New physics interpretations of the MiniBooNE excess at the MicroBooNE experiment

SLAC EPP Theory Seminar

Matheus Hostert

Perimeter Institute and University of Minnesota

University of Minnesota

Perimeter Institute

In this talk

- **The short-baseline puzzle**

- **Interpreting the latest MicroBooNE results**
    - Model-independent considerations
    - The impact on an eV-sterile neutrinos

- **Future directions:**
    - More data at short-baseline detectors
    - Alternative explanations (e+e-, coherent photons, etc)

Collaborators

Argüelles et al, arXiv:2111.10359

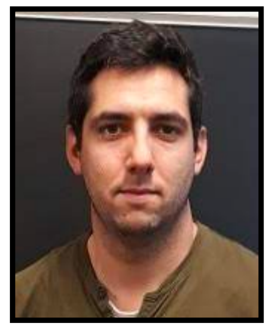
Carlos Argüelles
Harvard University

Ivan Estebán
Ohio State University

Kevin Kelly
CERN

Joachim Kopp
CERN

Pedro Machado
Fermilab



Ivan Martinez-Soler
Harvard University

Yuber F. Perez-Gonzalez
Durham University

Open questions in the neutrino sector

Neutrino oscillation experimental program

- Is there **CP violation** in the lepton sector?
- Which neutrino is the heaviest, 3 or 2 (Normal or Inverted **Ordering**)?
- Can we measure and over-constrain the **PMNS**, like CKM?

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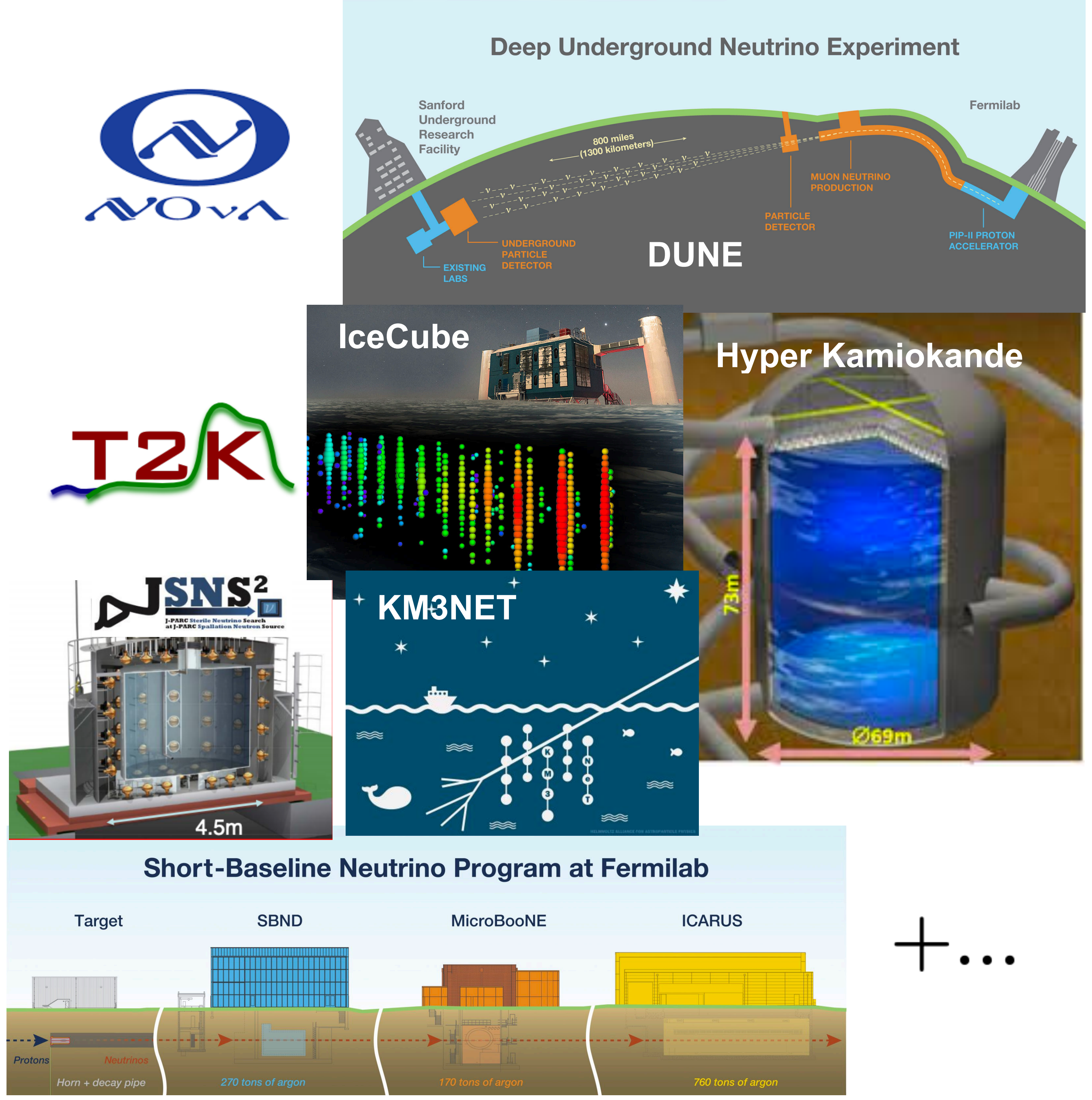

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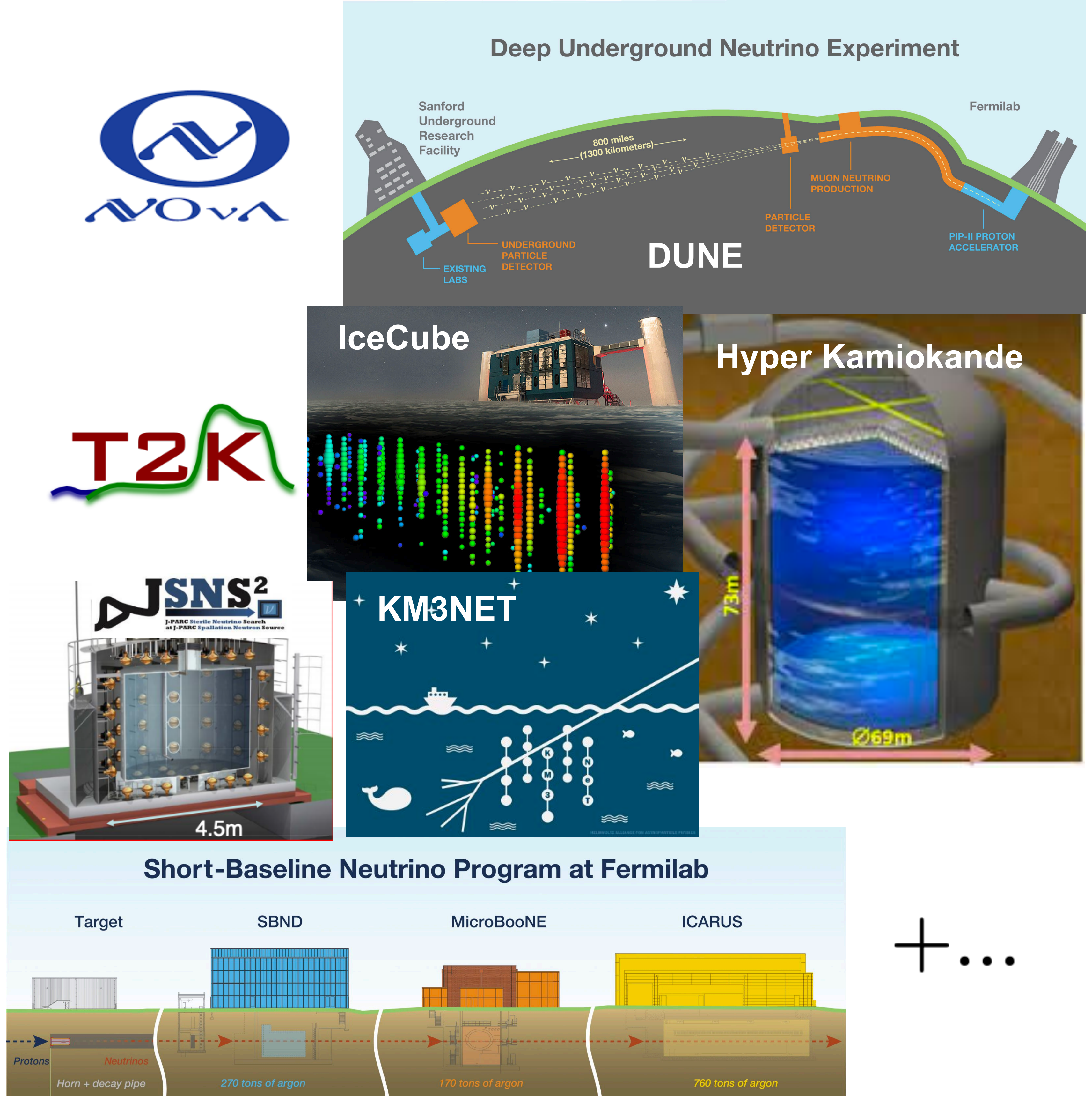

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This talk:

- Do we see any more surprises along the way? “New” new physics?

Open questions in the neutrino sector

Neutrino oscillation experimental program

- Is there **CP violation** in the lepton sector?
- Which neutrino is the heaviest, 3 or 2 (Normal or Inverted **Ordering**)?
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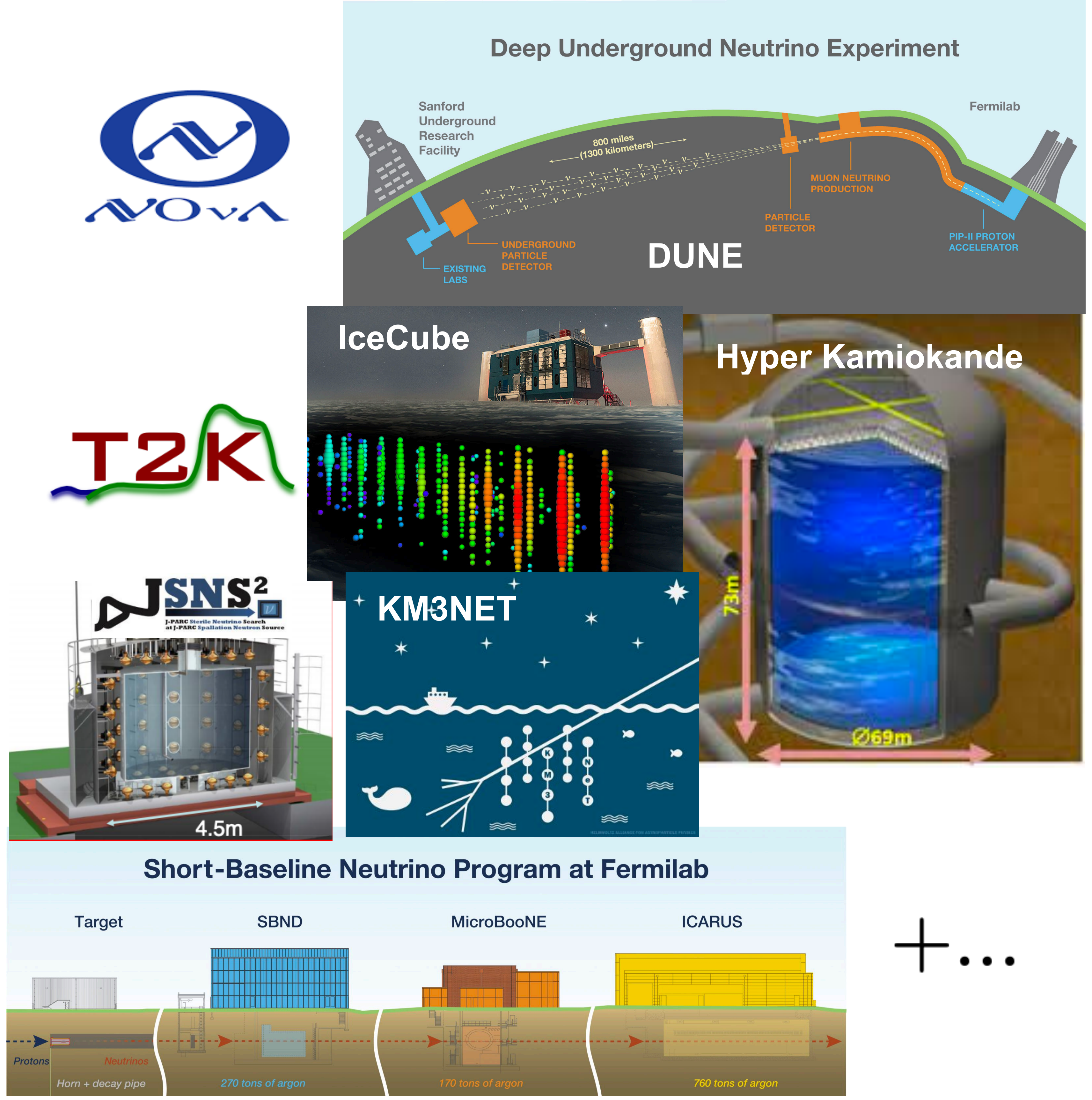
Can also have important consequences for this program



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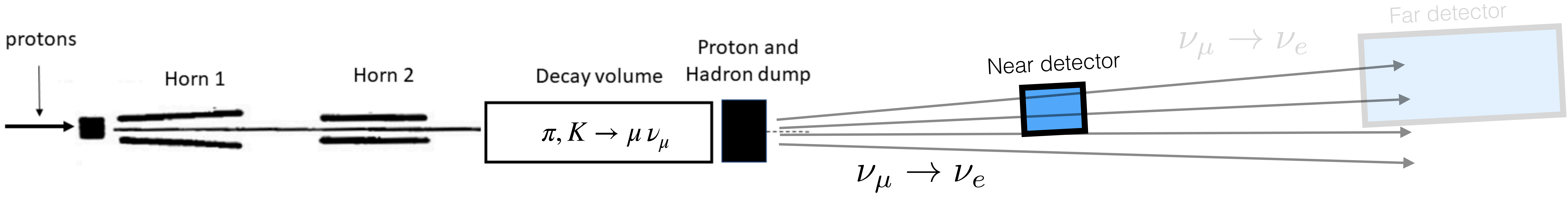
This talk:

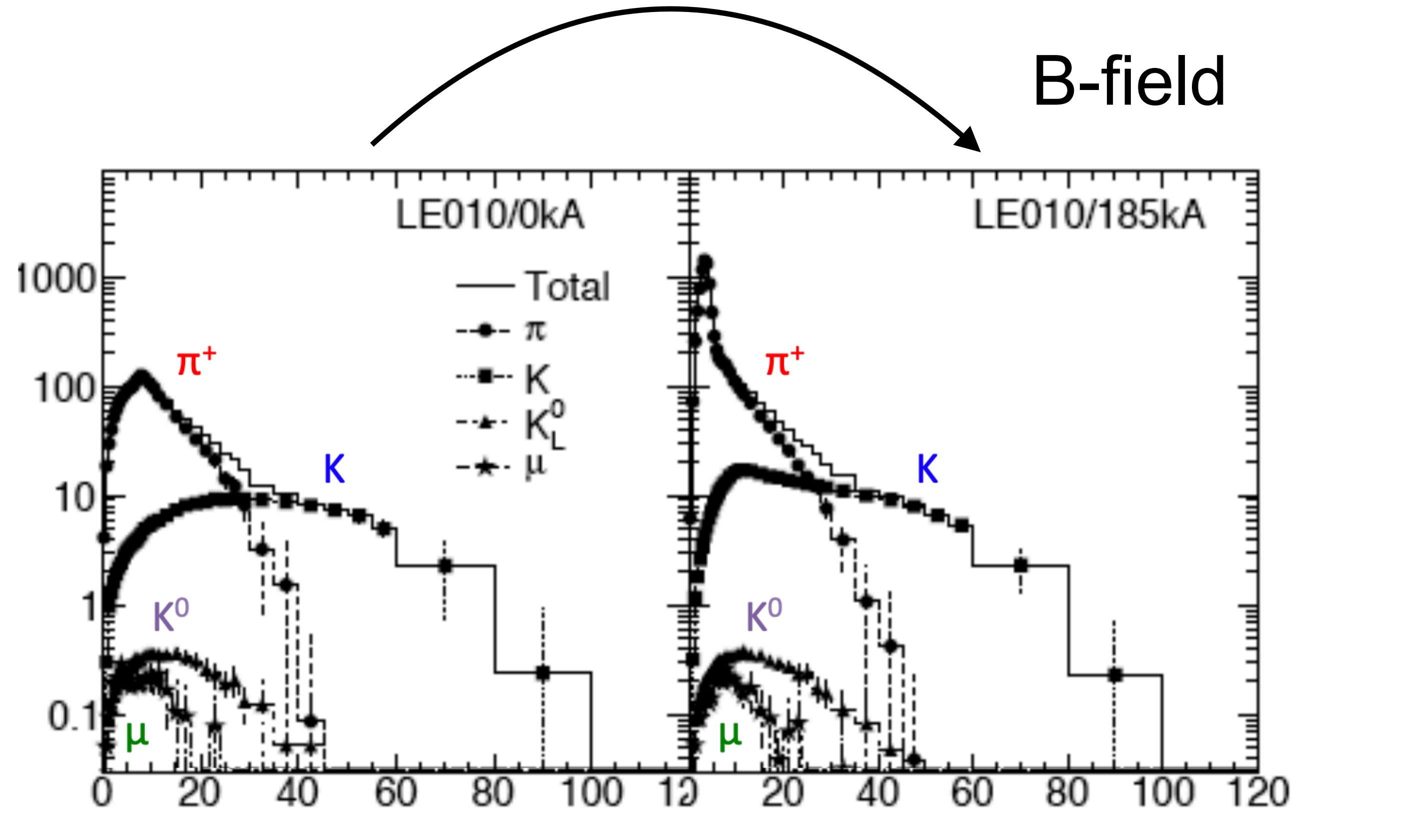
- Do we see any more surprises along the way? “New” new physics?

Some context

Some context and oscillation notation

Accelerator neutrino experiment:





Z. Pavlovic, PhD thesis

Some context and oscillation notation

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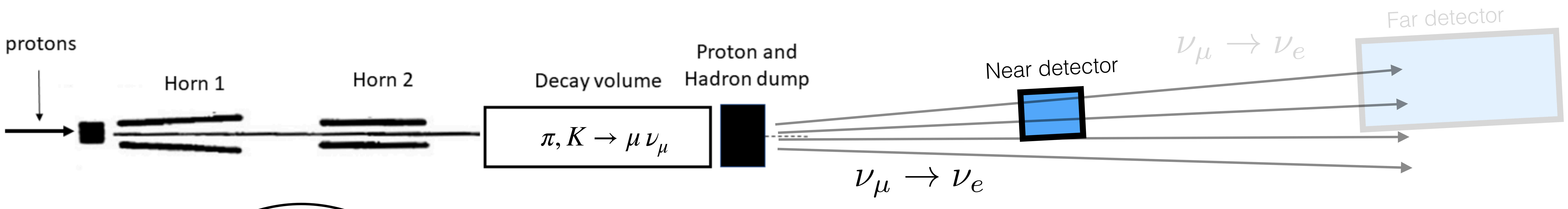

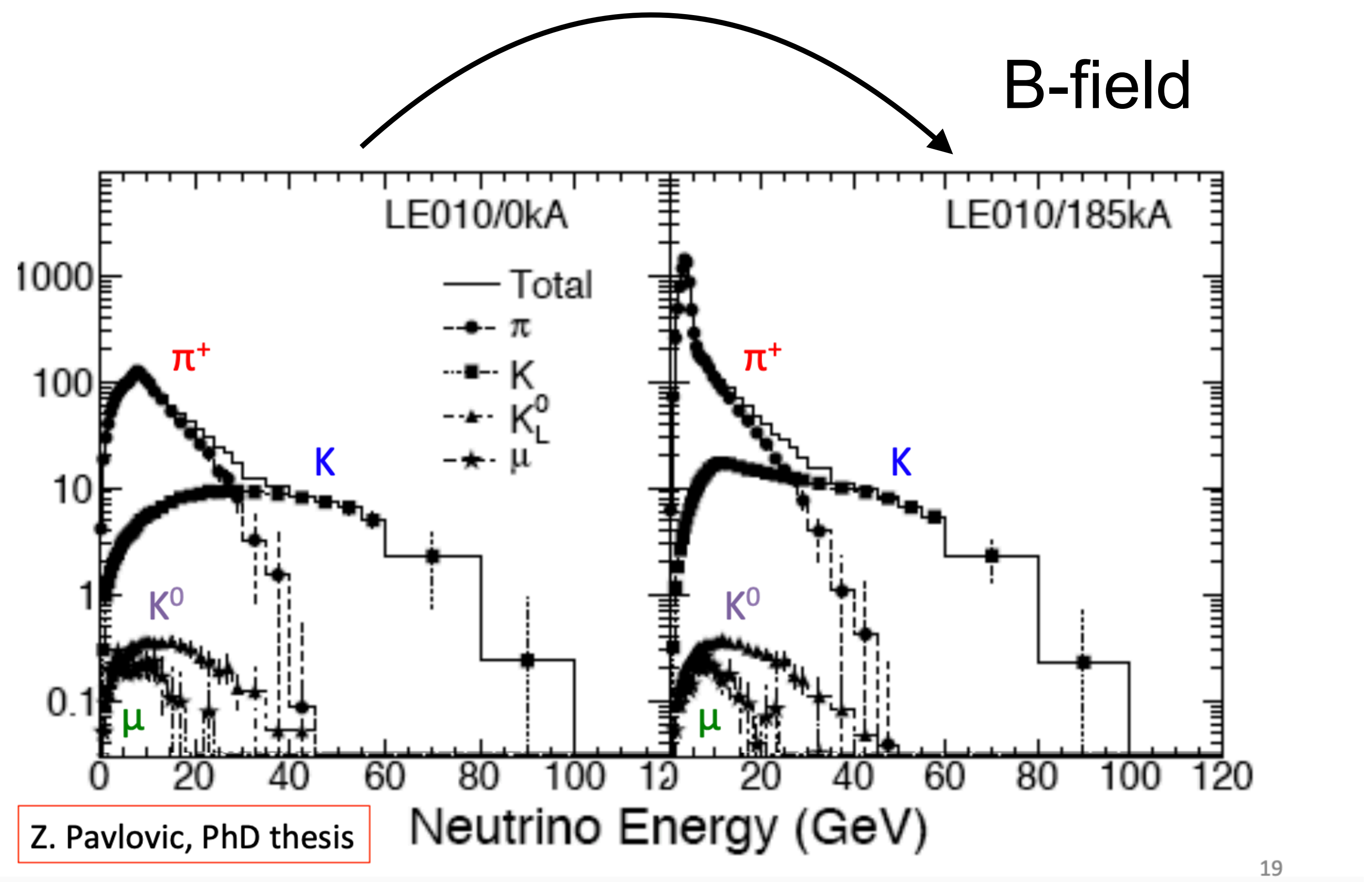

SBL oscillations can develop due to a mostly-sterile neutrino:

$$\Delta m^2_{41} \sim \mathcal{O}(1)\ \mathrm{eV}^2$$

Effectively a 2-neutrino oscillation system: $\Delta \equiv 1.27 \frac{\Delta m^2[\mathrm{eV}^2]\, L[\mathrm{m}]}{E[\mathrm{MeV}]}$

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \Delta = 1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)\sin^2 \Delta$$

$$P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta_{ee} \sin^2 \Delta = 1 - 4|U_{e 4}|^2(1 - |U_{e 4}|^2)\sin^2 \Delta$$

$$P_{\nu_\mu \to \nu_e} = \sin^2 2\theta_{e\mu} \sin^2 \Delta = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 \Delta$$

Short-baseline: search for oscillations that develop before atmospheric and solar frequencies.

$$\frac{L}{E} \sim \frac{100\ \mathrm{m}}{100\ \mathrm{MeV}}$$

The Short-Baseline Puzzle

The Short-Baseline Puzzle

(a historical detour)

Some history — SBL neutrino oscillations

Short-baseline oscillations have been discussed for a long time — even before we figured out the resolution to the Solar problem.

PS-191 (1984 at CERN)

Phys.Lett.B 181 (1986) 173-177

A total of 23 ± 8 excess events (3σ).

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Nucl.Phys.B 335 (1990) 517-545

Reports a 2σ excess.

$$\frac{\left(\nu_e/\nu_\mu\right)_{\text{obs}}}{\left(\nu_e/\nu_\mu\right)_{\text{pred}}} = 2.2 \pm 0.6$$

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Excess attributed to unknown systematics in both experiments.

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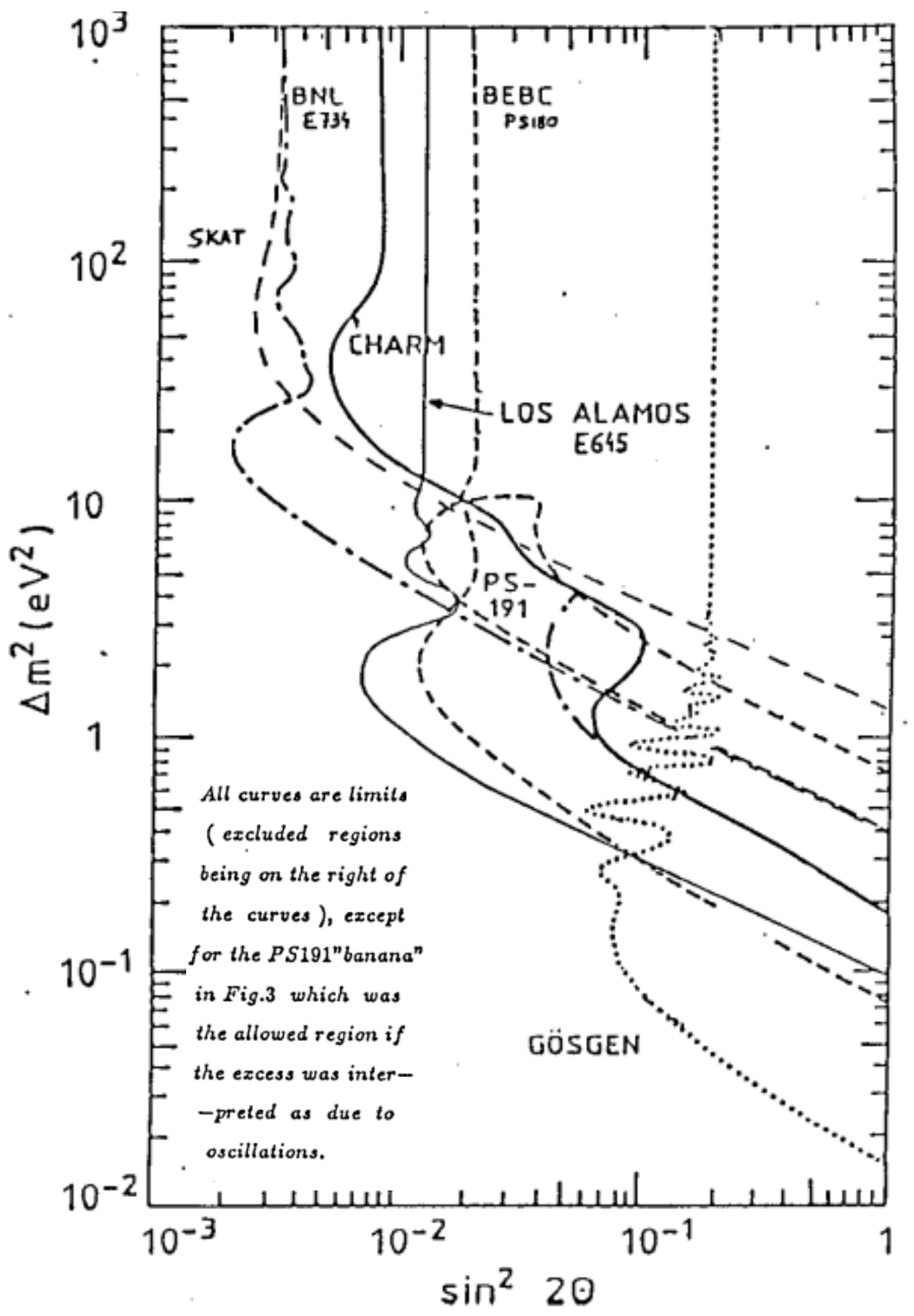
↓

CHARM (1983 PS-beam data, $\langle E_\nu \rangle \sim 1$ GeV)
SKAT ($\langle E_\nu \rangle \sim 8$ GeV)
LANL E615 (πDAR)

Excess was not seen at several other experiments.

Gregorio Bernardi, 1988 ICHEP 88. HEP-88-11



The Short-Baseline Puzzle

(Several years later…)

LSND & KARMEN

LSND: 1993 - 1998

Phys.Rev.D 64 (2001) 112007

KARMEN: 1990 - 2001

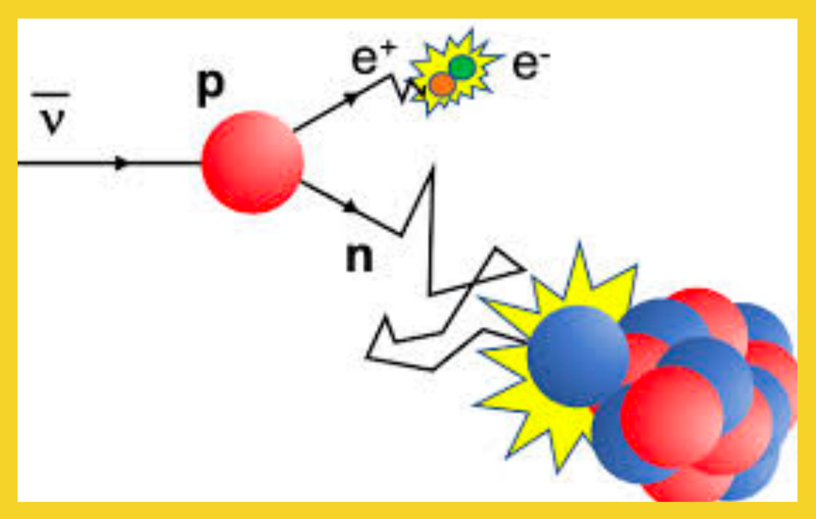
Phys.Rev.D 65 (2002) 112001

πDAR source

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

SBL oscillation

$$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$$



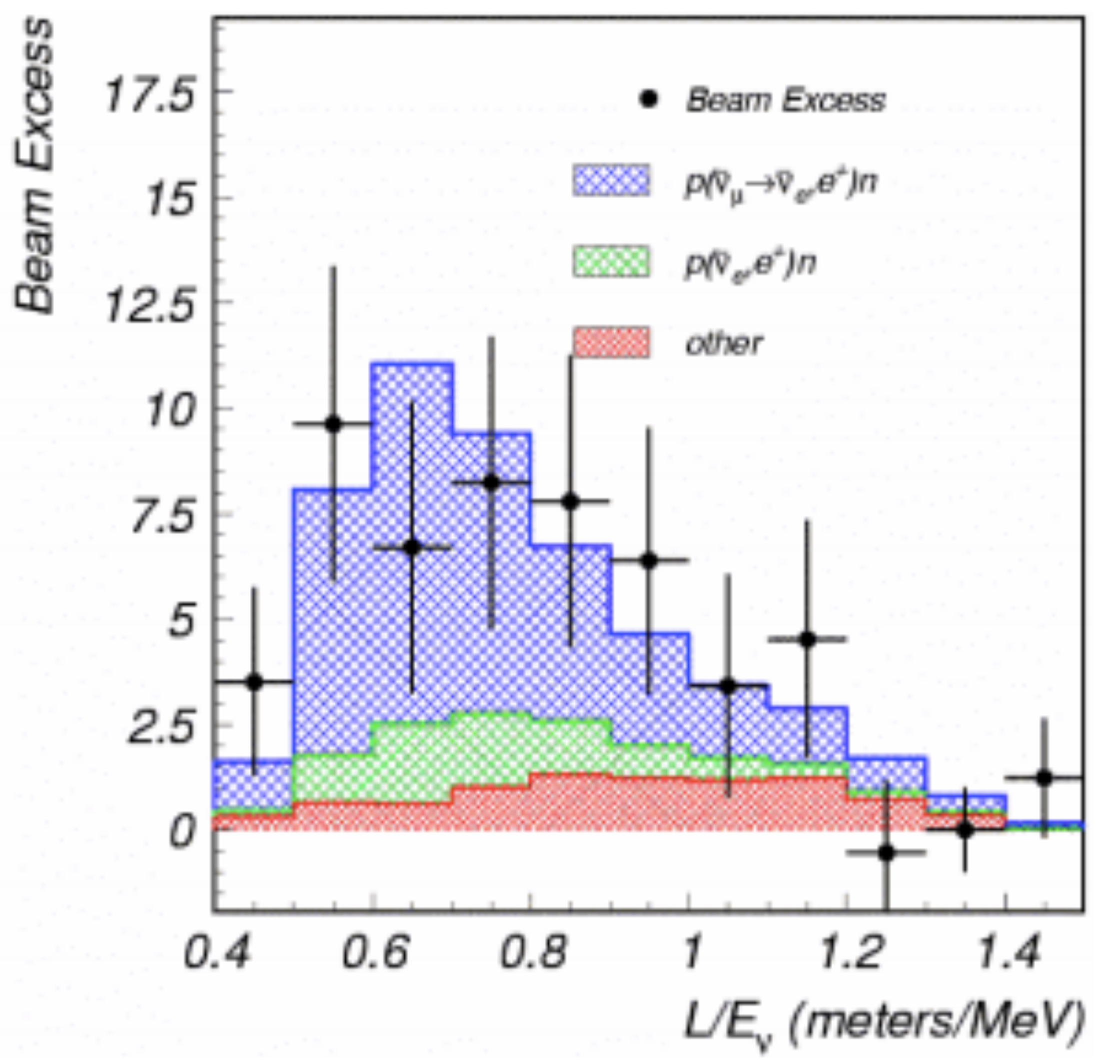
Inverse-Beta-decay detection

LSND & KARMEN

LSND: 1993 - 1998

Phys.Rev.D 64 (2001) 112007

1) 800 MeV proton beam, 1.8e23 POT.
2) π DAR and DIF:12º nu/p beam angle.
3) π- contamination: $\bar{\nu}_e/\bar{\nu}_\mu \sim 8 \times 10^{-4}$
4) Baseline of 30 m
5) ~167 tonnes of liquid scintillator
6) 8.3 m long detector.

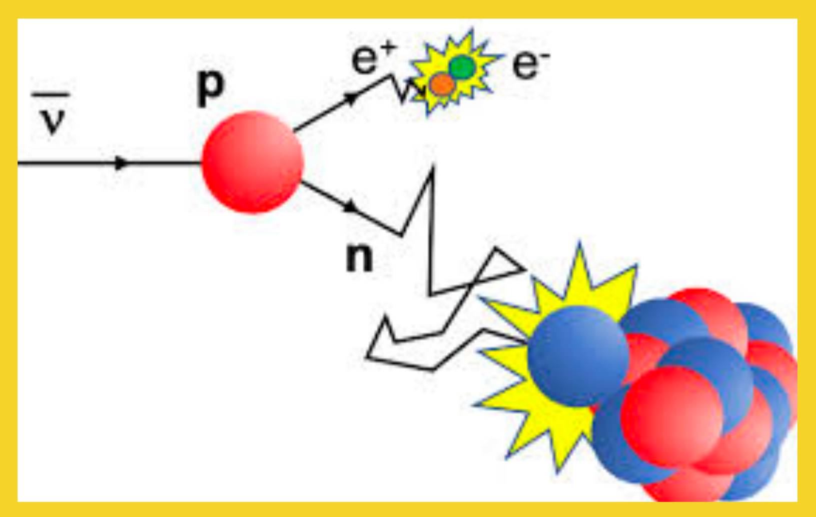


Excess: $87.9 \pm 22.4 \pm 6$ events
3.8σ significance

πDAR source

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

SBL oscillation $\quad \bar{\nu}_\mu \to \bar{\nu}_e$



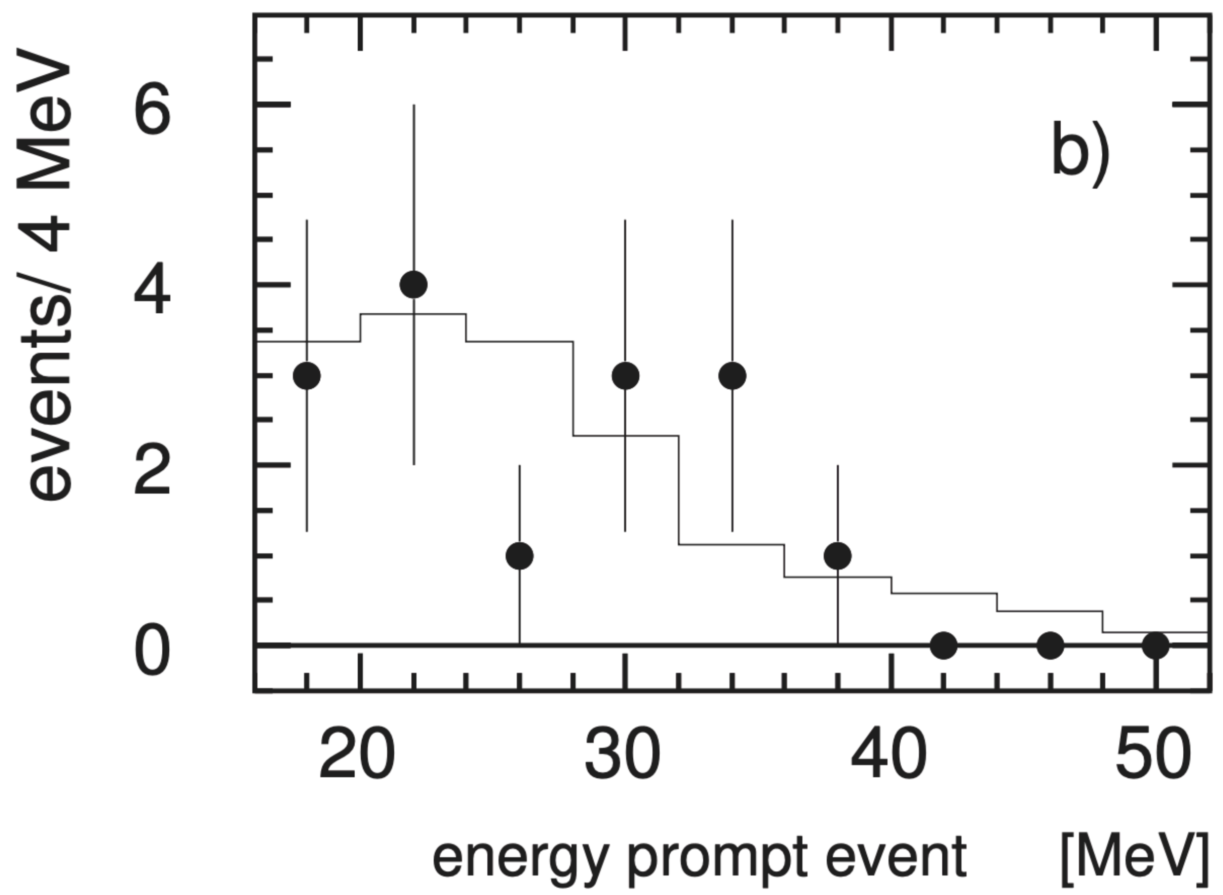
Inverse-Beta-decay detection

We needed more data.

KARMEN: 1990 - 2001

Phys.Rev.D 65 (2002) 112001

1) 800 MeV proton beam, 6e22 POT.
2) π mostly DAR. Detector 90º from p beam.
3) π- contamination: $\bar{\nu}_e/\bar{\nu}_\mu = 6.4 \cdot 10^{-4}$
4) Baseline of 17.7 m
5) ~57 tonnes of liquid scintillator
6) 3.5 m long detector.

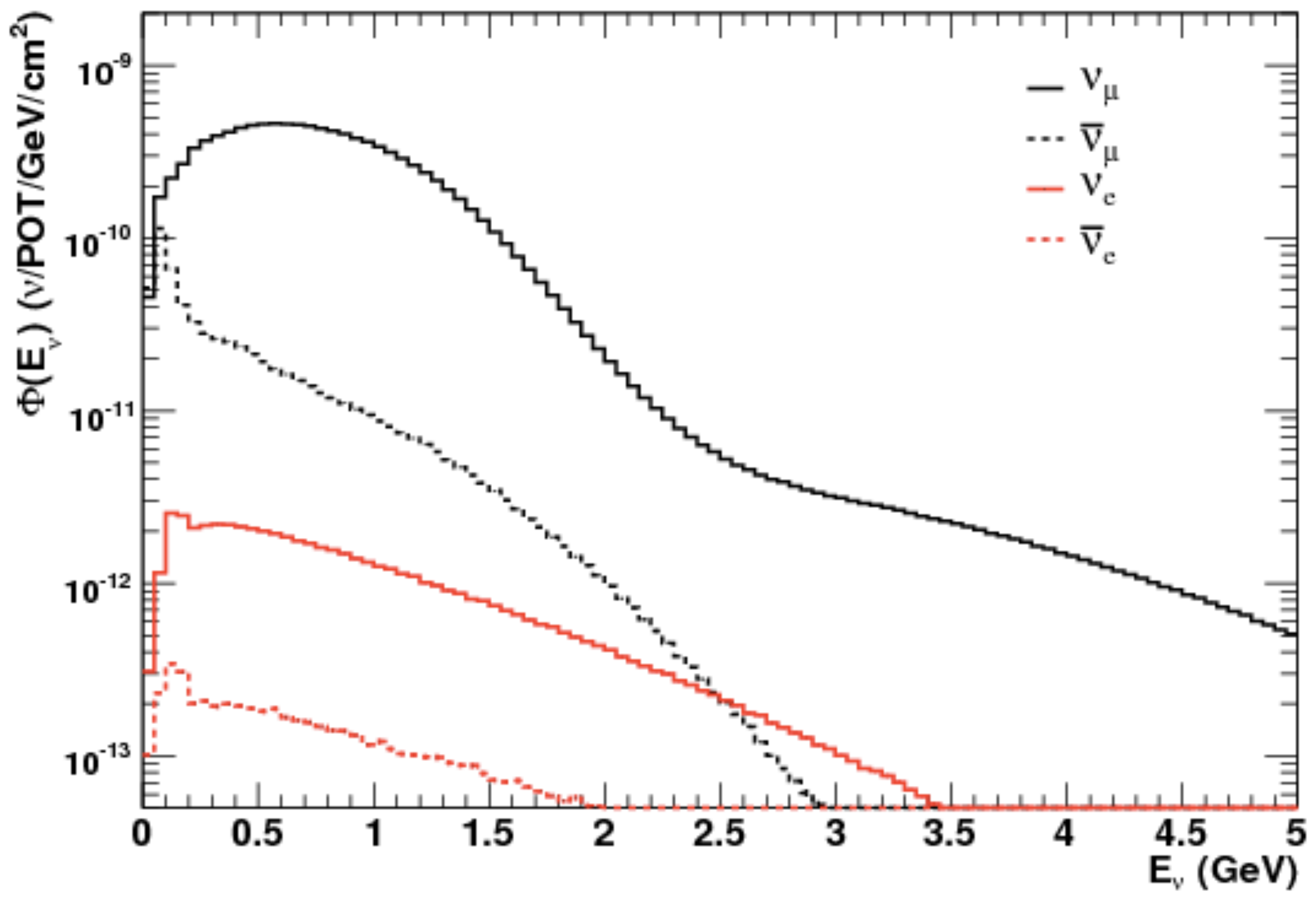


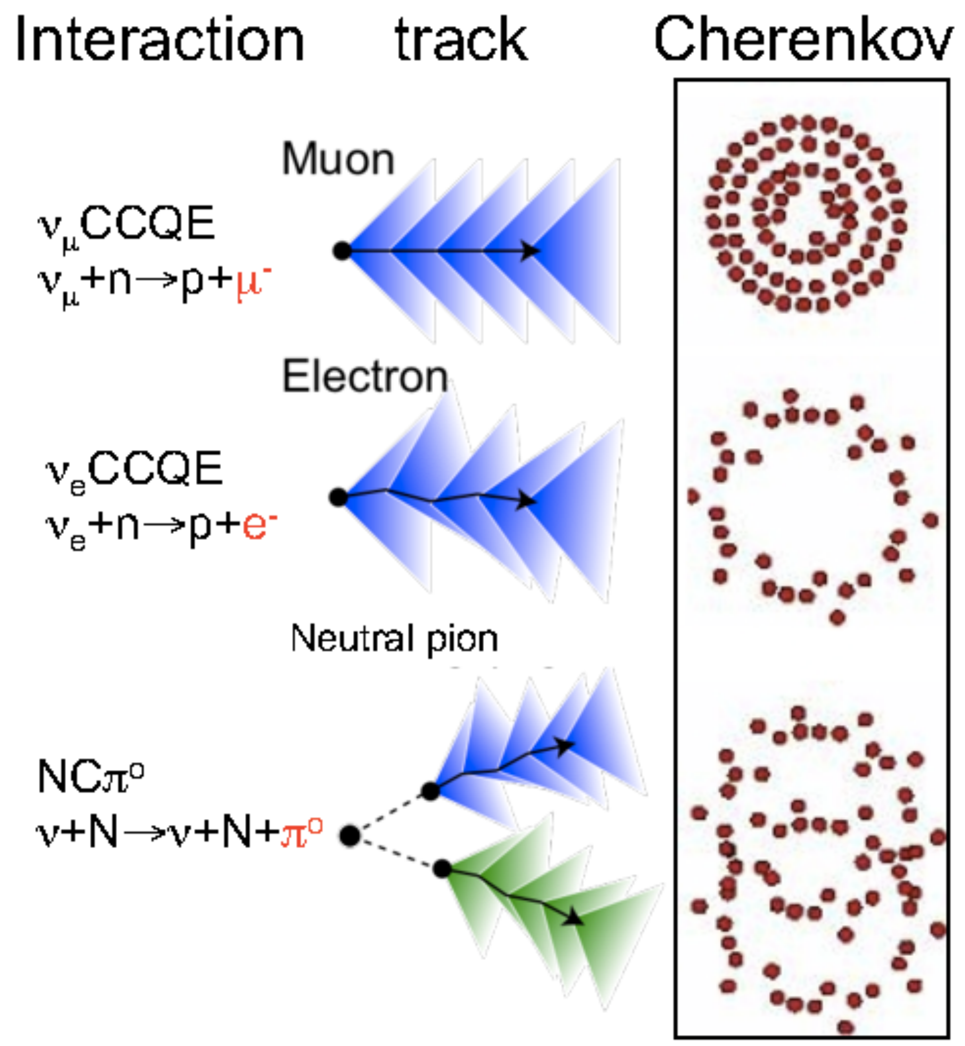
No excess observed,
but could not exclude LSND results.

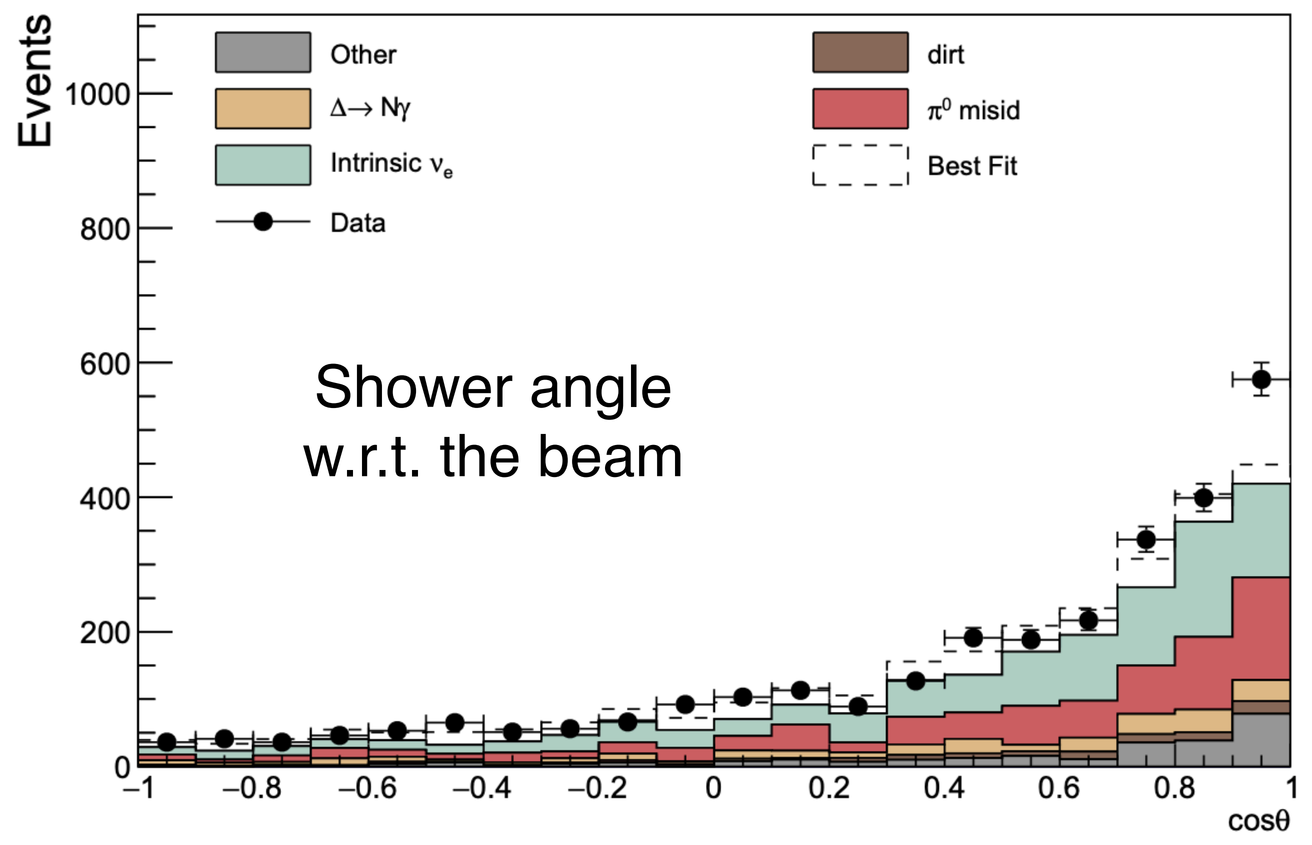
Latest MiniBooNE results:

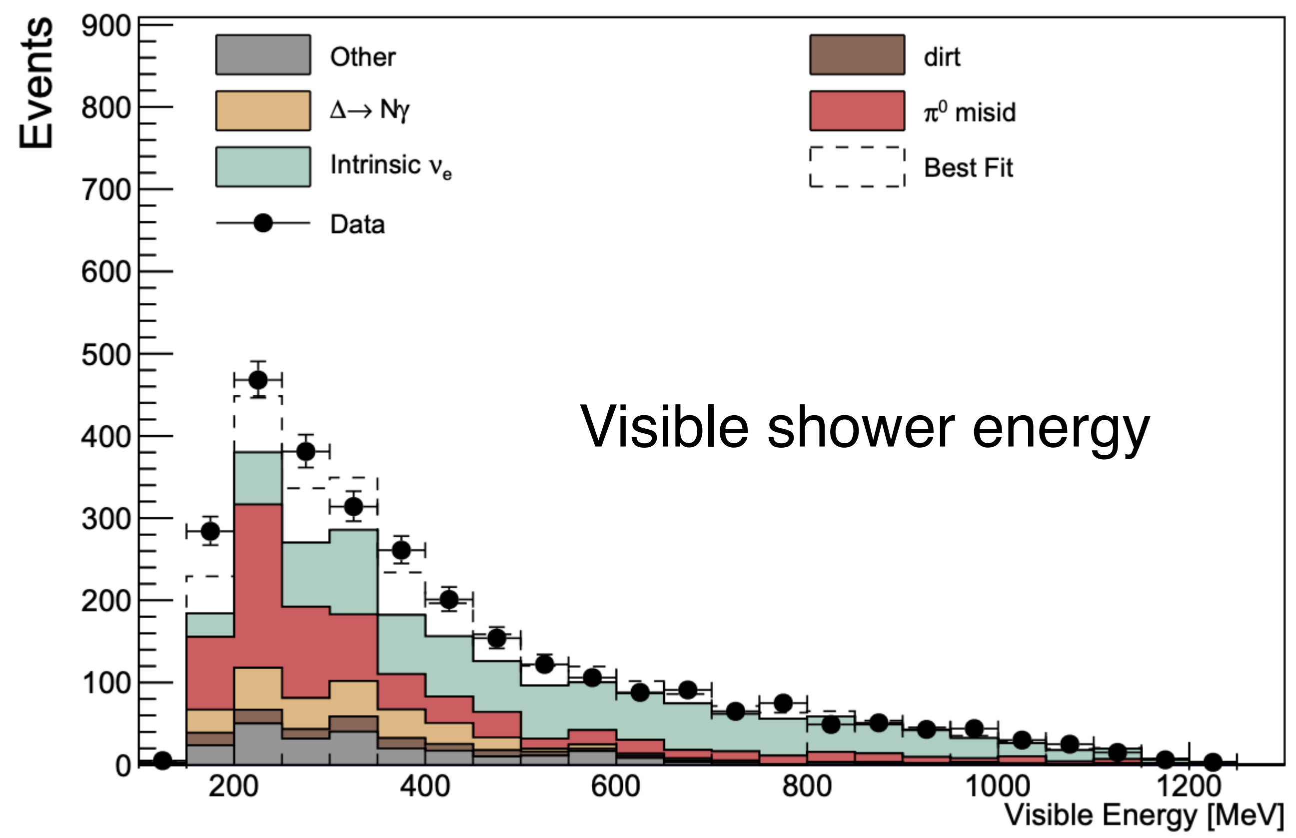
MiniBooNE coll., Phys. Rev. D 103, 052002 (2021)

MiniBooNE Collaboration, 0806.1449









To this day, the most sensitive SBL $\nu_\mu \to \nu_e$ appearance experiment.

638 ± 52 (stat.) $\pm$ 122.2 (sys.)

4.8σ significance
Systematics limited

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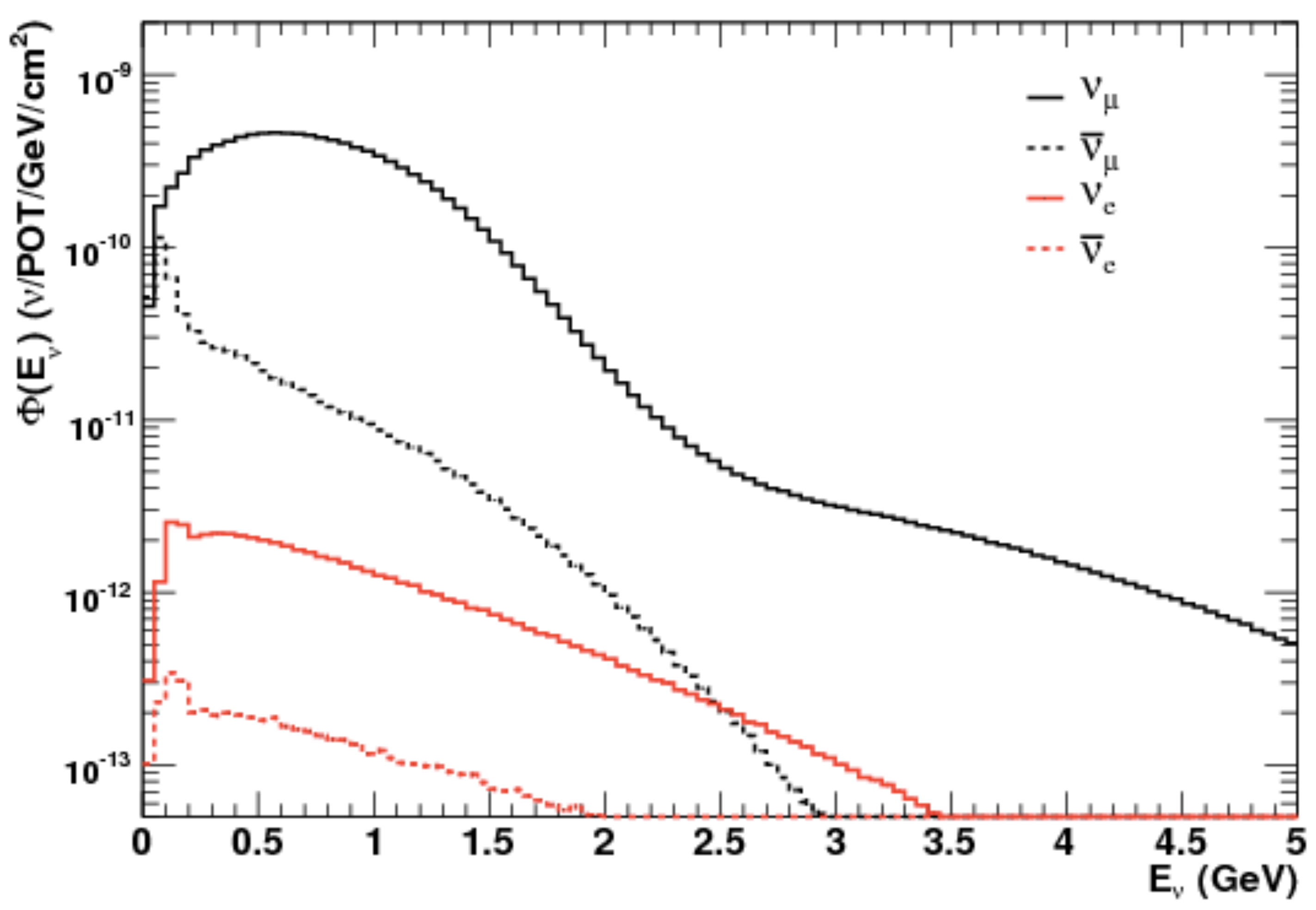

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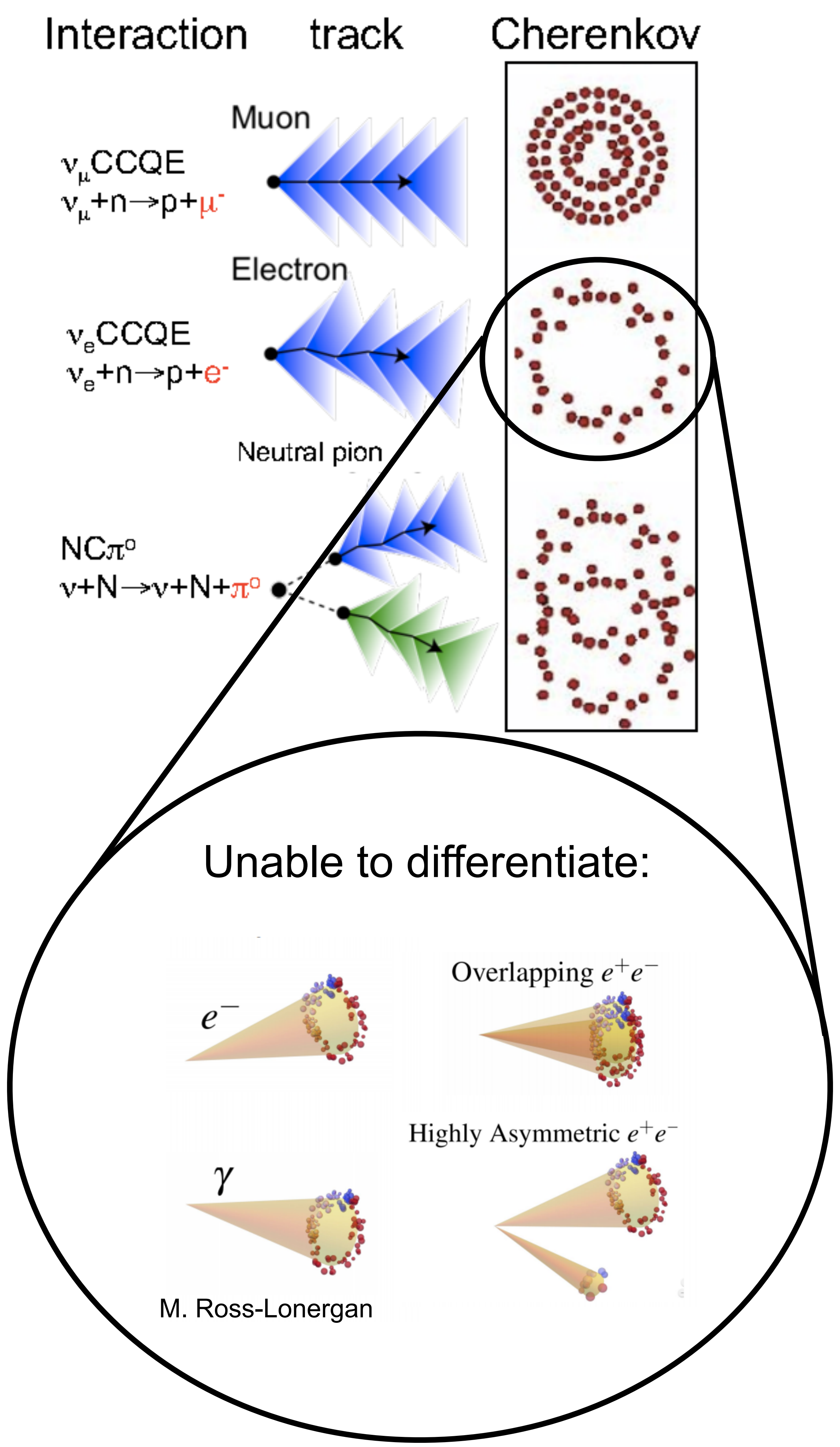

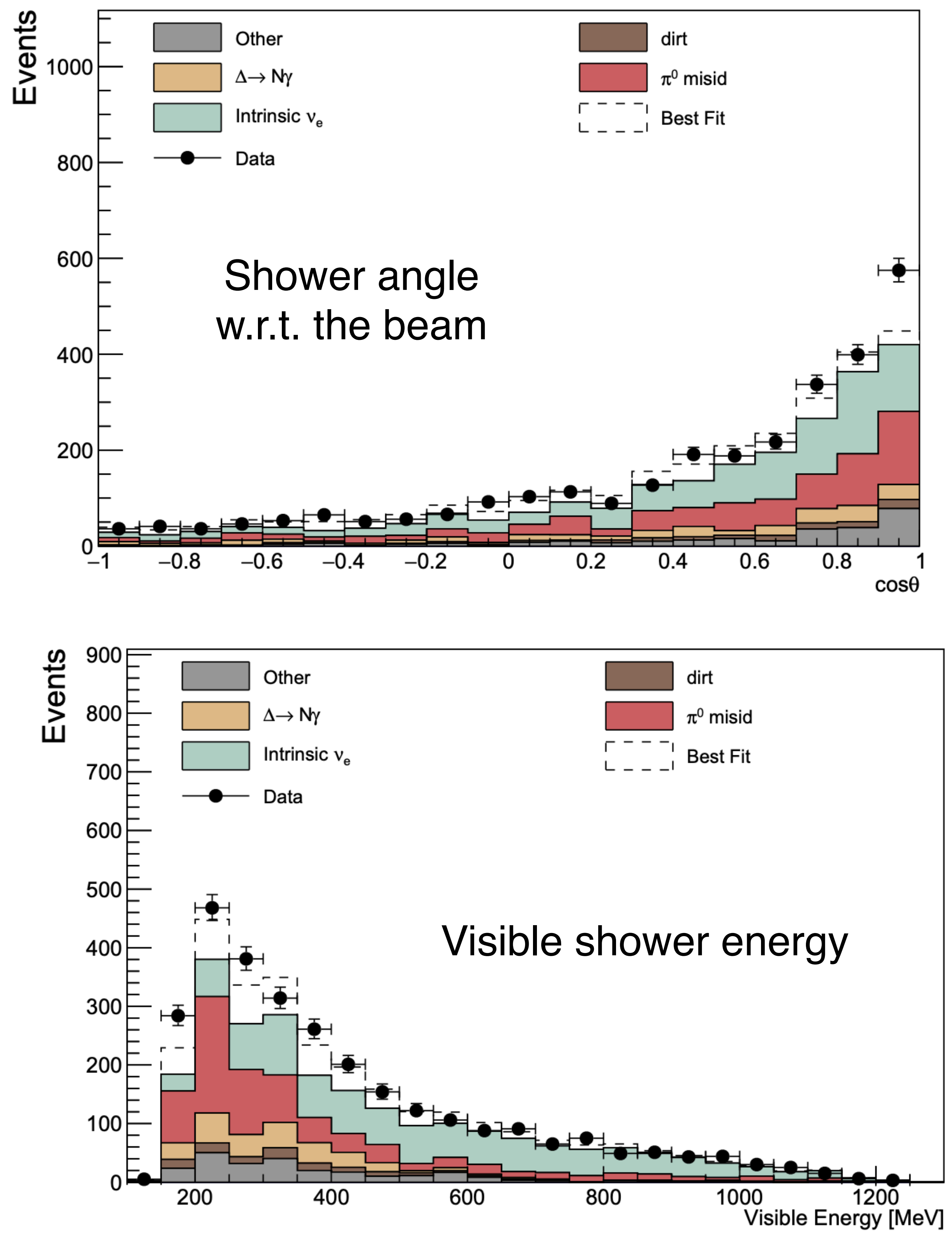

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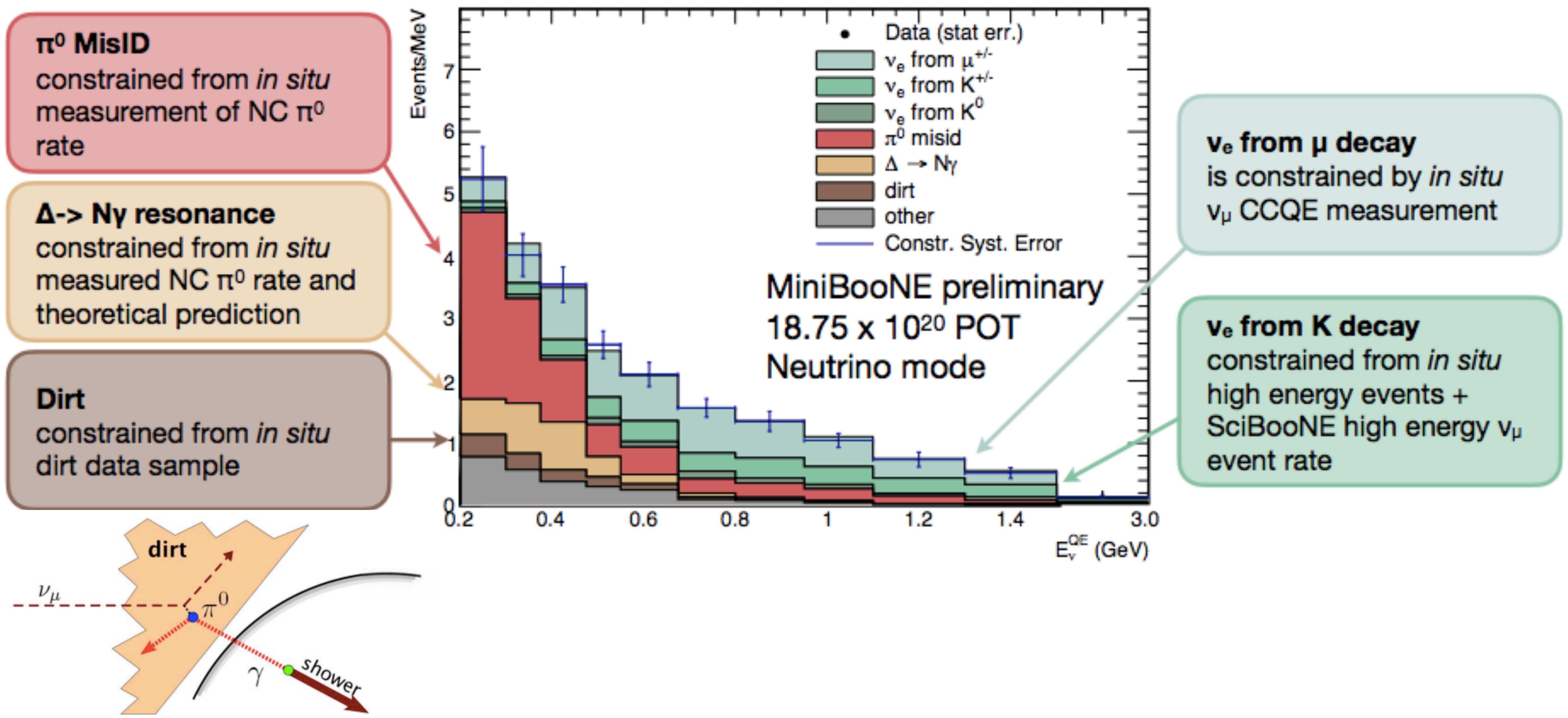
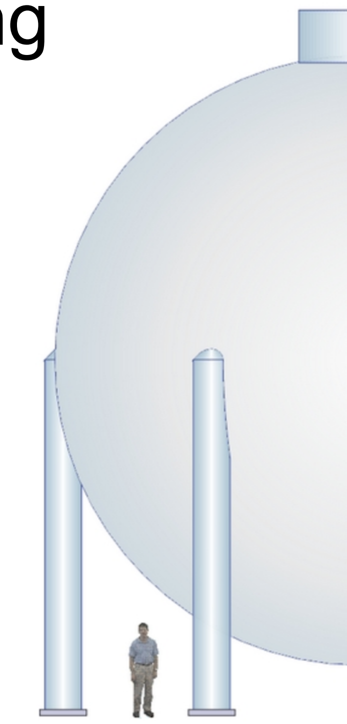
Data-Driven Background Estimates

Hourlier, Adrien, MiniBooNE Coll. Neutrino2020

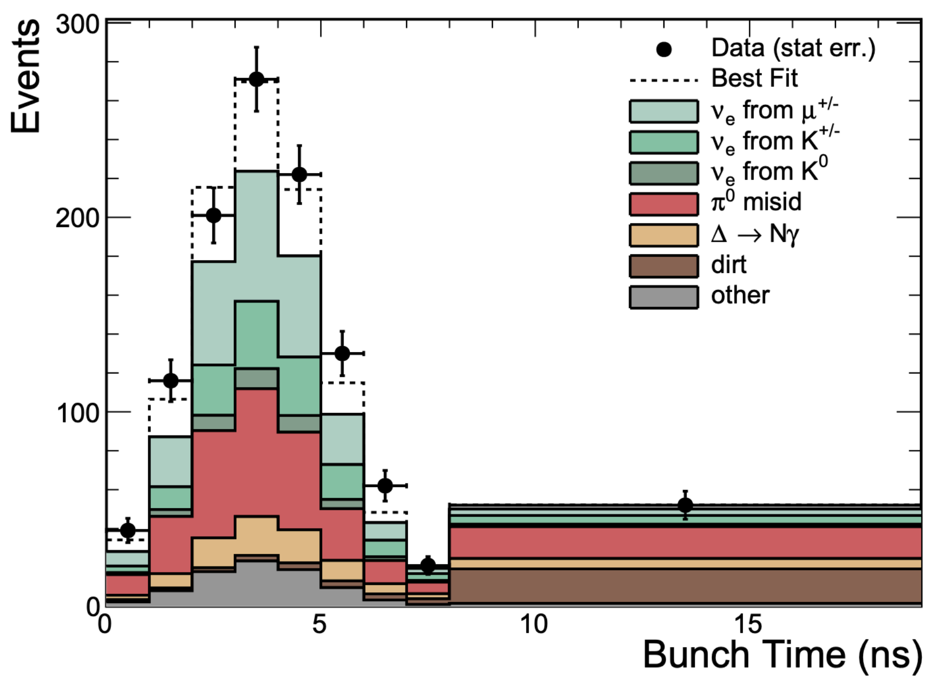


1) Significance increases when restricting to smaller fiducial volume

Selection	Excess	Significance
$R < 5$ m	560.6 ± 119.6	4.7σ
$R < 4$ m	$458.6 \pm 81.9.5$	5.6σ
$R < 3$ m	190.1 ± 41.2	4.6σ



2) Excess overlaps w/ beam time



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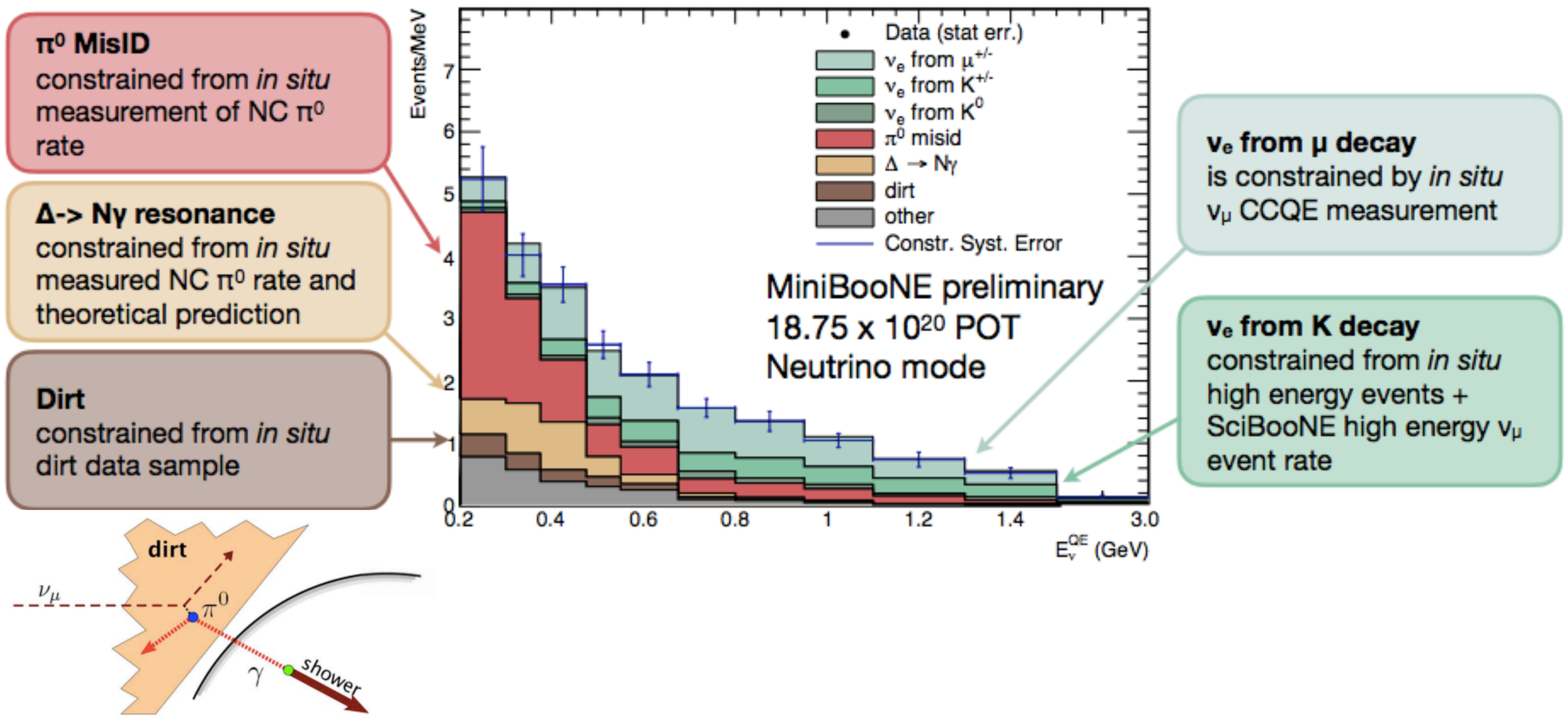

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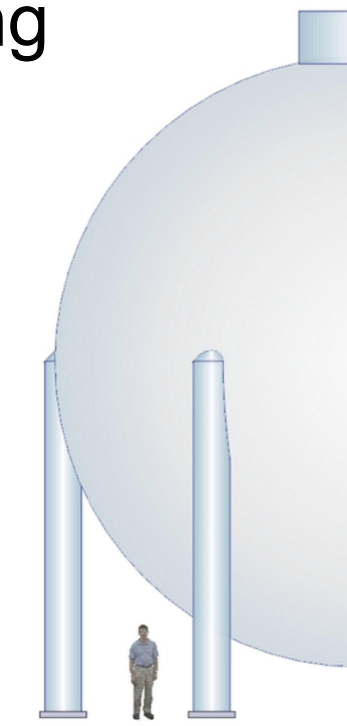

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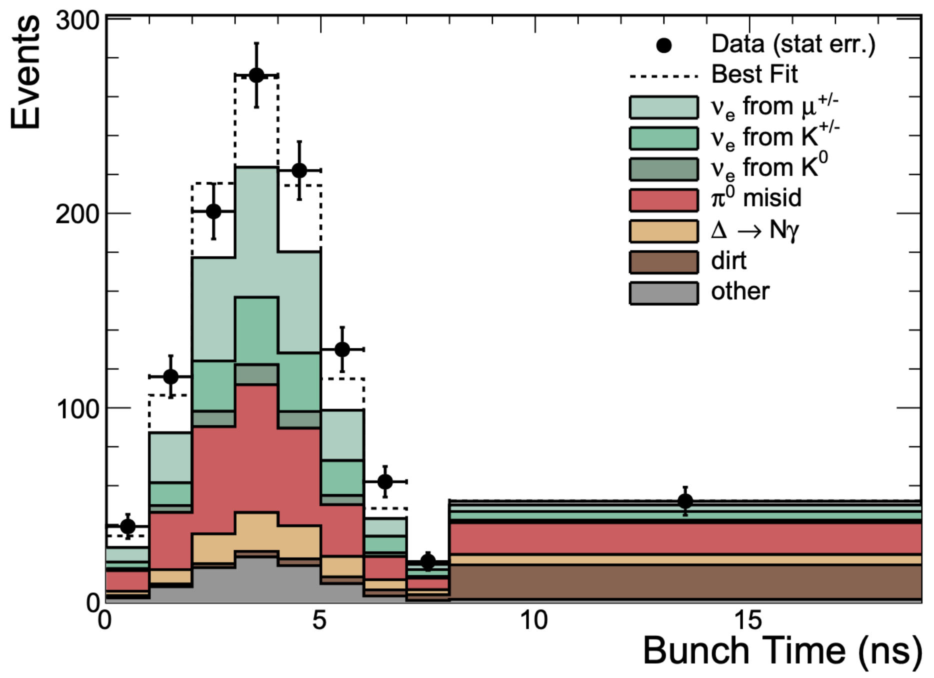


An Altarelli Cocktail for the MiniBooNE Anomaly?

Vedran Brdar[1,2,a] and Joachim Kopp[3,4,b]

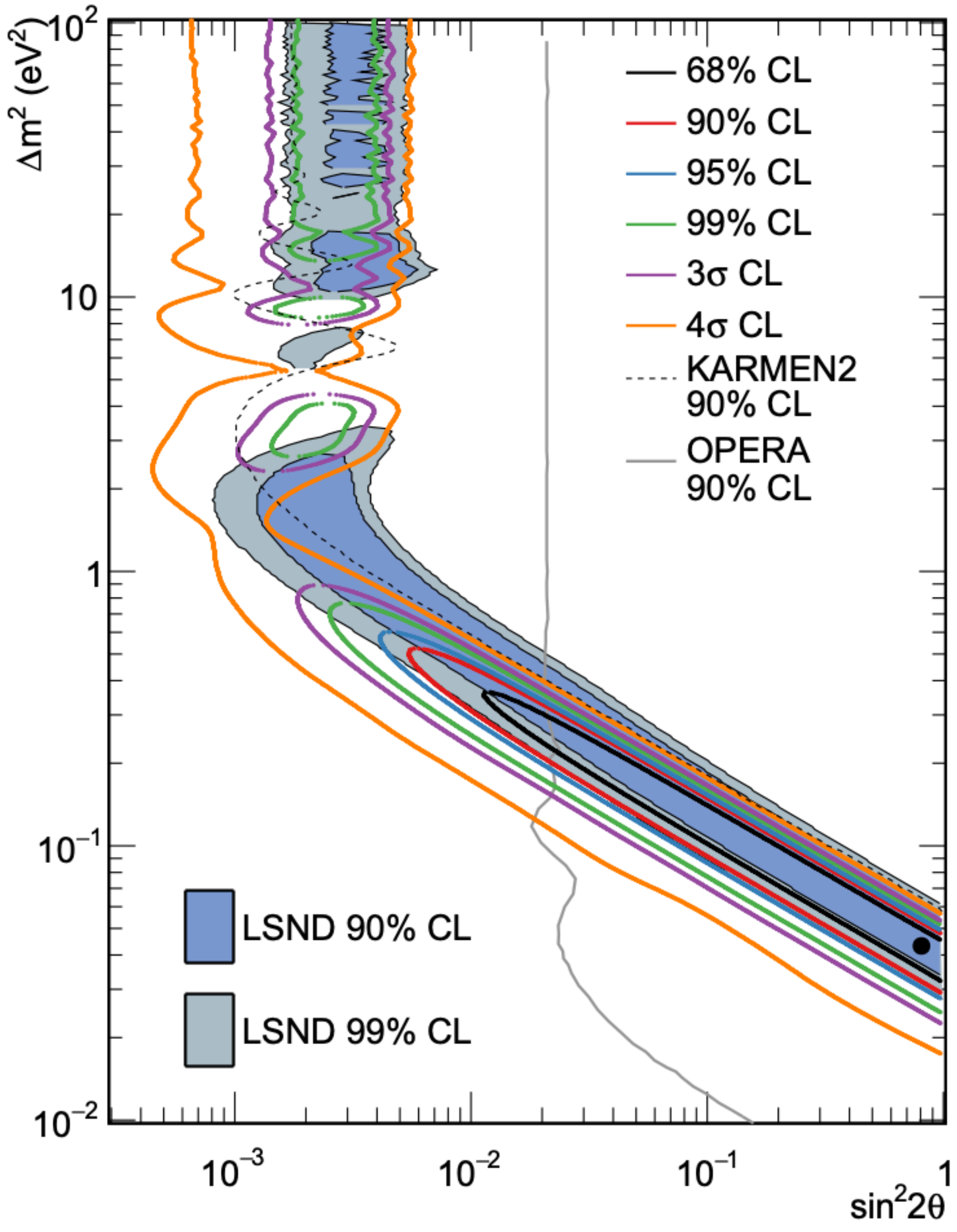
arxiv:2109.08157

→

We find that not even a combination of uncertainties in different channels adding up unfavorably (an "Altarelli cocktail") appears to be sufficient to resolve the MiniBooNE anomaly. Varying the radiative branching ratios of the Δ(1232) and N(1440) resonances by ±2σ, however, reduces its significance from 4σ to less than 3σ.

Is there enough evidence for a sterile neutrino?

A $\nu_\mu \to \nu_e$ **appearance** oscillation implies
ν_e and ν_μ disappearance.



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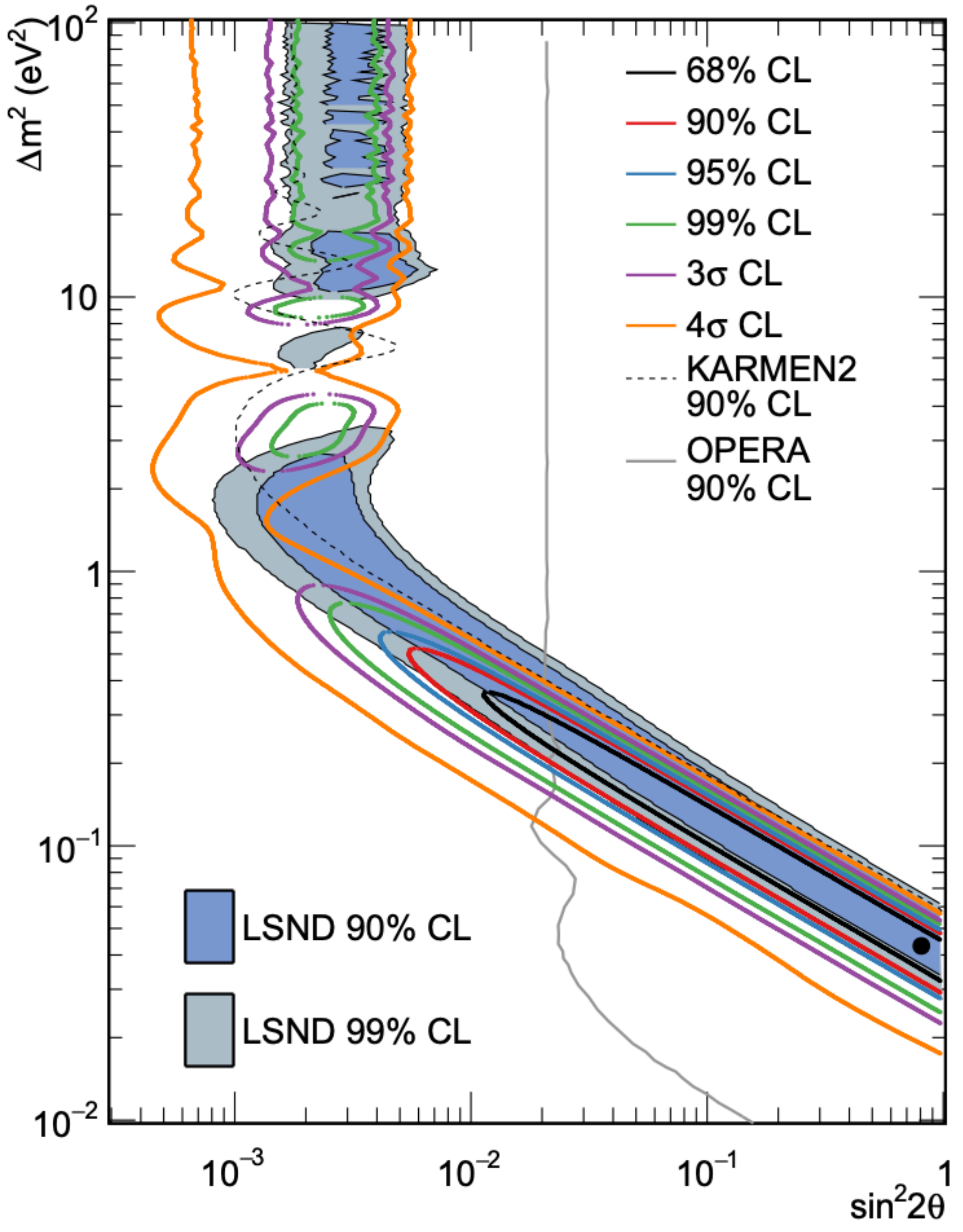
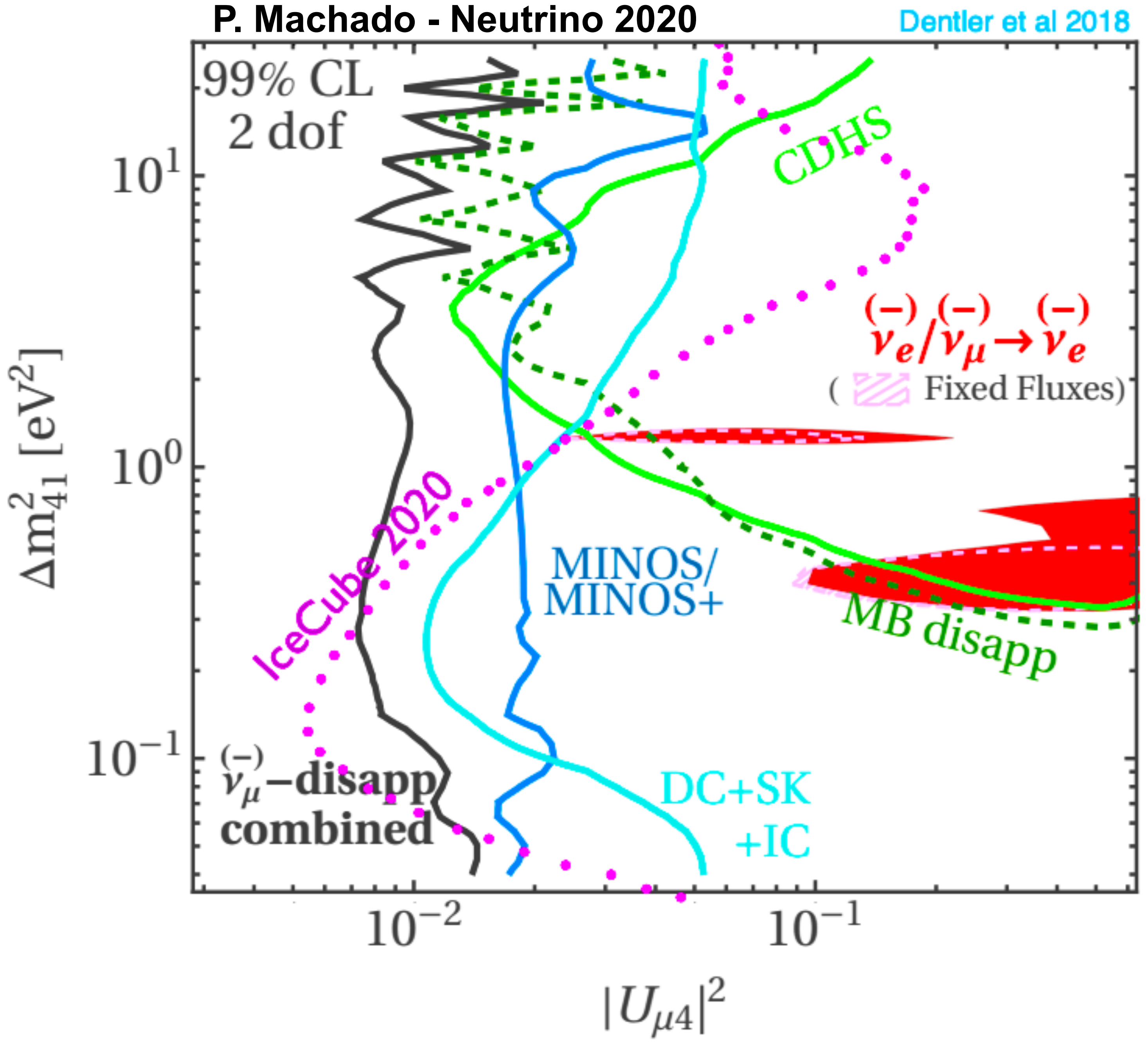
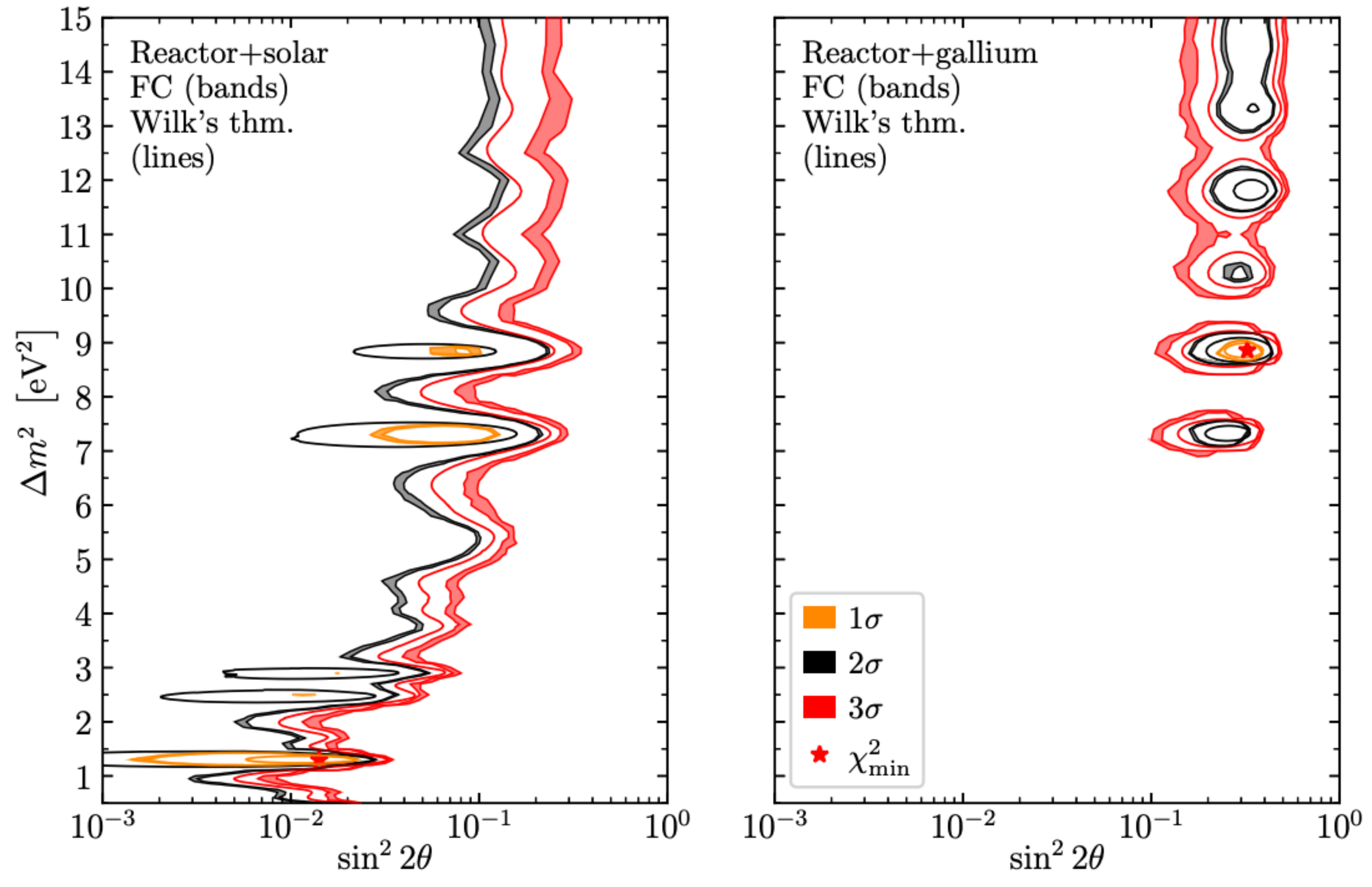




No ν_μ disappearance is observed,

Latest global-fit by J. M. Berryman et al, arXiv:2111.12530



Reactors and gallium experiments have been seeing (different) deficits in neutrino flux.

No single experiment gives conclusive evidence.

Inconclusive.

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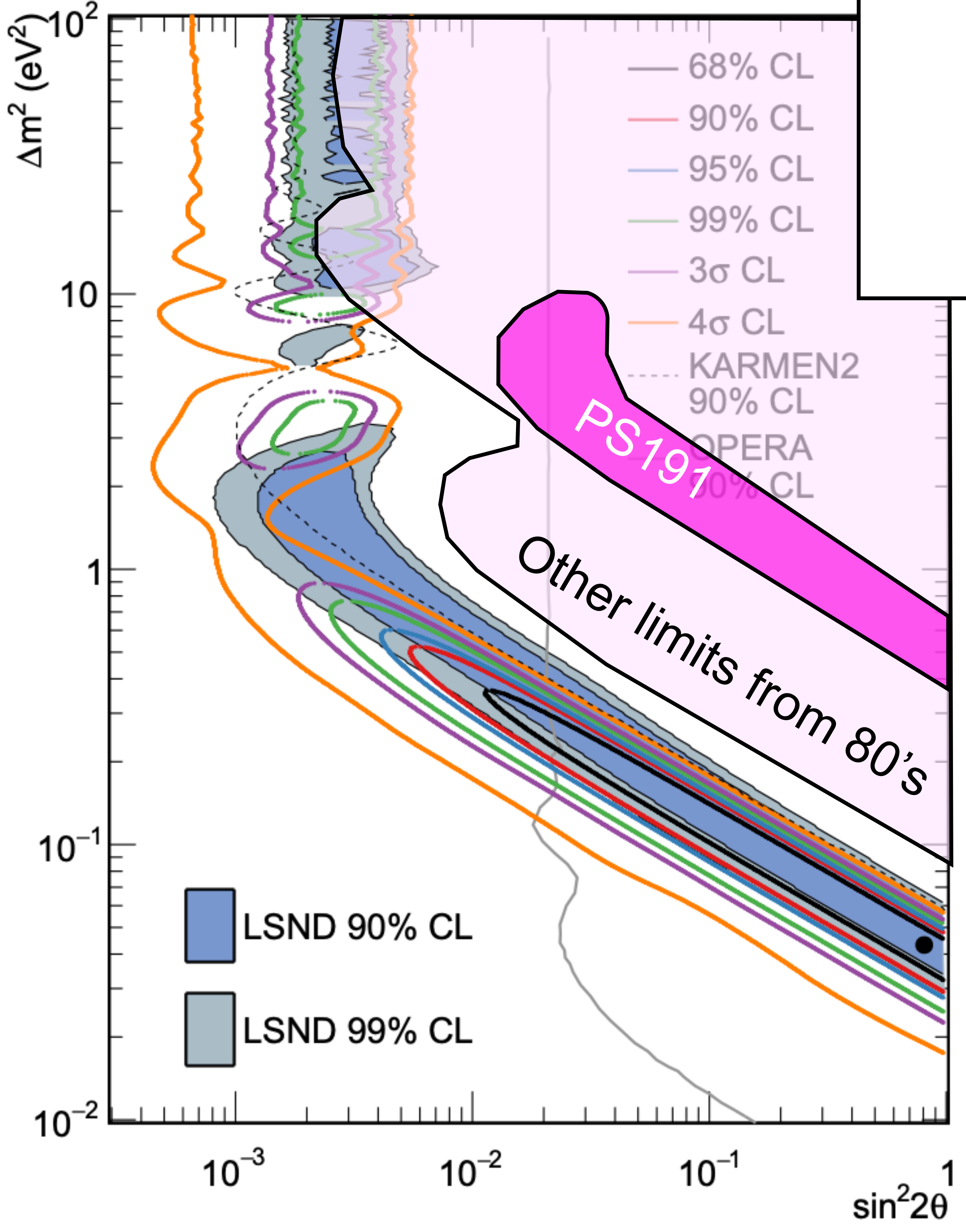

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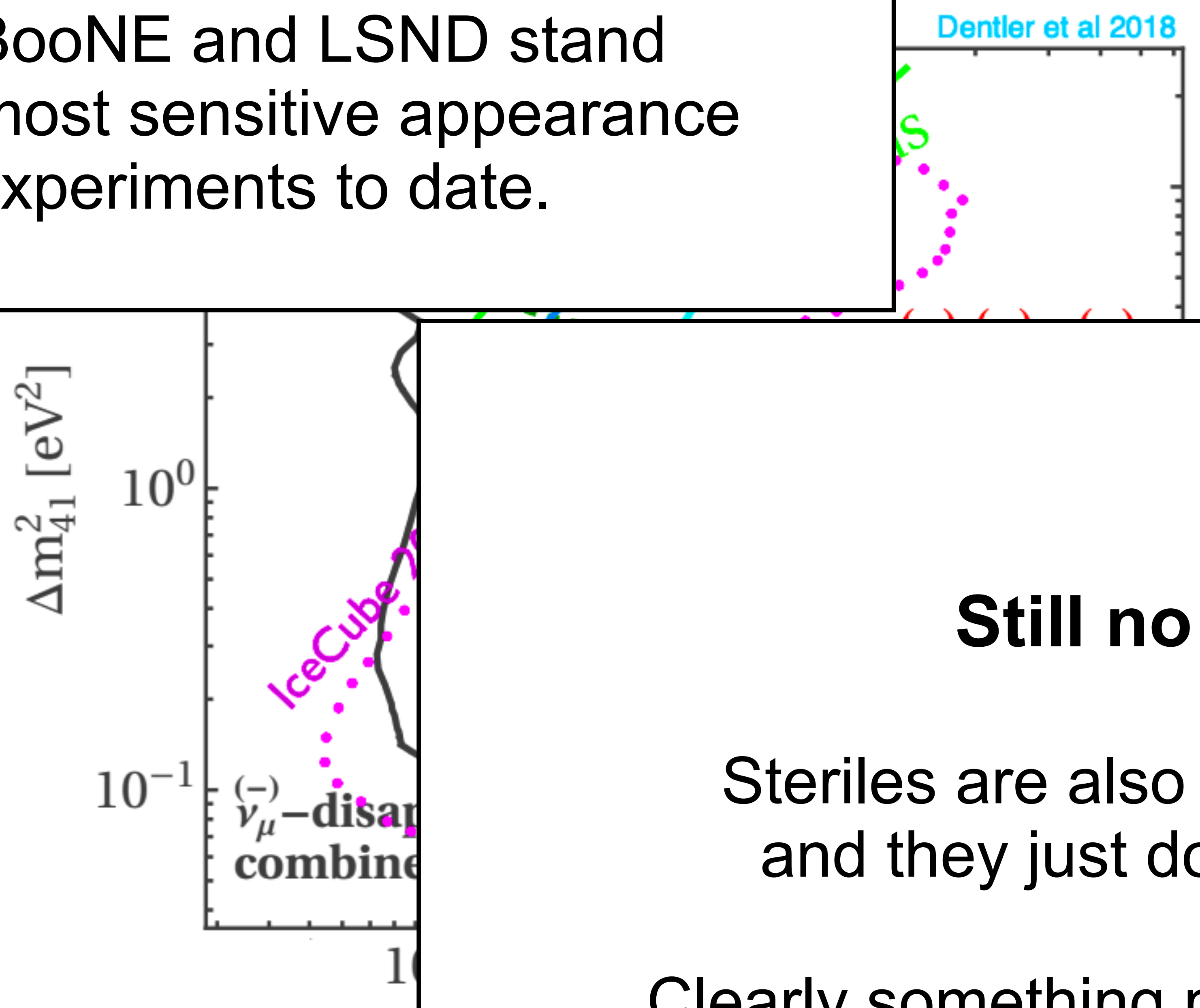
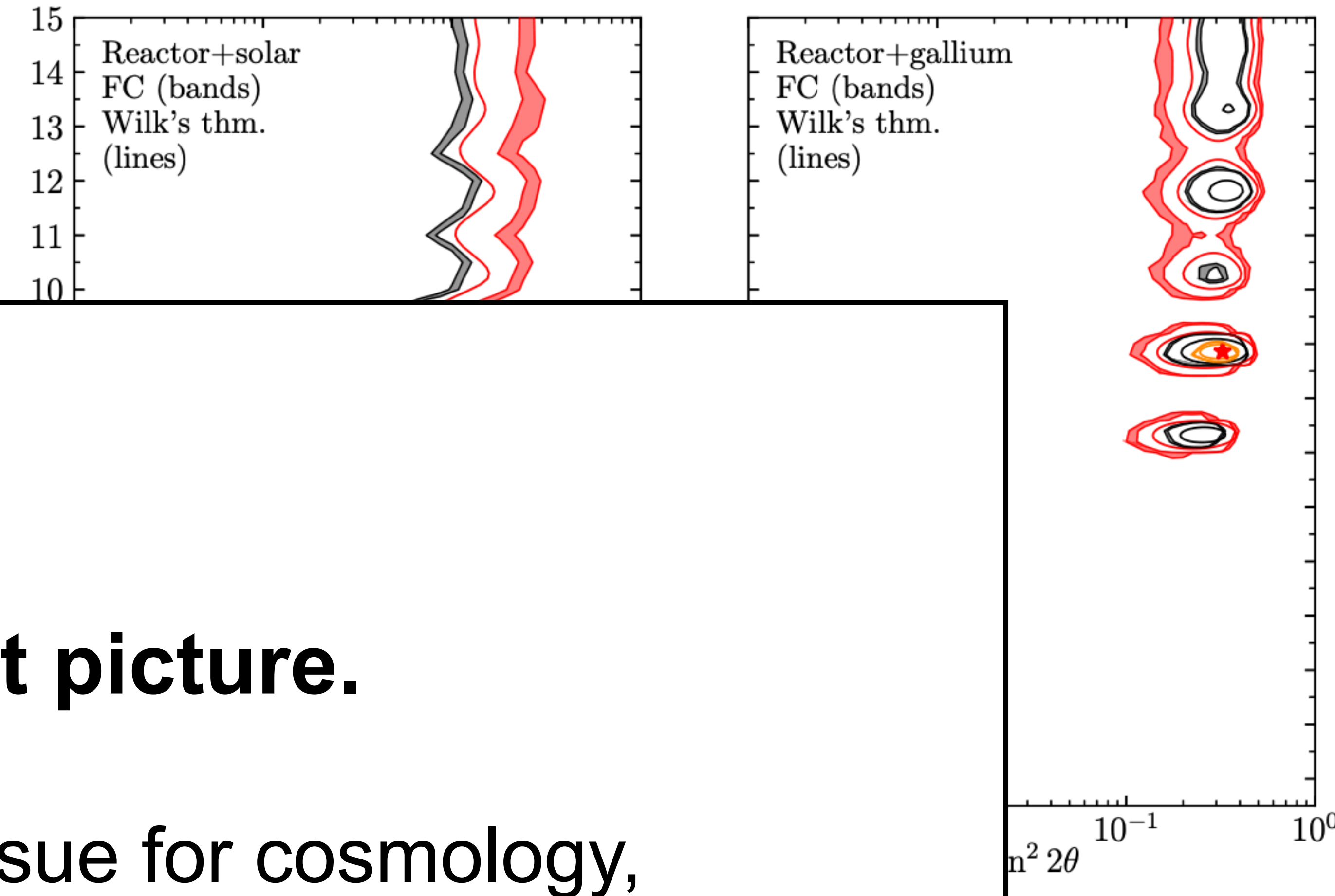


No ν_μ

+

ν_e disappearance

Latest global-fit by J. M. Berryman et al, arXiv:2111.12530



have been
trino flux.

ive evidence.

(1)

Huge progress.

MiniBooNE and LSND stand
as the most sensitive appearance
experiments to date.

(2)

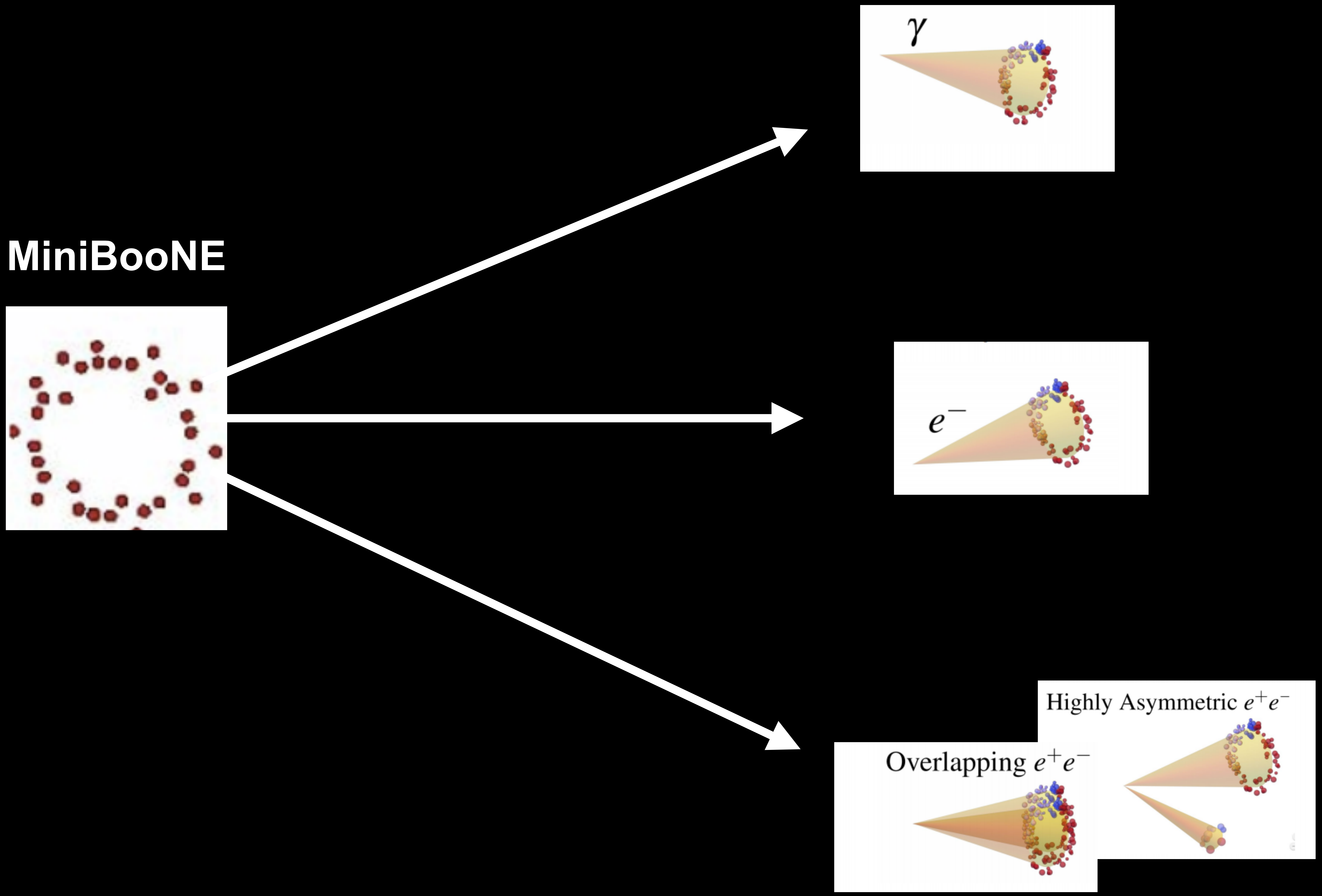
Still no coherent picture.

Steriles are also a major issue for cosmology,
and they just do not fit the global data well.

Clearly something more complicated is happening.

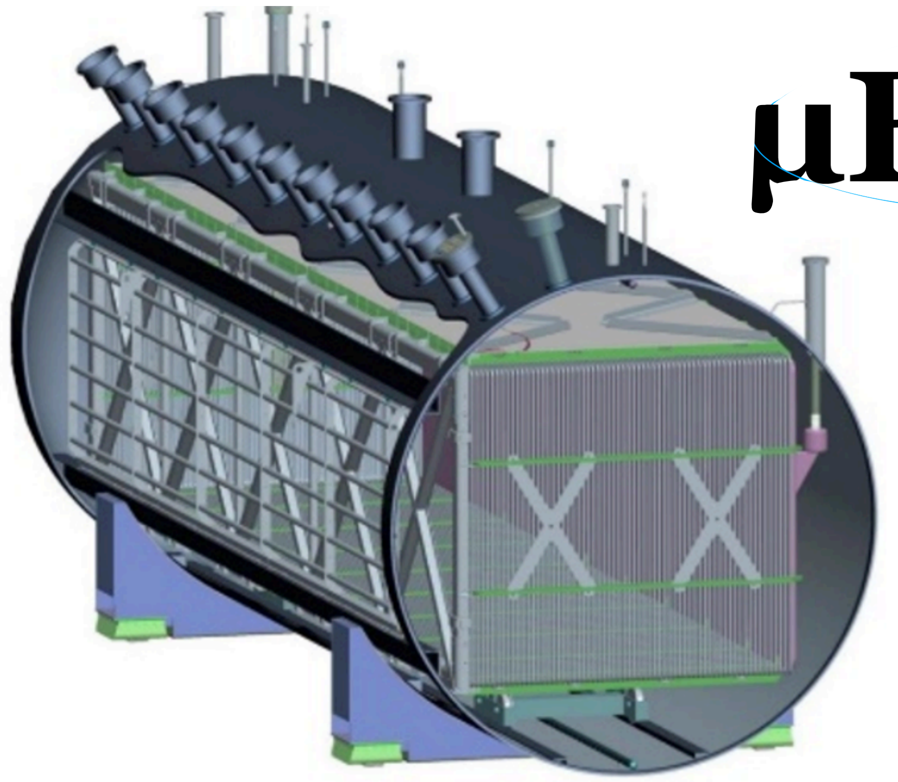
We needed a new generation of experimental searches.

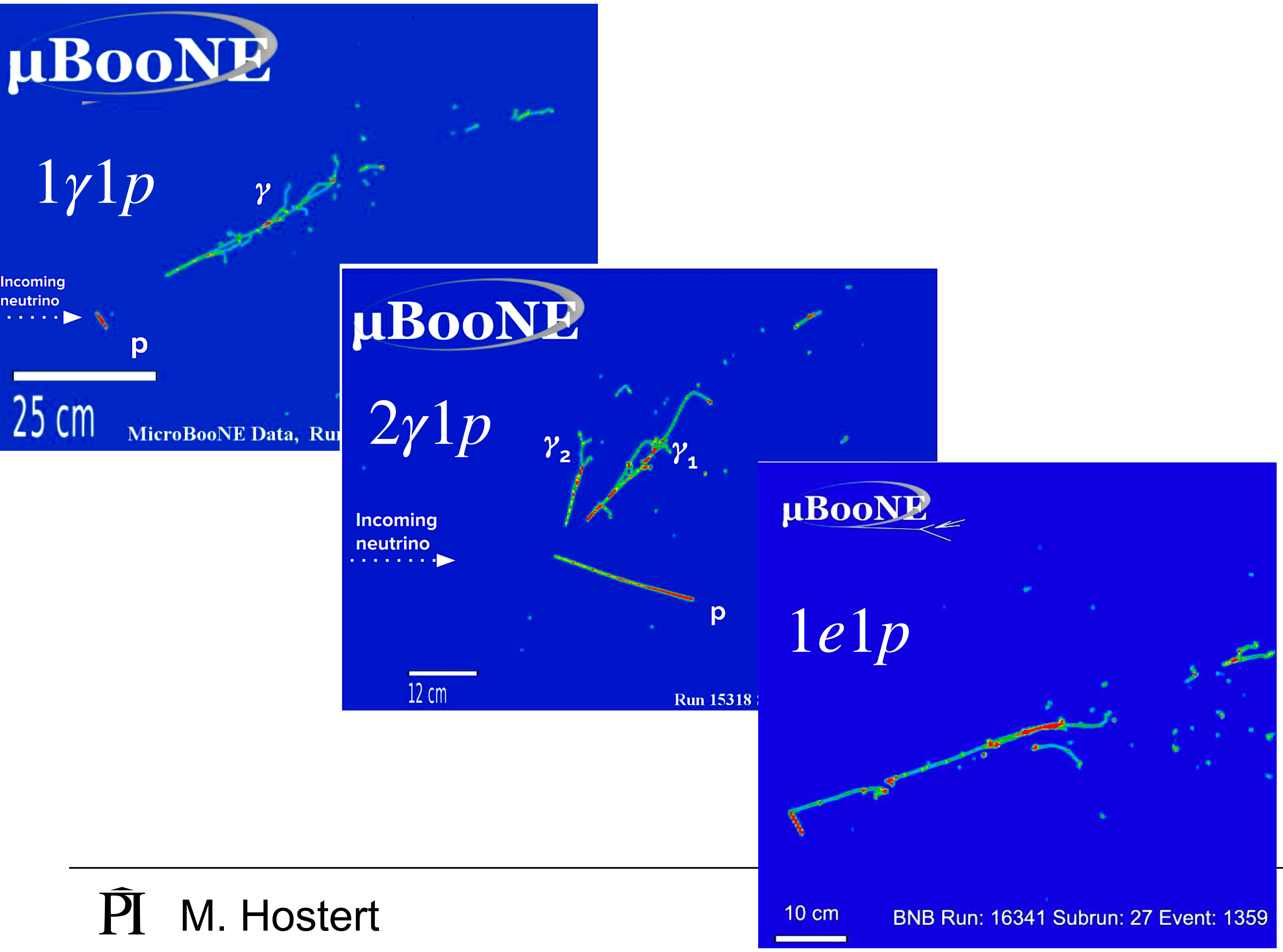
Latest results from MicroBooNE



MicroBooNE

Disentangling the final states behind the low-energy excess



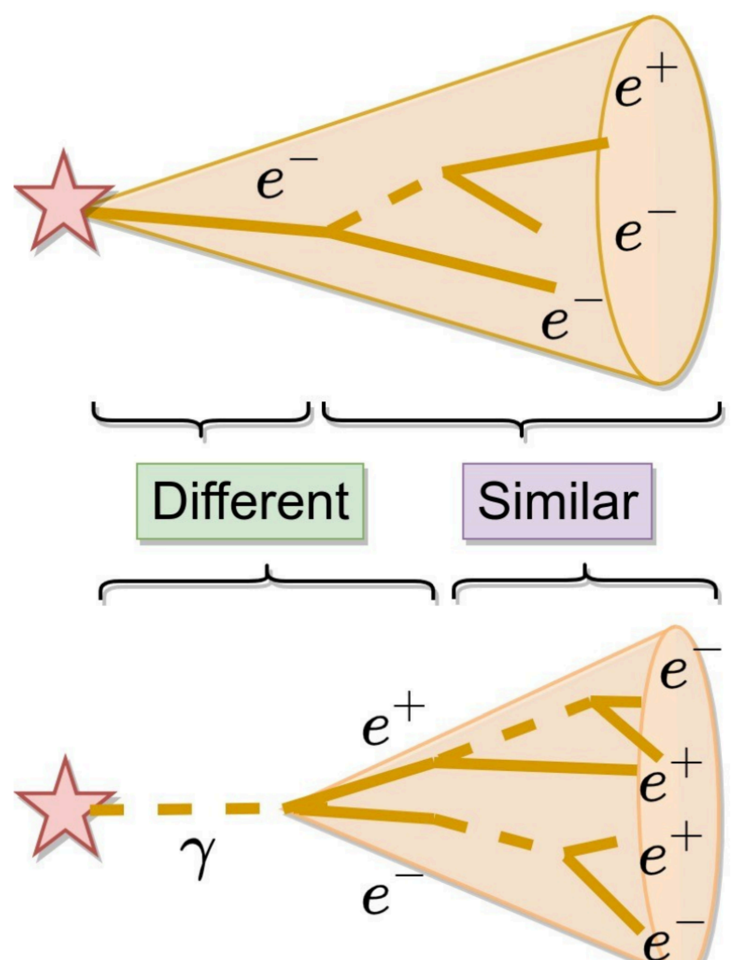


Liquid-Argon Time-Projection-Chamber (TPC)

3D images of charged particles produced in neutrino interactions

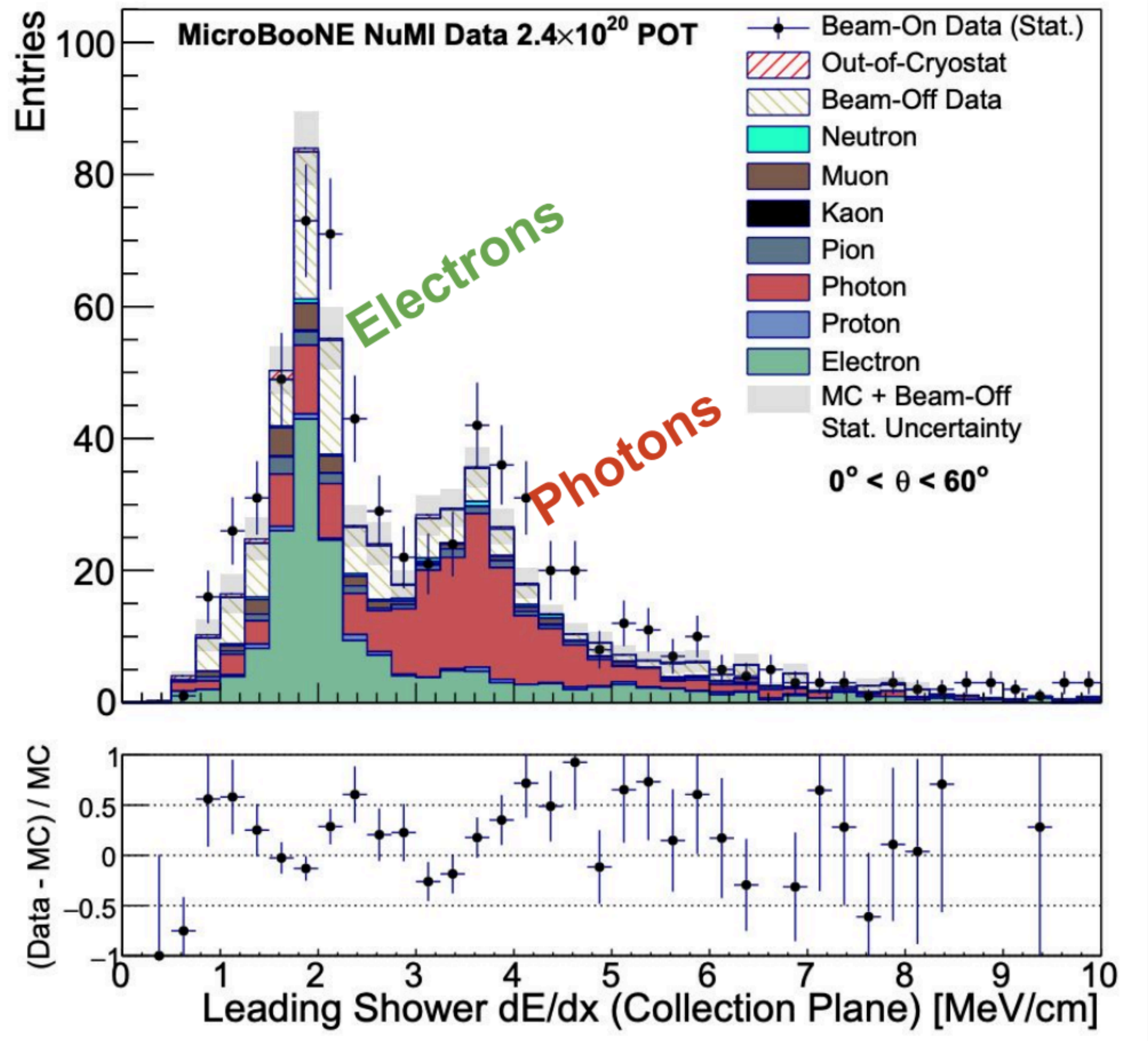
MicroBooNE is able to differentiate between electrons and photons:

I) vertex-shower separation



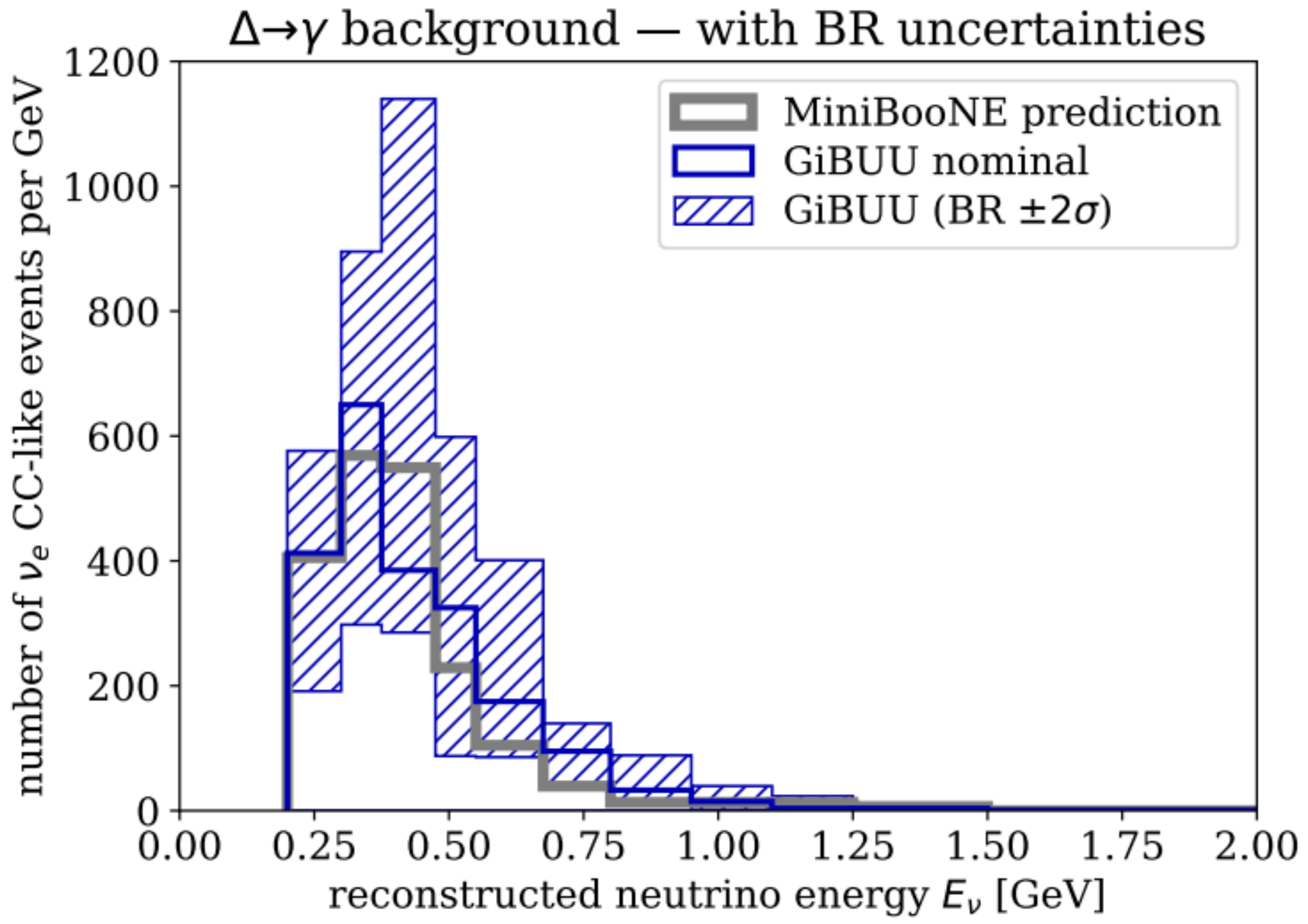
Wouter Van De Pontseele

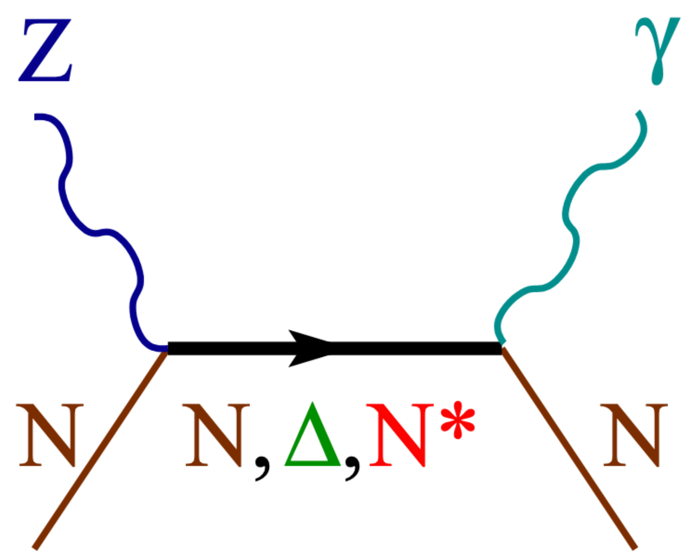
ii) dE/dx at the beginning of the shower



Single-photon results
Δ(1232) radiative decay

V. Brdar and J. Kopp, arxiv:2109.08157





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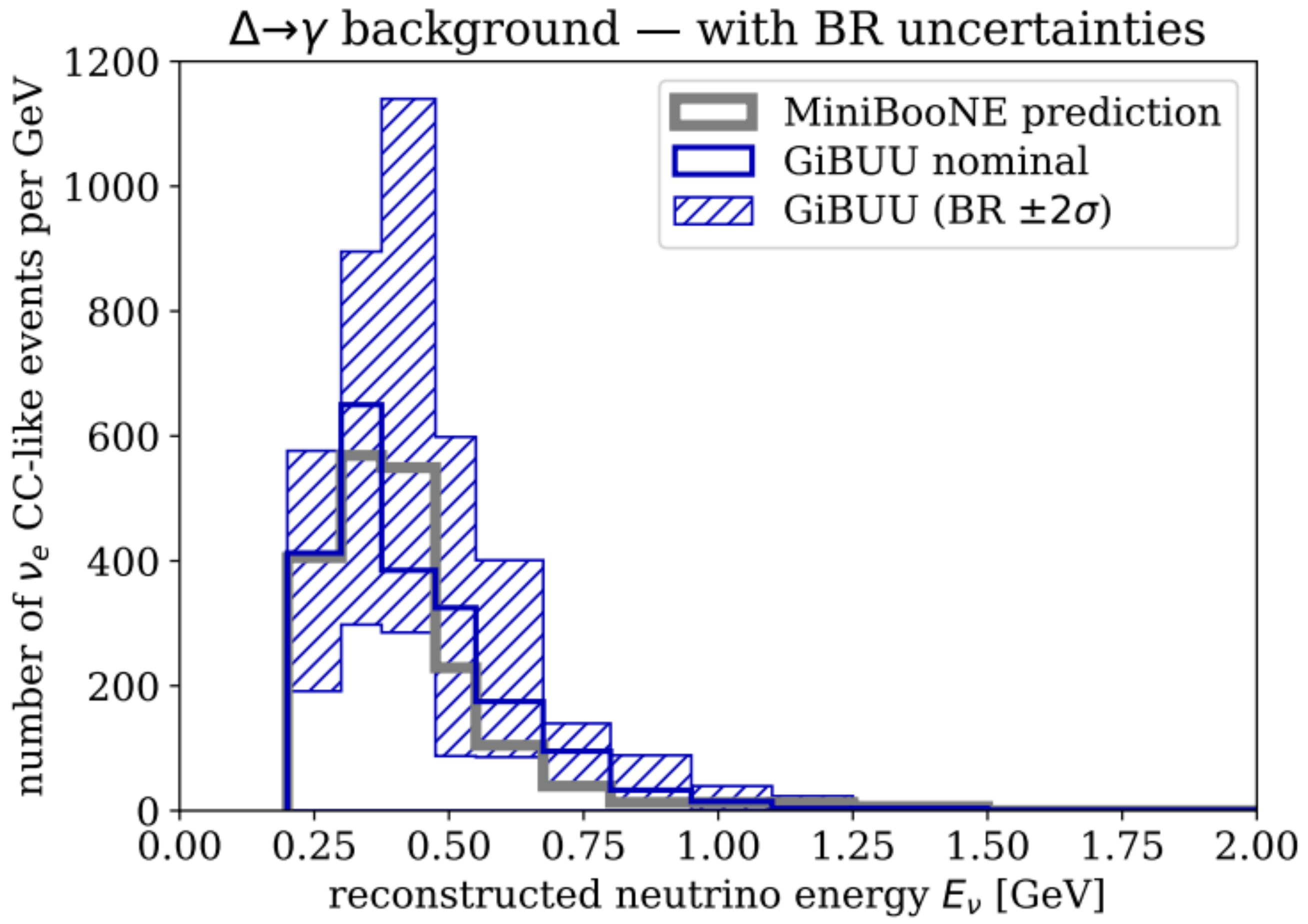
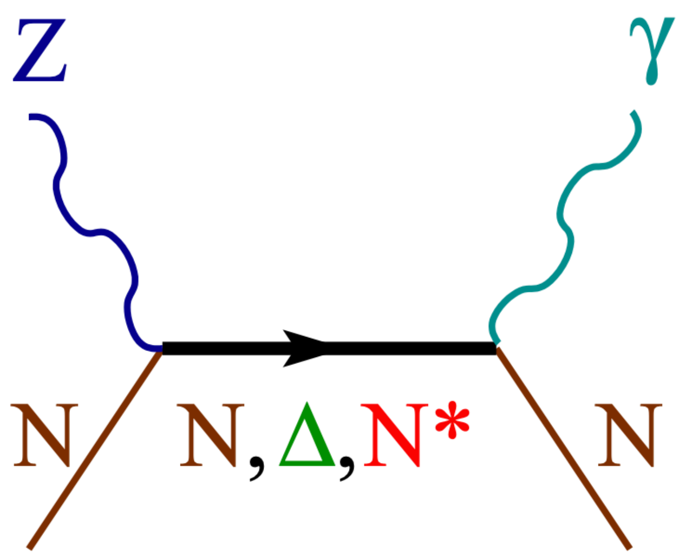
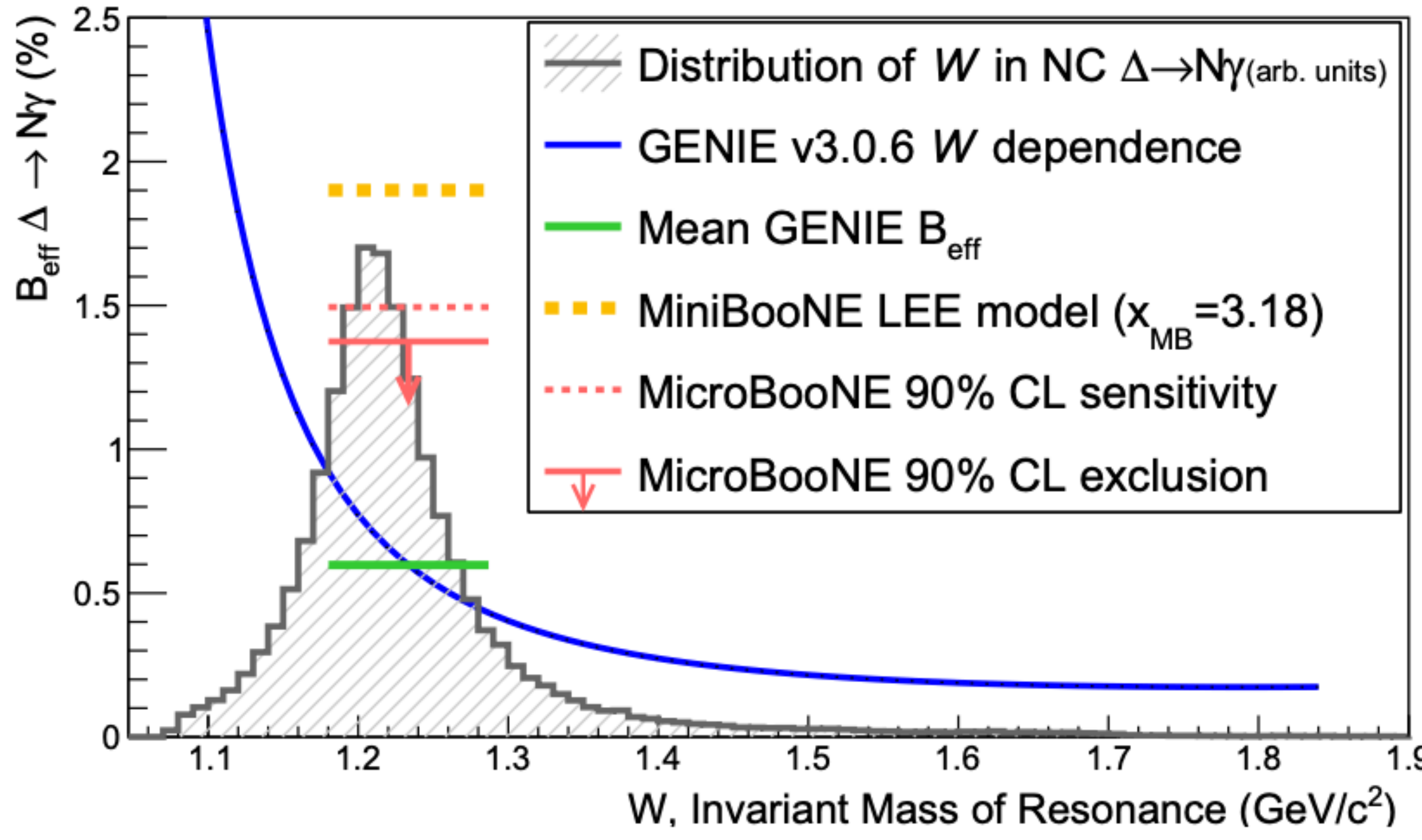
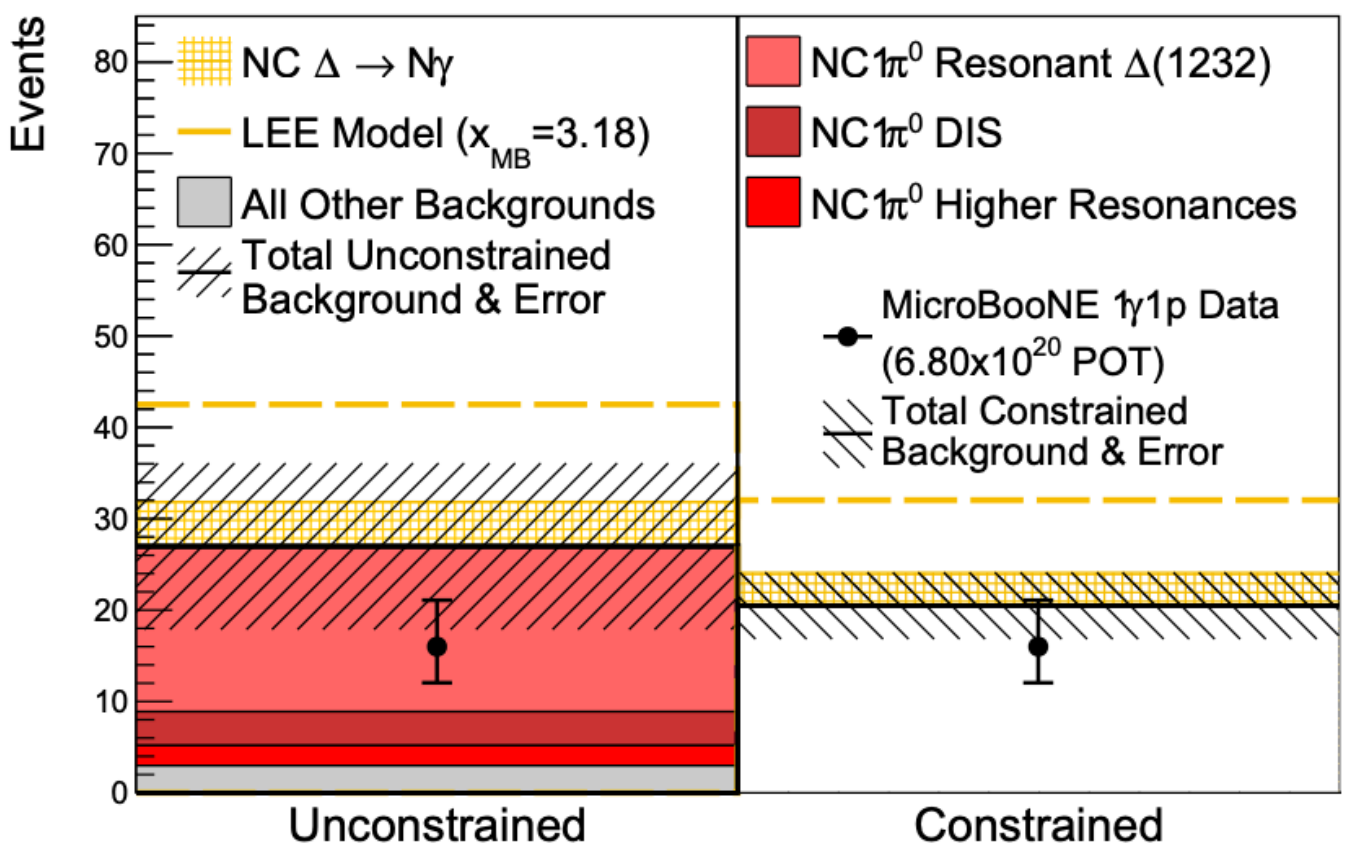






$1\gamma 1p$



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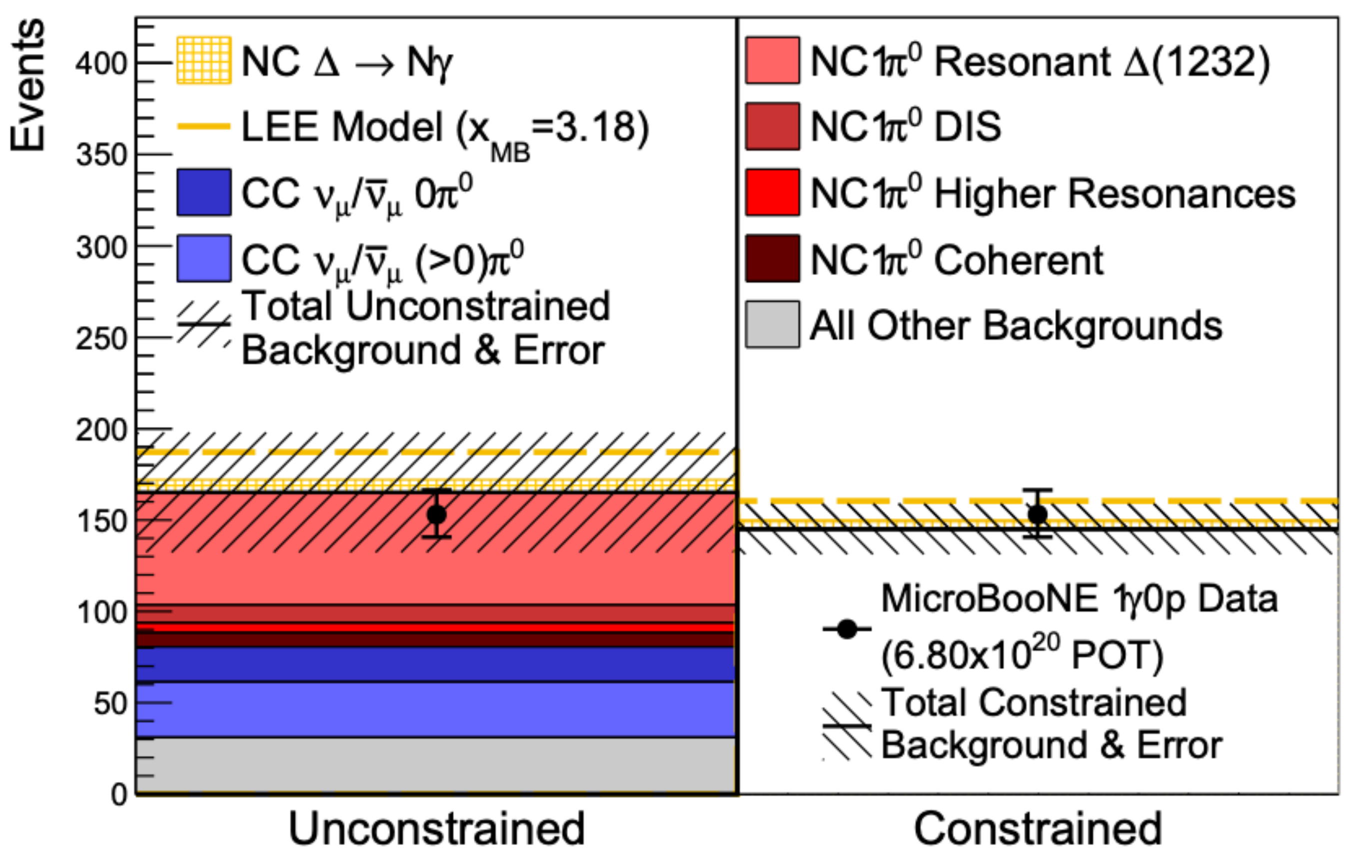


Conclusion:

$\Delta(1232)$ radiative constrained as an explanation of MiniBooNE:

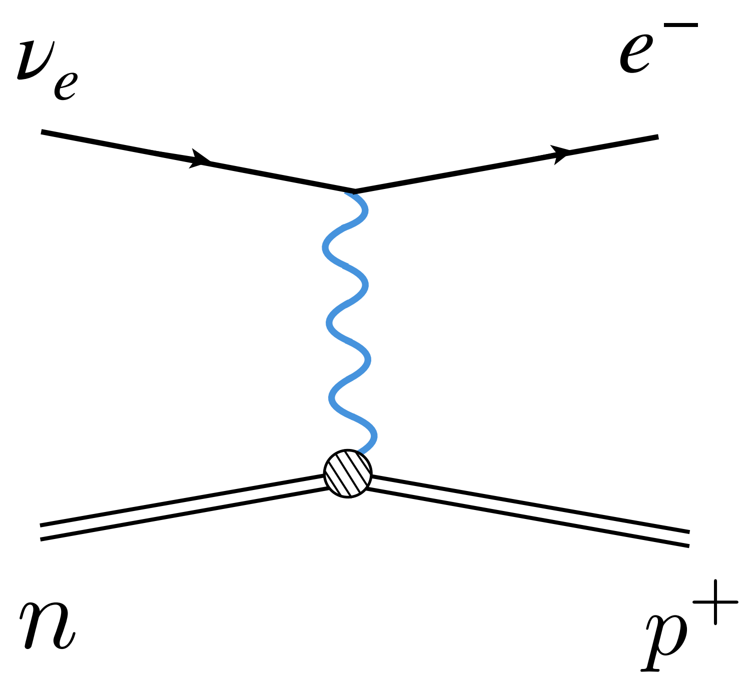
$$x_\Delta = \frac{\mathscr{B}_{\rm eff}(\Delta \to \gamma N)}{\mathscr{B}(\Delta \to \gamma N)}, \quad x_\Delta < 2.3 \ (90\,\%\,\mathrm{CL})$$

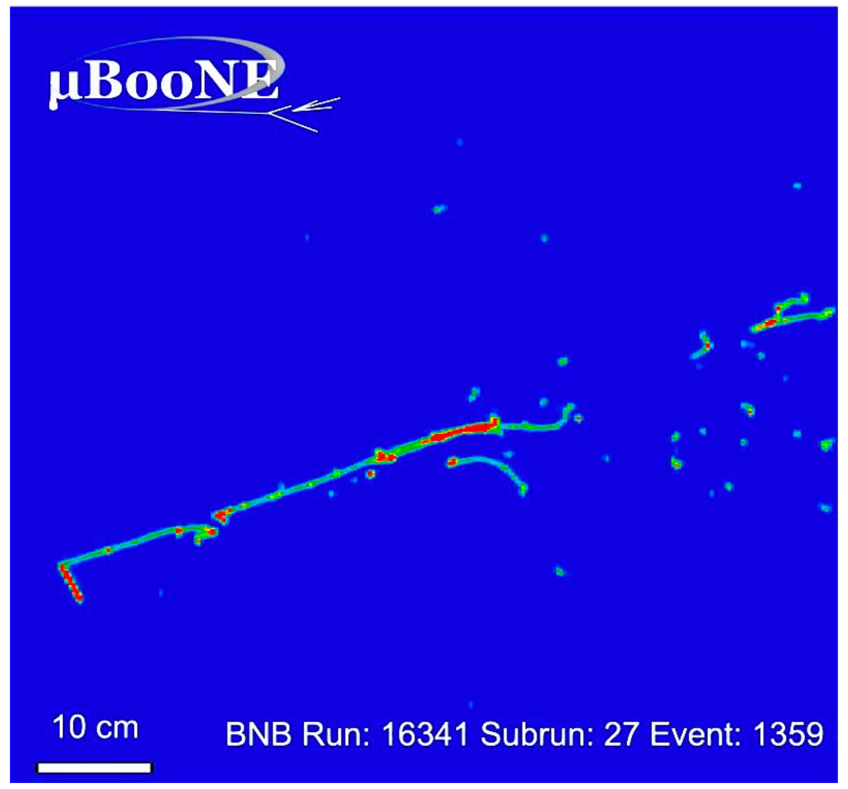
Other single-photon interpretations still untested:

- coherent photons
- new particles decaying to single photons

Electron-neutrino searches at MicroBooNE

Relevant for explanations based on
oscillations or any effective $\nu_\mu \to \nu_e$ appearance signals.





Instead of an oscillation search, MicroBooNE performed a dedicated search for what they call:

electron low-energy-excess (eLEE) signal model

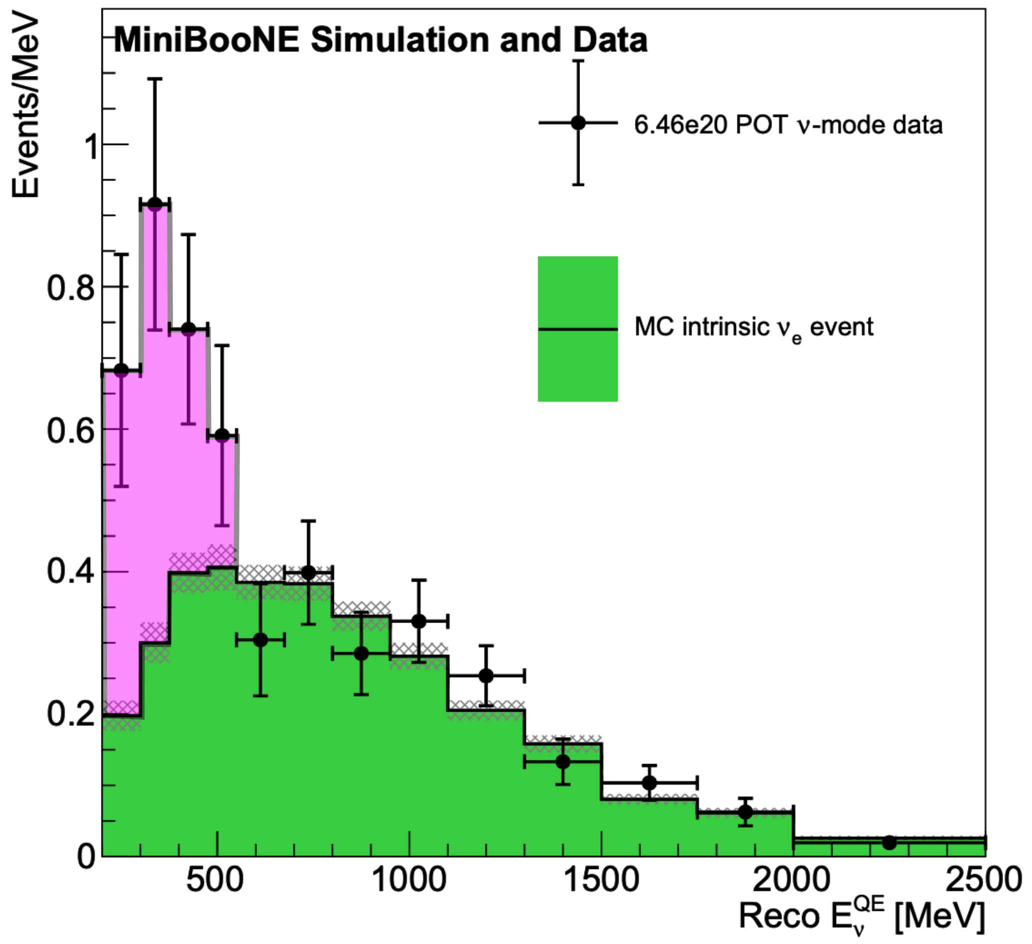
This is justified given the issues with sterile neutrinos, but what does it mean?

Electron-neutrino searches at MicroBooNE

The eLEE template

MiniBooNE

(non-ν_e backgrounds subtracted)



eLEE template

Central value of

$(\text{data})_i$ - $(\text{background})_i$

Electron-neutrino searches at MicroBooNE

The eLEE template

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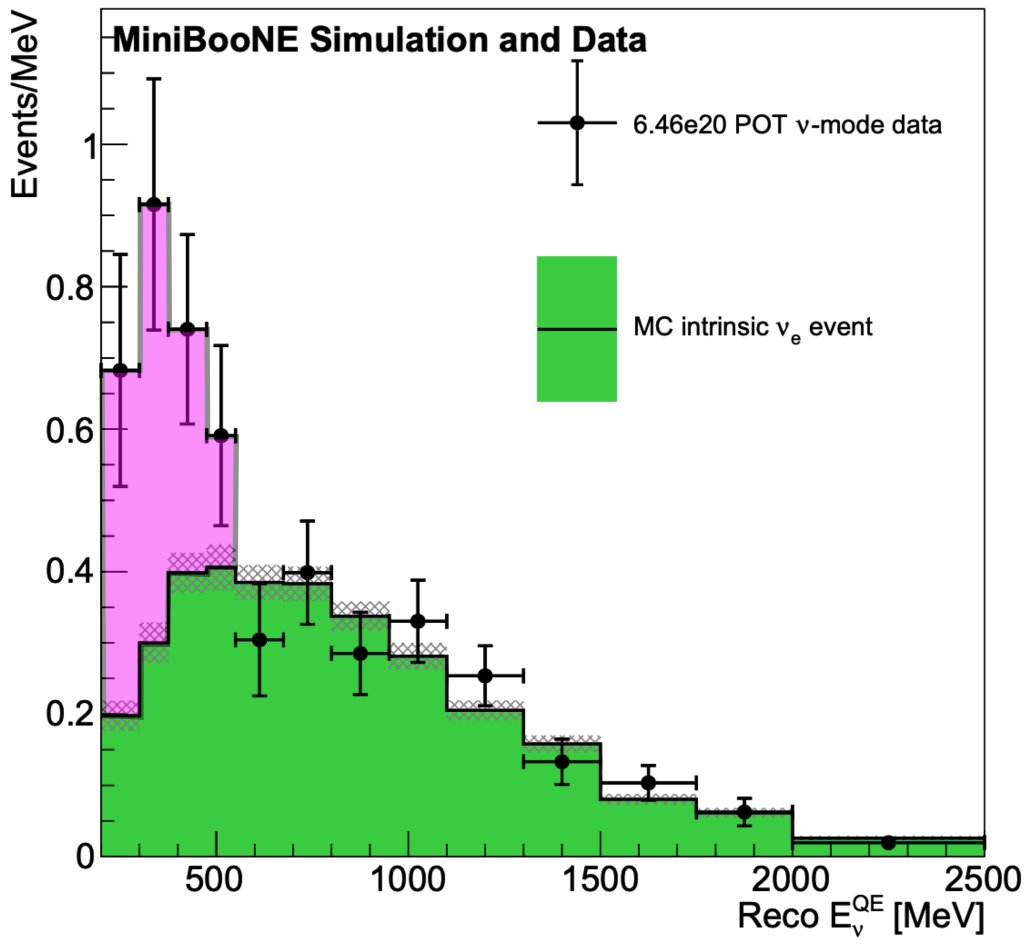
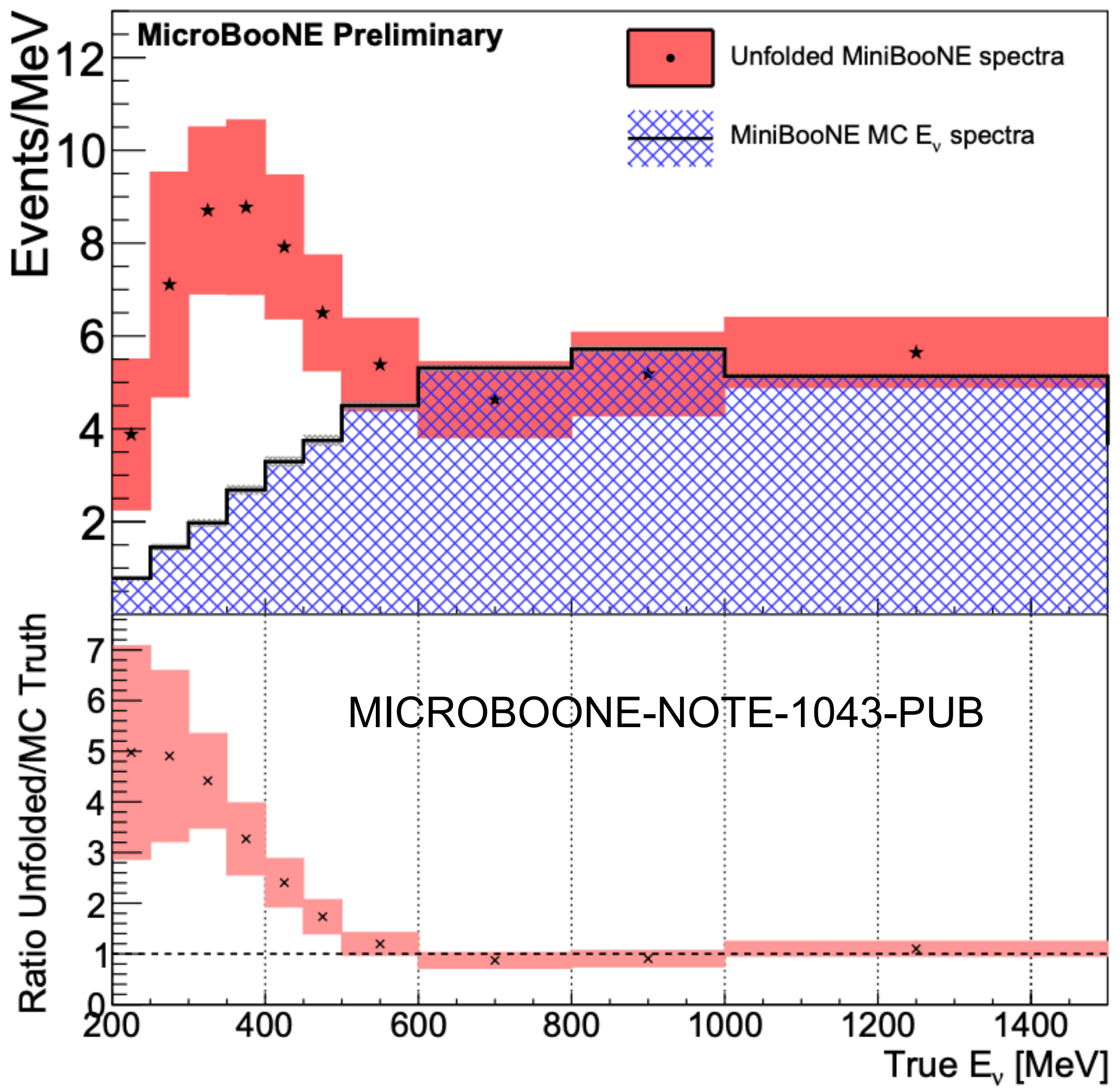


Unfold

MiniBooNE
Unfolded, **true** spectrum



eLEE template

Central value of

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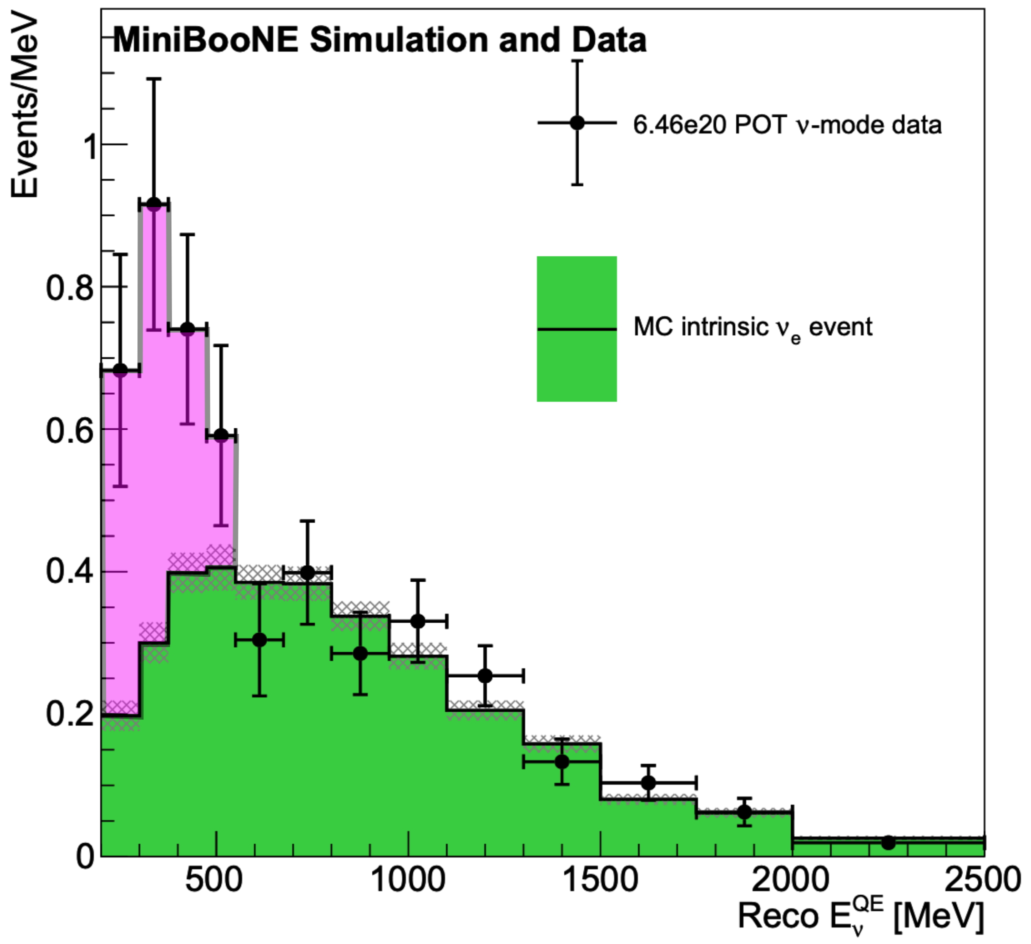
"**Unfold**" detector resolution, selection cuts, and efficiencies into a true ν_e spectrum.

Energy dependent modification to the intrinsic ν_e rate.

Electron-neutrino searches at MicroBooNE

The eLEE template

MiniBooNE
(non-ν_e backgrounds subtracted)



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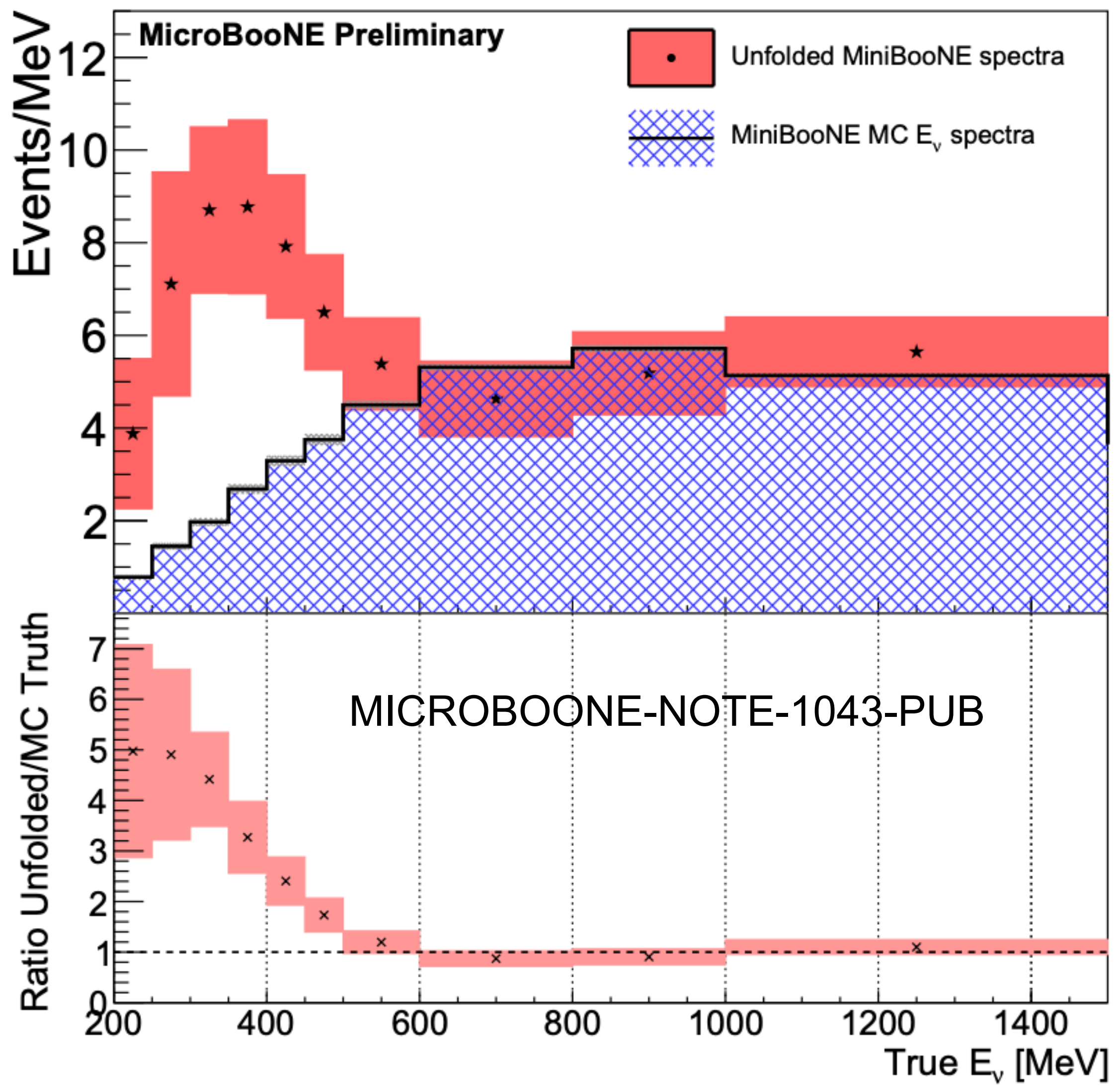

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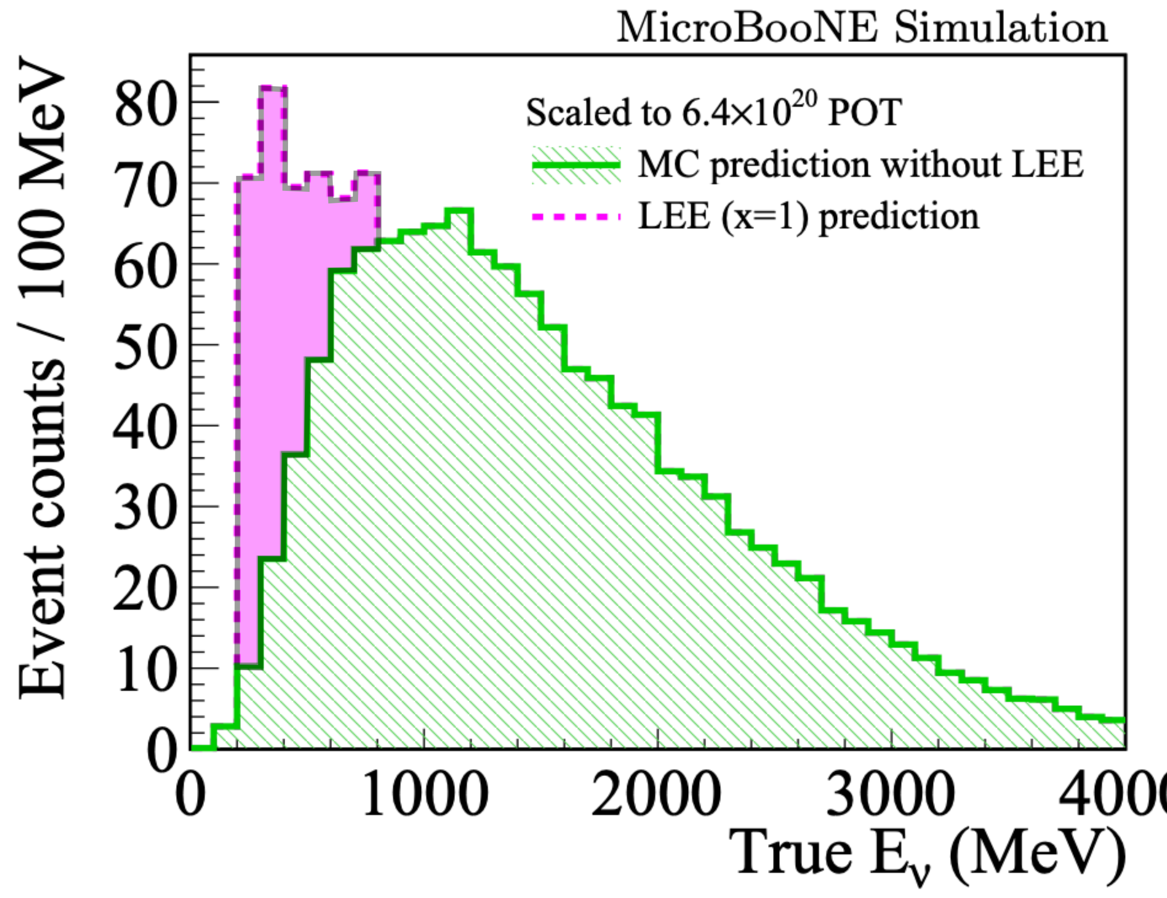
MicroBooNE selection

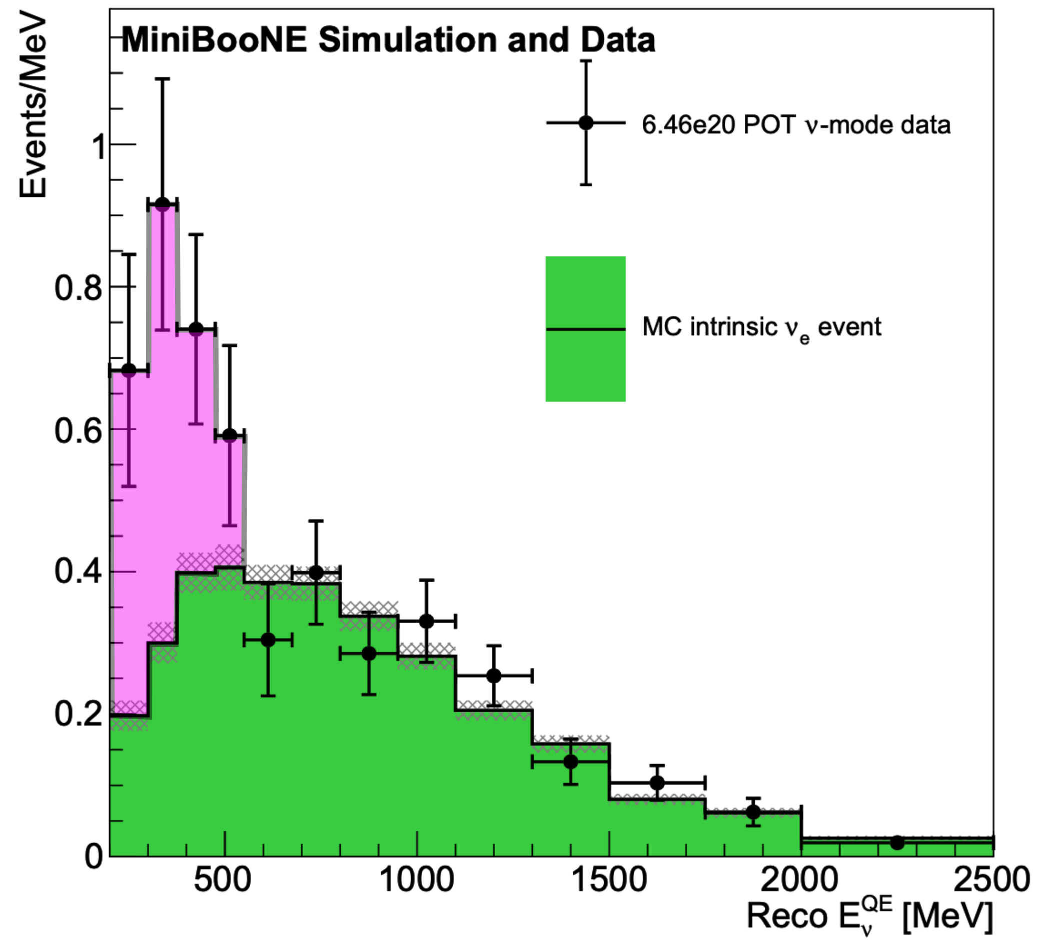


Use unfolded eLEE template to predict the event rate in a given MicroBooNE analysis.

Electron-neutrino searches at MicroBooNE

The eLEE template

MiniBooNE
(non-ν_e backgrounds subtracted)



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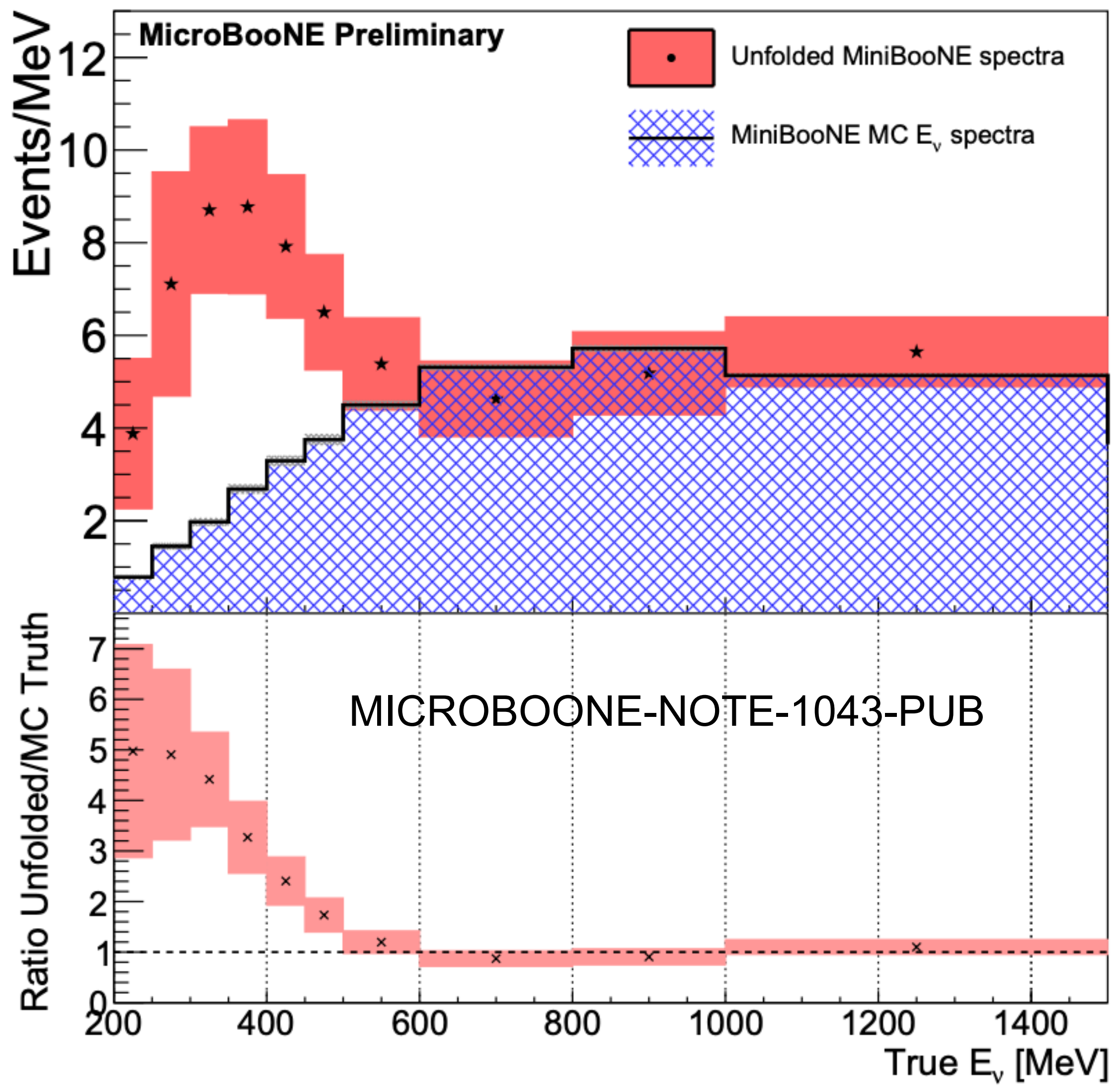

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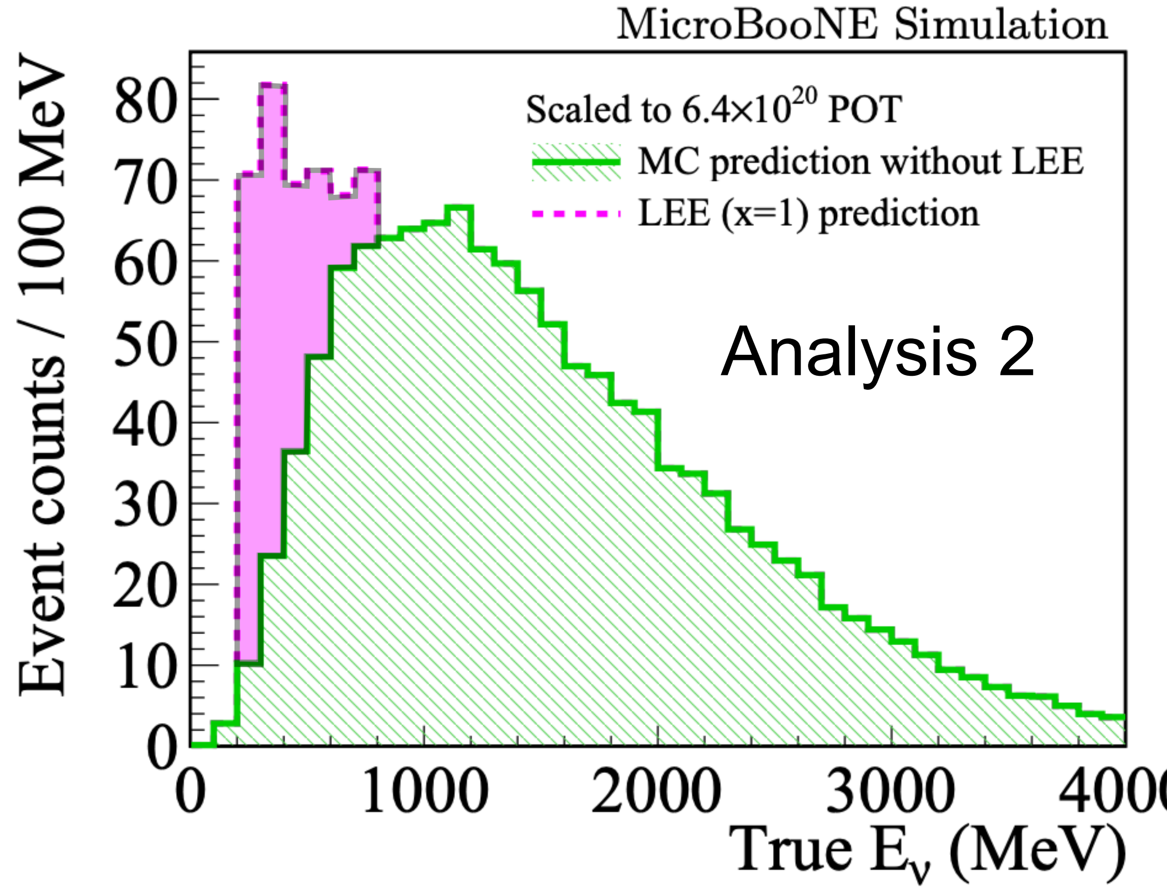
MicroBooNE selection

….analysis 1



… analysis 3

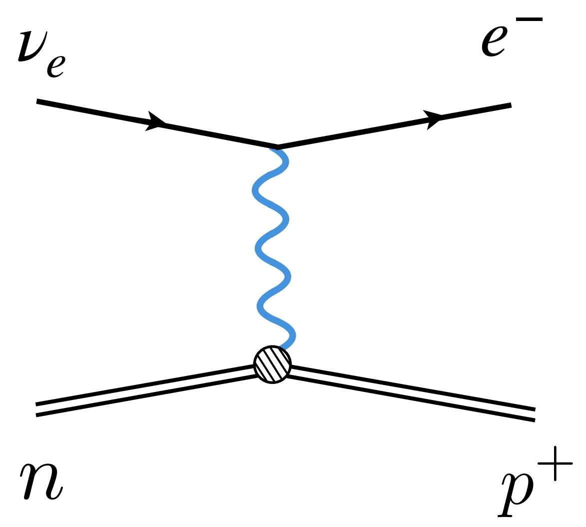
Use unfolded eLEE template to predict the event rate in a given MicroBooNE analysis.

Electron-neutrino searches at MicroBooNE

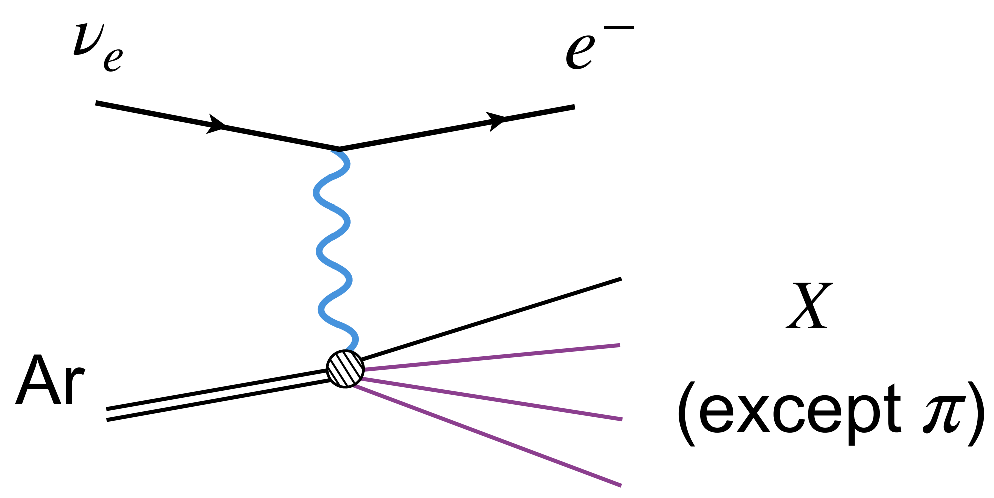
MicroBooNE’s three-prong approach

Different reconstruction algorithms and focus on different event classes

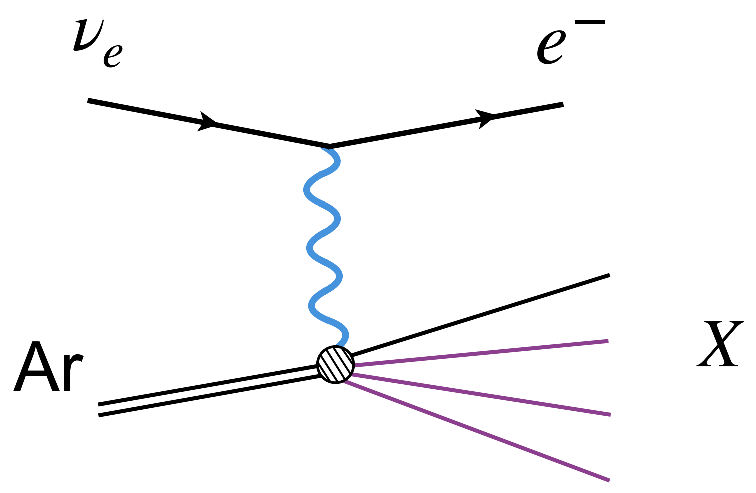
CCQE: $1e1p$
(Deep-Learning)



Pion-less: $1e1X$ **(except π)**
(Pandora-based)



Fully inclusive: $1e1X$
(Wire-Cell)



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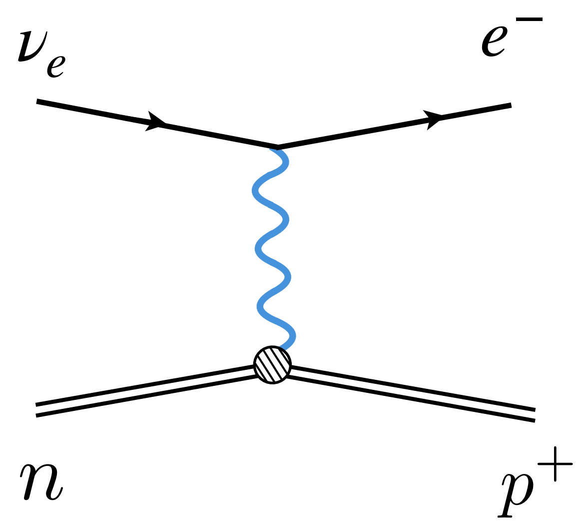

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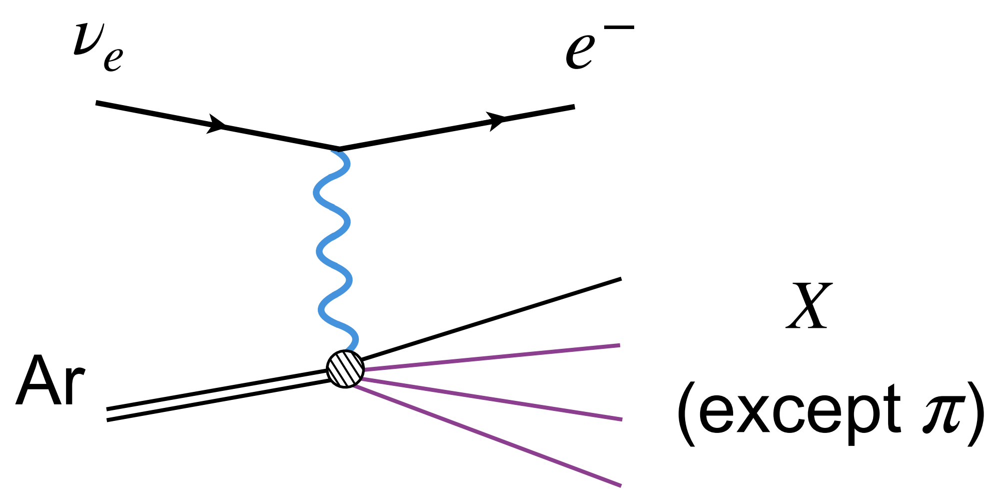

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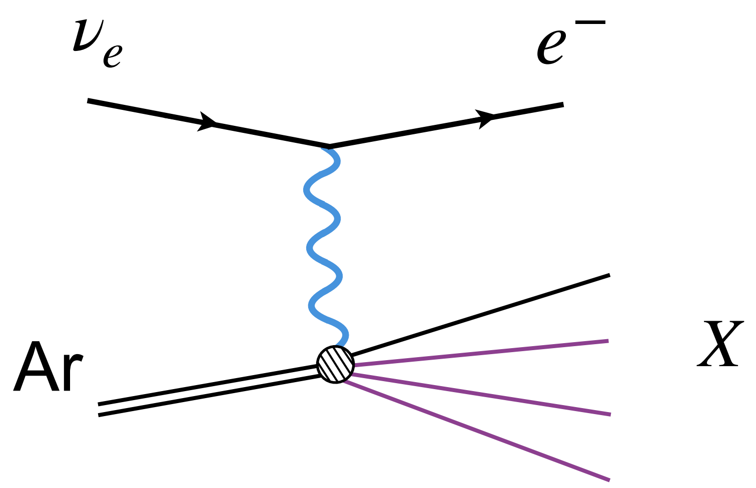
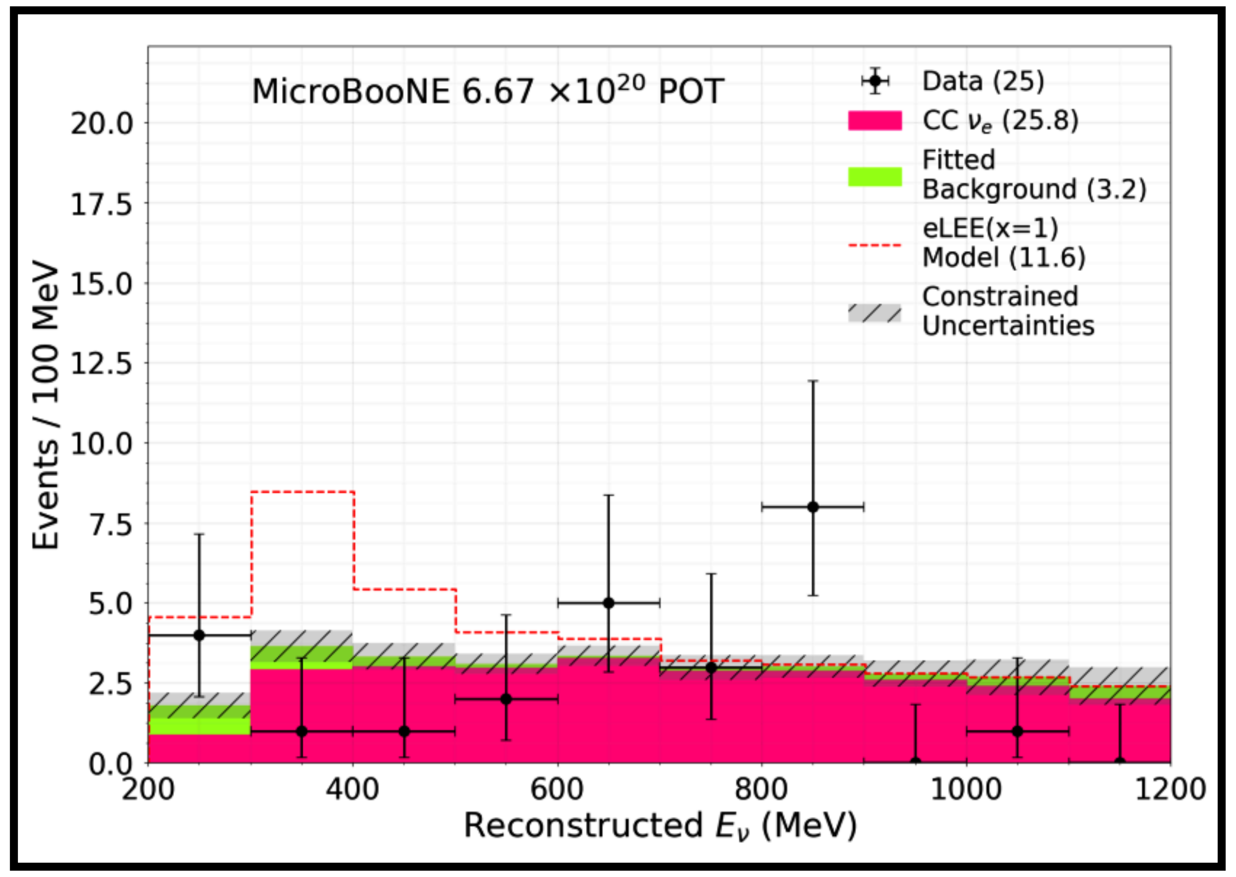
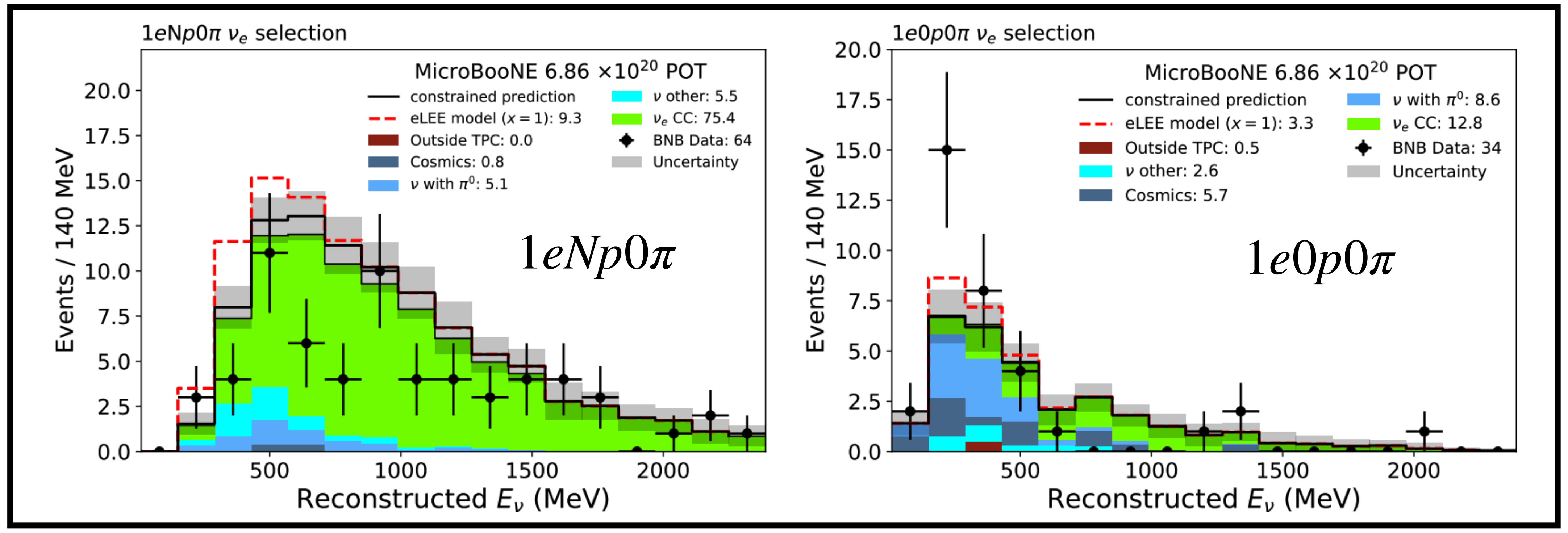
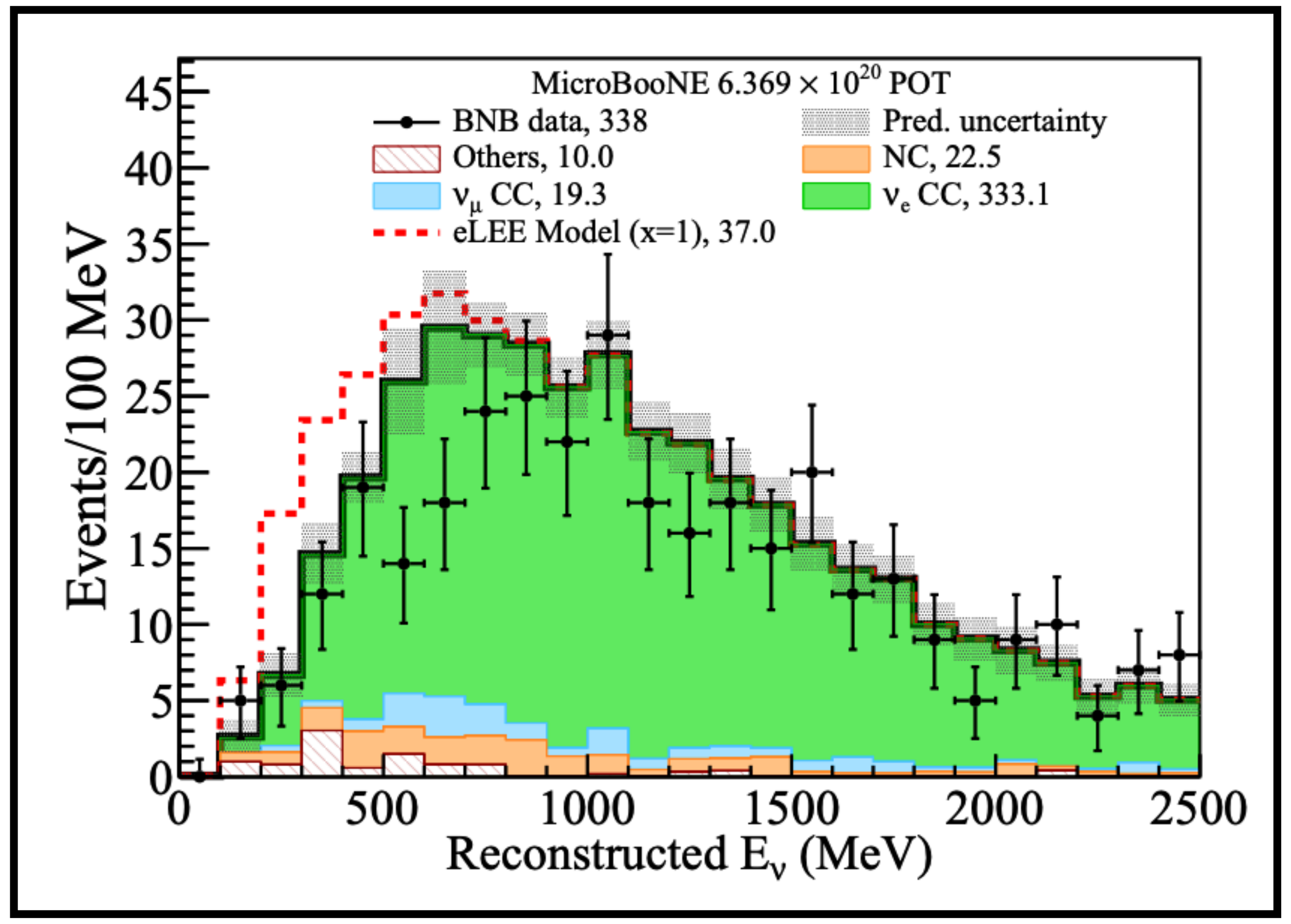


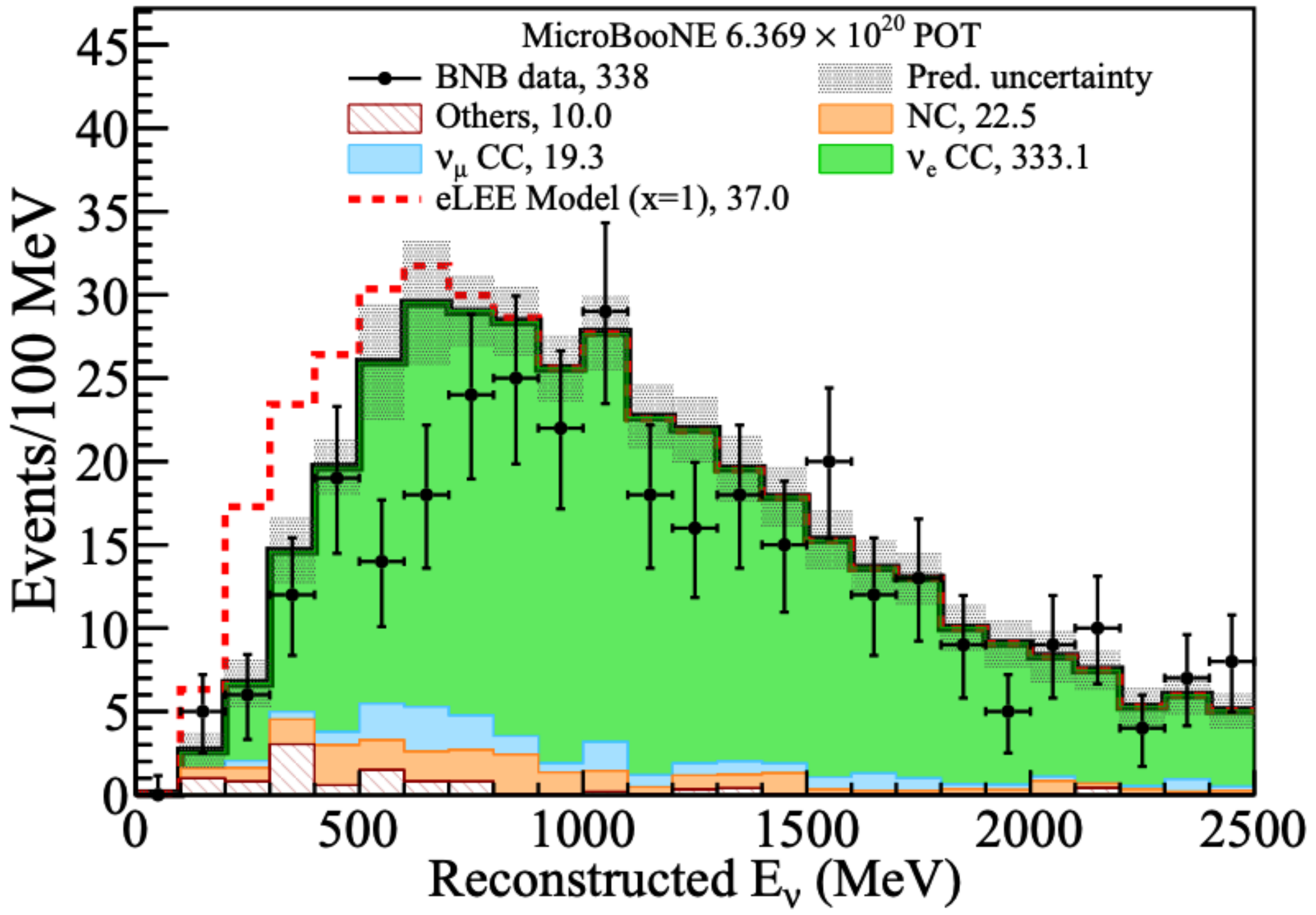






Electron-neutrino searches at MicroBooNE
The technical conclusion

For instance, in the Inclusive analysis:



No excess observed

+ slight deficit of events.

Electron-neutrino searches at MicroBooNE

The technical conclusion

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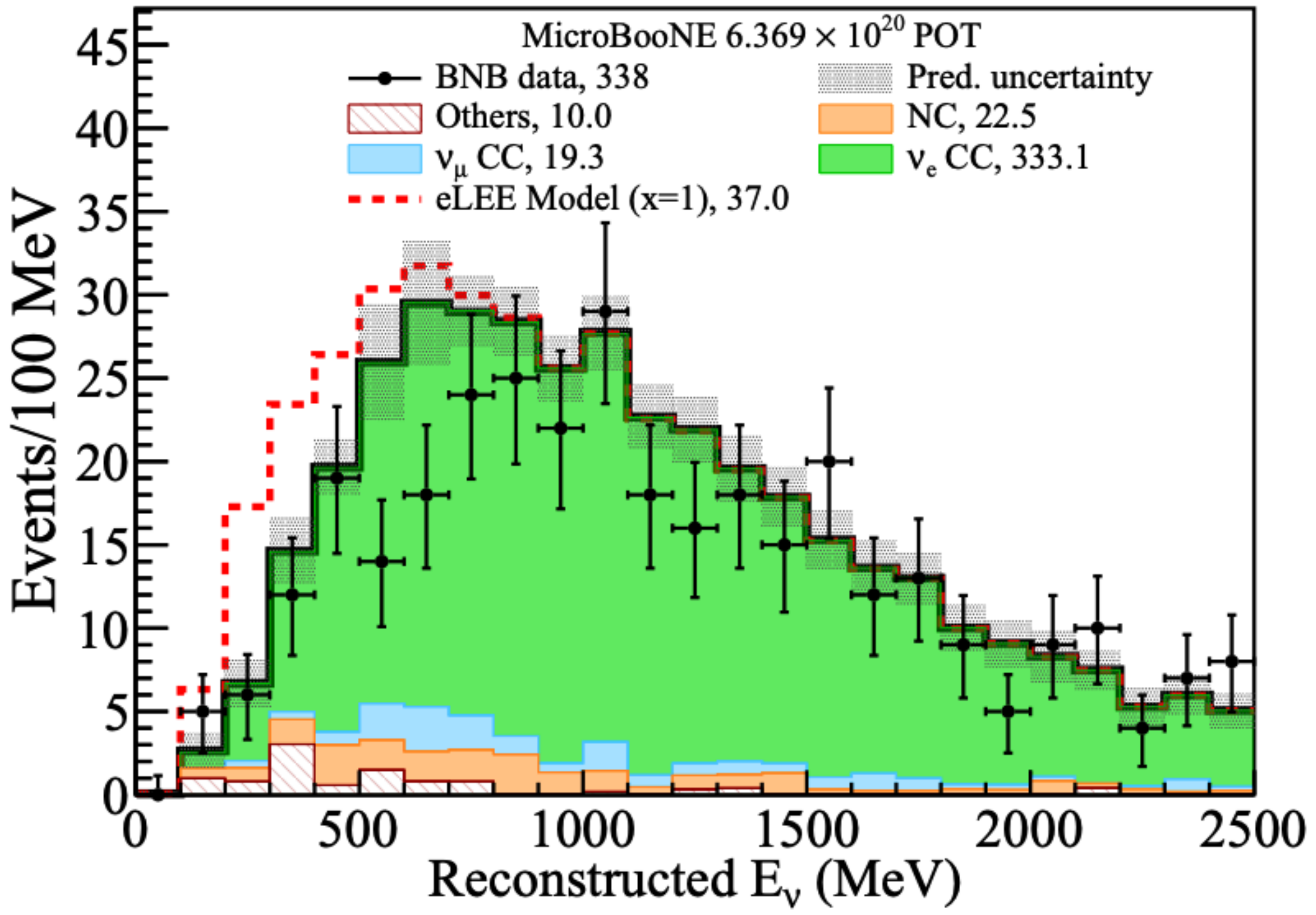

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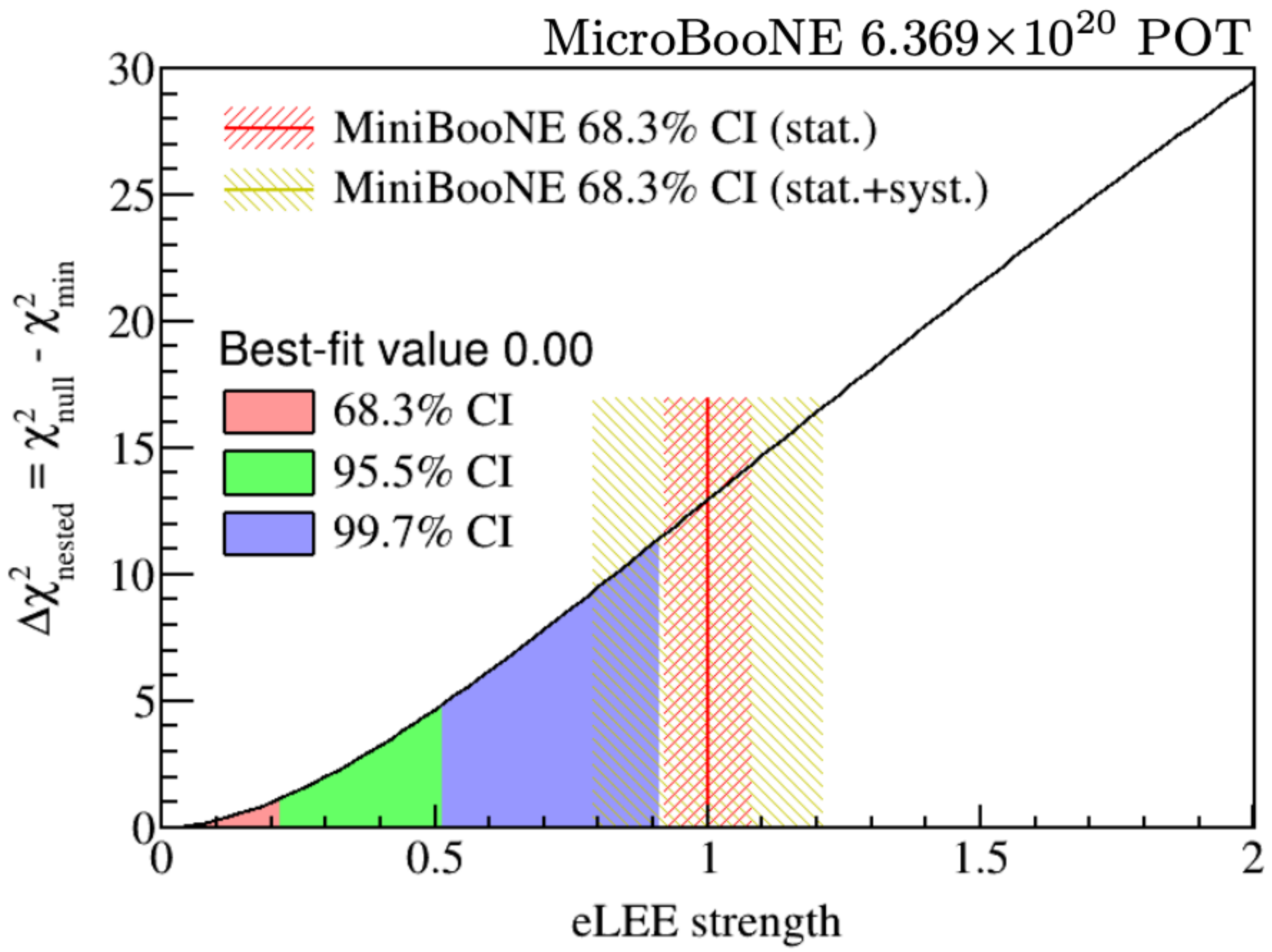

eLEE strength:
the overall normalization
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Electron-neutrino searches at MicroBooNE

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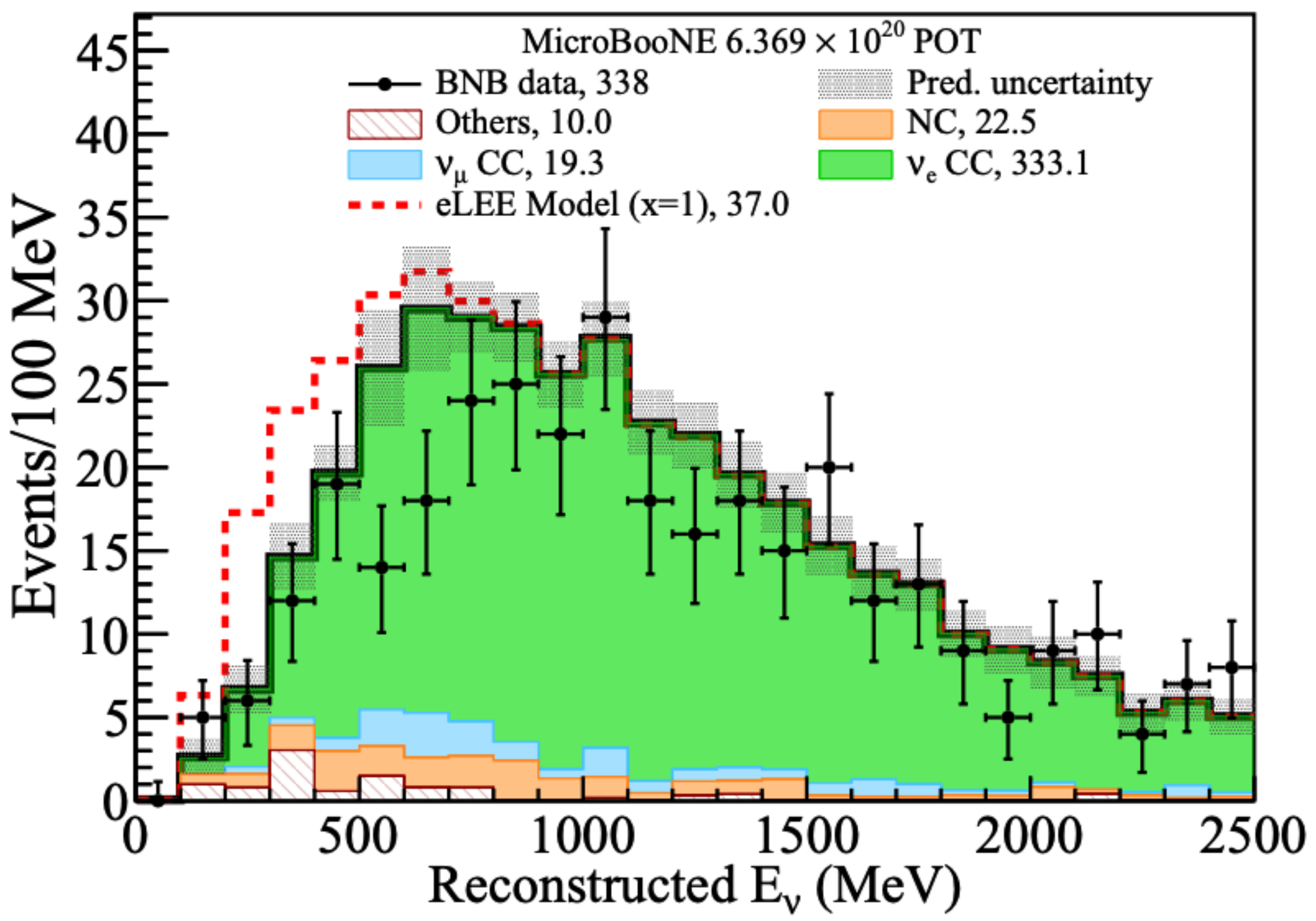

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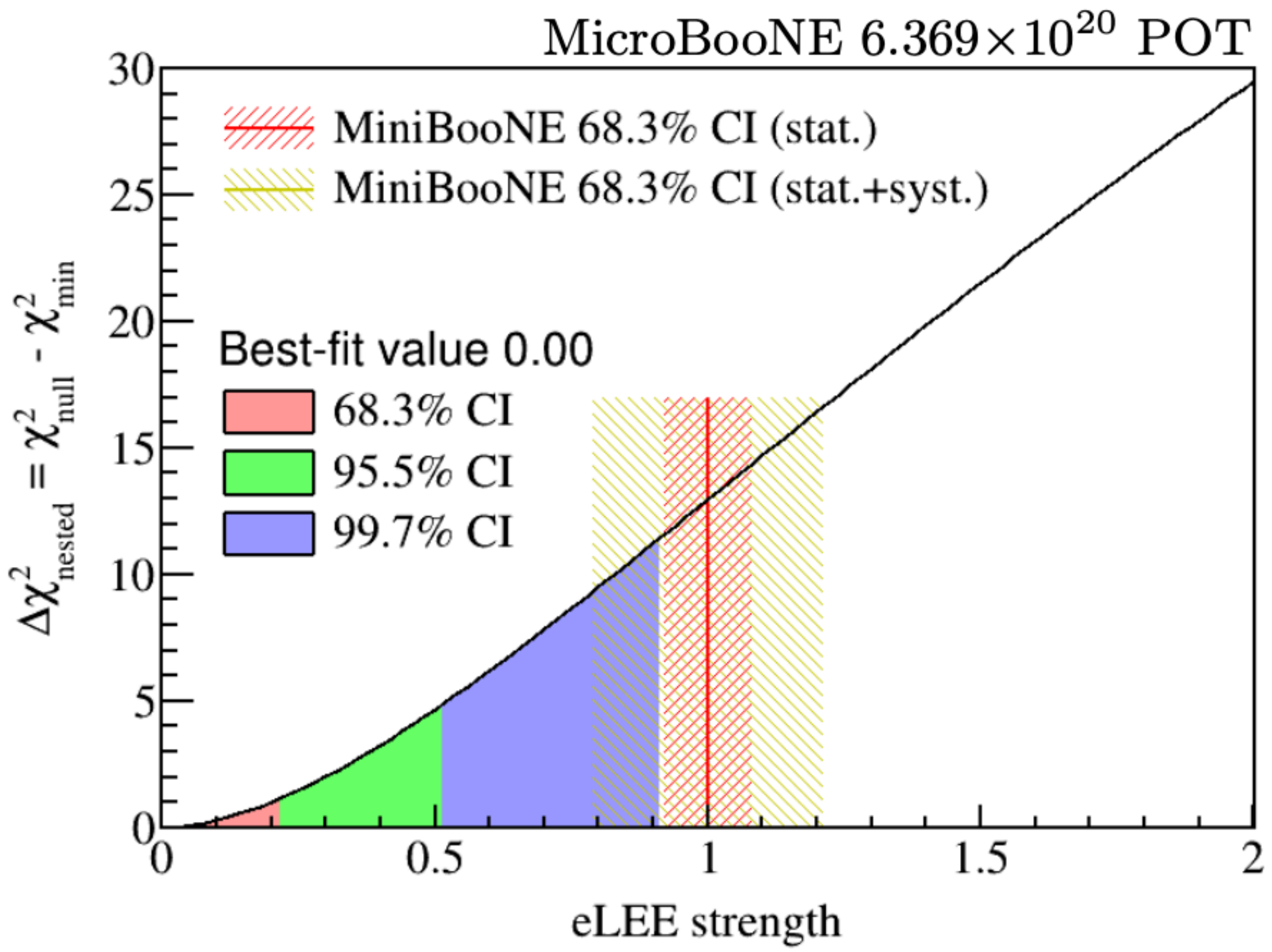

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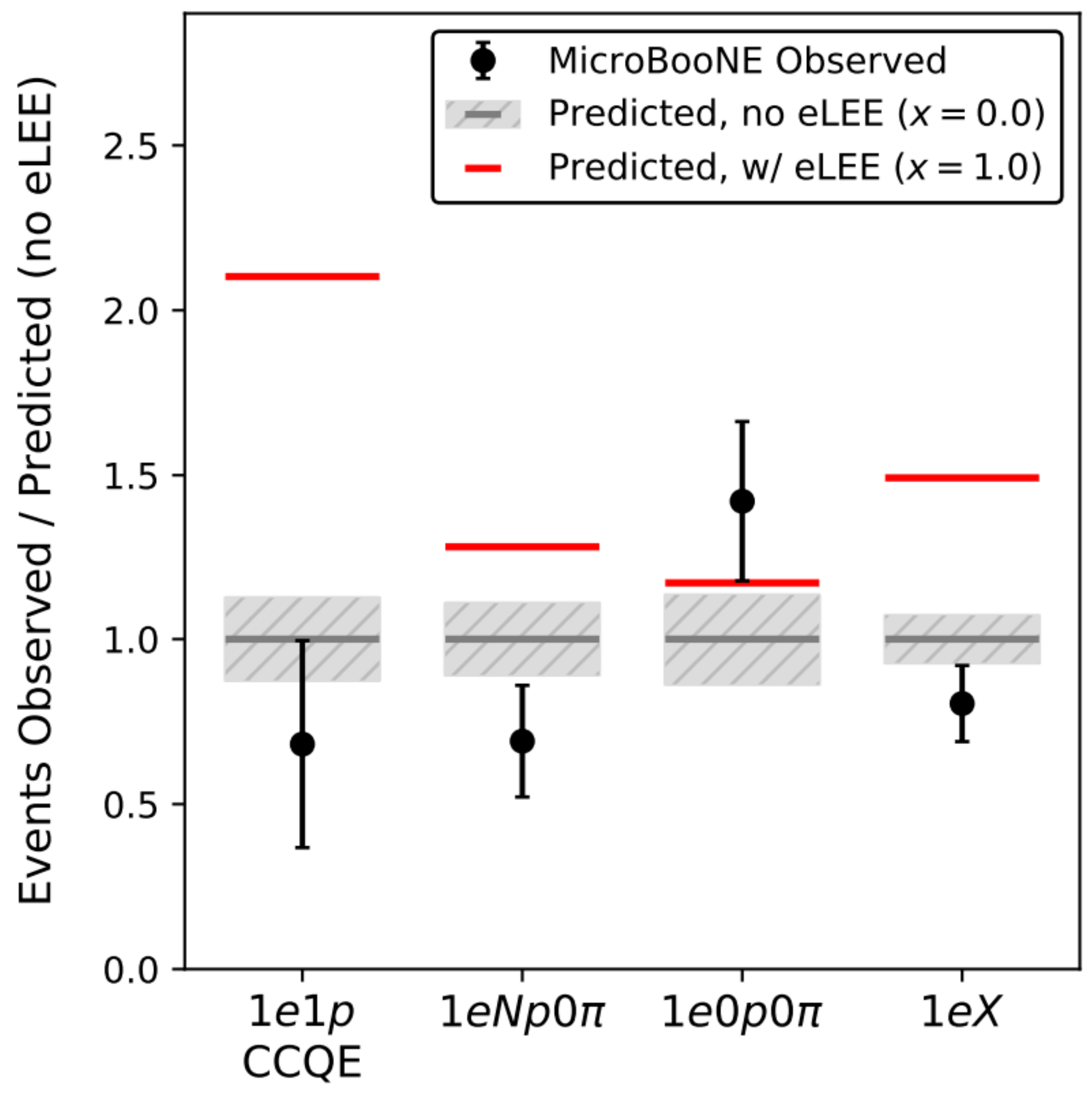

From *MicroBooNE coll., arXiv:2110.14054*

"… MicroBooNE rejects the hypothesis that ν_eCC interactions are fully responsible for that excess at > 97% CL for both exclusive (1e1p CCQE, 1eNp0π) and inclusive (1eX) event classes."

Electron-neutrino searches at MicroBooNE

The non-technical conclusions

Headlines:

Neutrino result heralds new chapter in physics

BBC

Scientists find no hint of sterile neutrino

PHYS.ORG

MicroBooNE experiment's first results show no hint of a sterile neutrino

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What the community is really thinking:

1. How about MiniBooNE systematics? What happens if we deviate from the central value of the eLEE template?
2. Are sterile neutrinos excluded? If so, where are the exclusion plots?
3. Does MicroBooNE put an end to the MiniBooNE anomaly?

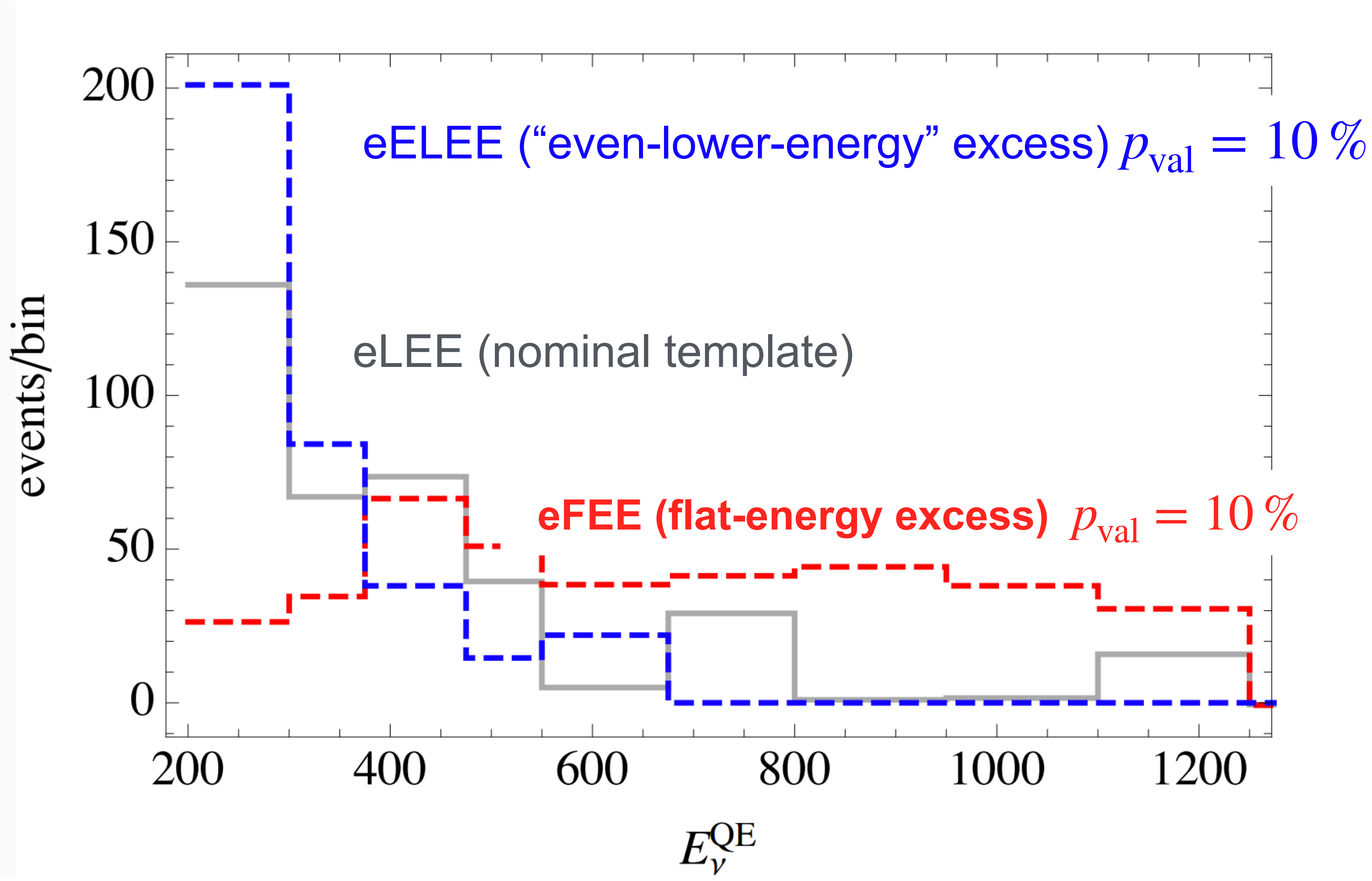
Q1

What happens if we deviate from the central value of the eLEE template?

Interpreting the MicroBooNE results in light of MiniBooNE systematics

New templates

By how much can we deviate from the central value of the eELEE?



What we call “the MiniBooNE excess” is very dependent on the background systematic uncertainties

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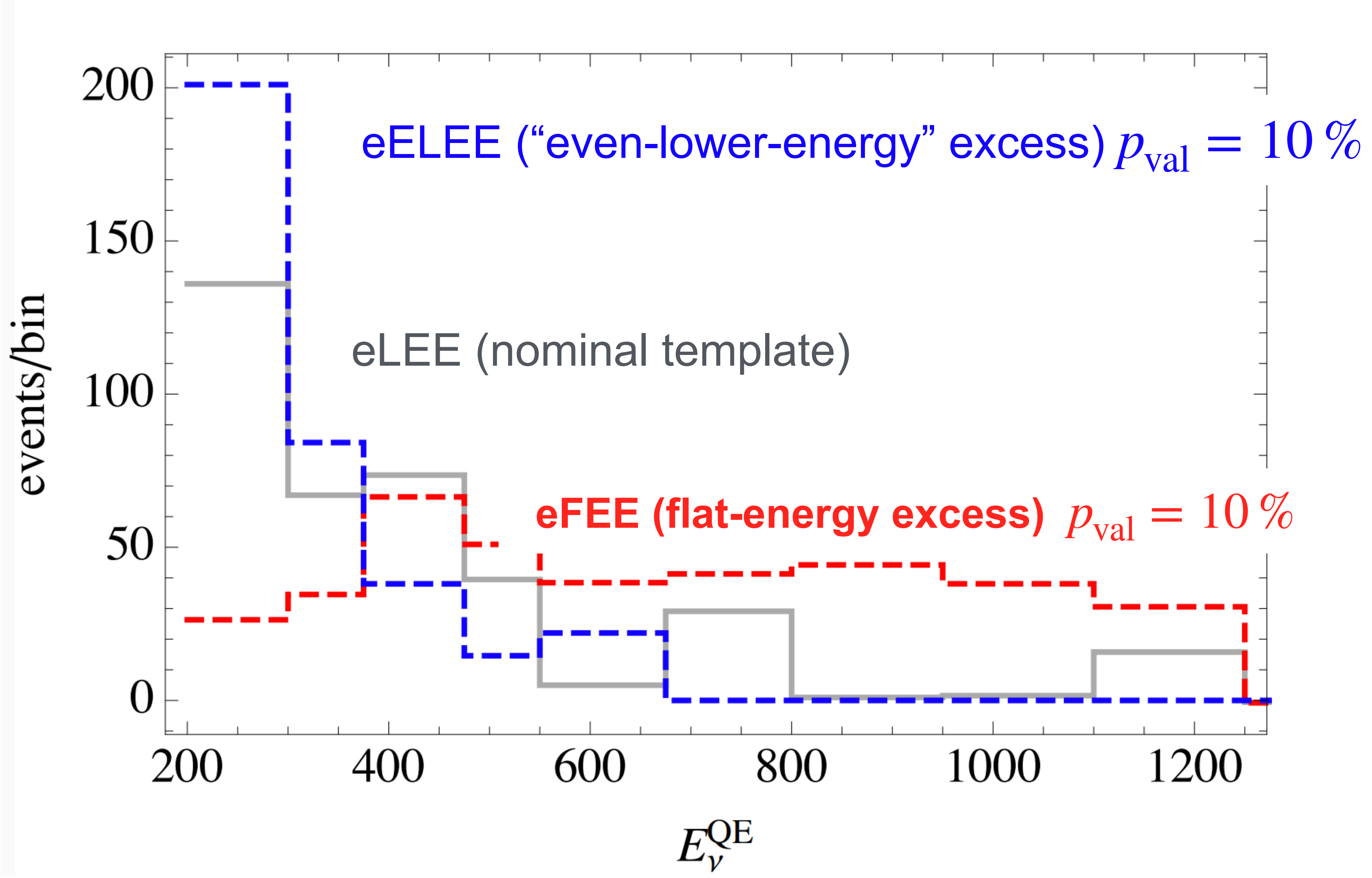

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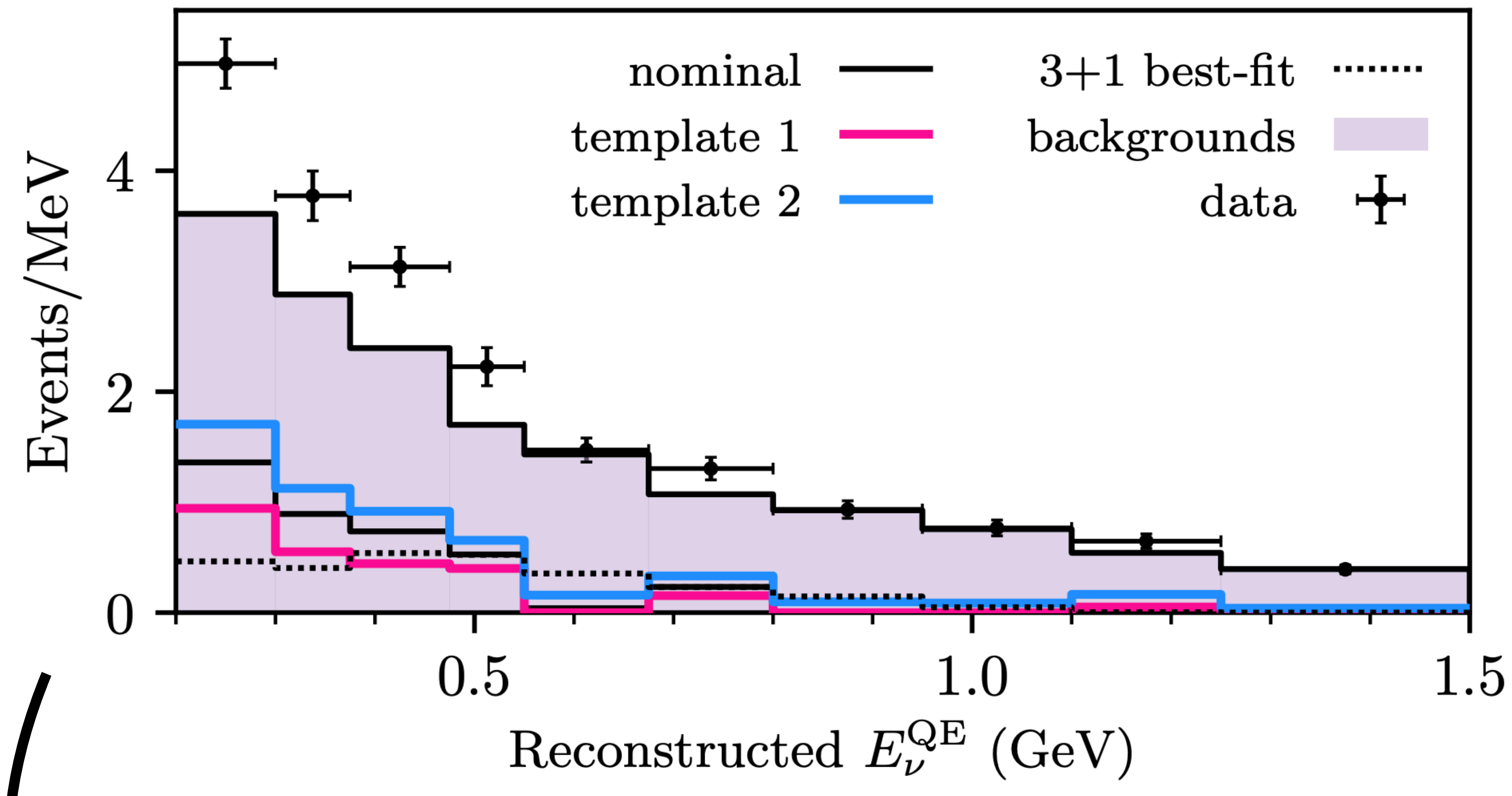
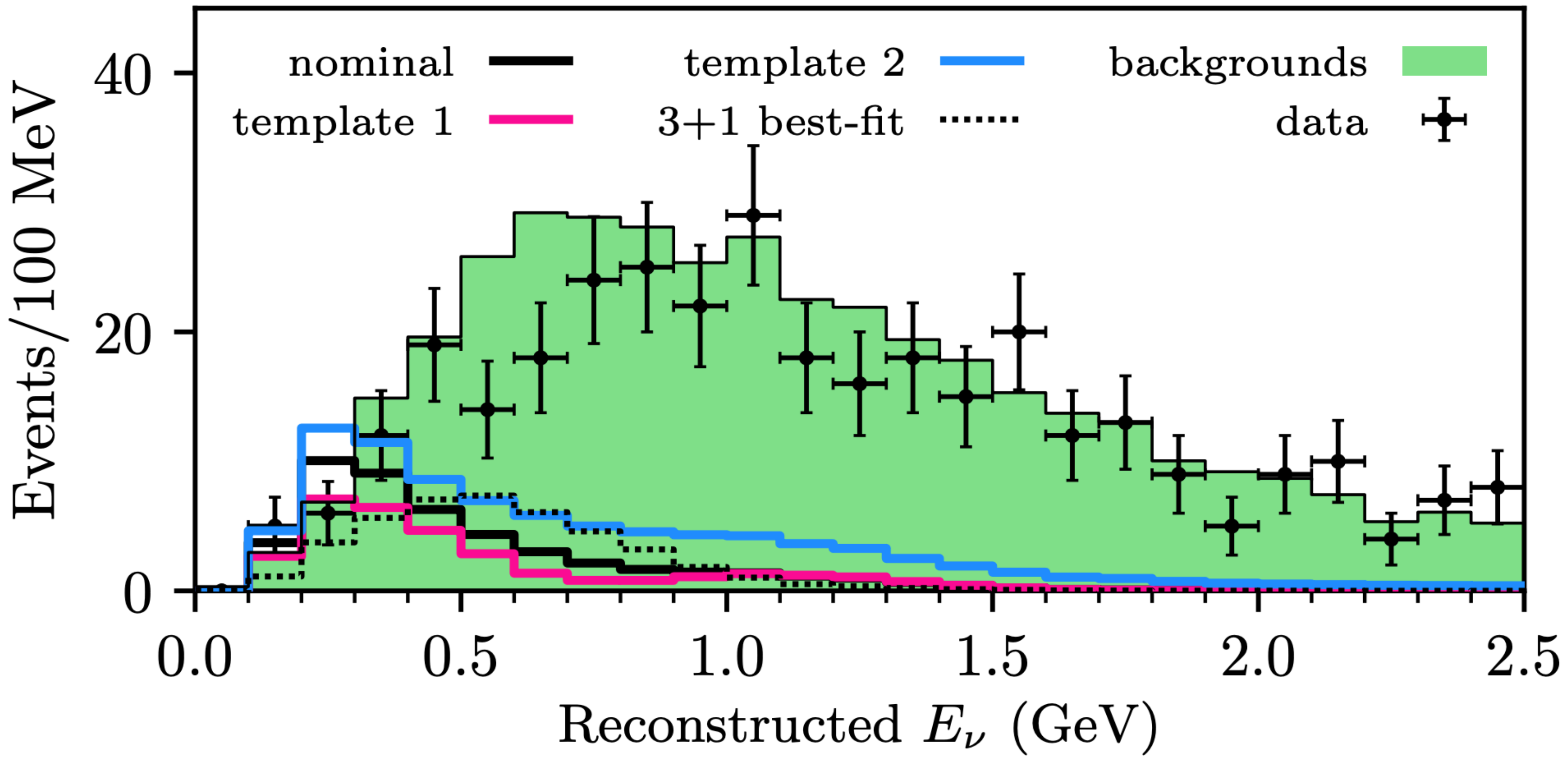


Unfold



Interpreting the MicroBooNE results in light of MiniBooNE systematics

Generalizing the template analysis

Our new approach:

Using a toy MCMC we generalize the MicroBooNE analysis to include systematic uncertainties:

1) Vary the normalization of 4 classes of MiniBooNE backgrounds,
2) Compute the MiniBooNE p-value,
3) Compute the MicroBooNE prediction with unfolding method,
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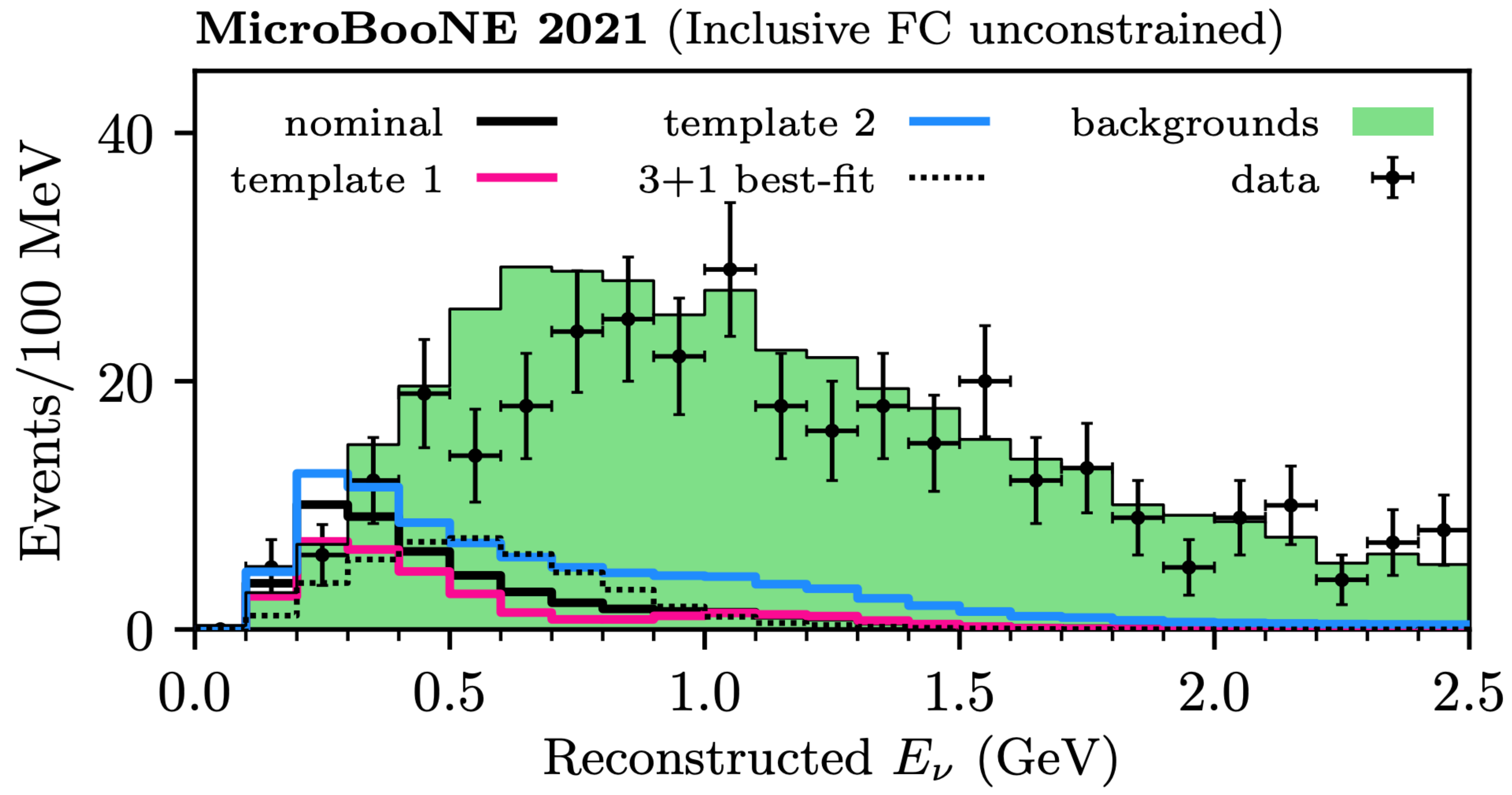

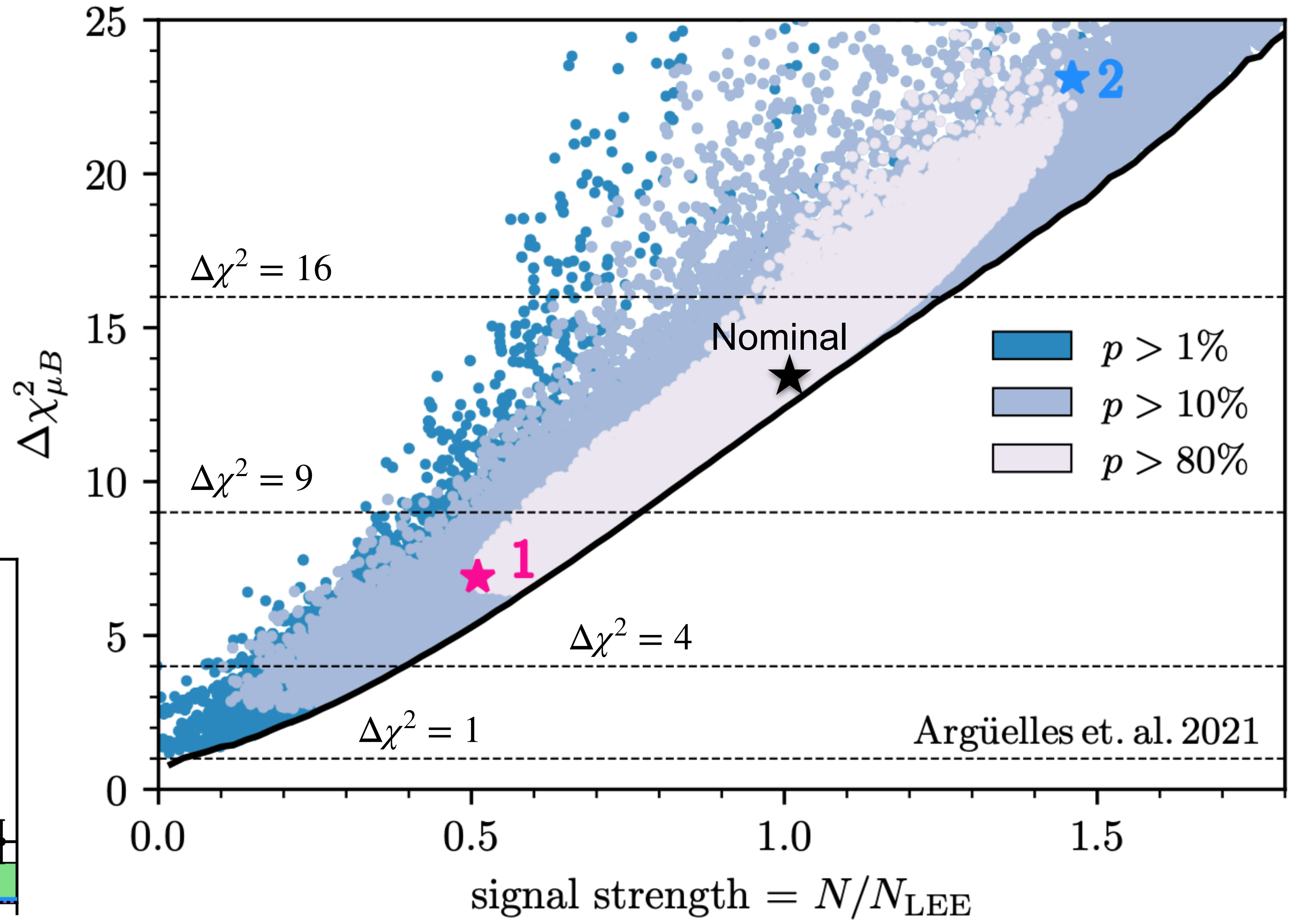

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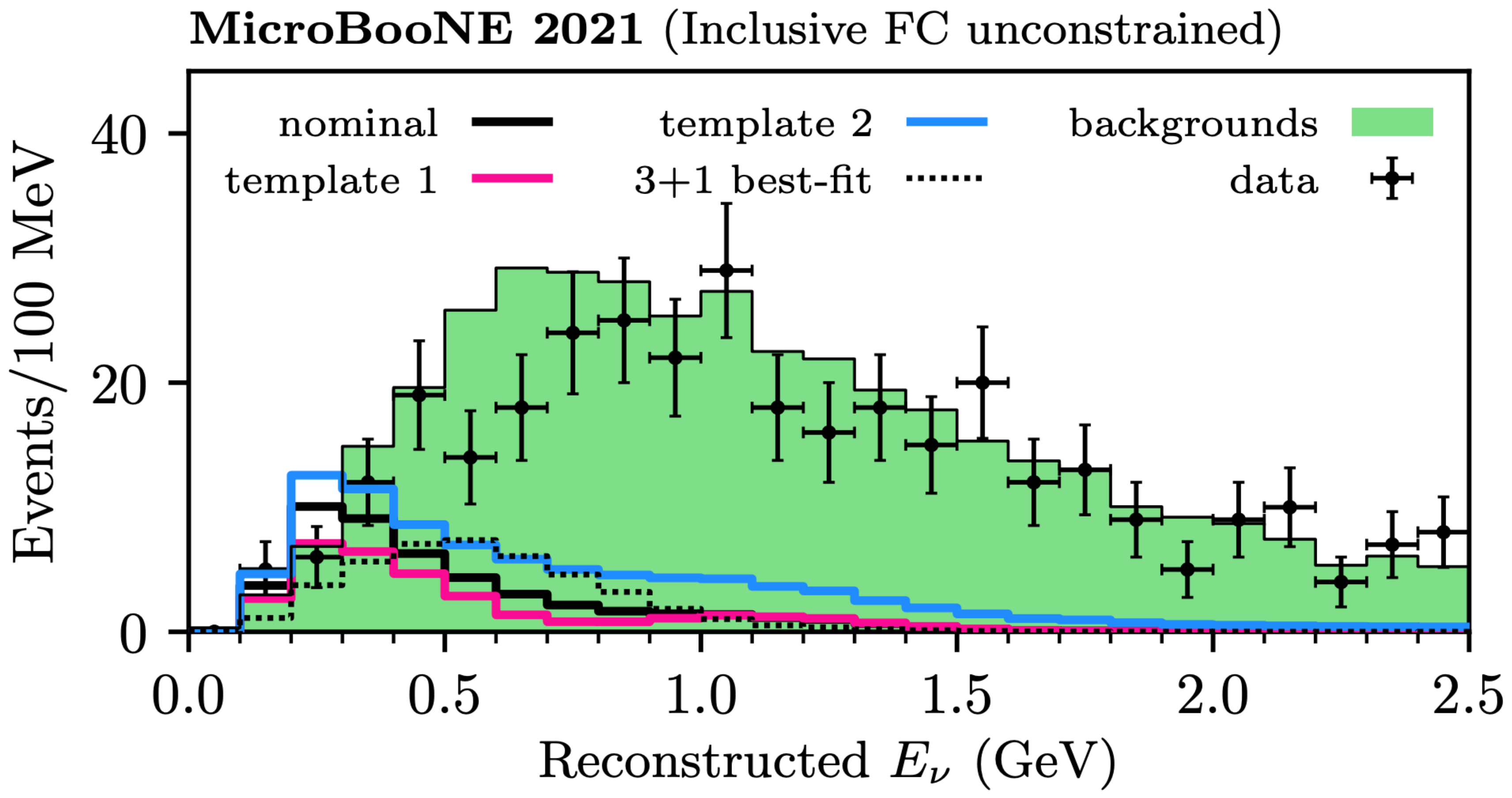
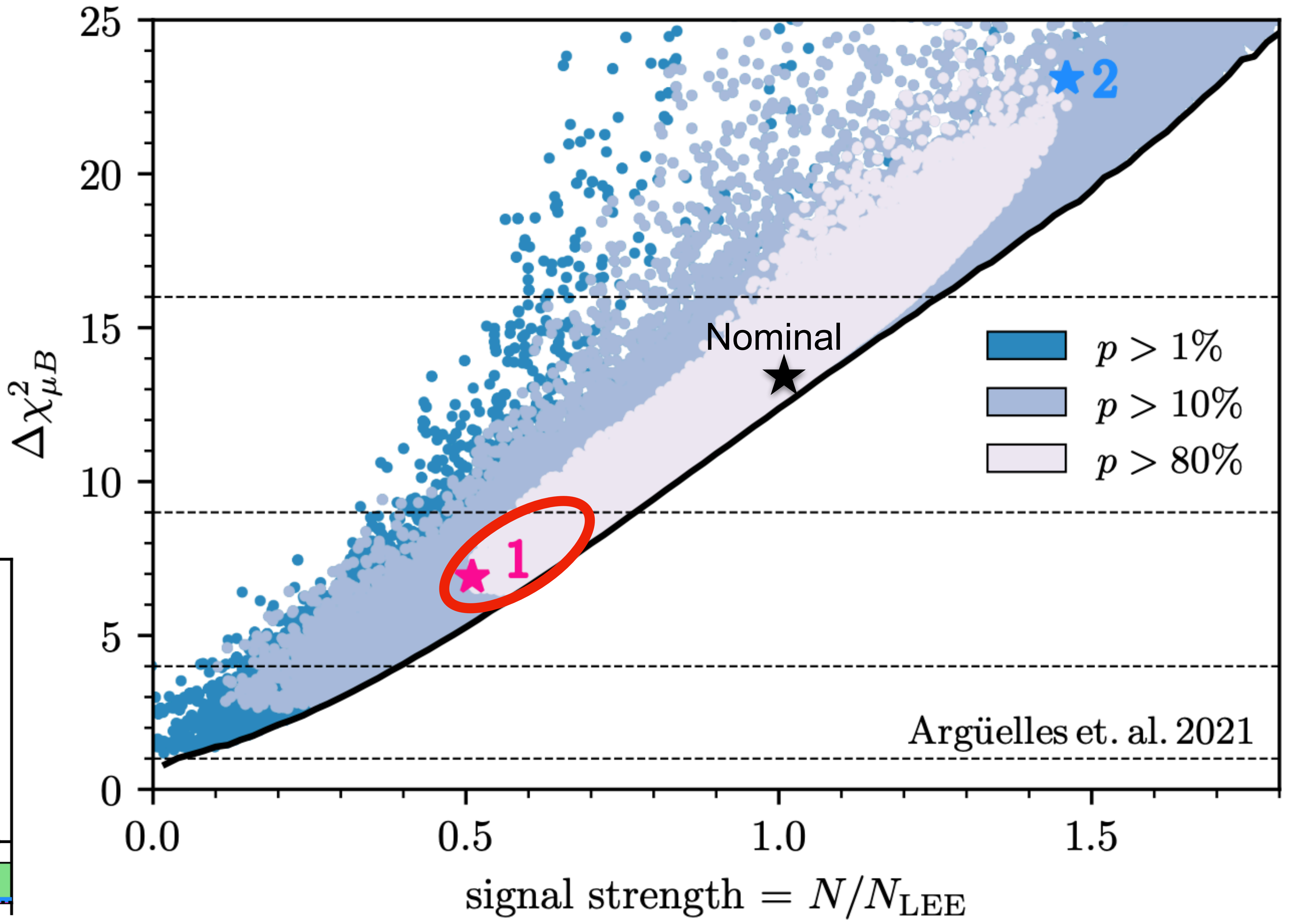


MicroBooNE's sensitivity can be much weaker or stronger to MiniBooNE templates that deviate from the nominal choice.



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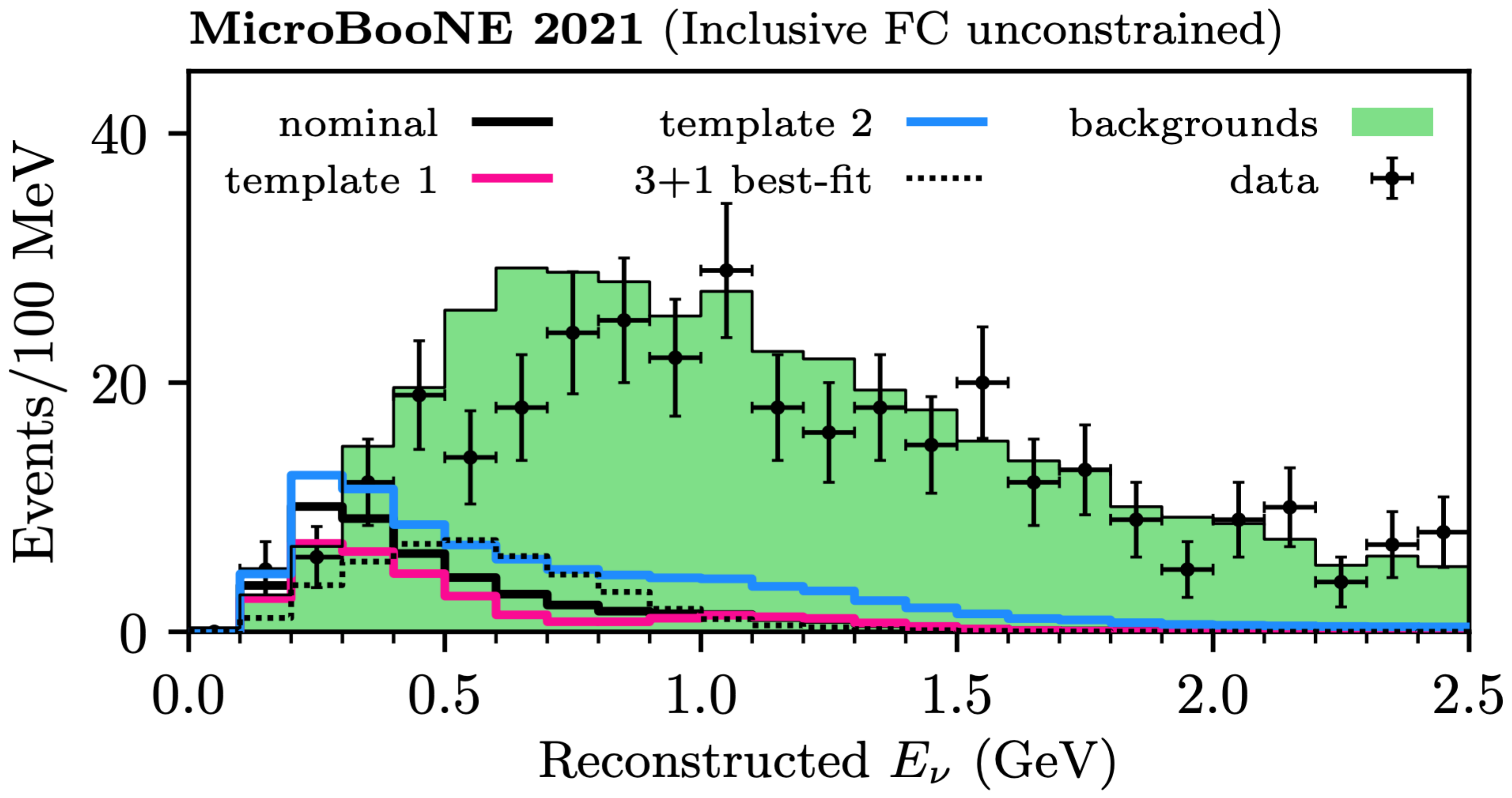

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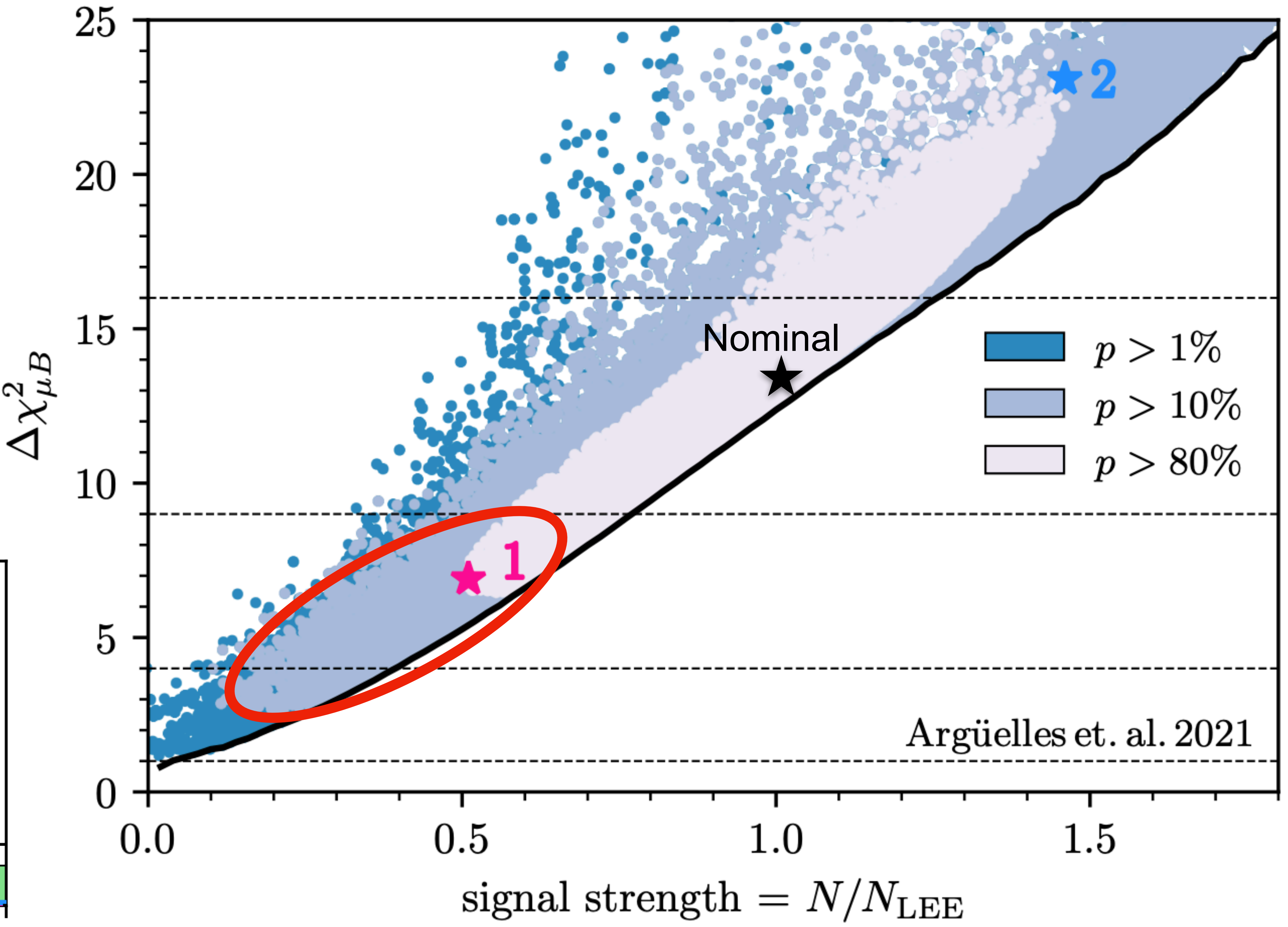

Q2

Are sterile neutrinos excluded? If so, where are the exclusion plots?

Sterile neutrinos at MicroBooNE
Fixed-background approach

Using MicroBooNE data releases:

(Inclusive* and CCQE)

we perform an oscillation analysis
to derive the limits on sterile neutrinos.

Oscillation search for **appearance only:**

$$\nu_\mu \to \nu_e$$

Backgrounds are not “oscillated”.

Inclusive

Only spectra and covariances available*

Energies ↑
Backgrounds. ↑
Statistics ↑
Intrinsics ↑

CCQE

Full data release available

Energies ↓
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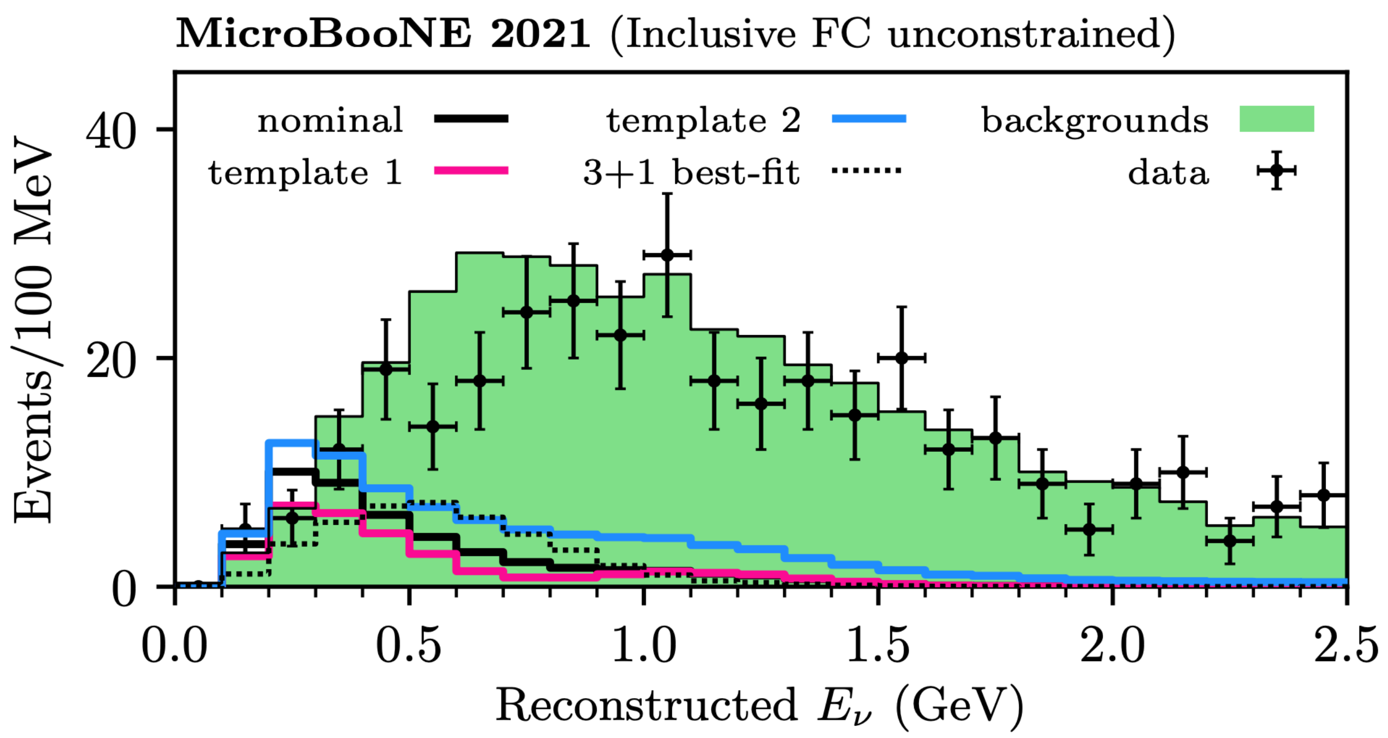

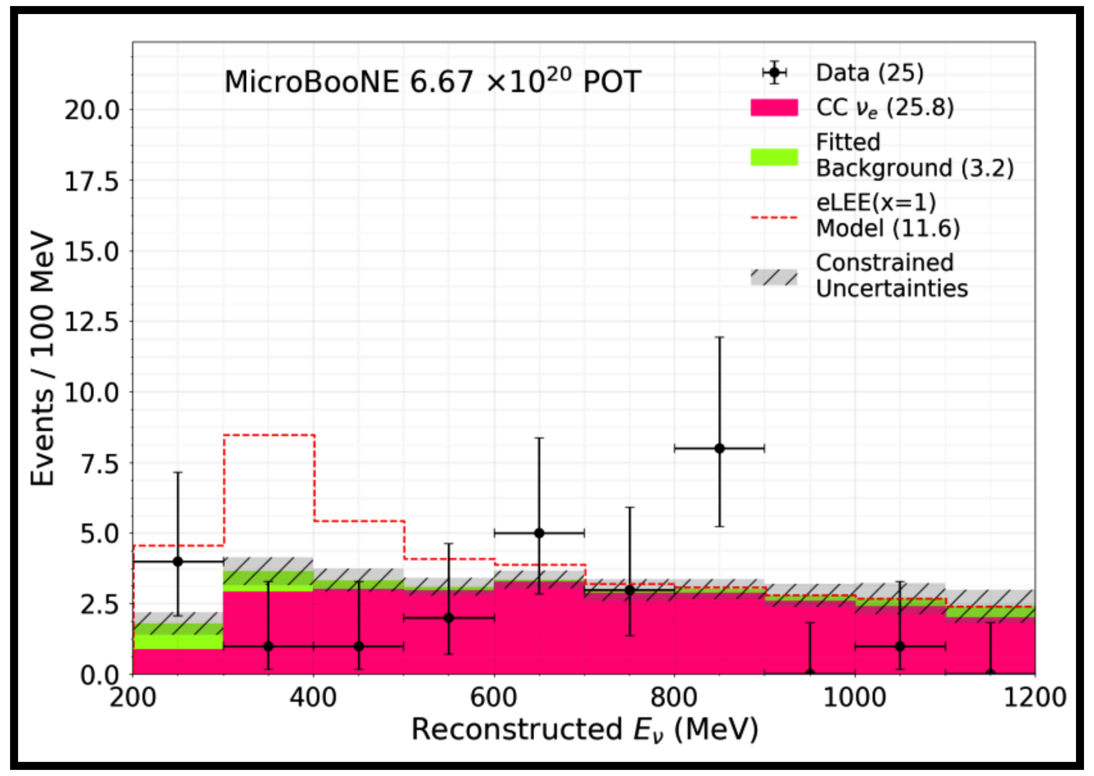

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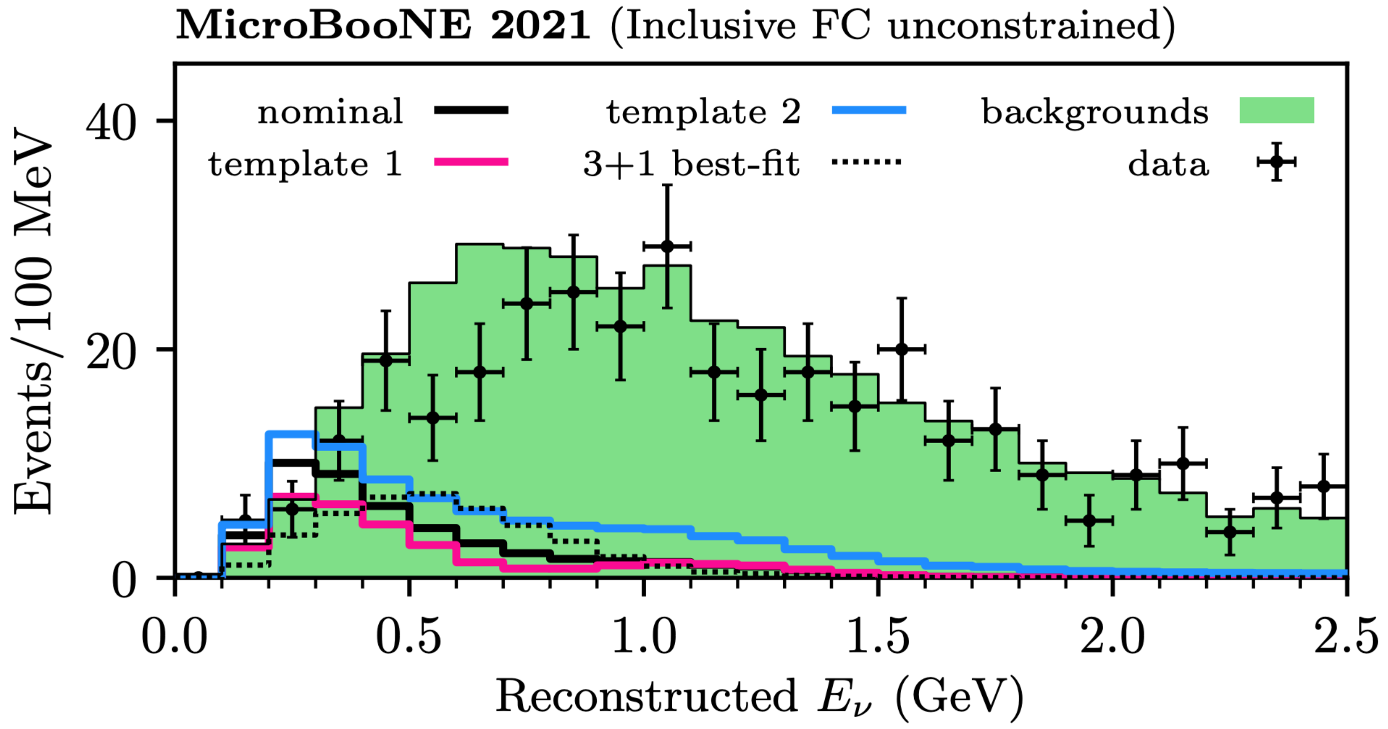

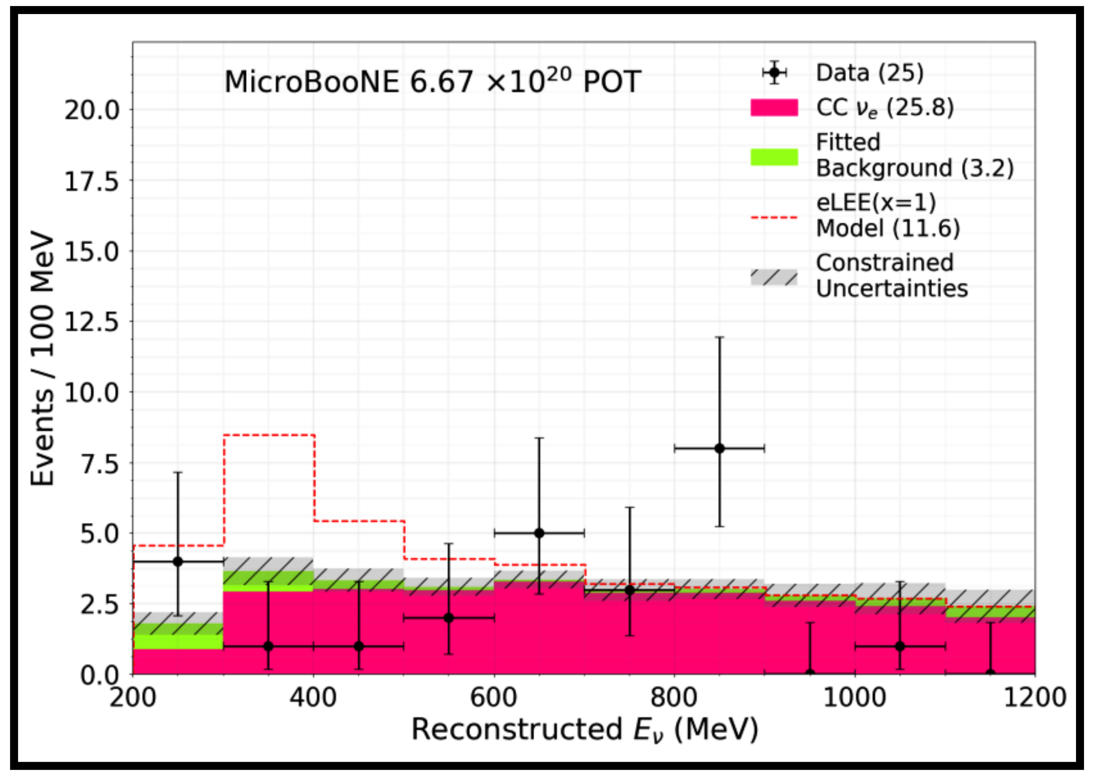

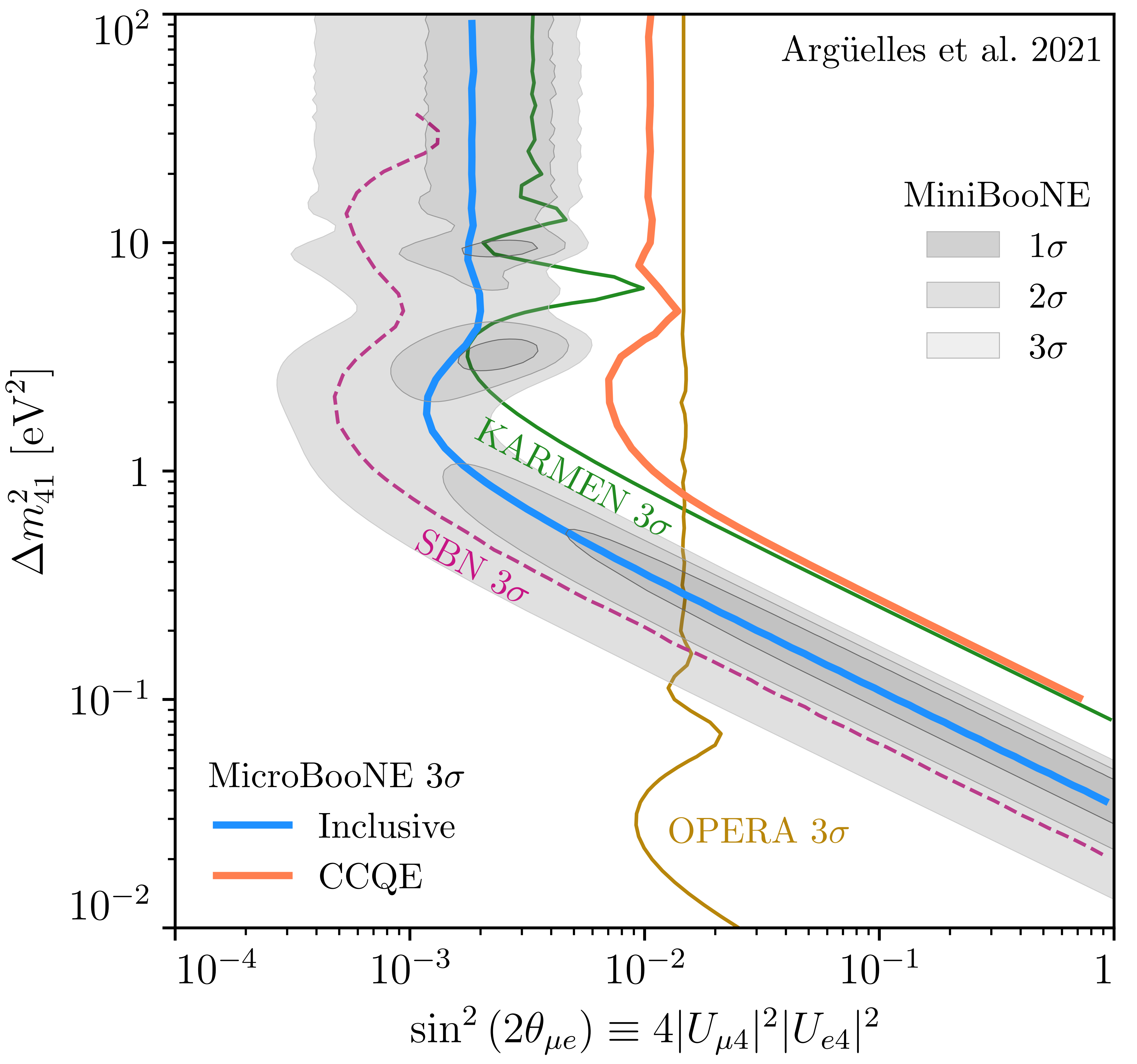

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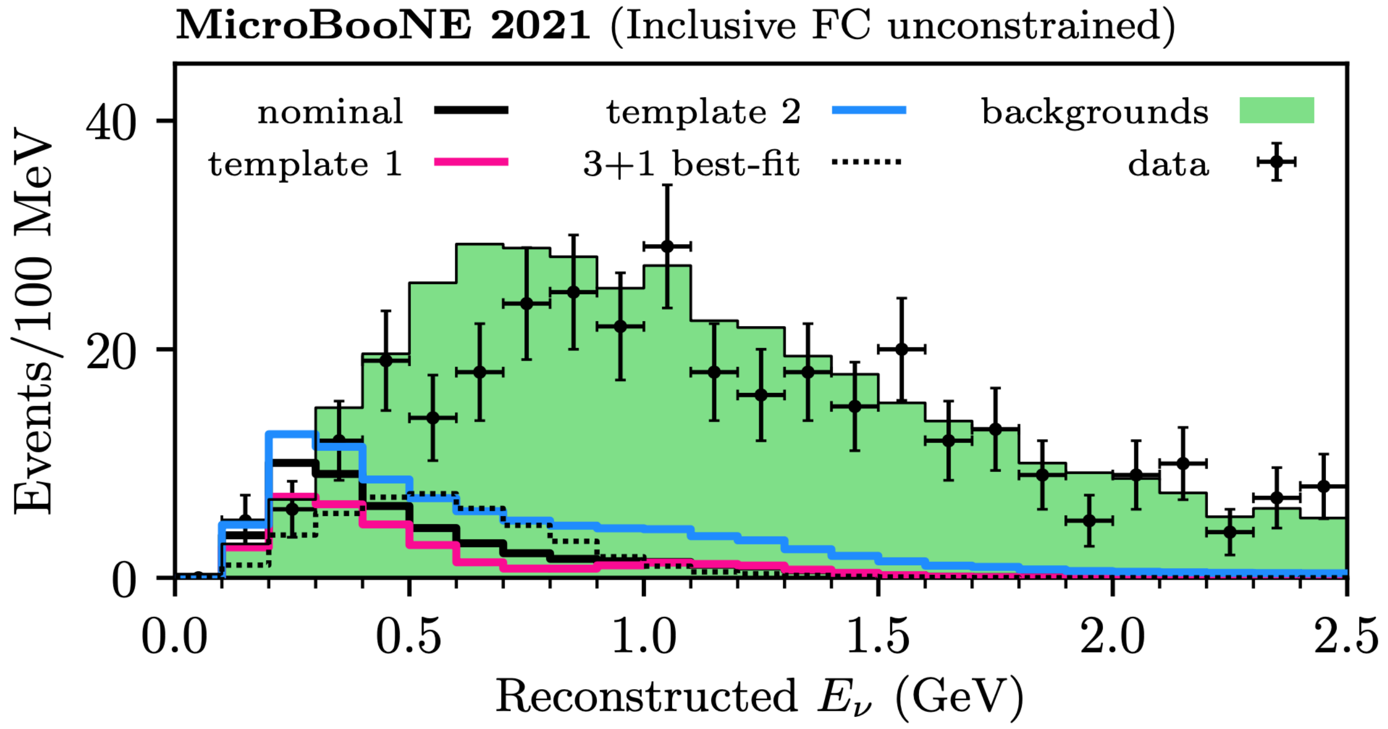
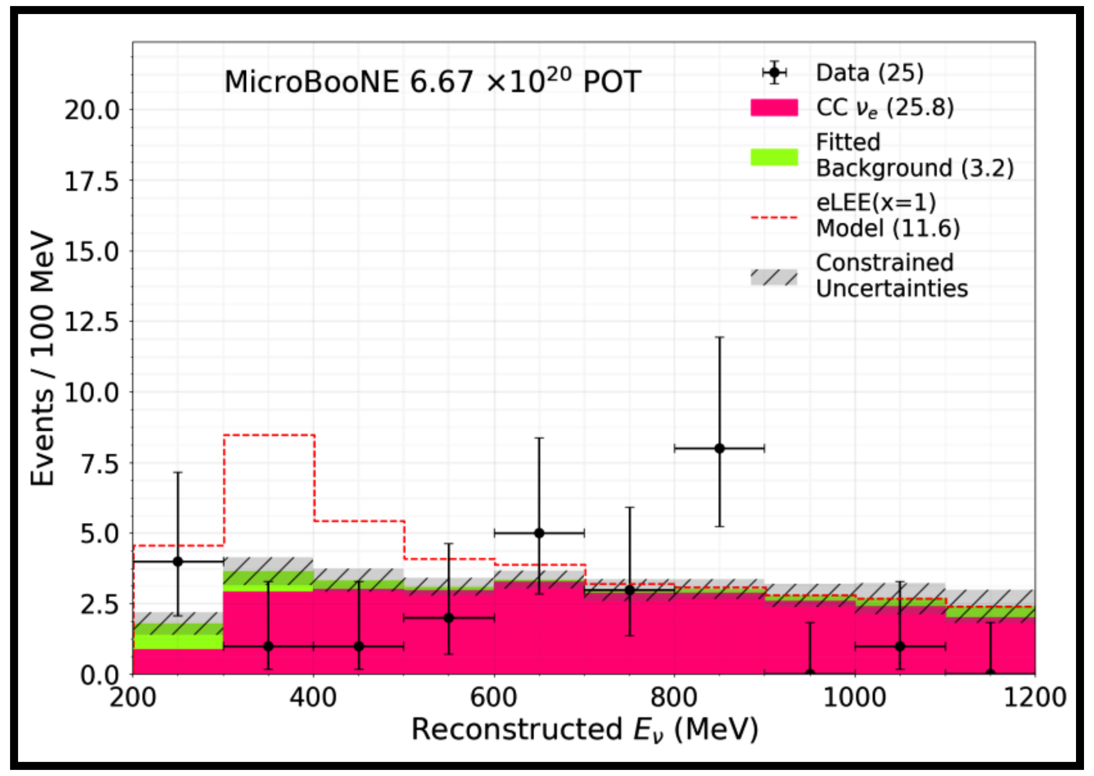
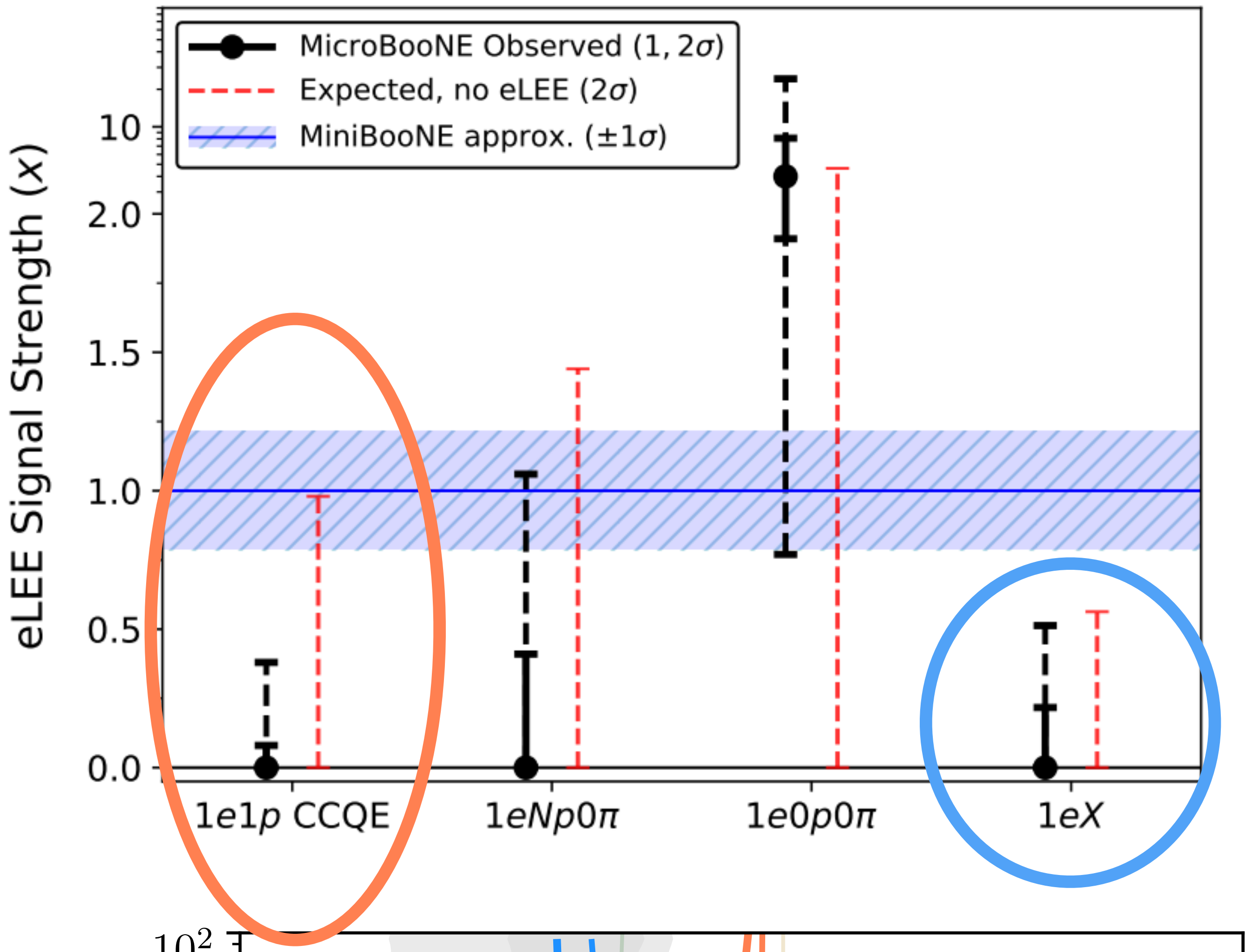
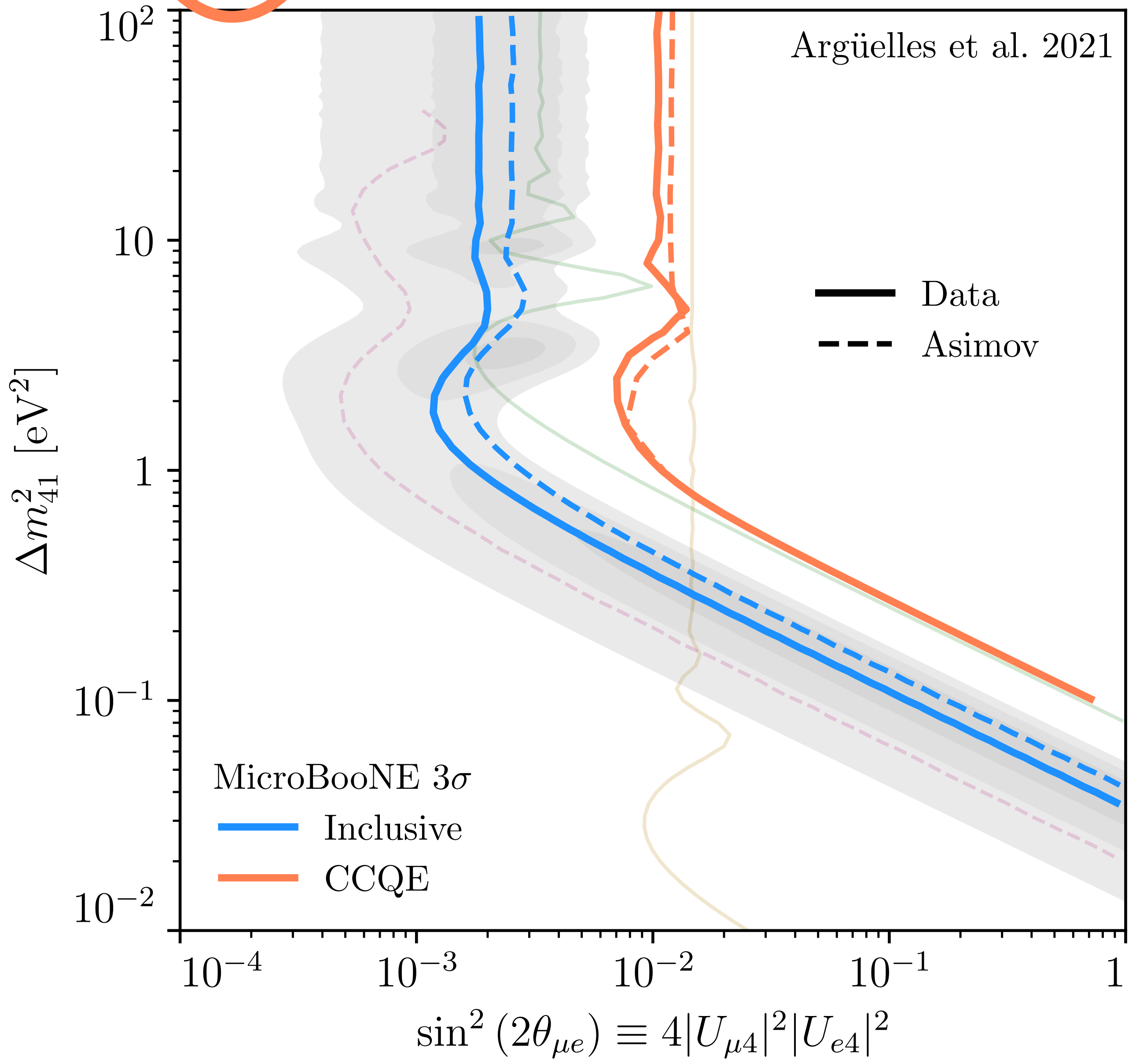






eLEE template
Sensitivity vs limit



Oscillation
Sensitivity vs limit

* efficiencies are derived from digitized smearing matrices.

Sterile neutrinos at MicroBooNE

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Using MicroE

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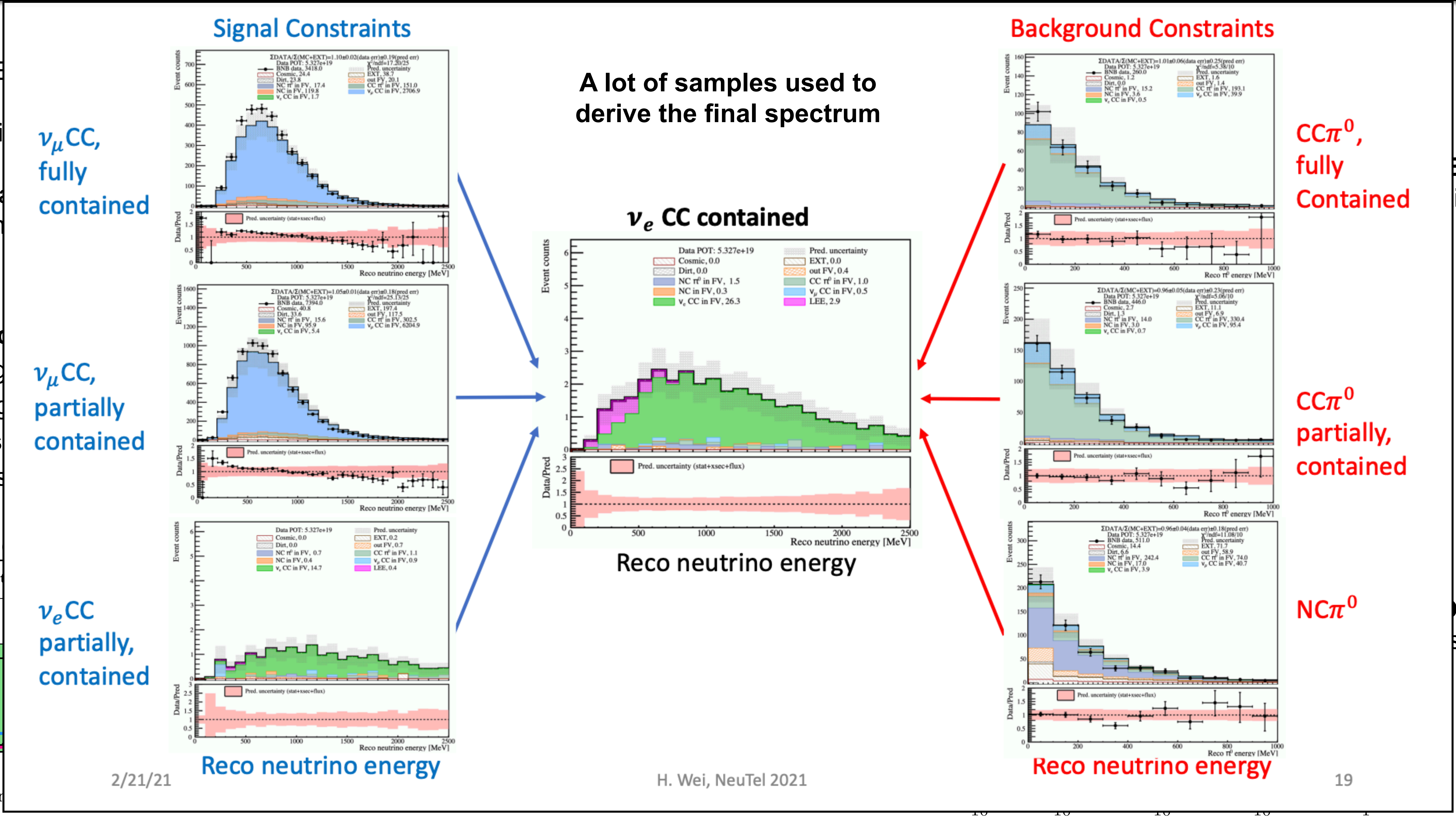
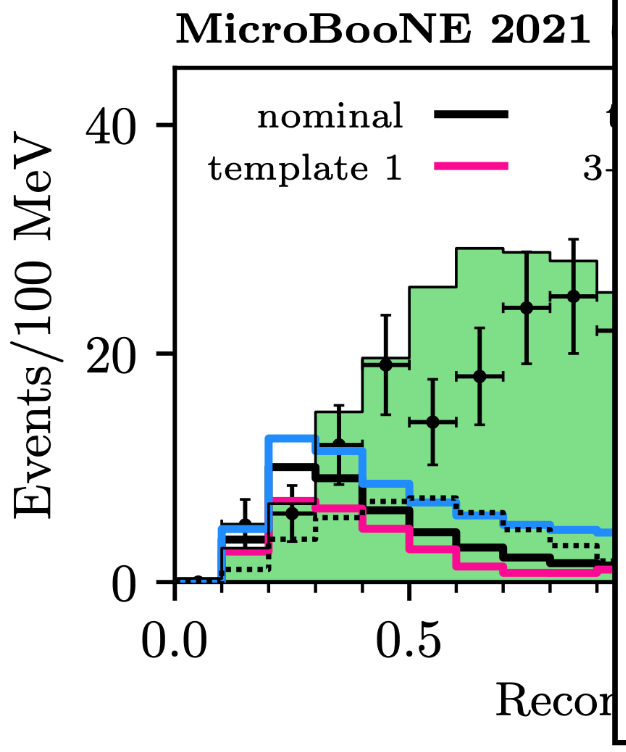




$\sin^2(2\theta_{\mu e}) \equiv 4|U_{\mu 4}|^2|U_{e4}|^2$

* efficiencies are derived from digitized smearing matrices.

Sterile neutrinos at MicroBooNE

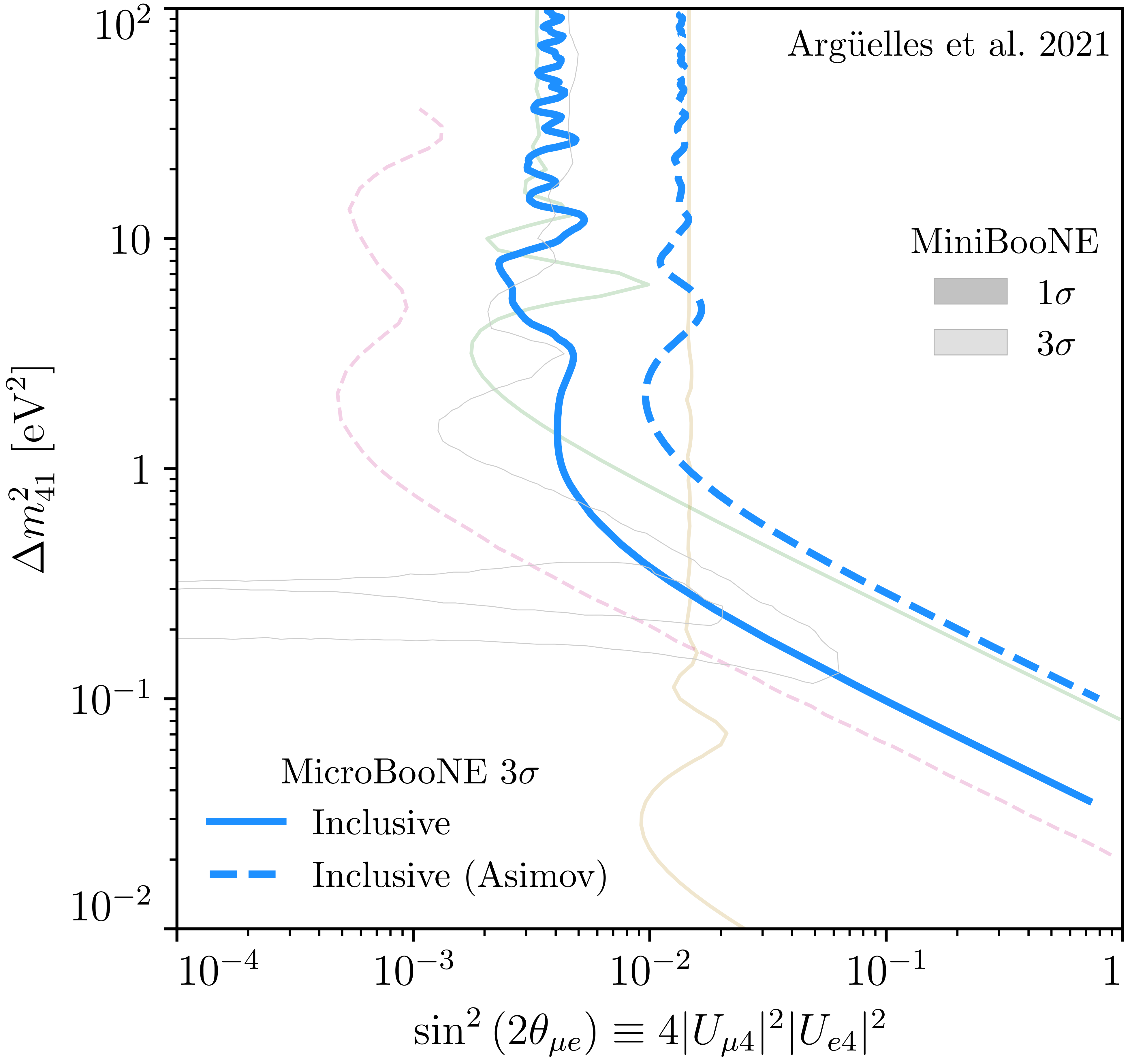
Oscillated-background approach

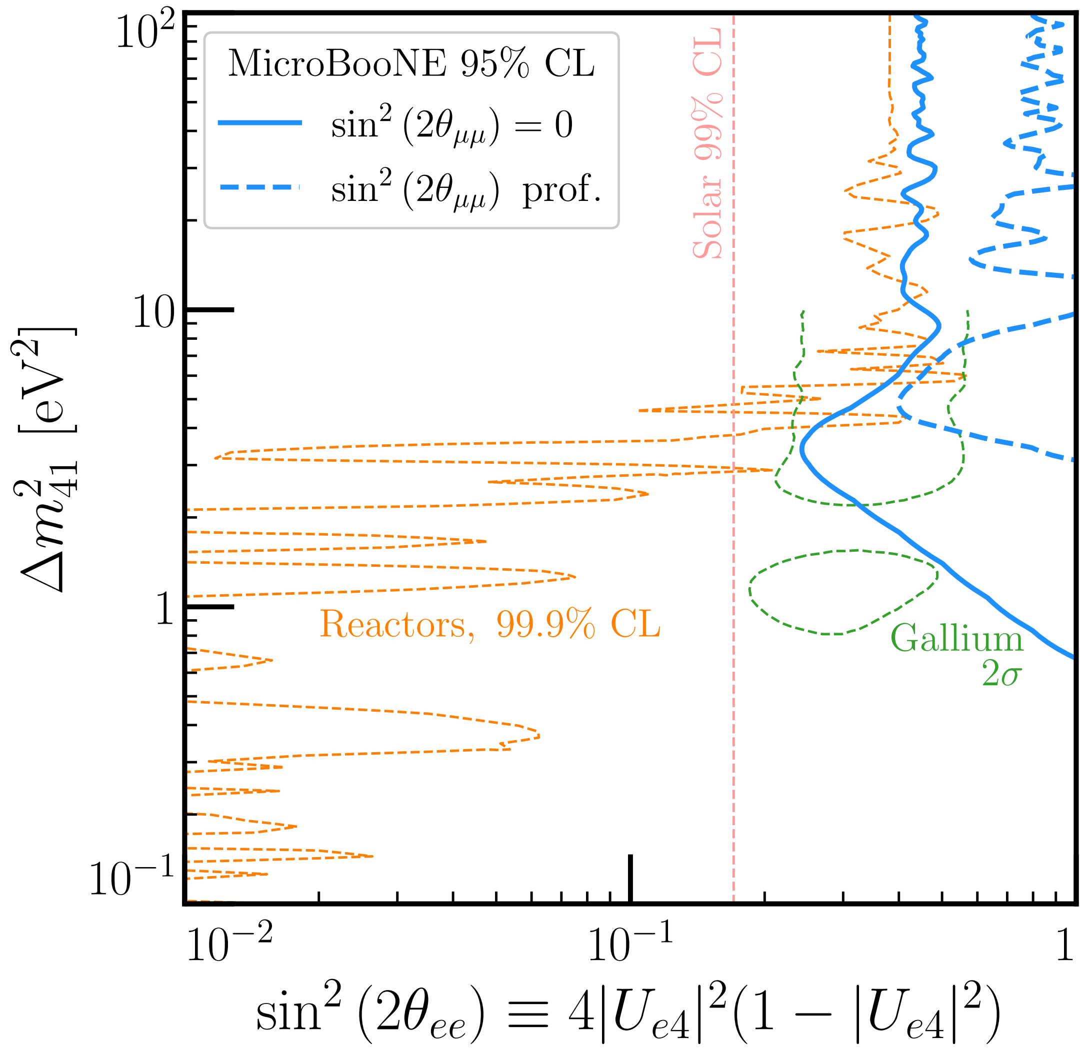
Fully consistent oscillation search:

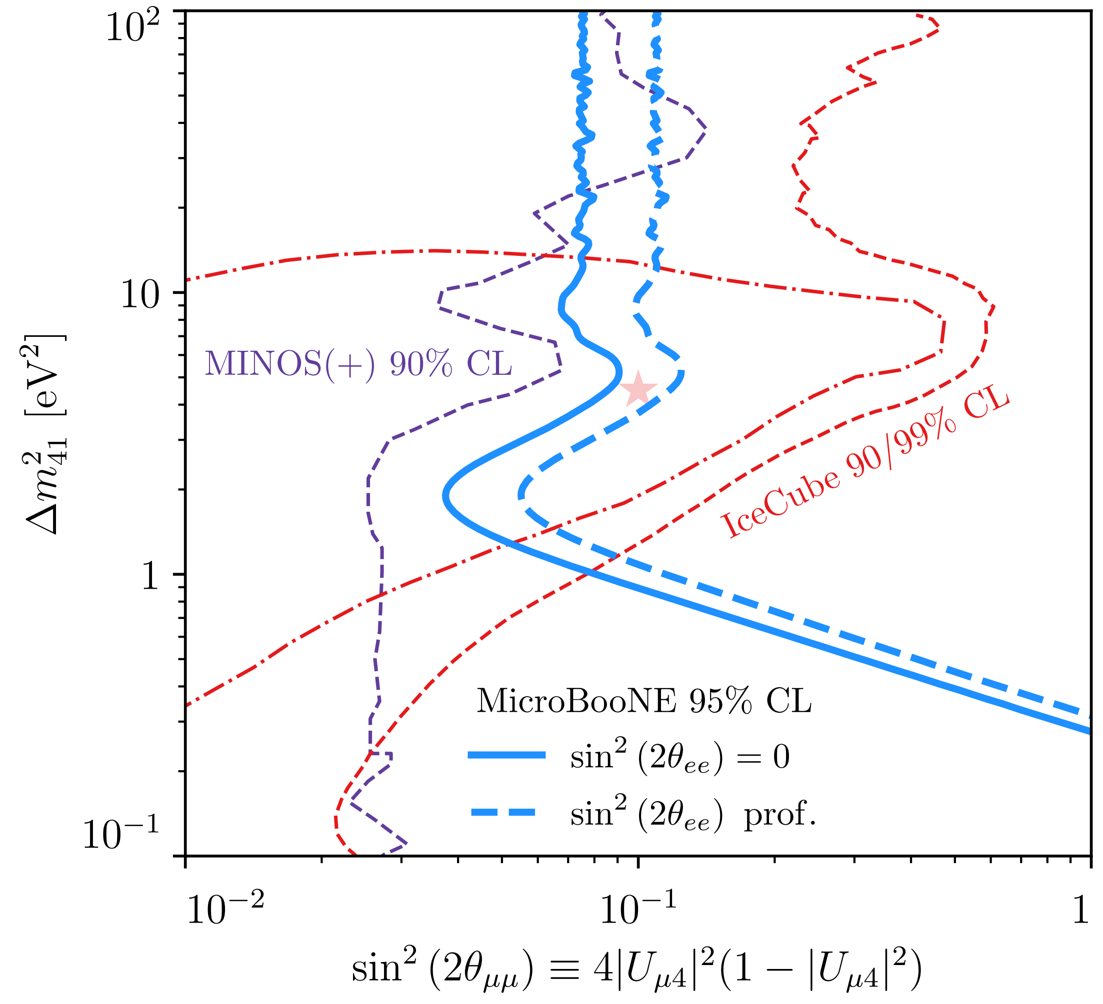
$$\nu_\mu \to \nu_\mu$$
$$\nu_\mu \to \nu_e$$
$$\nu_e \to \nu_e$$

Backgrounds are "oscillated".

A sterile neutrino interpretation of the MiniBooNE anomaly is still allowed by MicroBooNE data at 3σ



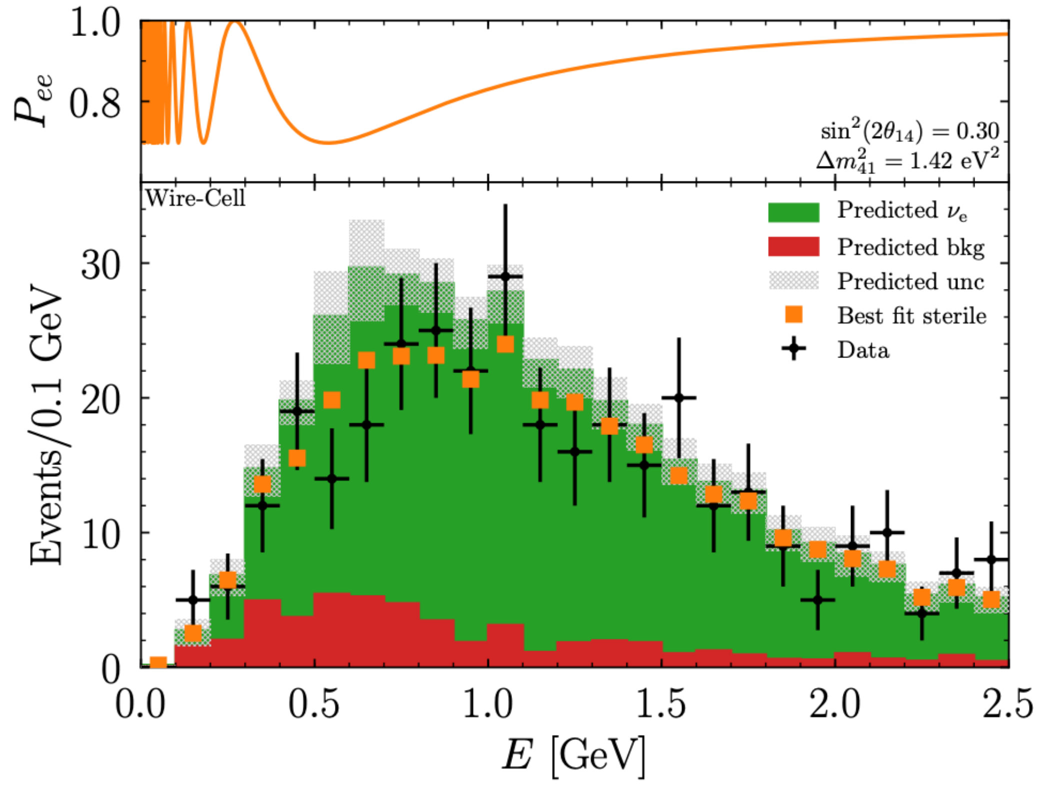




Sterile neutrinos at MicroBooNE
Oscillated-background approach

A naive inspection of the ν_e spectra at MicroBooNE suggests that ν_e disappearance may be at play.

P. Denton, arXiv:2111.05793



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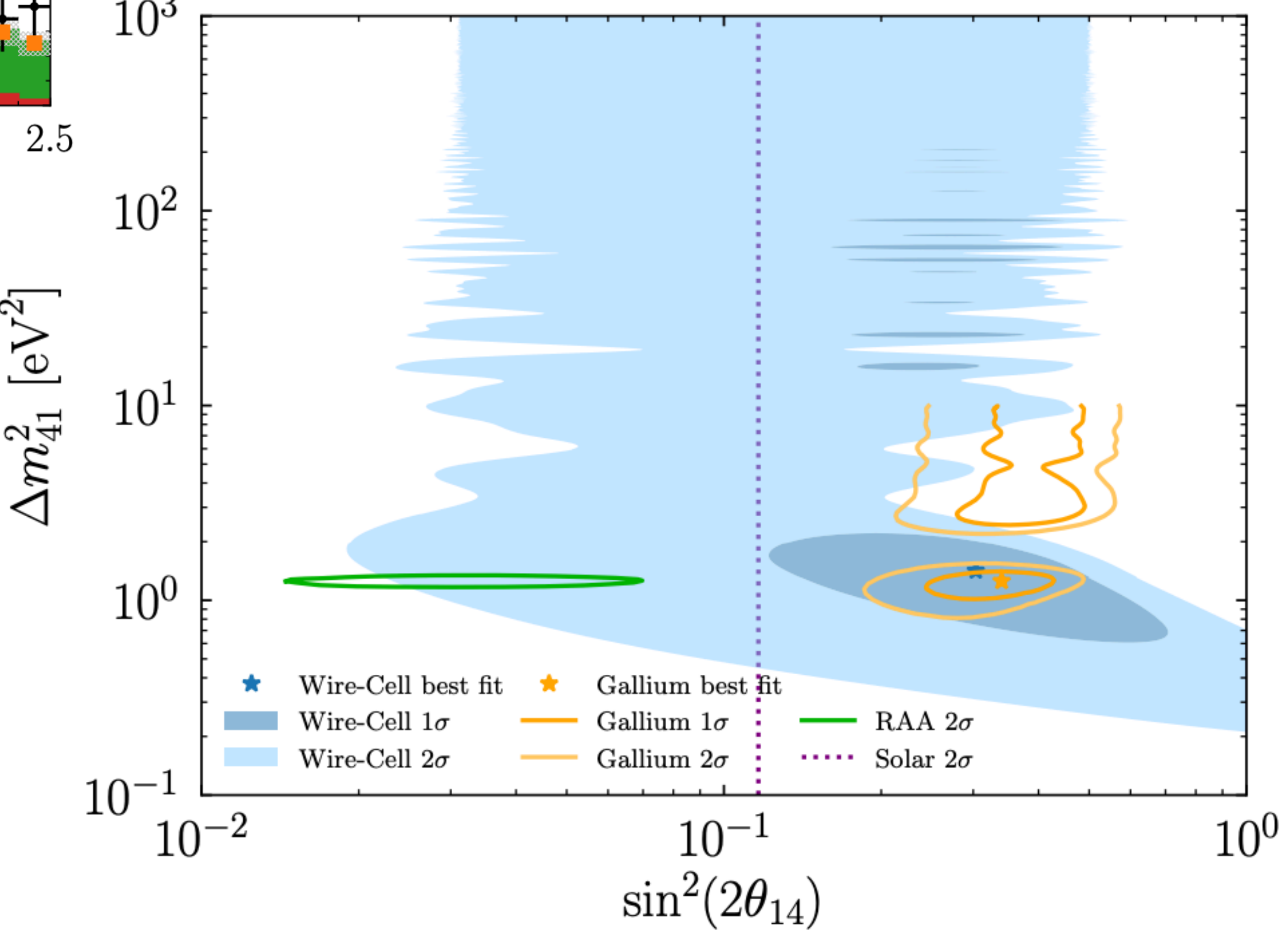
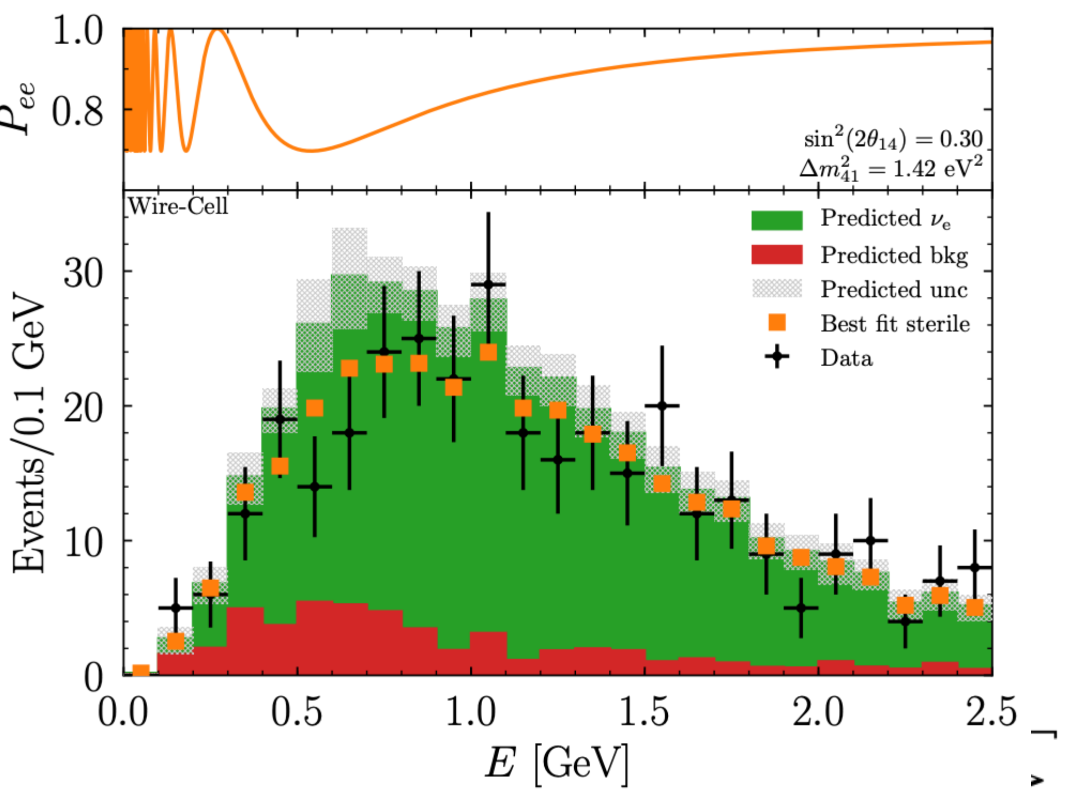


Sterile neutrinos at MicroBooNE
Oscillated-background approach

The deficit of ν_e events at MicroBooNE may be interpreted as evidence for ν_e disappearance.

P. Denton, arXiv:2111.05793



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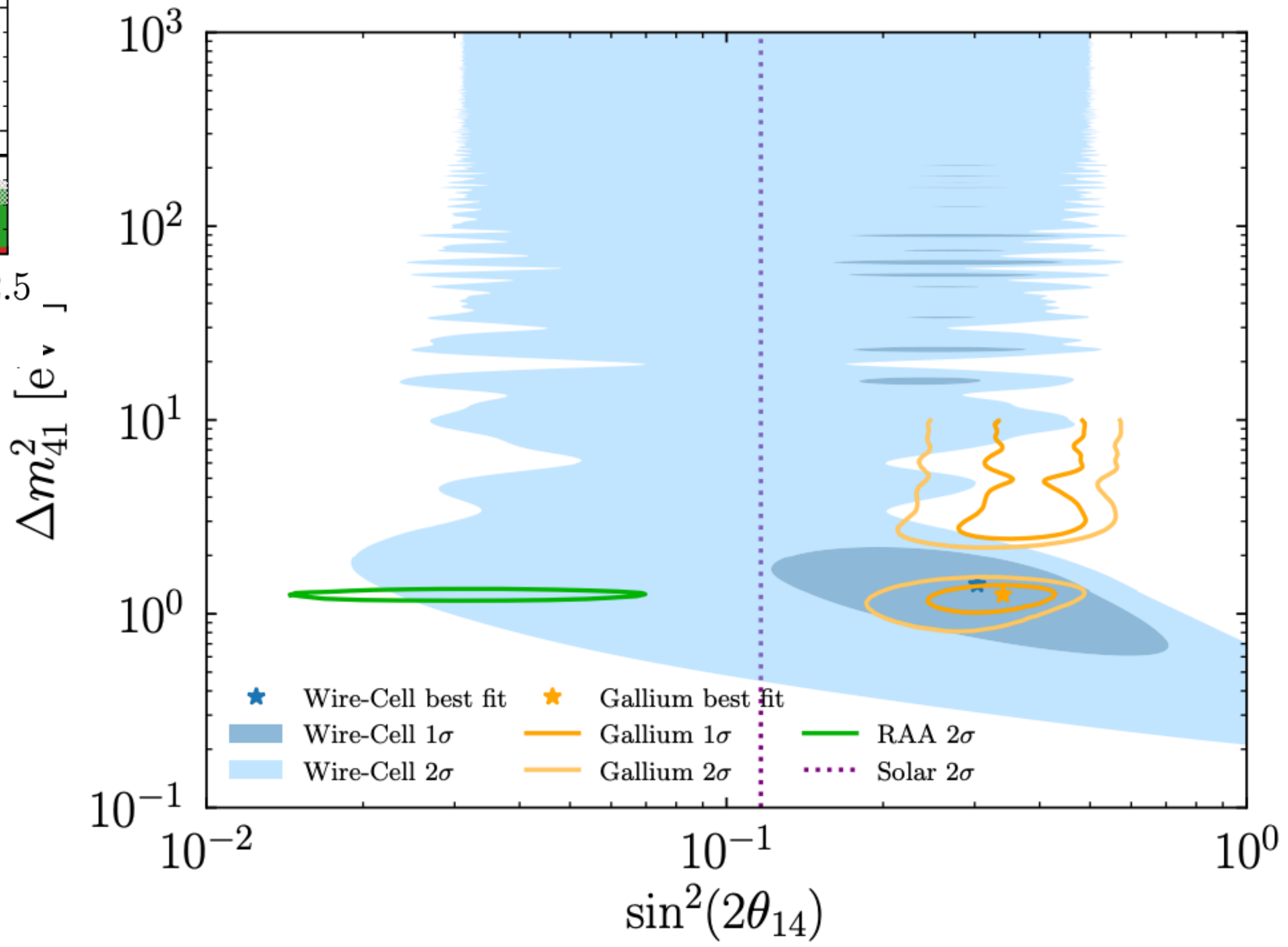
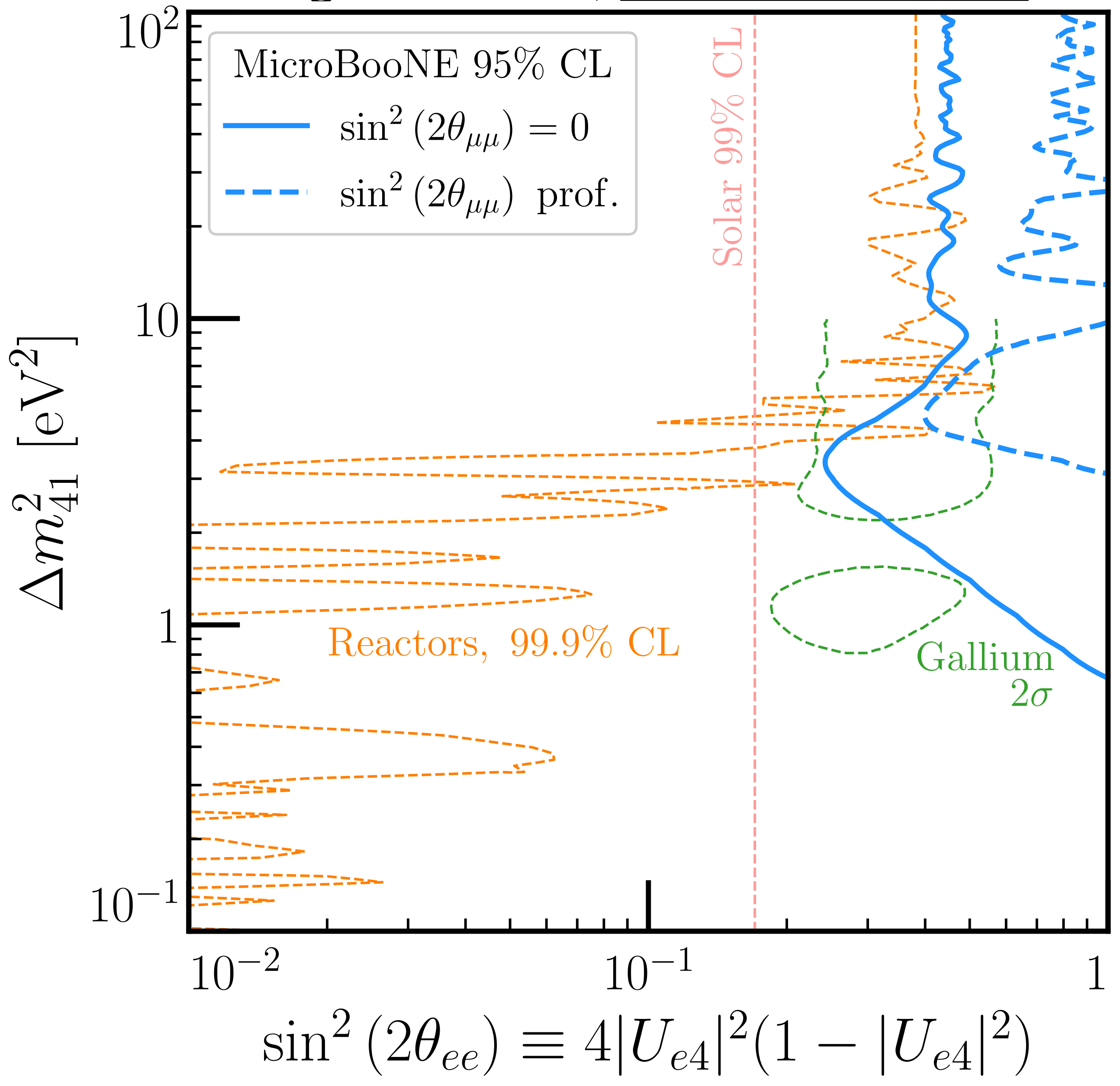


Argüelles et al, arXiv:2111.10359



Our best-fit point is

$$\Delta m^2_{41} = 1.38 \text{ eV}^2, \quad \sin^2 2\theta_{ee} = 0.2, \quad \sin^2 2\theta_{\mu\mu} = 0$$

with a significance of $0.95\,\sigma$.

We conclude that our results are consistent with no ν_e disappearance.

The discrepancy with P. Denton arises from:

i) Including all “side-band” samples and *their correlations*
ii) Computing oscillations before detector smearing.

Q3

Does MicroBooNE put an end to the MiniBooNE anomaly?

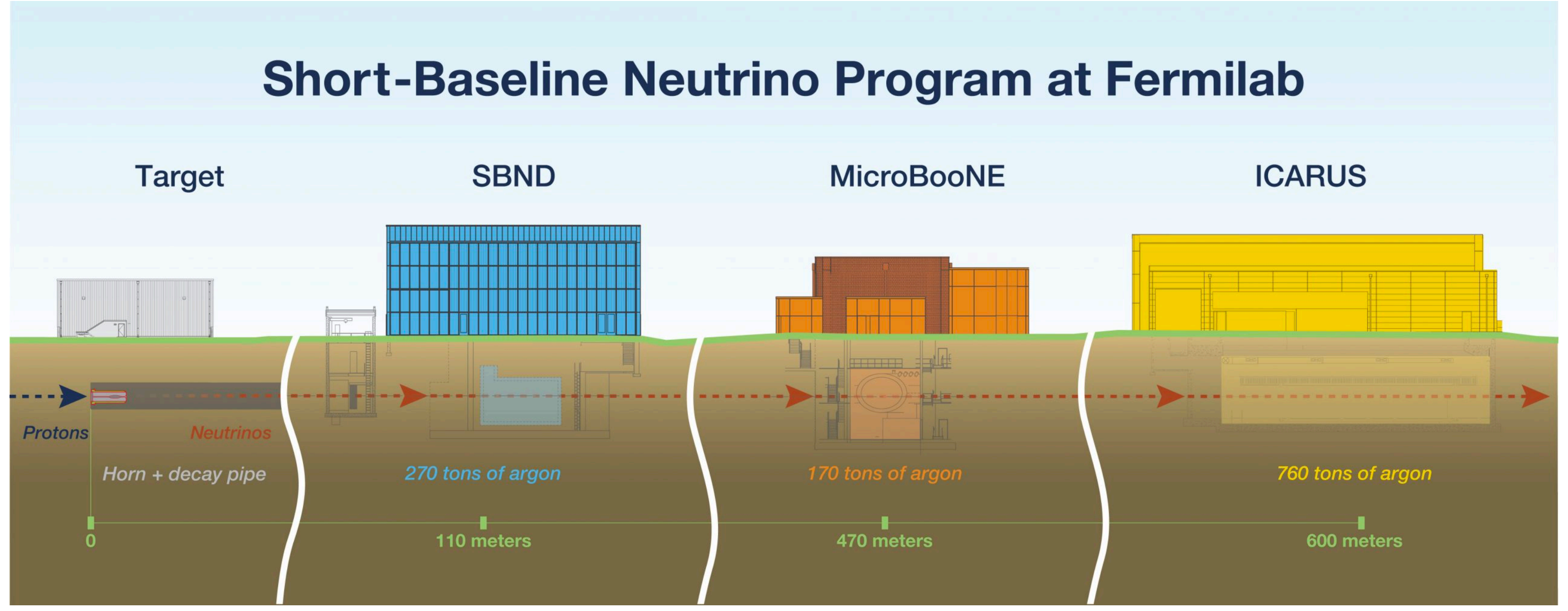
Clearly the answer is still no.

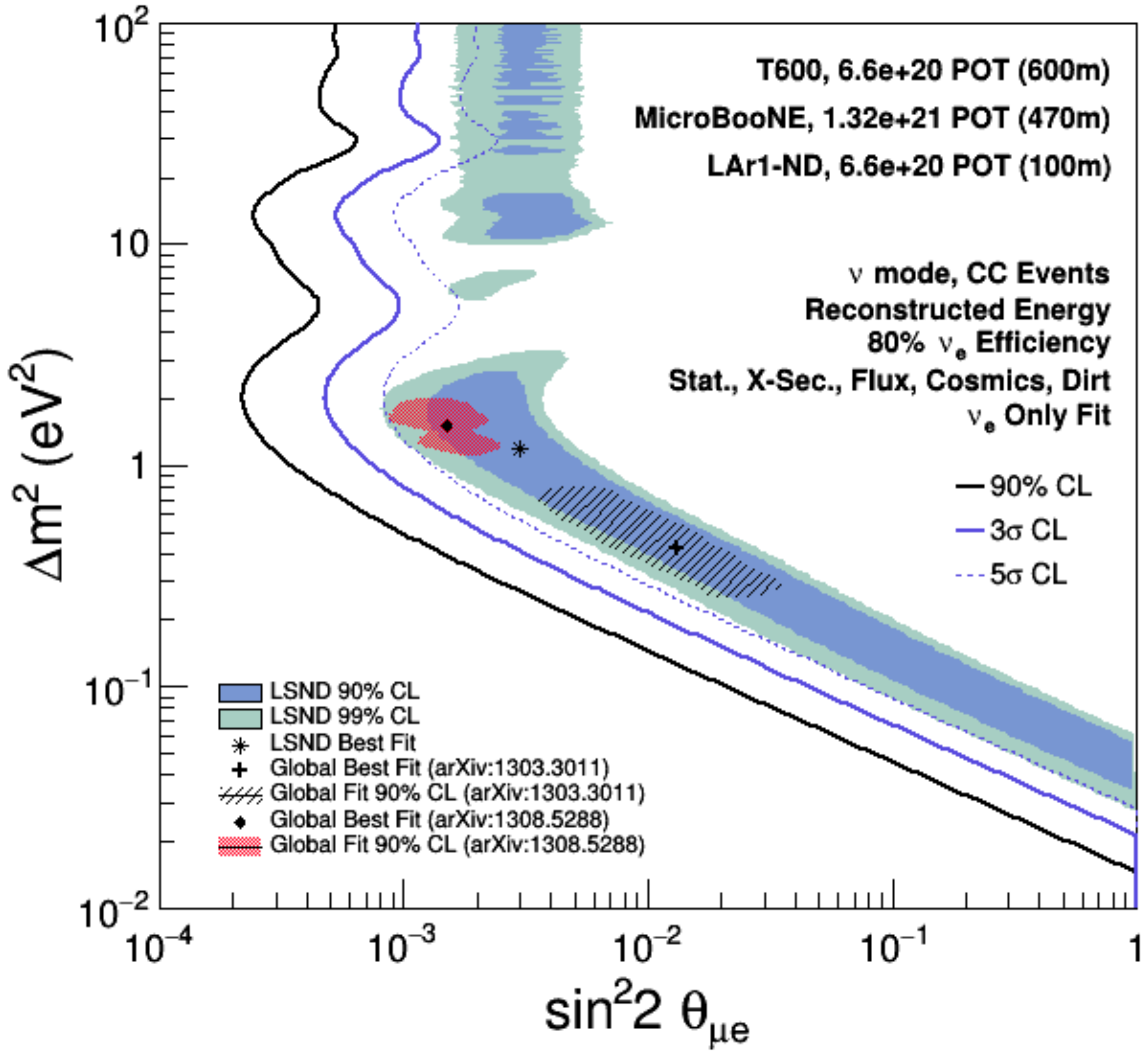
Moving forward

Full oscillation analysis should still be pursued by within the collaboration to confirm phenomenological study shown here.

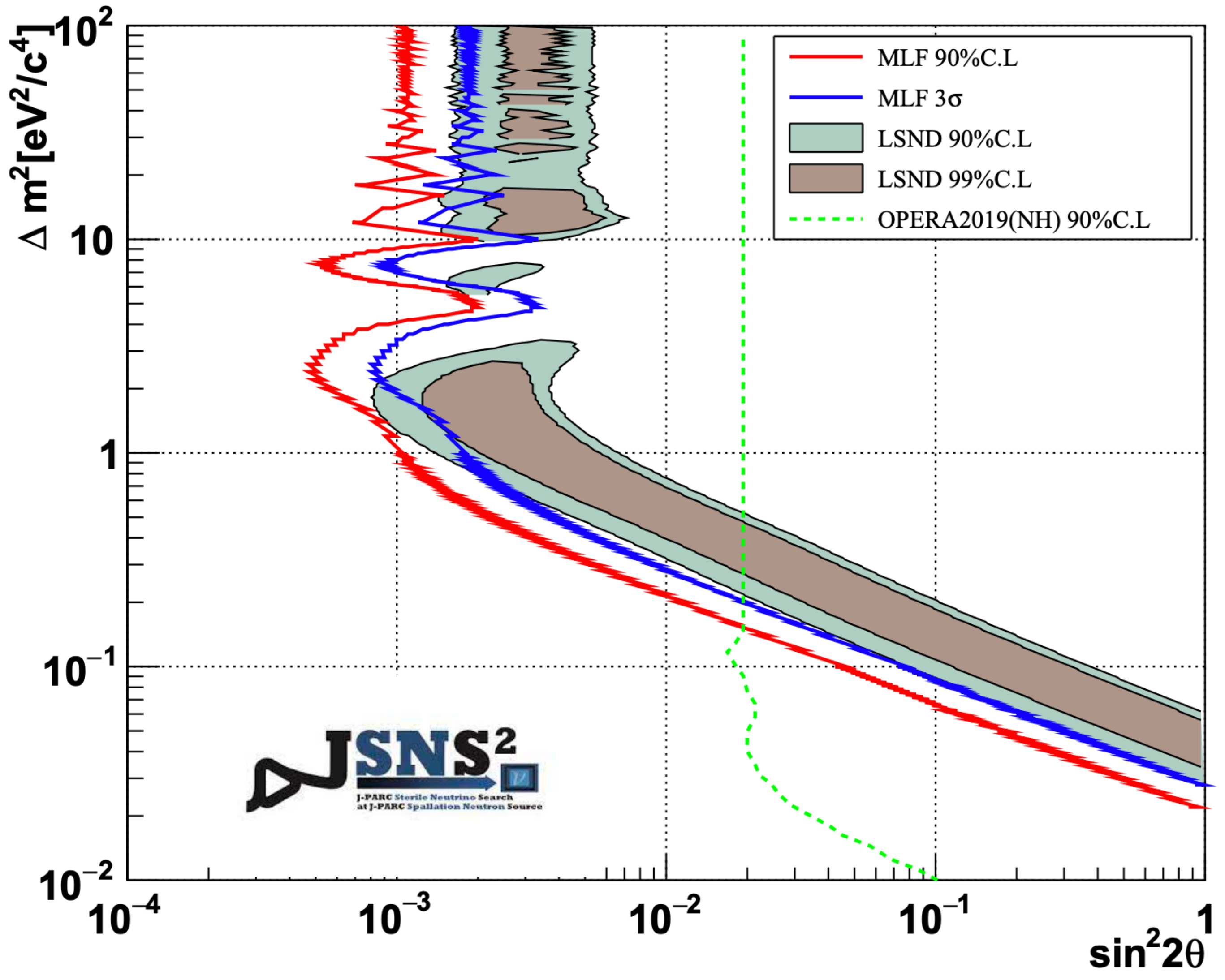
But to move forward, we need decisive results:

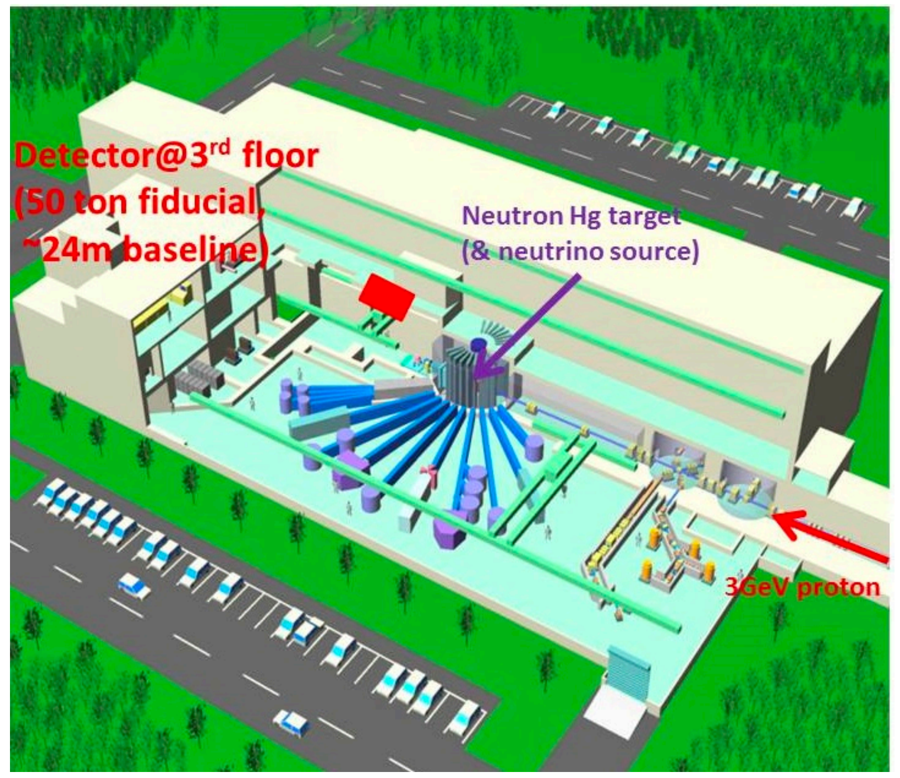
The Short-Baseline Neutrino Program @ FNAL





In the Japaneses Spallation Neutron Source, **JSNS^2 is performing a direct test of the LSND results.**





Other proposals remain untested

Several new proposals

New signatures:
Gninenko 1107.0279 — No LSND
Heavy neutrino O(MeV), magnetic moment, decay

Bertuzzo et al 1807.09877, Ballett et al 1808.02916, Arguelles et al 1812.08768
Heavy neutrino O(1-100MeV), light Z', decay
W. Abdallah et al 2010.06159 — ~~No LSND~~

Oscillations+:
Asaadi et al 1712.08019
Resonant matter effect — UV challenge

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eV steriles and extra dimensional shortcuts — not clear

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Long lived HNL O(MeV) mag moment — Delayed signal?

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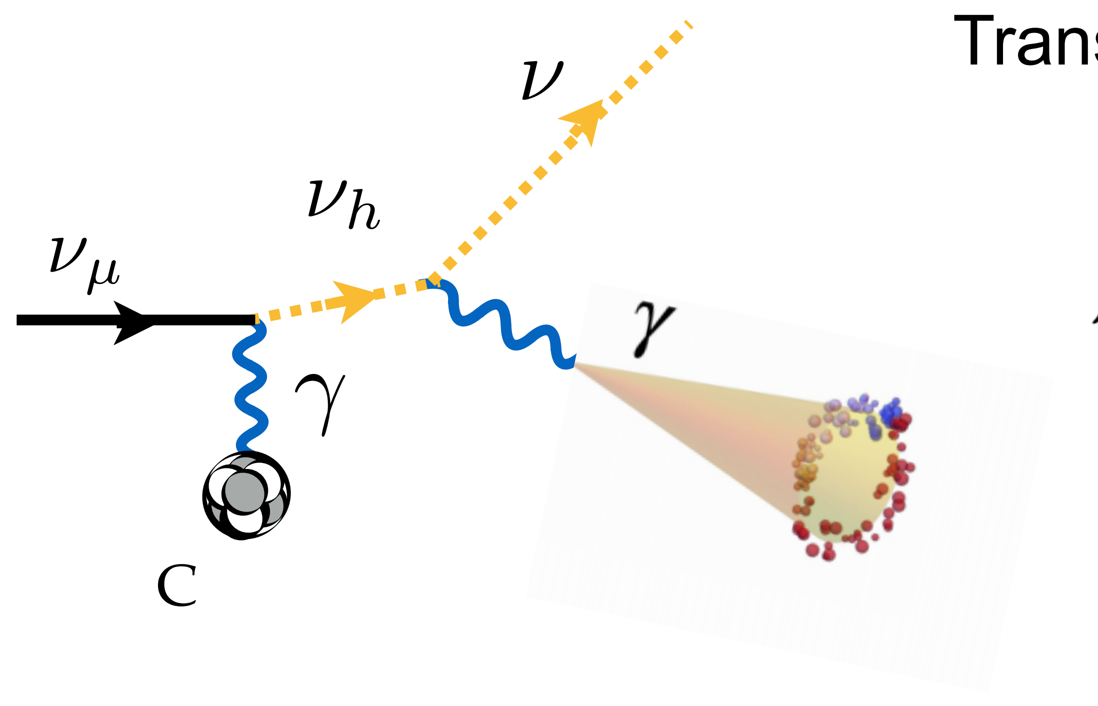
New physics
In scattering



Transition magnetic moment and dark neutrinos.

$$\mathcal{L}_\mu = \frac{\mu_\nu^\alpha}{2} F_{\mu\nu}\, \bar{\nu}_L^\alpha \sigma^{\mu\nu} N_R \,.$$

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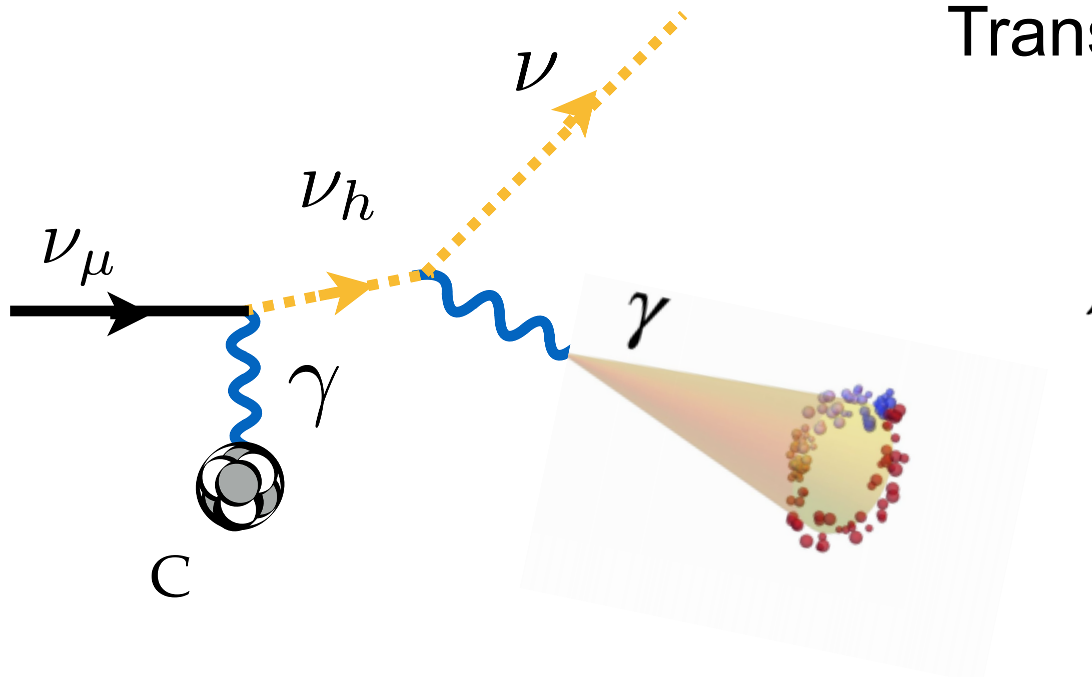

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New physics
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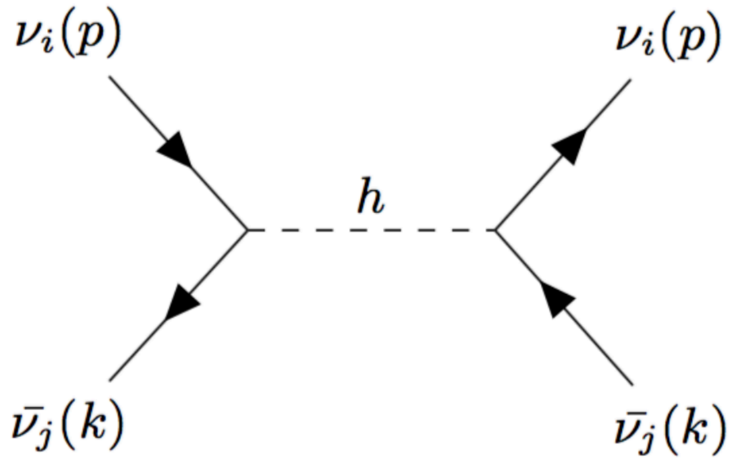
NSI's or even scattering on neutrino over-densitie

$$\mathcal{L}_{\rm NC} = -2\sqrt{2} G_F \sum_{f,P,\alpha,\beta} \varepsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$



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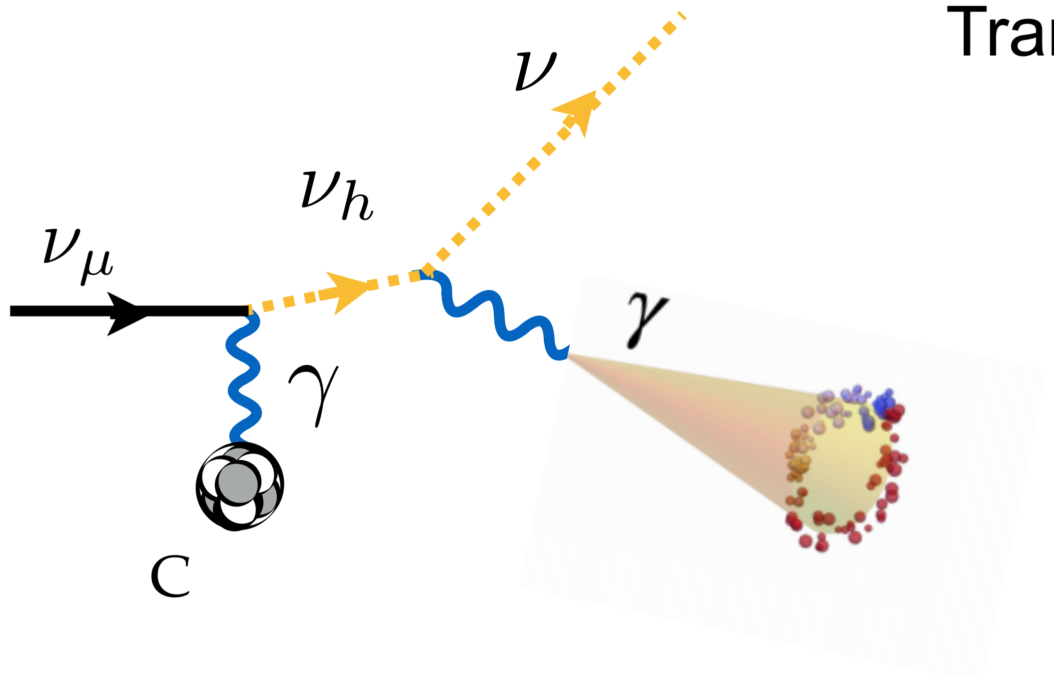

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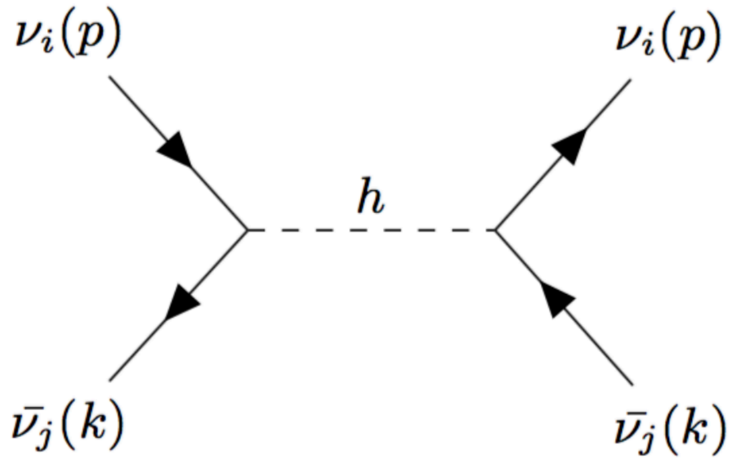
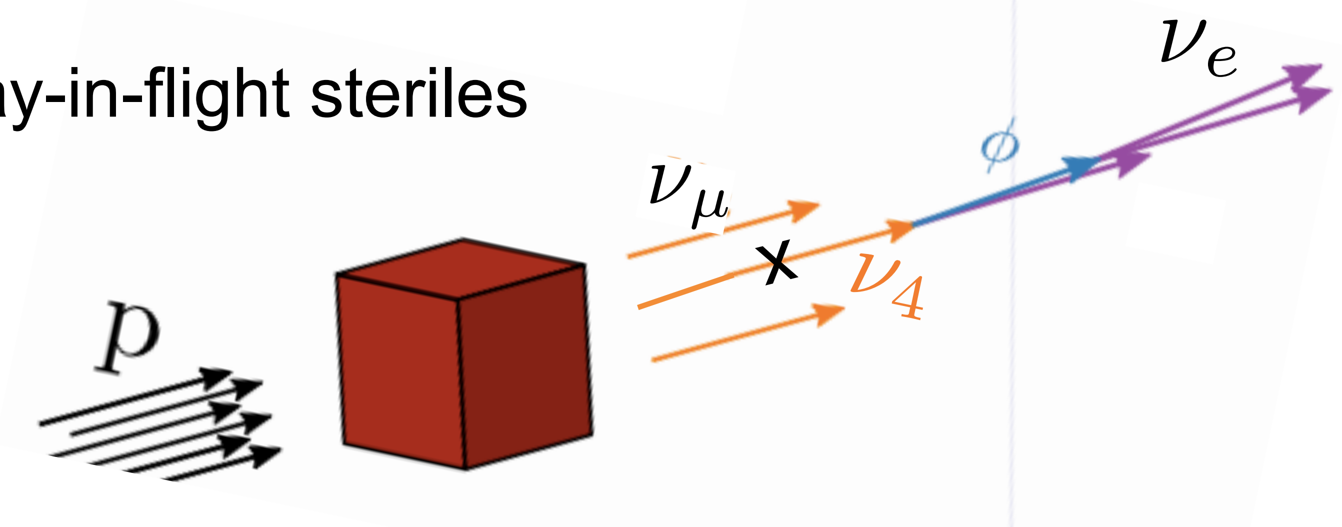


New "visible" states
in the beam

Decay-in-flight steriles

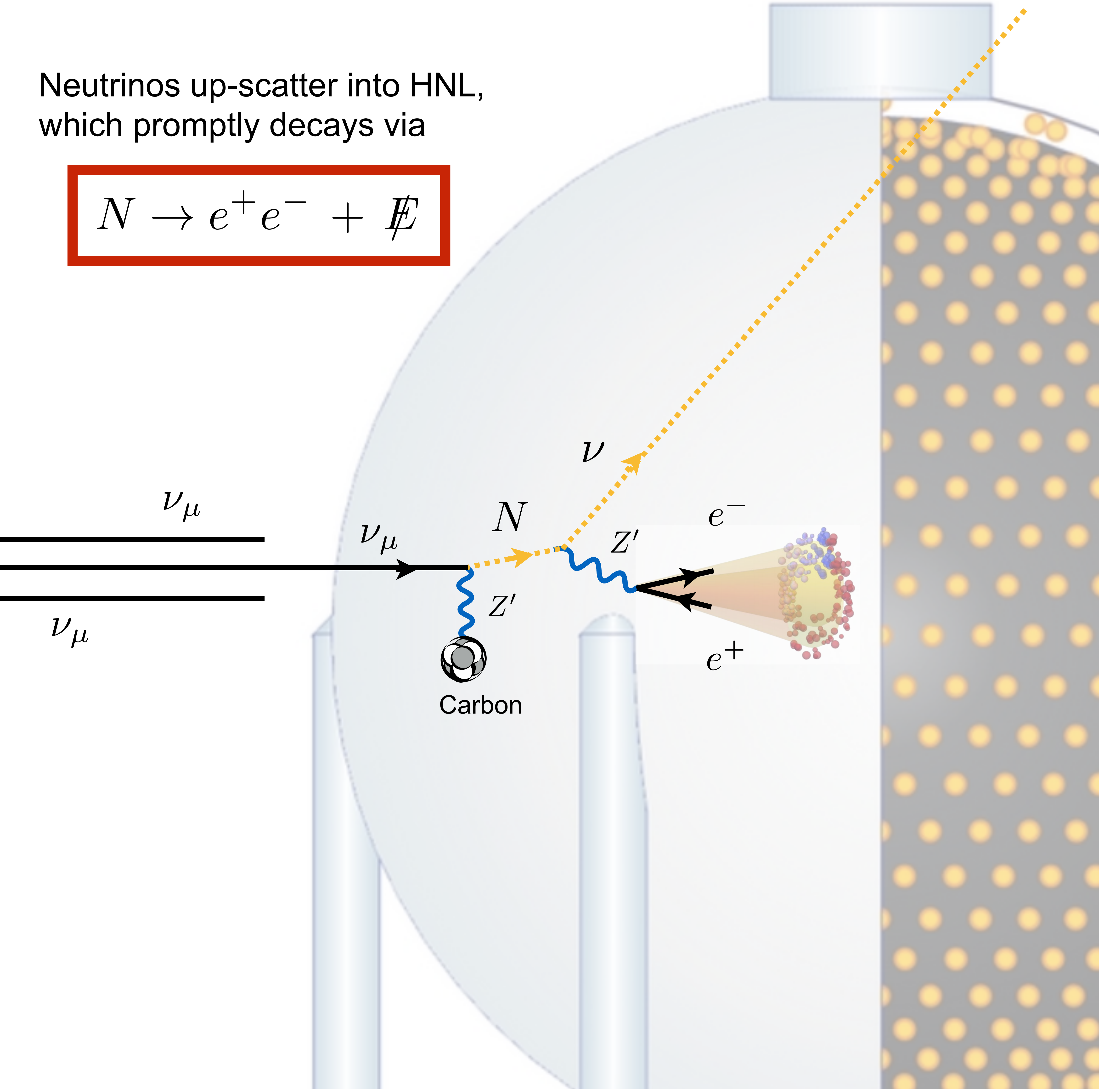


I. Esteban,10.5281/zenodo.3509890.

Heavy neutrinos + dark forces to accommodate MiniBooNE

Neutrinos up-scatter into HNL, which promptly decays via

$$N \to e^+ e^- + \not{E}$$



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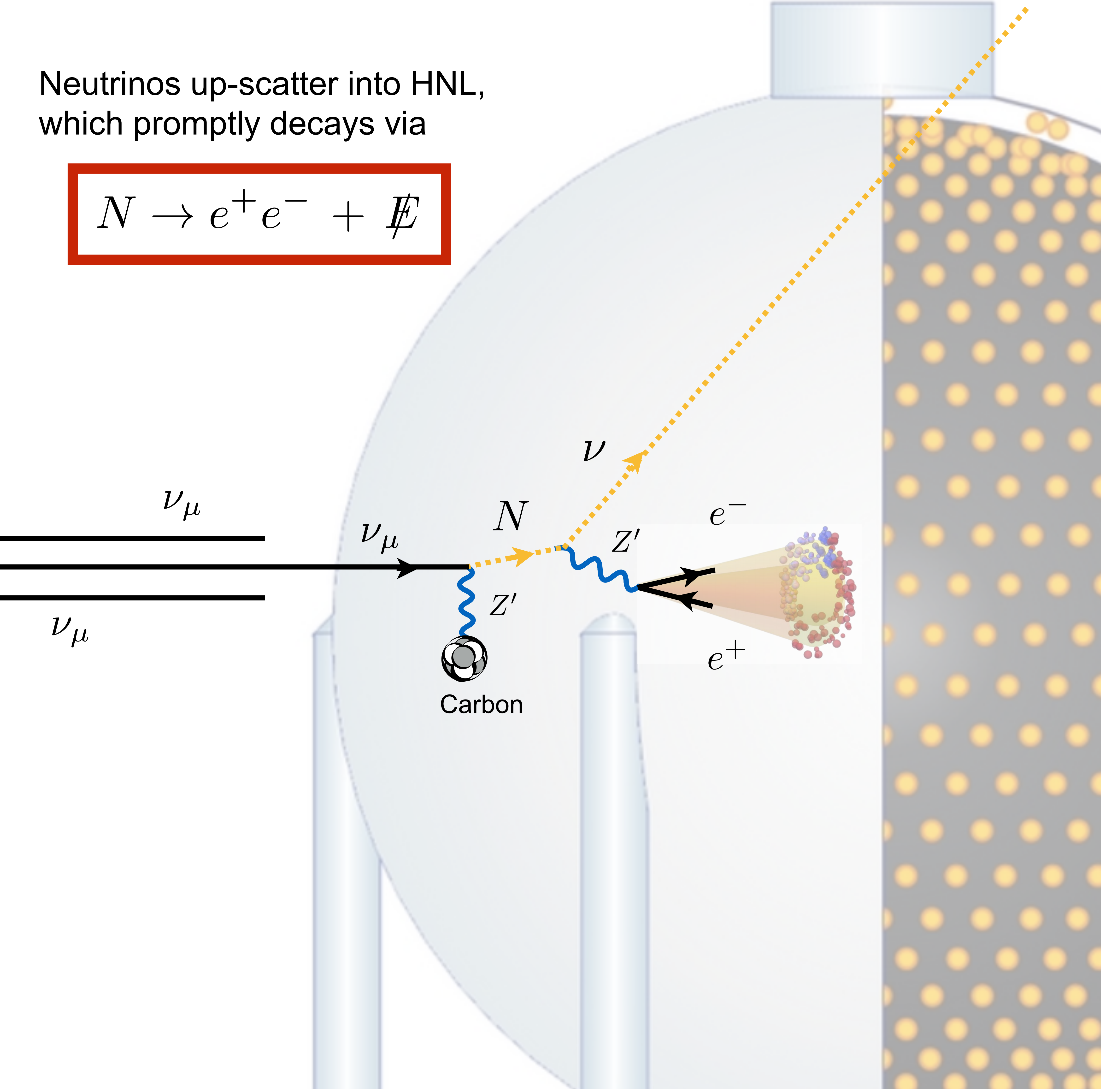


Dark sector coupled via neutrino portal + vector portal

$$\mathscr{L} \supset -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu} + y\, LHN + y' (\nu_D N)\Phi + g_D\, X_\mu (\nu_D \gamma^\mu \nu_D)$$

Light mediators (10 - 100s of MeV)

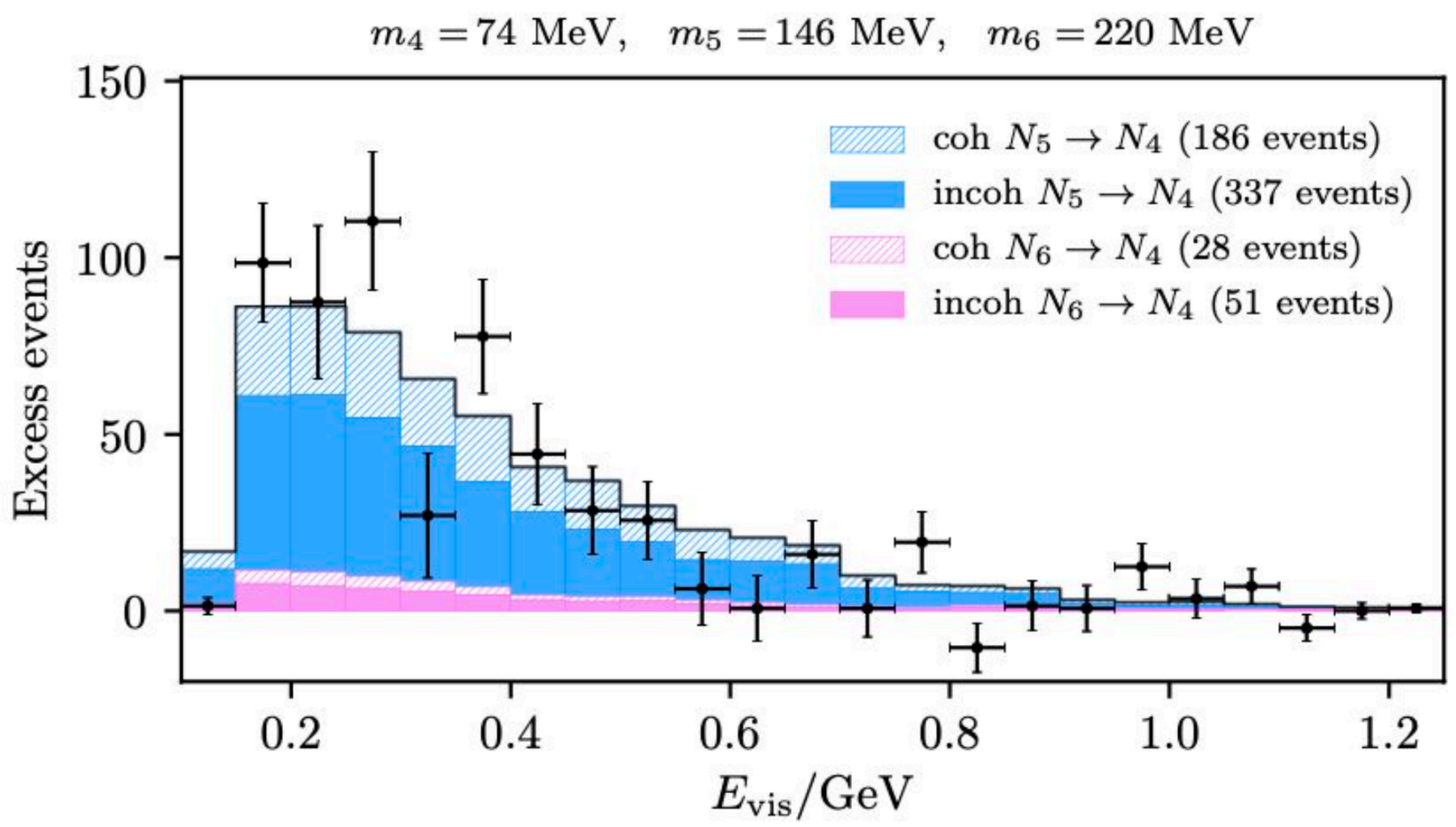
E. Bertuzzo et al., PRL121.241801
C. Argüelles, MH, Y. Tsai, *PRL*123.261801
+ …

Heavy mediators (~ GeV scale)

P. Ballett et al, PRD 99.071701
+ …

Inter-generational decays (~GeV scale)

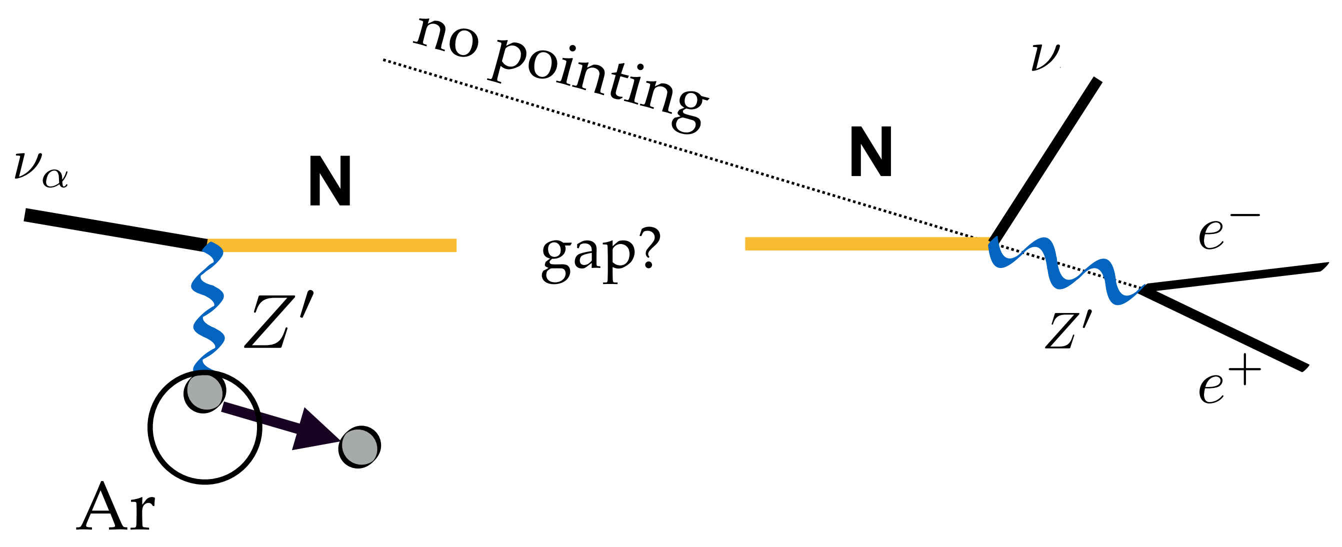
P. Ballett, MH, S. Pascoli arxiv:1903.07589
A. Abdullahi, MH, S. Pascoli, arXiv:2007.11813

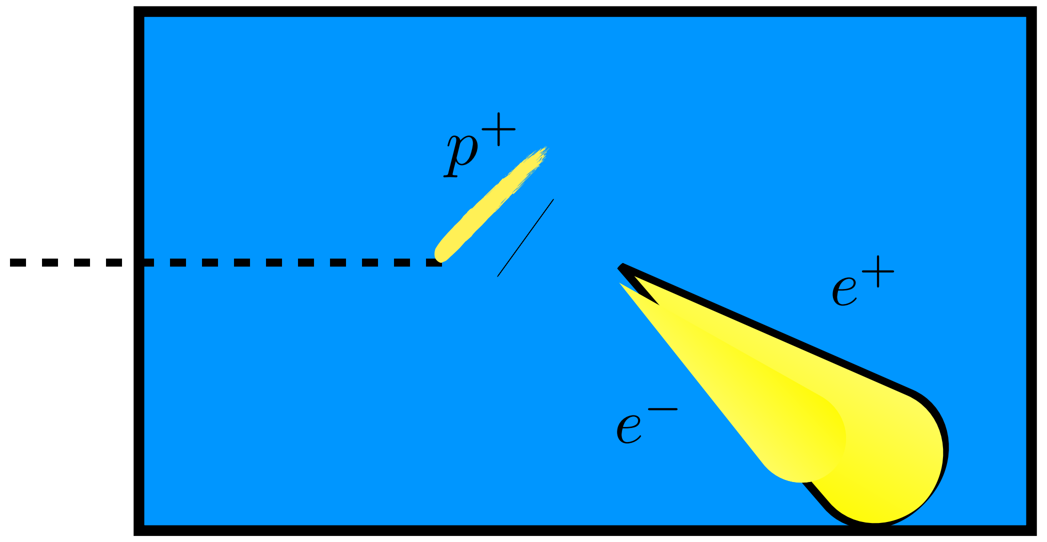


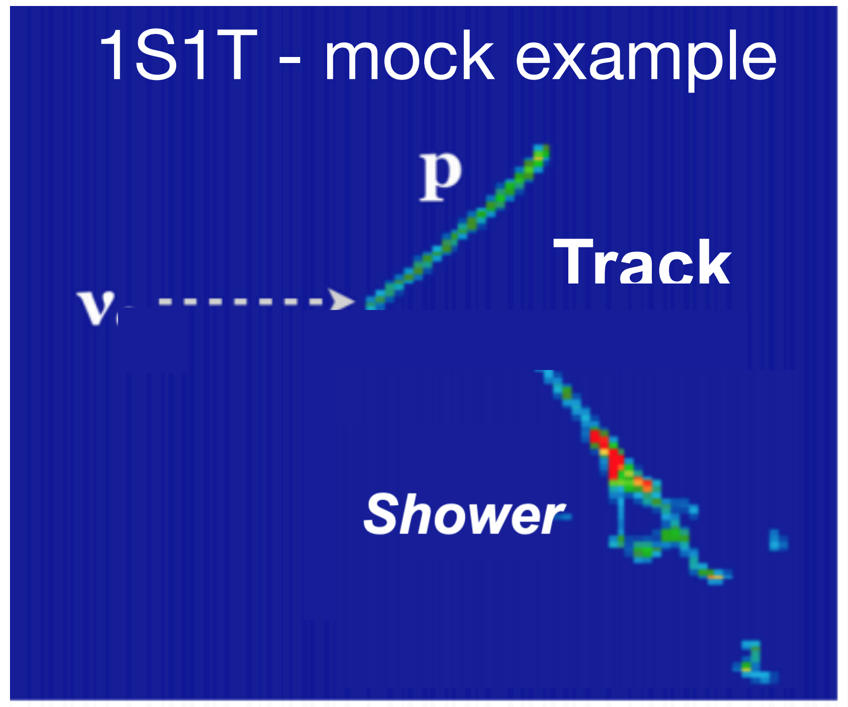
Dark neutrinos @ MicroBooNE

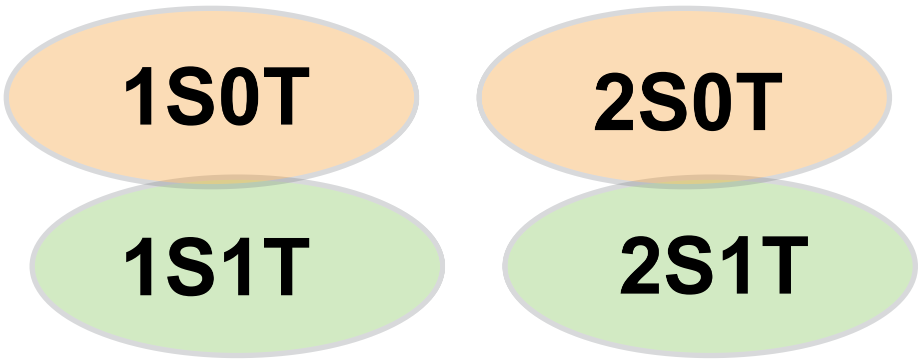
New generation of Liquid Argon detectors at Fermilab can search for (e+e-) events and will test MiniBooNE results.

Currently investigating these signatures in LAr together with microBooNE single-photon group.









Light Dark Photon: no proton so smaller efficiencies, but enhanced in LAr (A^2 coherent.)

Heavy Dark Photon: shower displaced from proton. *Mostly photon-like showers.*

Conclusions

The MiniBooNE “electron-like” excess remain unexplained.

For the first time, MicroBooNE has shed light on the origin of the excess in a LArTPC
Showed that it can disentangle the individual final states and topologies really well.

While a significant result, MicroBooNE still does not rule out ν_e interpretations of the MiniBooNE excess,
Including the sterile neutrino interpretation.

Several other models still untested
lots of work to do in e+e- pairs, single (coherent) photons, and other ν_e models.

Thank you!