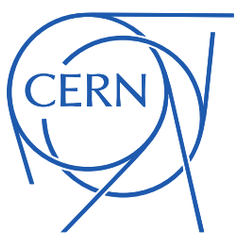
Neutrino Oscillation Anomalies

Joachim Kopp (CERN & JGU Mainz)
NBIA Neutrino School | July 2022



The Neutrino Portal

$$\mathcal{L} \supset y\, \bar{L}\, (i\sigma^2 H^*)\, N$$

☑ the only renormalizable coupling of the SM to a singlet fermion (aka “sterile neutrino” or “heavy neutral lepton”)

The Neutrino Portal

SM lepton doublet

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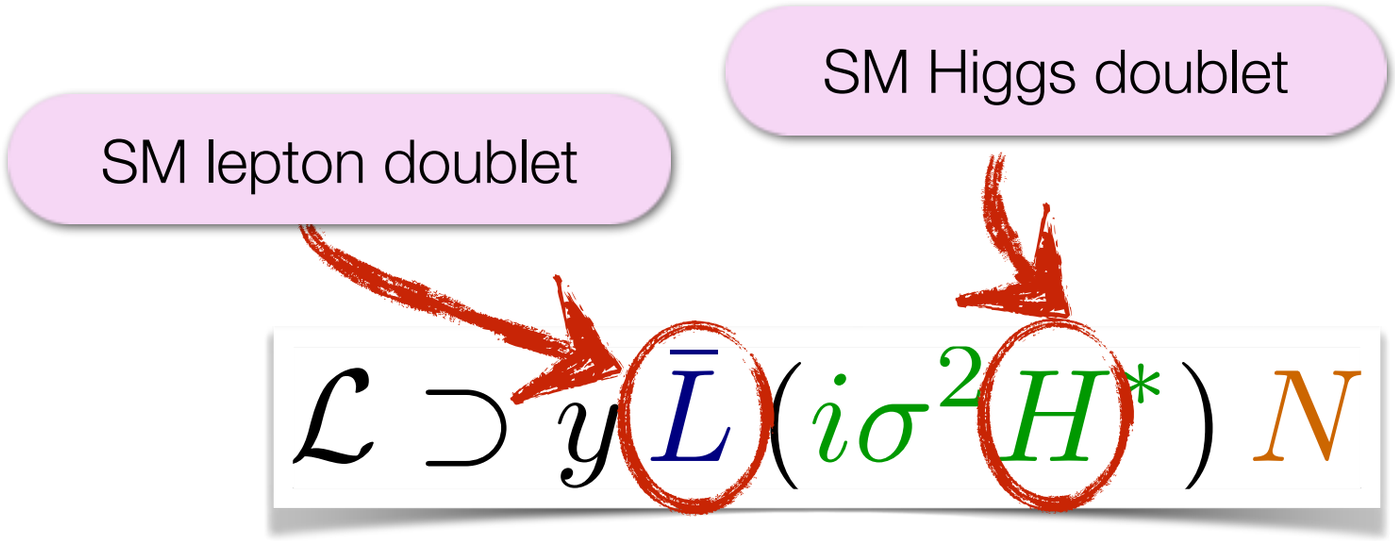


☑ the only renormalizable coupling of the SM to a singlet fermion (aka “sterile neutrino” or “heavy neutral lepton”)

The Neutrino Portal

SM Higgs doublet

SM lepton doublet

SM singlet fermion
(sterile neutrino)

$$\mathcal{L} \supset y \bar{L} (i\sigma^2 H^*) N$$

☑ the only renormalizable coupling of the SM to a singlet fermion (aka “sterile neutrino” or “heavy neutral lepton”)

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
    (thermal leptogenesis at m≫100 GeV, ARS leptogenesis at m<100 GeV)
  - can explain dark matter (m ~ keV)
  - can act a mediator to a dark sector (any mass)
  - can explain oscillation anomalies (m ~ eV)
    - ➠ Georgia Karagiorgi's talk

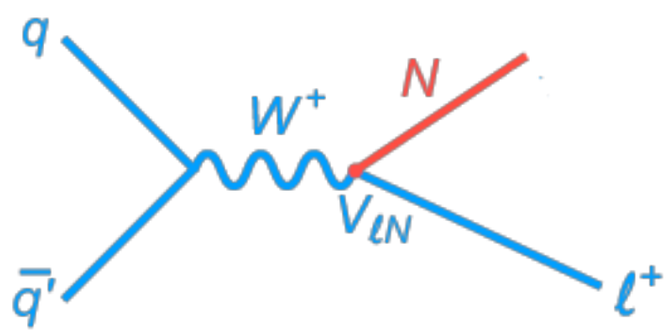
Neutrino Portal Phenomenology

$$\mathcal{L} \supset y\,\bar{L}\,(i\sigma^2 H^*)\,N$$

☑ new contribution to the ν mass matrix
leads to mass mixing between ν and *N*

➠ active–sterile neutrino oscillations

➠ *N* production in neutrino interactions



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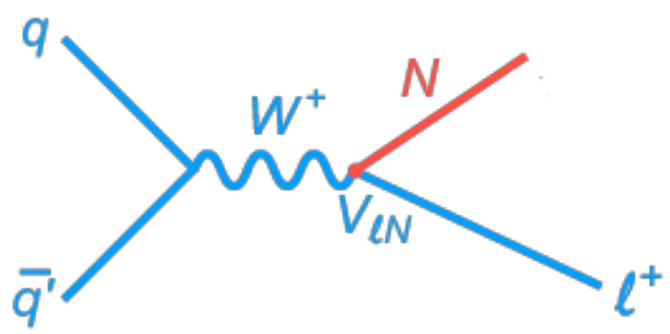

Neutrino Oscillations

☑ Initial state

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

☑ Transition probability

$$P_{\alpha\to\beta} = \left|\langle\nu_\beta| e^{-i\hat{H}T} |\nu_\alpha\rangle\right|^2$$

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

☑ Two flavor approximation

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \qquad P_{\alpha\to\beta} \simeq \sin^2 2\theta \sin^2 \frac{\Delta m^2 T}{4E}$$

Neutrino Oscillations

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

generalizes to
> 3 flavors

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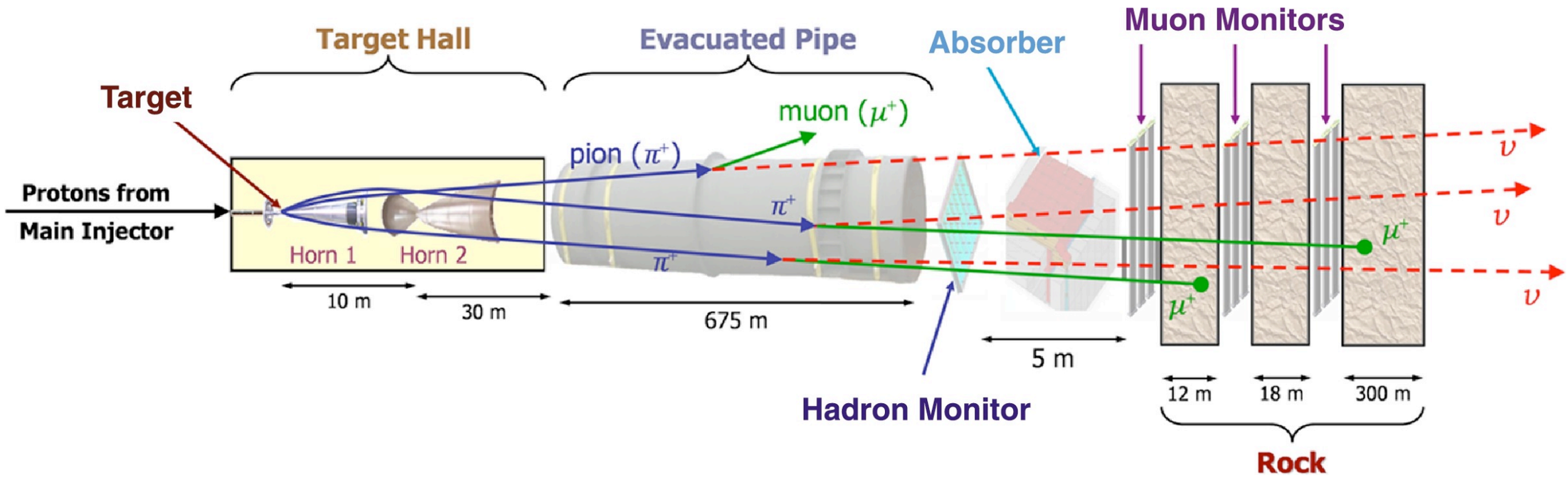
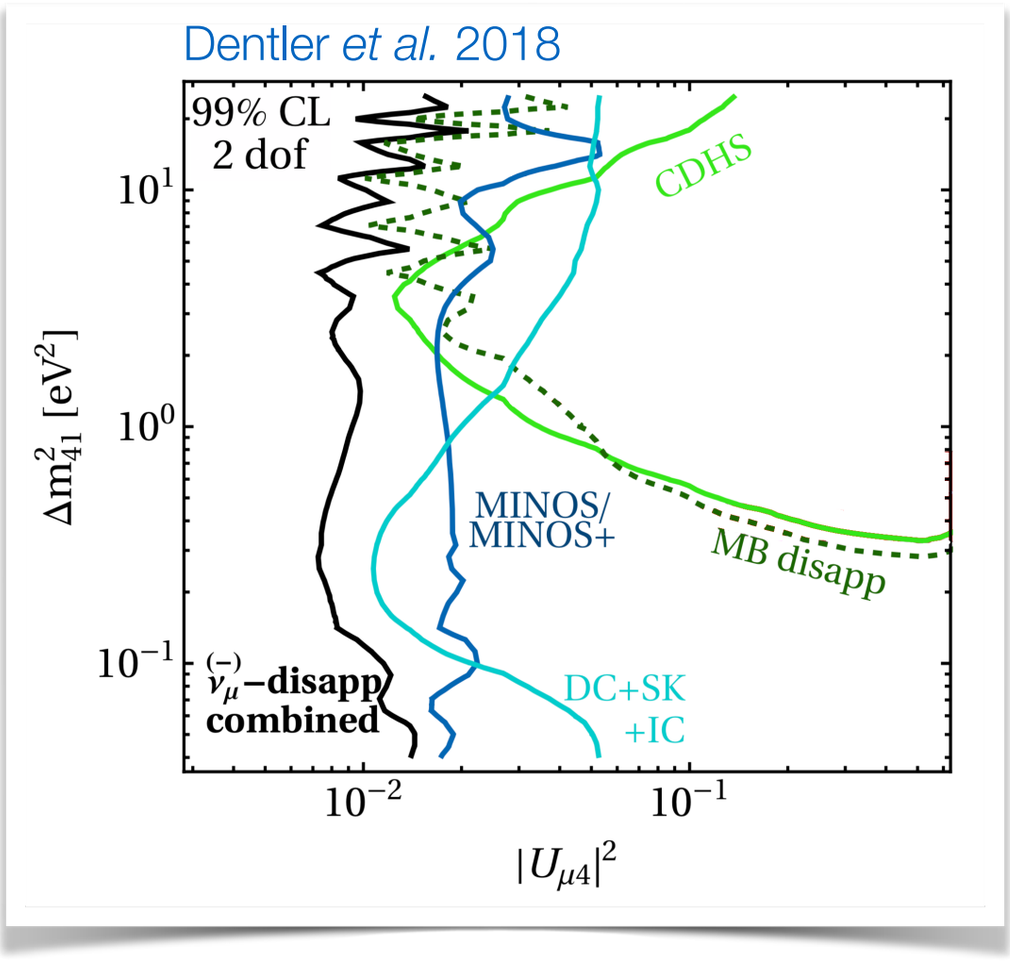


Oscillation Example: ν_μ Disappearance

- ☑ Use intense flux of ν_μ from pion decay in accelerator experiment or in the upper atmosphere
- ☑ Look for "missing" ν_μ at distances too short to be compatible with standard oscillations



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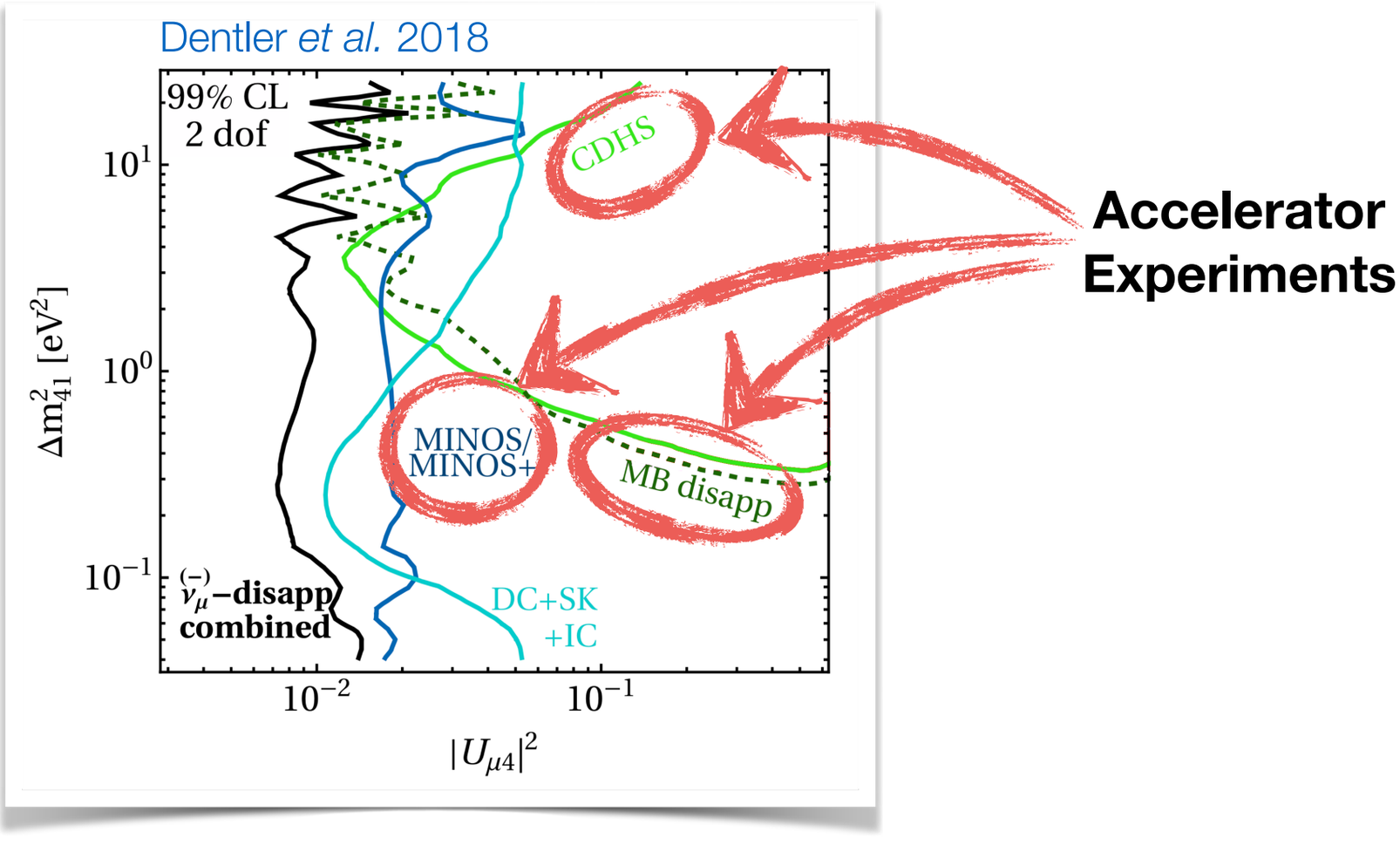

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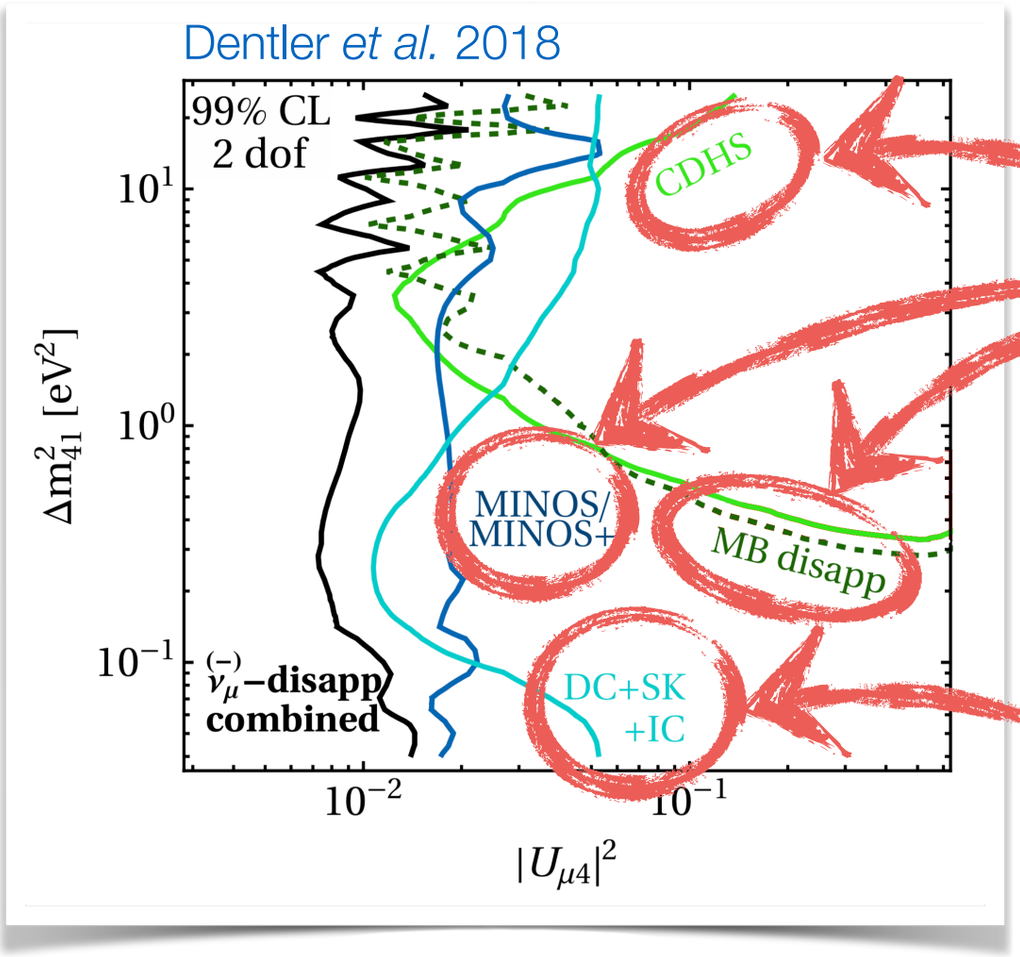

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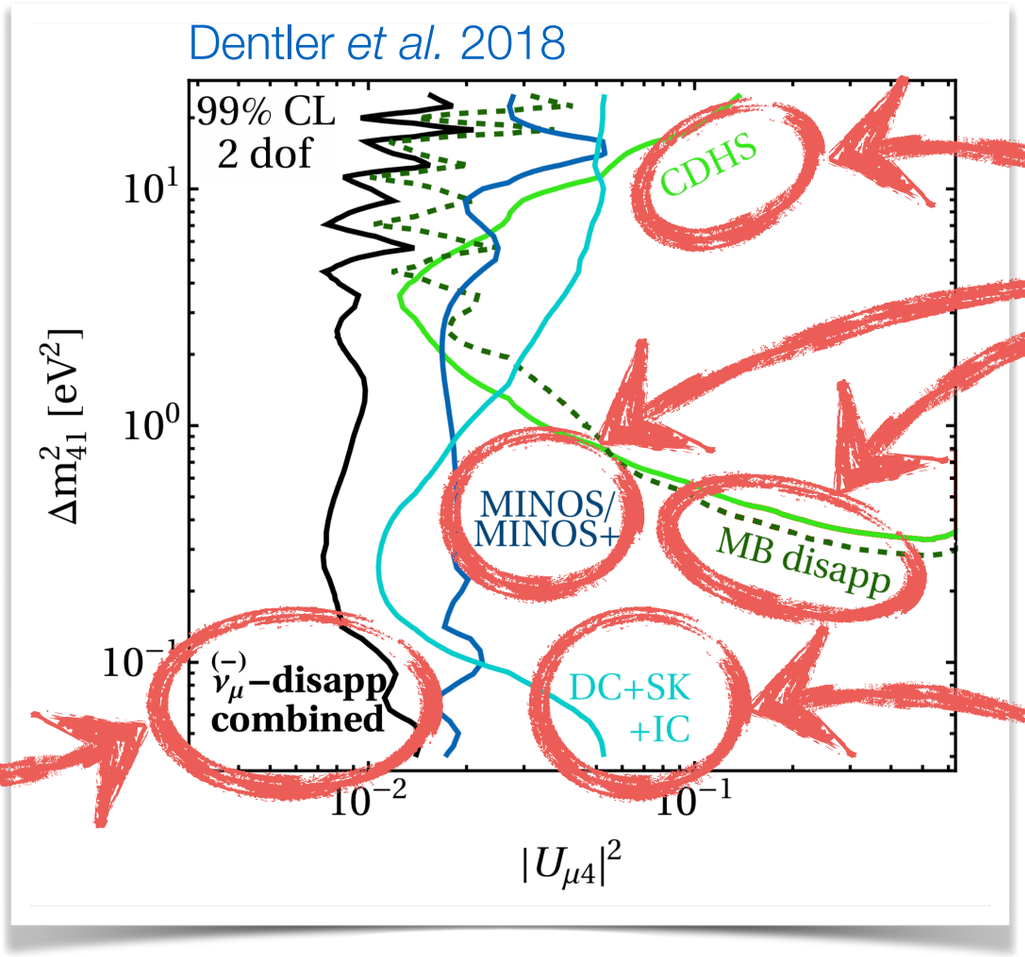


Accelerator Experiments

Combined Fit

Atmospheric Neutrinos

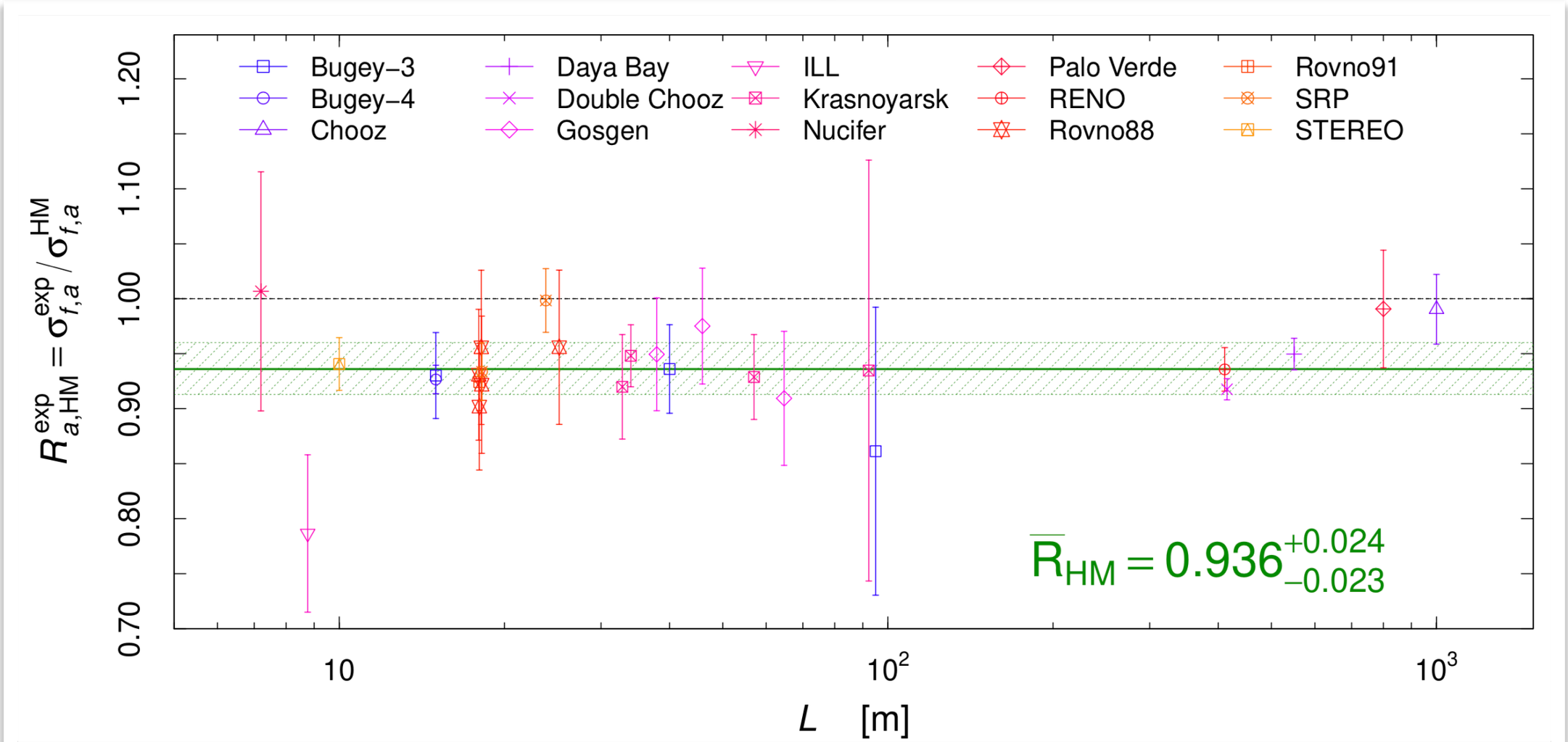
Short-Baseline Anomalies

Interestingly, some experiments have presented results consistent with oscillations involving sterile neutrinos

Anomaly #1: Reactor Neutrino Fluxes

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

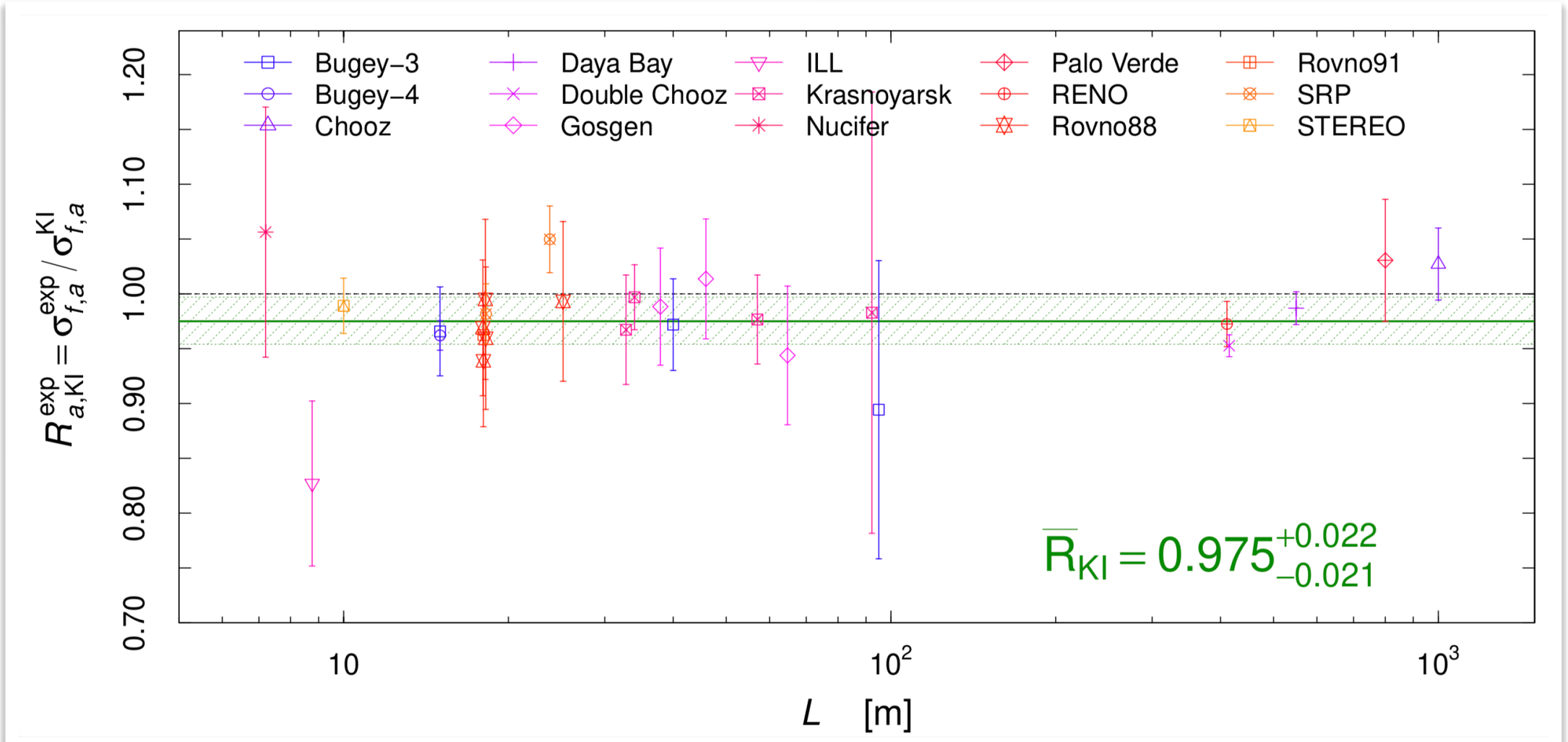
➠ oscillations of $\bar{\nu}_e$ into sterile neutrinos $\bar{\nu}_s$?



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)



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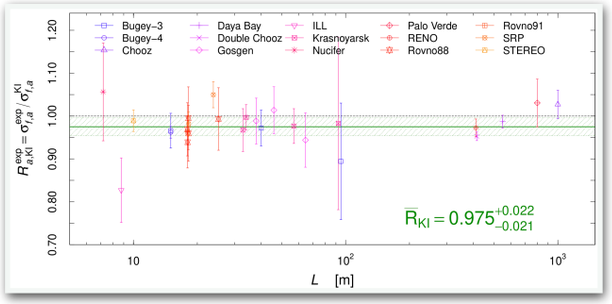

reactor flux anomaly:
resolved with new input data
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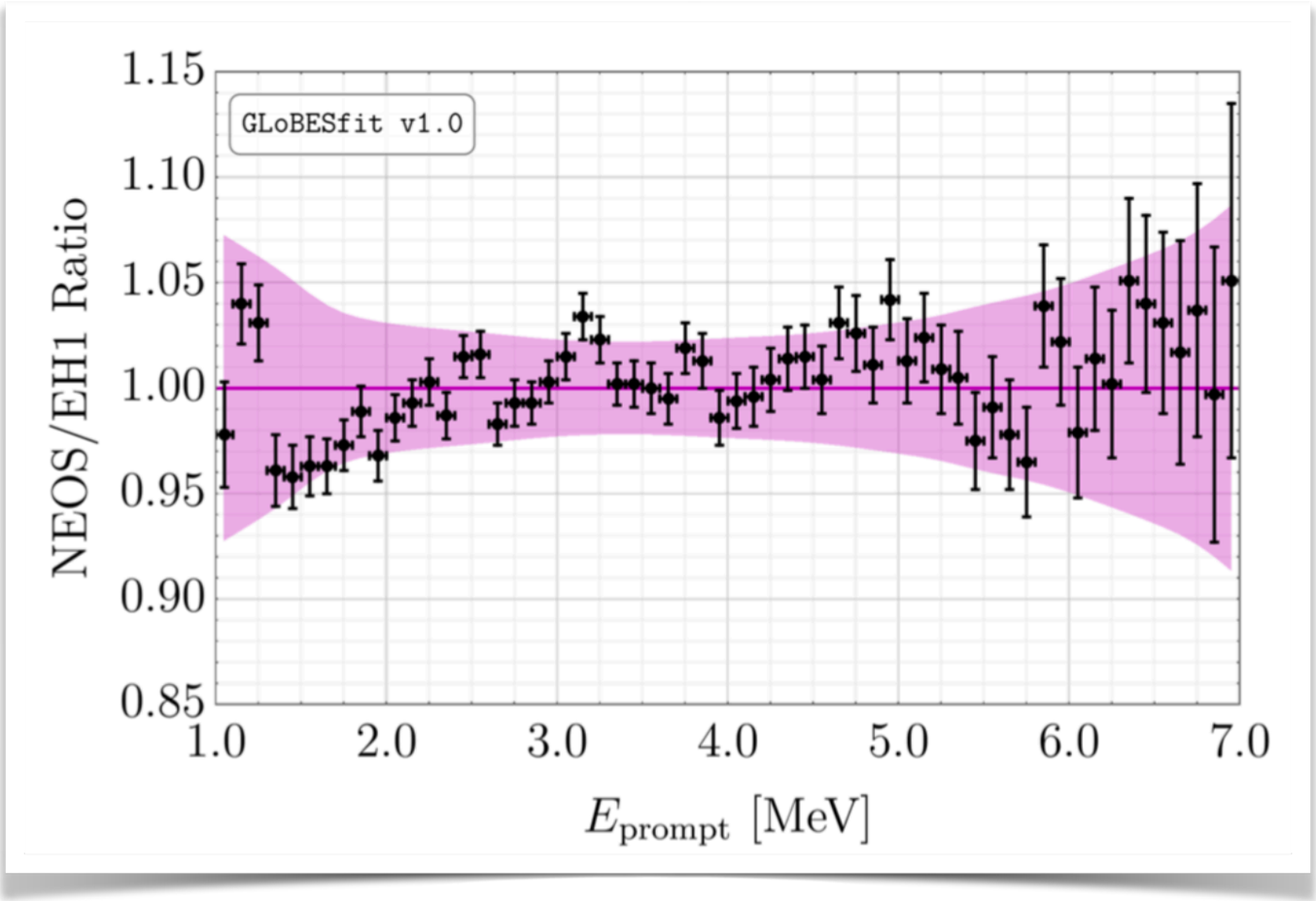
Anomaly #2: Reactor Spectra



- ☑ 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

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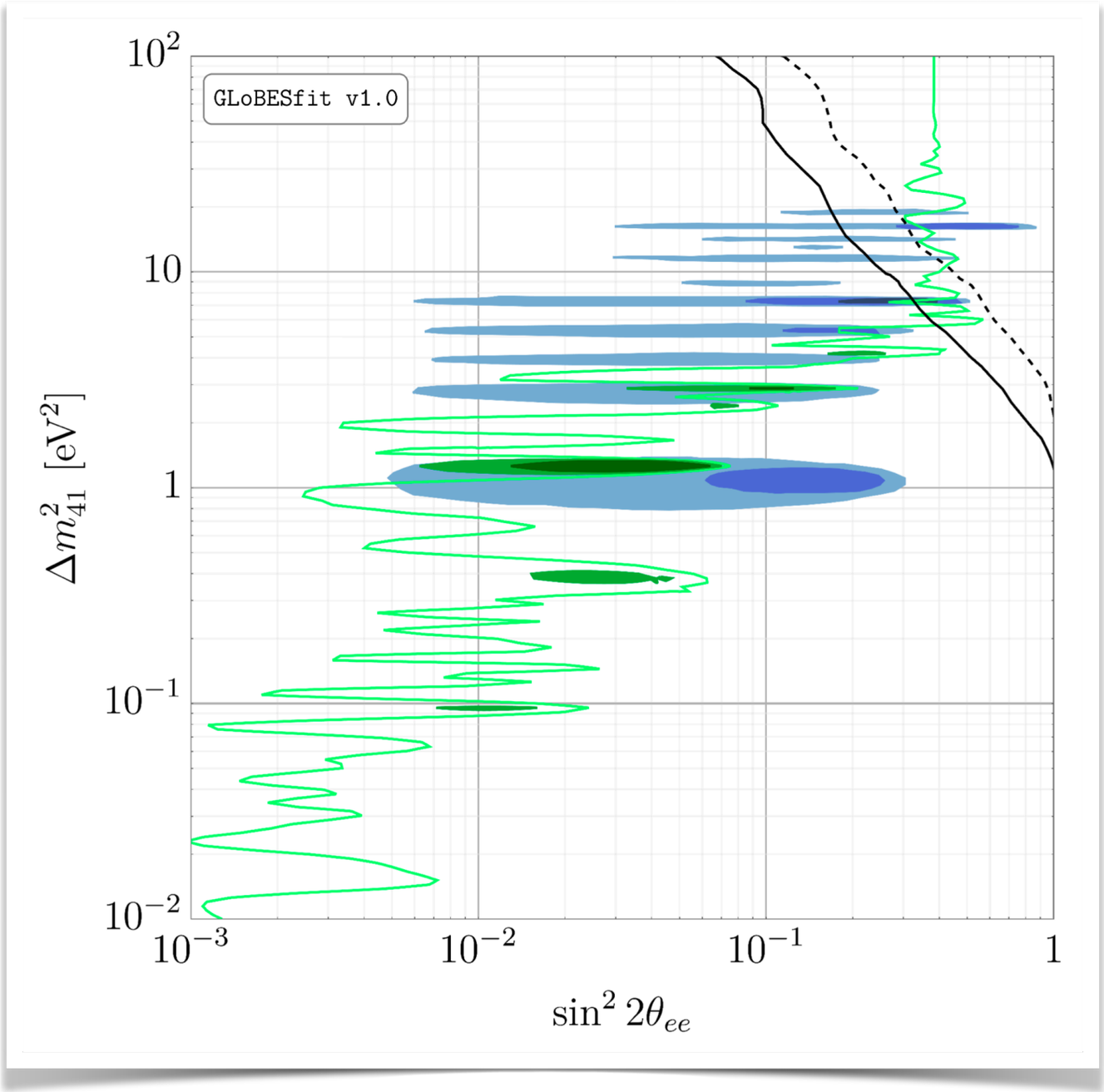

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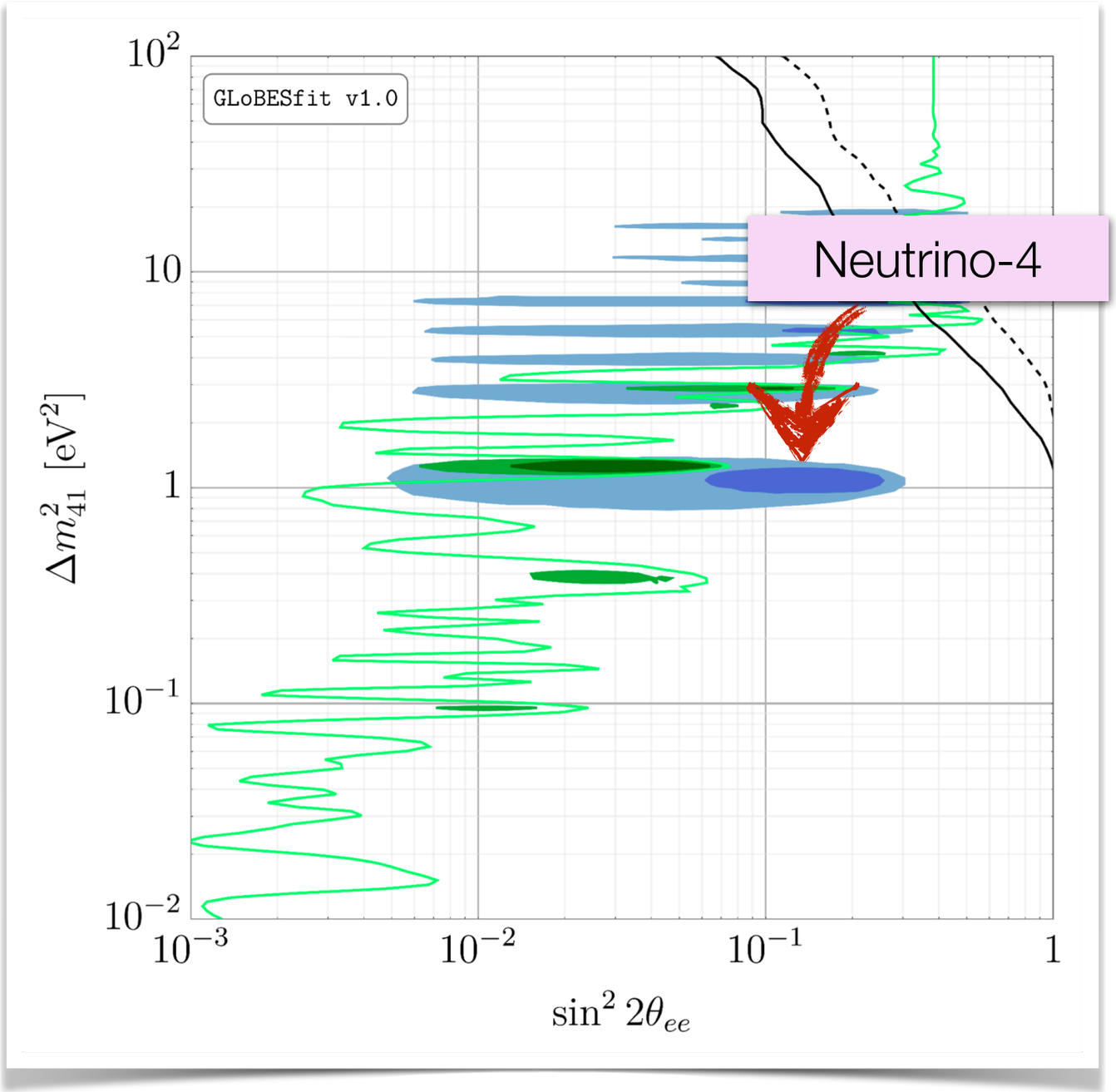

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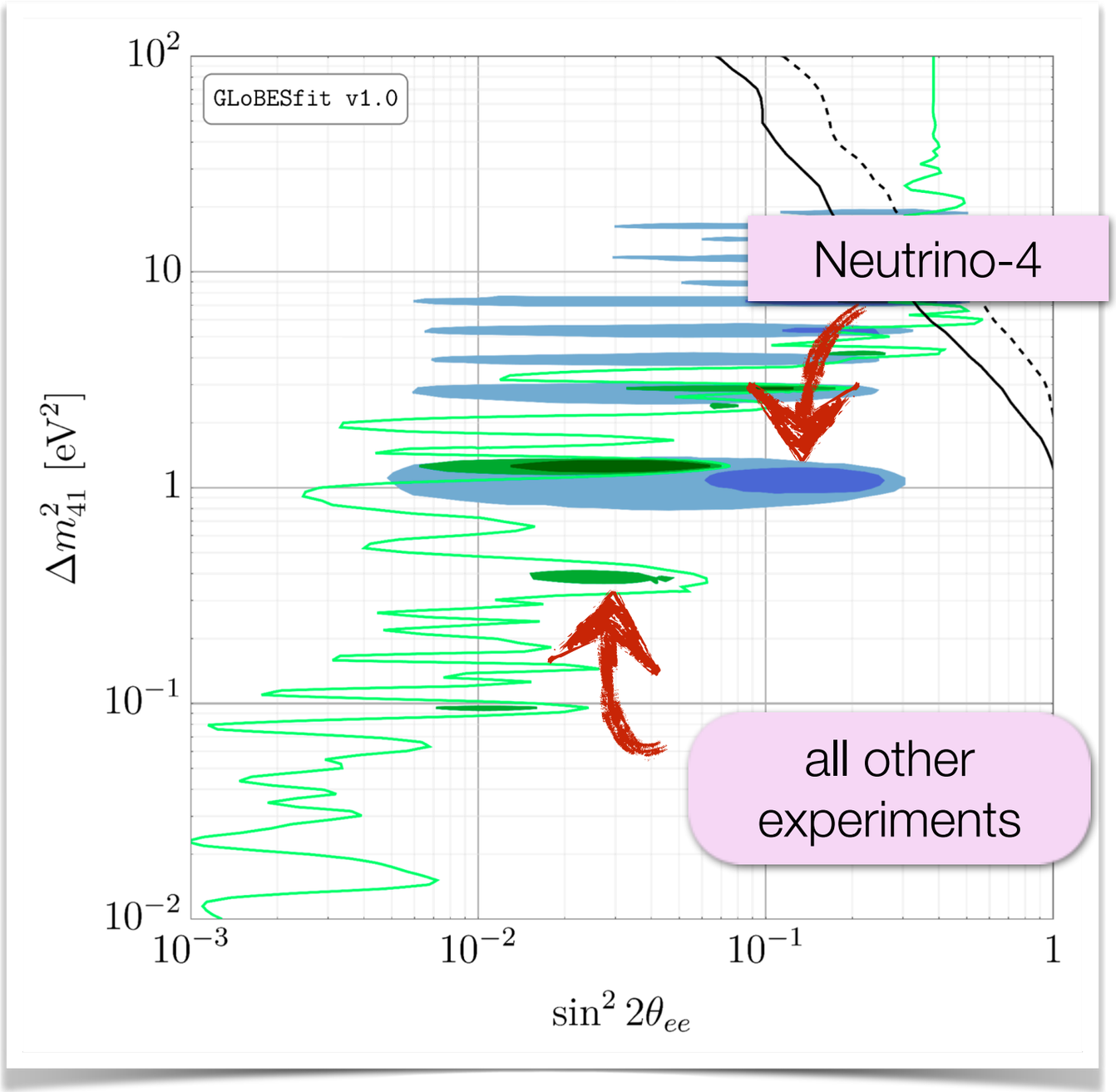

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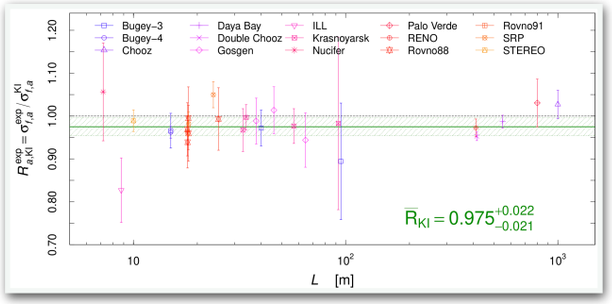
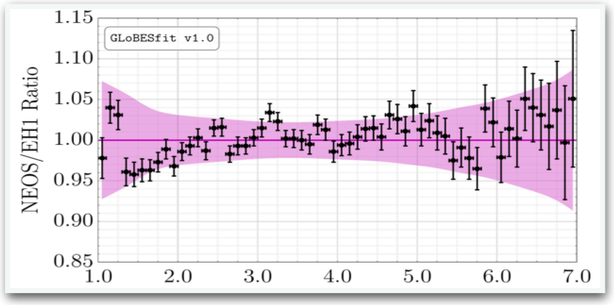




reactor flux anomaly:
resolved with new input data
to flux calculation

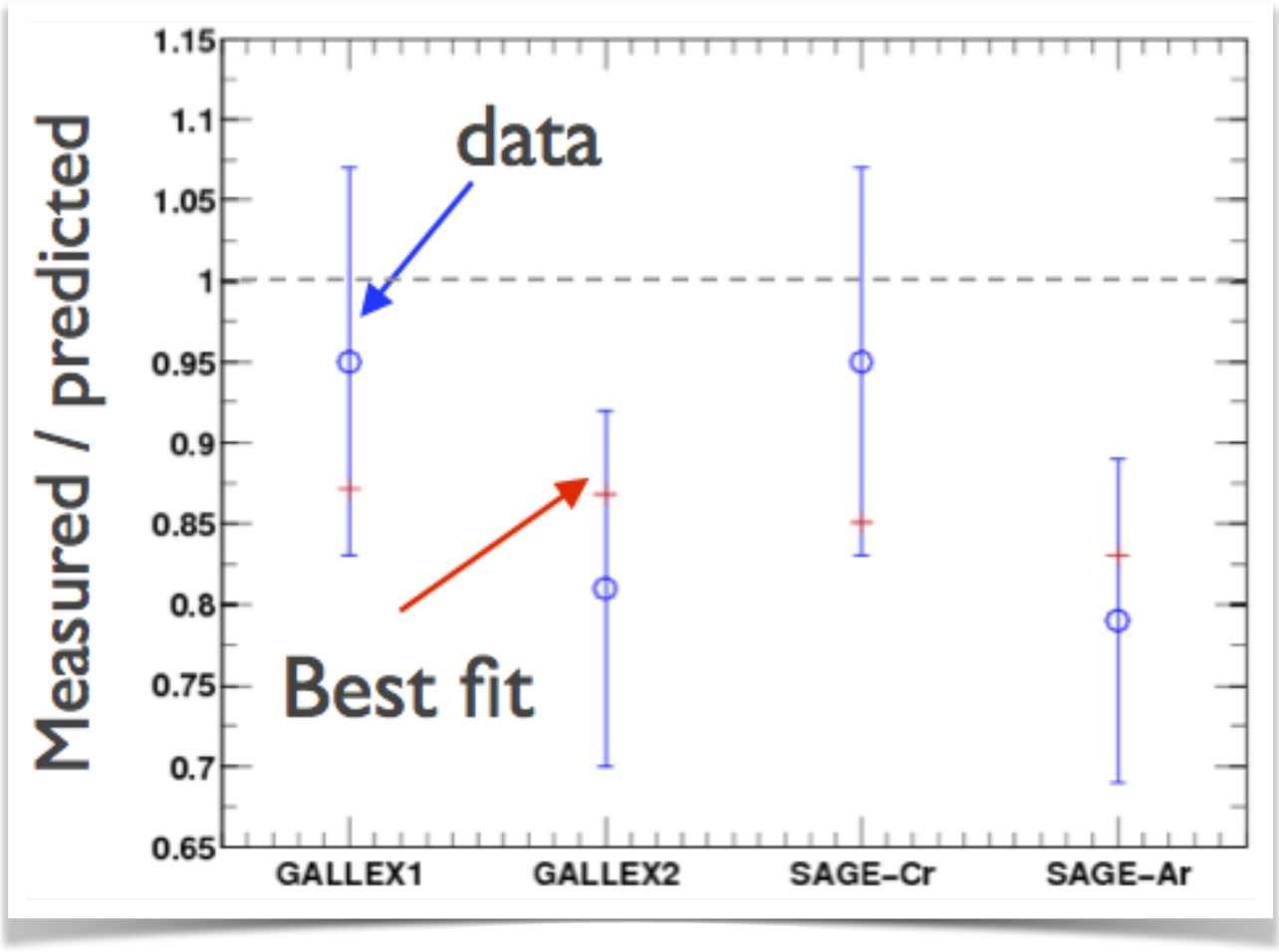
reactor spectra:
unresolved

Anomaly #3: the Gallium Anomaly

- ☑ Experiments with intense radioactive sources
- ☑ Neutrino detection via

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

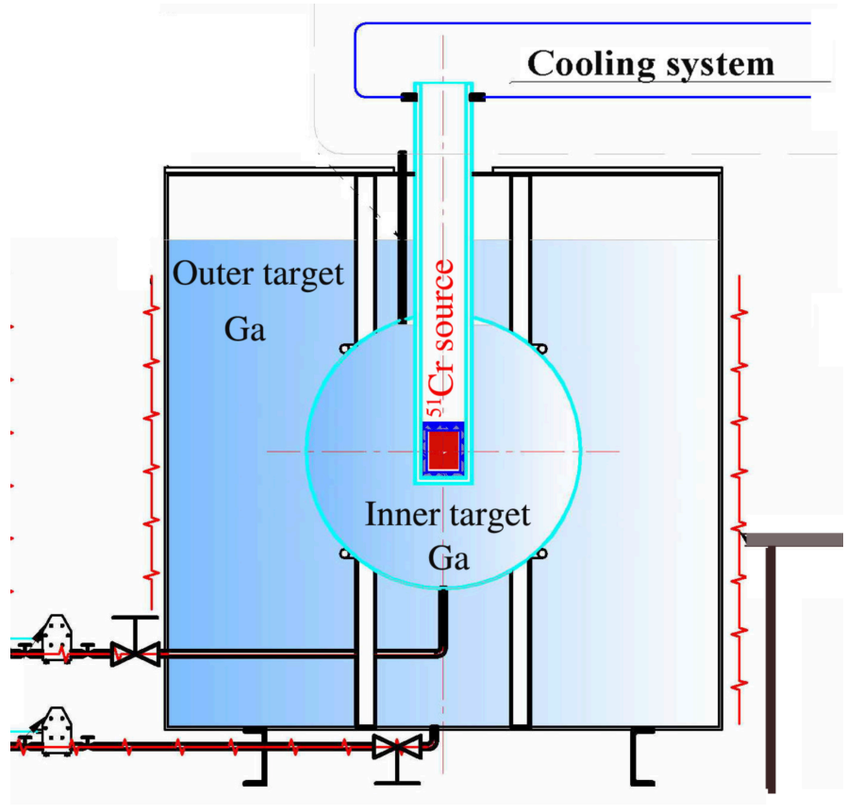
- ☑ ~3σ deficit
- ☑ ν_e disappearance into sterile state?
- ☑ would require very large mixing
  (conflict with reactor observations)



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

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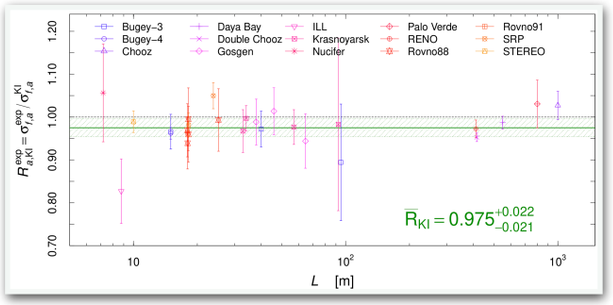

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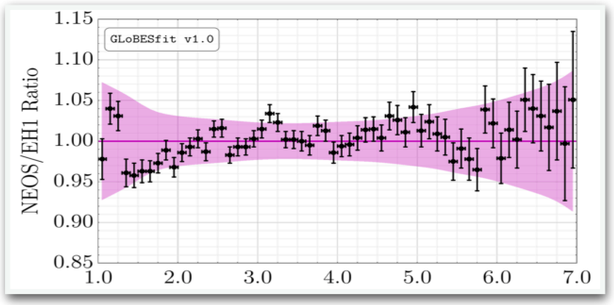

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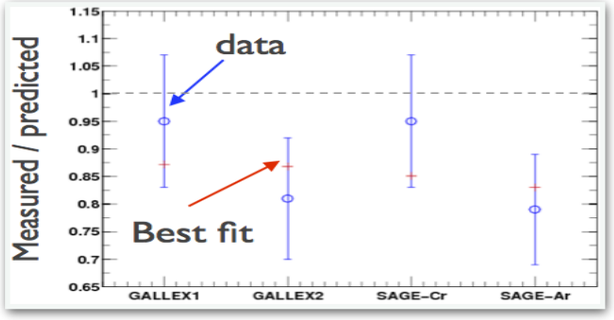
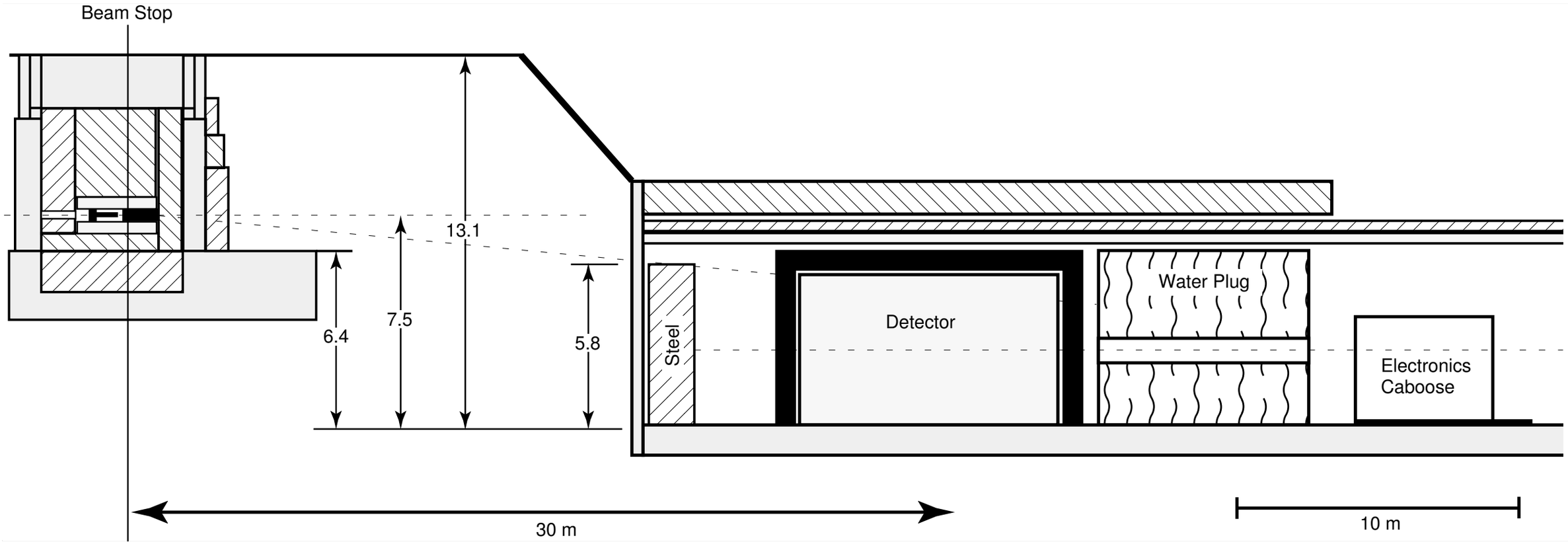


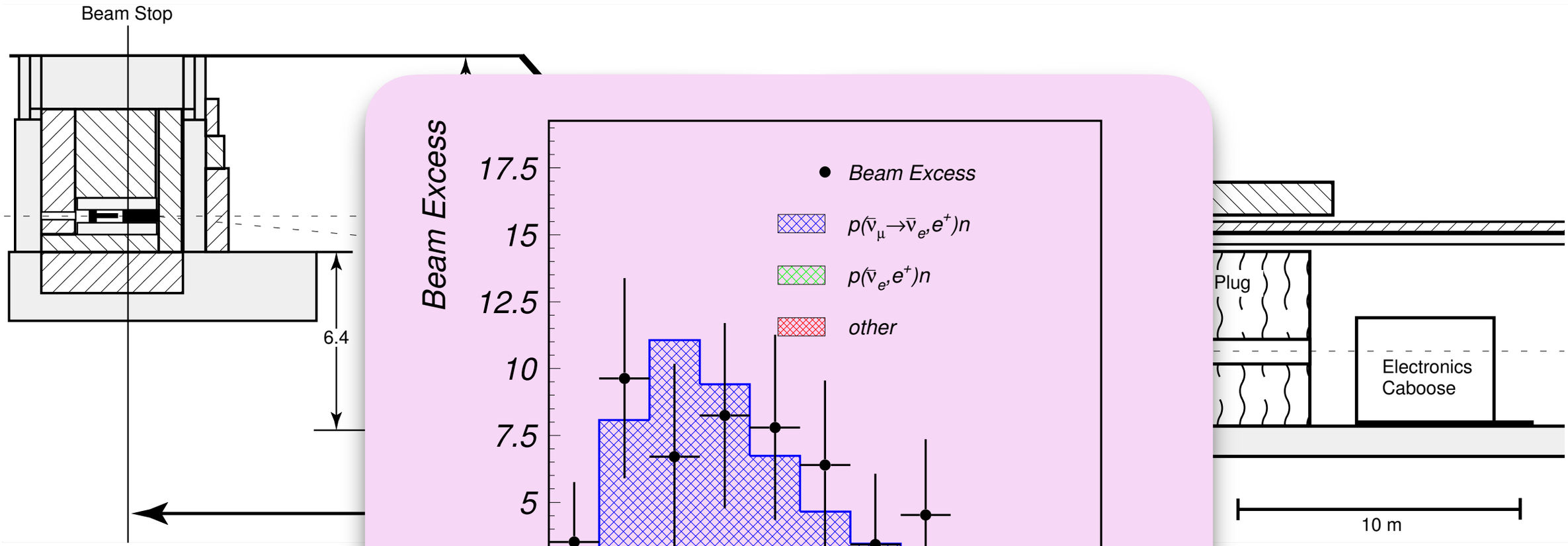
gallium anomaly:
unresolved, recently reinforced

Anomaly #4: LSND



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

Anomaly #4: LSND



LSND Collaboration, hep-ex/0104049

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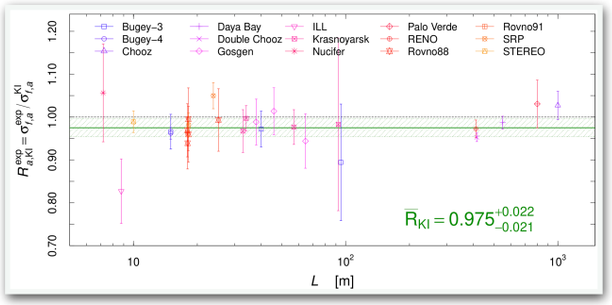

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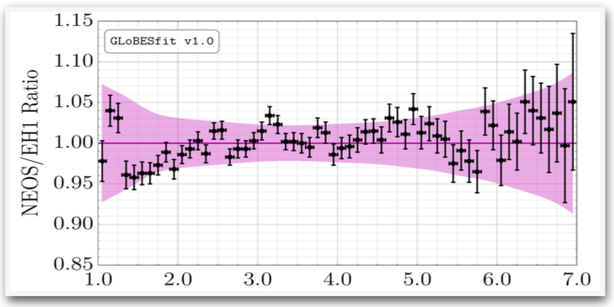

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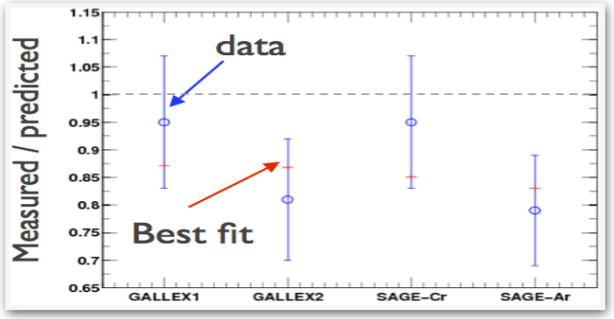

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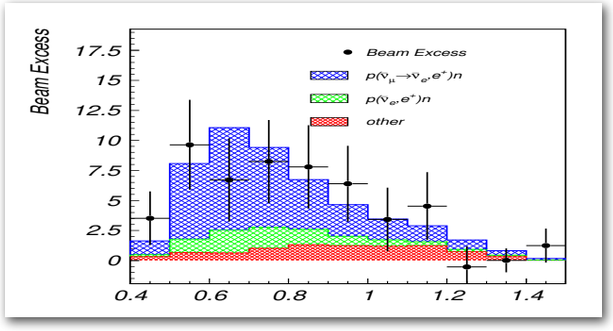

$\bar{\nu}_e$ appearance in LSND
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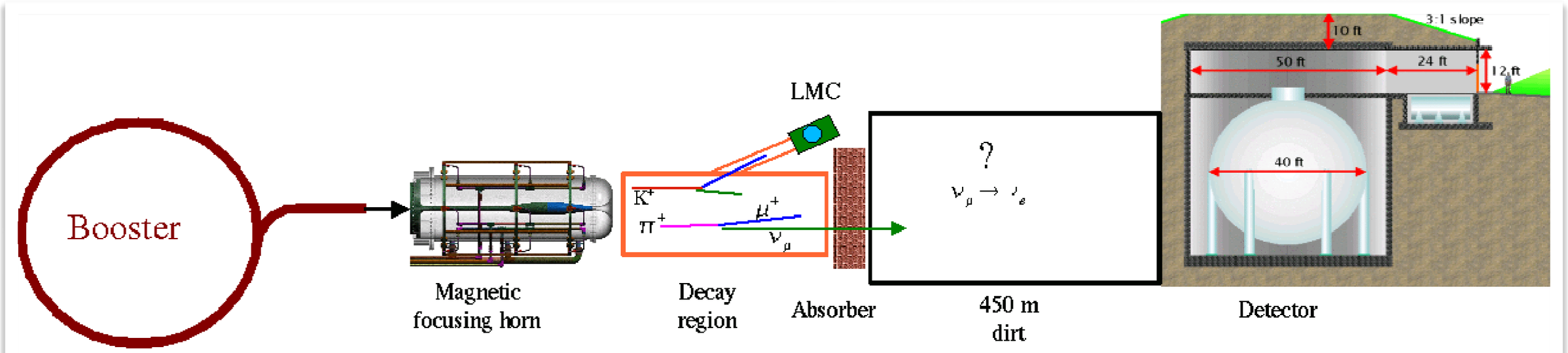
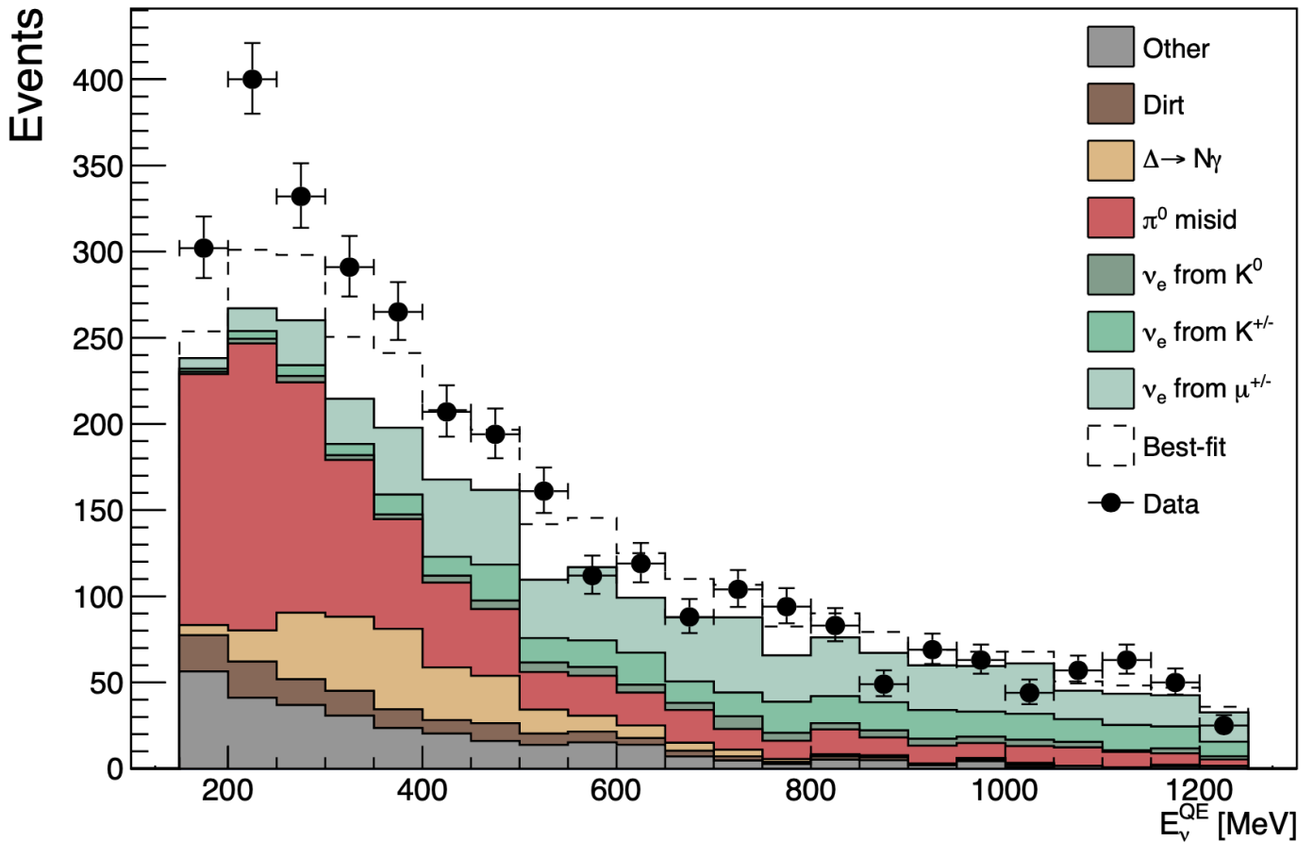
Anomaly #5: MiniBooNE

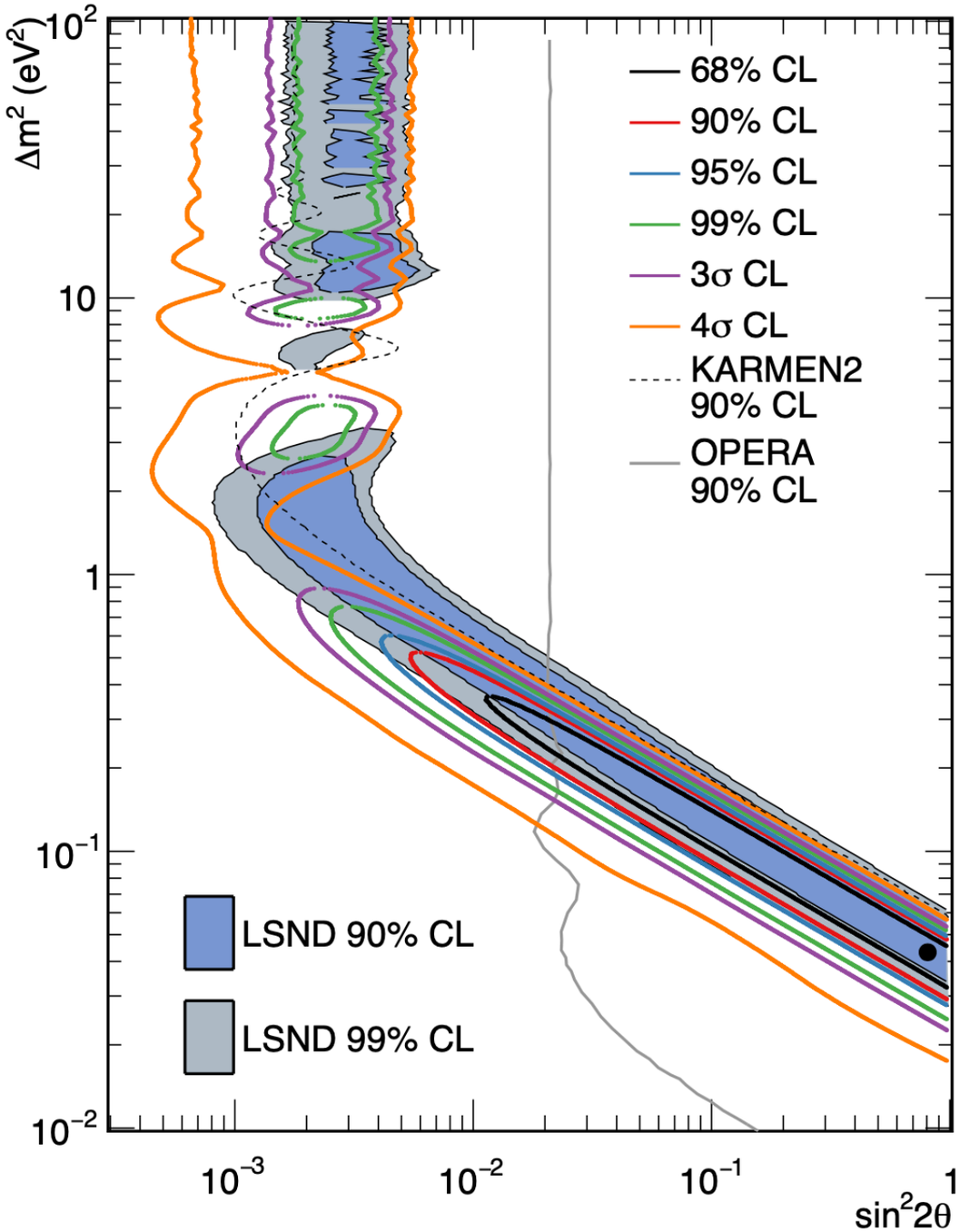


Anomaly #5: MiniBooNE

- ☑ Unexplained low-*E* excess
- ☑ Consistent with LSND
- ☑ L/E too small for std. oscillati



MiniBooNE Collaboration arXiv:2006.16883



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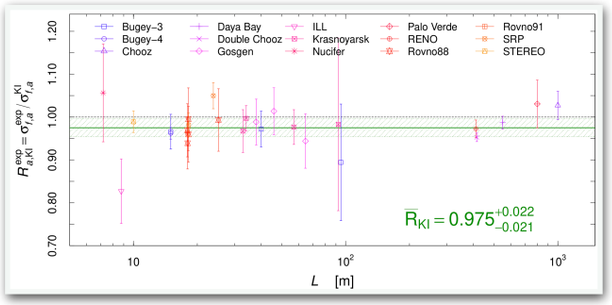

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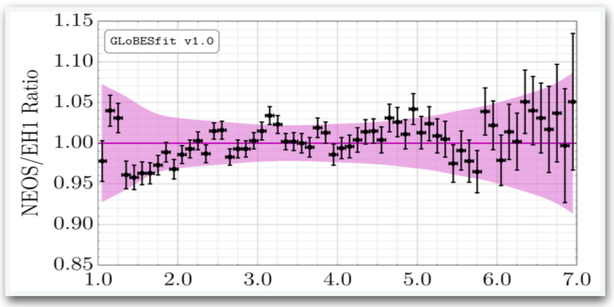

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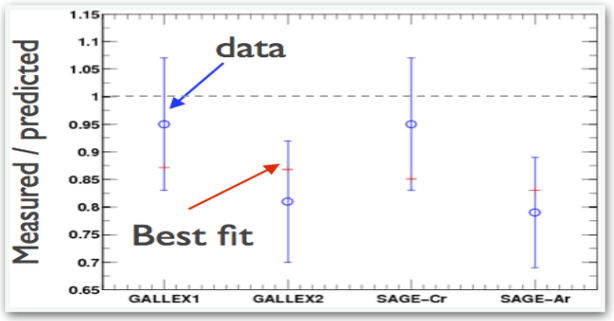

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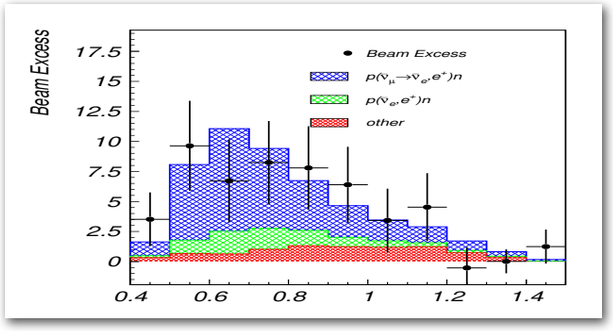

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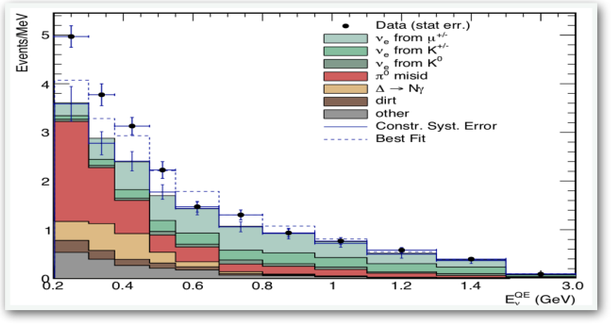
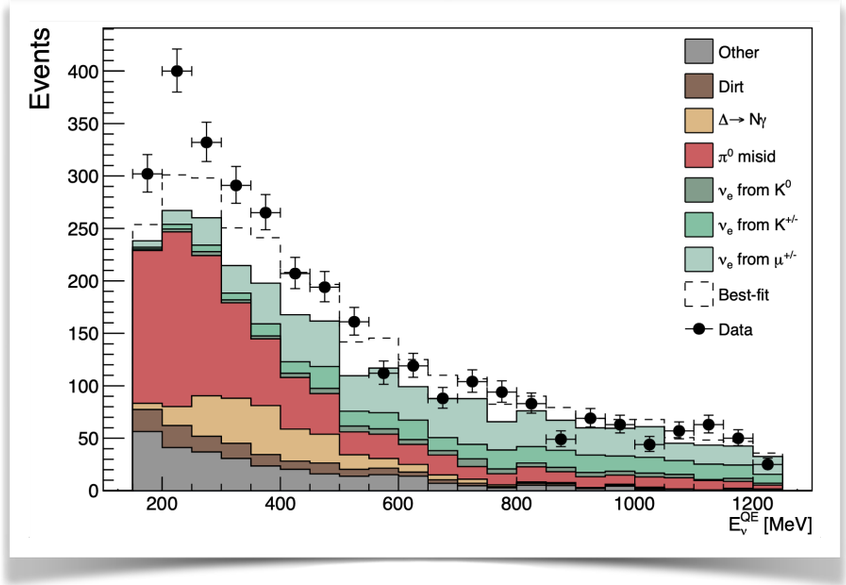


MiniBooNE
→ following slides

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^-



$\Delta \rightarrow \gamma N$

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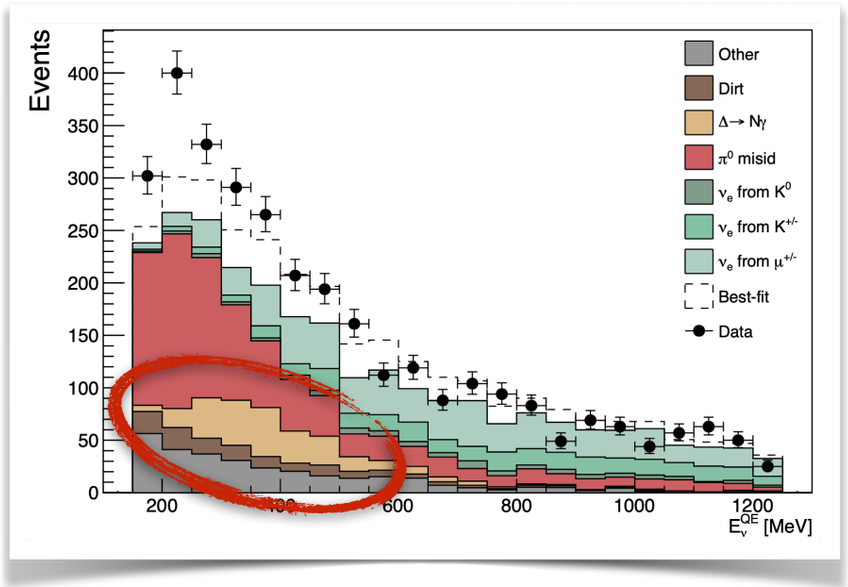
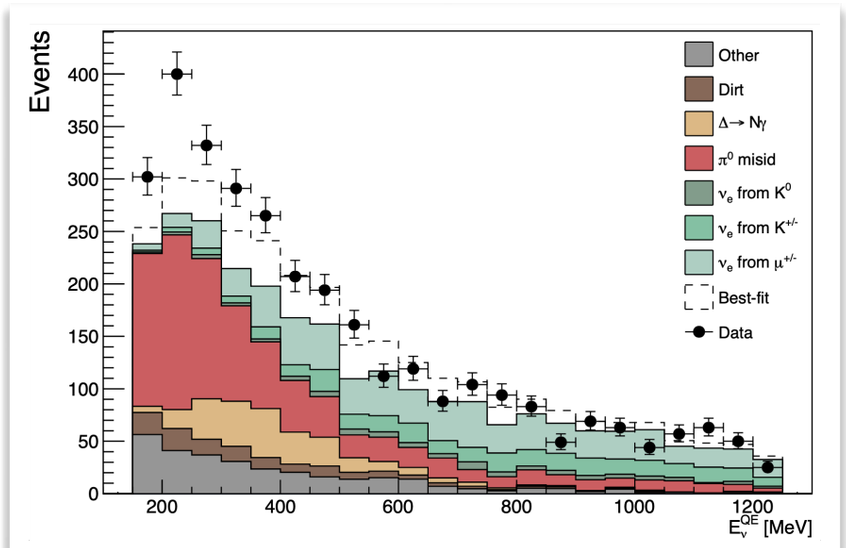


Δ → γ N

- ☑ 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

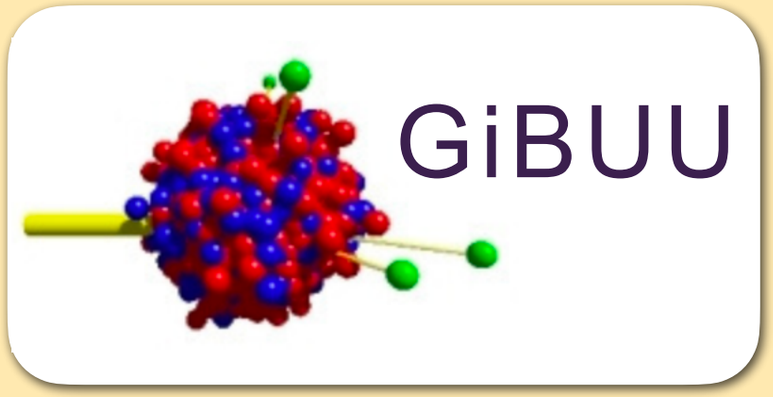
Neutrino Event Generators

Phenomenological

- ☑ different physics models for different kinematic regimes (smooth transitions in between)
- ☑ separation between ν-nucleon interaction, final state interactions, etc.
- ☑ tuneable to data
- ☑ but theoretically inconsistent
- ☑ e.g. GENIE, NuWro, NUANCE

First Principles

- ☑ unified theoretical framework (quantum transport equations for baryons & mesons)
- ☑ theoretically consistent
- ☑ not easily unable to data
- ☑ e.g. GiBUU



Cross Section Uncertainties

- ☑ Large systematic uncertainties in
  - Composition of neutrino beam
  - Neutrino interaction cross sections

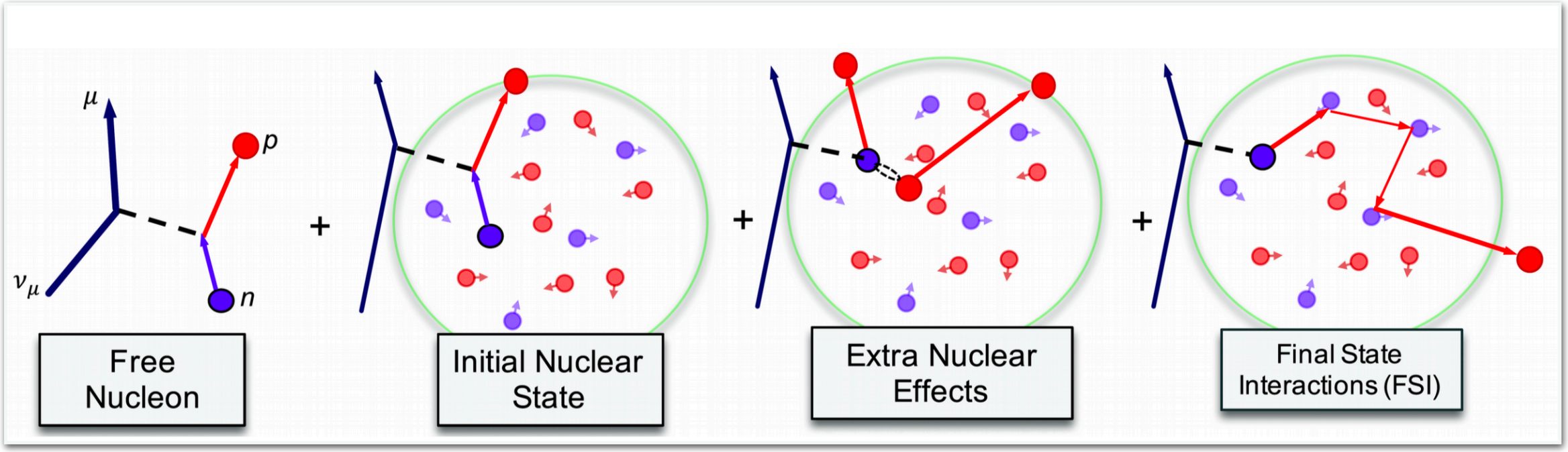


Image Credit: Callum Wilkinson

Understanding Neutrino Interactions

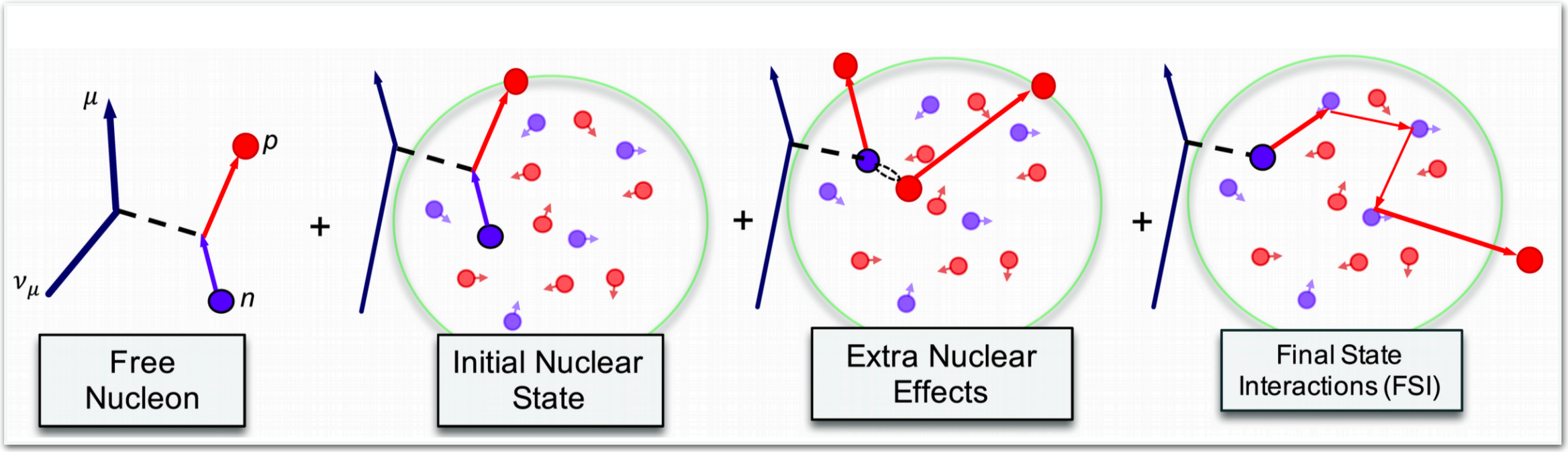


Image Credit: Callum Wilkinson

Understanding Neutrino Interactions

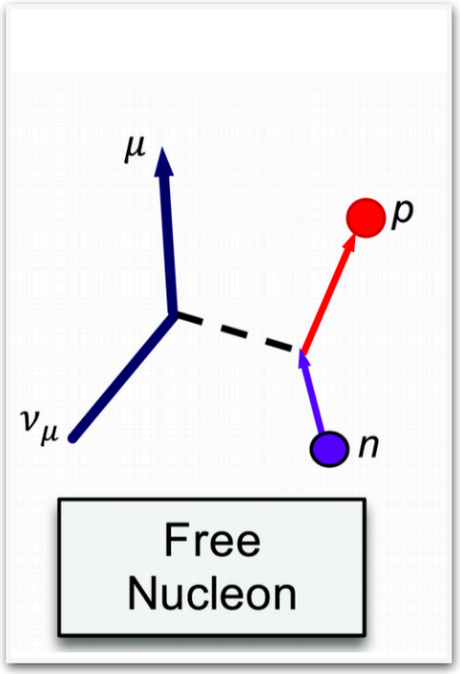


Image Credit: Callum Wilkinson

Understanding Neutrino Interactions

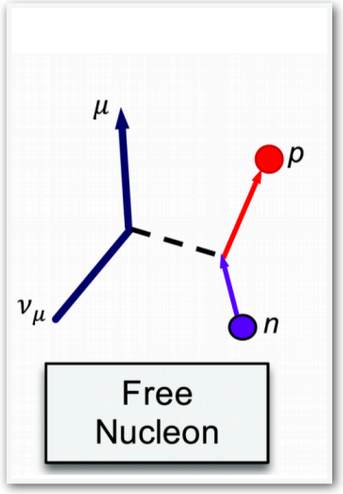
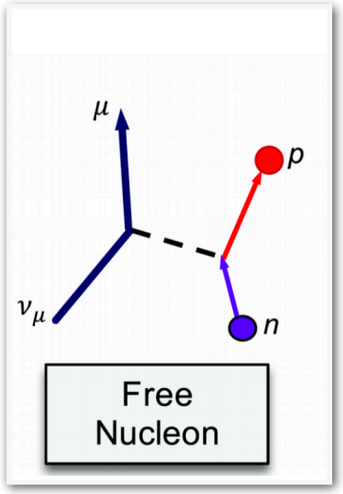


Image Credit: Callum Wilkinson

Understanding Neutrino Interactions



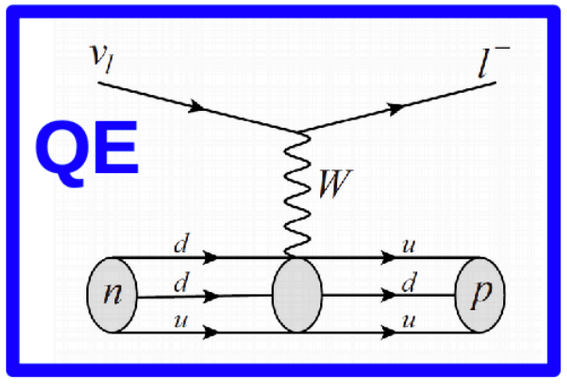


Image Credit: Callum Wilkinson

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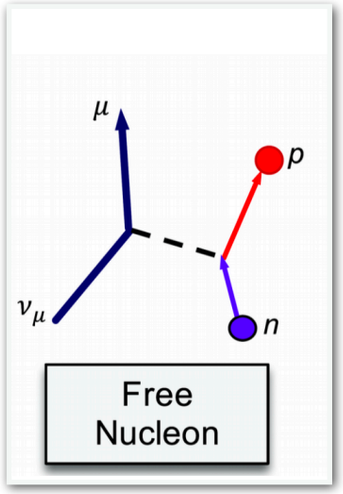
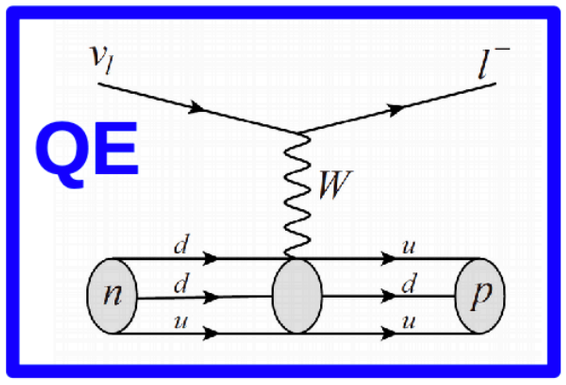




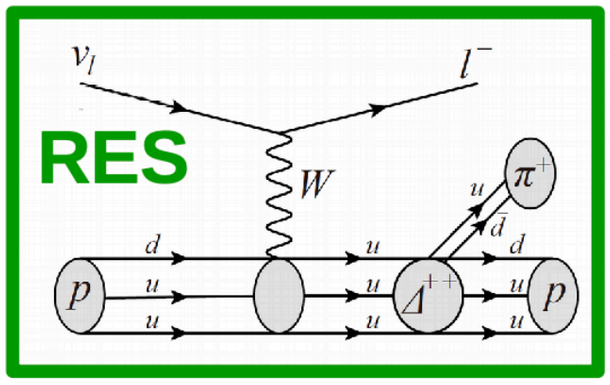
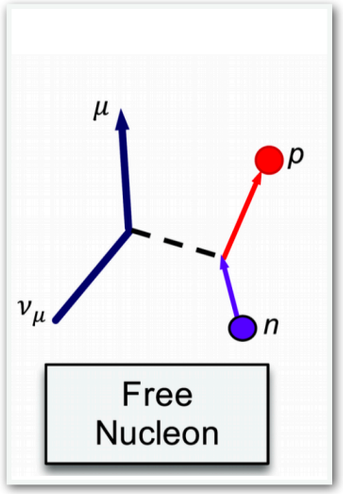
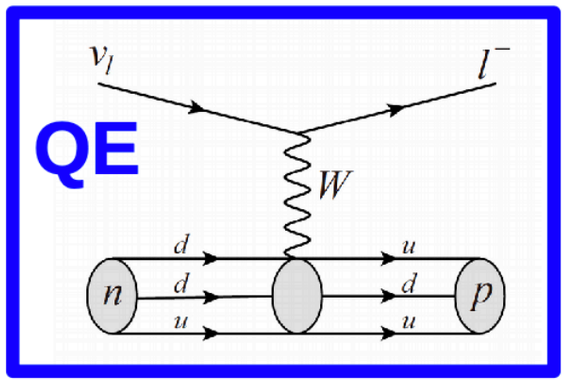
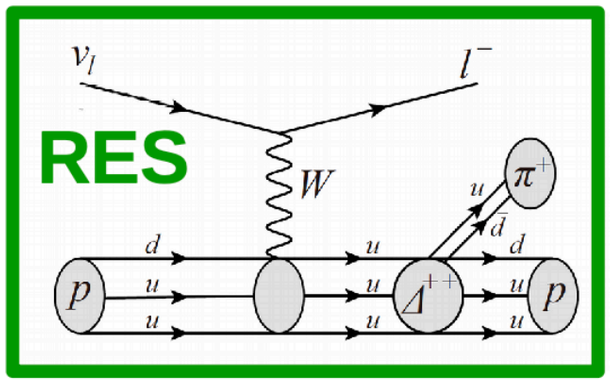


Image Credit: Callum Wilkinson

Understanding Neutrino Interactions







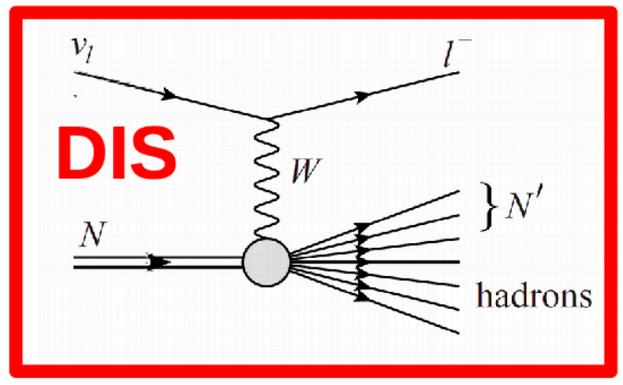
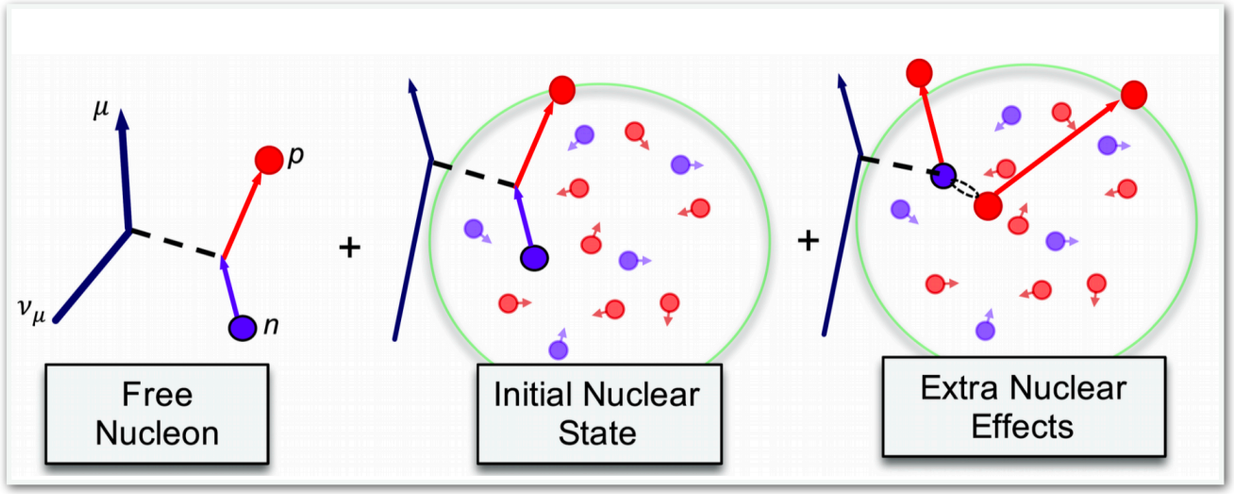
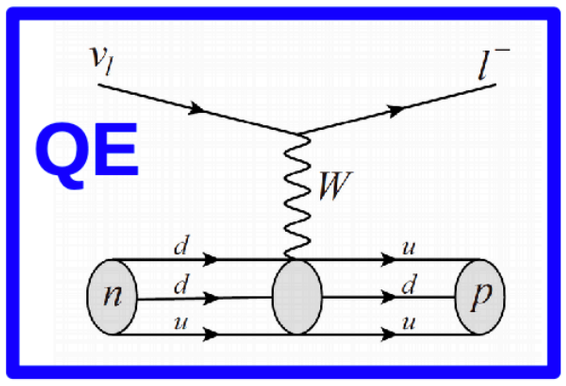
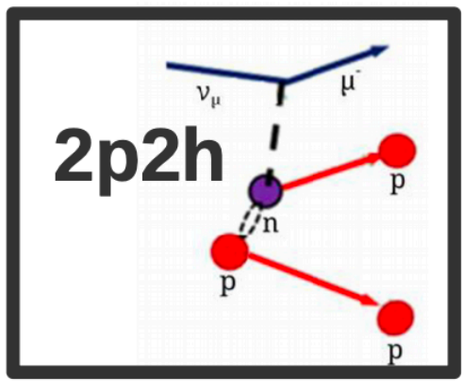


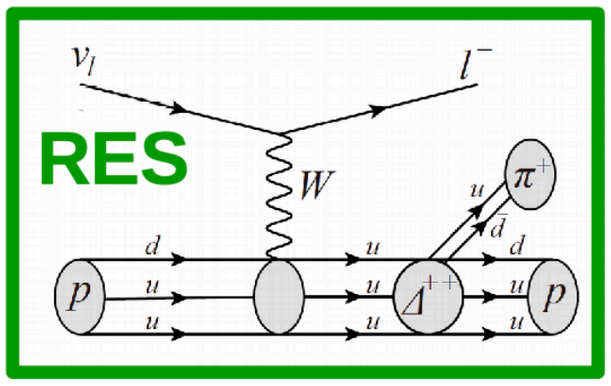
Image Credit: Callum Wilkinson

Understanding Neutrino Interactions









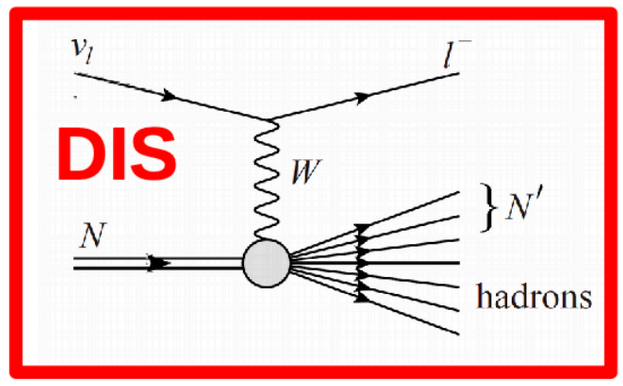
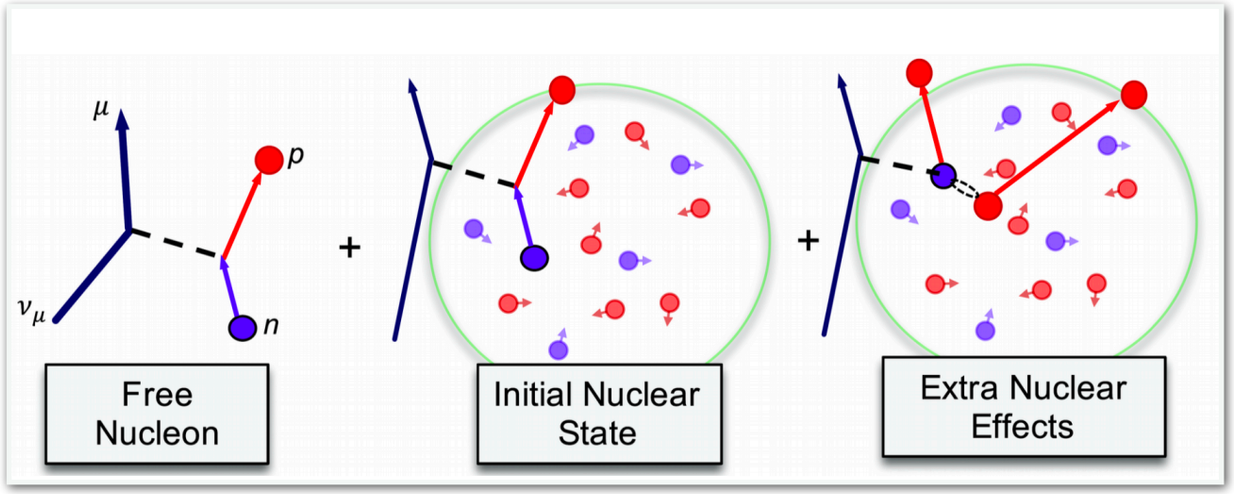
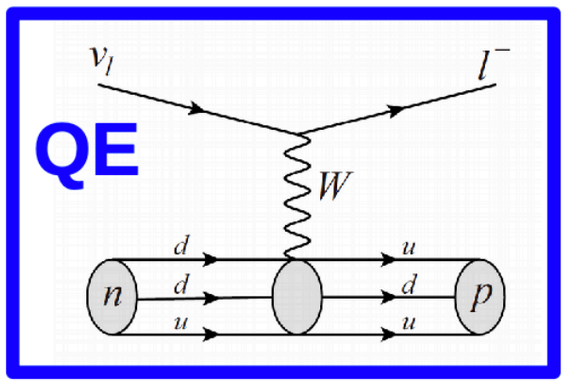
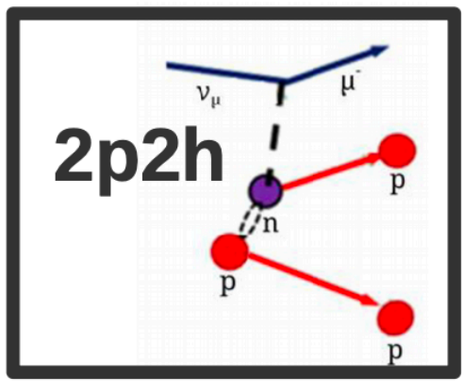


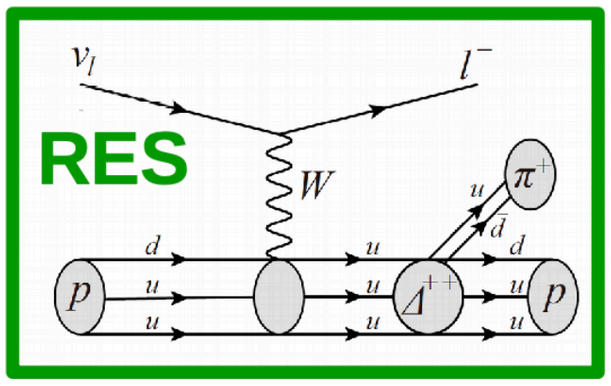
Image Credit: Callum Wilkinson

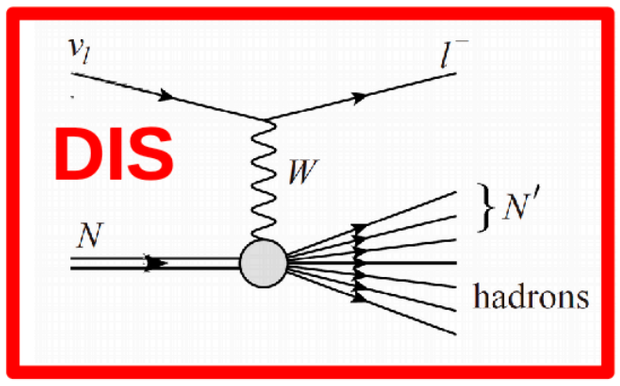
Understanding Neutrino Interactions

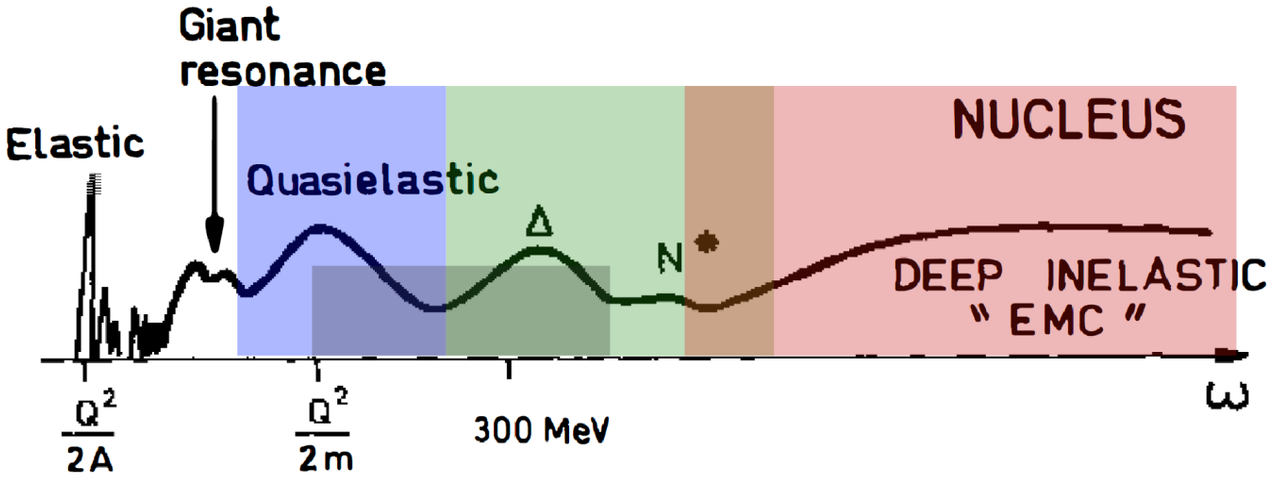










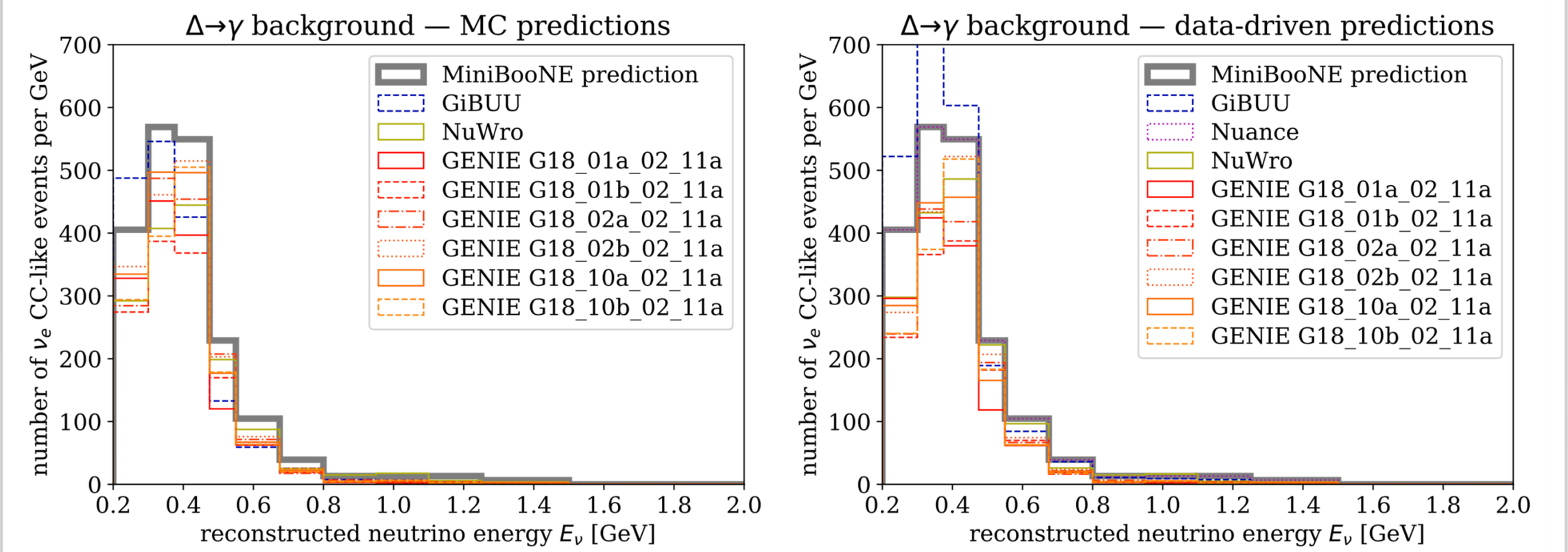


multi-nucleon effects are crucial

Image Credit: Callum Wilkinson

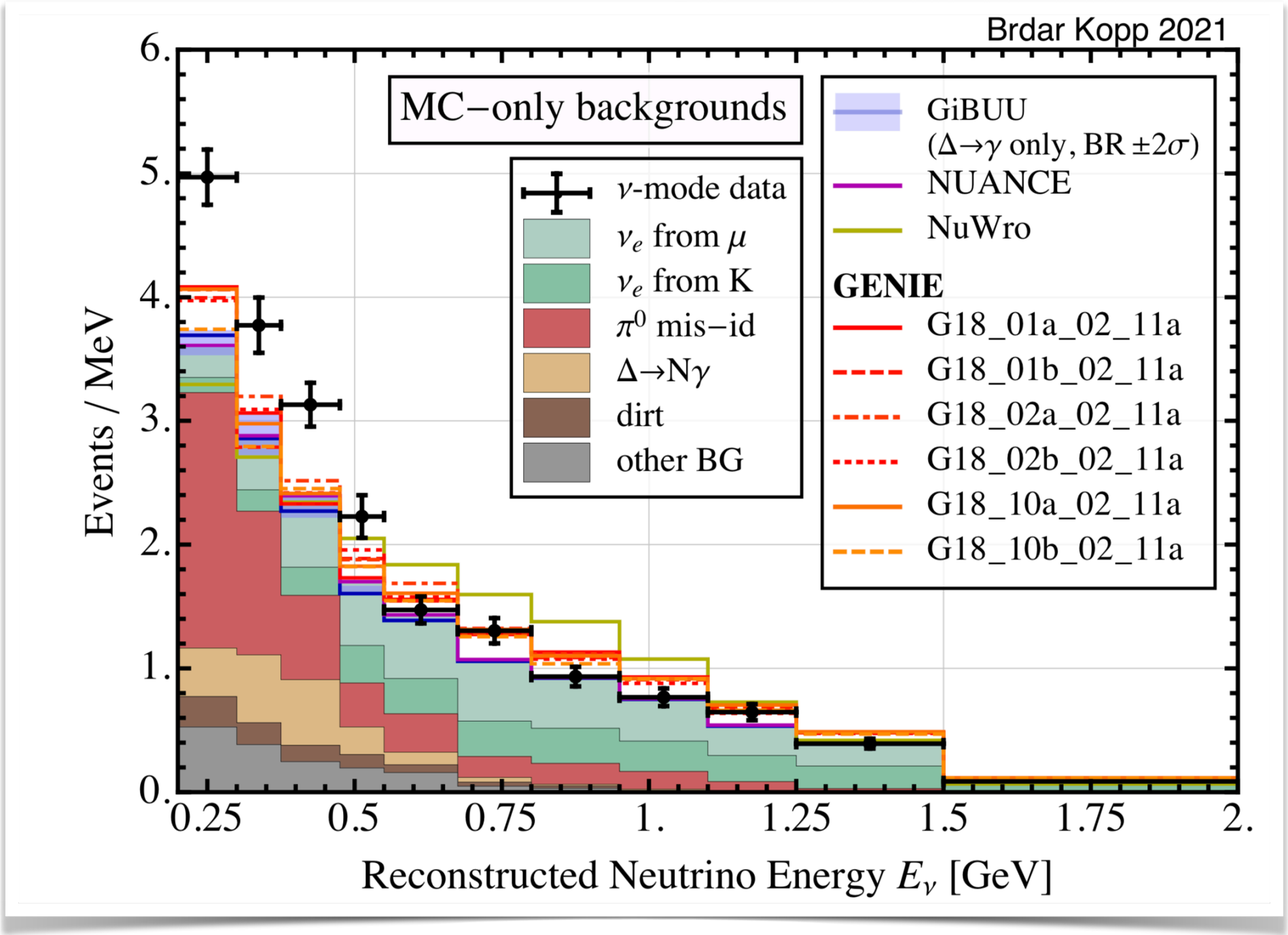
Δ → γ N: Comparison of Generators

Brdar JK, arXiv:2109.08157

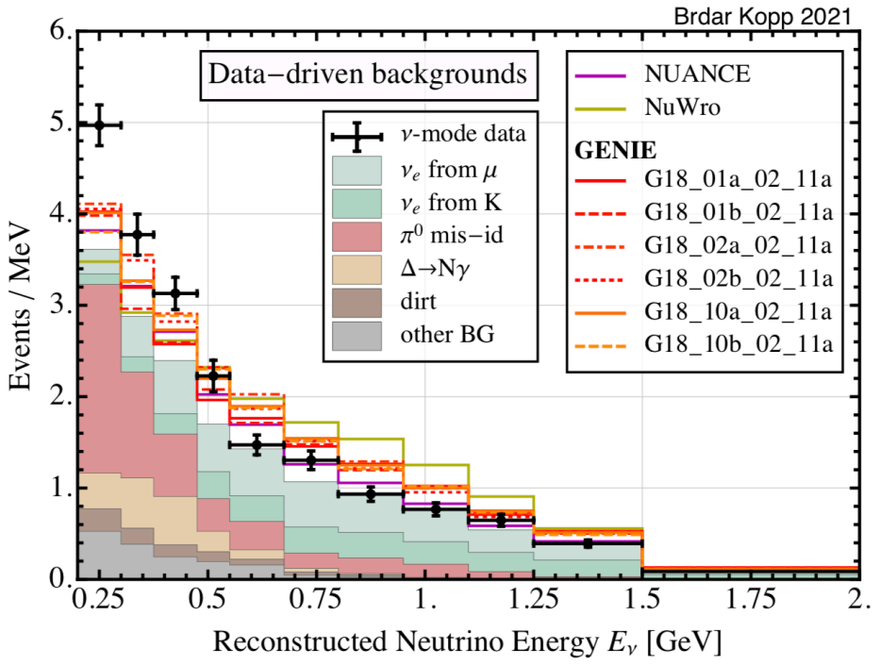


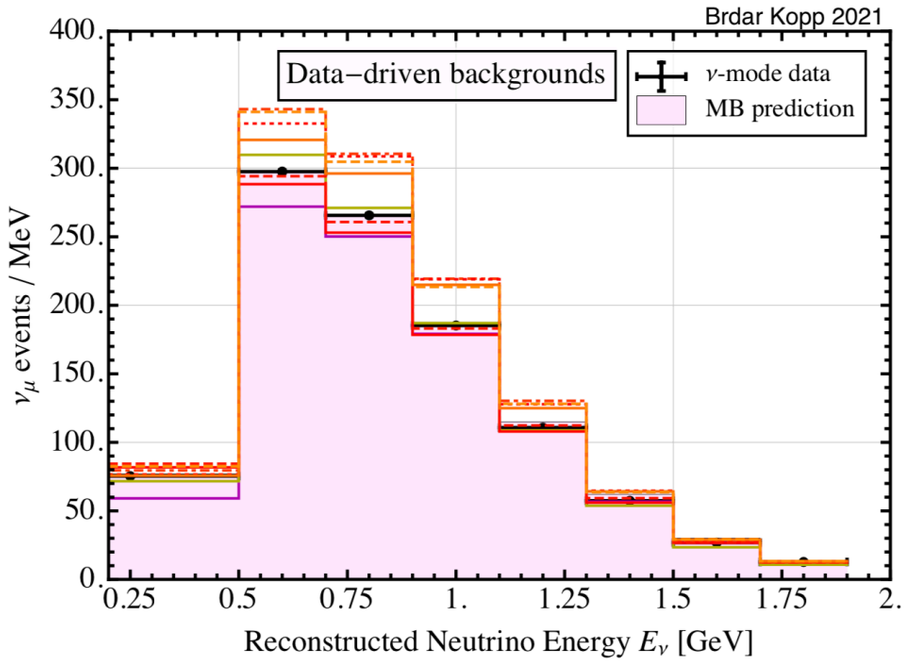
- ☑ histograms calibrated to NUANCE
  (the generator used by MiniBooNE)
- ☑ using our own implementation of radiative resonance decays
  in GiBUU, NuWro, NUANCE

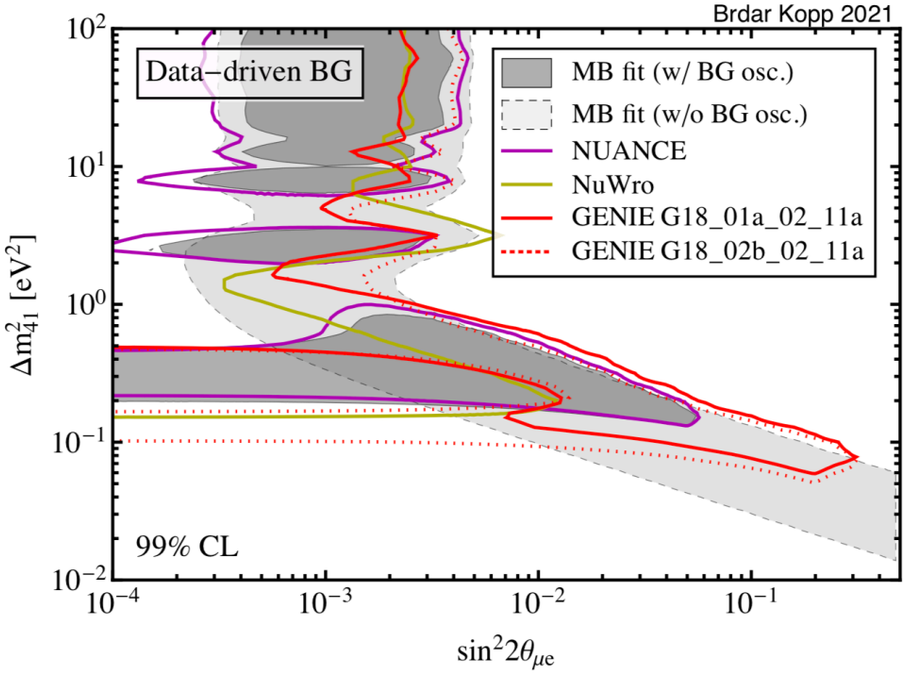
All Backgrounds: Comparison of Generators

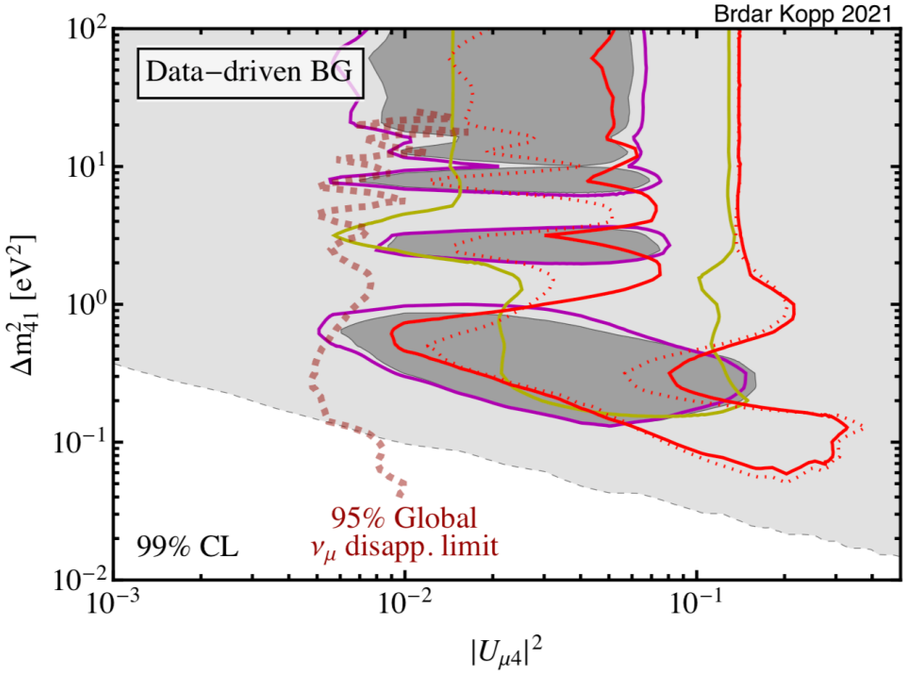


3+1 Models in MB: Comparison of Generators



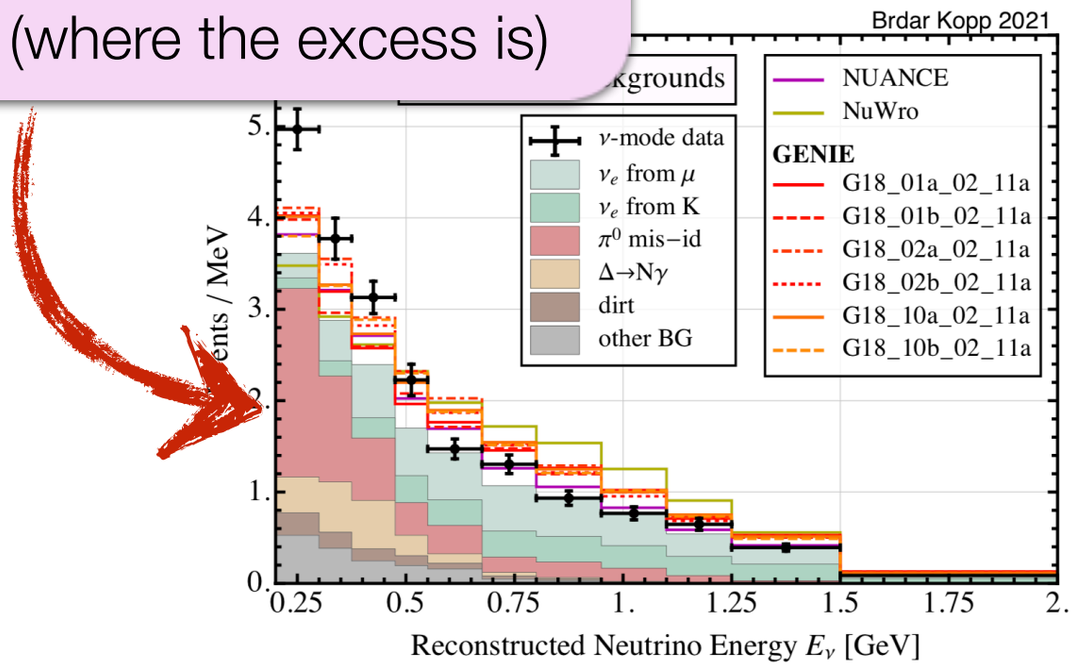


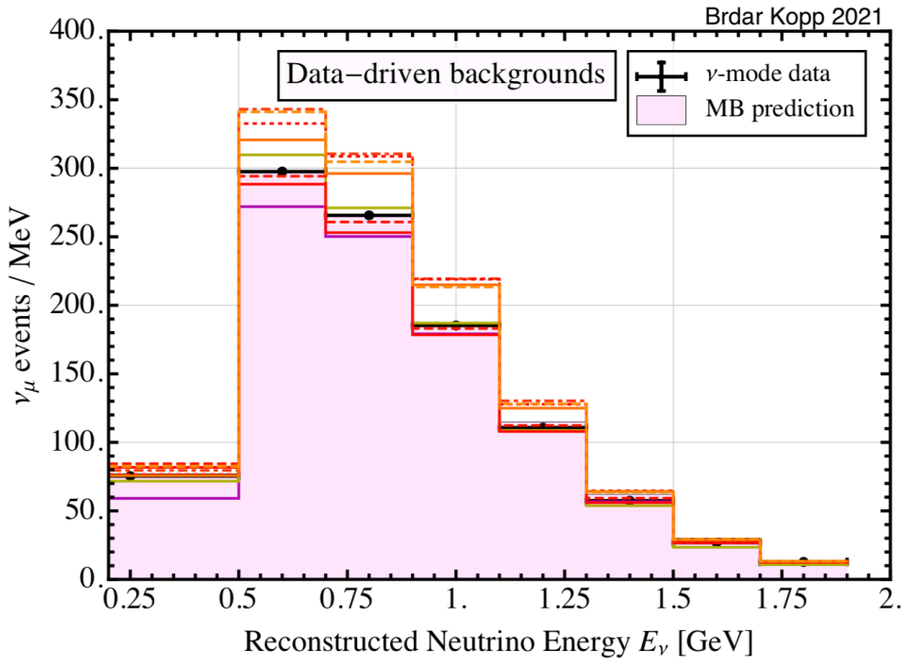


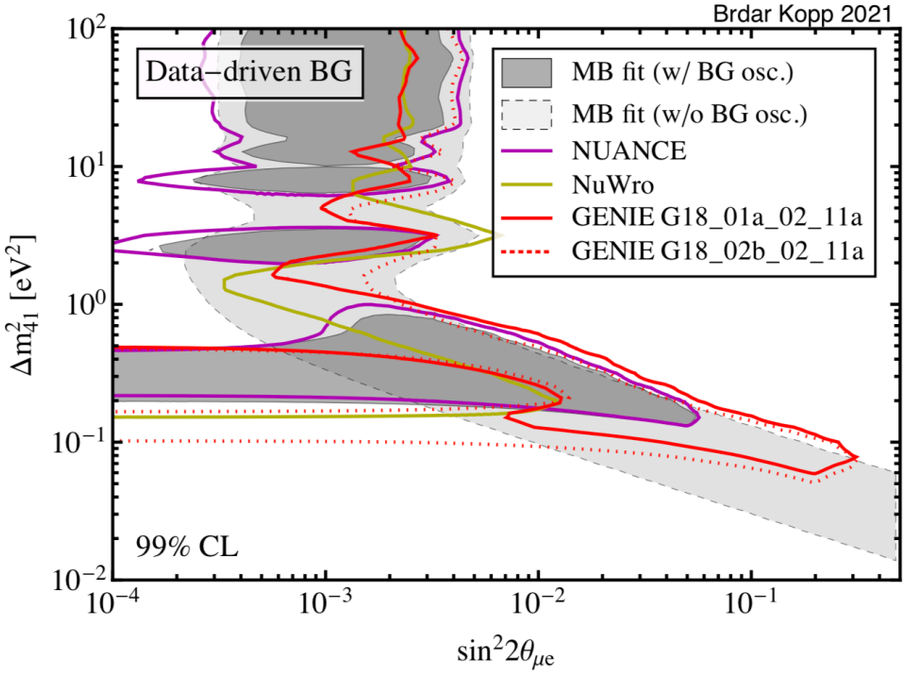


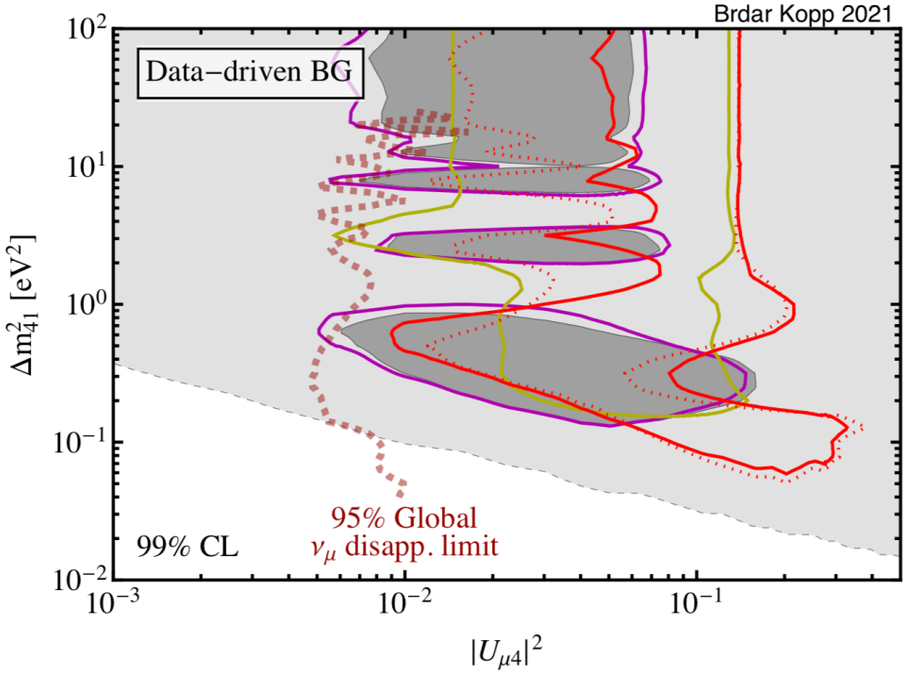
3+1 Models in MB: Comparison of Generators

ν_e spectrum
(where the excess is)









3+1 Models in MB: Comparison of Generators

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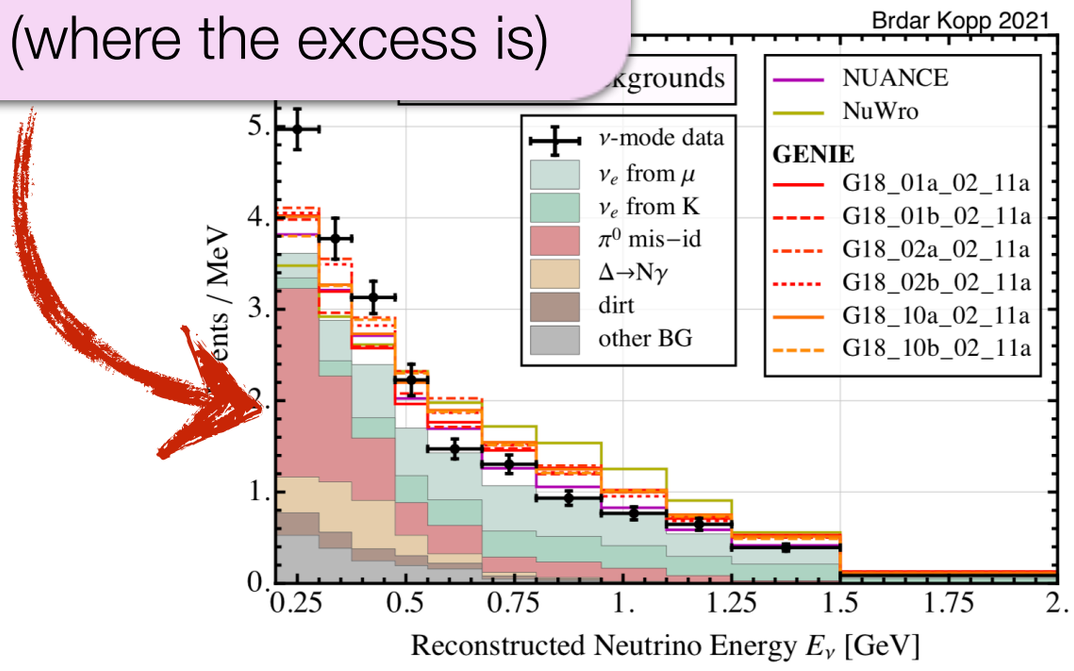
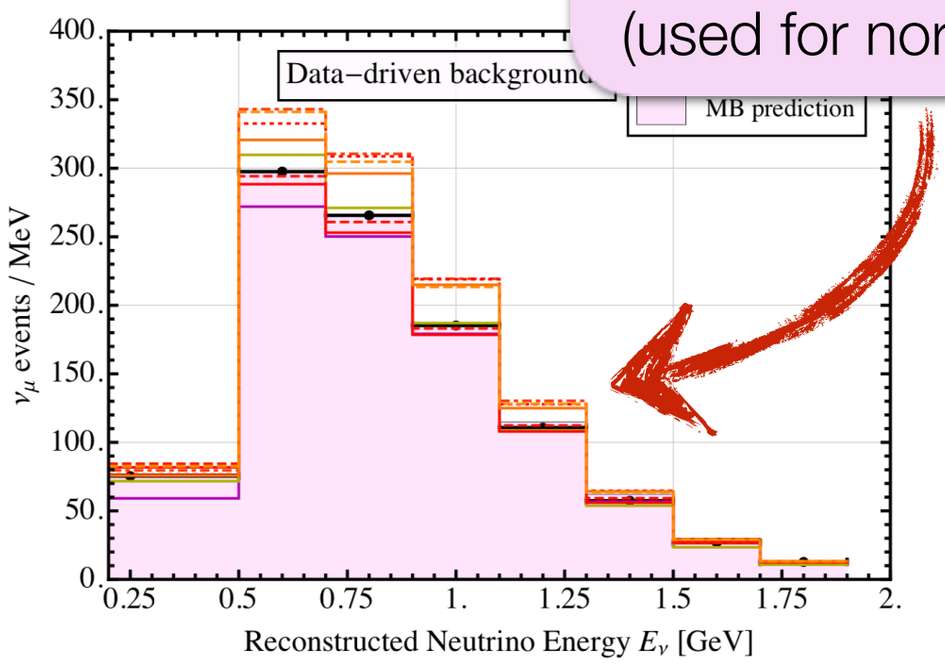
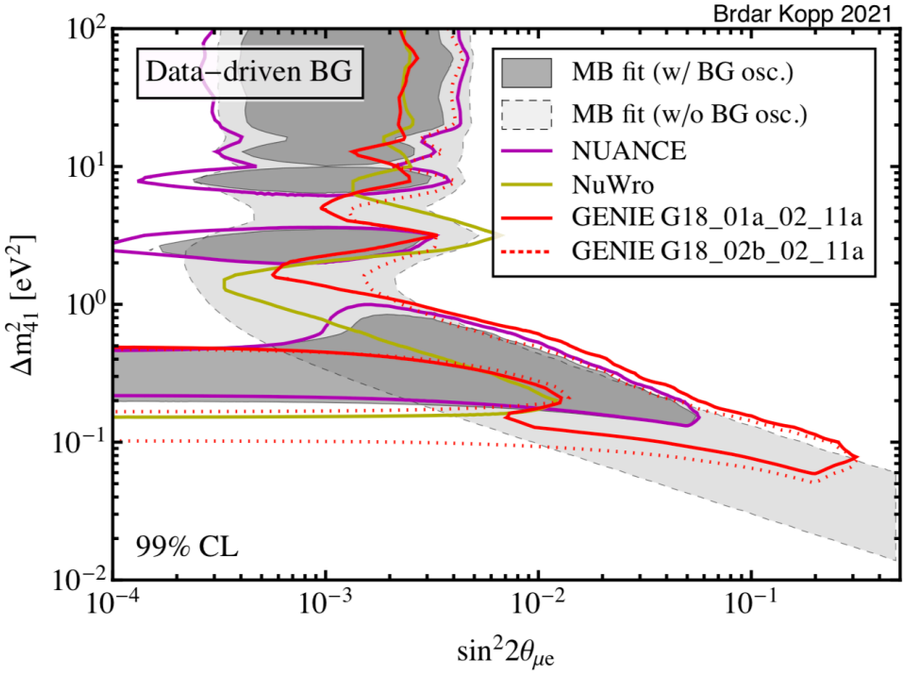
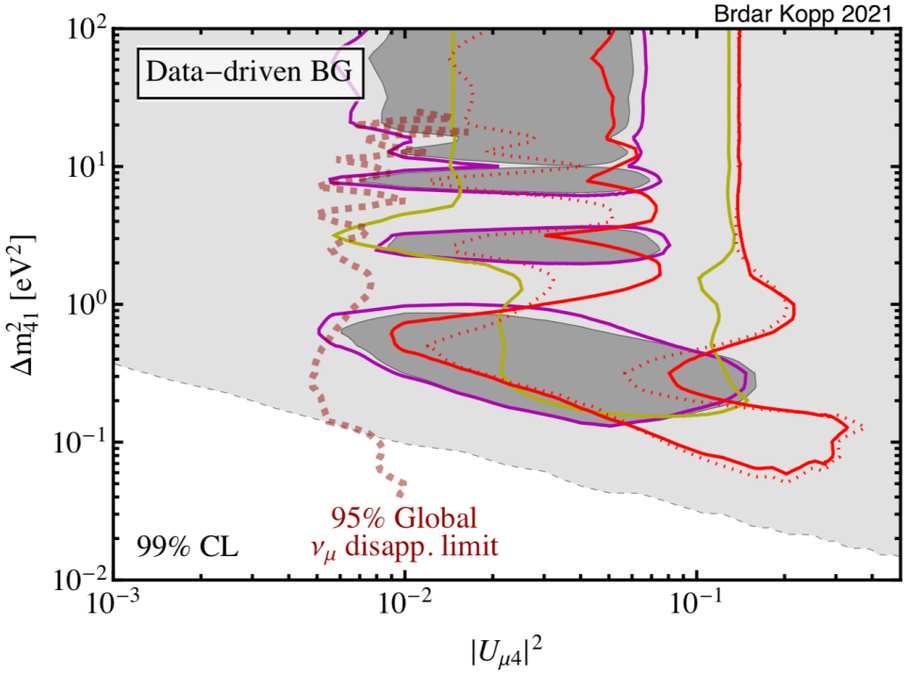


ν_μ spectrum
(used for normalization)







3+1 Models in MB: Comparison of Generators

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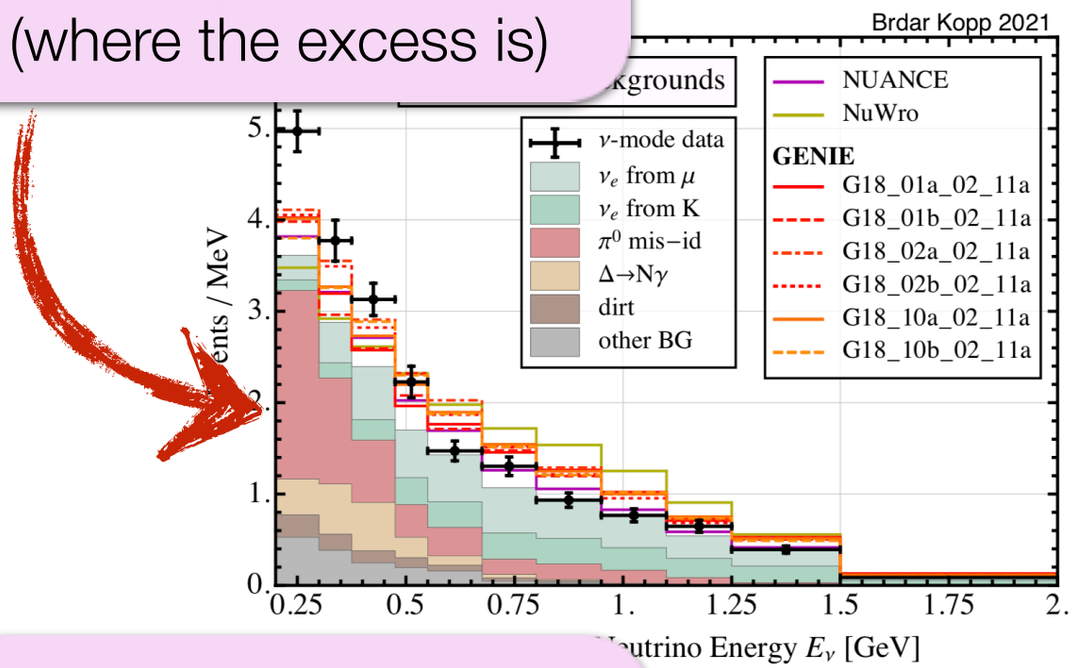
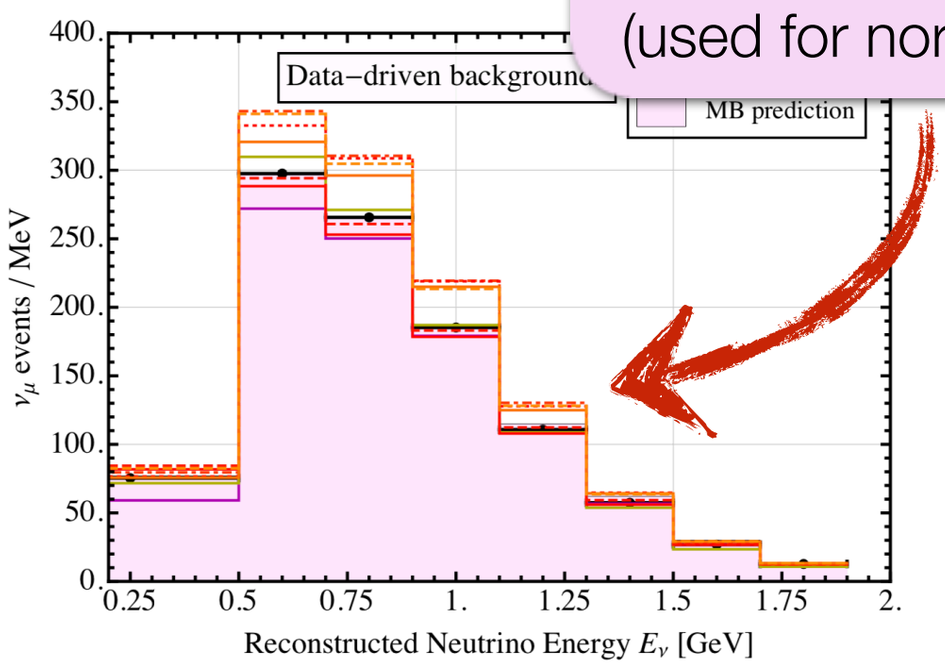
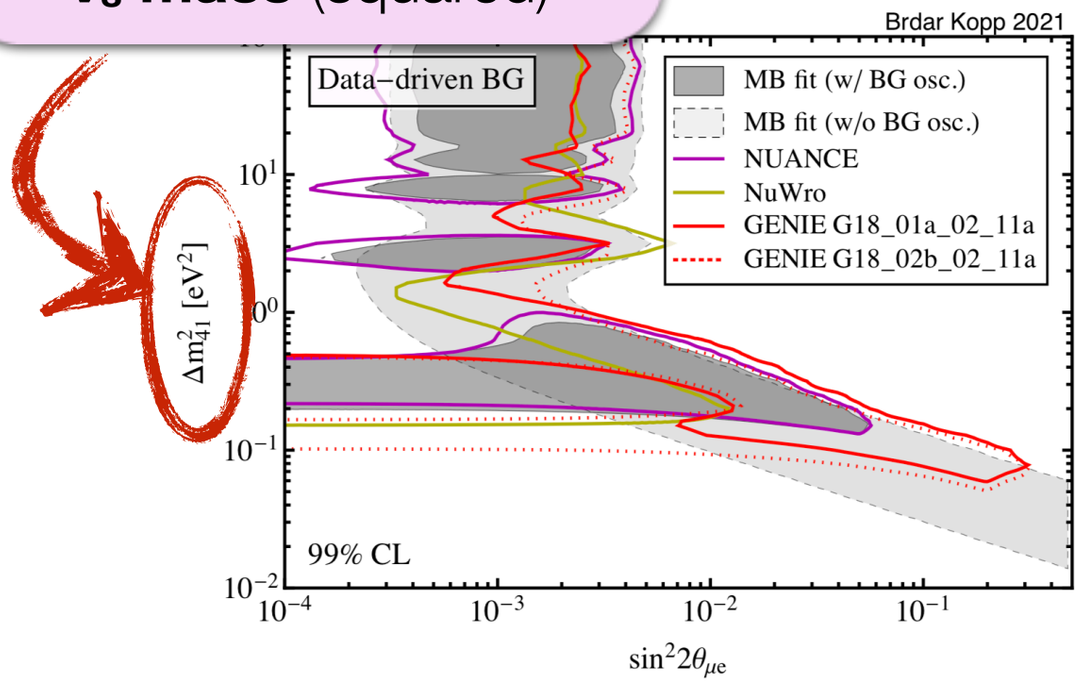
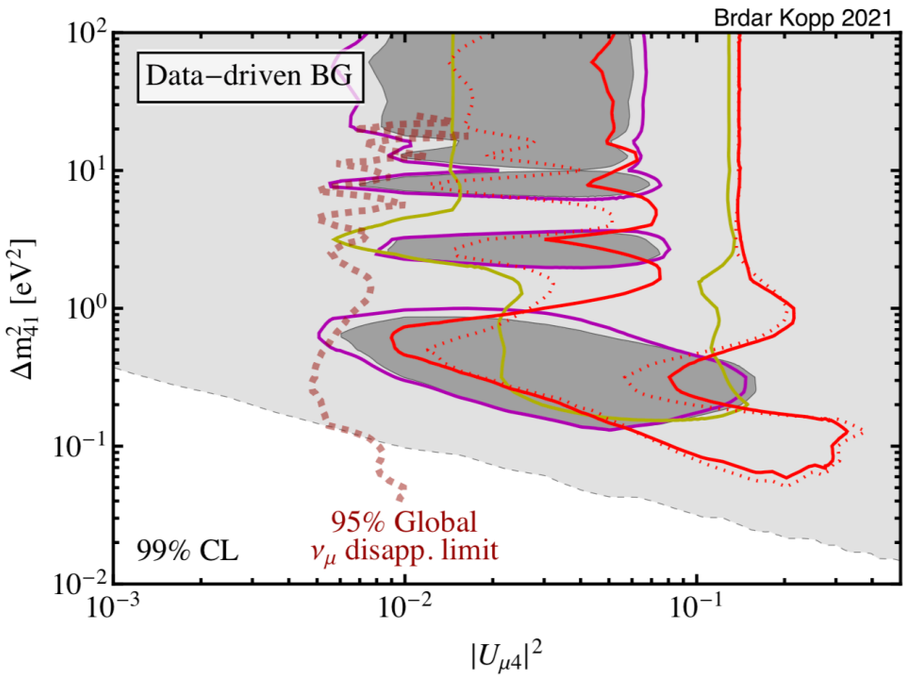


ν_μ spectrum
(used for normalization)



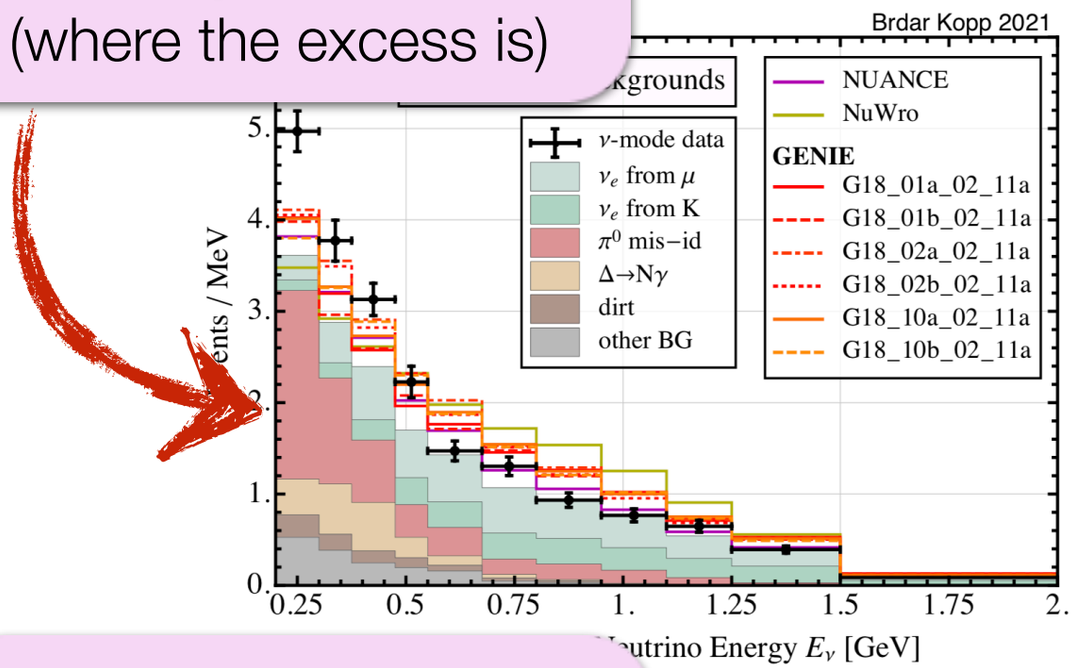
ν_s mass (squared)



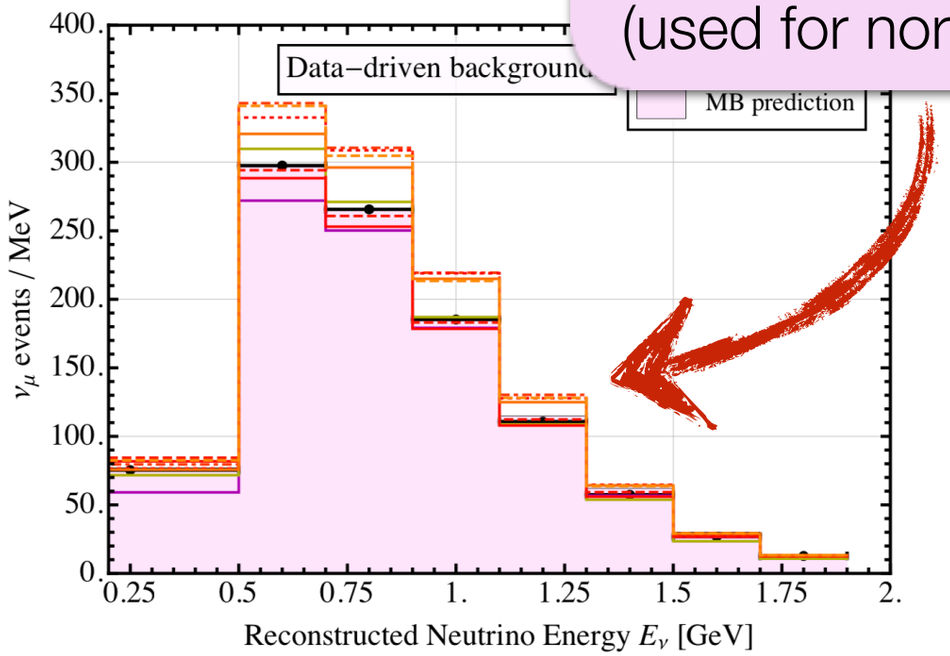


3+1 Models in MB: Comparison of Generators

ν_e spectrum
(where the excess is)

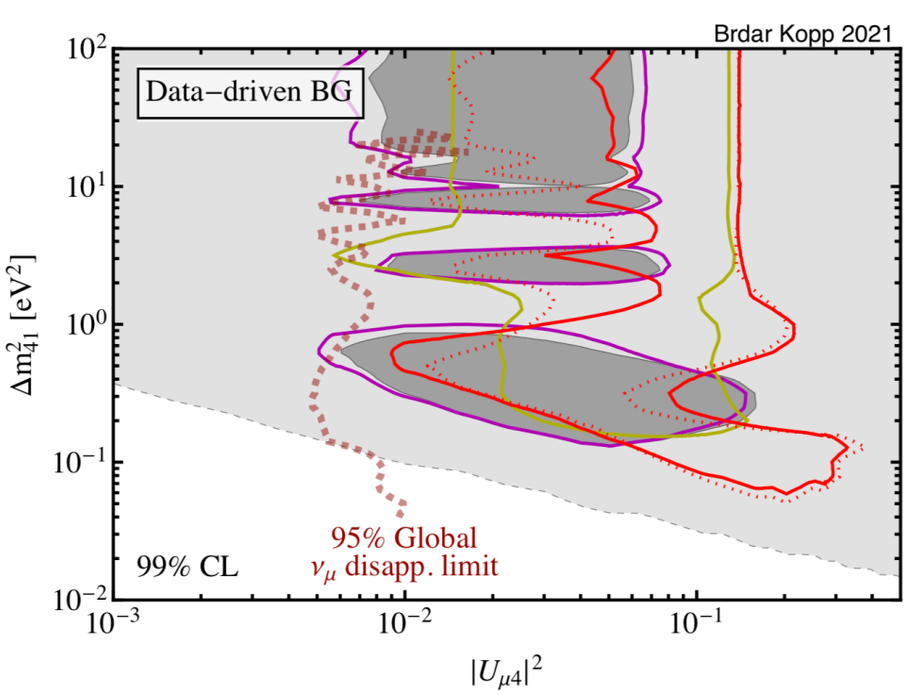


ν_μ spectrum
(used for normalization)



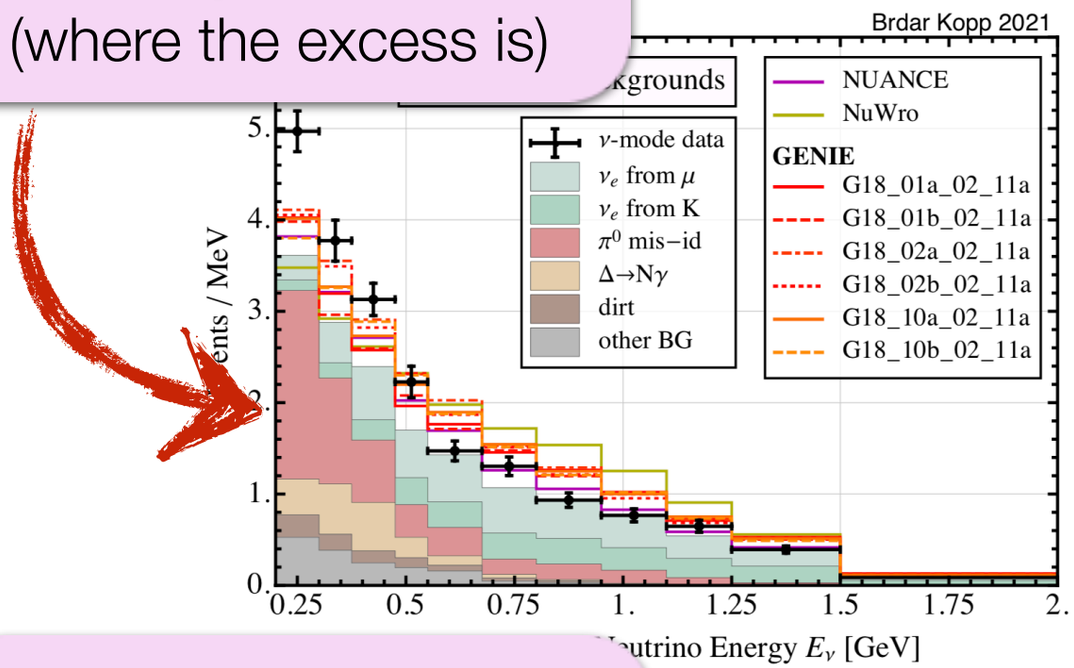
ν_s mass (squared)

effective ν_e–ν_μ mixing angle
$\sin^2 2\theta_{\mu e} = |U_{e4}|^2 |U_{\mu 4}|^2$

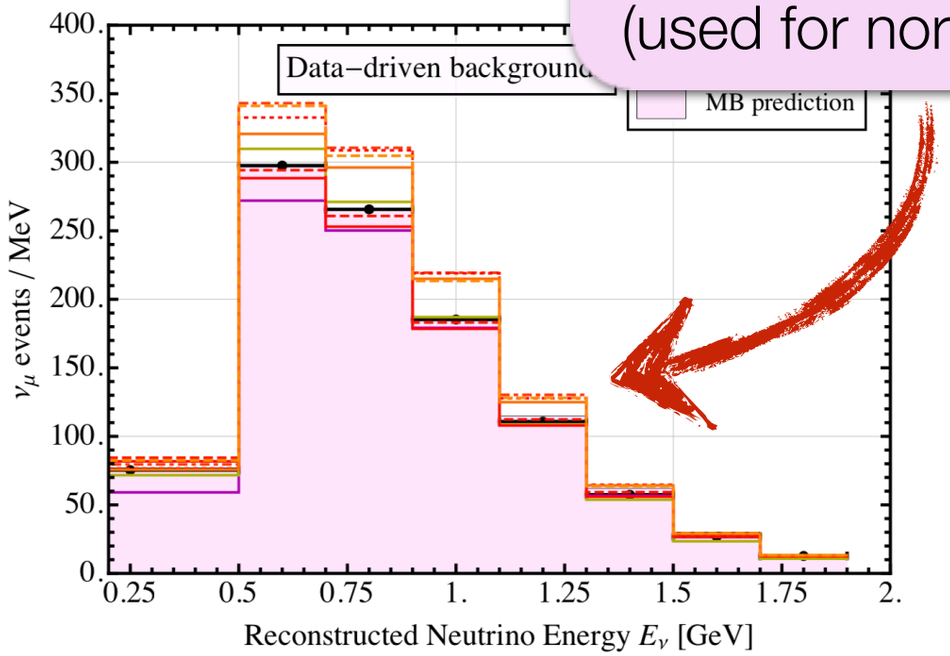


3+1 Models in MB: Comparison of Generators

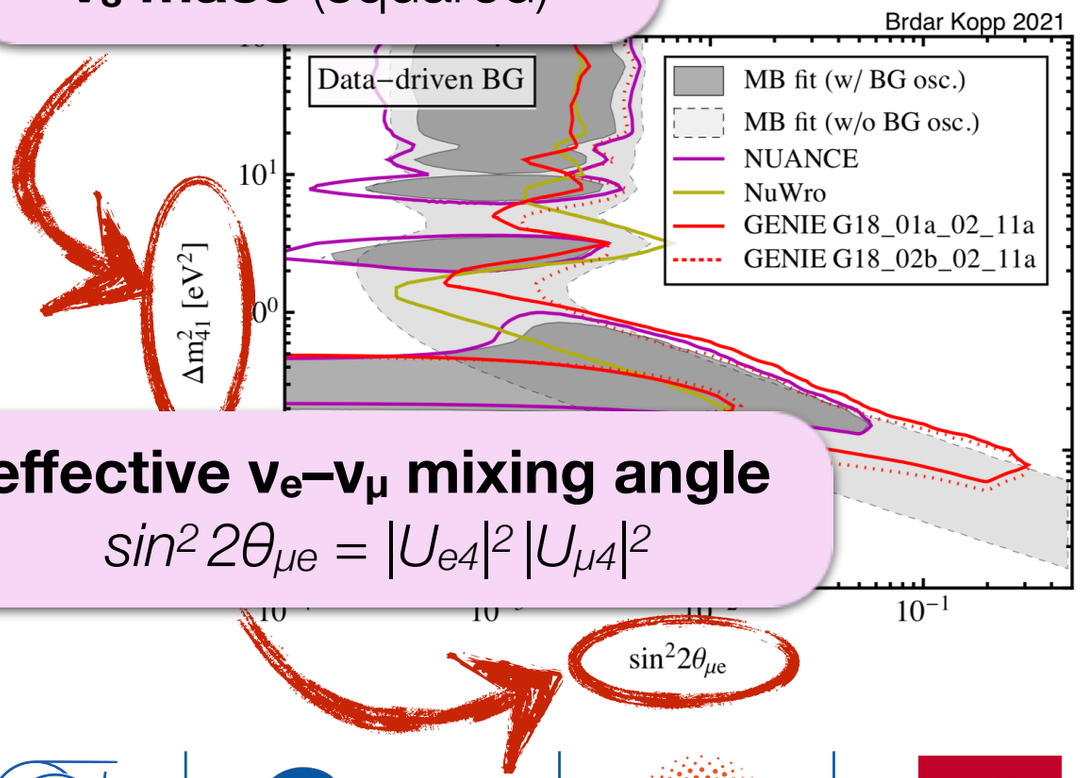
ν_e spectrum
(where the excess is)



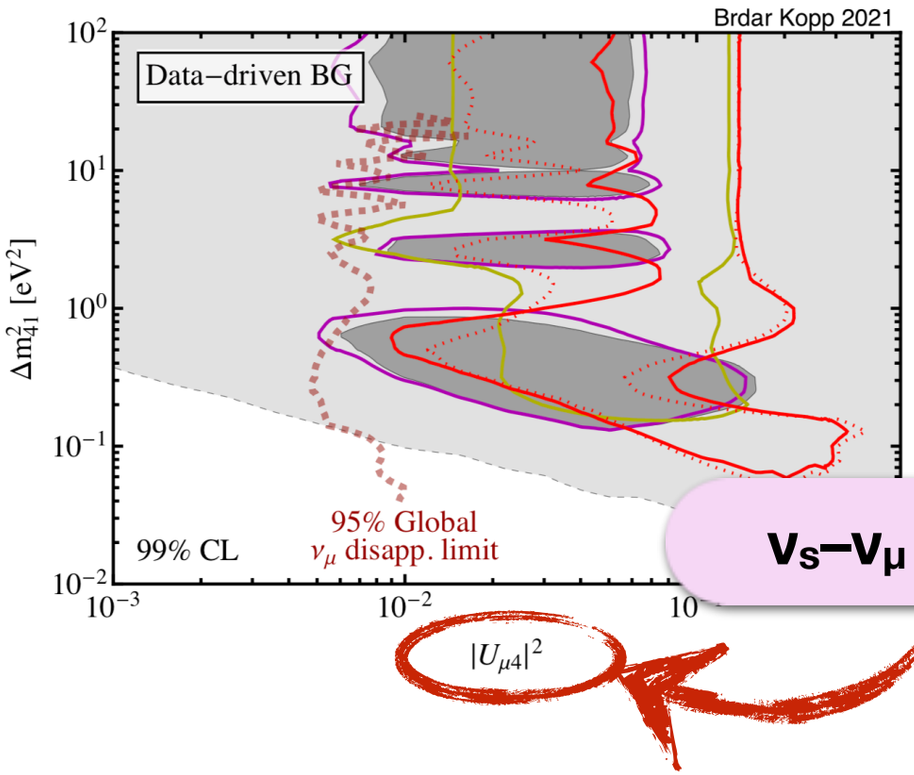
ν_μ spectrum
(used for normalization)



ν_s mass (squared)

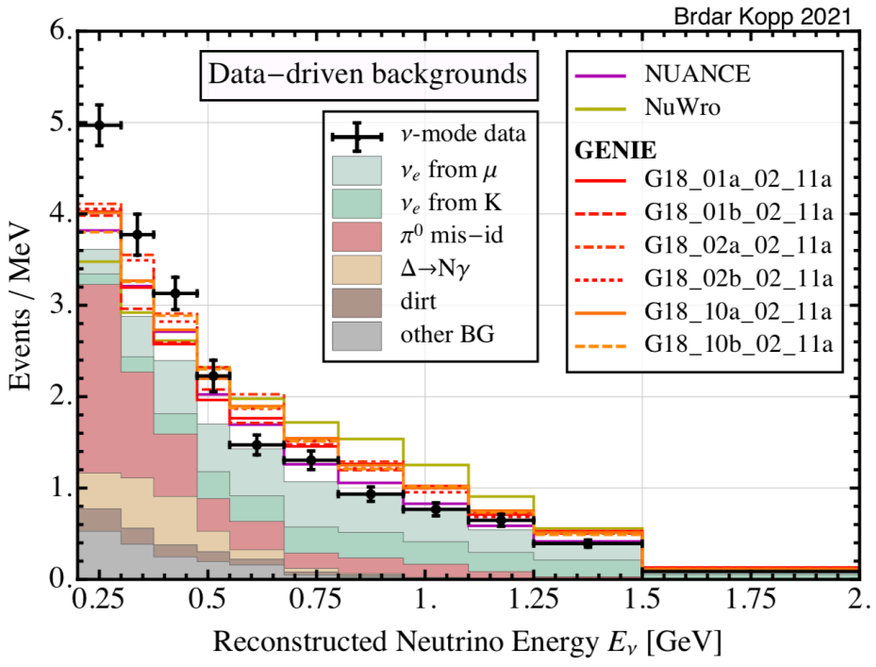


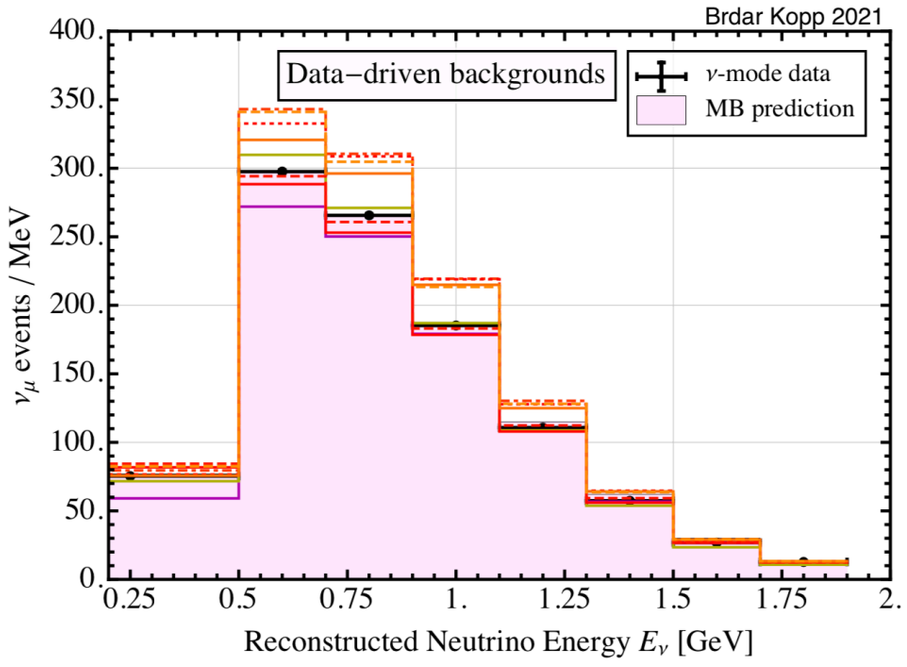
effective ν_e–ν_μ mixing angle
$\sin^2 2\theta_{\mu e} = |U_{e4}|^2 \, |U_{\mu 4}|^2$

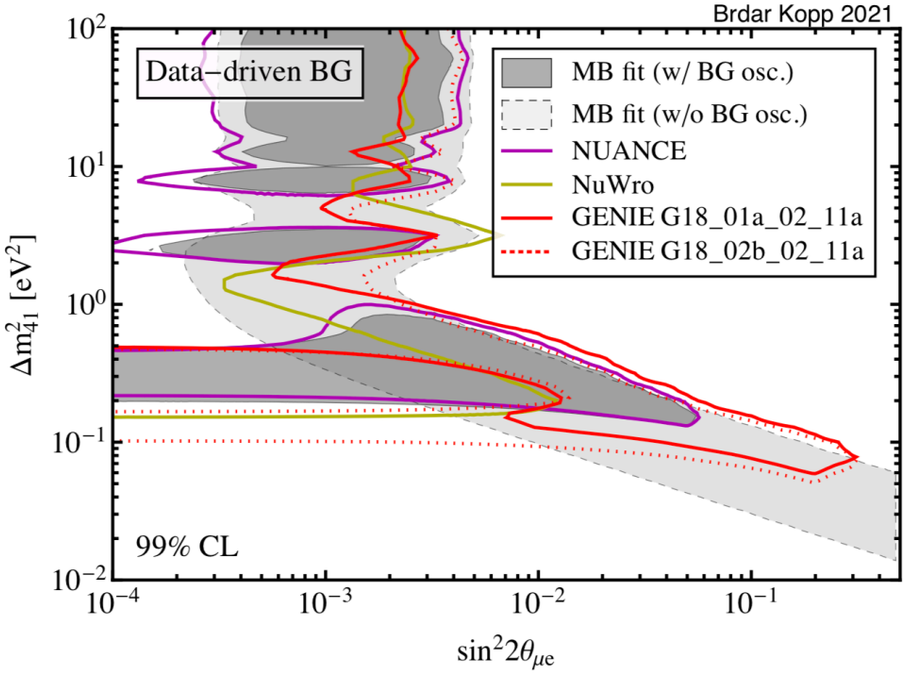


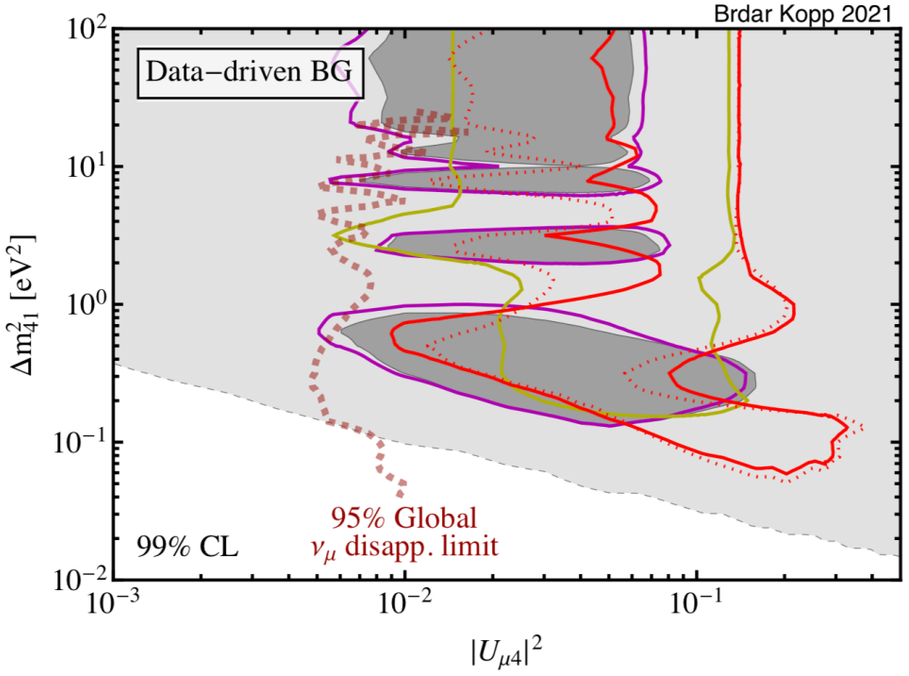
ν_s–ν_μ mixing

3+1 Models in MB: Comparison of Generators

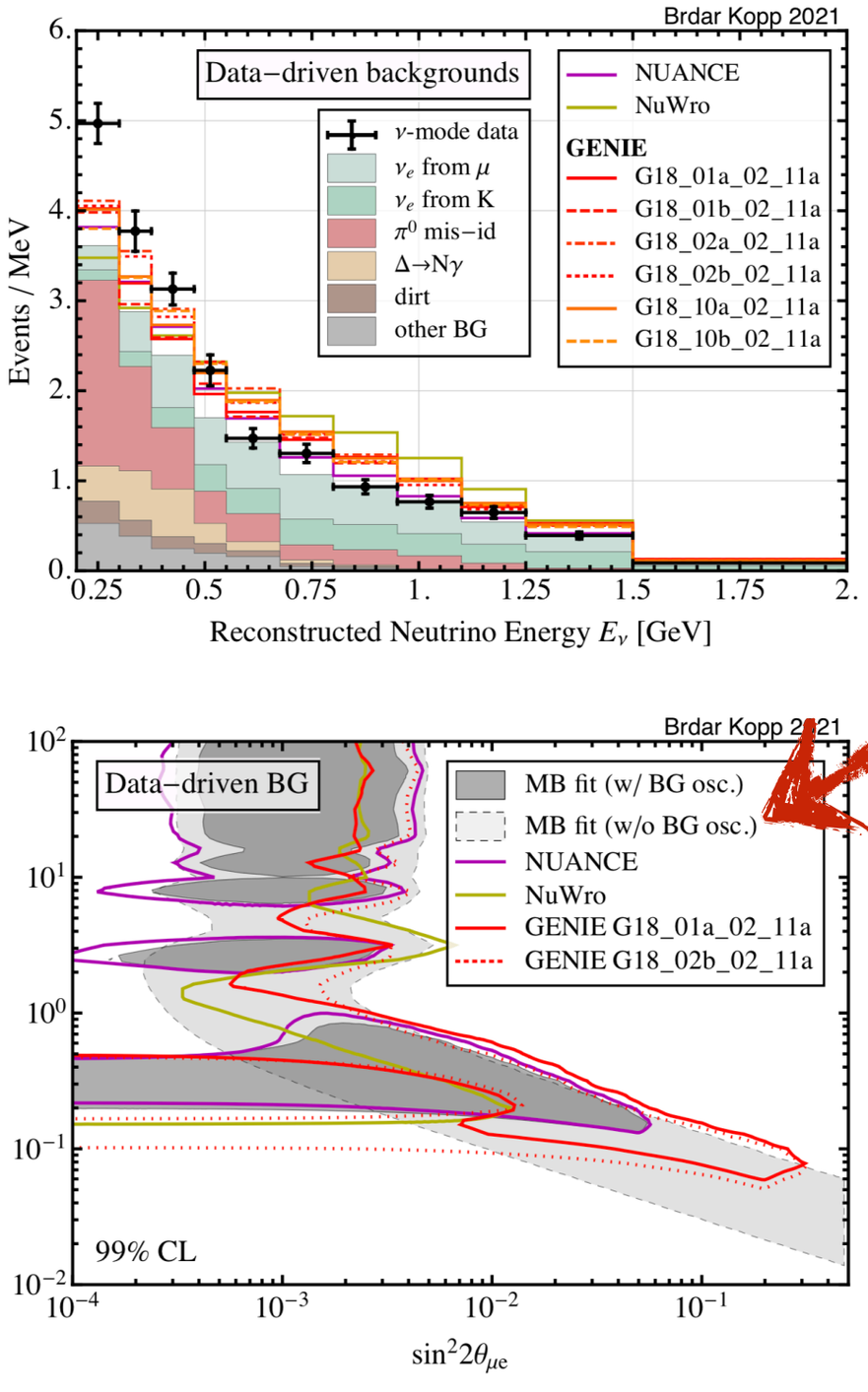


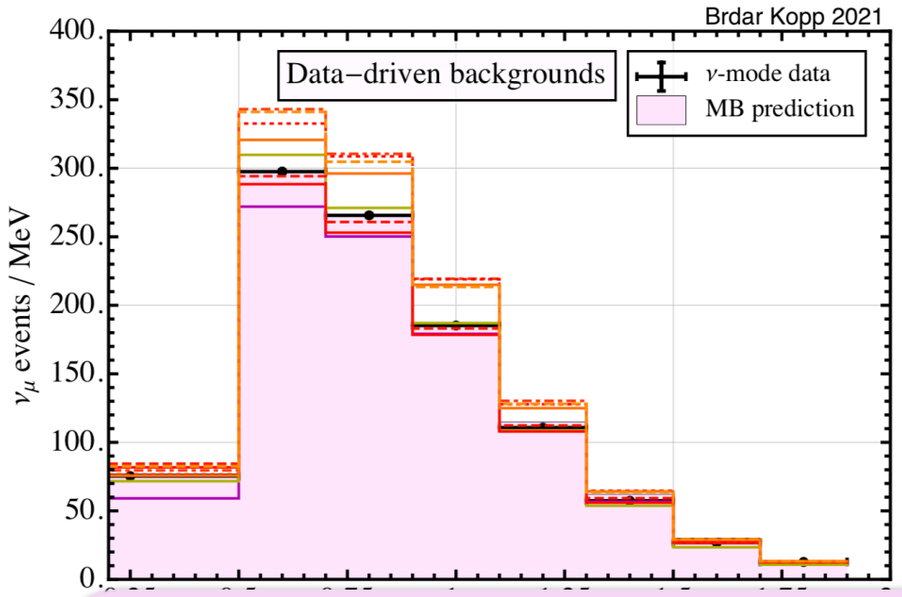




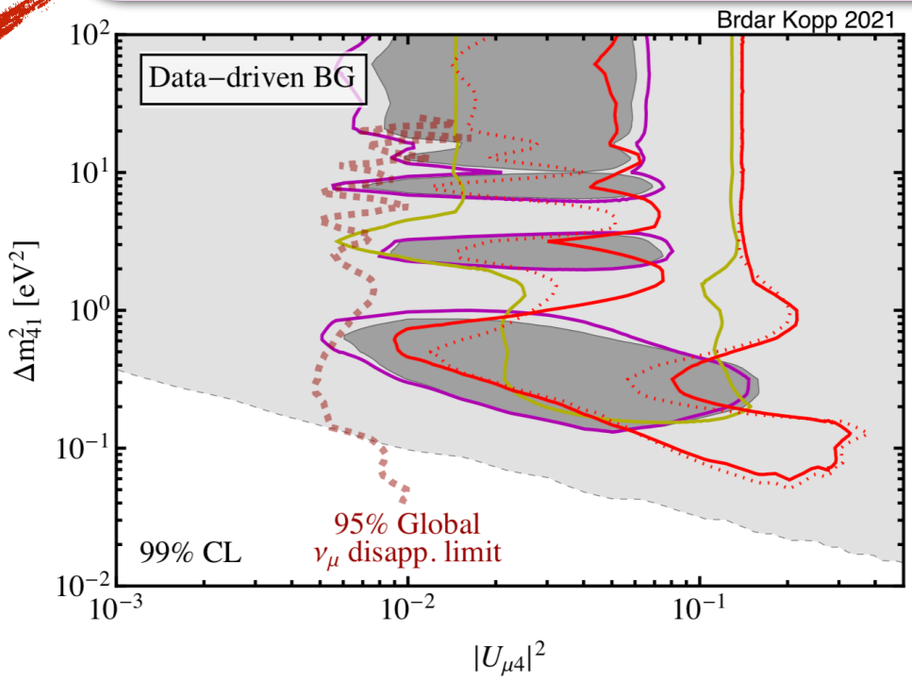


3+1 Models in MB: Comparison of Generators

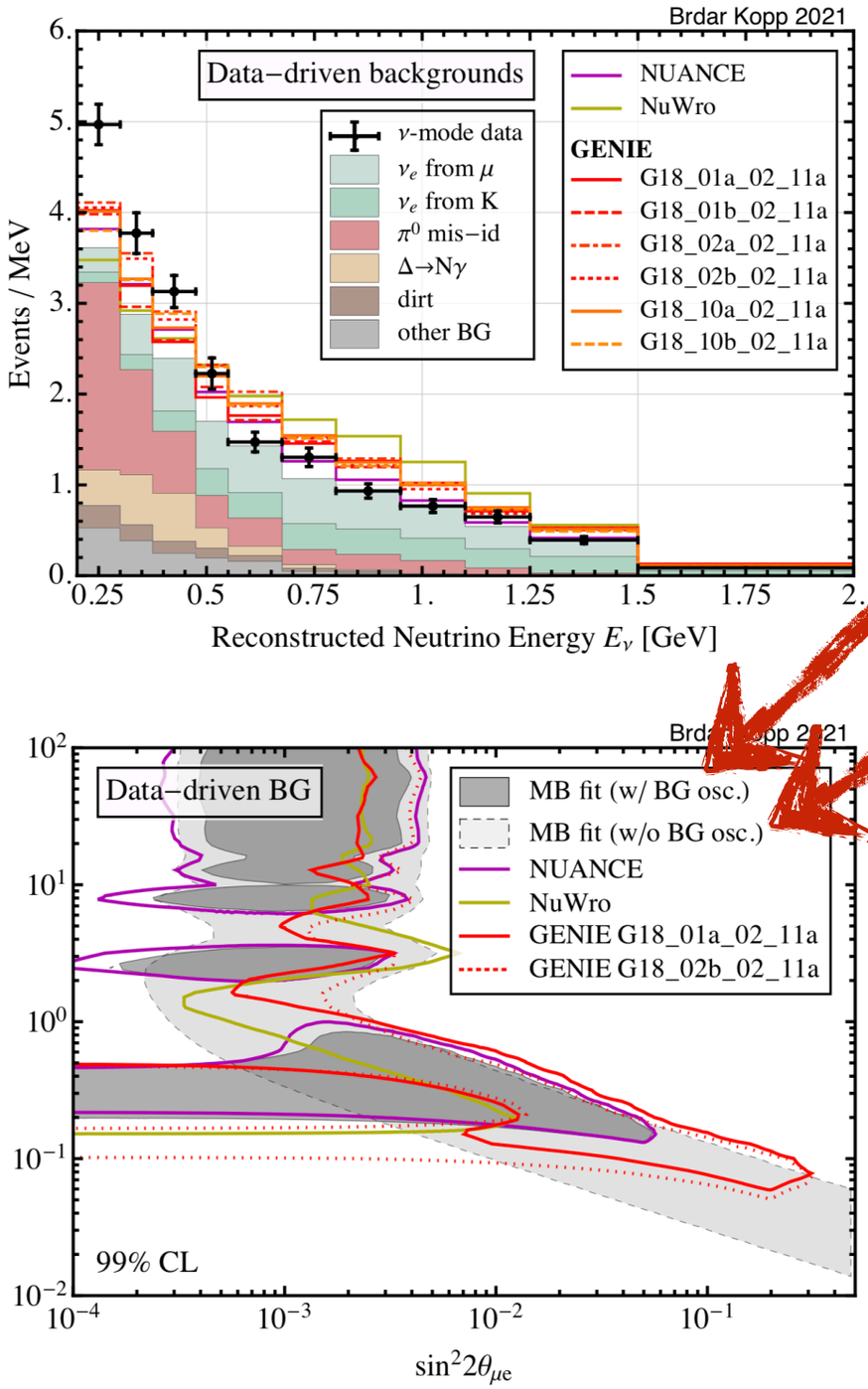


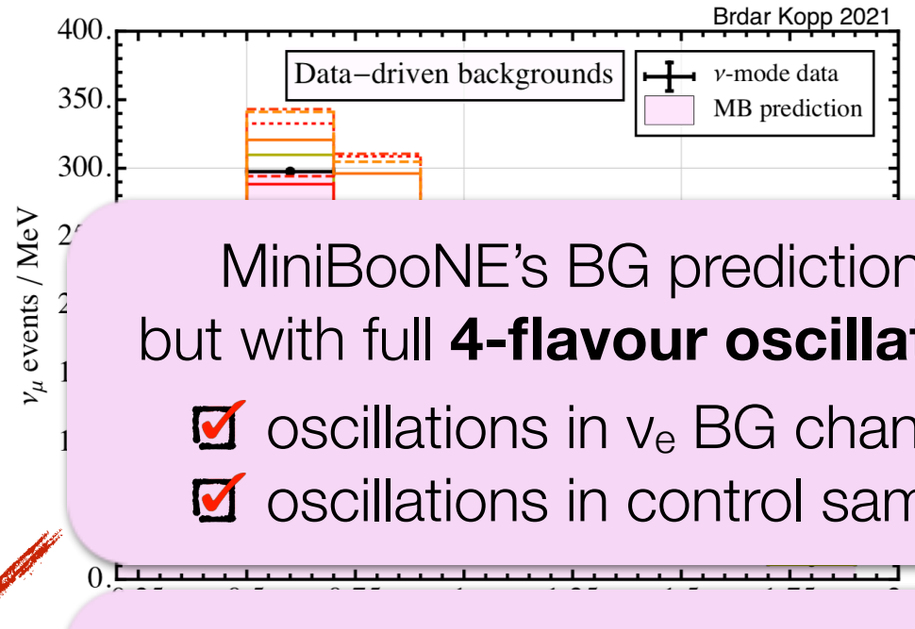


MiniBooNE's fit (2-flavour oscillations)



3+1 Models in MB: Comparison of Generators

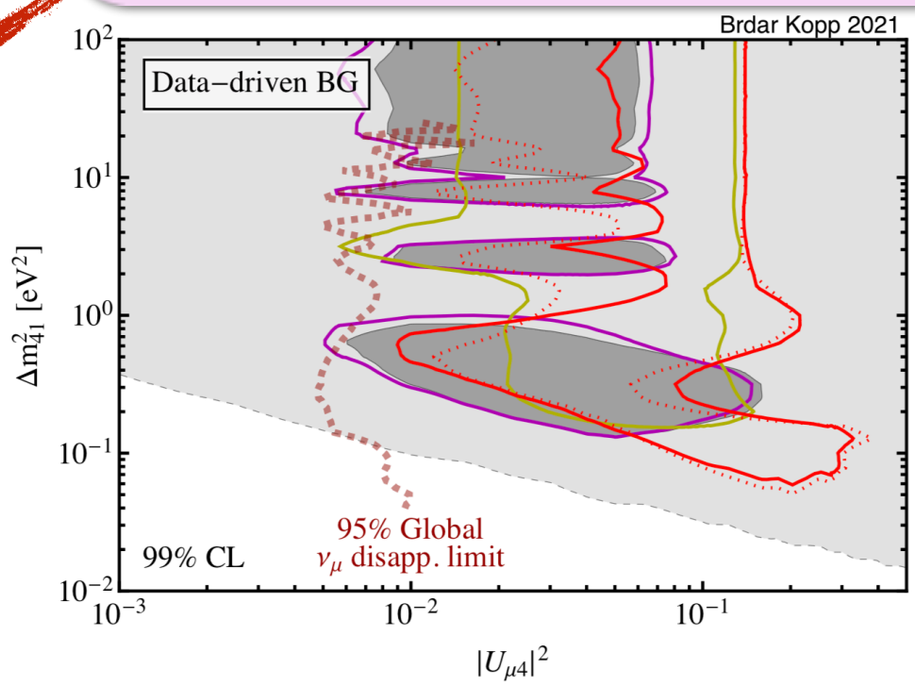




MiniBooNE's BG predictions,
but with full **4-flavour oscillations**

- ☑ oscillations in ν_e BG channels
- ☑ oscillations in control sample

MiniBooNE's fit (2-flavour oscillations)



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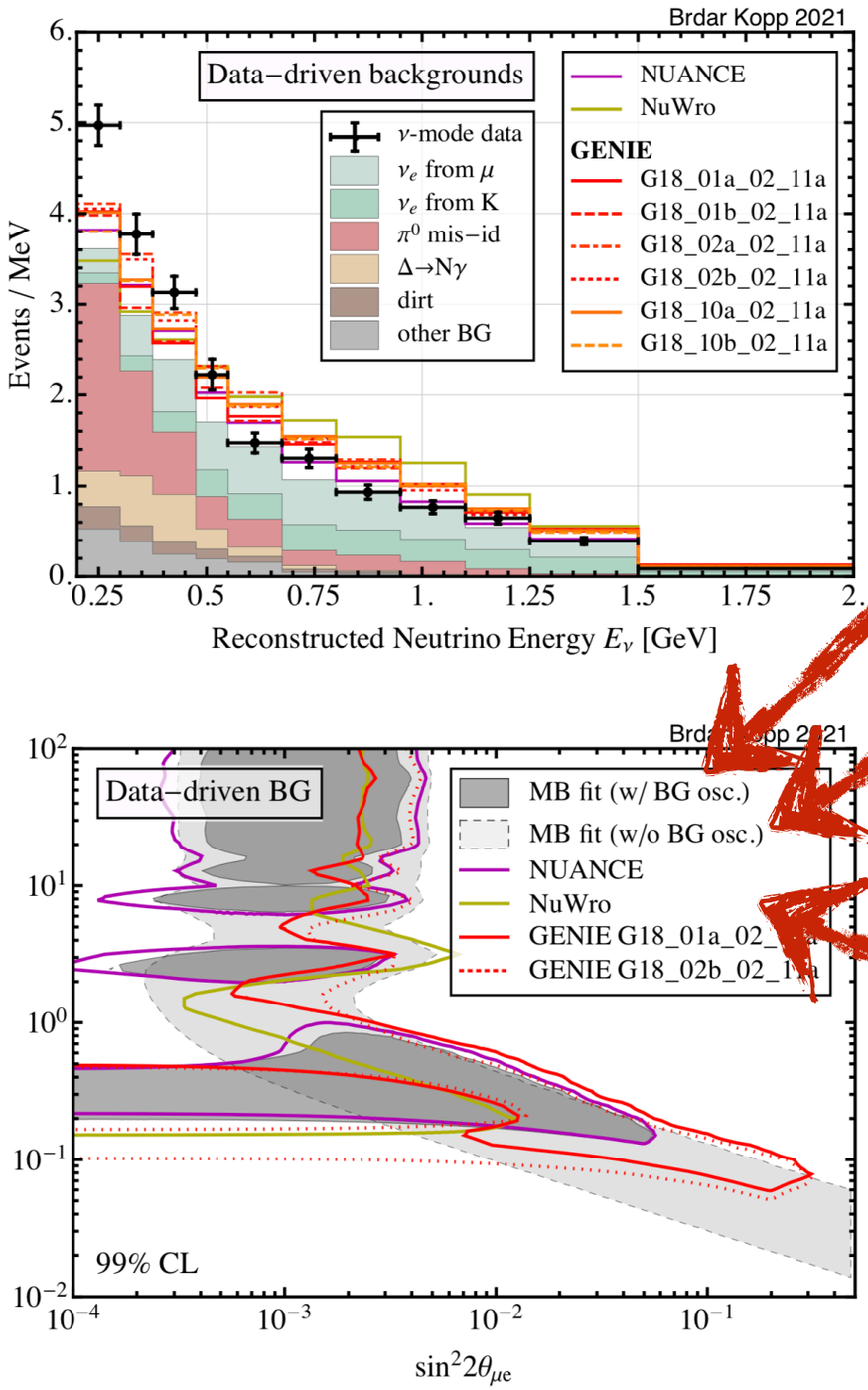

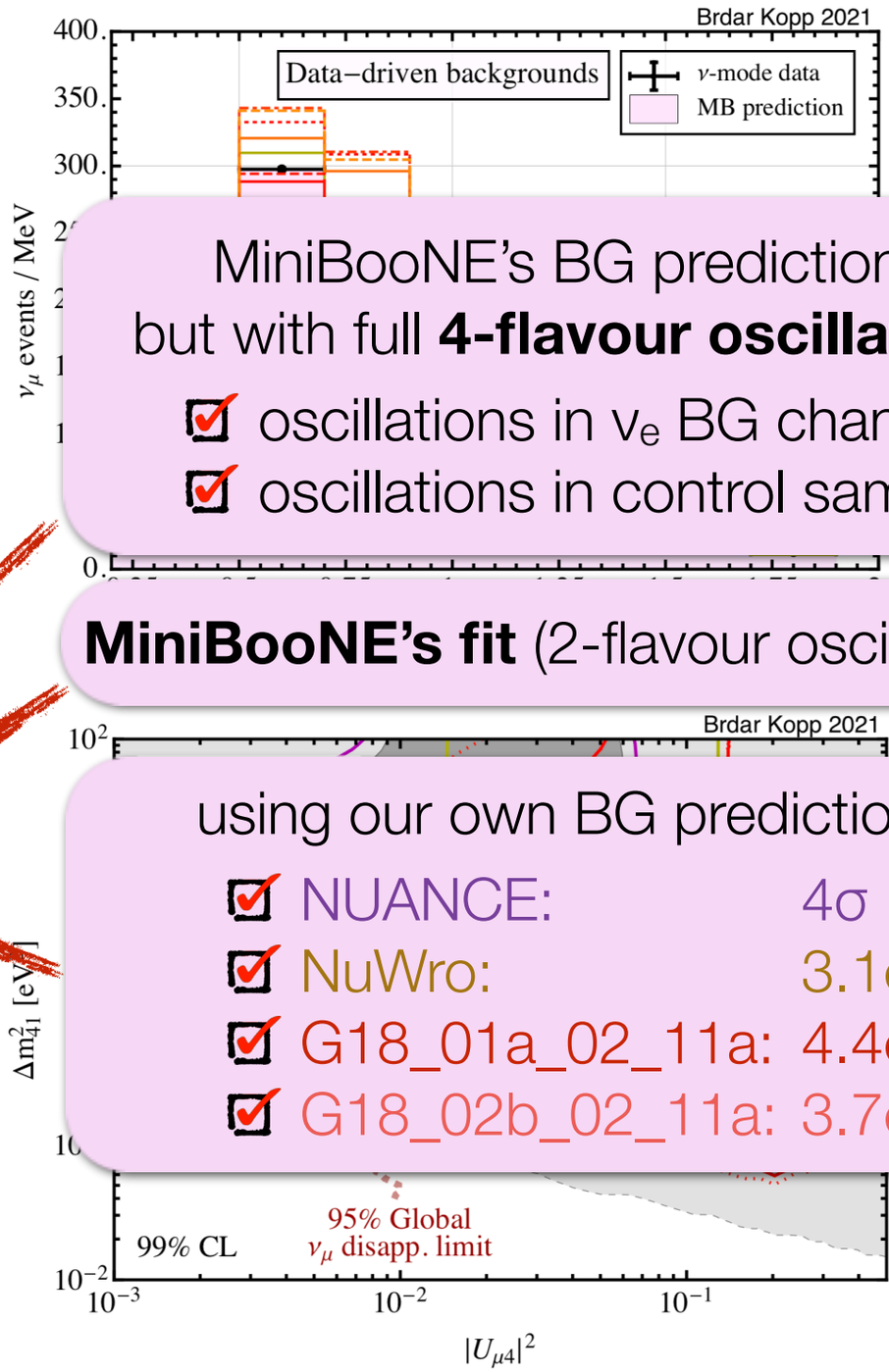

MiniBooNE's BG predictions,
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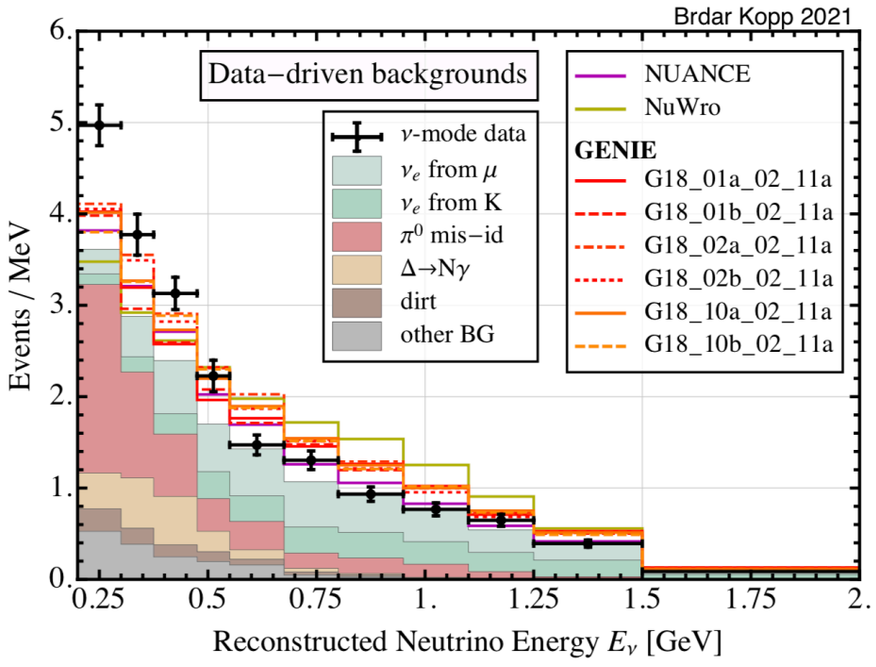
- ☑ oscillations in ν_e BG channels
- ☑ oscillations in control sample

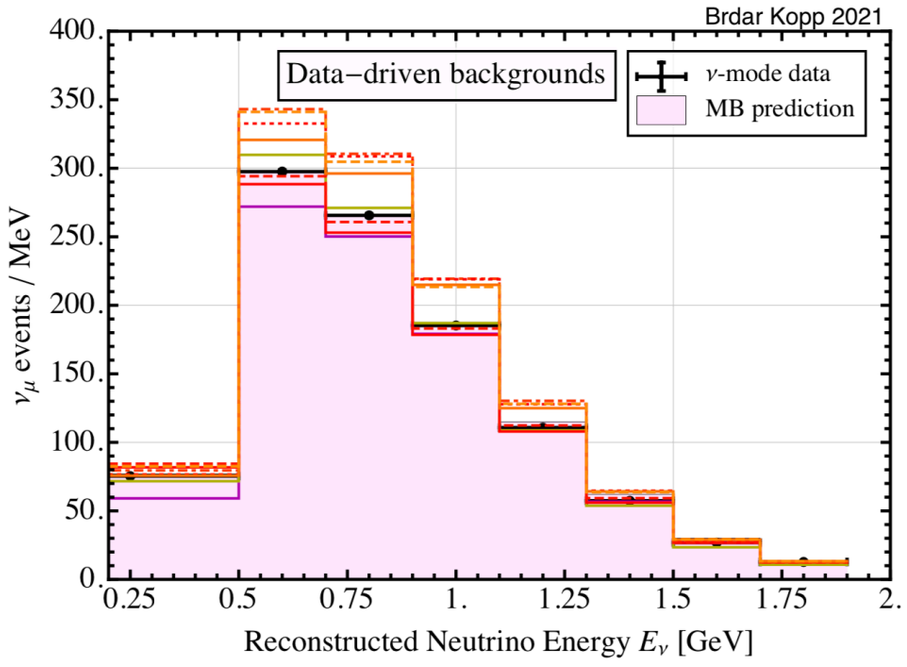
MiniBooNE's fit (2-flavour oscillations)

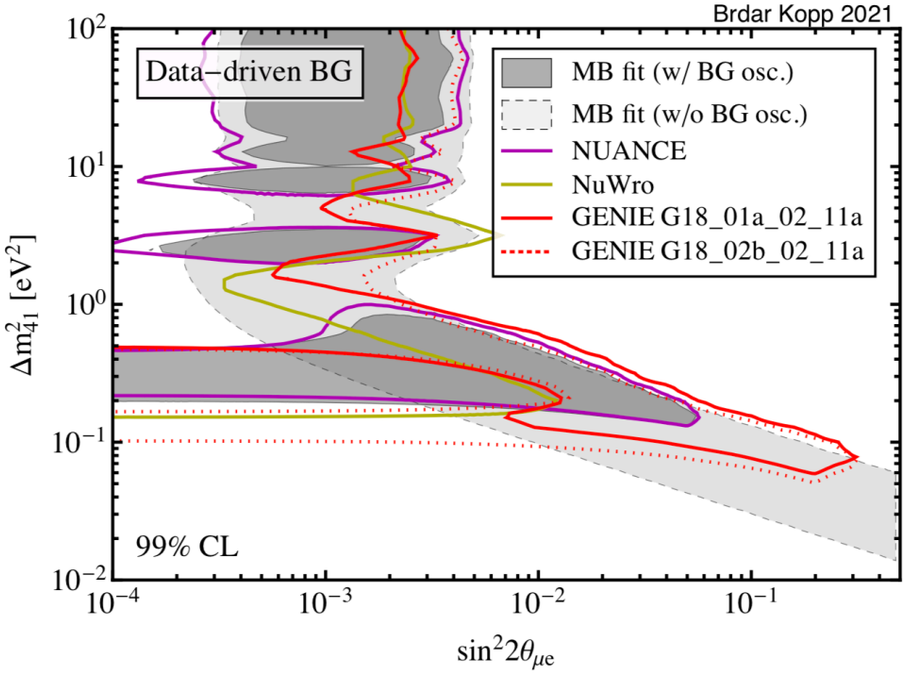
using our own BG predictions:

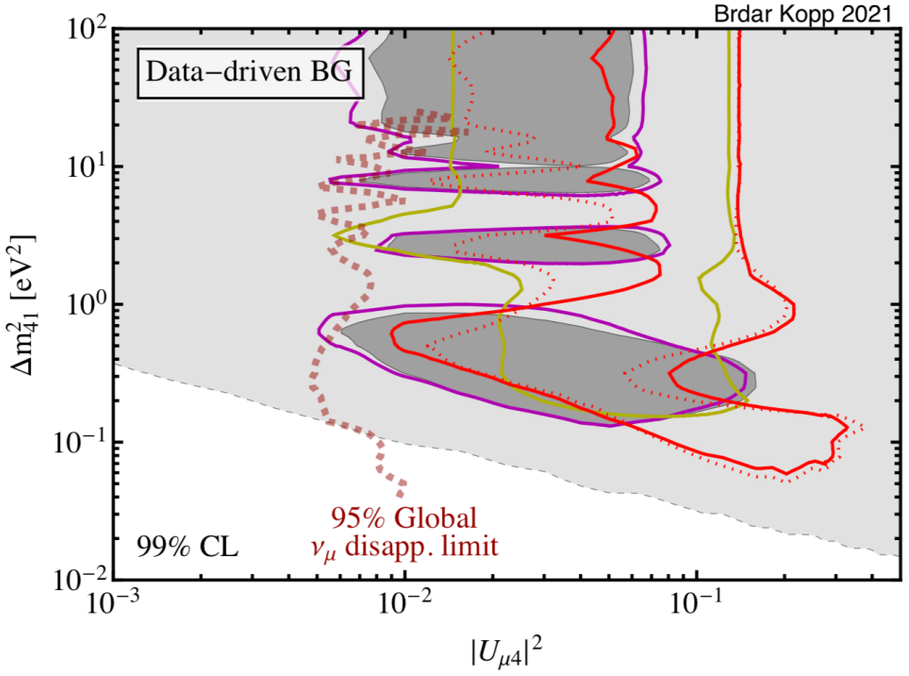
- ☑ NUANCE: 4σ
- ☑ NuWro: 3.1σ
- ☑ G18_01a_02_11a: 4.4σ
- ☑ G18_02b_02_11a: 3.7σ

3+1 Models in MB: Comparison of Generators









Light Sterile Neutrinos: The Global Picture

☑ In the short-baseline limit oscillation channels are related:

$$P_{\nu_e \to \nu_e} \simeq 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$

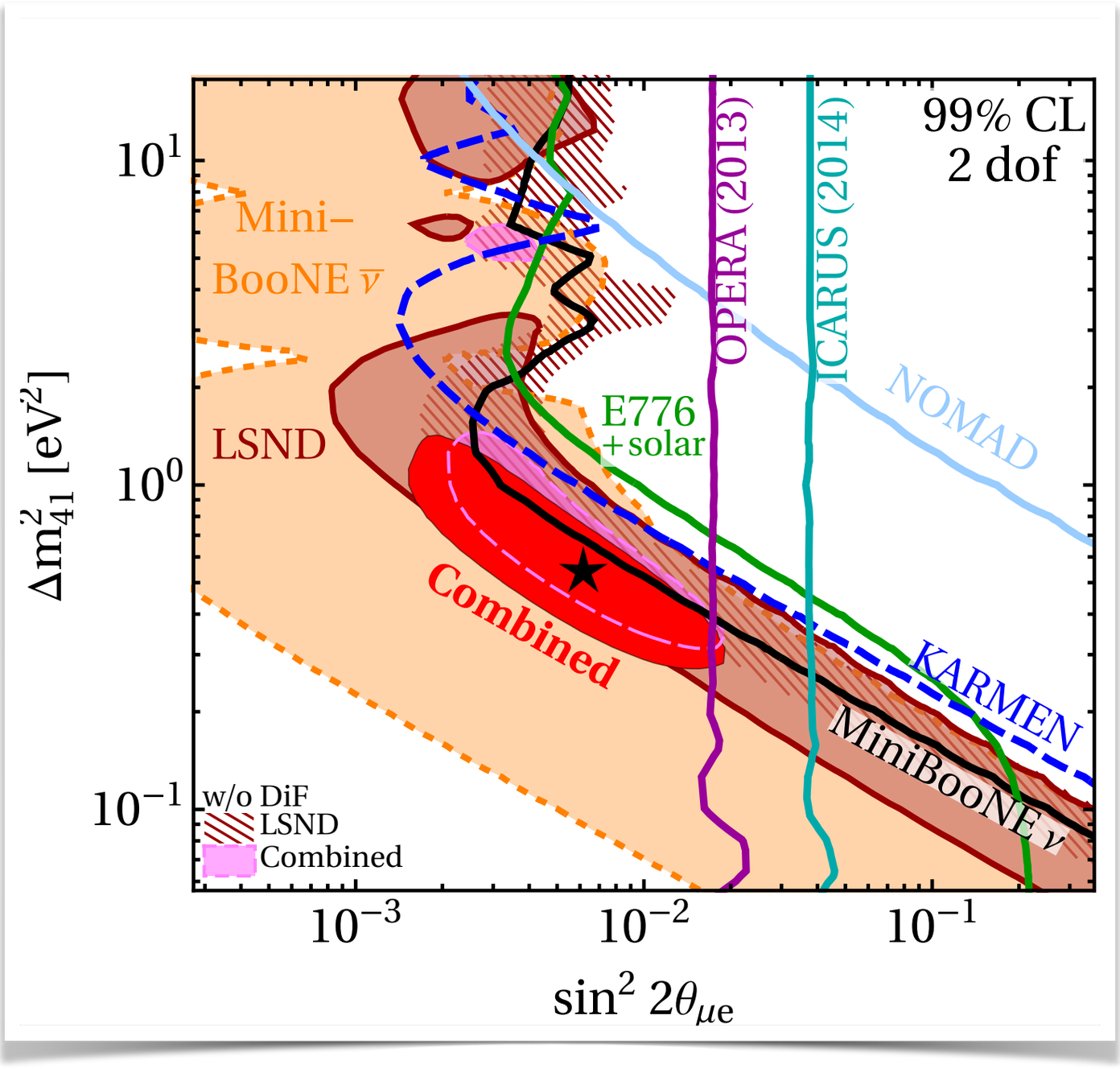
$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$

$$P_{\nu_\mu \to \nu_e} \simeq 2|U_{e4}|^2|U_{\mu 4}|^2$$

(for $4\pi E/\Delta m^2_{41} \ll L \ll 4\pi E/\Delta m^2_{31}$)

☑ Models can be over-constrained.

$\nu_\mu \rightarrow \nu_e$ appearance



Dentler Hernández JK Machado Maltoni Martinez Schwetz, *in preparation*

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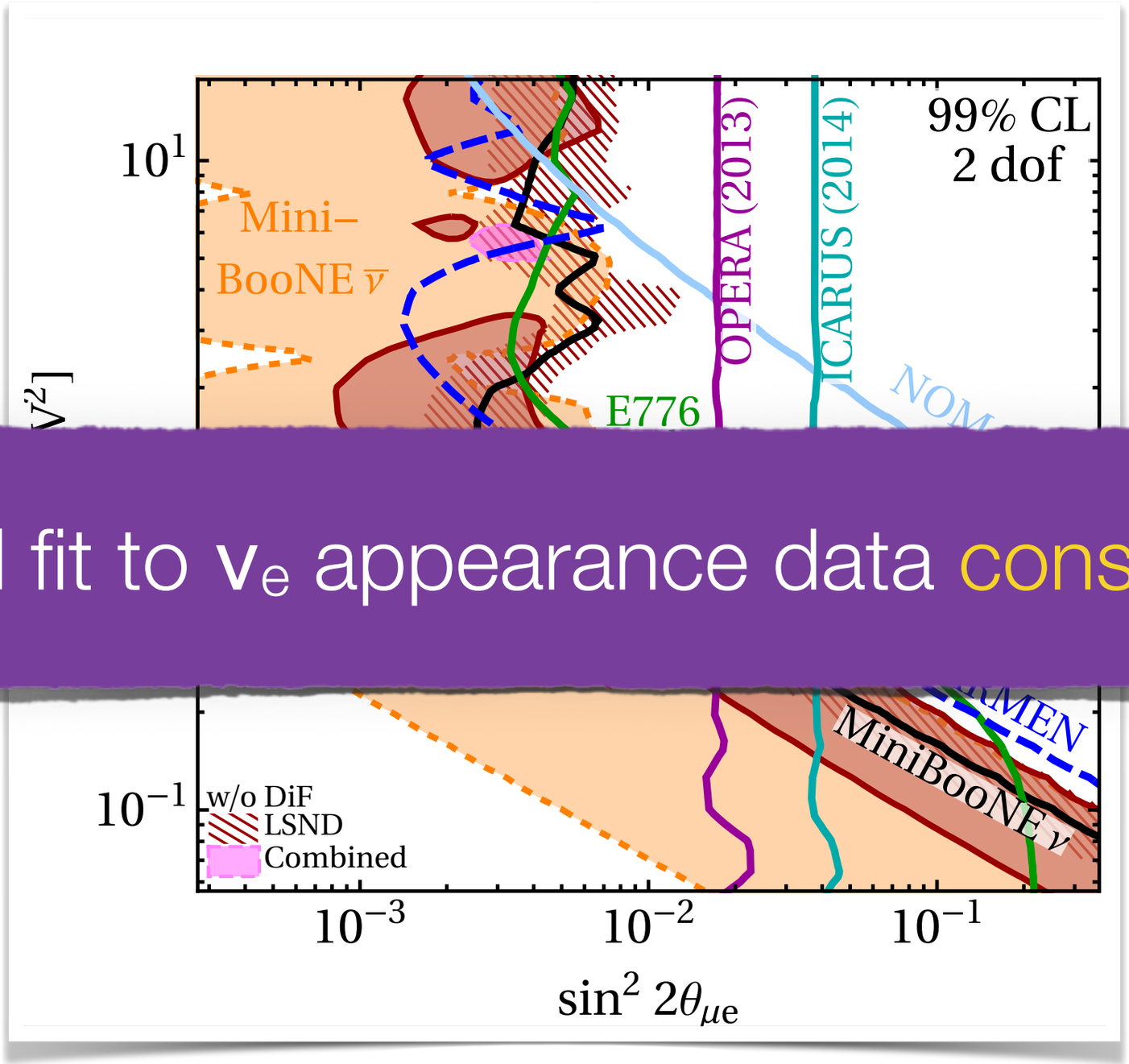
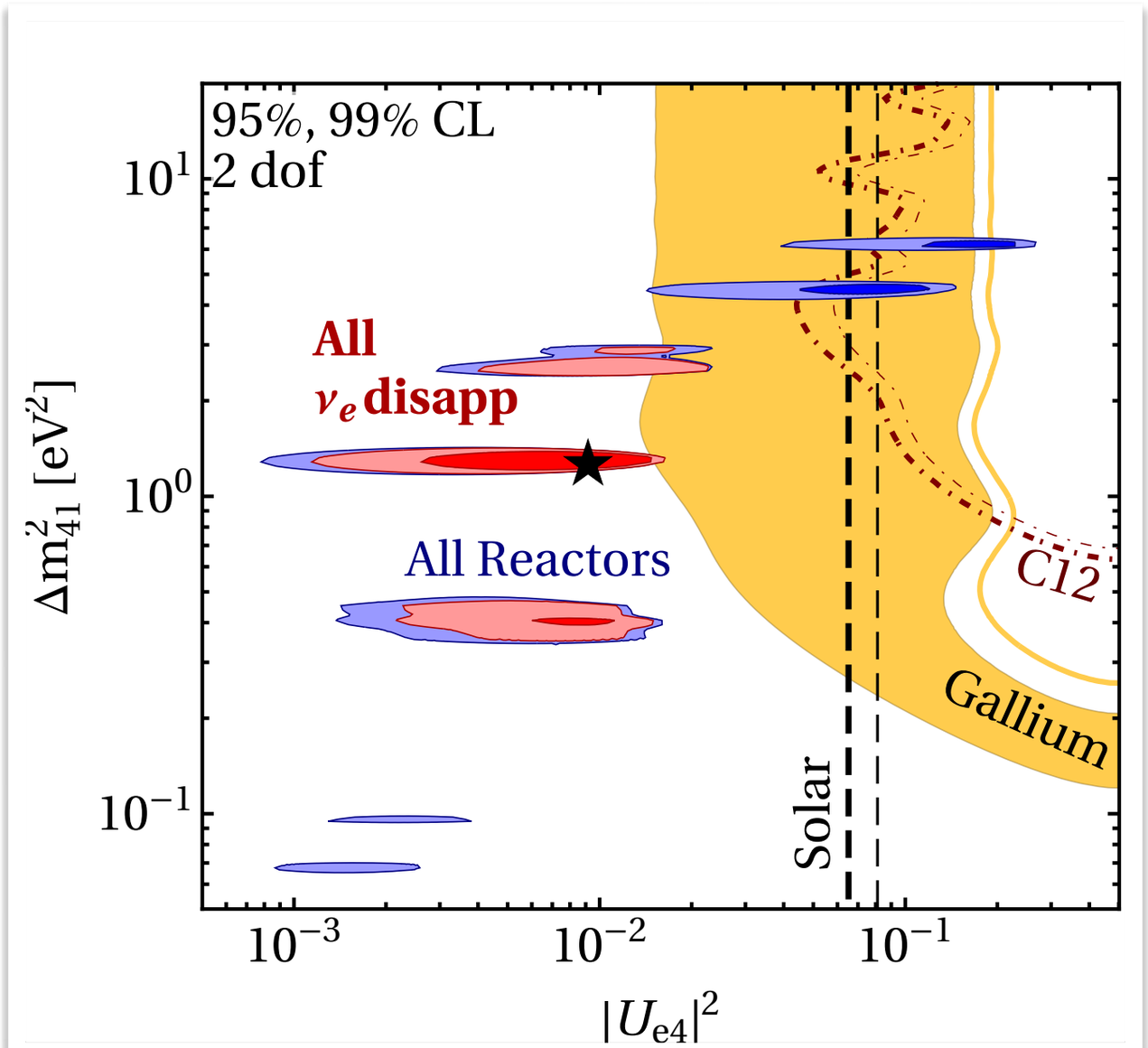


Global fit to ν_e appearance data consistent.

Dentler Hernández JK Machado Maltoni Martinez Schwetz, *in preparation*

Global Fit to ν_e and $\bar{\nu}_e$ Disappearance



Dentler Hernández JK Maltoni Schwetz 1709.04294

Dentler Hernández JK Machado Maltoni Martinez Schwetz, *in preparation*

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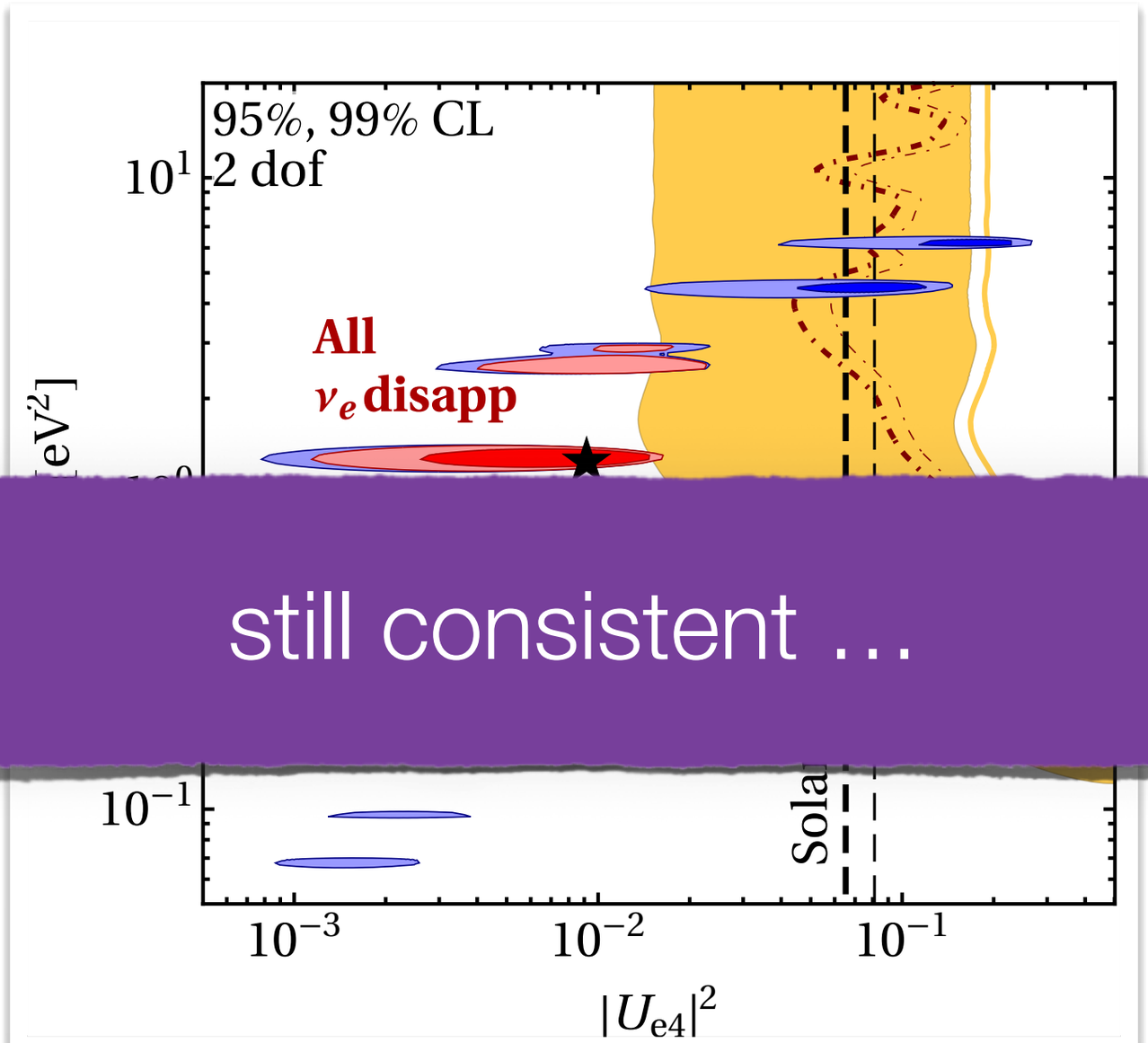
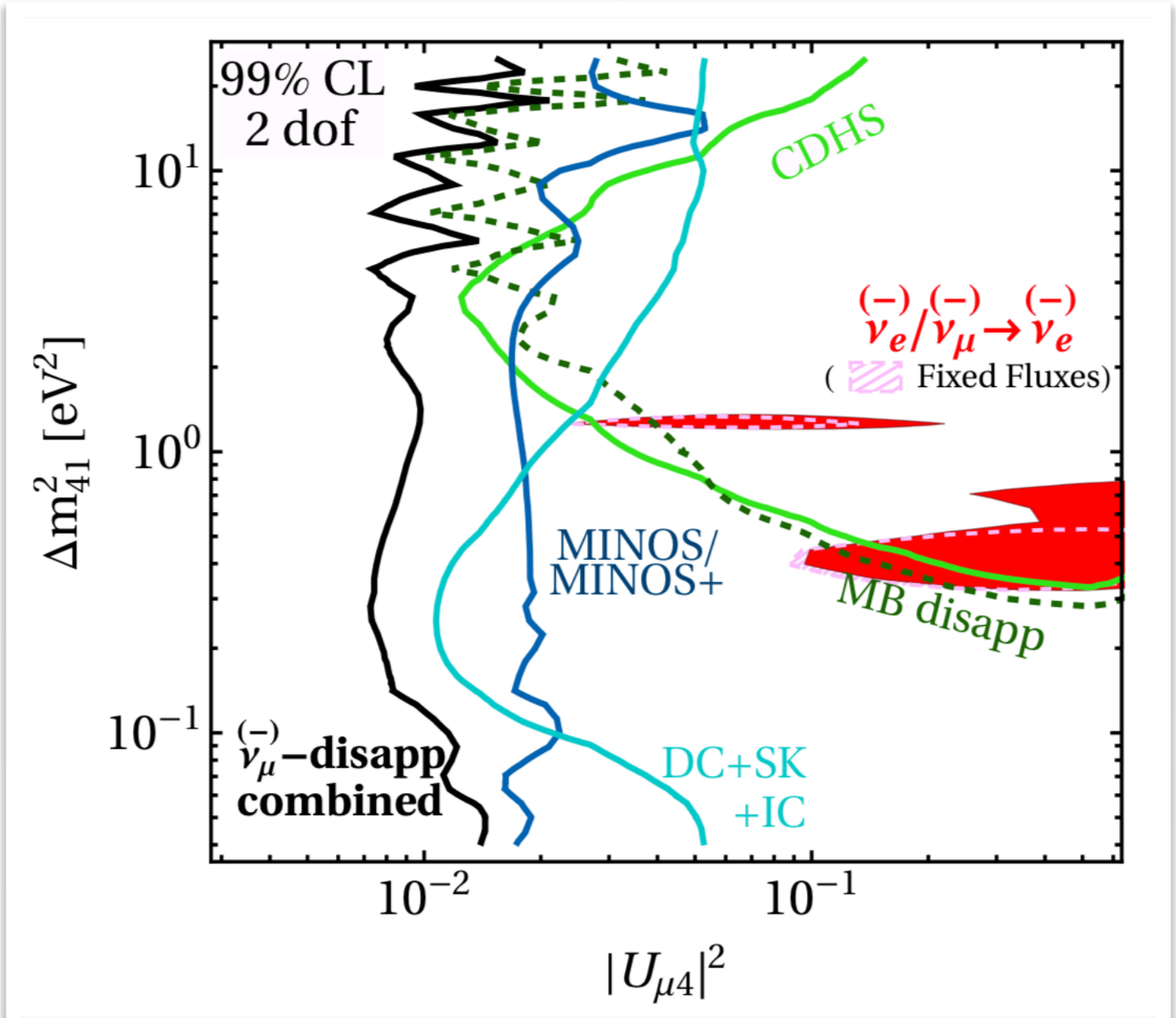


still consistent …

Dentler Hernández JK Maltoni Schwetz 1709.04294
Dentler Hernández JK Machado Maltoni Martinez Schwetz, *in preparation*

Sterile Neutrinos?

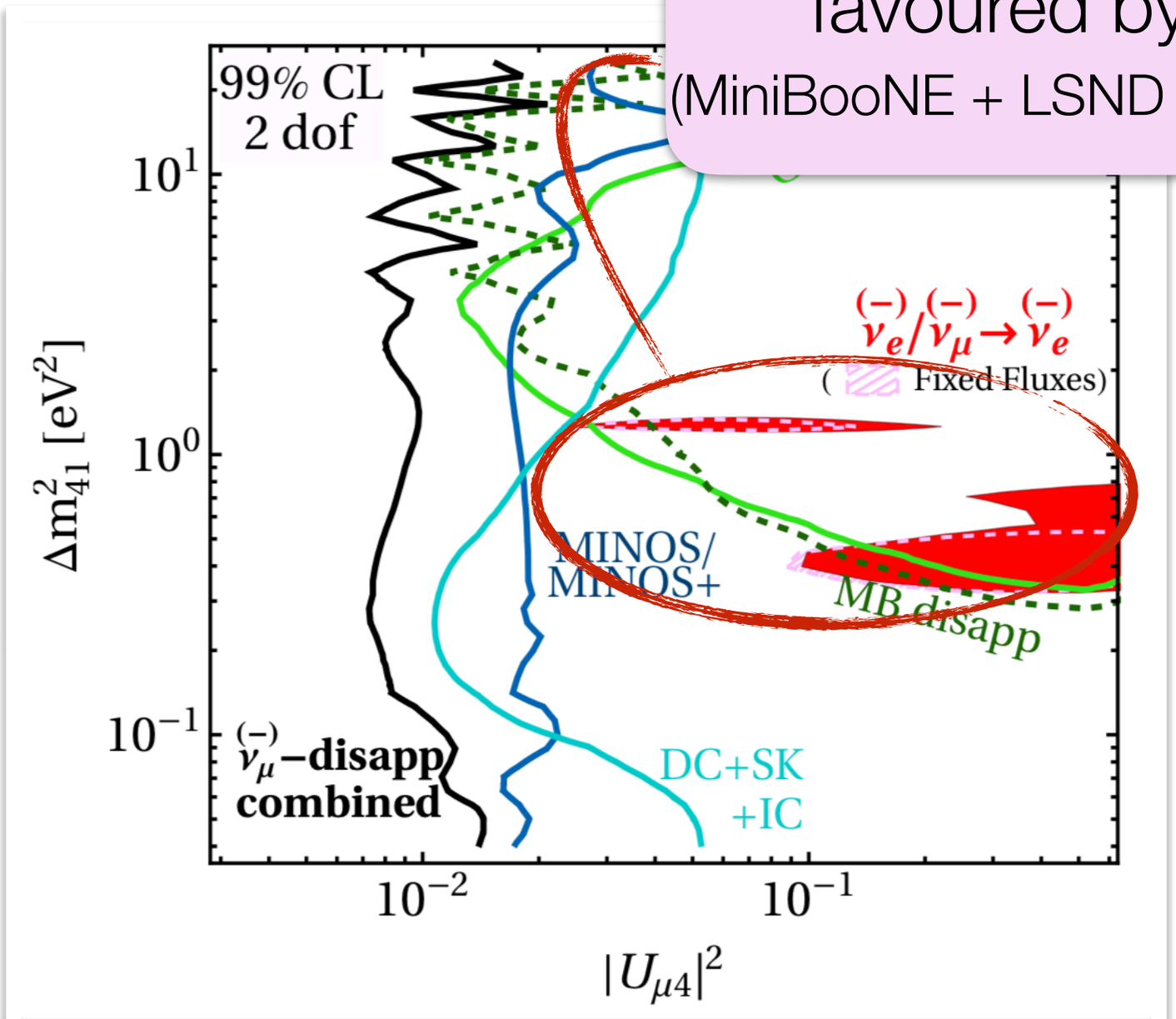


Dentler Hernandez JK Machado Maltoni Martinez Schwetz, 1803.10661
see also works by Collin Argüelles Conrad Shaevitz, 1607.00011
Gariazzo Giunti Laveder Li, 1703.00860

Sterile Neutrinos?

favoured by anomalies

(MiniBooNE + LSND + reactors + gallium



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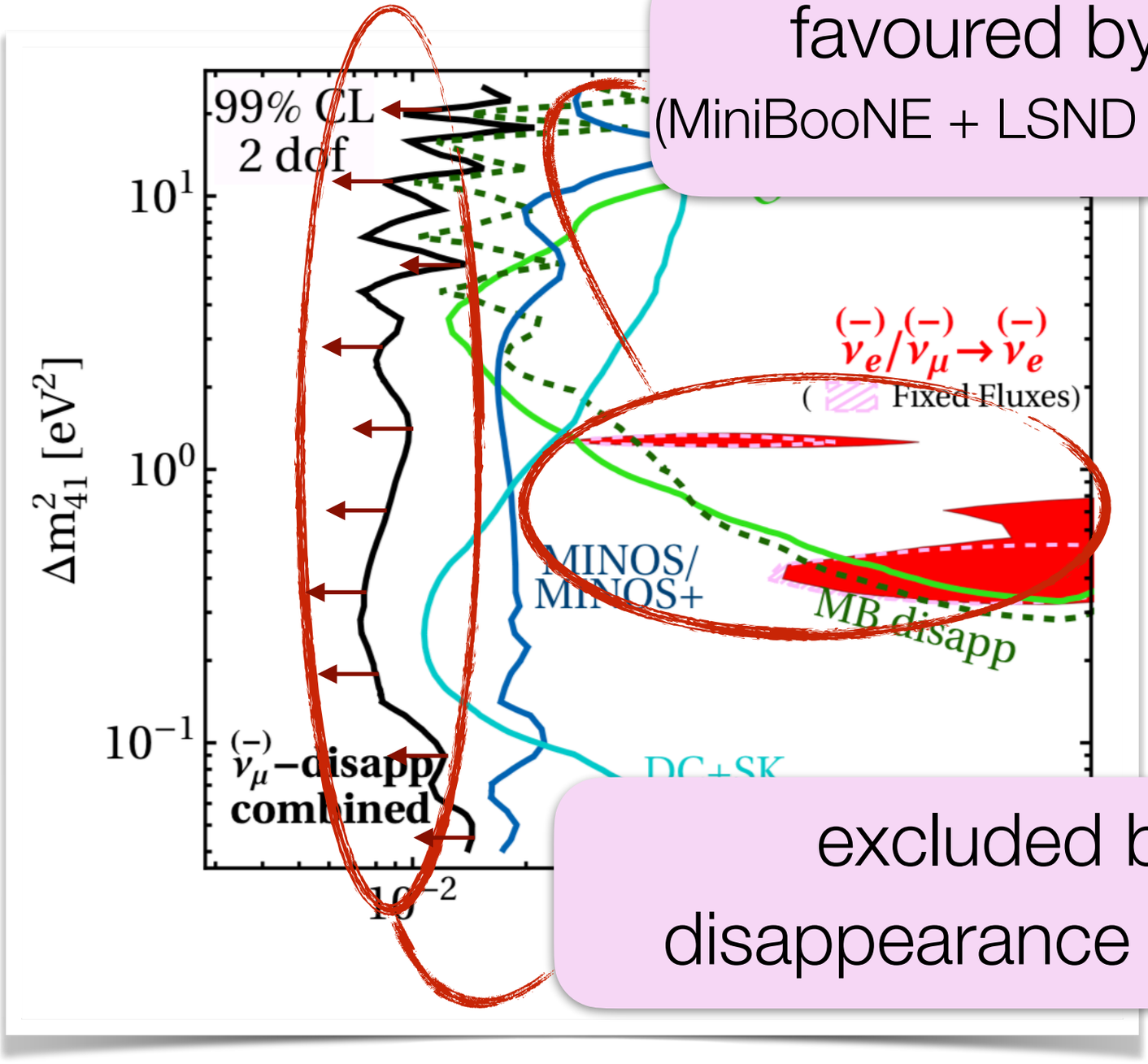

excluded by ν_μ disappearance searches

Dentler Hernandez JK Machado Maltoni Martinez Schwetz, 1803.10661
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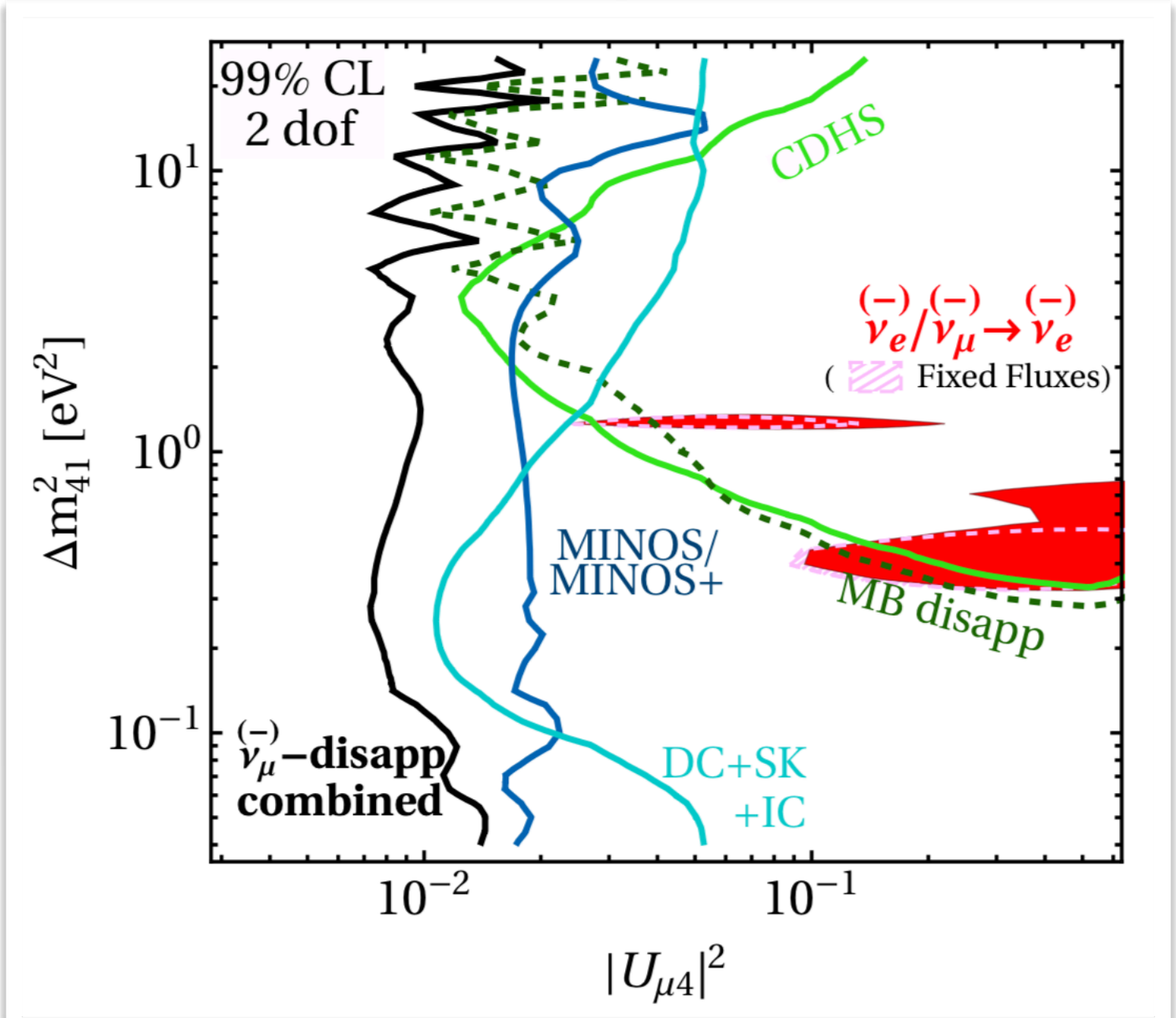

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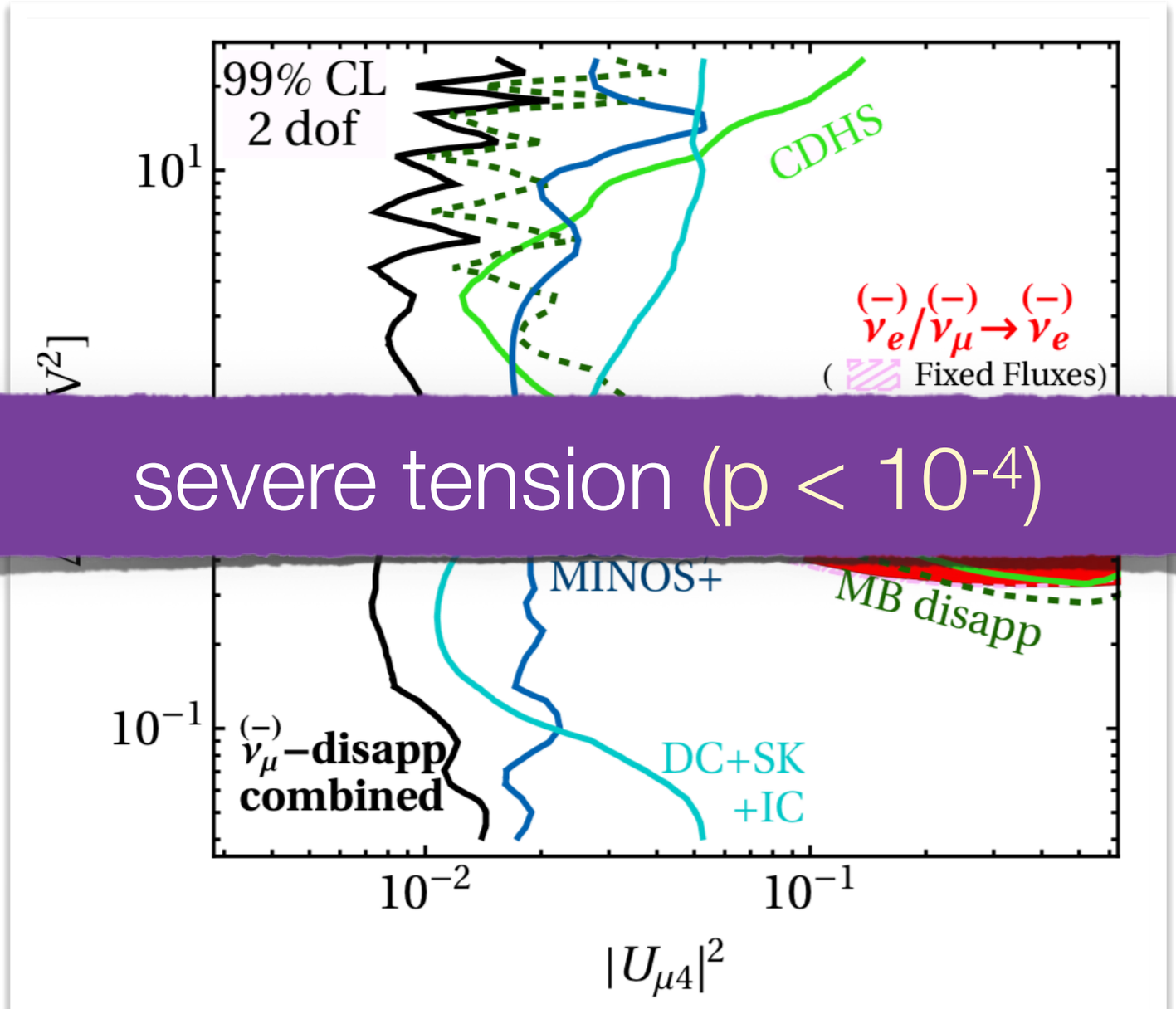

severe tension ($p < 10^{-4}$)

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

Sterile Neutrinos Cosmology

Problems don't end here.

An extra neutrino species is in severe tension with cosmology.

Standard picture: ν_s production via oscillation at T ≳ MeV

$N_{eff} \lesssim 3.38$ ⚡

$\Sigma m_\nu \lesssim 0.23$ eV ⚡

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energy density in relativistic particles
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$\Sigma m_\nu \lesssim 0.23$ eV ⚡

sum of neutrino masses
affects structure formation
sterile neutrino compatible with anomalies
would imply $\Sigma m_\nu \sim 1$ eV

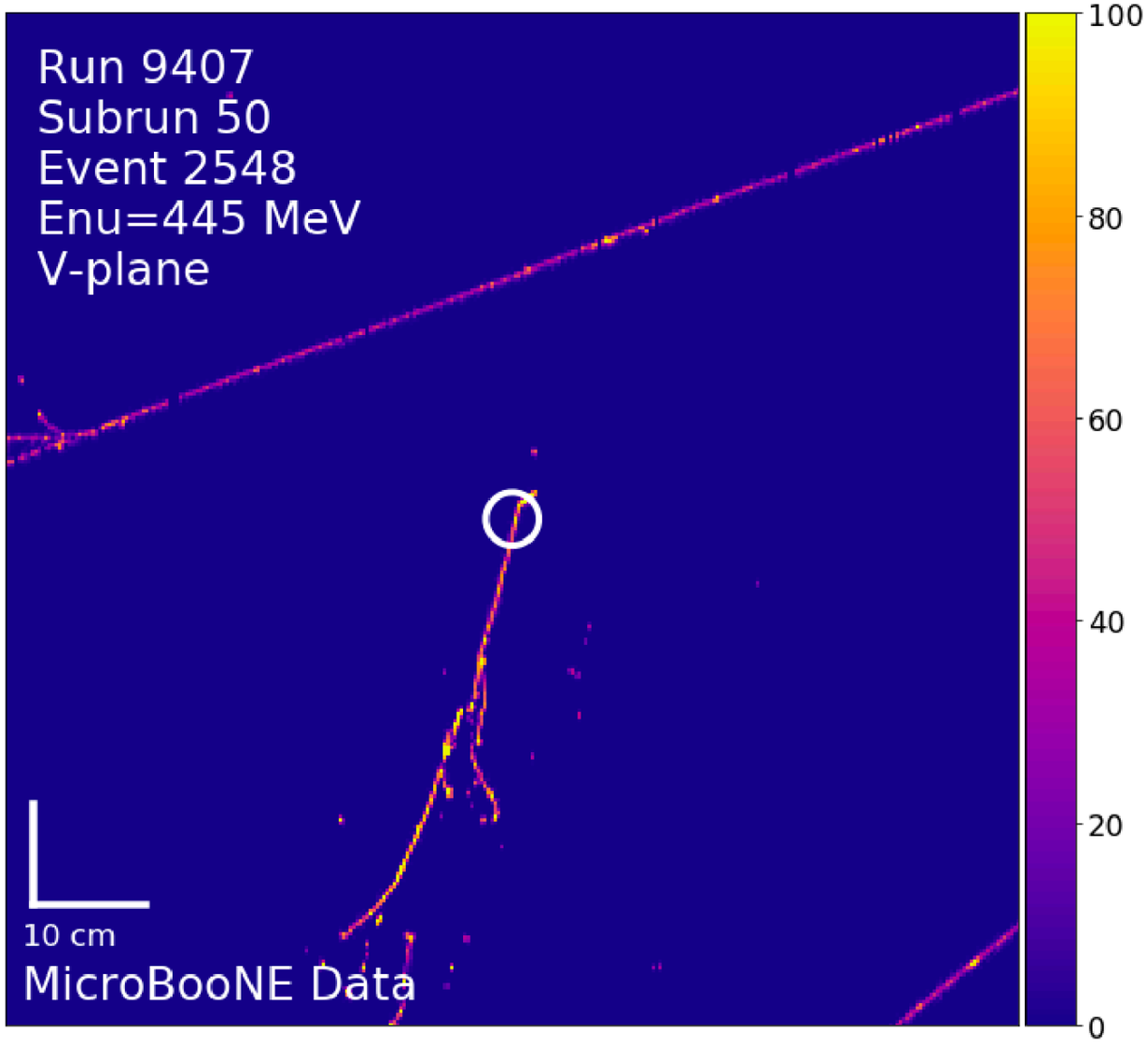
To Do List for Neutrino Anomalies

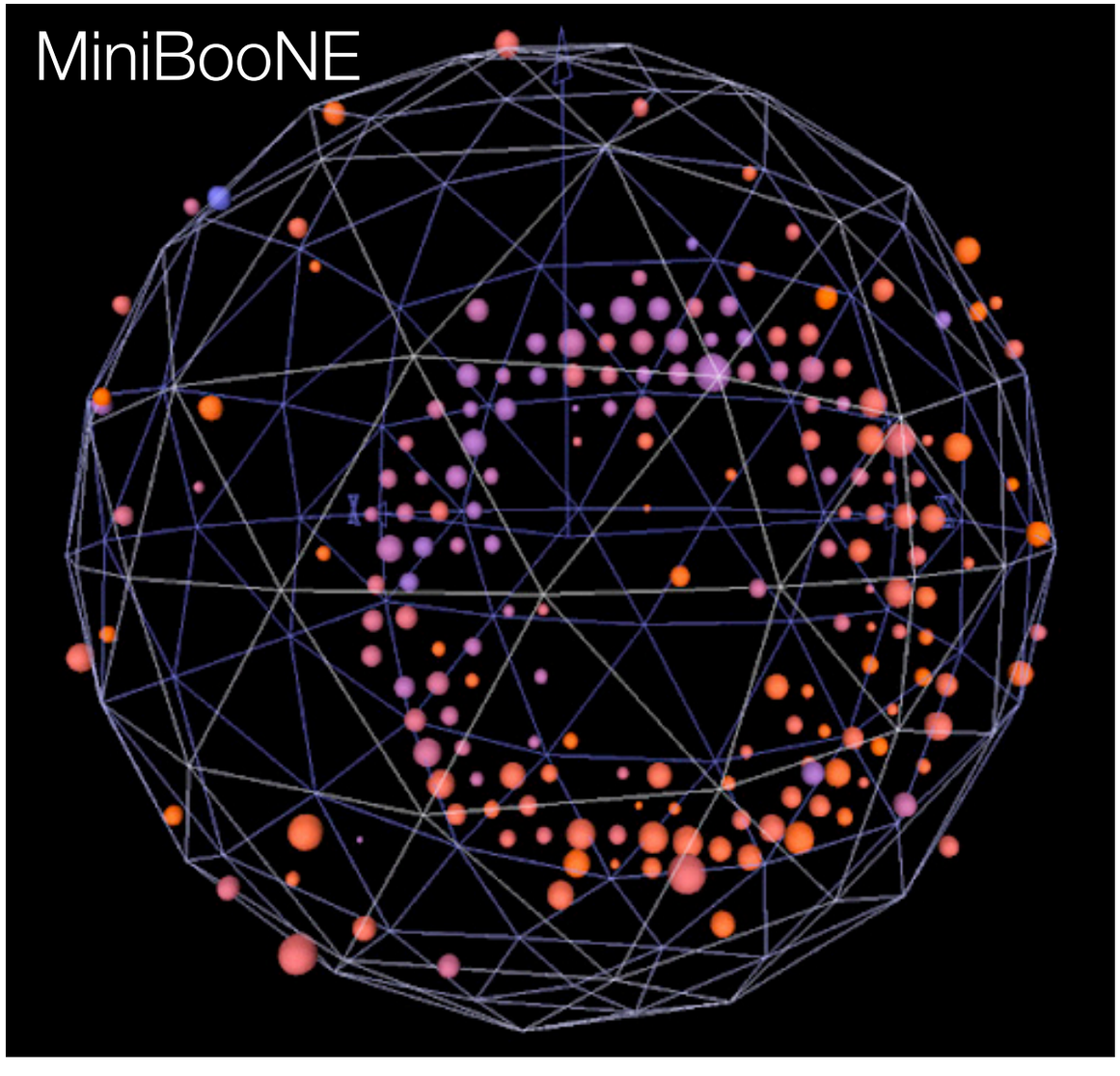
- ★ scrutinize anomalies for unknown systematics (need 4 independent effects!)
- ★ scrutinize also null results!
- ★ extended models?

MicroBooNE

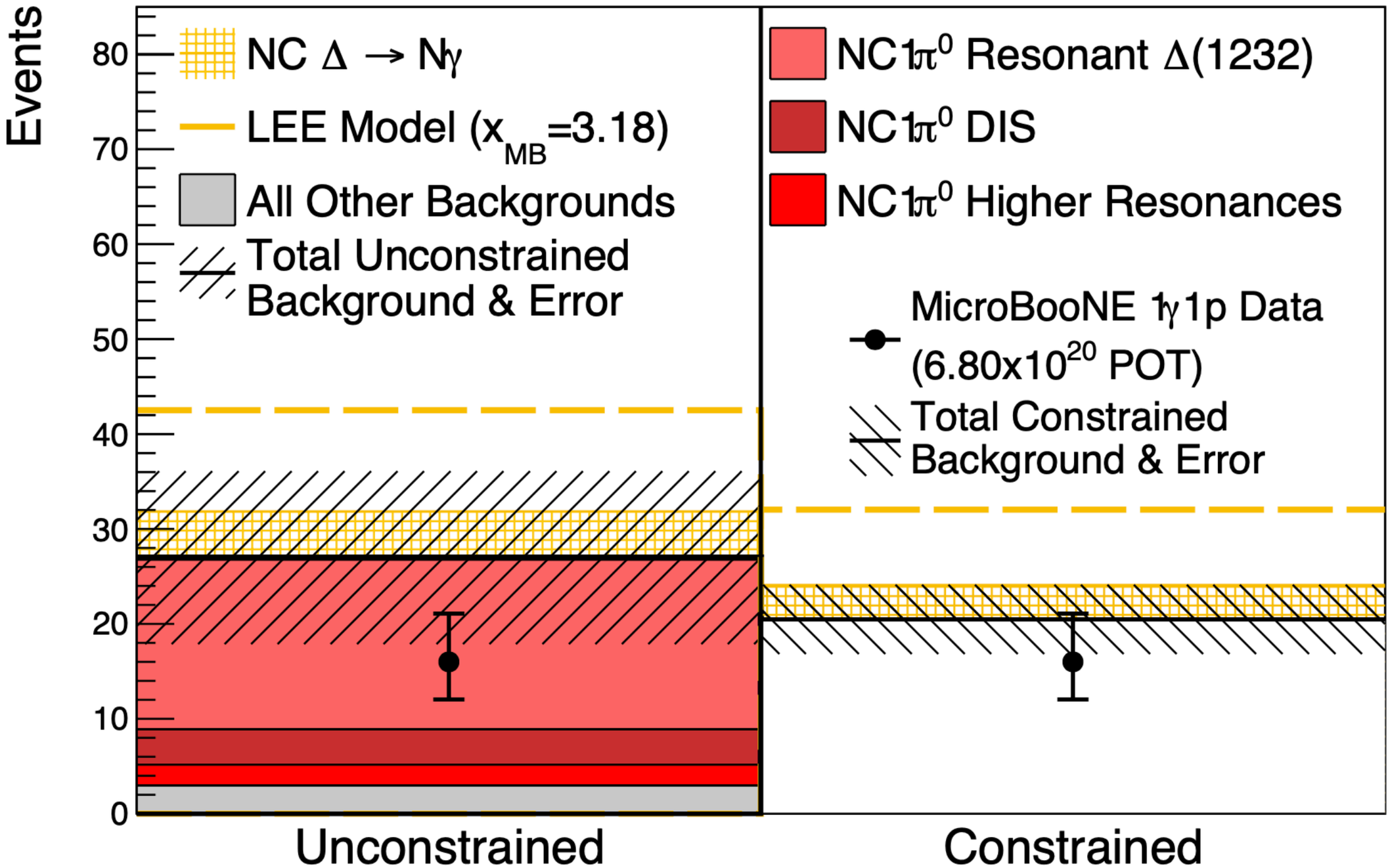
- ☑ 80 ton LAr TPC
- ☑ Very good event reconstruction capabilities
  - can distinguish $e^{\pm}$ from γ

MiniBooNE vs. MicroBooNE



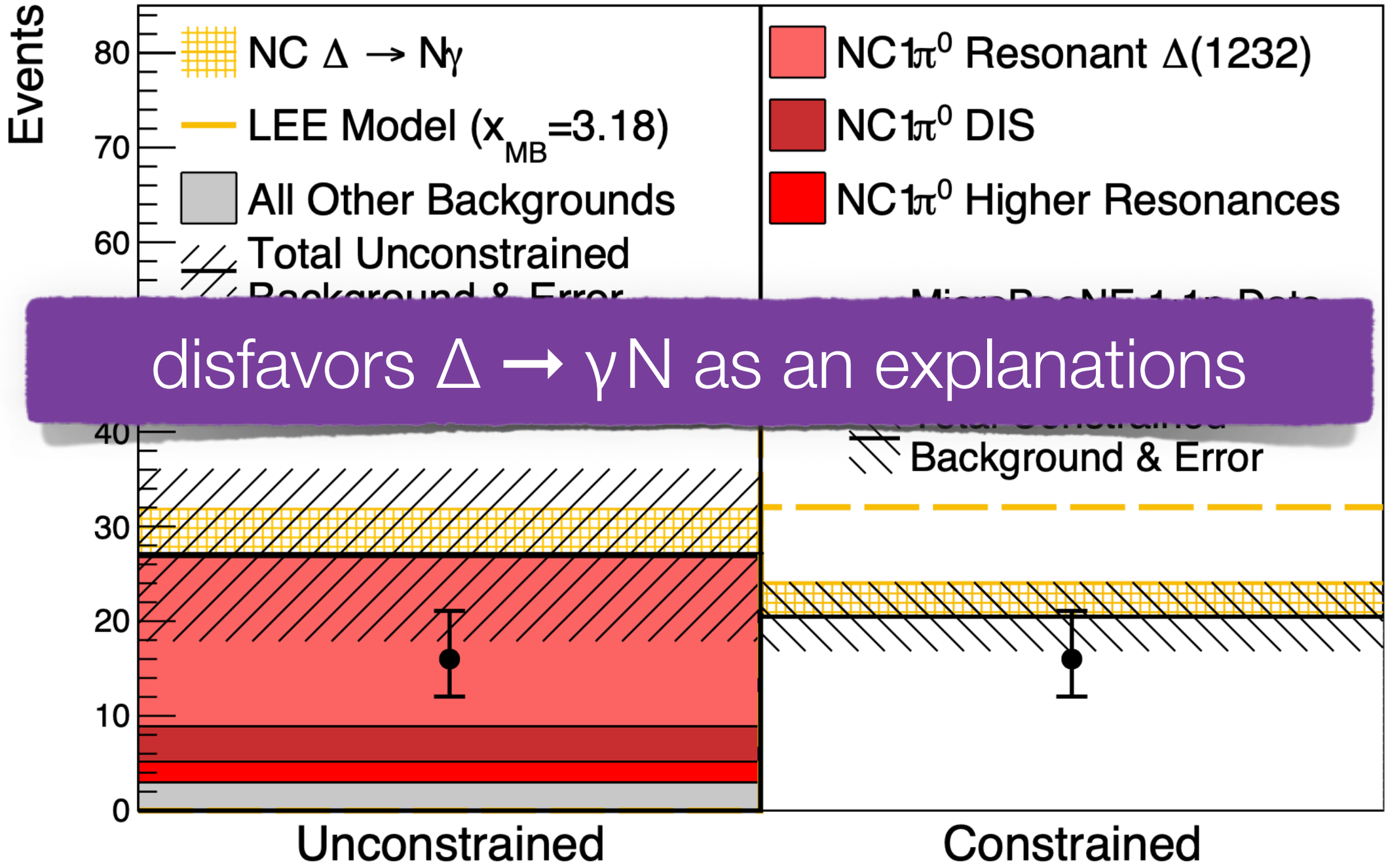


Δ → γ N: MicroBooNE



MicroBooNE arXiv:2110.00409

Δ → γ N: MicroBooNE



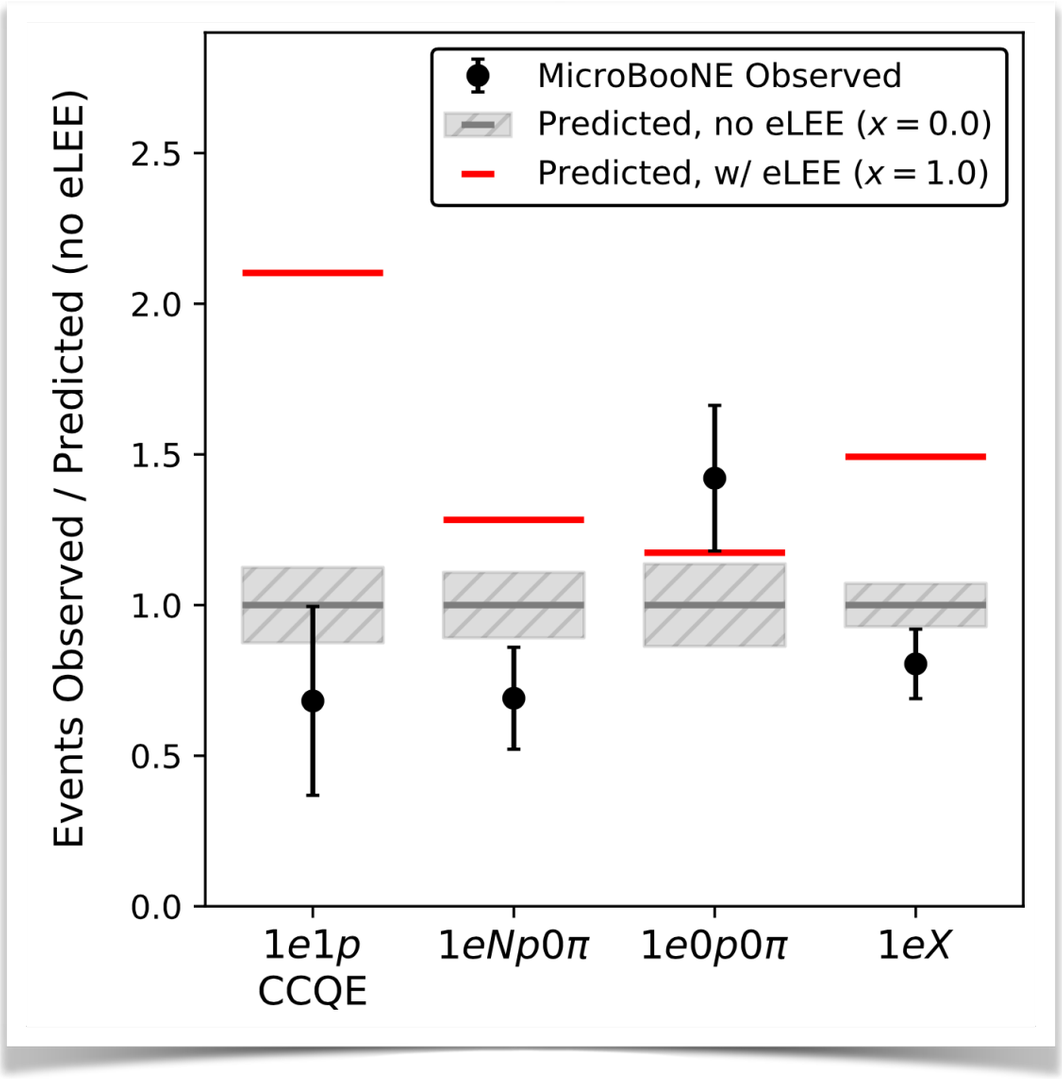
disfavors Δ → γN as an explanations

MicroBooNE arXiv:2110.00409

A True ν_e signal?

☑ Tested by MicroBooNE in several channels

☑ No support for interpretation of MiniBooNE excess as ν_e



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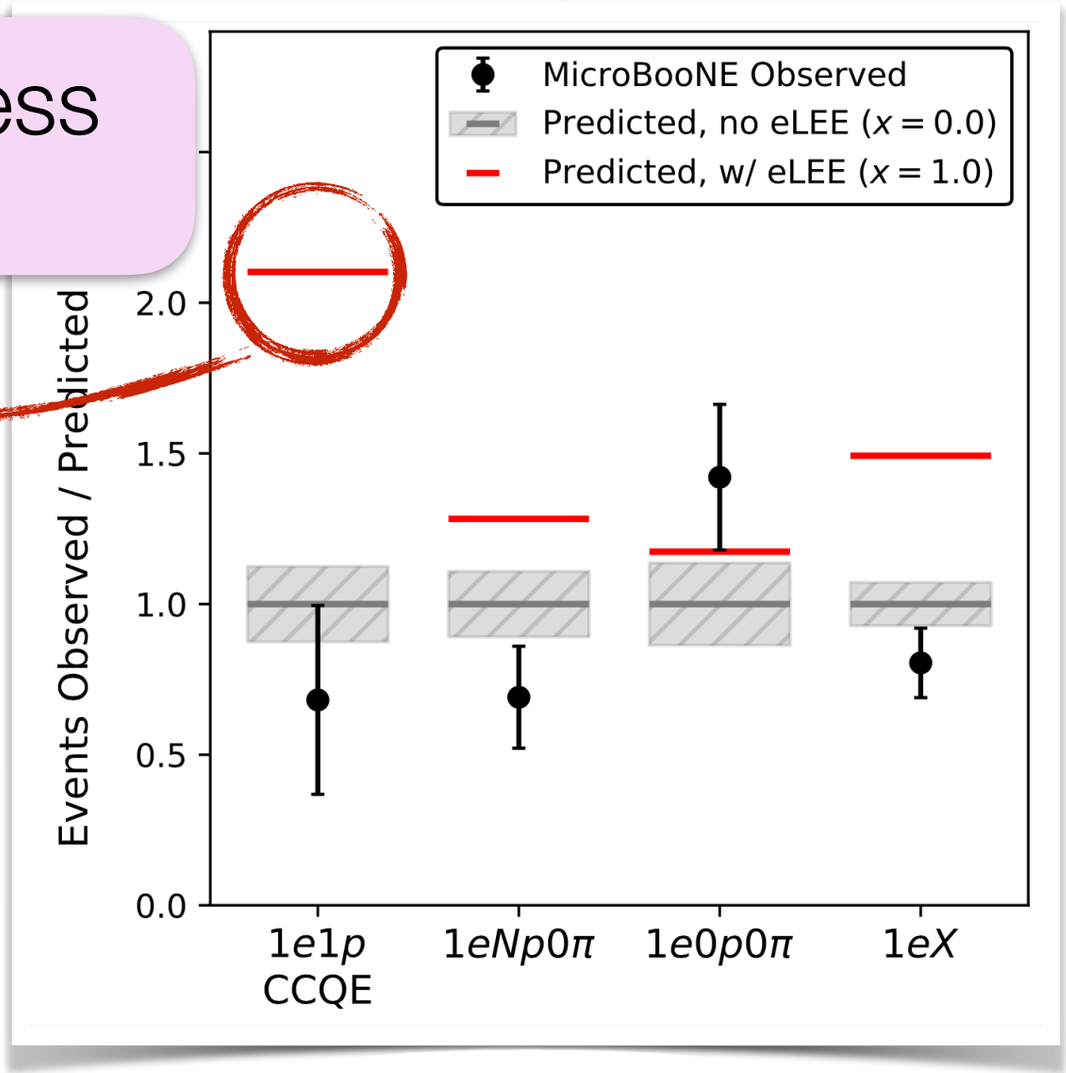
MiniBooNE excess
central value



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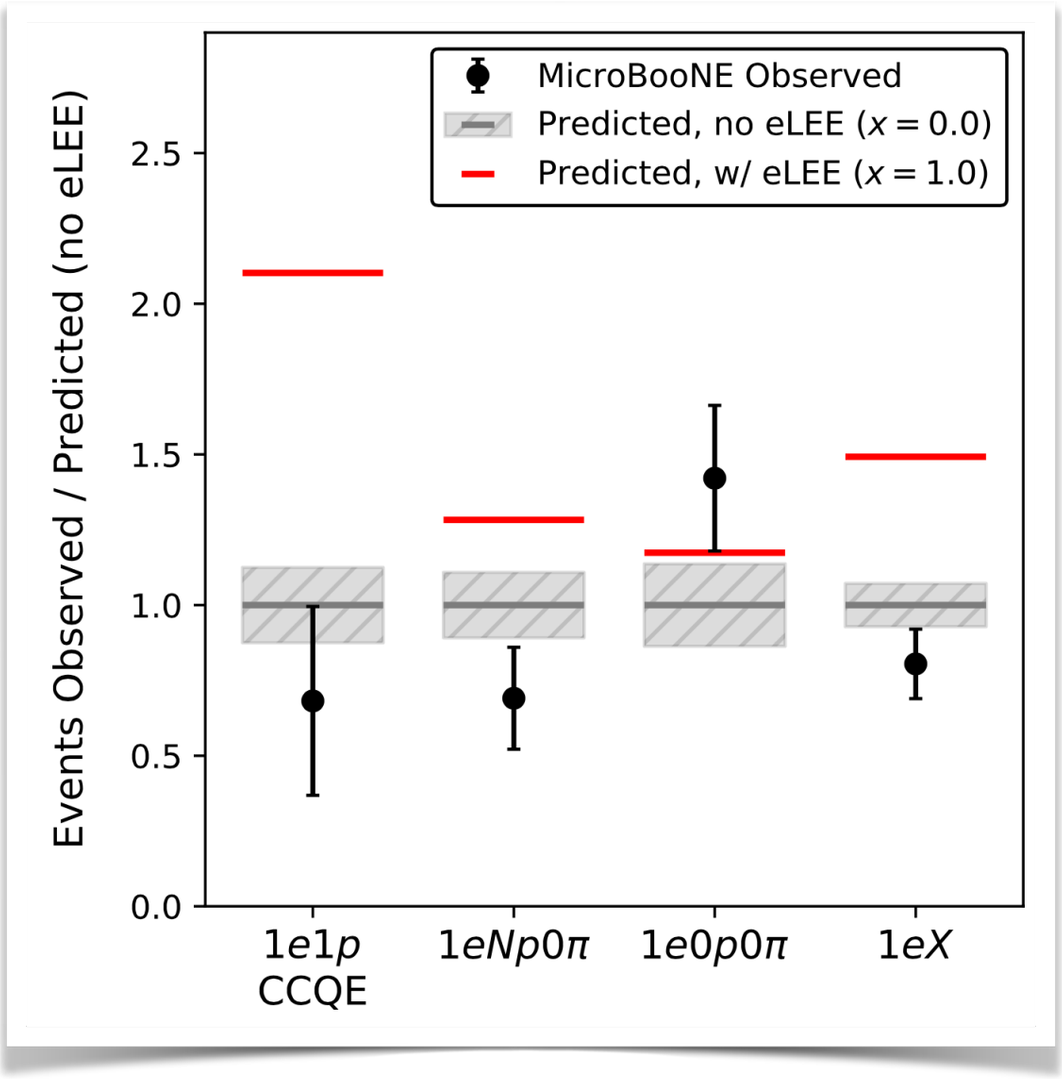
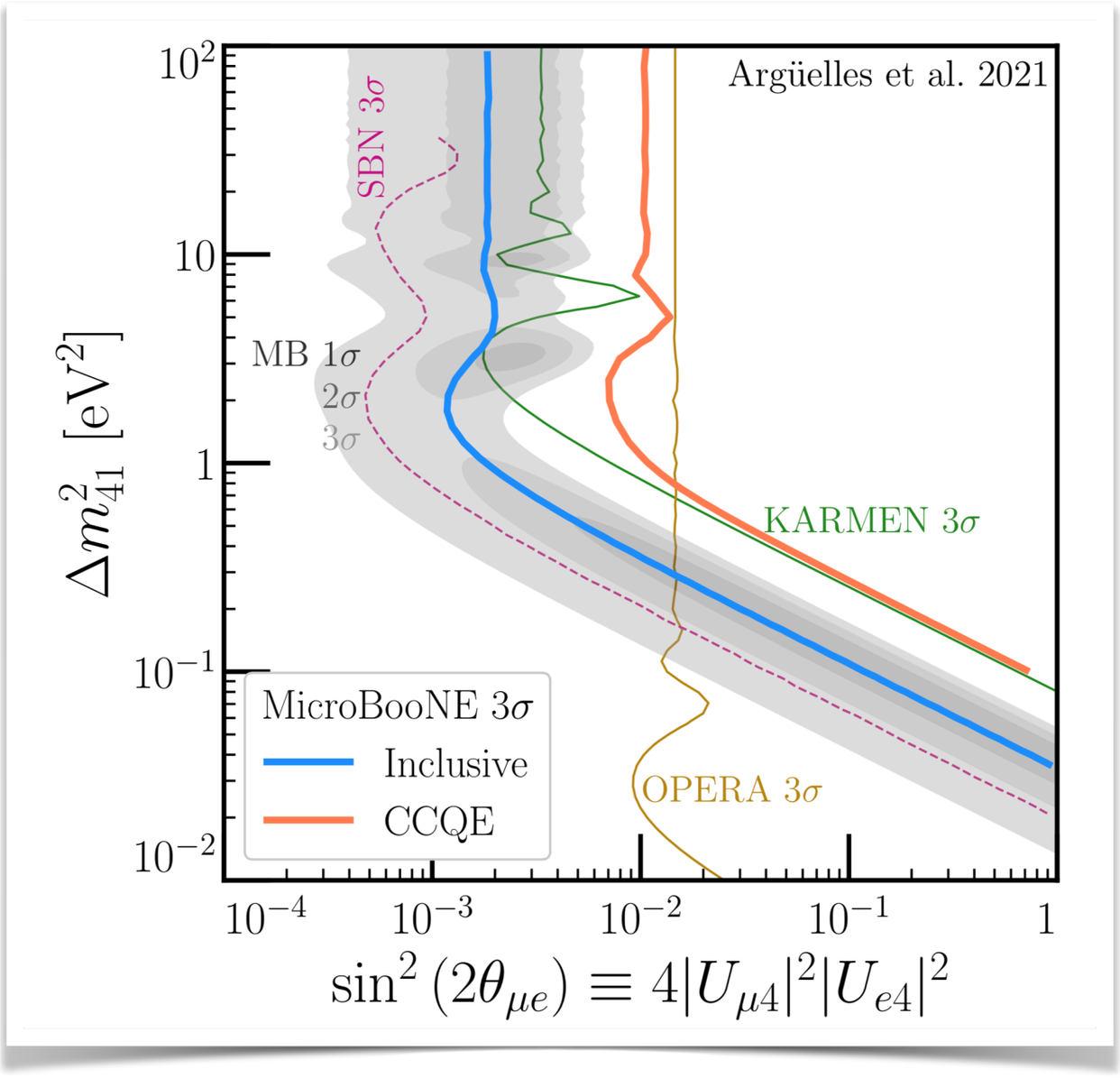


MiniBooNE vs. μBooNE



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

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

☑ ...

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

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): $\nu_s \to \nu_a + \Phi$

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

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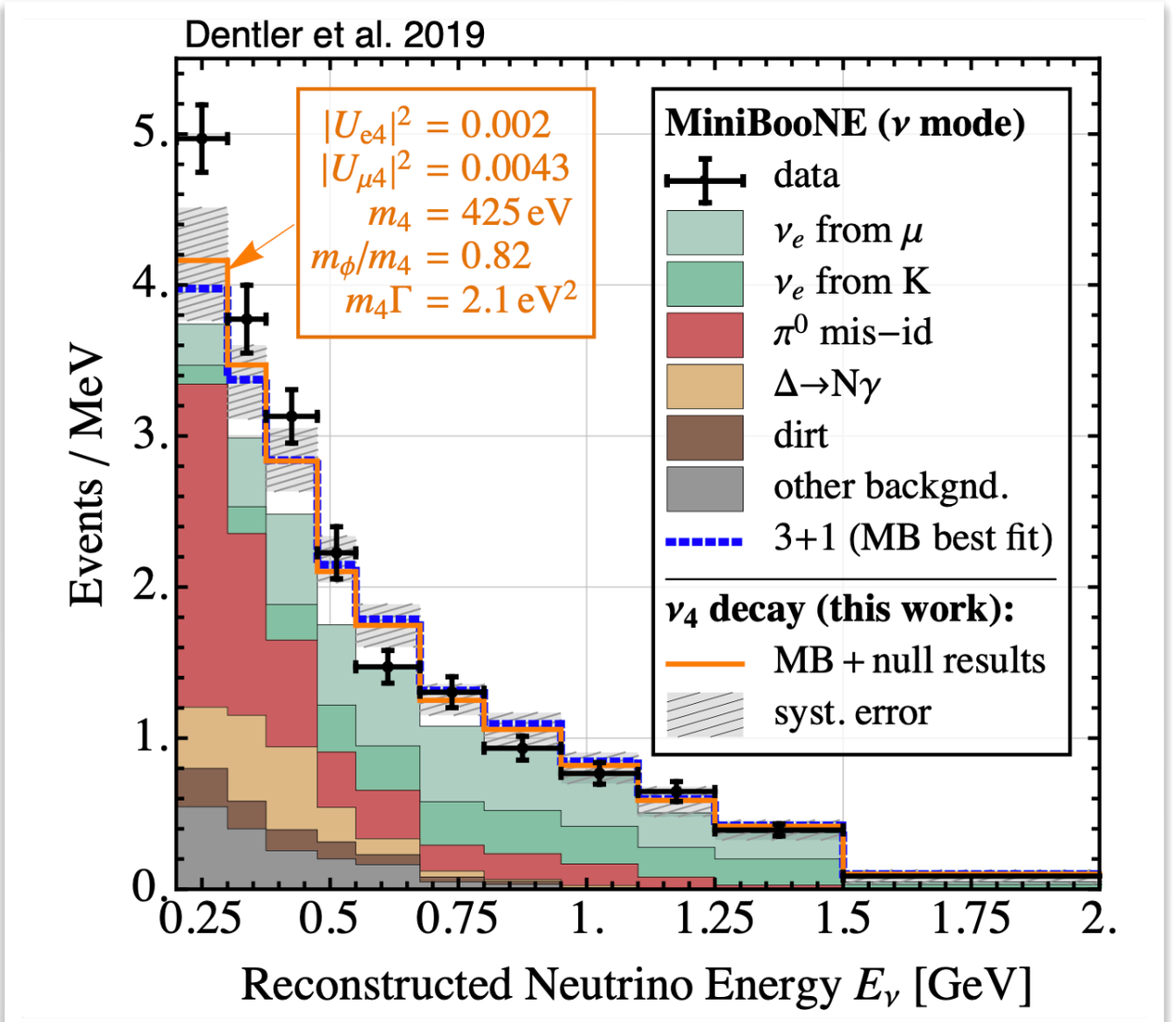

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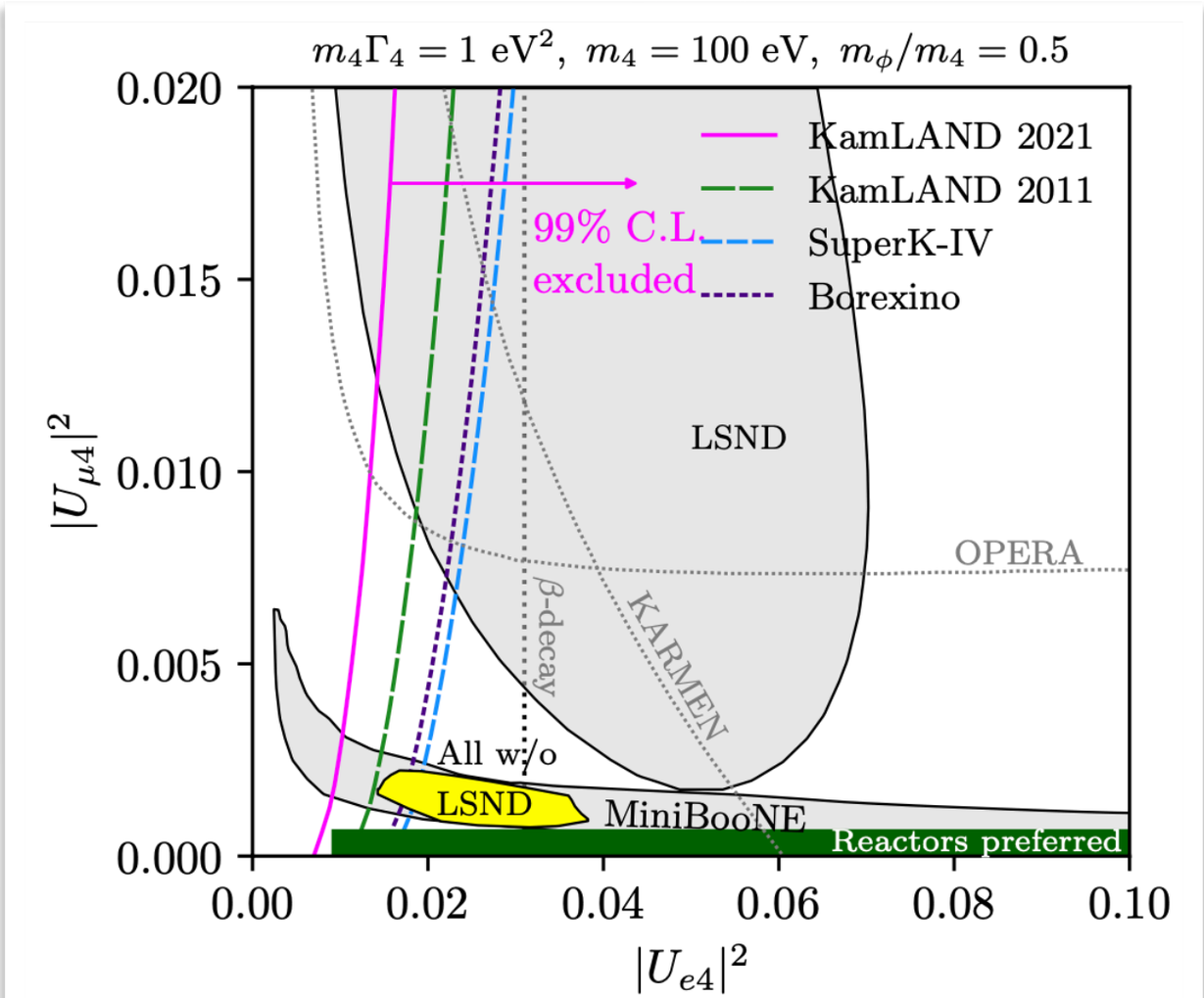

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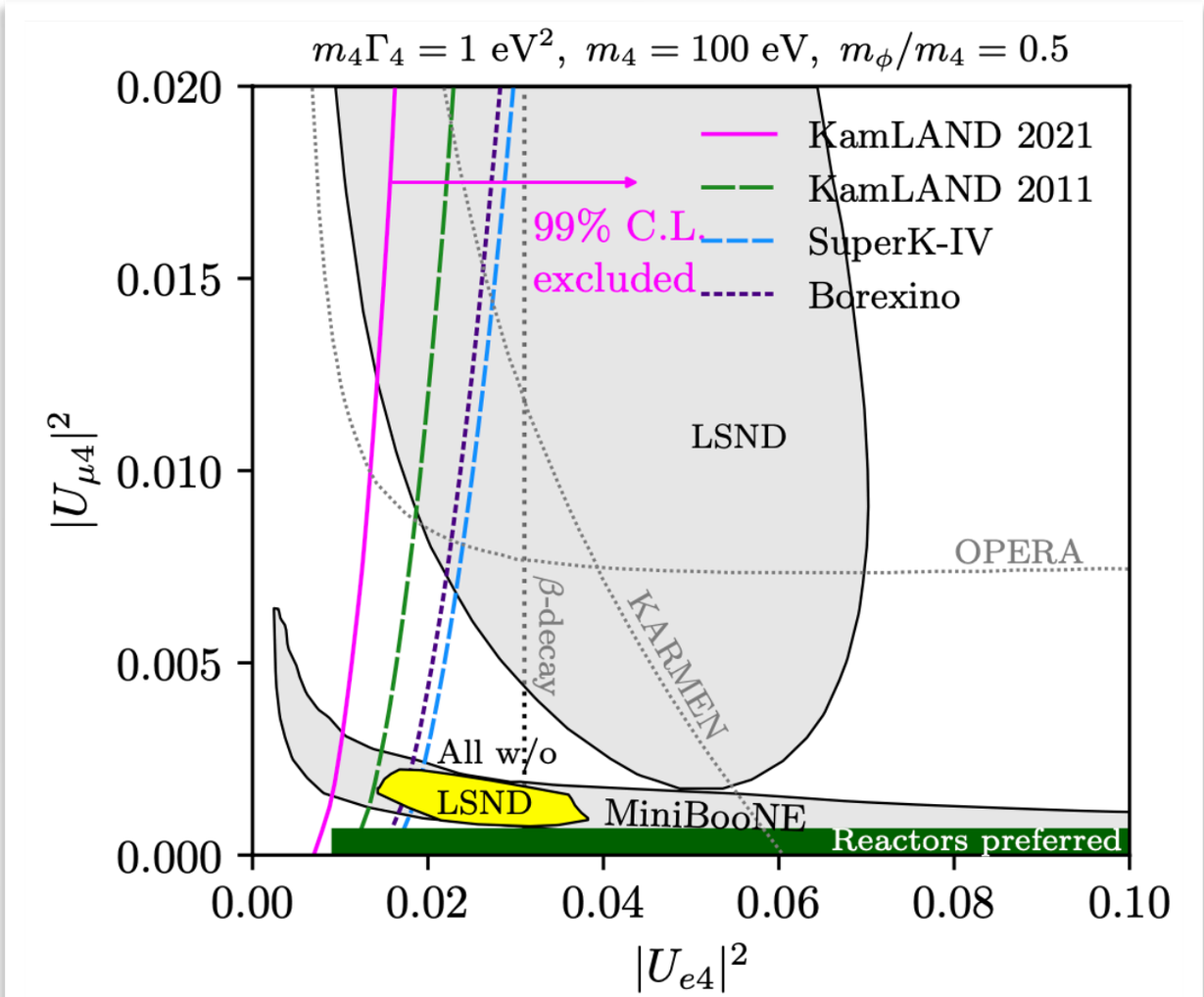
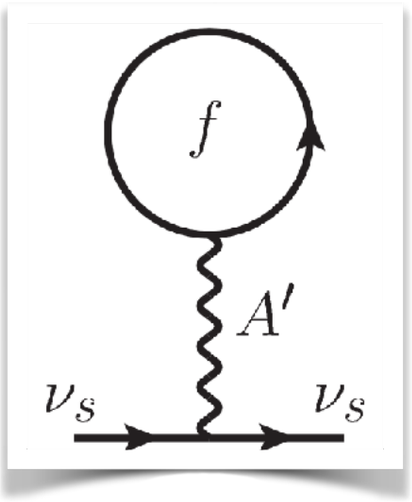
- ☑ simultaneous fit with LSND disfavoured by solar $\bar{\nu}$

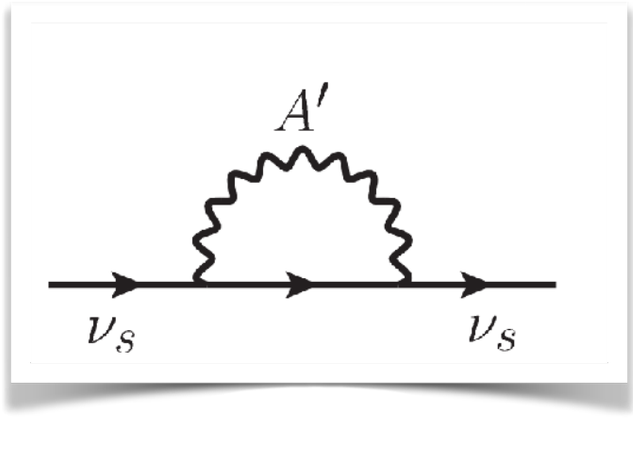


Dentler Esteban JK Machado, 1911.01427
de Gouvea Peres Prakash Stenico 1911.01447
Hostert Pospelov 2008.11851

Why is this not Inconsistent with N_{eff}?

- ☑ ν_s coupled to new force carrier
- ☑ Neutrino self-energy contributes to effective potential V^{eff}





Hannestad Hansen Tram arXiv:1310.5926
Dasgupta JK arXiv:1310.6337

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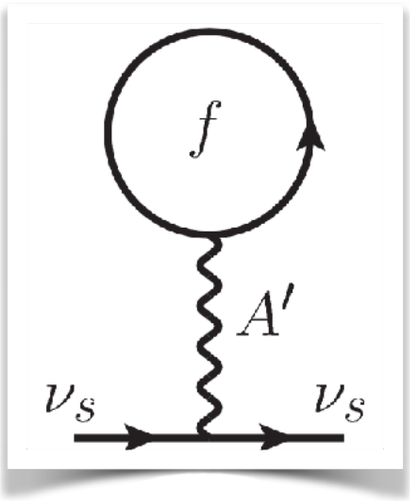

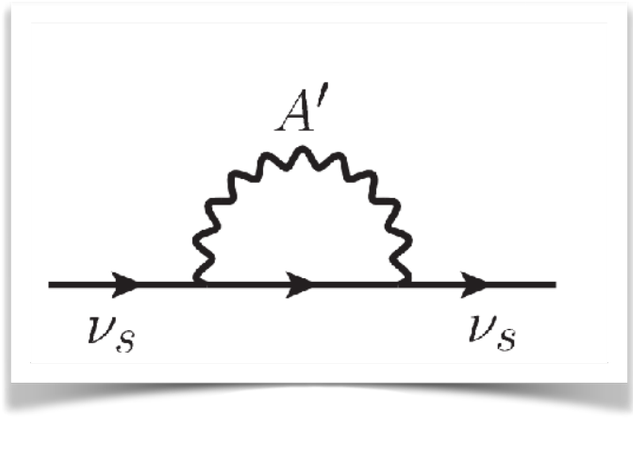

- ☑ Thermal propagators

$$S(p) = (\not{p} + m)\left[\frac{1}{p^2 - m^2} + i\Gamma_f(p)\right]$$

$$D^{\mu\nu}(p) = (-g^{\mu\nu} + p^\mu p^\nu / M^2)\left[\frac{1}{p^2 - M^2} + i\Gamma_b(p)\right]$$

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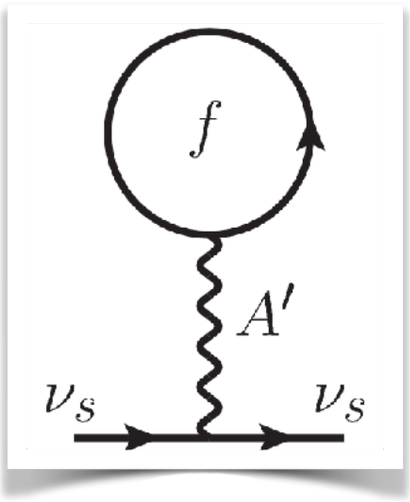
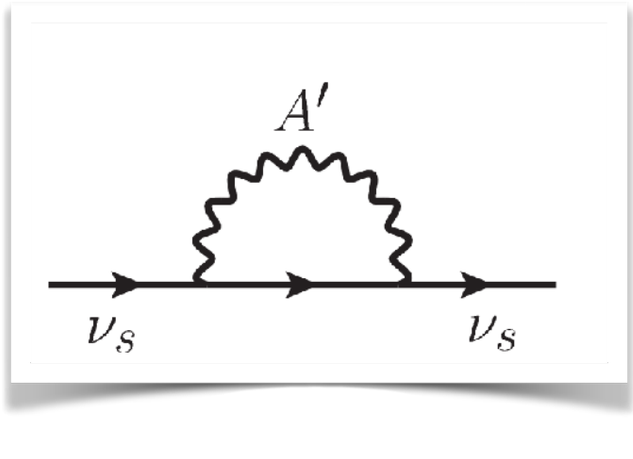




- ☑ Thermal propagators

$$\Gamma_{f,b}(p) = 2\pi\delta(p^2 - m^2)n_{f,b}(p)$$

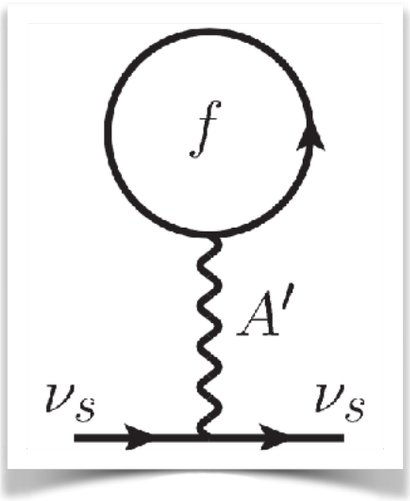
$$S(p) = (\not{p} + m)\left[\frac{1}{p^2 - m^2} + i\Gamma_f(p)\right]$$

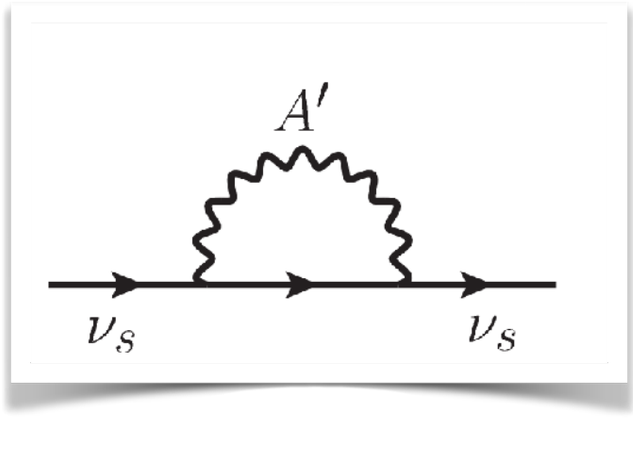
$$D^{\mu\nu}(p) = (-g^{\mu\nu} + p^\mu p^\nu / M^2)\left[\frac{1}{p^2 - M^2} + i\Gamma_b(p)\right]$$

Hannestad Hansen Tram arXiv:1310.5926
Dasgupta JK arXiv:1310.6337

Why is this not Inconsistent with N_{eff}?

- ☑ ν_s coupled to new force carrier
- ☑ Neutrino self-energy contributes to effective potential V^{eff}





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$$\Gamma_{f,b}(p) = 2\pi\delta(p^2 - m^2)\, n_{f,b}(p)$$

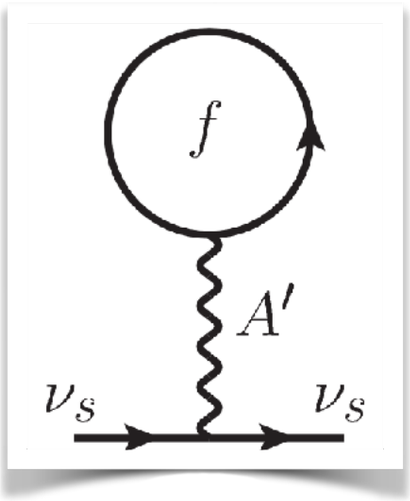
$$n_{f,b}(p) = [e^{|p\cdot u|/T_s} \pm 1]^{-1}$$

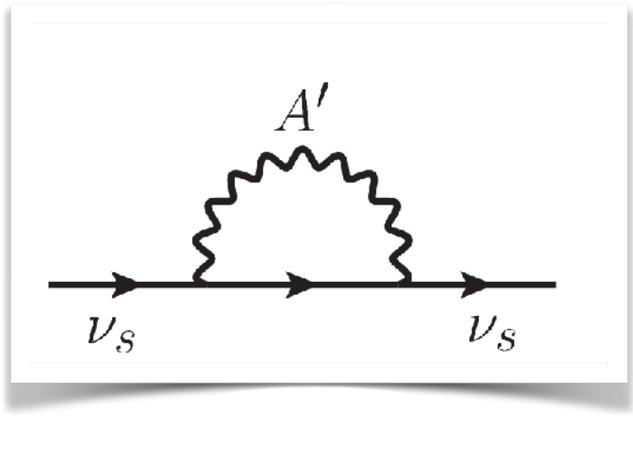
Hannestad Hansen Tram arXiv:1310.5926
Dasgupta JK arXiv:1310.6337

Why is this not Inconsistent with N_{eff}?

☑ Assume ν_s charged under a new *U(1)'* gauge group

☑ Neutrino self-energy contributes to effective potential V^{eff}





MSW potential $V \sim n_f - n_{\bar{f}}$

thermal correction $V \sim T^\alpha$

☑ Effective mixing angle:

$$\sin^2 2\theta_{\rm eff} = \frac{\sin^2 2\theta}{\sin^2 2\theta + \left(\cos 2\theta - \frac{2EV^{\rm eff}}{\Delta m^2}\right)^2}$$

Why is this not Inconsistent with N_{eff}?

☑ Assume ν_s charged under a new *U(1)'* gauge group

☑ Neutrino self-energy contributes to effective potential V^{eff}

★ ν_s production strongly suppressed at high *T*

★ cosmological constraints avoided

MSW potential $V \sim n_f - n_{\bar{f}}$

thermal correction $V \sim T^a$

☑ Effective mixing angle:

$$\sin^2 2\theta_{\rm eff} = \frac{\sin^2 2\theta}{\sin^2 2\theta + \left(\cos 2\theta - \frac{2EV^{\rm eff}}{\Delta m^2}\right)^2}$$

A Solution to the H_0 Tension?

- ☑ long-standing tension between early ($z \sim 1\,000$) and late ($z \sim$ few) measurements of the Hubble parameter H_0.
- ☑ fractional increase of N_{eff} might alleviate this tension
  (N_{eff} ↗ ➟ sound horizon ↘ ➟ H_0 ↗ needed to make it appear bigger today)
- ☑ But overall cosmological fit does not improve
  (worse fit to high-ℓ, lensing, and BAO data)

Archidiacono *et al.* arXiv:2006.12885