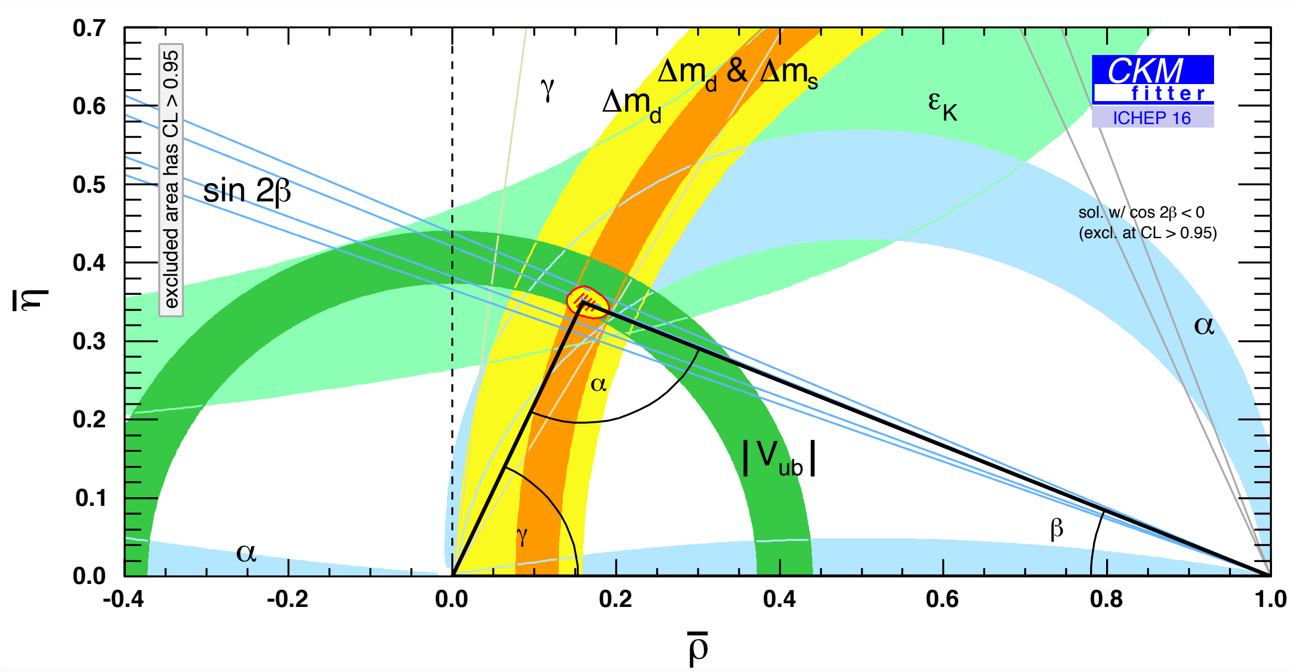
Are there more than three neutrino species?

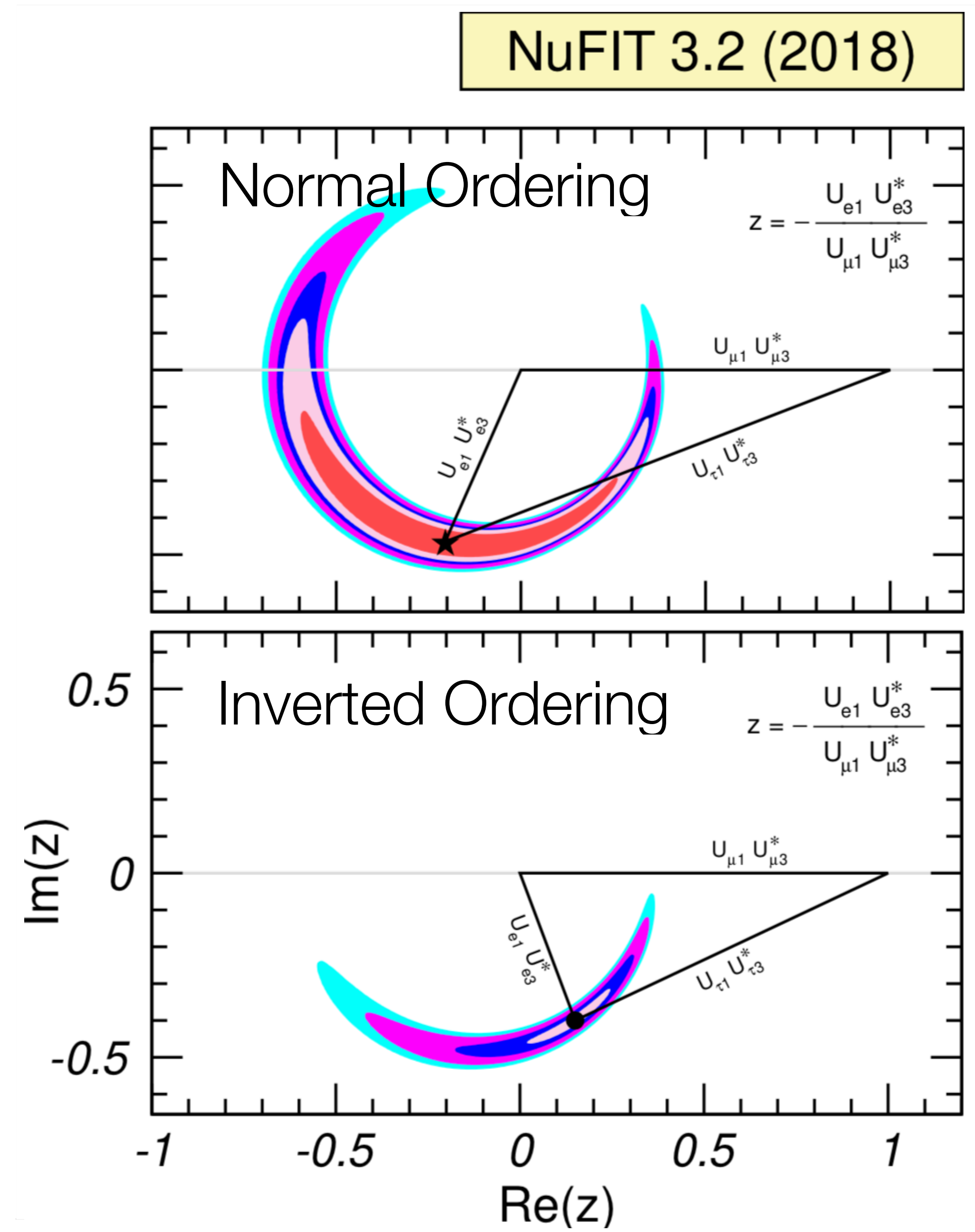
Joachim Kopp (CERN & Uni Mainz)
Seminar at INFN Rome | 16 May 2022

Precision Flavour Physics

Quarks

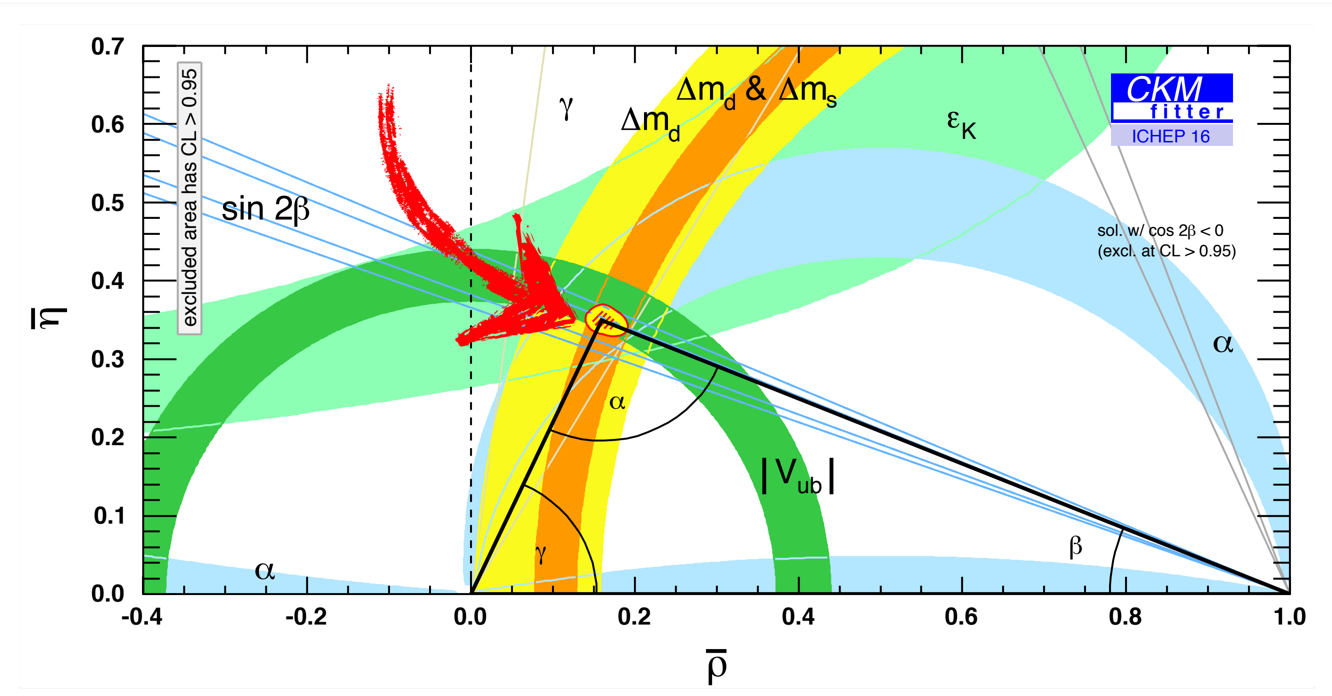


Leptons

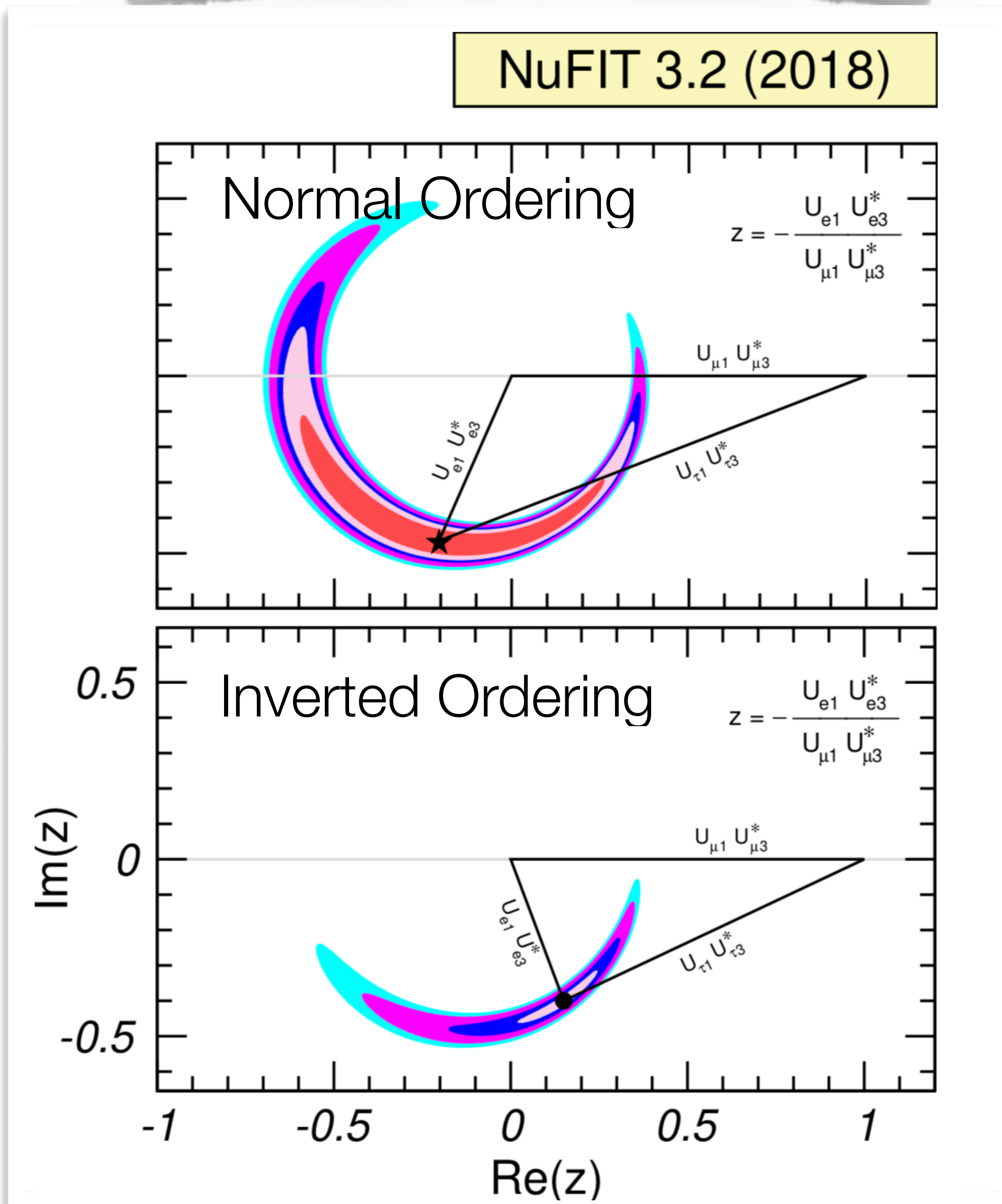


Precision Flavour Physics

Quarks



Leptons



Precision Flavour Physics

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

Precision Flavour Physics

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

Mass Eigenstate
(well-defined energy)

Precision Flavour Physics

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

Mass Eigenstate
(well-defined energy)

Flavor Eigenstate
(well-defined coupling)

Precision Flavour Physics

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

Flavor Eigenstate
(well-defined coupling)

Mass Eigenstate
(well-defined energy)

Mixing Matrix
(3x3, unitary)

Precision Flavour Physics

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

Flavor Eigenstate
(well-defined coupling)

Mass Eigenstate
(well-defined energy)

Mixing Matrix
(3x3, unitary)

Mixing Matrix:

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

Precision Flavour Physics

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

Flavor Eigenstate
(well-defined coupling)

Mass Eigenstate
(well-defined energy)

Mixing Matrix
(3x3, unitary)

Mixing Matrix:

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

Large
close to maximal

Precision Flavour Physics

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

Flavor Eigenstate
(well-defined coupling)

Mass Eigenstate
(well-defined energy)

Mixing Matrix
(3x3, unitary)

Mixing Matrix:

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

Large
close to maximal

Large
but non-maximal

Precision Flavour Physics

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

Flavor Eigenstate
(well-defined coupling)

Mass Eigenstate
(well-defined energy)

Mixing Matrix
(3x3, unitary)

Mixing Matrix:

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

Large
close to maximal

Small
but non-negligible (~0.1)

Large
but non-maximal

Precision Flavour Physics

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

Flavor Eigenstate
(well-defined coupling)

Mass Eigenstate
(well-defined energy)

Mixing Matrix
(3x3, unitary)

Mixing Matrix:

Unknown

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

Large
close to maximal

Small
but non-negligible (~0.1)

Large
but non-maximal

Long Baseline vs. Short Baseline

- Studying ν oscillations requires long baseline (source—detector distance) due to large oscillation lengths
- Here, however: short-baseline experiments
  - some were built before the SM oscillation lengths were known
  - some are motivated by non-oscillation physics (cross-section measurements etc.)
- Several of these experiments have seen anomalous results → rest of this talk

Outline

- ☑ Short-Baseline Anomalies
- ☑ SM Explanations for the MiniBooNE Anomaly?
- ☑ Sterile Neutrinos?
- ☑ Other BSM Proposals

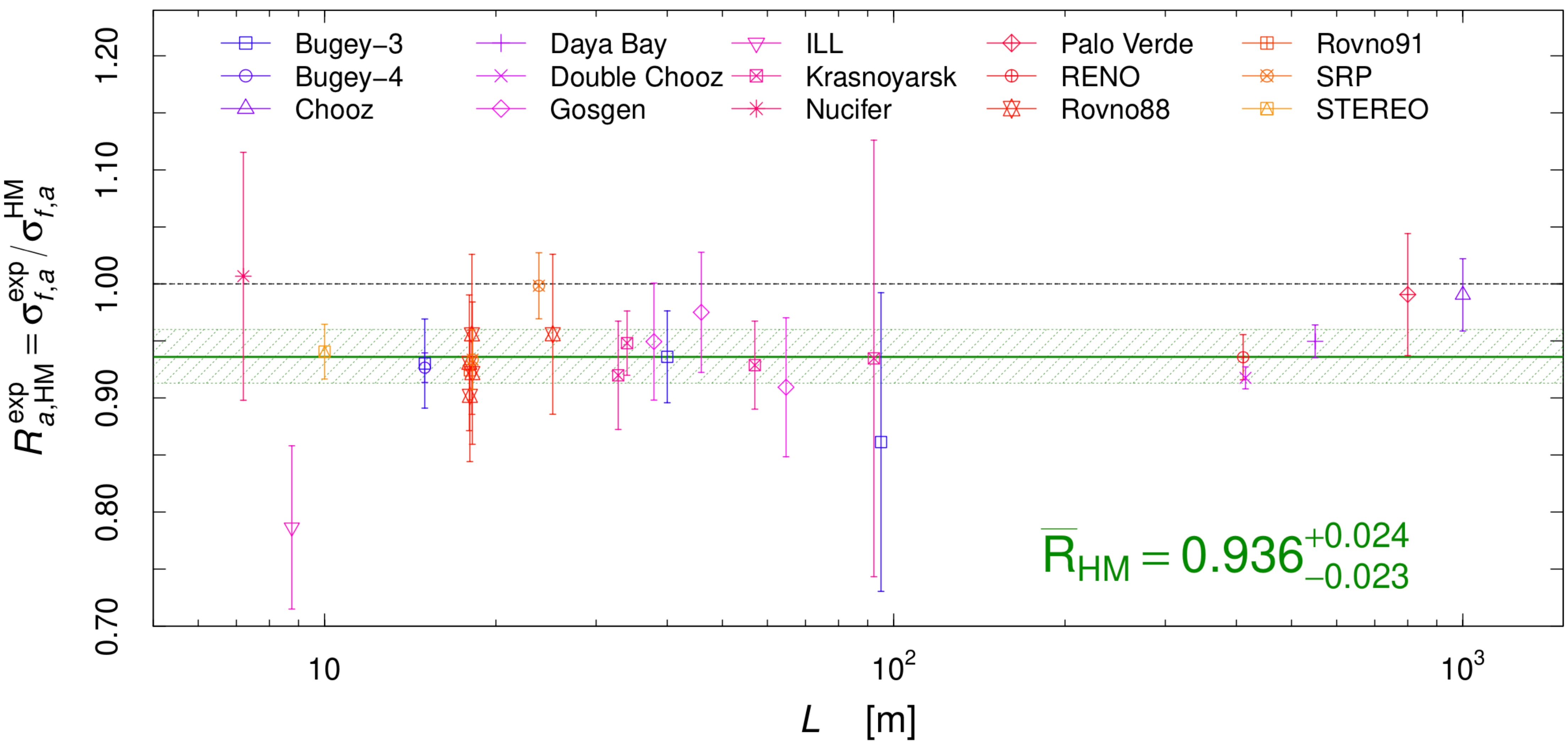
Short-Baseline Anomalies

Anomaly #1: Reactor Neutrino Fluxes

$\bar{\nu}_e$ flux from nuclear reactors ~ 3.5% (~ 3σ) below prediction

oscillations of $\bar{\nu}_e$ into sterile neutrinos $\bar{\nu}_s$?

Mueller *et al.* 1101.2663, Huber 1106.0687, Giunti *et al.* 2110.06820



Light Sterile Neutrinos

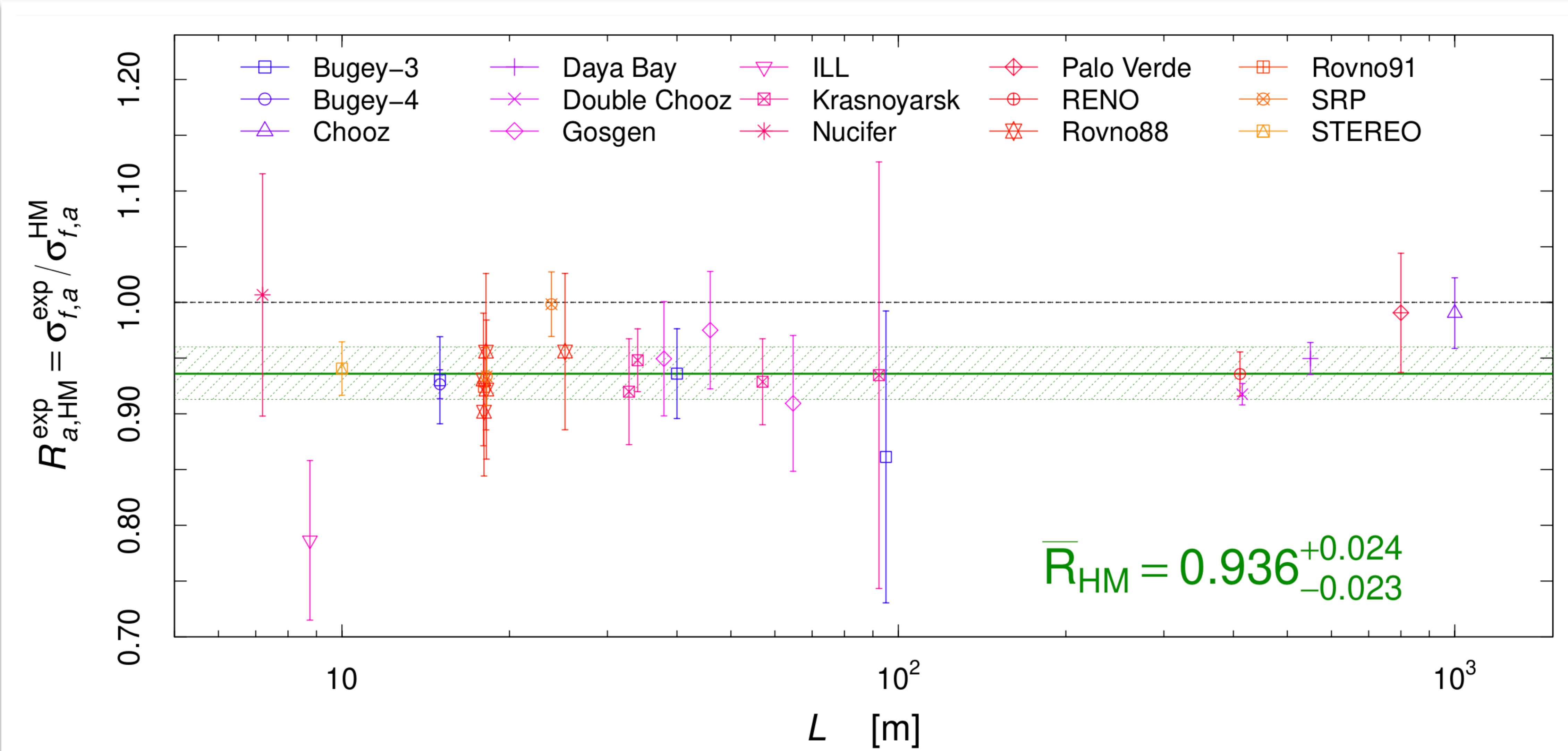
Definition: sterile neutrino = SM singlet fermion

- ☑ Very generic extension of SM
  - can be leftover of extended gauge multiplet
- ☑ Useful phenomenological tool
  - can explain ν masses (seesaw mechanism, m ~ TeV…M_{Pl})
  - can explain cosmic baryon asymmetry (leptogenesis, m≫100 GeV)
  - can explain dark matter (m ~ keV)
  - can explain oscillation anomalies (m ~ eV)
    Promote mixing matrix to 4 x 4, oscillation formula unchanged:

$$P_{\alpha\to\beta} = \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \exp\left[-i(E_j - E_k)T\right]$$

Anomaly #1: Reactor Neutrino Fluxes

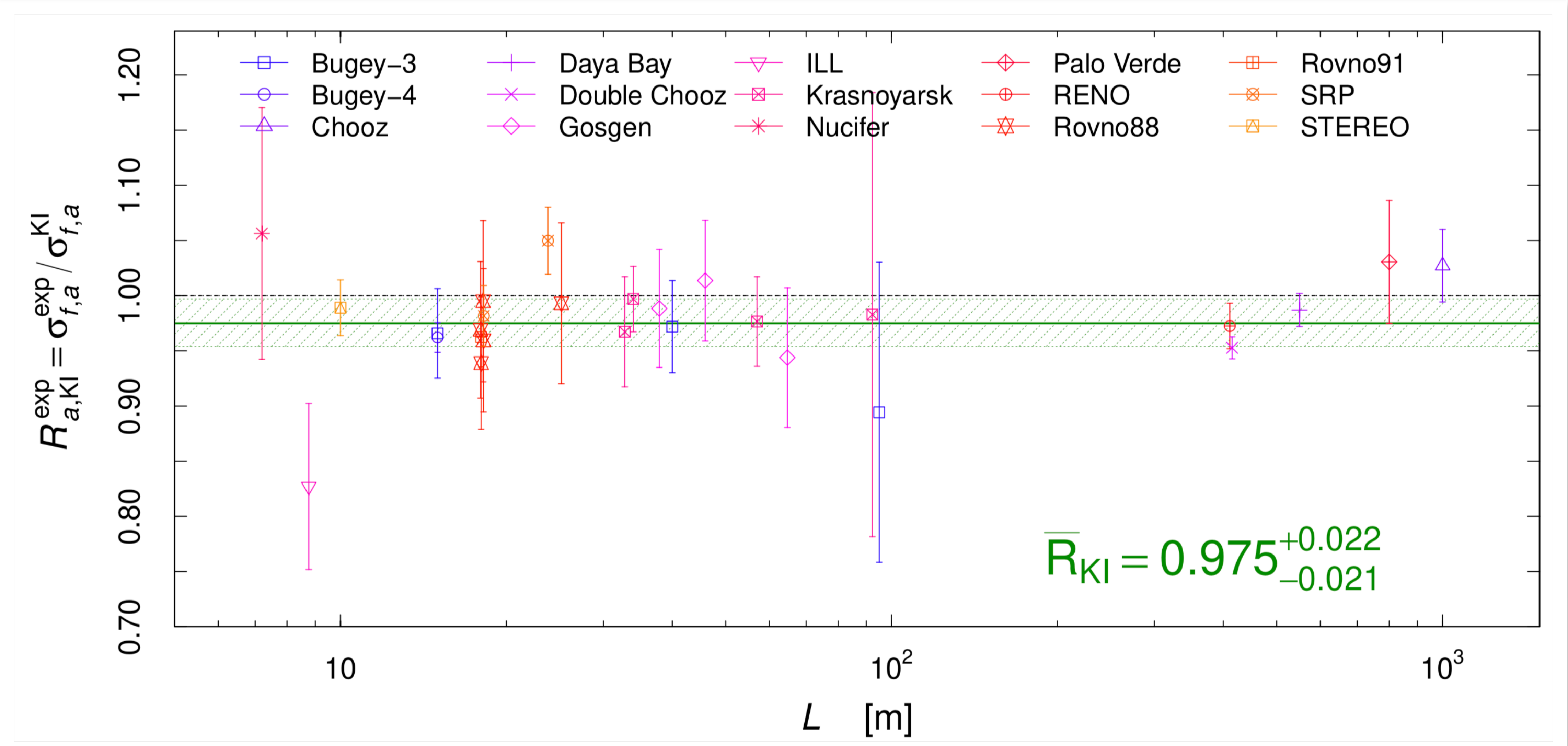
With updated input data to flux calculation
(new β spectra from ^{235}U fission)



Kopeikin Skorokhvatov Titov arXiv:2103.01684
Berryman Huber arXiv:2005.01756
Giunti Li Ternes Xin arXiv:2110.06820

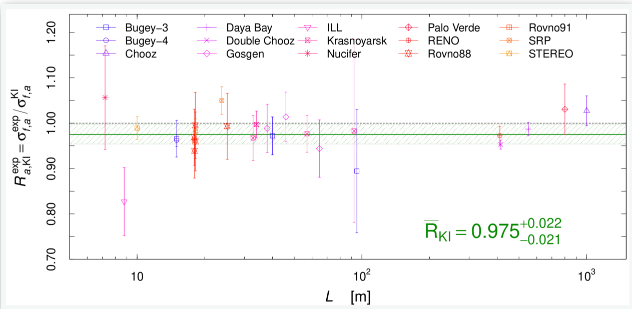
Anomaly #1: Reactor Neutrino Fluxes

With updated input data to flux calculation
(new β spectra from ^{235}U fission)



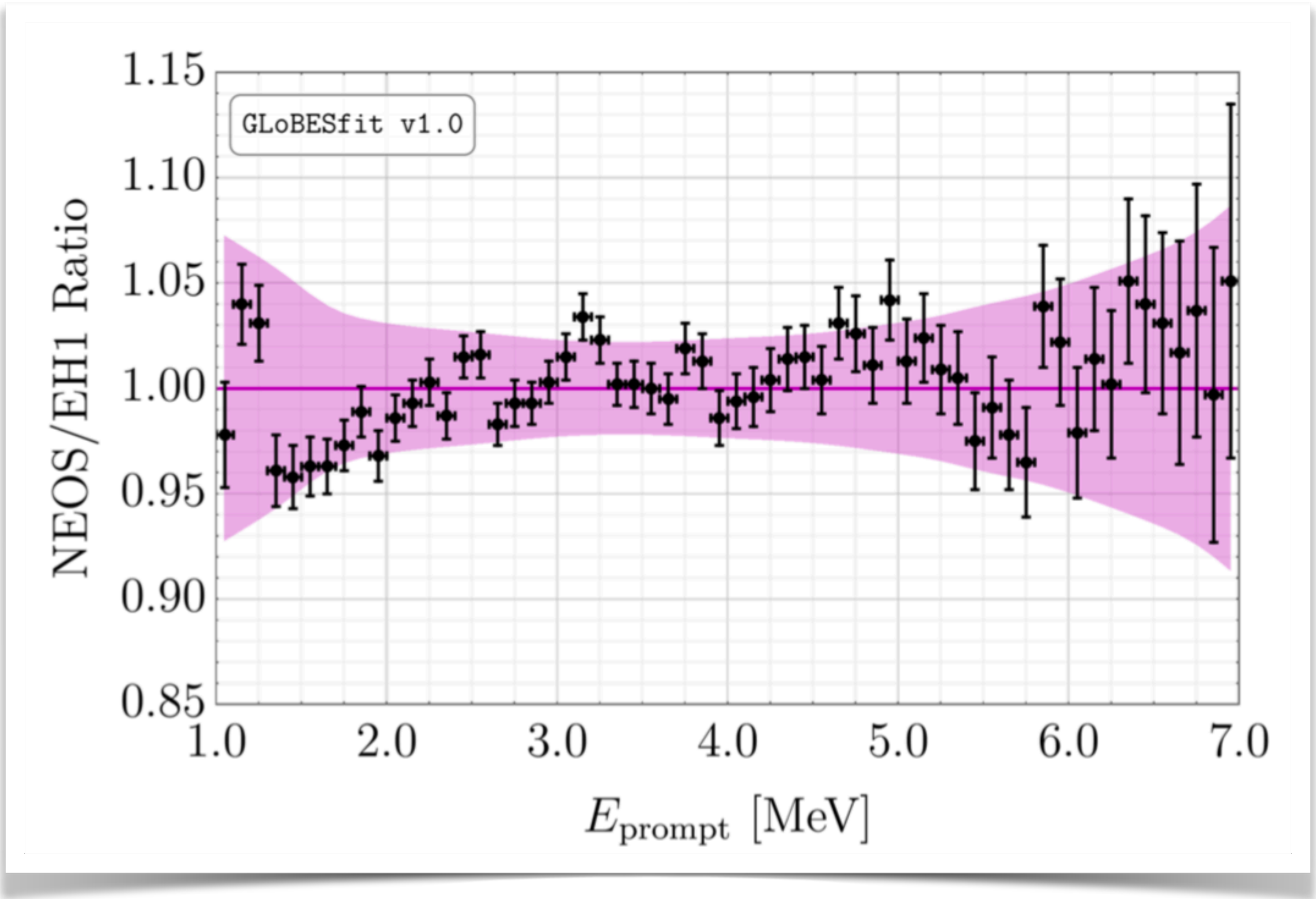
Kopeikin Skorokhvatov Titov arXiv:2103.01684
Berryman Huber arXiv:2005.01756
Giunti Li Ternes Xin arXiv:2110.06820

Short-Baseline Anomalies



reactor flux anomaly:
resolved with new input data
to flux calculation

Anomaly #2: Reactor Spectra

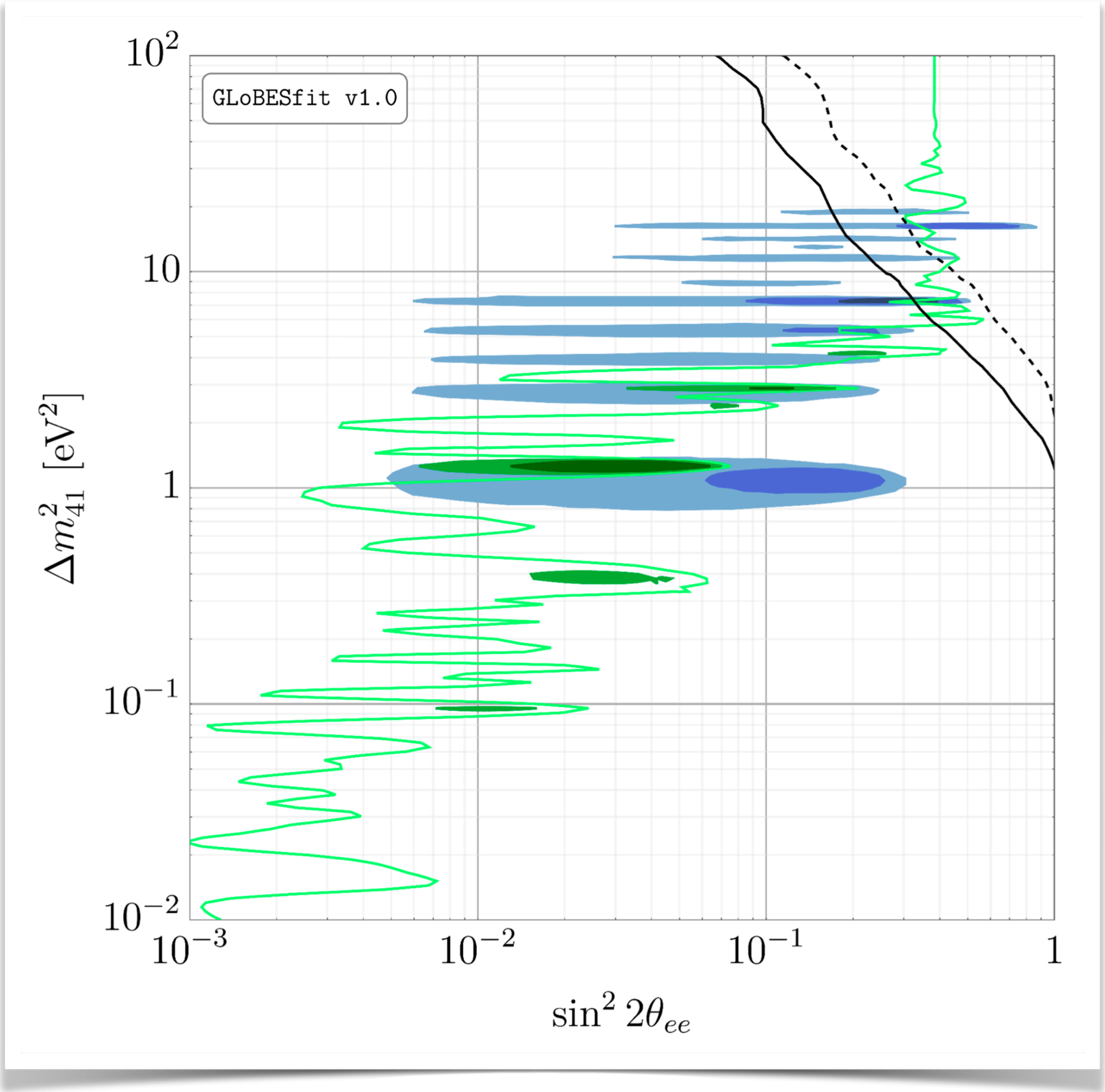


- ☑ spectral "wiggles" in several experiments
  - can be interpreted as signal of neutrino oscillations
- ☑ Use ratios of spectra at different baselines
  - makes results independent of flux predictions

Berryman Huber arXiv:2005.01756

CERN | Neutrino PLATFORM | erc | JG|U

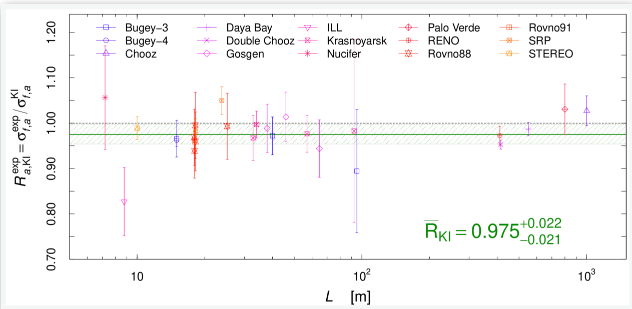
Anomaly #2: Reactor Spectra

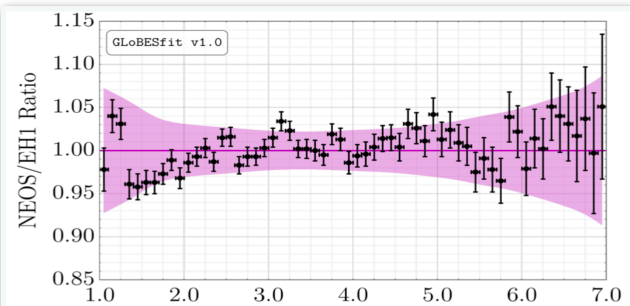


- ☑ spectral "wiggles" in several experiments
  - can be interpreted as signal of neutrino oscillations
- ☑ Use ratios of spectra at different baselines
  - makes results independent of flux predictions

Berryman Huber arXiv:2005.01756

Short-Baseline Anomalies





reactor flux anomaly:
resolved with new input data
to flux calculation

reactor spectra:
unresolved

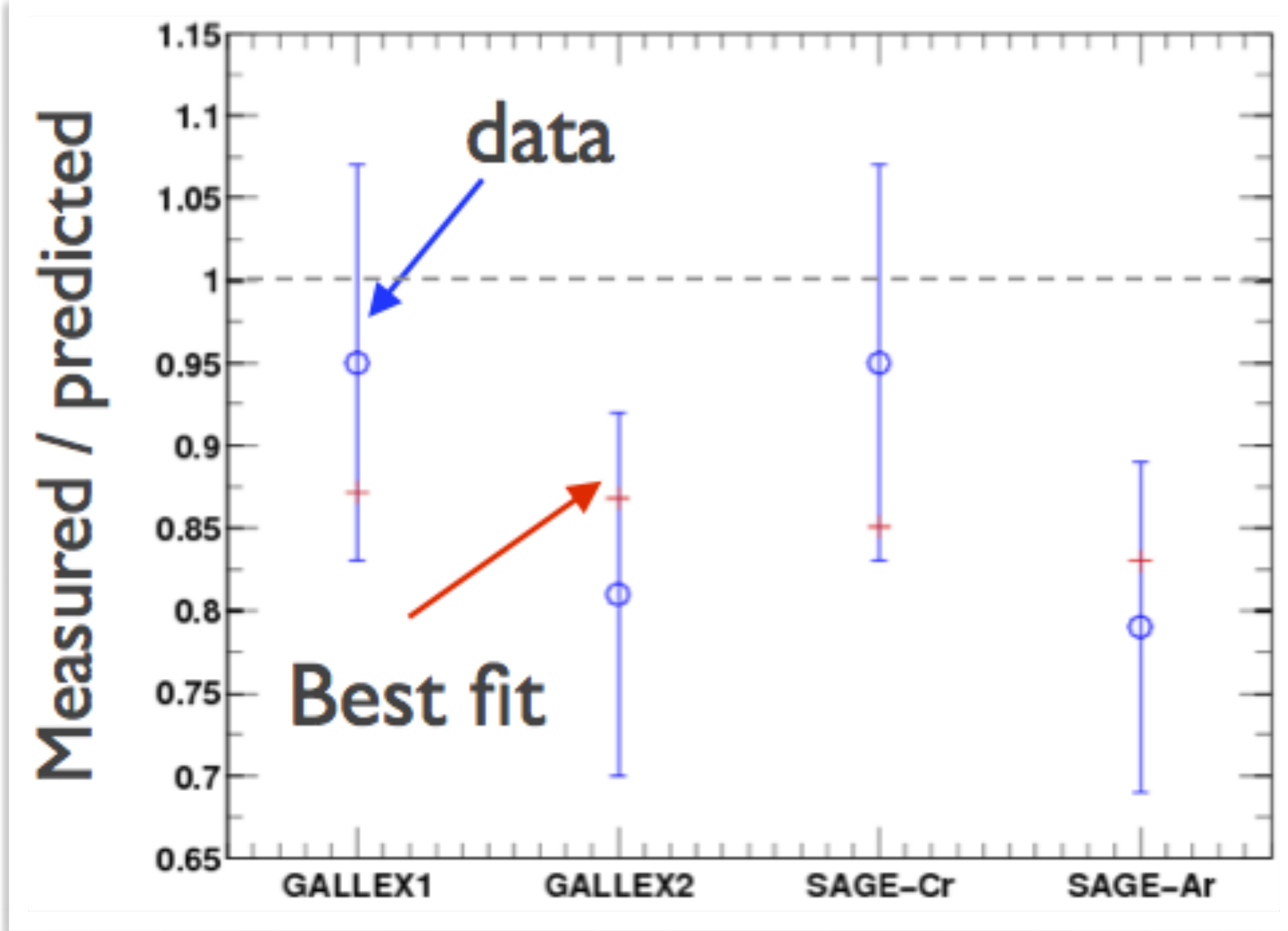
?

Anomaly #3: the Gallium Anomaly

- Experiments with intense radioactive sources
- Neutrino detection via

$$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$$

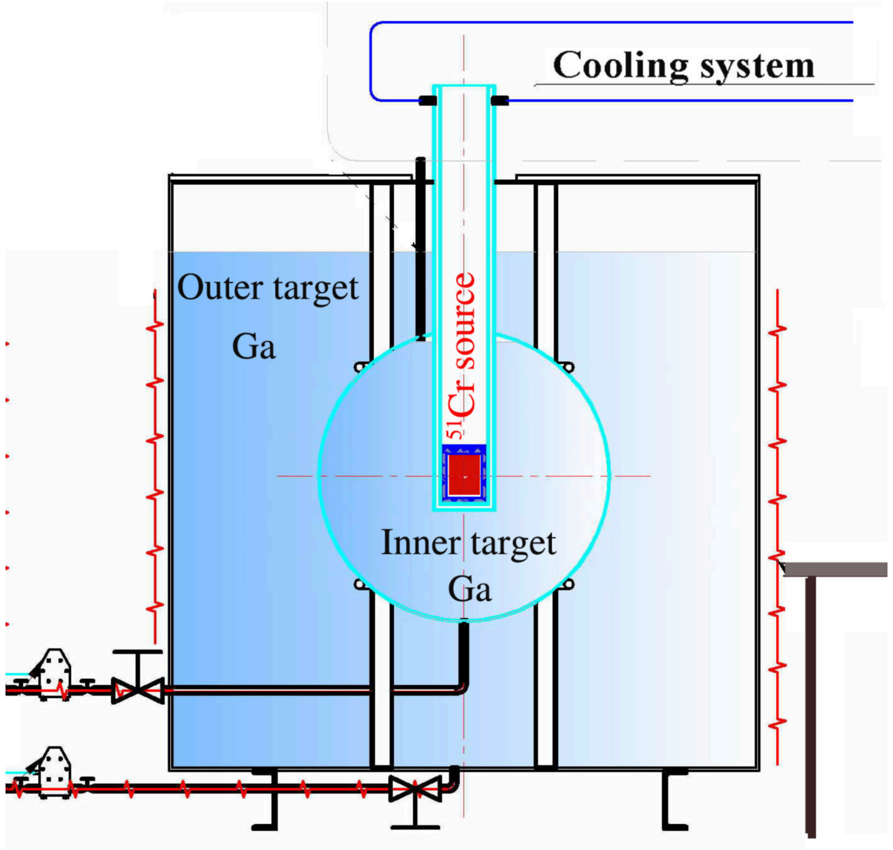
- ~3σ deficit
- ν_e disappearance into sterile state?
- would require very large mixing (conflict with reactor observations)



Giunti Laveder 1006.3244

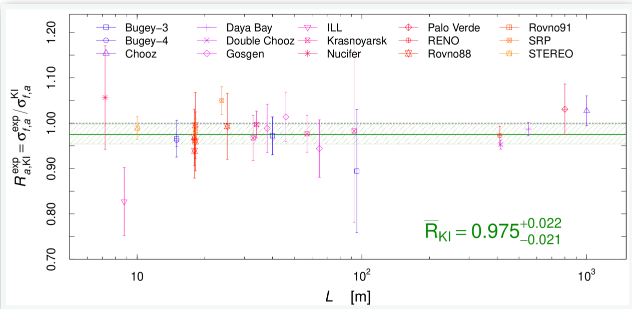
Anomaly #3: the Gallium Anomaly

- recently confirmed by BEST
- two independent target volumes
  (hoping to see oscillation pattern)
- radiochemistry similar to other gallium experiments
  (correlated systematics?)
- but: past experiments cross-calibrated with solar neutrinos

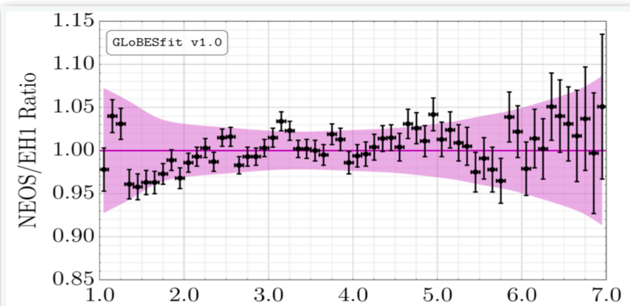


BEST arXiv:2109.11482
Barinov Gorbunov arXiv:2109.14654

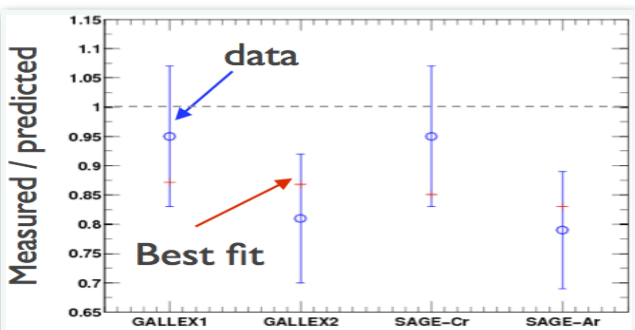
Short-Baseline Anomalies



reactor flux anomaly:
resolved with new input data to flux calculation ✓

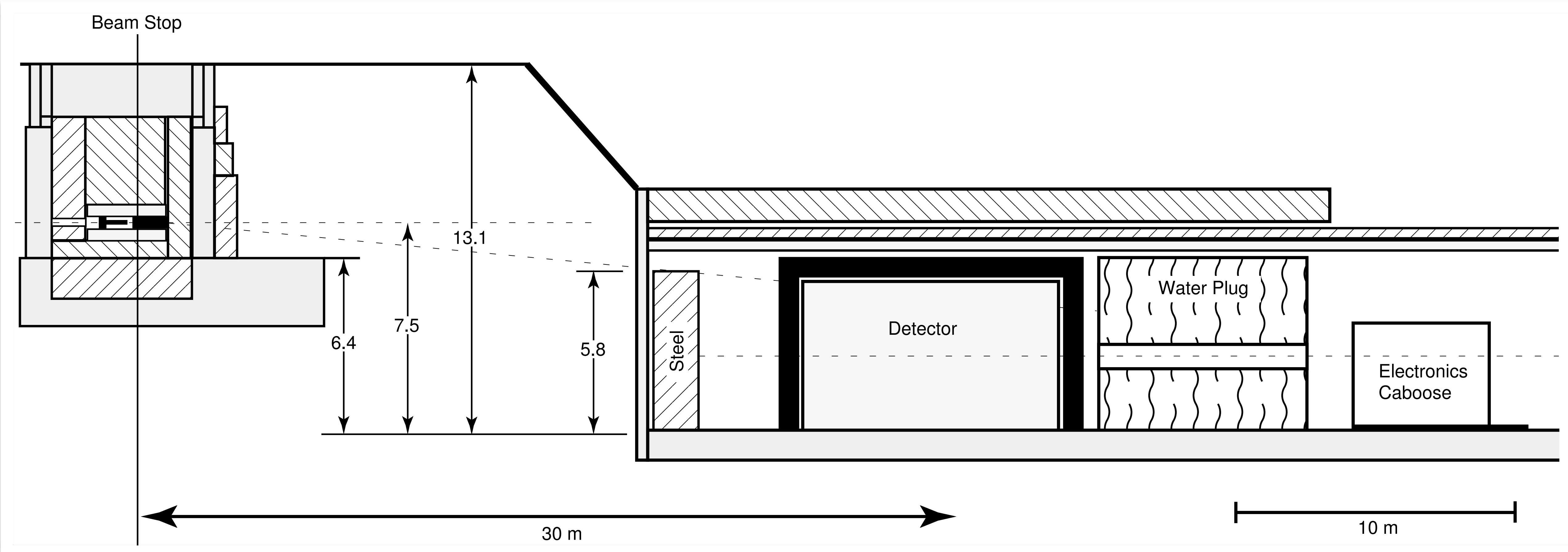


reactor spectra:
unresolved ?



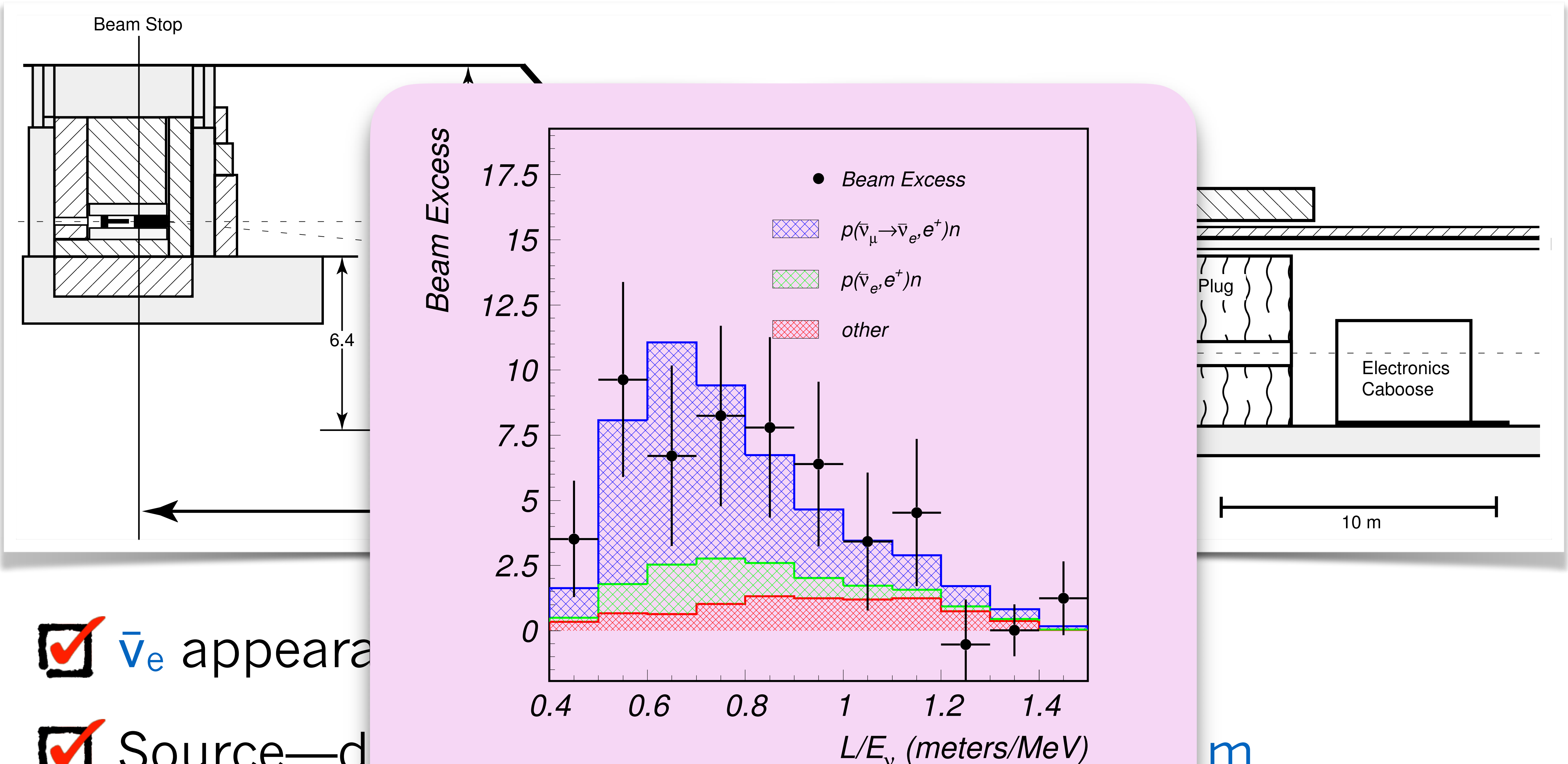
gallium anomaly:
unresolved, recently reinforced ?

Anomaly #4: LSND



- ☑ $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam
- ☑ Source—detector distance ("baseline") ~ 30 m
- ☑ $\nu_\mu \to \nu_e$ oscillations?

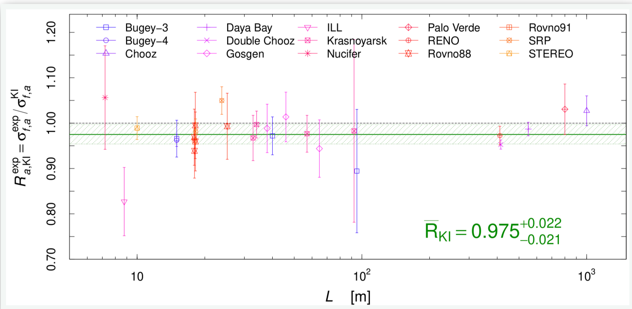
Anomaly #4: LSND



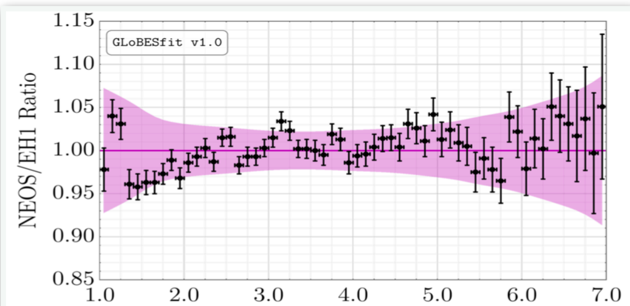
LSND Collaboration, [hep-ex/0104049](hep-ex/0104049)

- ☑ $\bar{\nu}_e$ appeara
- ☑ Source—d … m
- ☑ $\nu_\mu \rightarrow \nu_e$ oscillations?

Short-Baseline Anomalies

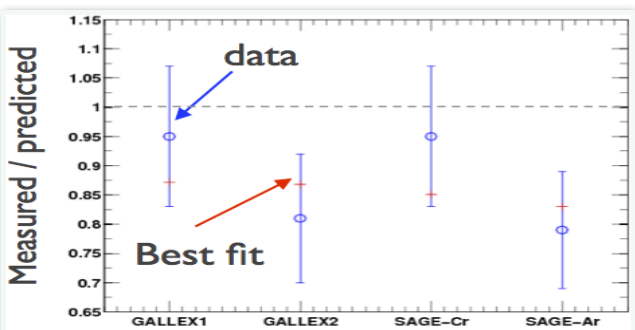


reactor flux anomaly:
resolved with new input data
to flux calculation



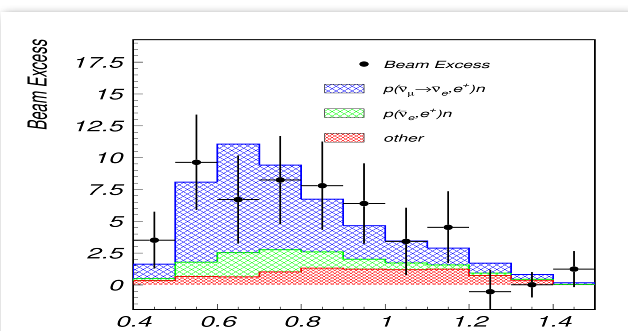
reactor spectra:
unresolved

?



gallium anomaly:
unresolved, recently reinforced

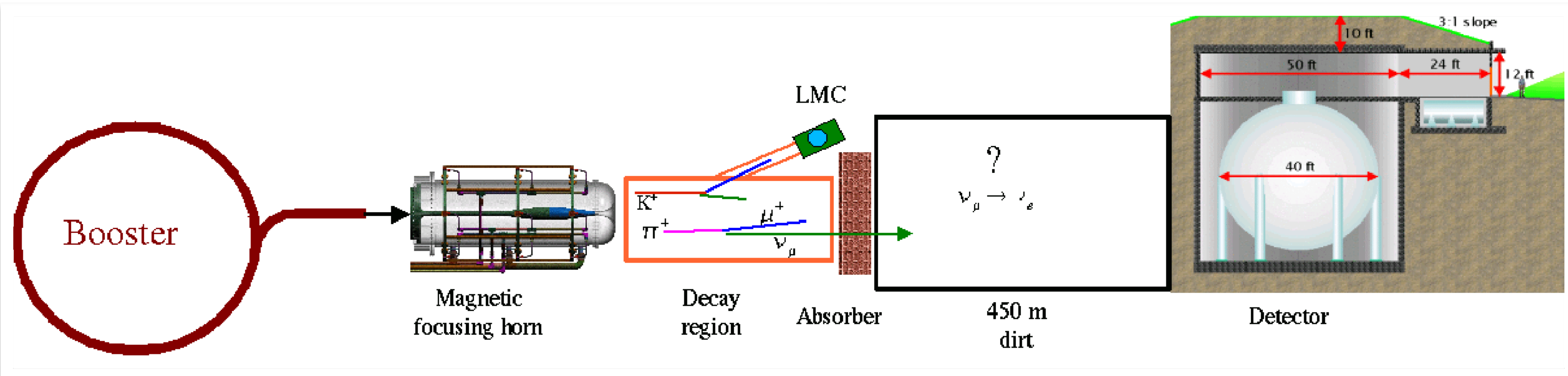
?



$\bar{\nu}_e$ appearance in LSND
unresolved

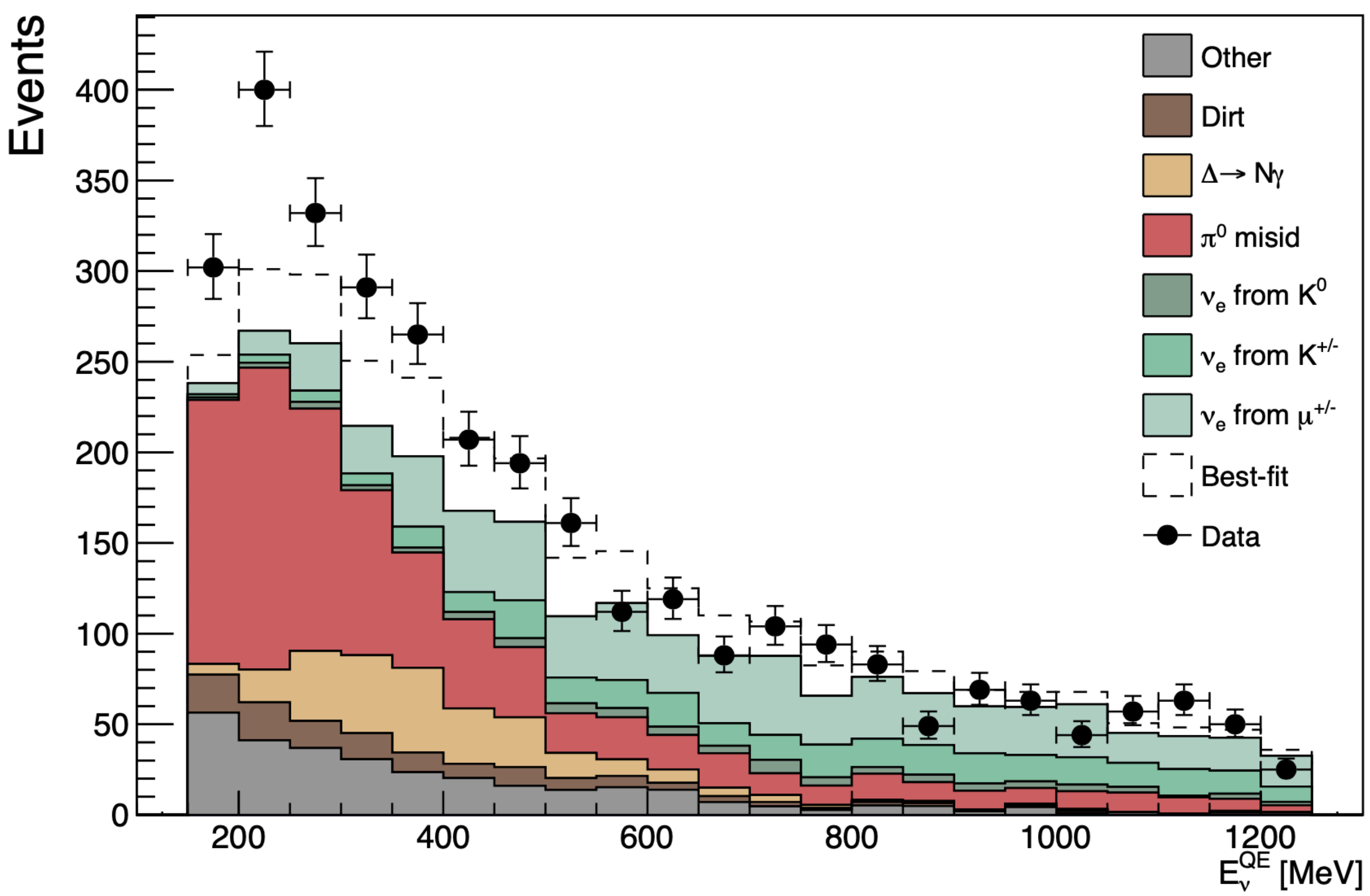
?

Anomaly #5: MiniBooNE

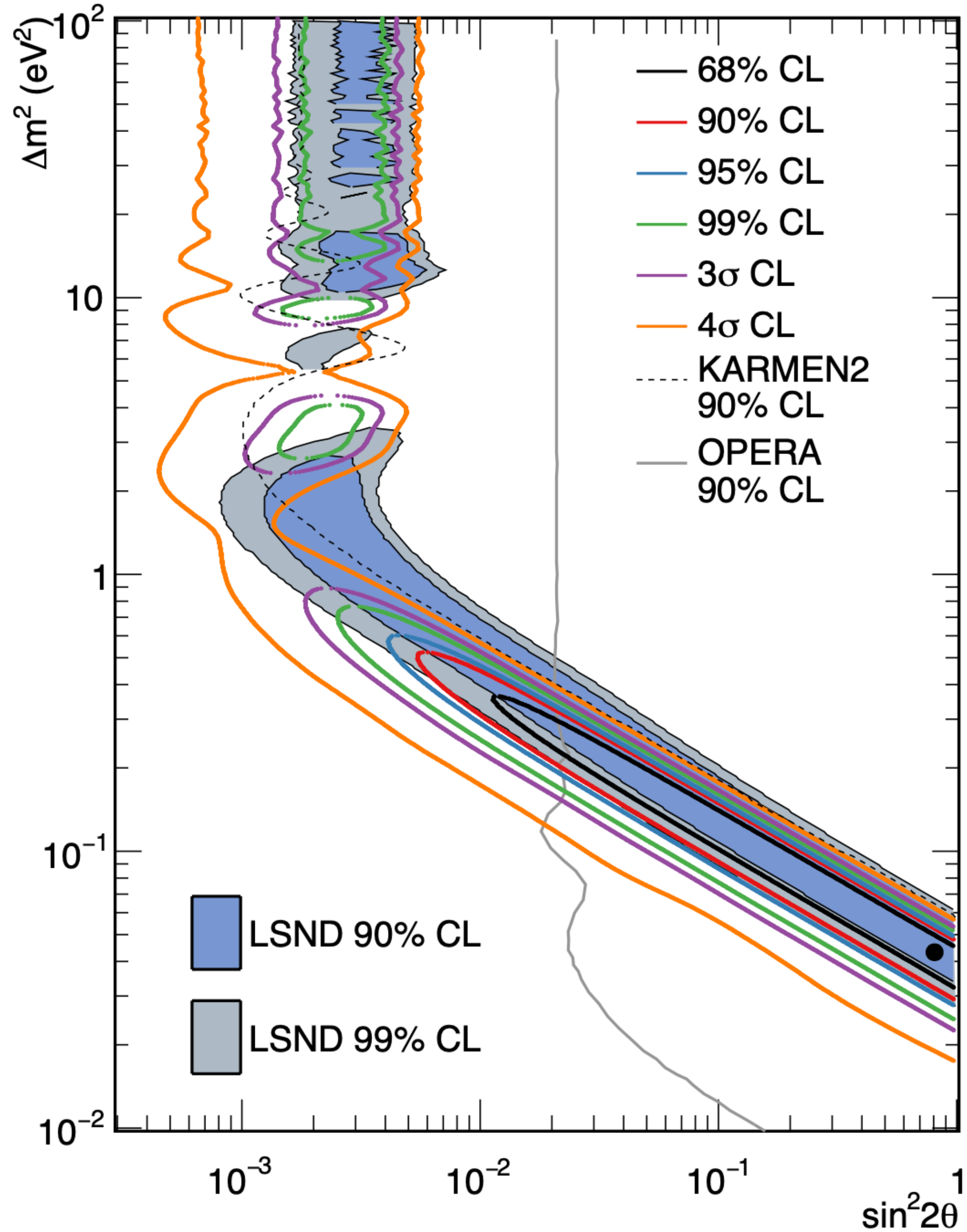


Anomaly #5: MiniBooNE

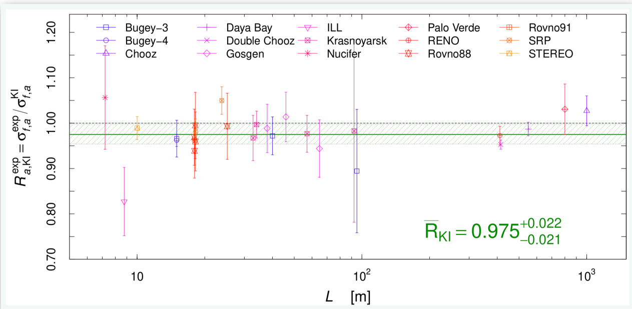
- ☑ Unexplained low-E excess
- ☑ Consistent with LSND
- ☑ L/E too small for std. oscillations (wrong Δm^2)



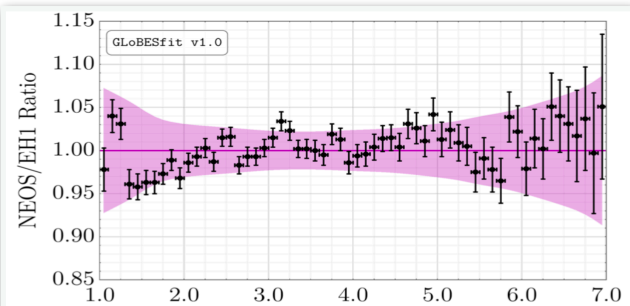
MiniBooNE Collaboration arXiv:2006.16883



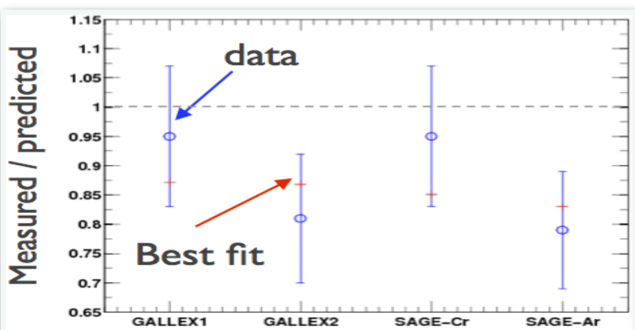
Short-Baseline Anomalies



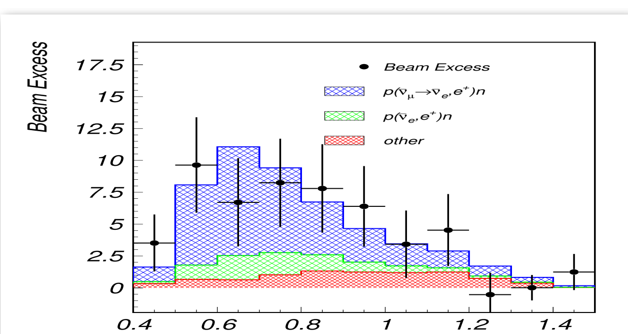
reactor flux anomaly:
resolved with new input data to flux calculation ✔



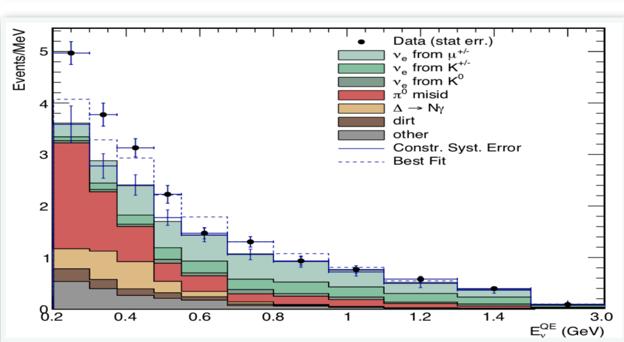
reactor spectra:
unresolved ?



gallium anomaly:
unresolved, recently reinforced ?



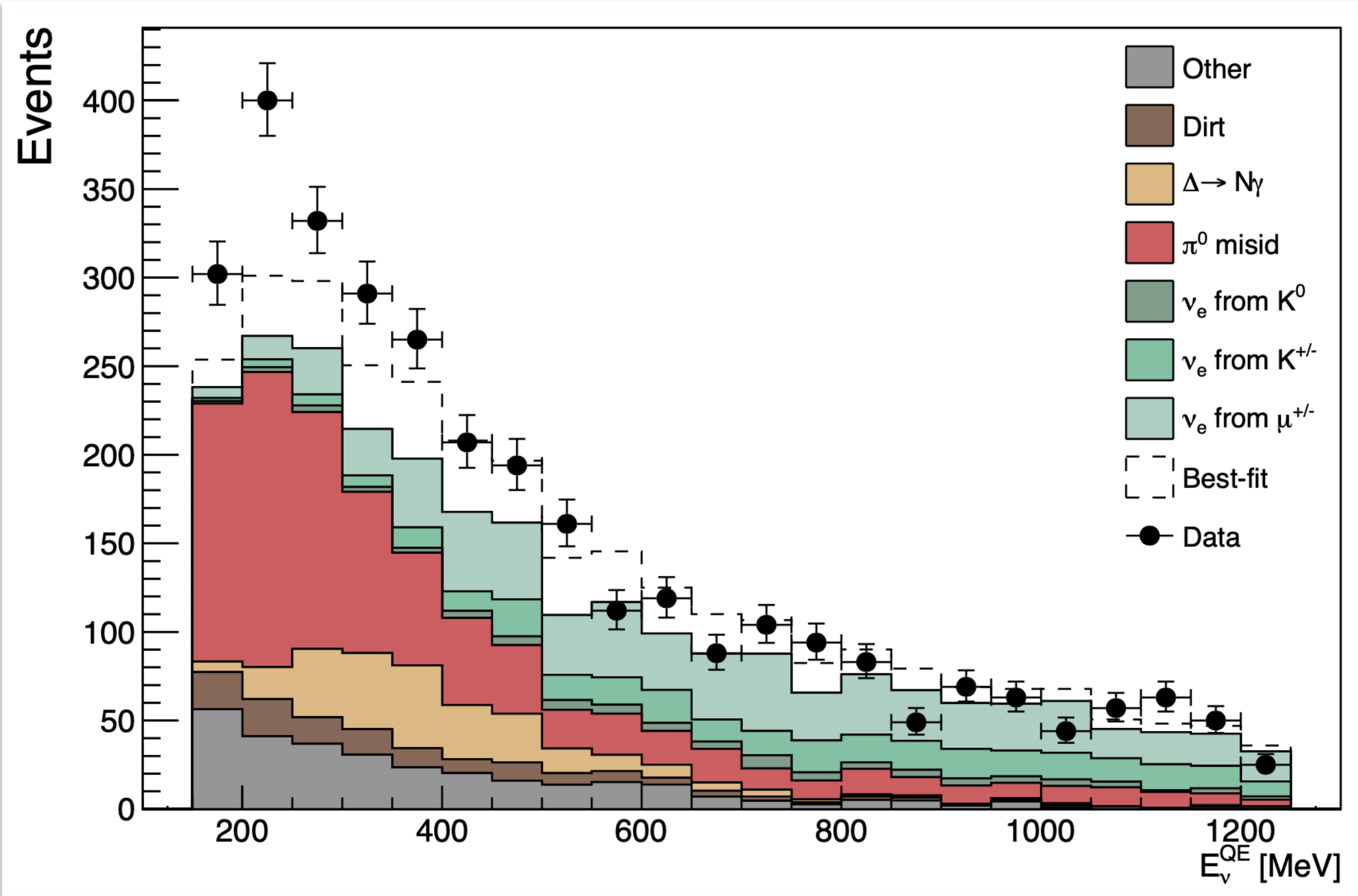
$\bar{\nu}_e$ appearance in LSND
unresolved ?



MiniBooNE
→ rest of this talk

Standard Model Explanations for MiniBooNE?

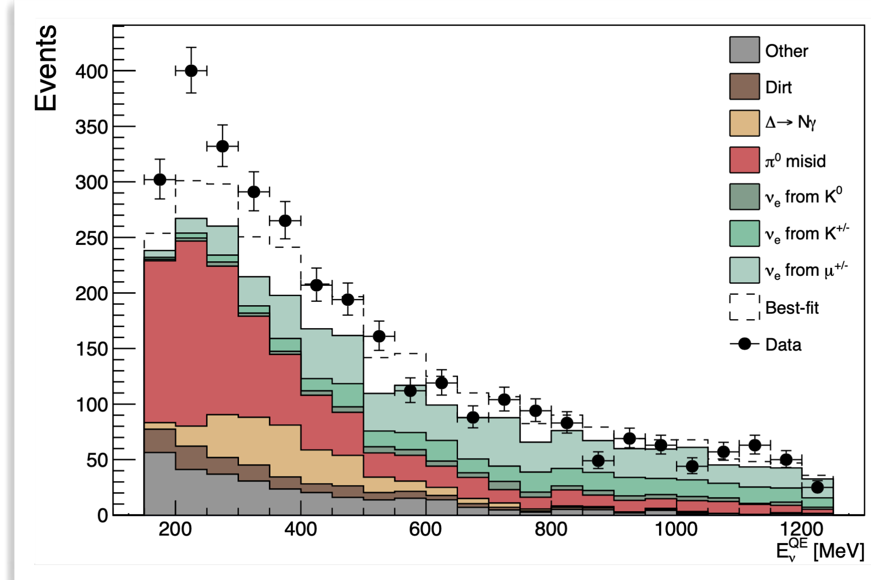
MiniBooNE Backgrounds



MiniBooNE 2020

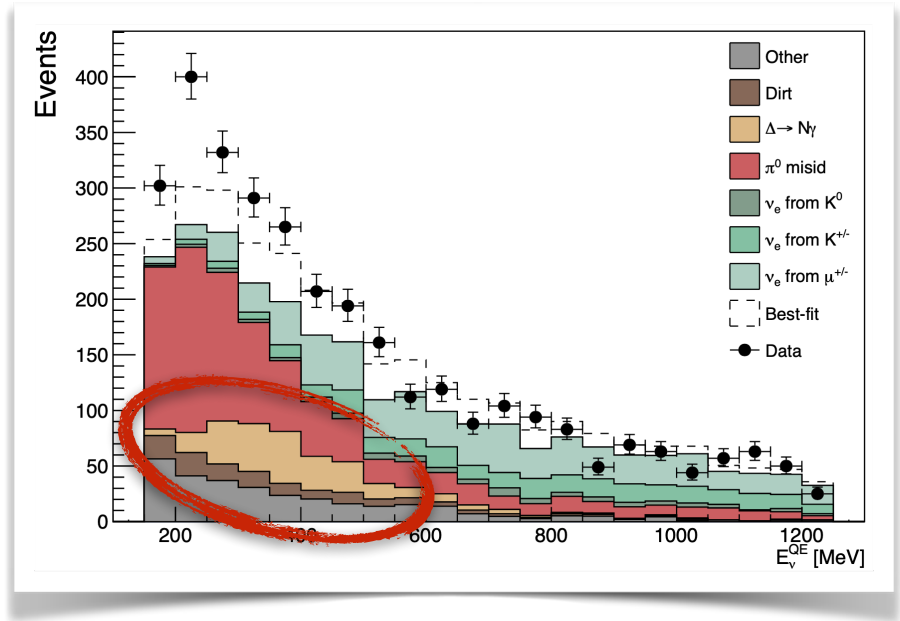
Δ → γ N

- Neutral current neutrino interaction:
  $\nu + N \rightarrow \nu + \Delta(1232)$
- Δ(1232) mostly decays to $\pi + N$
- But a rare decay exists to $\gamma + N$
- MiniBooNE cannot distinguish
  γ from e^-



Δ → γ N

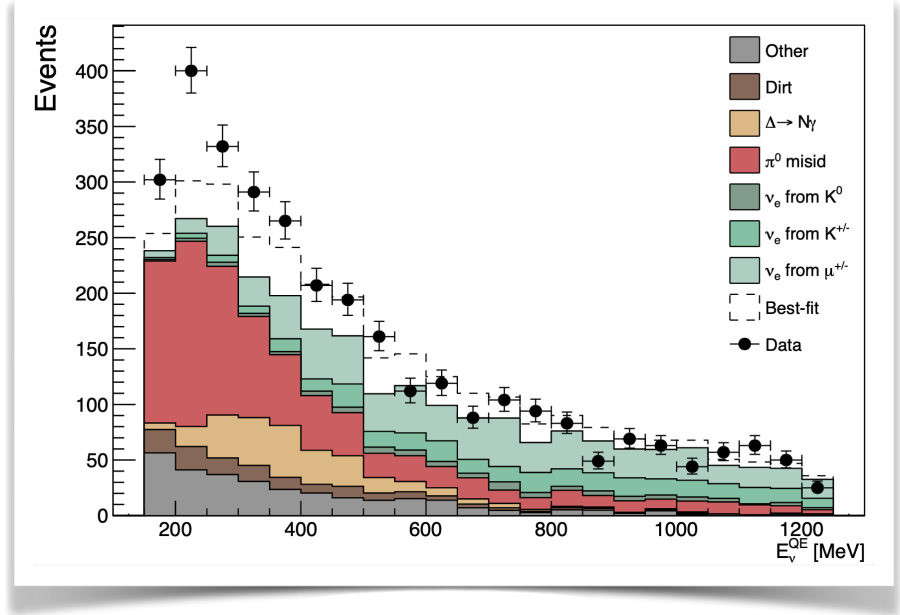
- Neutral current neutrino interaction:
  ν + N → ν + Δ(1232)
- Δ(1232) mostly decays to π + N
- But a rare decay exists to γ + N
- MiniBooNE cannot distinguish γ from e⁻



Δ → γ N

- Δ production rate can be estimated from Δ → πN
- Pions may be absorbed on their way out of the nucleus
  - may excite another Δ resonance
    ➠ Δ → γN enhanced by ~factor 2
  - or may be absorbed
    ➠ control region suppressed by ~factor 2

Ioannisian 1909.08571
Giunti Ioannisian Ranucci 1912.01524



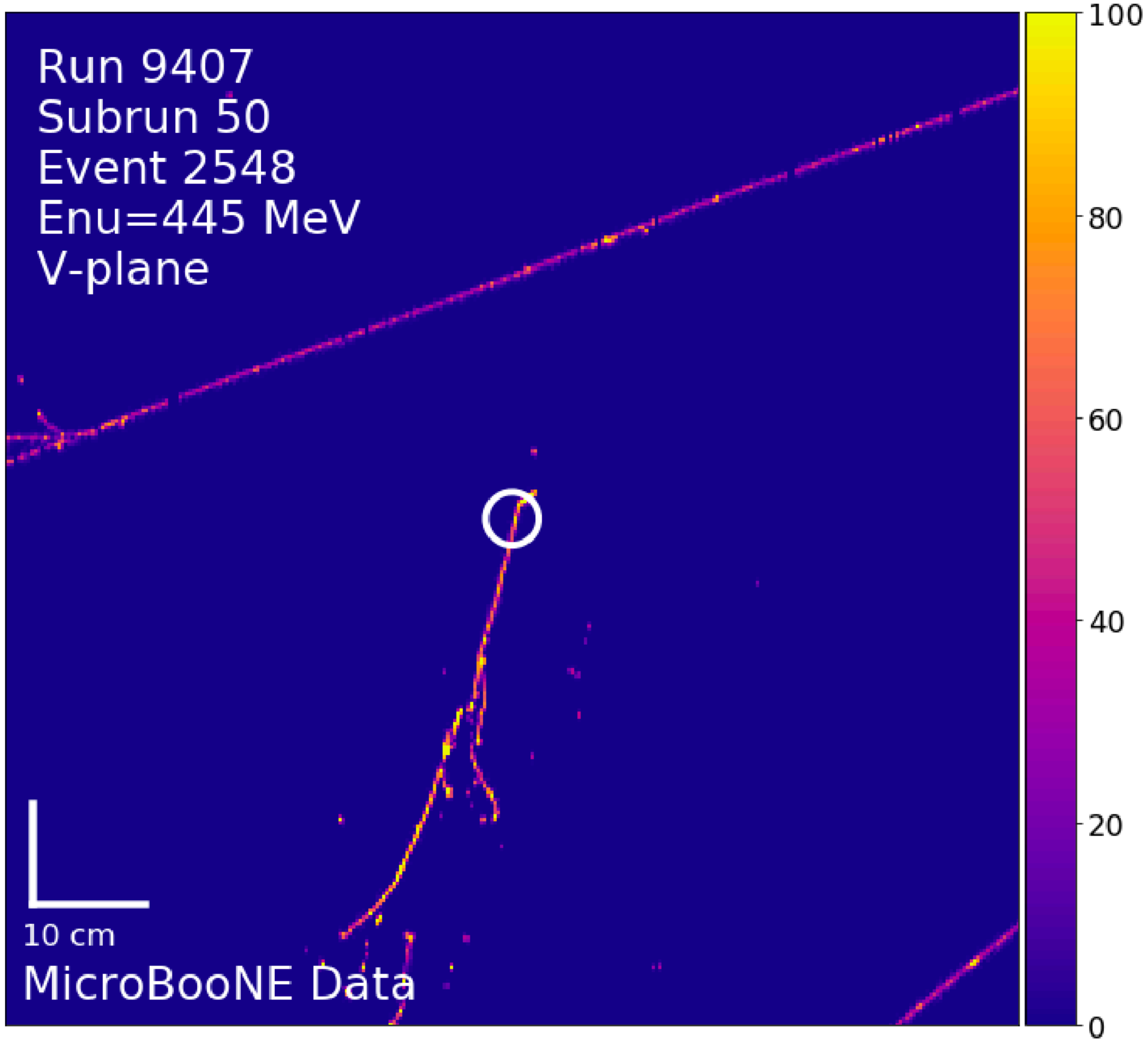
- This factor 2 has been taken into account by MiniBooNE

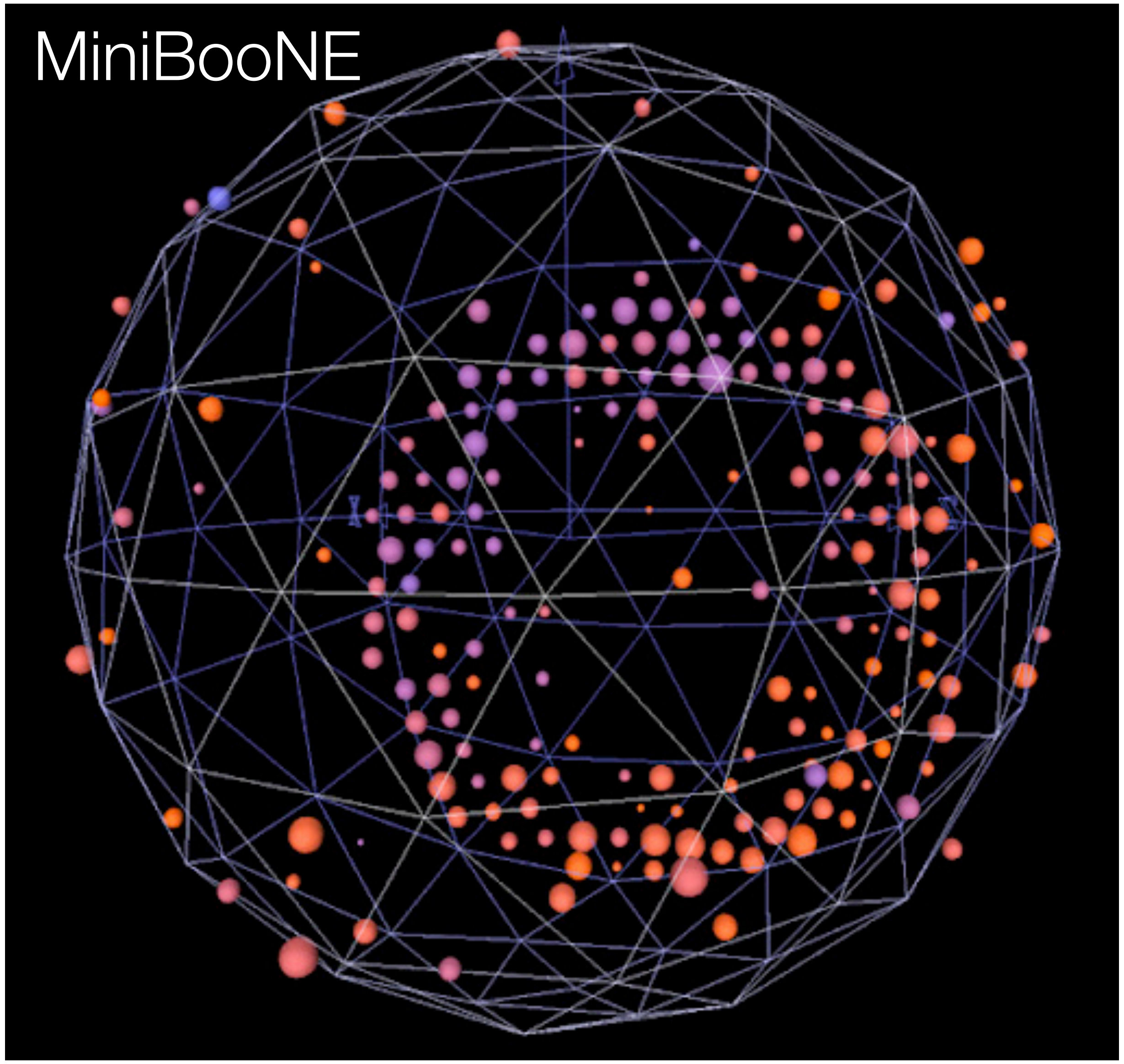
private communication from Bill Louis

MicroBooNE

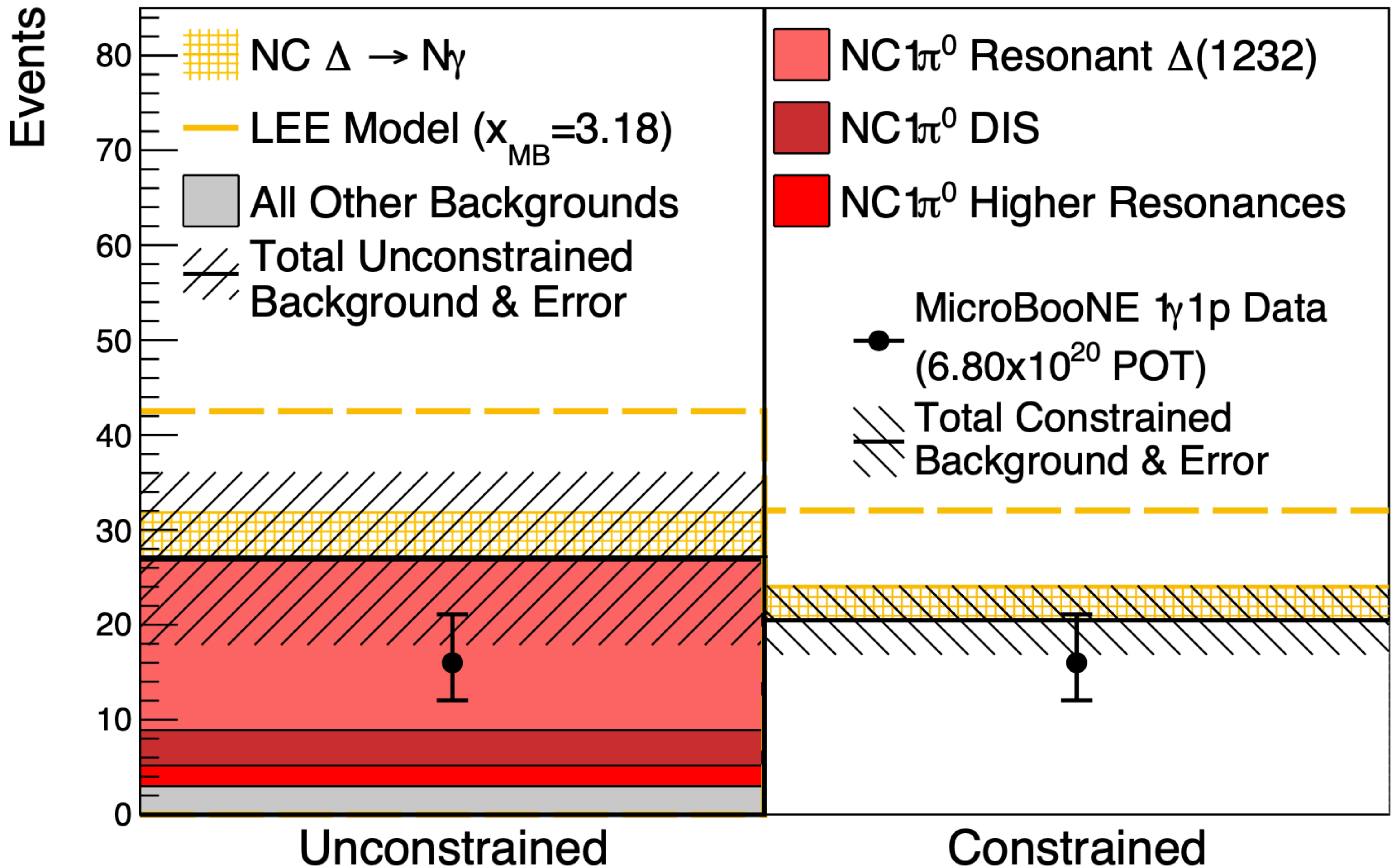
- ☑ 80 ton LAr TPC
- ☑ Very good event reconstruction capabilities
  - can distinguish $e^{\pm}$ from γ

MiniBooNE vs. MicroBooNE





Δ → γ N: MicroBooNE



MicroBooNE arXiv:2110.00409

Other Processes

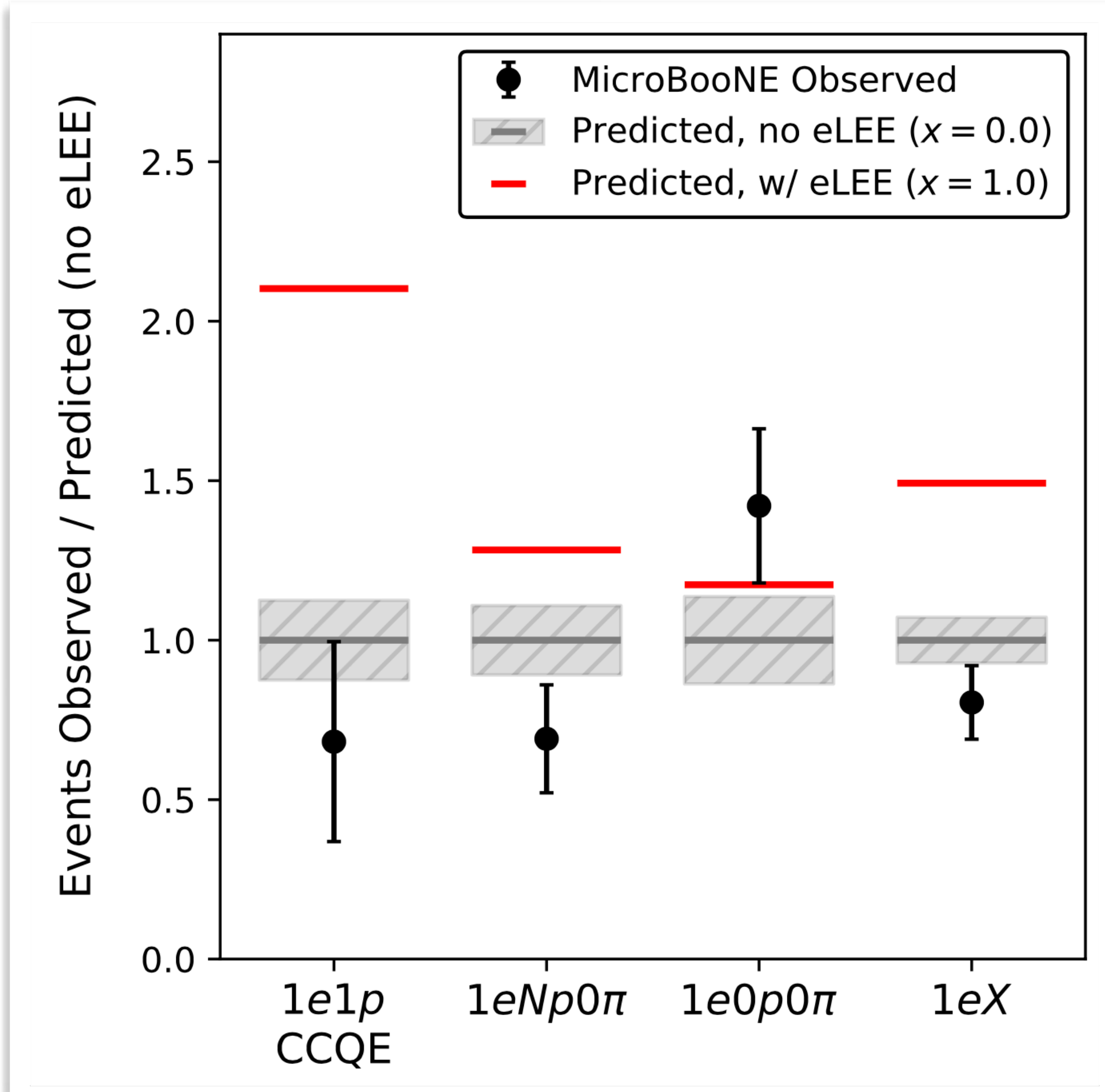
- single-photon production unrelated to the $\Delta(1232)$
  - not yet tested by MicroBooNE
    ($\Delta \rightarrow \gamma N$ search highly optimised for that particular channel)
  - no known processes capable of producing the excess
- single electrons
  - would need to come from ν_e interaction → sterile ν
  - or something even for exotic
- boosted e^+e^- pairs
  - only in "new physics" models

Sterile Neutrinos?

CERN | Neutrino PLATFORM | erc | JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

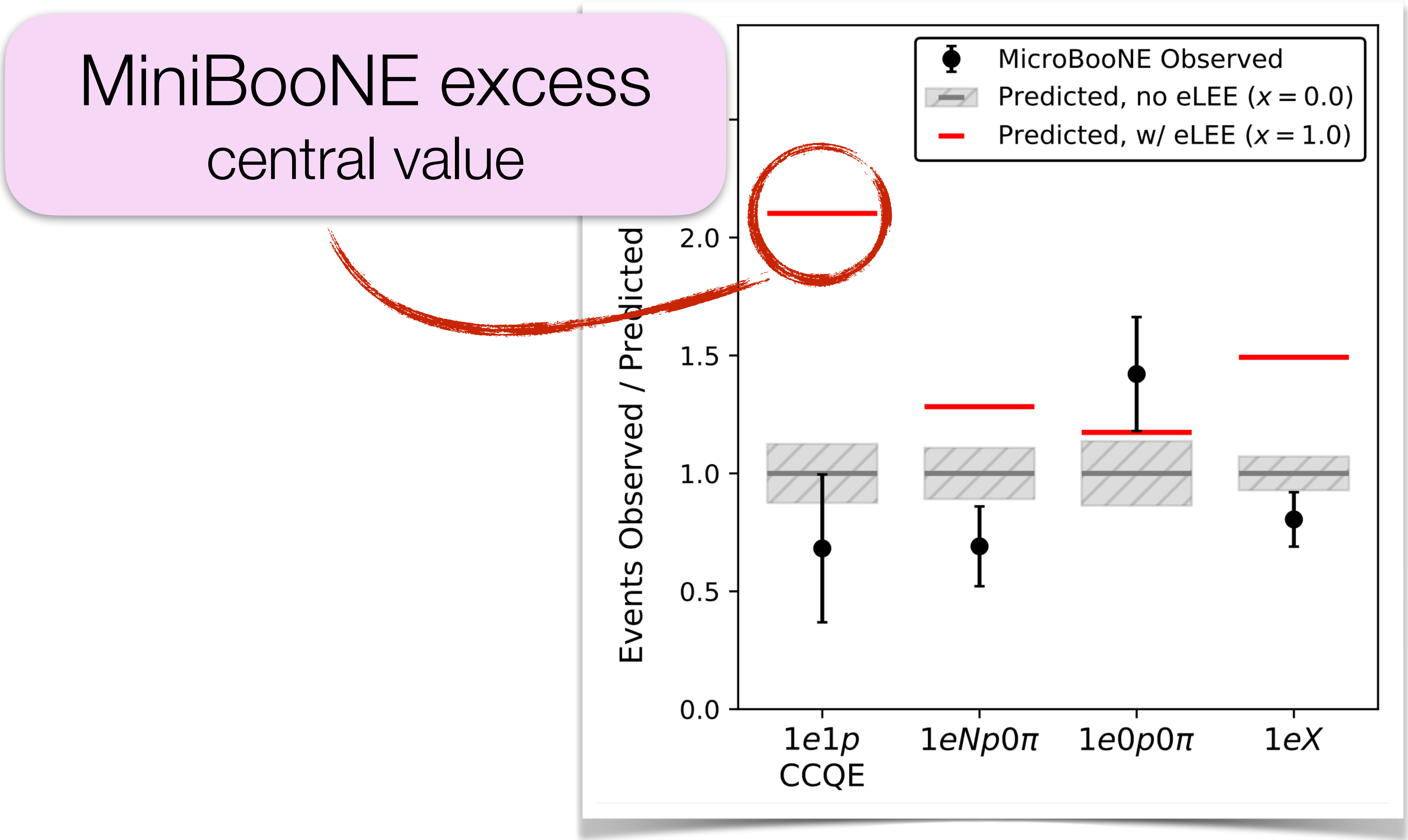
A True ν_e signal?

- ☑ Tested by MicroBooNE in several channels
- ☑ No support for interpretation of MiniBooNE excess as ν_e



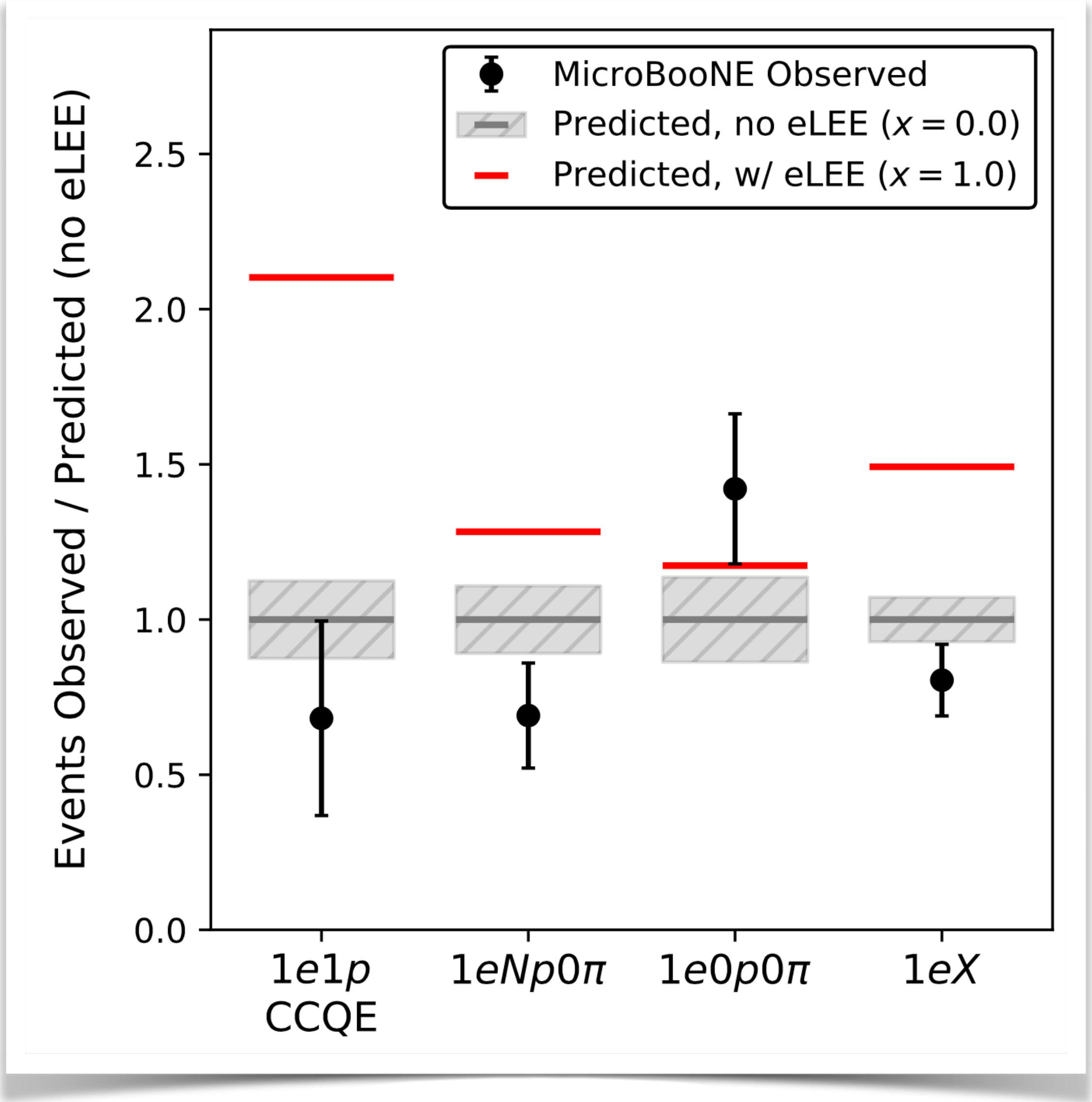
A True ν_e signal?

- ☑ Tested by MicroBooNE in several channels
- ☑ No support for interpretation of MiniBooNE excess as ν_e

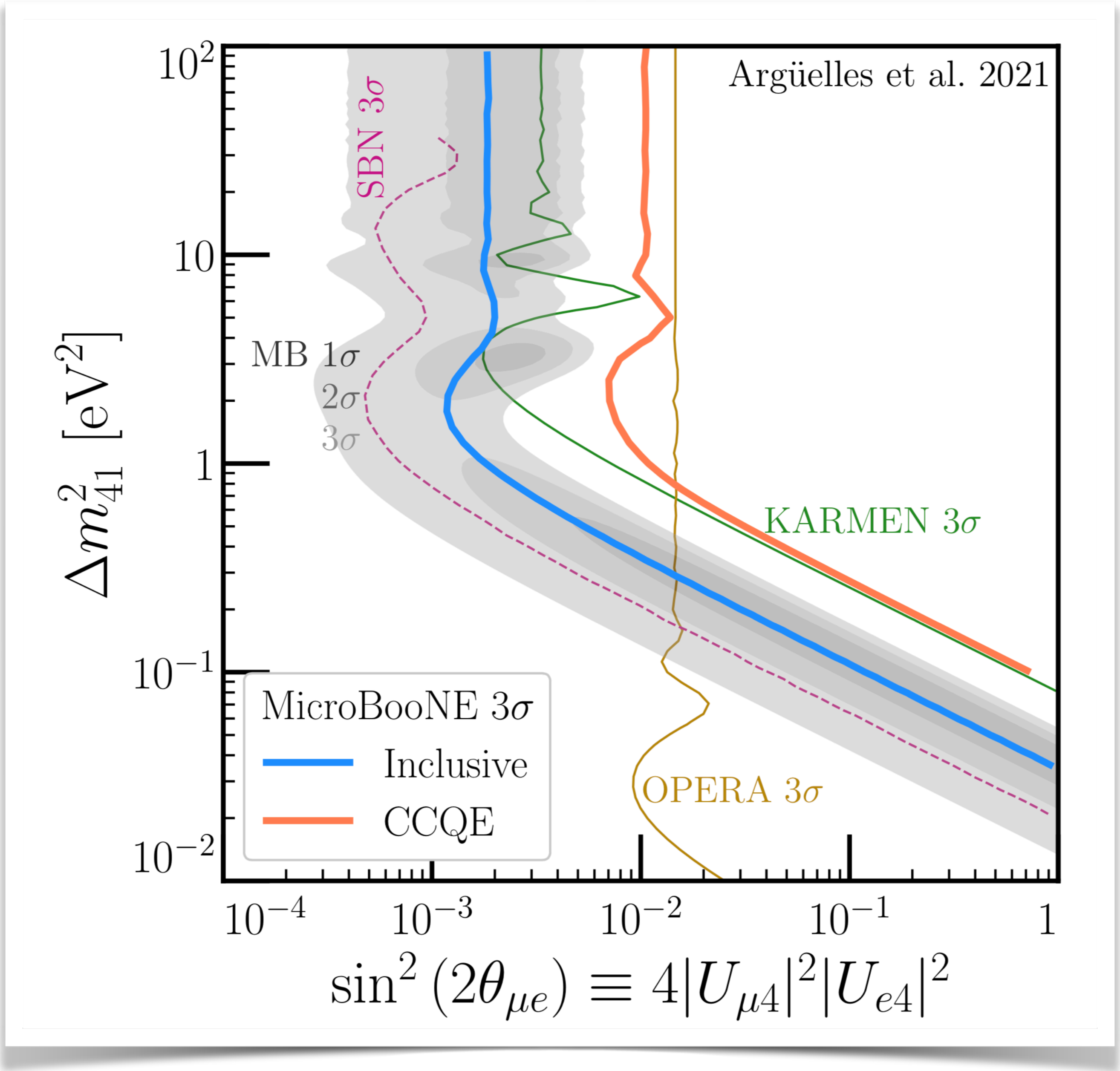


A True ν_e signal?

- ☑ Tested by MicroBooNE in several channels
- ☑ No support for interpretation of MiniBooNE excess as ν_e

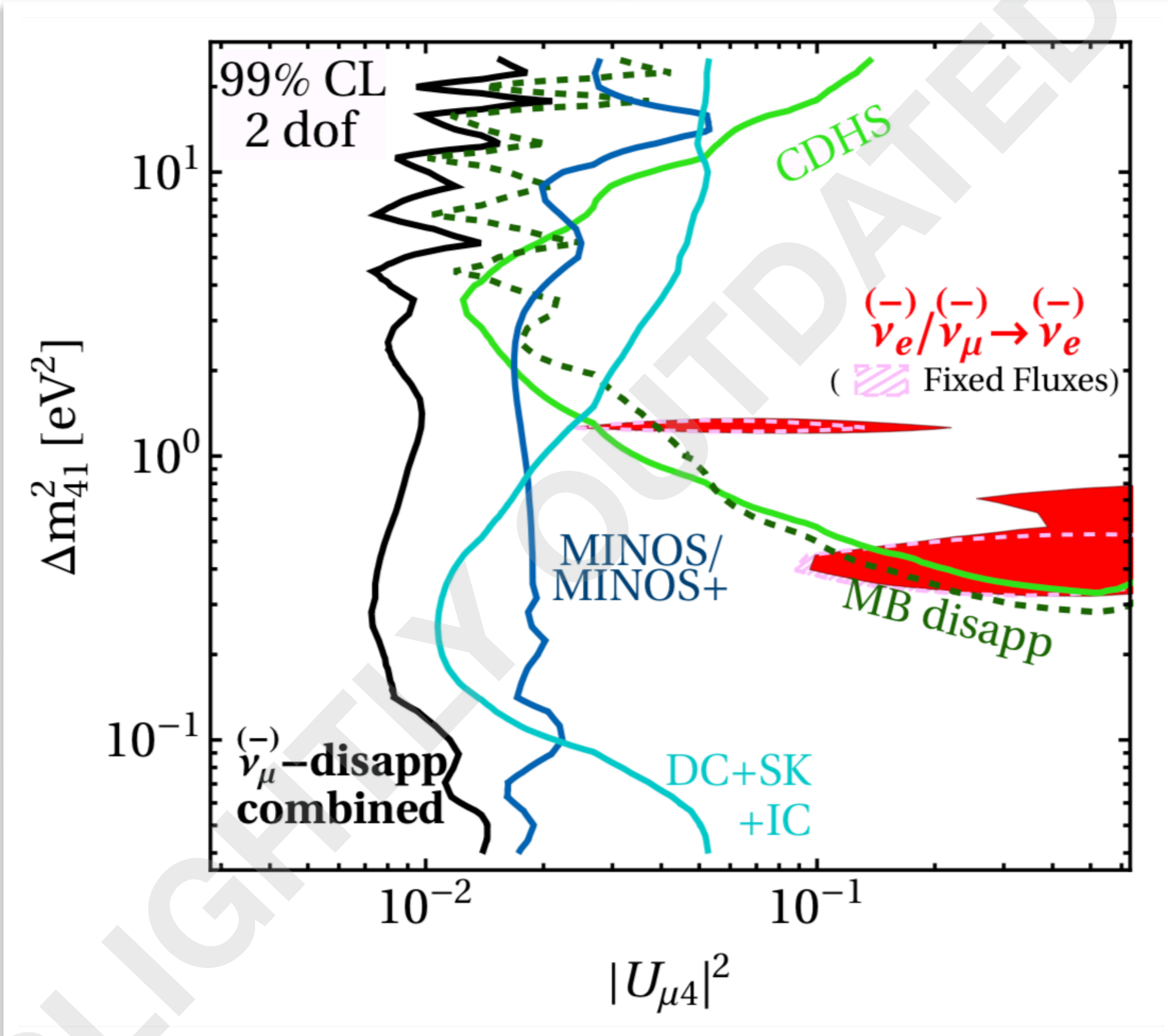


Compatibility Between MiniBooNE and μBooNE



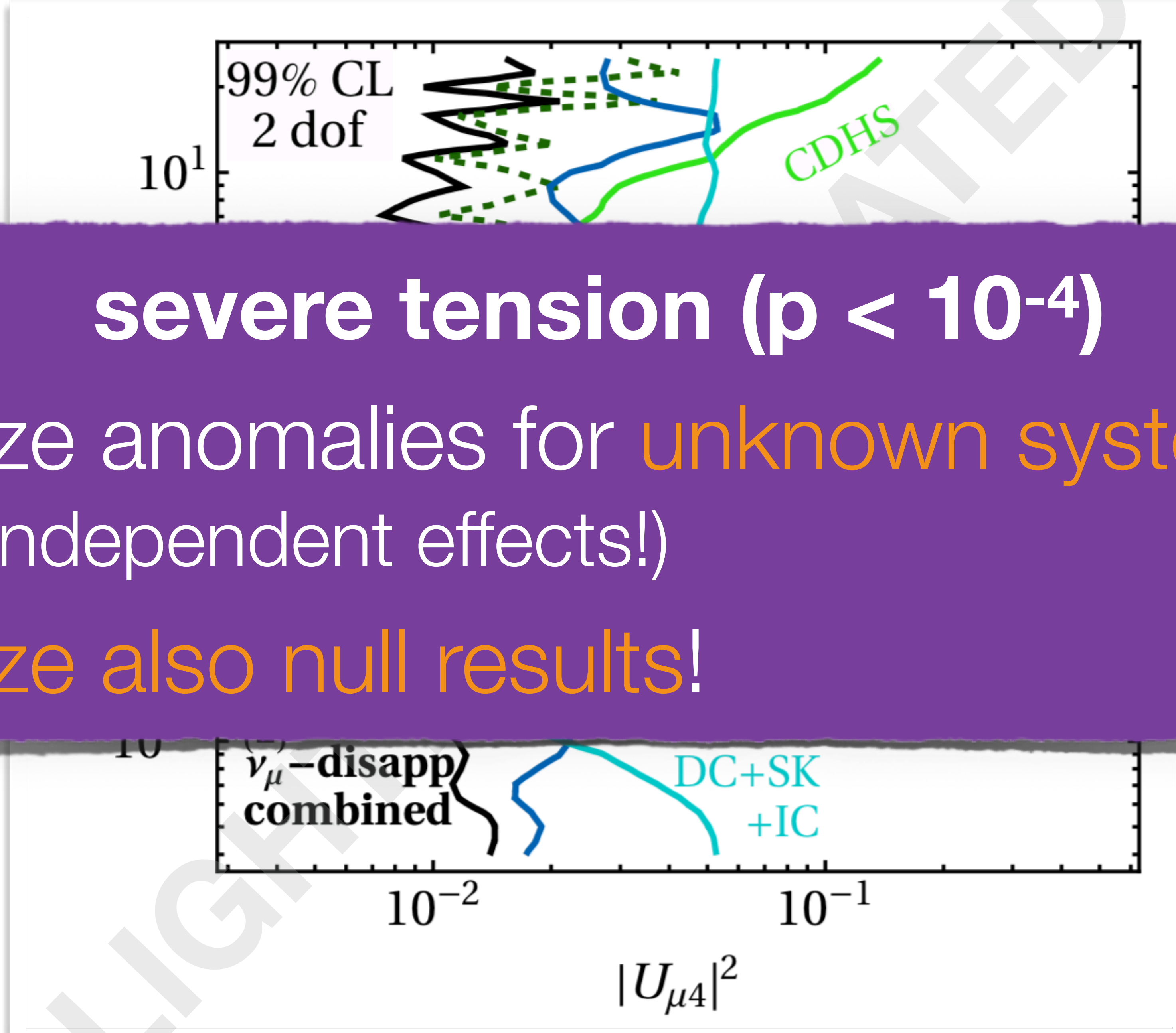
- ☑ 2σ regions overlap
- ☑ relatively good sensitivity driven by downward fluctuation

Tension in Global Sterile Neutrino Fits



Dentler Hernandez JK Machado Maltoni Martinez Schwetz, 1803.10661
see also works by Collin Argüelles Conrad Shaevitz, 1607.00011
Gariazzo Giunti Laveder Li, 1703.00860

Tension in Global Sterile Neutrino Fits



severe tension ($p < 10^{-4}$)

- ☆ scrutinize anomalies for unknown systematics (need 4 independent effects!)
- ☆ scrutinize also null results!

Dentler Hernandez JK Machado Maltoni Martinez Schwetz, 1803.10661
see also works by Collin Argüelles Conrad Shaevitz, 1607.00011
Gariazzo Giunti Laveder Li, 1703.00860

Other BSM Proposals

Other Proposals (1)

- ☑ Decay of O(keV) sterile neutrinos to active neutrinos

  Dentler Esteban JK Machado 1911.01427
  de Gouvea Peres Prakash Stenico 1911.01447
  Hostert Pospelov 2008.11851

- ☑ New resonance matter effects from neutrinophilic Higgs

  Asaadi Church Guenette Jones Szelc 1712.08019

- ☑ Altered dispersion relations

  Döring Päs Sicking Weiler 1808.07460
  Barenboim Martinez-Mirave Ternes Tortola 1911.02329

- ☑ Sterile ν + non-standard interactions

  Liao Marfatia Whisnant 1810.01000

- ☑ Mixed O(1 eV) ν_s oscillation and O(100 MeV) ν_s decay

  Vergani Kamp Diaz Argüelles Conrad Shaevitz Uchida 2105.06470

Other Proposals (2)

- ☑ Decay of heavy ν_s produced in beam

  Palomares-Ruiz Pascoli Schwetz hep-ph/0505216
  Gninenko 1101.4004
  Bai Lu Lu Salvado Stefanek 1512.05357
  Hernandez-Cabezudo Schwetz 1909.09561
  Magill Plestid Pospelov Tsai 1803.03262

- ☑ Decay of ν_s or new scalars produced in the detector

  Alvarez-Ruso Saul-Sala 1705.00353
  Bertuzzo Jana Machado Zukanovich-Funchal 1807.09877
  Abdullahi Hostert Pascoli 2007.11813
  Ballett Pascoli Ross-Lonergan 1808.02915
  Dutta Ghosh Li 2006.01319
  Abdallah Gandhi Roy 2010.06159

- ☑ Decay of axion-like particles

  Chang Chen Ho Tseng 2102.05012

- ☑ A model-independent approach

  Brdar Fischer Smirnov 2007.14411

- ☑ …

Decaying Sterile Neutrinos

Dentler Esteban JK Machado, 1911.01427
de Gouvea Peres Prakash Stenico 1911.01447
Hostert Pospelov 2008.11851

Decaying Sterile Neutrinos

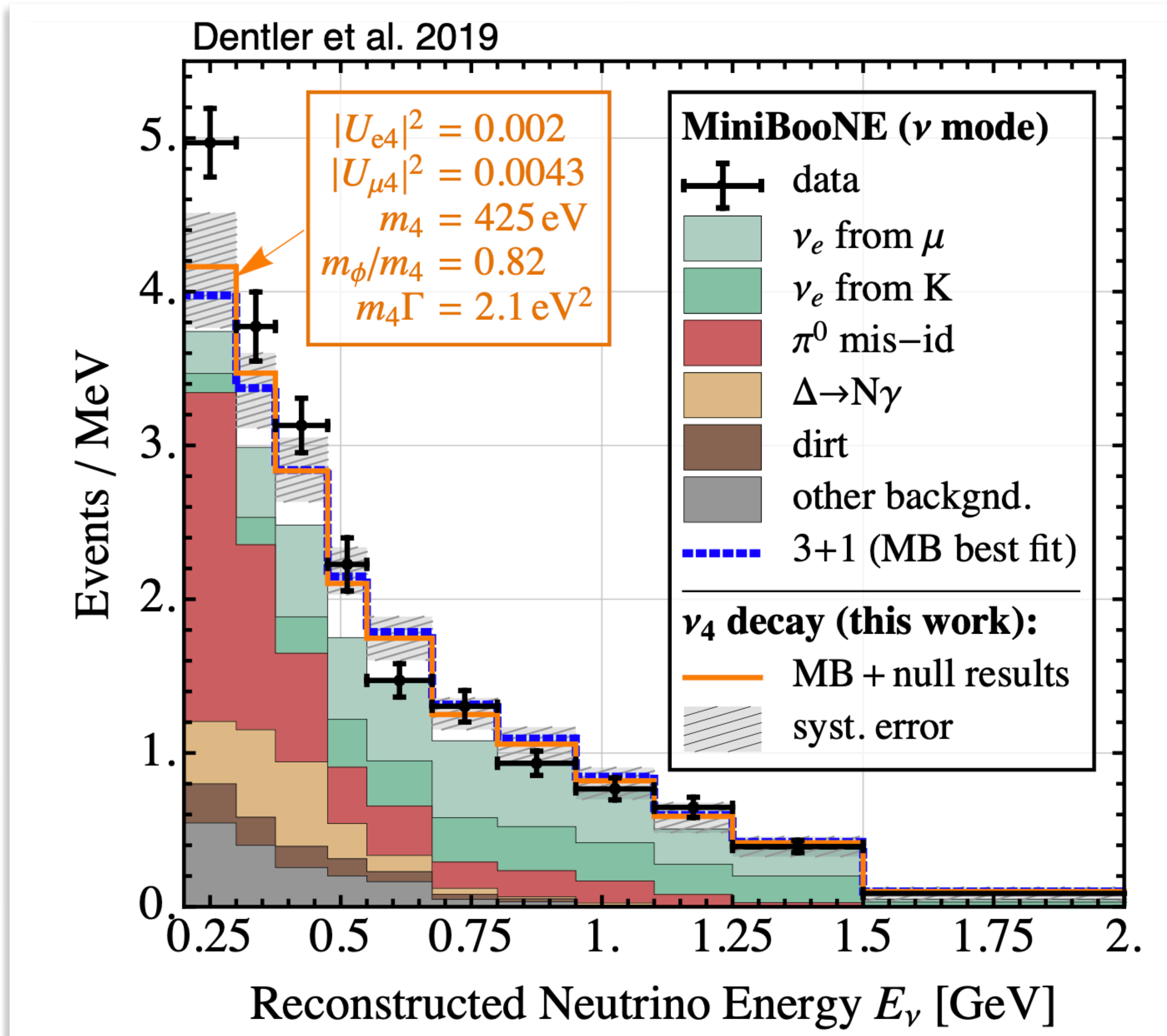
- Idea: production of sterile neutrinos that quickly decay back into active neutrinos (+ light new scalar): $\nu_s \to \nu_a + \Phi$

$$\mathcal{L} \supset -g\,\bar{\nu}_s \nu_s \phi - \sum_{a=e,\mu,\tau,s} m_{\alpha\beta}\,\bar{\nu}_\alpha \nu_\beta$$

Dentler Esteban JK Machado, 1911.01427
de Gouvea Peres Prakash Stenico 1911.01447
Hostert Pospelov 2008.11851

Decaying Sterile Neutrinos

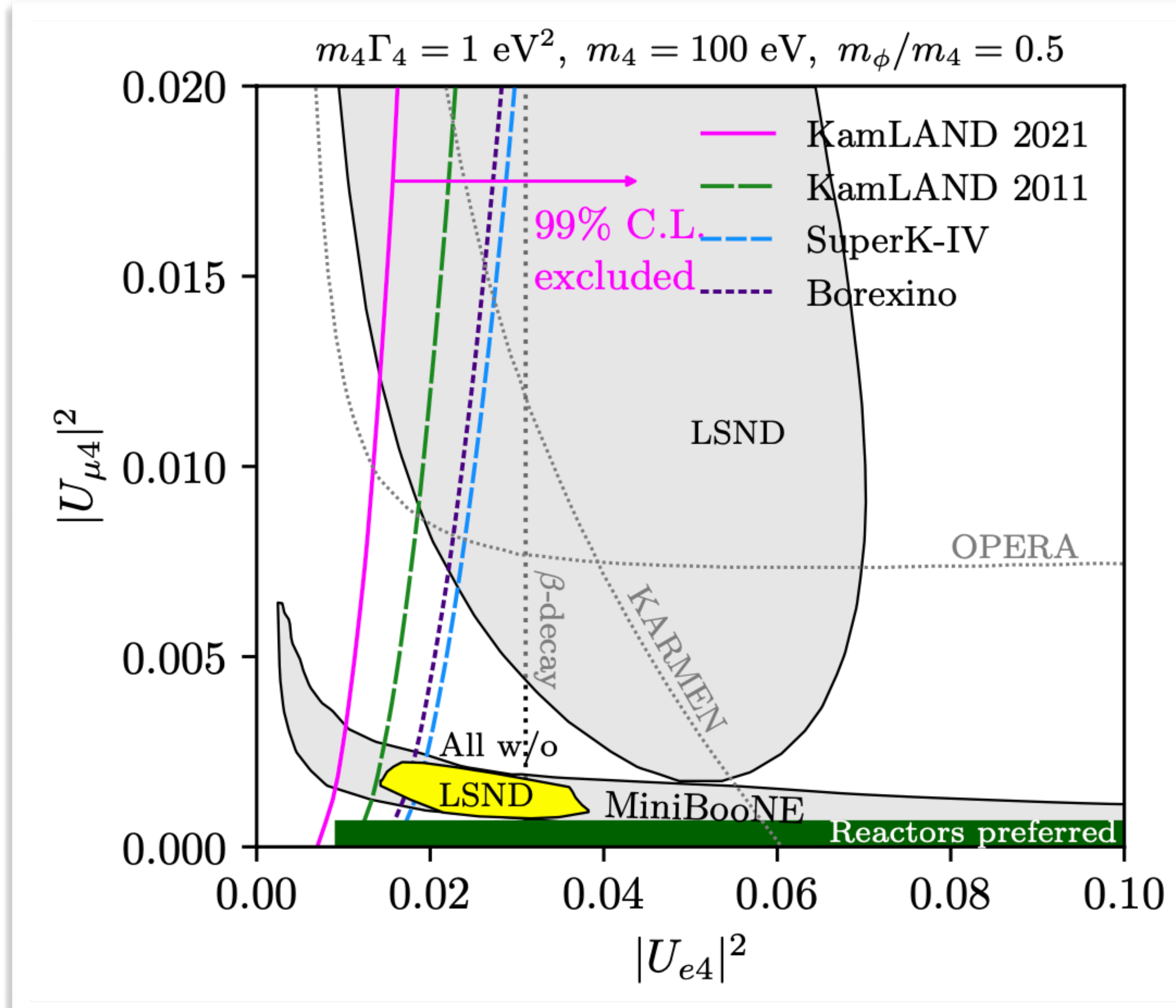
- **Idea:** production of sterile neutrinos that quickly decay back into active neutrinos (+ light new scalar): $\nu_s \to \nu_a + \Phi$
- Excellent fit to MiniBooNE data



Dentler Esteban JK Machado, 1911.01427
de Gouvea Peres Prakash Stenico 1911.01447
Hostert Pospelov 2008.11851

Decaying Sterile Neutrinos

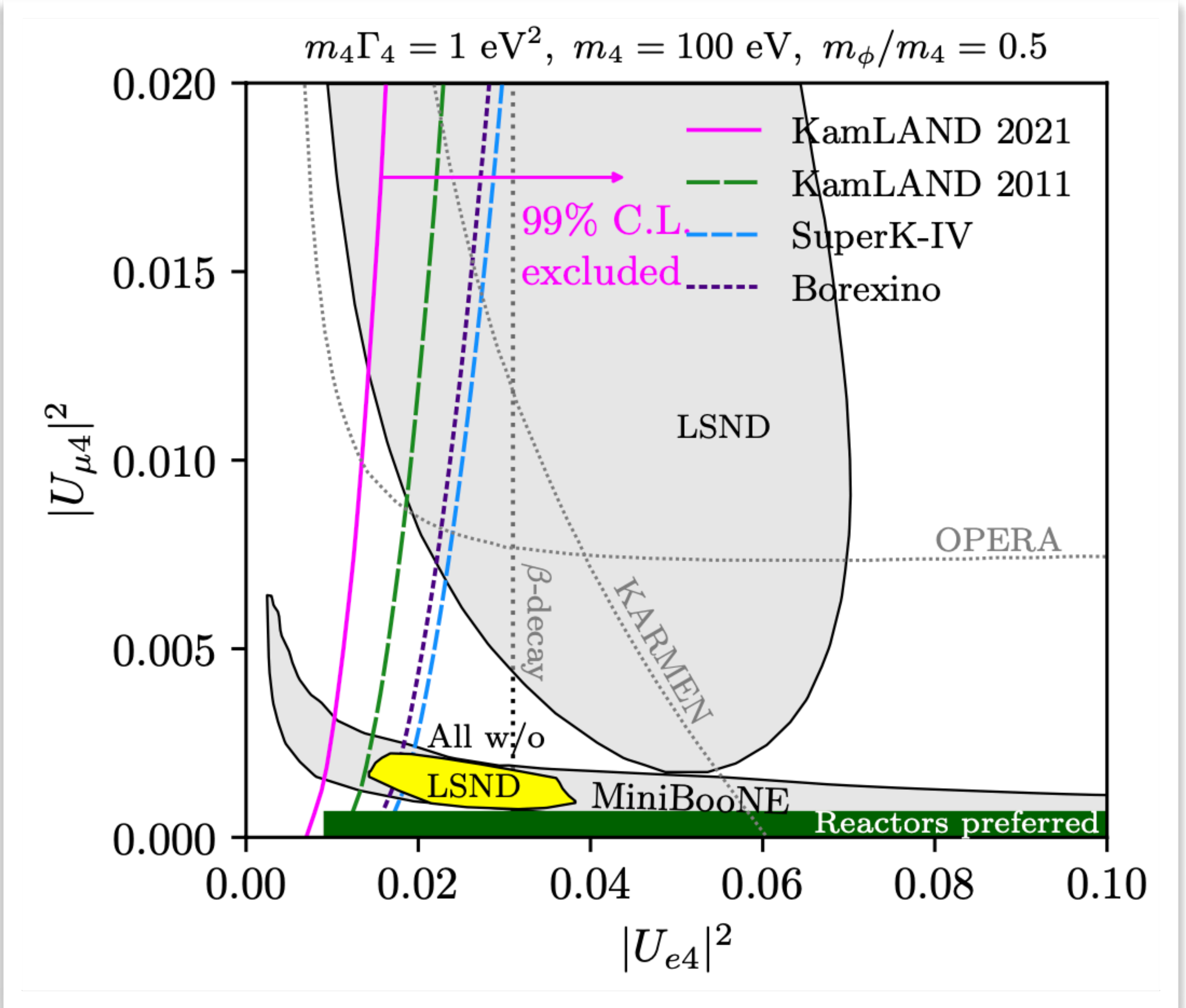
- Idea: production of sterile neutrinos that quickly decay back into active neutrinos (+ light new scalar): $\nu_s \rightarrow \nu_a + \Phi$
- Excellent fit to MiniBooNE data
- Consistent with all null results (incl. cosmology)



Dentler Esteban JK Machado, 1911.01427
de Gouvea Peres Prakash Stenico 1911.01447
Hostert Pospelov 2008.11851

Decaying Sterile Neutrinos

- Idea: production of sterile neutrinos that quickly decay back into active neutrinos (+ light new scalar): $\nu_s \rightarrow \nu_a + \Phi$
- Excellent fit to MiniBooNE data
- Consistent with all null results (incl. cosmology)
- simultaneous fit with LSND disfavoured by solar $\bar{\nu}$



Dentler Esteban JK Machado, 1911.01427
de Gouvea Peres Prakash Stenico 1911.01447
Hostert Pospelov 2008.11851

Future MicroBooNE Searches

MicroBooNE's 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	$1\gamma 0p$	$1\gamma 1p$	$1\gamma X$
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							✔	✔	✔

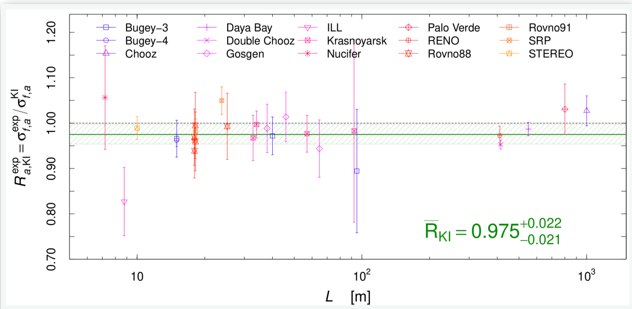
* Requires heavy sterile/other new particles also

µBooNE

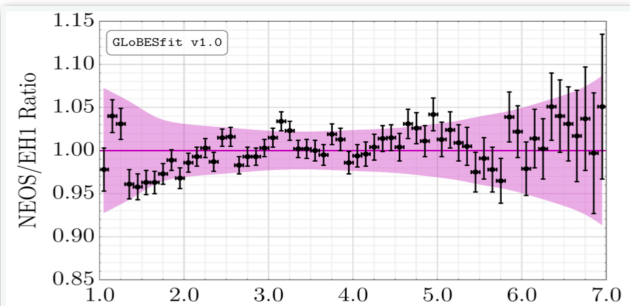
slide by Matthew Toups

Summary

Short-Baseline Anomalies

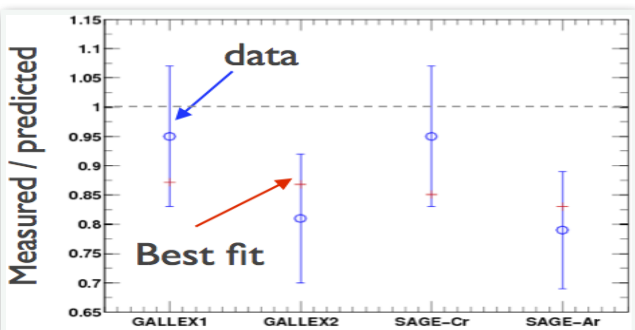


reactor flux anomaly:
resolved with new input data
to flux calculation



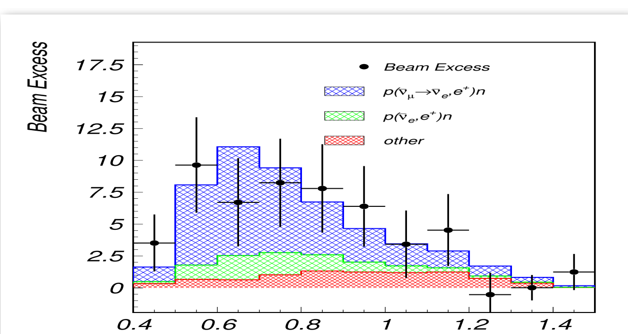
reactor spectra:
unresolved

?



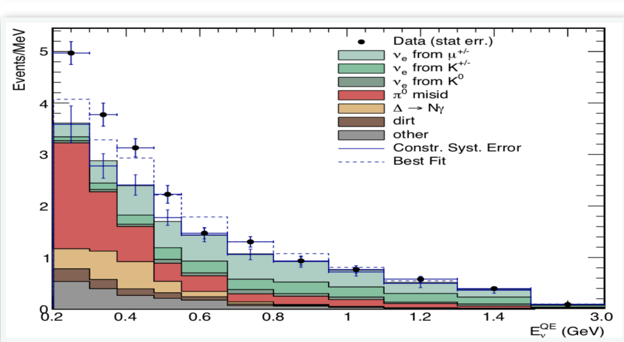
gallium anomaly:
unresolved, recently reinforced

?



$\bar{\nu}_e$ appearance in LSND
unresolved

?



MiniBooNE
unresolved
μBooNE / SBN are game-changers

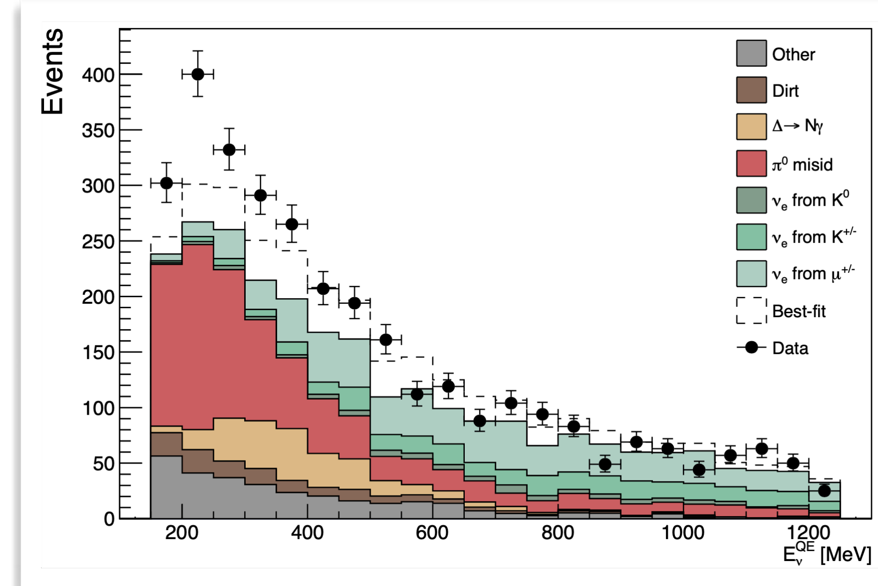
??

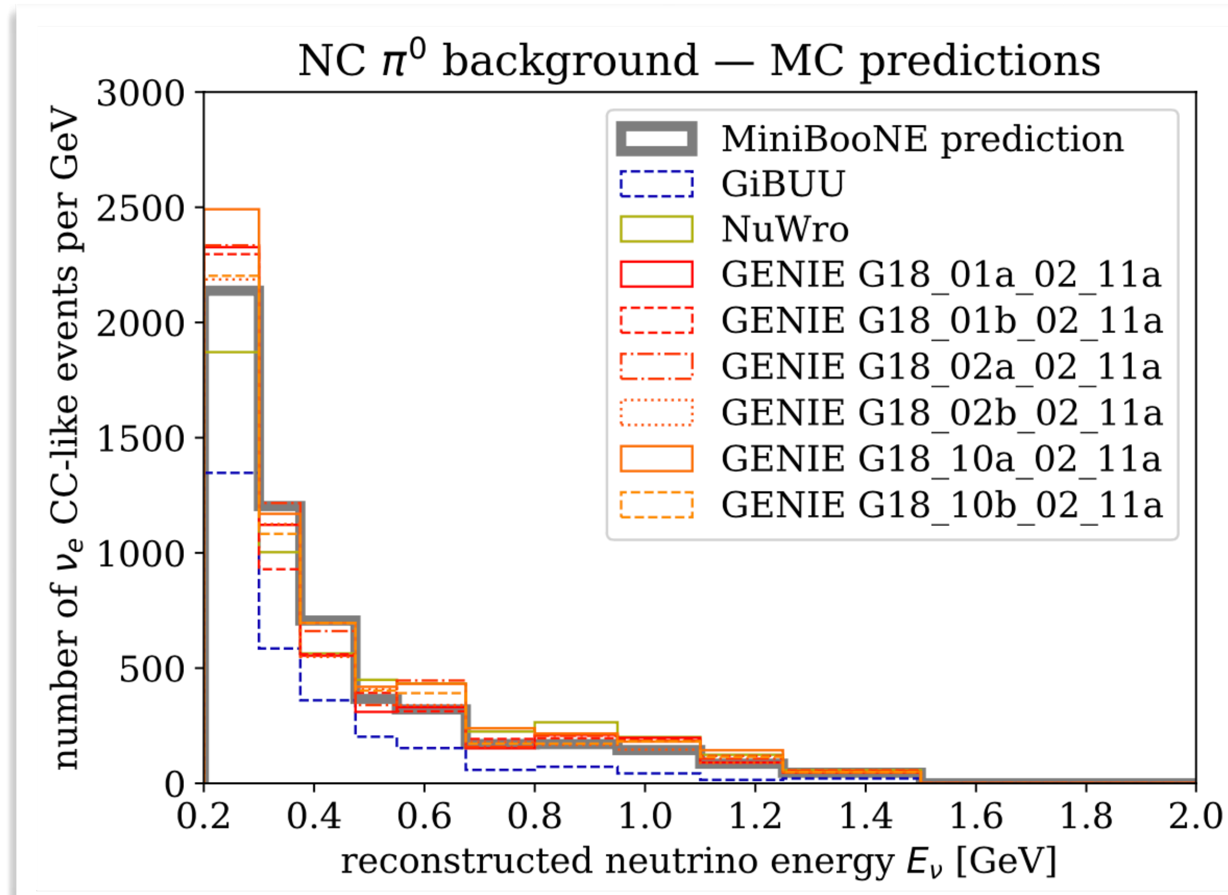
Thank You!

Bonus Slides

π^0

- ☑ ν-induced π^0 prod. is measured → data-driven estimate
- ☑ Rarely, one photon from $\pi^0 \to \gamma\,\gamma$ is missed
  - may be too close to the other γ
  - conversion outside active volume
- ☑ Problem with translation from control sample to signal region?
  - unlikely after >10 years
- ☑ Good agreement with non-data-driven estimates

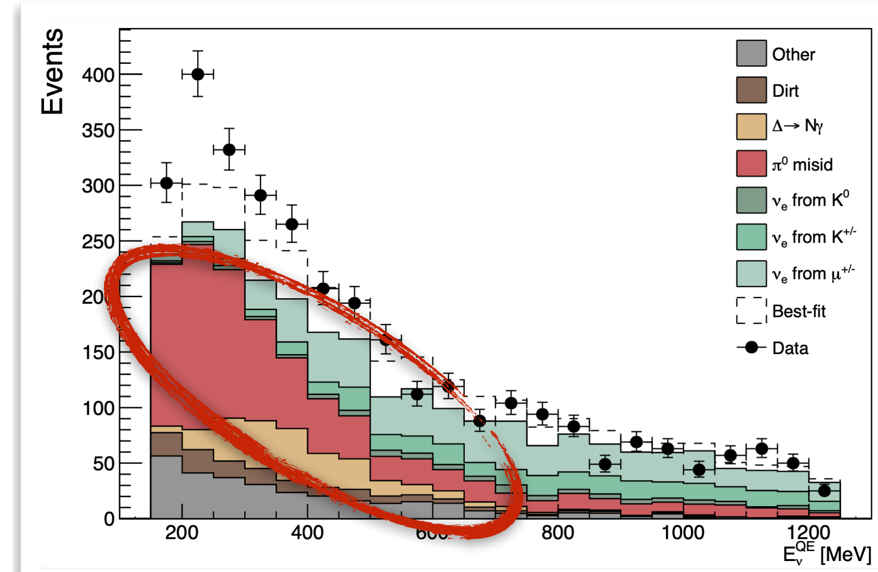


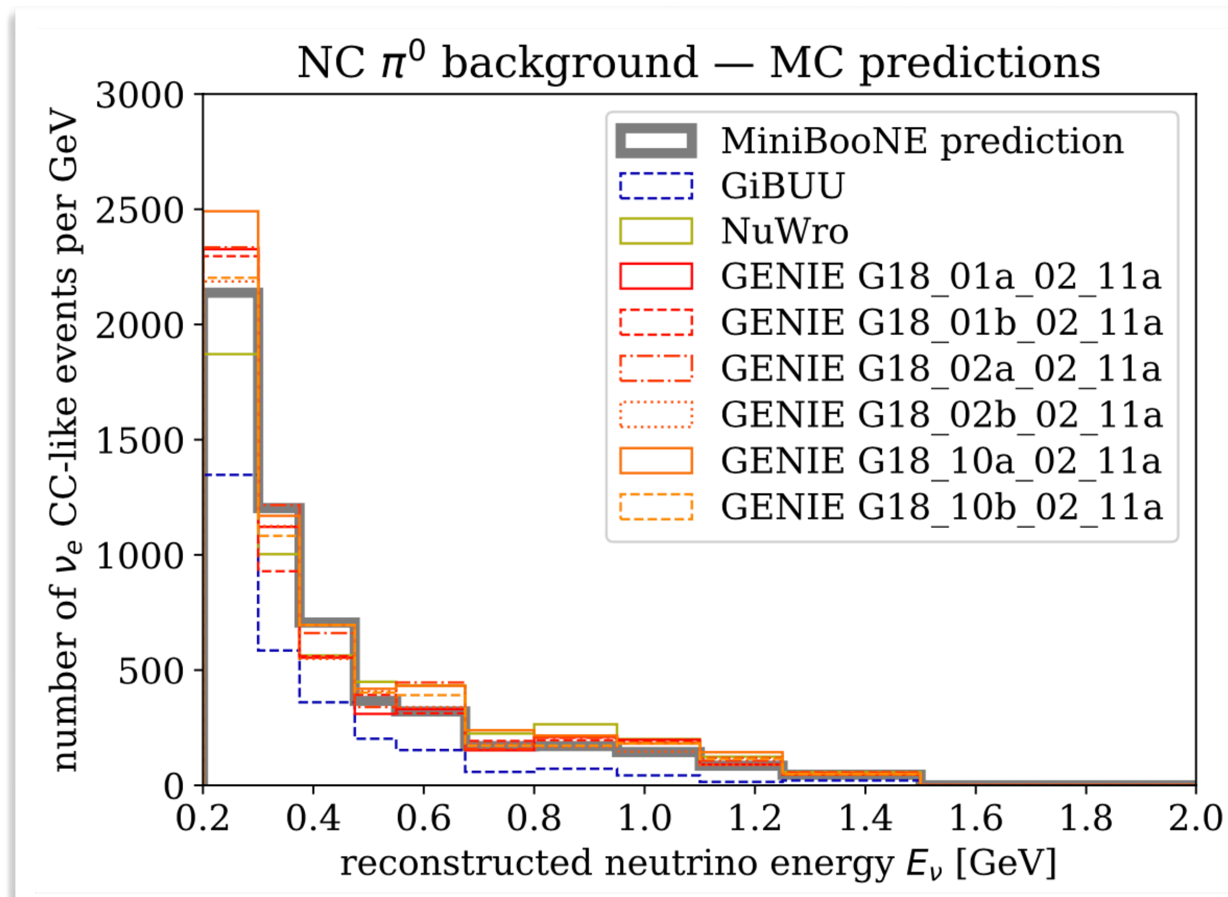


Brdar Kopp arXiv:2109.08157

π^0

- ☑ ν-induced π^0 prod. is measured
  → data-driven estimate
- ☑ Rarely, one photon from
  $\pi^0 \to \gamma\,\gamma$ is missed
  - may be too close to the other γ
  - conversion outside active volume
- ☑ Problem with translation from control sample to signal region?
  - unlikely after >10 years
- ☑ Good agreement with non-data-driven estimates





Brdar Kopp arXiv:2109.08157