NEUTRINO EXPERIMENTAL ANOMALIES AND RESULTS

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UK Annual Theory Meeting
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UNIVERSITY OF OXFORD

There have been a number of anomalies observed in the past 20-odd years that don't quite fit with the three-neutrino picture we know and love

Experiment	Type	Anomaly
LSND	DAR	$\bar{\nu}_e$ appearance
MiniBooNE	SBL accel.	ν_e appearance
MiniBooNE	SBL accel.	$\bar{\nu}_e$ appearance
GALLEX/SAGE/BEST	Source - e capture	ν_e disappearance
Reactors	Beta decay	$\bar{\nu}_e$ rate
		$\bar{\nu}_e$ shape
ANITA	High energy	High-energy events

Disclaimer: not an exhaustive list!

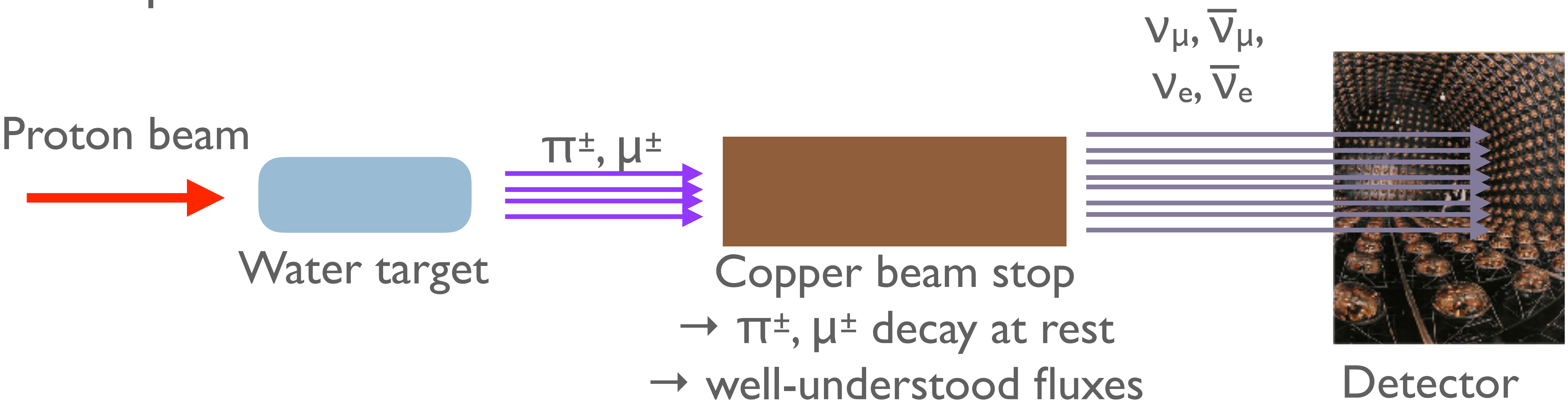
See also:
R. Guennette, "Short-Baseline Neutrinos", APS-DPF 2019 link
G. Karagiorgi, "Short-baseline neutrino experiments and phenomenology", INSS 2019 link
K. N. Abazajian et. al., Light Sterile Neutrinos: A White Paper, arXiv:1204.5379 [hep-ph] (2012) link

MY PERSONAL BIAS

- Overview of (some) existing neutrino anomalies
- MiniBooNE anomaly
  - MicroBooNE recent results
  - Possible interpretations

ANOMALIES: LSND

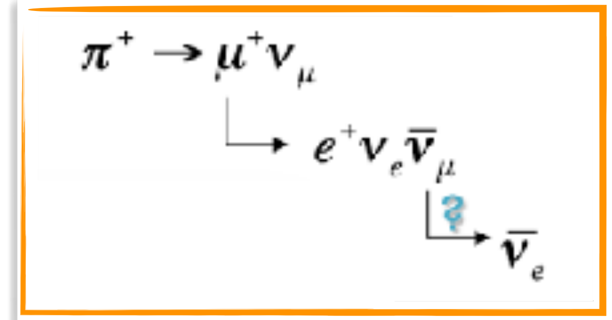
- **L**iquid **S**cintillator **N**eutrino **D**etector: μ^+ decay at rest experiment at Los Alamos National Lab

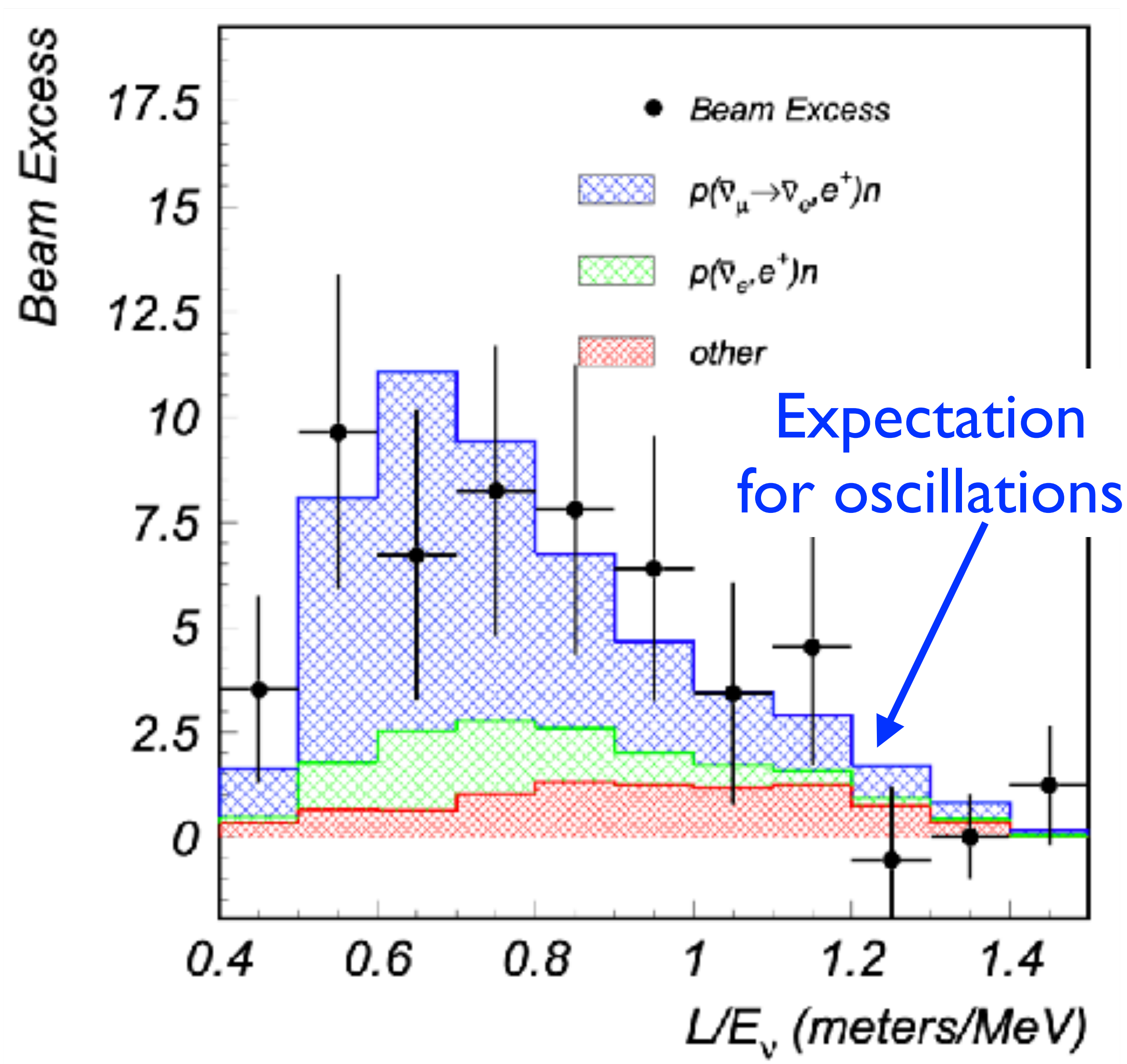


$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

Phys. Rev. D 64, 112007

ANOMALIES: LSND

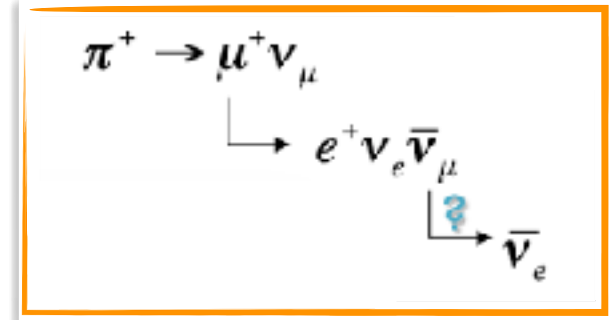


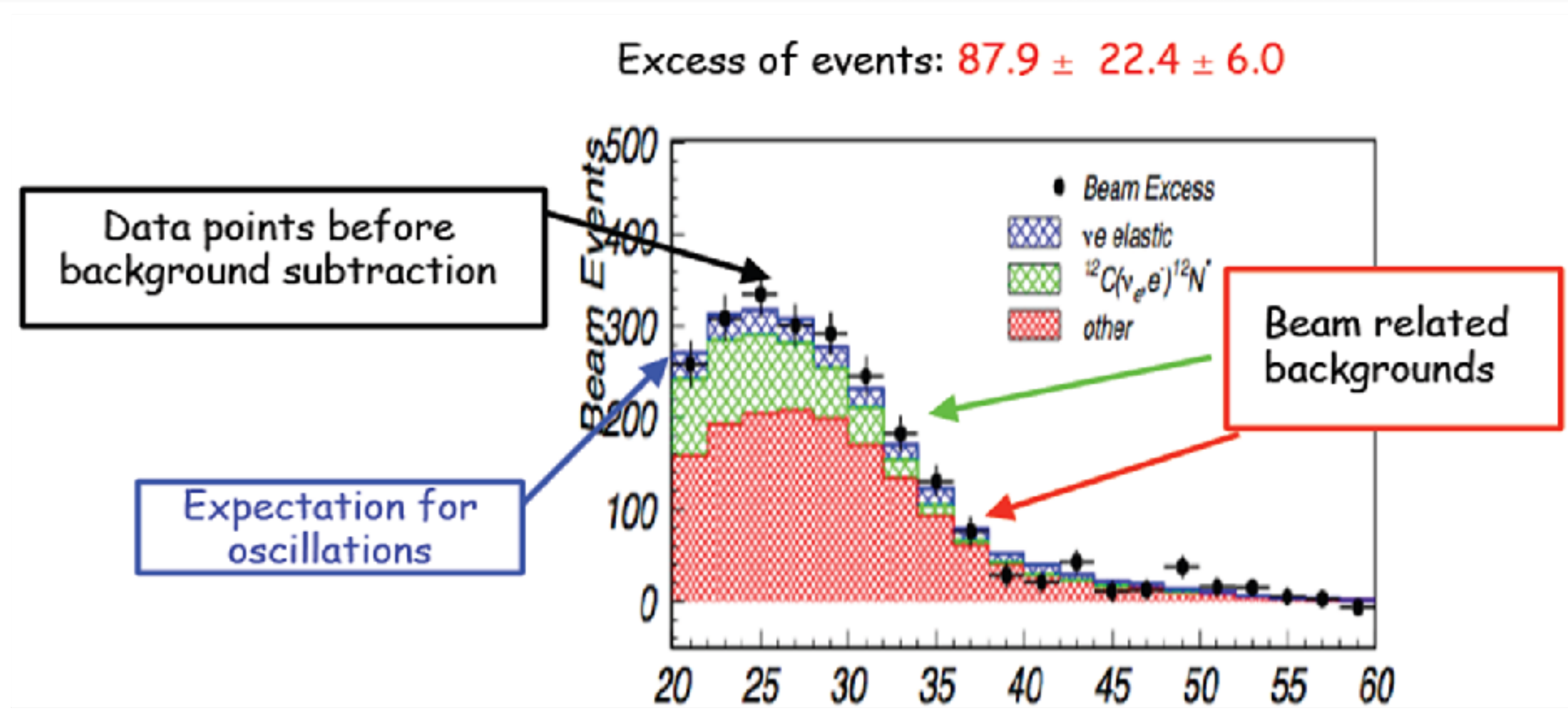


Phys. Rev. D 64, 112007

- Observed excess of $\bar{\nu}_e$ at 3.8σ
- If interpreted as two-flavour neutrino oscillation, requires **Δm^2~0.2-10eV^2**
- **Not consistent with any known Δm^2**
- Interestingly, **KARMEN** at ISIS DAR neutrino source at RAL **did not see an excess**
  - KARMEN: 17.7m from source, LSND: 30m

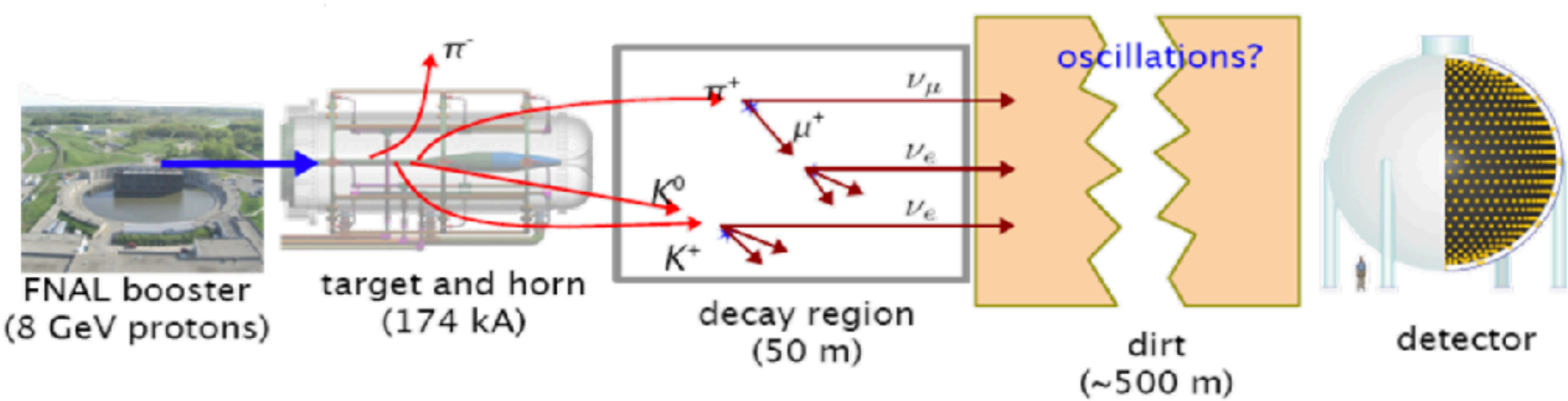
ANOMALIES: LSND





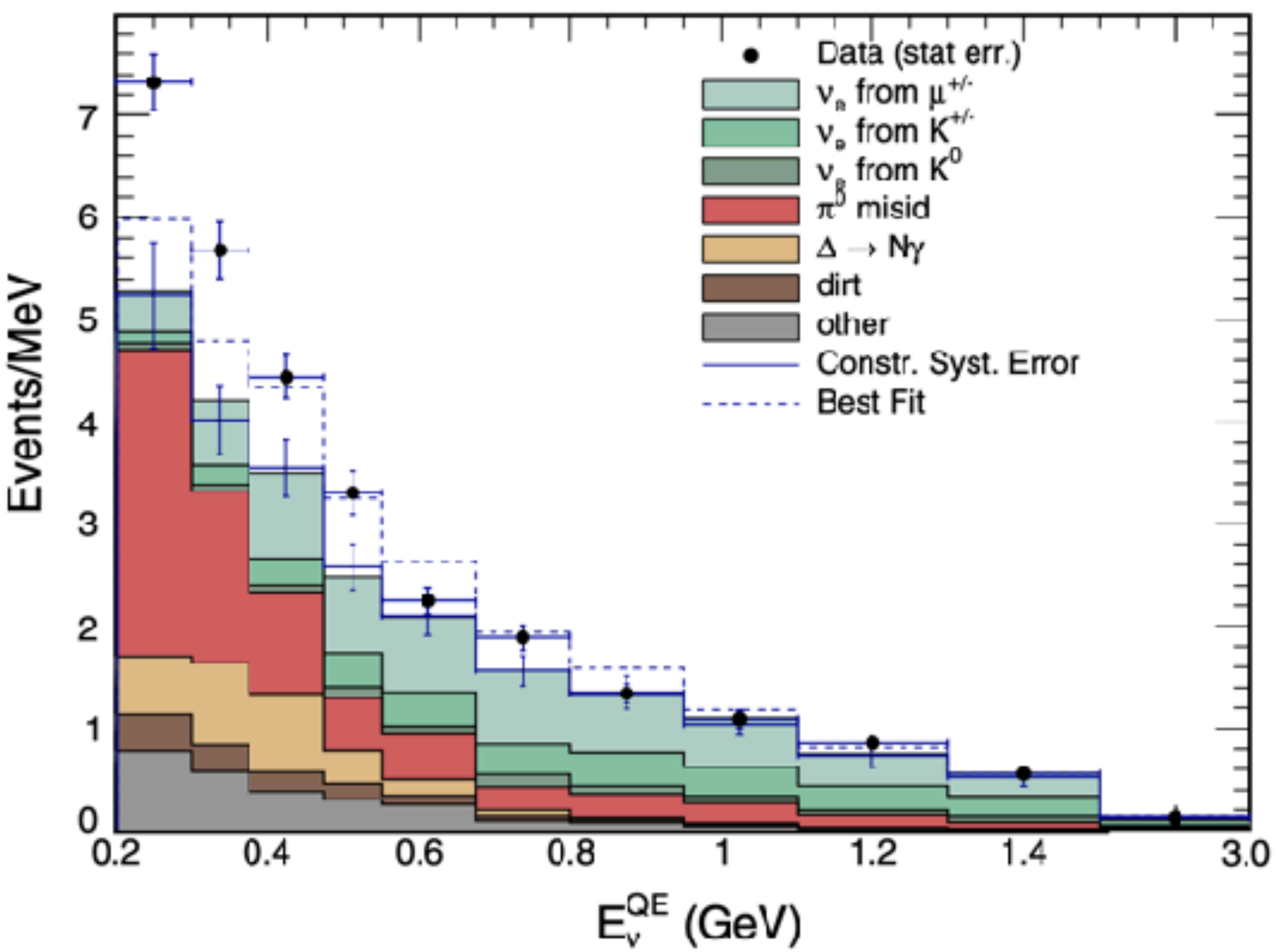
Phys. Rev. D 64, 112007

ANOMALIES: MINIBOONE



- Similar L/E as LSND: if an oscillation really exists, should see it here too
- Different energy, detector, beam, event signatures, backgrounds

ANOMALIES: MINIBOONE



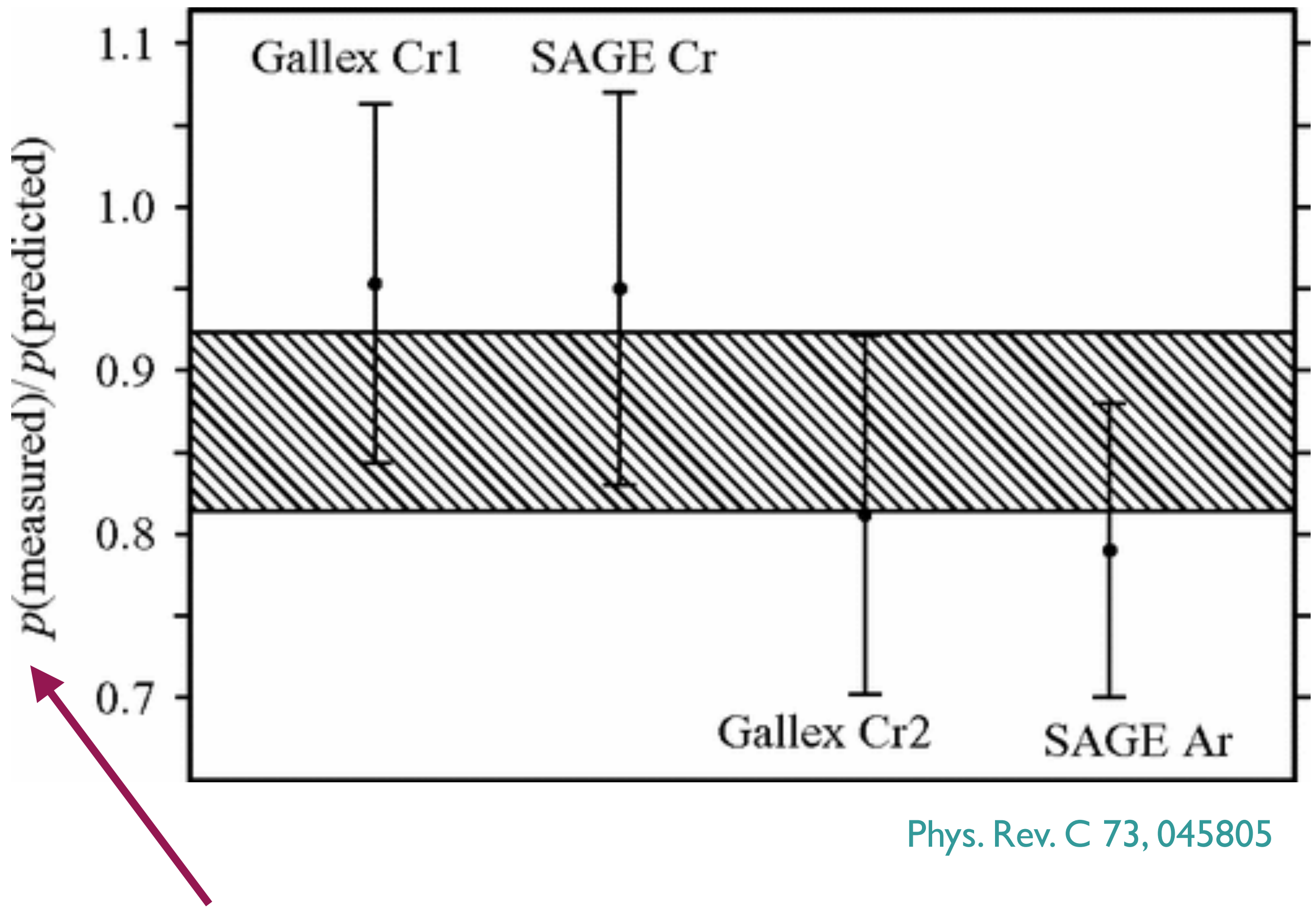
- Recently released updated results (2021) with x2 more data than original anomaly (2009)
- 4.8σ excess of measured ν_e and $\overline{\nu}_e$ over prediction, focused at low energy
- Consistent with LSND results: combined significance of 6.1σ
- Best fit for neutrino oscillation hypothesis: $\Delta m^2 = 0.04\ eV^2$

Phys. Rev. D 103, 052002

GALLIUM ANOMALY: GALLEX AND SAGE

- Solar neutrino experiments using Gallium for neutrino detection
- Tested using ^{51}Cr and ^{37}Ar radioactive sources - measured 2.8σ deficit of ν_e
- Could be explained by neutrino oscillations with $\Delta m^2 > 0.35 eV^2$ (best fit $\Delta m^2 \sim 2 eV^2$)
- SAGE: "A probable explanation for this low result is that the cross section … has been overestimated"

Phys. Rev. C 80, 015807 (2009)



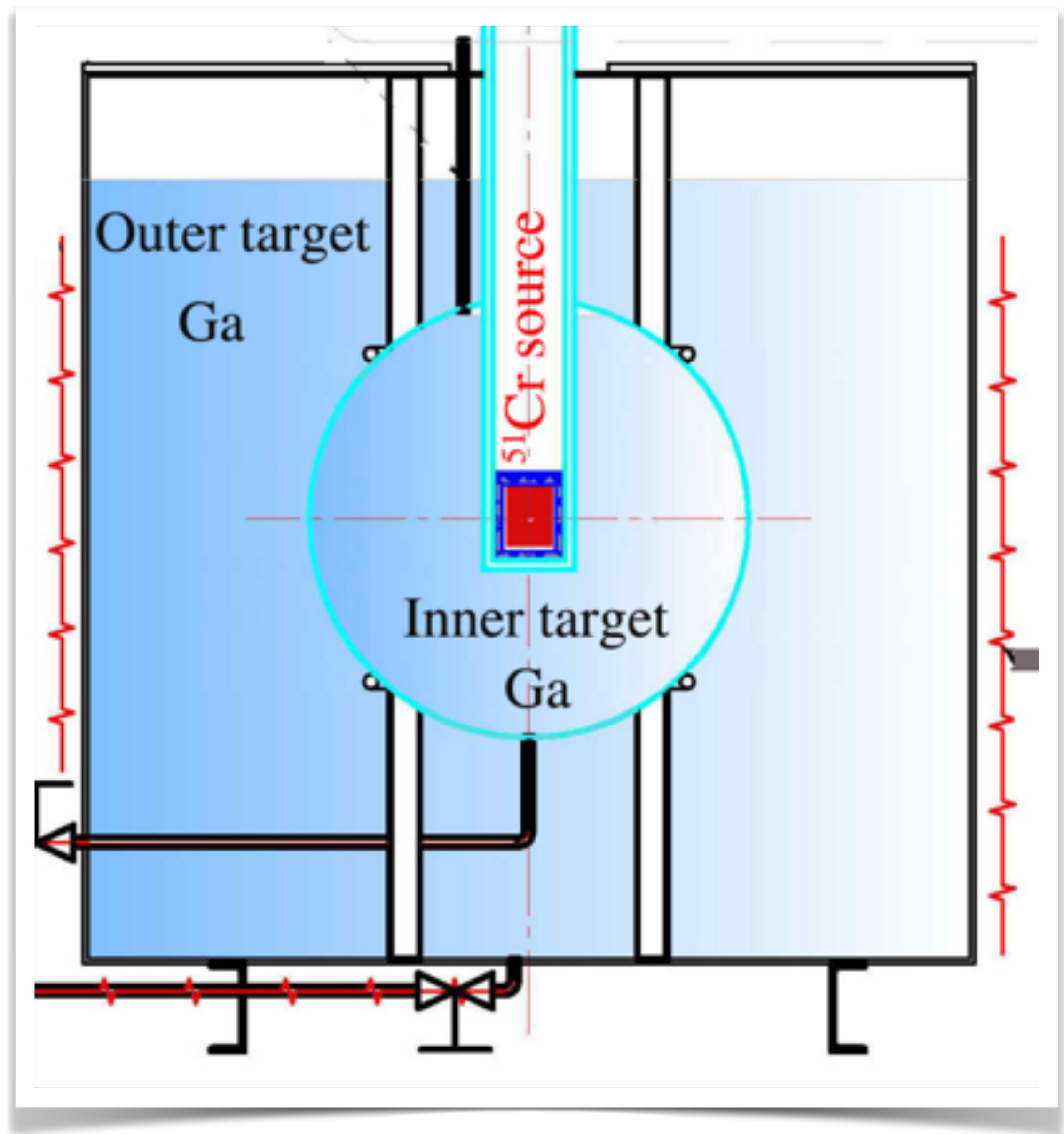
Phys. Rev. C 73, 045805

y-axis: ratio to expectation, R

R=1 → no oscillations

GALLIUM ANOMALY: BEST

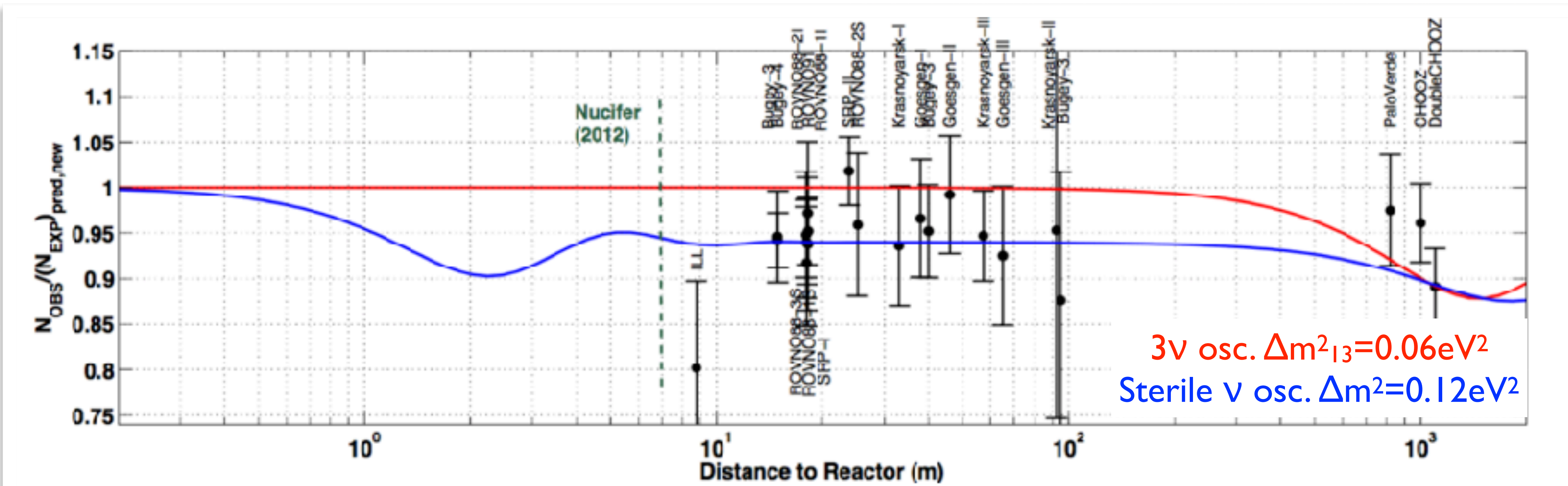
- BEST collaboration recently presented a new result: gallium measurement using a chromium-51 source
- Inner target: R=0.791±0.05
- Outer target: R=0.766±0.05
- Gallium anomaly reaffirmed with significantly smaller error bars
- Favours $\Delta m^2 > 1 eV^2$ (best fit: $3.3 eV^2$)



arXiv:2109.11482 [nucl-ex]

ANOMALIES: REACTOR $\overline{\nu}_e$ RATE

- New calculation of neutrino flux from nuclear reactors by multiple groups* in 2011: ~3σ (3.5%) deficit in $\overline{\nu}_e$
- Could be explained by neutrino oscillation $\Delta m^2 \sim 0.12 eV^2$
- However…

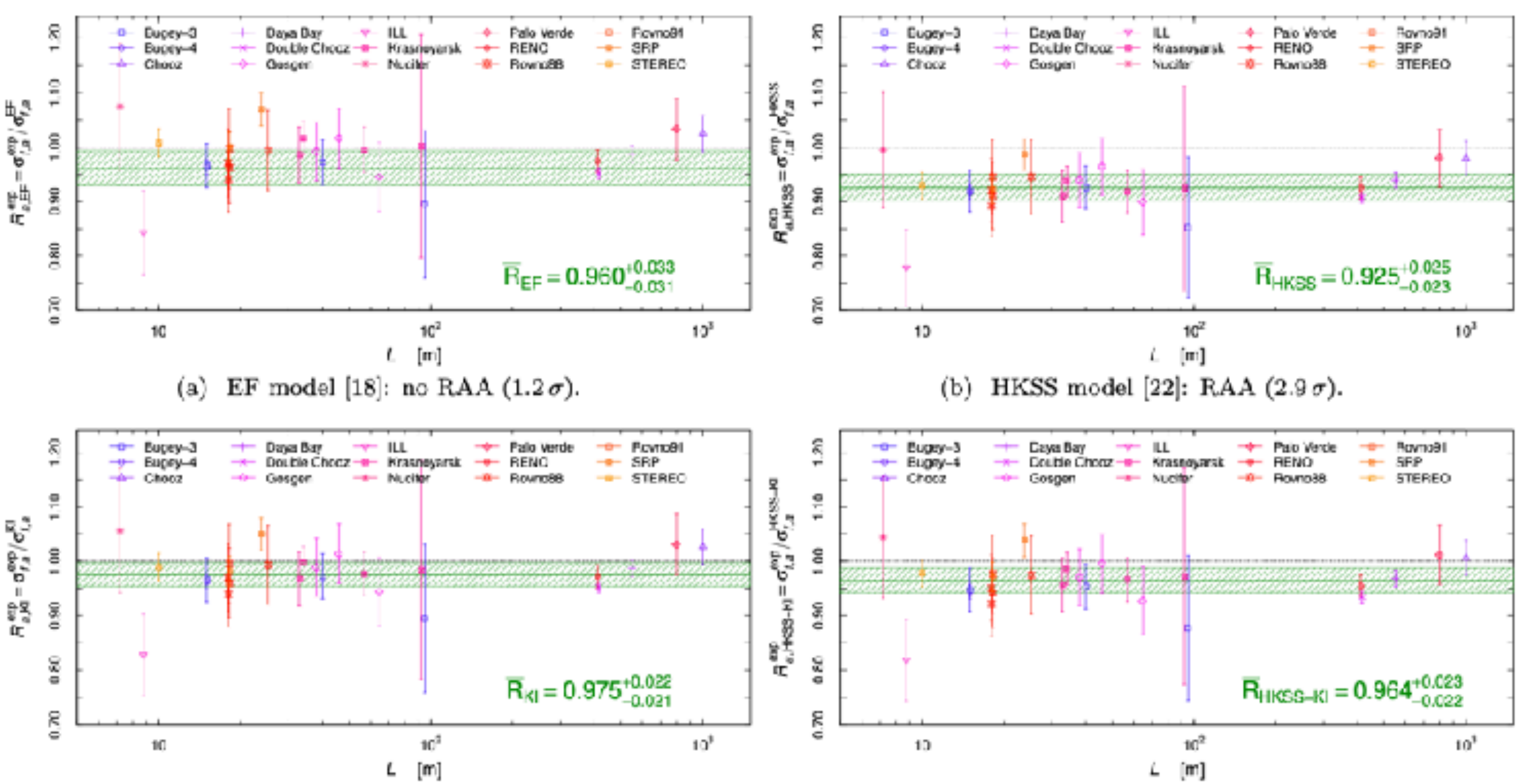


Mention et. al, Phys. Rev. D 83, 073006 (2011)

*Mueller et. al., Phys. Rev. C 83, 054615 (2011), Huber Phys Rev C 84, 024617 (2011)

ANOMALIES: REACTOR $\overline{\nu}e$ RATE

Updated models reduce deficit → tension with Gallium anomaly



(a) EF model [18]: no RAA (1.2 σ).
(b) HKSS model [22]: RAA (2.9 σ).
(c) KI model [24]: no RAA (1.1 σ).
(d) HKSS-KI model: no RAA (1.5 σ).

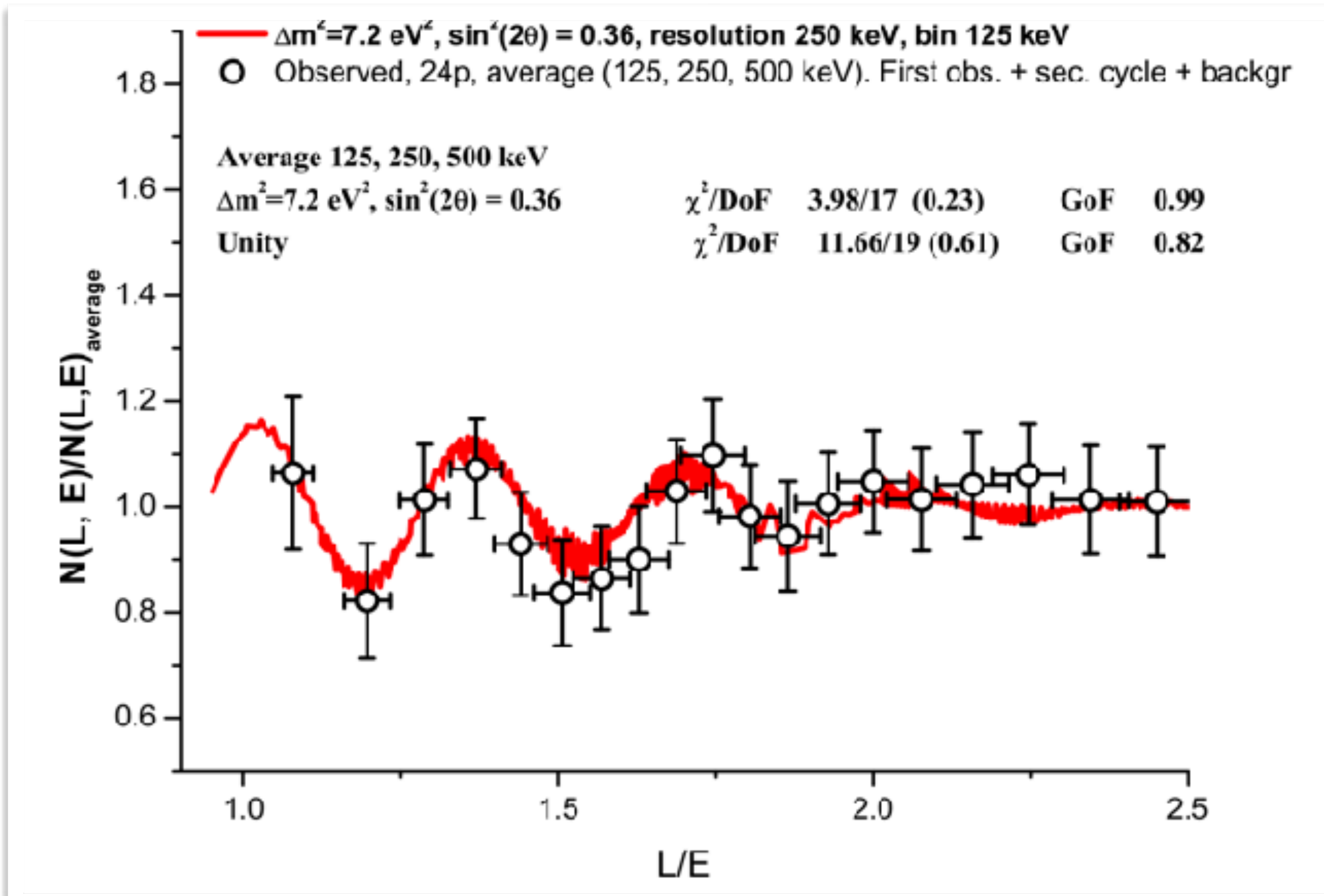
C. Giunti et. al., arXiv:2110.06820 [hep-ph]

ANOMALIES: REACTOR $\bar{\nu}_e$ SHAPE

Neutrino-4

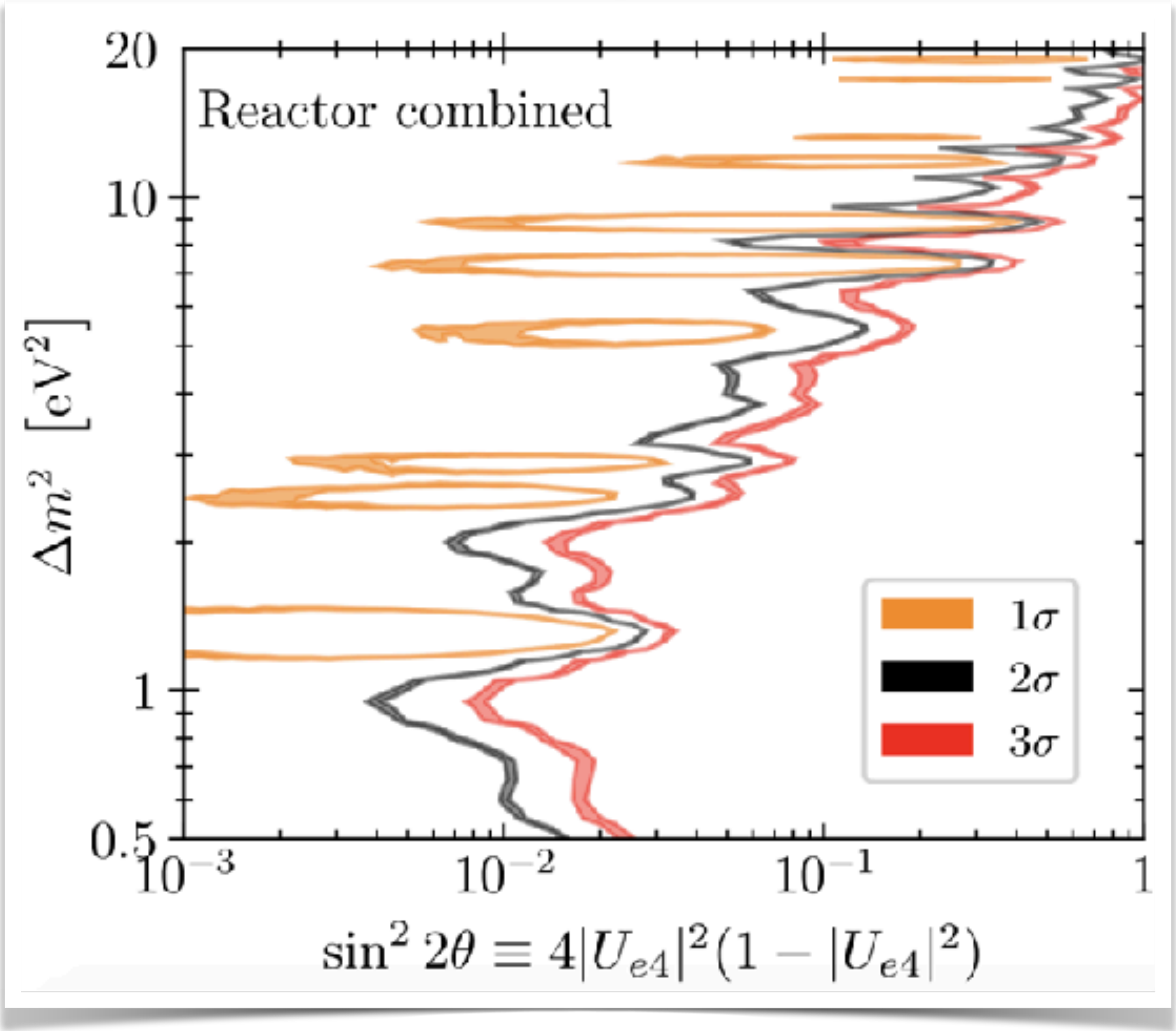
Phys. Rev. D 104, 032003 (2021)

- 6-12m from centre of active zone of the SM-3 reactor
- Spectrum ratio measurement
- Report 2.7σ indication of oscillations with $\Delta m^2 = 7.2 eV^2$



ANOMALIES: REACTOR $\overline{\nu}_e$ SHAPE

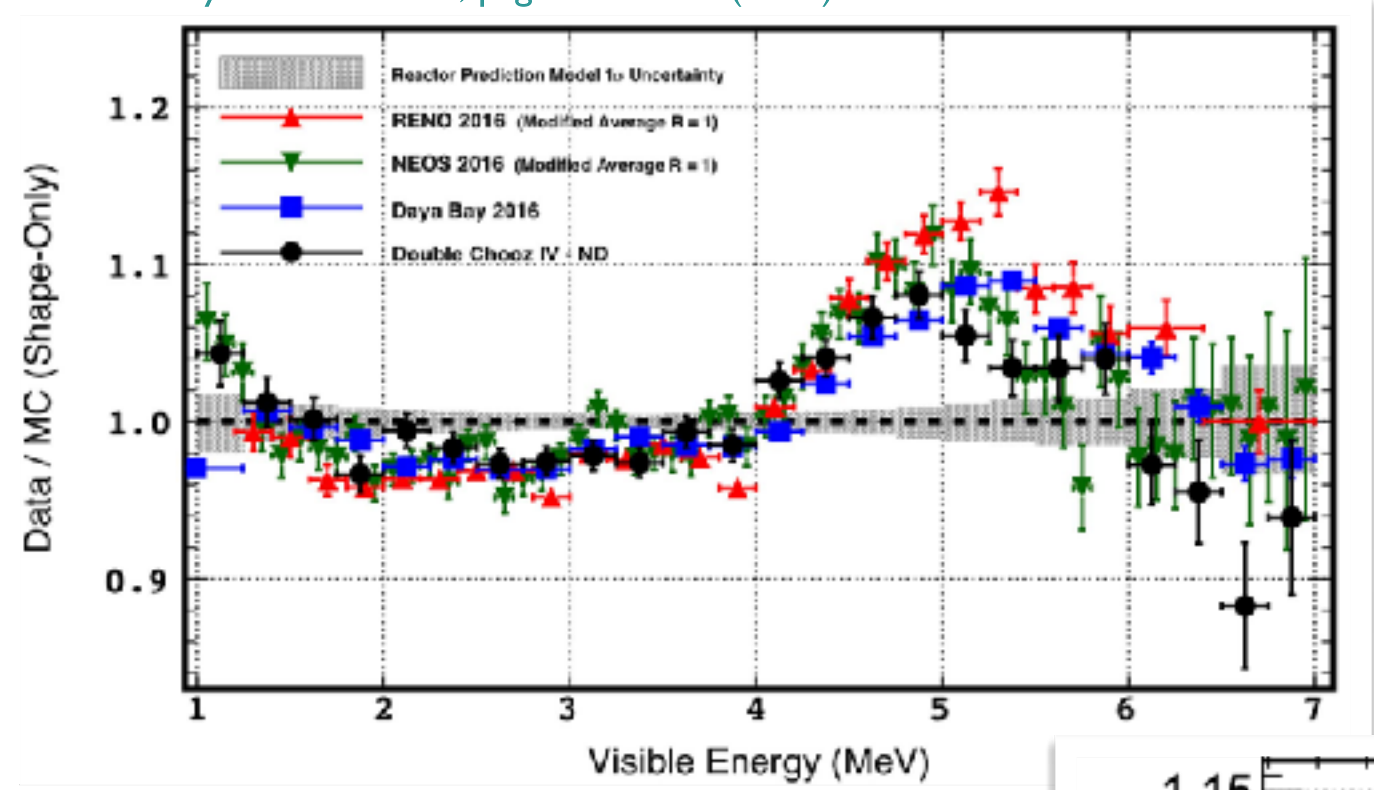
PROSPECT
STEREO
DANSS
Neutrino-4
NEOS



Berryman et. al., arXiv:2111.12530 [hep-ph]

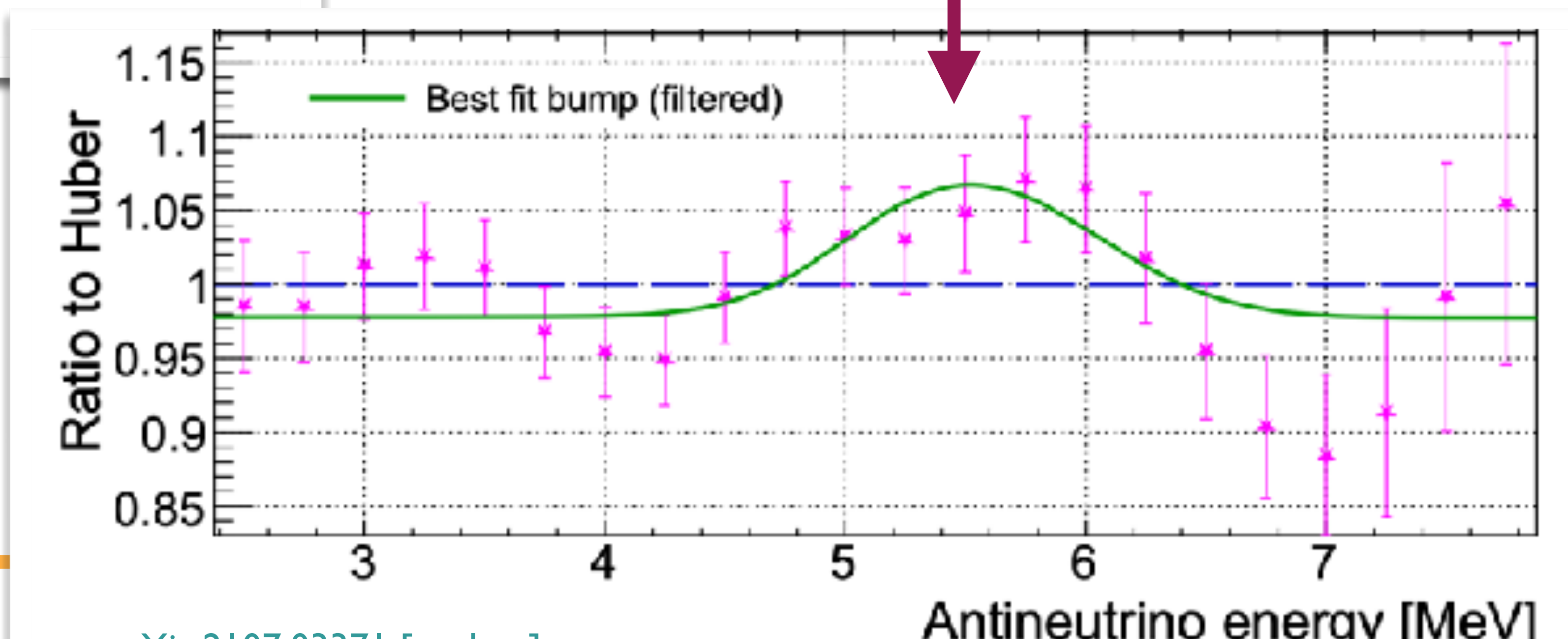
ANOMALIES: THE 5 MEV BUMP

Nature Physics volume 16, pages 558–564 (2020)



RENO
NEOS
Daya Bay
Double Chooz

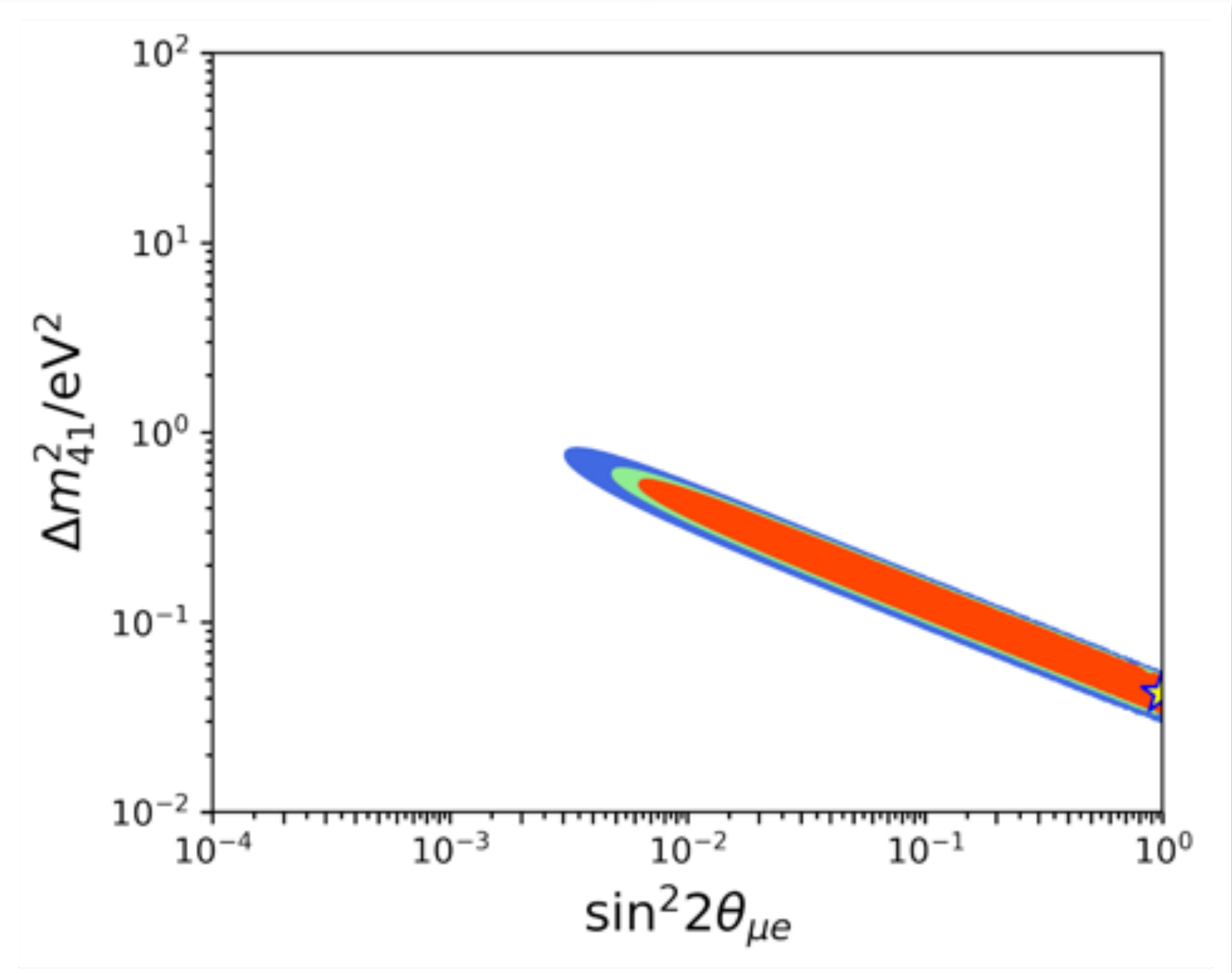
PROSPECT+STEREO



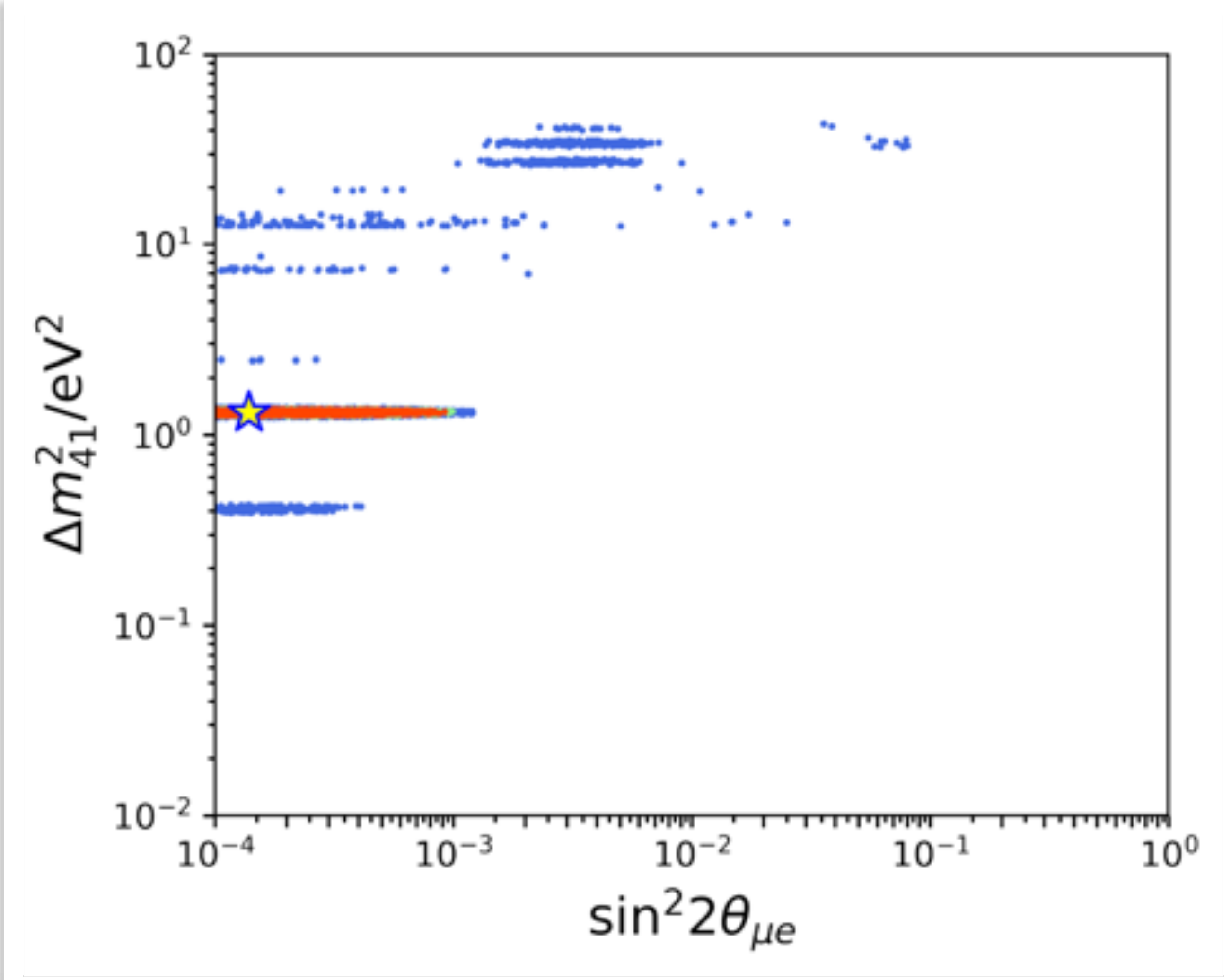
arXiv:2107.03371 [nucl-ex]

STERILE NEUTRINOS?

Diaz et. al., Phys. Rep. 884 (2020) 1-59

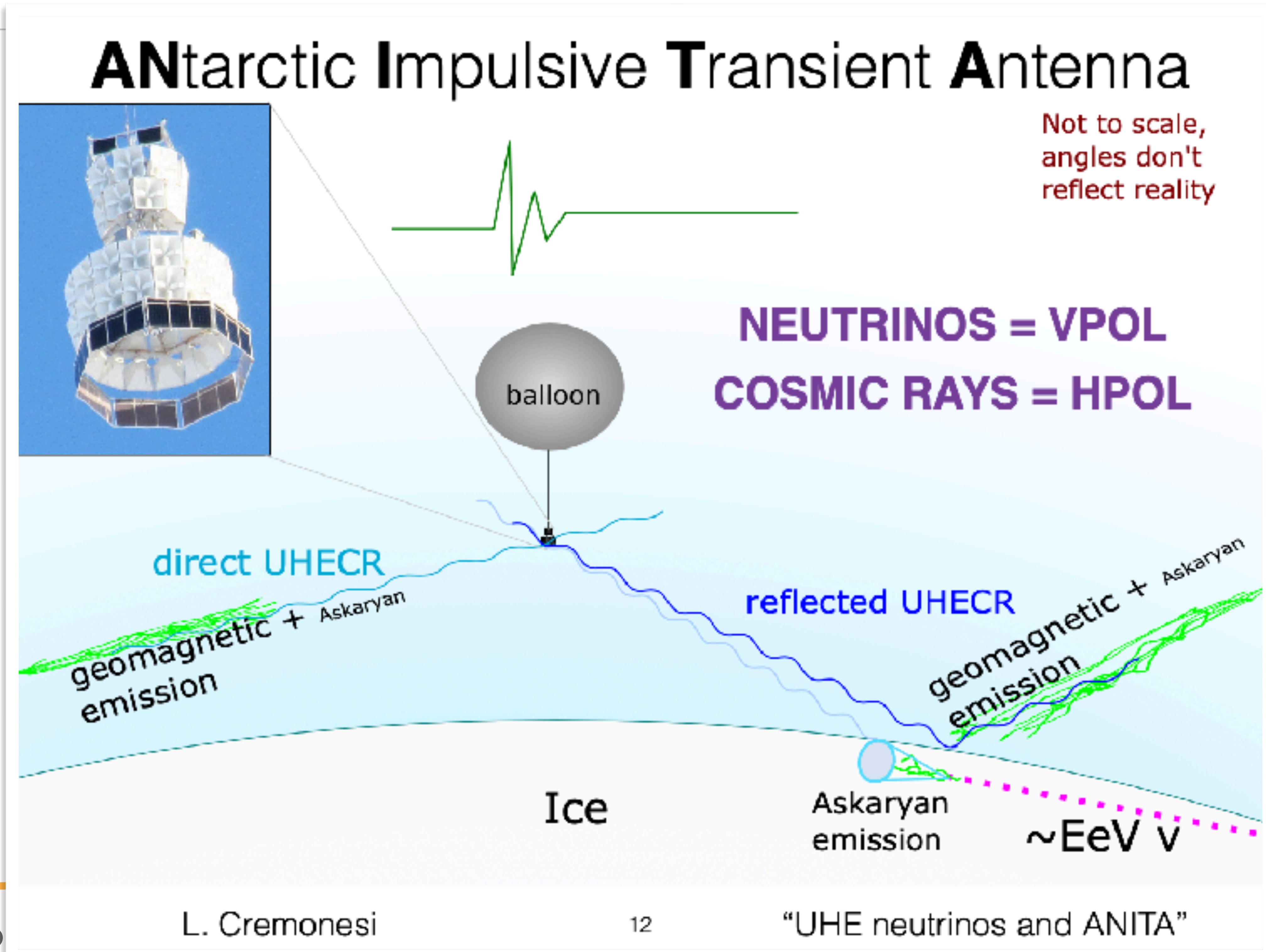


Appearance



Disappearance

AND NOW FOR SOMETHING COMPLETELY DIFFERENT



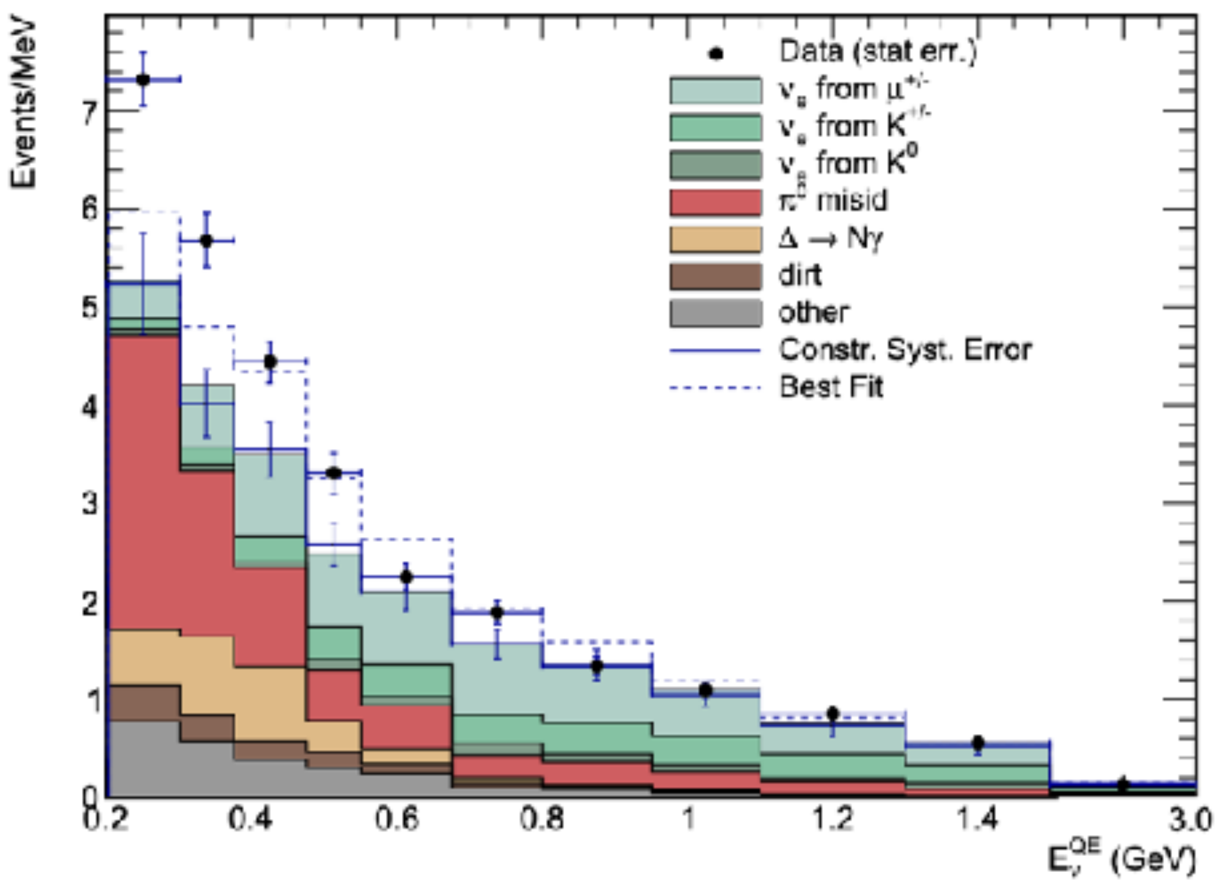
Slide from L. Cremonesi, QMUL

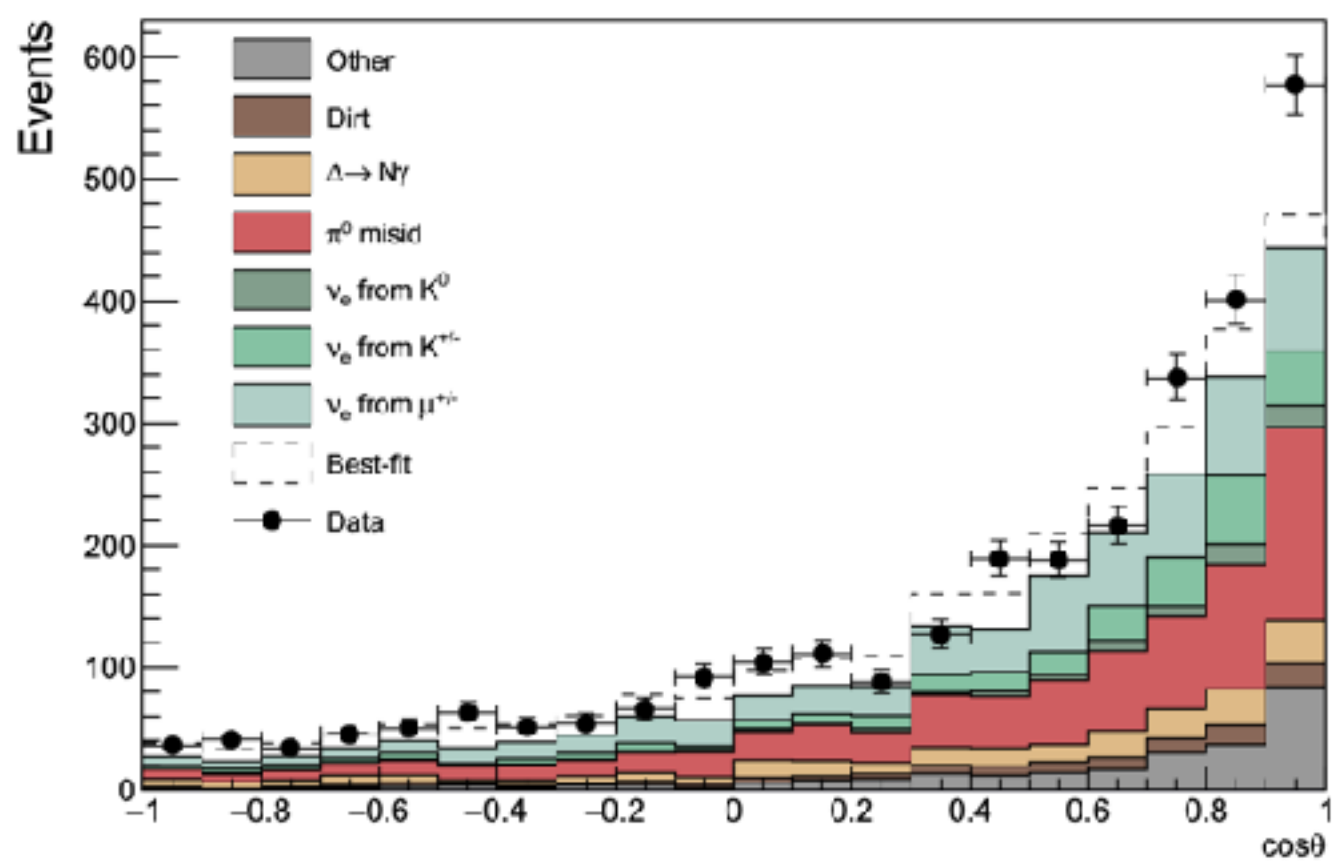
ANITA ANOMALIES

- ANITA can see events in **vertical** or **horizontal** polarisations
  - Vertical → most **neutrino** signals
  - Horizontal → usually **cosmic rays**
- Detected neutrinos (10^{18}eV) expected to be at **shallow angles**
- Mystery: ANITA-1 and ANITA-2 saw 2 events at **steep angles** coming directly at the detector, compatible with a tau decay. **No SM particle would survive** travelling through the Earth at those energies
- Mystery 2: ANITA-4 did not see any of those events, but did see a weird **new class of "horizon" events** that they didn't see before (courtesy of new and improved detector?)

INVESTIGATING THE MINIBOONE ANOMALY

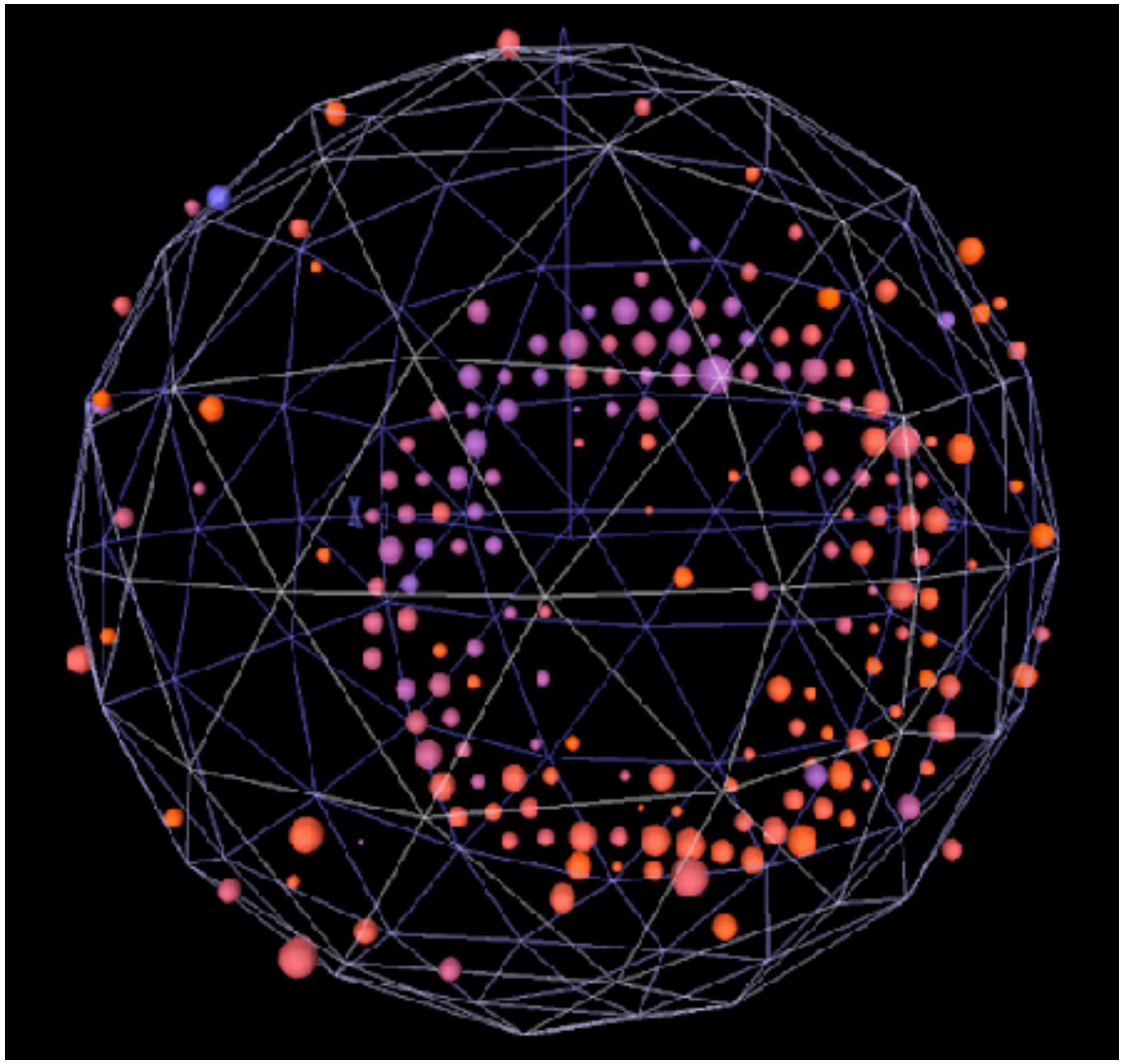
THE MINIBOONE LOW-ENERGY EXCESS (LEE)



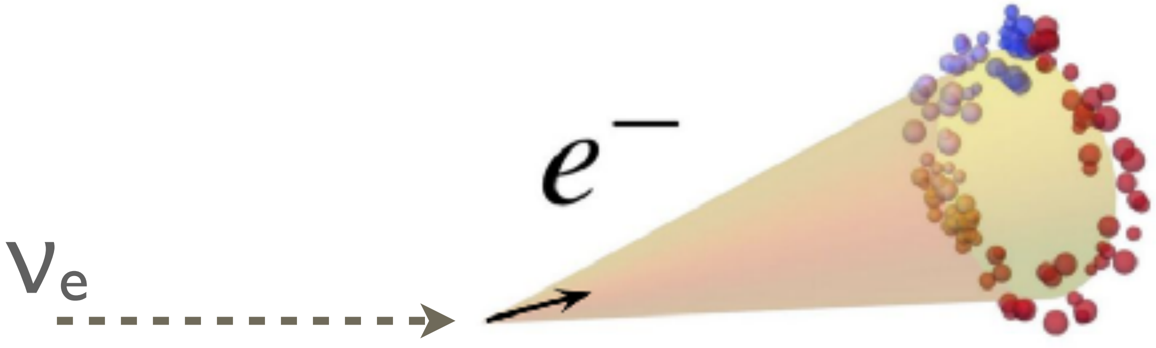


Phys. Rev. D 103, 052002

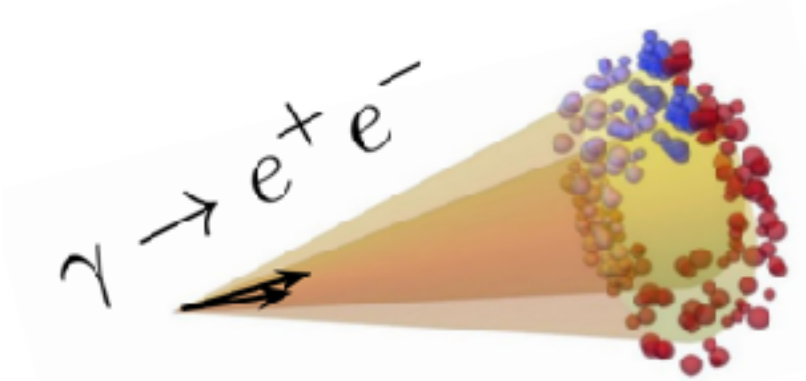
MINIBOONE



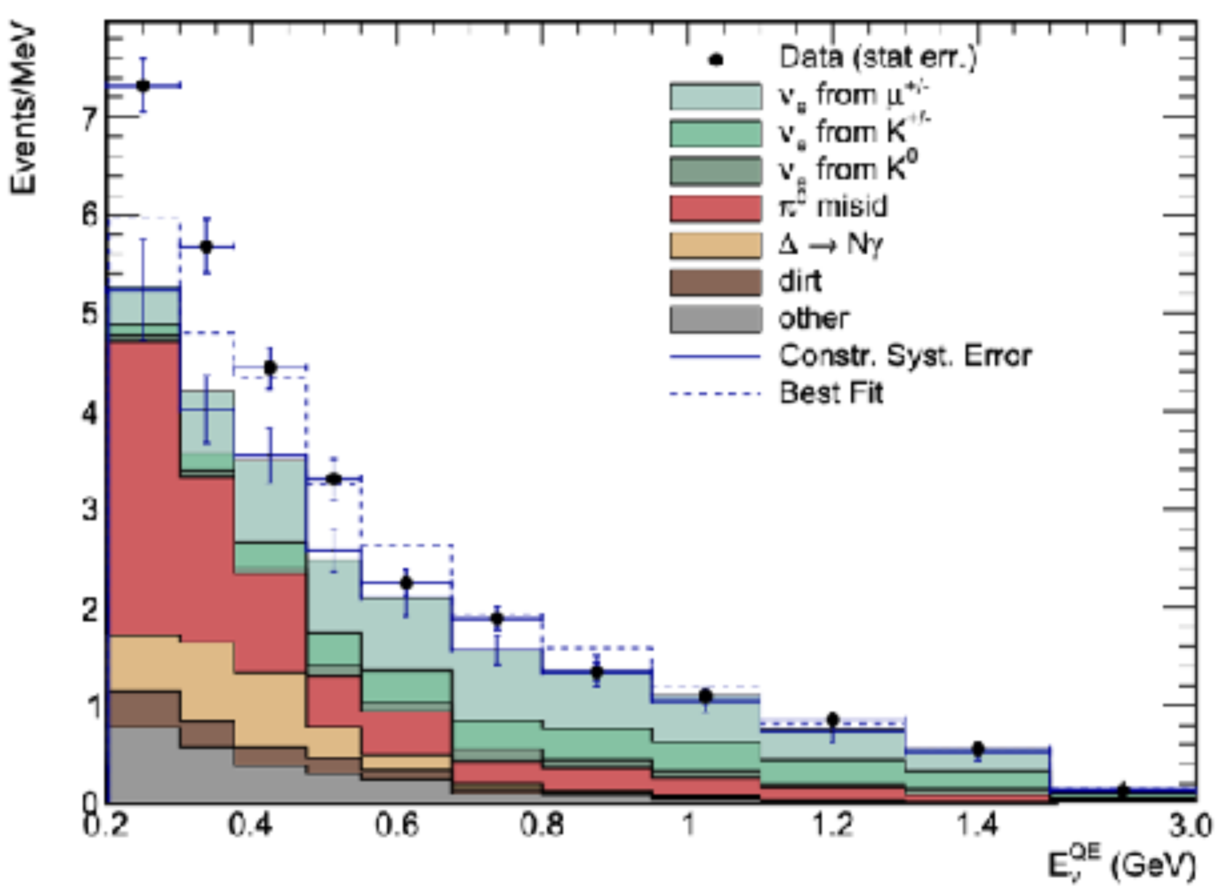
- 800-ton mineral oil (CH_2) Cherenkov detector
- Detect Cherenkov ring from **electrons** produced in ν_e **CC scattering** interactions



- However, **photons** produce identical Cherenkov rings



THE MINIBOONE LOW-ENERGY EXCESS (LEE)

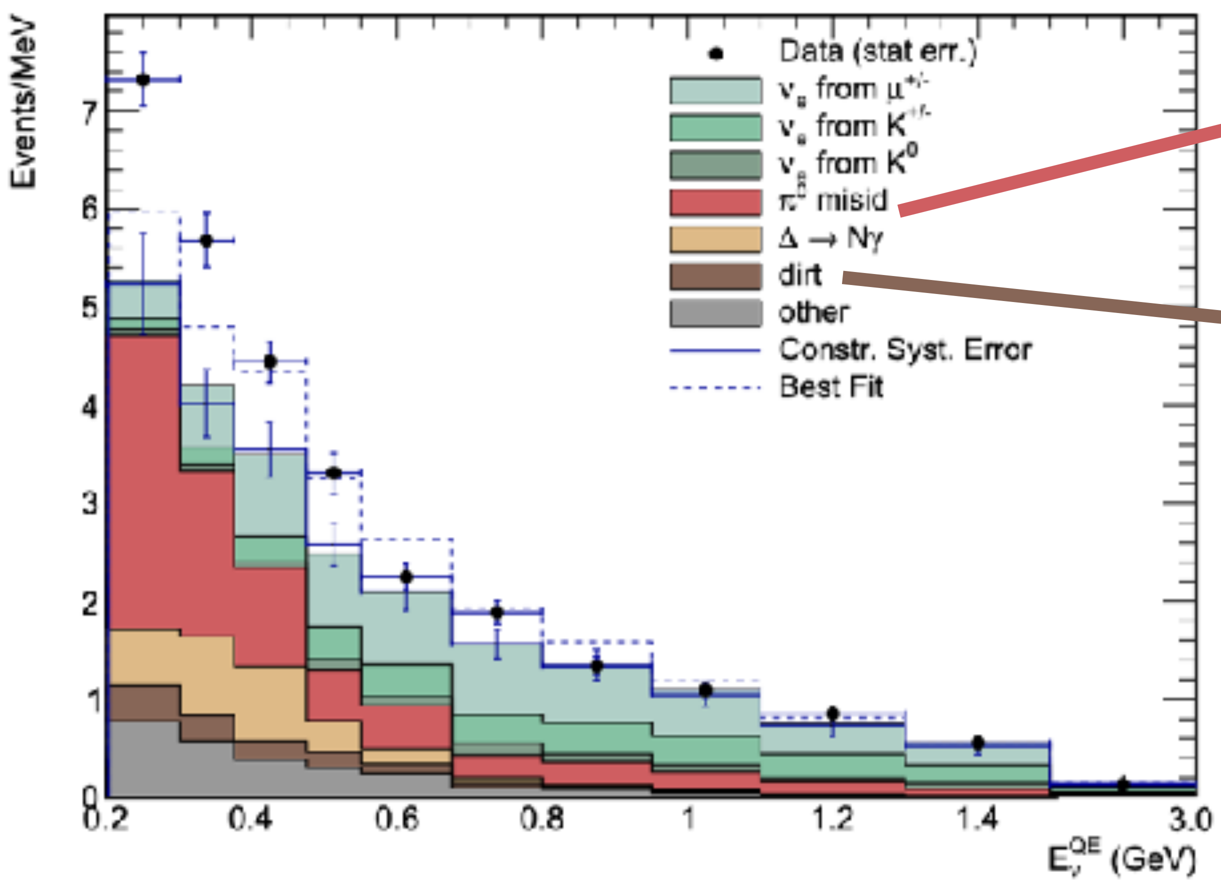


Is the excess electrons?

- Sterile neutrino oscillations → difficult to explain MiniBooNE excess and all other global data
- Best-fit 2-neutrino sterile oscillation appearance spectrum does not predict data well at very low energies
- More complex models can help
  - Mixed oscillations and decay
  - Resonance matter effects
  - Additional sterile neutrinos
  - Non-unitary mixing
  - …and many more!

I'll come back to this!

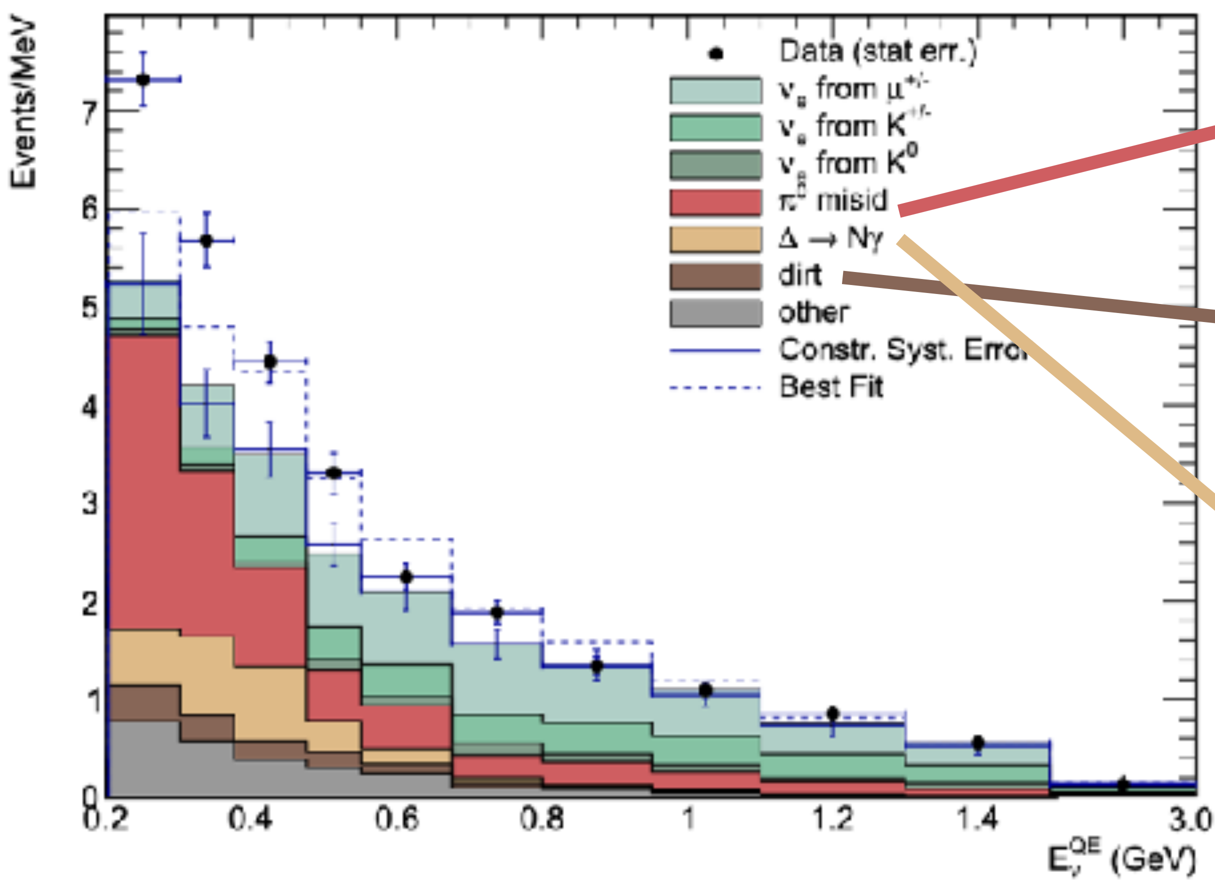
THE MINIBOONE LOW-ENERGY EXCESS (LEE)



Is the excess photons?

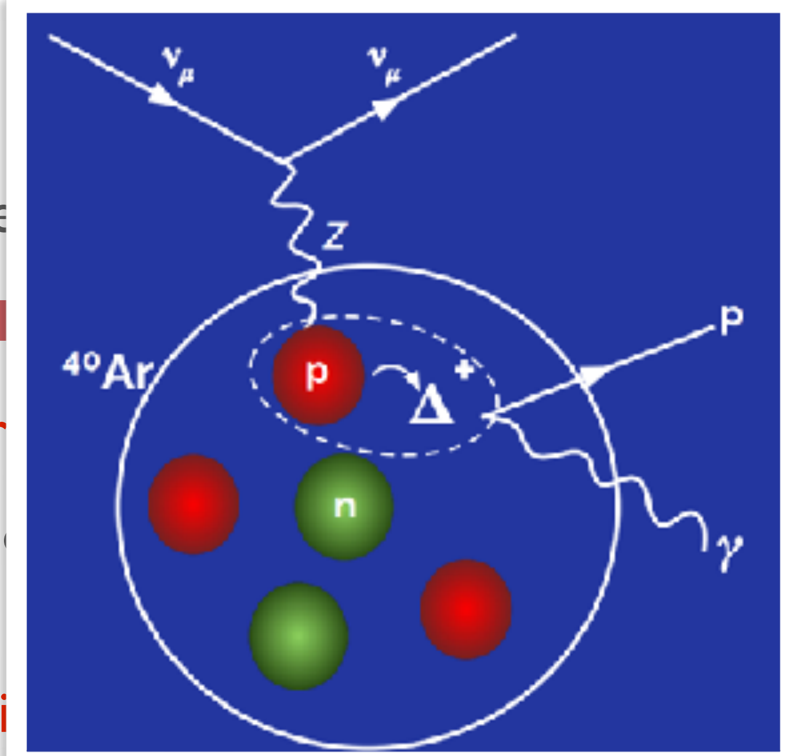
- Several sources of photon backgrounds:
- **NCπ⁰ mis-ID**
  - → measured in-situ
- **Dirt** (neutrino interactions outside the detector)
  - → beam timing

THE MINIBOONE LOW-ENERGY EXCESS (LEE)



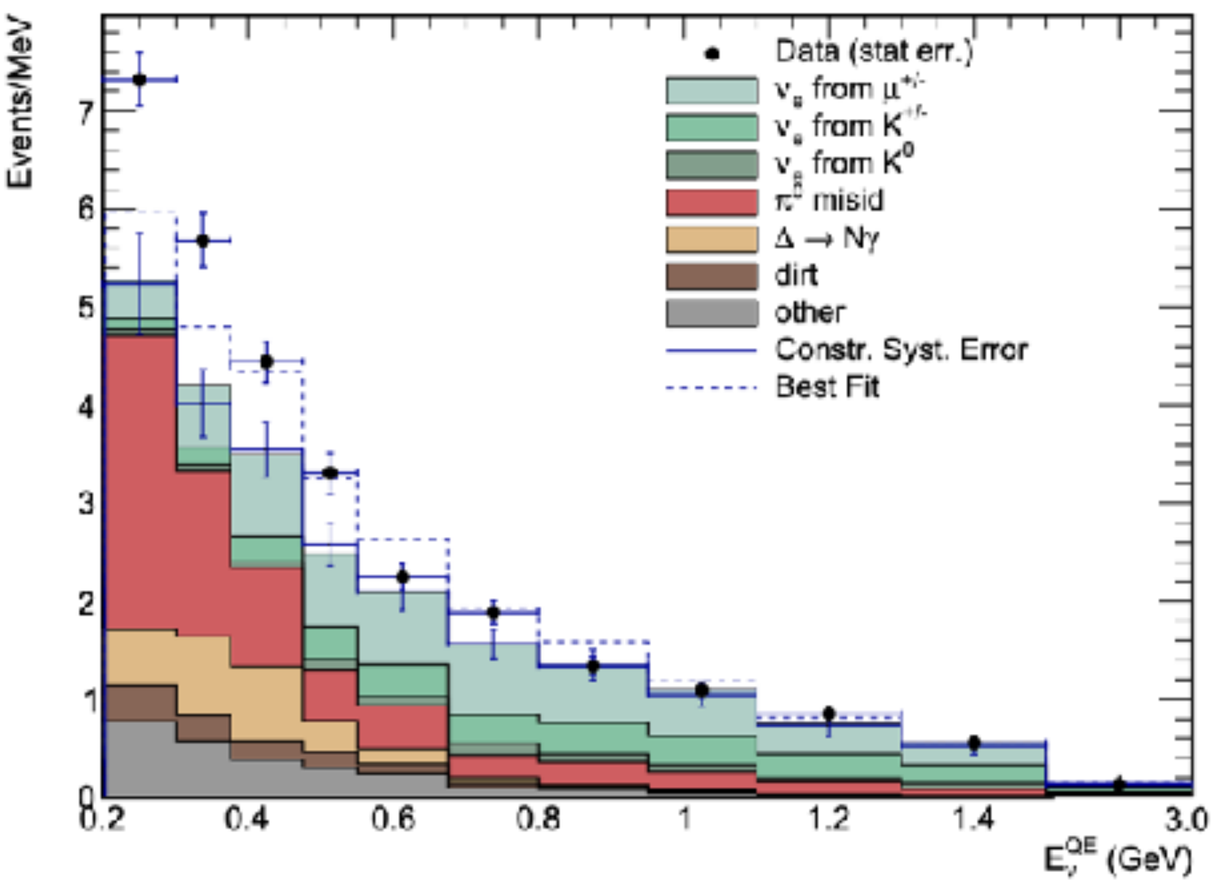
Is the excess

- Several source
  - **NCπ⁰ mis-I**
    - → measur
  - **Dirt** (neutrin detector)
    - → beam ti



- **NC Δ→Nγ**
  - → not constrained directly - predicted from NCπ⁰ rate and theoretical branching fraction
  - Need x3.18 increase to explain excess
  - → to be investigated…

THE MINIBOONE LOW-ENERGY EXCESS (LEE)



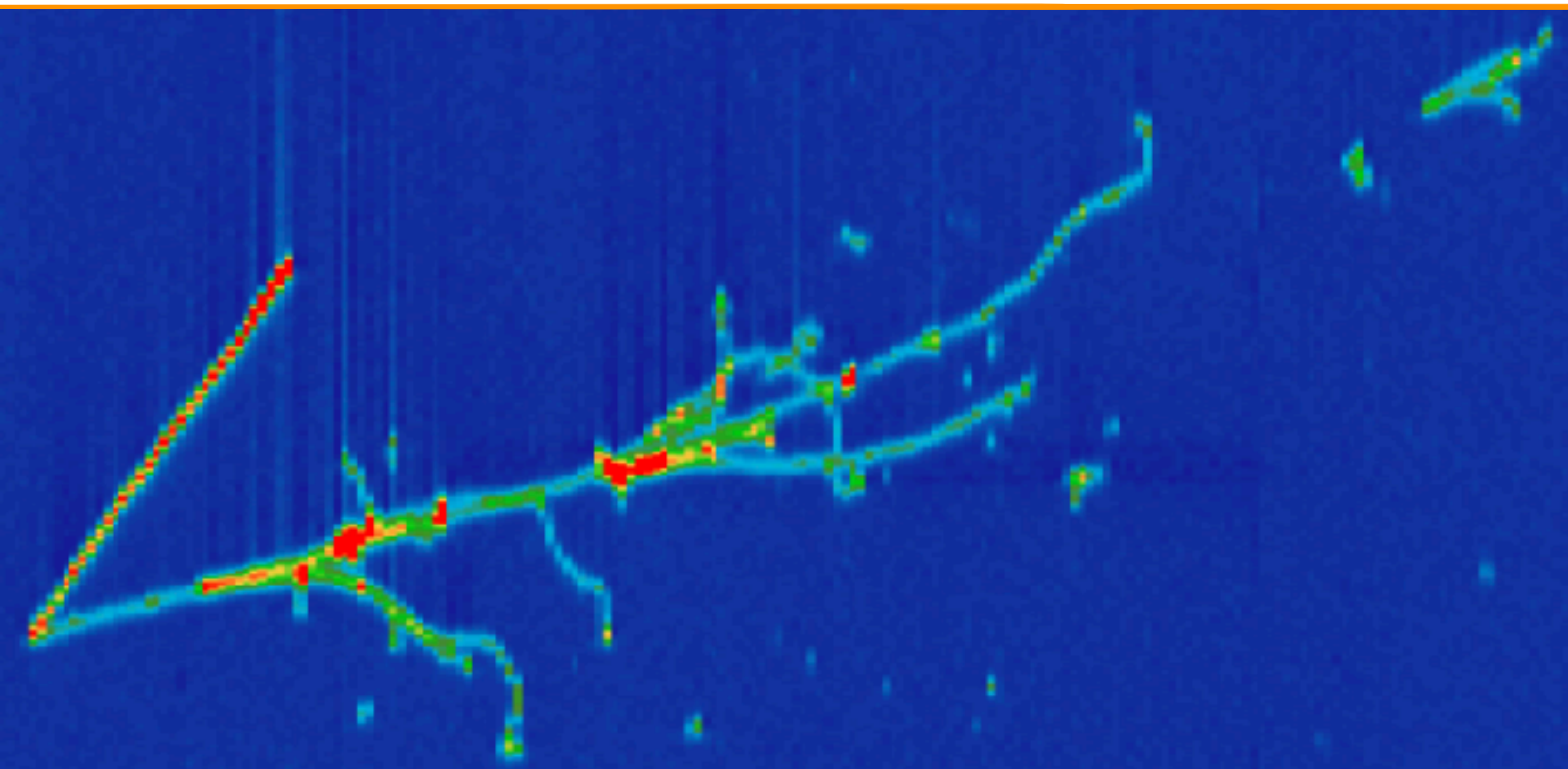
Or neither?

- Rich phenomenology developed in recent years
- Could be e^+e^- pairs from decays of new particles?
- Or something else?
- I'll come back to this too!

For now, it's clear that we need more information…

More information can come from Liquid Argon TPCs (LArTPCs)

- Bubble-chamber style resolution
- Calorimetric information
- Automated reconstruction
- → enable incredible precision measurements at scale
- Placing these detectors in a high-intensity neutrino beam will allow testing of a variety of models that could explain these anomalies




Rail Station 14

MicroBooNE: 170 ton Liquid Argon Time Projection Chamber (LArTPC)

- Stable detector operation since 2015: **longest-running LArTPC to date**
  - >95% DAQ uptime
  - 1.52×10^{21} POT collected in total (analyses shown here use subsets, not full POT)

Grateful to Fermilab Accelerator Division, Cryogenics team, and Operations team!

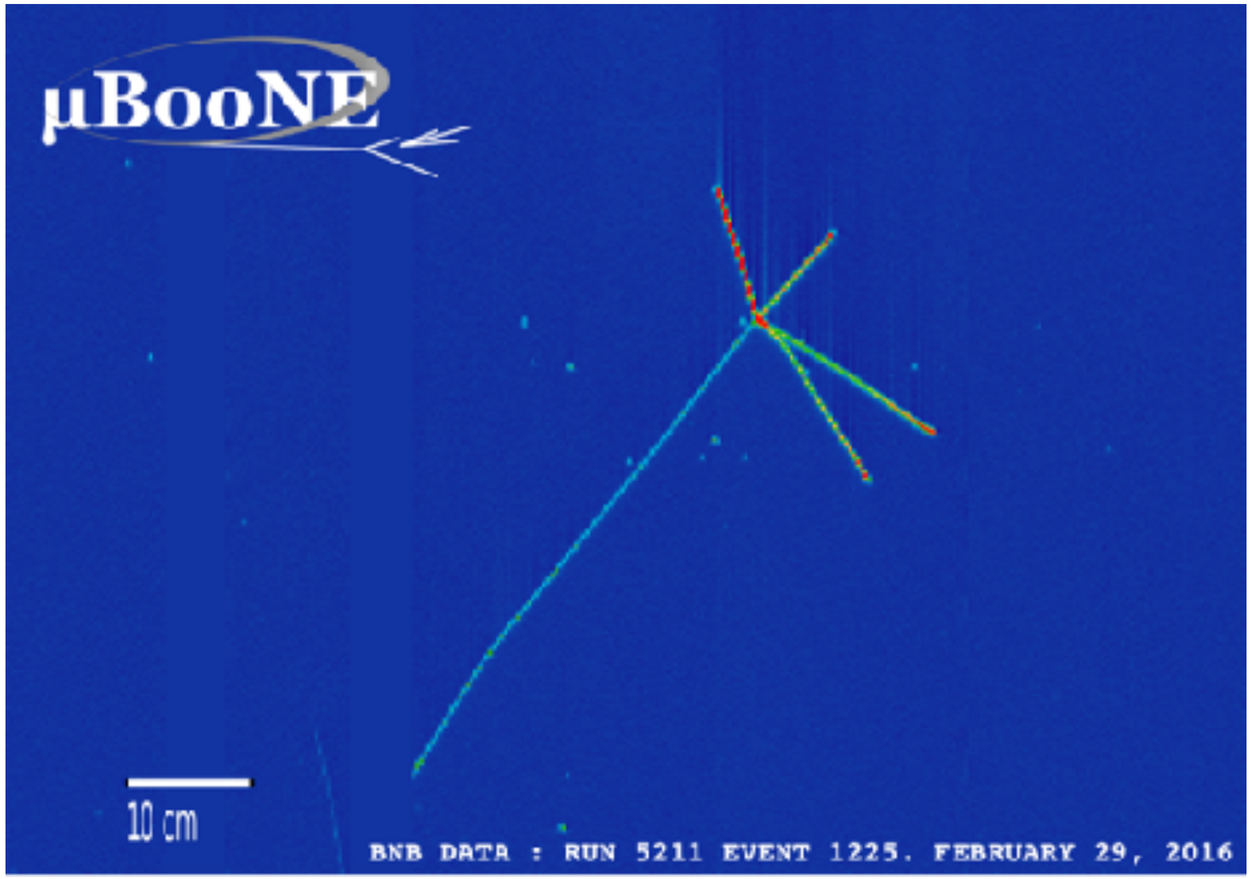
LArTPC STRENGTH: LOW DETECTION THRESHOLDS

Phys. Rev. Lett. 125, 201803 (2020)
Phys. Rev. D 102, 112013 (2020)
JINST 15, P03022 (2020)
arXiv:2110.14065 [hep-ex]
arXiv:2110.13978 [hep-ex]
arXiv:2110.14080 [hep-ex]

- **Low thresholds** → access to new information about nuclear effects, neutrino interactions
- Example: proton detection thresholds

Phys. Rev. D 98, 032003 (2018)

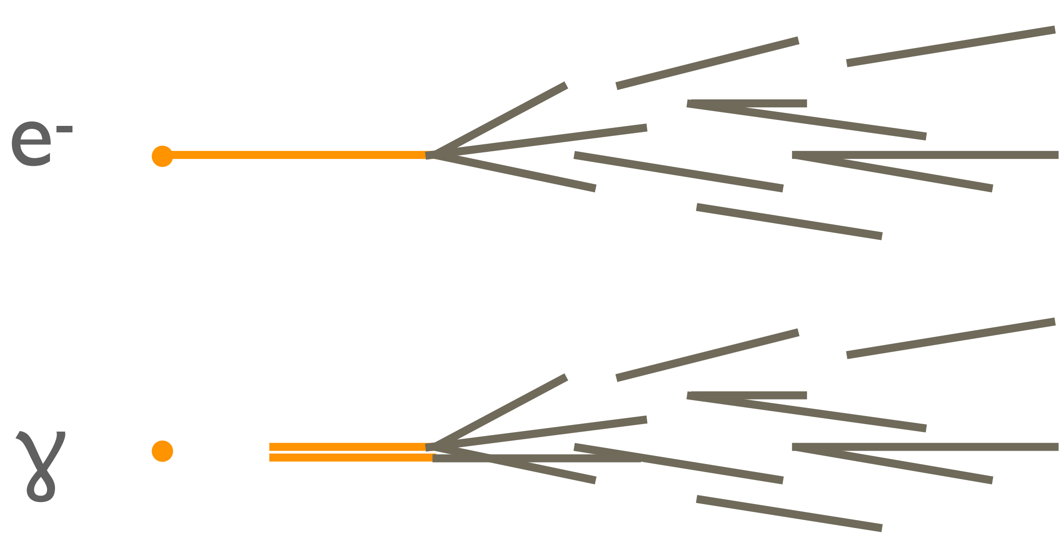
- MicroBooNE: **250 MeV/c**
- ArgoNeuT: **200 MeV/c**
  Phys. Rev. D 90, 012008 (2014)
- T2K: 500 MeV/c
- MINERvA: 450 MeV/c
  Phys. Rev. D 99, 012004 (2019)

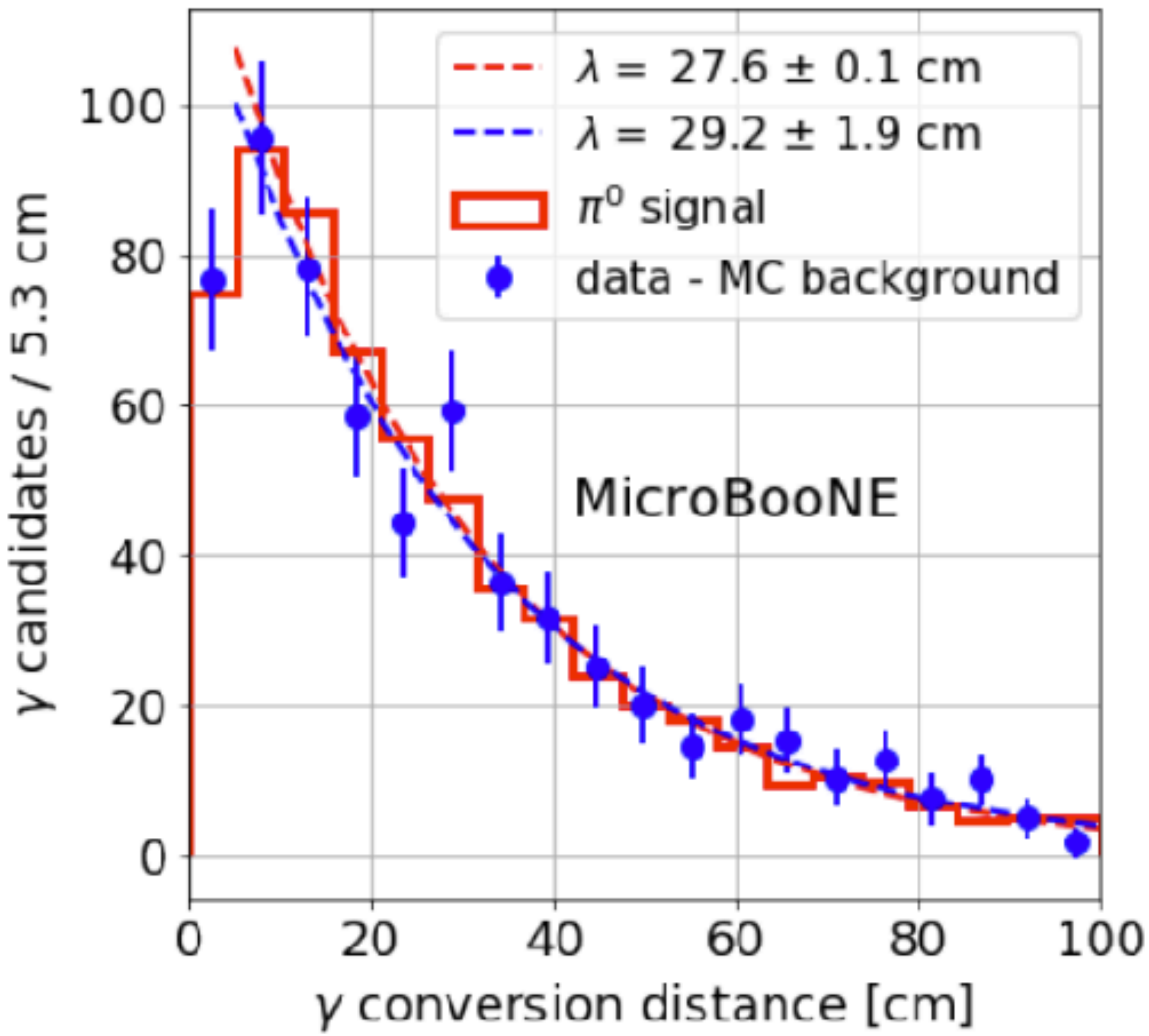


LARTPC STRENGTH: ELECTRONS AND PHOTONS

Phys. Rev. D 104, 052002 (2021)

- **Electrons and photons produce showers in LArTPCs**
- Distinguish using dE/dx at start of shower and start point





μBooNE

LARTPC STRENGTH: ELECTRONS AND PHOTONS

Phys. Rev. D 104, 052002 (2021)

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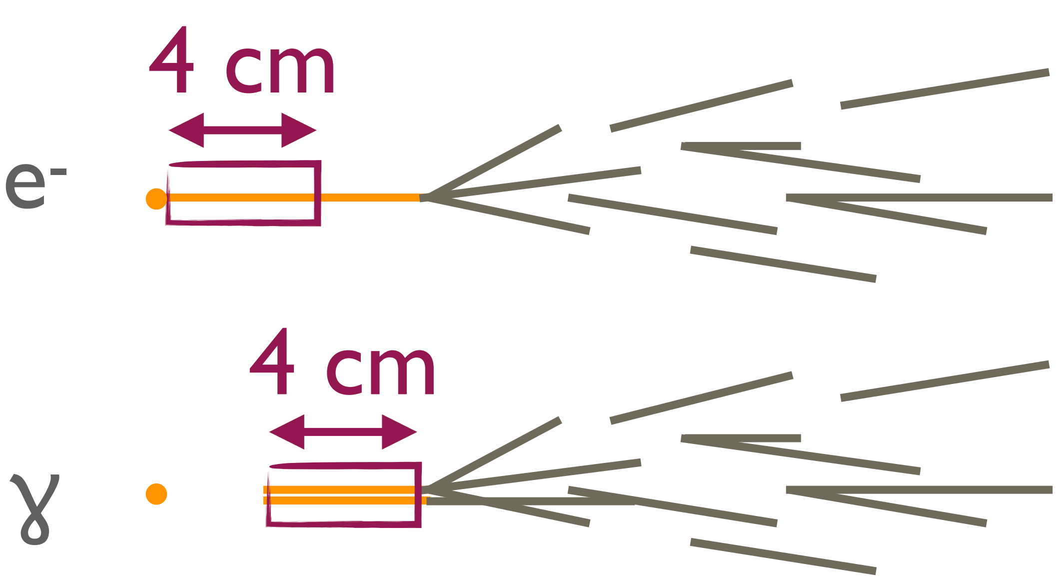
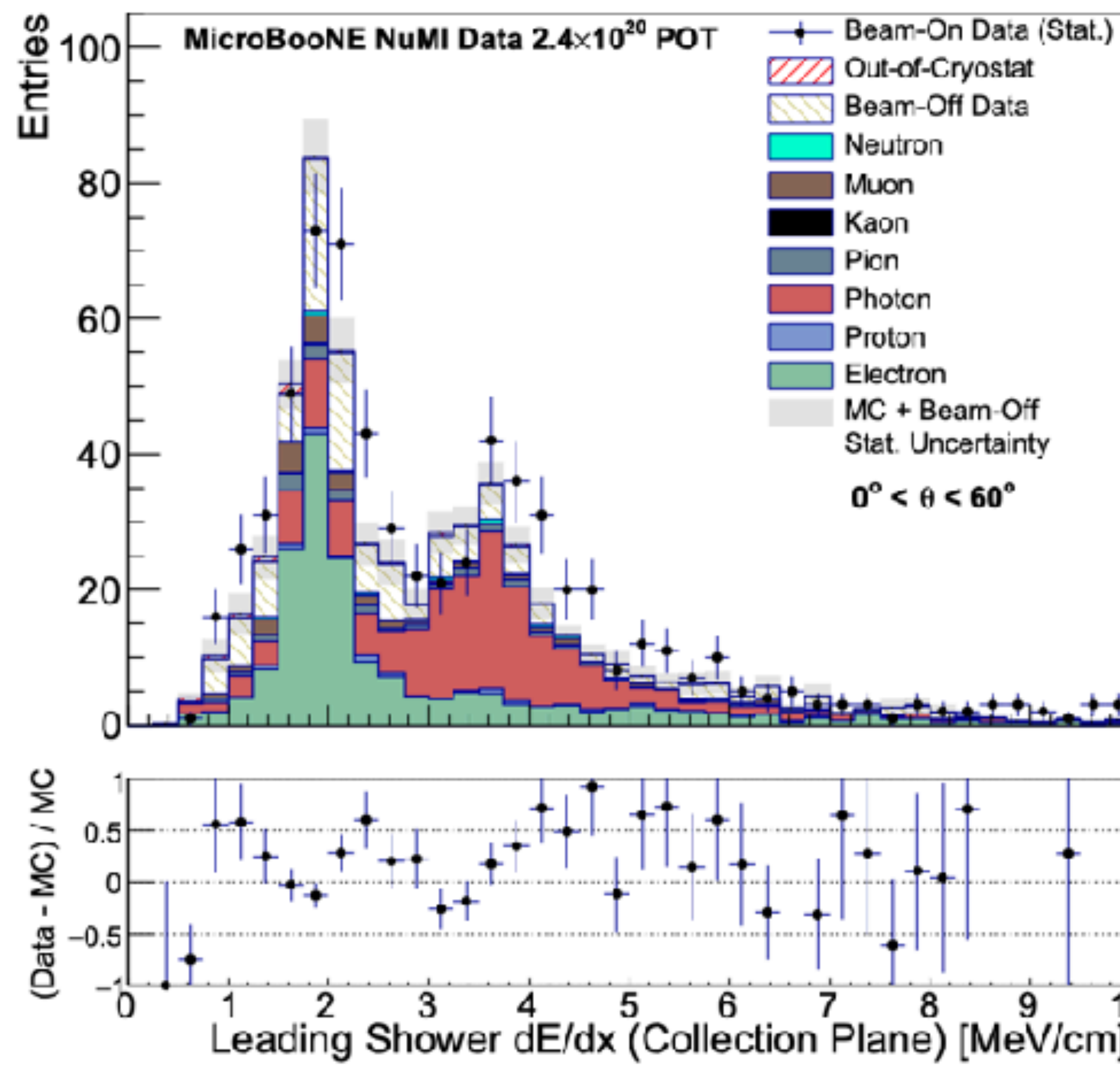
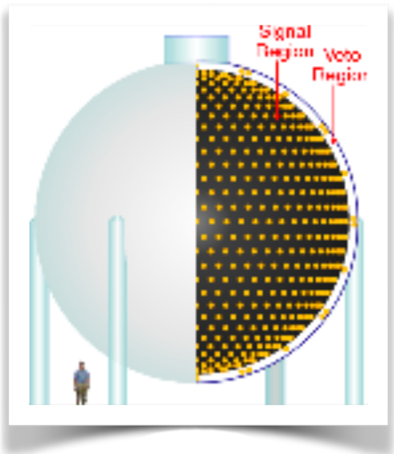


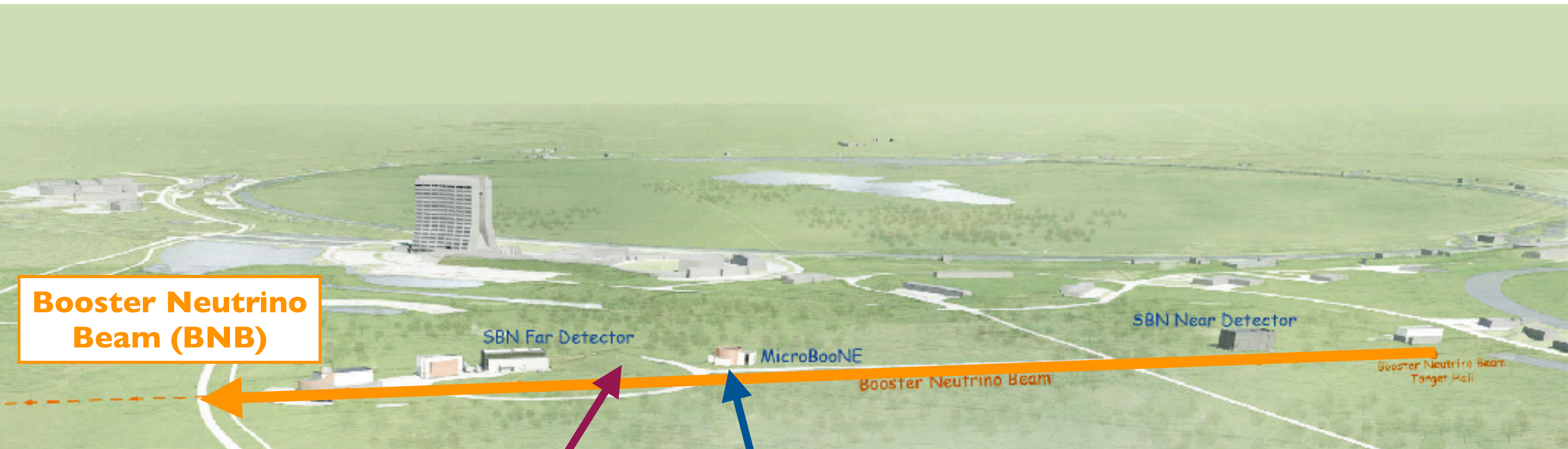


SHORT-BASELINE NEUTRINOS AT FERMILAB

MiniBooNE

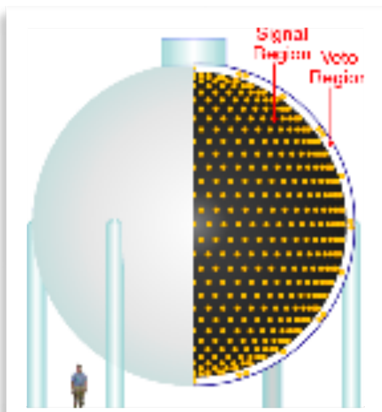


SHORT-BASELINE NEUTRINOS AT FERMILAB



MiniBooNE

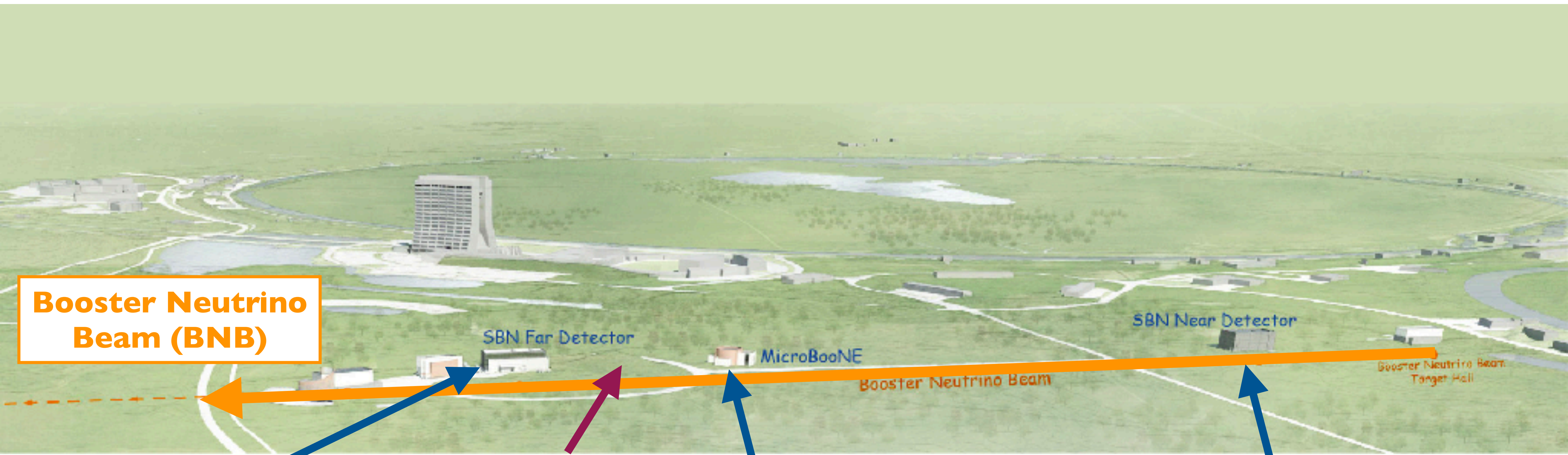
500m



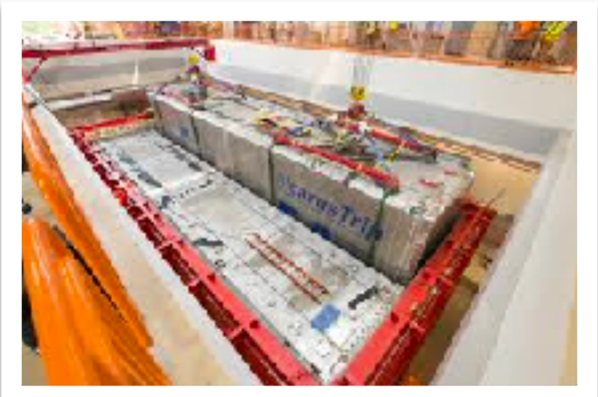
MicroBooNE

470m

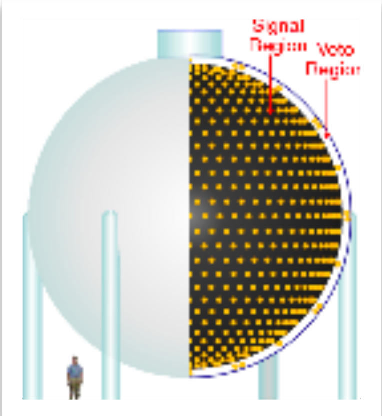
SHORT-BASELINE NEUTRINOS AT FERMILAB



ICARUS

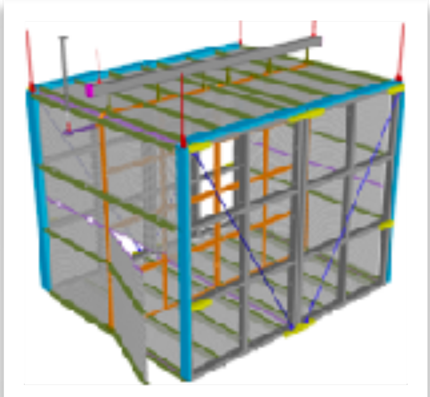


MiniBooNE



MicroBooNE

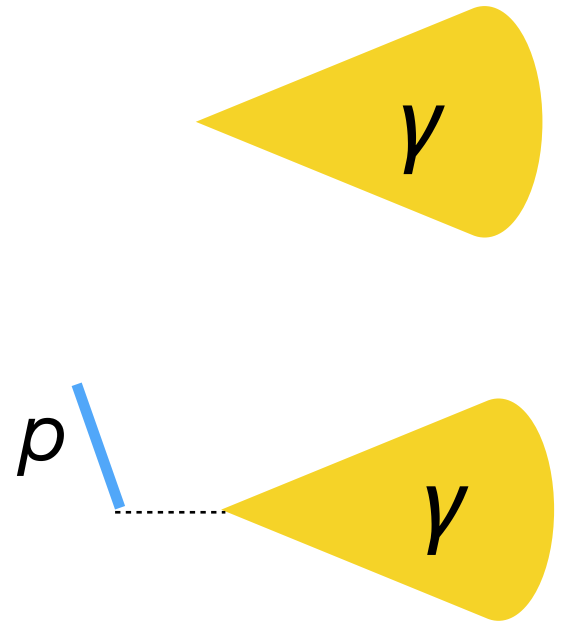
SBND



OUR SELECTIONS

Photon search

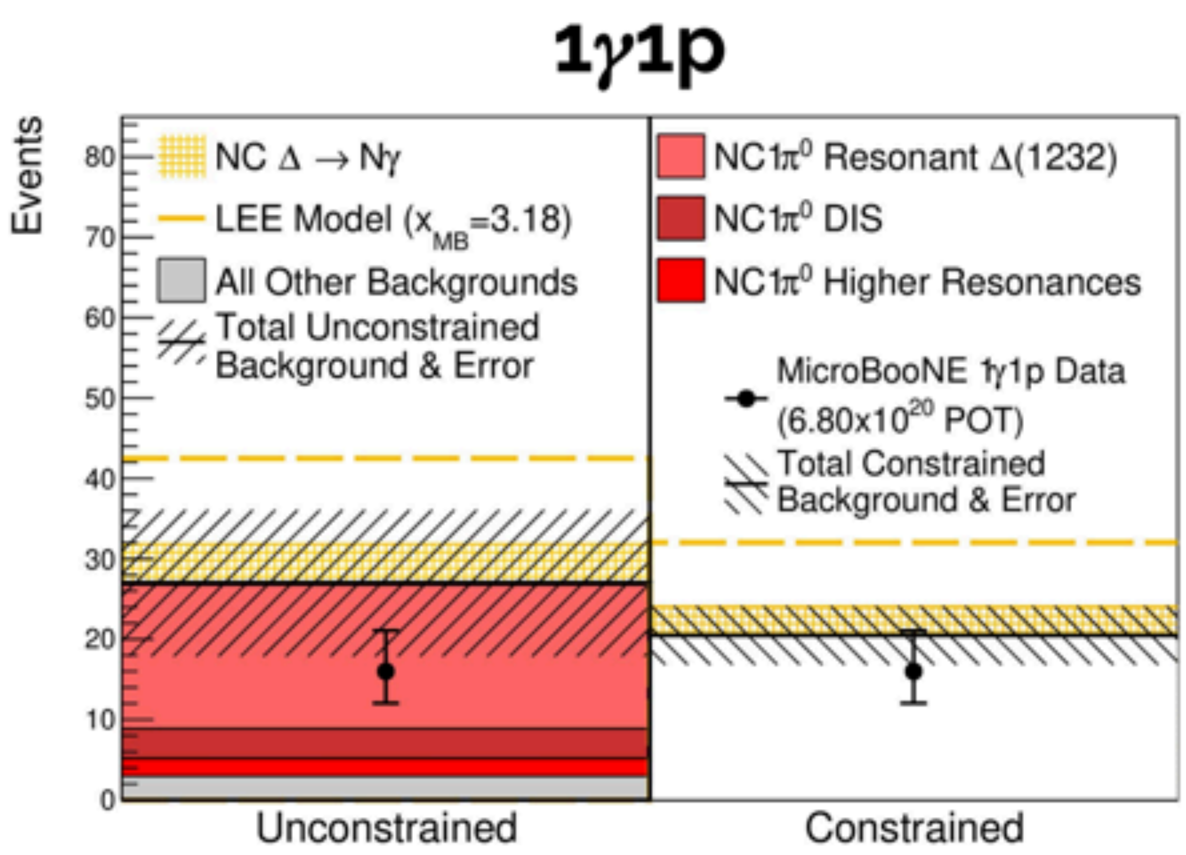
Target Δ→Nɣ:
1ɣ0p and 1ɣ1p



arXiv:2110.00409 [hep-ex]

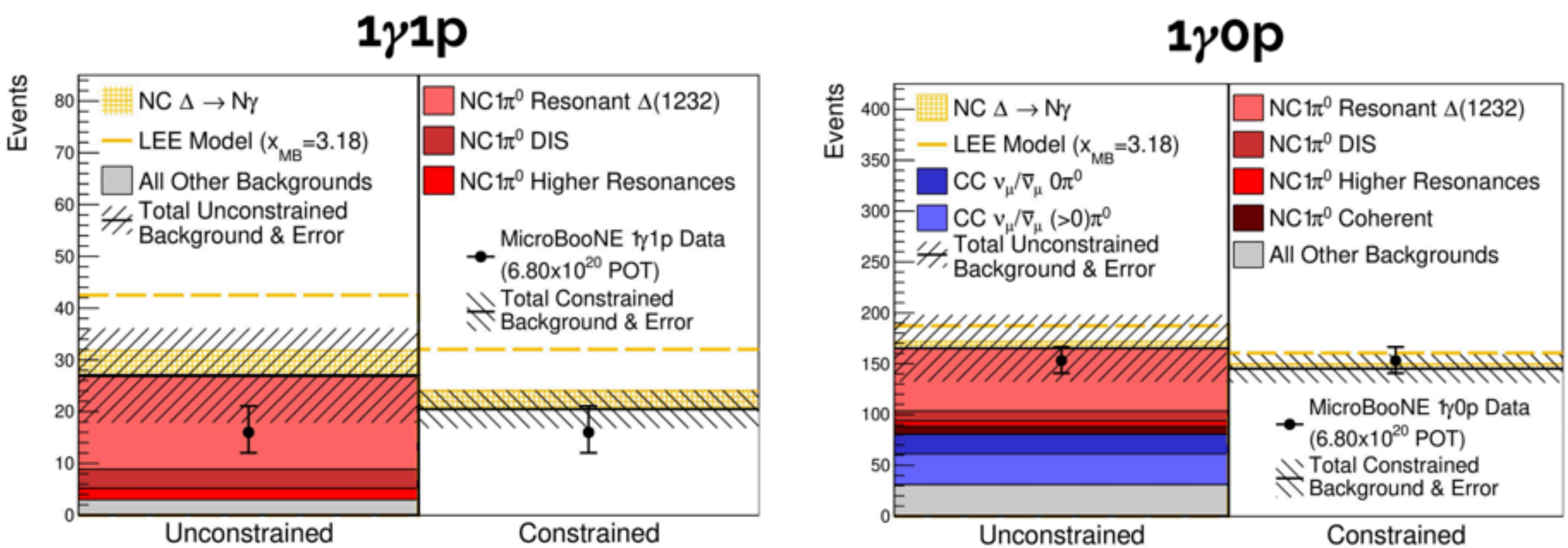
SINGLE PHOTON SEARCH

arXiv:2110.00409 [hep-ex]



SINGLE PHOTON SEARCH

arXiv:2110.00409 [hep-ex]



No evidence of an excess in either sample

SINGLE PHOTON SEARCH

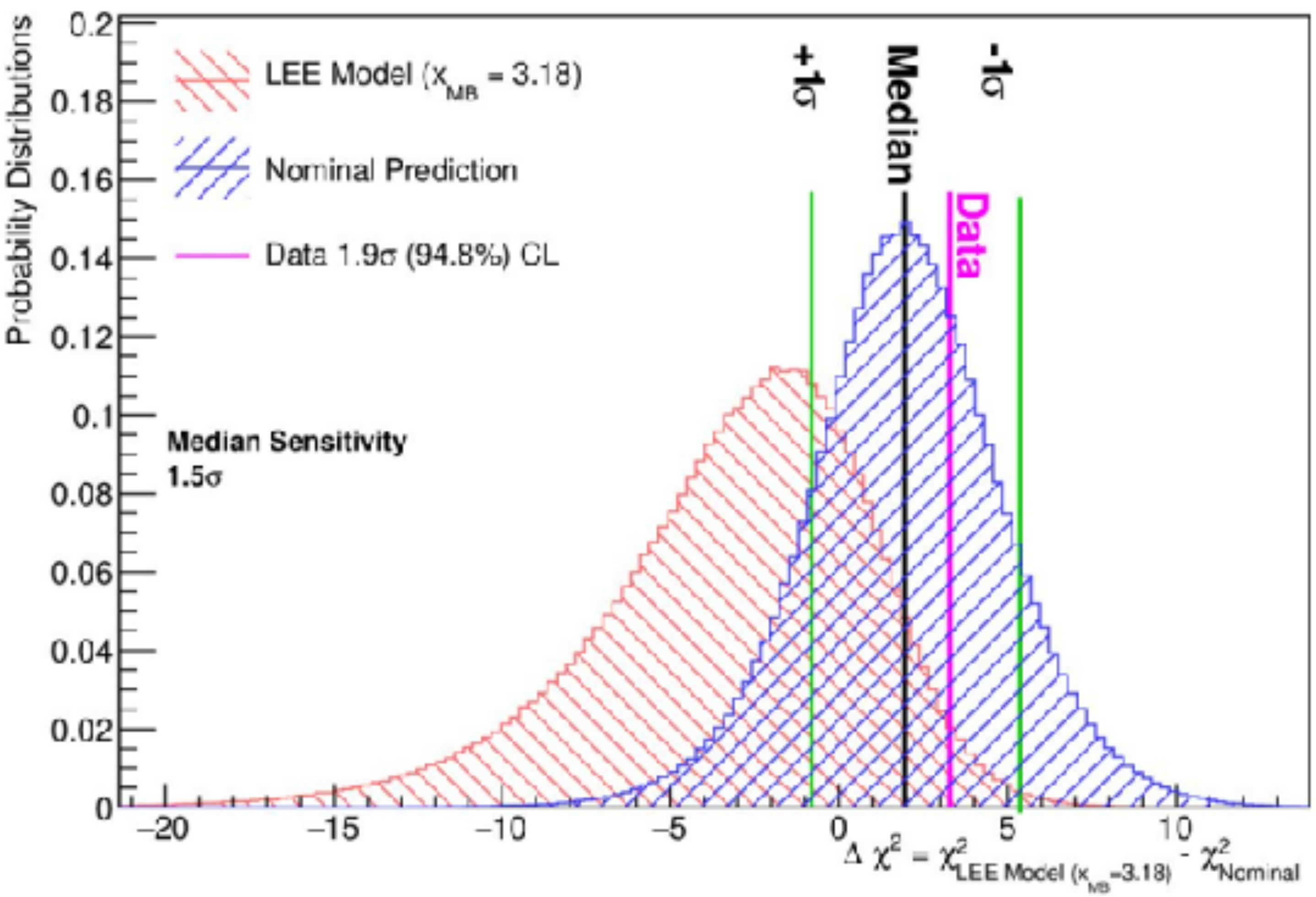
arXiv:2110.00409 [hep-ex]

- Simple hypothesis test: use combined Neyman-Pearson χ^2 as test statistic

Nucl. Inst. Meth. A 961 (2020) 163677

- Data consistent with nominal $\Delta \rightarrow N\gamma$ prediction

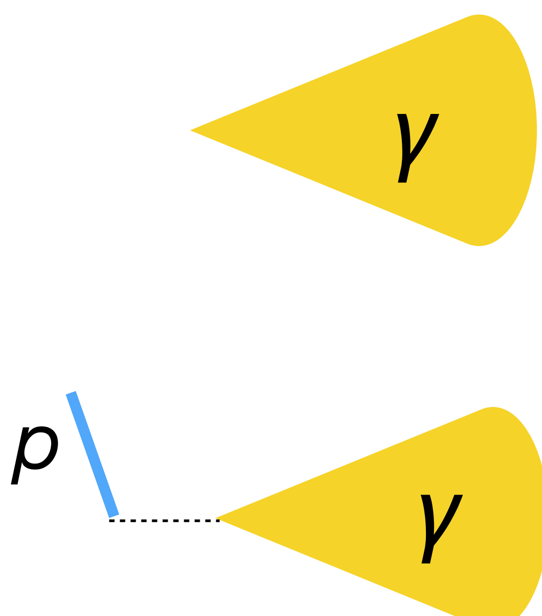
- Data **rejects LEE model hypothesis** in favour of nominal prediction at **94.8% CL**



OUR SELECTIONS

Photon search

Target $\Delta \rightarrow N\gamma$:
$1\gamma0p$ and $1\gamma1p$

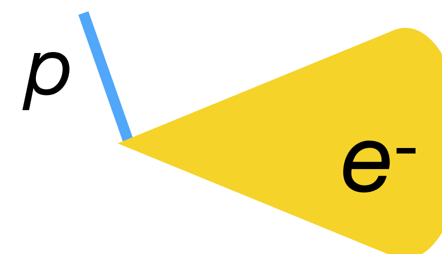


arXiv:2110.00409 [hep-ex]

Electron searches

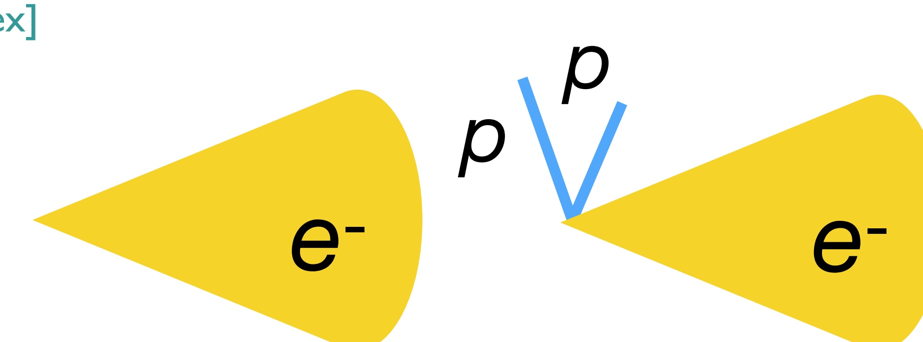
arXiv:2110.14080 [hep-ex]

CCQE-like:
1e1p



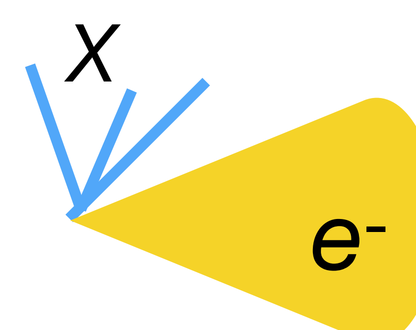
arXiv:2110.14065 [hep-ex]

CC0π:
1e0p and
1eNp



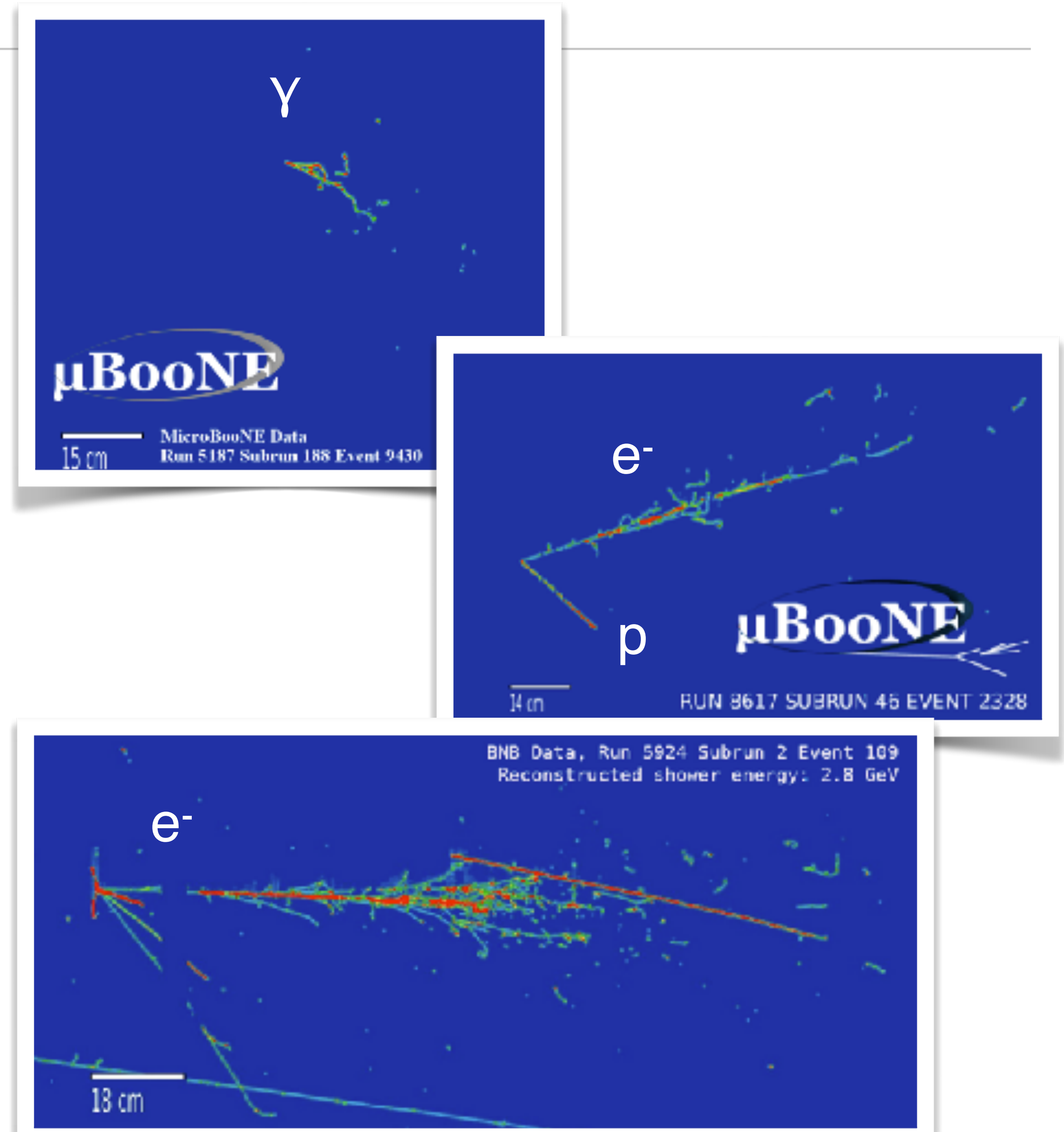
arXiv:2110.13978 [hep-ex]

Inclusive:
1eX



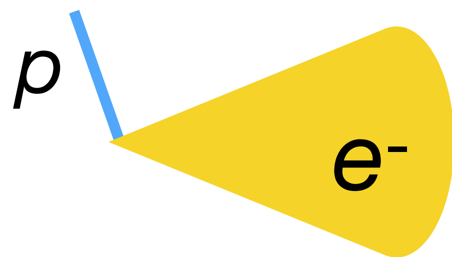
A NOTE ON NEUTRINO ENERGY

- Each analysis selects **different combinations of particles**
- Each analysis uses a **different reconstruction paradigm**
- Electron-search results presented as a function of reconstructed neutrino energy
  - Remember we have to estimate neutrino energy from the particles we measure
  - → reconstructed neutrino energy != true neutrino energy
  - → AND **reco→true mapping is different between analyses**



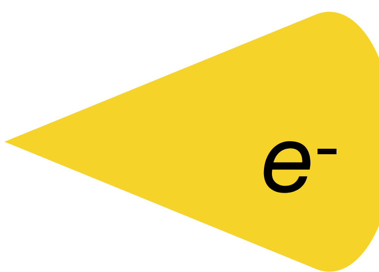
ν_e SEARCH

1e1p



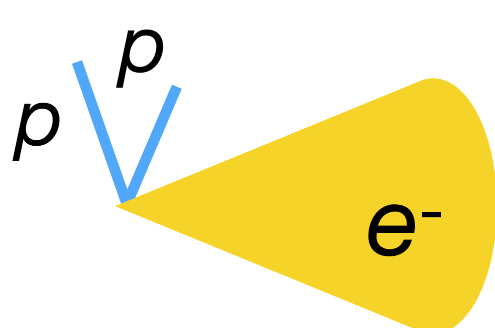
arXiv:2110.14080 [hep-ex]

1e0p



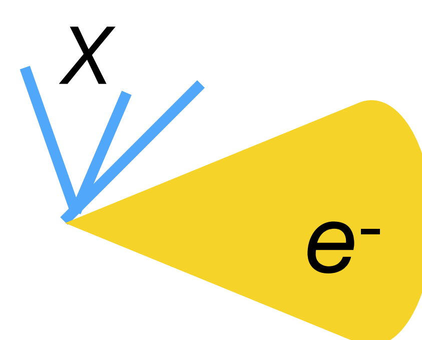
arXiv:2110.14065 [hep-ex]

1eNp



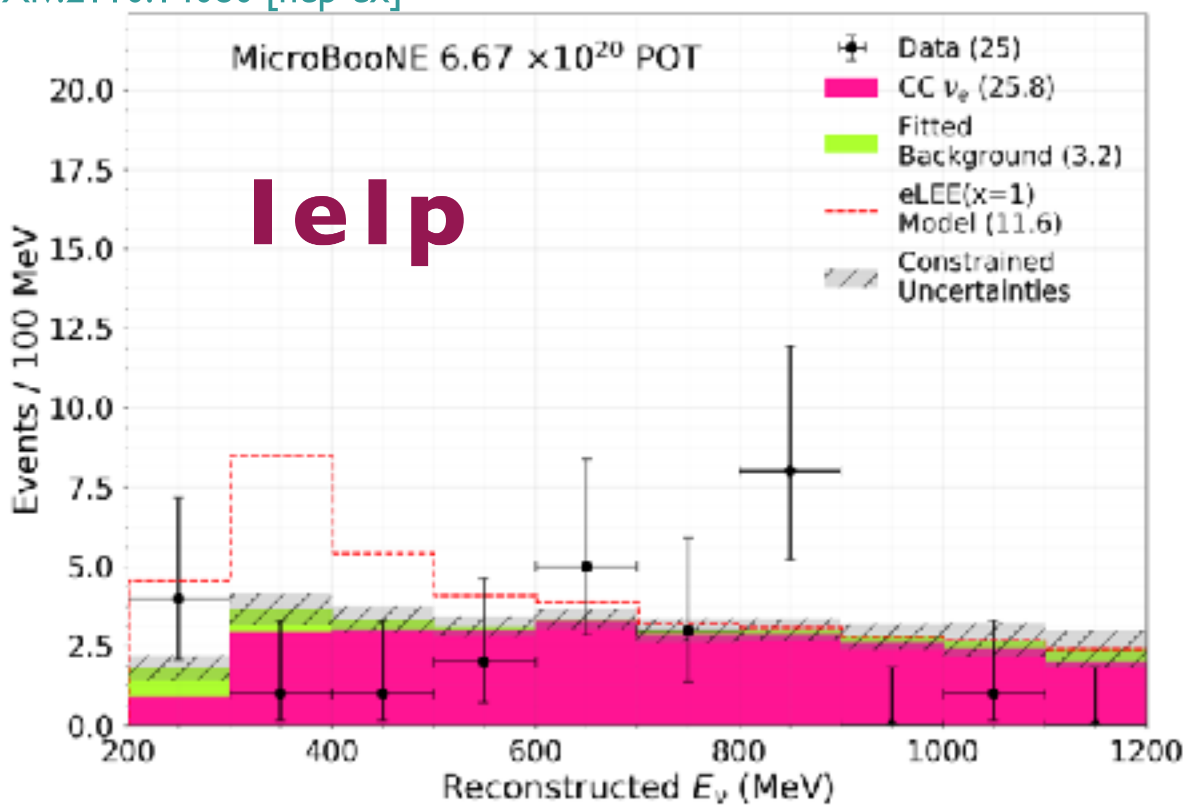
arXiv:2110.14065 [hep-ex]

1eX

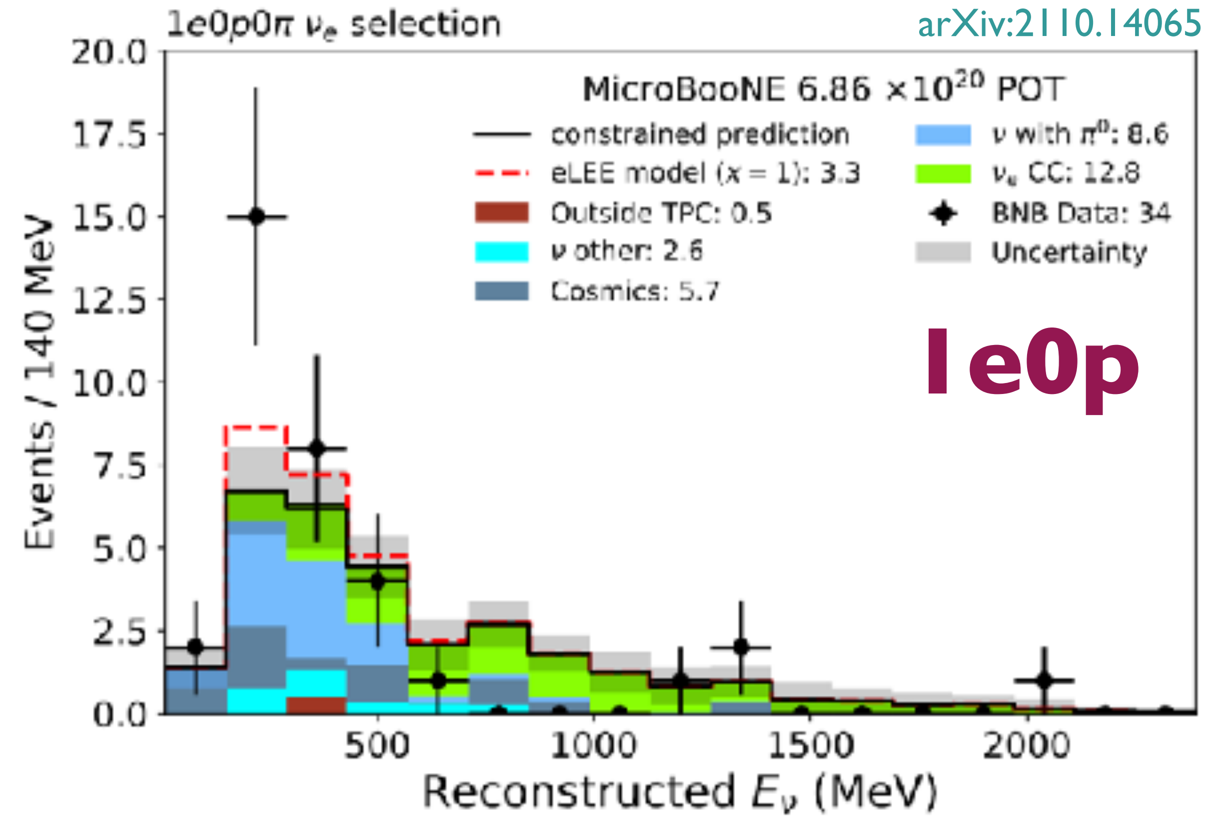


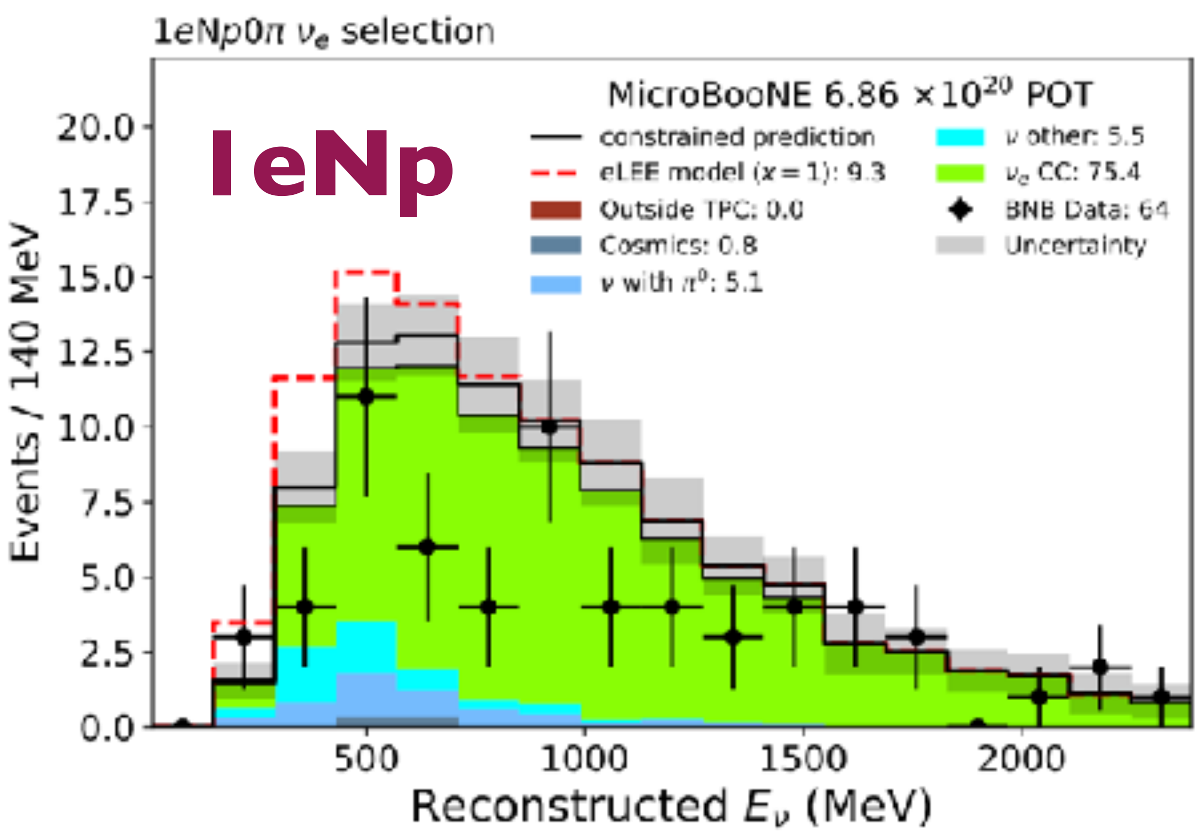
arXiv:2110.13978 [hep-ex]

arXiv:2110.14080 [hep-ex]

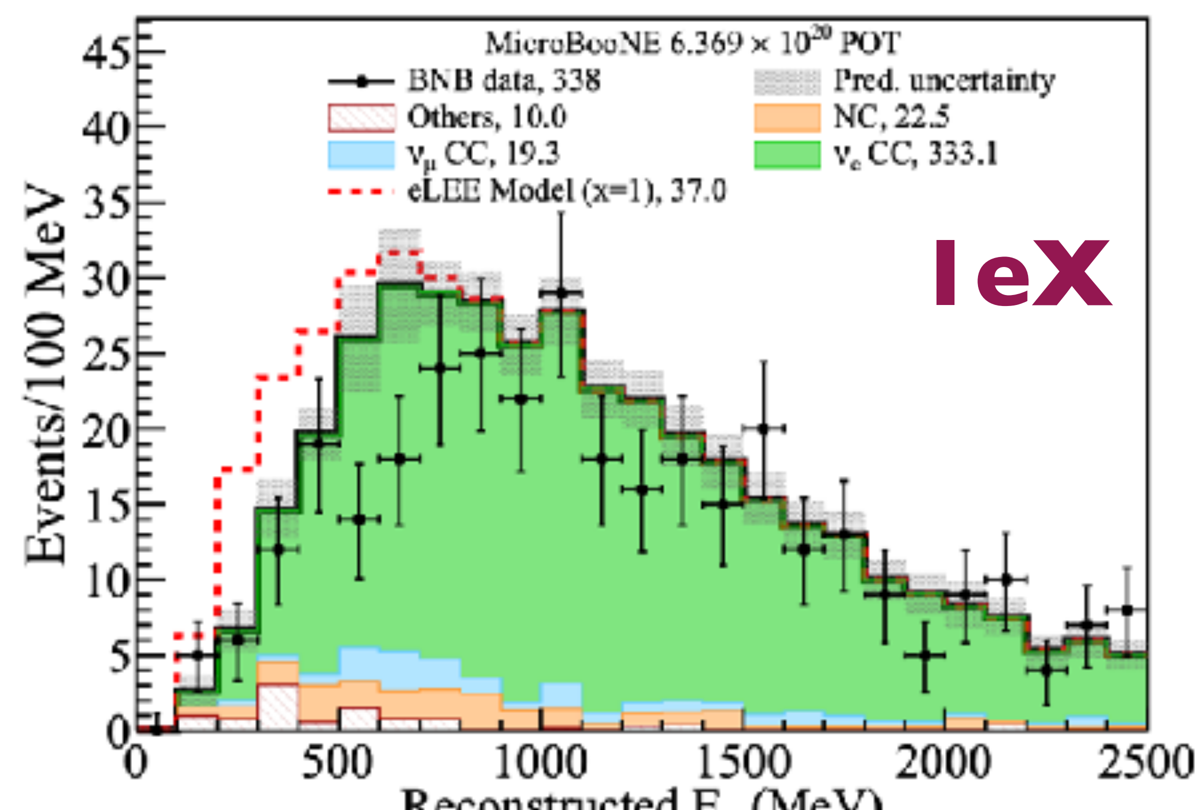


arXiv:2110.14065 [hep-ex]

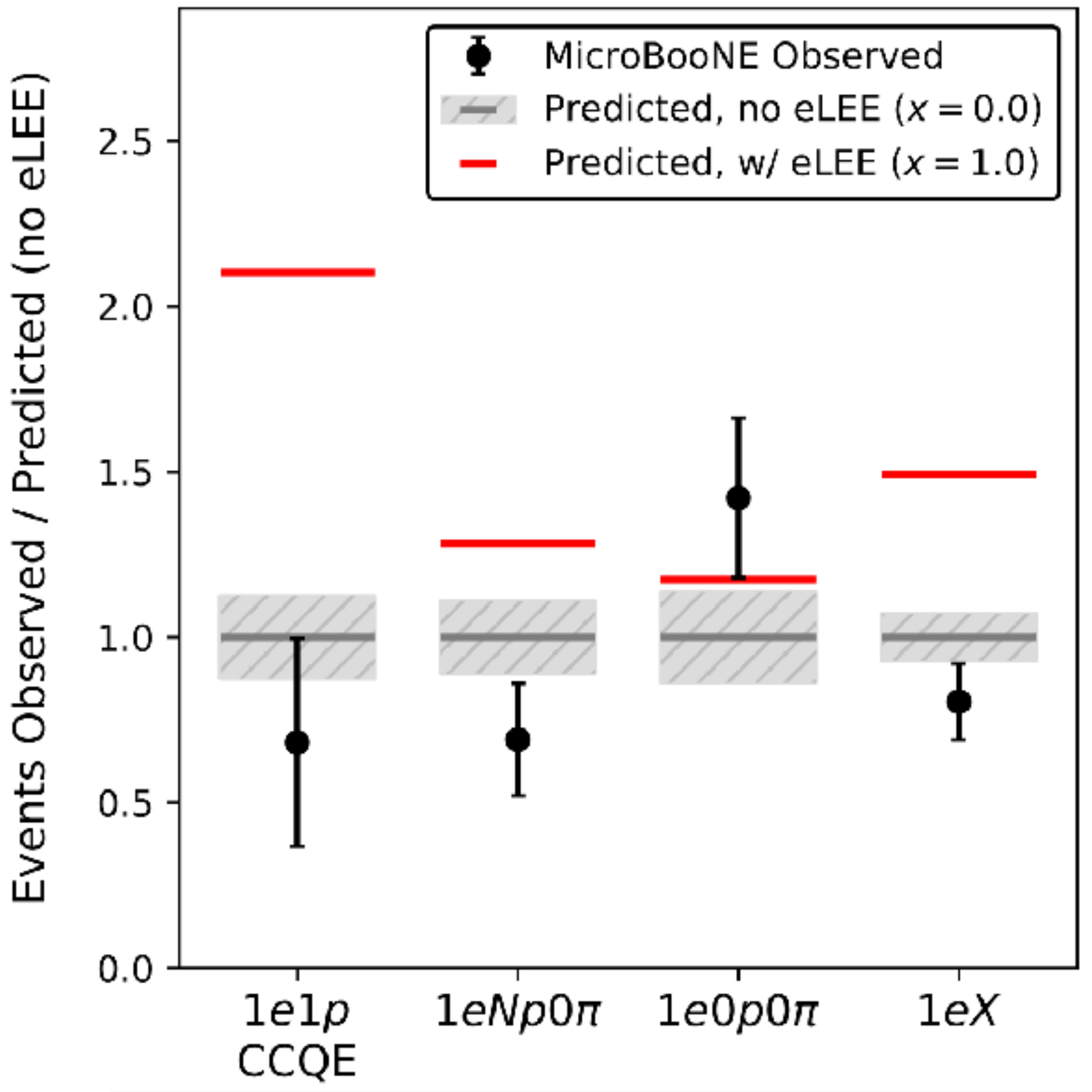




arXiv:2110.14065 [hep-ex]



arXiv:2110.13978 [hep-ex]



arXiv:2110.14054 [hep-ex]

INTERPRETATIONS

These slides heavily inspired by
P. Machado, Fermilab PAC, November 2021

EVOLVING THEORY LANDSCAPE

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

Produces True Electrons

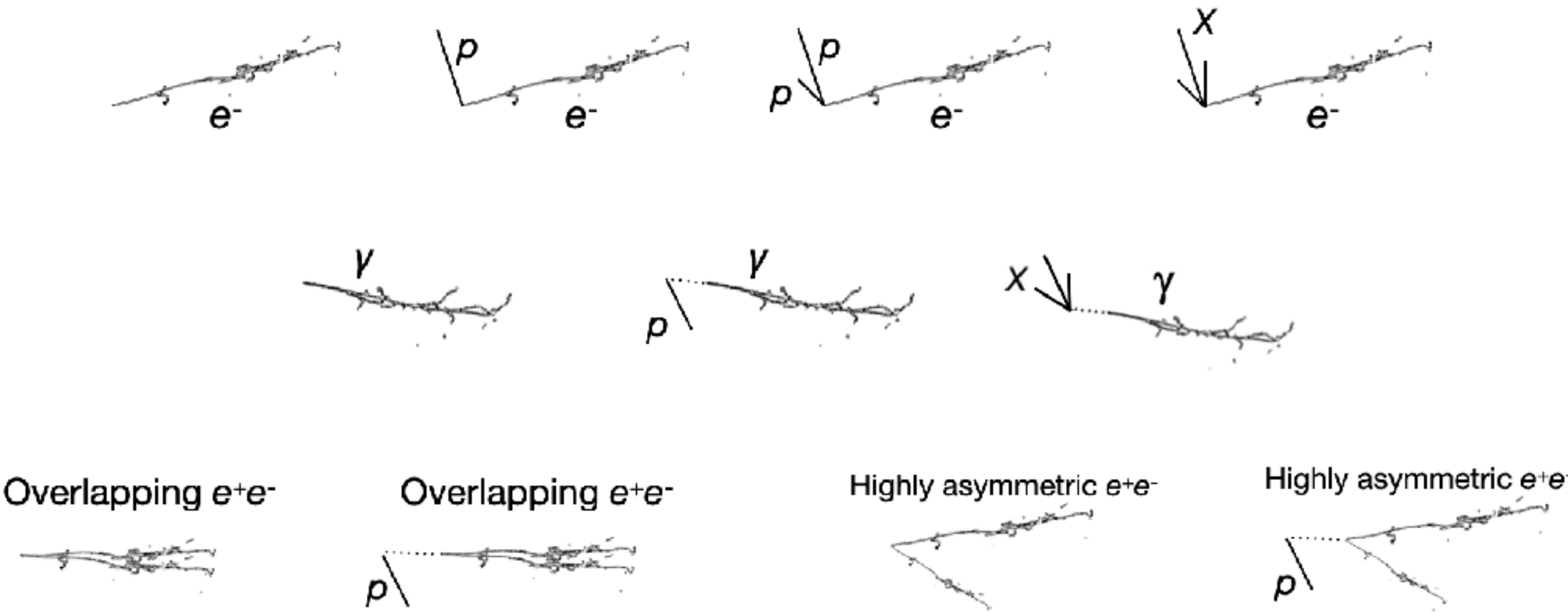
Produces True Photons

Produces e^+e^- pairs

Caution: not an exhaustive list!

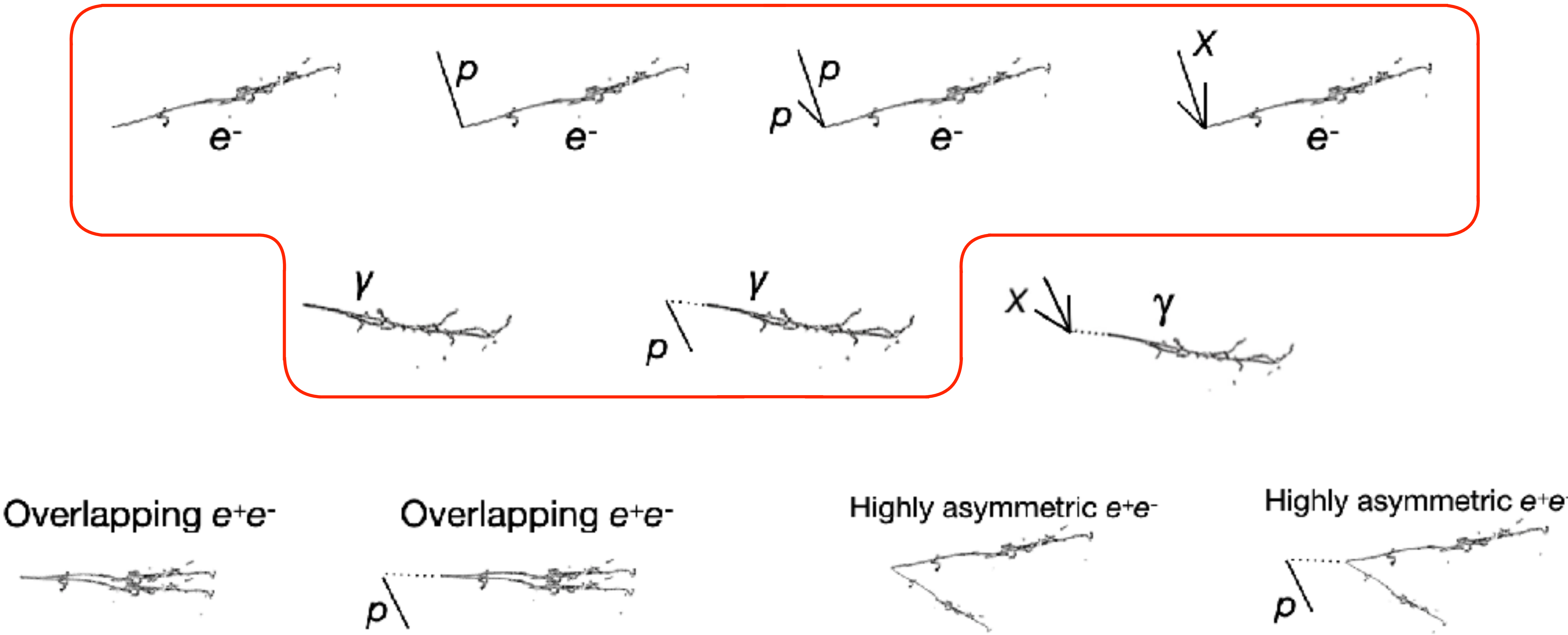
This is meant to be representative only

LANDSCAPE OF POSSIBLE TOPOLOGIES



LANDSCAPE OF POSSIBLE TOPOLOGIES

MicroBooNE's first LEE results



EXPLORATION OF THE MINIBOONE EXCESS

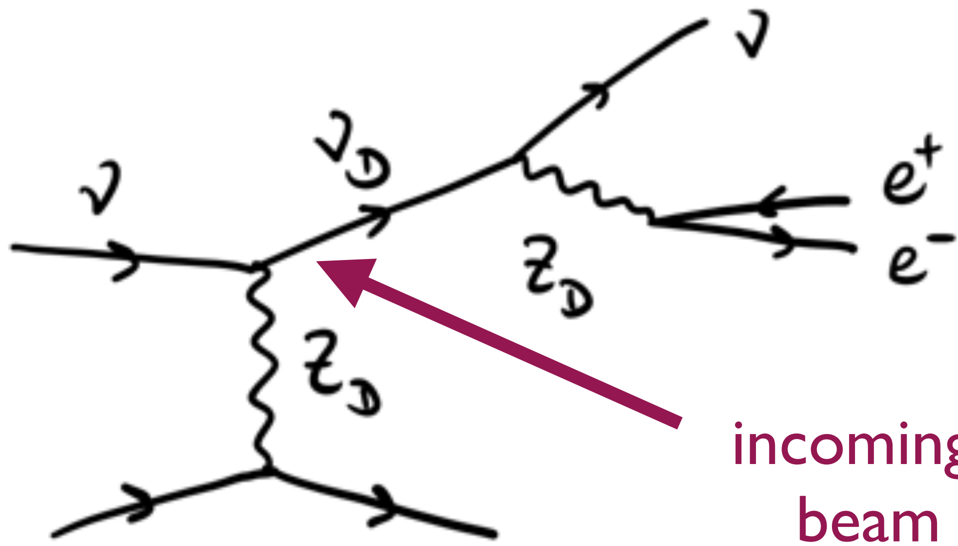
First series of results (1/2 the MicroBooNE data set)

Models \ Reco topology	1e0p	1e1p	1eNp	1eX	e^+e^- + nothing	e^+e^-X	$1\gamma0p$	$1\gamma1p$	$1\gamma X$
eV Sterile ν Osc	✔	✔	✔	✔					
Mixed Osc + Sterile ν	✔ [7]	✔ [7]	✔ [7]	✔ [7]			✔ [7]		
Sterile ν Decay	✔ [13,14]	✔ [13,14]	✔ [13.14]	✔ [13,14]			✔ [4,11,12,15]	✔ [4]	✔ [4]
Dark Sector & Z' *	✔ [2,3]				✔ [2,3]	✔ [2,3]	✔ [1,2,3]	✔ [1,2,3]	✔ [1,2,3]
More complex higgs *					✔ [10]	✔ [10]	✔ [6,10]	✔ [6,10]	✔ [6,10]
Axion-like particle *					✔ [8]		✔ [8]		
Res matter effects	✔ [5]	✔ [5]	✔ [5]	✔ [5]					
SM γ production							✔	✔	✔

*Requires heavy sterile/other new particles also

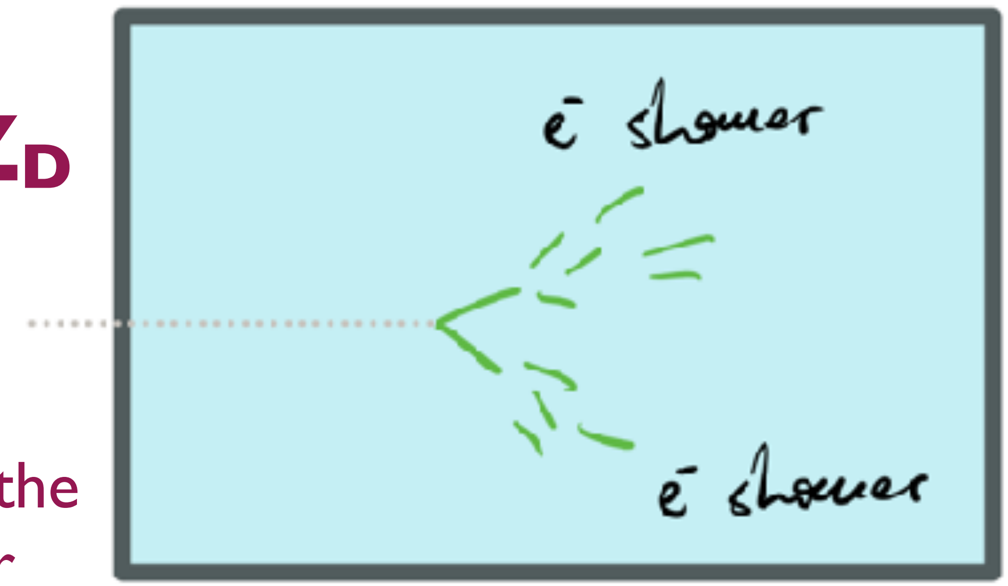
DARK NEUTRINOS

Ballett, Pascoli, Ross-Lonergan PRD 2019
Ballett, Hostert, Pascoli PRD 2020
Bertuzzo, Jana, Machado, Zukanovich PRL 2018
Bertuzzo, Jana, Machado, Zukanovich PLB 2019
Arguelles, Hostert, Tsai PRL 2019

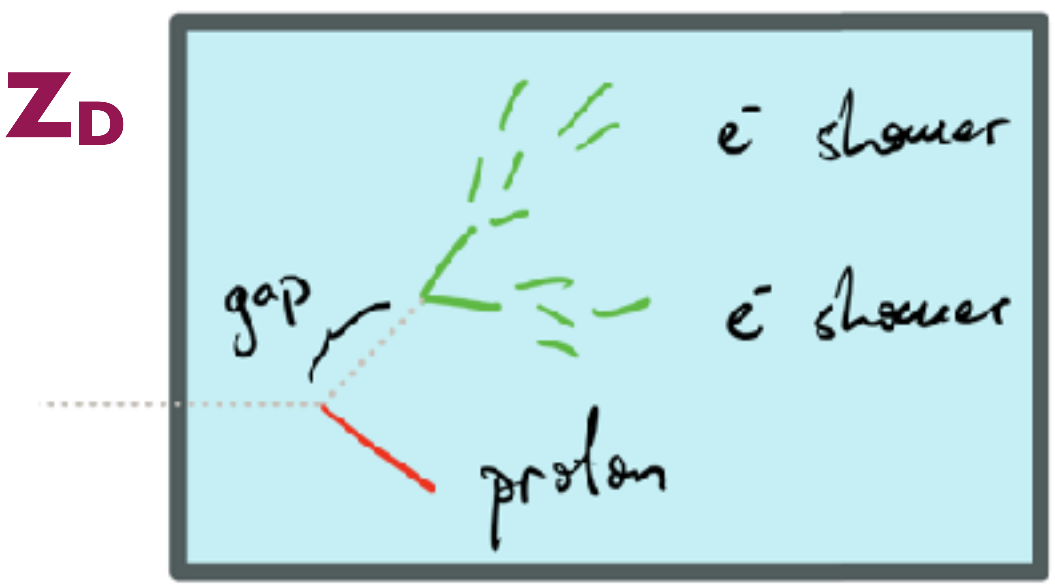


incoming neutrinos from the beam scatter/up-scatter inside the detector

Light Z_D



Heavy Z_D



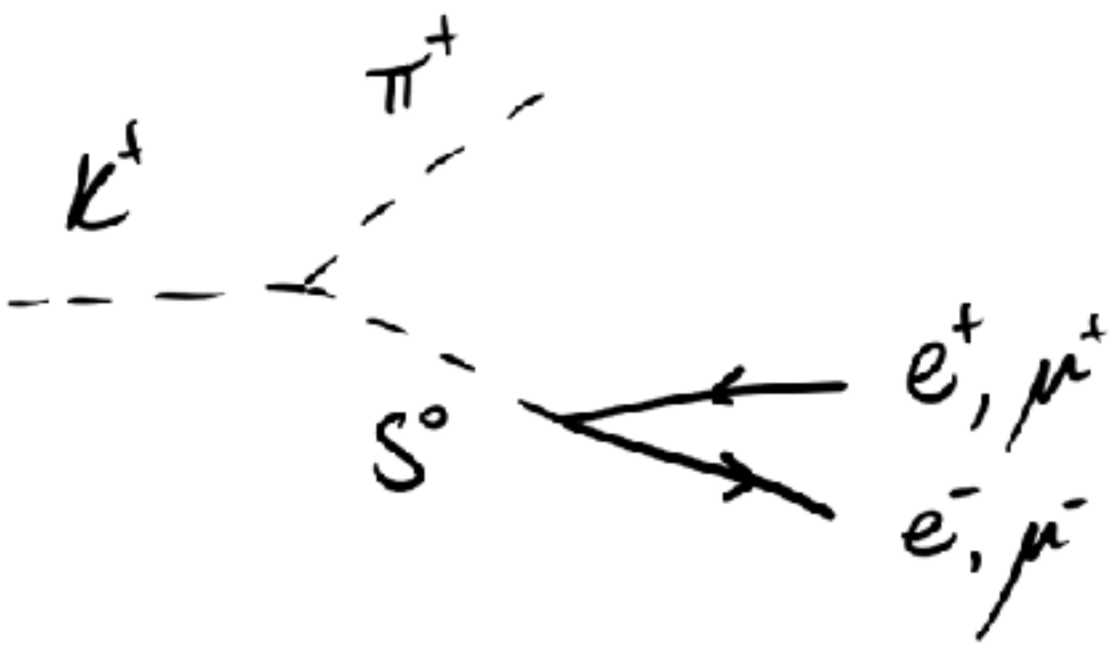
Motivation:

- Origin of neutrino masses
- Dark sector portal
- Fit to MiniBooNE energy and angular spectrum

HIGGS PORTAL SCALARS

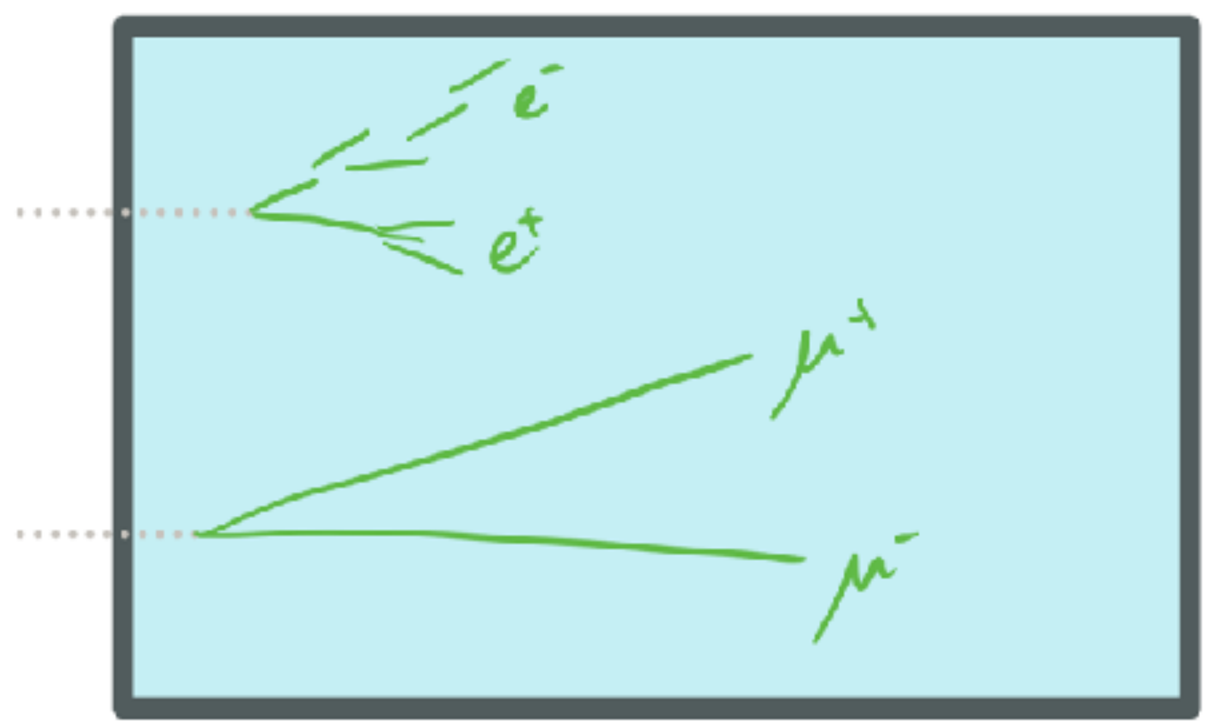
Batell, Berger, Ismail PRD 2019

Patt, Wilczek 2006



Experimental signature:

- No hadronic activity
- e^+e^- or $\mu^+\mu^-$
- Invariant mass

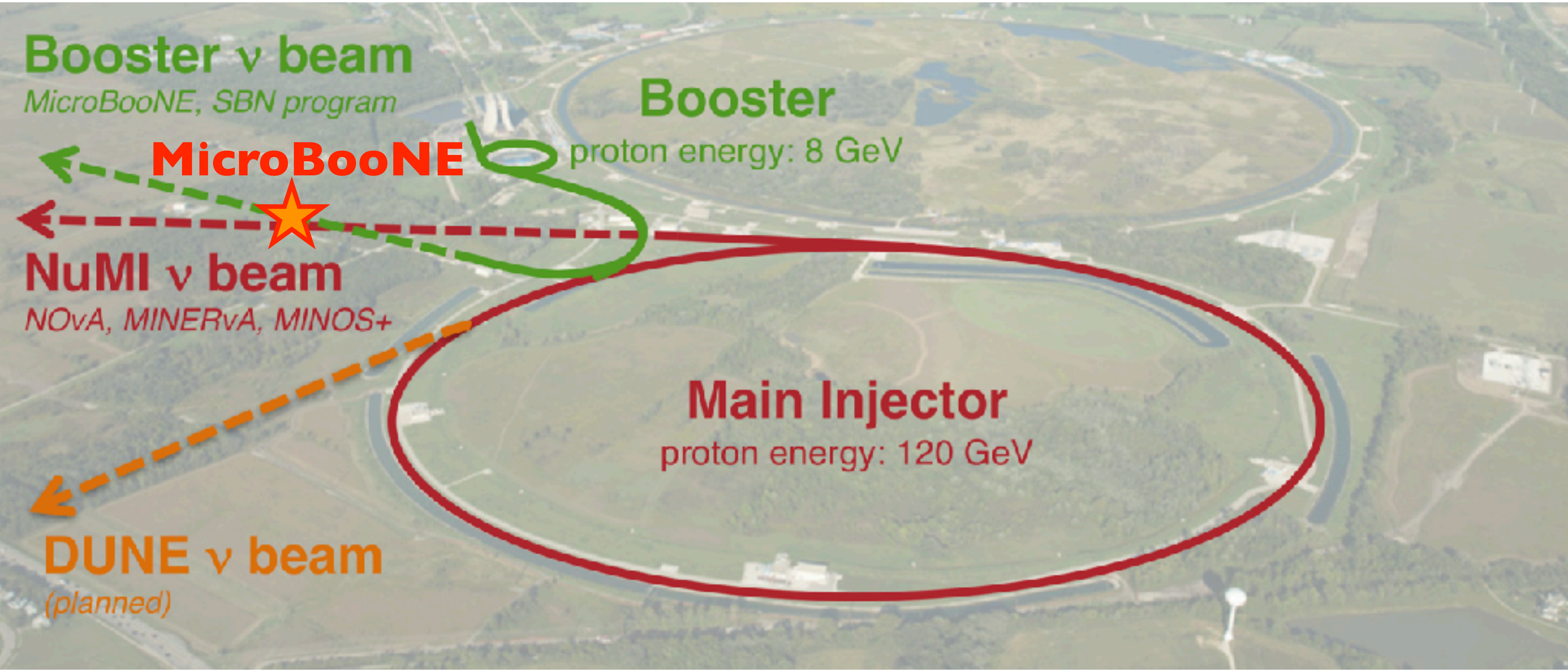


Motivation:

- Portal to dark sector
- Connection to Higgs sector
- Experimental synergy with HNL search

MICROBOONE'S HIGGS PORTAL SCALARS SEARCH

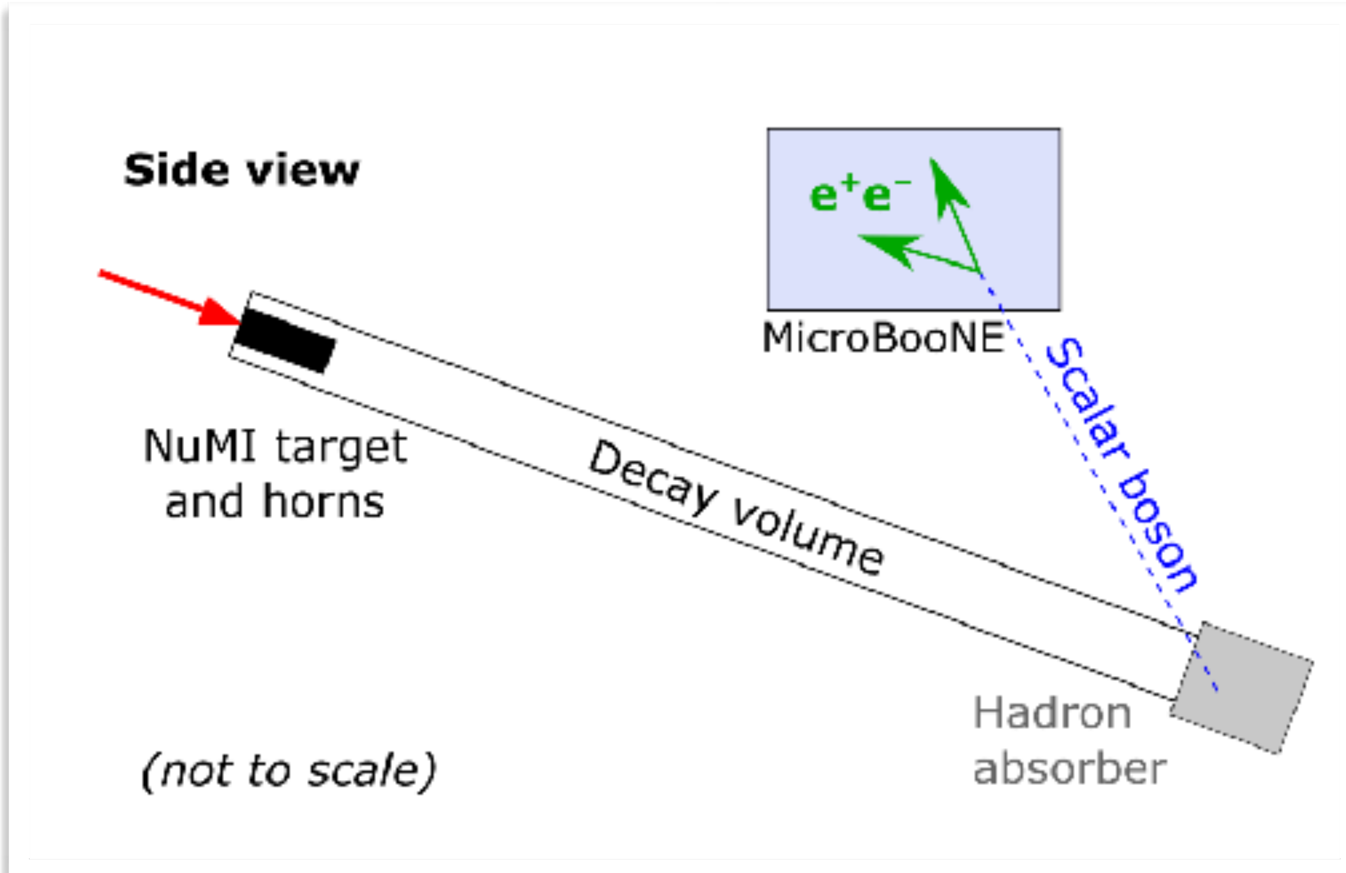
Phys. Rev. D 101, 052001 (2020)



MICROBOONE'S HIGGS PORTAL SCALARS SEARCH

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

- Motivated by KOTO anomaly:
  - In 2019 KOTO collaboration reported four $K^0_L \rightarrow \pi^0 \nu\bar{\nu}$ + invisible decay candidates
  - 2 orders of magnitude above standard model $K^0_L \rightarrow \pi^0 \nu\bar{\nu}$ prediction
- Search for **e^+e^- decays** from **scalars coming from NuMI hadron absorber**
  - **1 event observed** → 95% C.L. excludes KOTO central value



MICROBOONE'S HIGGS PORTAL SCALARS SEARCH

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- Motivated by KOTO anomaly:
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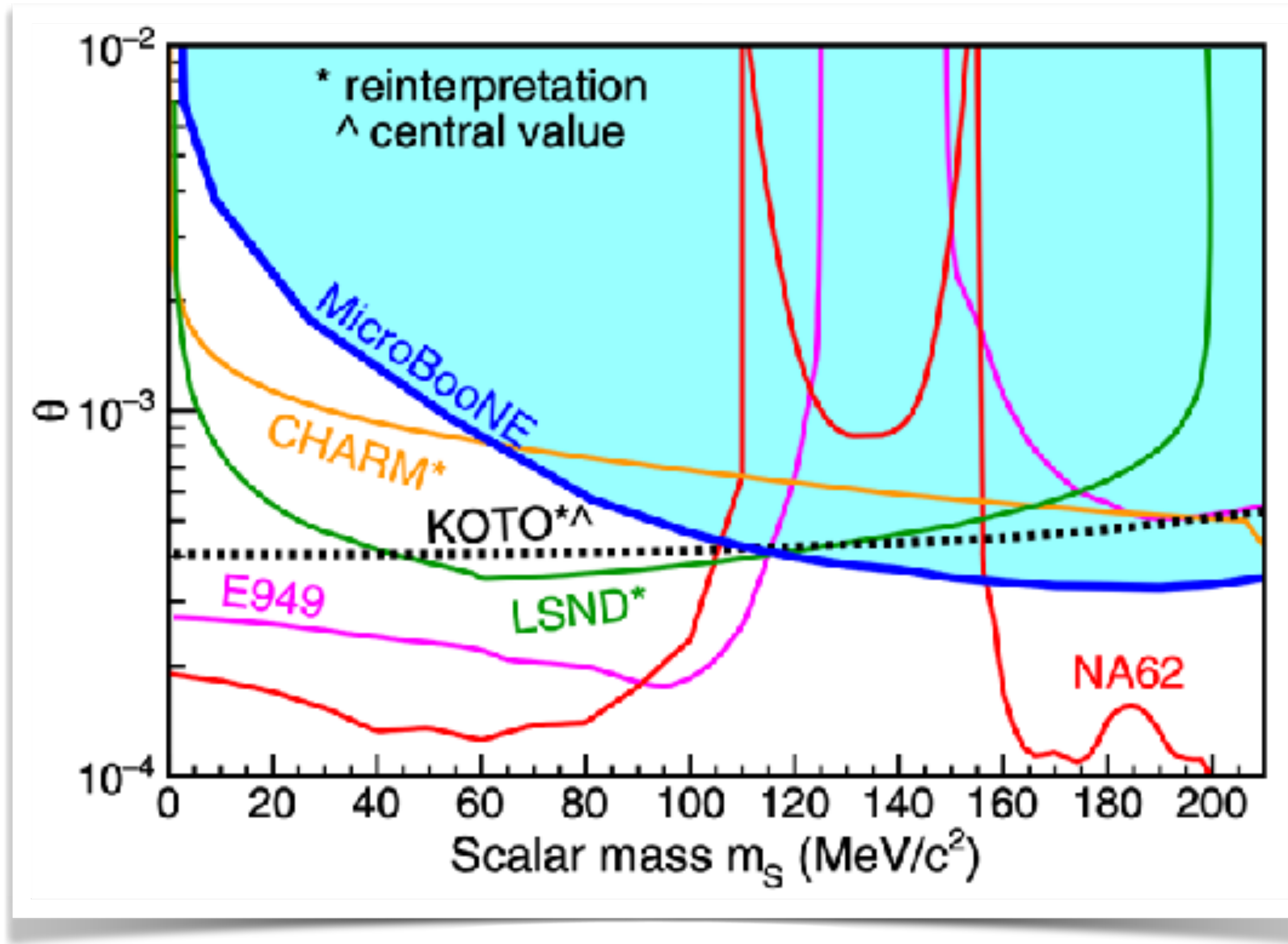
  - 2 orders of magnitude above standard model $K^0_L \to \pi^0 \nu\bar{\nu}$ prediction
- Search for **e⁺e⁻ decays** from **scalars coming from NuMI hadron absorber**
  - **1 event observed** → 95% C.L. excludes KOTO central value



Too many papers to list, but see

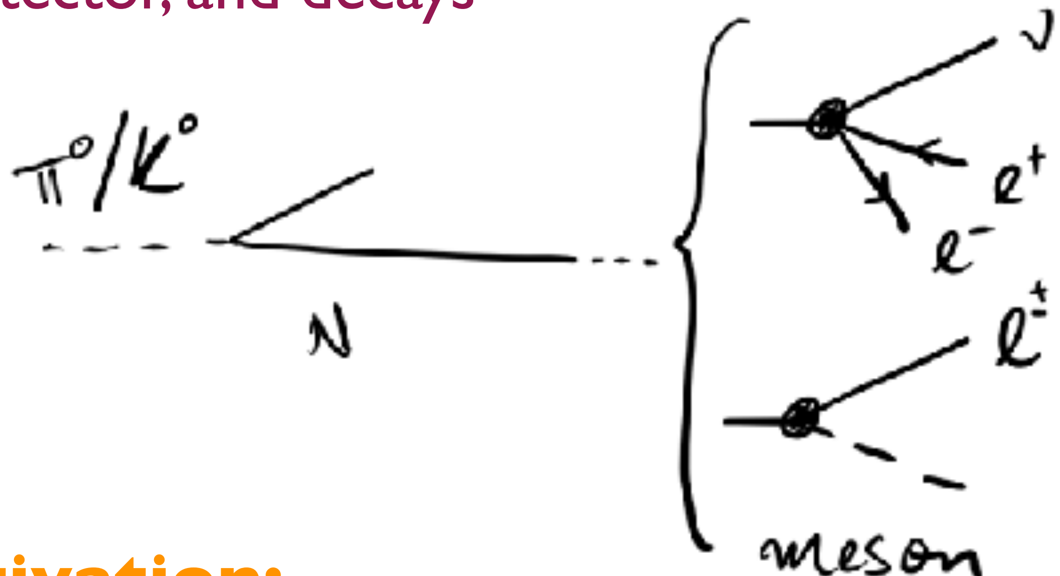
Ballett, Pascoli, Ross-Lonergan PRD 2019

Ballett, Pascoli, Ross-Lonergan JHEP 2017

Kelly, Machado PRD 2021

HEAVY NEUTRAL LEPTONS

HNL produced in beam decay pipe, propagates to detector, and decays



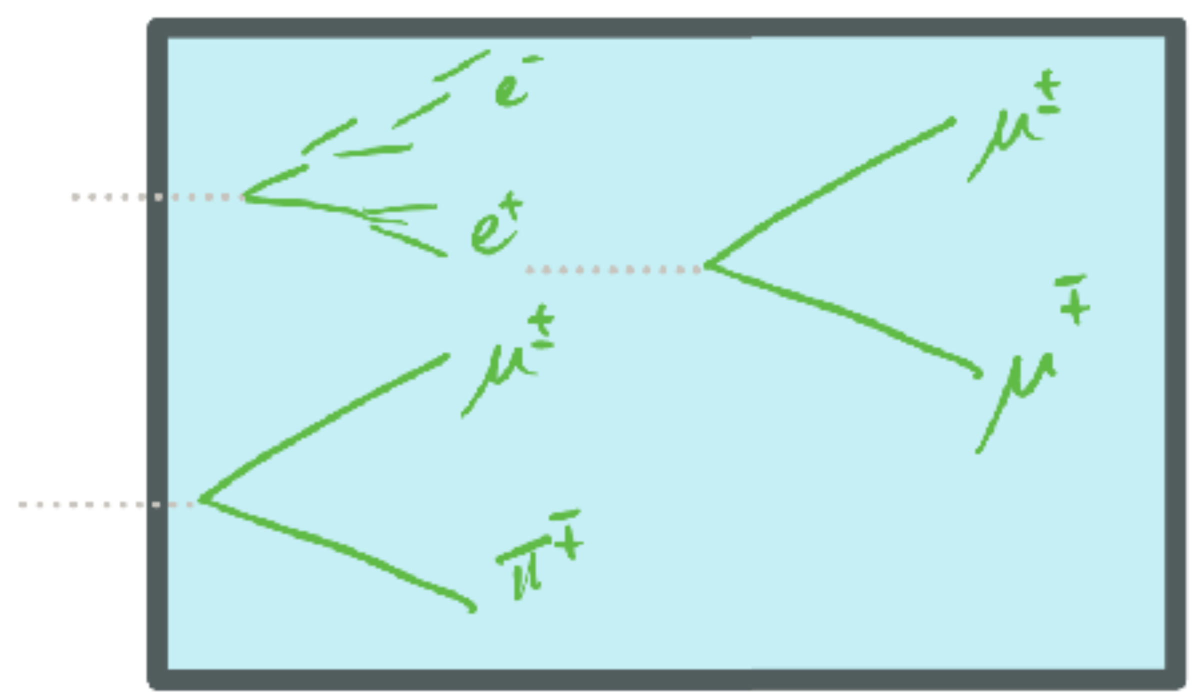
Motivation:

- Possibly related to neutrino mass
- Dirac vs Majorana nature of HNLs can be probed, if discovered

Experimental signature:

- Several possibilities
- Delayed timing w.r.t. beam neutrinos
- Reconstruct invariant mass?

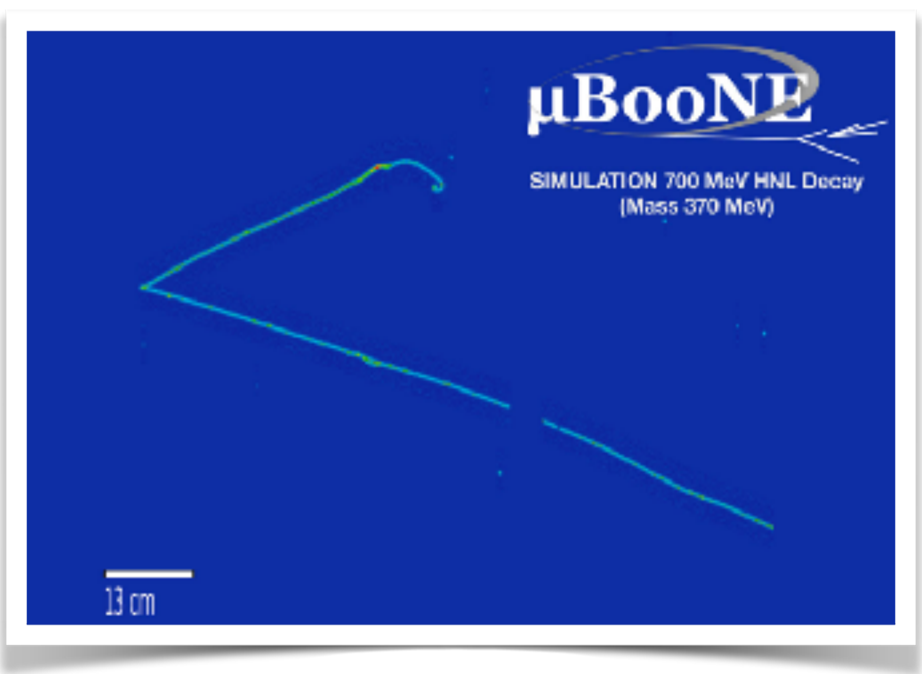
Less likely/ harder to explain mB anomaly

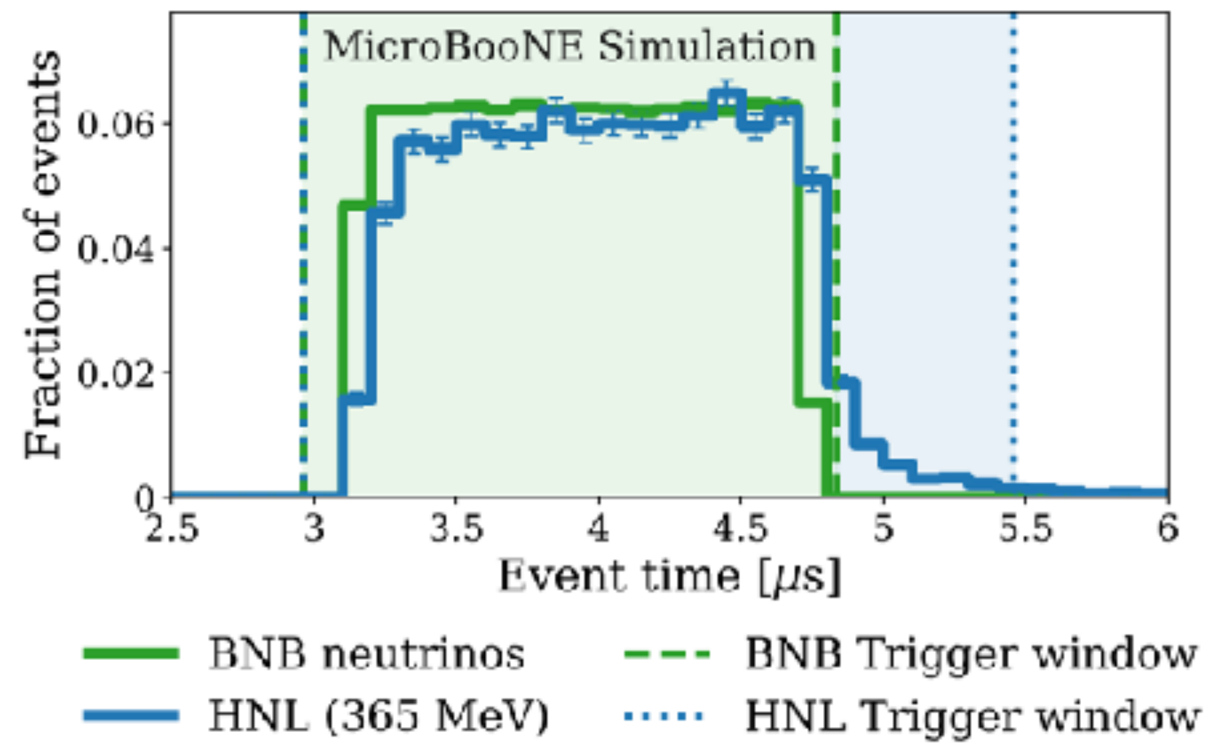


MICROBOONE'S HNL SEARCH

Phys. Rev. D 101, 052001 (2020)

- Search for HNLs decaying to μπ pairs
- Dedicated trigger configuration to detect HNL decays that occur after the neutrino beam spill

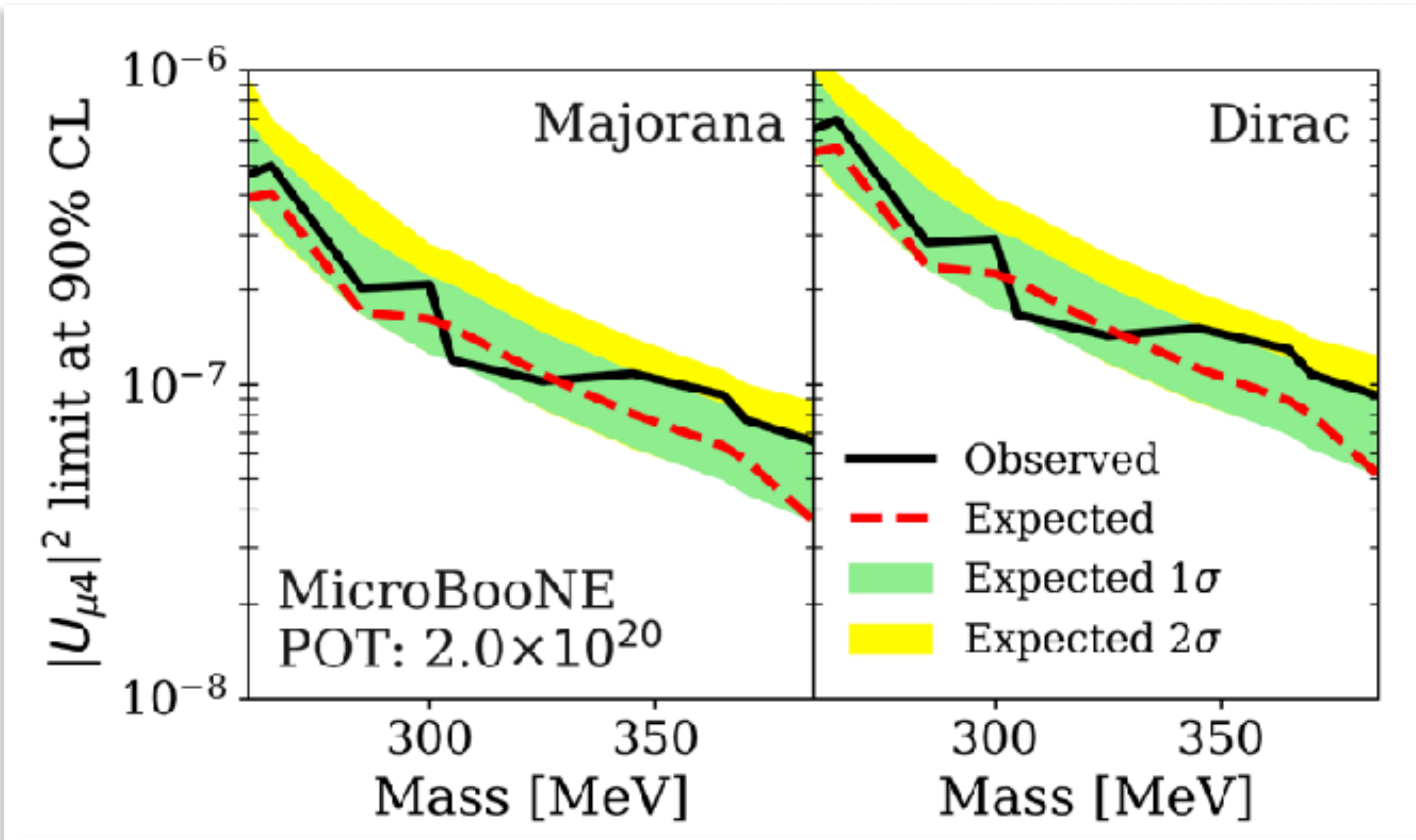




MICROBOONE'S HNL SEARCH

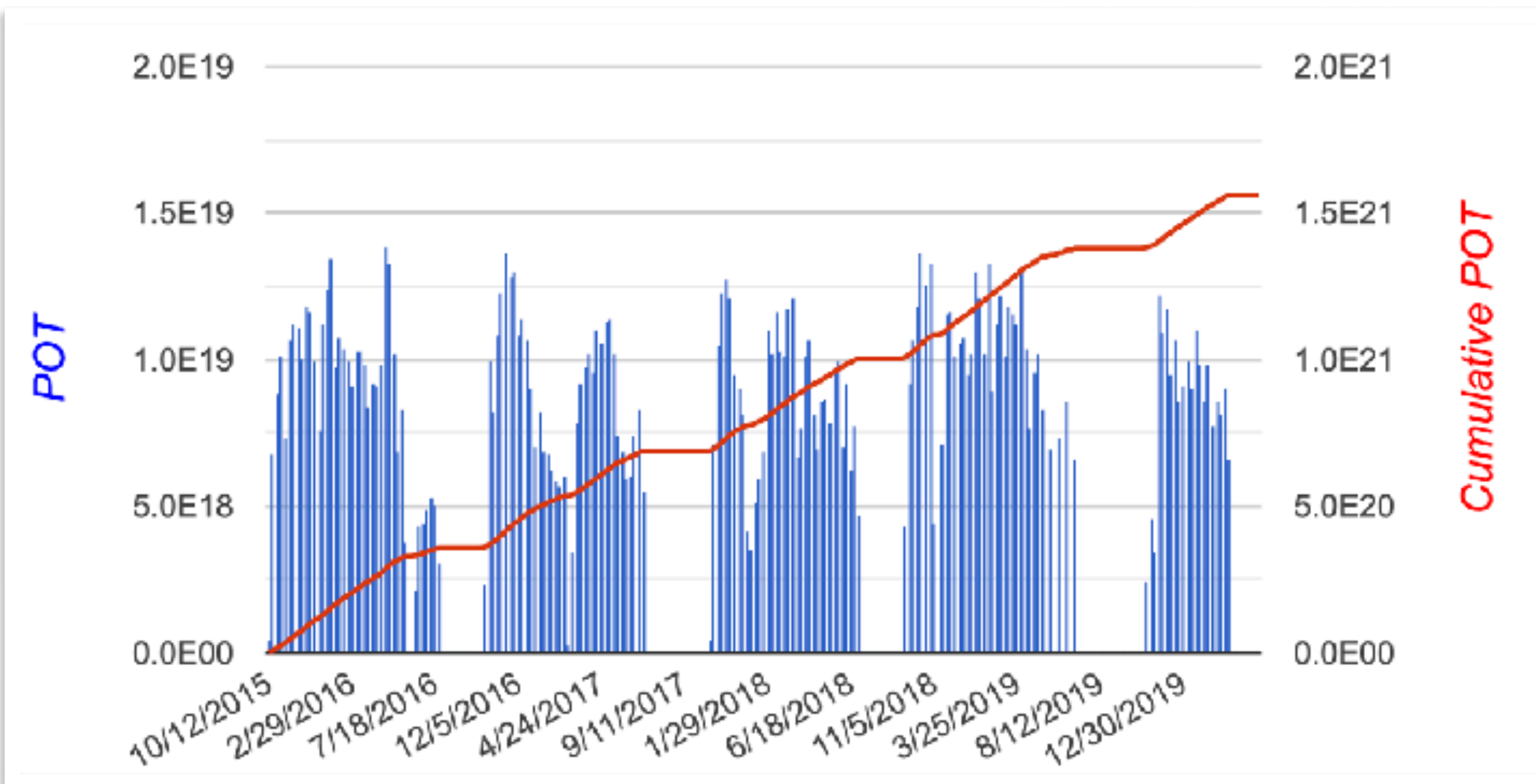
Phys. Rev. D 101, 052001 (2020)

Set upper limits on extended PMNS matrix element $|U_{\mu 4}|^2$ → most constraining experimental limits at higher masses



WHAT'S NEXT?

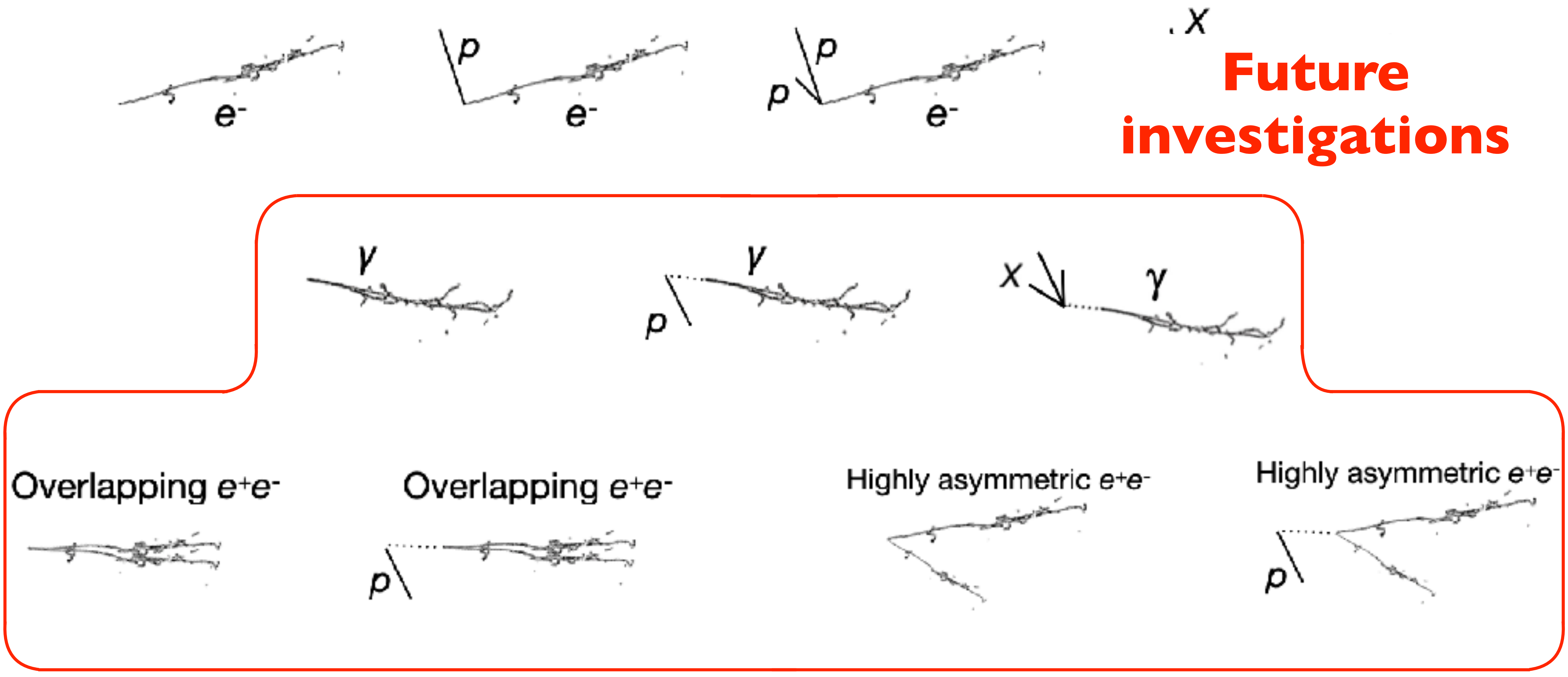
BNB Data collection: Protons on Target (POT)



Analysed ~$7x10^{20}$ POT

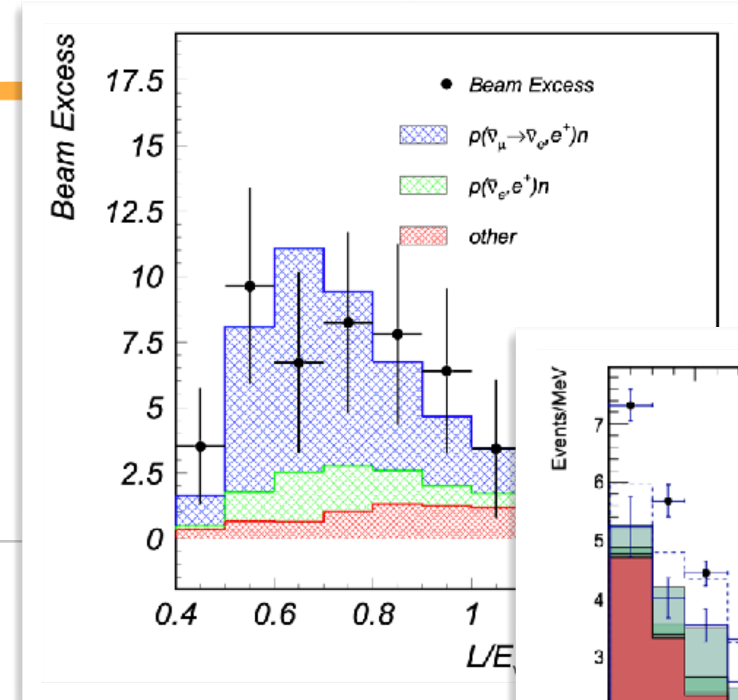
Approximately the same again still to come!

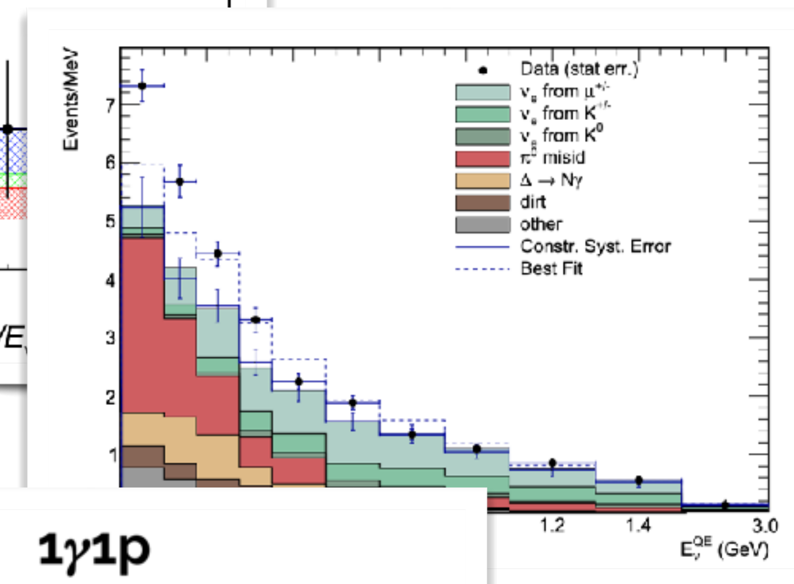
WHAT'S NEXT?

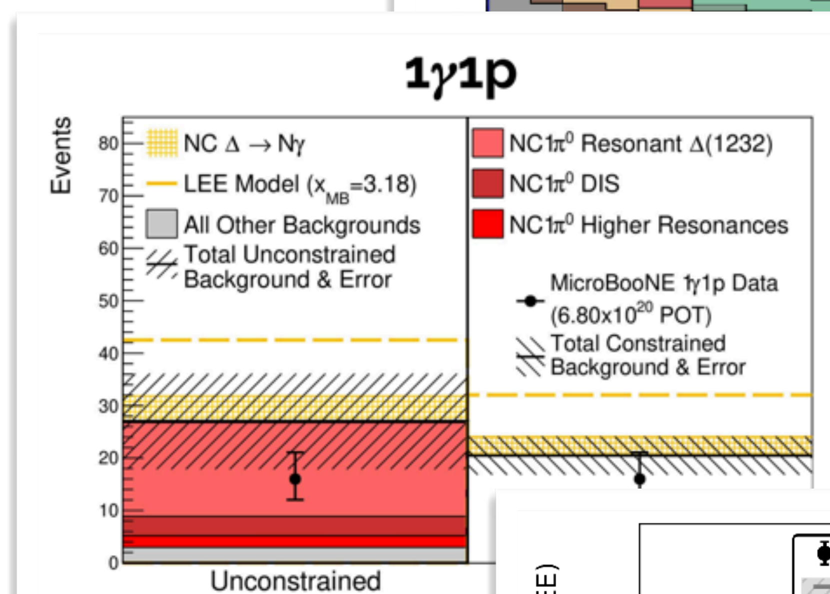

e-
p
e-
p
p
e-
. X
Future investigations
γ
γ
p
X
γ
Overlapping e+e-
Overlapping e+e-
p
Highly asymmetric e+e-
Highly asymmetric e+e-
p

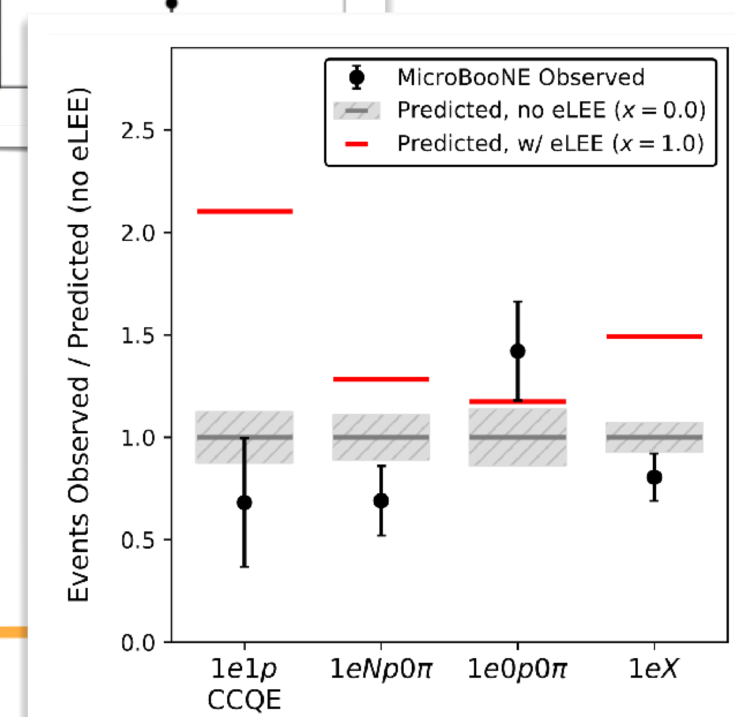
SUMMARY

- A number of **anomalies** exist that can't be explained in the 3-neutrino paradigm
- Could hint at interesting **new physics?**
- MicroBooNE investigation of the MiniBooNE anomaly shows no evidence for excess in **single electron** or **Δ→Nɣ single photon** samples
- **More data** (x2 data statistics), **more analyses**, and **more experiments** (SBN) will soon add to this picture!

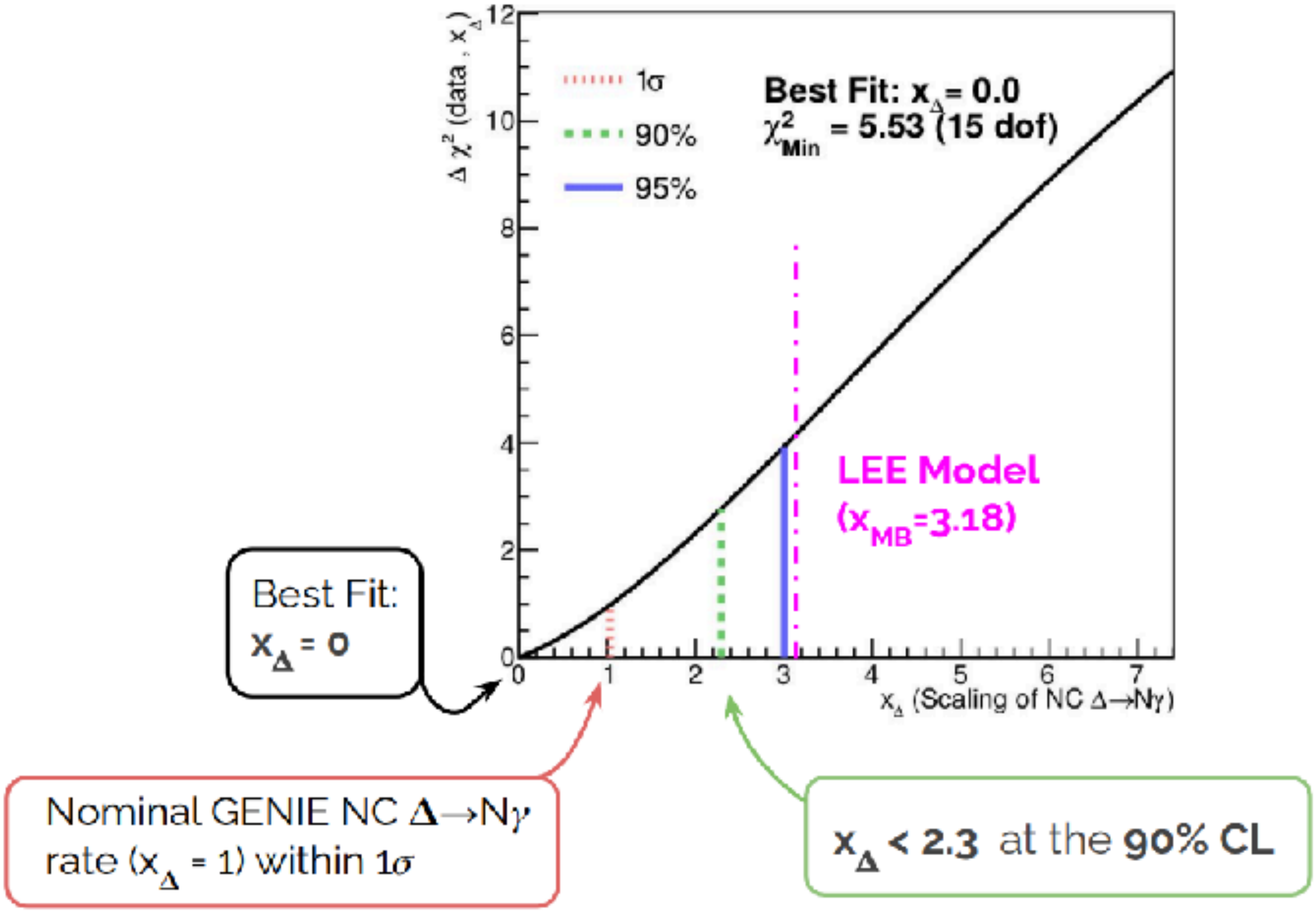




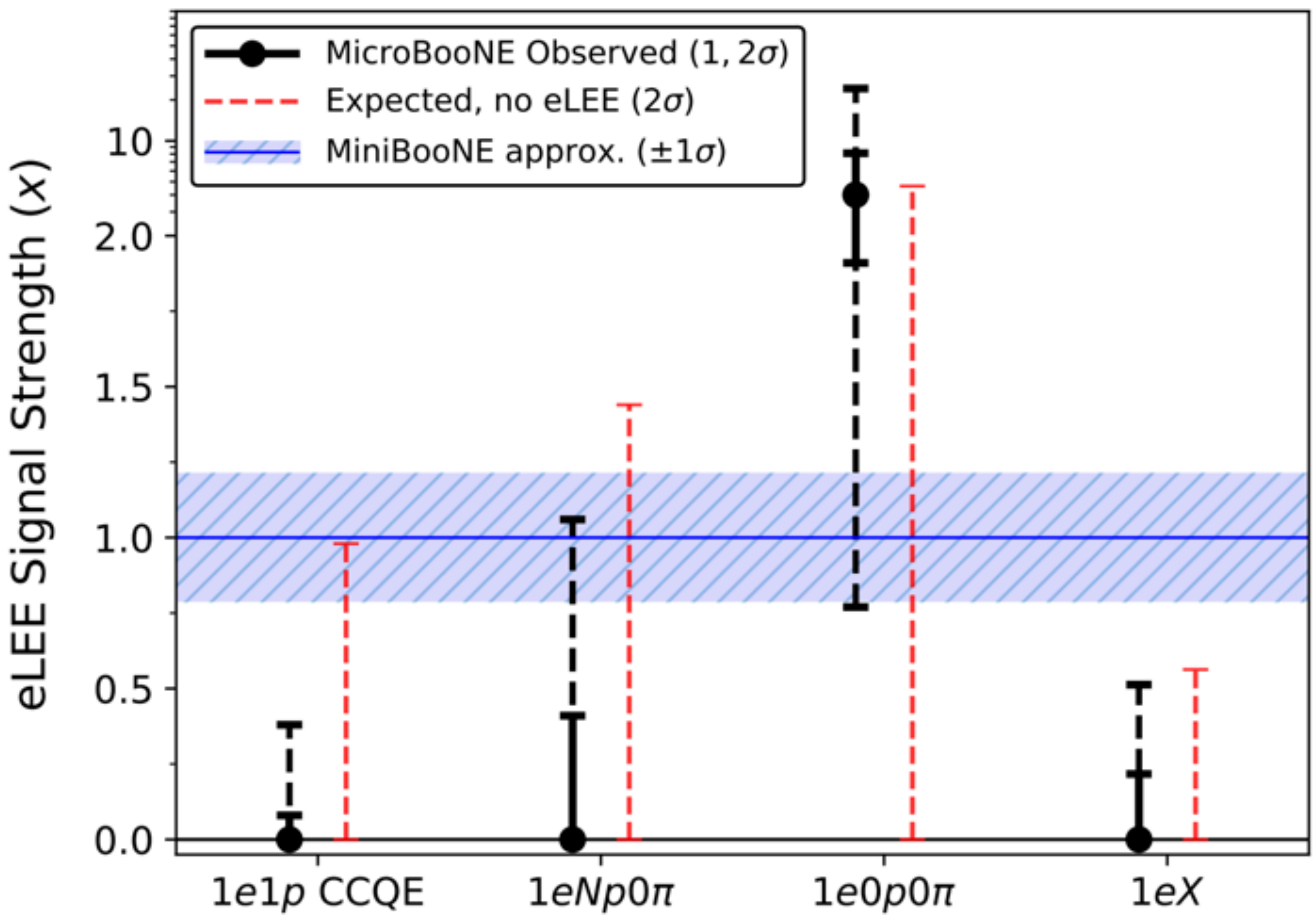


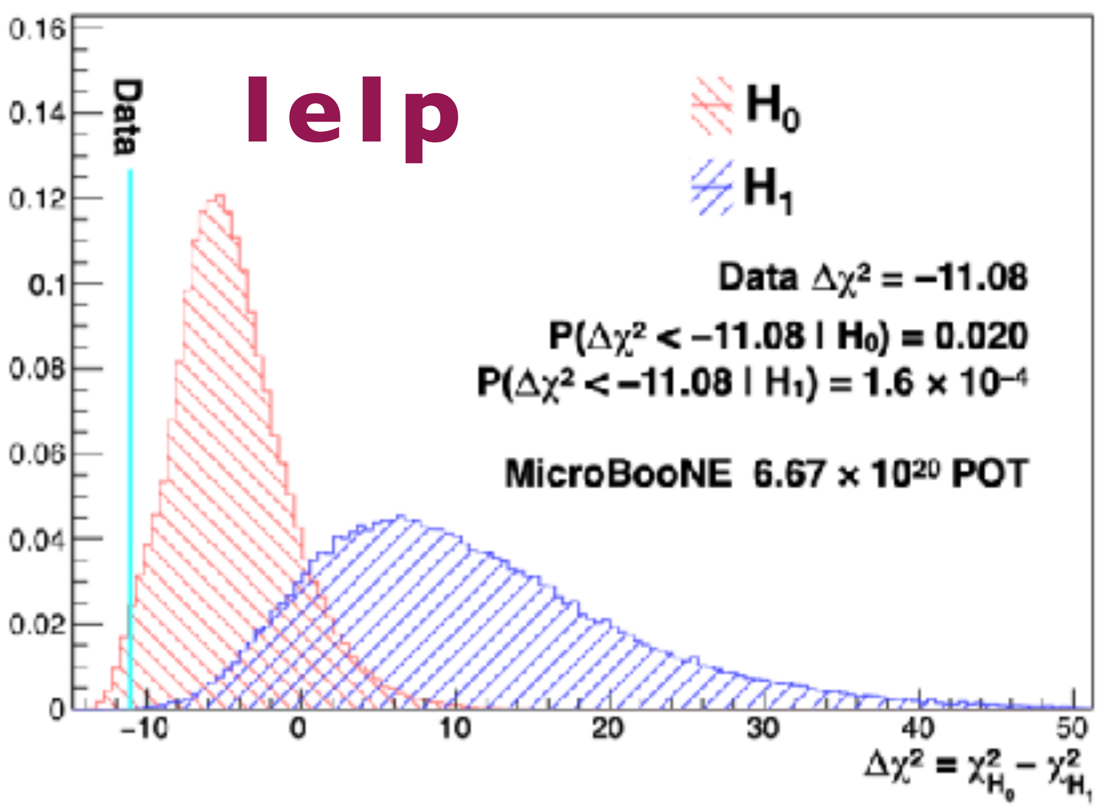


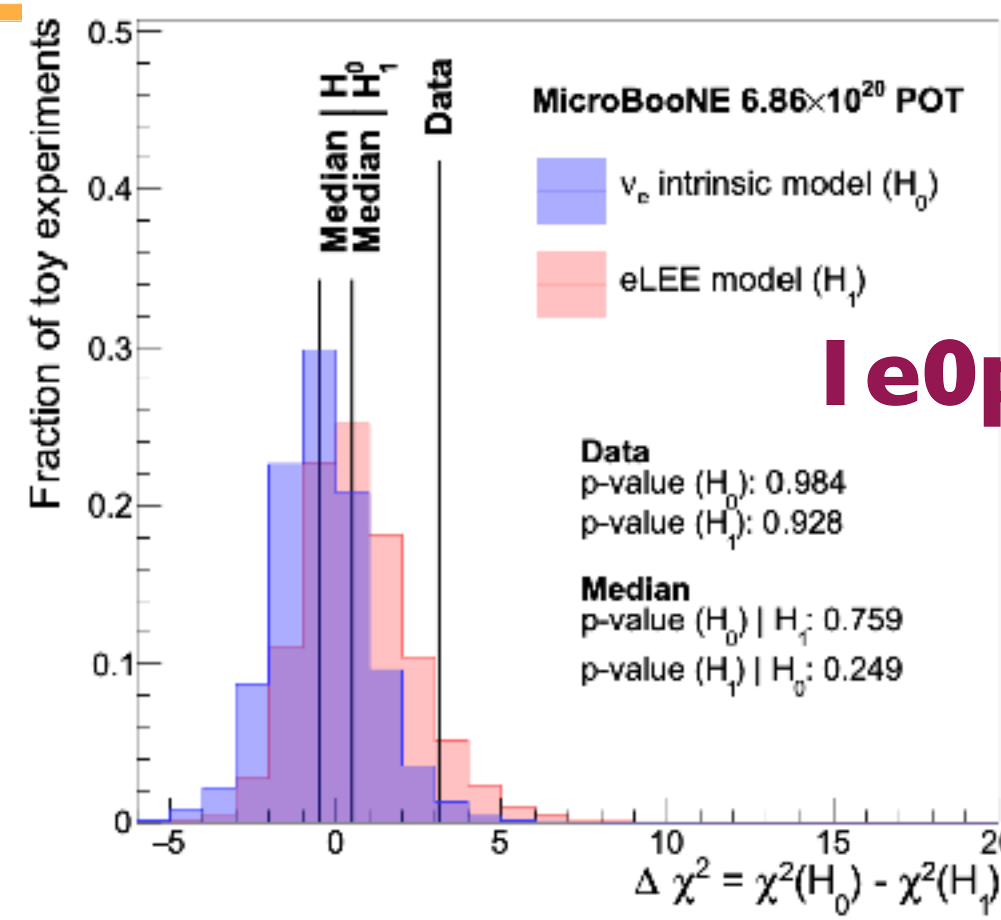
SINGLE PHOTON SEARCH

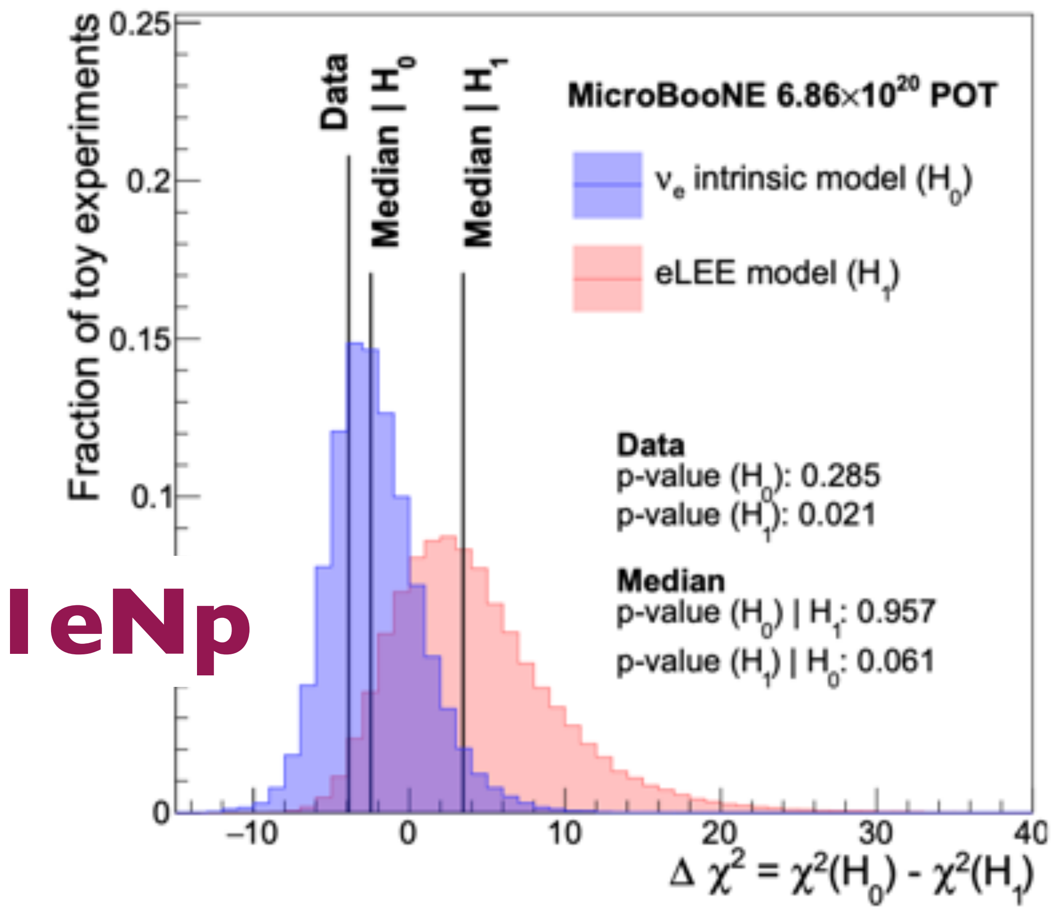


Slide credit: Mark R-L

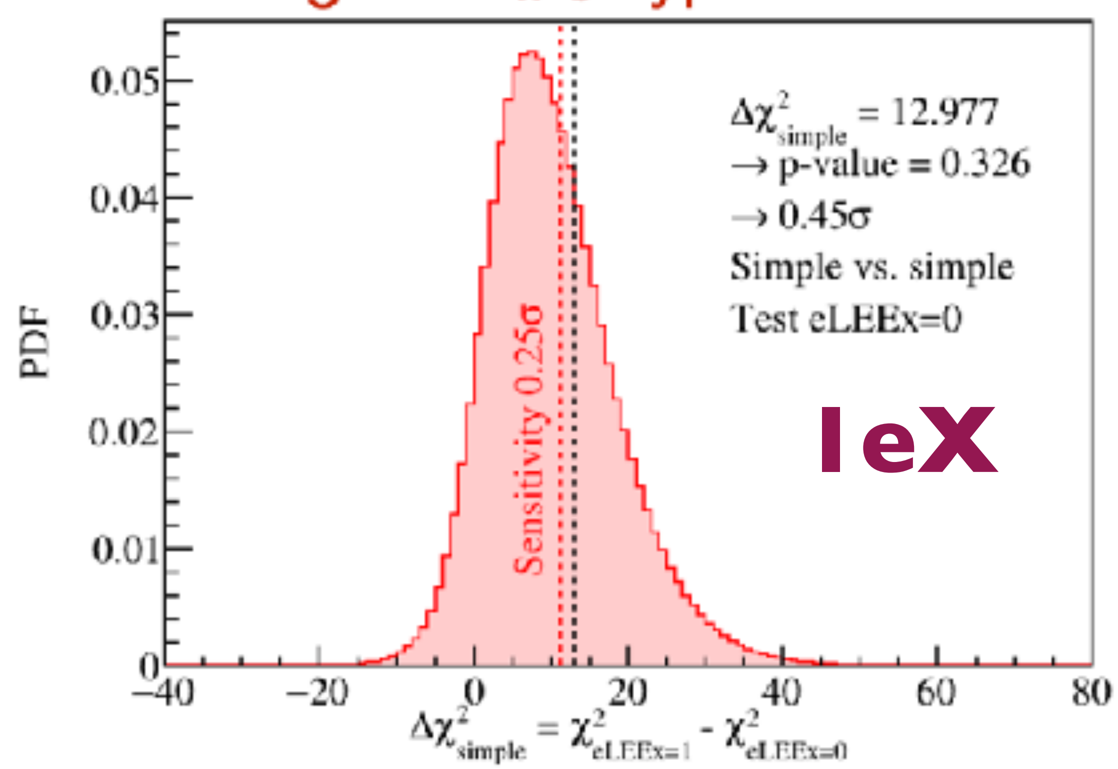

MicroBooNE Observed (1, 2σ)
Expected, no eLEE (2σ)
MiniBooNE approx. (±1σ)
eLEE Signal Strength (x)
10
2.0
1.5
1.0
0.5
0.0
1e1p CCQE
1eNp0π
1e0p0π
1eX





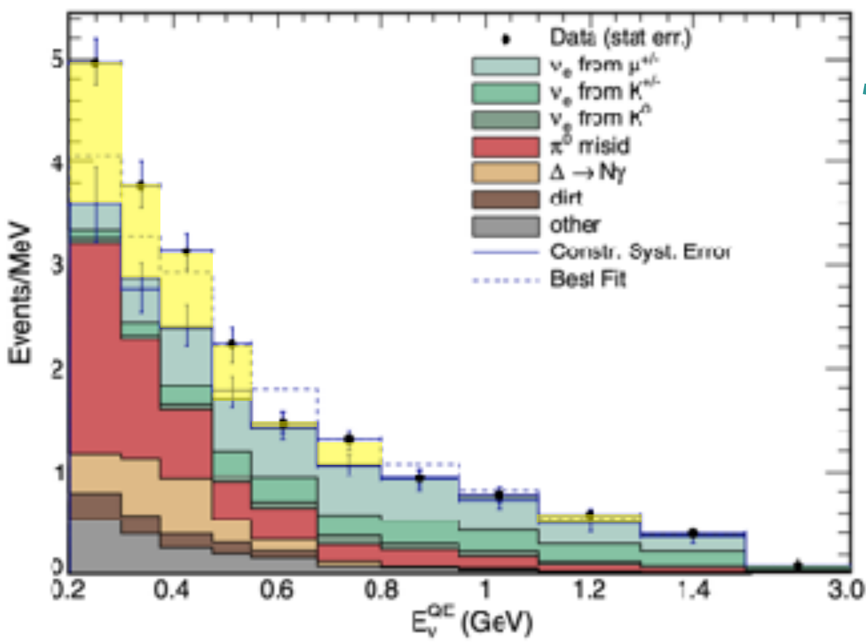


assuming $eLEE_{x=0}$ hypothesis is true



A SIMPLE MODEL OF THE MINIBOONE EXCESS

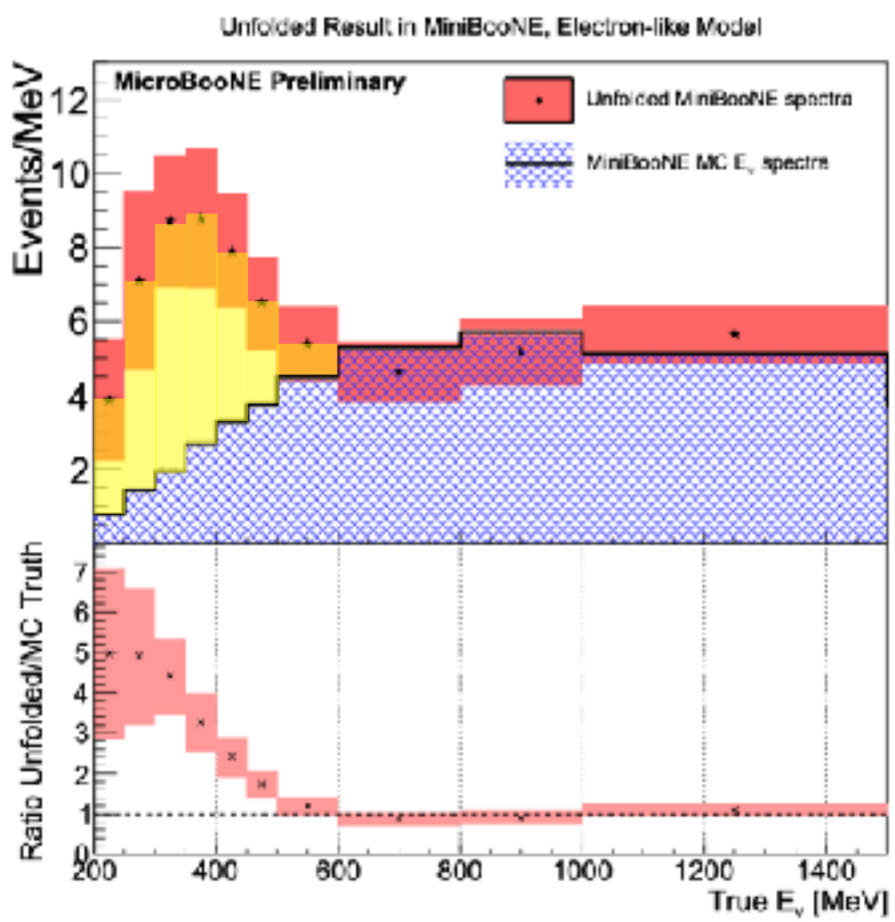
ν_e

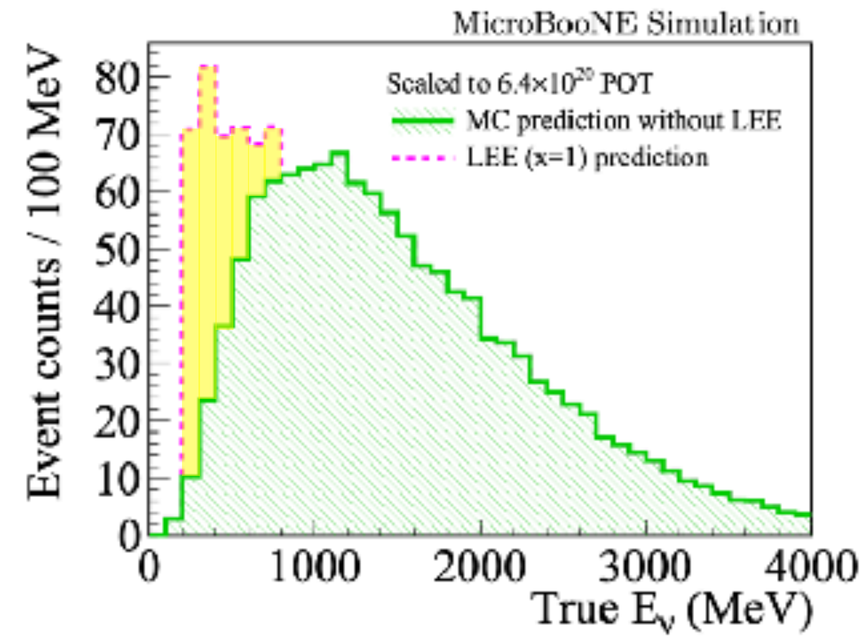


Take **excess** reported in MiniBooNE's 2018 results

Phys. Rev. Lett. 121, 221801

Unfold to true energy, assuming excess is entirely **electron neutrino**



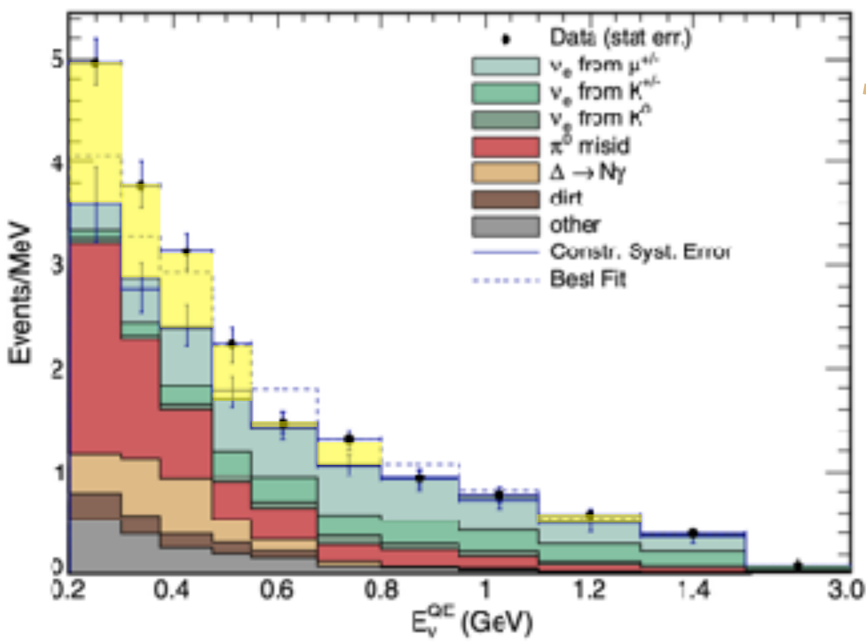


Apply to MicroBooNE to find **expected excess**

Allow normalisation (x) to float

A SIMPLE MODEL OF THE MINIBOONE EXCESS

$\Delta \rightarrow N\gamma$



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Phys. Rev. Lett. 121, 221801

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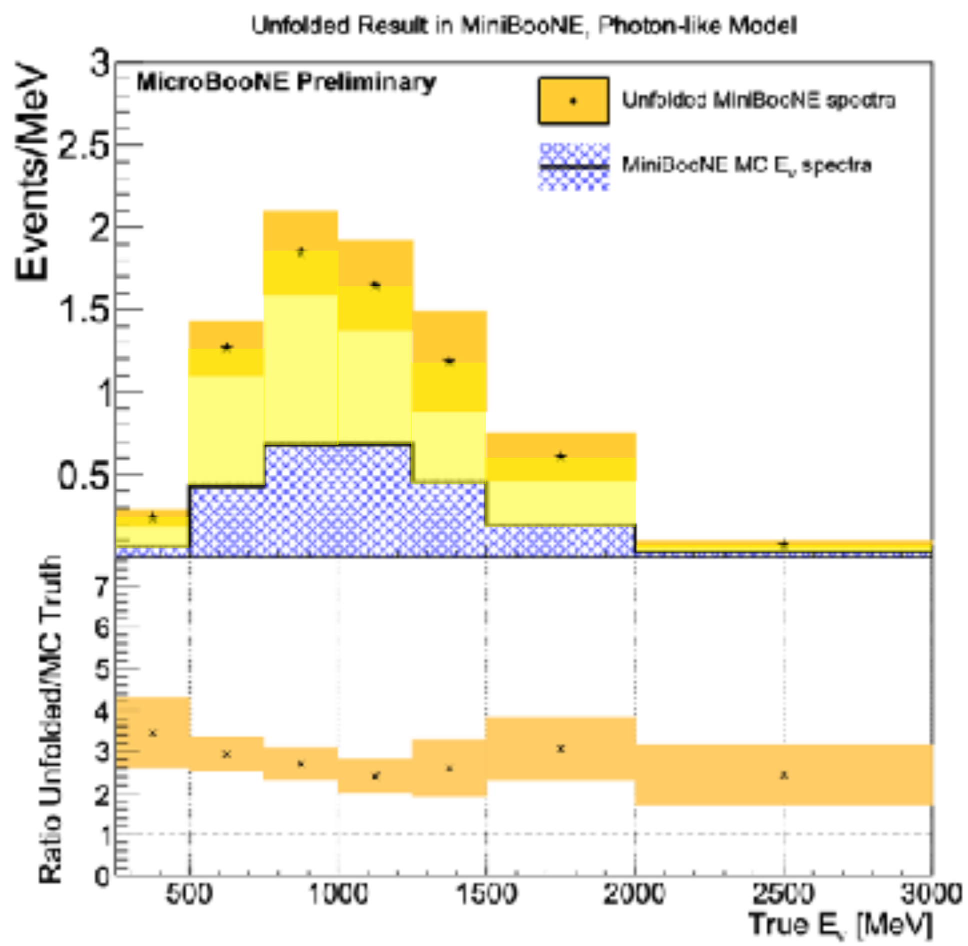
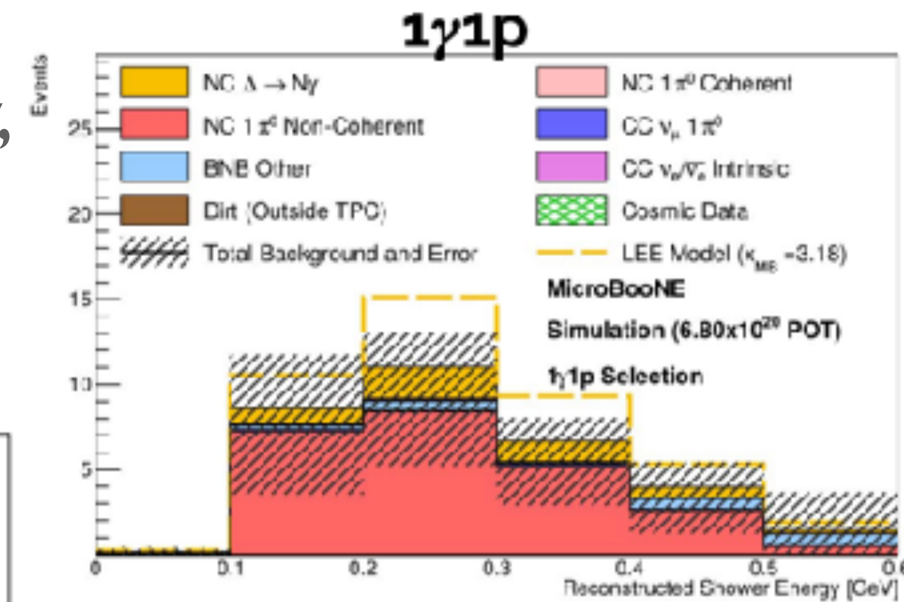


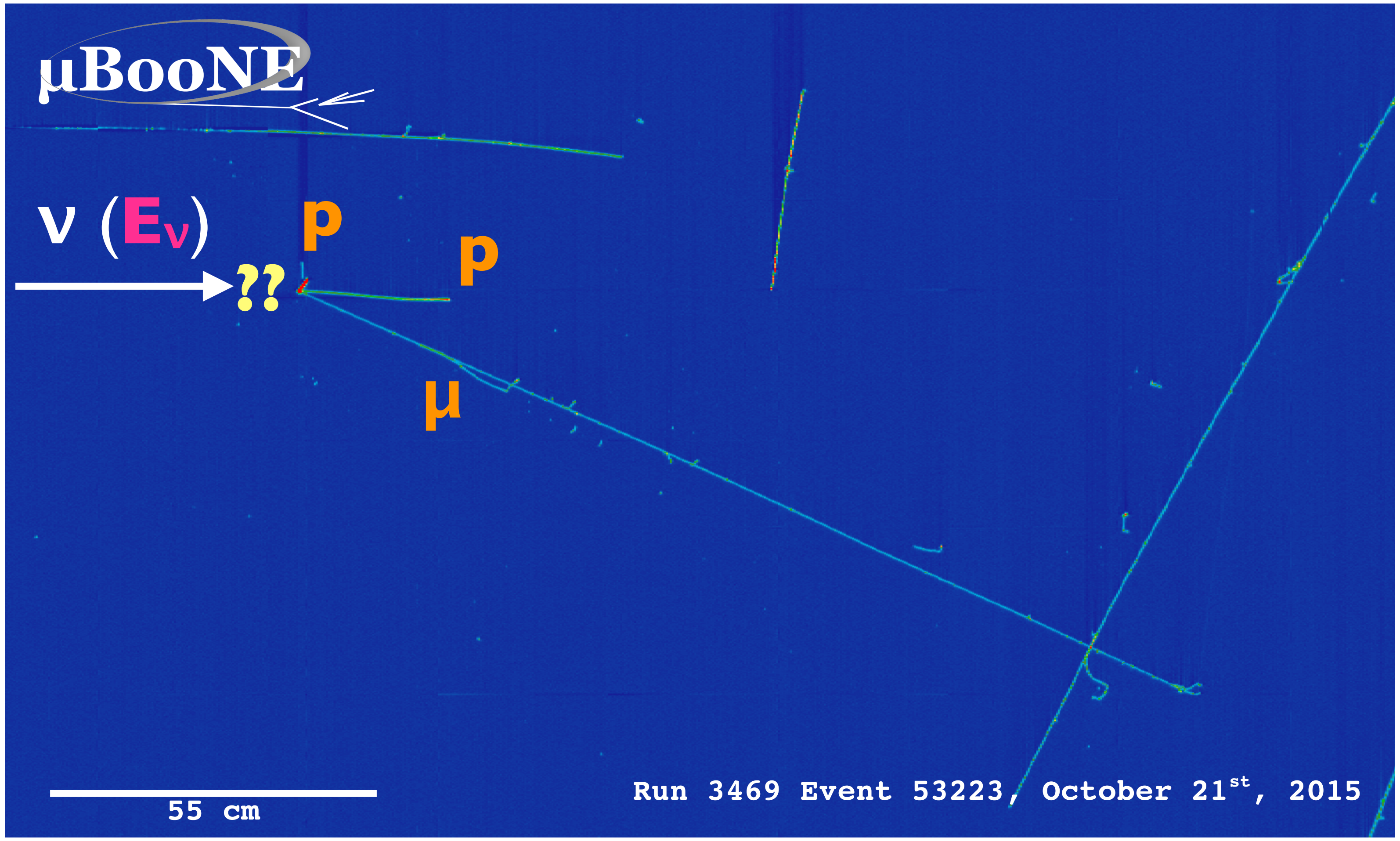


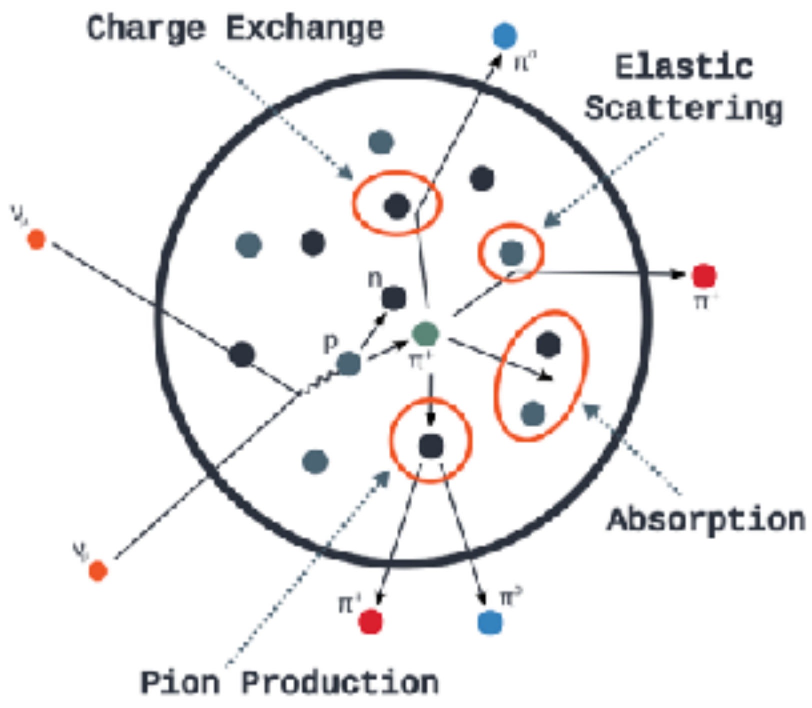
Flat normalisation enhancement of x3.18 could explain excess

Use as model for $\Delta \rightarrow N\gamma$ search

DOING THE MEASUREMENT

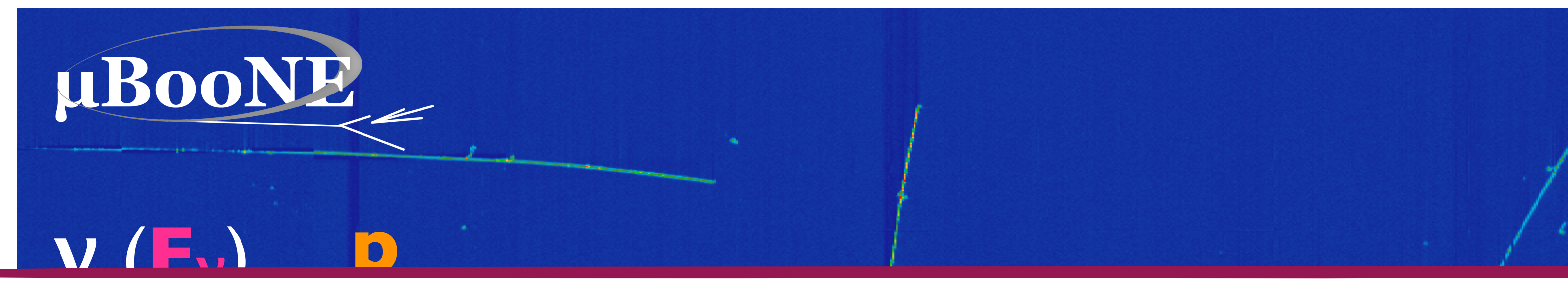
Tune neutrino interaction model to external data

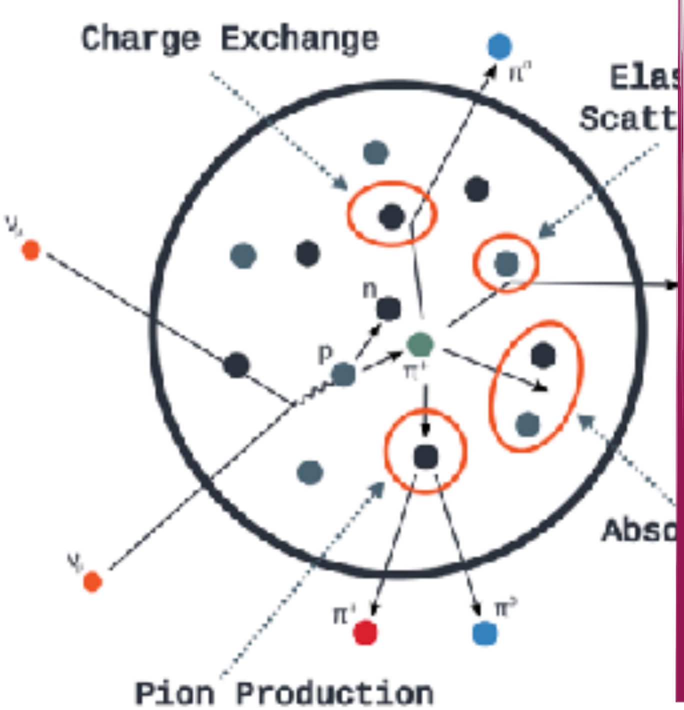




DOING THE MEASUREMENT

Tune neutrino interaction model to external data





Accurate model required to:

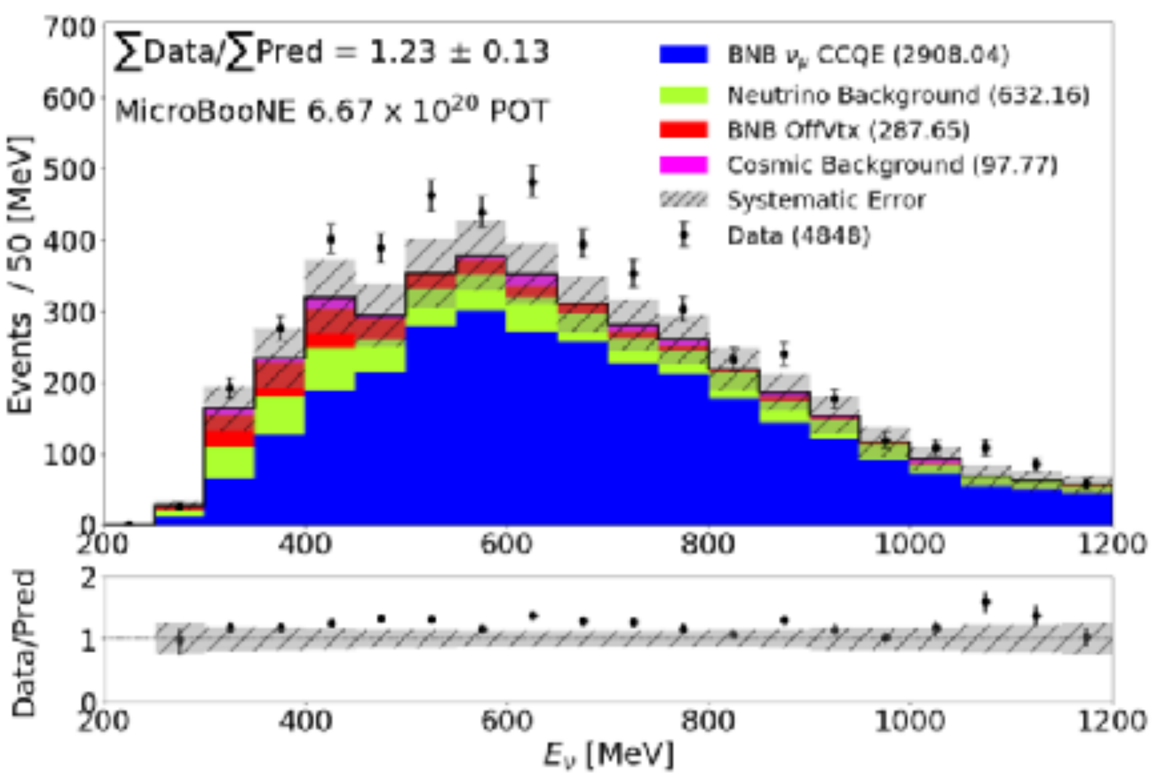
- predict mapping of reconstructed to true neutrino energy
- provide correlations between data samples (see next step of analysis)

Accurate estimation of uncertainties can be more important than central-value model prediction

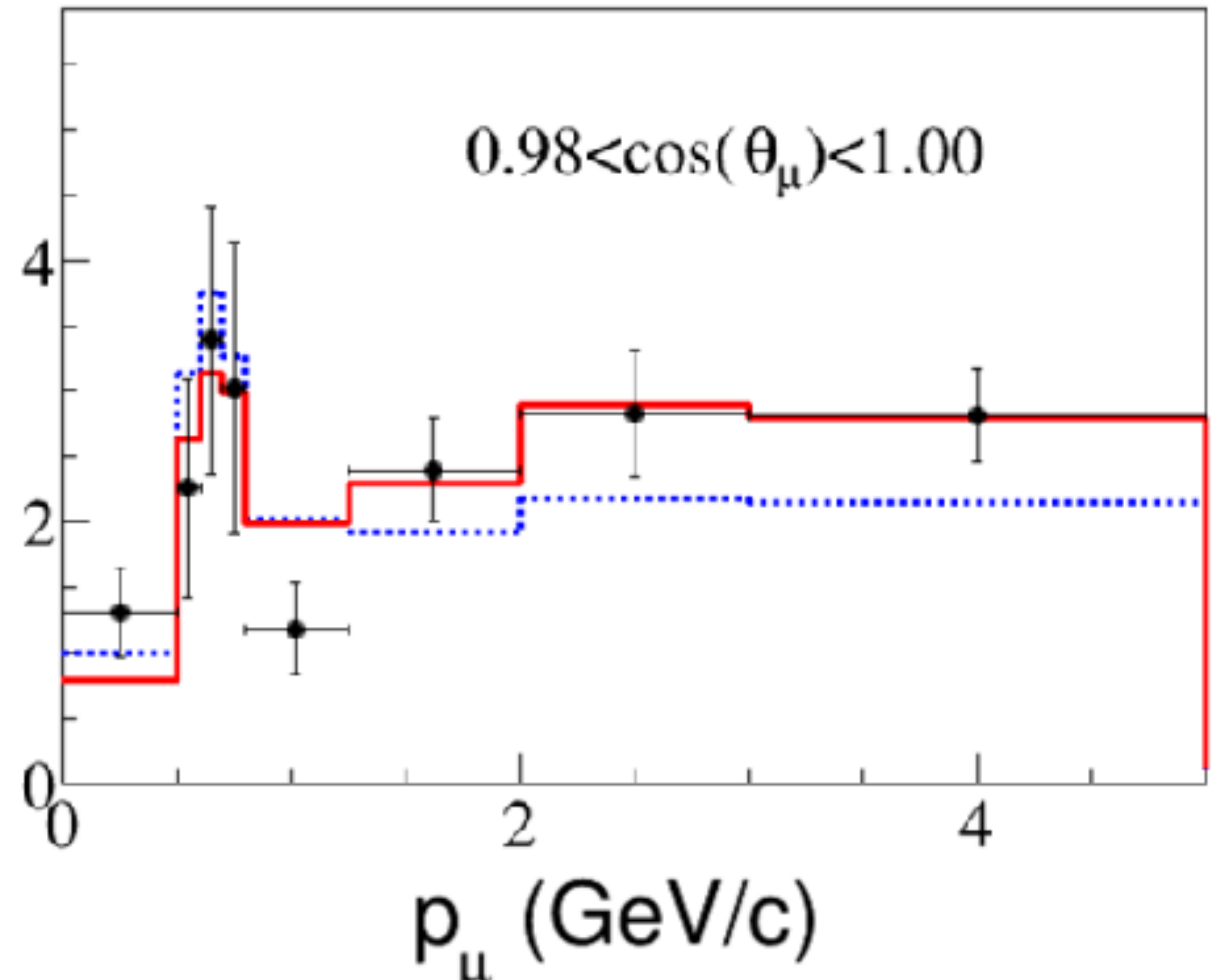
DOING THE MEASUREMENT

Tune neutrino interaction model to external data

ν_μ CCQE-like



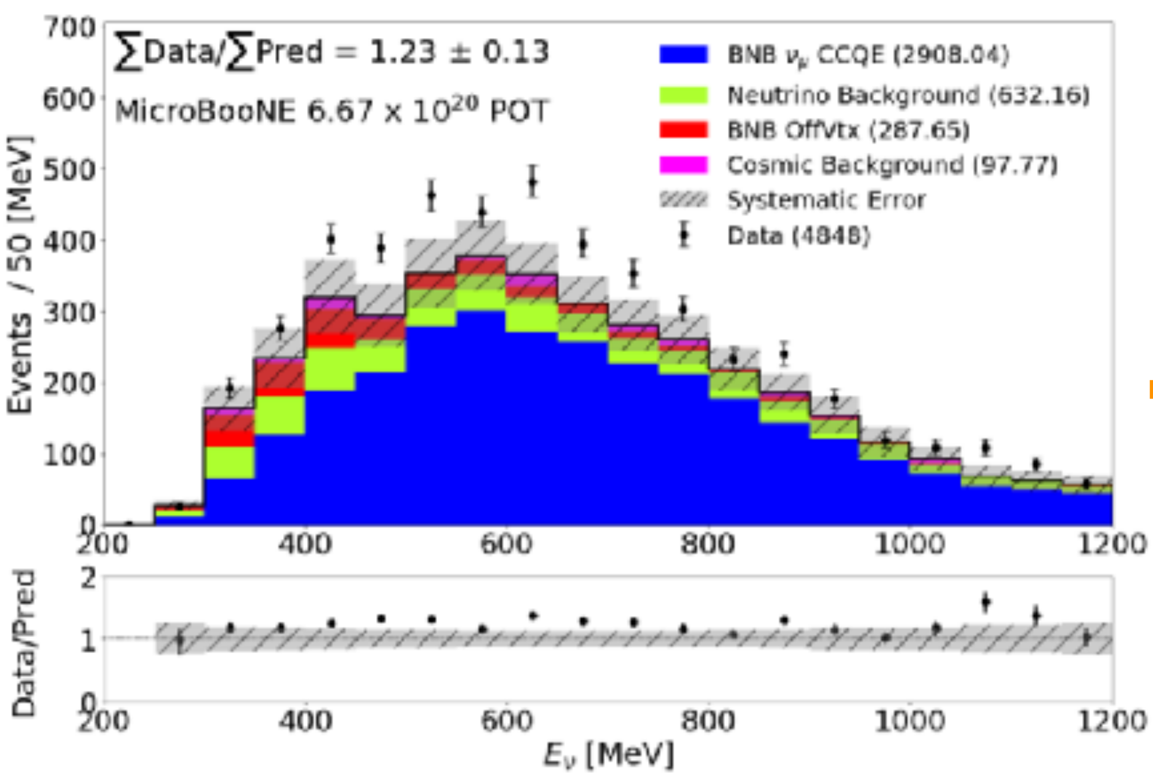
GENIE v3 (untuned) χ^2=115.3/67 bins
MicroBooNE Tune χ^2=63.8/67 bins
T2K Data



DOING THE MEASUREMENT

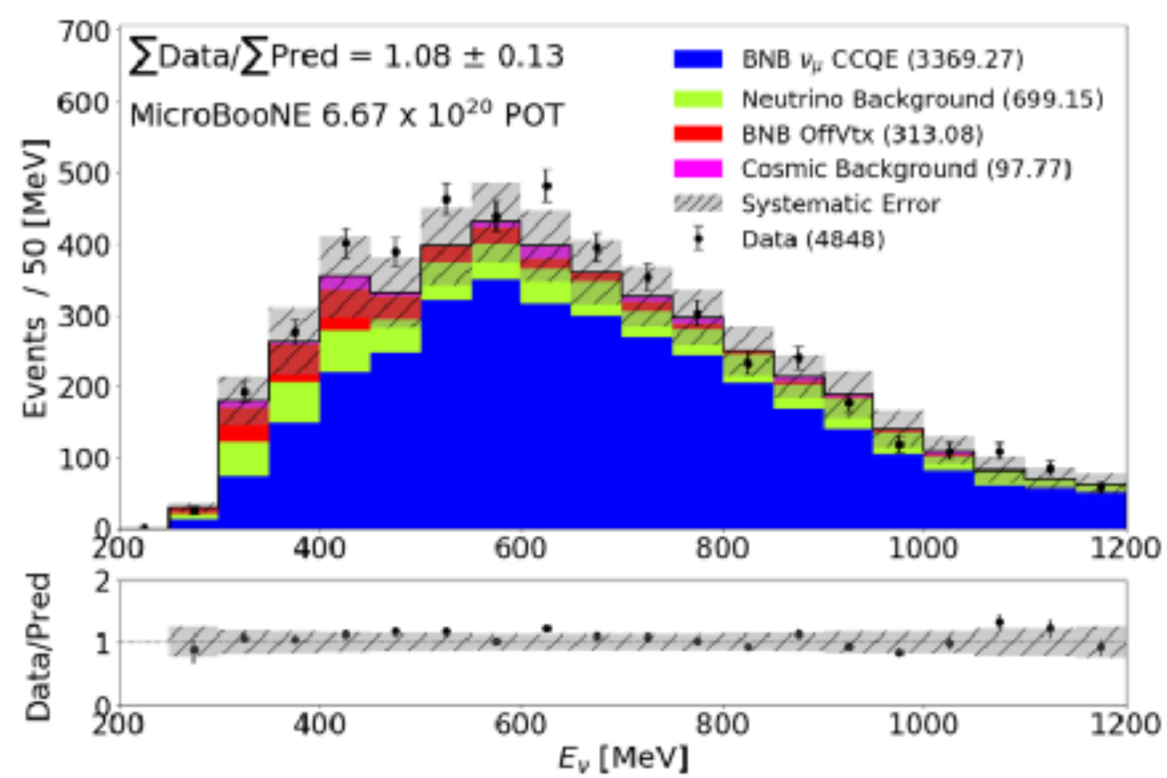
Tune neutrino interaction model to external data

ν_μ CCQE-like



ν_μ CCQE-like

Data/prediction: 1.23 → 1.08



DOING THE MEASUREMENT

Tune neutrino interaction model to external data → Sideband data sample → data-driven signal prediction

"Sideband" → independent (i.e. non-signal) data sample

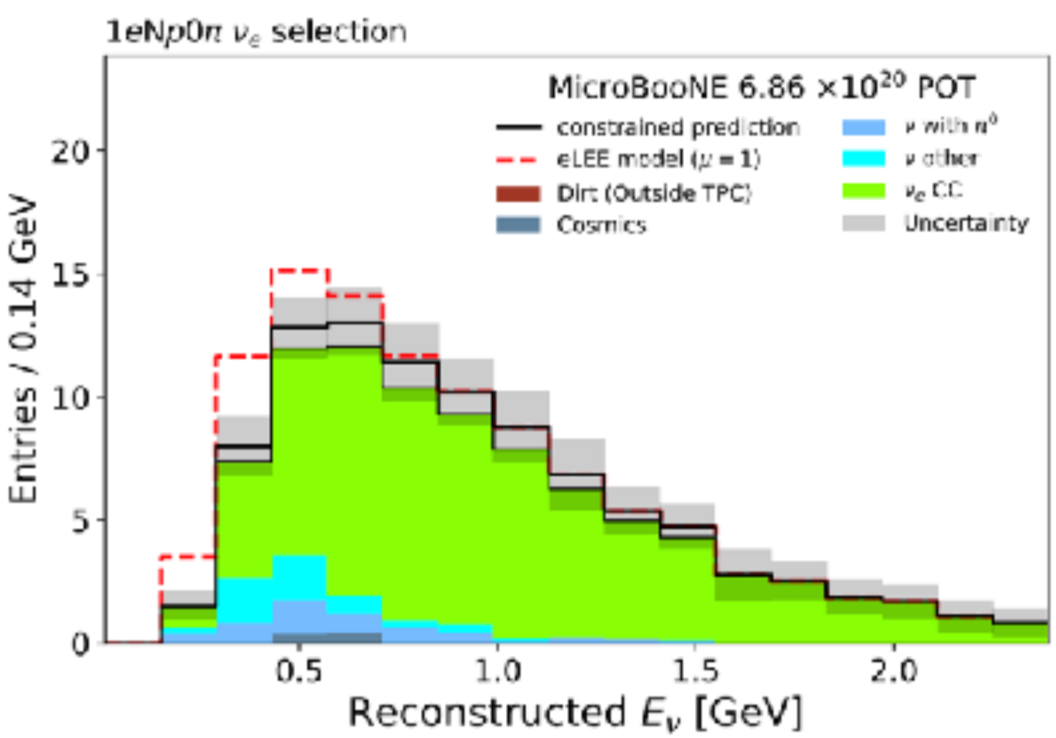
Use to:

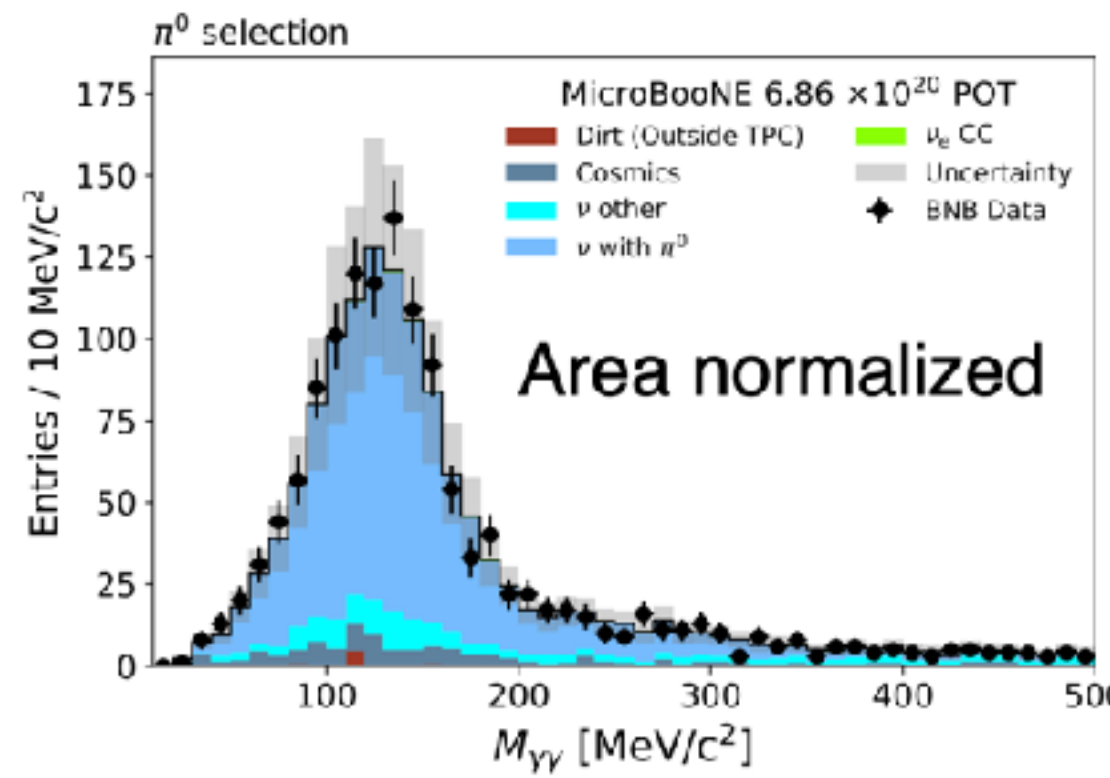
- validate analysis strategy and modelling
- constrain backgrounds in signal sample
- further constrain models to provide data-driven prediction for signal region

DOING THE MEASUREMENT

Tune neutrino interaction model to external data → Sideband data sample → data-driven signal prediction

ν_e selection sidebands: π^0 and ν_μ

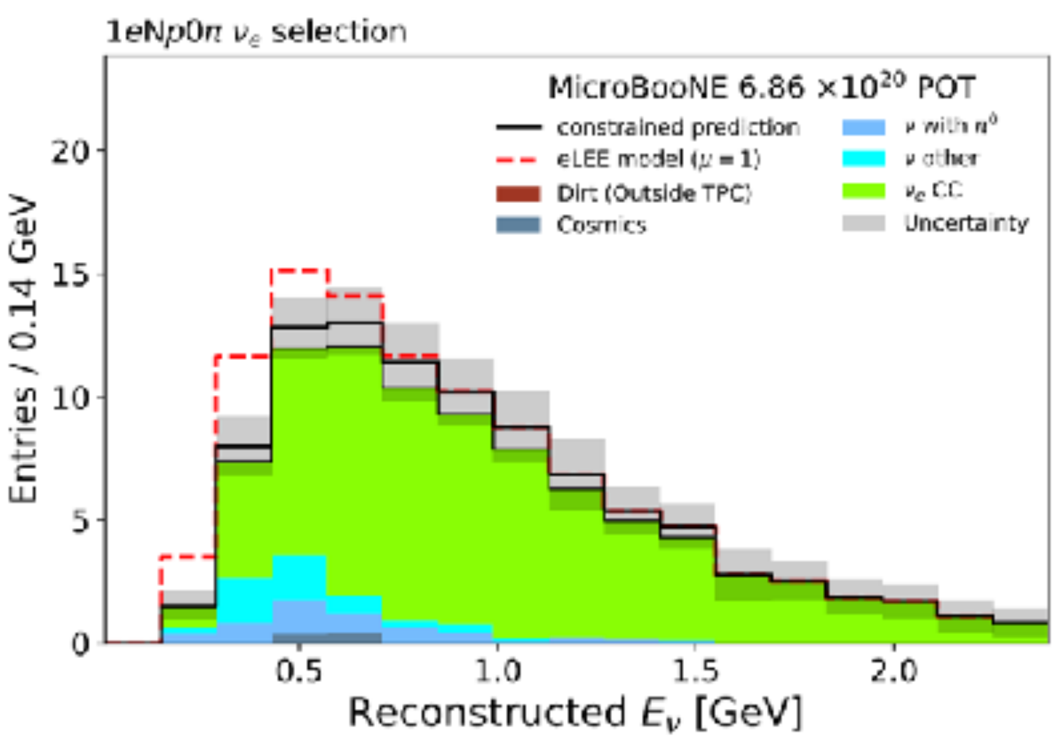


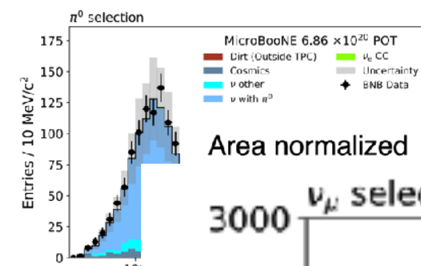


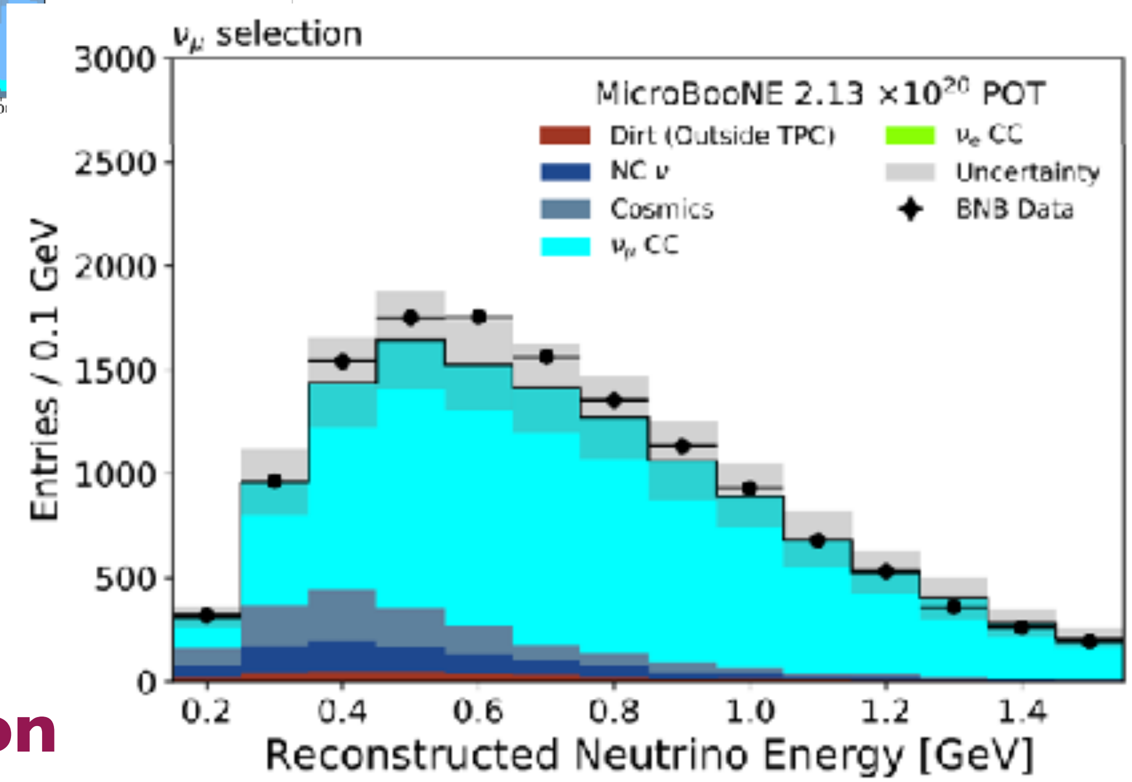
DOING THE MEASUREMENT

Tune neutrino interaction model to external data → Sideband data sample → data-driven signal prediction

ν_e selection sidebands: π^0 and ν_μ





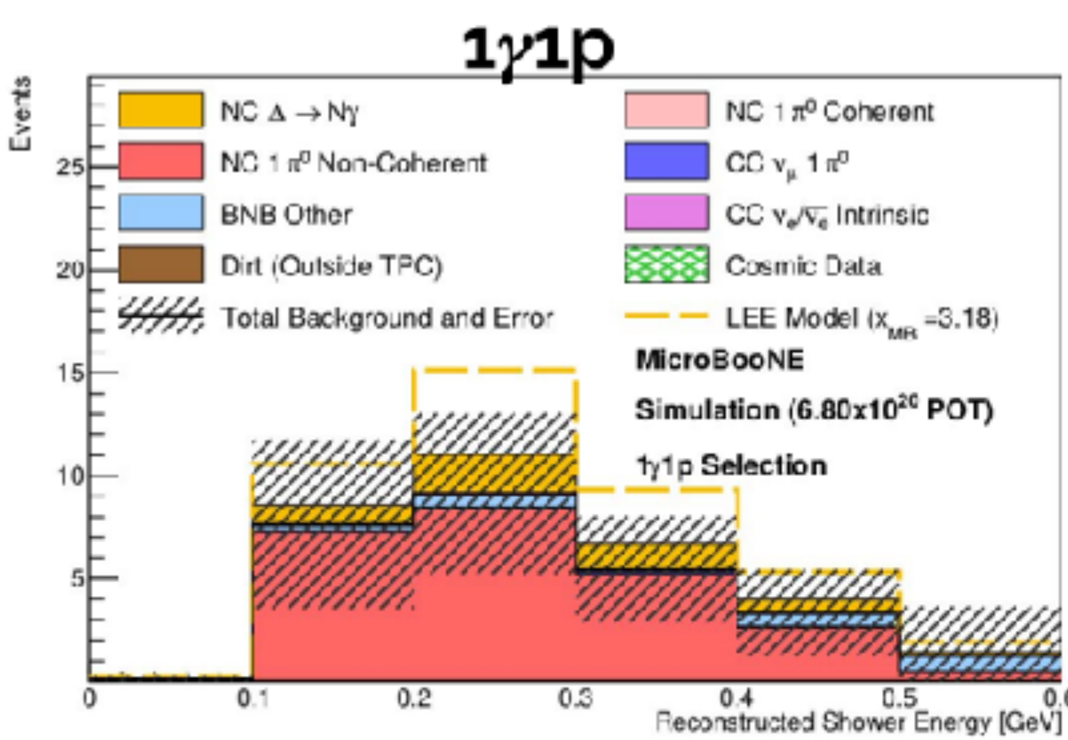


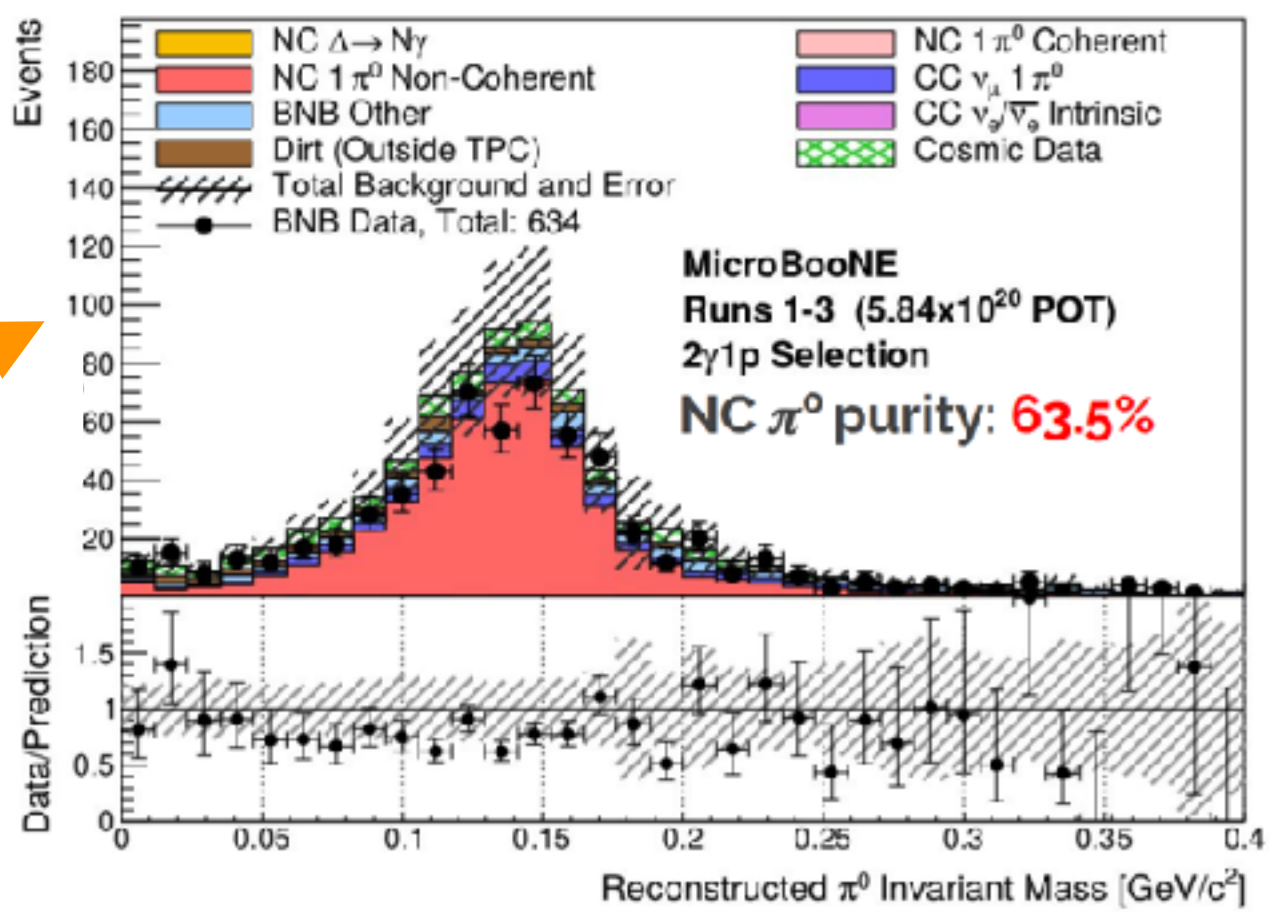
ν_μ measurement constrains ν_e prediction and reduces uncertainty

DOING THE MEASUREMENT

Tune neutrino interaction model to external data → Sideband data sample → data-driven signal prediction

$\Delta \rightarrow N\gamma$ sideband: $NC\pi^0$



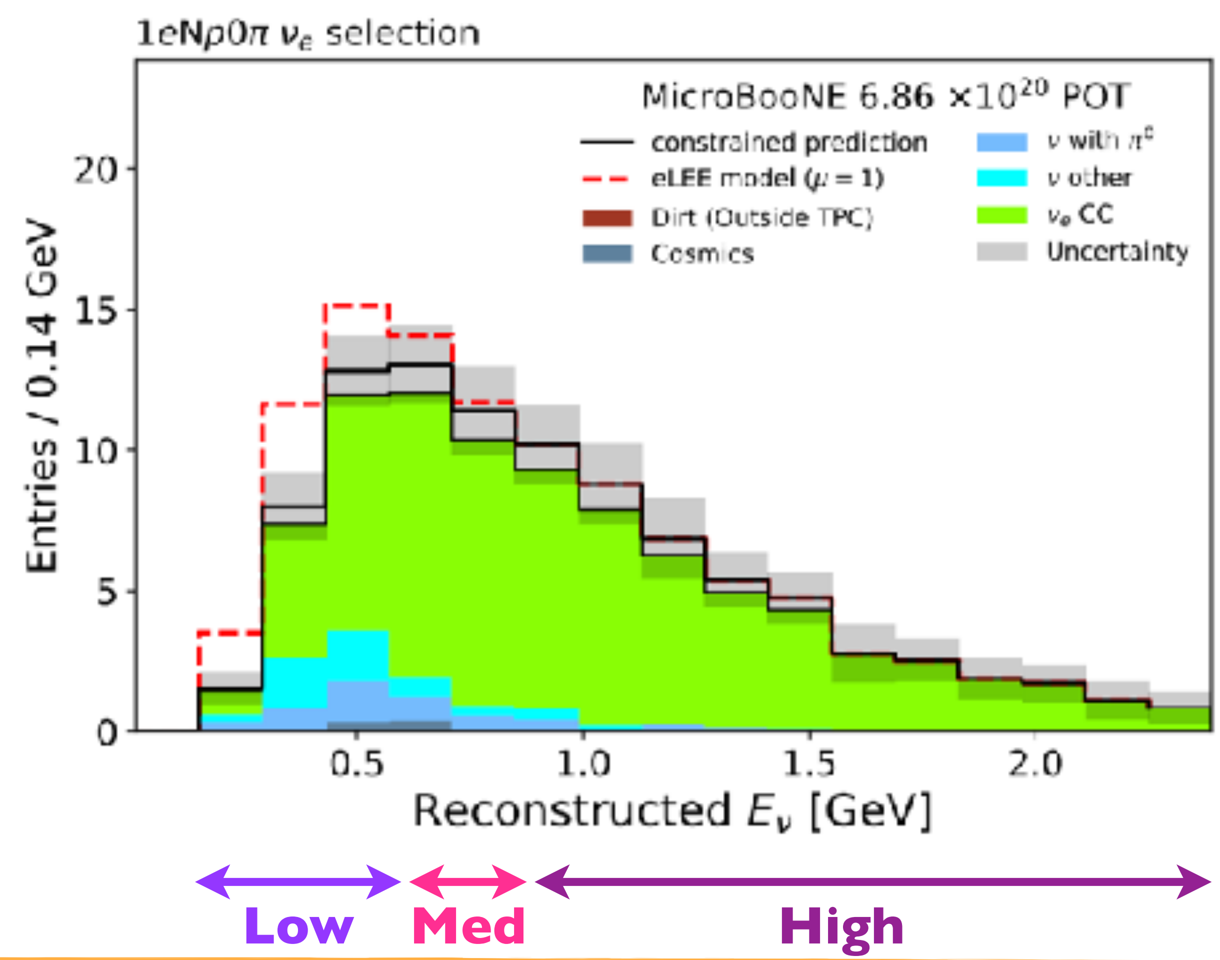


DOING THE MEASUREMENT

Tune neutrino interaction model to external data → Sideband data sample → data-driven signal prediction → Staged unblinding

Blind analysis strategy:

- Limited open data sample
- Analysis of sideband data sets
- Blind analysis of fake data sets
- Progressive ν_e unblinding



DOING THE MEASUREMENT

Tune neutrino interaction model to external data → Sideband data sample → data-driven signal prediction → Staged unblinding → Statistical tests

1) Simple hypothesis test

- Does the data prefer the LEE model over the non-LEE model?

2) Signal strength measurement

- Use Feldman-Cousins procedure to measure best-fit signal strength (x) assuming a linear scaling of the LEE model