From Mini to Micro:
New physics explanations of MiniBooNE at the MicroBooNE experiment

University of Toronto
HEP seminar

UNIVERSITY OF MINNESOTA

Matheus Hostert

Perimeter Institute and University of Minnesota

PERIMETER INSTITUTE

This talk

- Basics of accelerator neutrino experiments
- Short-baseline oscillations?
- Interpreting recent MicroBooNE results
- Alternative directions — going beyond oscillations.

Collaborators

Argüelles et al, arXiv:2111.10359

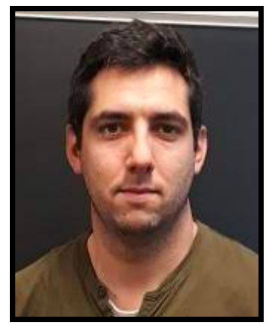
Carlos Argüelles
Harvard University

Ivan Estebán
Ohio State University

Kevin Kelly
CERN

Joachim Kopp
CERN

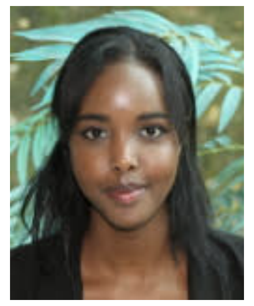
Pedro Machado
Fermilab



Ivan Martinez-Soler
Harvard University

Yuber F. Perez-Gonzalez
Durham University

A. Abdullahi, MH, S. Pascoli arxiv:2007.11813, arXiv:220x.xxxx



Asli Abdullahi
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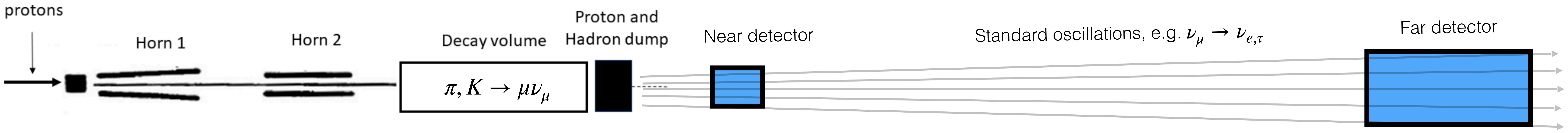
Uni of Bologna

Accelerator neutrino experiments



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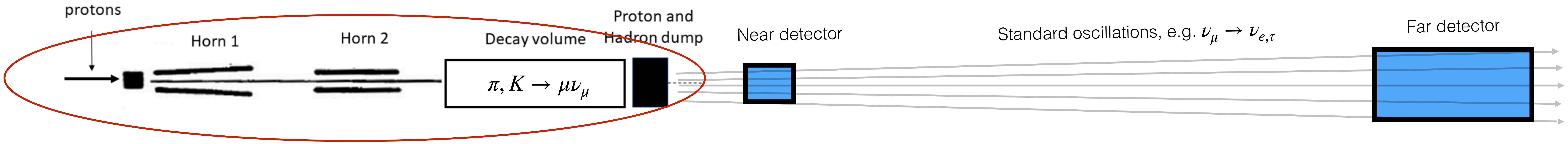
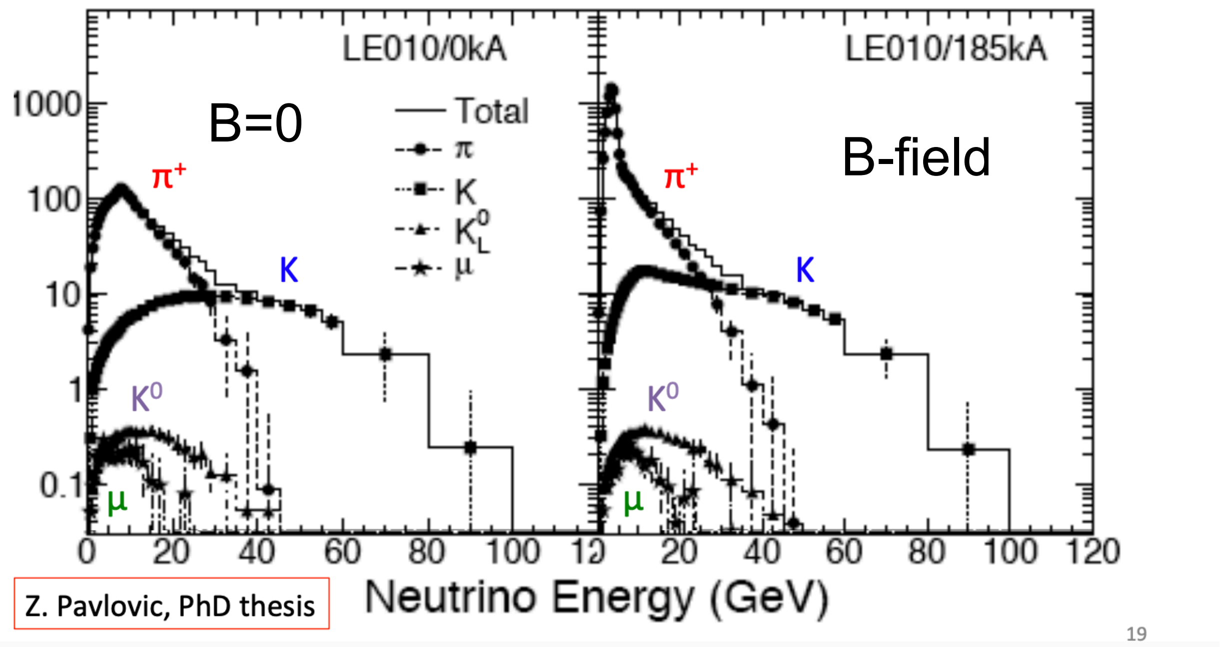
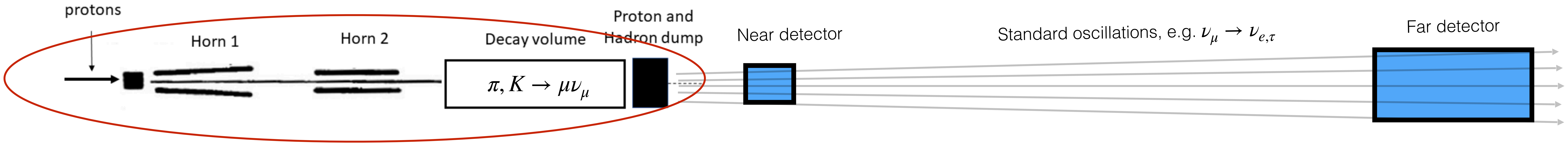


Neutrino fluxes



Z. Pavlovic, PhD thesis

Accelerator neutrino experiments



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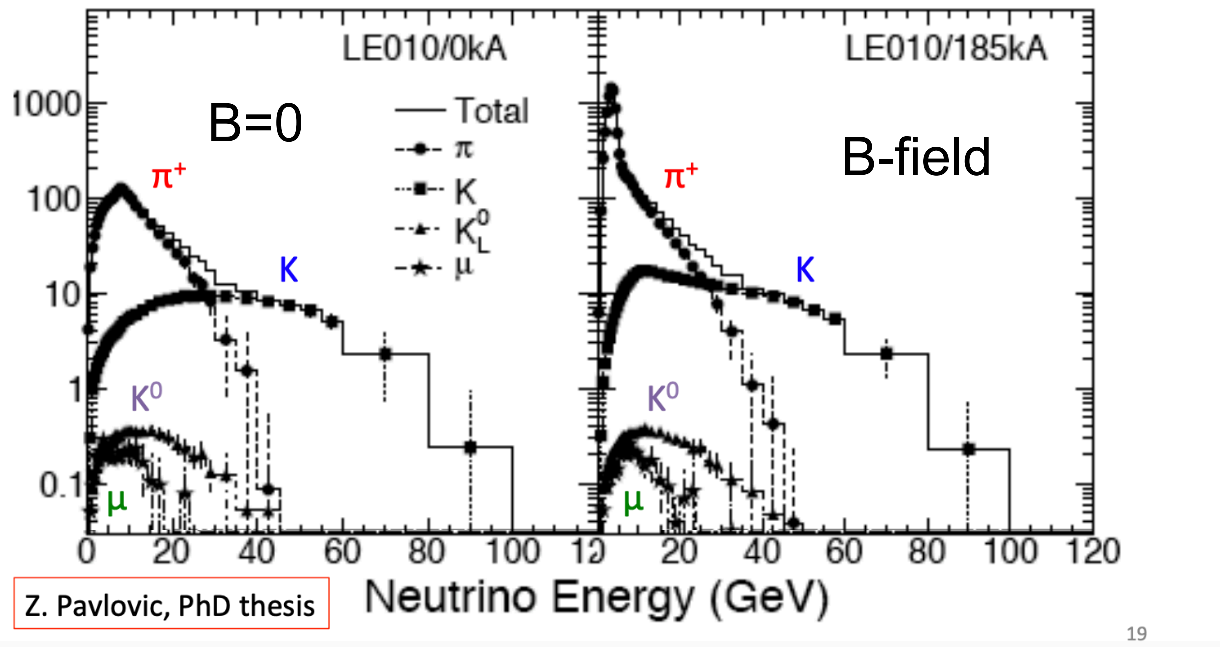
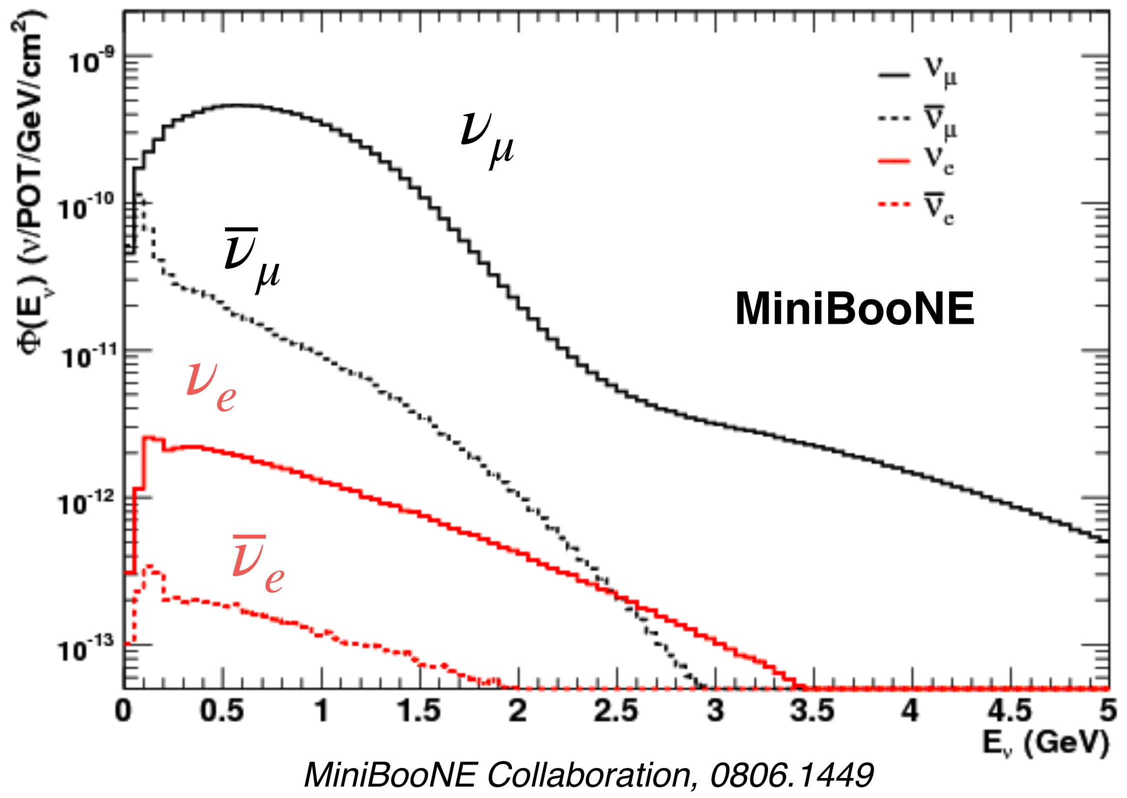
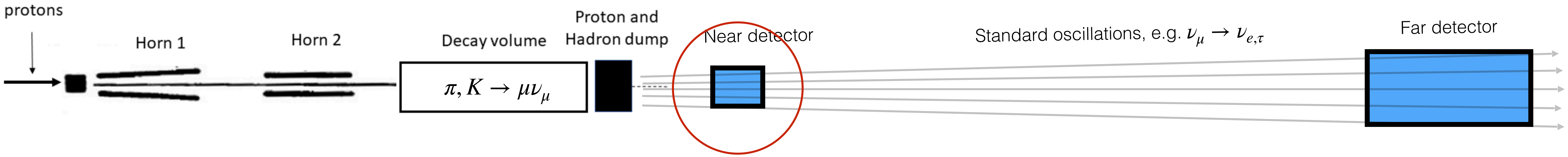




MiniBooNE Collaboration, 0806.1449



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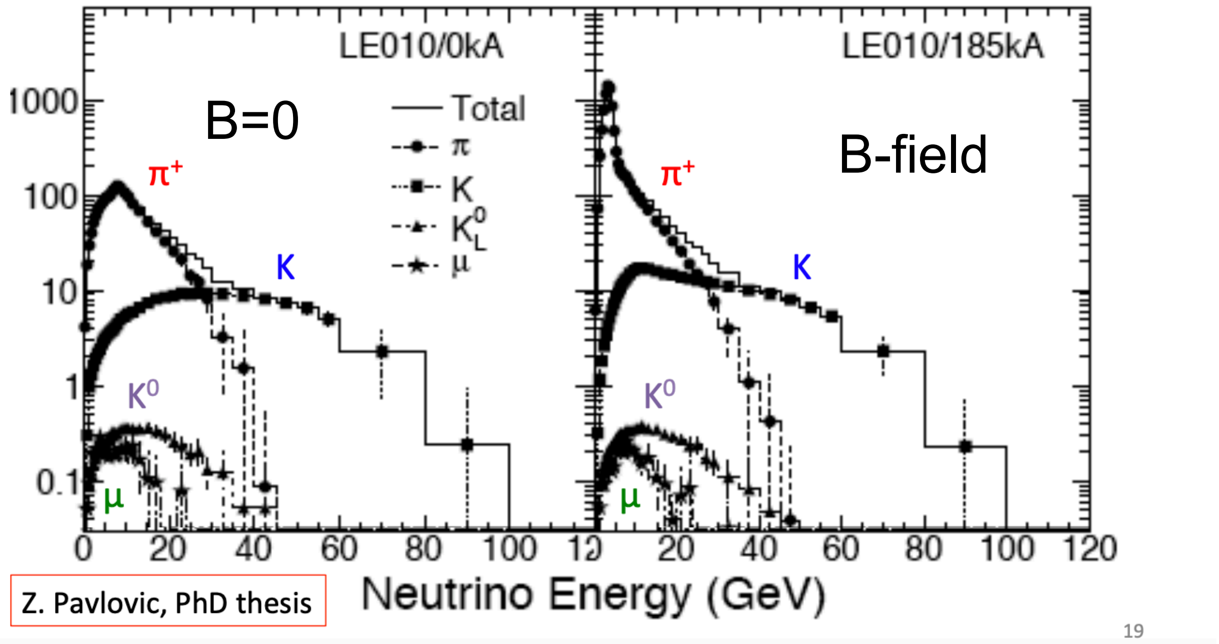

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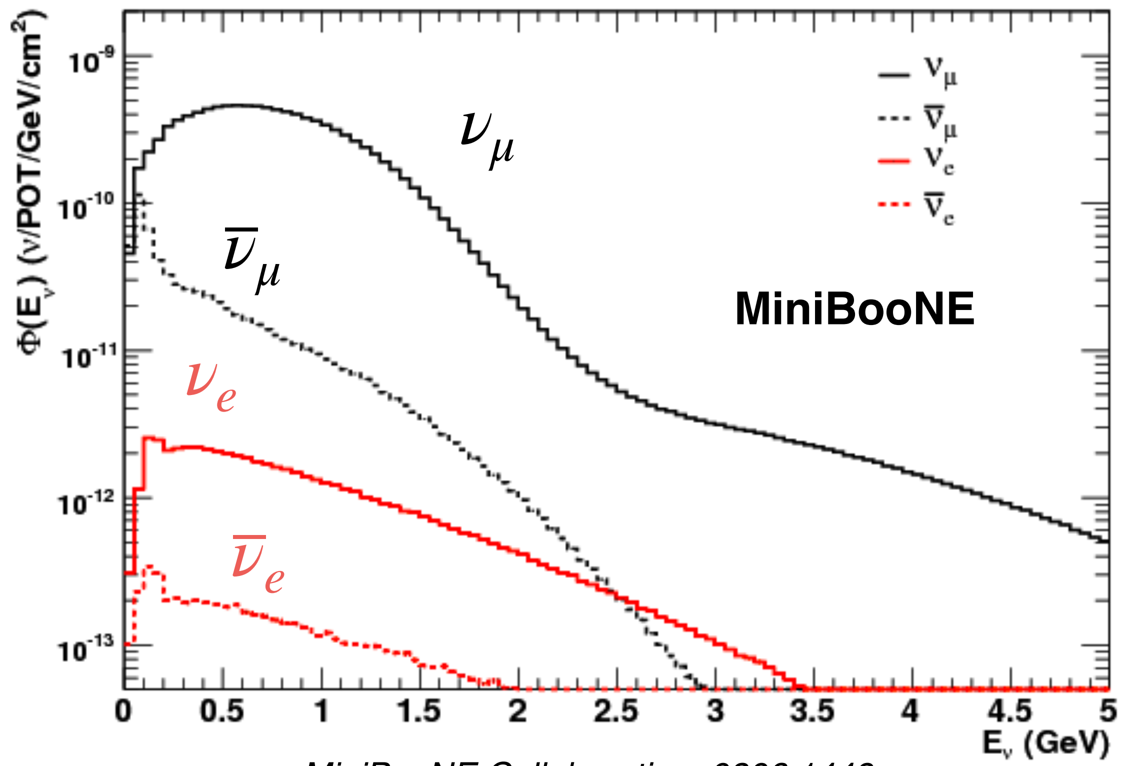

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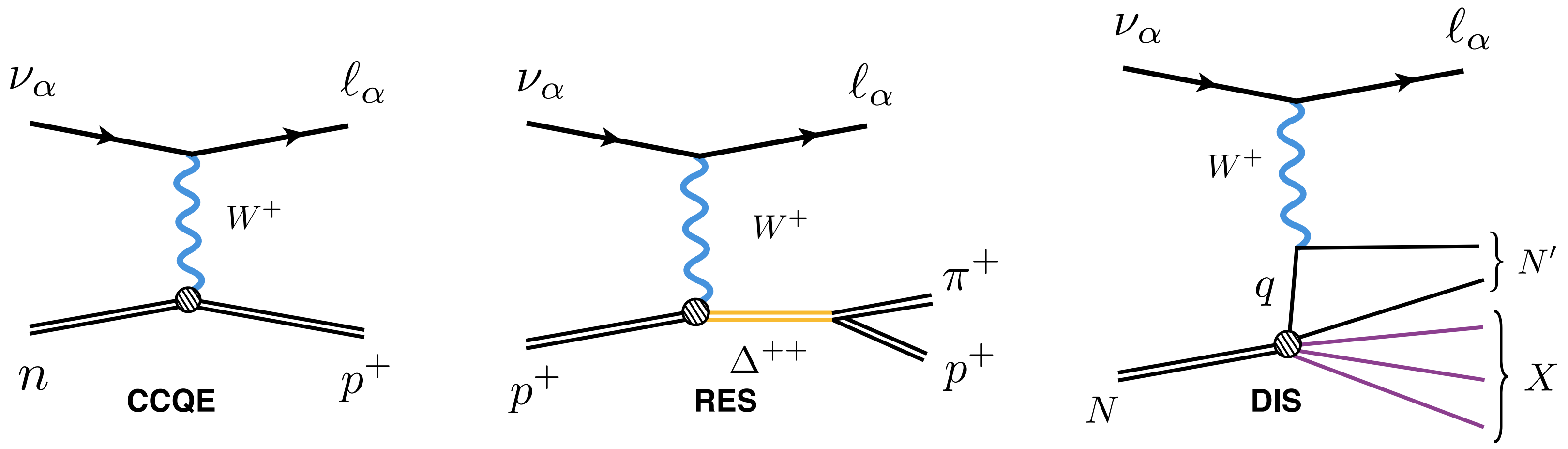
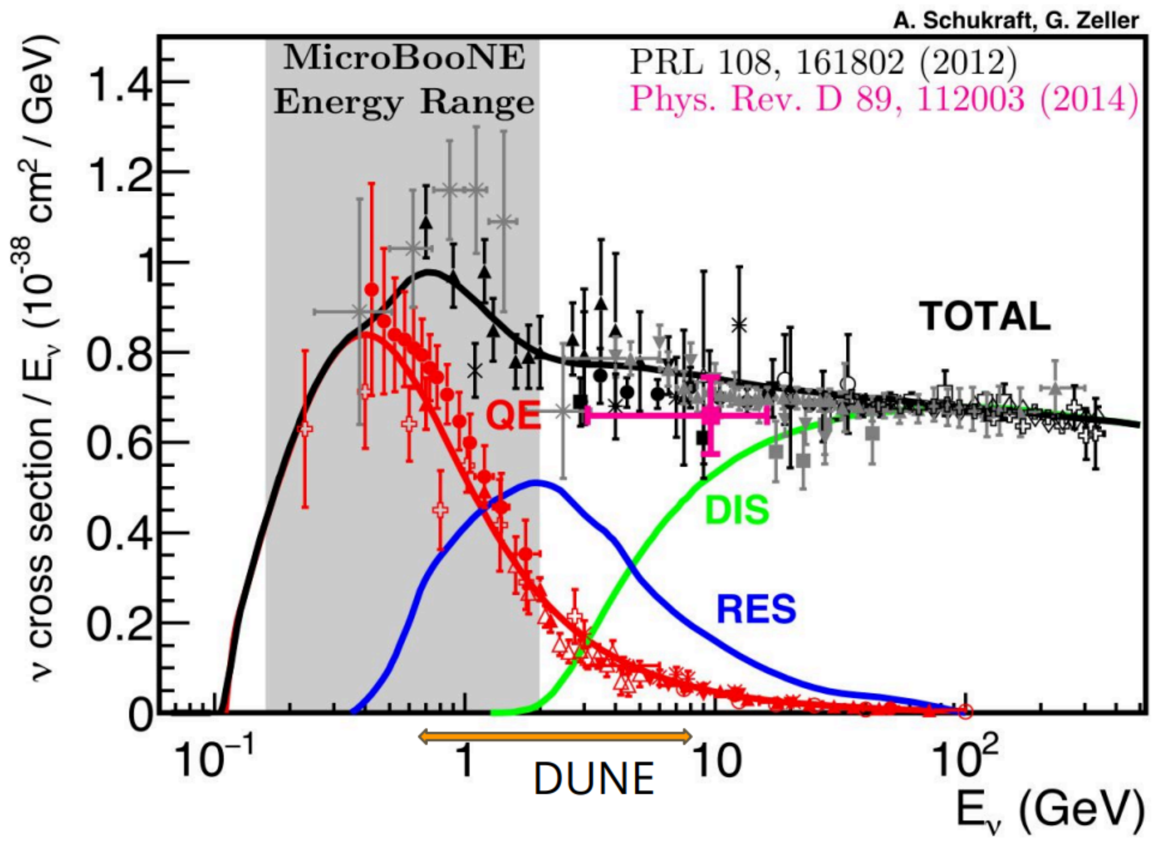
Neutrino cross sections





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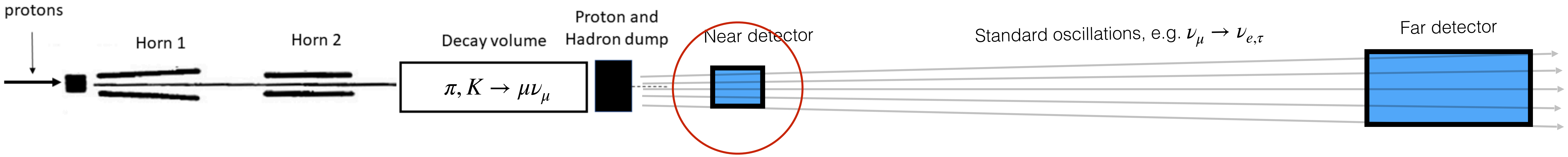

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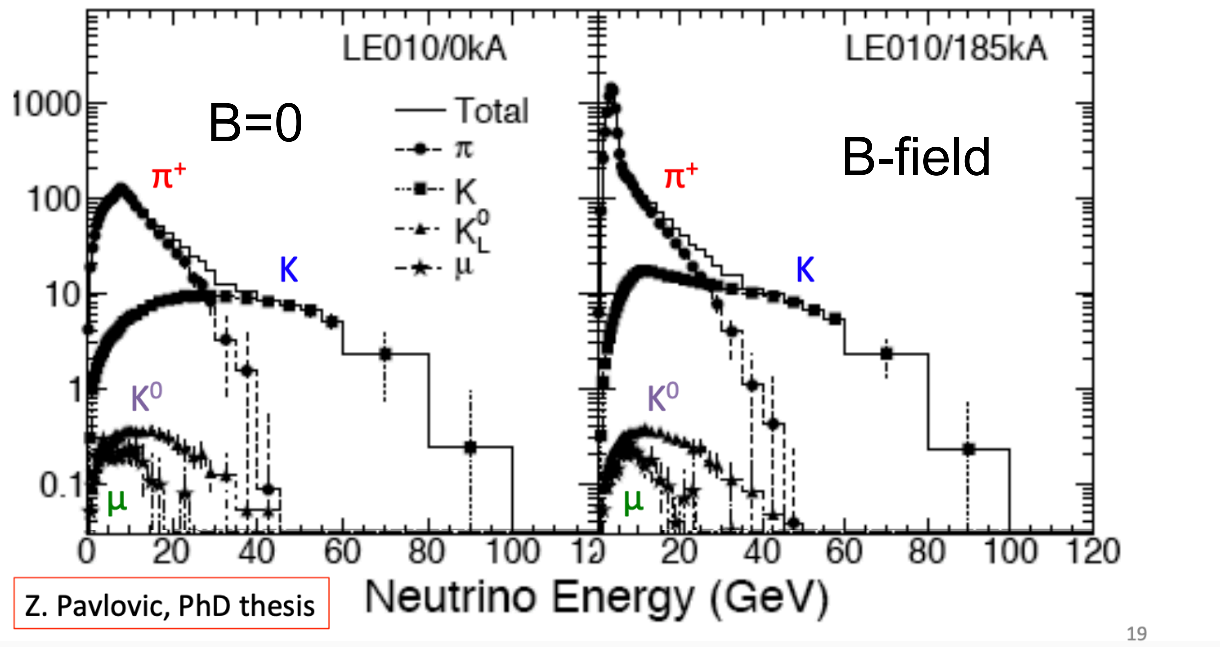

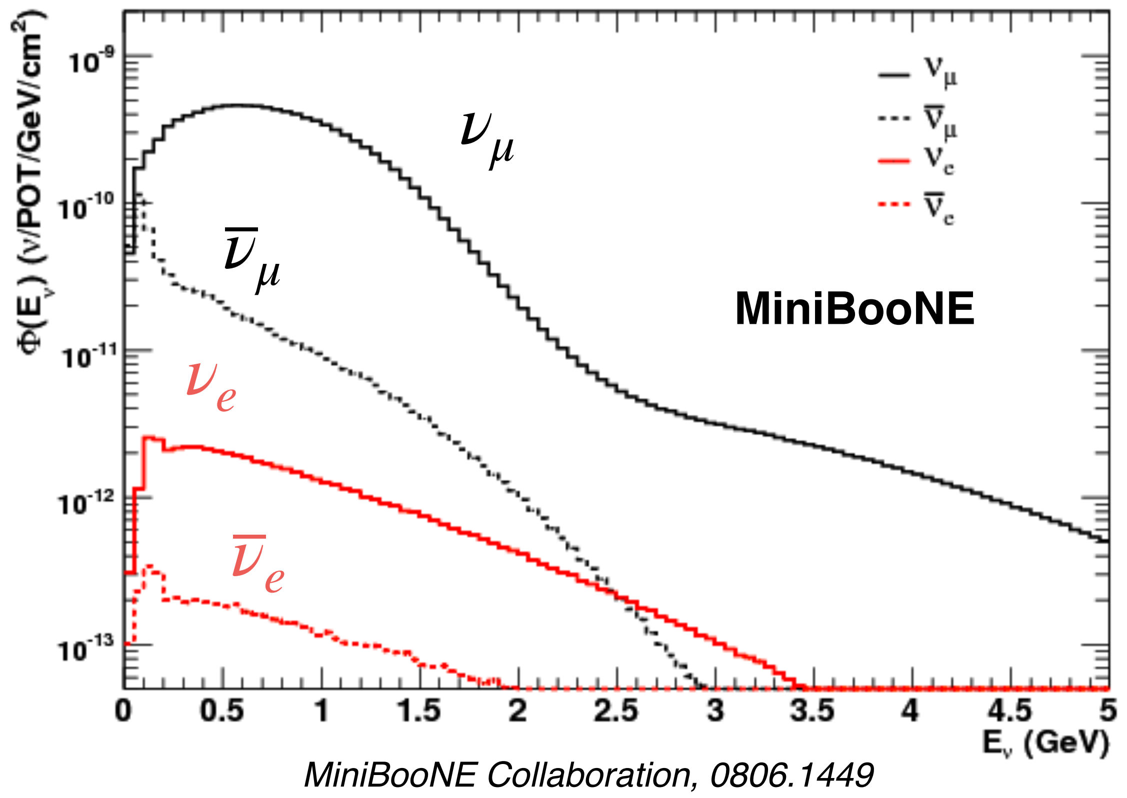

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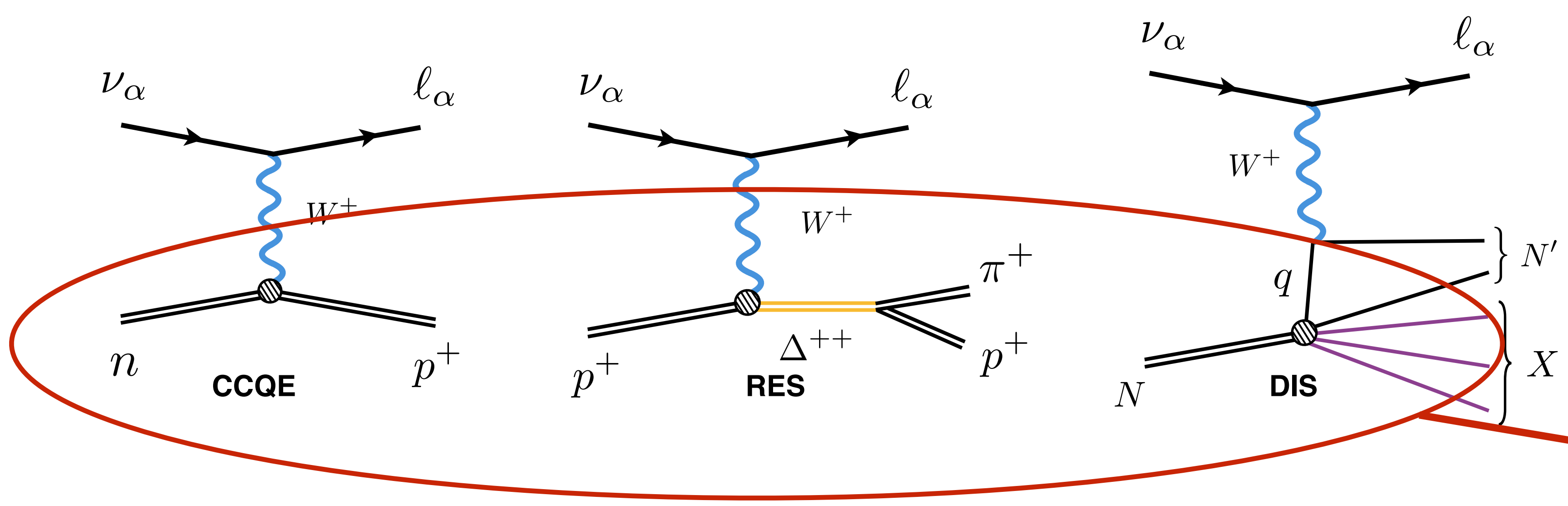
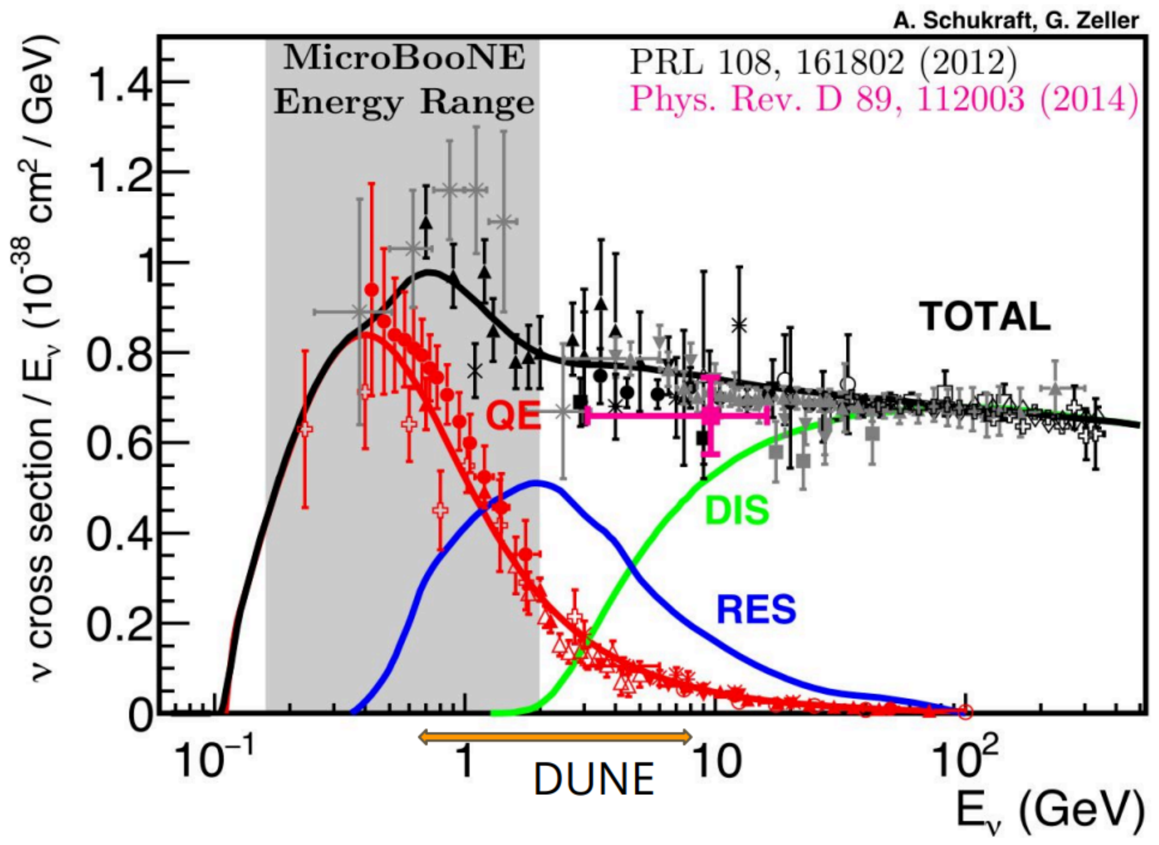
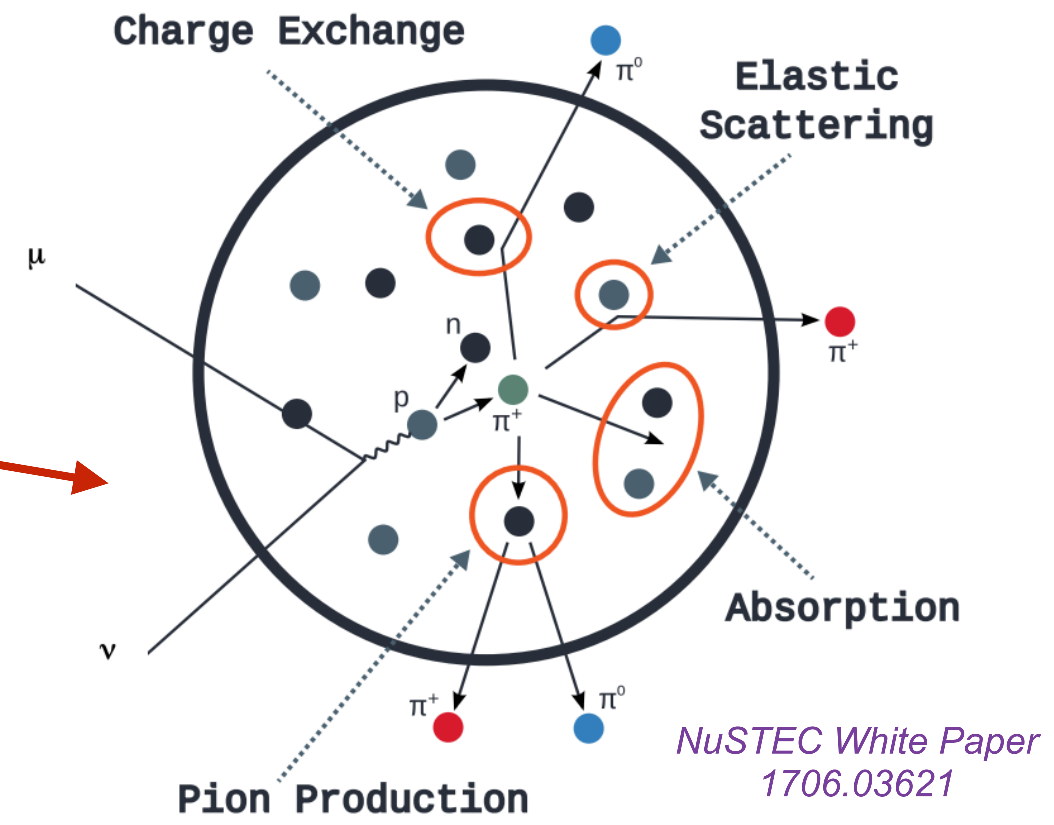


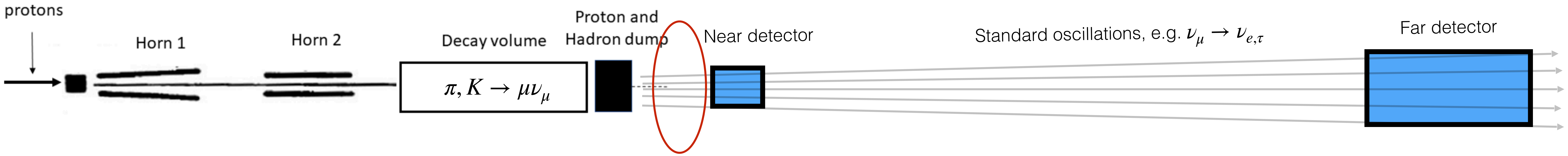


Neutrino-nucleus scattering



Exclusive final states $(1e\,1\pi, \pi^0 p^+,$ etc)
not necessarily from underlying "hard process"

Accelerator neutrino experiments



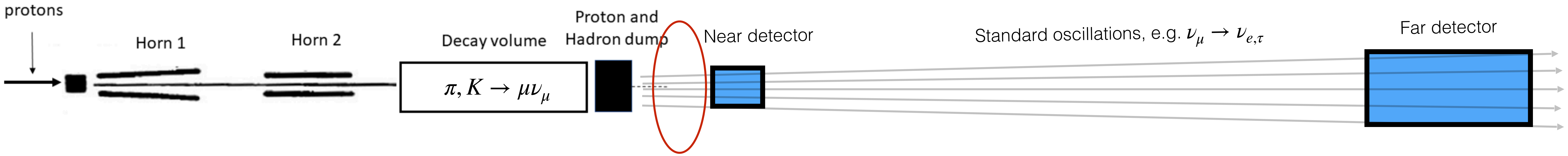
Short-baseline: search for oscillations that develop before atmospheric and solar frequencies.

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

Can develop due to a light mostly-sterile neutrino:

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

Accelerator neutrino experiments



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

$$P_{\nu_\mu\to\nu_\mu} = 1 - \sin^2 2\theta_{\mu\mu}\sin^2\Delta = 1 - 4|U_{\mu4}|^2(1-|U_{\mu4}|^2)\sin^2\Delta$$

$$P_{\nu_e\to\nu_e} = 1 - \sin^2 2\theta_{ee}\sin^2\Delta = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2\Delta$$

$$P_{\nu_\mu\to\nu_e} = \sin^2 2\theta_{e\mu}\sin^2\Delta = 4|U_{e4}|^2|U_{\mu4}|^2\sin^2\Delta$$

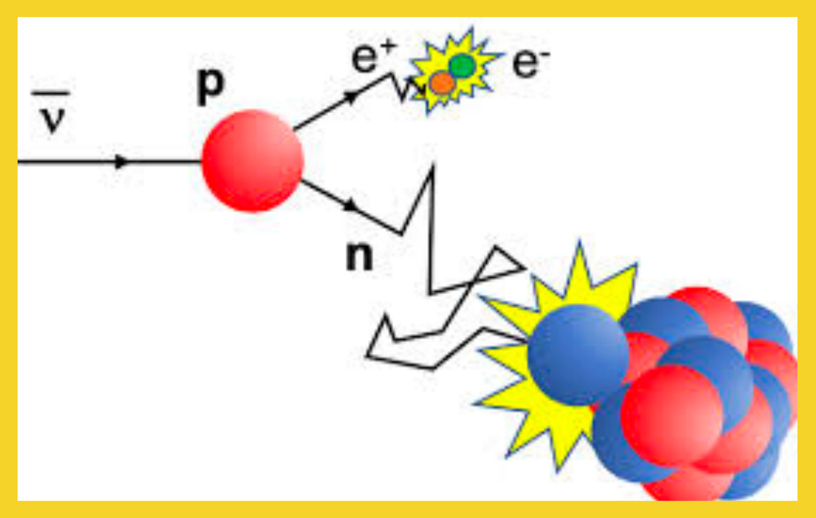
The Short-Baseline Puzzle

LSND & KARMEN

πDAR source

$$\begin{array}{llll} \pi^+ \to & \mu^+ & + \; \nu_\mu & \\ & \downarrow & & \\ & e^+ & + \; \nu_e & + \; \bar{\nu}_\mu \end{array}$$

oscillation? $\quad \overline{\nu}_\mu \to \overline{\nu}_e$



Inverse-Beta-decay detection

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.

πDAR source

$$\begin{array}{lllll} \pi^+ \rightarrow & \mu^+ & + & \nu_\mu & \\ & \downarrow & & & \\ & e^+ & + & \nu_e & + \; \bar{\nu}_\mu \end{array}$$

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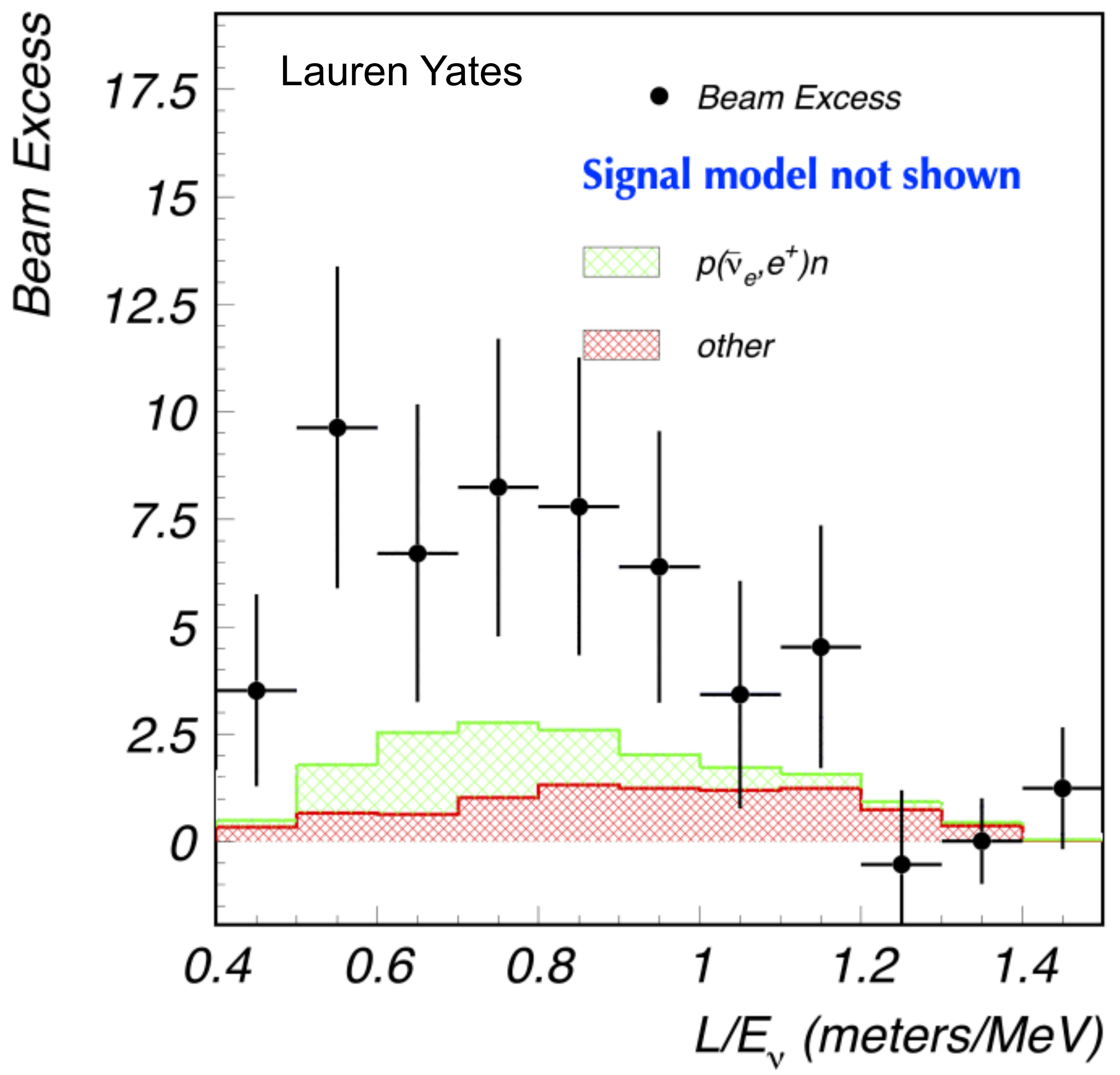
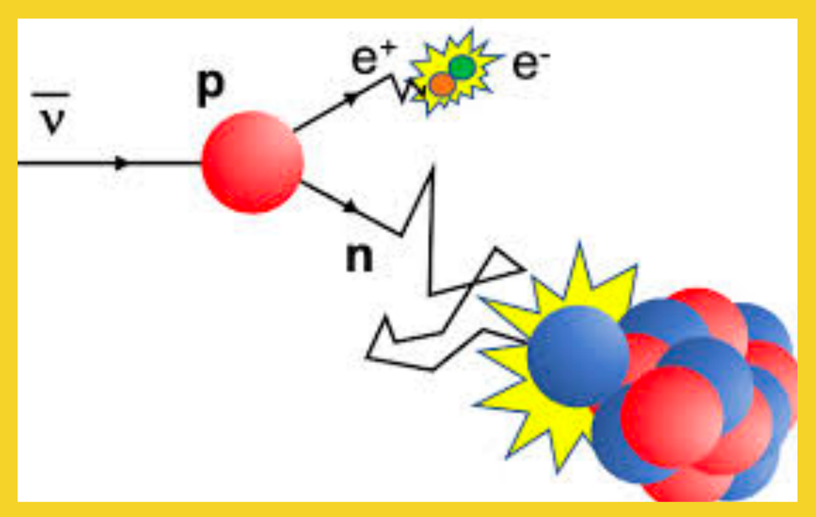


Excess: $87.9 \pm 22.4 \pm 6$ events
3.8σ significance



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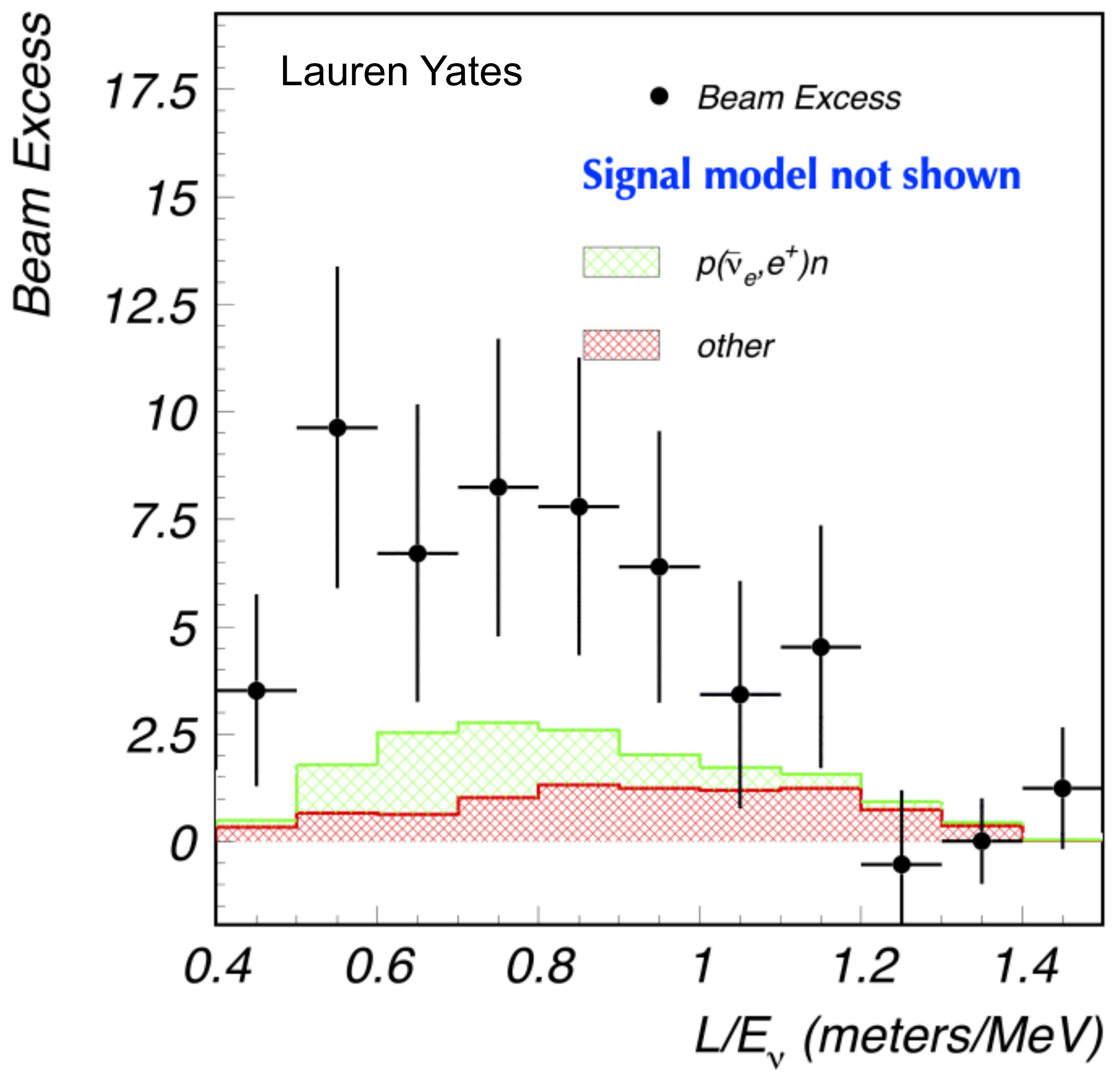

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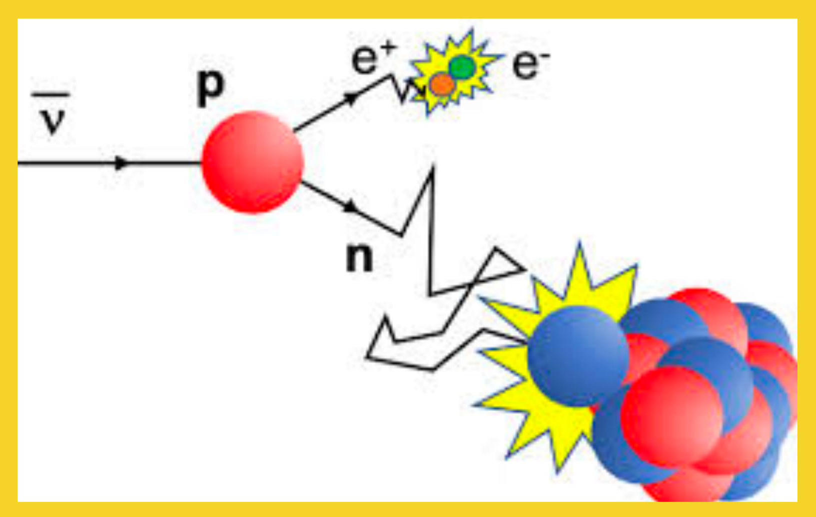
3.8σ significance

πDAR source

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

oscillation? $\bar{\nu}_\mu \to \bar{\nu}_e$



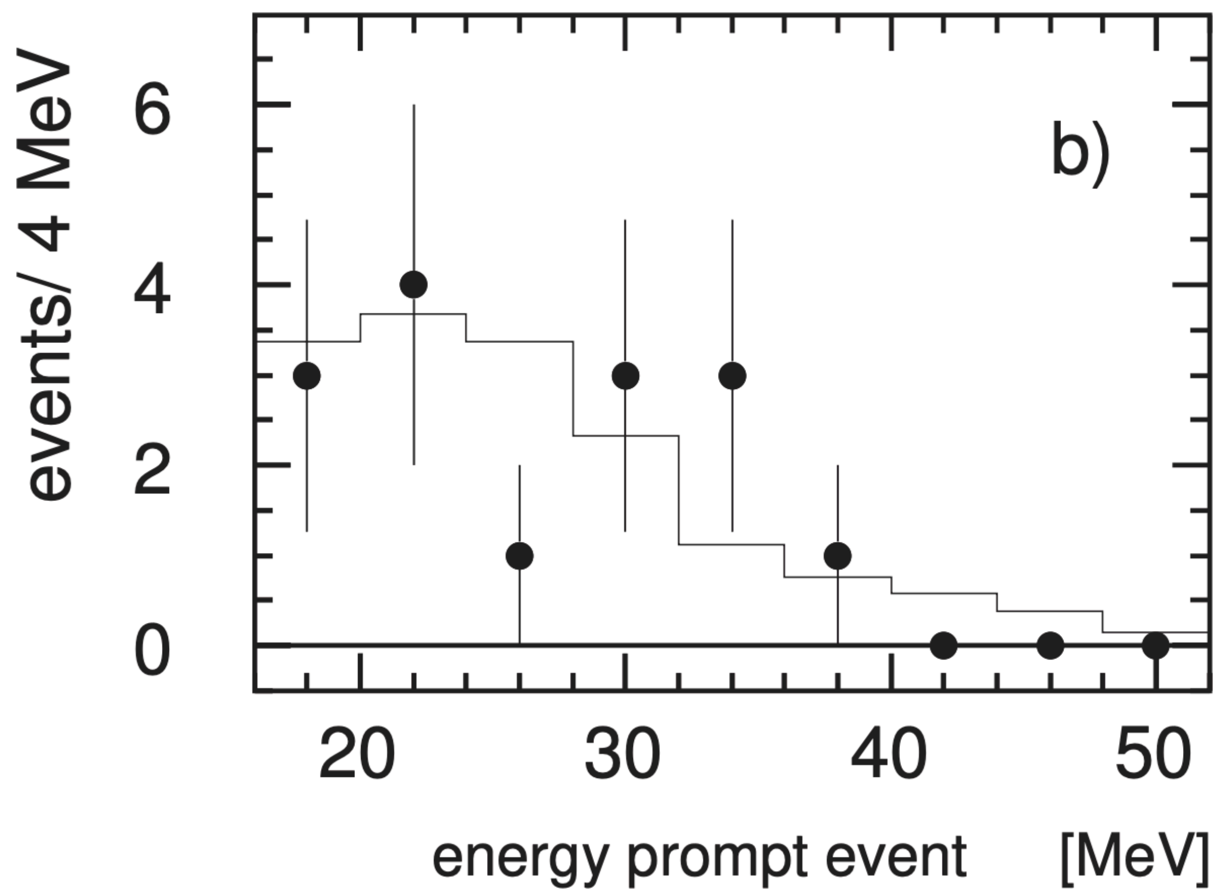
Inverse-Beta-decay detection

More data was needed

KARMEN: 1990 - 2001

Phys.Rev.D 65 (2002) 112001

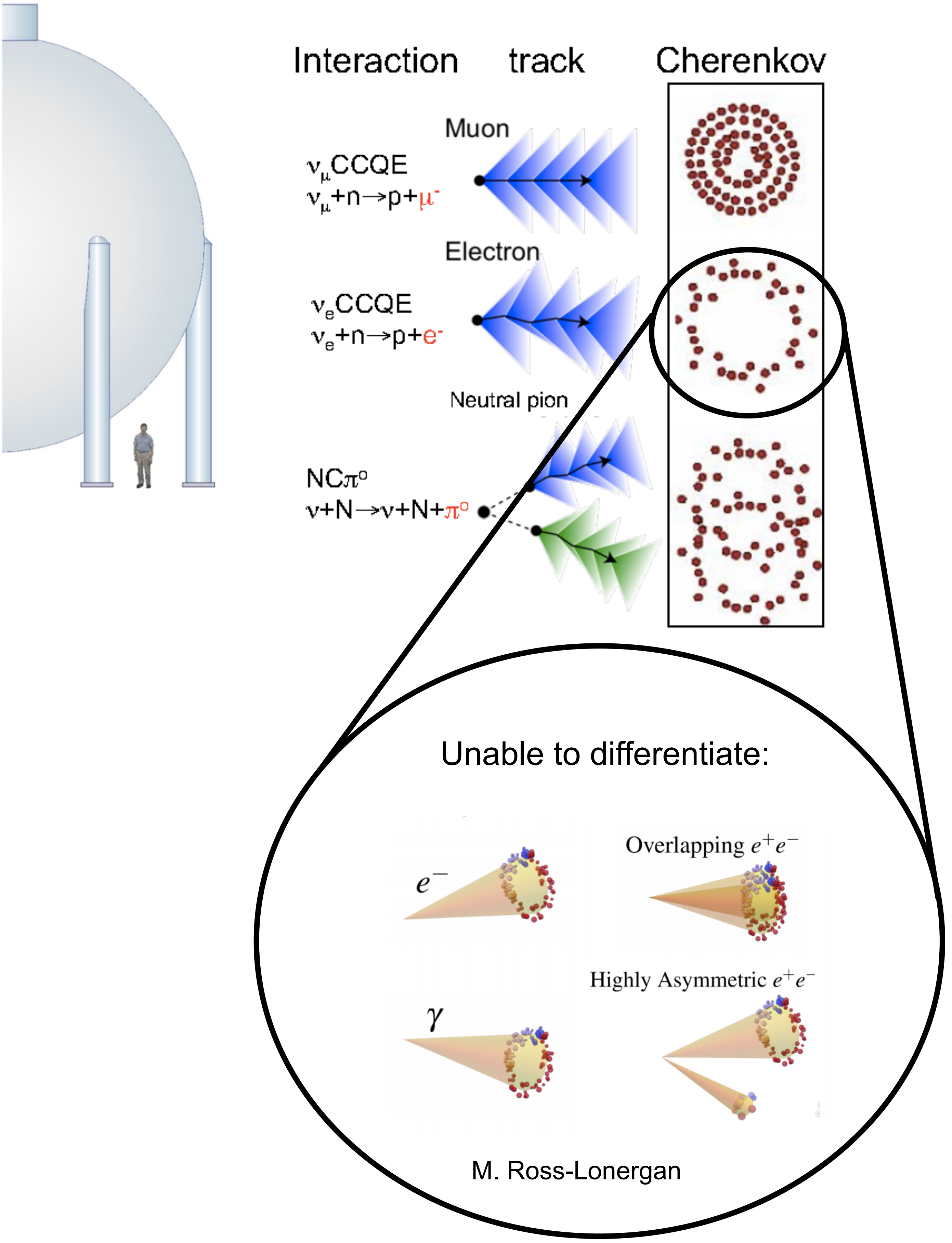
1) 800 MeV proton beam, 6e22 POT.
2) π mostly DAR. Detector 90º from p beam.
3) π^- contamination: $\bar{\nu}_e/\bar{\nu}_\mu = 6.4\cdot 10^{-4}$
4) Baseline of 17.7 m
5) ~57 tonnes of liquid scintillator
6) 3.5 m long detector.



No excess observed,
but could not exclude LSND results.

Latest MiniBooNE results:

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



The MiniBooNE excess

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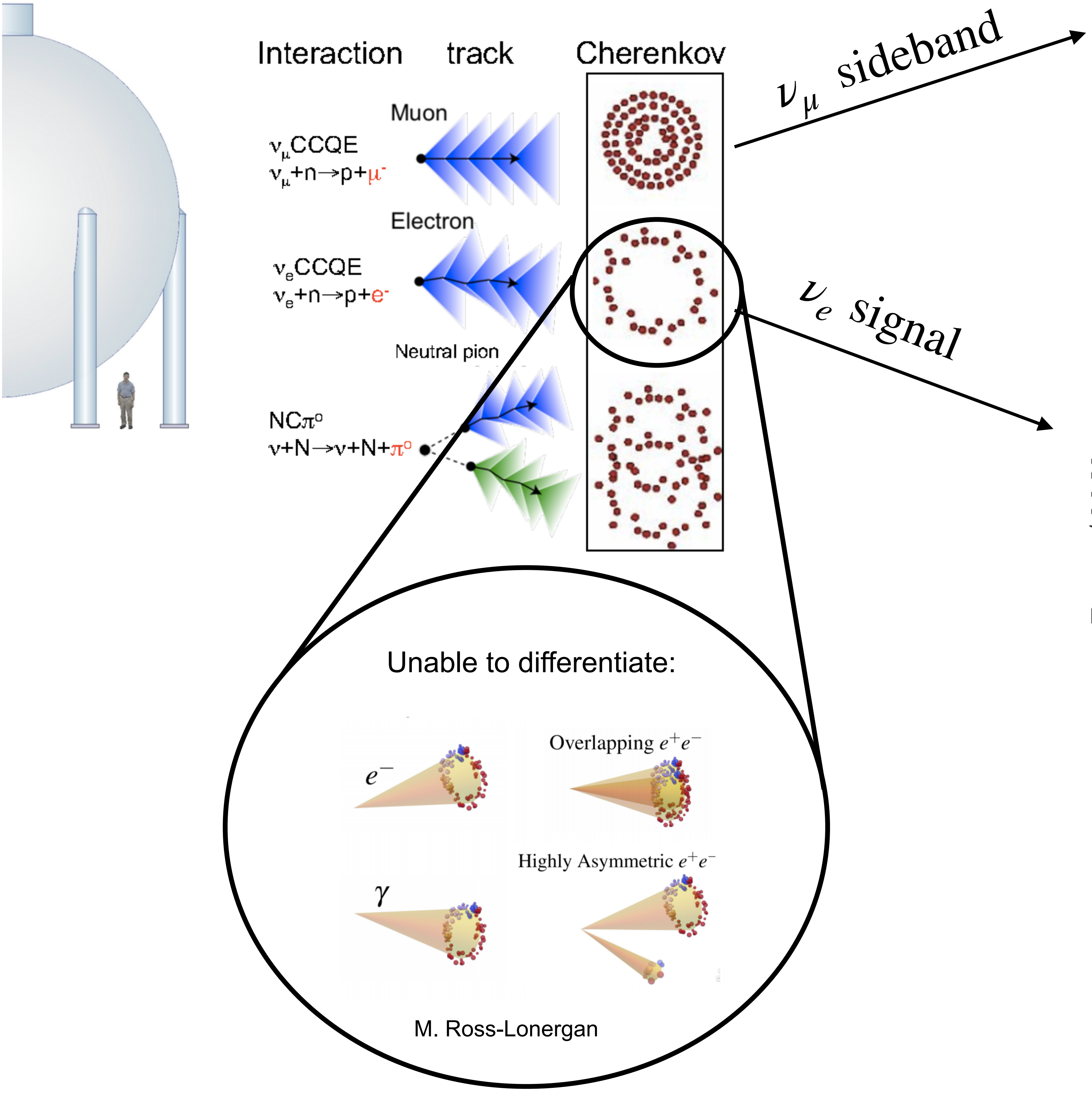

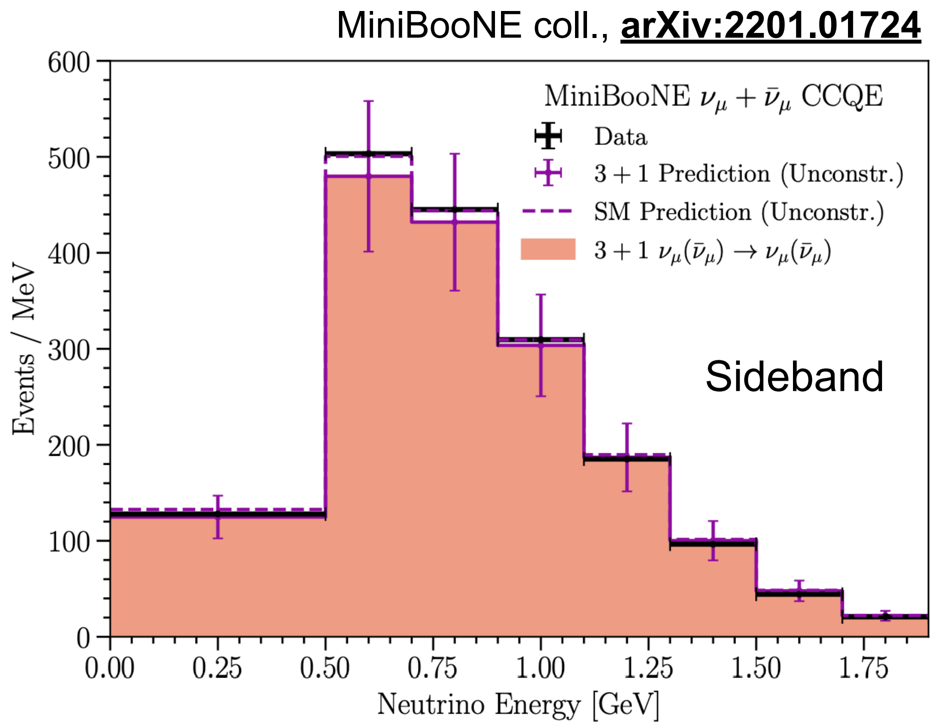

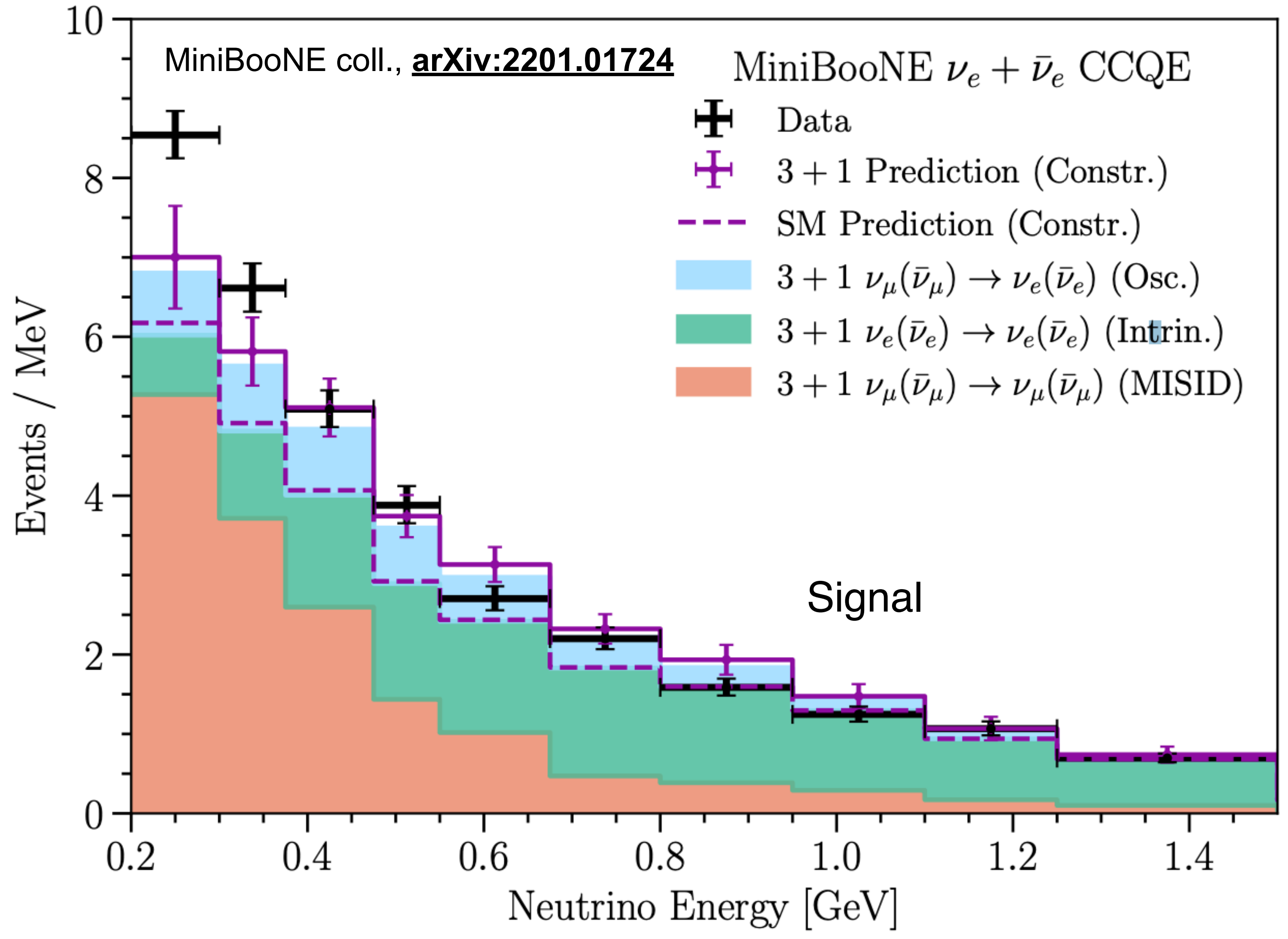

638 ± 52(stat.) $\pm$ 122.2(sys.)

4.8σ significance

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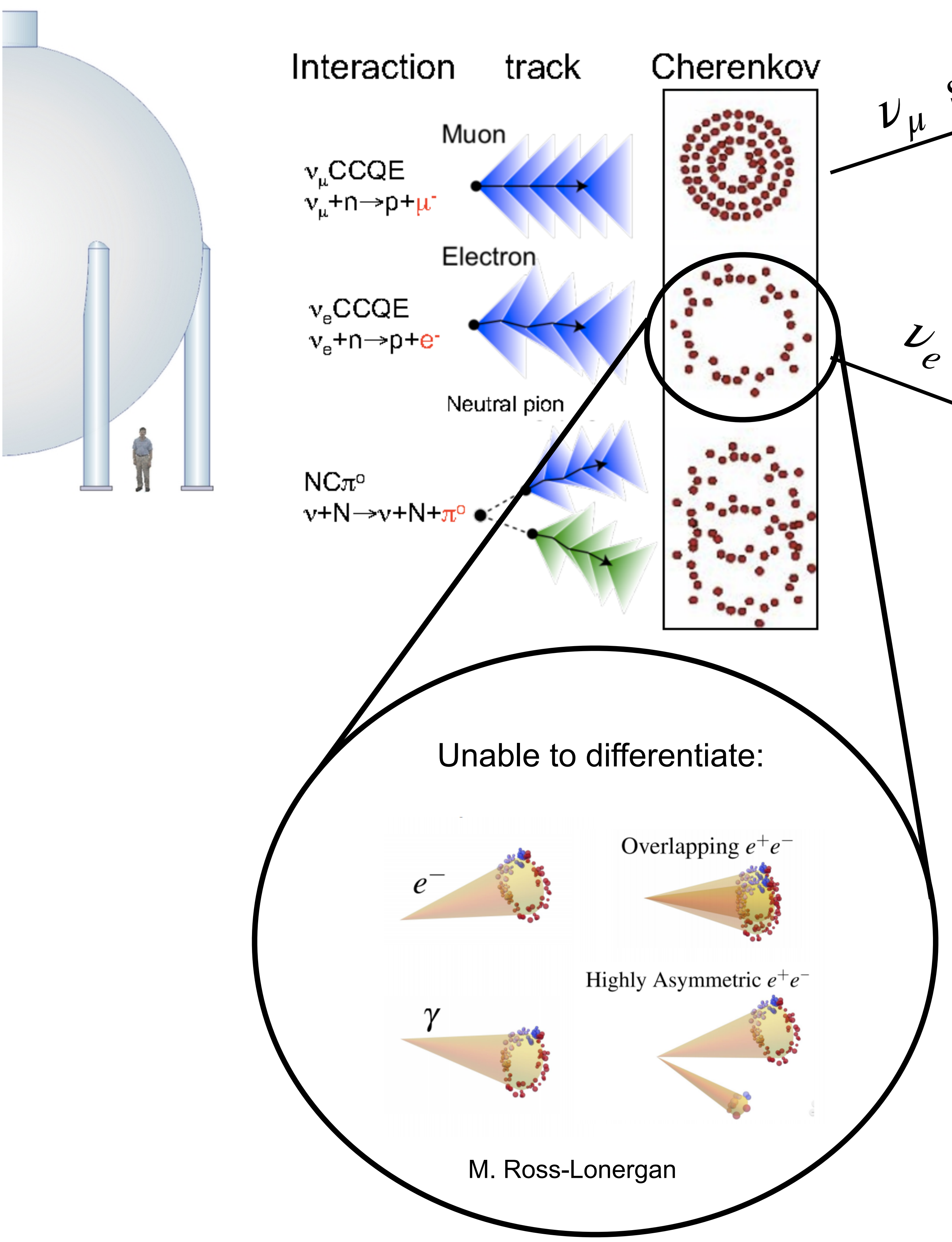
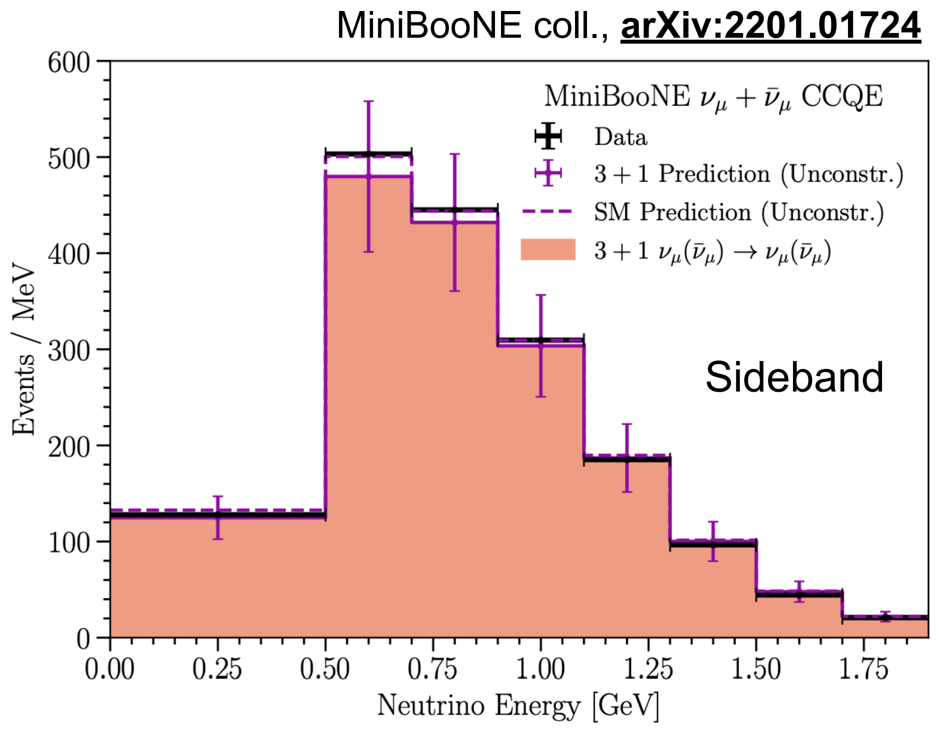
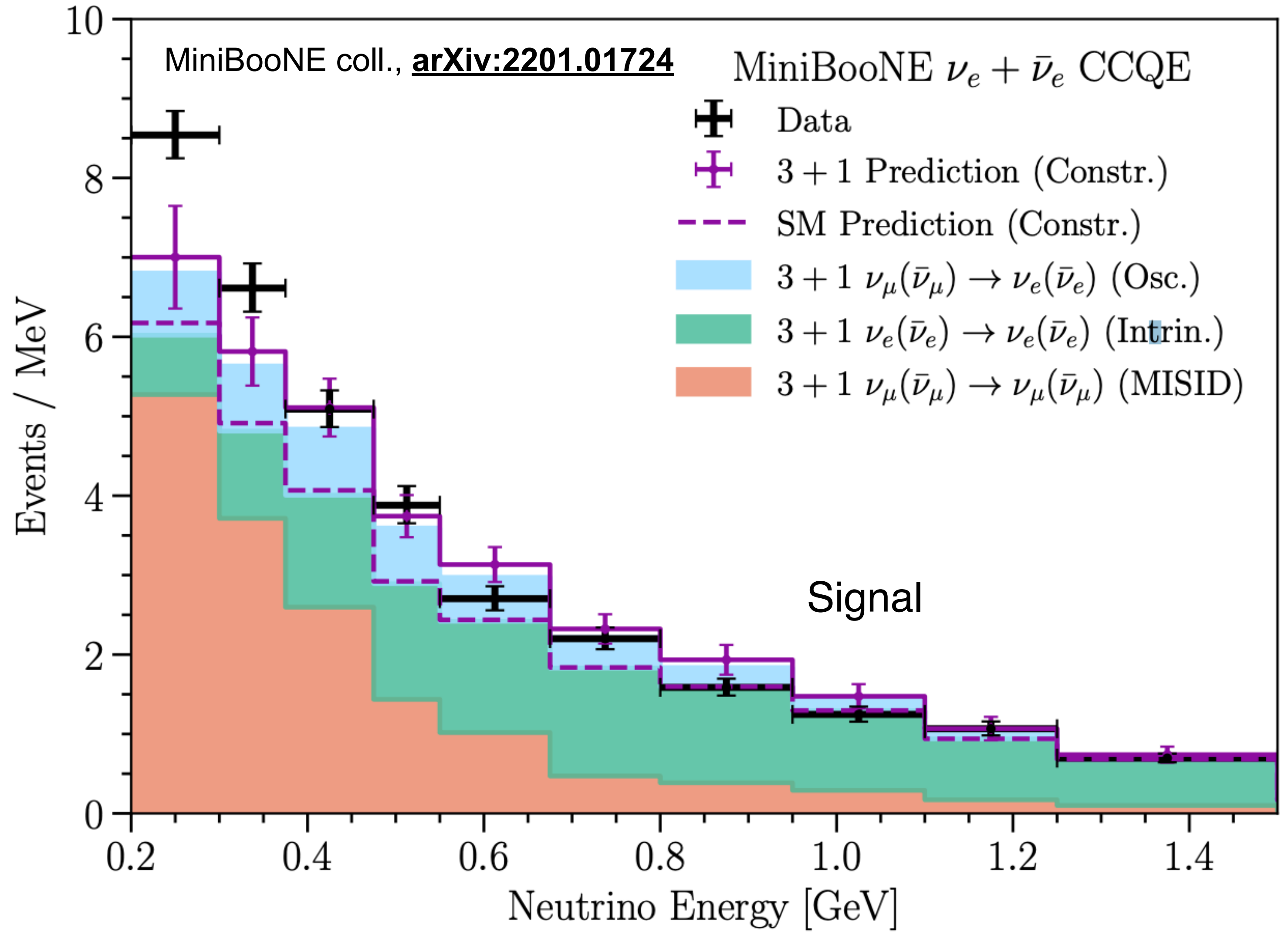
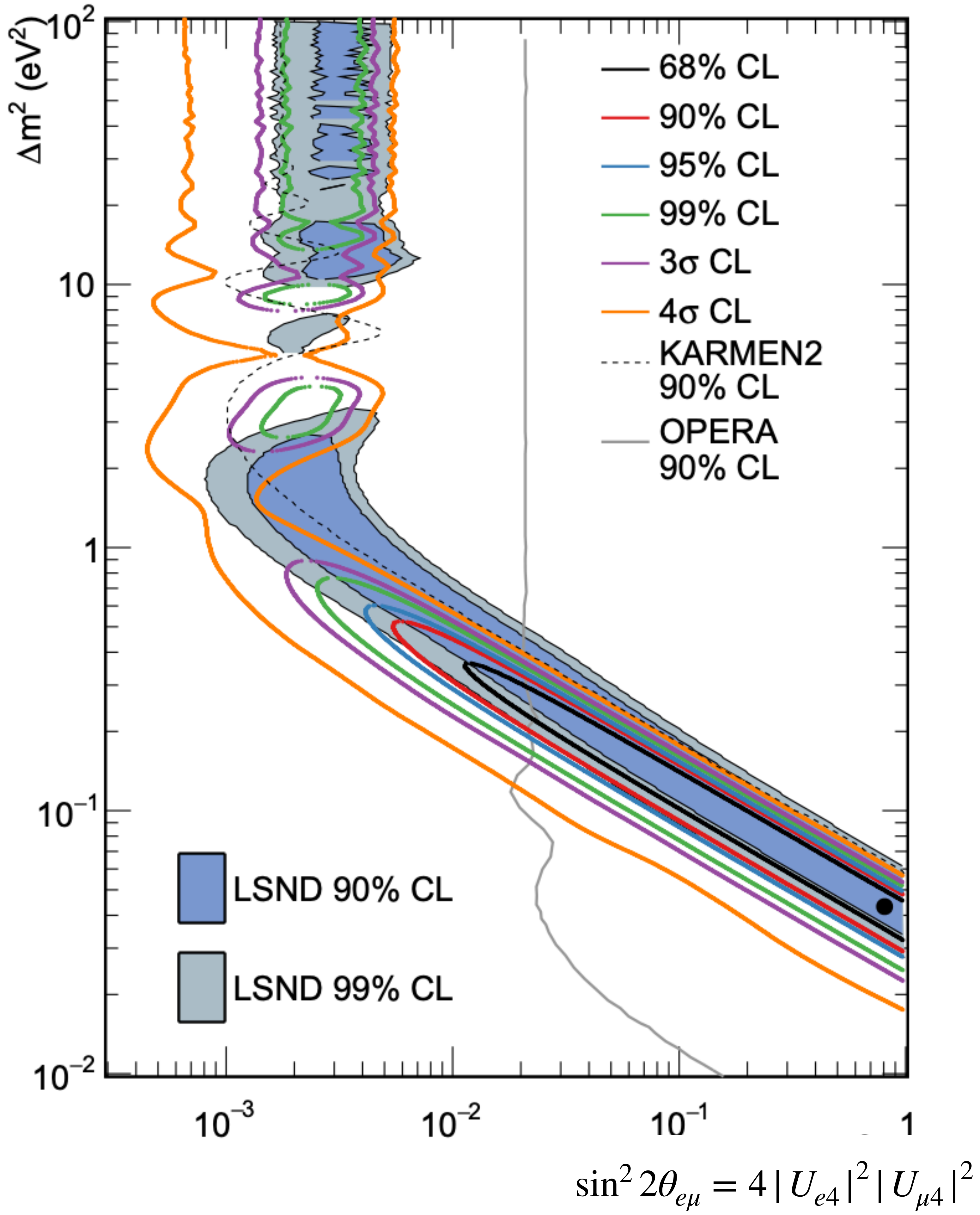


ν_μ sideband

ν_e signal







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Best-fit oscillation: $\chi^2/\mathrm{ndf} = 21.7/15.5$, with $p_{\mathrm{val}} = 12.3\,\%$

Bkg only fit: $\chi^2/\mathrm{ndf} = 50.7/17.3$, with $p_{\mathrm{val}} = 0.01\,\%$

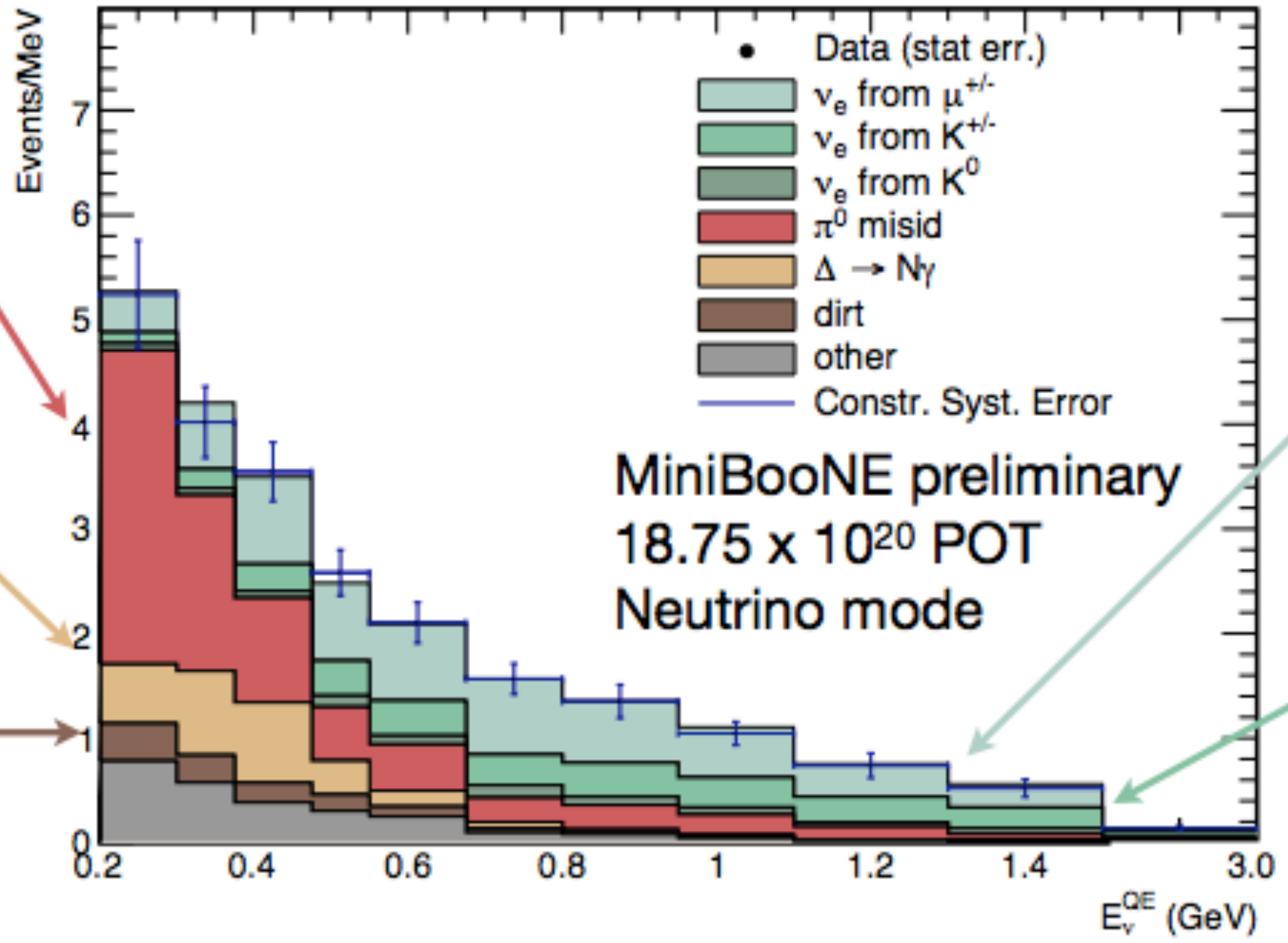
Data-driven background estimates

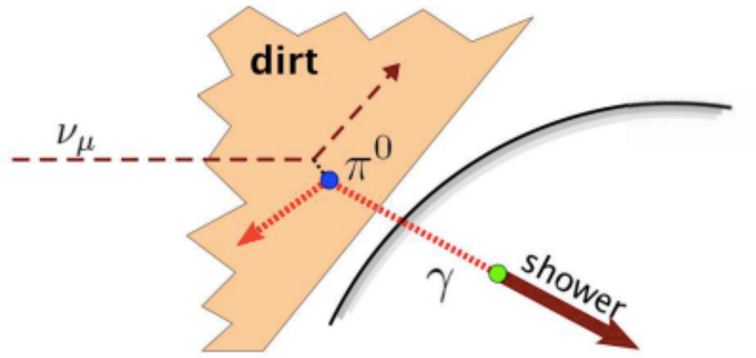
Hourlier, Adrien, MiniBooNE Coll. Neutrino2020

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

$\Delta \to N\gamma$ resonance
constrained from *in situ* measured NC π^0 rate and theoretical prediction

Dirt
constrained from *in situ* dirt data sample



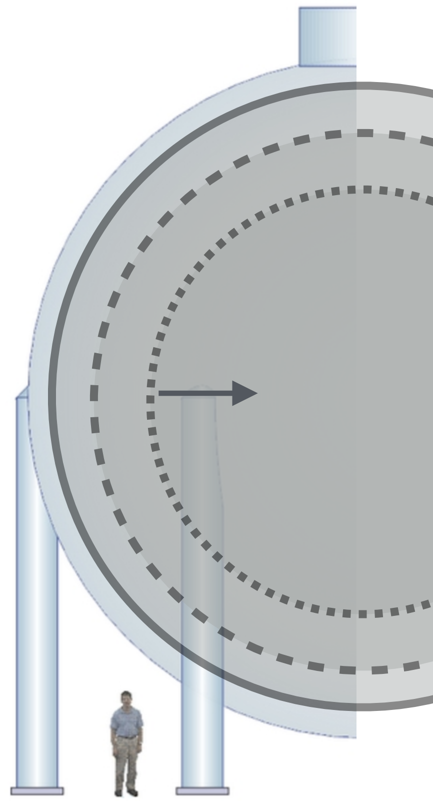


ν_e from μ decay
is constrained by *in situ* ν_μ CCQE measurement

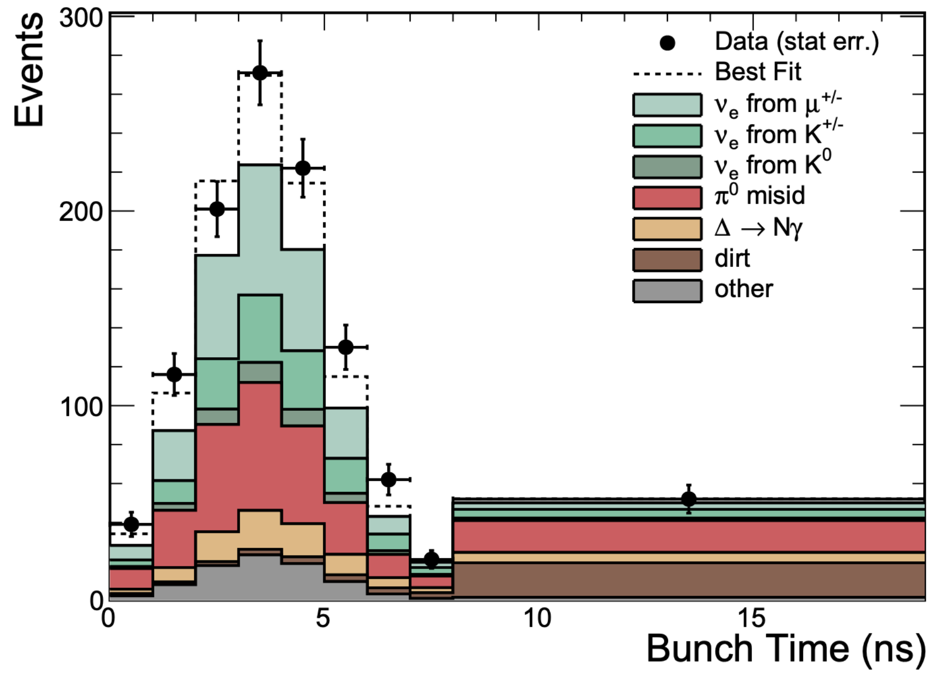
ν_e from K decay
constrained from *in situ* high energy events + SciBooNE high energy ν_μ event rate

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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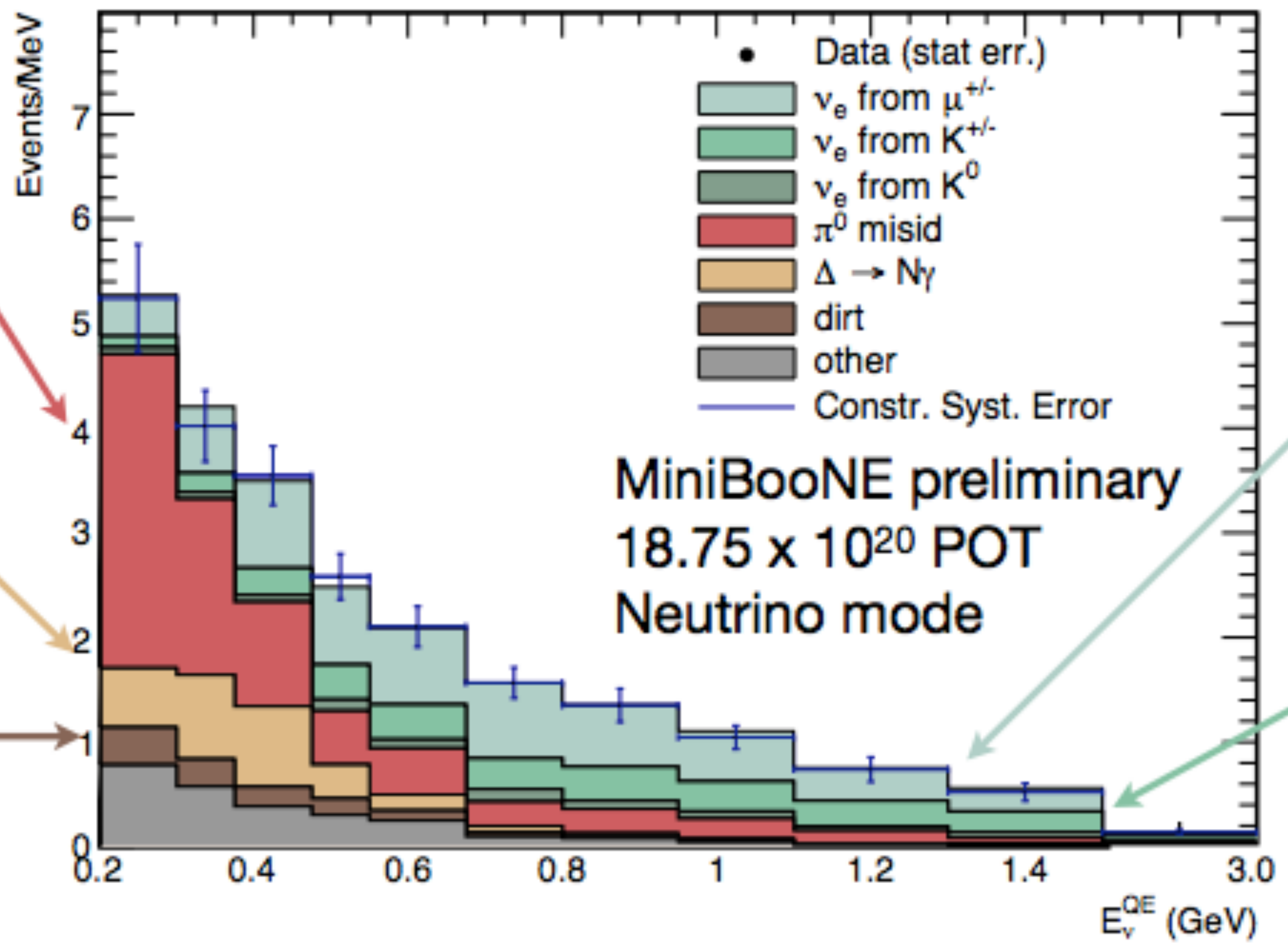

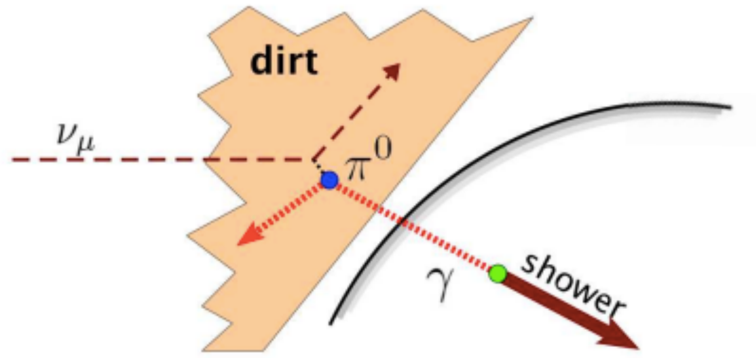

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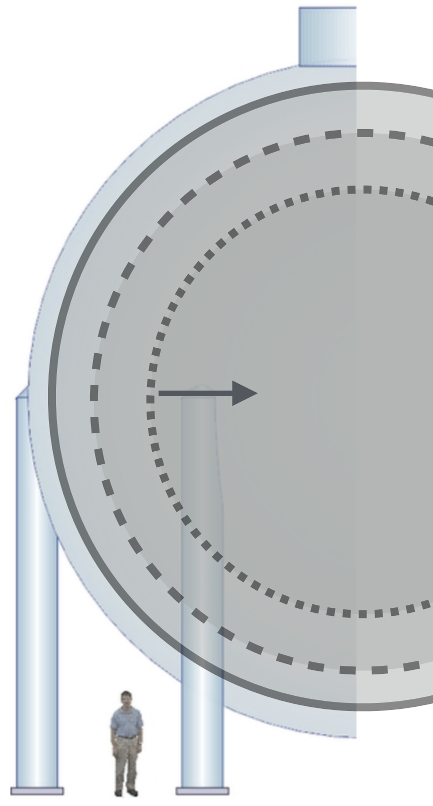

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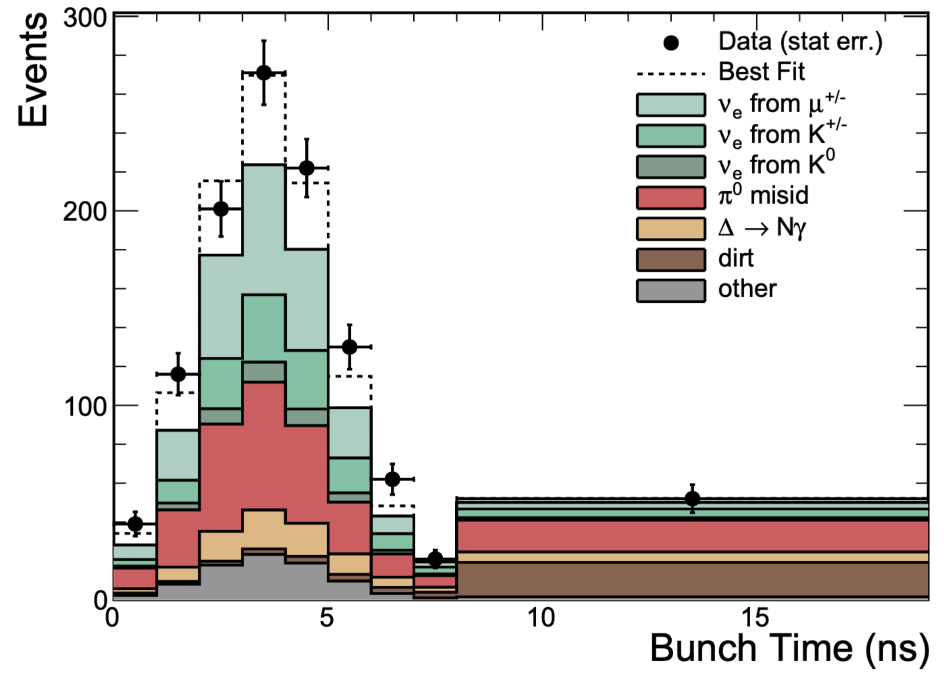


An Altarelli Cocktail for the MiniBooNE Anomaly?

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

arxiv:2109.08157

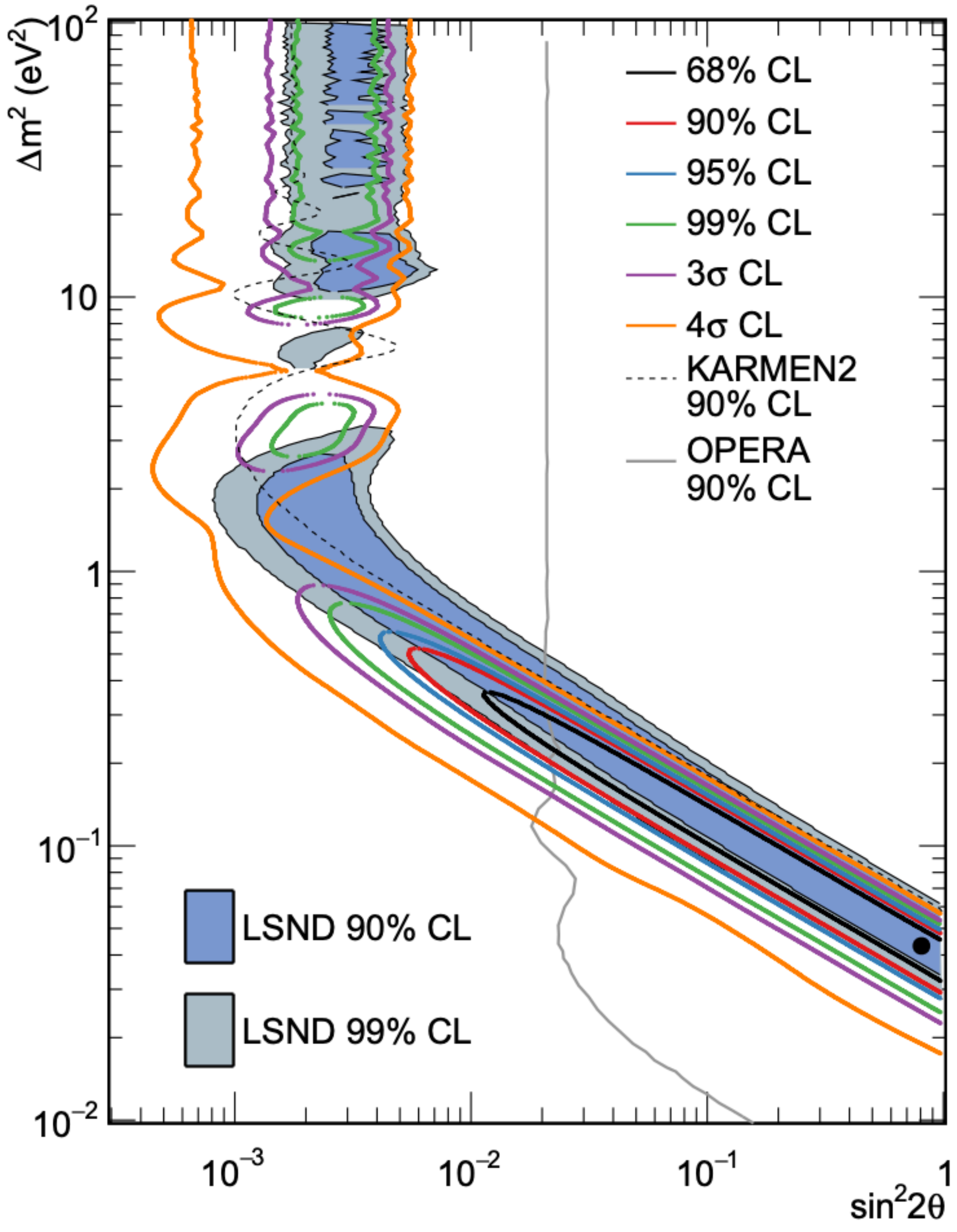
→

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 $\Delta(1232)$ and $N(1440)$ resonances by $\pm 2\sigma$, 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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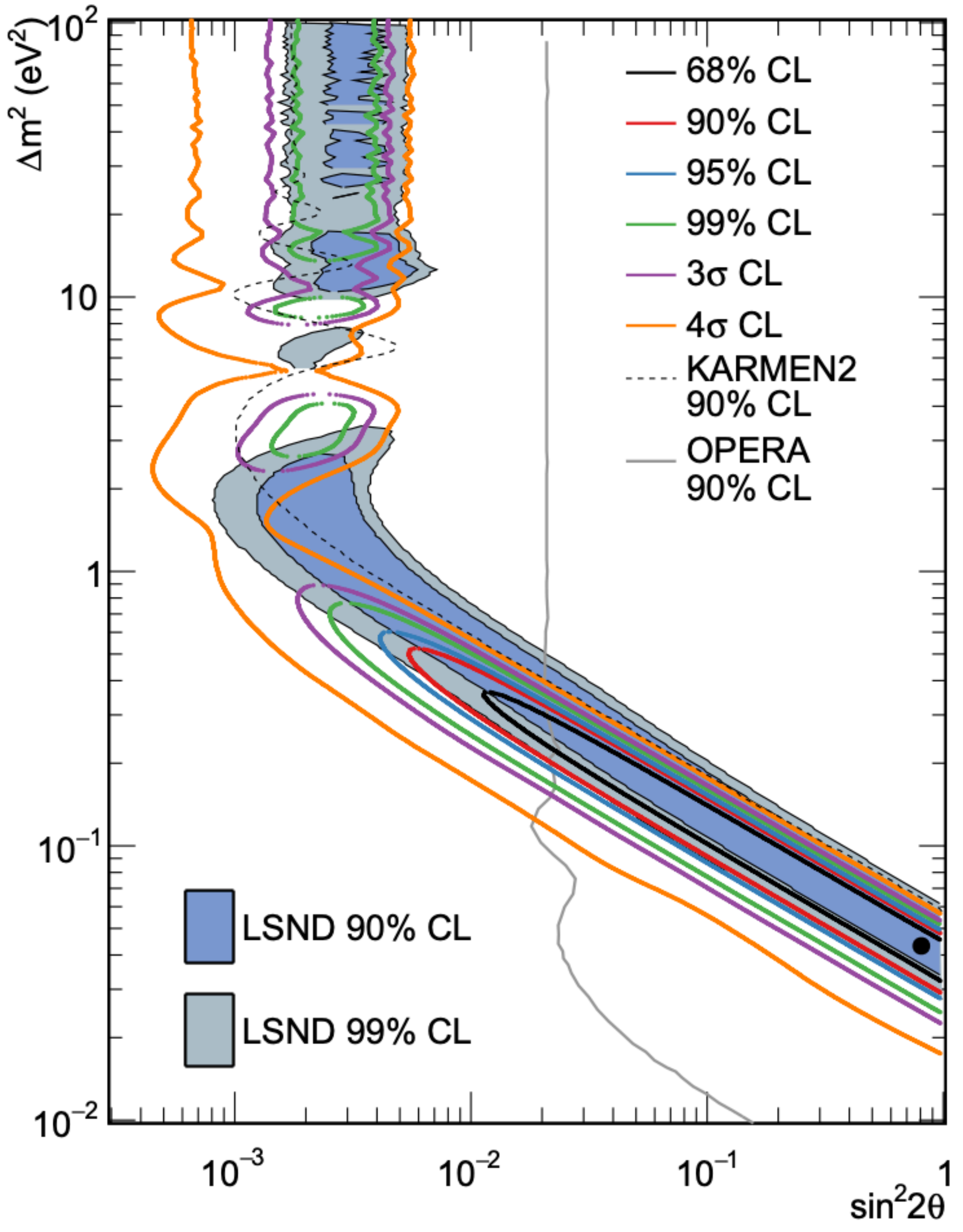
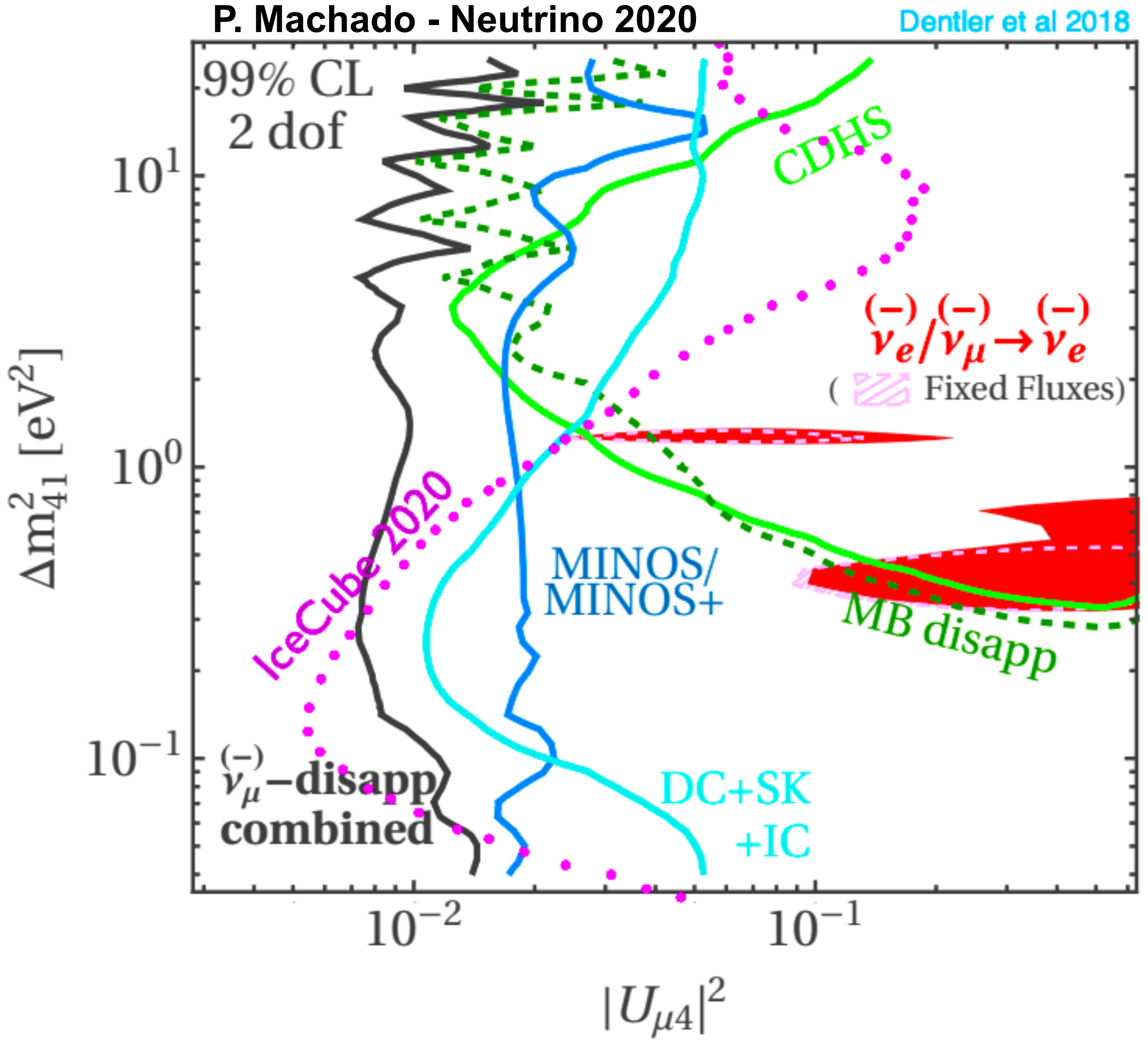
ν_μ disappearance

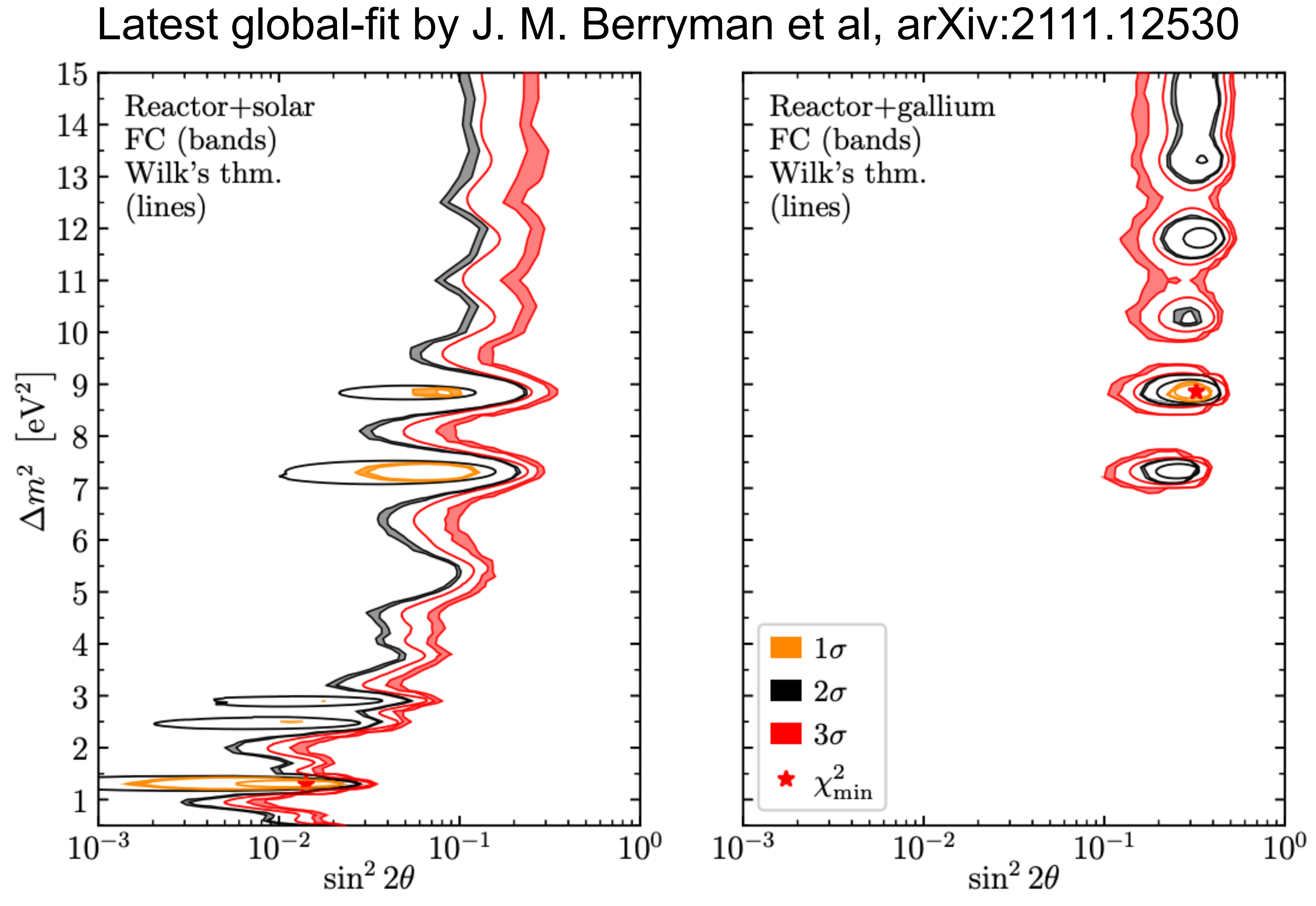
+

ν_e disappearance





No ν_μ disappearance is observed,



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

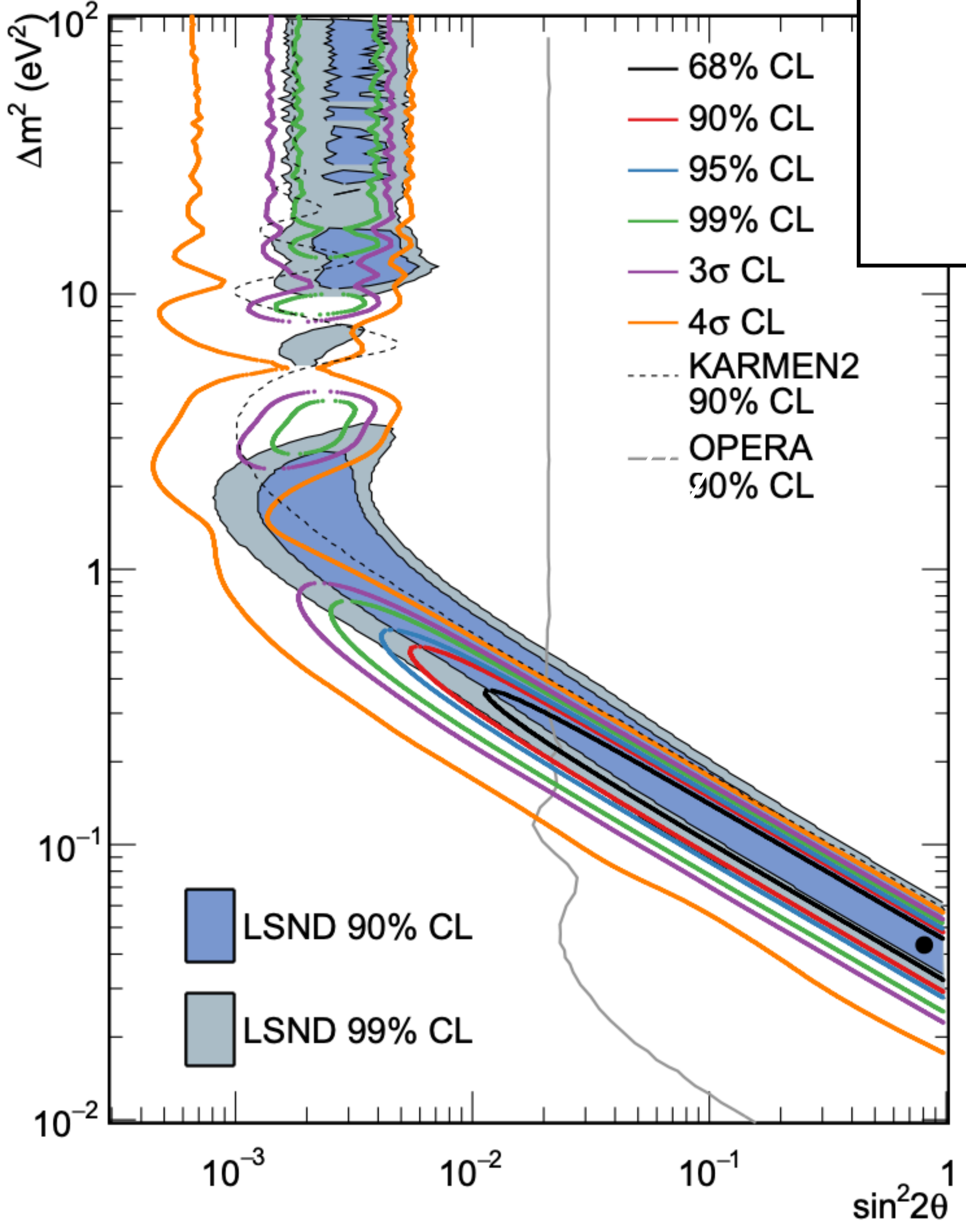
No single experiment gives conclusive evidence.

Inconclusive.

Is there enough evidence for a sterile neutrino?

A $\nu_\mu \to \nu_e$ **appearance** oscillation im... ...ce

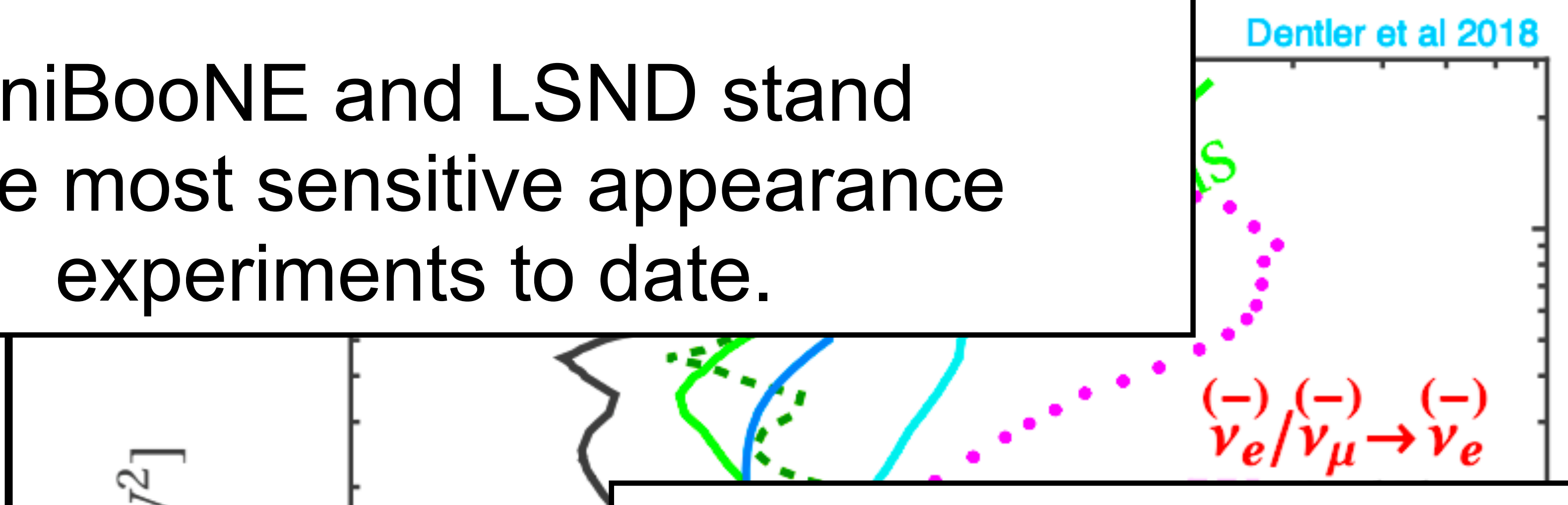
ν_e and ν_μ disappearance.



(1)

Huge progress.

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

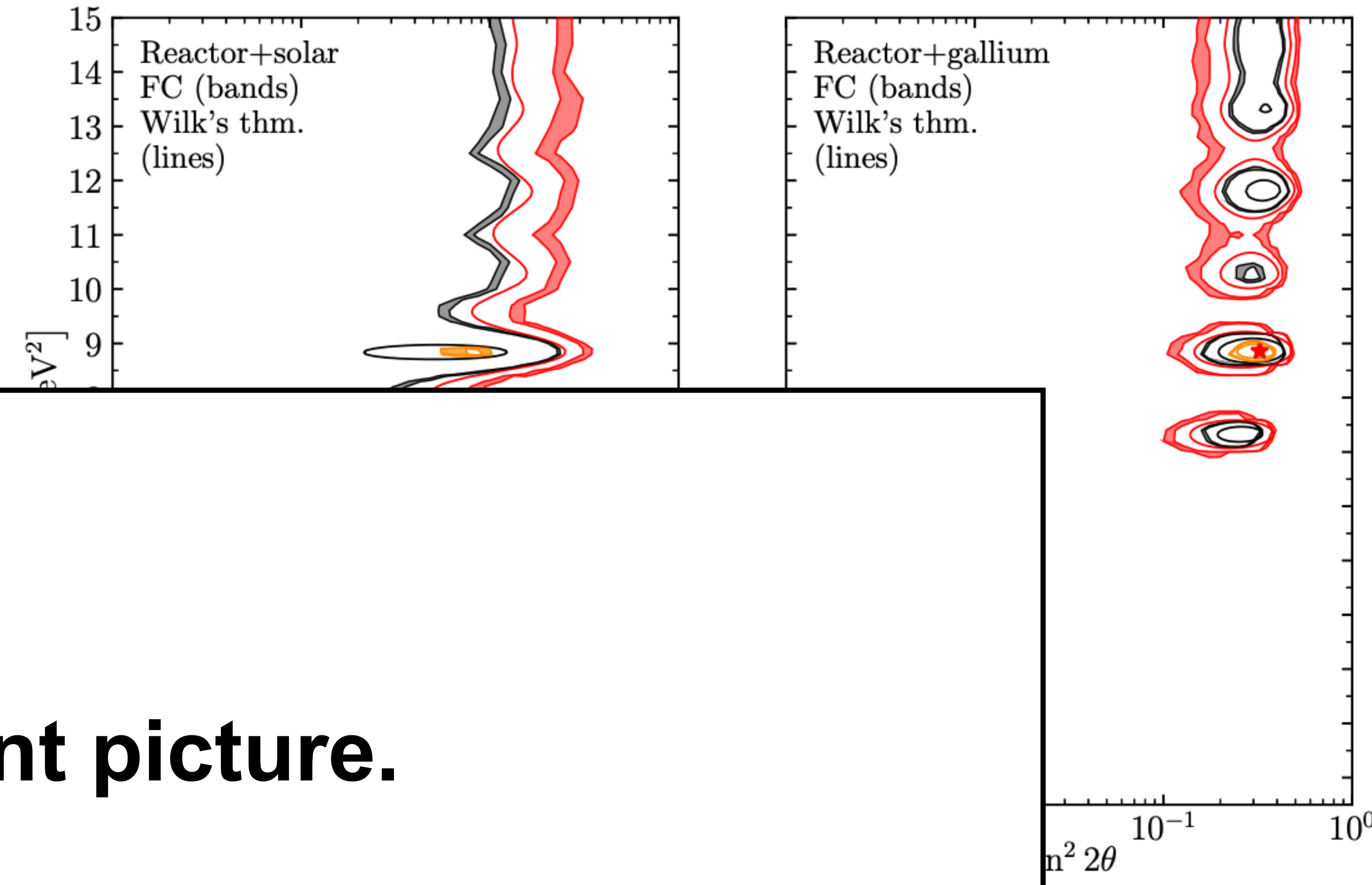


No ν_μ disappearance is observed,

+

ν_e disappearance

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



... have been ... trino flux.

... ive evidence.

Inconclusive.

(2)

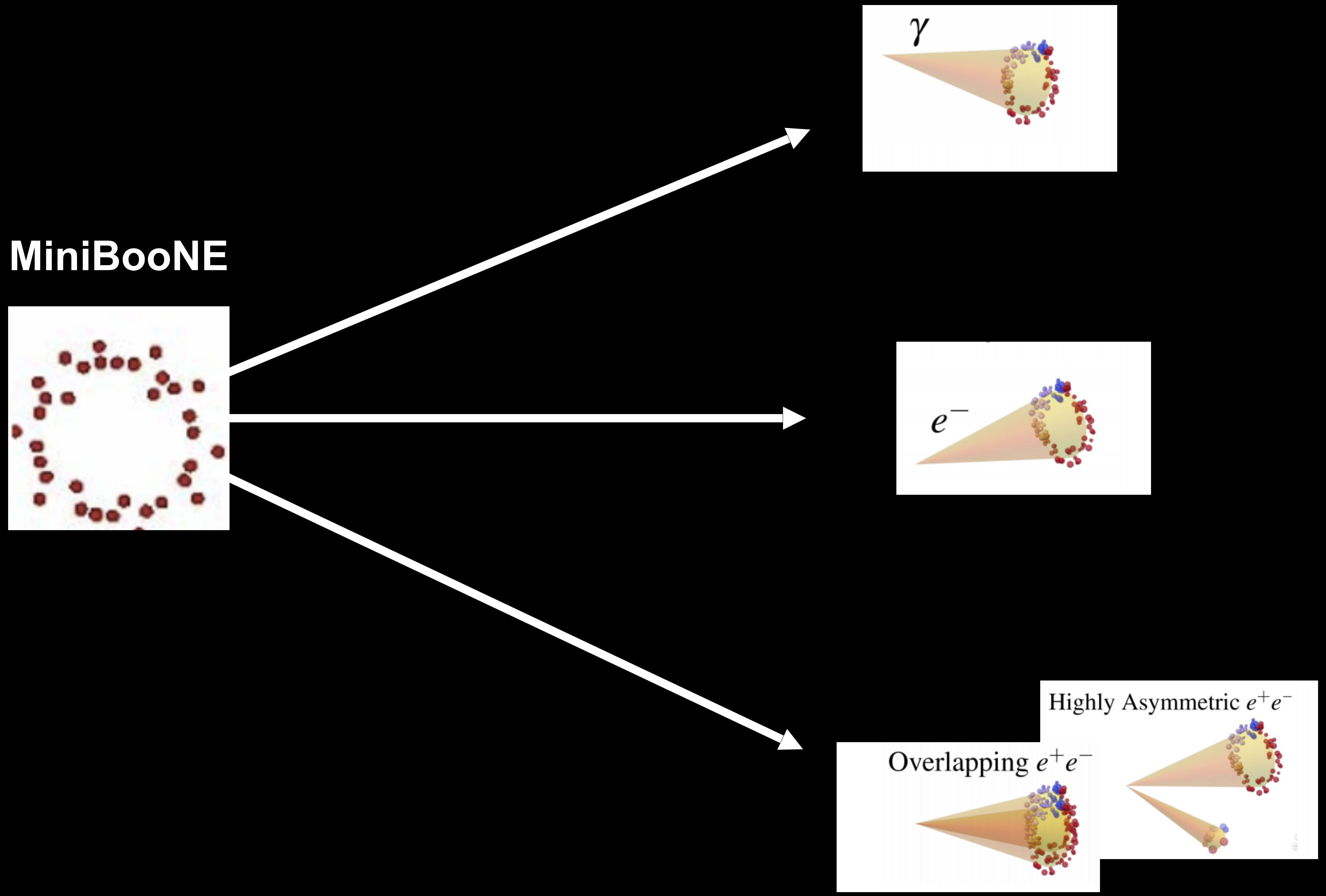
Still no coherent picture.

Light sterile neutrinos do not fit the global data well

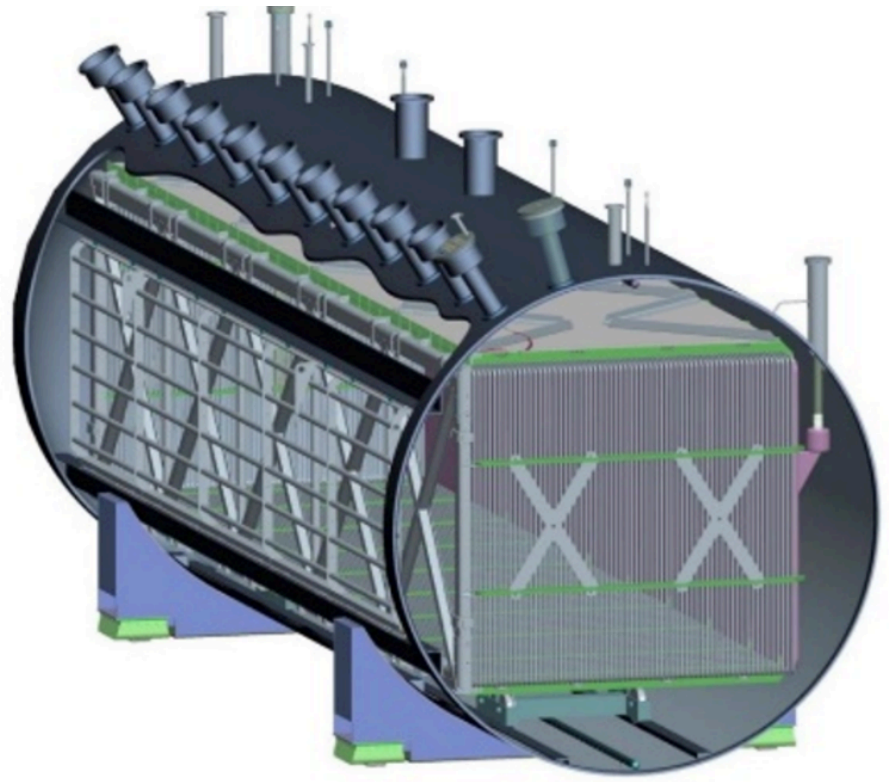
They are also a major issue for cosmology…

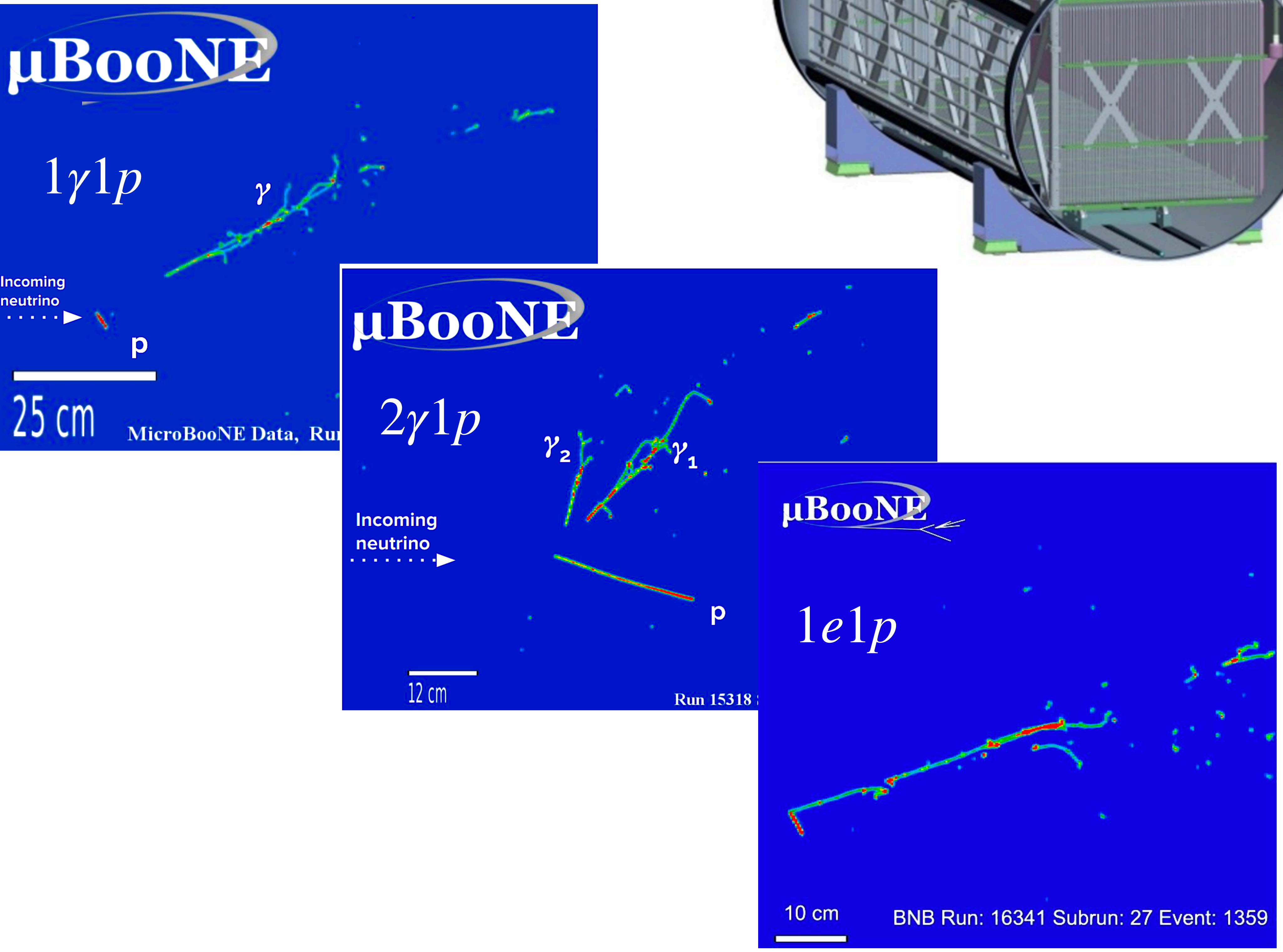
Clearly, something more complicated may be happening.

Latest results from MicroBooNE



MicroBooNE
Disentangling the final states behind the low-energy excess



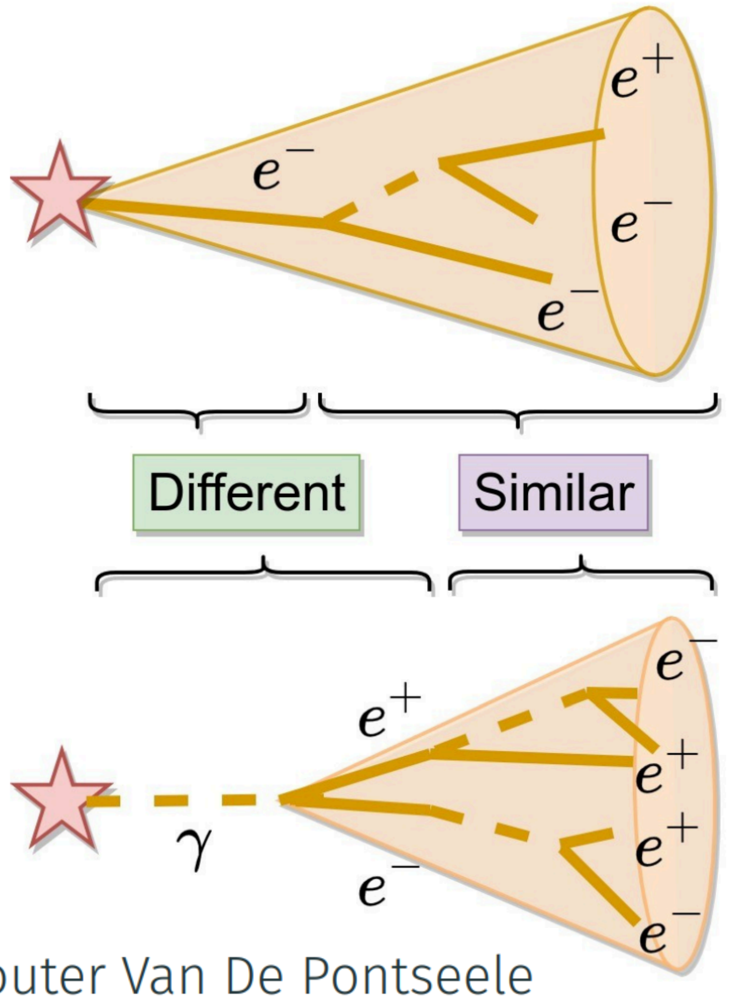


Liquid-Argon Time-Projection-Chamber (TPC)

3D images of charged particles produced in neutrino interactions

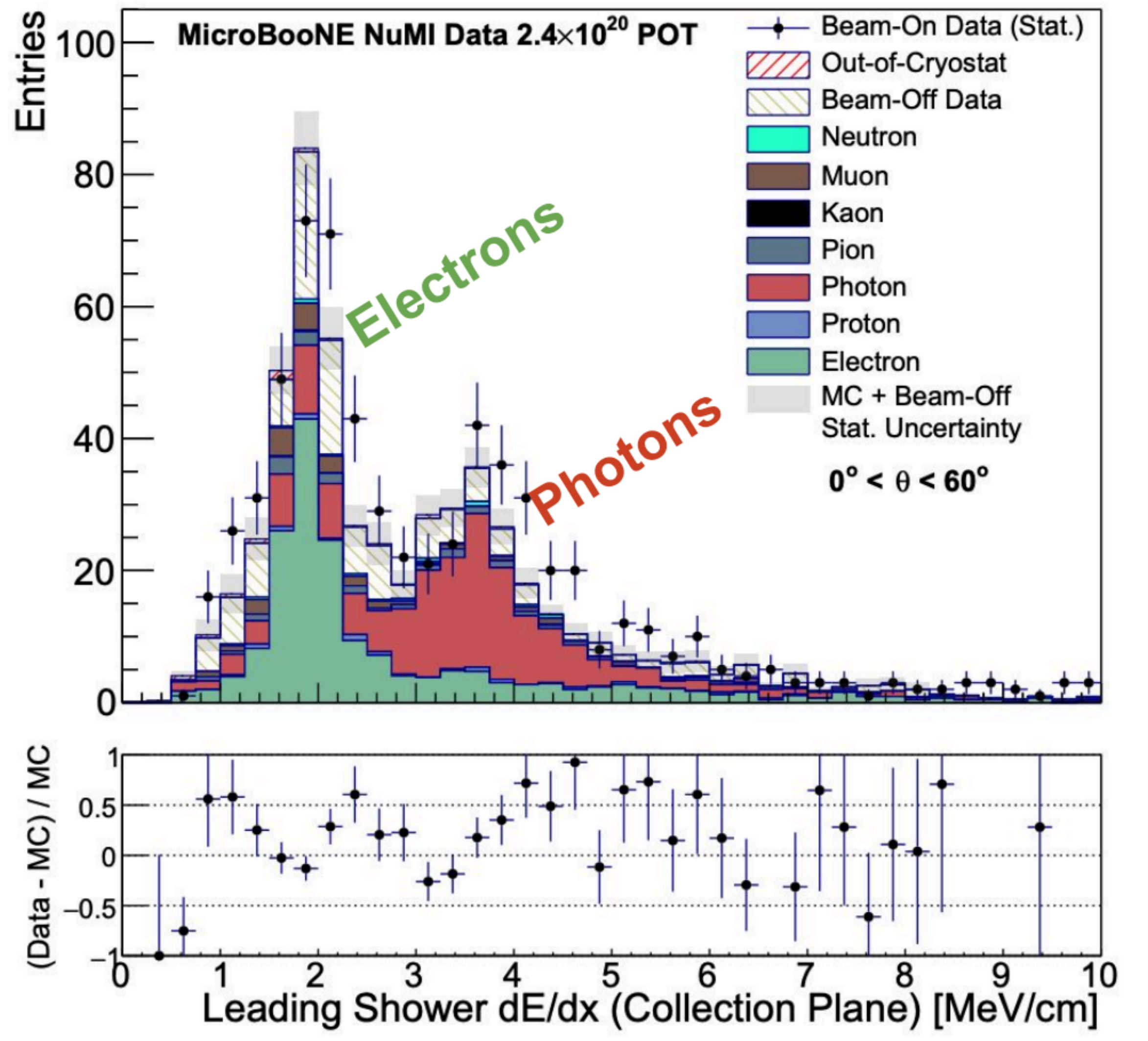
MicroBooNE is able to differentiate between electrons and photons:

I) vertex-shower separation



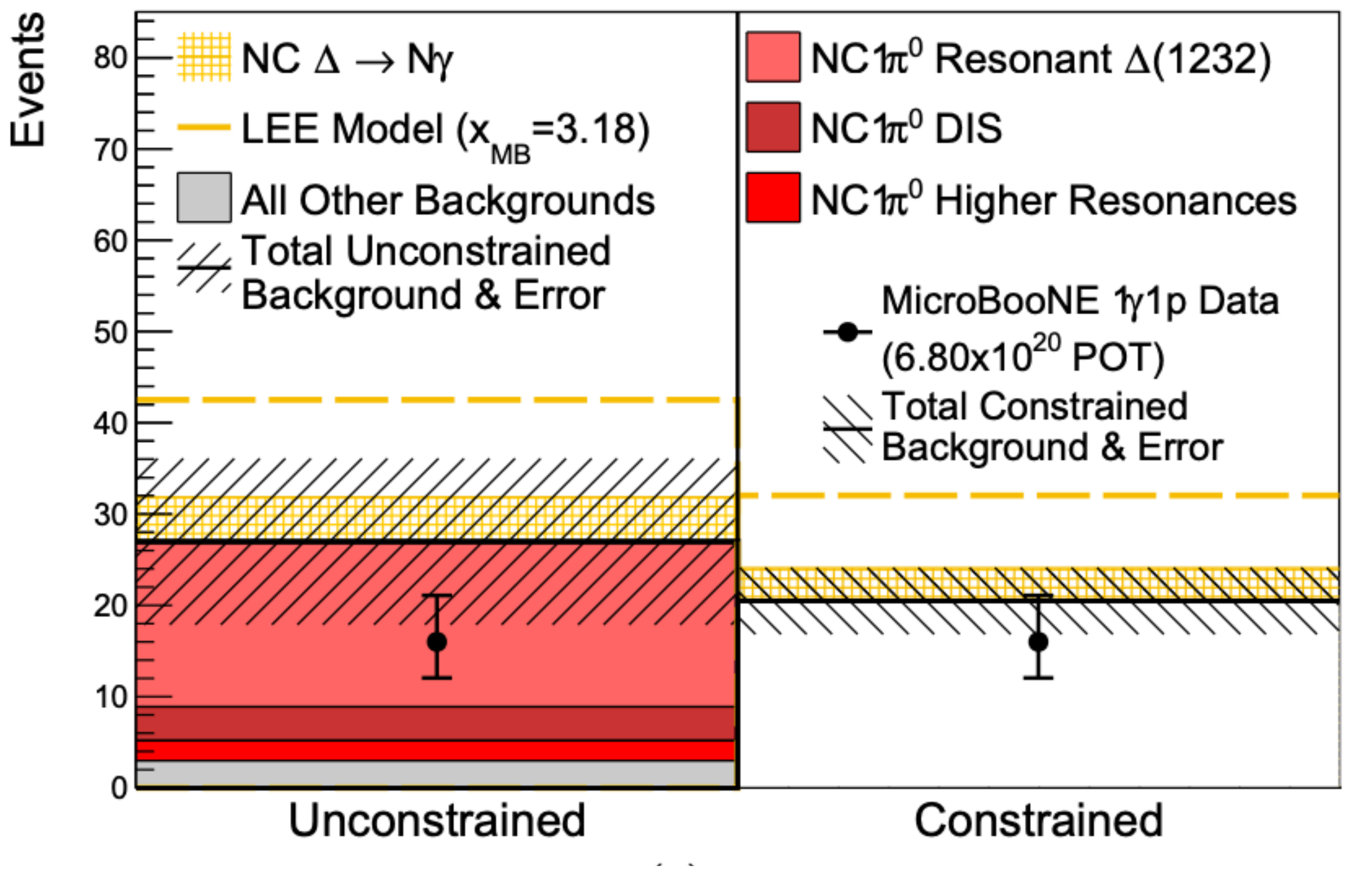
Wouter Van De Pontseele

ii) dE/dx at the beginning of the shower

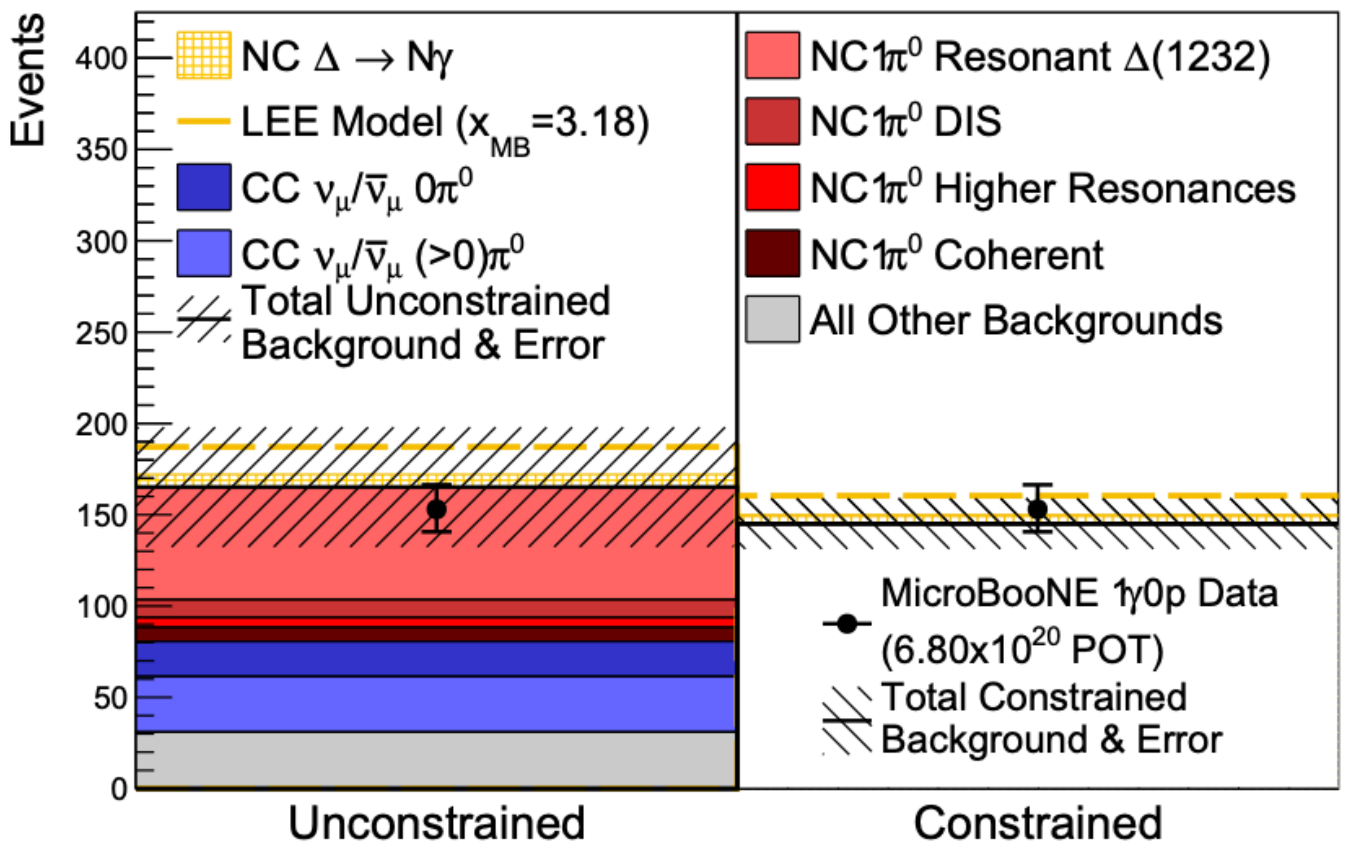


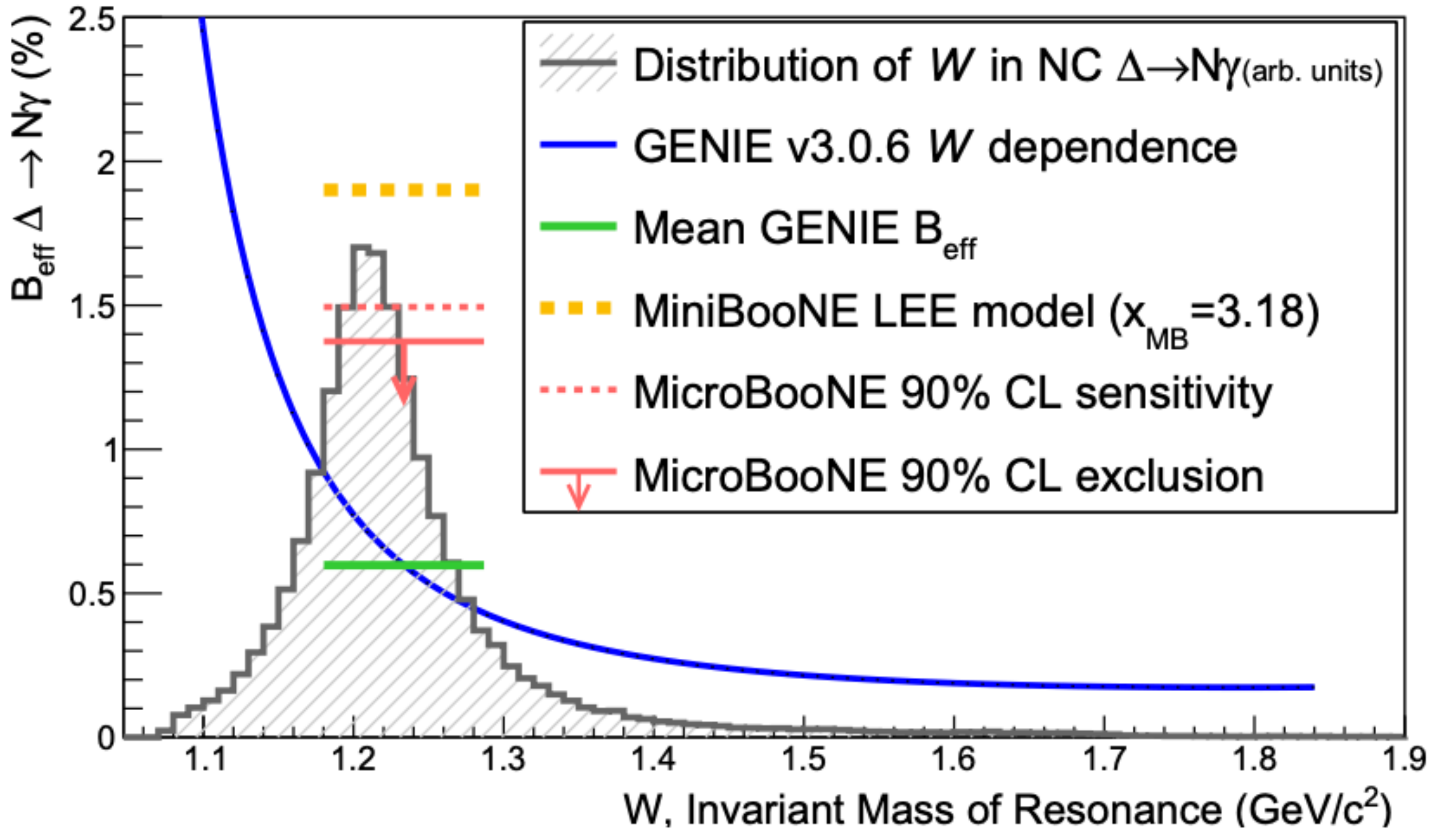
Single-photon search
Δ(1232) radiative decay

$1\gamma 1p$



$1\gamma 0p$





Conclusion:

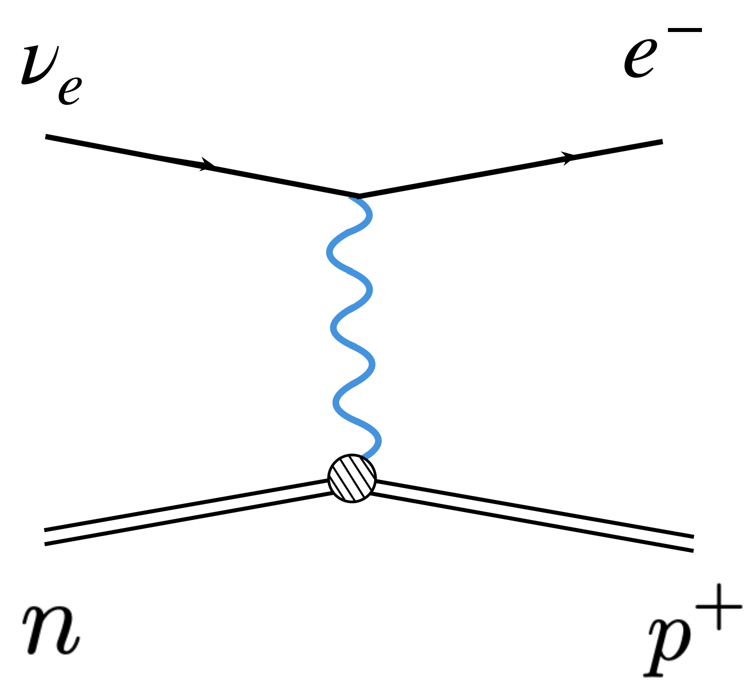
$\Delta(1232)$ radiative constrained as an explanation of MiniBooNE:

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

Other single-photon interpretations still untested:

- coherent photons
- new particles decaying to single photons

Electron-neutrino searches at MicroBooNE



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

the electron low-energy-excess signal model, a.k.a.

the eLEE template

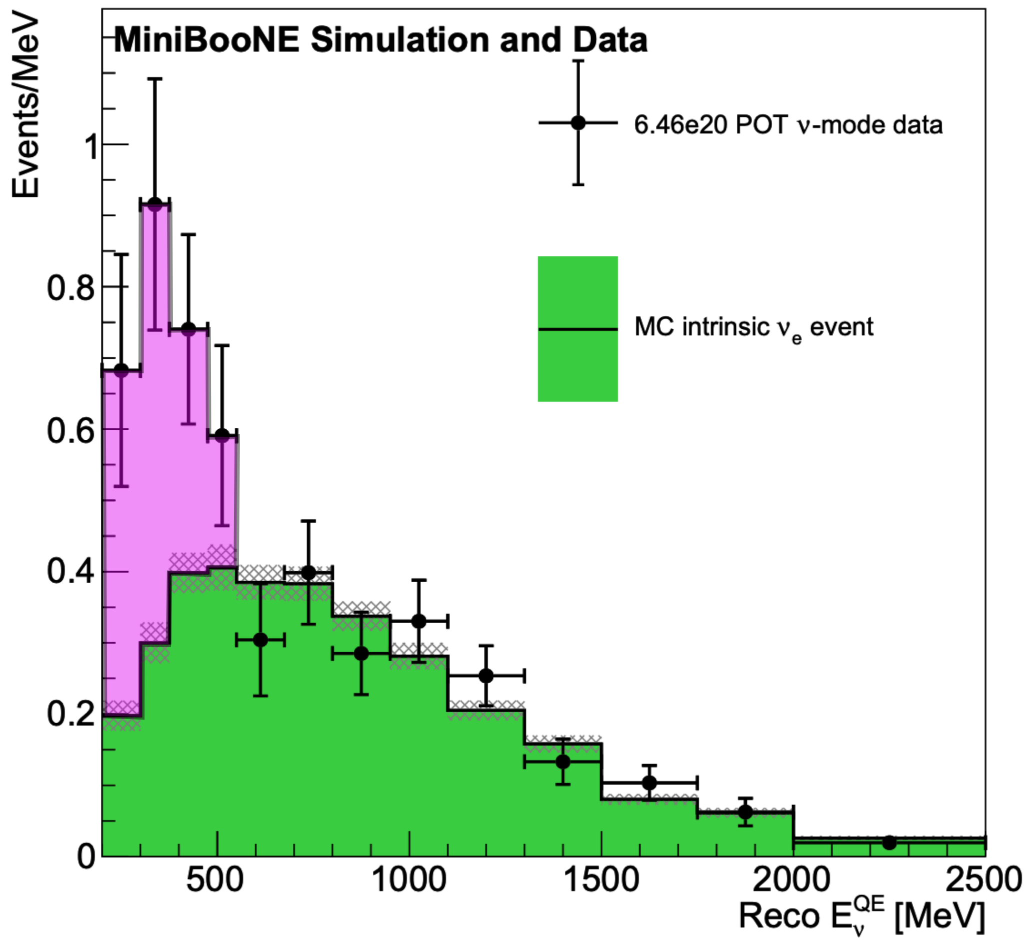
What does it mean?

Electron-neutrino searches at MicroBooNE

The eLEE template

MiniBooNE

(non-ν_e backgrounds subtracted)



eLEE template

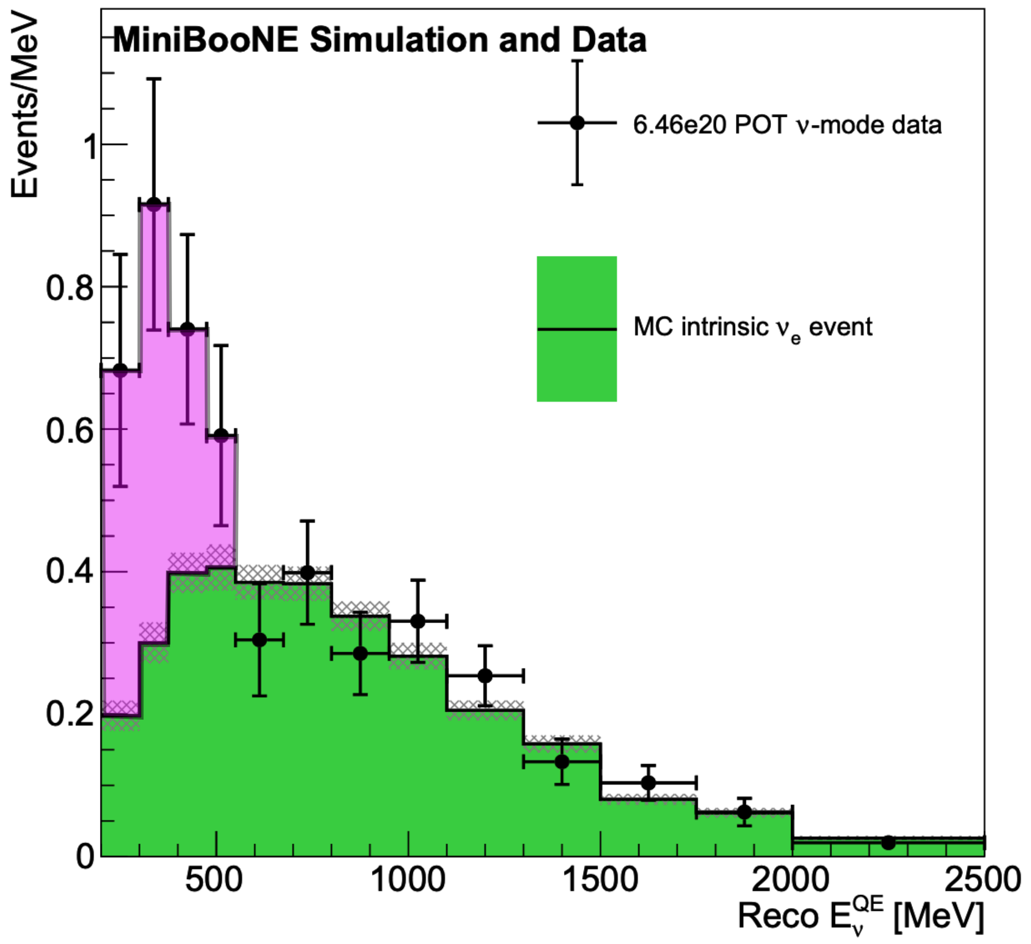
Central value of

(data)$_i$ - (background)$_i$

Electron-neutrino searches at MicroBooNE

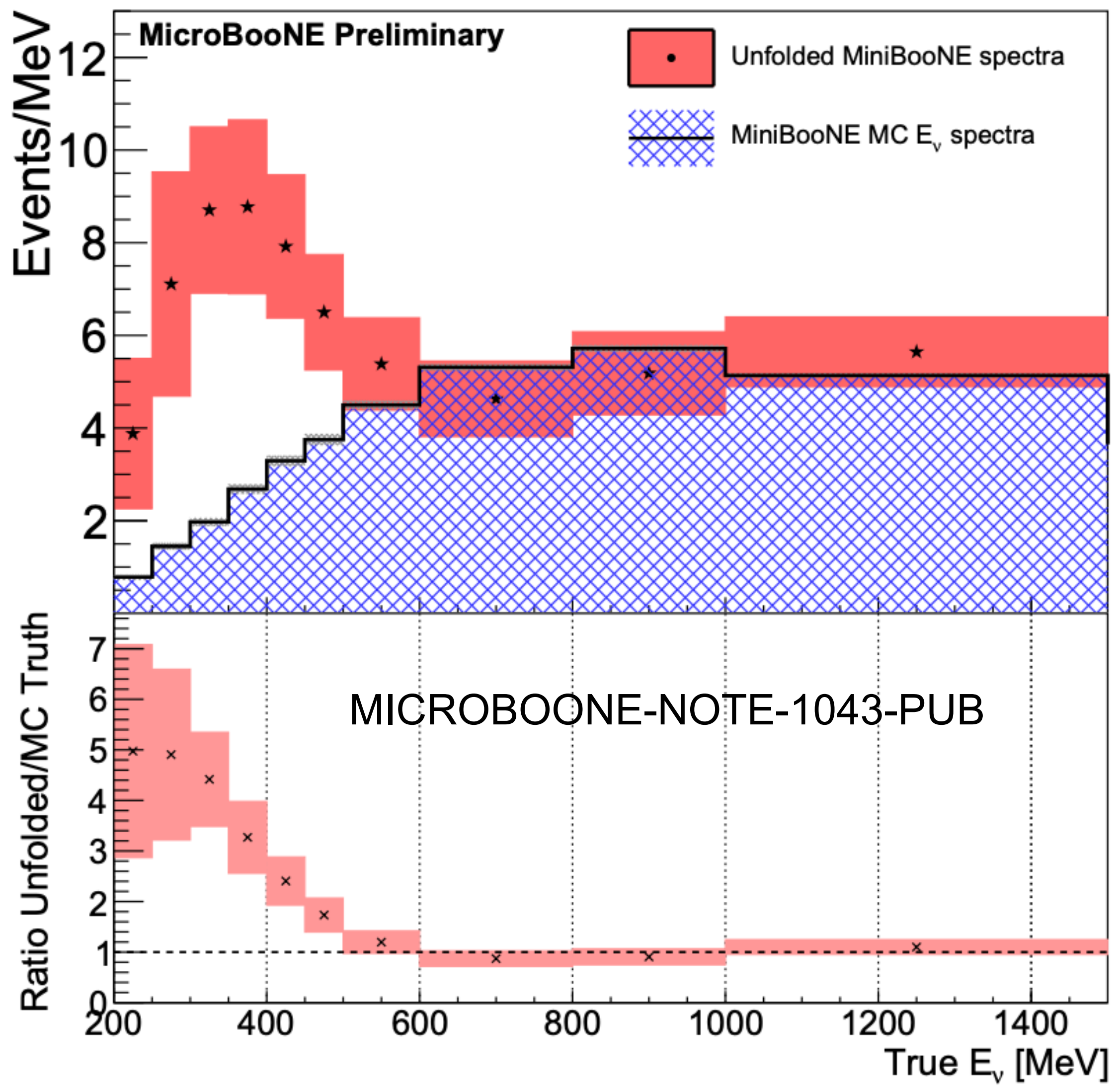
The eLEE template

MiniBooNE
(non-ν_e backgrounds subtracted)



Unfold

MiniBooNE
Unfolded, **true** spectrum



eLEE template

Central value of

(data)$_i$ - (background)$_i$

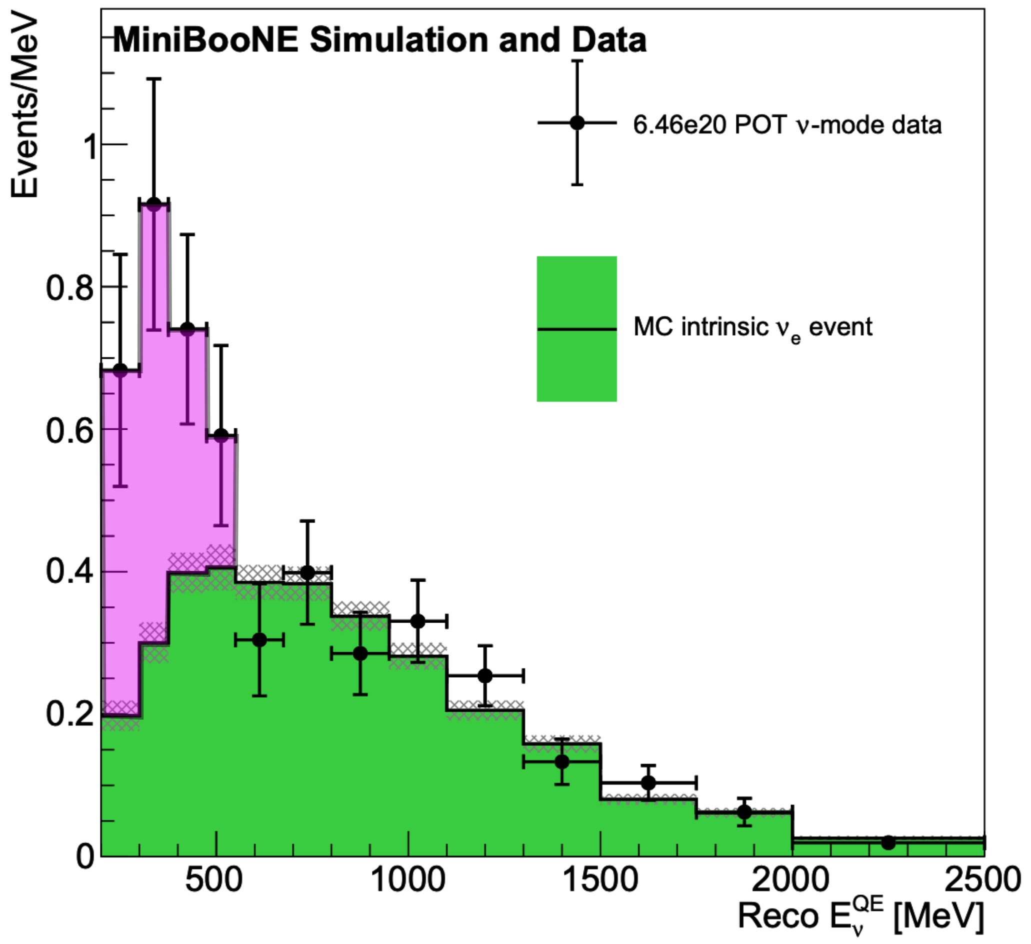
"**Unfold**" detector resolution, selection cuts, and efficiencies into a true ν_e spectrum.

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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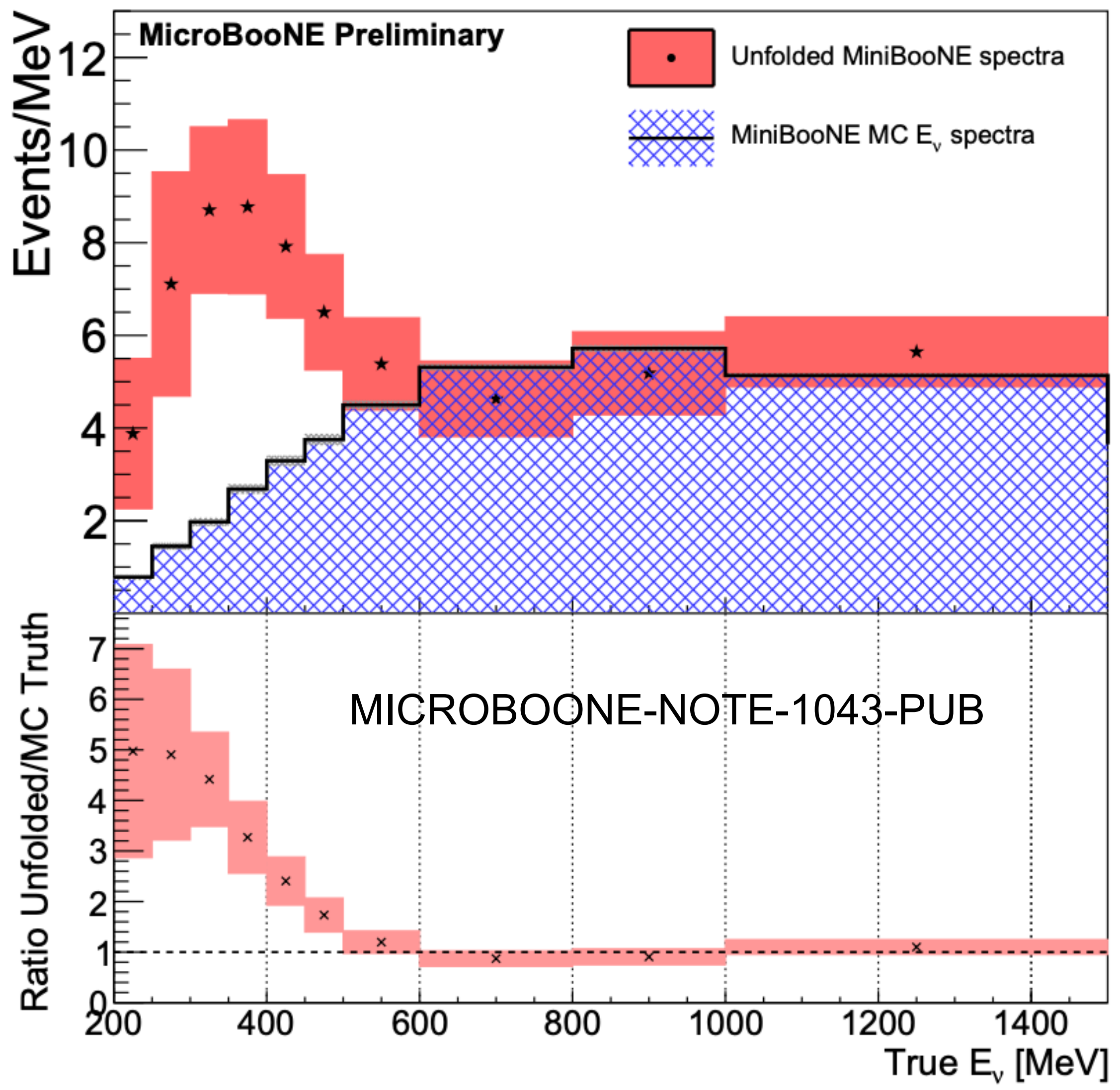

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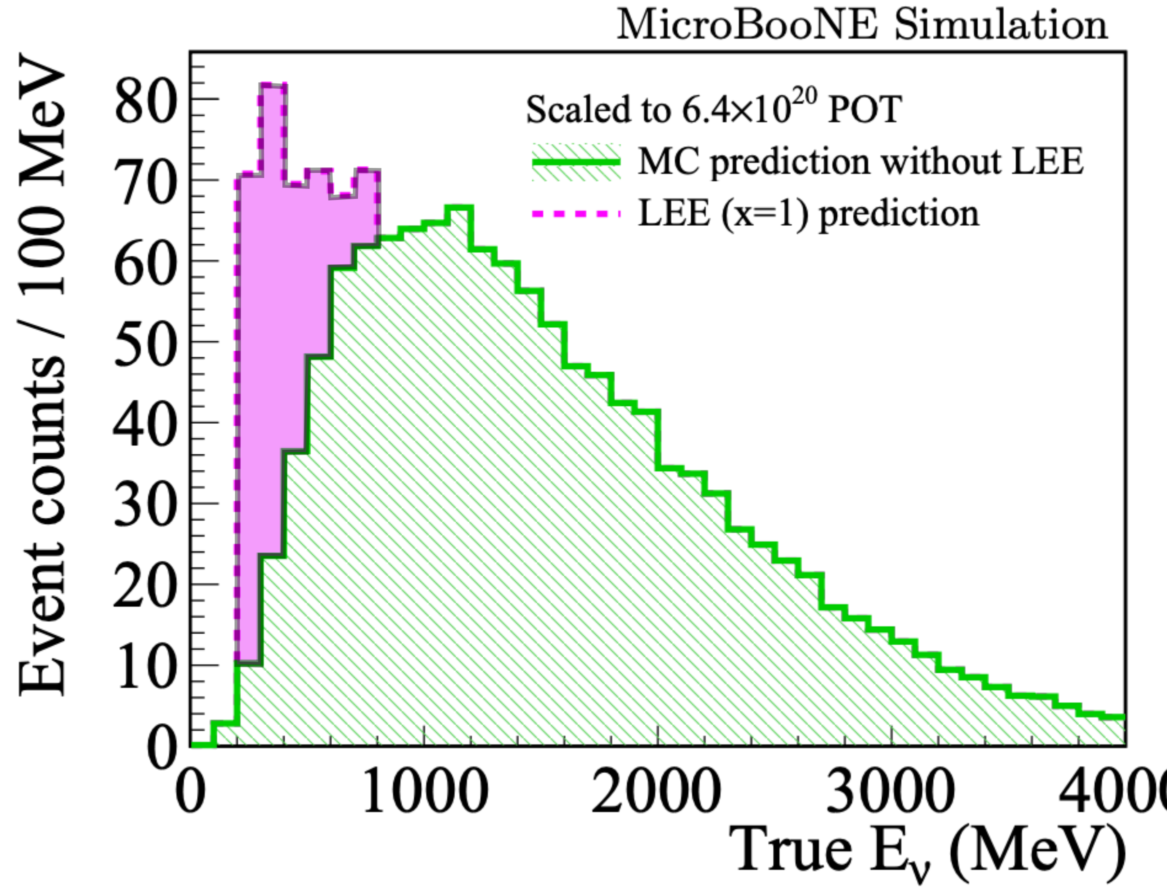
Energy dependent modification to the intrinsic ν_e rate.

MicroBooNE selection

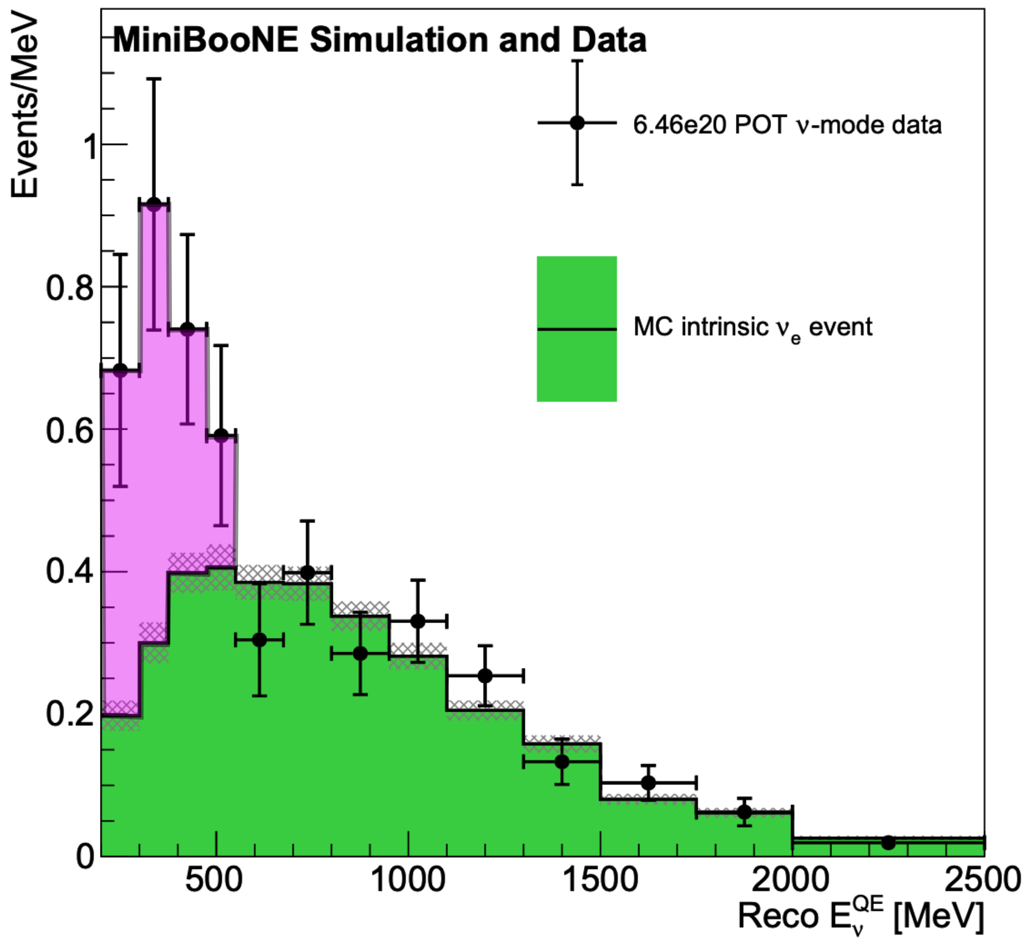


Use unfolded eLEE template to predict the event rate in a given MicroBooNE analysis.

Electron-neutrino searches at MicroBooNE

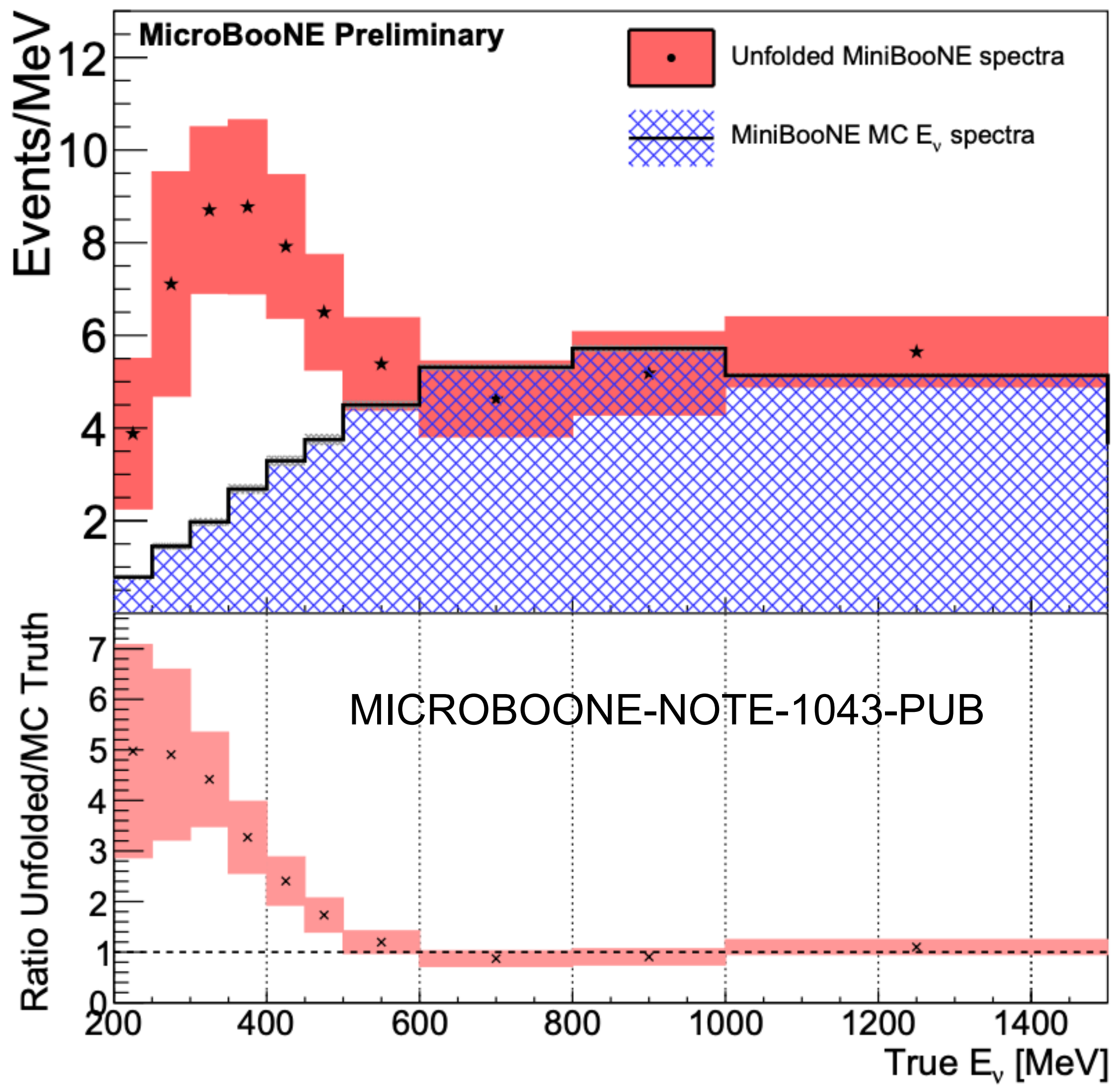
The eLEE template

MiniBooNE
(non-ν_e backgrounds subtracted)



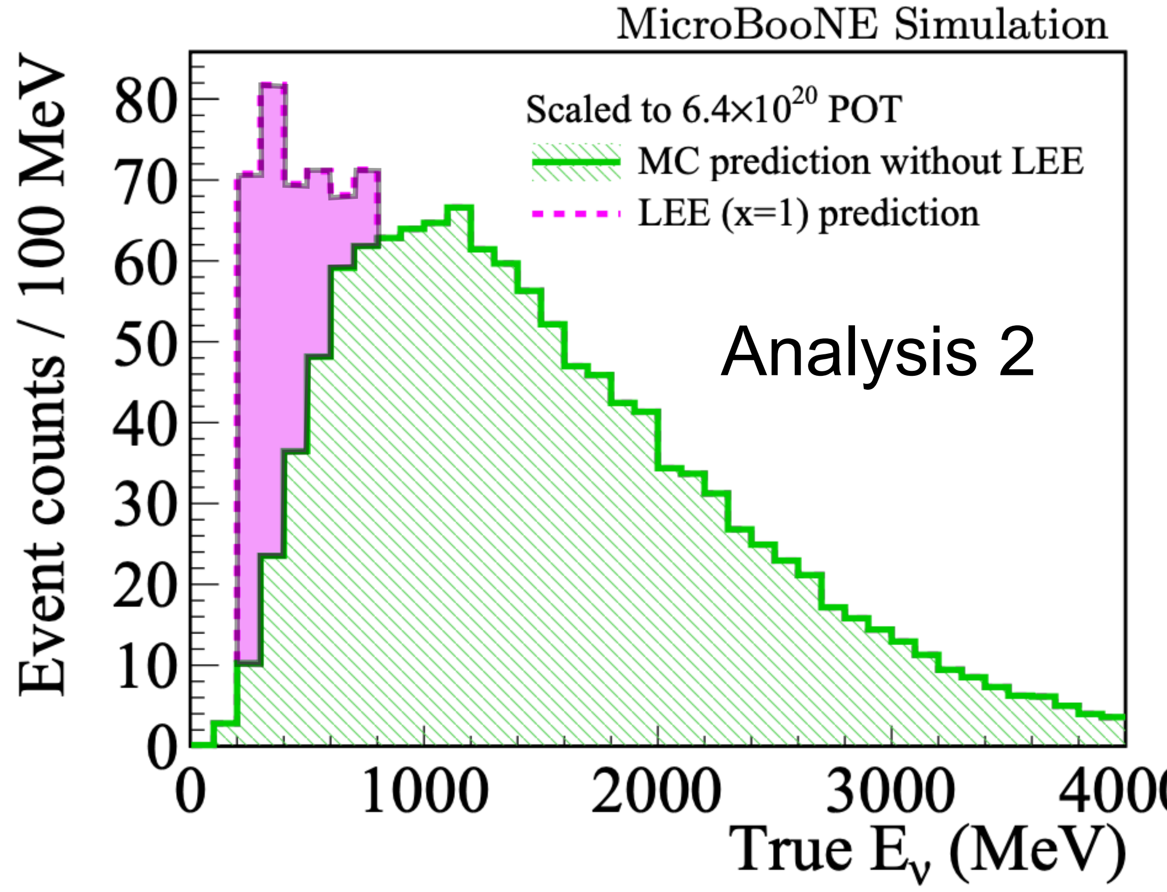
Unfold

MiniBooNE
Unfolded, **true** spectrum



MicroBooNE selection

….analysis 1



… analysis 3

eLEE template

Central value of

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

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

Energy dependent modification to the intrinsic ν_e rate.

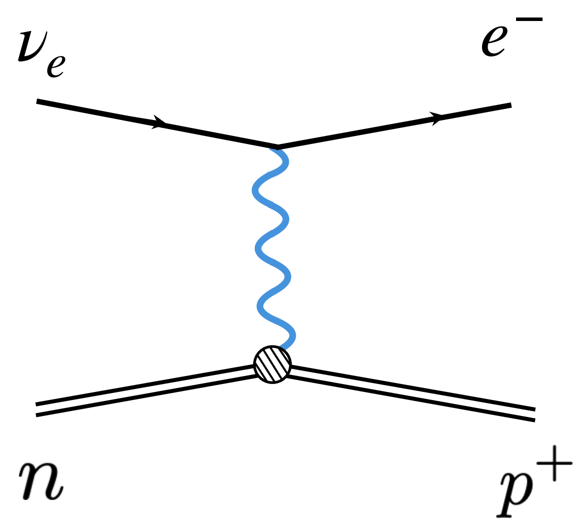
Use unfolded eLEE template to predict the event rate in a given MicroBooNE analysis.

Electron-neutrino searches at MicroBooNE

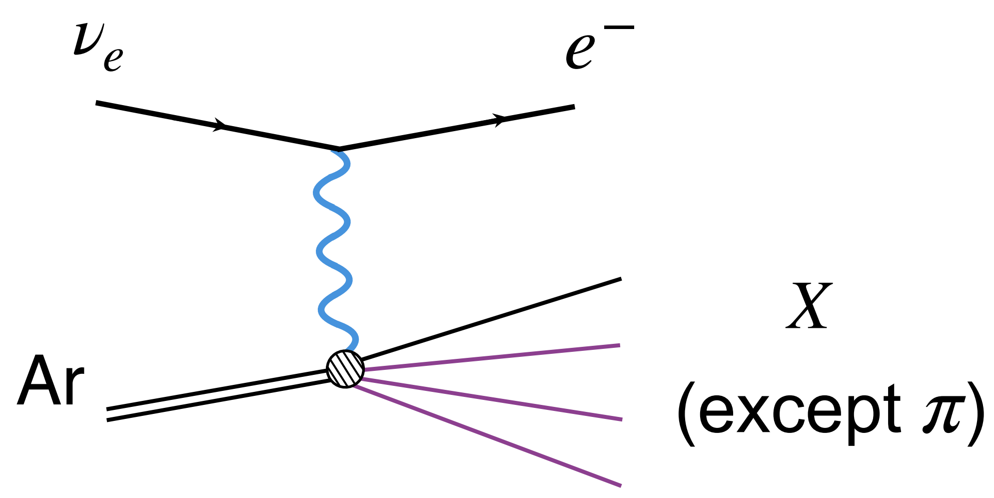
MicroBooNE’s three-prong approach

Different reconstruction algorithms and focus on different event classes

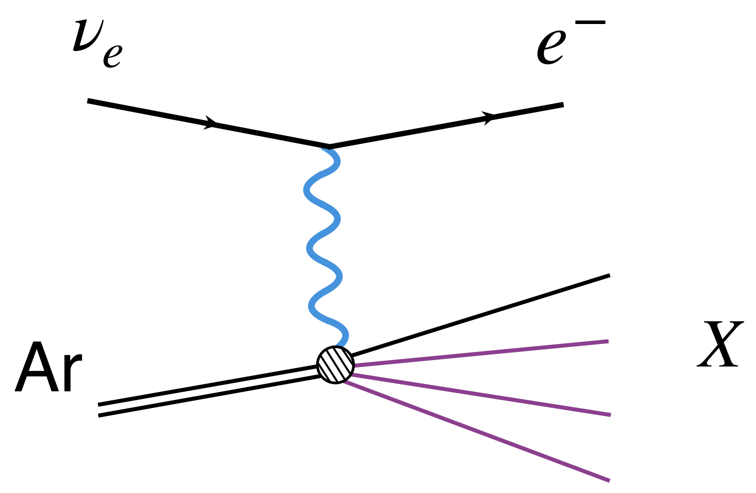
CCQE: $1e1p$
(Deep-Learning)



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



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



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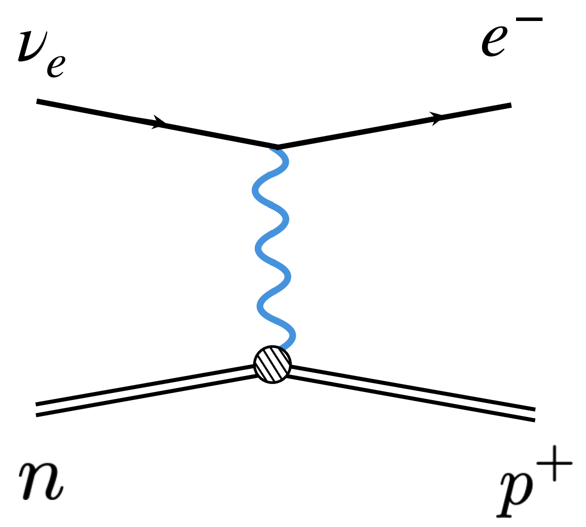

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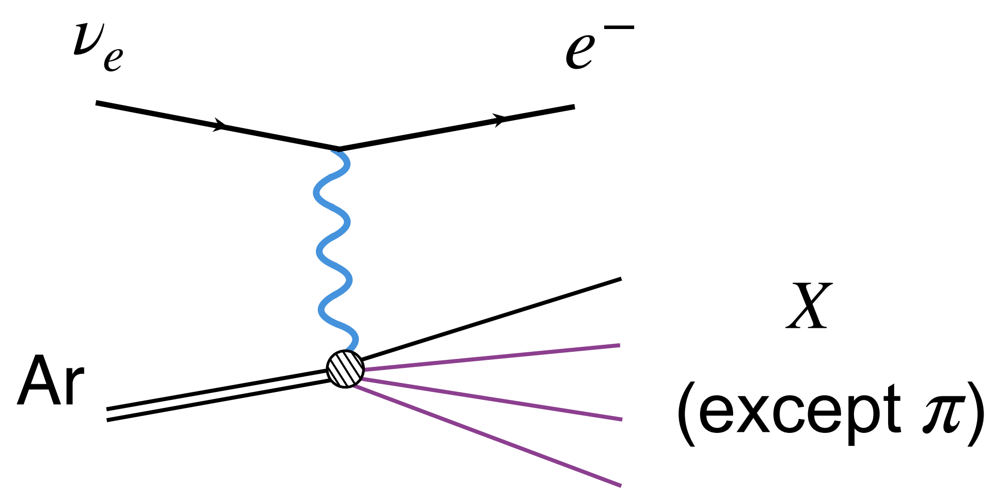

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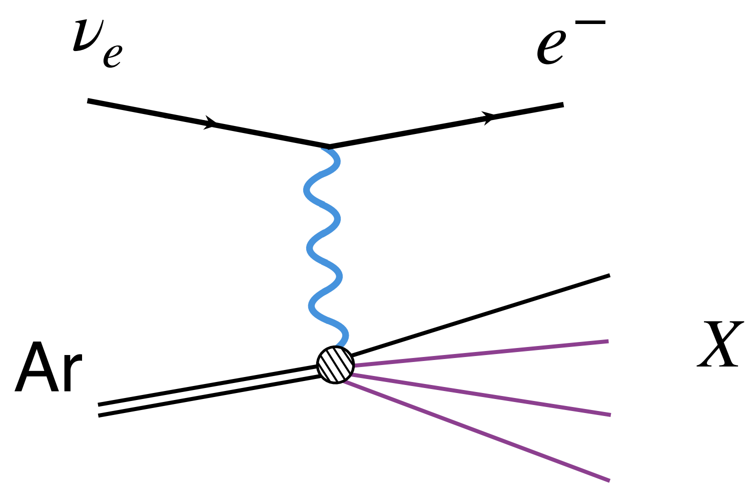
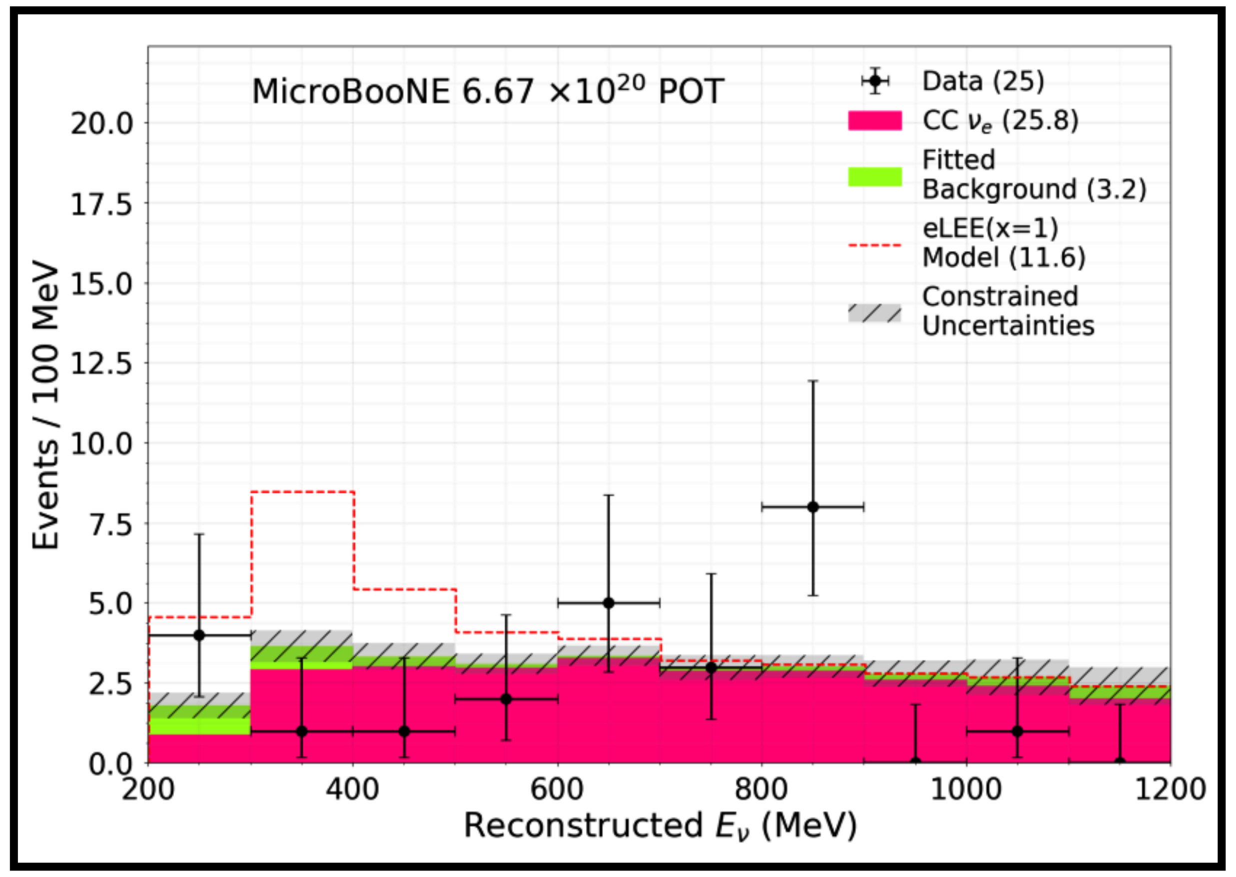
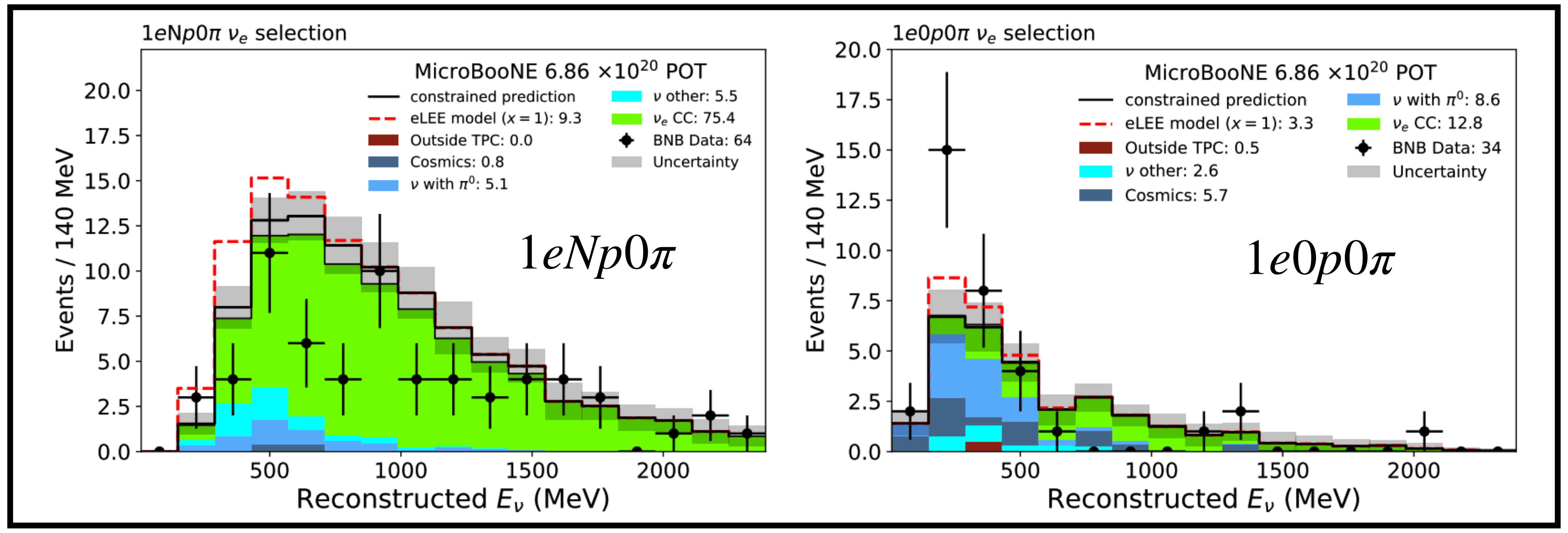
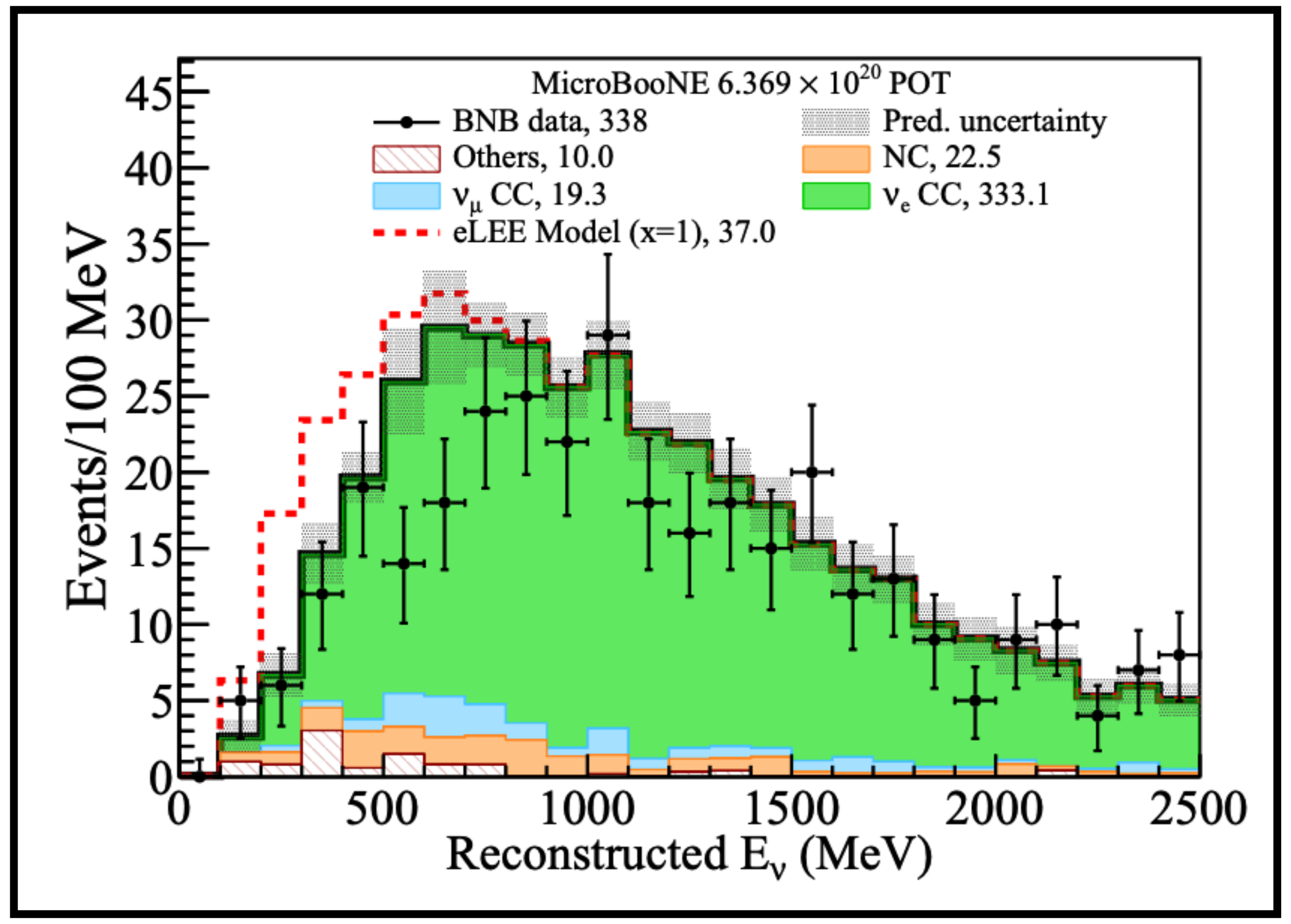




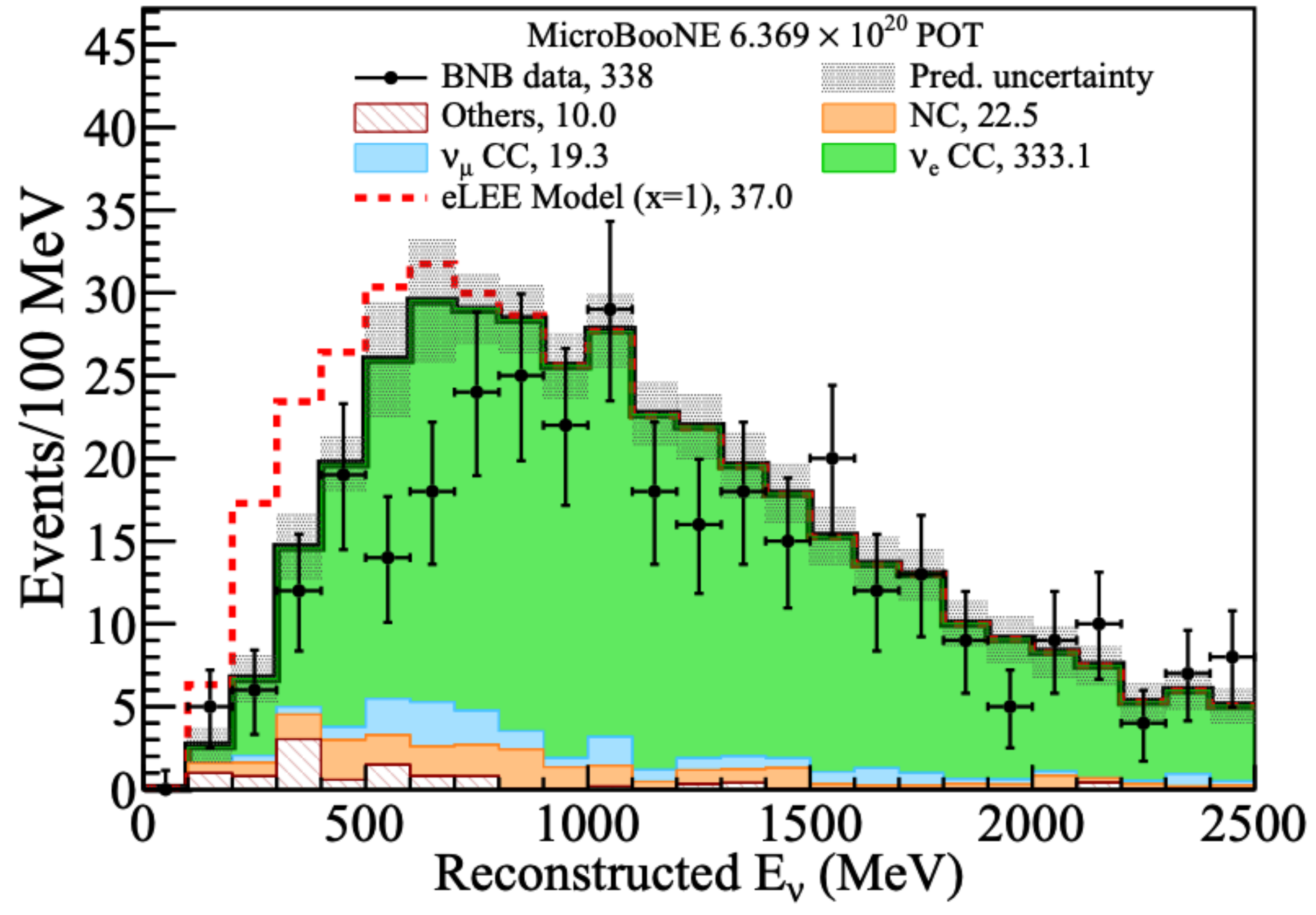


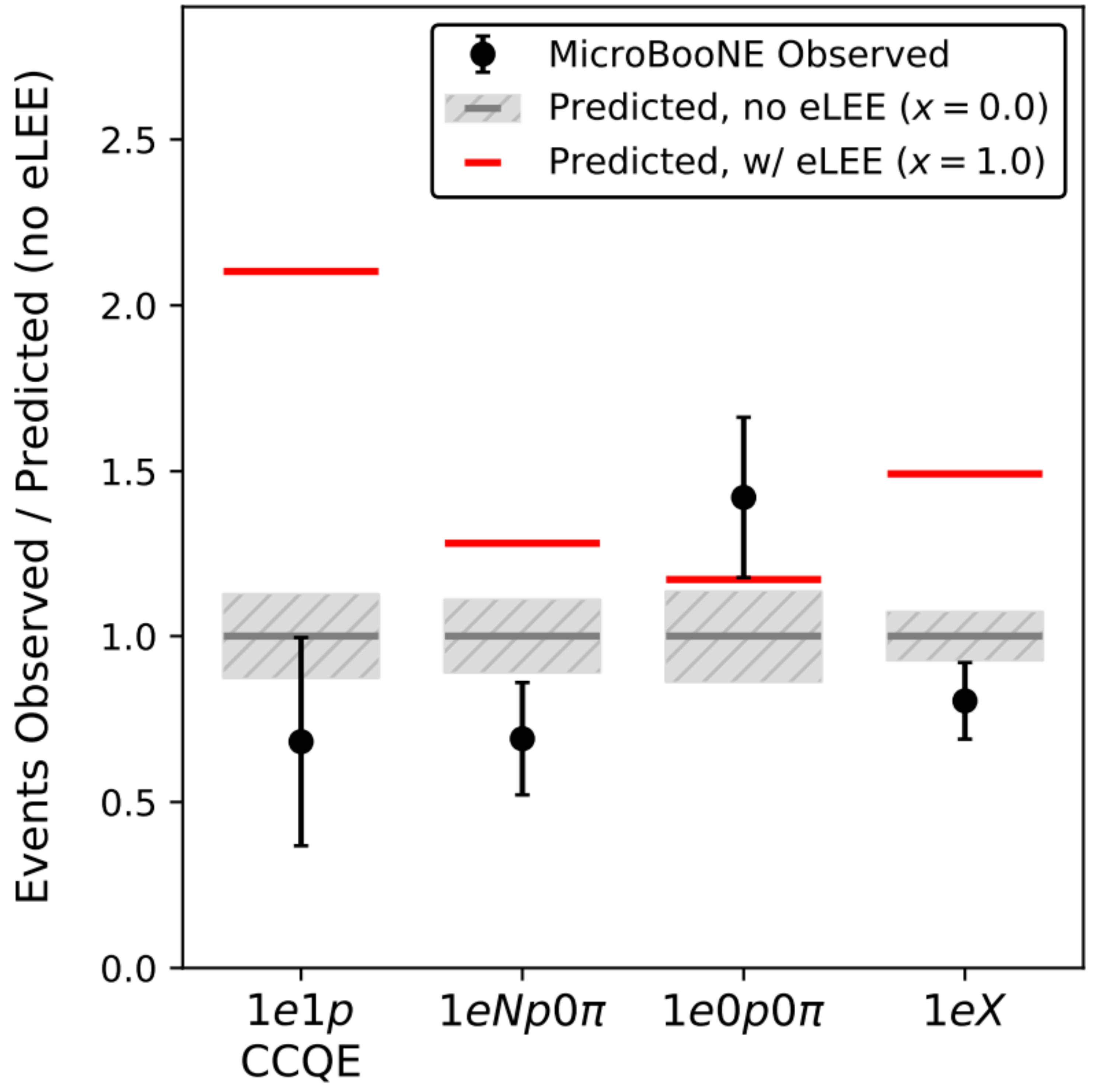


Electron-neutrino searches at MicroBooNE

The technical conclusion

For instance, in the Inclusive analysis:





No excess observed

+ slight deficit of events.

"… 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."

From *MicroBooNE coll., arXiv:2110.14054*

Electron-neutrino searches at MicroBooNE

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
Fermilab

Sterile neutrinos ruled out by MicroBooNE, but mysterious excess remains unexplained
physicsworld

But several questions remain:

1. How about MiniBooNE systematics?
2. What are the limits on sterile neutrinos?
3. Are all explanations disfavored?

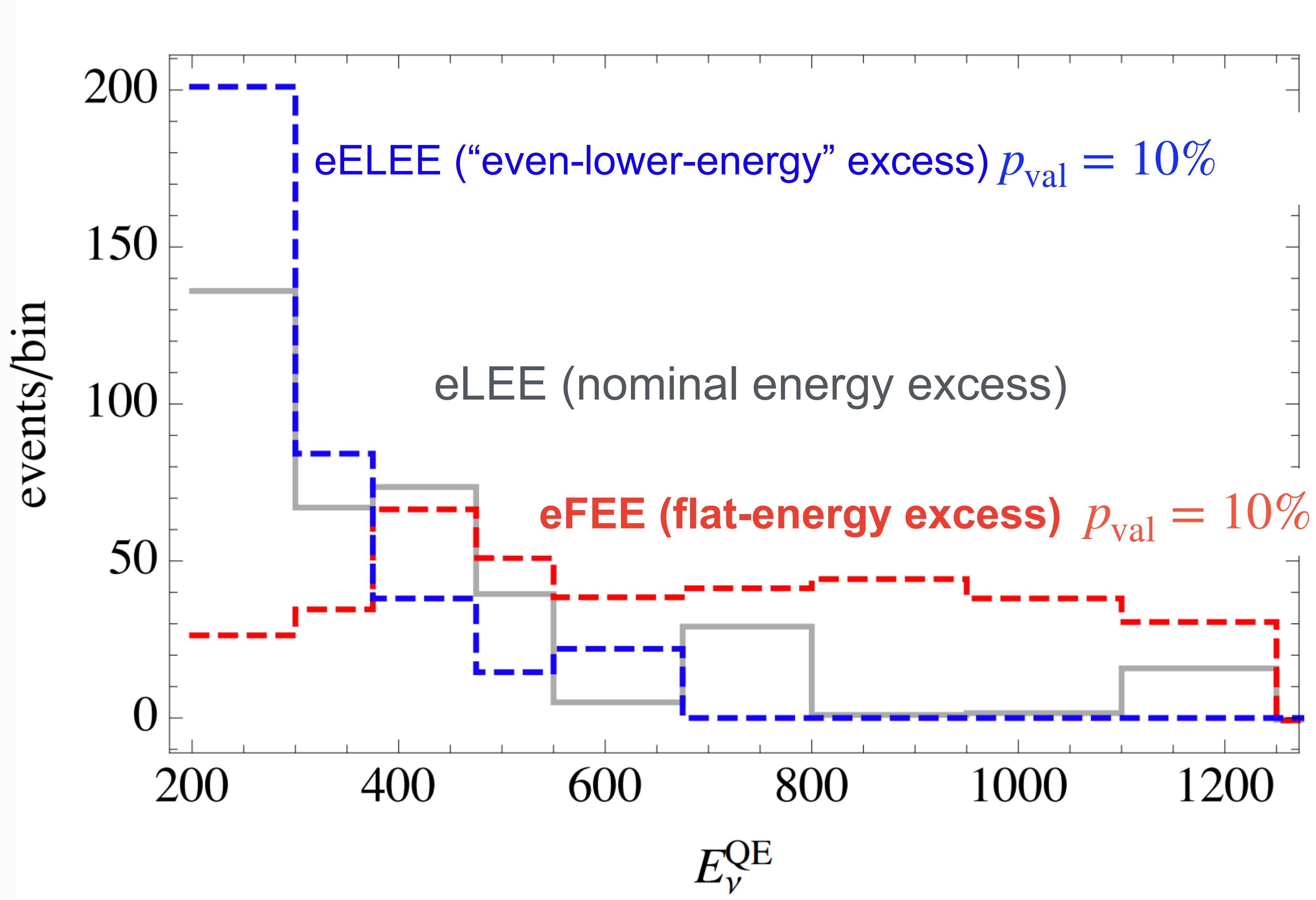
Q1

How about MiniBooNE systematics?

Interpreting the MicroBooNE results in light of MiniBooNE systematics

New templates

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



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

Interpreting the MicroBooNE results in light of MiniBooNE systematics

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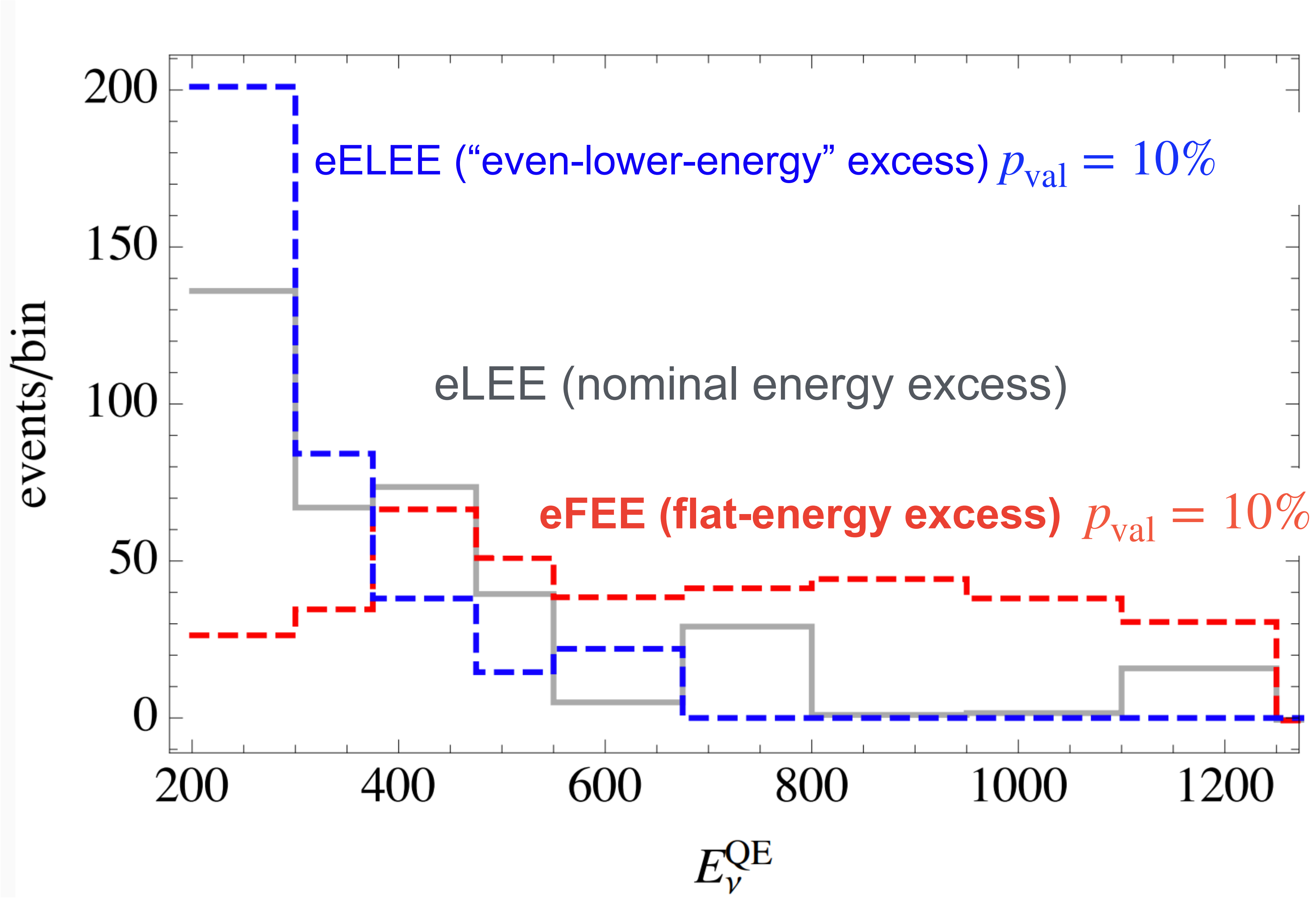

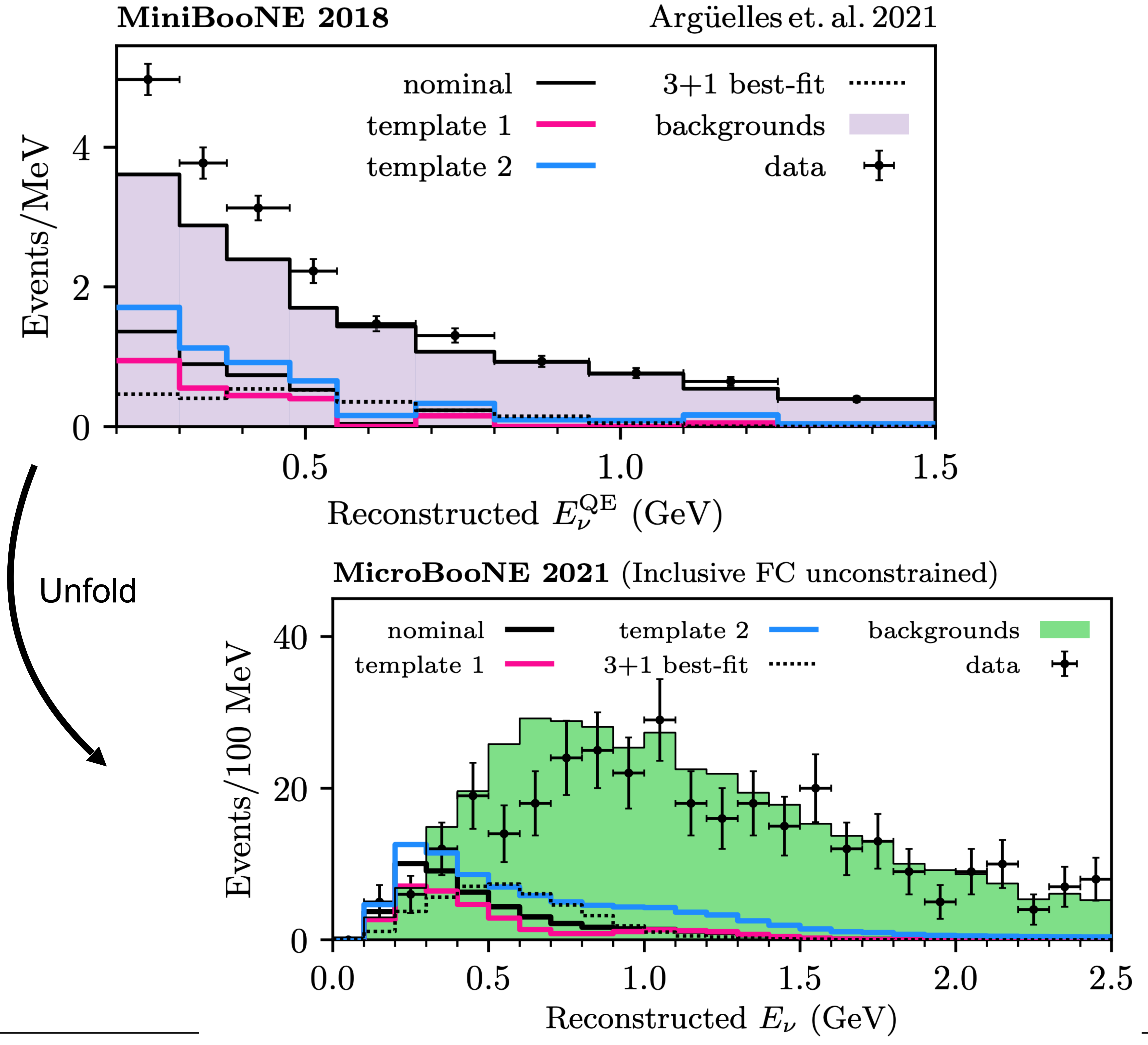

What we call “the MiniBooNE excess” is very dependent on the background systematic uncertainties

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,
4) Compute the χ^2 of the new template at MicroBooNE

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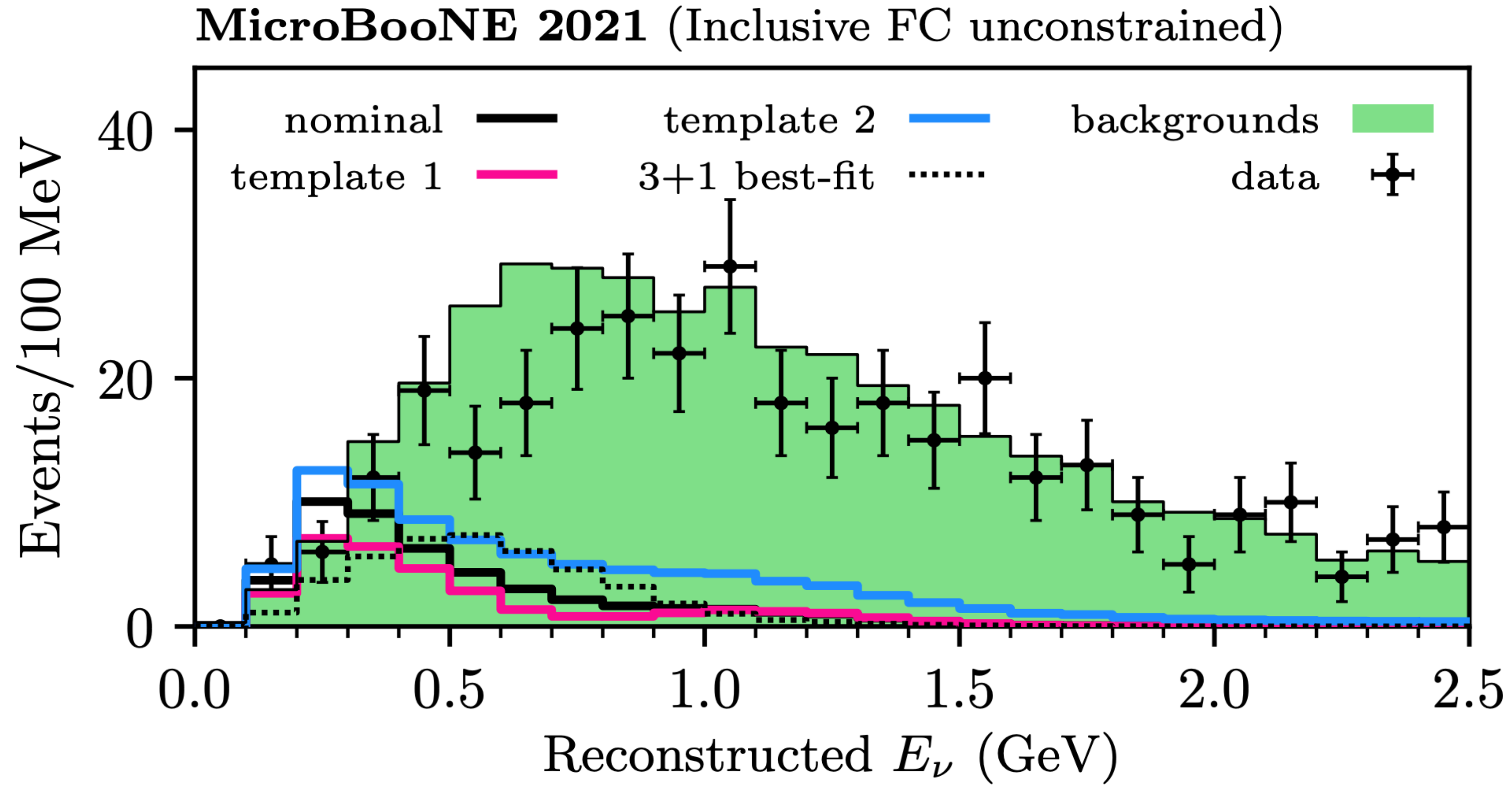
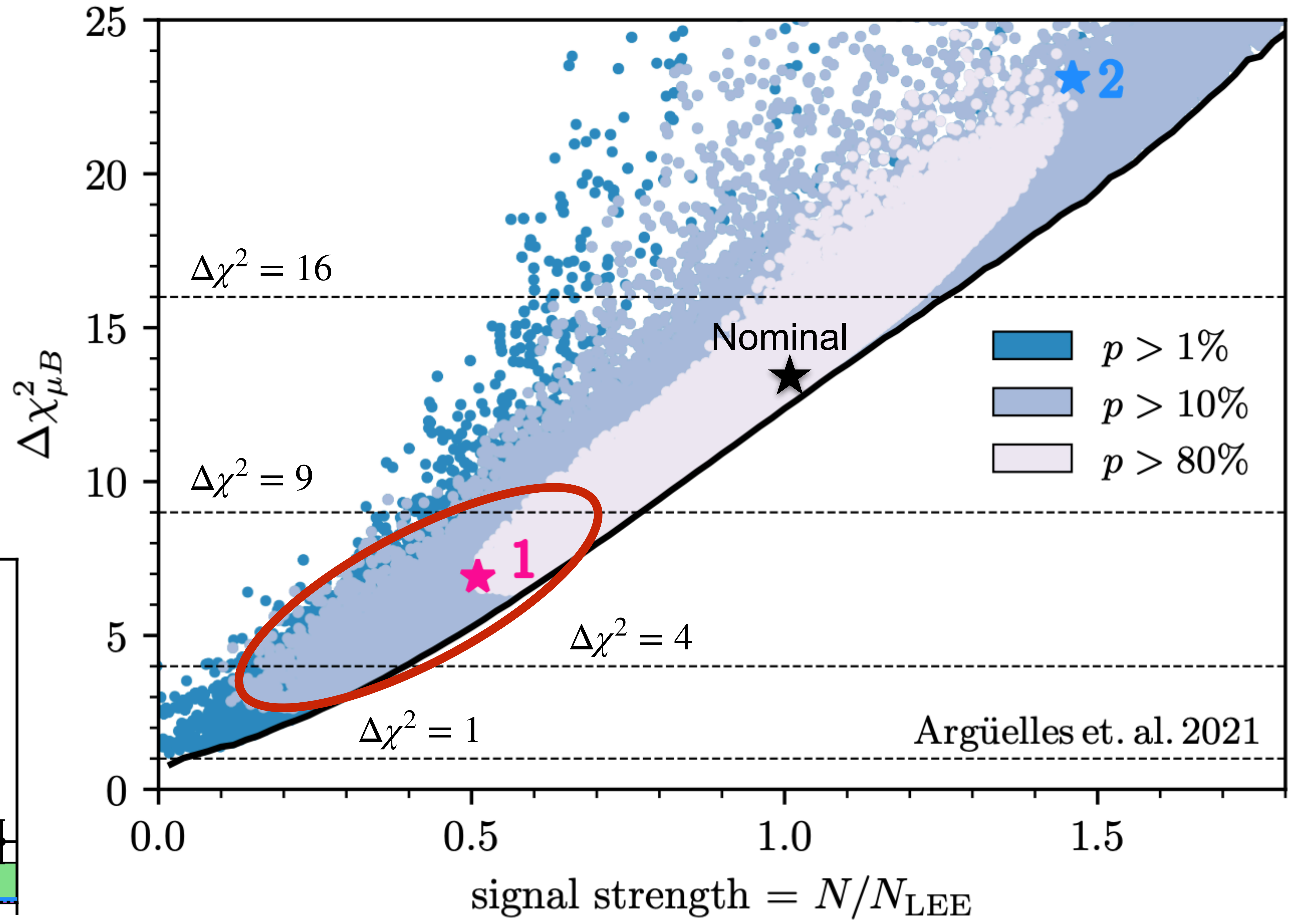




Q2

What are the limits on sterile neutrinos?

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:**

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

Inclusive

Energies ↑

Backgrounds. ↑

Statistics ↑

Intrinsics ↑

Only spectra and covariances available*

CCQE

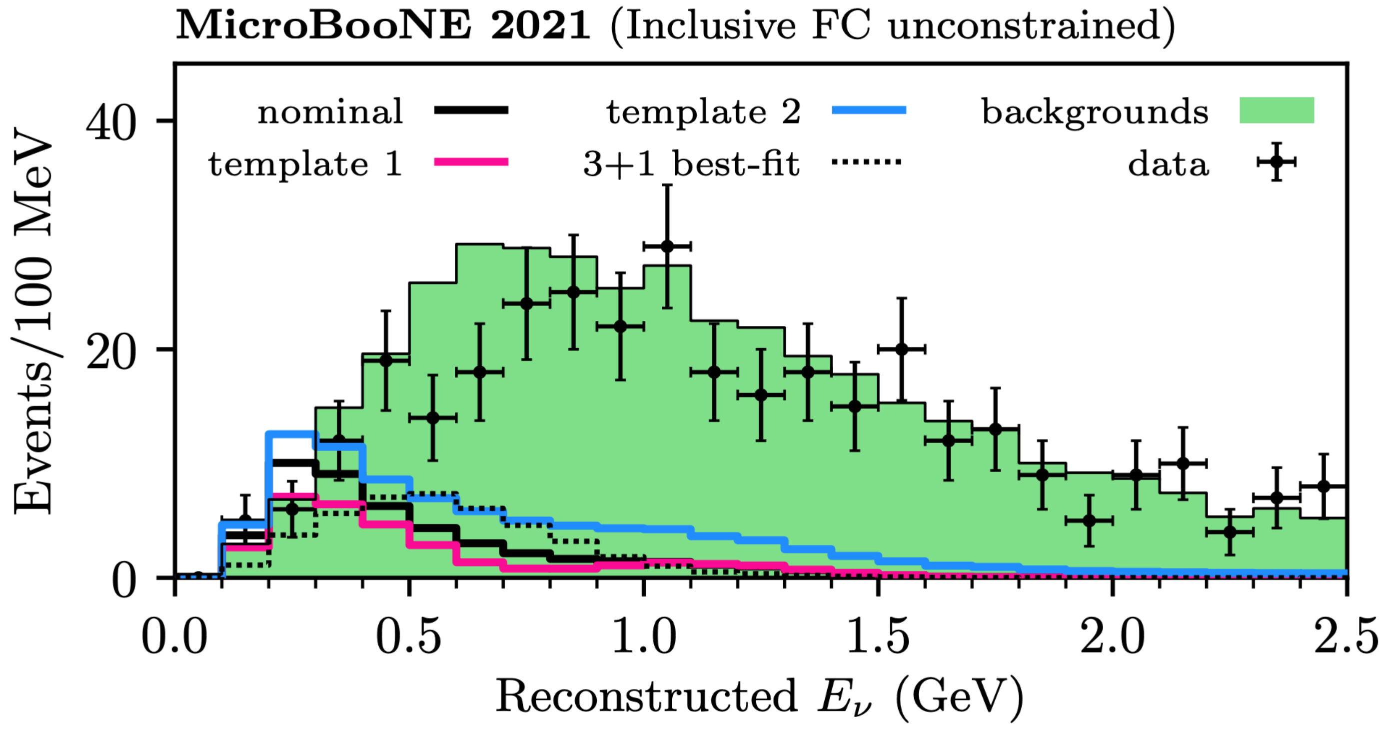
Energies ↓

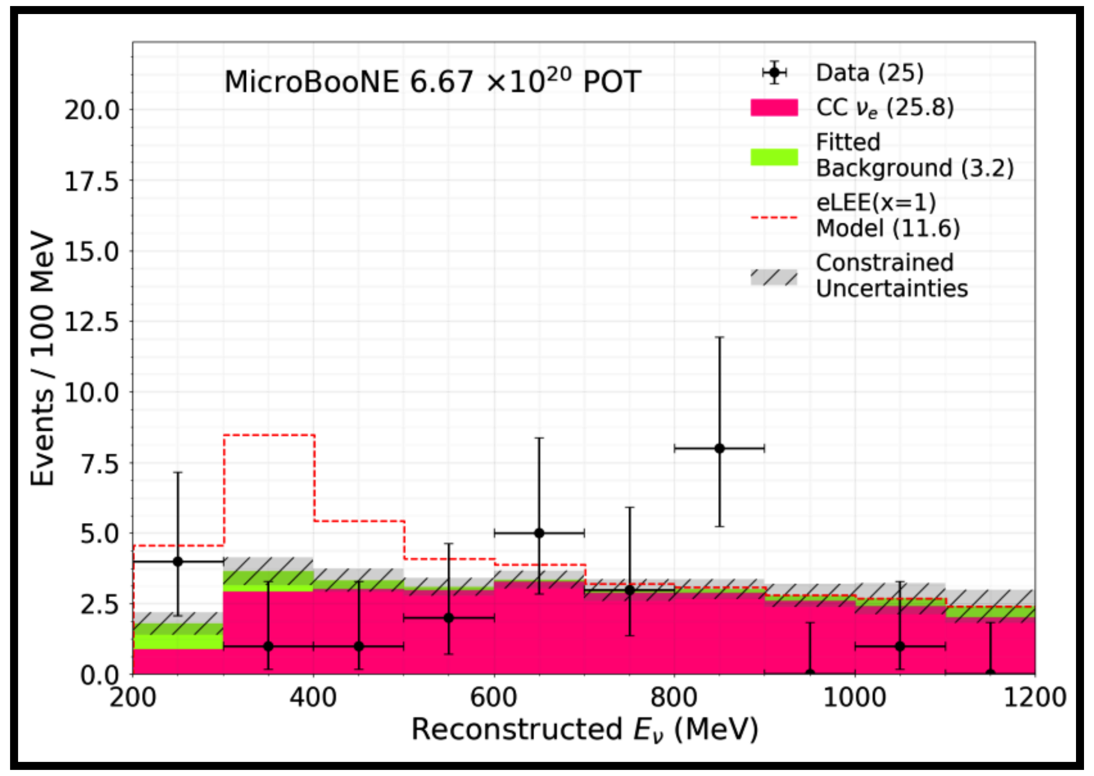
Backgrounds ↓

Statistics ↓

Intrinsics ↓

Full data release available





* efficiencies are derived from digitized smearing matrices.

Sterile neutrinos at MicroBooNE
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CCQE
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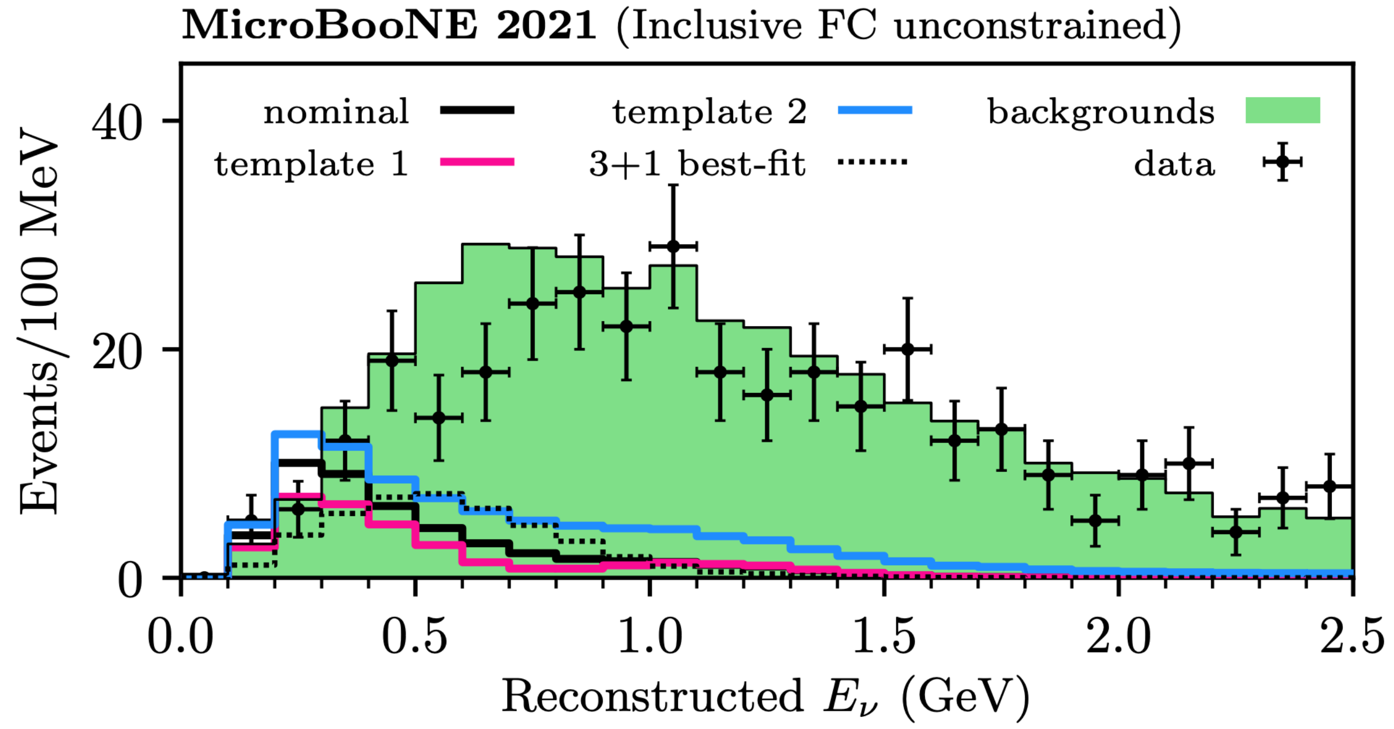

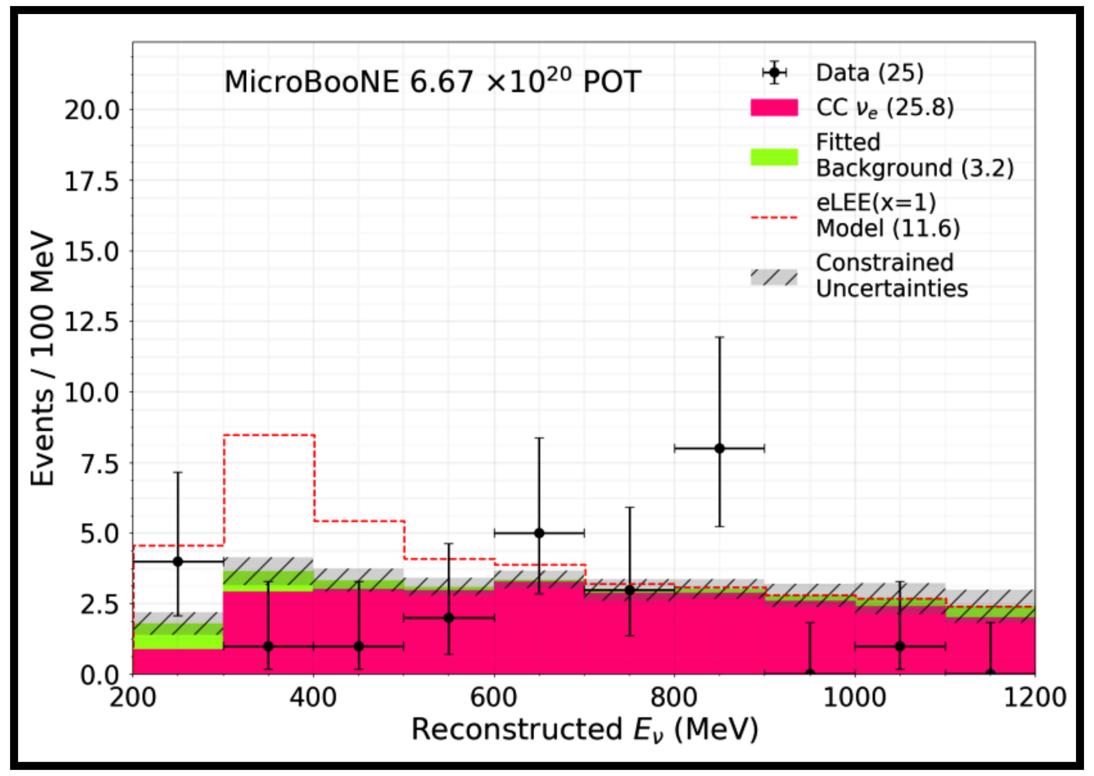

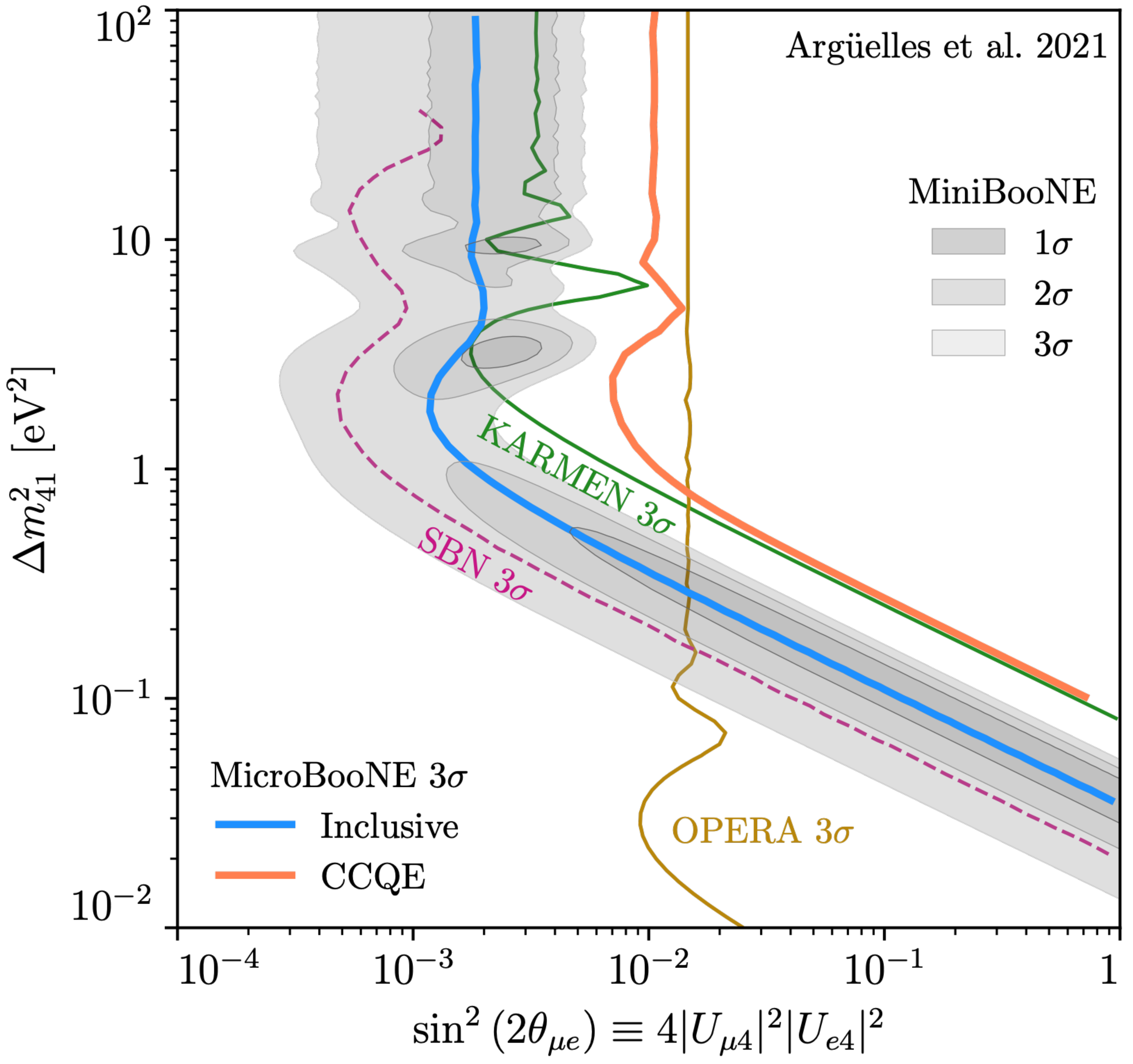

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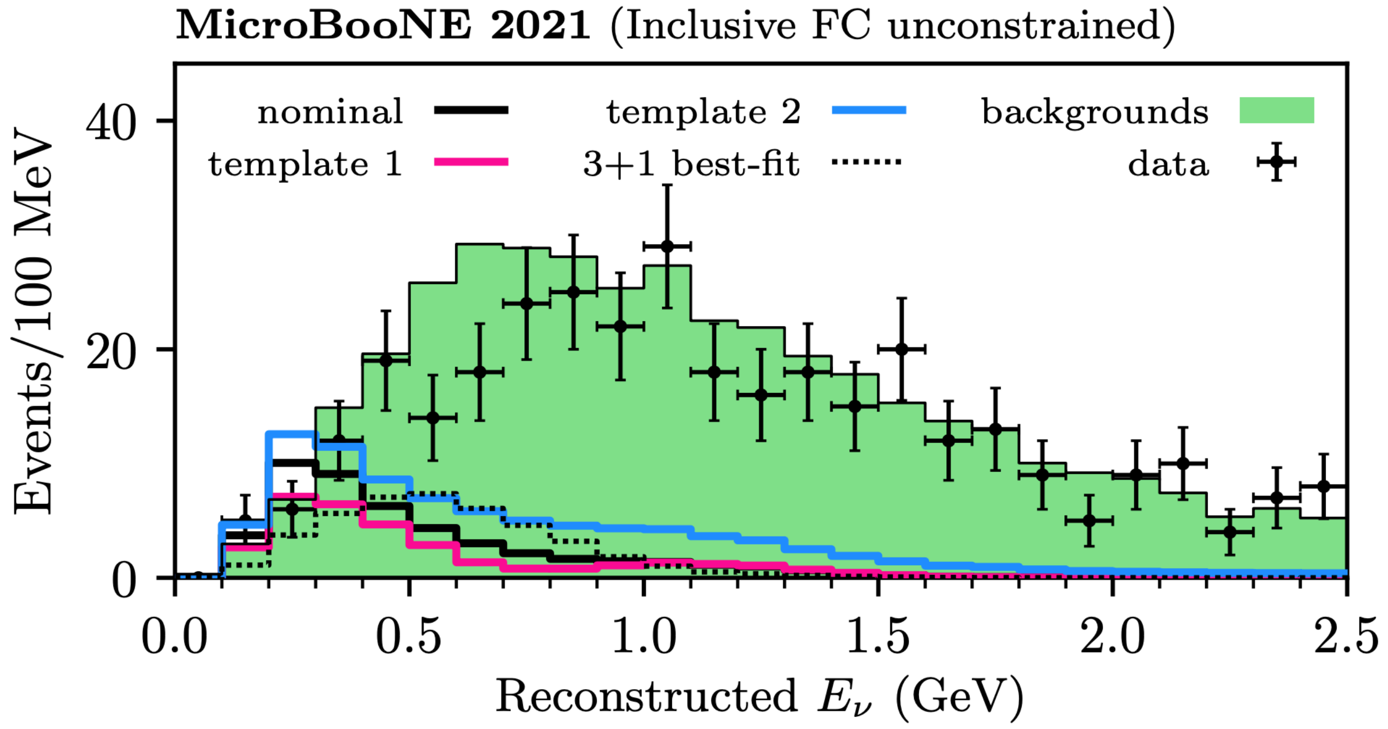
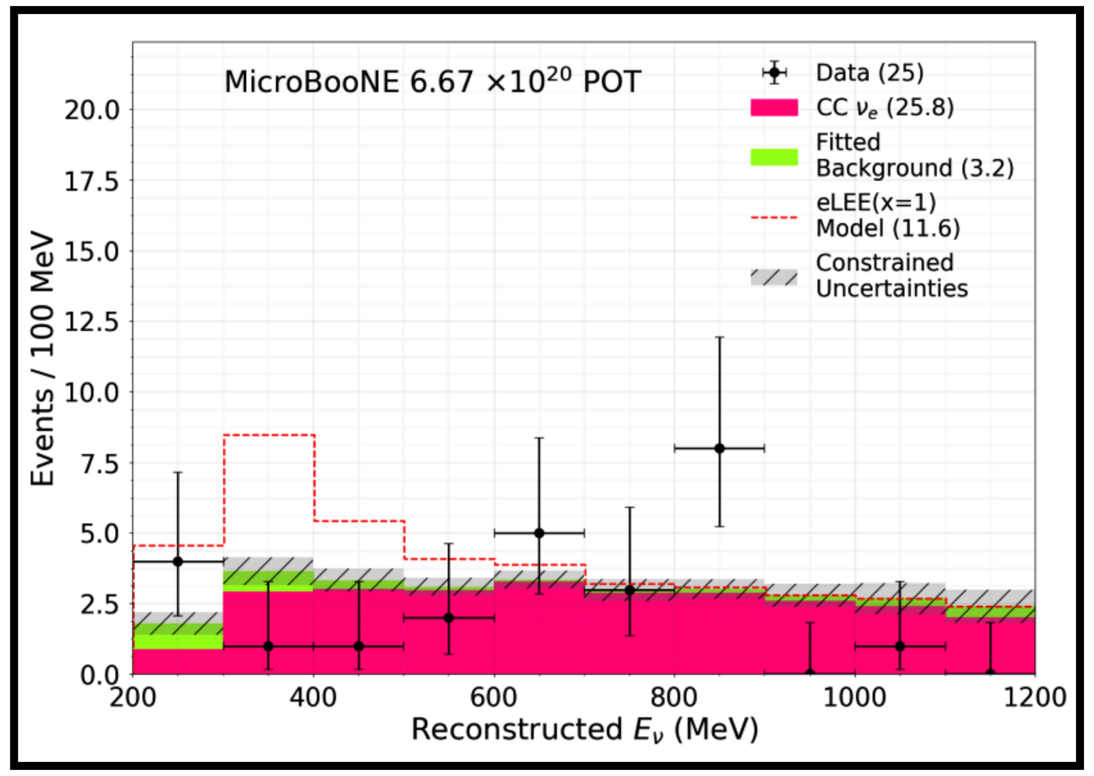
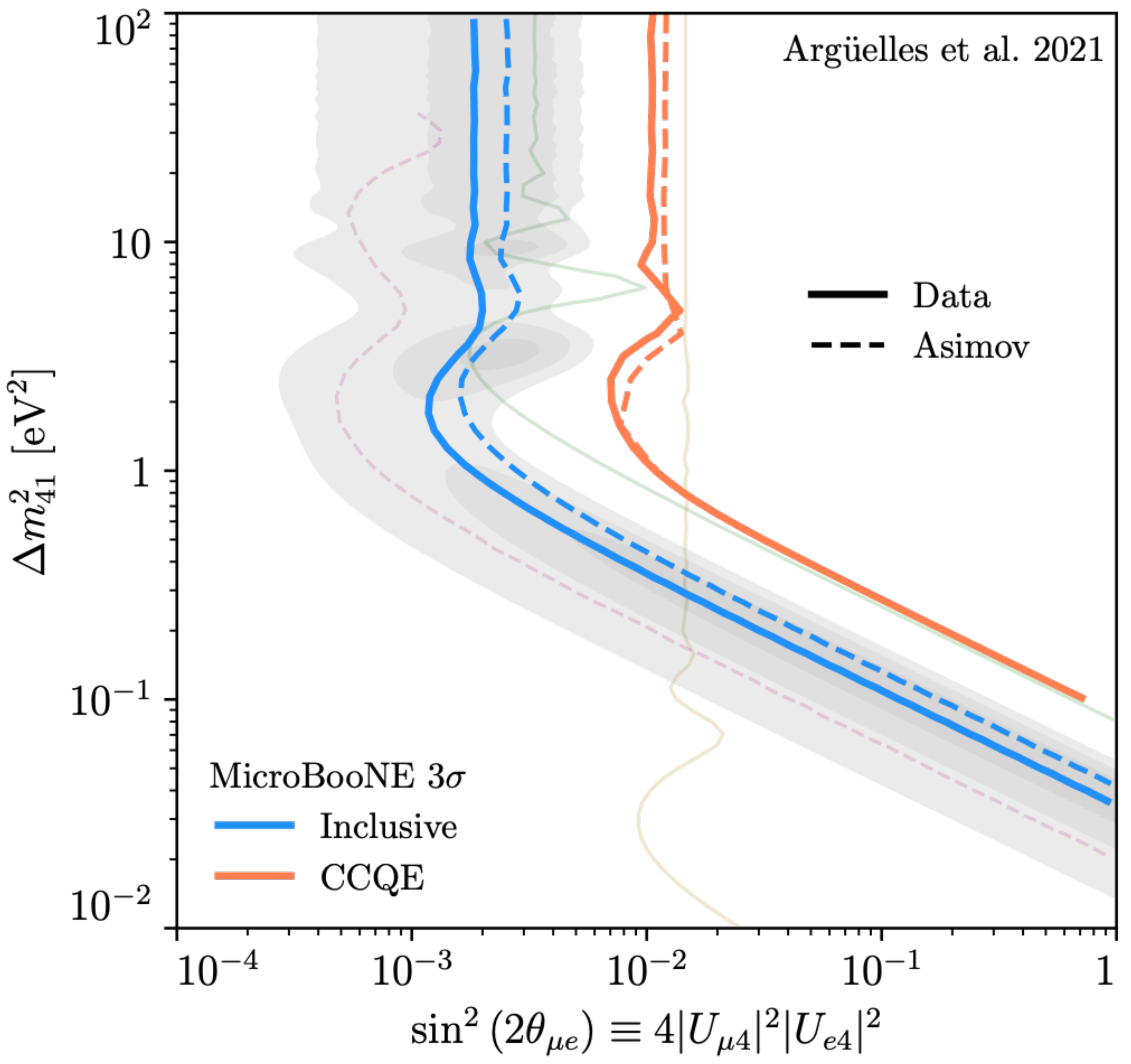




Oscillation
Sensitivity vs limit



* efficiencies are derived from digitized smearing matrices.

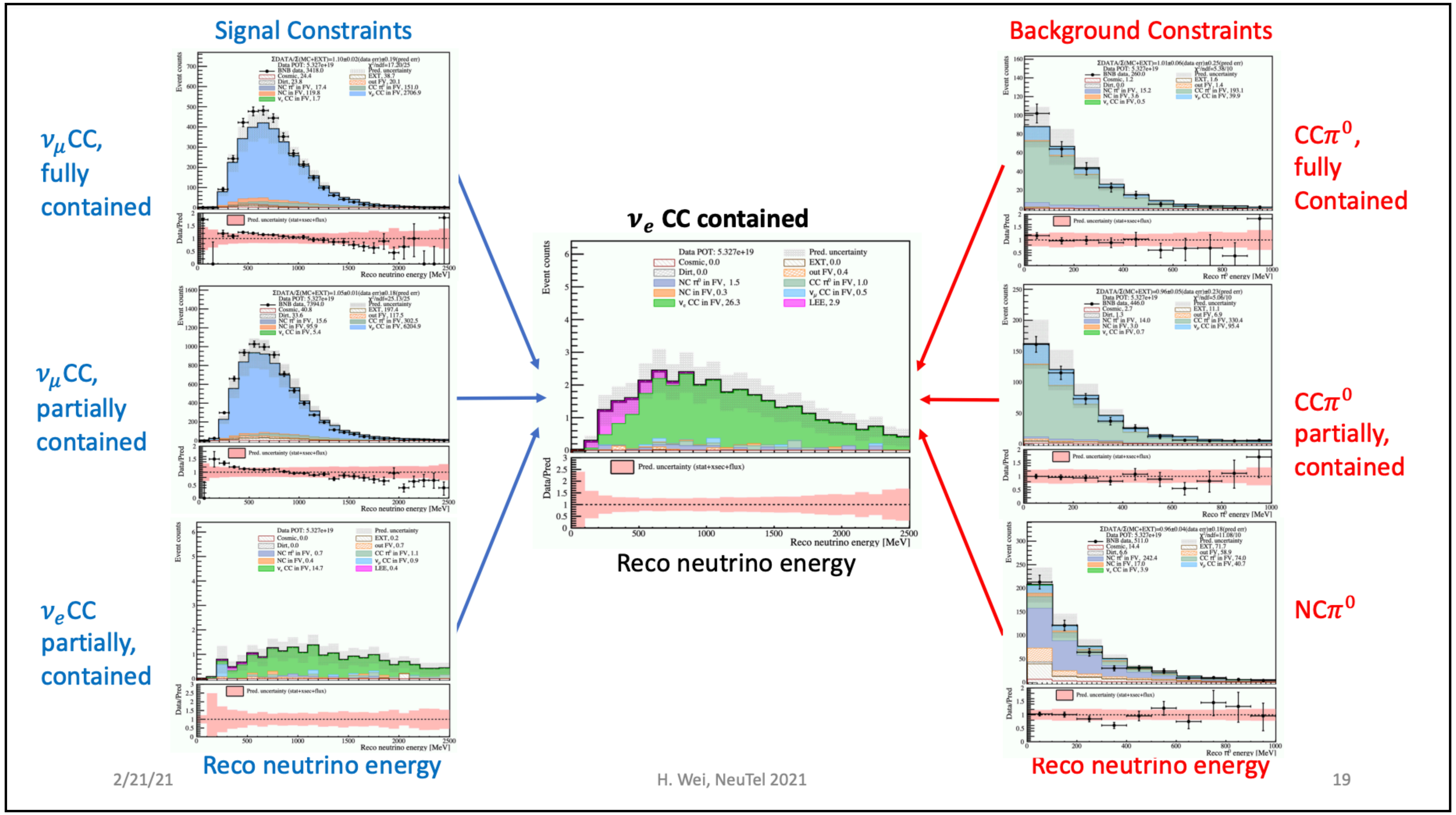
Sterile neutrinos at MicroBooNE
Fixed-background approach

A lot of samples were used to derive the final ν_e spectrum.

A consistent oscillation model can modify all of these samples due to disappearance:

$$\nu_\mu \to \nu_s$$

$$\nu_e \to \nu_s$$



Sterile neutrinos at MicroBooNE

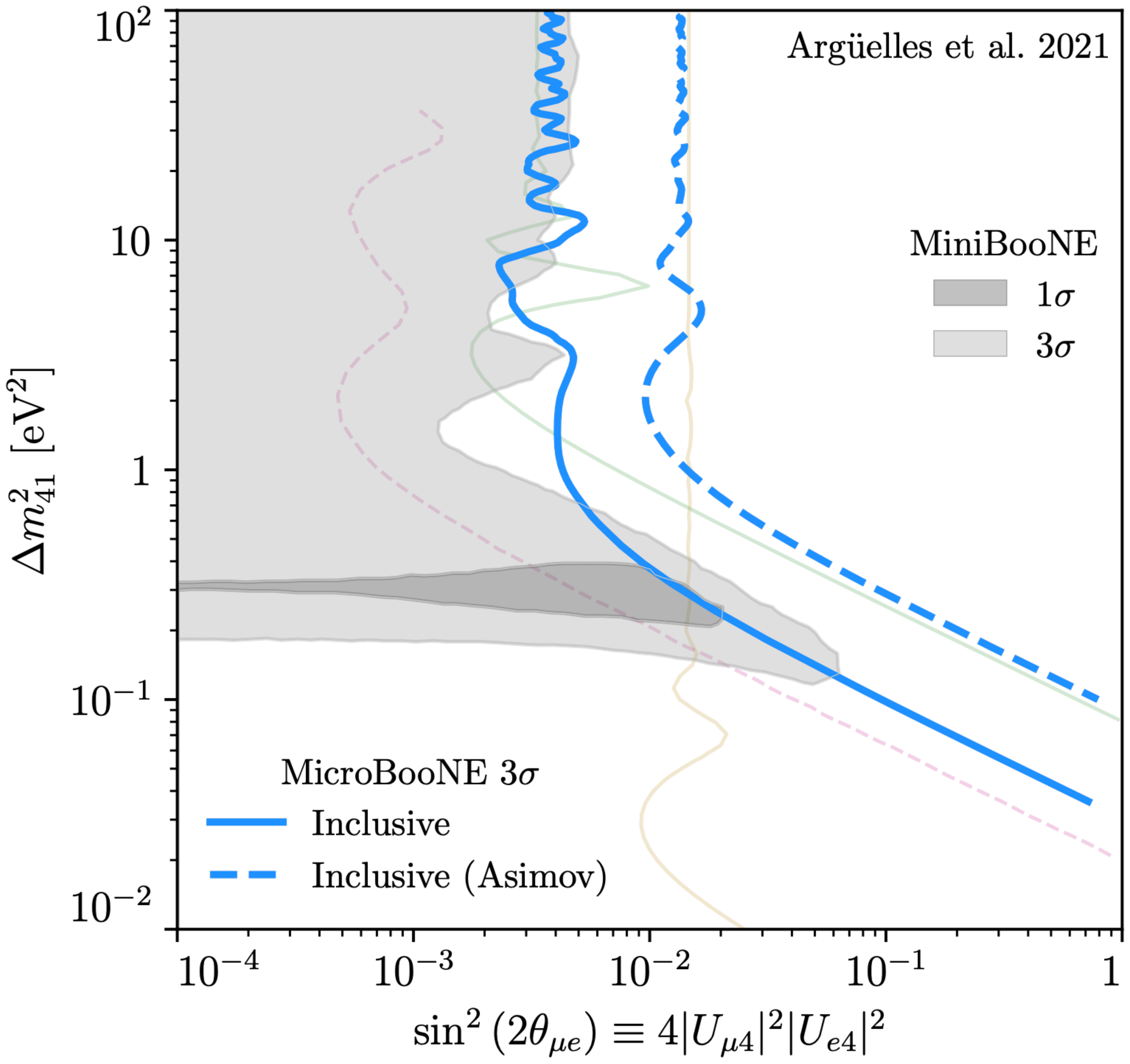
Oscillated-background approach

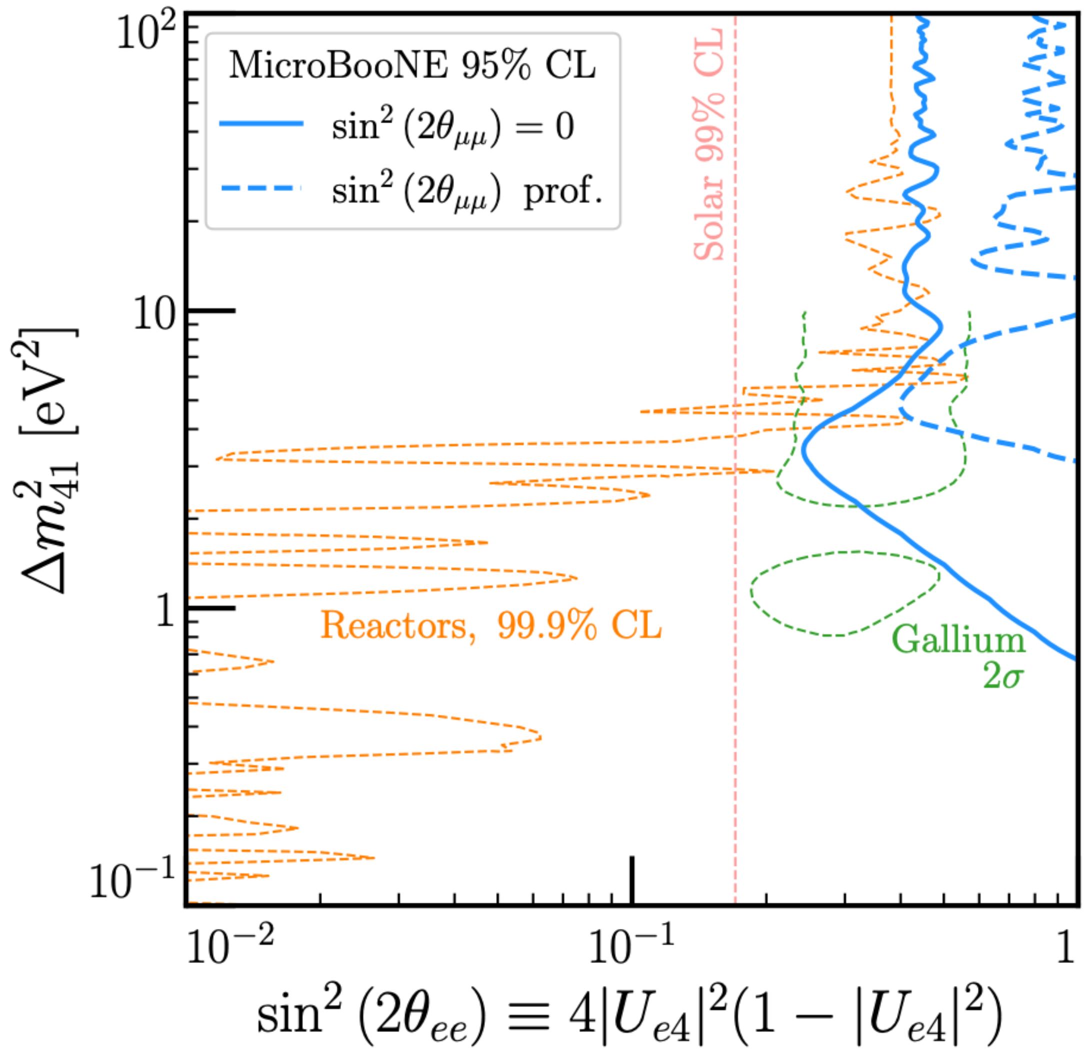
Fully consistent oscillation search:

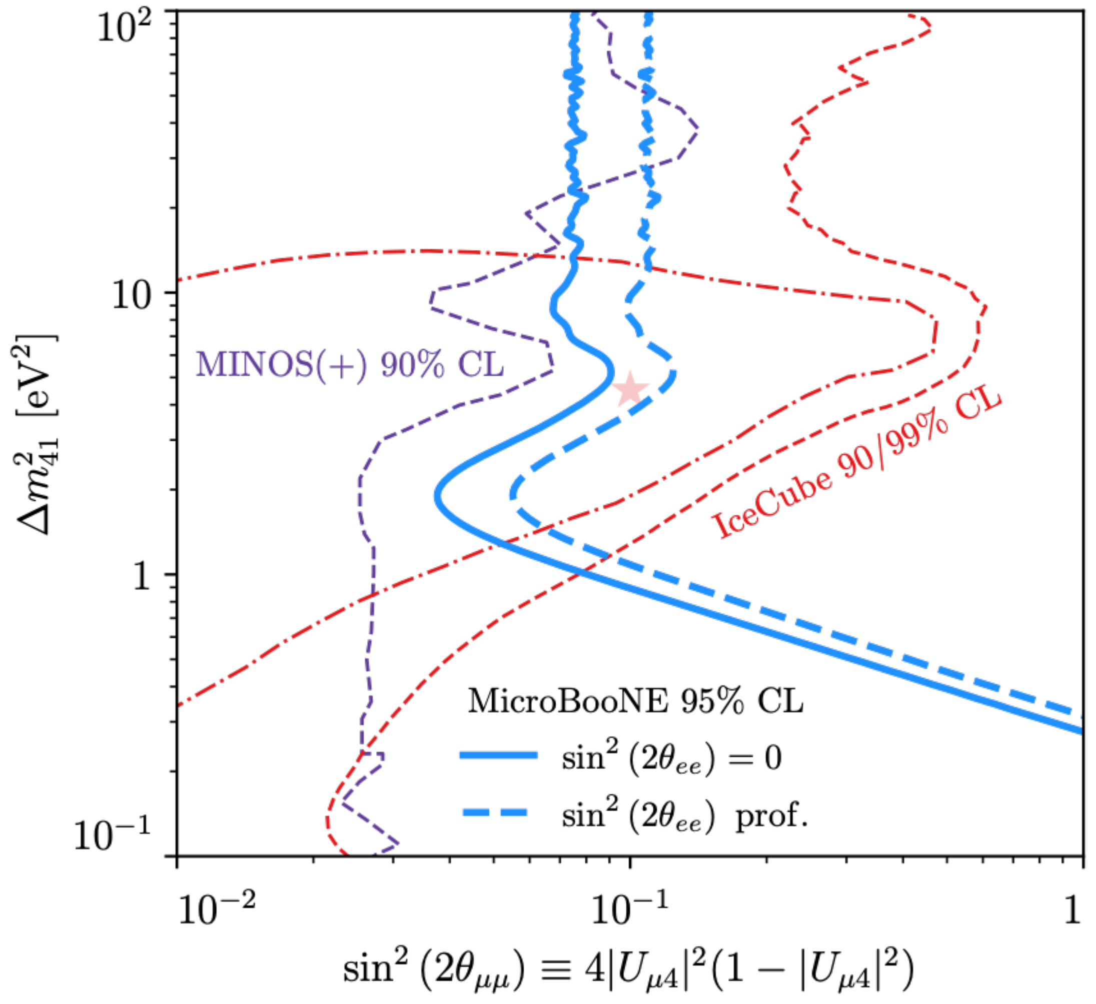
$$\nu_\mu \to \nu_\mu$$
$$\nu_\mu \to \nu_e$$
$$\nu_e \to \nu_e$$

Backgrounds are "oscillated".

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







Sterile neutrinos at MicroBooNE

"Joint fit" of MiniBooNE and MicroBooNE

MiniBooNE coll., **arXiv:2201.01724**

To properly assess the impact of MicroBooNE on steriles, we need a "joint fit" w/

MicroBooNE + MiniBooNE data.

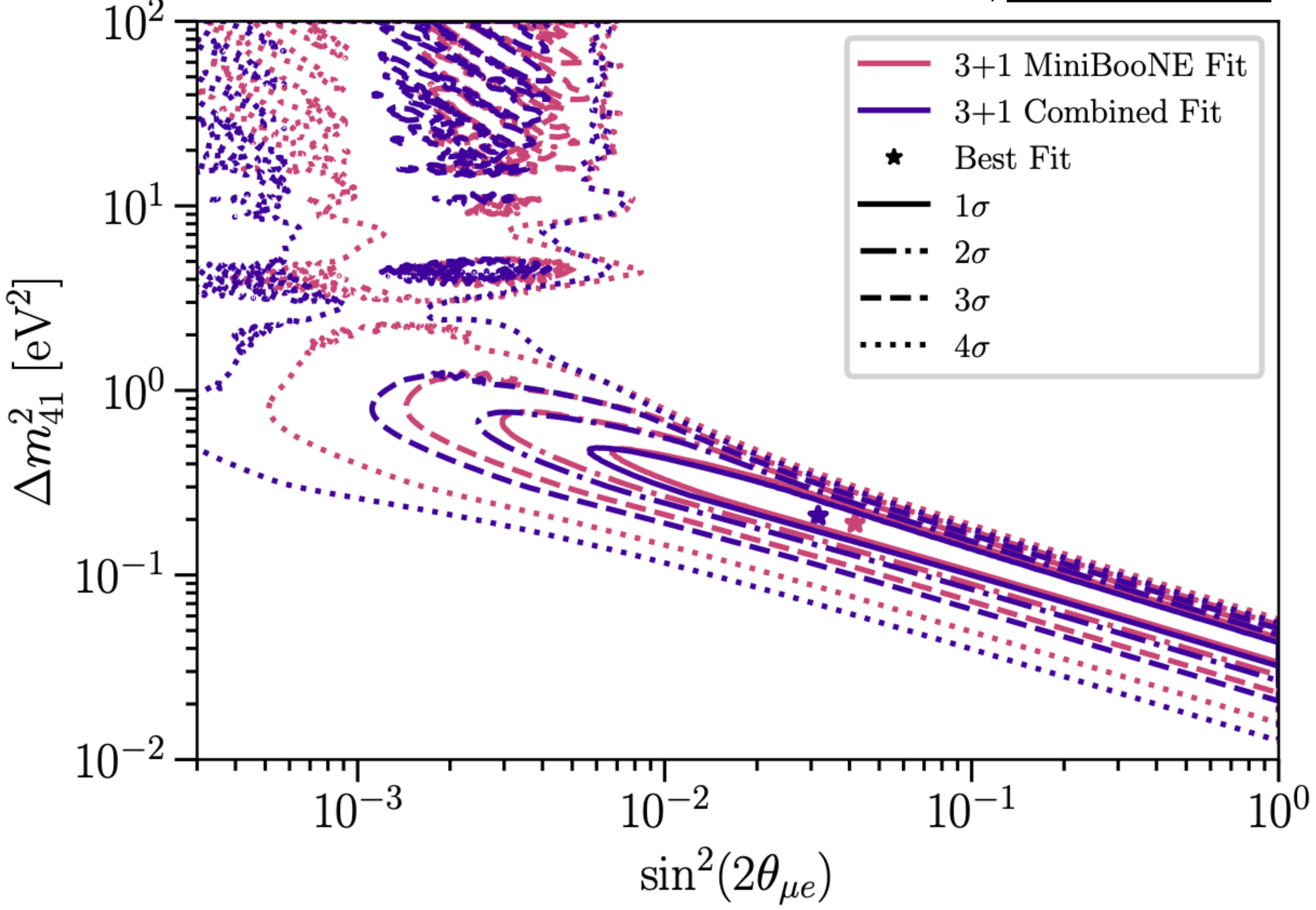
A "joint fit" performed by MiniBooNE collaboration, using MicroBooNE's CCQE data (the less sensitive one).

Suggests that MicroBooNE's data does **not** have a big impact on the MiniBooNE regions of preference.

No correlations included.

This is important (same beam, "similar" cross sections).

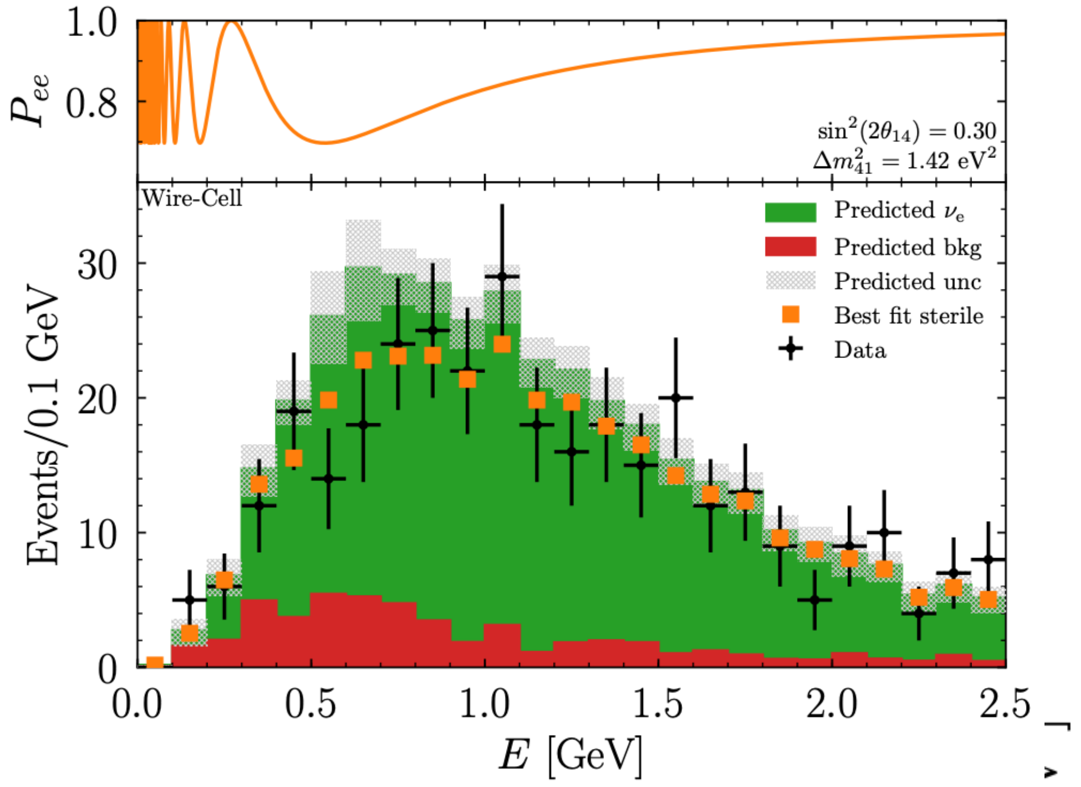
MiniBooNE coll., **arXiv:2201.01724**



Sterile neutrinos at MicroBooNE
Oscillated-background approach

Can the deficit of ν_e events at MicroBooNE
be interpreted as evidence for ν_e disappearance?

P. Denton, arXiv:2111.05793



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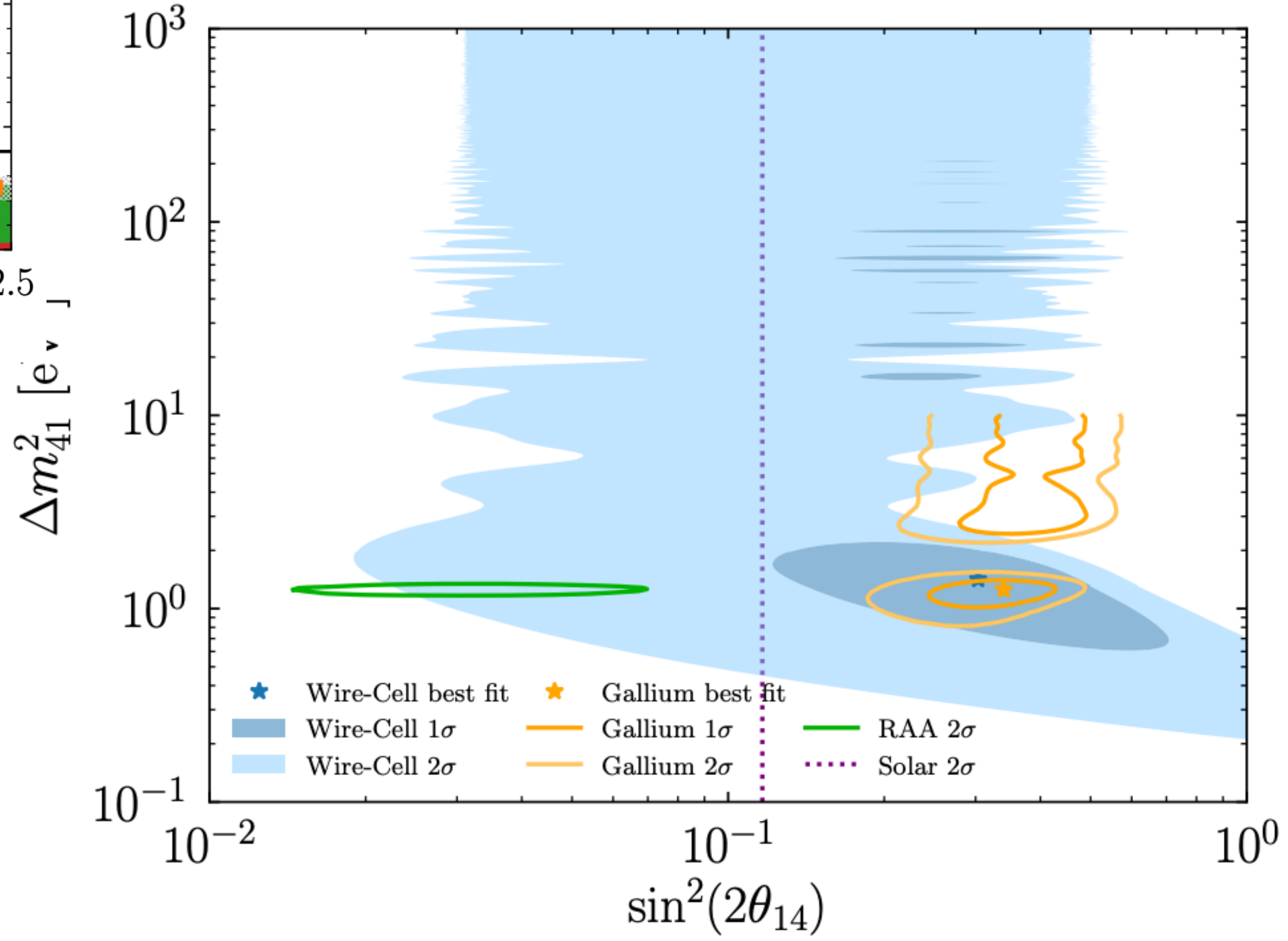

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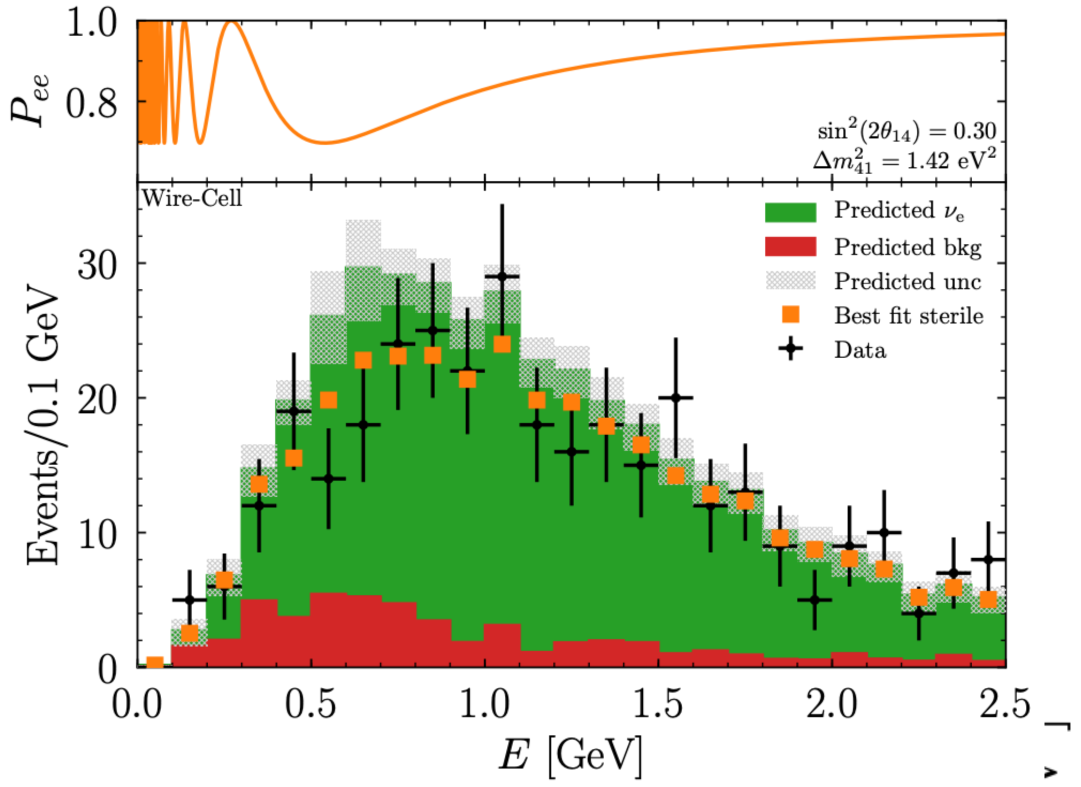

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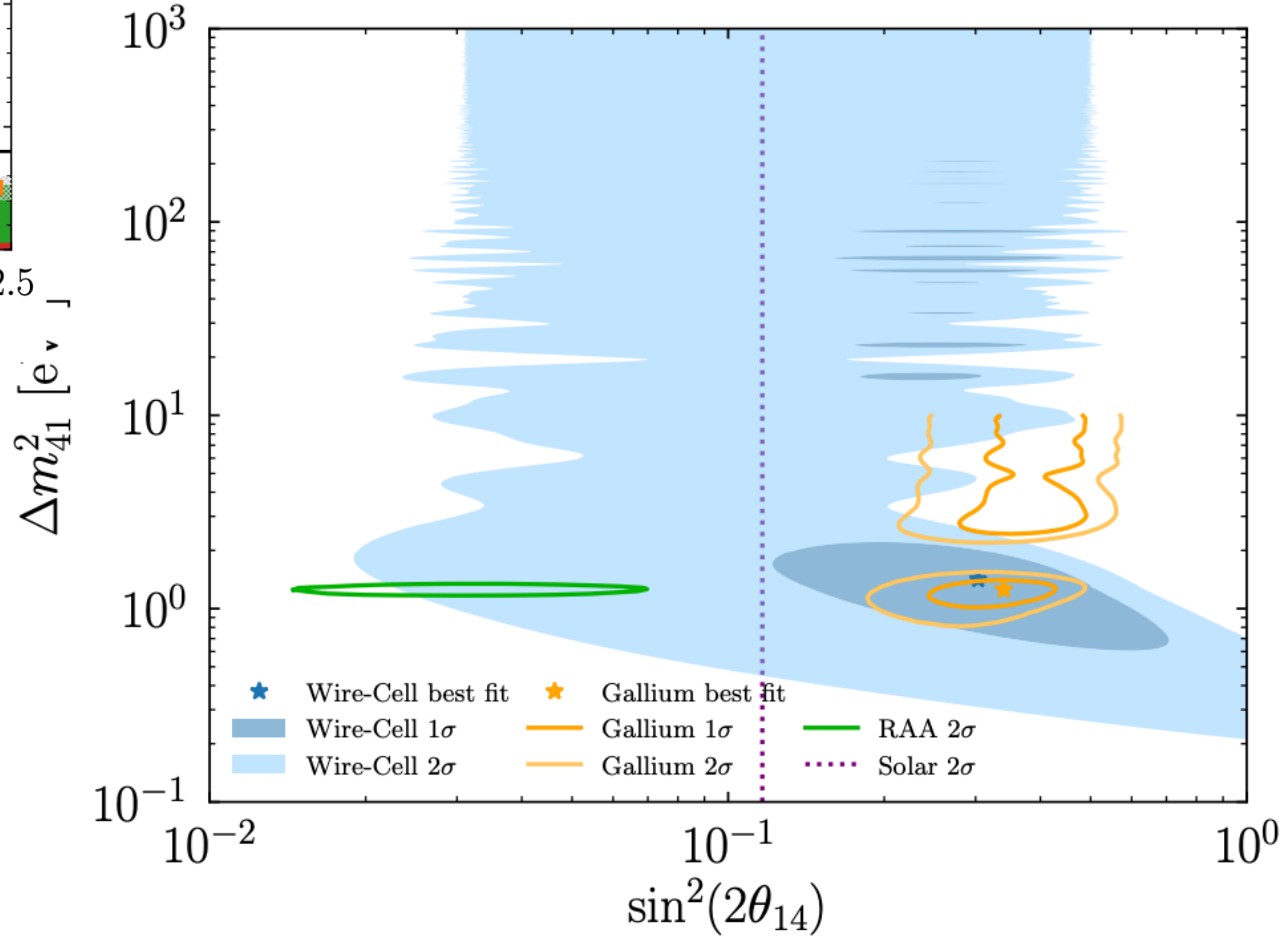
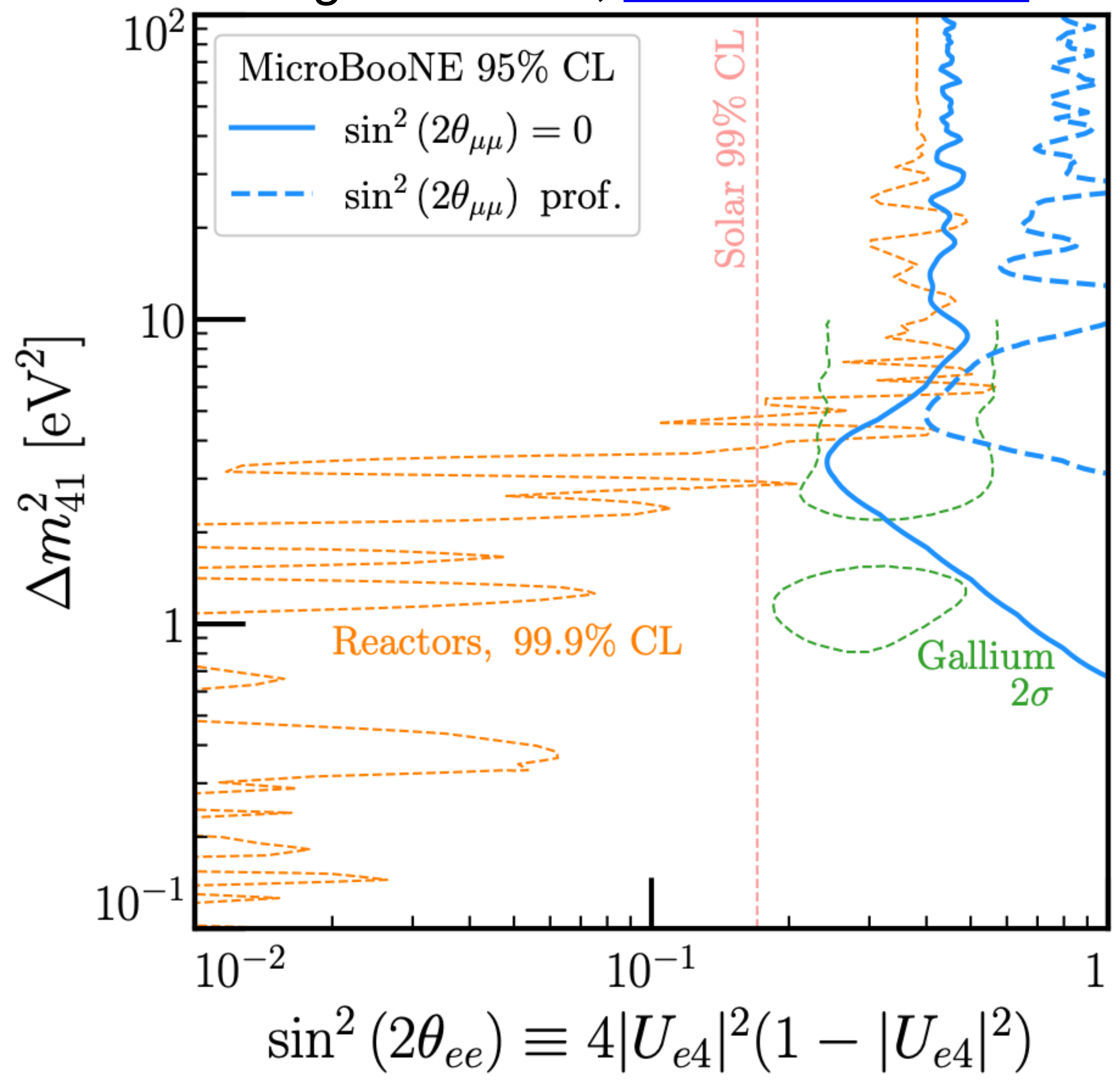


Argüelles et al, arXiv:2111.10359



Our best-fit point is

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

with a significance of 0.95σ.

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

The discrepancy with P. Denton may arise from:

i) Including all "side-band" samples and *their correlations*
ii) Implementing detector smearing consistently

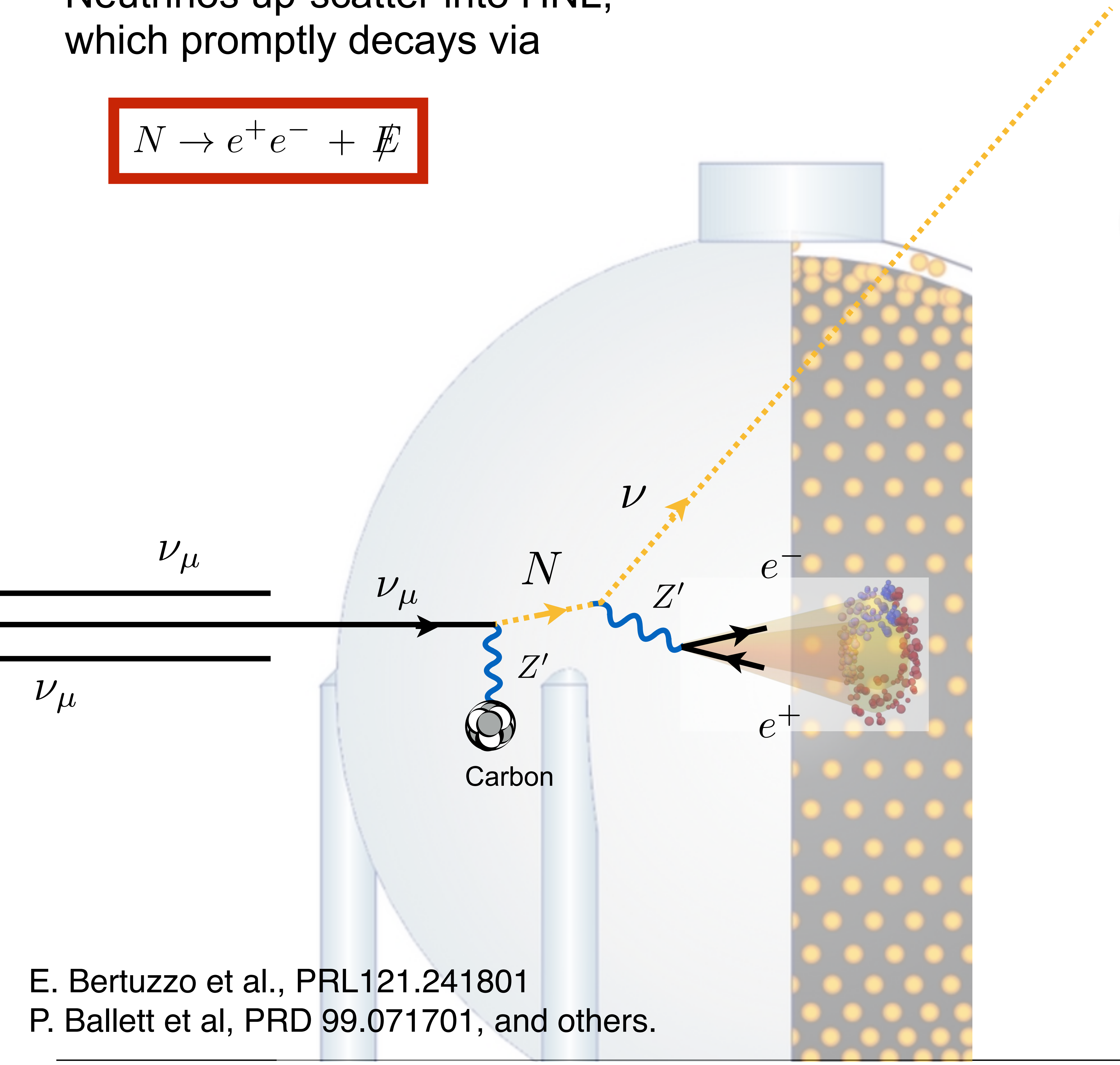
Q3

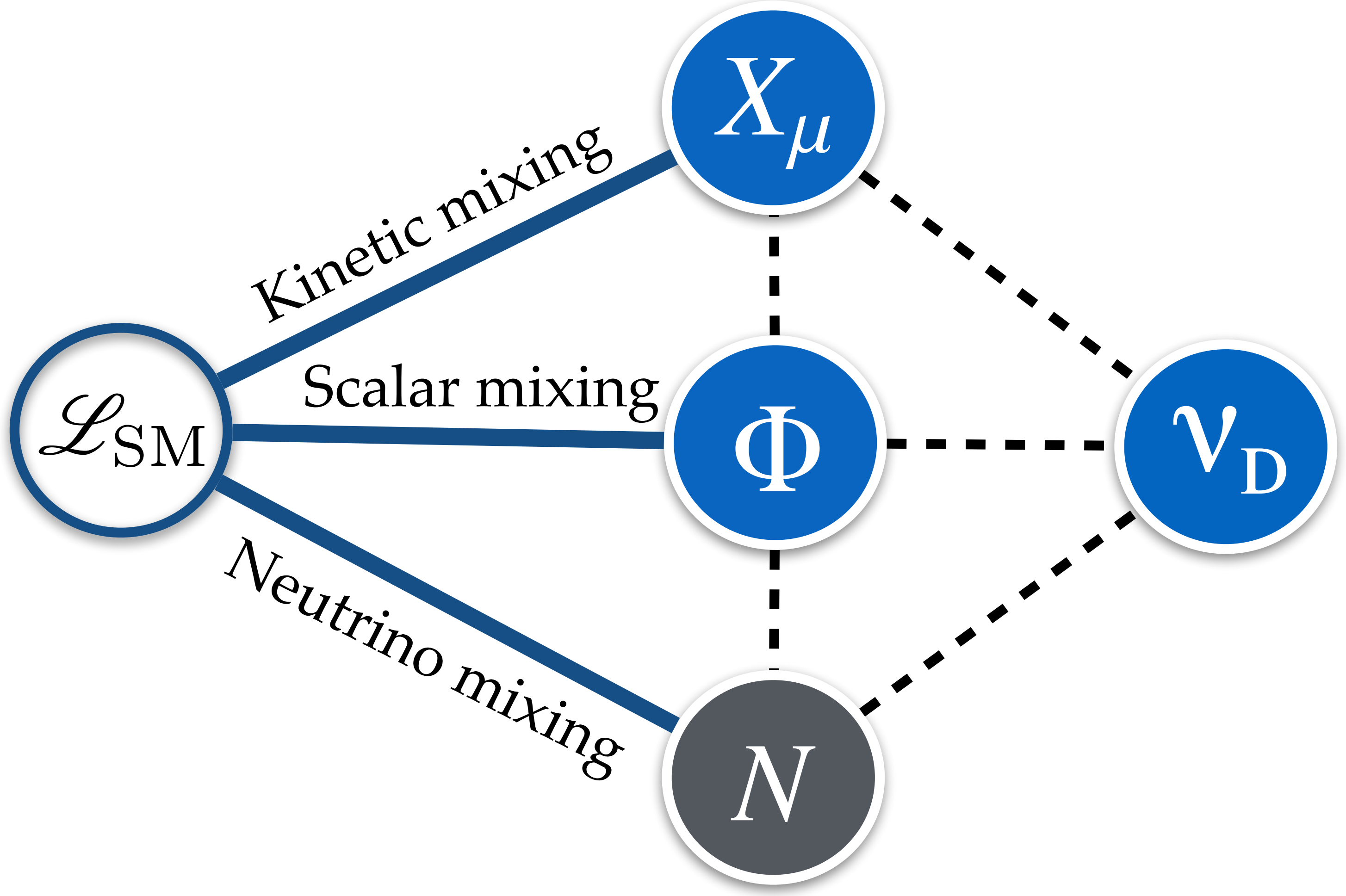
Are all explanations disfavored?

Dark neutrino sectors
Heavy neutrinos interacting via the dark photon

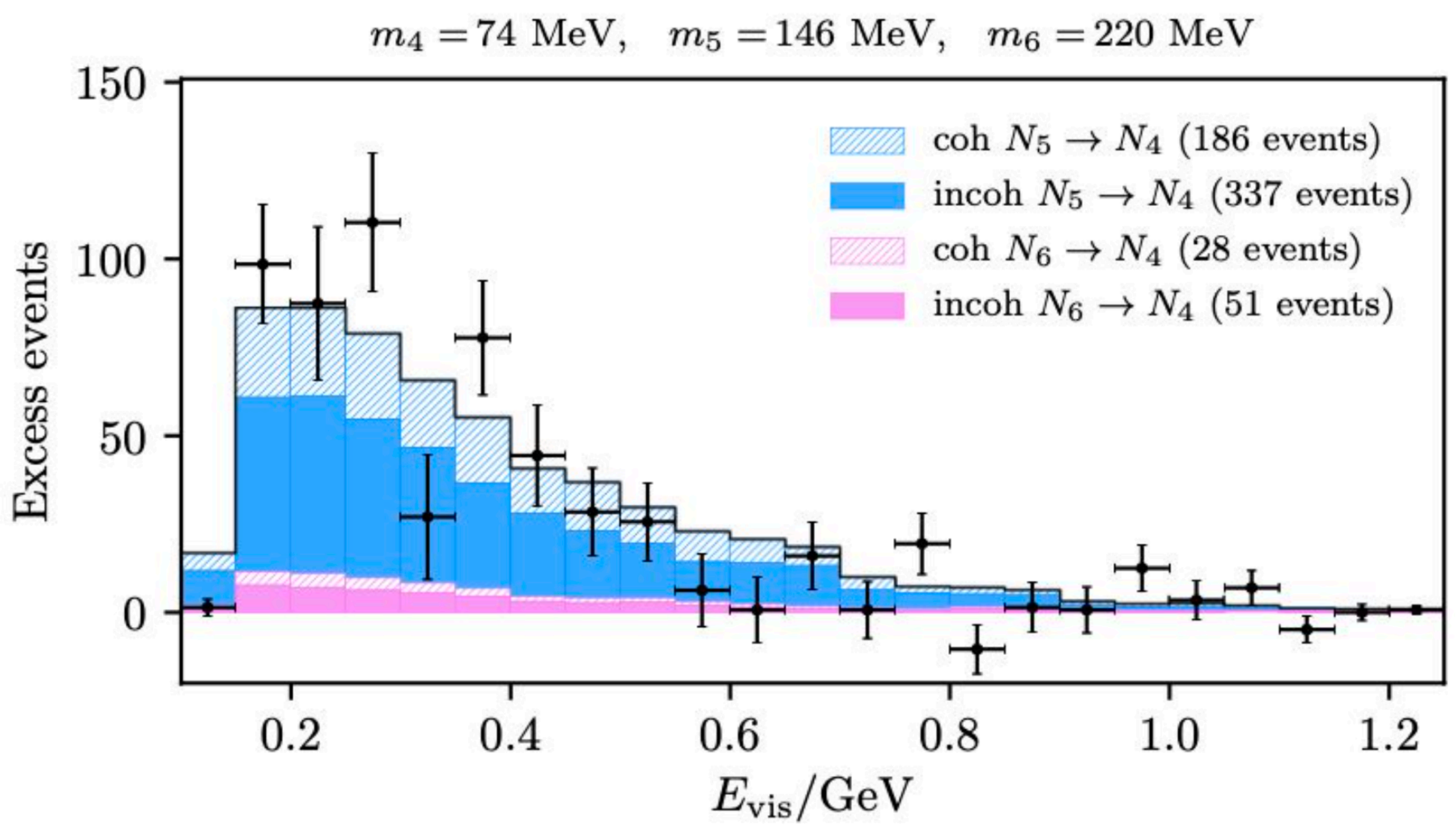
Neutrinos up-scatter into HNL, which promptly decays via

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





A. Abdullahi, MH, S. Pascoli, arXiv:2007.11813



E. Bertuzzo et al., PRL121.241801
P. Ballett et al, PRD 99.071701, and others.

Dark neutrino sectors

Heavy neutrinos interacting via the dark photon

A. Abdullahi, J. Hoefken, MH, D. Massaro, S. Pascoli, *in progress*

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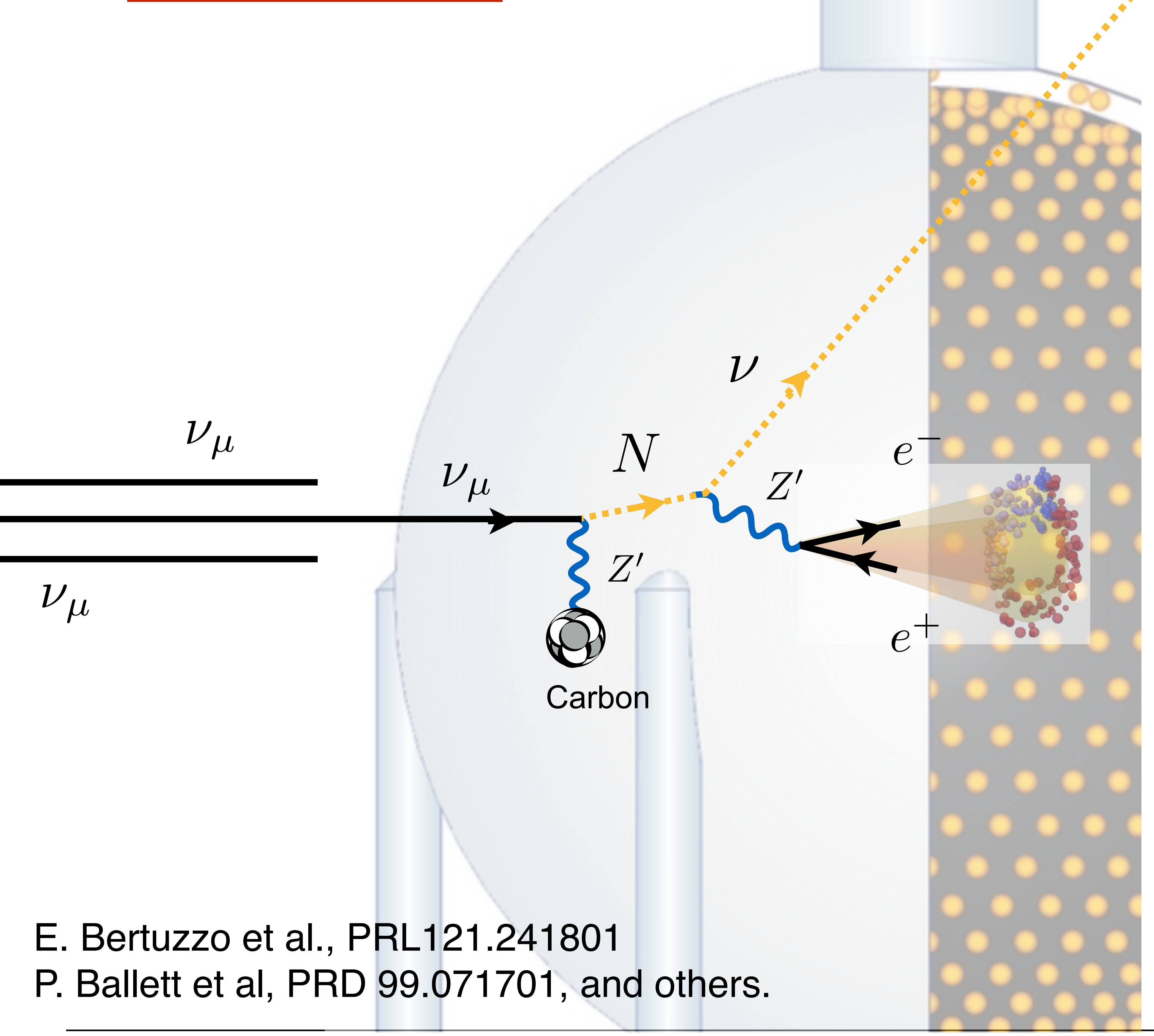
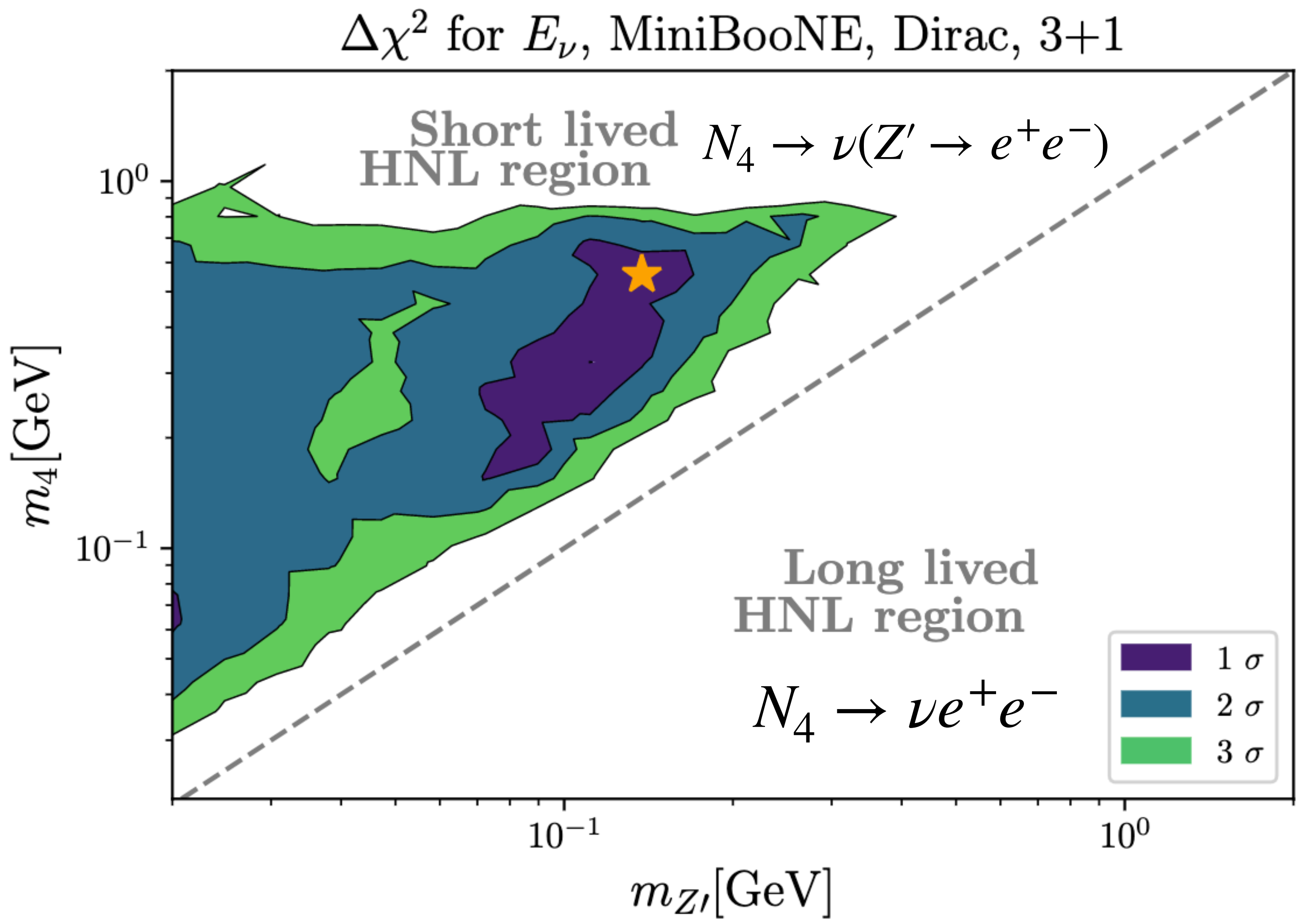
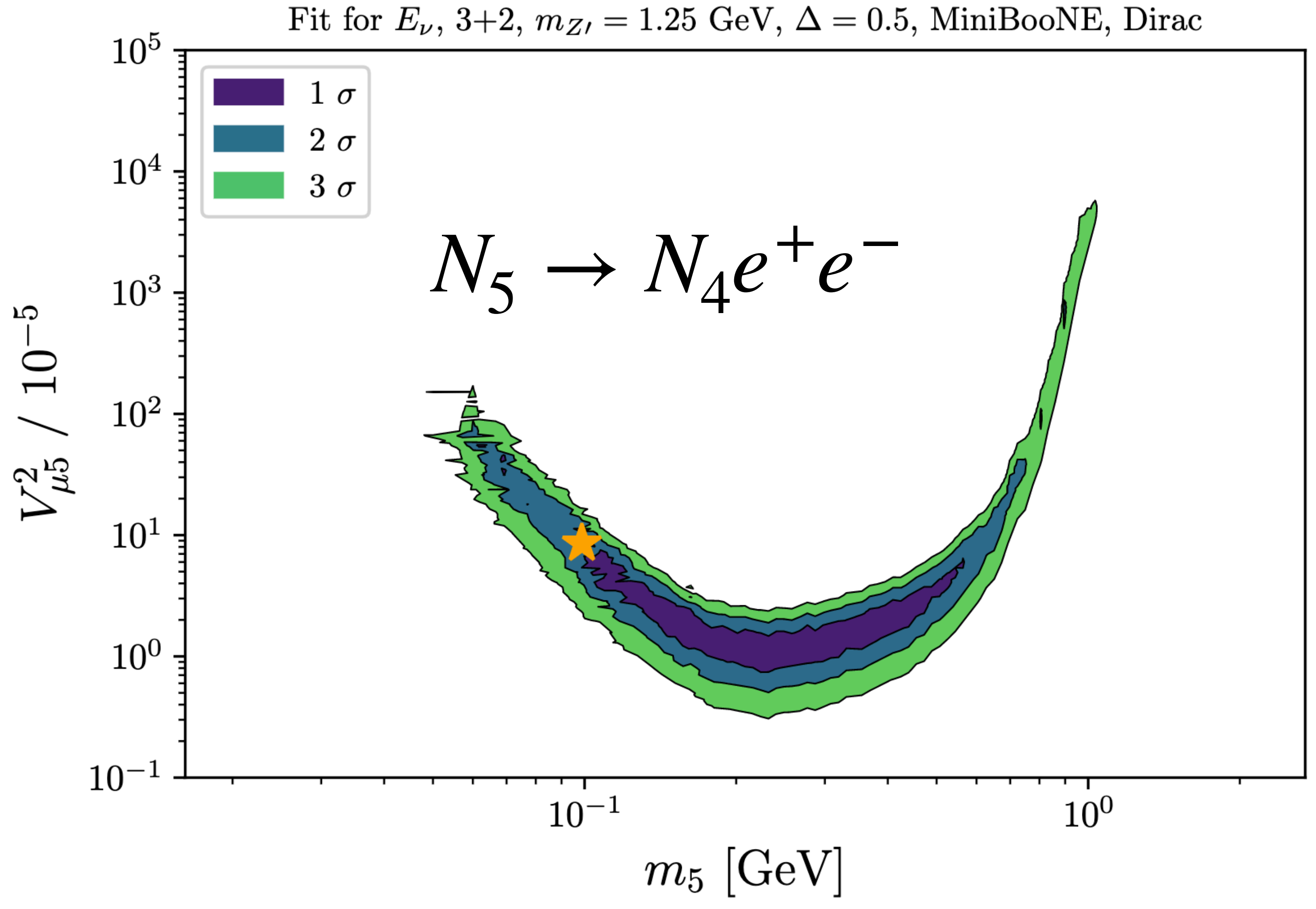


Upcoming: dedicated MC generator for new physics in neutrino-nucleus scattering





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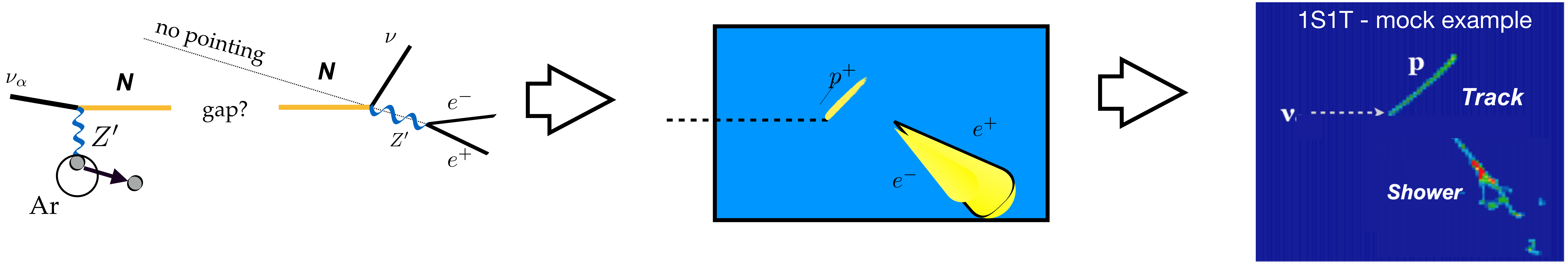
MicroBooNE searches for e+e-

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.



1S0T	2S0T
1S1T	2S1T

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 remains unexplained.

For the first time, MicroBooNE has shed light on the origin of the excess in a LArTPC.

While a significant result, MicroBooNE still does not rule out most explanations to the MiniBooNE excess (including $\nu_\mu \to \nu_e$ oscillations).

Other models still untested,
including e+e- pairs, single (coherent) photons, and other ν_e models.

Thank you!