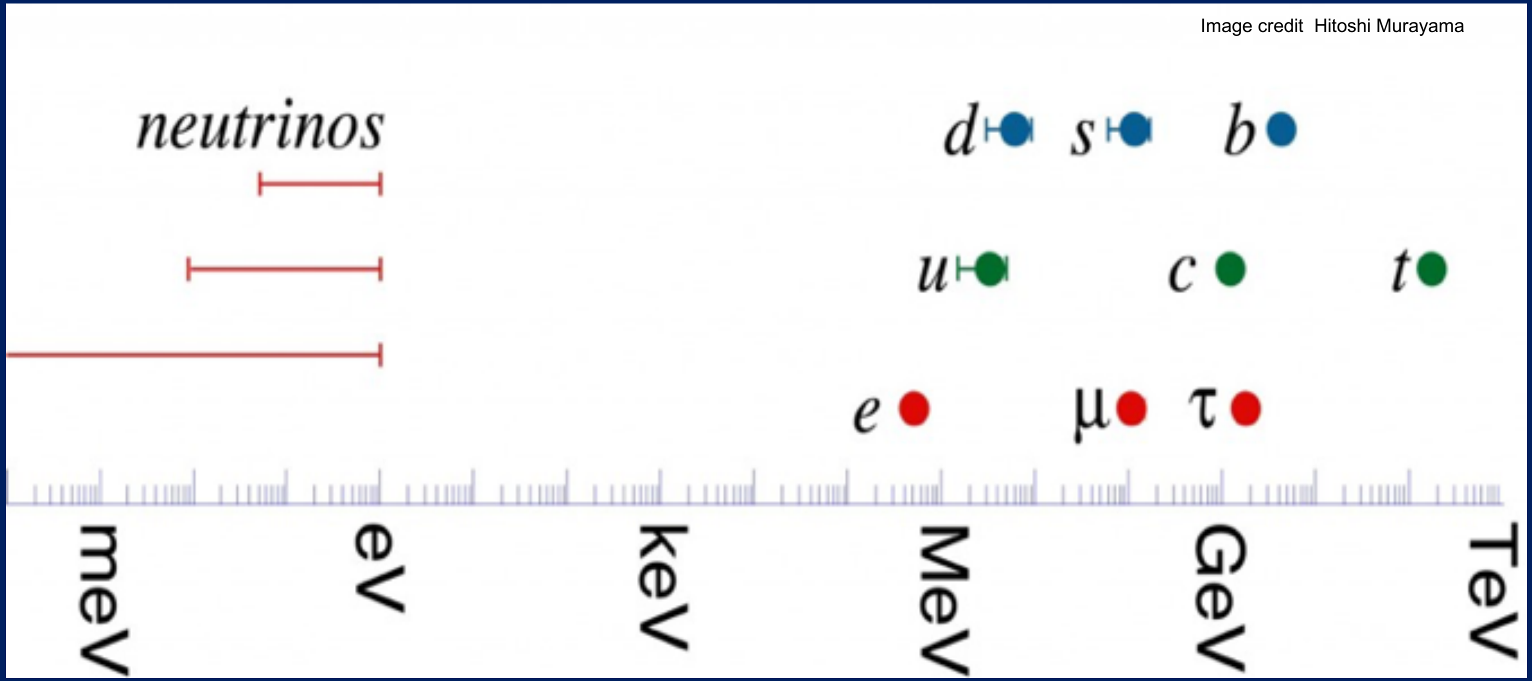
Enrico Fermi

Neutrino Energy few MeV

$\sigma = 10^{-44}$ cm$^2$

Interaction Probability $= 10^{-11}$

$10^{-39}$ cm$^2$ = 1 fb




W und Z Bosons

Photon

Gluons

Higgs Boson

# Neutrino oscillations

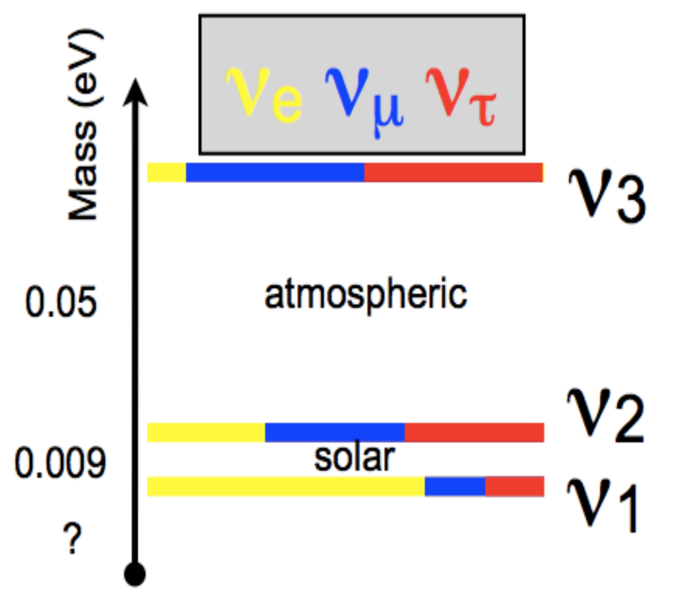
flavor — atmospheric — cross-mixing — solar — mass

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The PMNS matrix

Two-neutrino approximation

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} \cdot \sin^2\left(1.27\Delta m_{ij}^2 \frac{L}{E}\right)$$



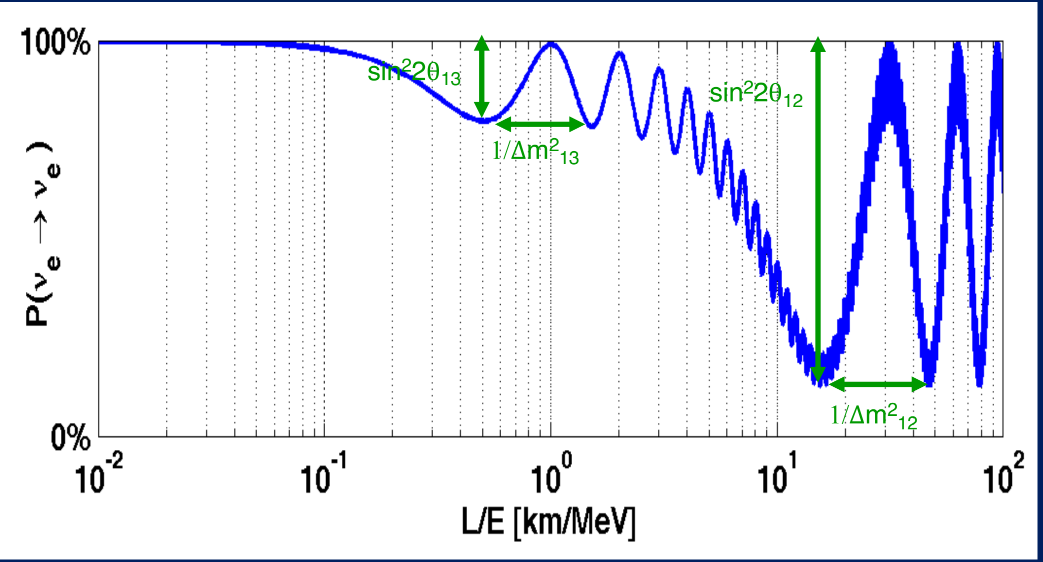

- Three angles $\theta_{12}$, $\theta_{23}$ and $\theta_{13}$
- CP violating phase(s) $\delta_{CP}$
- Two mass-squared differences $\Delta m^2_{21}$ and $\Delta m^2_{23}$

# A global experimental effort

KamLAND, Double Chooz, Daya Bay, RENO, Gösgen, SNO, SK, T2K, MINOS, NOvA, OPERA, ICARUS, IceCube, ANTARES, GERDA, LEGEND, …

| Parameter | best-fit | $3\sigma$ |
| --- | --- | --- |
| $\Delta m^2_{21}$ $[10^{-5}$ eV $^2]$ | 7.37 | 6.93 – 7.96 |
| $\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$ | 2.56 (2.54) | 2.45 – 2.69 (2.42 – 2.66) |
| $\sin^2\theta_{12}$ | 0.297 | 0.250 – 0.354 |
| $\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$ | 0.425 | 0.381 – 0.615 |
| $\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$ | 0.589 | 0.384 – 0.636 |
| $\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$ | 0.0215 | 0.0190 – 0.0240 |
| $\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$ | 0.0216 | 0.0190 – 0.0242 |
| $\delta/\pi$ | 1.38 (1.31) | $2\sigma$: (1.0 - 1.9) ($2\sigma$: (0.92-1.88)) |

PDG update Dec 2017

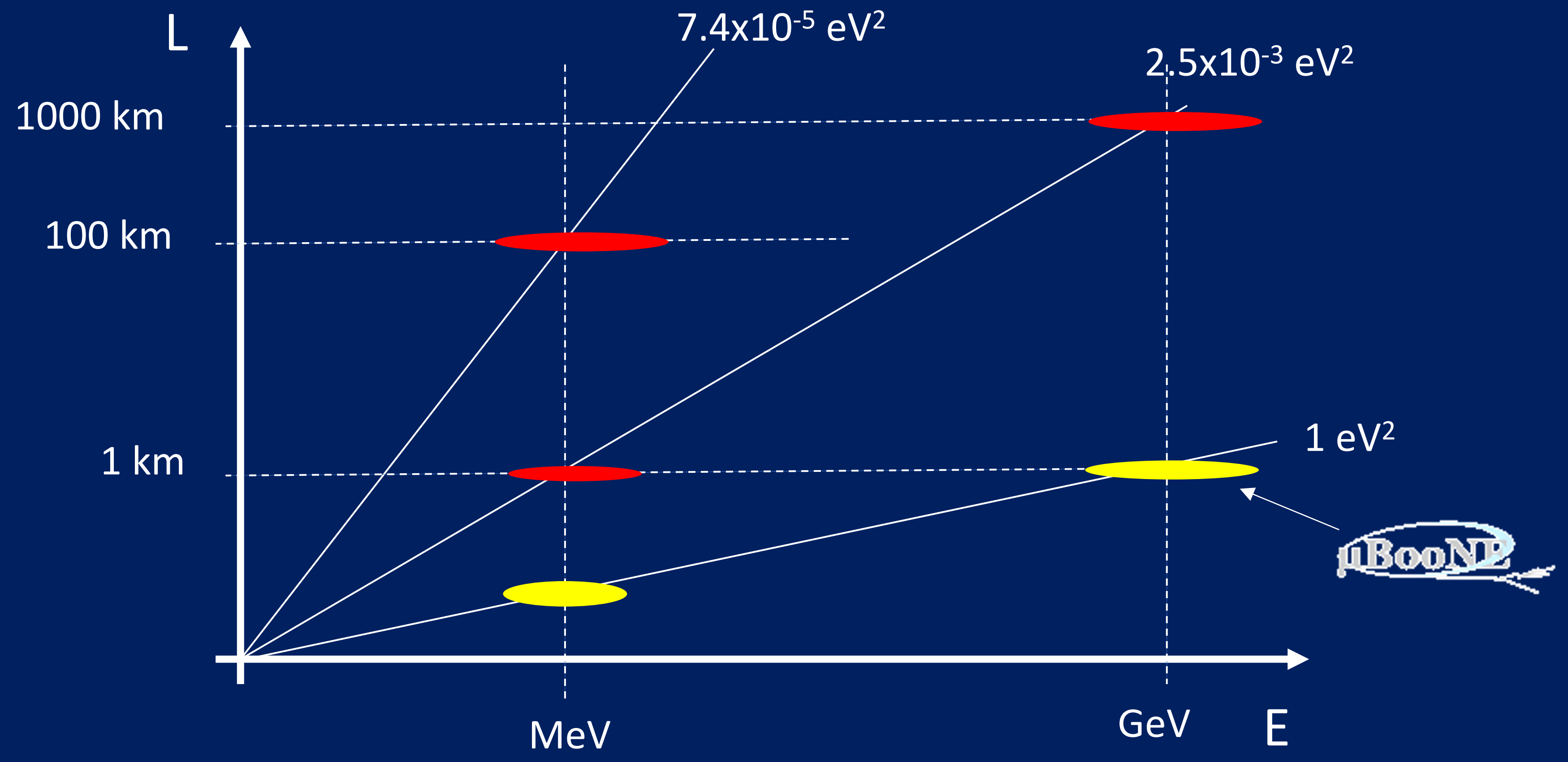



$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{13} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{12} L}{4E}\right),$$

Generally consistent picture, **some tensions, open questions, anomalies**

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} \cdot \sin^2\left(1.27\Delta m^2_{ij}\frac{L}{E}\right)$$

UNIVERSITÄT BERN
AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS




(over-)simplified schematic, not considering:

- Three (four) neutrinos
- Neutrino and Antineutrino
- Appearance and disappearance
- Mixing angles

- Short Base-Line:
  - Sensitivity to high $\Delta m^2$
  - High rates ($1/R^2$), statistics to measure cross sections

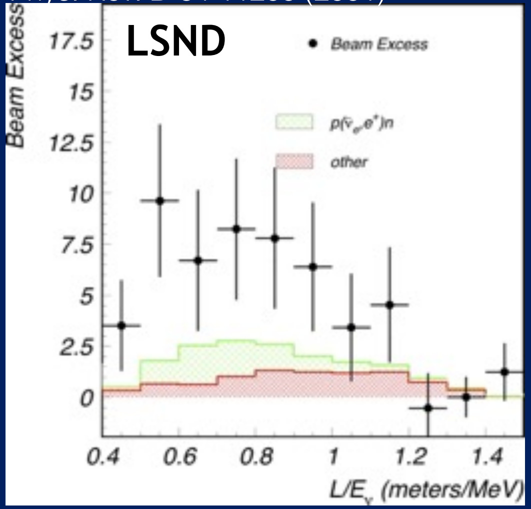
UNIVERSITÄT BERN

AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

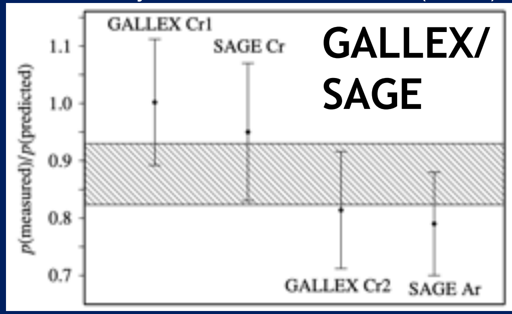
# Short-baseline Anomalies

- Series of anomalous results seen at short-baselines using a variety of neutrino sources
  - LSND $\nu_e$ excess
  - MiniBooNE $\nu_e$/anti-$\nu_e$ excess
  - GALLEX/SAGE/BEST $\nu_e$ deficit
  - Reactor $\nu_e$ deficit
    Recent re-evaluation: arXiv:2110.06820
- Interpretations focused on oscillations driven by "vanilla" eV-scale sterile neutrinos
- Disfavored by non-observation of $\nu_\mu$ disappearance, so explanation requires a richer phenomenology

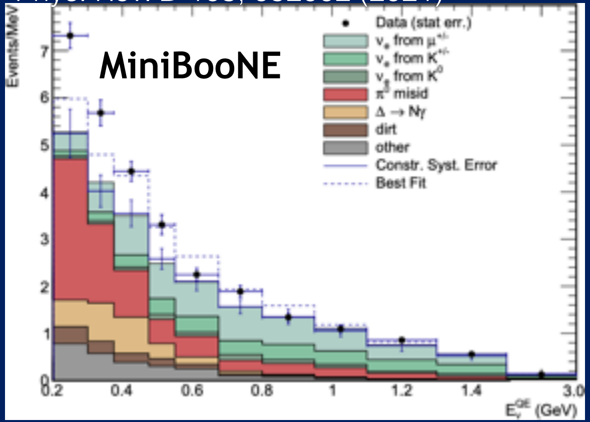
Phys. Rev. D 64 11200 (2001)

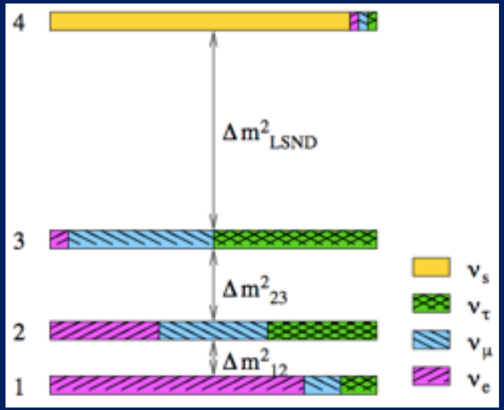


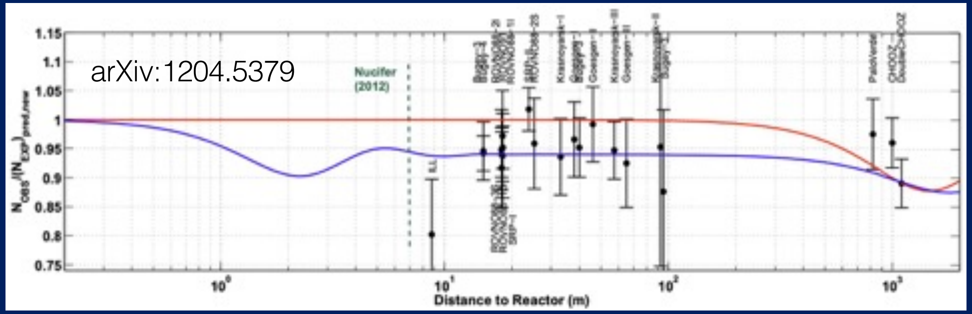

Phys. Rev. C 73, 045805 (2006)




Phys. Rev. D 103, 052002 (2021)



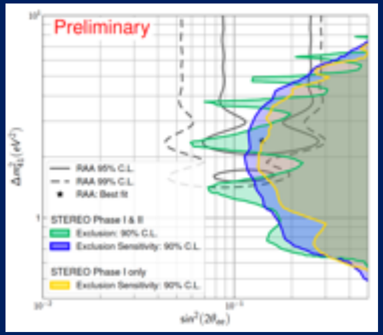



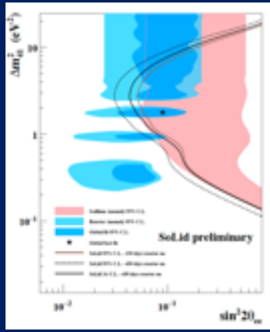



# Sterile neutrino searches, exclusions, hints

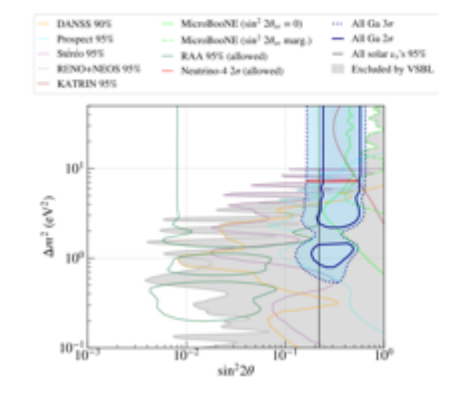
UNIVERSITÄT BERN
AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

## @highly enriched reactors



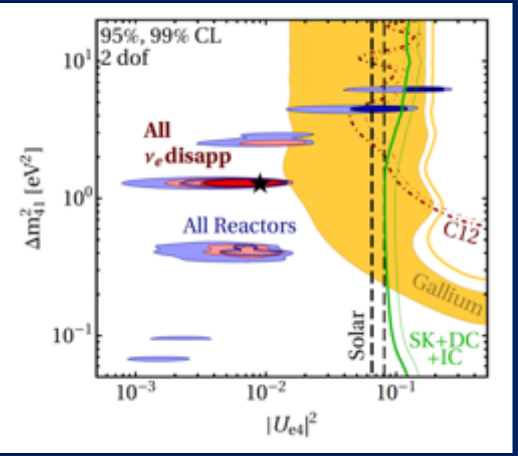

## Radioactive sources



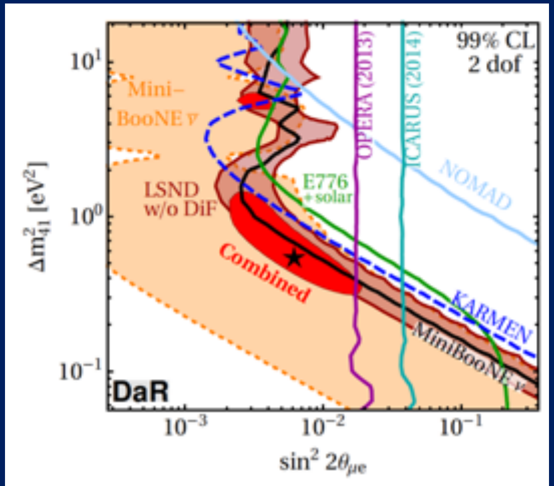

BEST arxiv:2109.11482

## Combinations

Nu-e disappearance arxiv:1803.10661

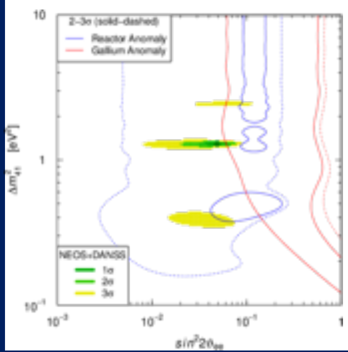



Nu-e appearance arxiv:1803.10661



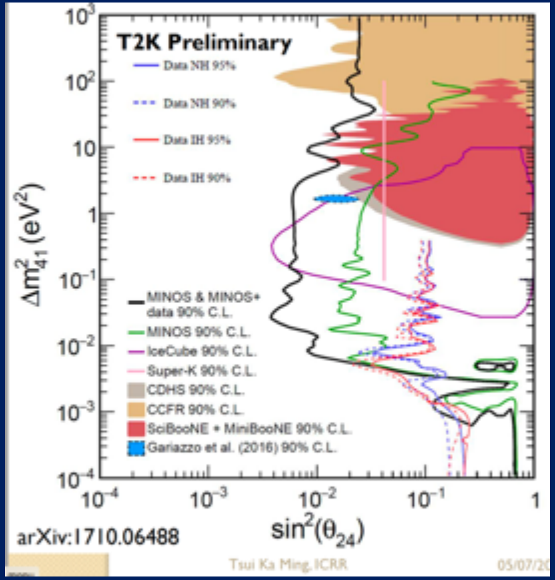

## Movable detectors

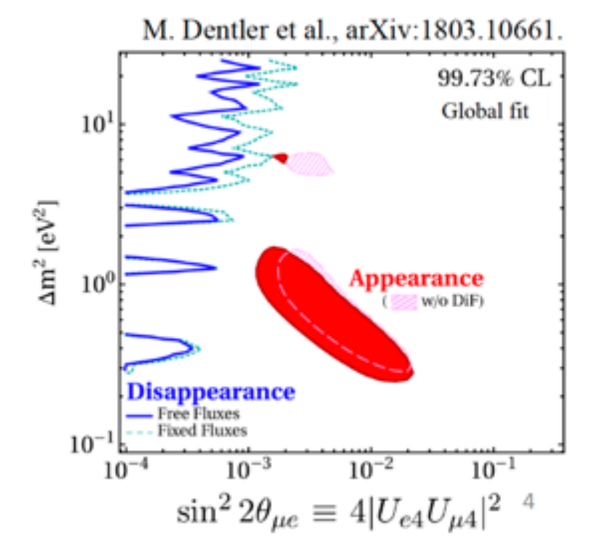
**DANSS on a lifting platform**
**A week cycle of up/middle/down position**



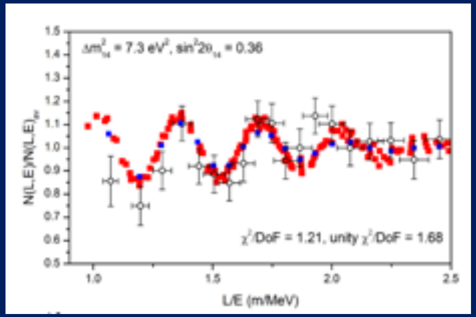

Phys.Lett. B782 (2018) 13-21

## Long baseline




Neutrino-4
PRD 104 (2021) 032003



| Experiment name | Type | Oscillation channel | Significance |
|---|---|---|---|
| LSND | Low energy accelerator | muon to electron (antineutrino) | 3.8σ |
| MiniBooNE | High(er) energy accelerator | muon to electron (antineutrino) | 2.8σ |
| MiniBooNE | High(er) energy accelerator | muon to electron (neutrino) | 4.8σ |
| Reactors | Beta decay | electron disappearance (antineutrino) | (varies) |
| BEST/GALLEX/SAGE | Source (electron capture) | electron disappearance (neutrino) | ~4-5σ |

Recent re-evaluation:
arXiv:2110.06820

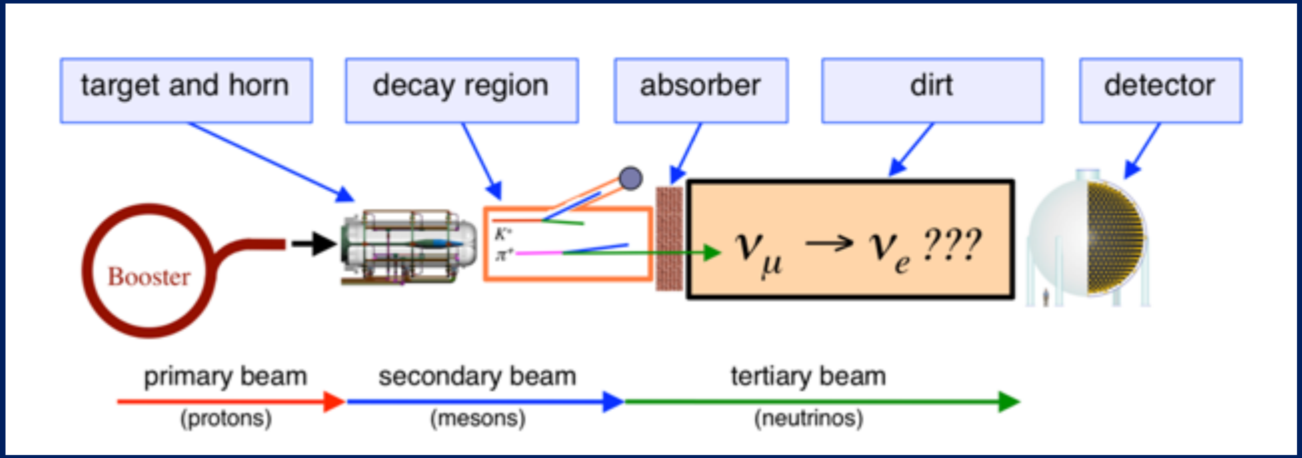
# MiniBooNE
@Fermilab (2002--)

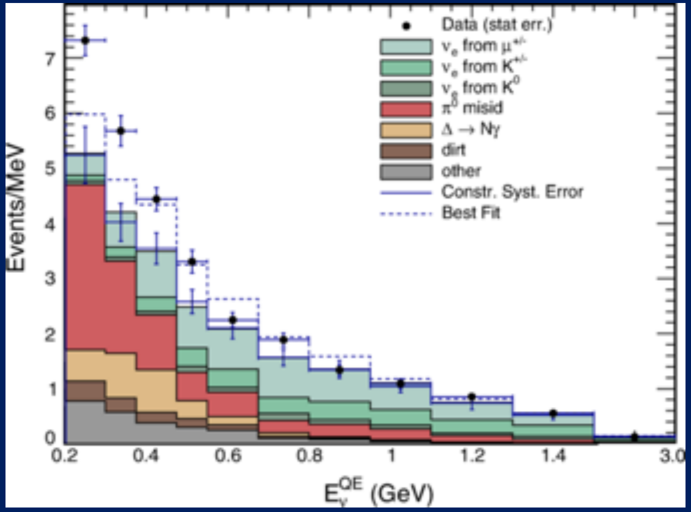
L/E ~ 1 MeV/m
E~800 MeV
L~600 m

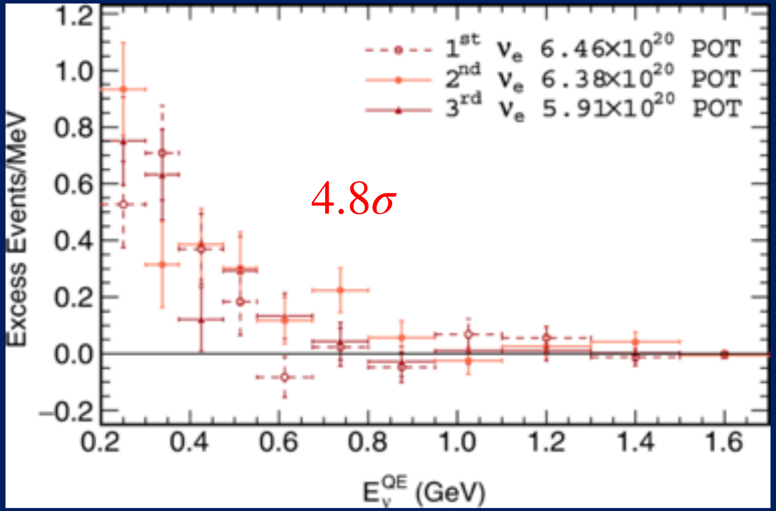
**$\Delta m^2 \sim 1\ eV^2$**

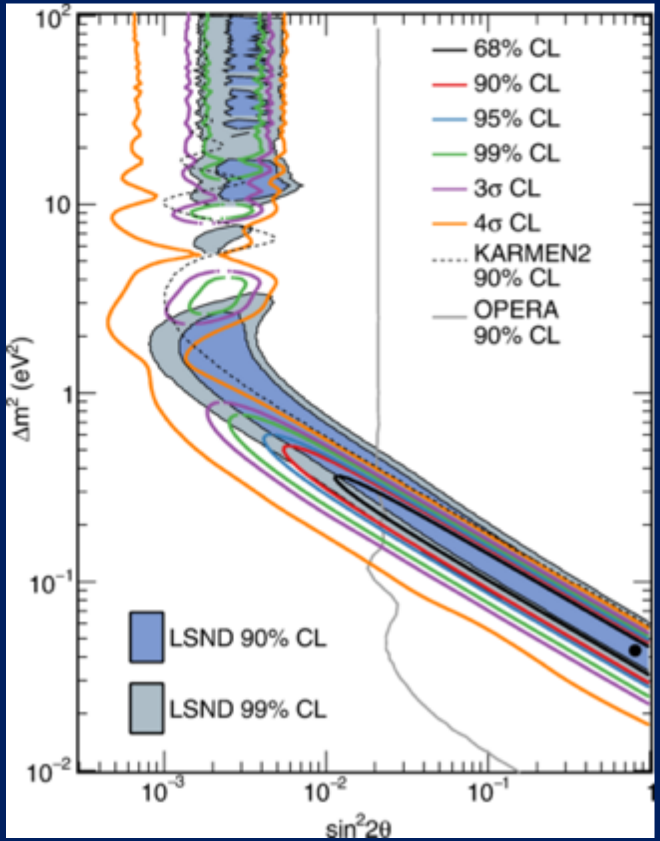
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{ij} \cdot \sin^2\left(1.27\Delta m^2_{ij}\frac{L}{E}\right)$$

UNIVERSITÄT BERN
AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS



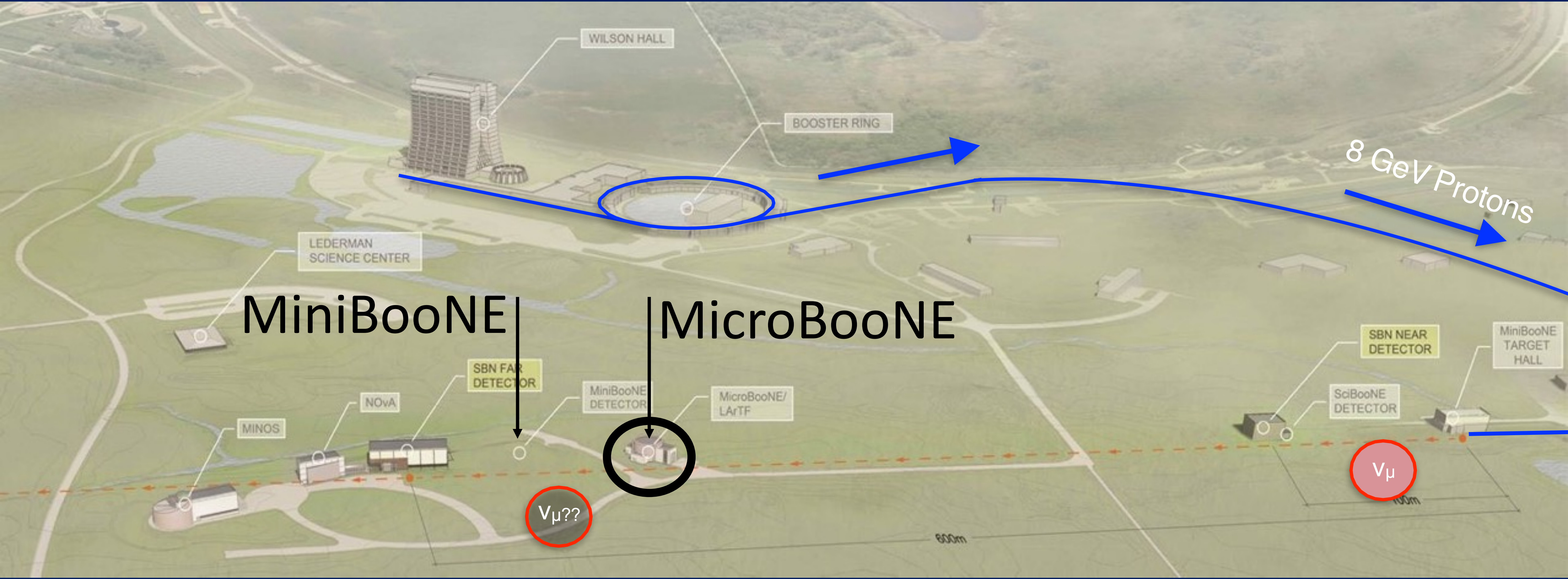




Phys. Rev. D 103, 052002 (2021)

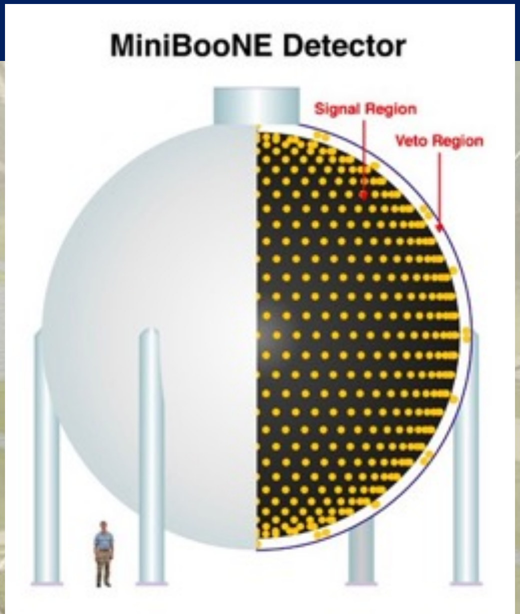
# The Booster Neutrino Beam Line at Fermilab

UNIVERSITÄT BERN
AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

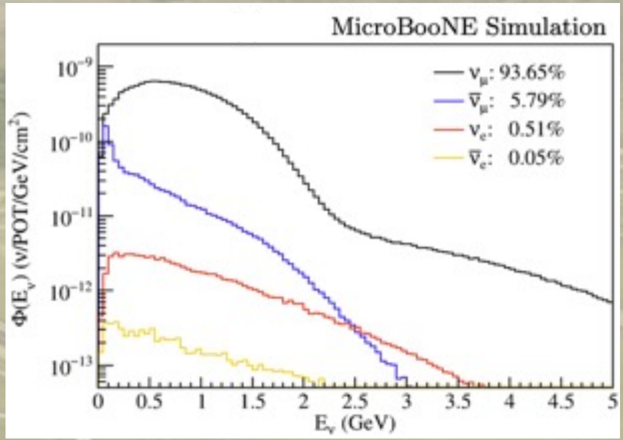


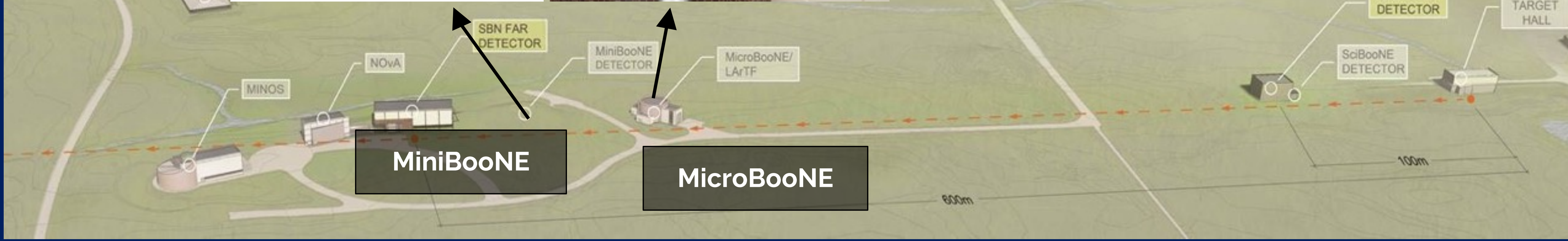
# The Booster Neutrino Beam Line at Fermilab



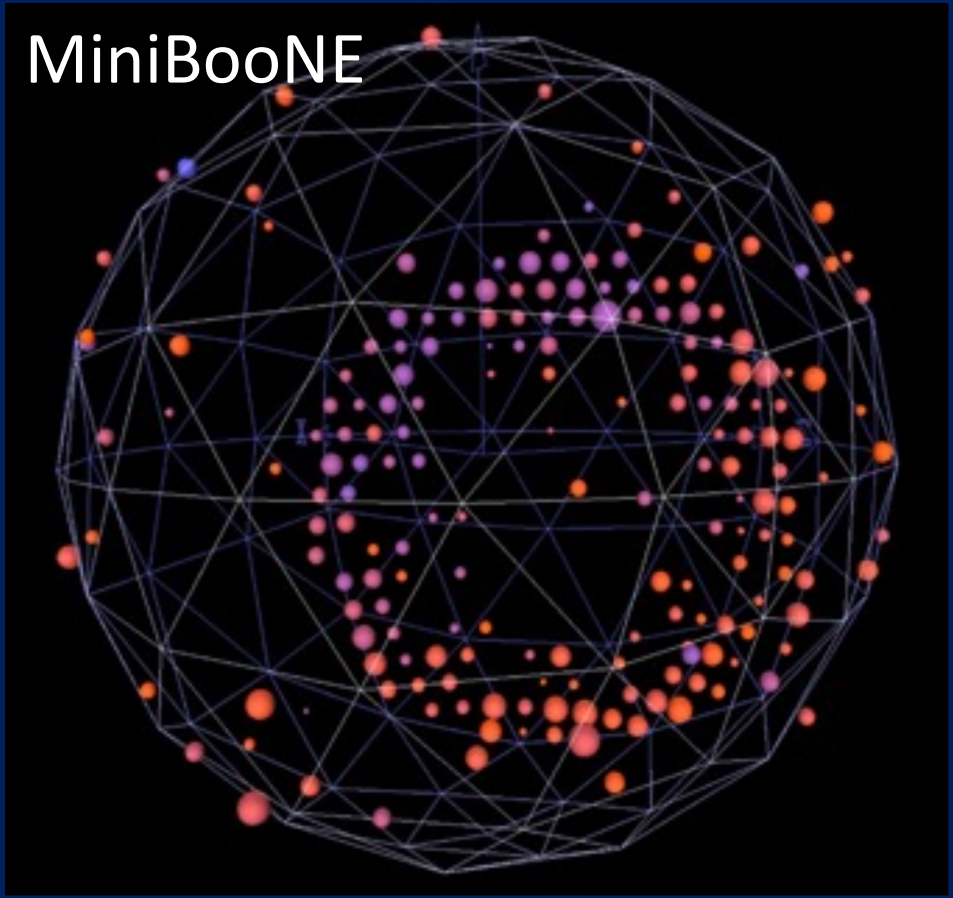


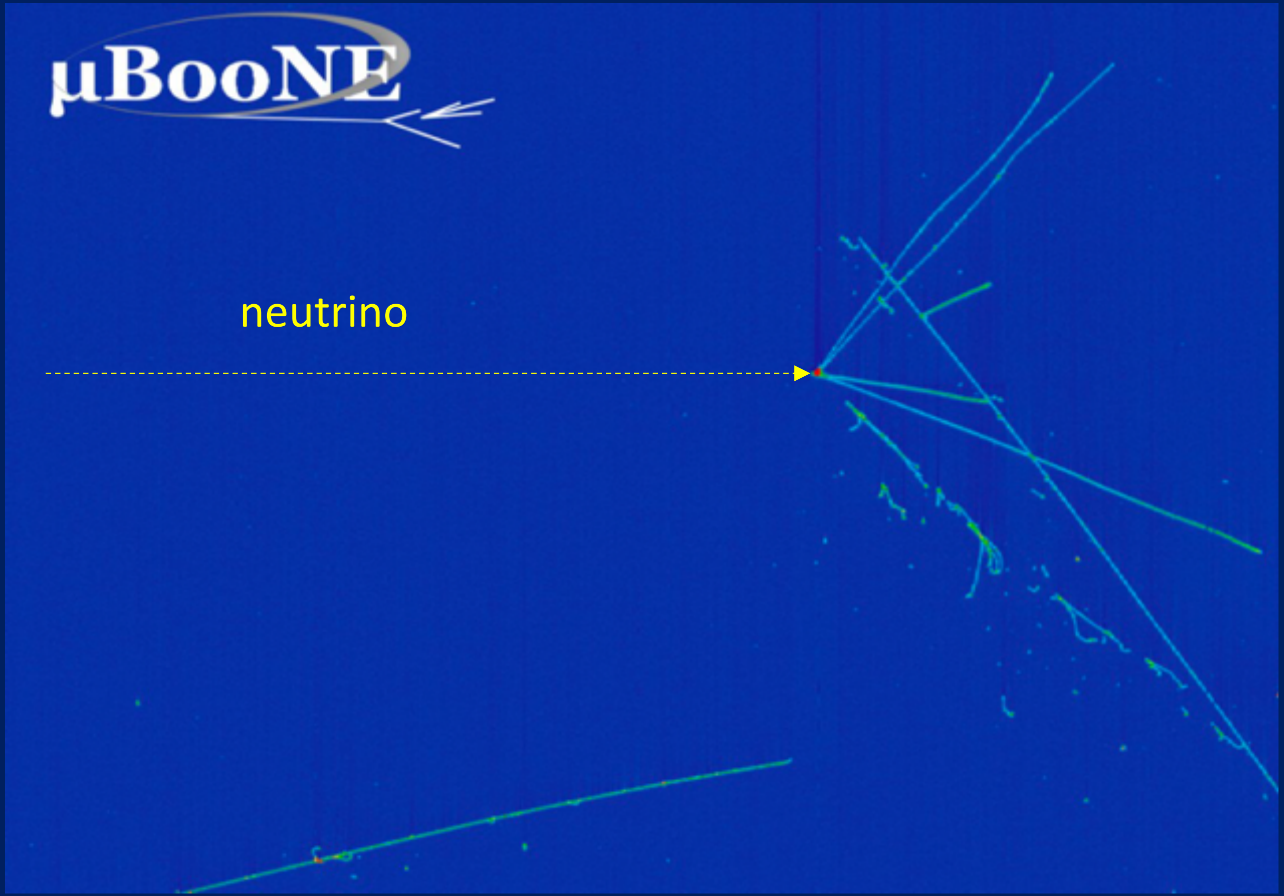


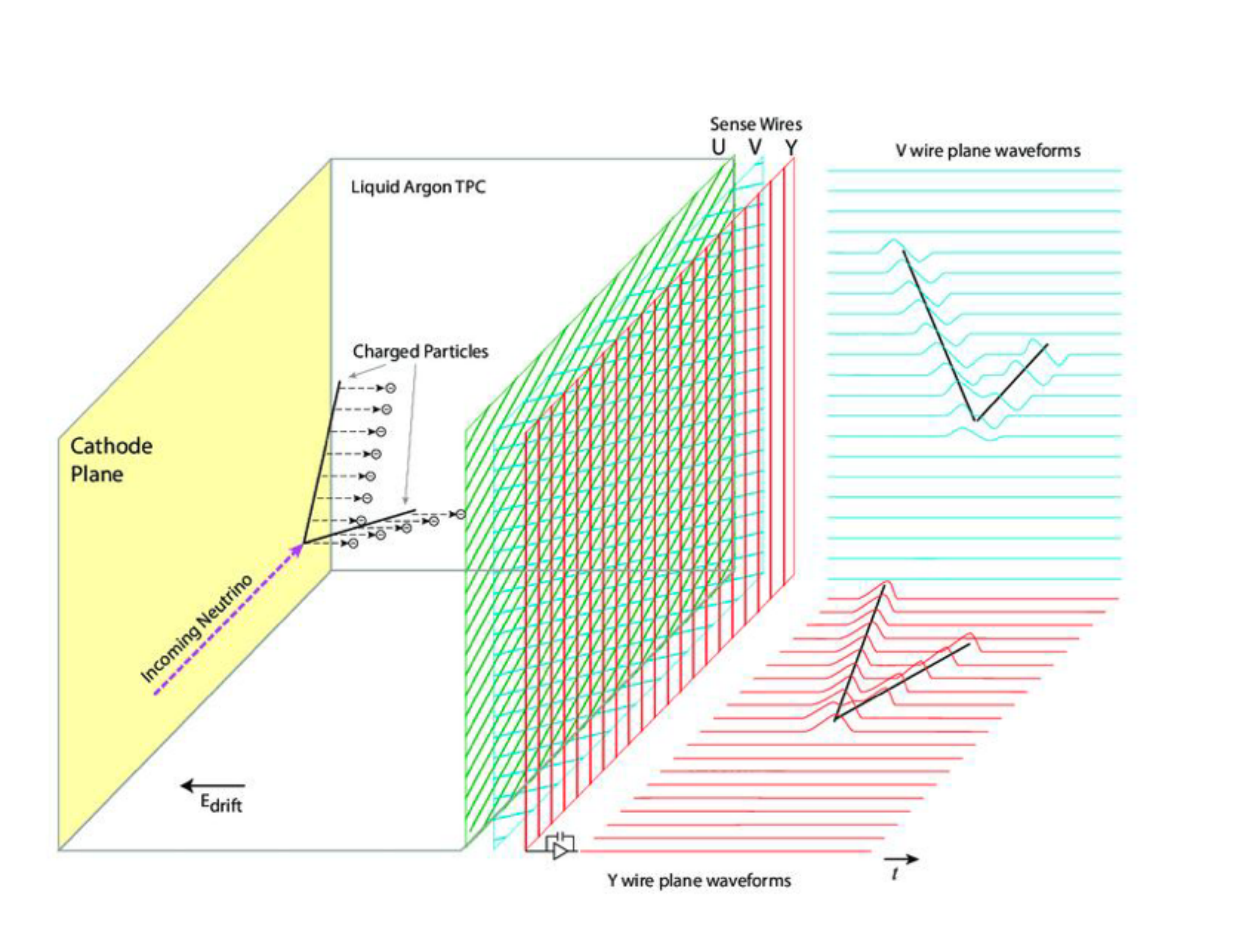


UNIVERSITÄT BERN
AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

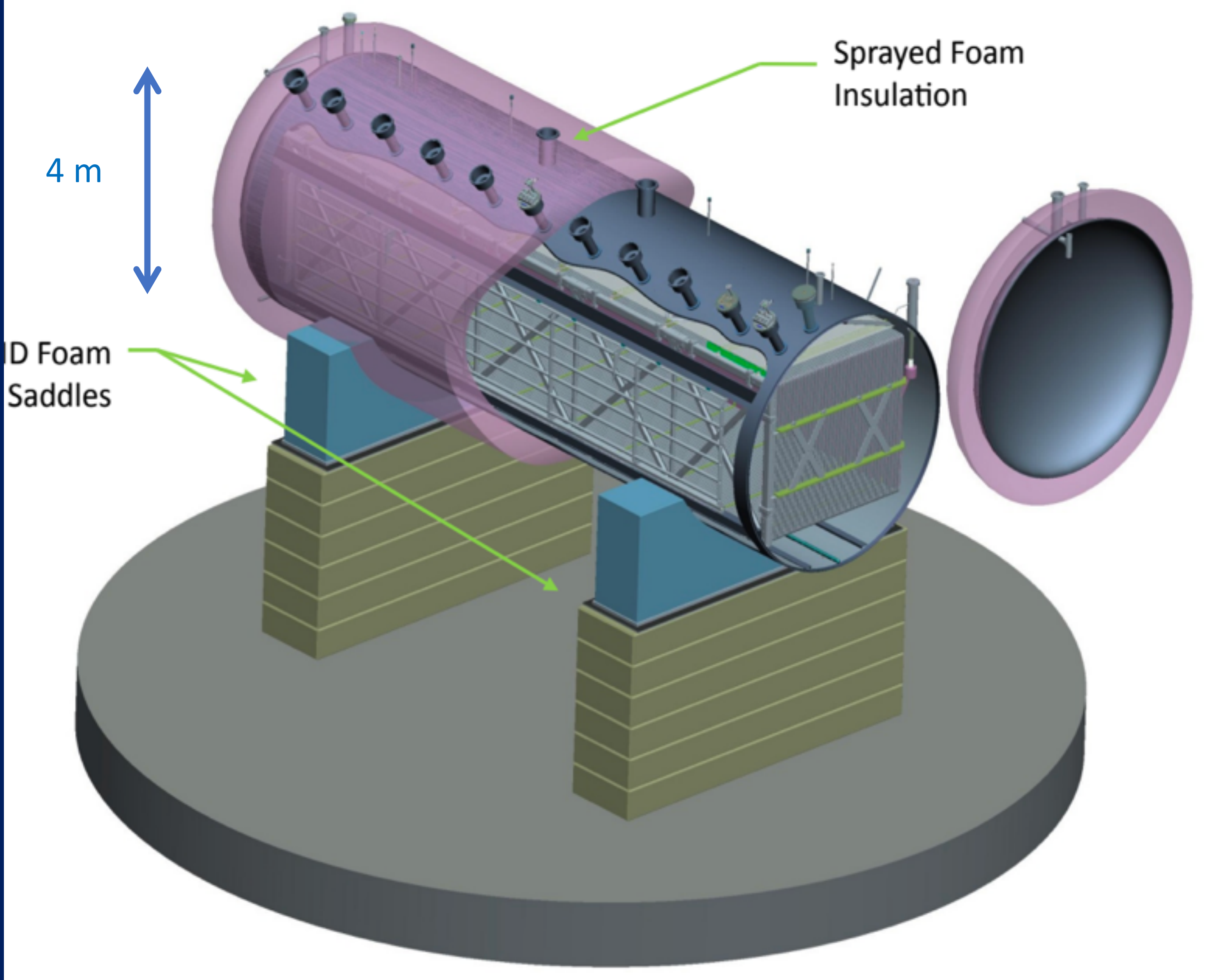





UNIVERSITÄT BERN

AEC
ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS



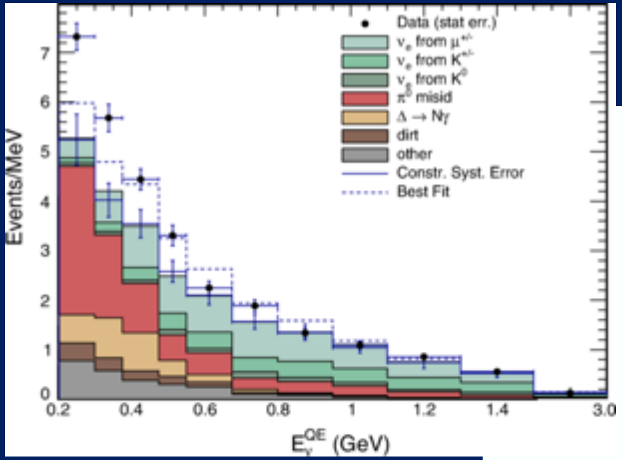
Sprayed Foam
Insulation
4 m
D Foam
Saddles

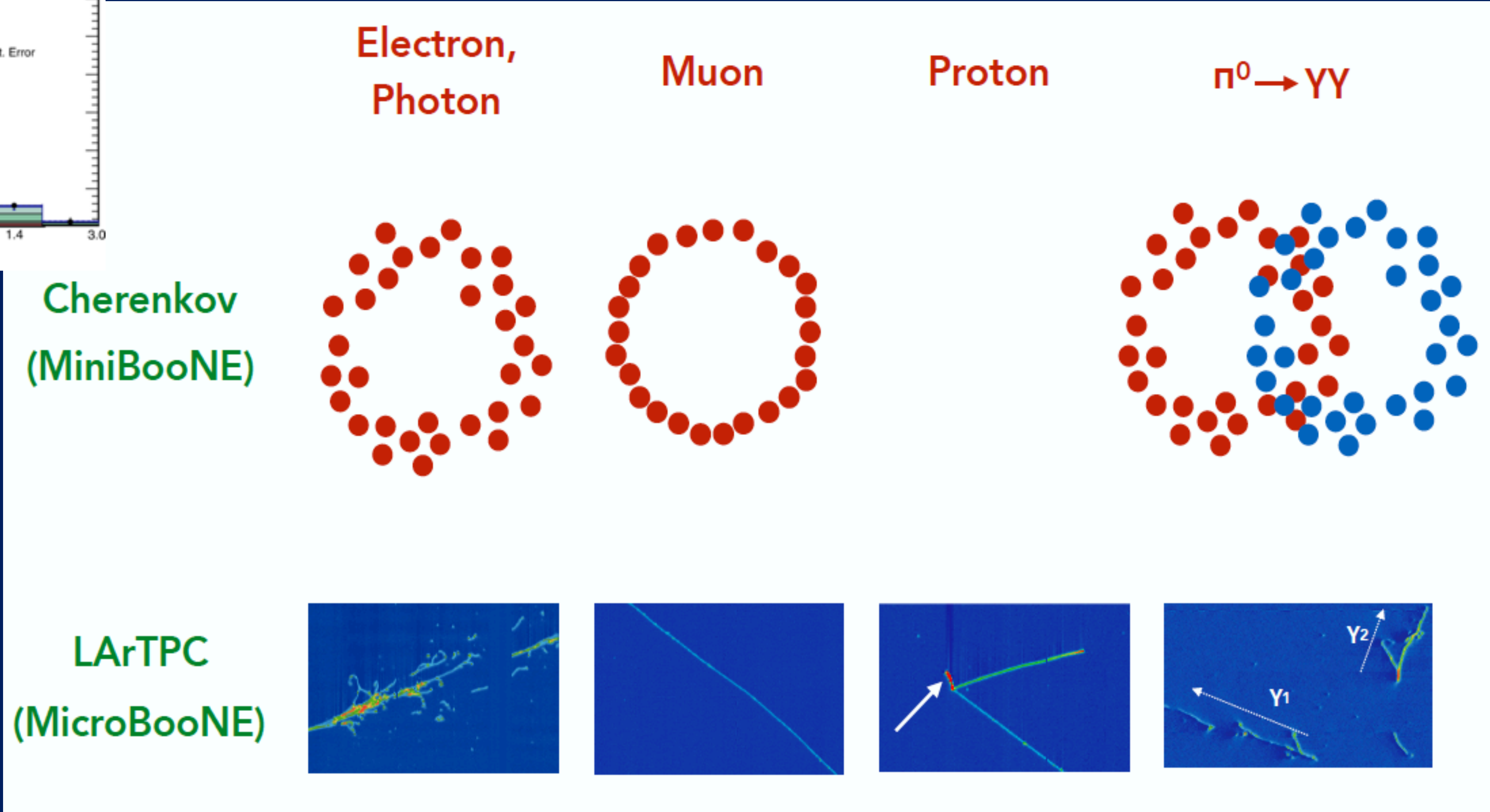

# MicroBooNE

UNIVERSITÄT BERN
AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

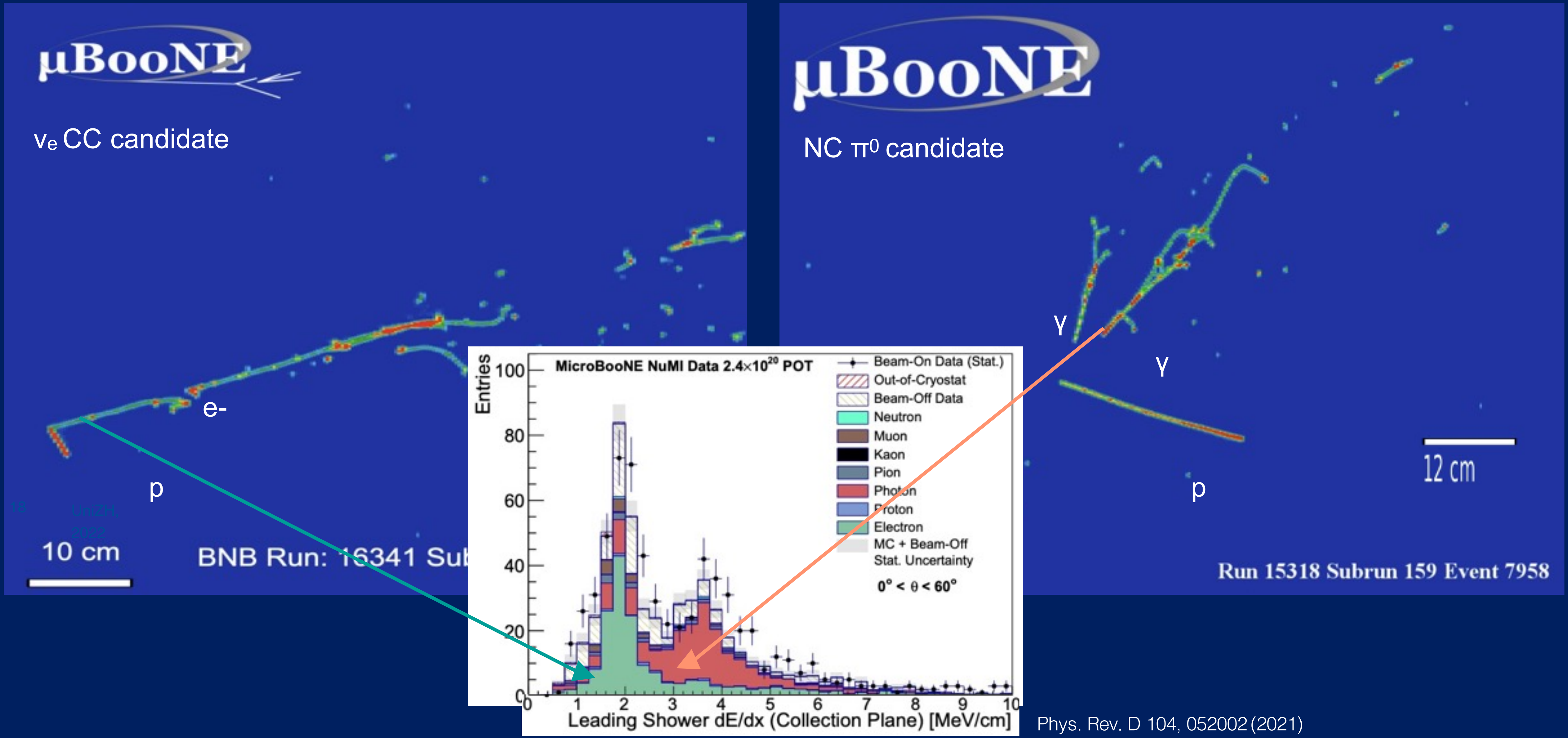
- June 2012
  - Start of TPC construction
- March 2013
  - Cryostat delivery
- December 2013
  - Install TPC in cryostat
- • June 2014
  - Transport detector
- • December 2014
  - Detector installation complete
- • June 2015
  - Fill detector with liquid argon
- • August 2015
  - Turn on detector
- • October 2015
  - Start neutrino beam data-taking

# Investigating the MiniBooNE excess with a Liquid Argon TPC



# LArTPC — Fully Active Tracking Calorimeter

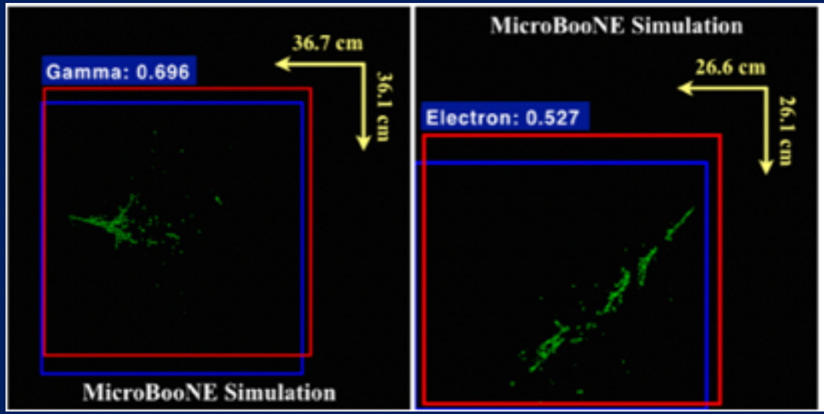


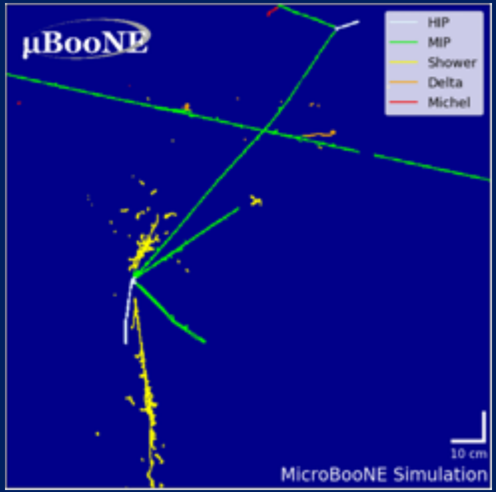

Phys. Rev. D 104, 052002 (2021)

# Developed three automated reconstructions

Convolutional Neural Network
Deep Learning image recognition

JINST 12, P03011 (2017)

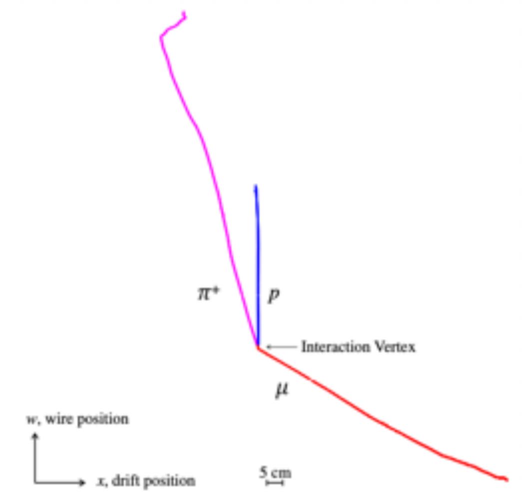


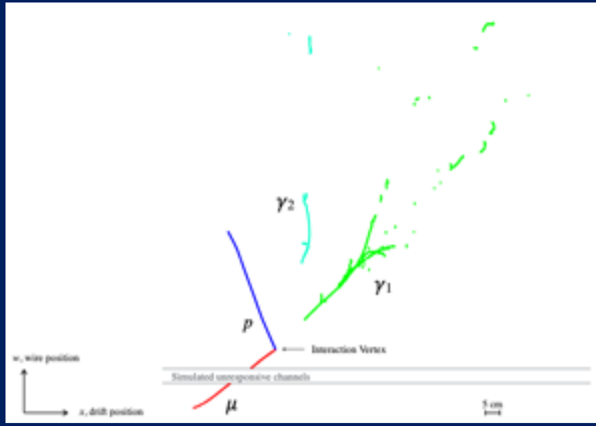




Phys. Rev. D103, 052012 (2021)

Multi-algorithm pattern recognition "Pandora"

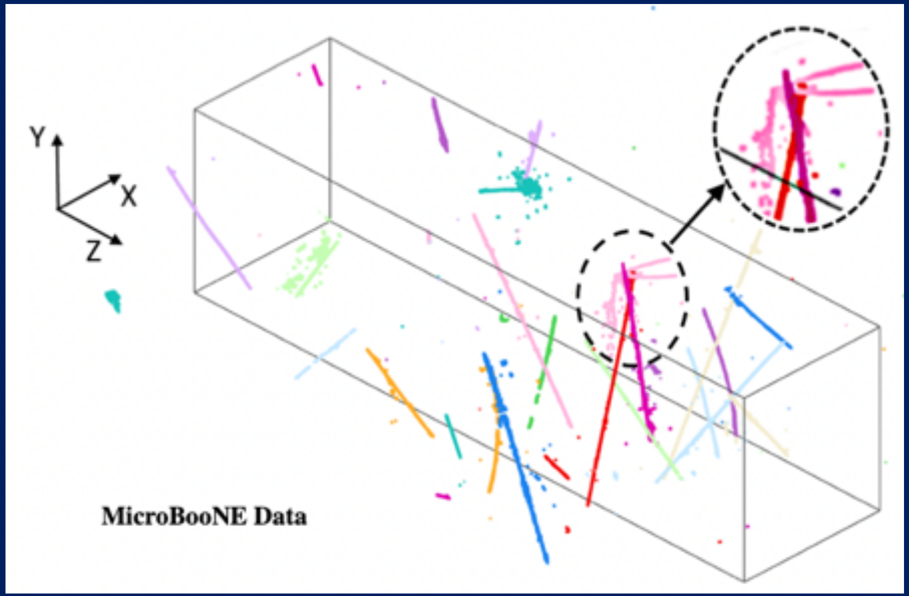
Eur. Phys. J. C78, 1, 82 (2018)



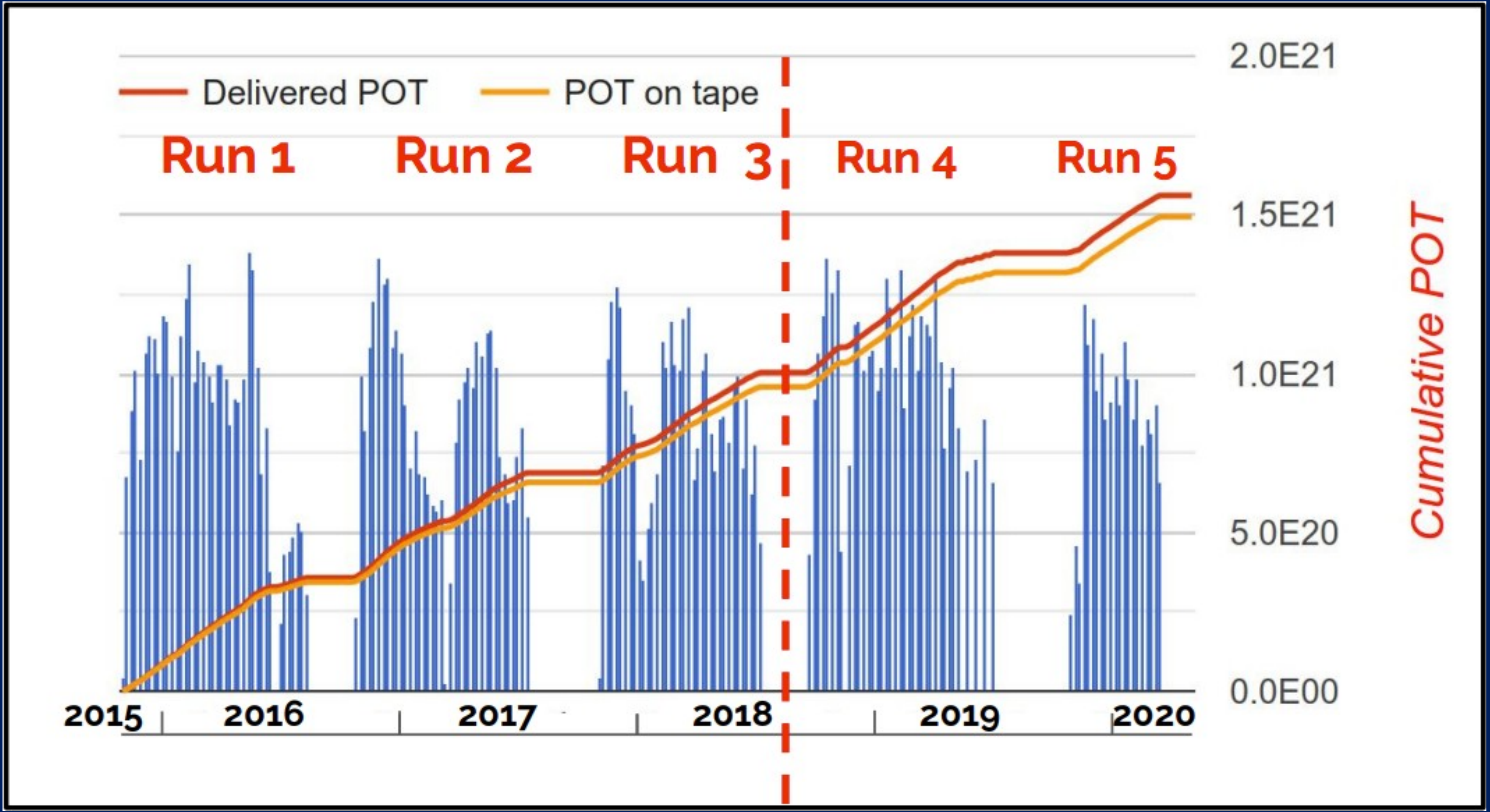

3D space-point "Wire-Cell"

JINST 16, P06043 (2021)



# Data Sample




Delivered POT
POT on tape
Run 1
Run 2
Run 3
Run 4
Run 5
2.0E21
1.5E21
1.0E21
5.0E20
0.0E00
Cumulative POT
2015
2016
2017
2018
2019
2020

# MicroBooNE Science Output

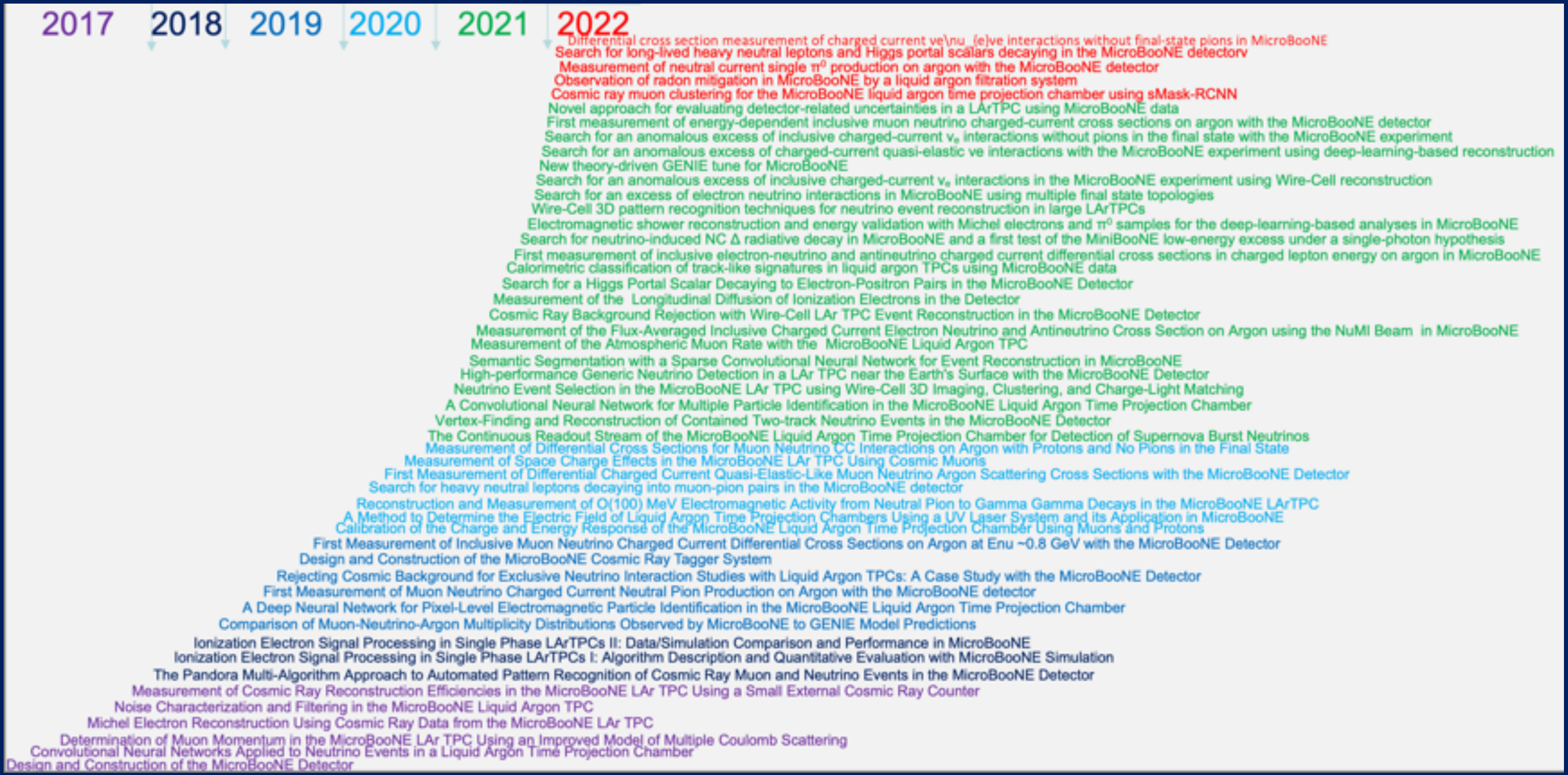
UNIVERSITÄT BERN
AEC
ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

50 papers
- ~1/2 JINST,
  ~1/2 Phys Rev, EPJC

>75public notes
- Sharing with the community as we go

50 PhD theses

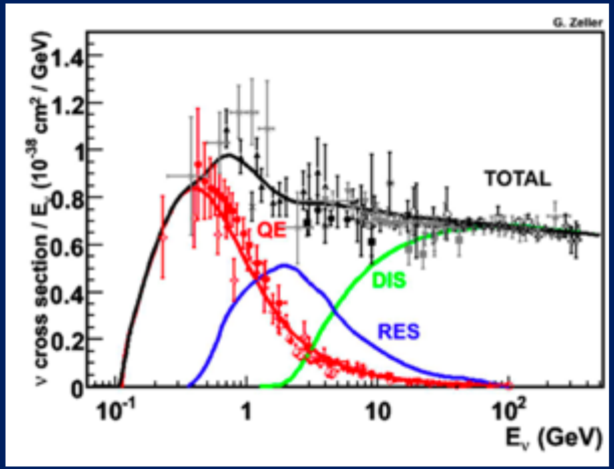
Demonstration of particle reconstruction, event (interaction) reconstruction, physics results for various topologies



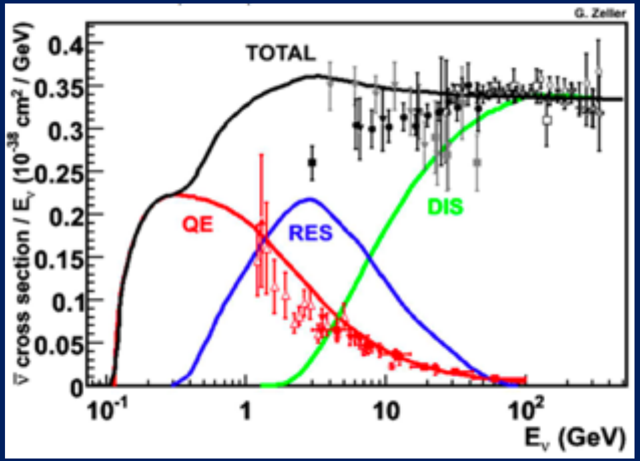
# Neutrino interaction measurements

UNIVERSITÄT BERN
AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

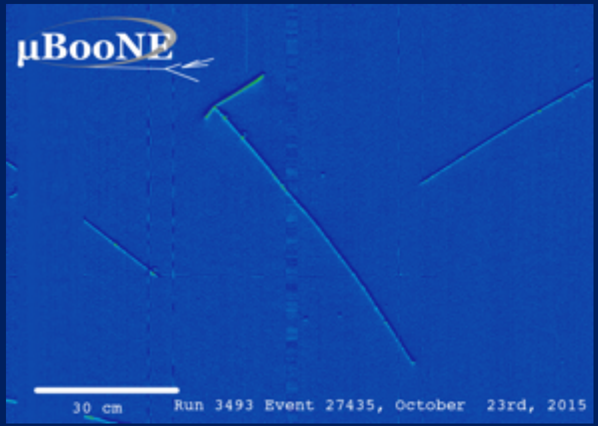
Neutrino



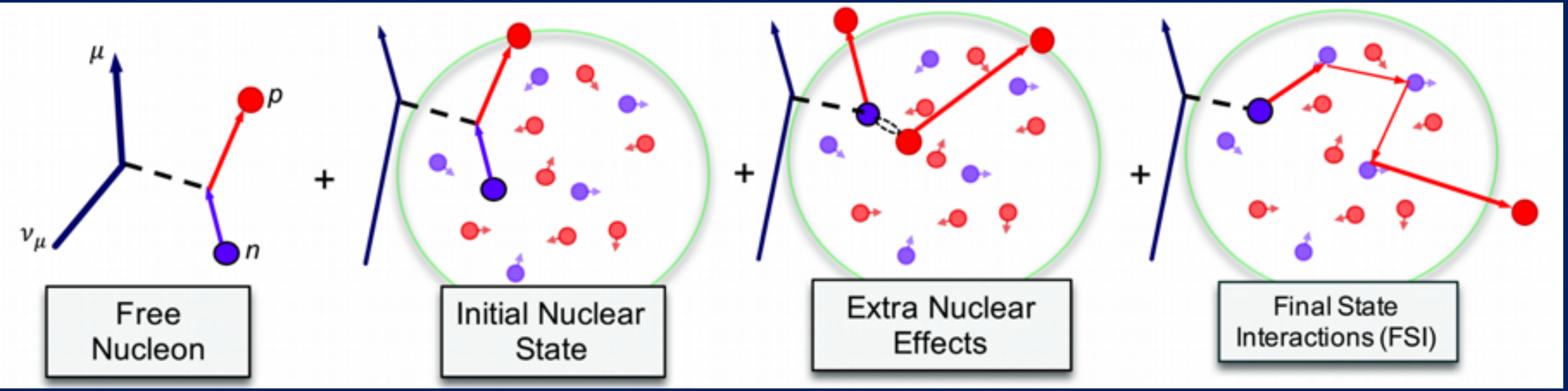

Anti-neutrino

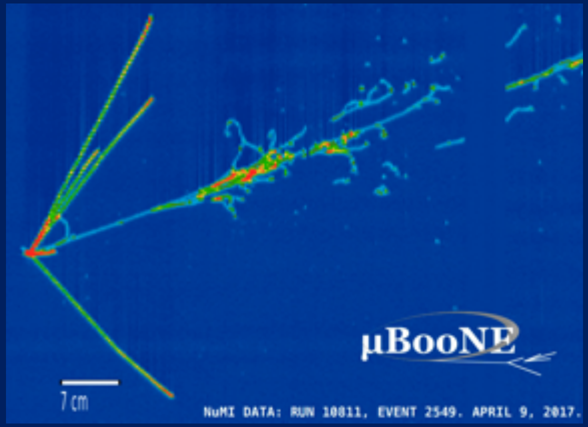



Rev. Mod. Phys. 84, 1307–1341 (2012)

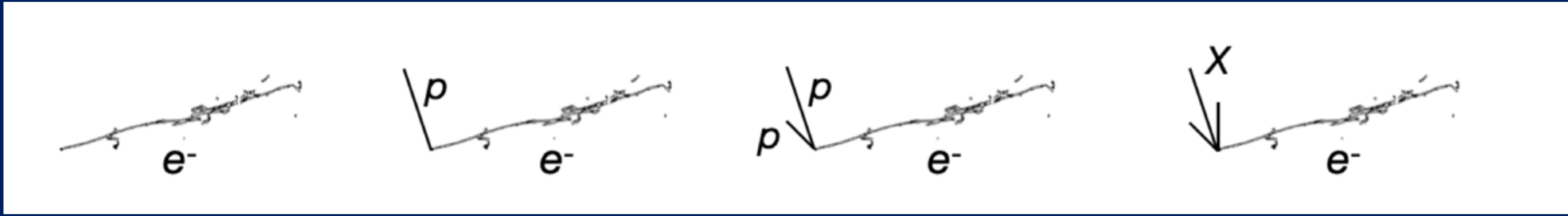


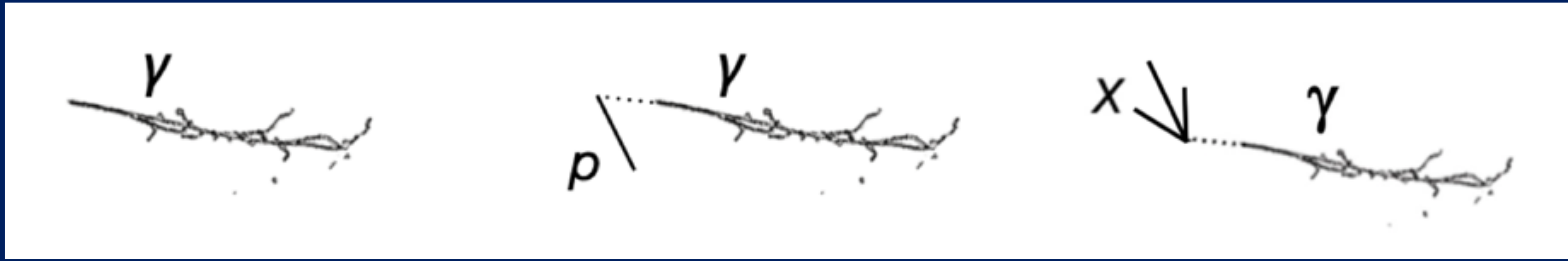

Nuclear physics

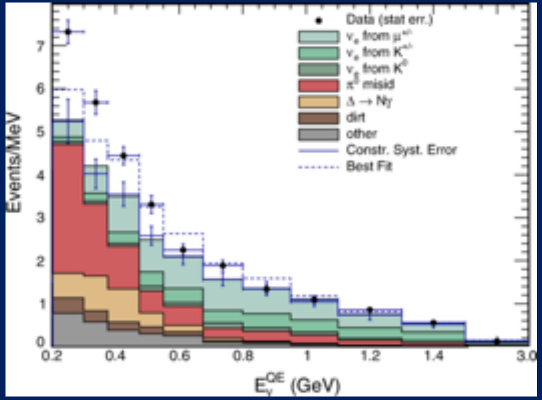


# Approaching a measurement of $\nu_e$ or Δ




We need to:

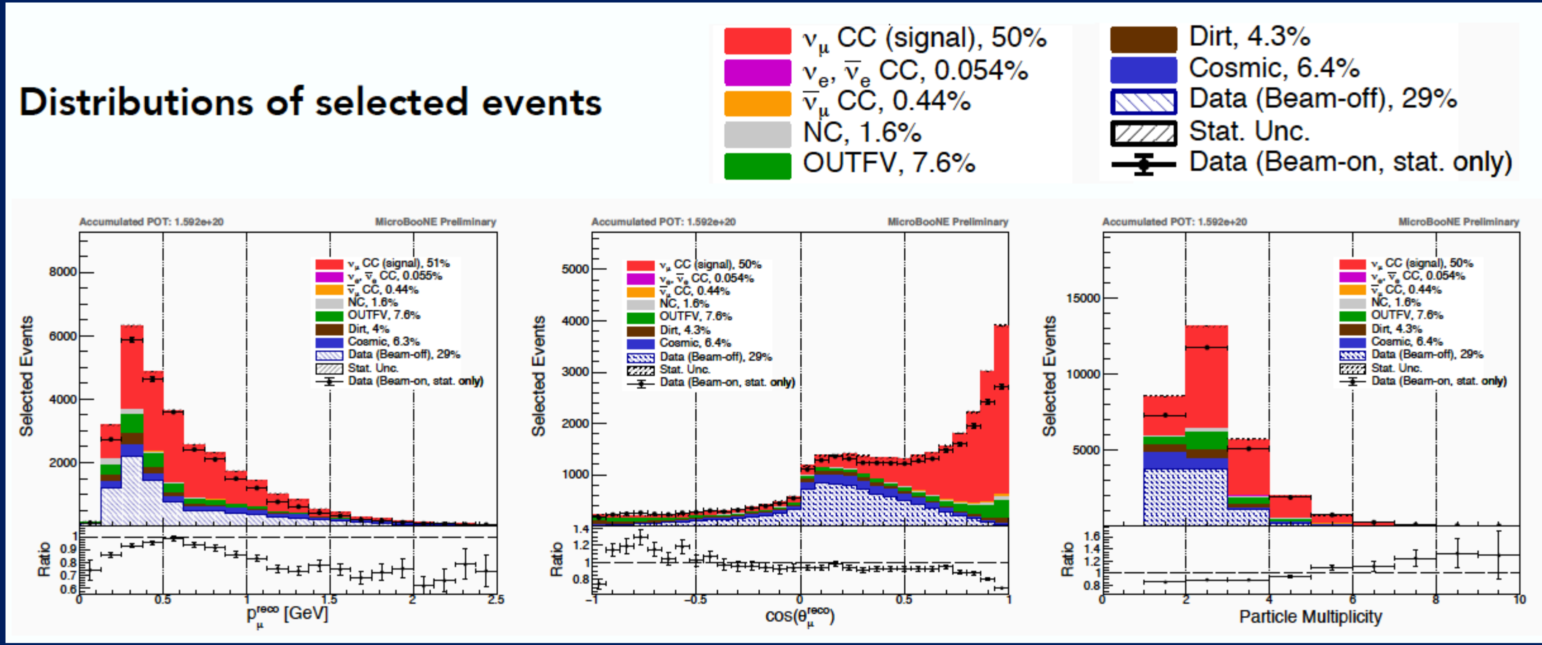
- identify neutrino intereactions, vertices $\nu_e$ or $\nu_\mu$ and control systematics
- reconstruct muons, protons, electrons, photons
- identify particles and topologies at the vertex

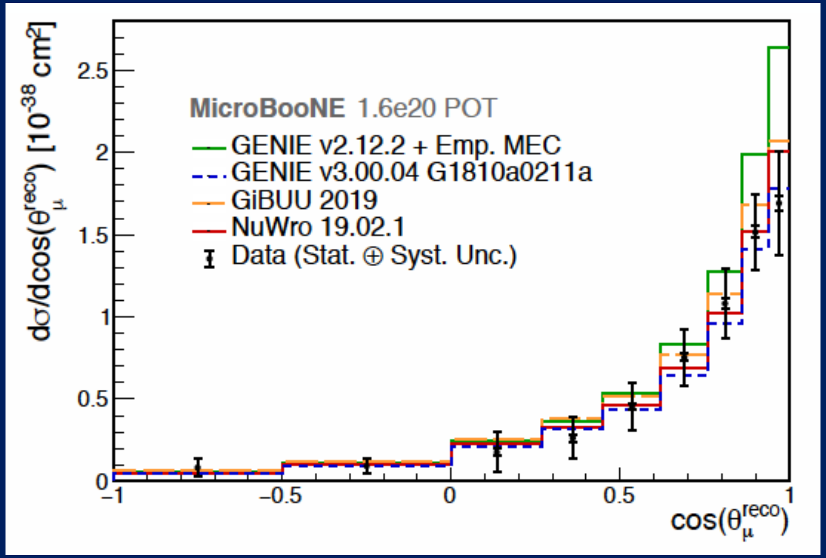
# CC $\nu_\mu$ inclusive double differential cross section

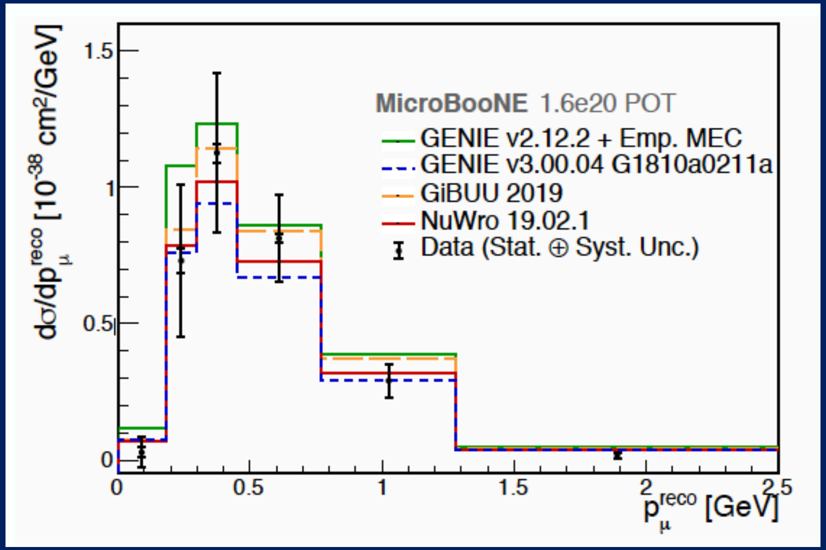
Universität Bern
AEC Albert Einstein Center for Fundamental Physics

CC $\nu_\mu + Ar \rightarrow \mu + X$

Phys. Rev. Lett. 123, 131801 (2019)

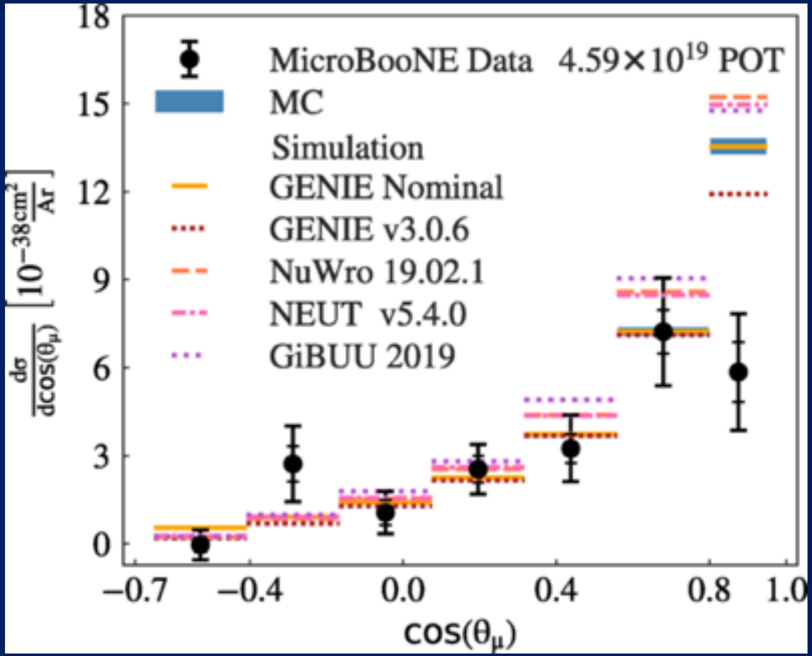


# More topologies

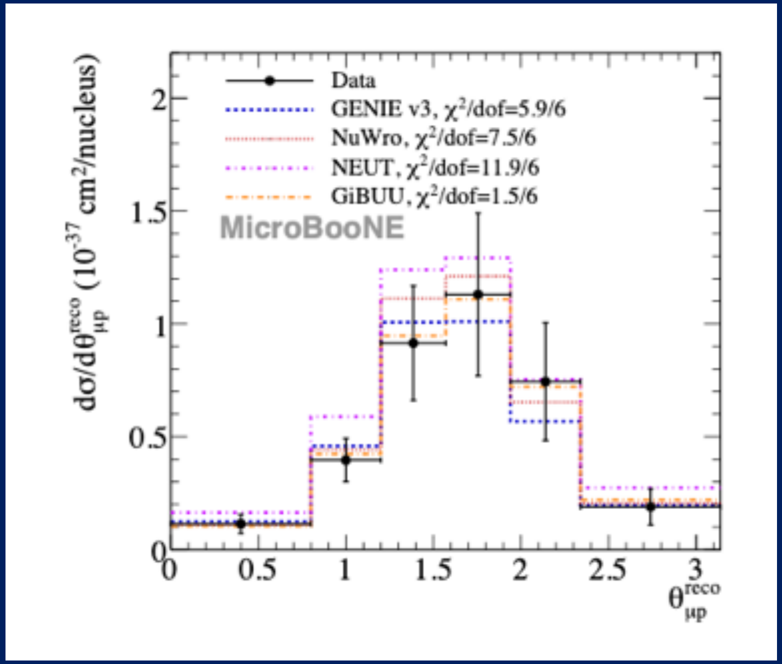
Phys. Rev. Lett. 125, 201803 (2020)




**CC Quasi-Elastic**
1 muon
+ 1 p in the final state
(+ nucleus)

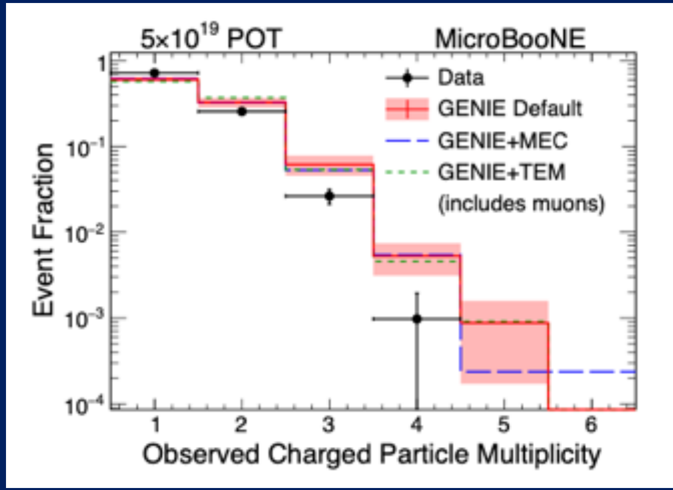
Phys. Rev. D 102, 112013 (2020)

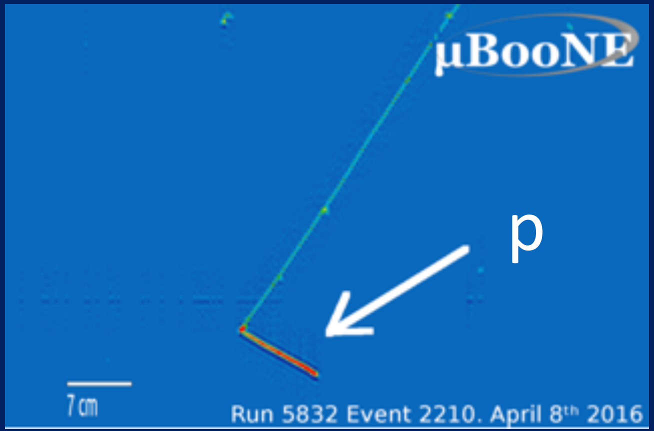
**CC Np**
1 muon any protons, no $\pi$'s

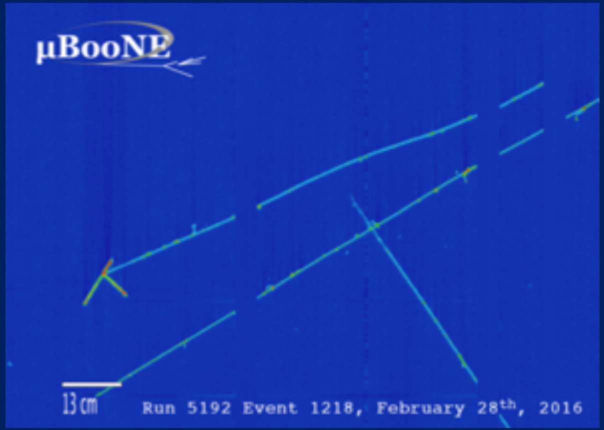



Eur. Phys. J. C79, 248 (2019)

**CC counting tracks**
1 muon any track



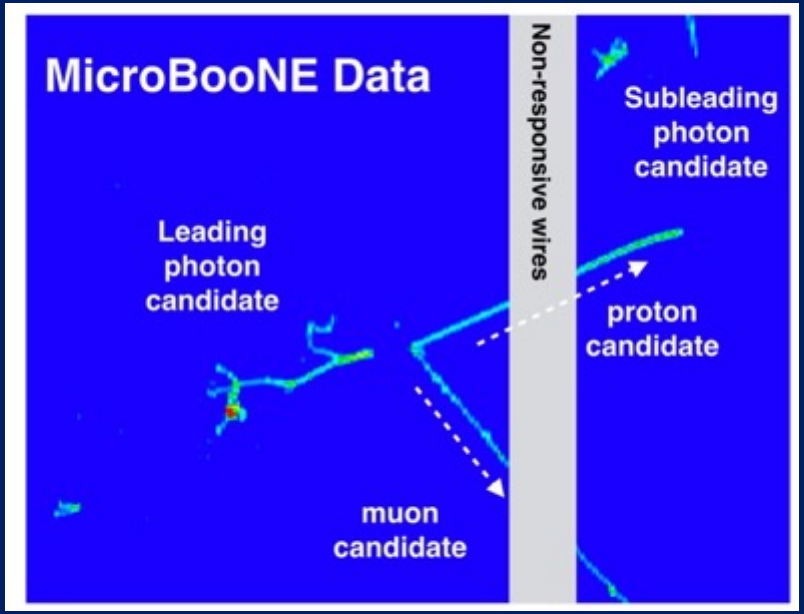



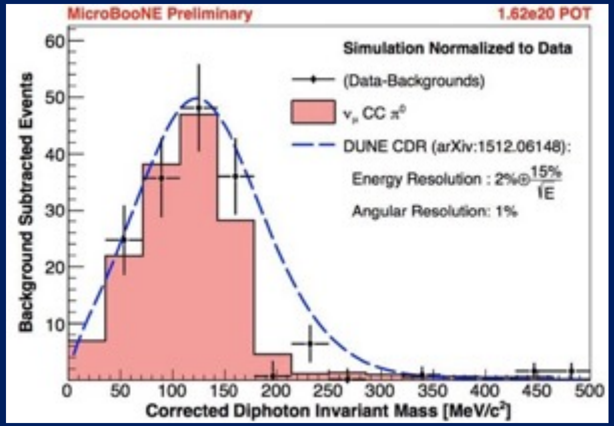



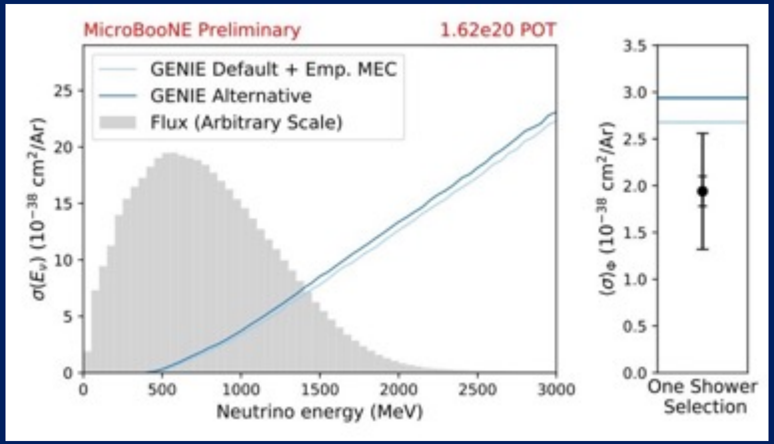
# Cross section measurement using reconstruction of electromagnetic showers

CC $\nu_\mu + Ar \rightarrow \mu + (\pi^0 \rightarrow \gamma\gamma) + X$

Phys. Rev. D99, 091102(R) (2019)



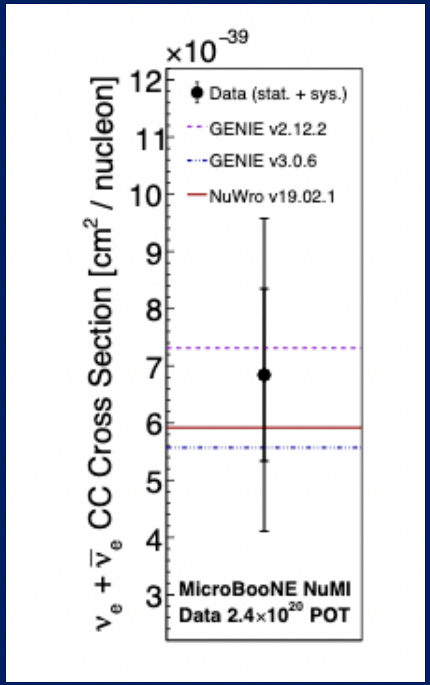




CC $\nu_e + Ar \rightarrow e + X$

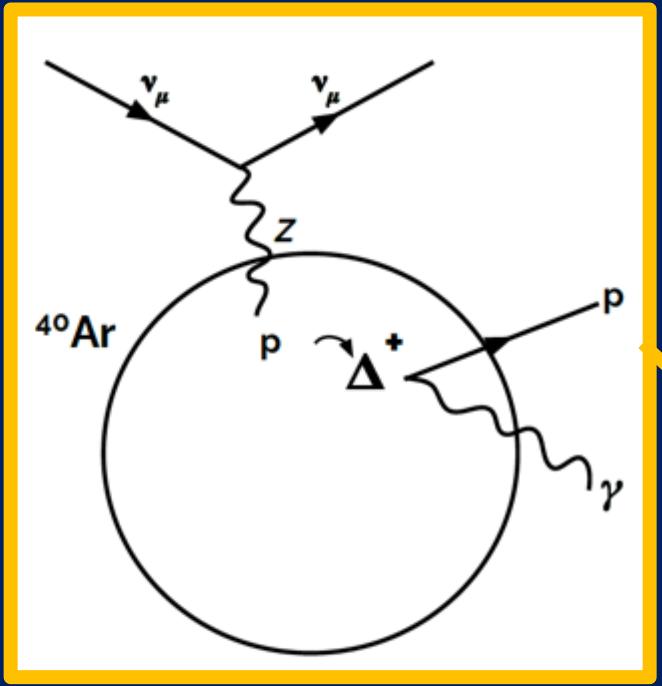
NuMI beam

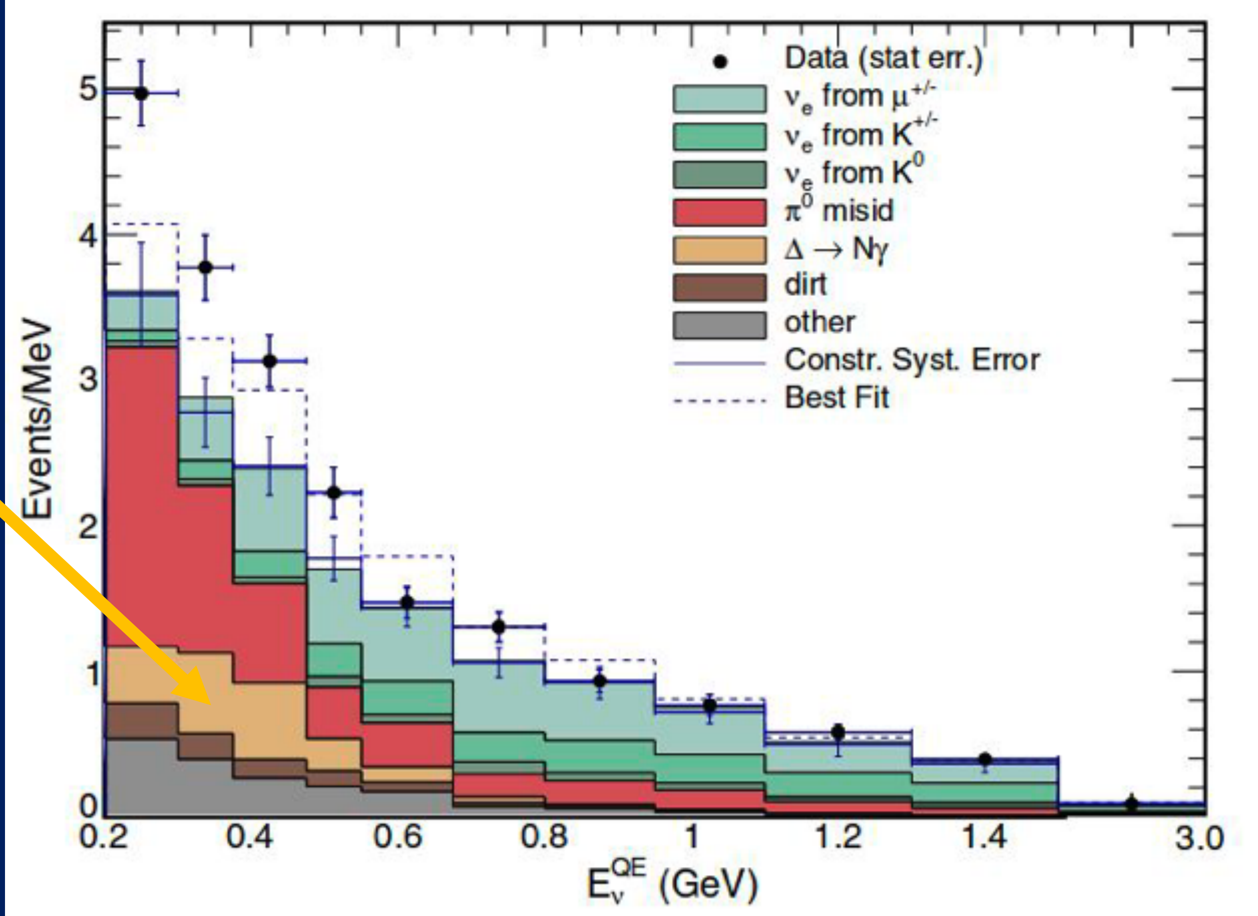
arXiv:2101.04228

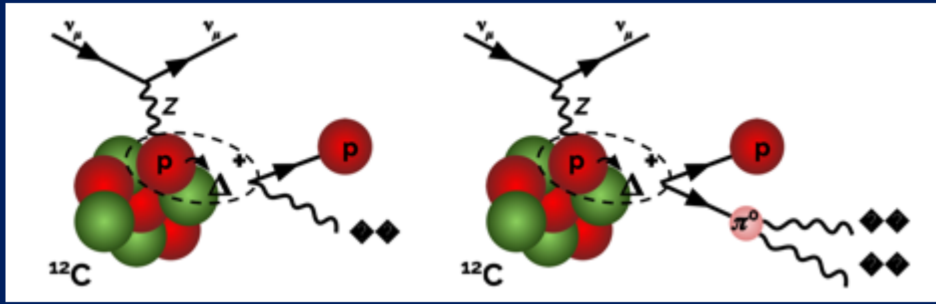


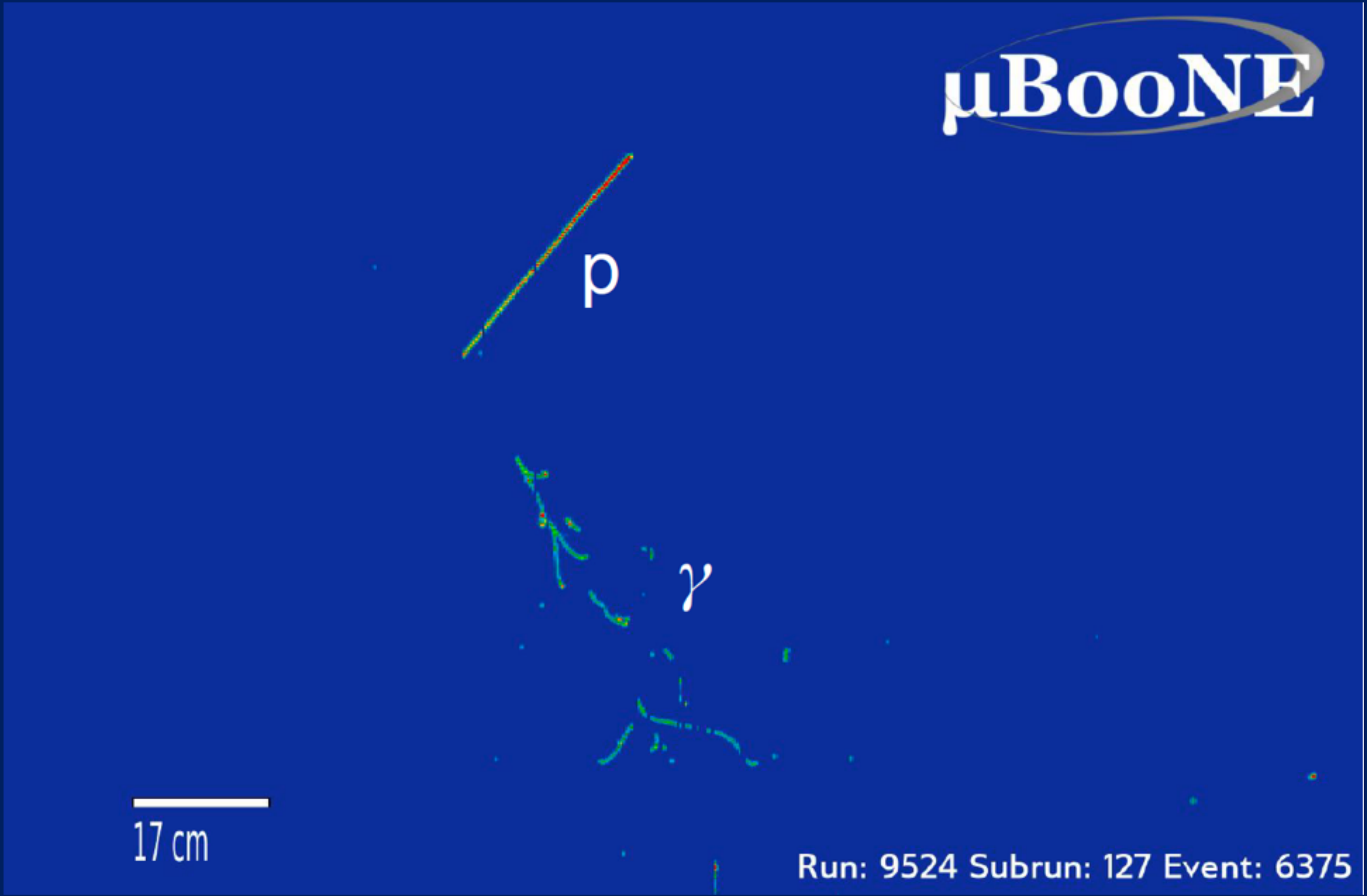
# Is the MiniBooNE excess coming from events with single photons ?

UNIVERSITÄT BERN
AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS



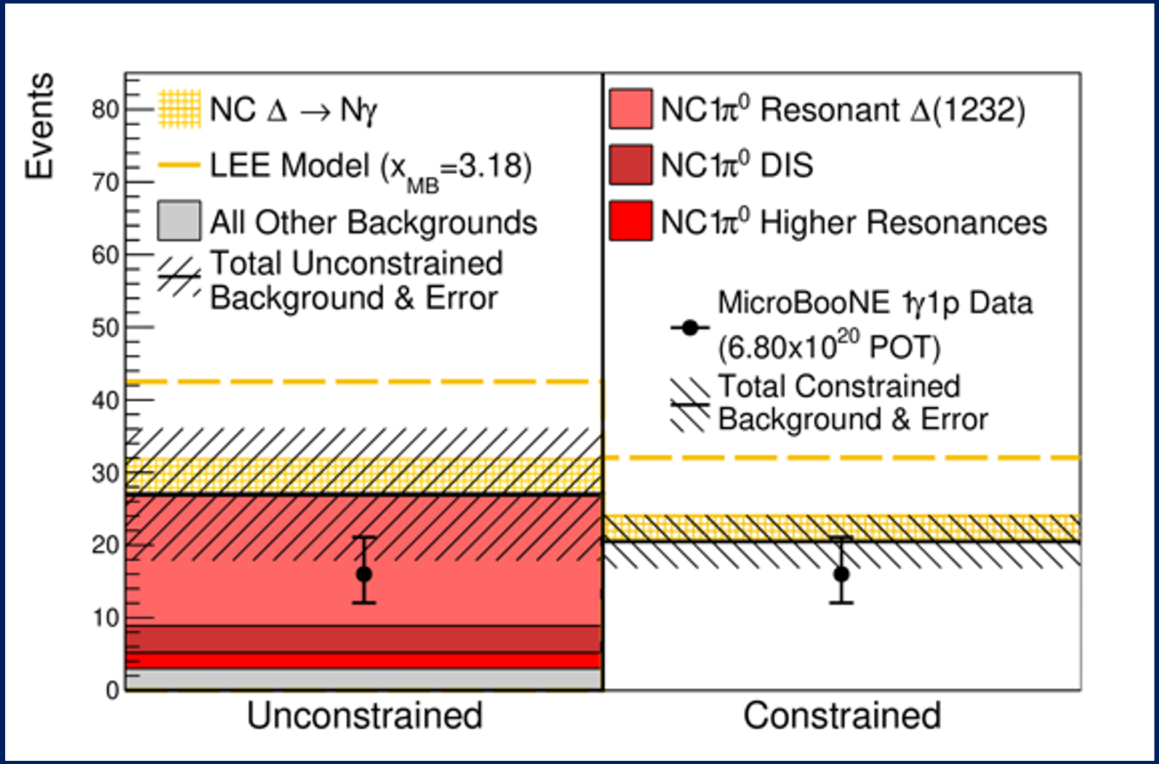




µBooNE
p
γ
17 cm
Run: 9524 Subrun: 127 Event: 6375

# NC Δ resonance results

https://arxiv.org/abs/2110.00409
PRL 128 (2022), 111801

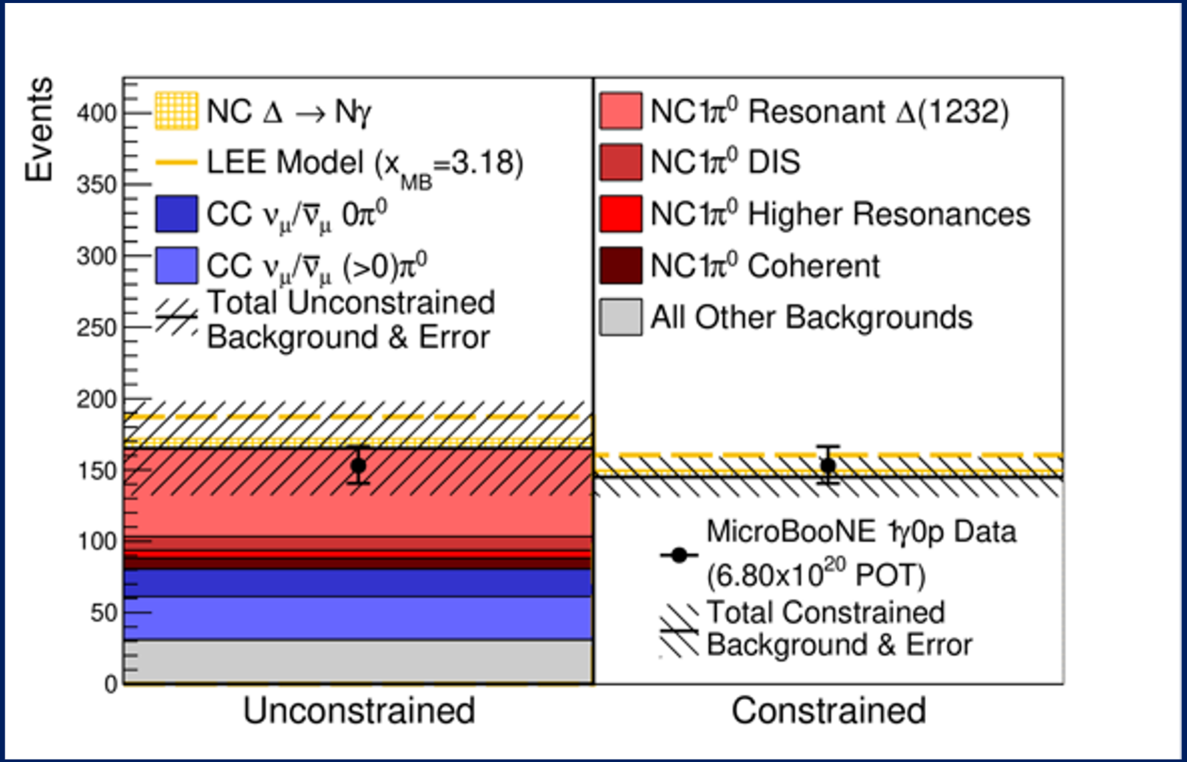
## 1γ1p




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

**16**
Data Events Observed

## 1γ0p (scatter on n)




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

**153**
Data Events Observed

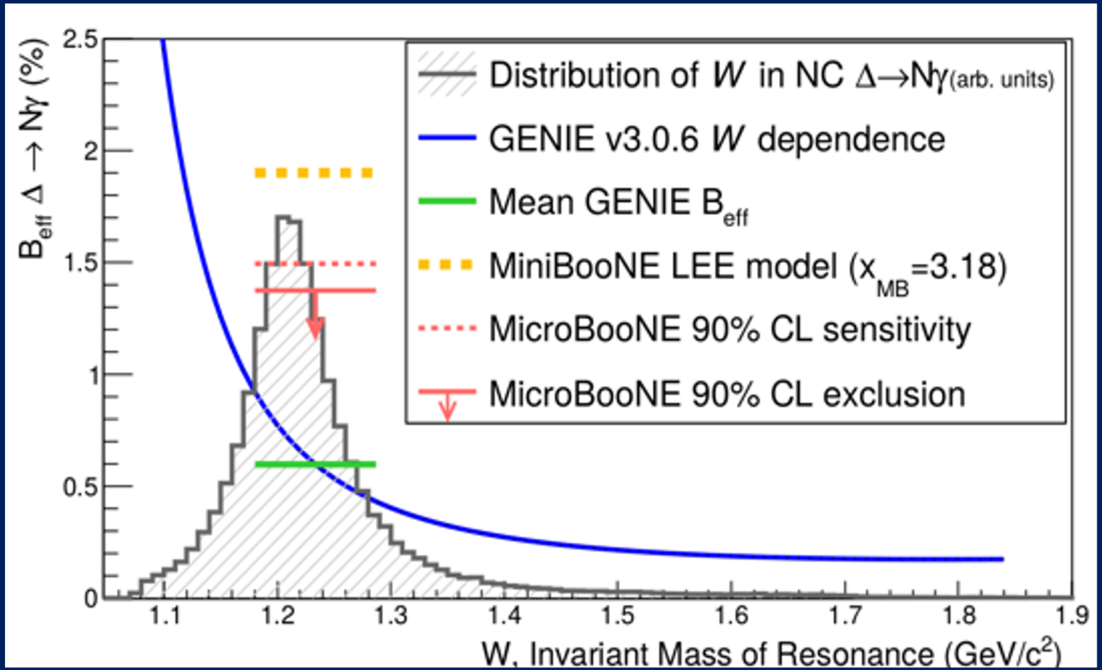
# Interpretation

- Set a bound at 90% CL. on the effective branching fraction of **Δ**→N$\gamma$:

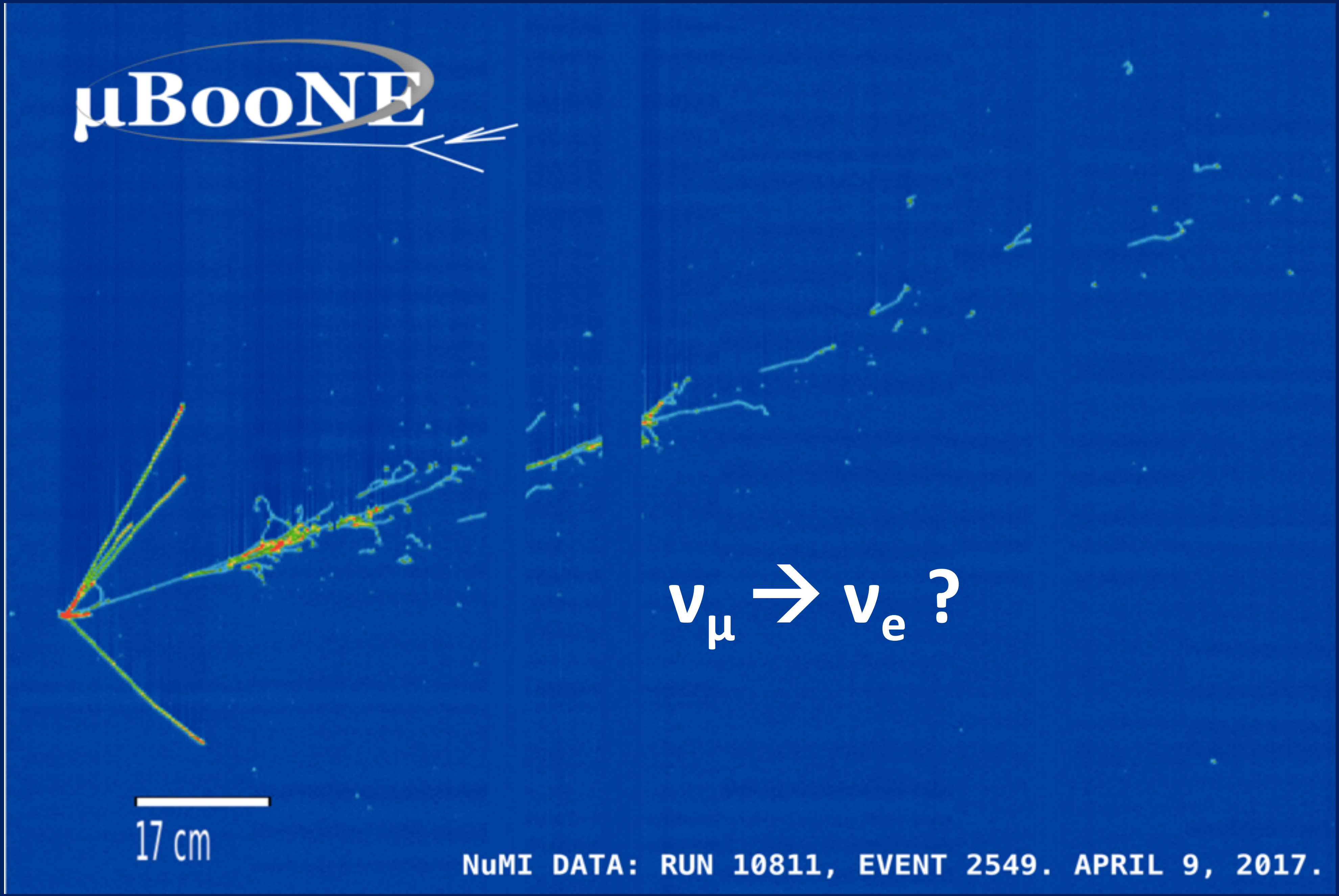
$$\mathcal{B}_{\text{eff}}(\Delta \to N\gamma) < 1.38\%$$

  - Nominal GENI simulation : $B_{eff}$ = 0.6%,
  - Expected sensitivity: < 1.5% 90% CL
  - This represents a greater than 50-fold improvement over the world's best limit on such neutrino-induced NC **Δ**→N$\gamma$ production at the O(1 GeV) scale

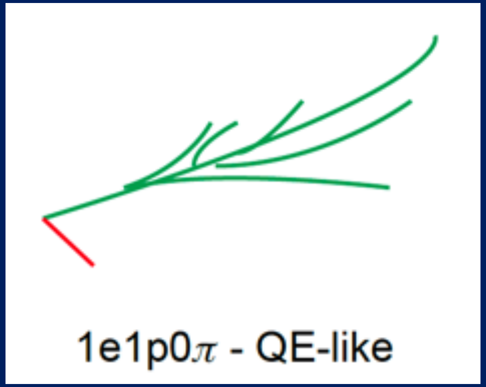
- Two-hypothesis test, excess of NC **Δ**→N$\gamma$ by a factor 3.2 vs. nominal production: excess disfavoured at 94.8% CL




PRL 128 (2022), 111801

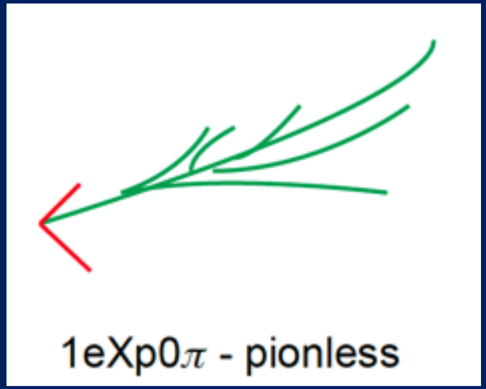

μBooNE
$\nu_\mu \rightarrow \nu_e$ ?
17 cm
NuMI DATA: RUN 10811, EVENT 2549. APRIL 9, 2017.

# Three target topologies



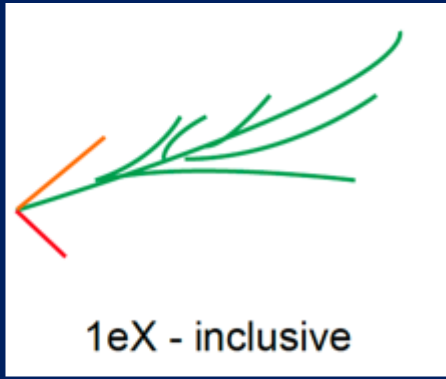


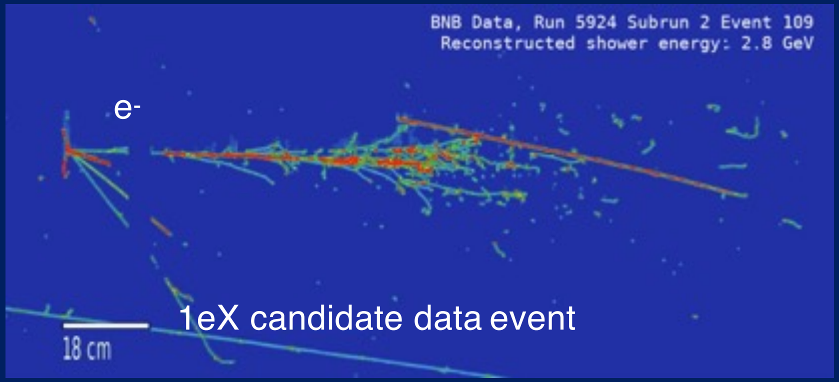
- Most understood topology and kinematics
- Low statistics
- Convolutional Networks
- Best differentiation of signal





- "Best compromise"
- Multi-algorithm reconstruction
- Most supporting cross section measurements
- Nuclear modelling




- Most inclusive
- Includes complex topologies
- Best sensitivity overall
- "Wire-Cell" space point reconstruction

# Example Wire-cell reconstruction chain

UNIVERSITÄT BERN

AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

noise filtering

signal processing

3D imaging

clustering

charge-light matching

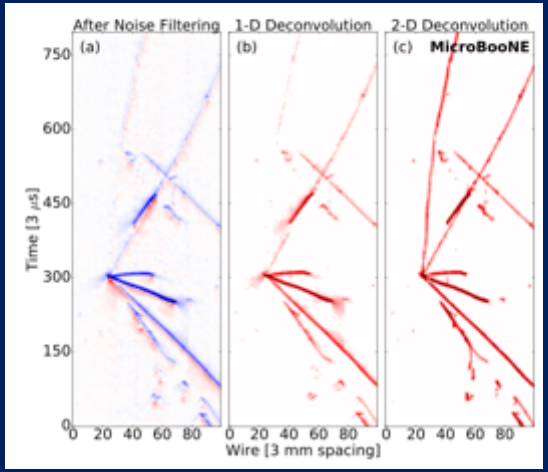
3D trajectory & dQ/dx fitting

cosmic muon tagger

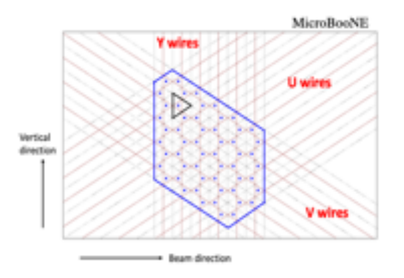
multi-track fitting

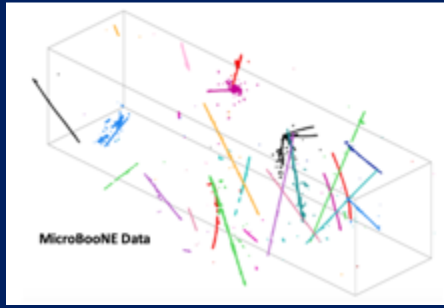
3D vertexing

particle identification

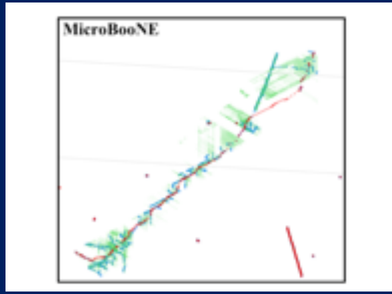


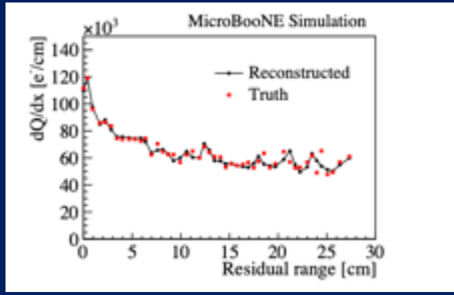

JINST 12 P08003 (2017)
JINST 13 P07006 (2018)
JINST 13 P07007 (2018)



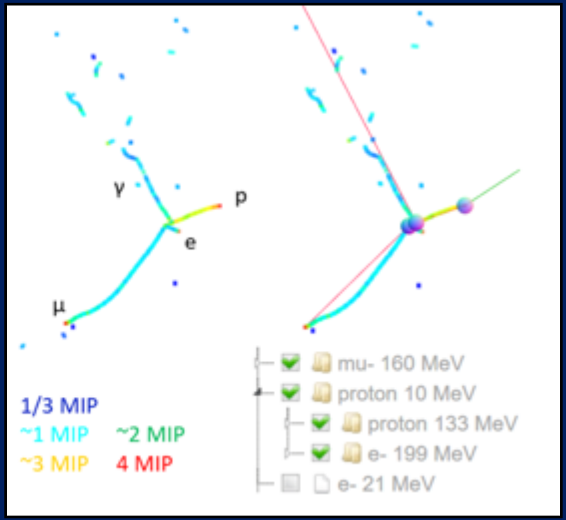




JINST 13 P05032 (2018)
JINST 16 P06043 (2021)



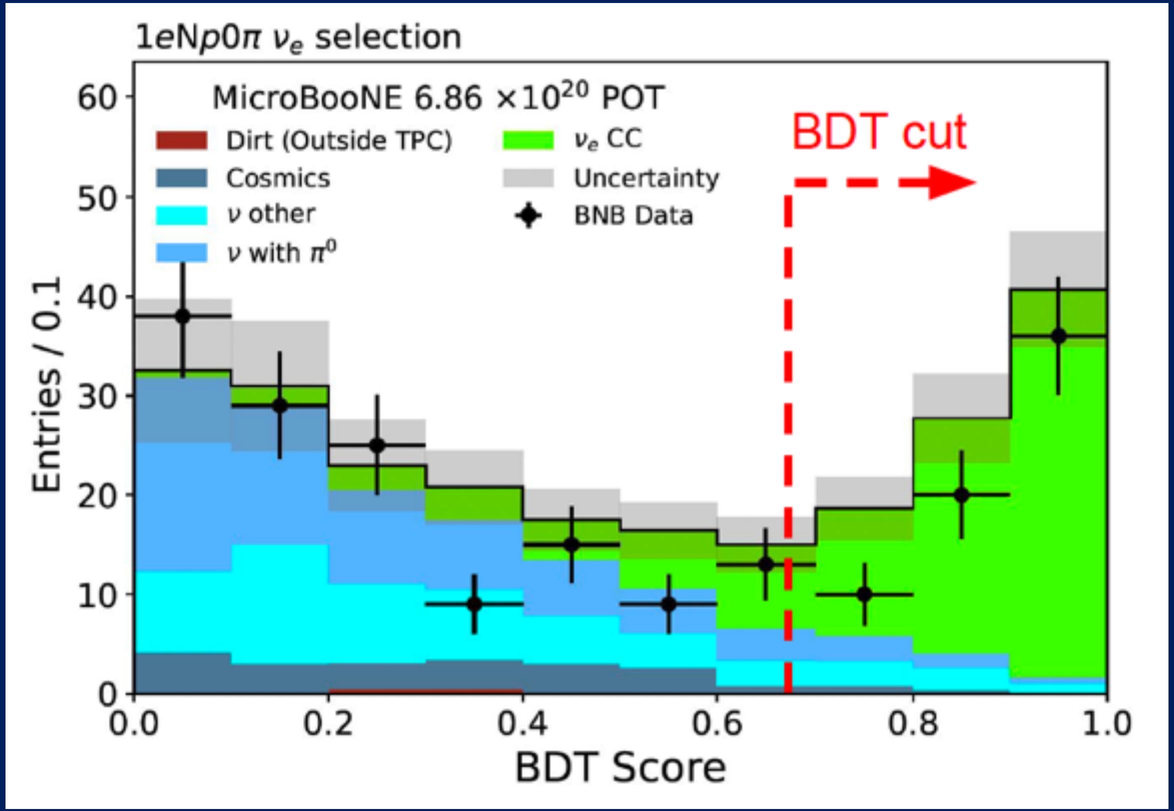

Phys. Rev. Applied 15 064071 (2021)




JINST 17, P01037 (2022)

# Event selection

- Pre-selection to reject most cosmic ray interactions
- Each analysis uses ML and BDTs to select electron neutrinos
  - Example of the pionless 1eNp0Pi analysis on the right
- All analyses reach **high purity**
- Validation in side-bands (blind analysis)

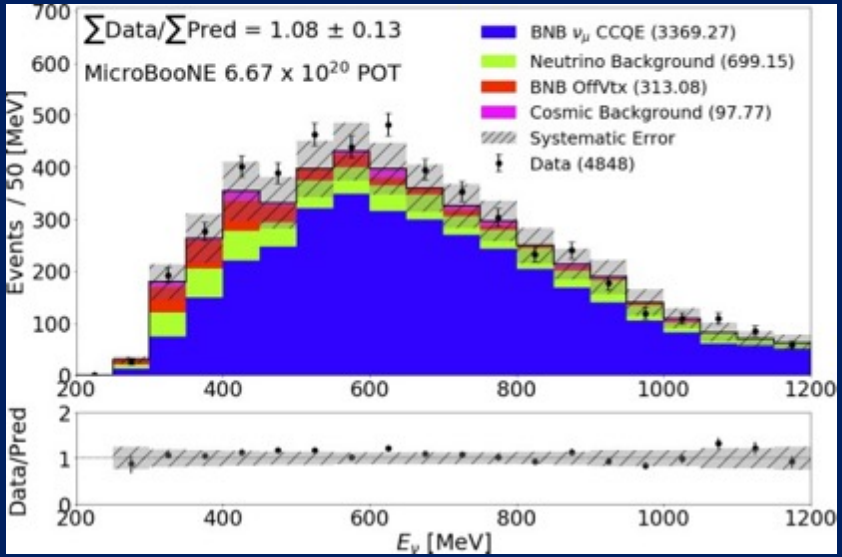


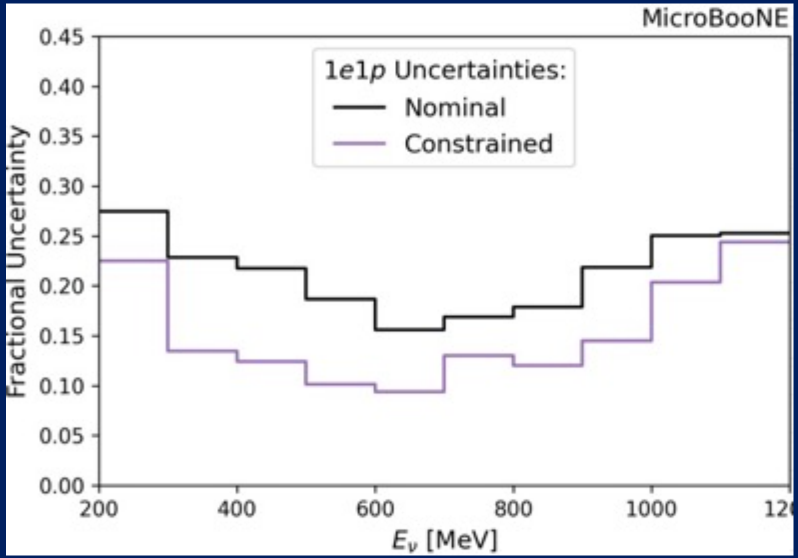
# Data-Driven $\nu_e$ Rate Prediction

- Leverage $\nu_\mu$ and $\nu_e$ correlations
  - Common flux parentage
  - Lepton universality

- High-statistics νμ sidebands, joint covariance matrix
  - $\nu_\mu$ measurement constrains $\nu_e$ prediction and reduces uncertainty

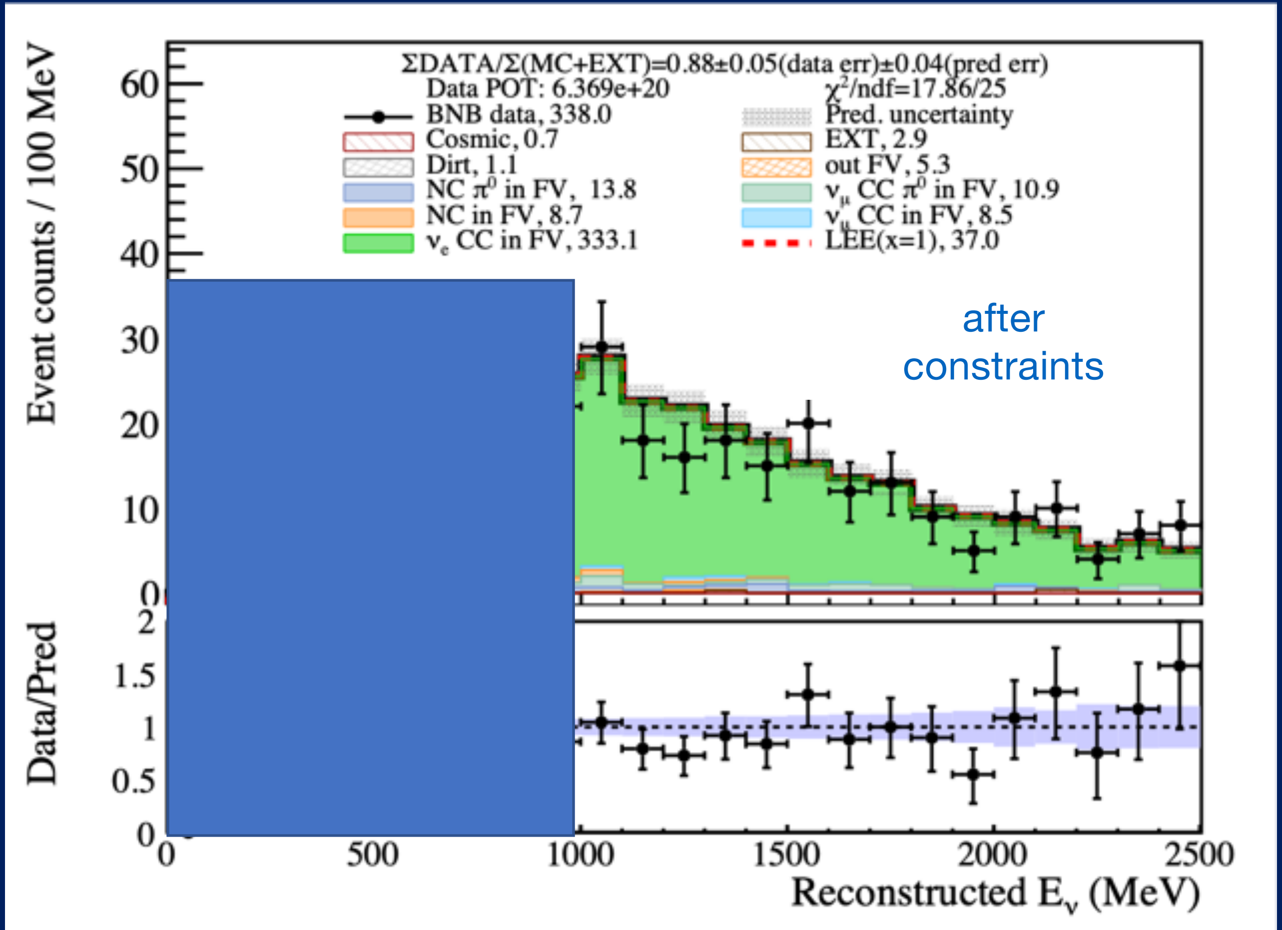
- Is the data consistent with the constrained νe expectation?
  - $\chi^2$ goodness-of-fit test



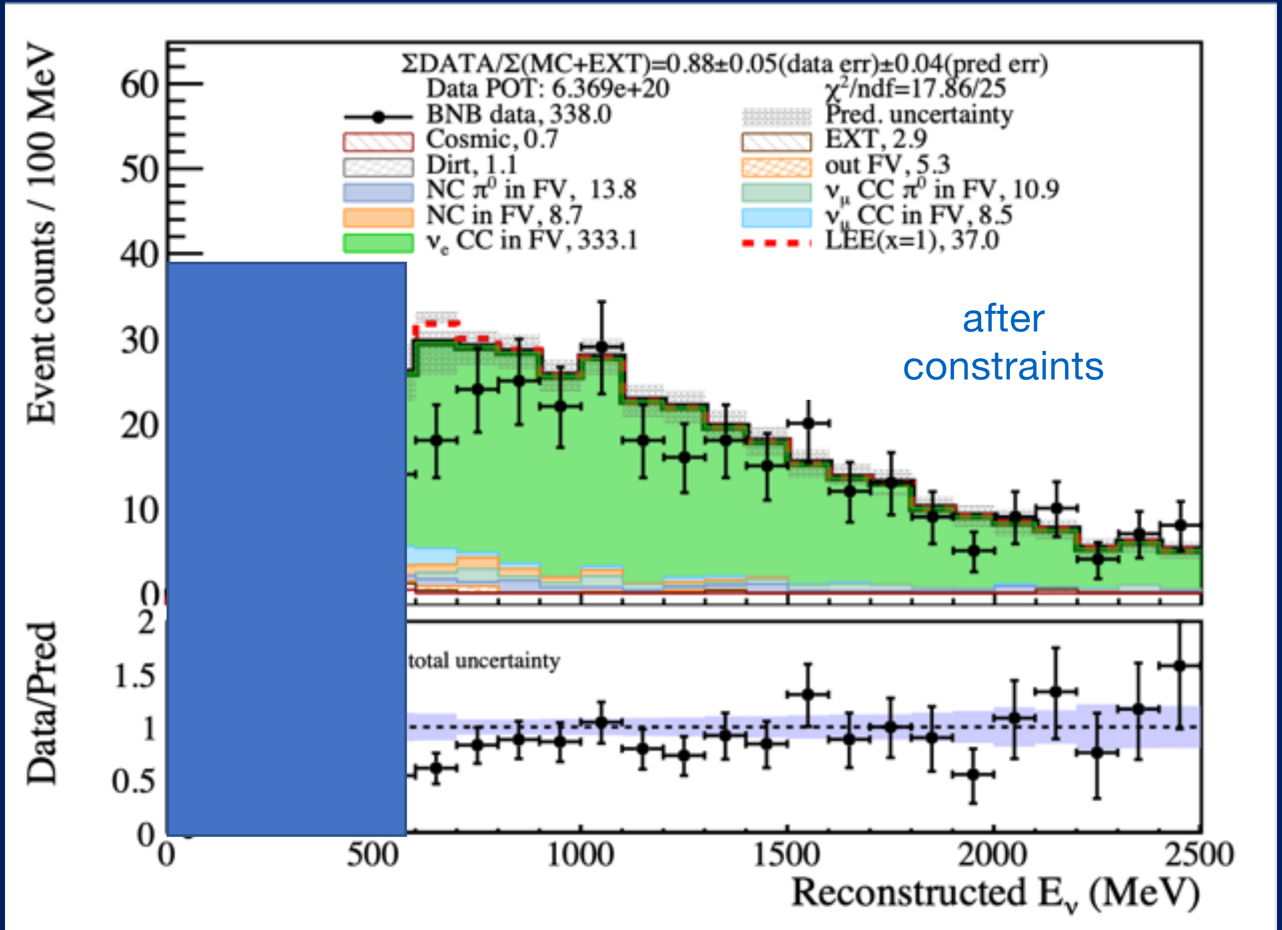
# Blind analysis box opening

UNIVERSITÄT BERN
AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS



# Blind analysis box opening

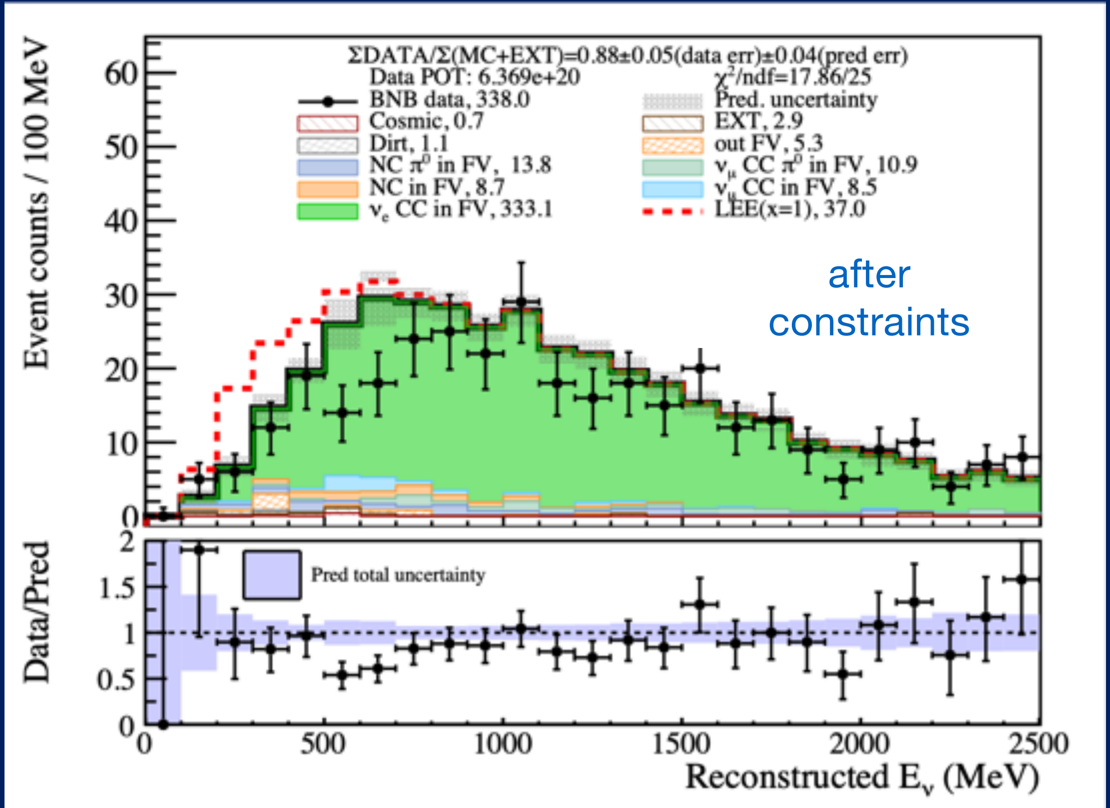




# Blind analysis box opening

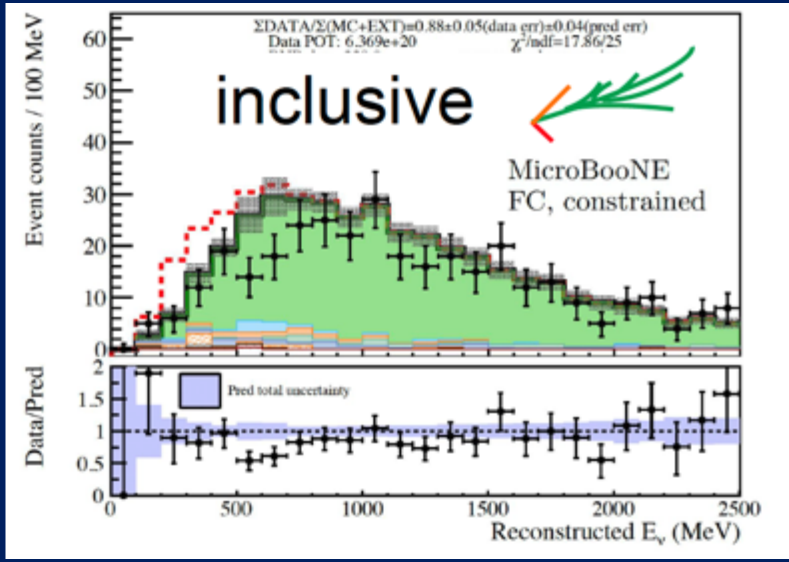
- Observed 56 events in reconstructed E$_\nu$ 0-600 MeV range
- After constraints, we predict
  - 69.6 ± 5.0 (sys) ± 8.0 (stat) events with no LEE hypothesis (eLEE$_{x=0}$)
  - 103.8 ± 7.4 (sys) ± 9.0 (stat) events with LEE hypothesis (eLEE$_{x=1}$)
- Data agrees better with eLEE$_{x=0}$ than eLEE$_{x=1}$

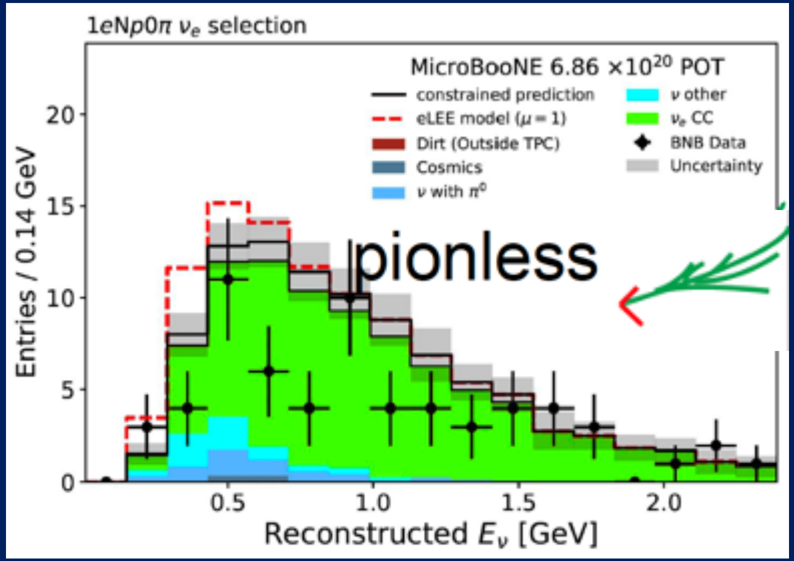
| Category | Evts w/o constr. | Evts w/ constr. |
|---|---|---|
| Beam $\nu_e$CC | 42.6 ± 10.6 | 51.5 ± 2.6 |
| $\nu_\mu$CC $\pi^0$ | 0.6 ± 0.8 | 0.8 ± 0.8 |
| $\nu_\mu$CC (non-$\pi^0$) | 3.9 ± 4.2 | 3.1 ± 3.1 |
| NC $\pi^0$ | 4.5 ± 2.3 | 4.3 ± 1.6 |
| NC (non-$\pi^0$) | 3.0 ± 1.4 | 2.9 ± 1.2 |
| Out of FV | 3.8 ± 2.0 | 3.4 ± 1.6 |
| Dirt | 1.0 ± 1.0 | 1.2 ± 0.9 |
| Cosmic | 0.3 ± 0.6 | 0.5 ± 0.6 |
| EXT (beam-off data) | 1.9 ± 1.7 | |
| Pred. total (eLEE$_{x=0}$) | 61.5 ± 15.3 ± 7.7 | 69.6 ± 5.0 ± 8.0 |
| Pred. total (eLEE$_{x=1}$) | 91.8 ± 23.4 ± 8.7 | 103.8 ± 7.4 ± 9.0 |
| BNB data | 56 | |

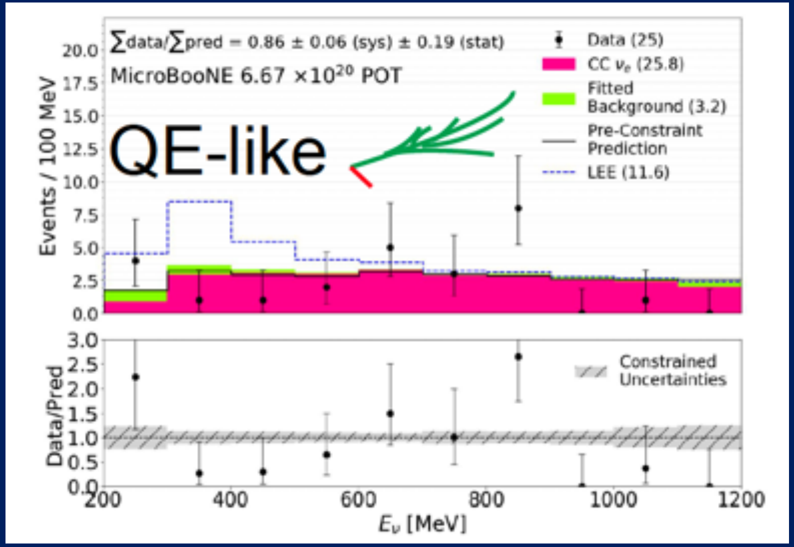


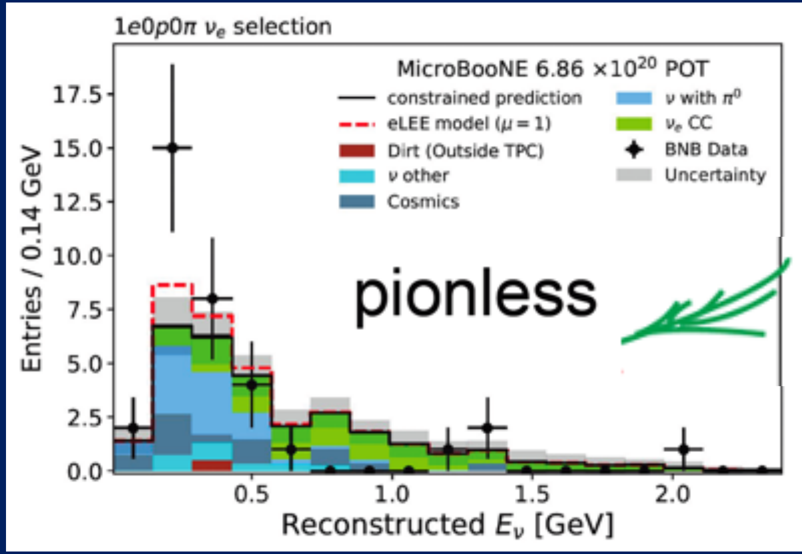

**No excess of low energy $\nu_e$ candidates is observed!**

# Same result in all analyses




Phys. Rev. Lett. 128, 241801 (2022)
Phys. Rev. D105, 112005 (2022) (inclusive)
Phys. Rev. D105, 112004 (2022) (pionless)
Phys. Rev. D105, 112003 (2022) (QE)

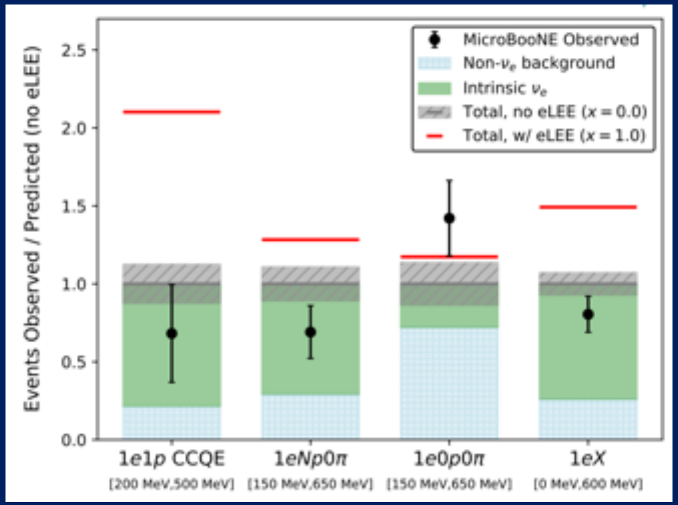
# Statistical analysis

- Ensemble testing
- $\chi^2$ goodness-of-fit
- H0: x=0; no LEE
- H1 : x=; w/LEE
- $\Delta\chi^2$
- An additional signal strength fit

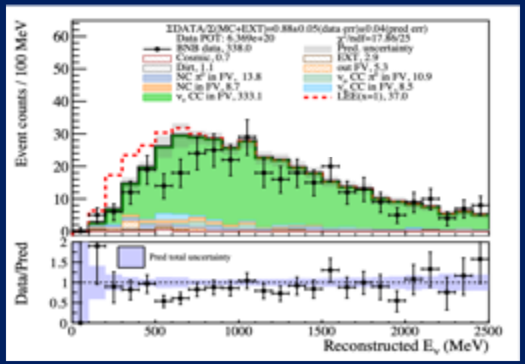
All analyses:

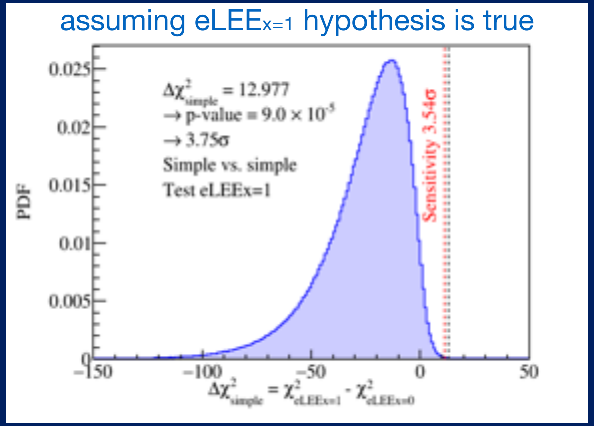
**Final fit results**

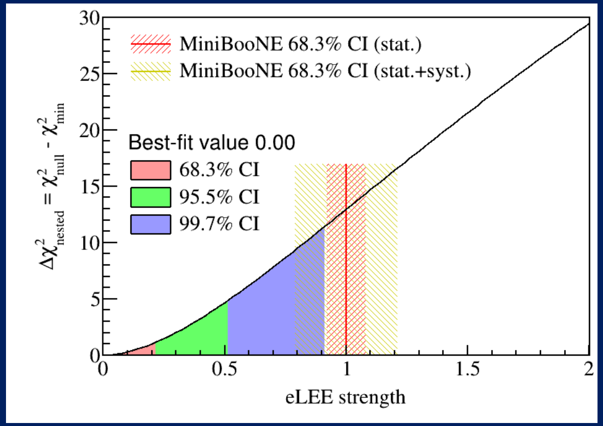
| | 1e1p CCQE | 1eNp0π | 1e0p0π | 1eX |
|---|---|---|---|---|
| $E_\nu$ (MeV) | 200-1200 | 150-1550 | 150-1550 | 0-2500 |
| $p\ (\chi^2_{x=0})$ | $1.4 \times 10^{-2}$ | 0.18 | 0.13 | 0.85 |
| $p\ (\Delta\chi^2 < \text{obs.})$, w/ eLEE | $1.6 \times 10^{-4}$ | $2.1 \times 10^{-2}$ | 0.93 | $9.0 \times 10^{-5}$ |
| $x$ observed, $1\sigma$ | [0.00,0.08] | [0.00,0.41] | [1.91,8.10] | [0.00,0.22] |
| $x$ observed, $2\sigma$ | [0.00,0.38] | [0.00,1.06] | [0.77,24.3] | [0.00,0.51] |
| $x$ expected upper limit, $2\sigma$ | 0.98 | 1.44 | 4.64 | 0.56 |



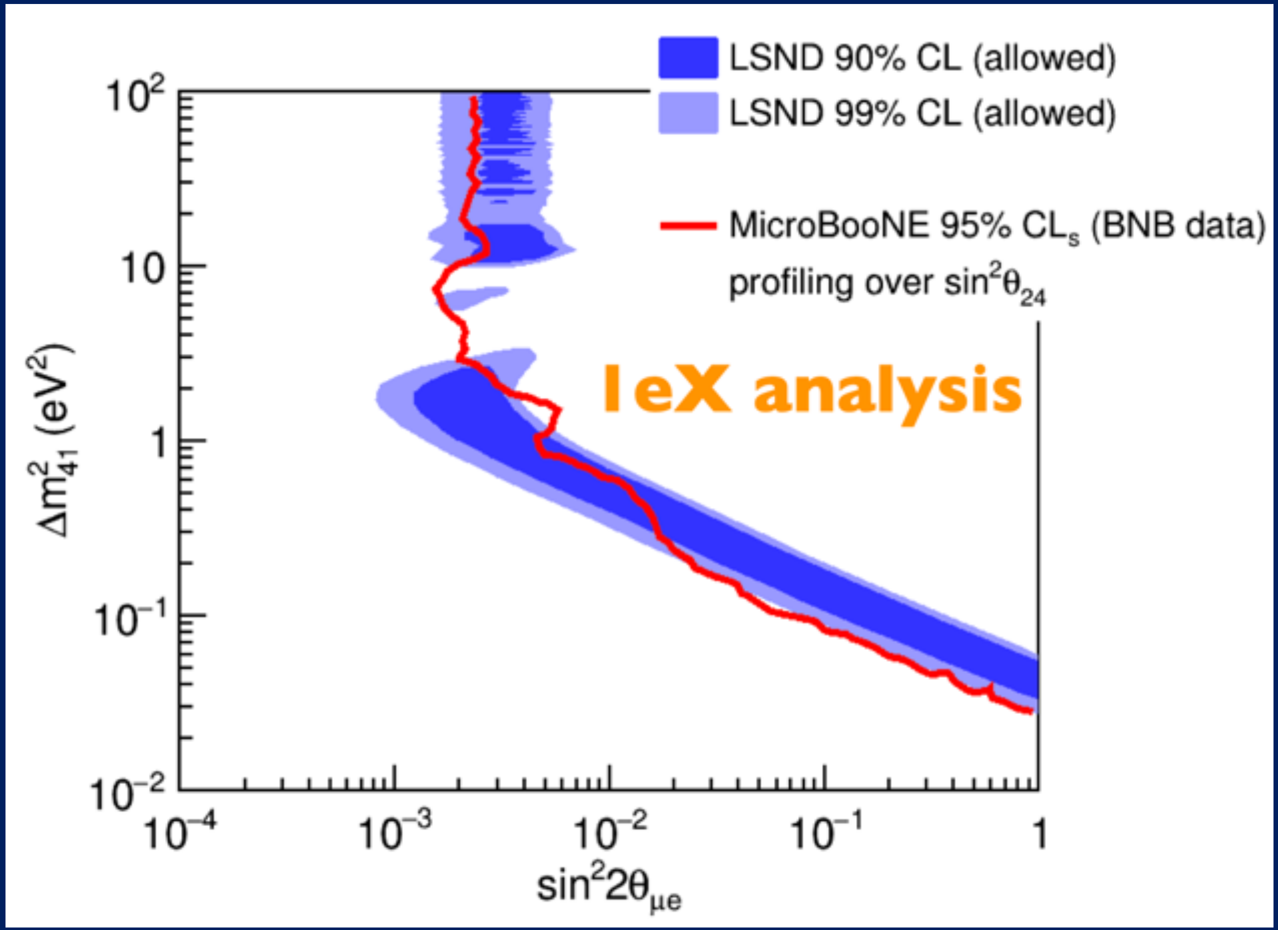

Example inclusive 1eX analysis:



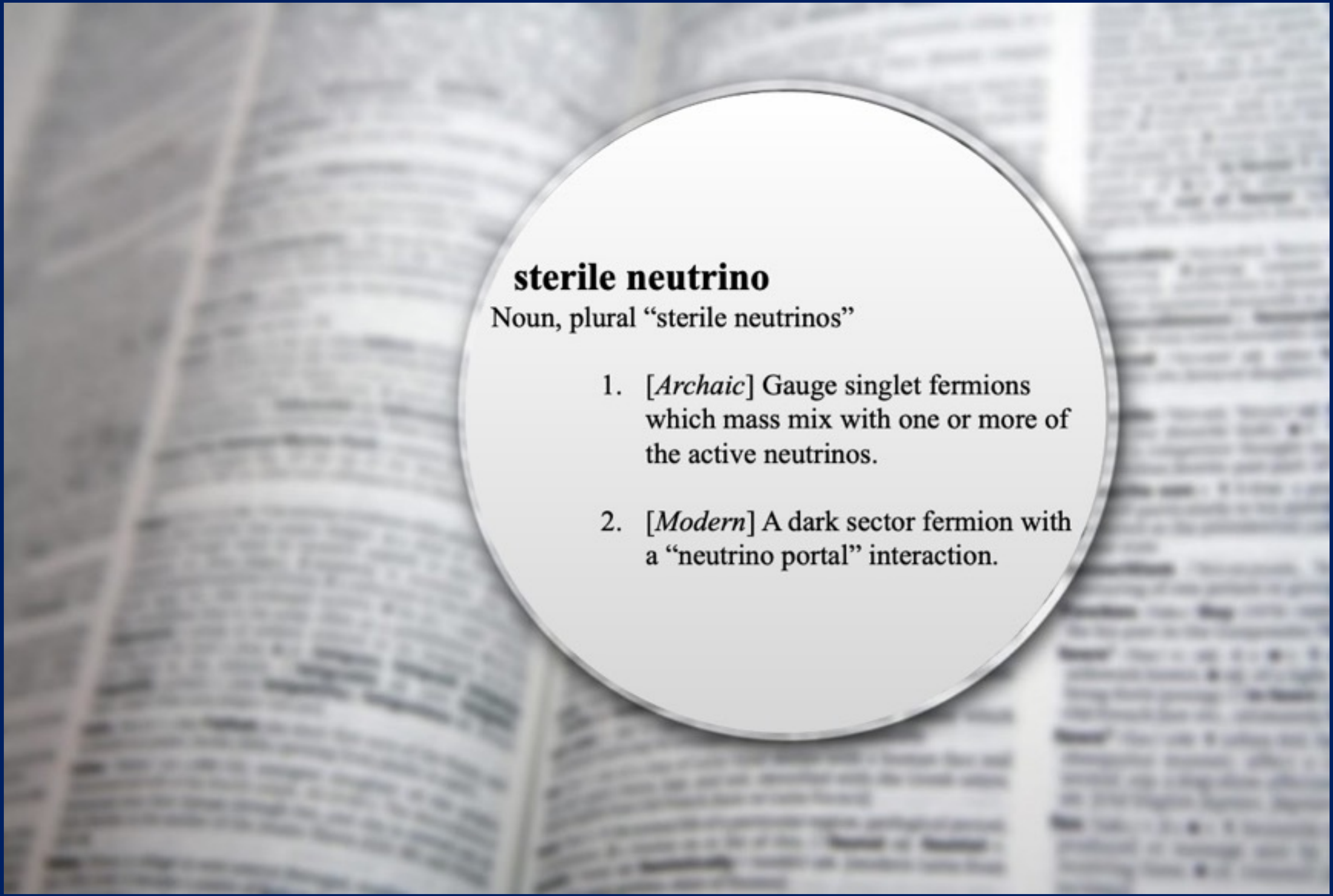



# LSND compatibility




MICROBOONE-NOTE-1116-PUB




"Theoretical Landscape for Sterile Neutrinos", Ian Shoemaker

UNIVERSITÄT BERN

AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

# Evolving Theory Landscape

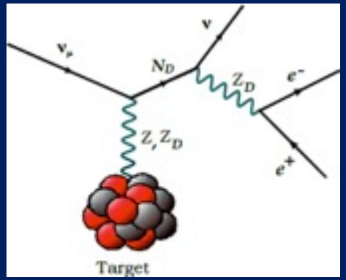
Motivated by attempts to explain the new MiniBooNE results as well as other experimental data; eg., $\nu_e$ appearance but no $\nu_\mu$ disappearance *(Caution: not an exhaustive list!)*

- 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)*

Produces true electrons

Produces true photons

Produces $e^+e^-$ pairs




PRL 121, 241801 (2018)

- Many of these models predict more complex final states ($e^+e^-$) and/or differing levels of hadronic activity

→ *The hadronic state is becoming increasingly more important as a model discriminator*

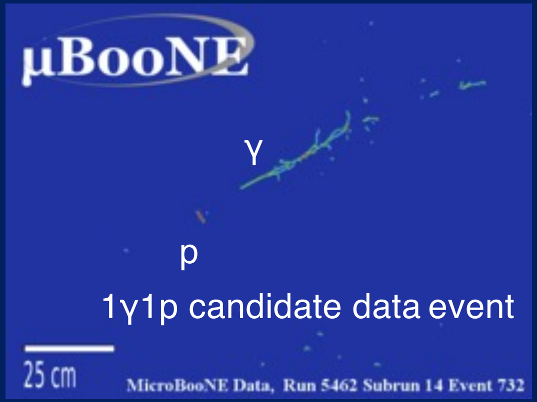
- We are fortunate that LArTPCs are sensitive to these possibilities

# Summary

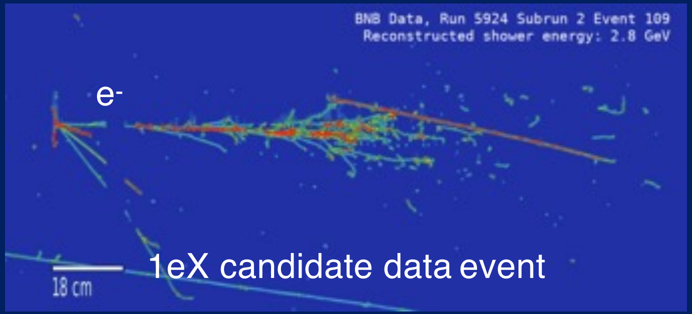
UNIVERSITÄT BERN
AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

- Built MicroBooNE to investigate anomalous excess of data (sterile neurrino ?)
- Developed automated reconstruction for LArTPCs, validated through physics publications
- Published differential cross sections in a variety of topologies
- Foundational work for DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT
- Searched for excess photon events: no excess
  - Disfavour the interpretation of MiniBooNE LEE as a x3.18 enhancement of NC $\Delta \rightarrow N\gamma$ rate
- Searched for excess electron neutrino events: no excess
  - Reject simple eLEE model of the MiniBooNE low energy excess at >97% for both exclusive and inclusive event classes at 94.8% CL
- New analyses being prepared
- New ideas certain to come
- More experiments

SBN Program





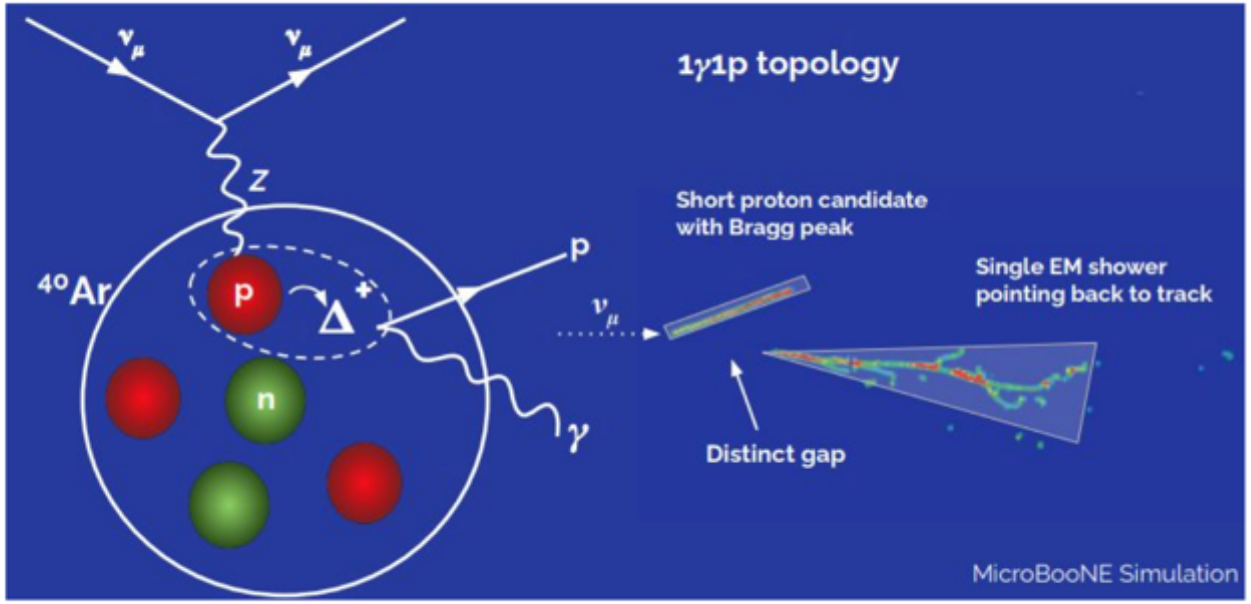


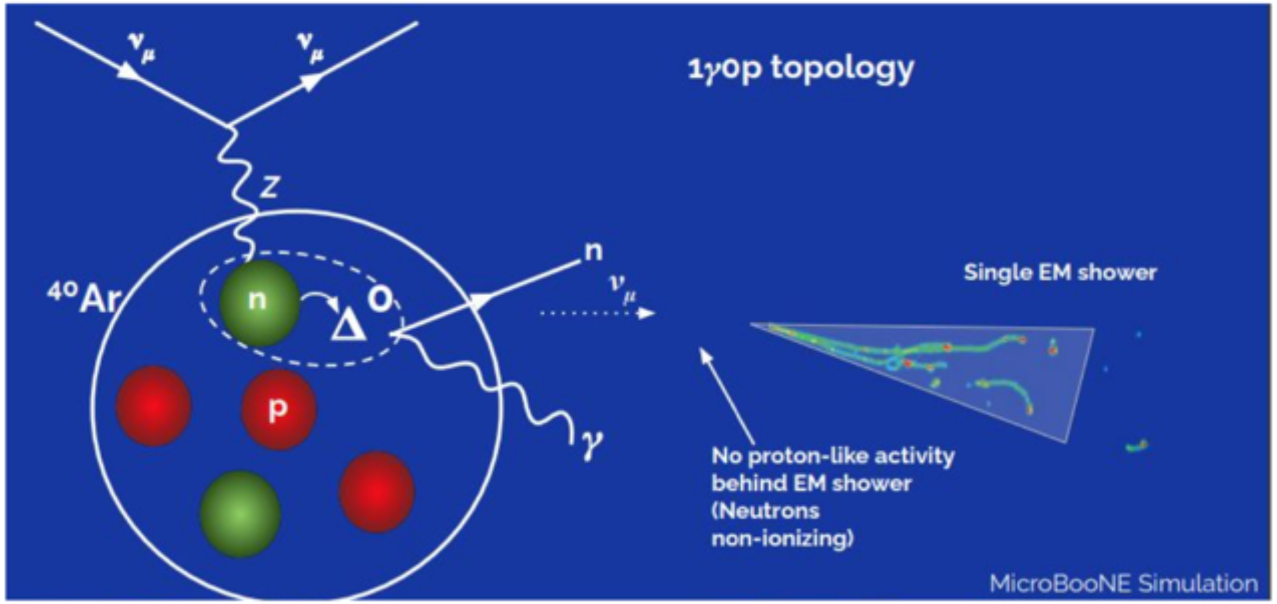
+++++++

# BACKUP

+++++++

**NC $\Delta \rightarrow N\gamma$:** Delta (1232MeV) baryon resonance production, followed by radiative decay:



# MicroBooNE's Exploration of the MiniBooNE Excess

UNIVERSITÄT BERN
AEC
ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

First series of results (1/2 the MicroBooNE data set)

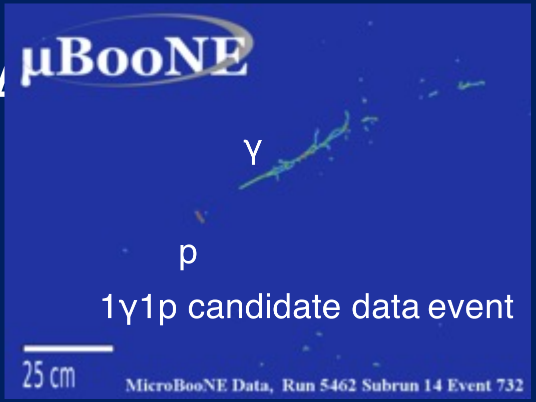
| Models \ Reco topology | 1e0p | 1e1p | 1eNp | 1eX | $e^+e^-$ + nothing | $e^+e^-X$ | $1\gamma 0p$ | $1\gamma 1p$ | $1\gamma X$ |
|---|---|---|---|---|---|---|---|---|---|
| eV Sterile $\nu$ Osc | ✔ | ✔ | ✔ | ✔ | | | | | |
| Mixed Osc + Sterile $\nu$ | ✔ [7] | ✔ [7] | ✔ [7] | ✔ [7] | | | ✔ [7] | | |
| Sterile $\nu$ 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 $\gamma$ production | | | | | | | ✔ | ✔ | ✔ |

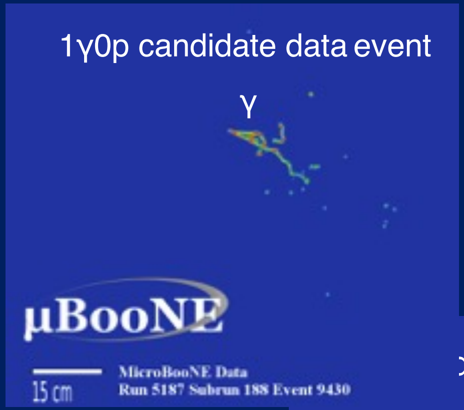
# MicroBooNE's First Series of LEE Search A

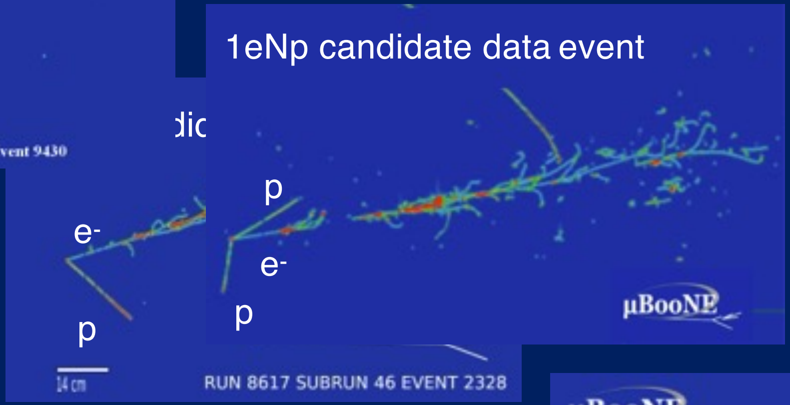
- Four independent analyses targeting different final states, hence probing different theoretical models

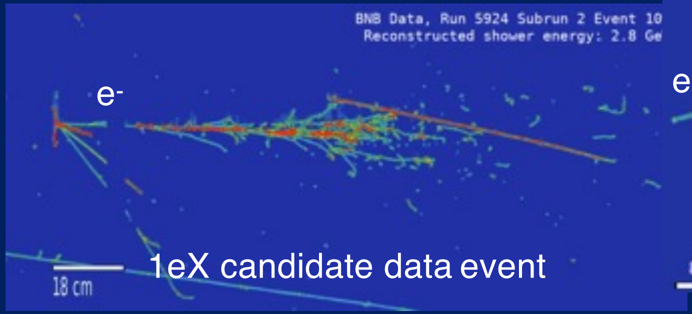
- Single photon analysis
  - Targeting NC Δ —> Nγ hypothesis (1γ0p, 1γ1p)

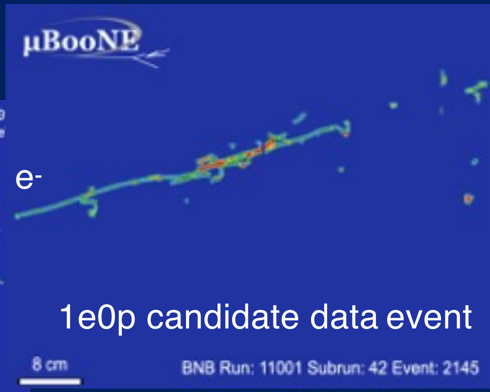
- Analyses searching for a $\nu_e$ rate excess
  - MiniBooNE-like final states (1eNp, 1e0p)
  - Restricting to quasi-elastic kinematics (1e1p)
  - All νe final states (1eX)



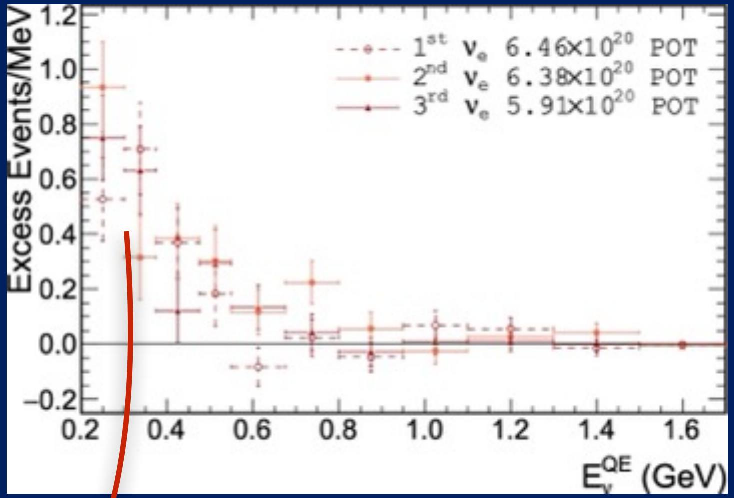



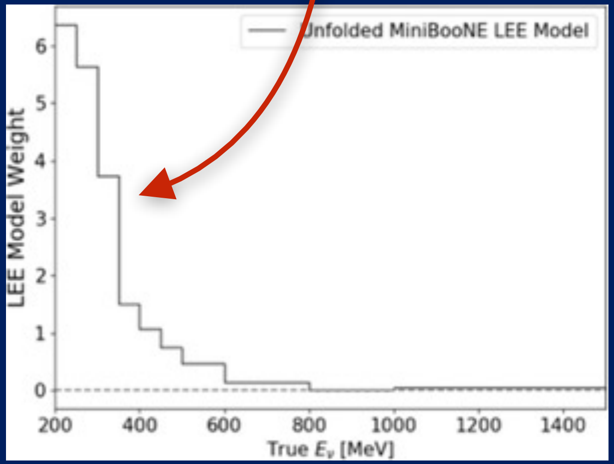



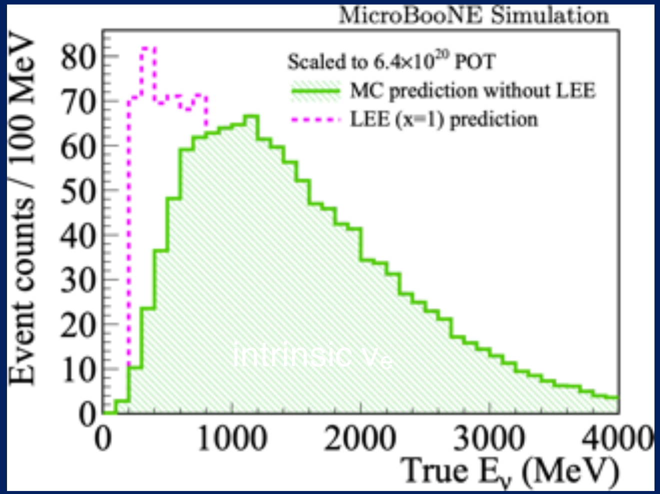
# Simple Model of the MiniBooNE Low Energy Excess

- Unfold 2018 MiniBooNE excess under $\nu_e$ hypothesis
  – Considers only $E_\nu$ dependence
- Derive scaling template to model enhancement of intrinsic $\nu_e$ rate in the Booster Neutrino Beam
- Apply to MicroBooNE allowing normalization to float
- Does the data prefer the constrained $\nu_e$ prediction or this simple "eLEE" model?
  – $\Delta\chi^2$ hypothesis testing

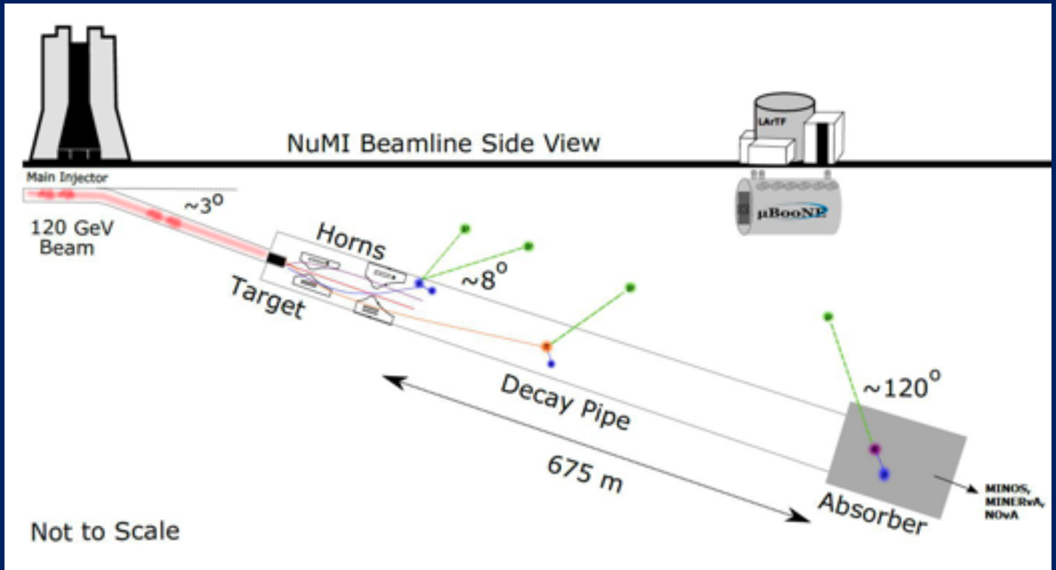
Phys. Rev. D 103, 052002 (2021)

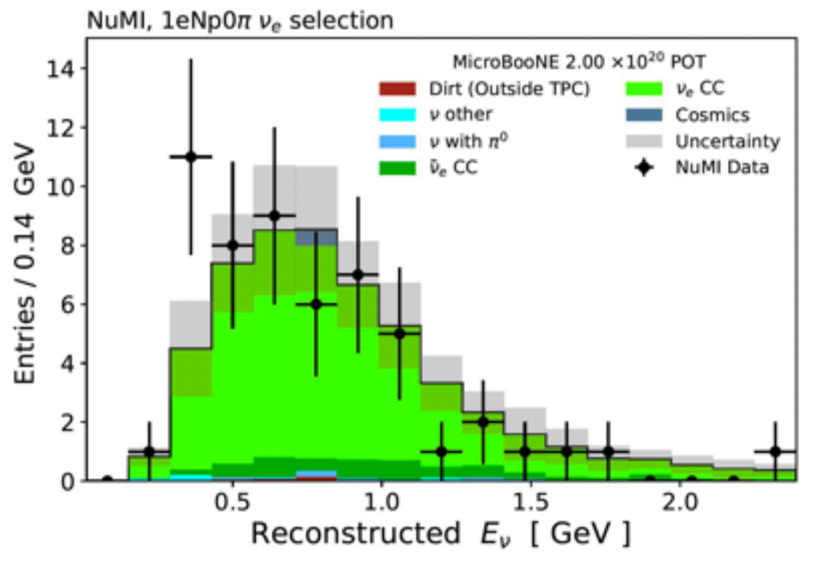


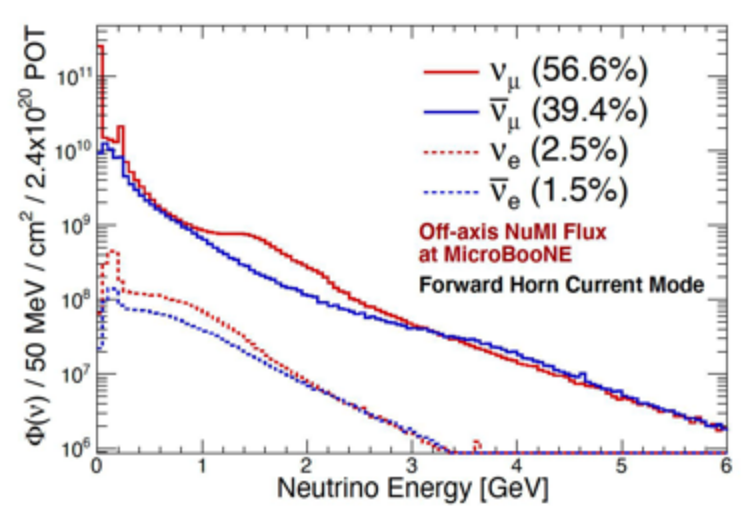



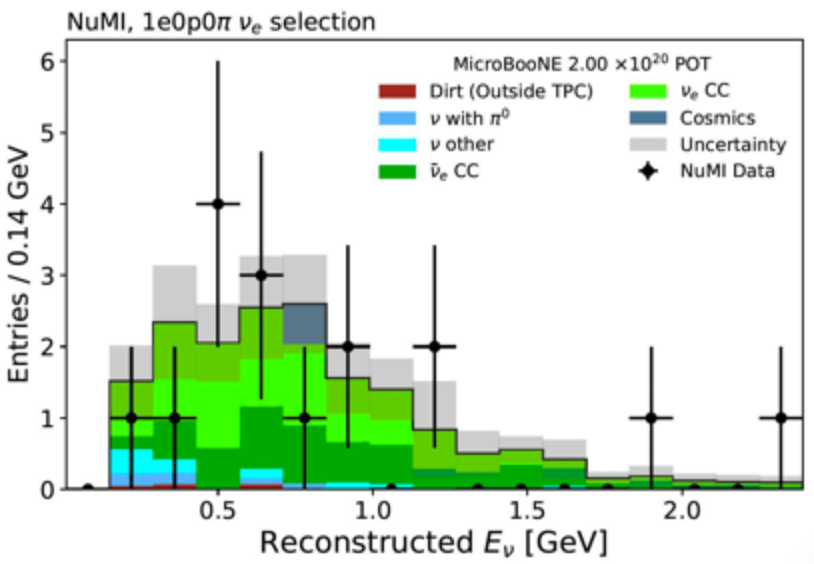



# A second beam… NuMI



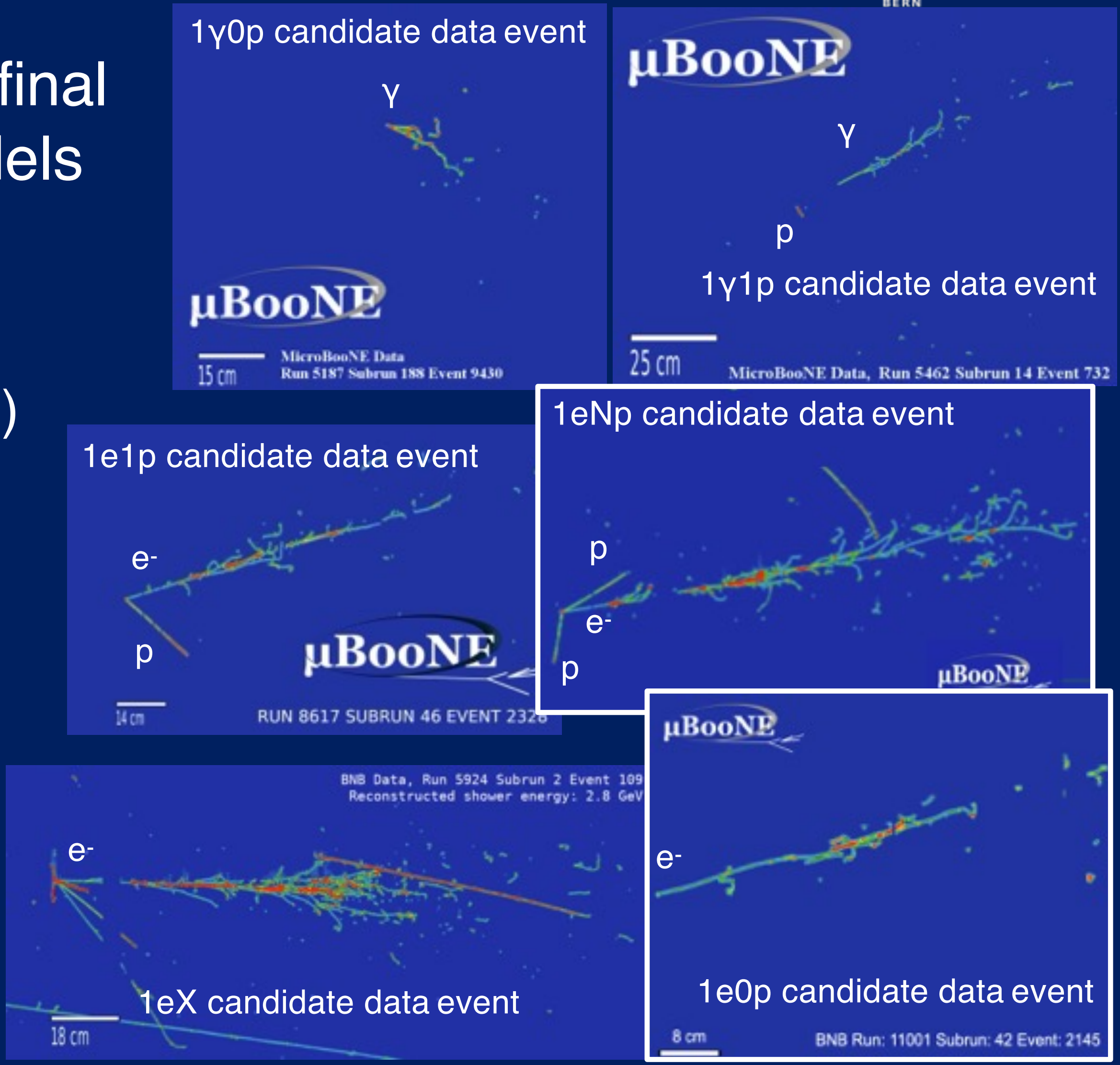



# MicroBooNE's First Series of LEE Search Analyses

Four independent analyses targeting different final states, hence probing different theoretical models

- Single photon analysis
  – Targeting NC Δ —> Nγ hypothesis (1γ0p, 1γ1p)

- Analyses searching for a $\nu_e$ rate excess
  – MiniBooNE-like final states (1eNp, 1e0p)
  – Restricting to quasi-elastic kinematics (1e1p)
  – All $\nu_e$ final states (1eX)

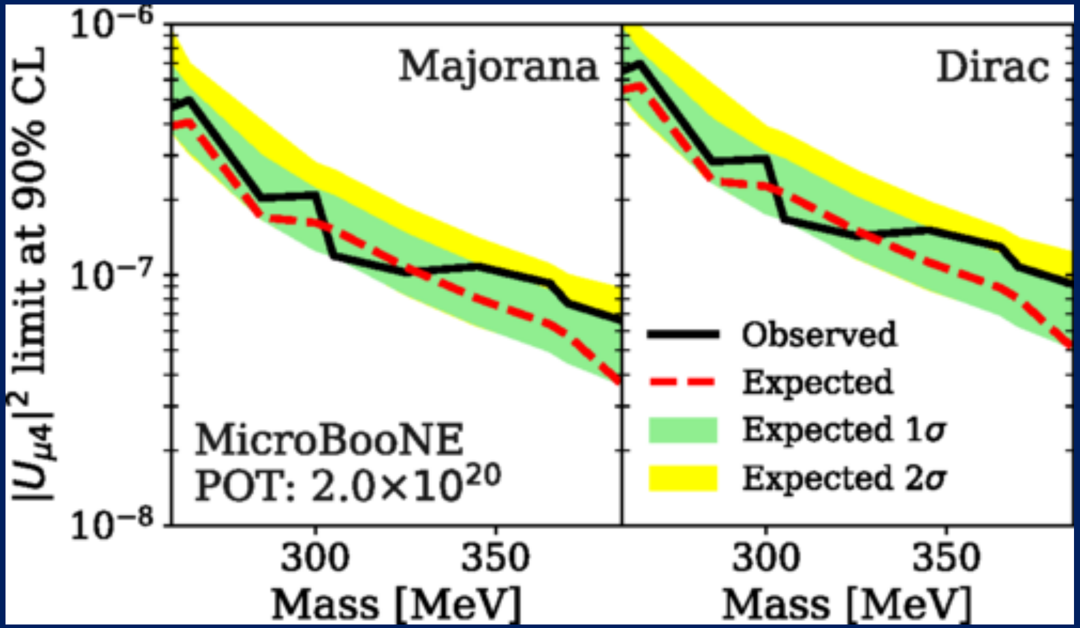


# Exotics

UNIVERSITÄT BERN
AEC
ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

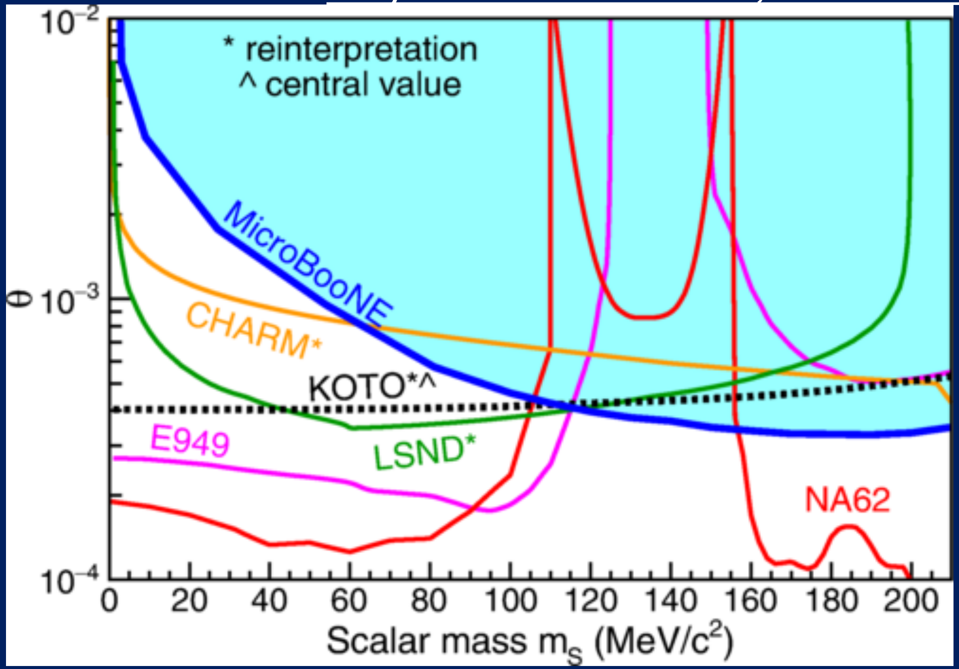
Search for **heavy neutral leptons** decaying into **muon-pion pairs** in the MicroBooNE detector

Phys. Rev. D101, 052001 (2020)

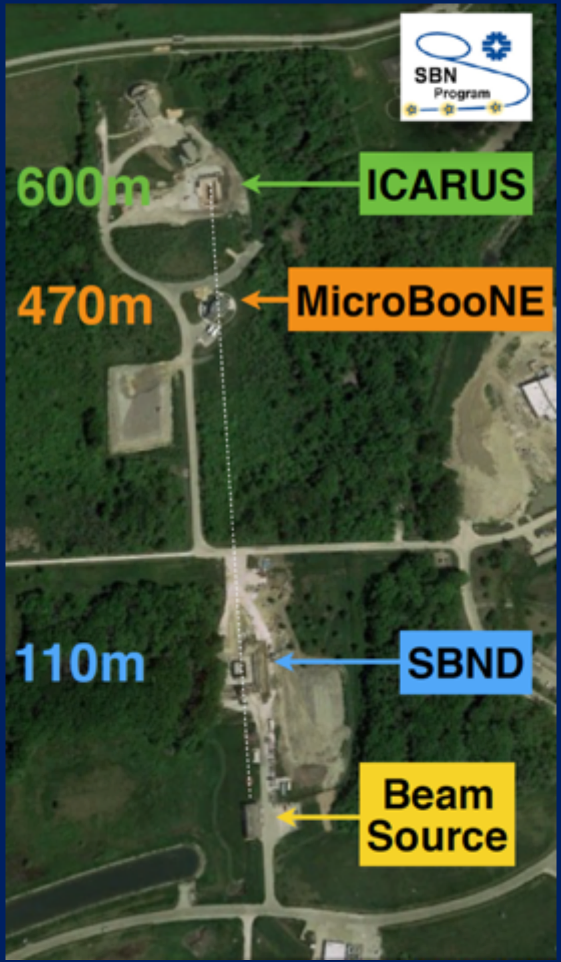


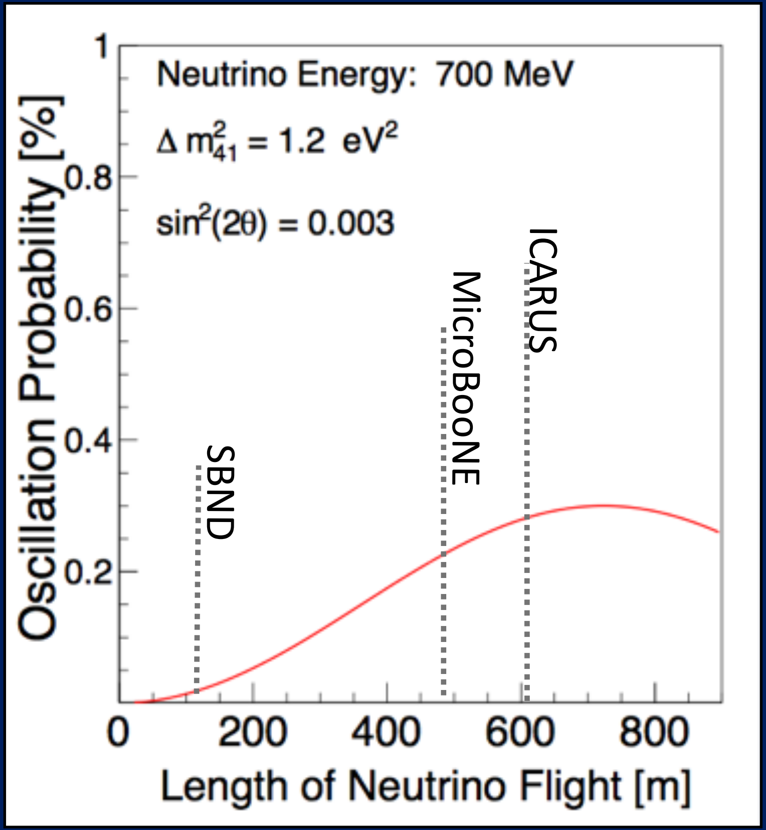

Search for a **Higgs portal scalar** decaying to **electron-positron pairs** in the MicroBooNE detector

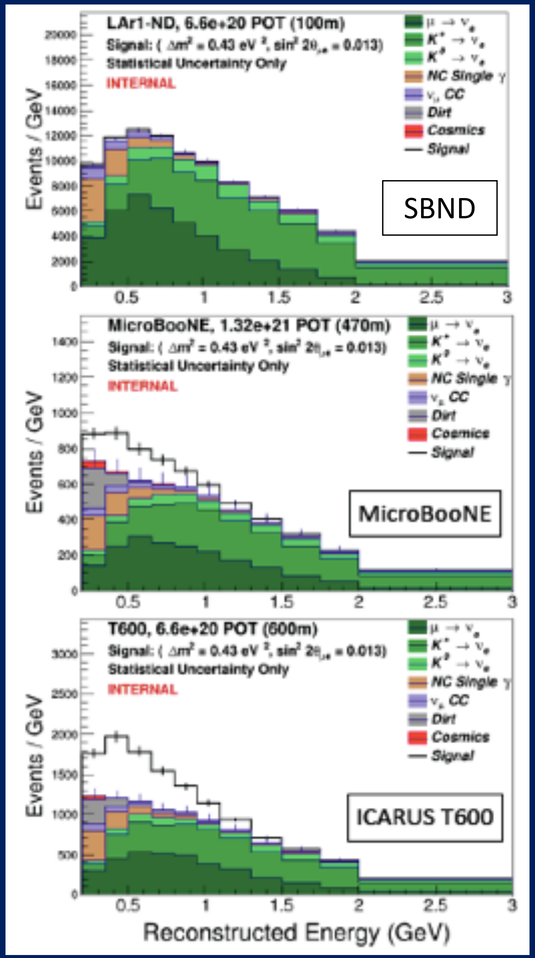
Phys. Rev. Lett. 127, 151803 (2021)

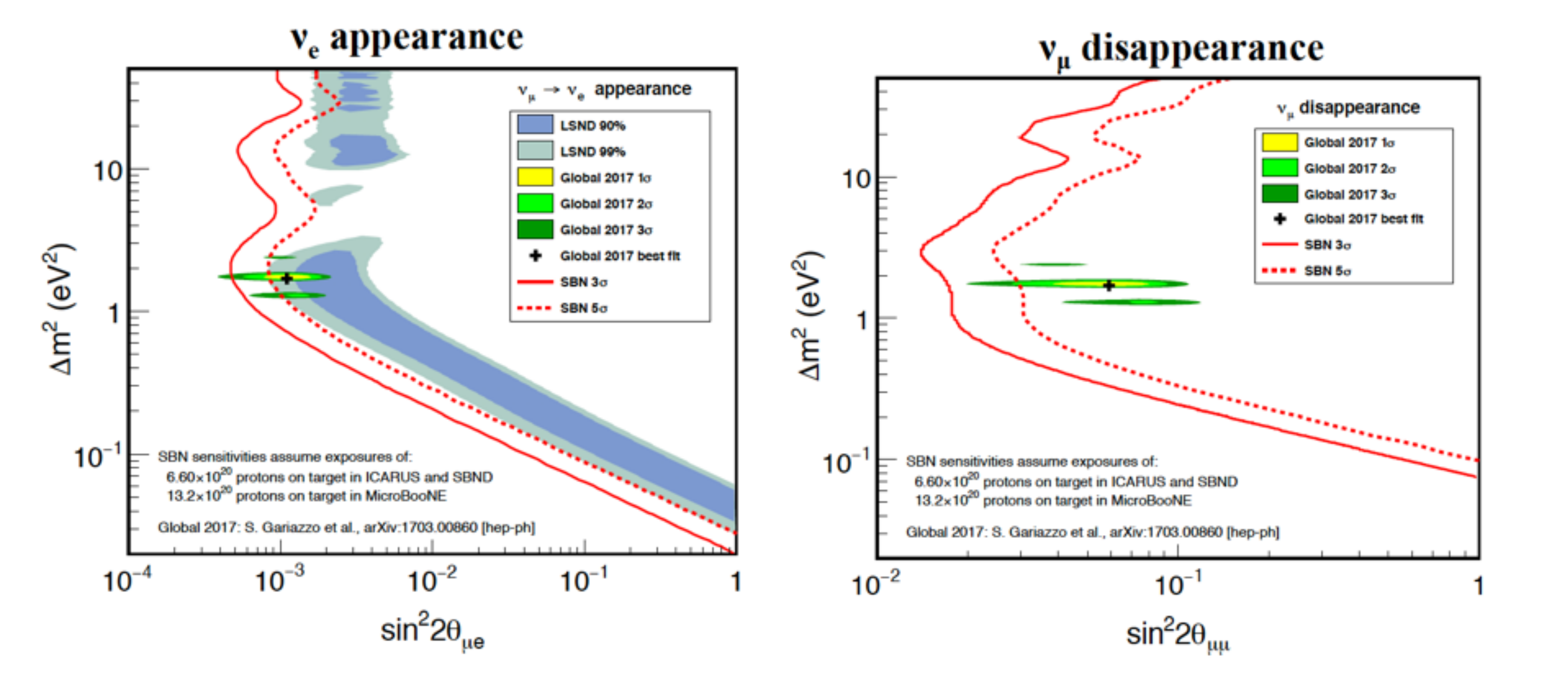


# Three-detector setup with LArTPCs



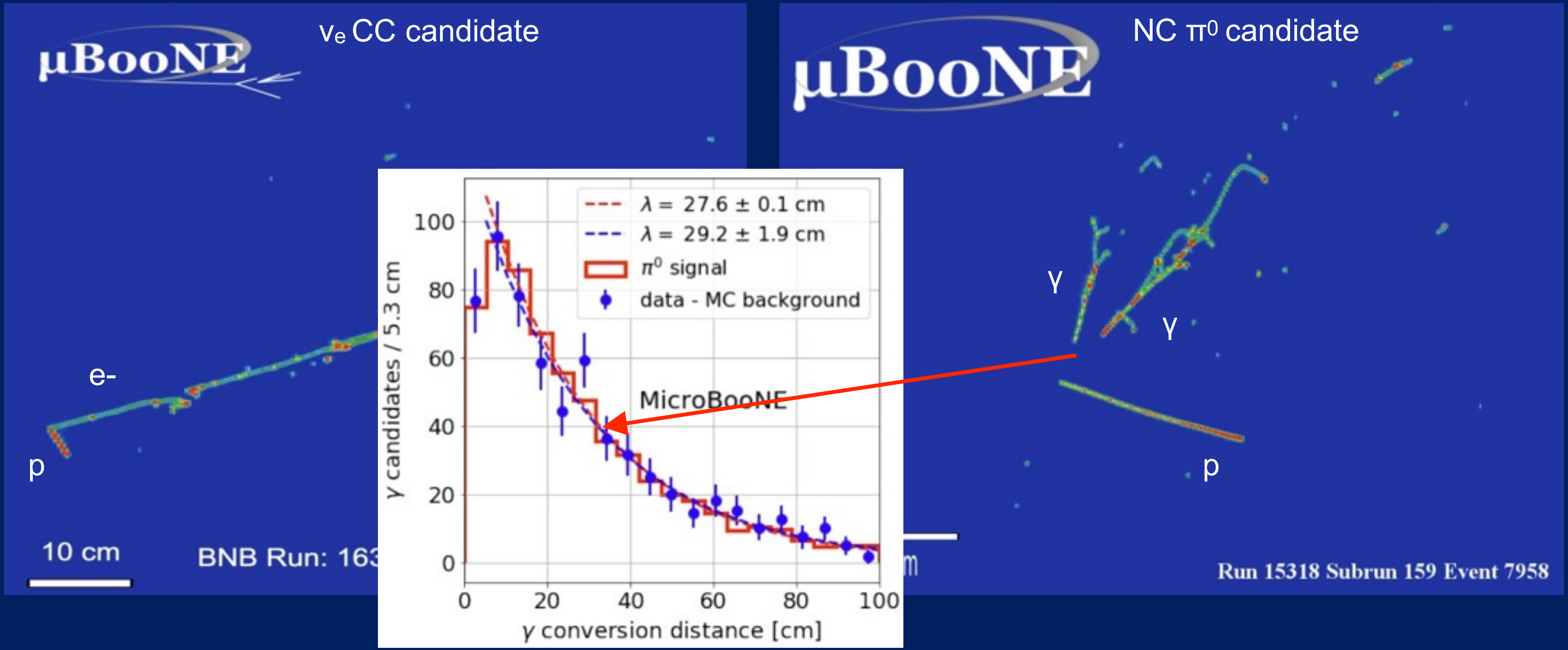





νe appearance
νμ → νe appearance
LSND 90%
LSND 99%
Global 2017 1σ
Global 2017 2σ
Global 2017 3σ
Global 2017 best fit
SBN 3σ
SBN 5σ
SBN sensitivities assume exposures of:
6.60×10^20 protons on target in ICARUS and SBND
13.2×10^20 protons on target in MicroBooNE
Global 2017: S. Gariazzo et al., arXiv:1703.00860 [hep-ph]
Δm² (eV²)
sin²2θμe
νμ disappearance
νμ disappearance
Global 2017 1σ
Global 2017 2σ
Global 2017 3σ
Global 2017 best fit
SBN 3σ
SBN 5σ
SBN sensitivities assume exposures of:
6.60×10^20 protons on target in ICARUS and SBND
13.2×10^20 protons on target in MicroBooNE
Global 2017: S. Gariazzo et al., arXiv:1703.00860 [hep-ph]
Δm² (eV²)
sin²2θμμ

# LArTPC — Fully Active Tracking Calorimeter

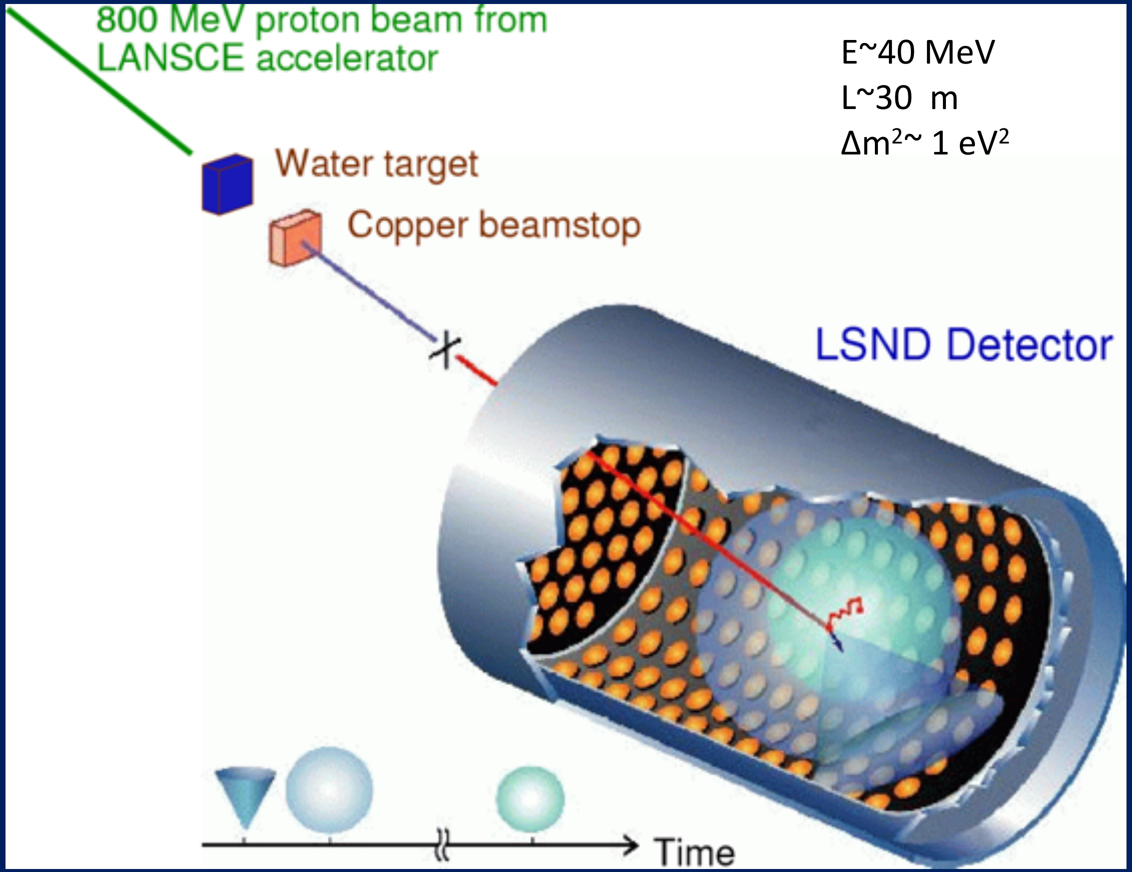
- Enables automated reconstruction of bubble-chamber-like images

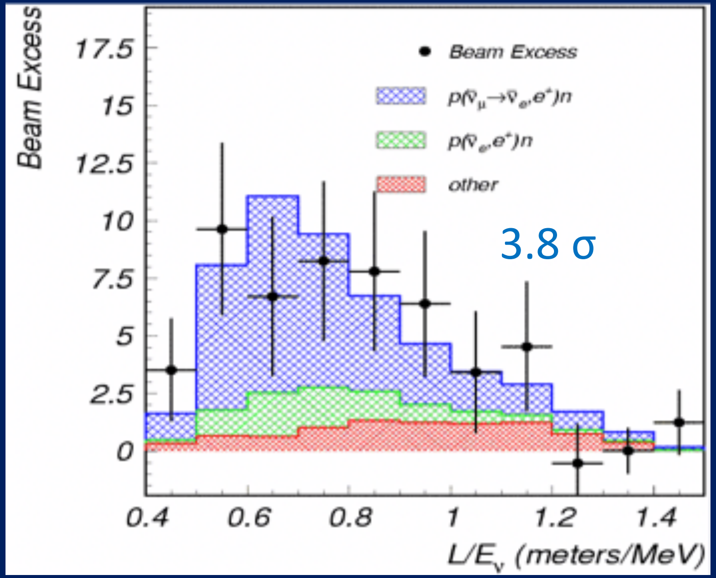


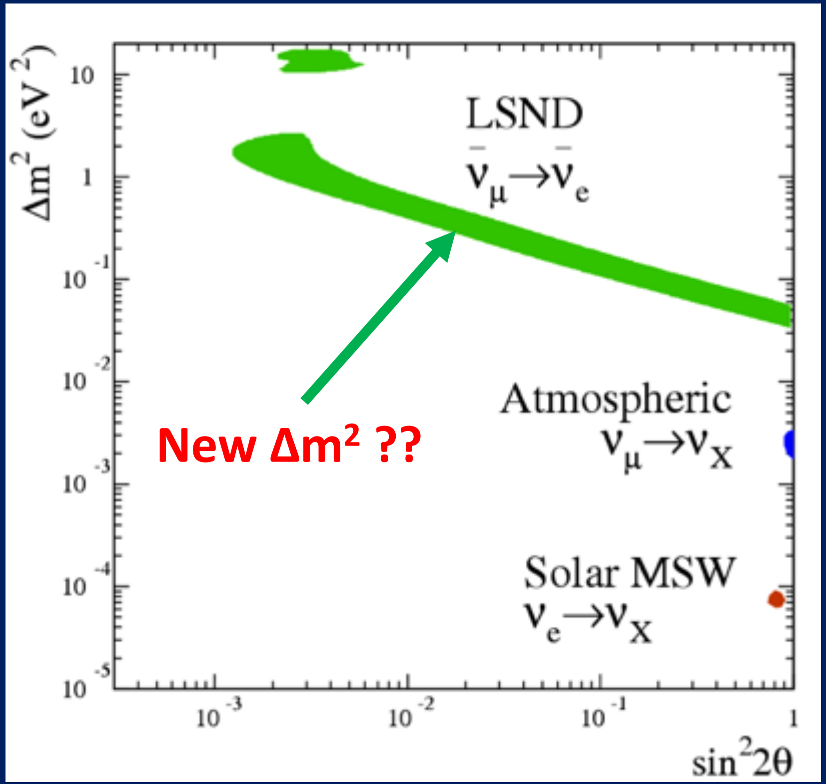

JINST 15, P02007 (2020)

# LSND

The **L**iquid **S**cintillator **N**eutrino **D**etector
at Los Alamos National Lab
1993 -- 1998



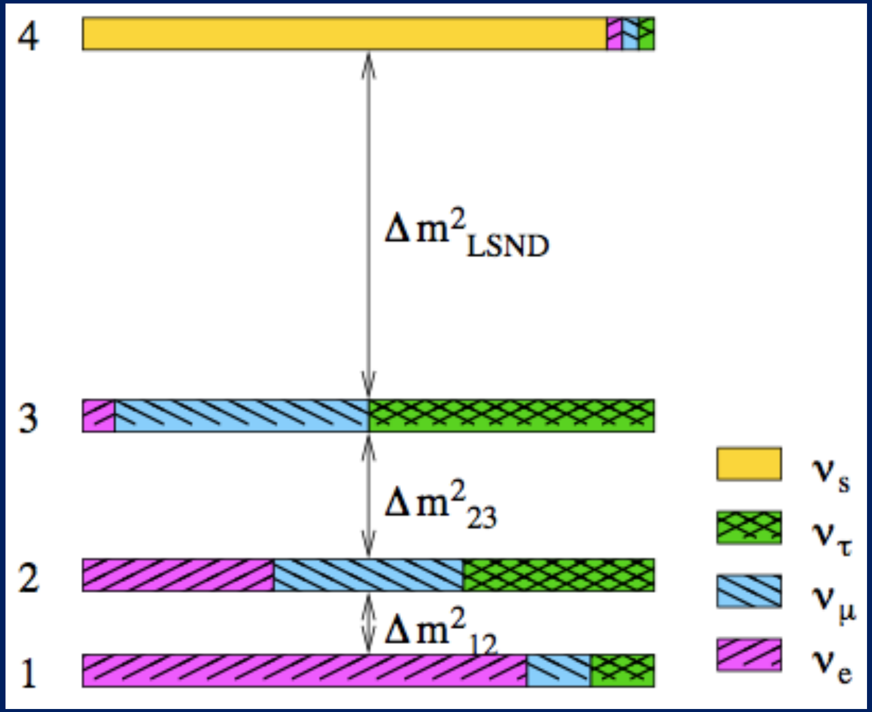




Two-neutrino approximation

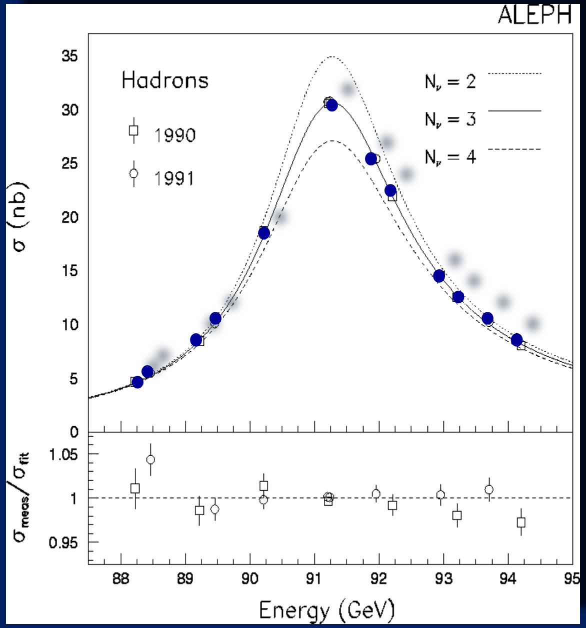
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{ij} \cdot \sin^2\left(1.27\,\Delta m_{ij}^2 \frac{L}{E}\right)$$

# $4^{th}$ neutrino mass state




# Constraints

$N_\nu$=3 from LEP




**Cosmology**

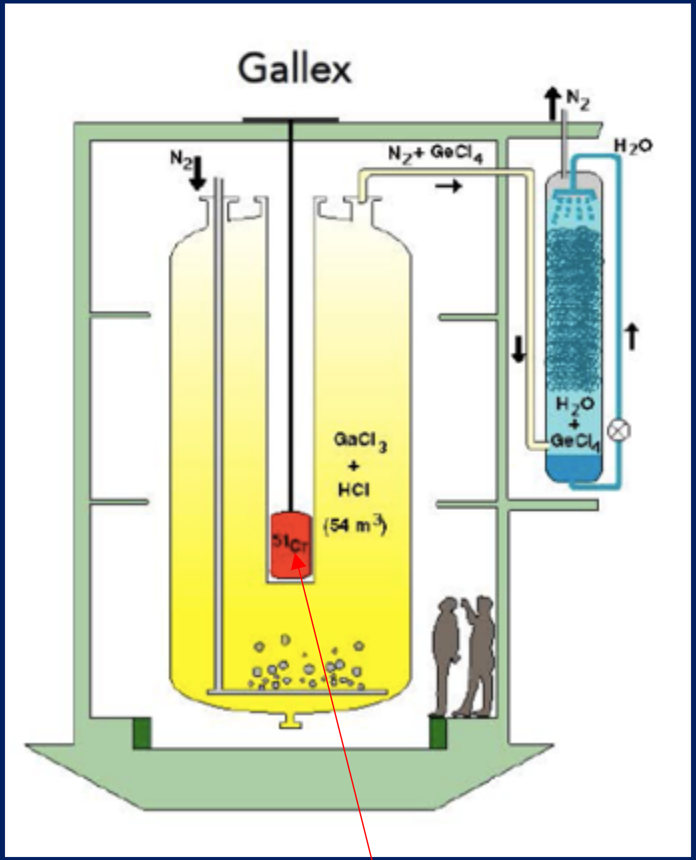
ΛCDM is sensitive to $\mathbf{N_\nu}$

(Large scale structures (BAO) and light nuclei abundance.)

Best fit is also consistent with $\mathbf{N_\nu}$ **=3** active neutrinos.

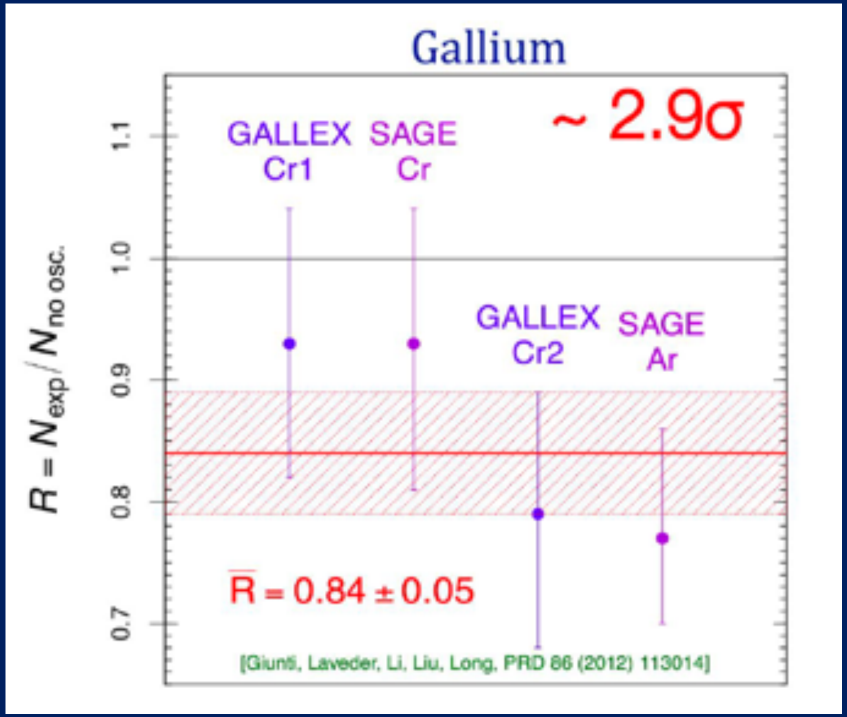
➔ **Sterile**

# Radioactive source experiments

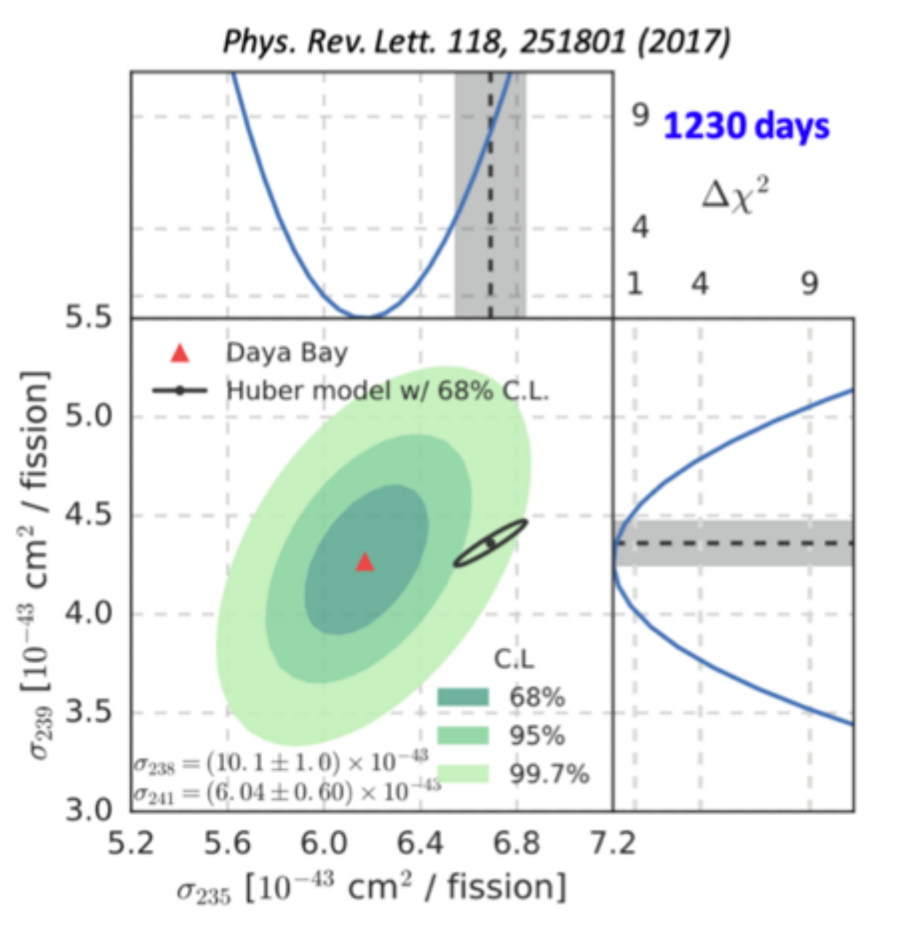



$^{51}$Cr

Electron neutrinos disappearing



# The reactor anomaly can be explained




Daya Bay (and RENO) results suggest that the neutrino flux from $^{235}U$ ~3 sigma below what expected from fission models so far

→ Need experiments at Highly Enriched Uranium reactors (20-90% $^{235}U$), i.e. research reactors to thoroughly test this μBooNE

*MicroBooNE*
15 papers
33 public notes

CC nu-mu double differential
arXiv:1905.09694

Cosmic Ray Rejection for CCQE
arXiv:1812.05679

Cosmic Ray Tagger
JINST 14, P04004 (2019)

CC Pi0 xsec
Phys. Rev. D99, 091102(R) (2019)

Deep NN e.m. reco
Phys. Rev. D99, 09200

Charged particle multiplicity
Eur. Phys. J. C79, 248 (2019)

Signal processing I and II
JINST 13, P07006 (2018) JINST 13, P07007 (2018)

Noise and filtering
JINST 12, P08003 (2017)

Pandora reconstruction
Eur. Phys. J. C78, 1, 82 (2018)

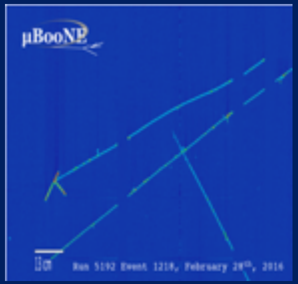
Multiple Coulomb Scattering
JINST 12 P10010 (2017)

Cosmic ray studies
JINST 12, P12030 (2017)

Michel electron reconstruction
JINST 12, P09014 (2017)

CNN use for LArTPC
JINST 12, P03011 (2017)

Detector paper
JINST 12, P02017 (2017)




Public notes

Purity of the LAr
Neutrino identification
Noise dependence on temperature

MC study of expected events
Cosmic shielding
NC event selection in MC
CC event from 5E19 POT
3D shower reconstruction
Detector stability
MCC7 Data/MC
Proton ID

Signal formation
Space charge
Side piercing tracks with t0
Drift electron lifetime

dE/dx calibration
Wire Cell reconstruction
Ar-39 use for calibration
Booster neutrino Flux
Reconstruction performance
Inclusive CC cross section
CCpi0 cross section
CC-Np cross section
Unfolding the MB signal
Search for single photon events
1mu1p selection and reconstruction
Electron neutrino selection
Electron neutrino selection

## 2019-2020
- Flagship results with flagship MC that makes extensive use of uB data as a constraint

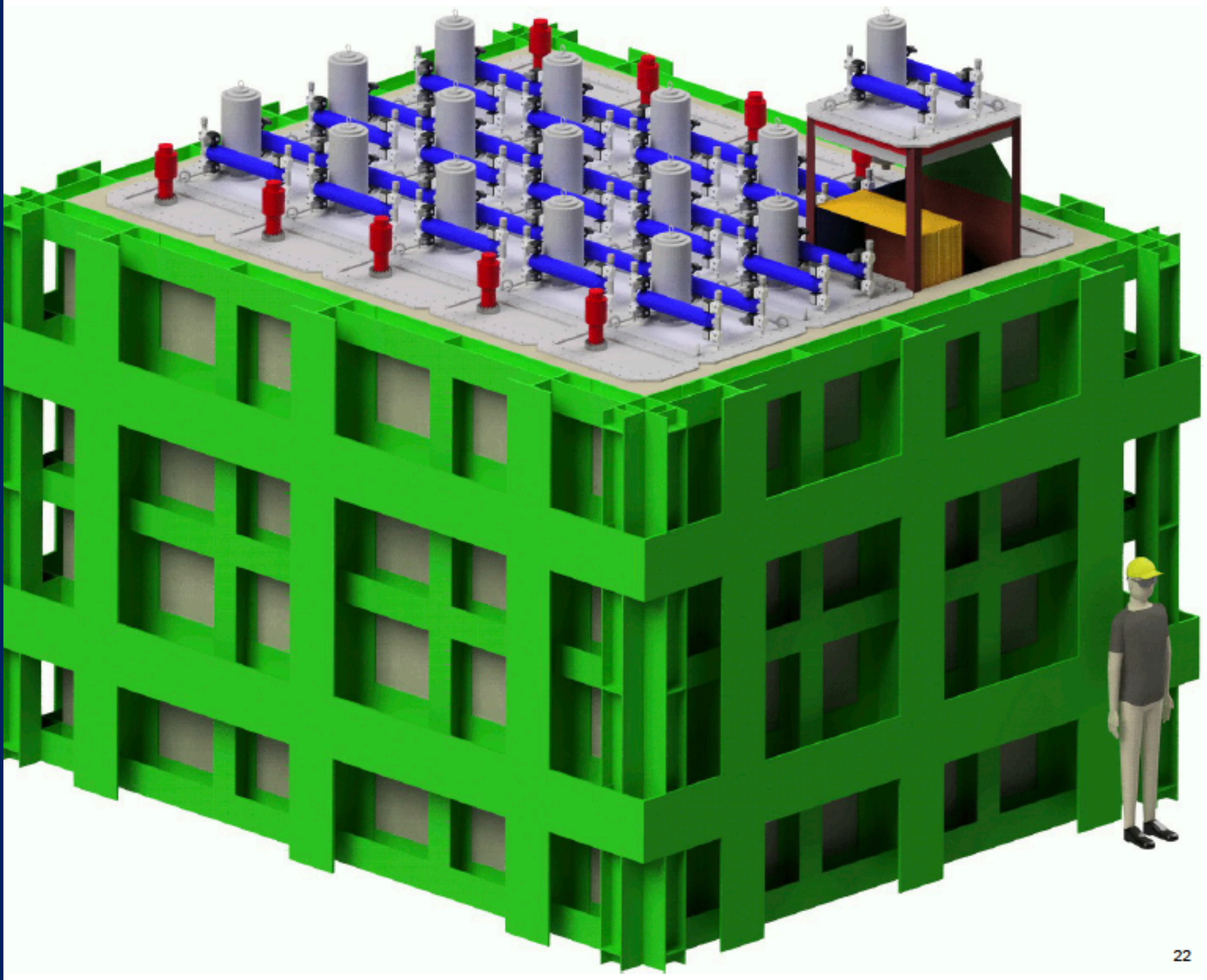
## 2018
- Exploiting MCC8 for 1st physics results
- Identified limitations in signal processing and efficiencies
- 1st iteration on calibrations, systematics
  → targeted development of a new MC (MCC9)

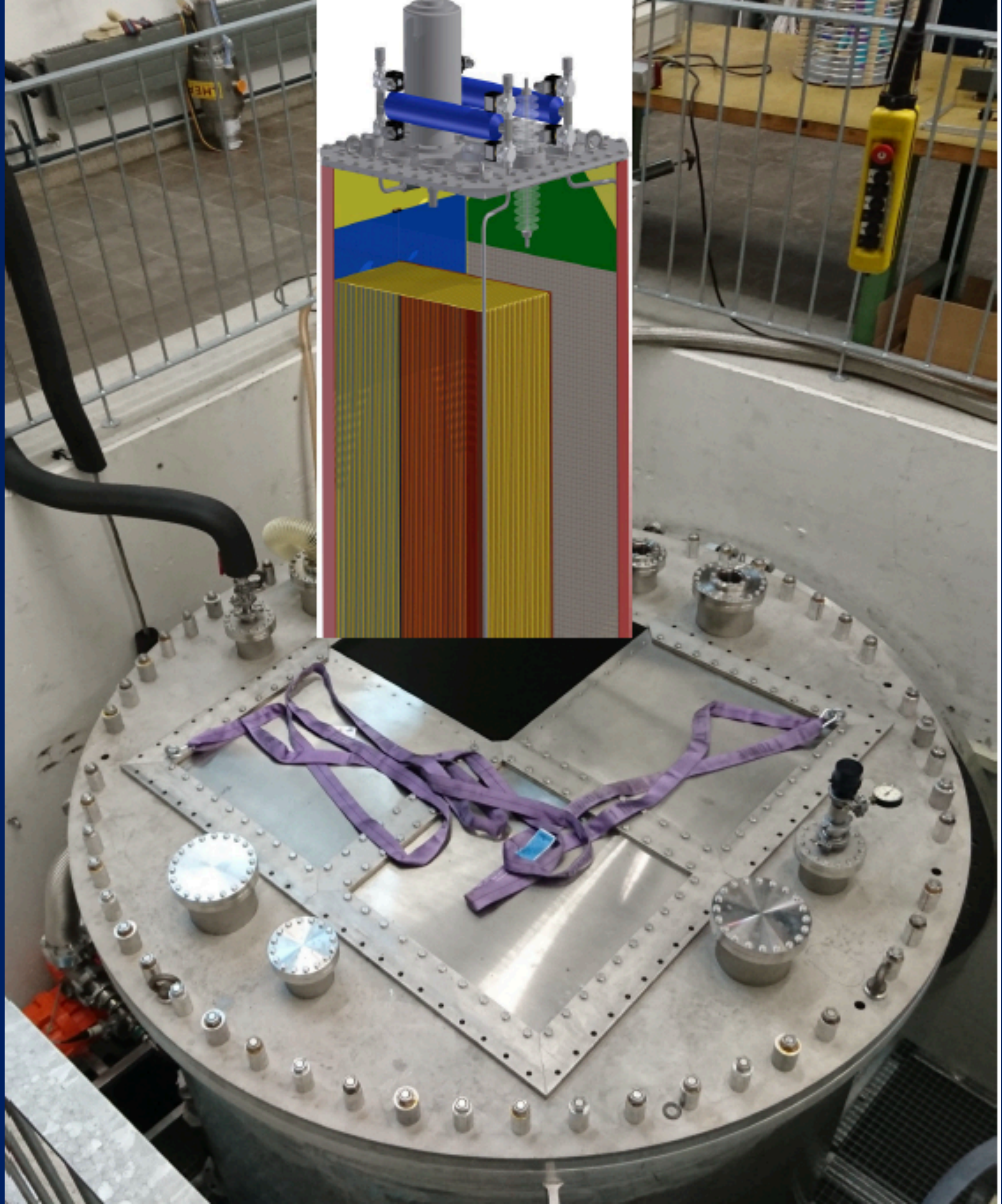
## 2017
- CRT installation
- Converging on a new robust MC (MCC8), first MC using data as input
- Efforts on modelling, first calibrations, particle ID, 1st systematics, computing speed up

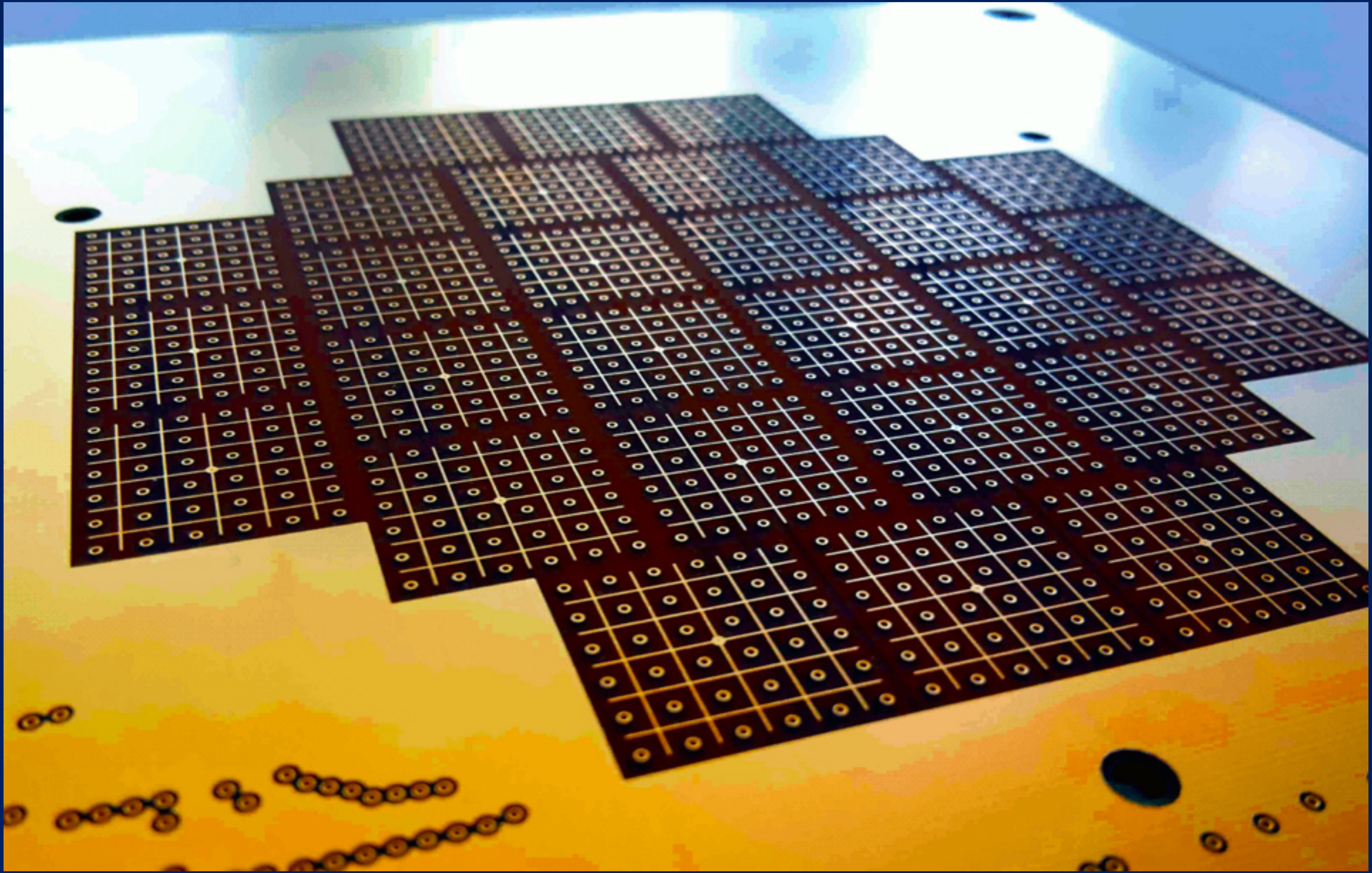
## 2016
- First MC release of automated LArTPC reconstruction (MCC7)
- Performance results and Data/MC discrepancies
- "Open development" phase, investigate novel ideas, major effort on low level and high level reconstruction

## 2015
- Detector turn on (October)
- Cosmic and beam data
- Immediate identification of neutrinos

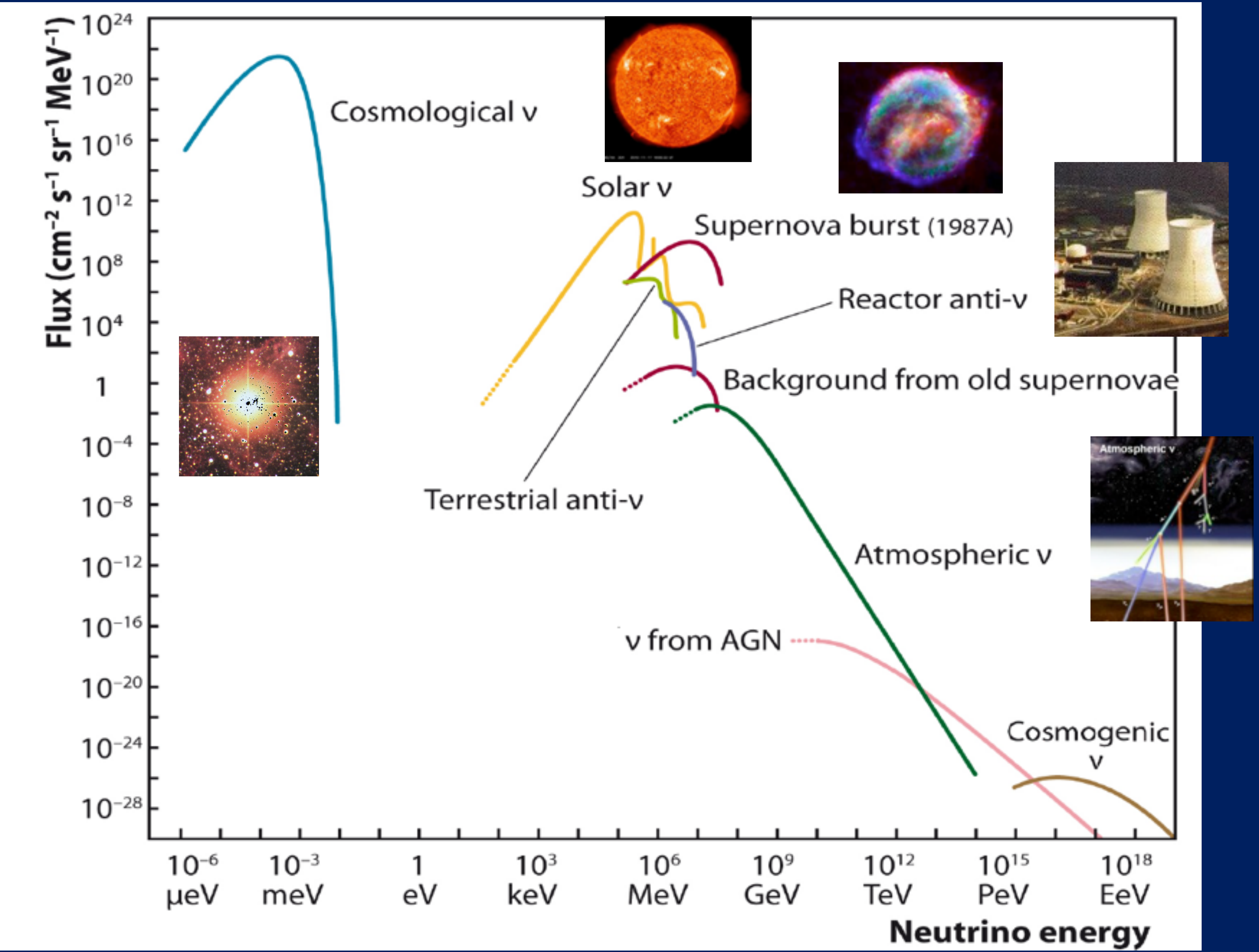
UNIVERSITÄT BERN
AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS


22

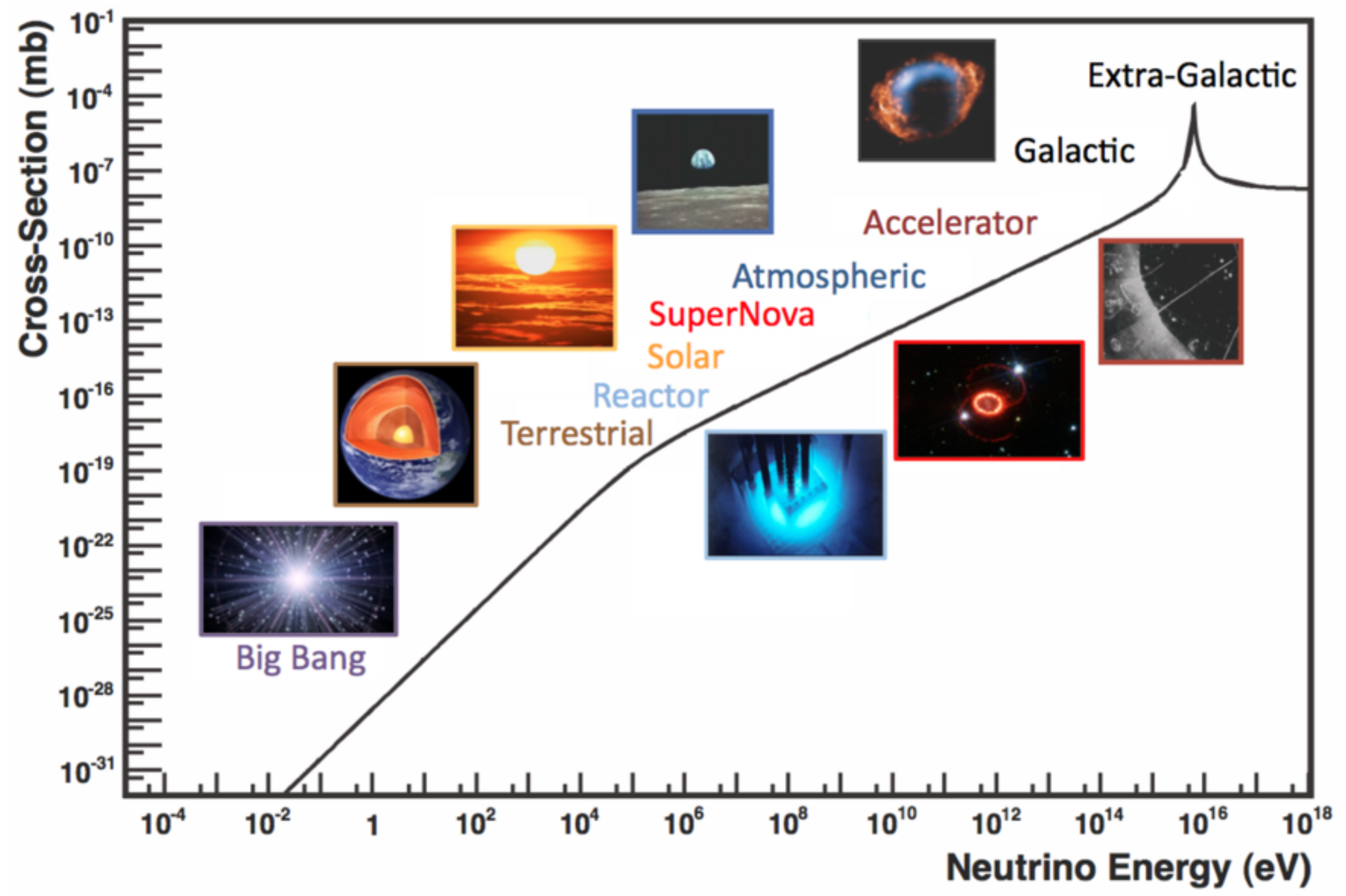




UNIVERSITÄT BERN
AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS



Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10²⁴
10²⁰
10¹⁶
10¹²
10⁸
10⁴
1
10⁻⁴
10⁻⁸
10⁻¹²
10⁻¹⁶
10⁻²⁰
10⁻²⁴
10⁻²⁸
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
Atmospheric ν
10⁻⁶ µeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy




UNIVERSITÄT BERN
AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS