The Search for Light Sterile Neutrinos & The Short Baseline Neutrino Program

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LPC Physics Forum
8/23/2018

3-Flavor Neutrino Oscillations

$$|\nu_\alpha> = \sum_i U^*_{\alpha i} |\nu_i>$$

Neutrino Flavor Eigenstates | Unitary Mixing Matrix | Neutrino Mass Eigenstates

$$|\nu_\alpha(L)\rangle \approx \sum_i U^*_{\alpha i} e^{-i(m_i^2/2E)L} |\nu_i\rangle$$

NuFit 3.2 (2018)
JHEP 01 (2017) 087

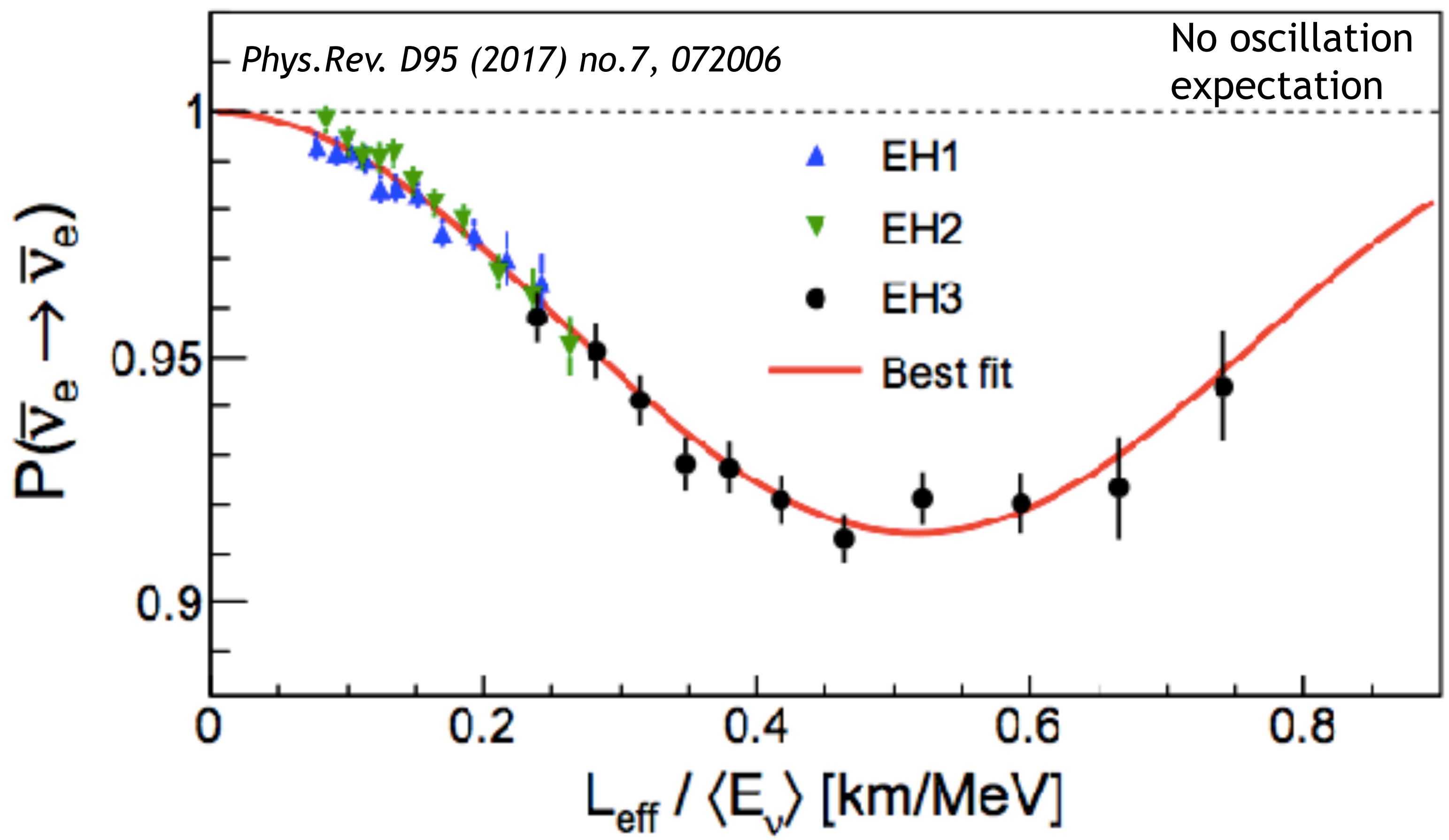
$$|U_{\alpha i}| = \begin{pmatrix} |c_{12}c_{13}| & |s_{12}c_{13}| & |s_{13}e^{-i\delta}| \\ |-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta}| & |c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta}| & |s_{23}c_{13}| \\ |s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta}| & |-c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta}| & |c_{23}c_{13}| \end{pmatrix} = \begin{pmatrix} 0.799 \to 0.844 & 0.516 \to 0.582 & 0.141 \to 0.156 \\ 0.242 \to 0.494 & 0.467 \to 0.678 & 0.639 \to 0.774 \\ 0.284 \to 0.521 & 0.490 \to 0.695 & 0.615 \to 0.754 \end{pmatrix}$$

$$\Delta m^2_{21} = 7.40^{+0.21}_{-0.20} \times 10^{-5}\text{eV}^2$$

$$|\Delta m^2_{32}| = +2.494^{+0.033}_{-0.031} \times 10^{-3}\text{eV}^2$$

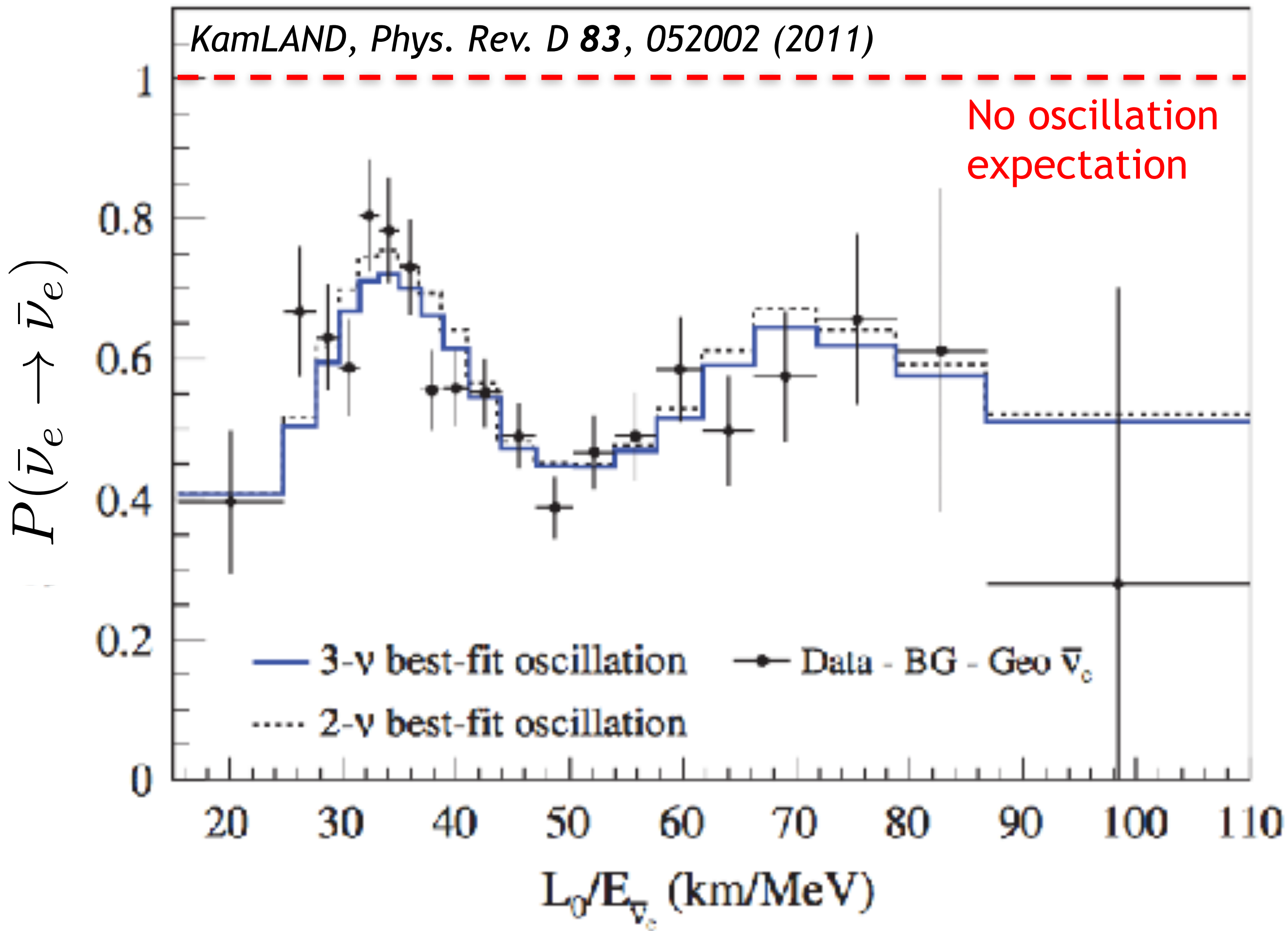
Daya Bay As A Case Study

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{1267\Delta m^2[\text{eV}^2]L\ [\text{km}]}{E_\nu\ [\text{MeV}]}\right)$$

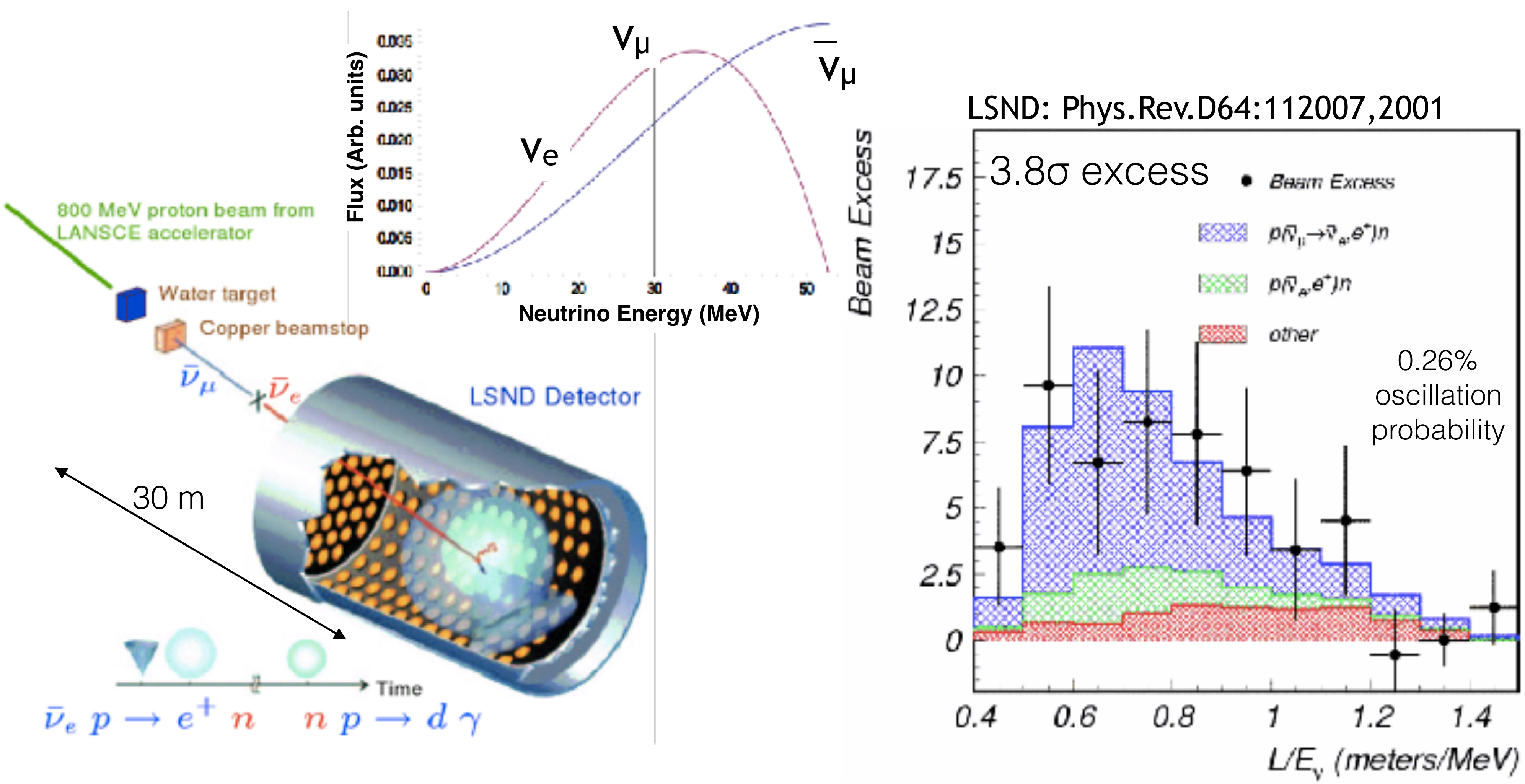


KamLAND As A Case Study

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{12}) \sin^2 \left(\frac{1267 \Delta m^2 [\text{eV}^2] L \ [\text{km}]}{E_\nu \ [\text{MeV}]} \right)$$



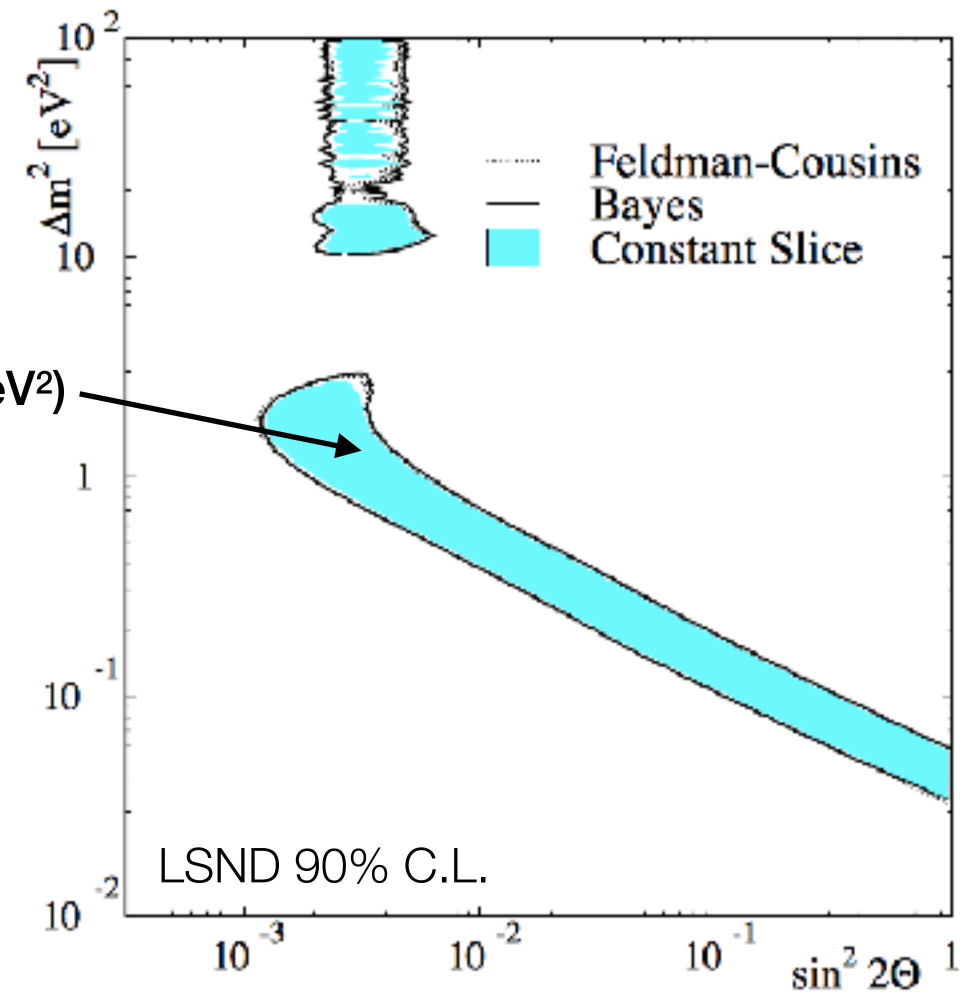
The LSND Experiment



Interpreting the Excess as Oscillations

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{\mu e} \sin^2 \left(\frac{1.267 \Delta m^2 [\mathrm{eV}^2] L[\mathrm{m}]}{E_\nu [\mathrm{MeV}]} \right)$$

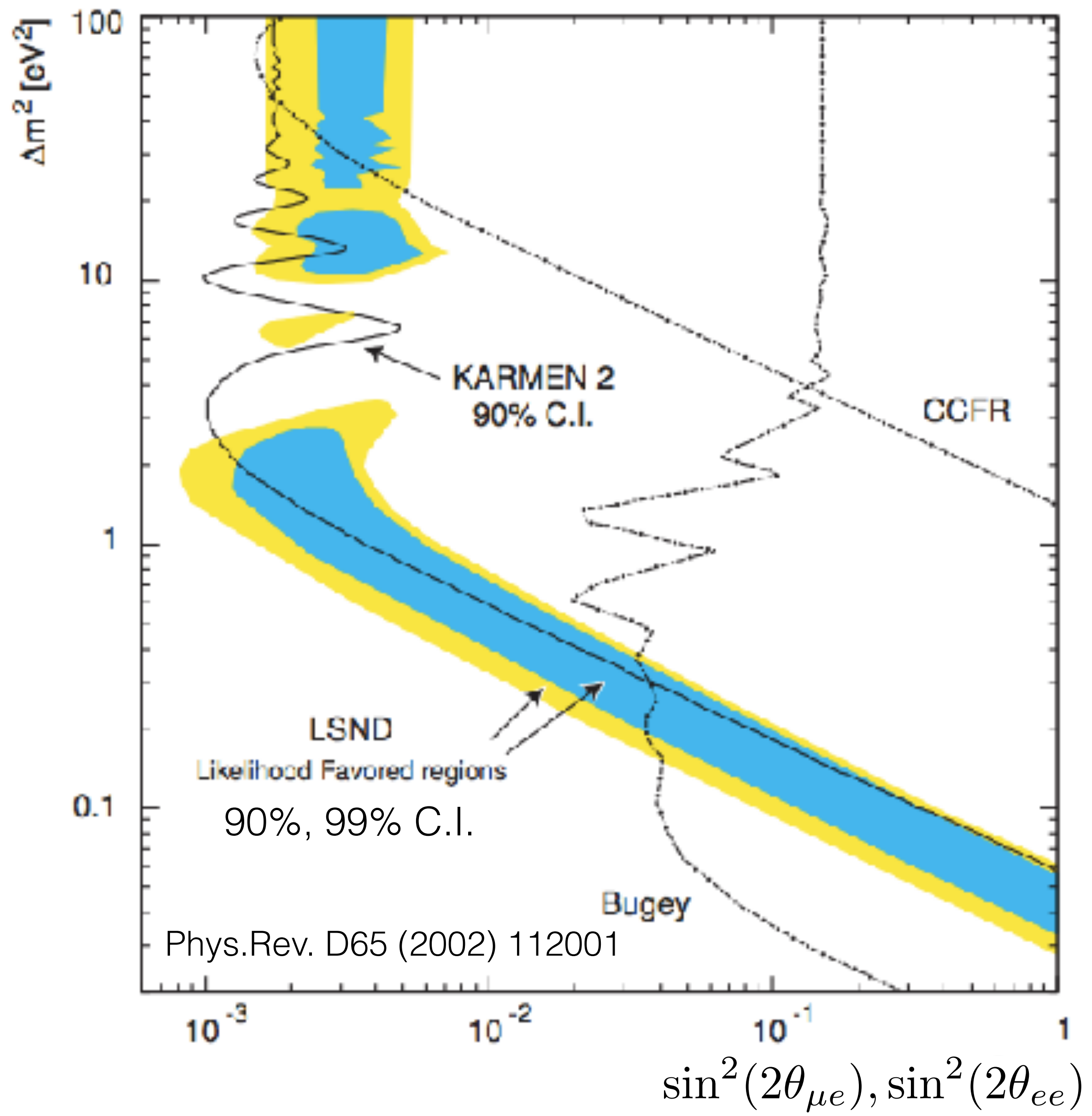
Best fit ($\sin^2 2\Theta$, Δm^2) = (0.003, 1.2 eV^2)



KARMEN Experiment

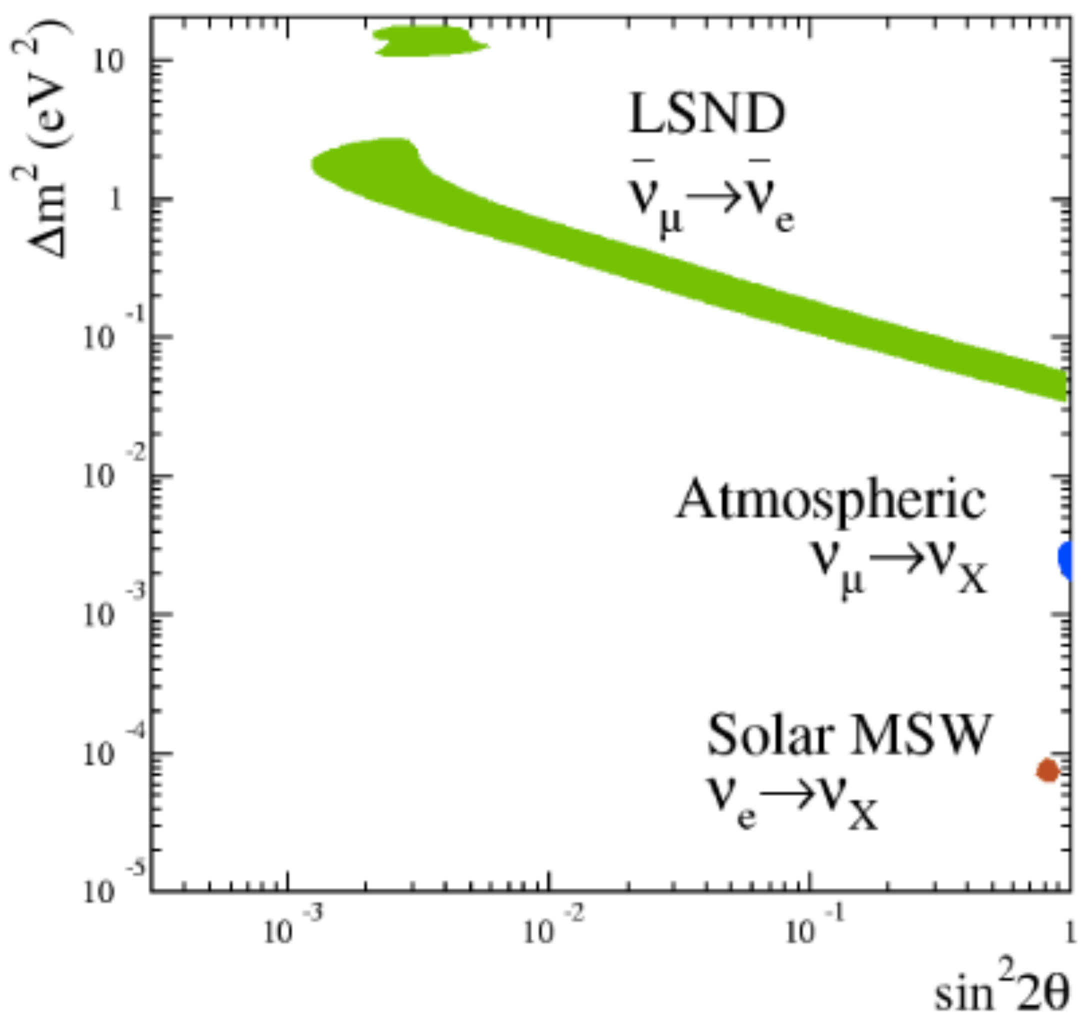
- Pulsed spallation neutron source
  - Muon decay at rest beam
  - Small duty factor —> cosmic rejection
- Detector 100 degrees of axis at a mean distance of 17.7 m

- Fundamentally, KARMEN does not see the excess of anti-electron neutrinos that LSND sees in its decay-at-rest beam



Additional Neutrino States

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{\mu e} \sin^2\left(\frac{1.267\Delta m^2[\mathrm{eV}^2]L[\mathrm{m}]}{E_\nu[\mathrm{MeV}]}\right)$$



3+1 Sterile Neutrino Model

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$$|U_{e4}| = \sin\theta_{14}$$
$$|U_{\mu4}| = \cos\theta_{14}\sin\theta_{24}$$
$$|U_{\tau4}| = \cos\theta_{14}\cos\theta_{24}\sin\theta_{34}$$

Short baseline approximation: $\Delta m^2_{32} = \Delta m^2_{31} = \Delta m^2_{21} = 0$

$$P(\nu_\alpha \to \nu_\beta) \simeq 4|U_{\alpha4}|^2|U_{\beta4}|^2 \sin^2(1.27\Delta m^2_{41} L/E)$$

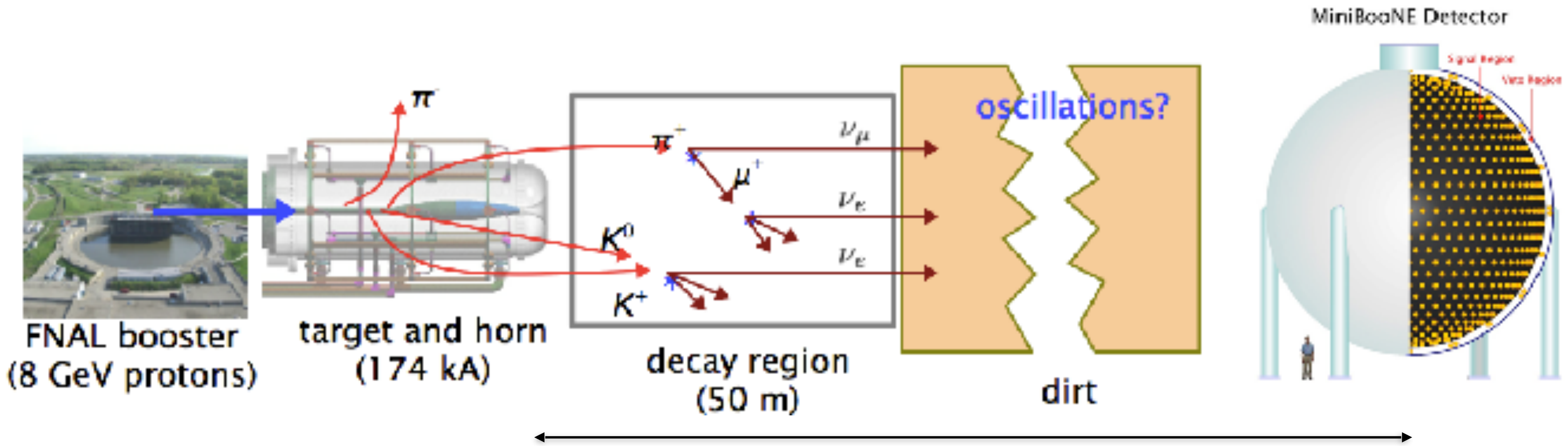
$$P(\nu_\alpha \to \nu_\alpha) \simeq 1 - 4(1-|U_{\alpha4}|^2)|U_{\alpha4}|^2 \sin^2(1.27\Delta m^2_{41} L/E)$$

If $|U_{\alpha4}|$, $|U_{\beta4}|$ << 1, then $P(\nu_\alpha \to \nu_\beta) \simeq \frac{1}{4}(1-P(\nu_\alpha \to \nu_\alpha))(1-P(\nu_\beta \to \nu_\beta))$

Why Use a 3+1 Model?

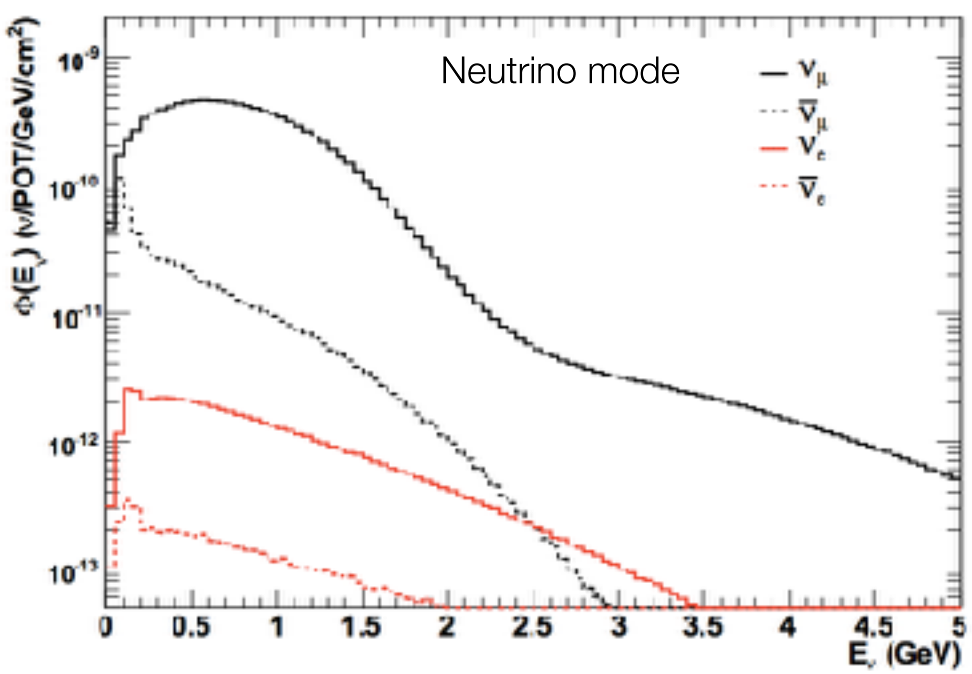
- Simple model extending 3-ν oscillation framework to include short baseline ν_e appearance
  - Rich phenomenology: ν_μ dis., ν_τ app., ν_e dis.
- Contains only a few free parameters, which can be over-constrained by experimental measurements at different L/E
  - Predictive, testable model containing new fundamental particles
- Not necessarily the model that describes nature or best fits global data
  - May be part of a more complex model
  - Nonetheless, provides a common benchmark to compare experimental sensitivities

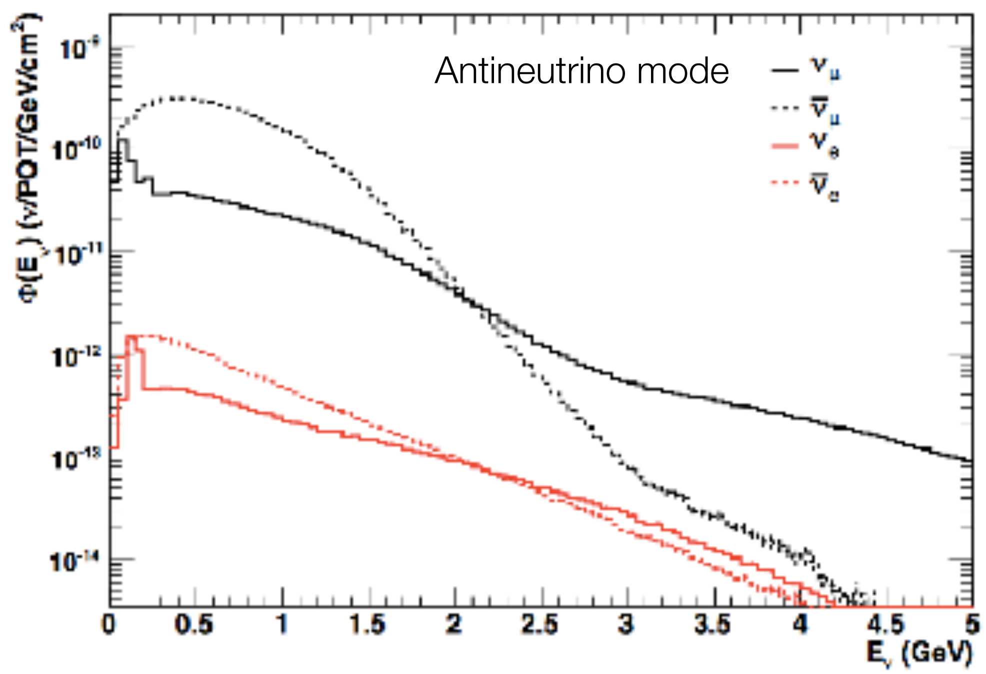
MiniBooNE Appearance Experiment



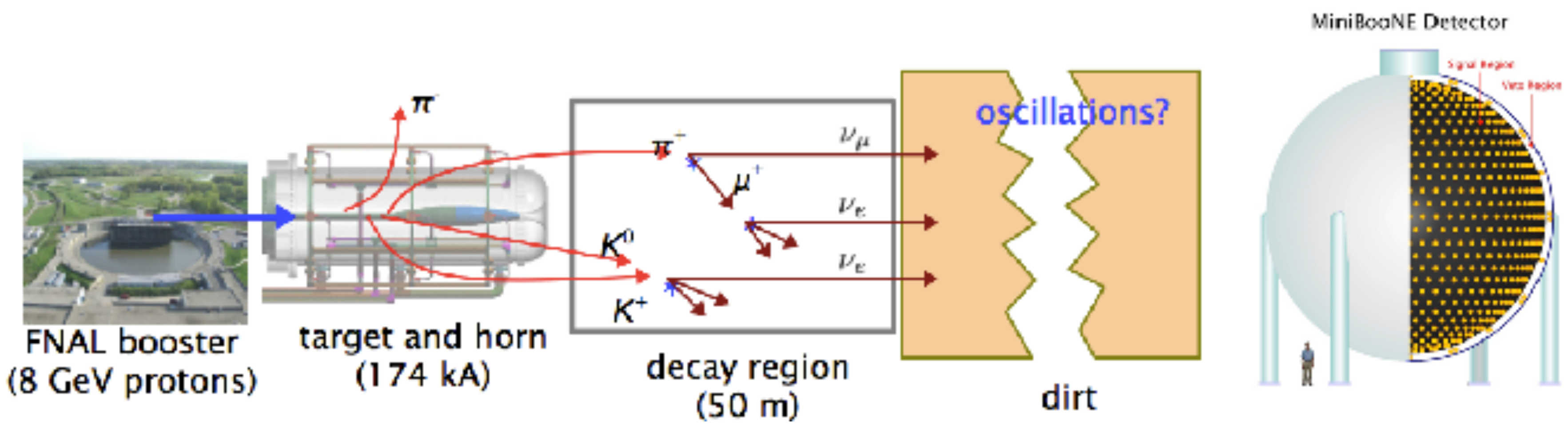
~ 500 m $(L/E \sim 1$ m/MeV$)$

PhysRevD.79.072002





MiniBooNE "Low Energy Excess"



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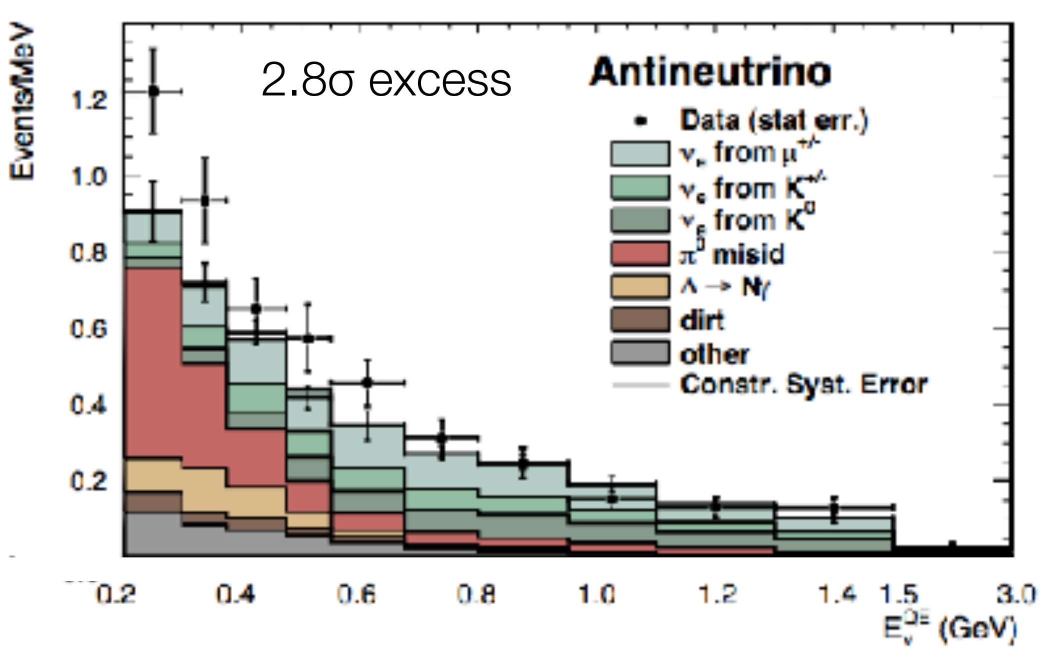
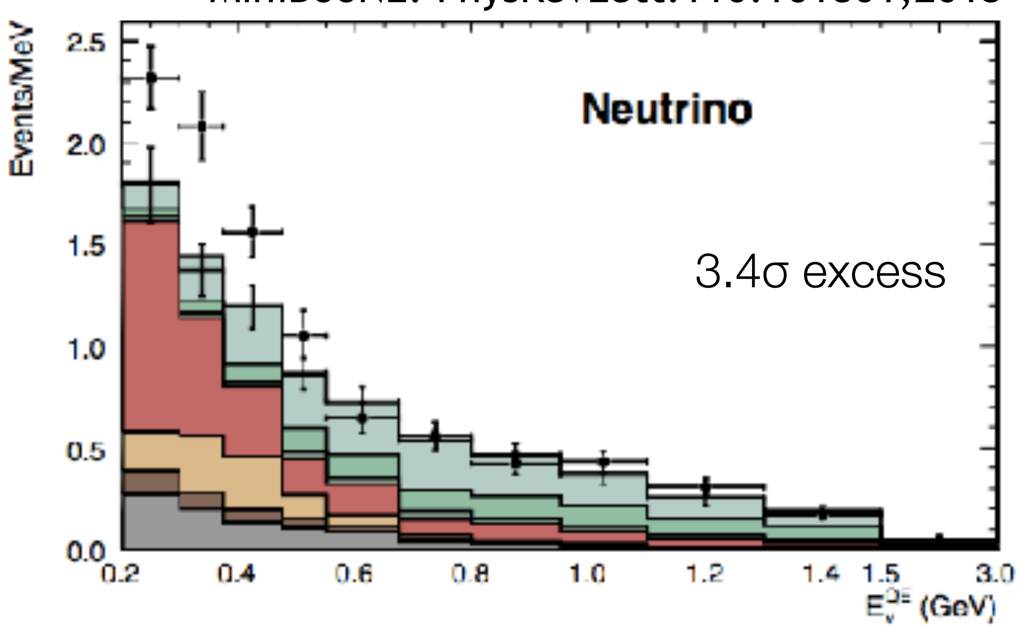
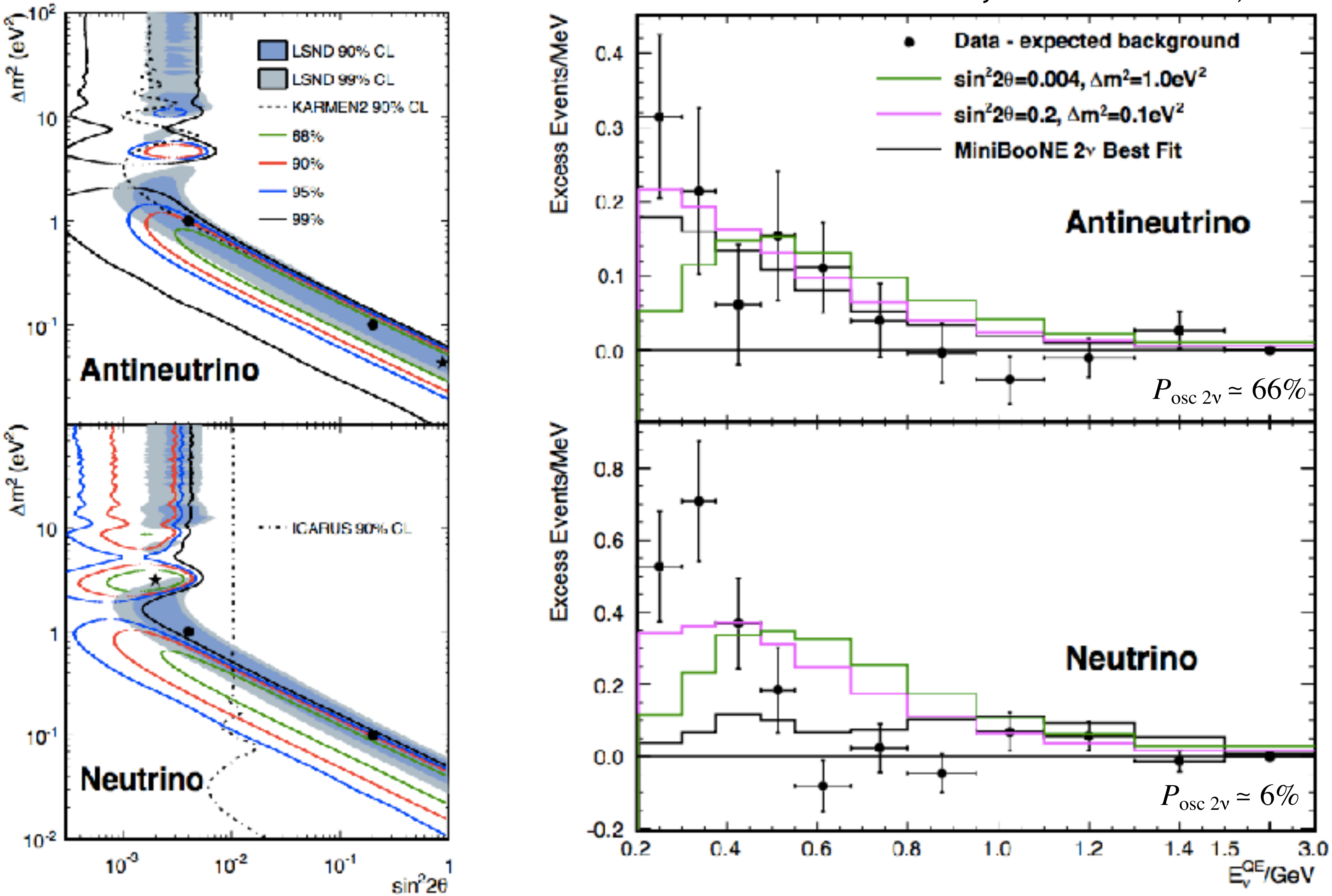
MiniBooNE: PhysRevLett.110.161801,2013



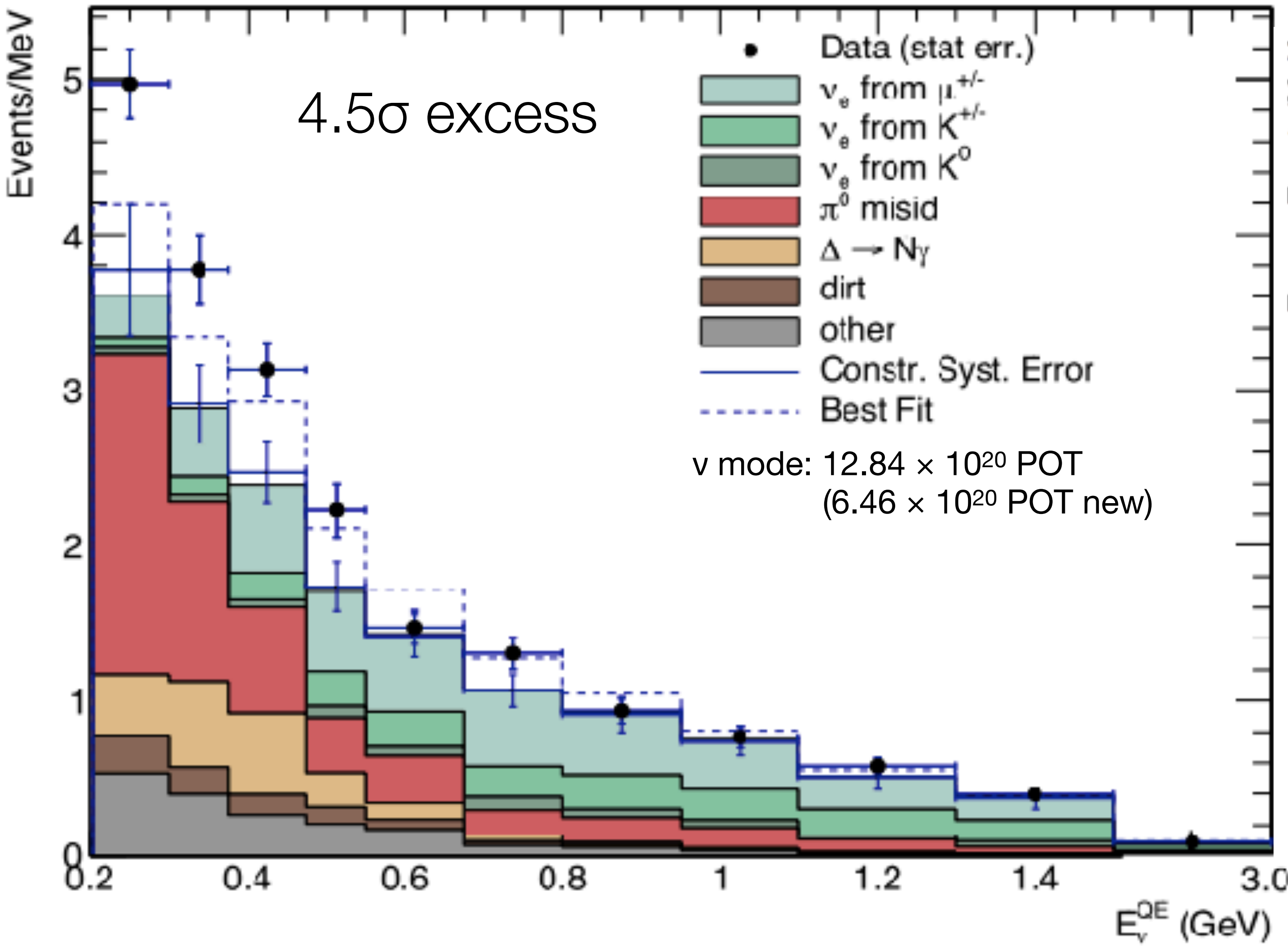


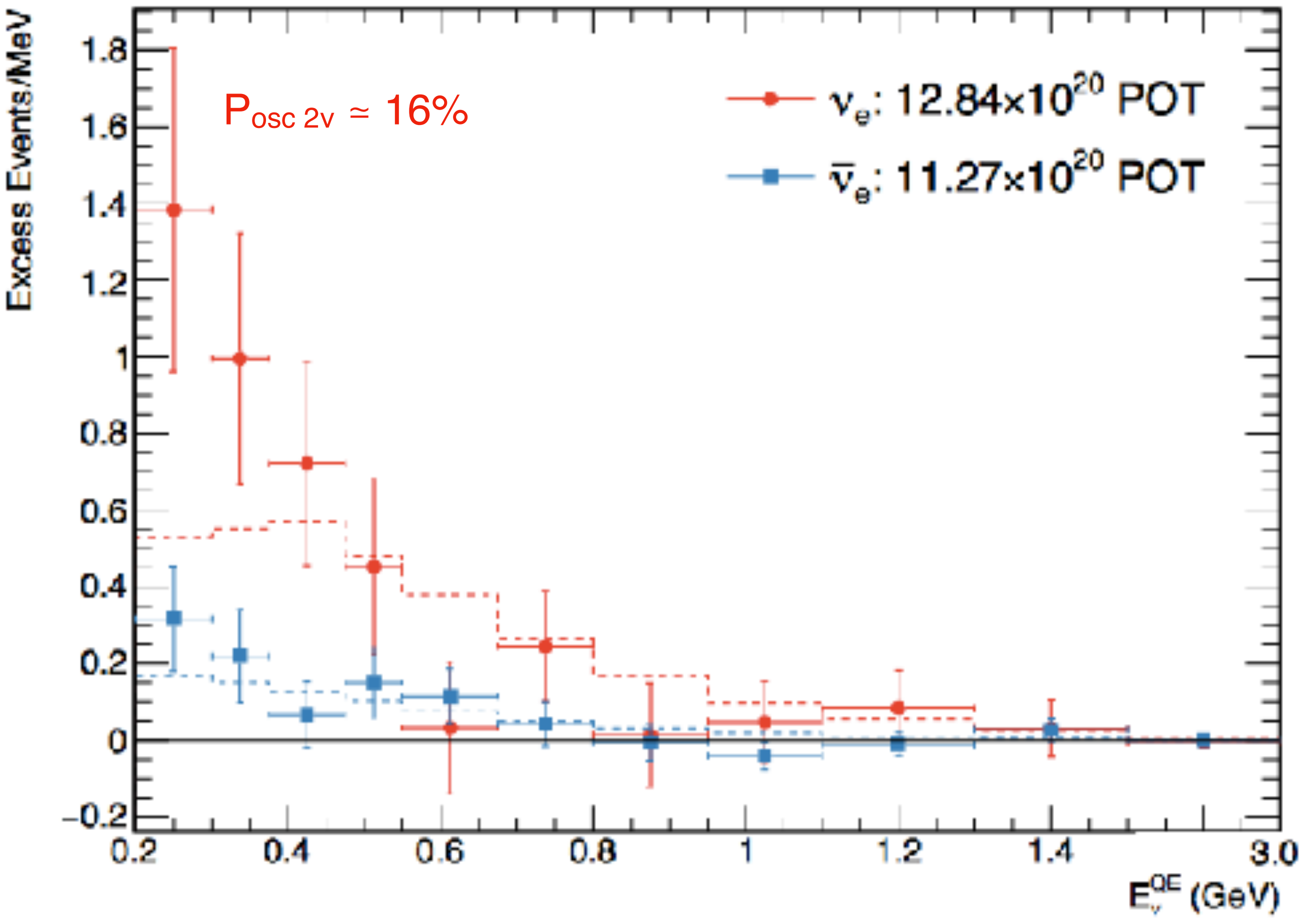
MiniBooNE: PhysRevLett.110.161801,2013



New MiniBooNE Result

arXiv:1805.12028





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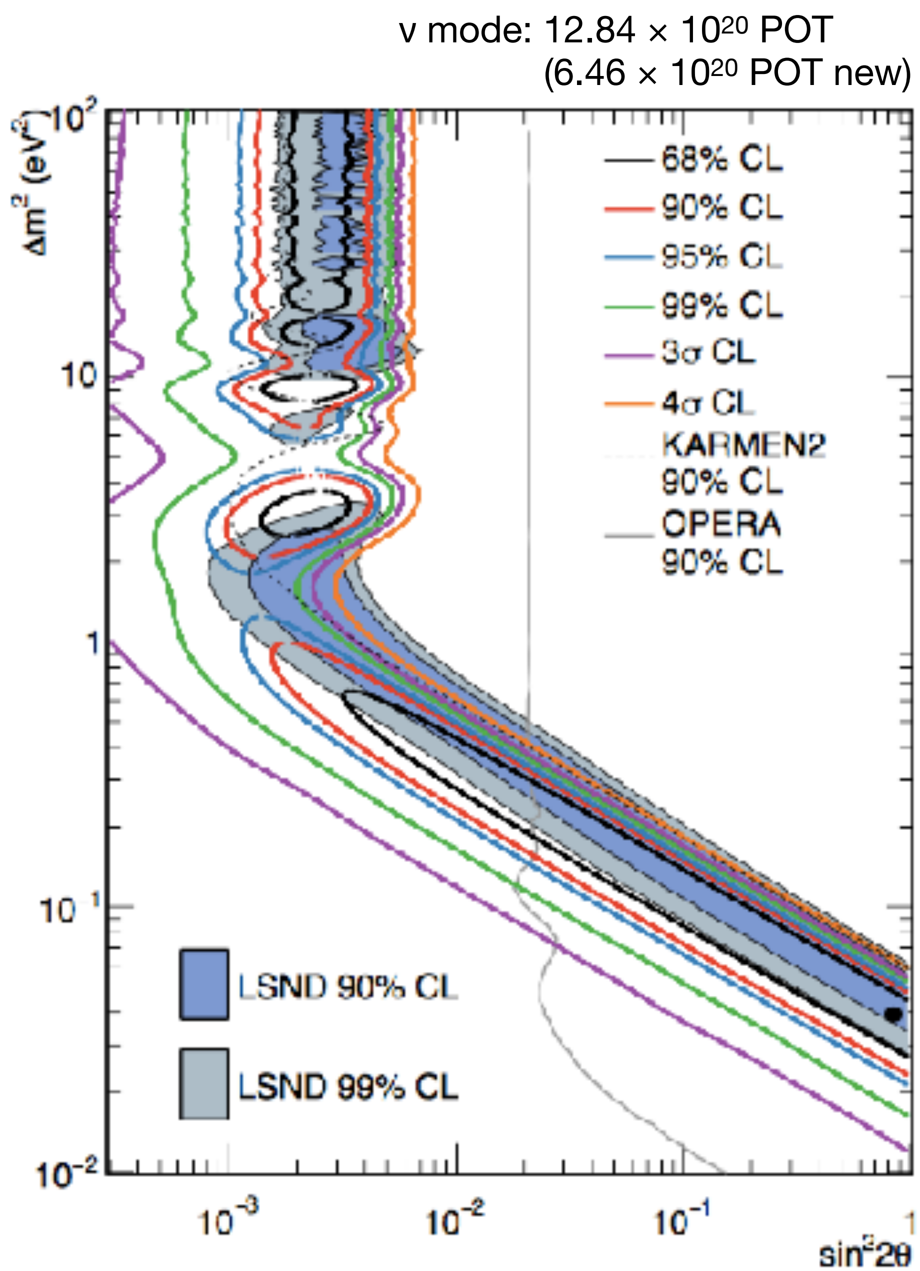
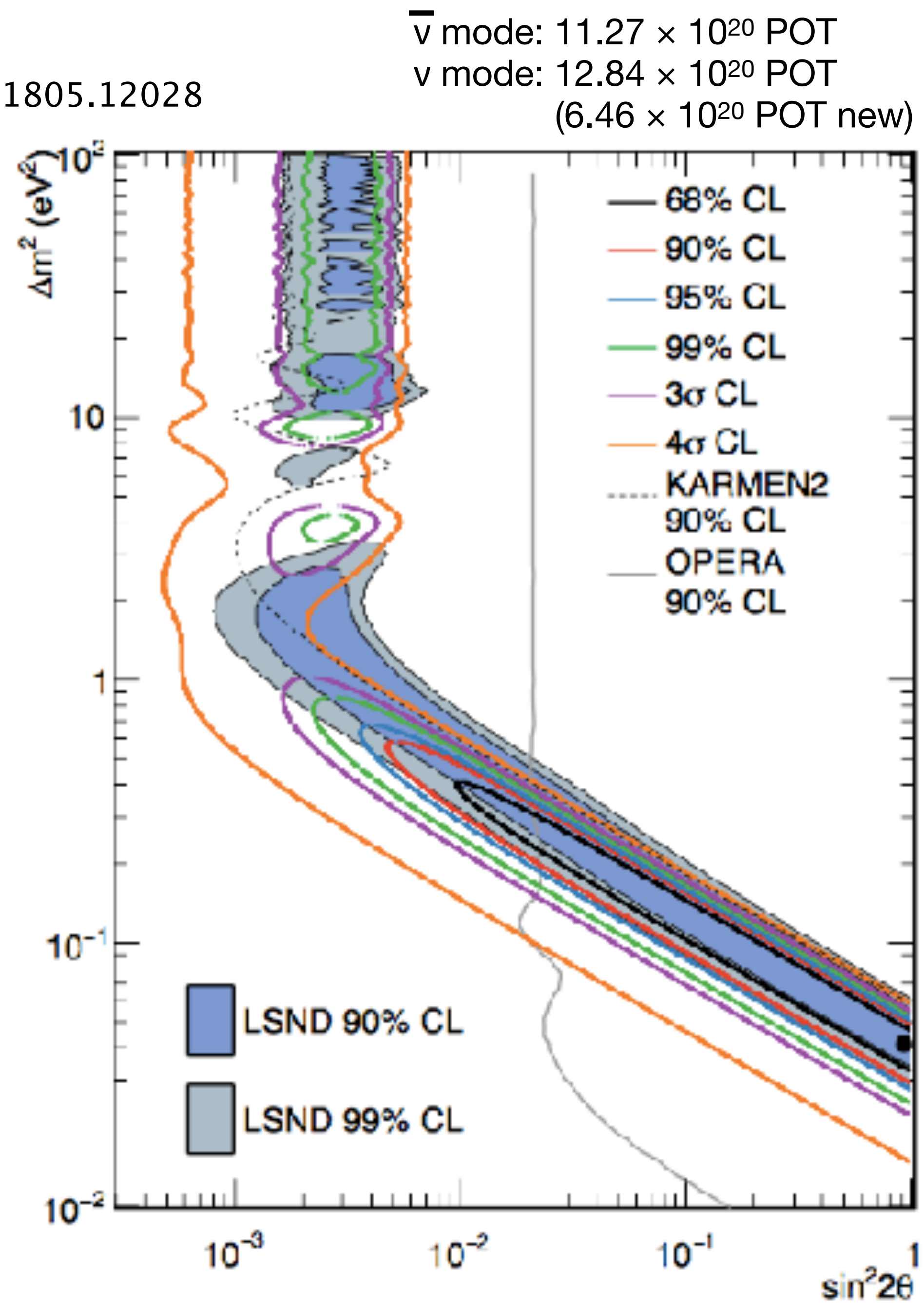


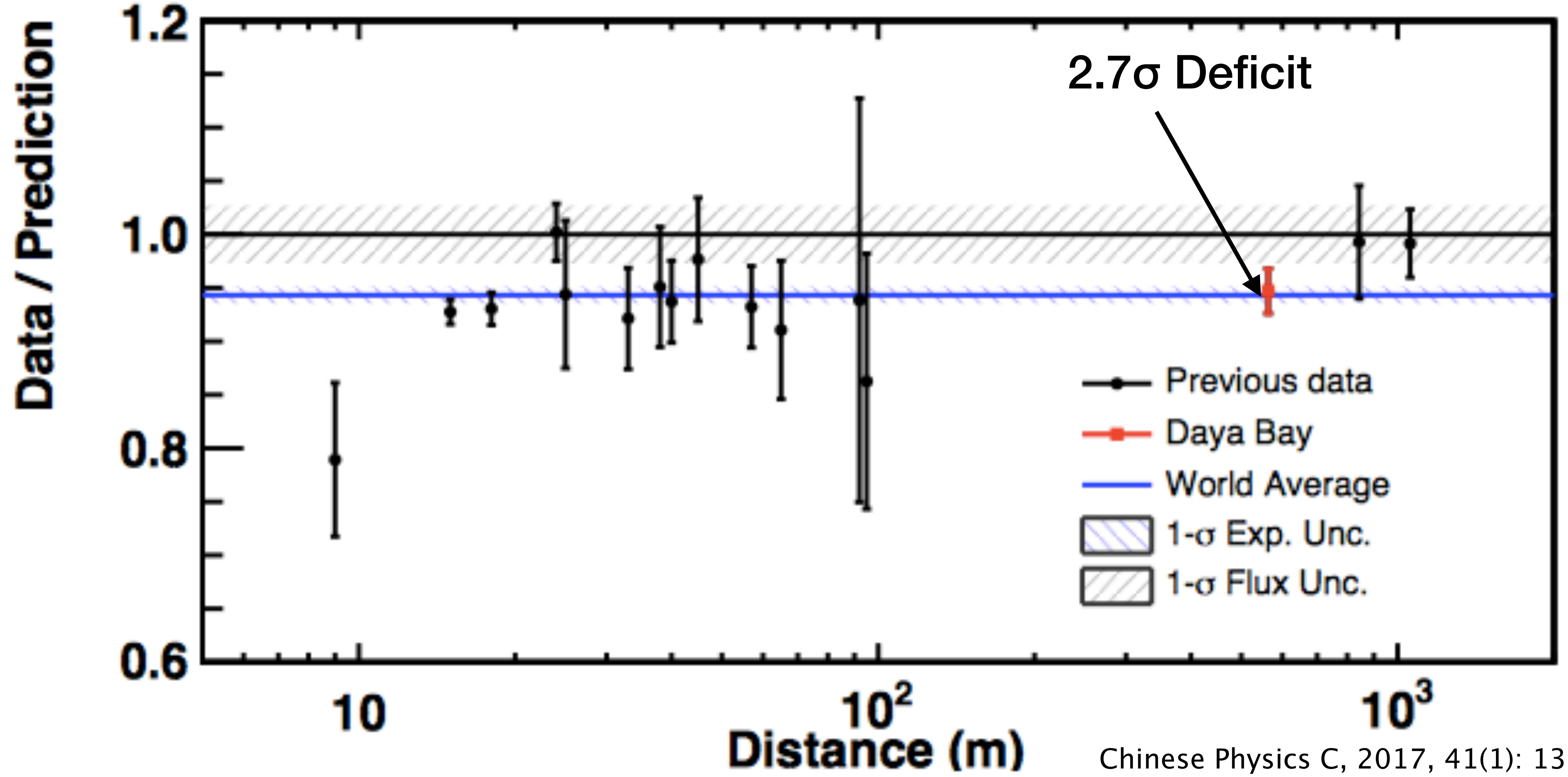


Reactor Neutrino Anomaly

Phys. Rev. D 83, 073006 (2011)

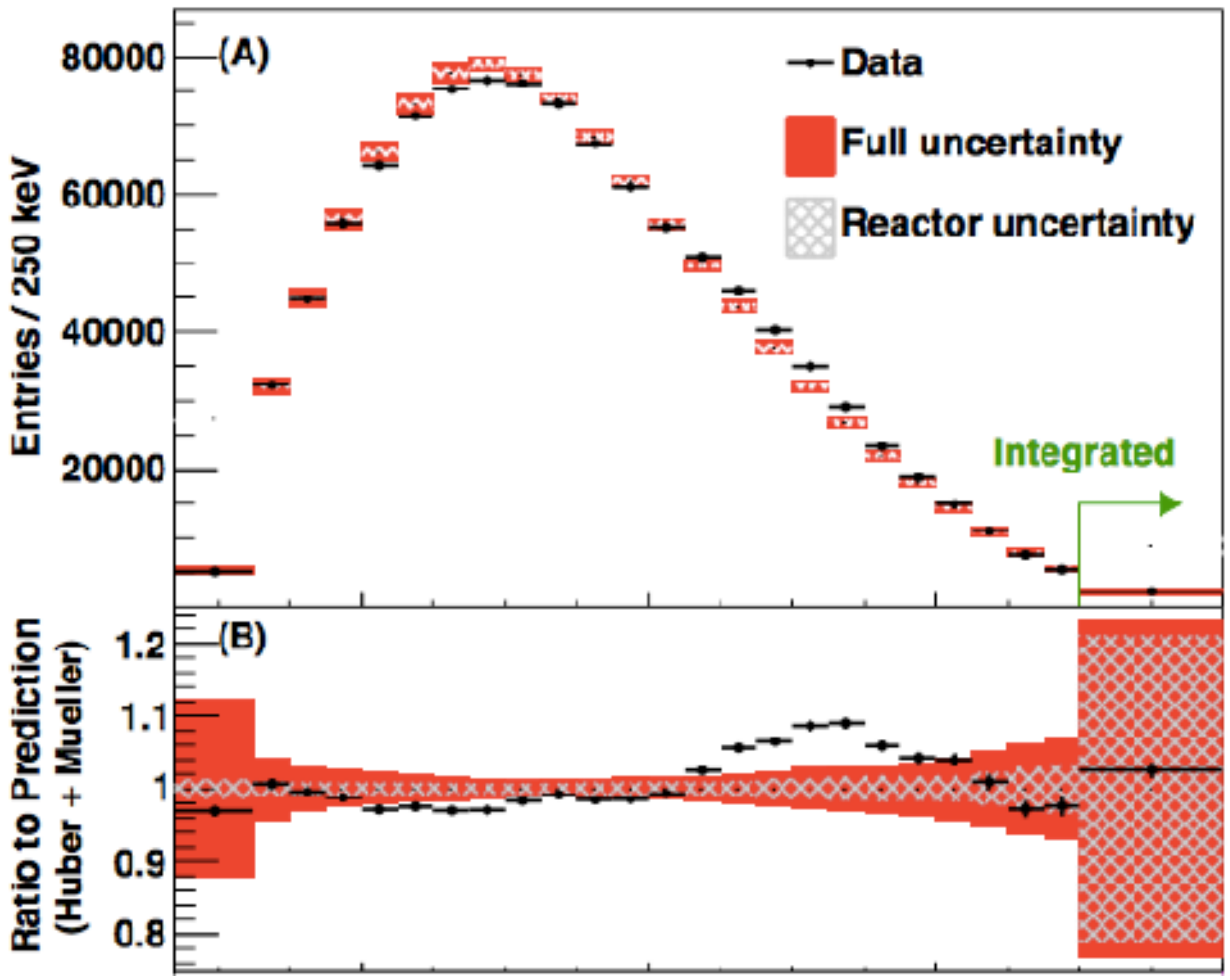
Very short baseline reactor experiments measure fewer neutrinos than predicted

→ Can be interpreted as oscillations into a sterile neutrino

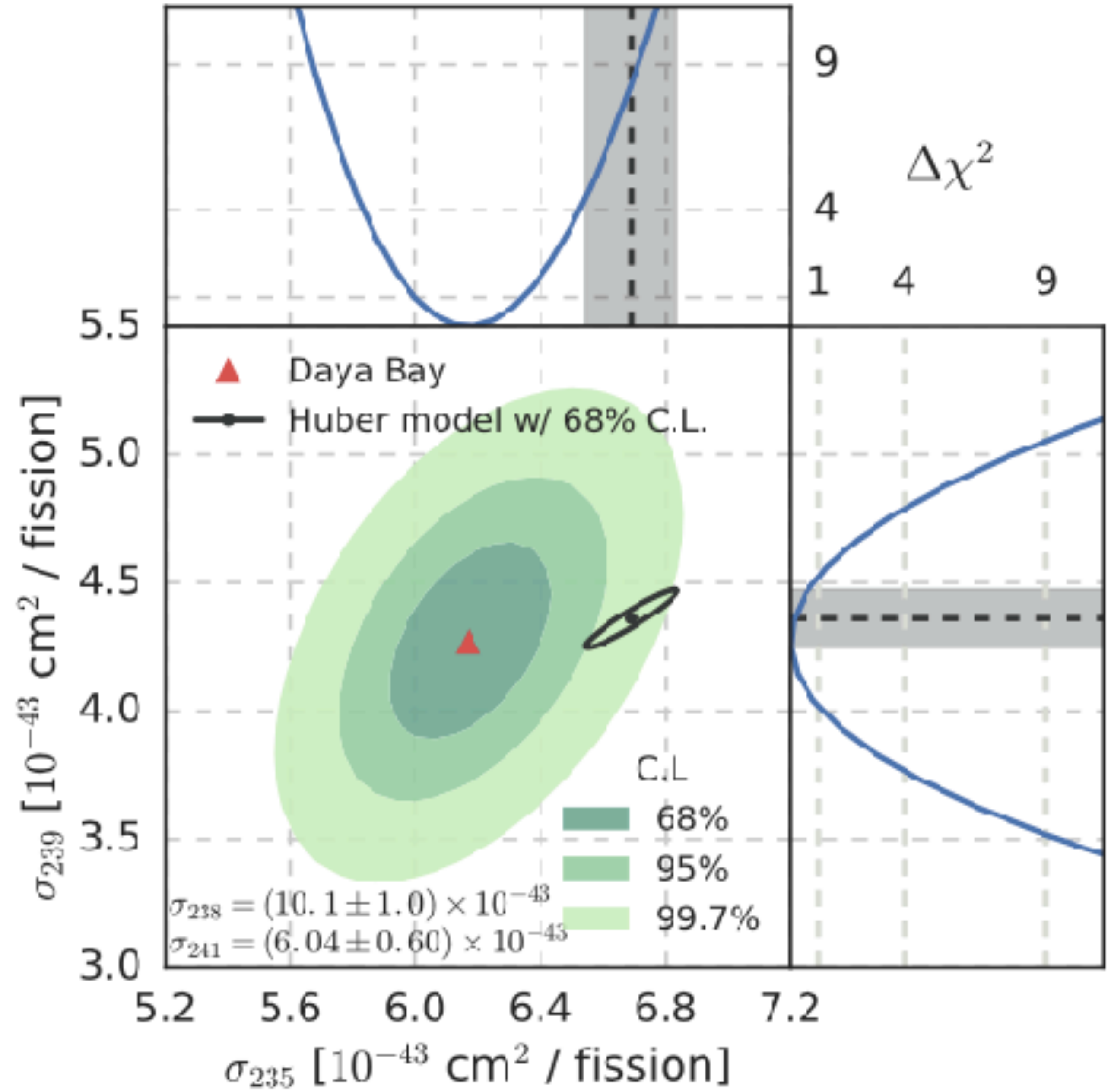


Chinese Physics C, 2017, 41(1): 13002-013002

Problems with the Reactor Flux



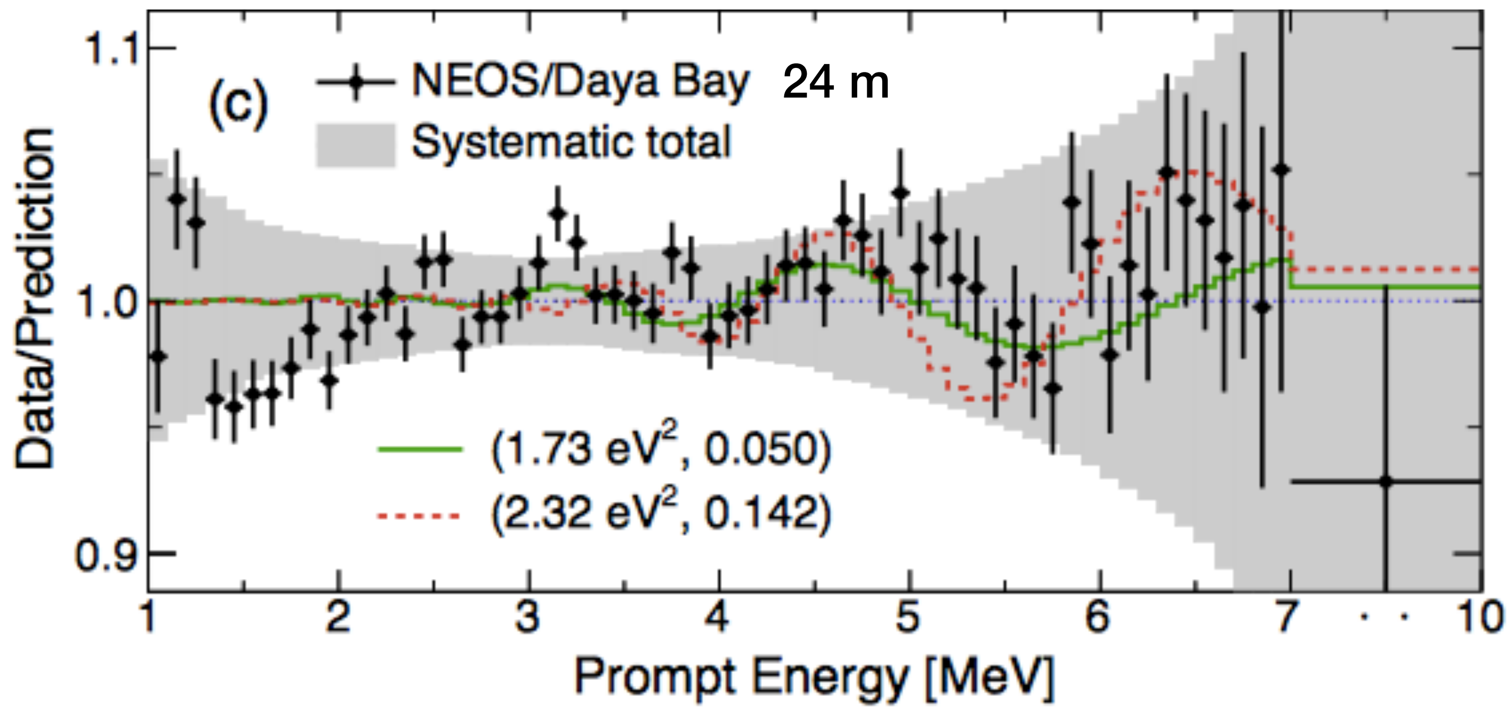
Chinese Physics C, 2017, 41(1): 13002-013002



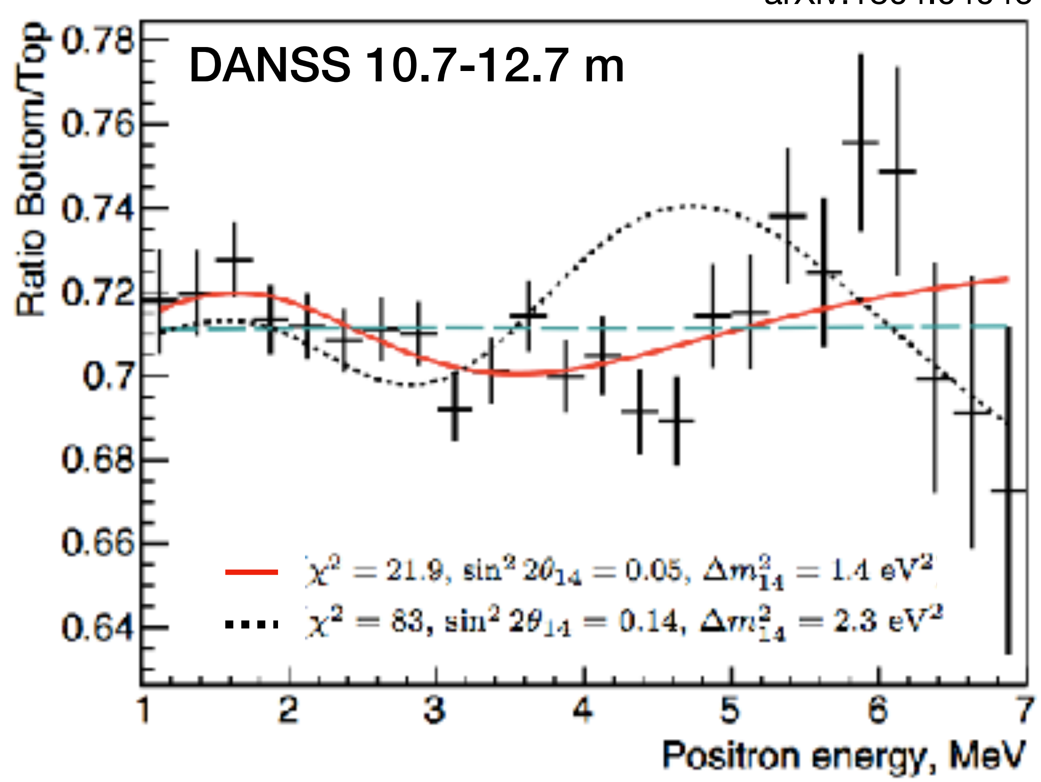
Phys. Rev. Lett. 118, 251801 (2017)

Data-to-data ratios don't completely rule sterile out

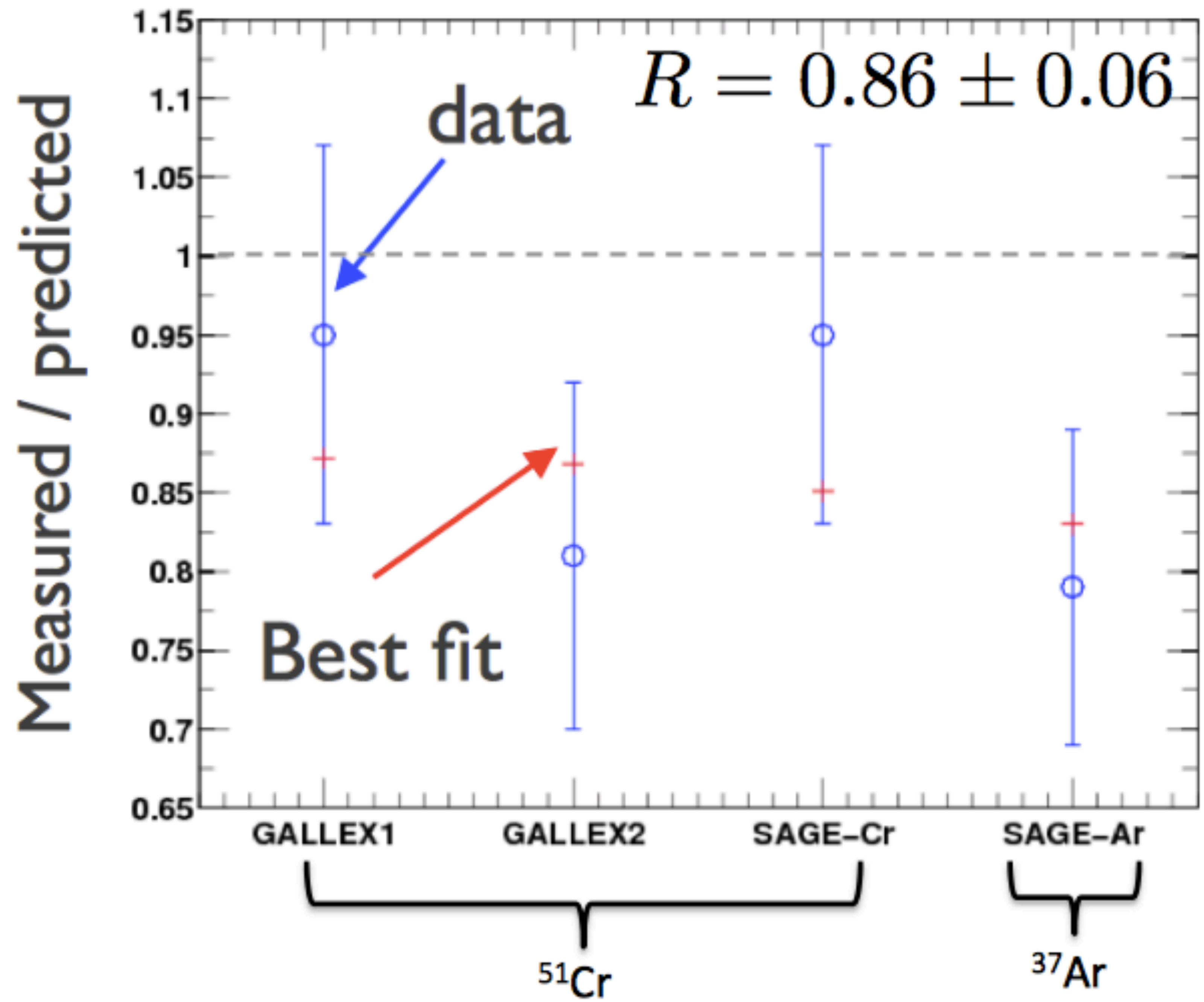
PRL 118 (2017) 121802



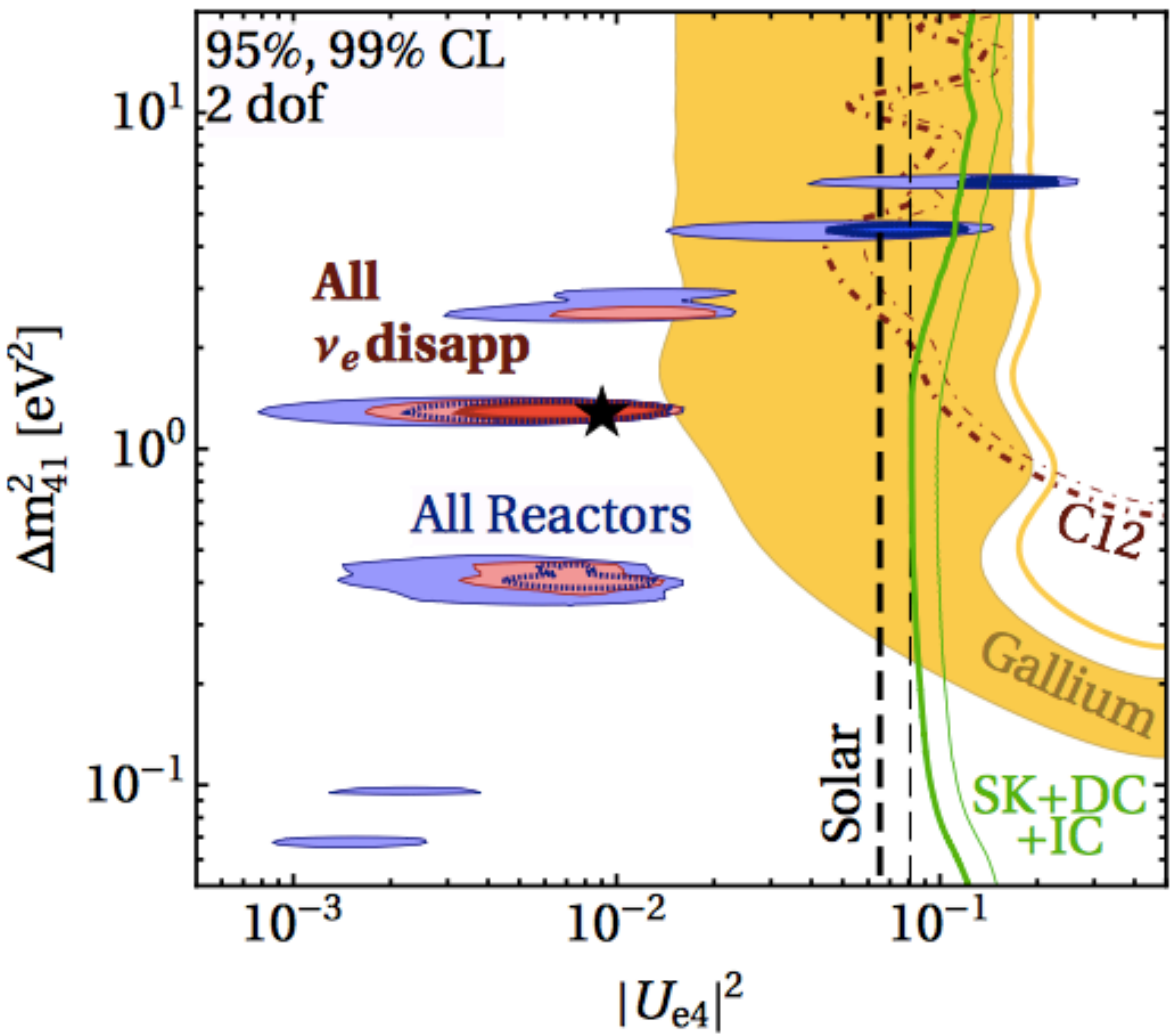
arXiv:1804.04046



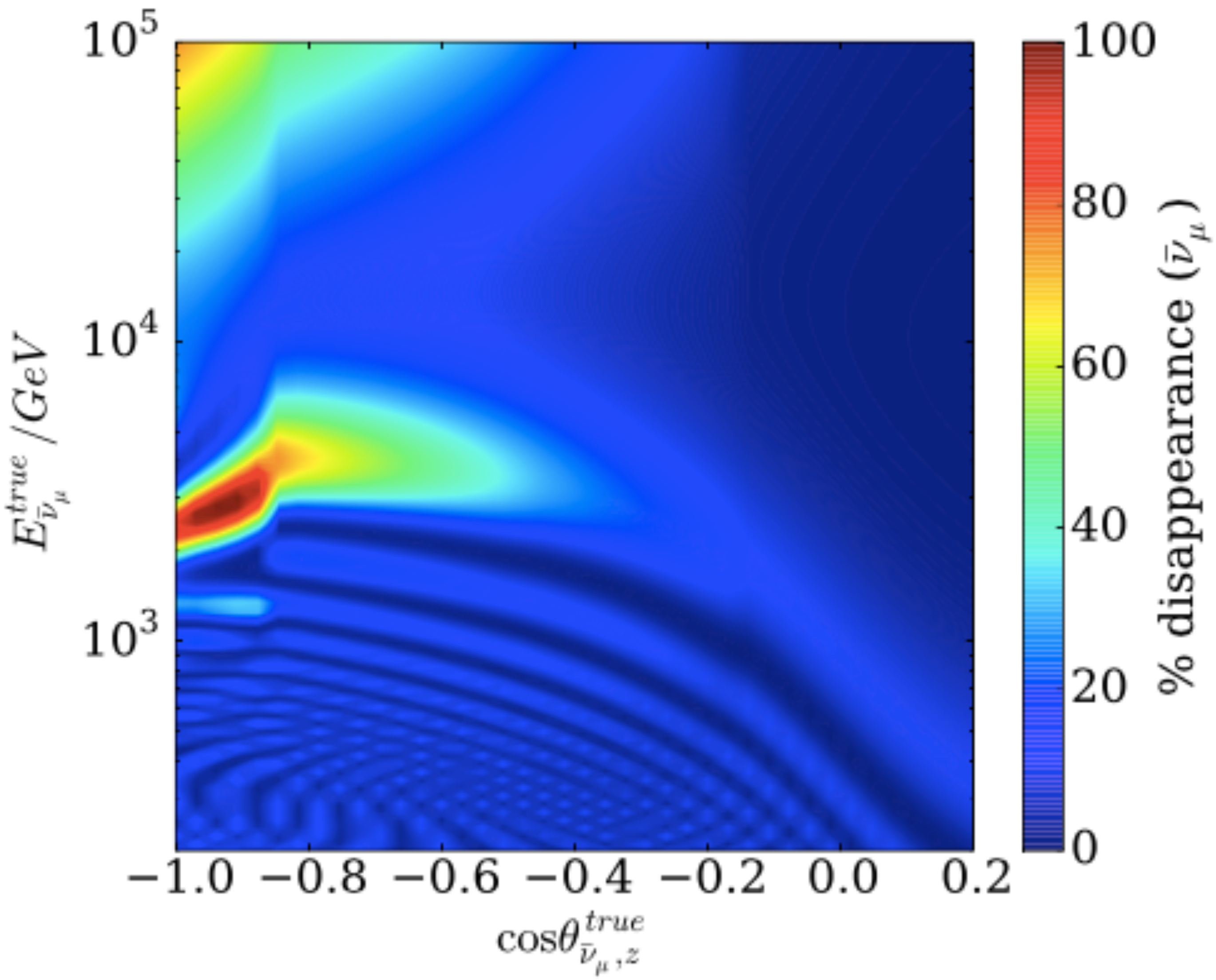
Deficits also observed from ν_e calibration sources in Gallium-based solar neutrino experiments



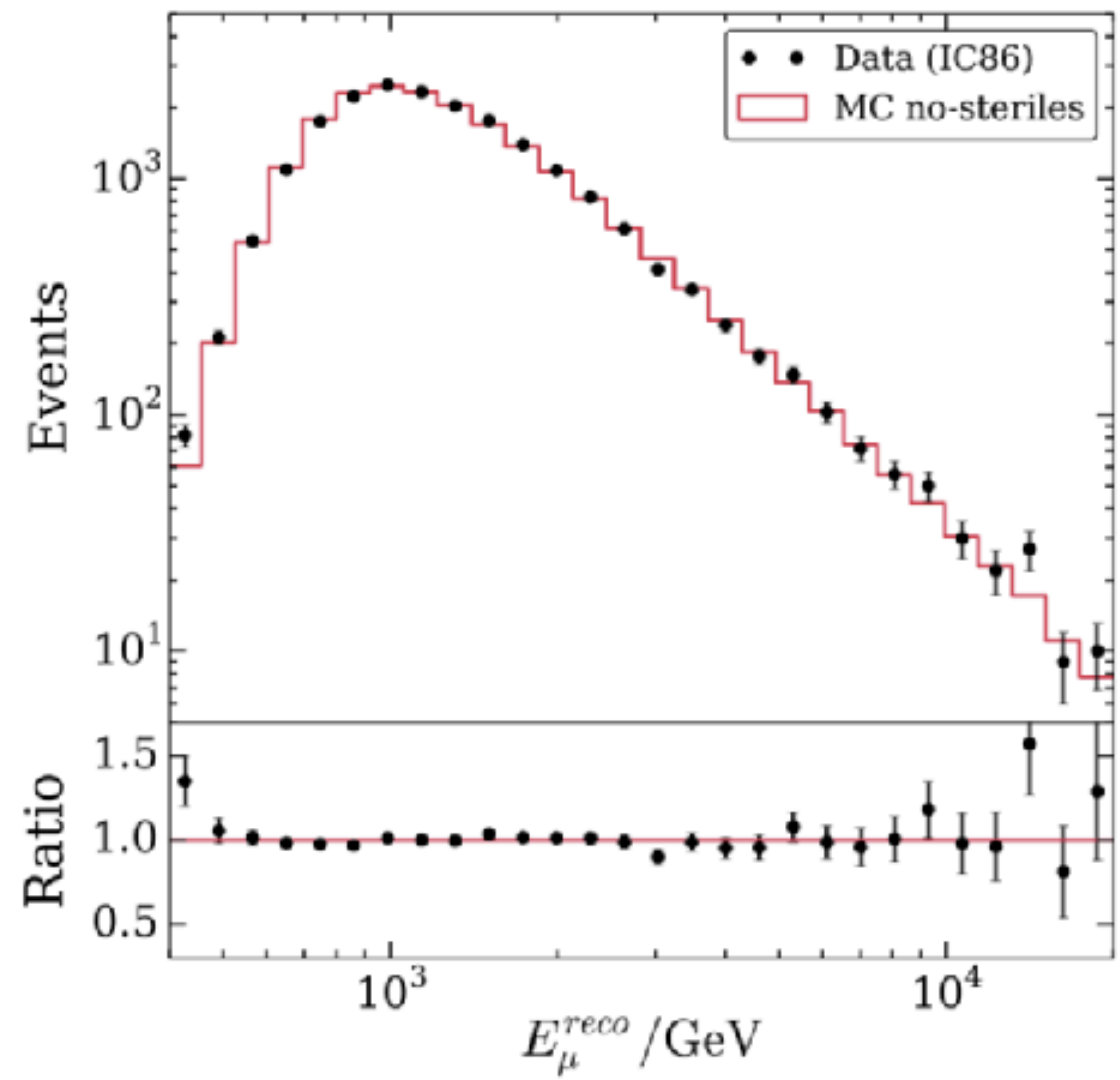
Modest Tension



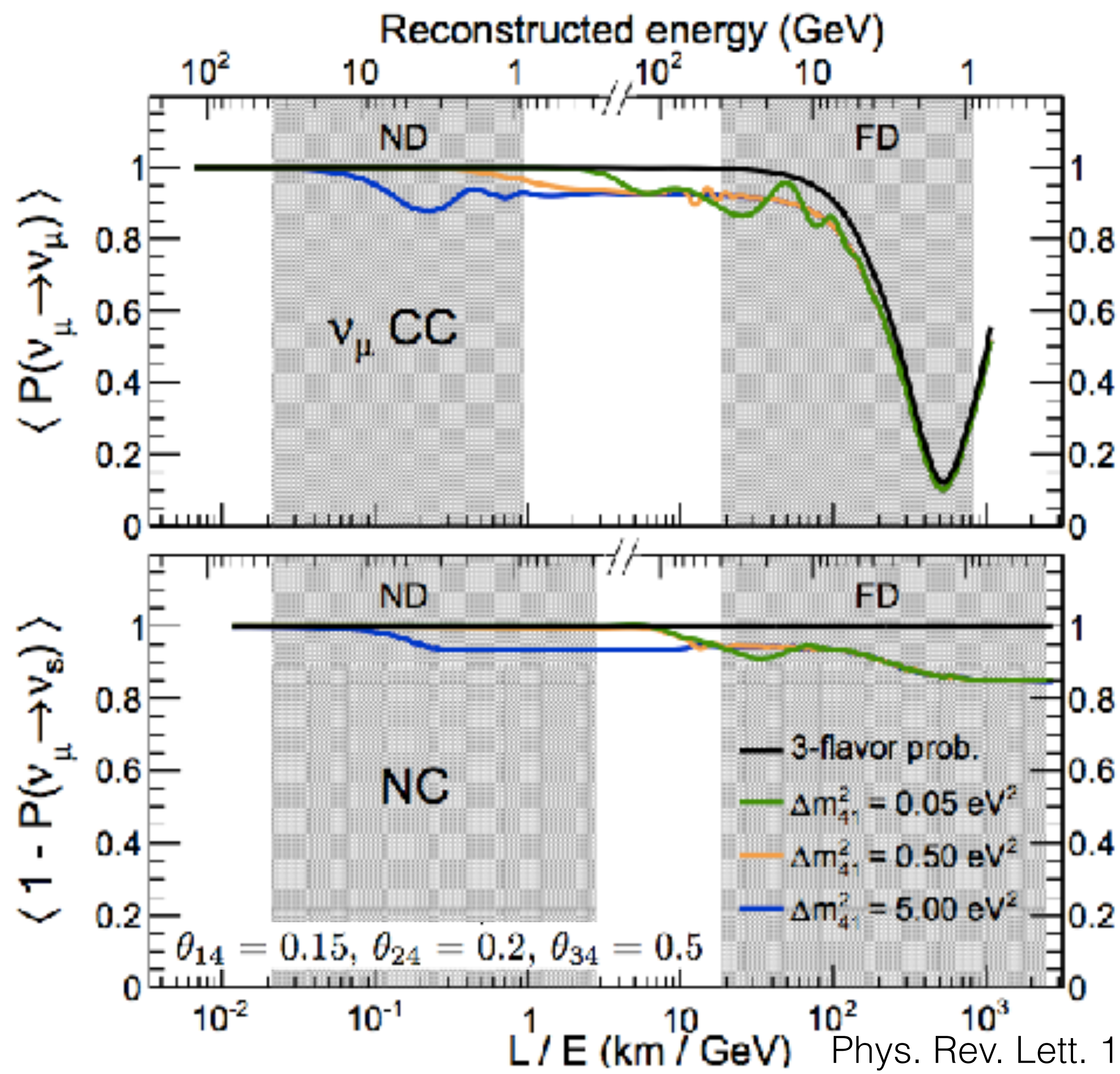
ν_μ Disappearance with Ice Cube



Phys. Rev. Lett. 117, 071801 (2016)

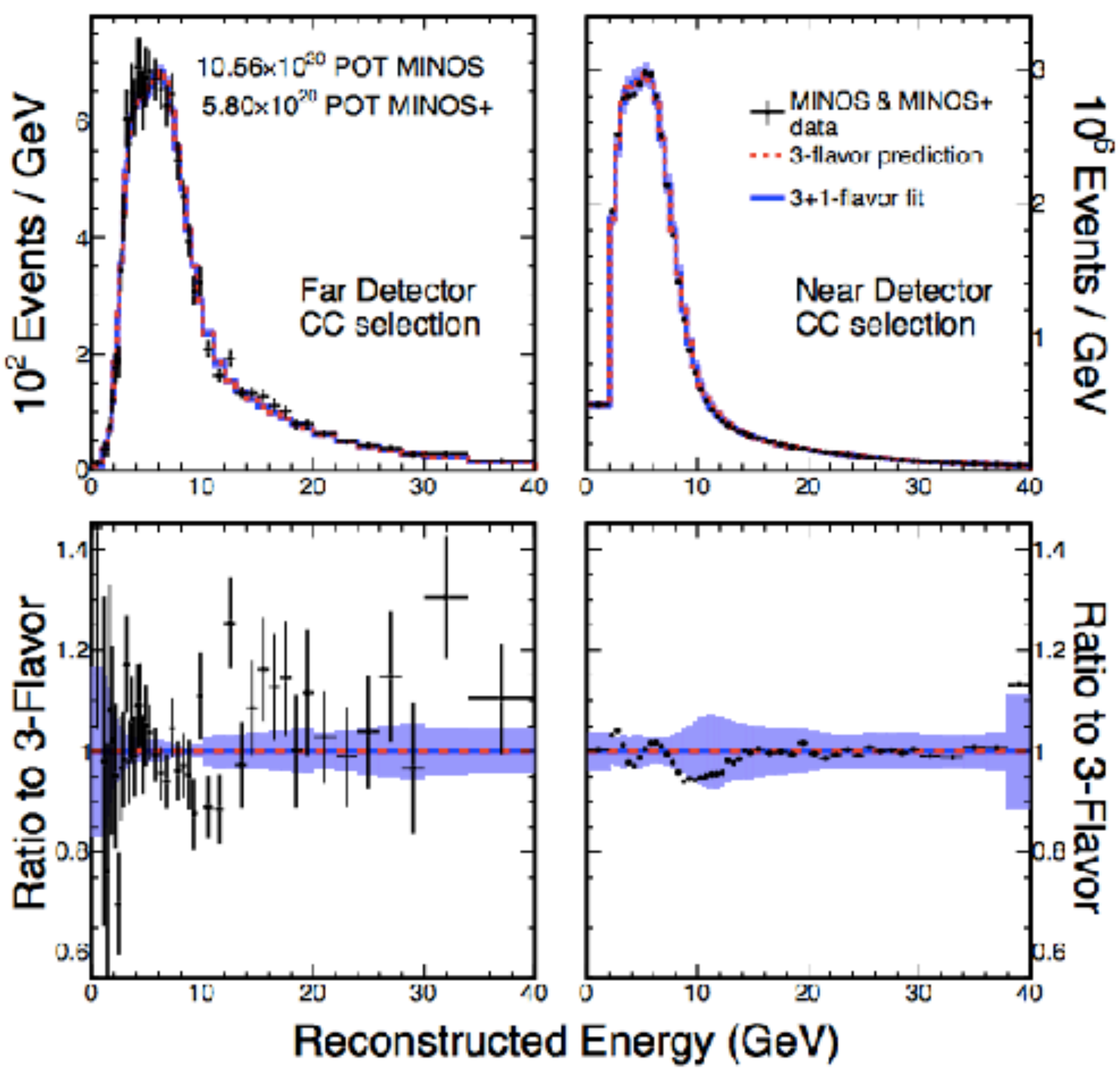


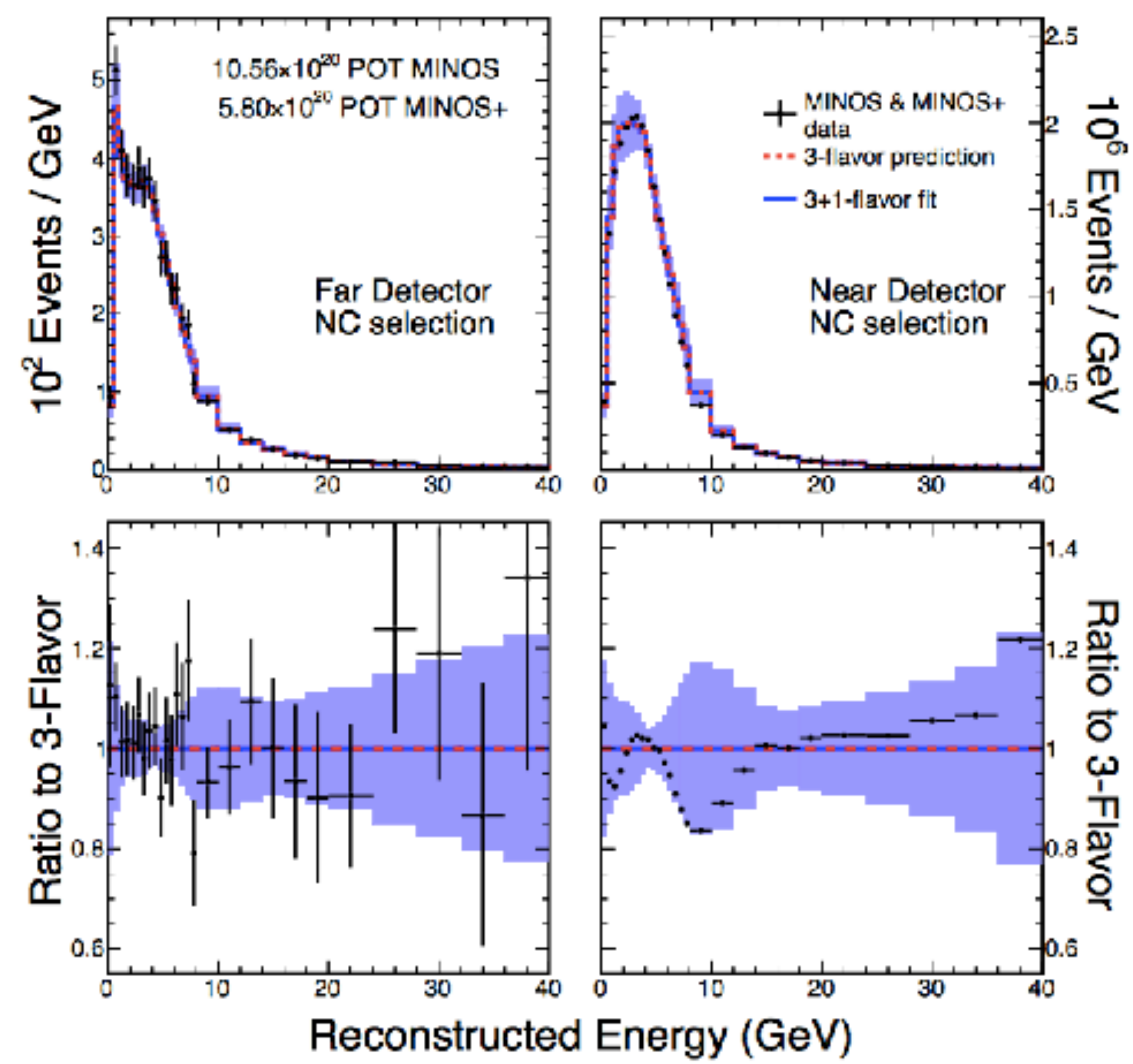
ν_μ Disappearance with Long Baseline Experiments



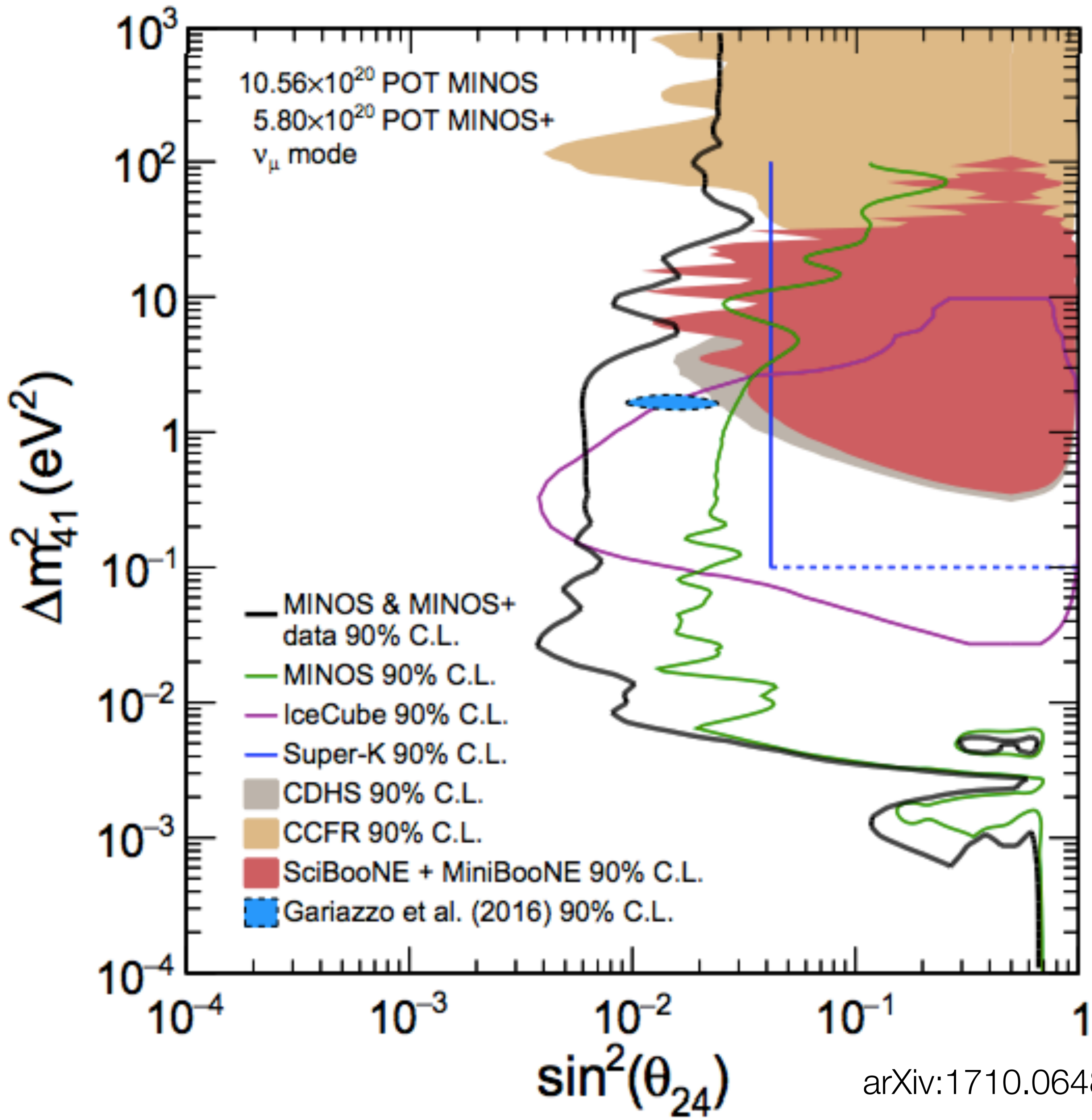
Phys. Rev. Lett. 117, 151803 (2016)

ν_μ Disappearance MINOS/MINOS+



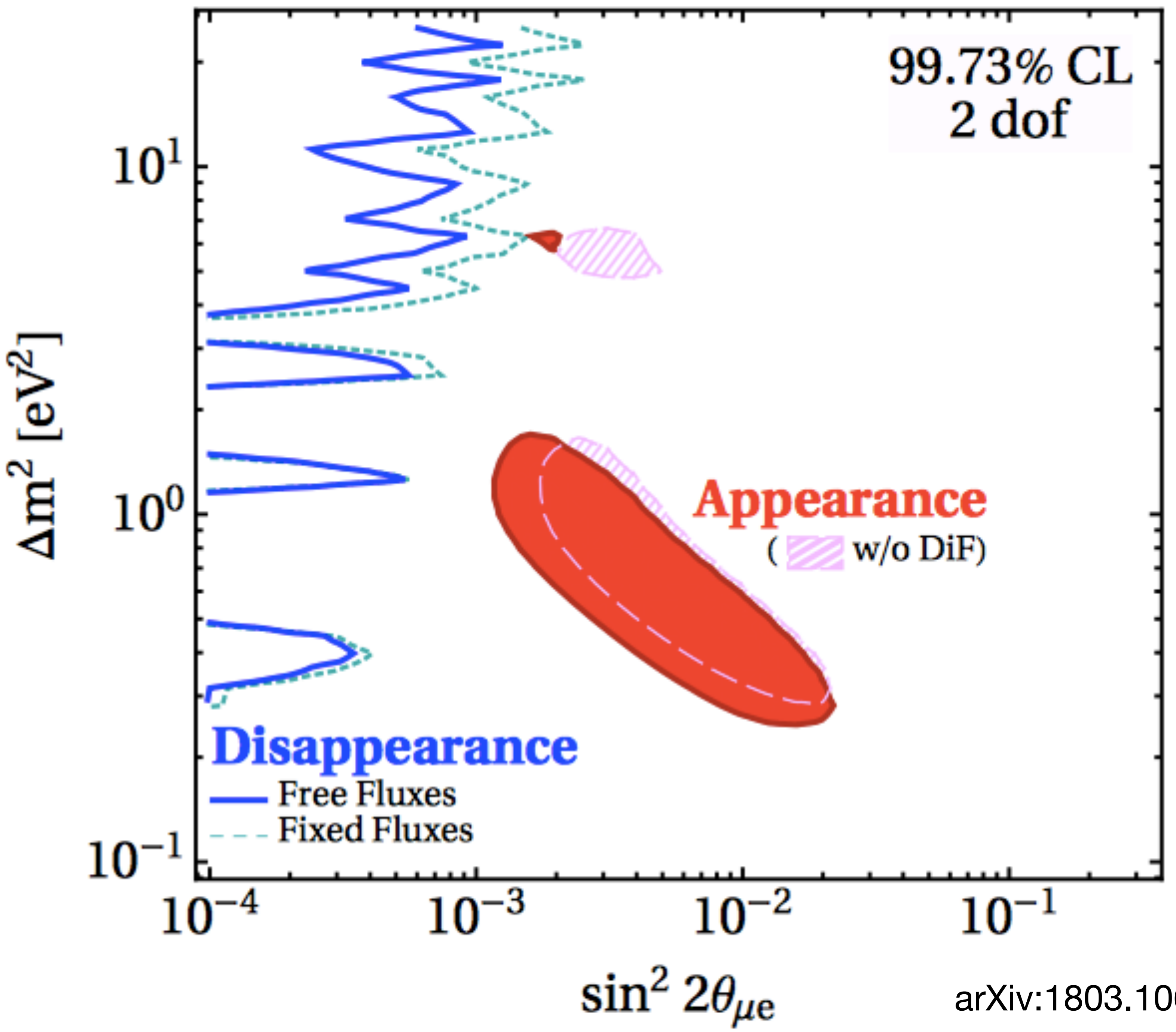


ν_μ Disappearance Allowed Regions



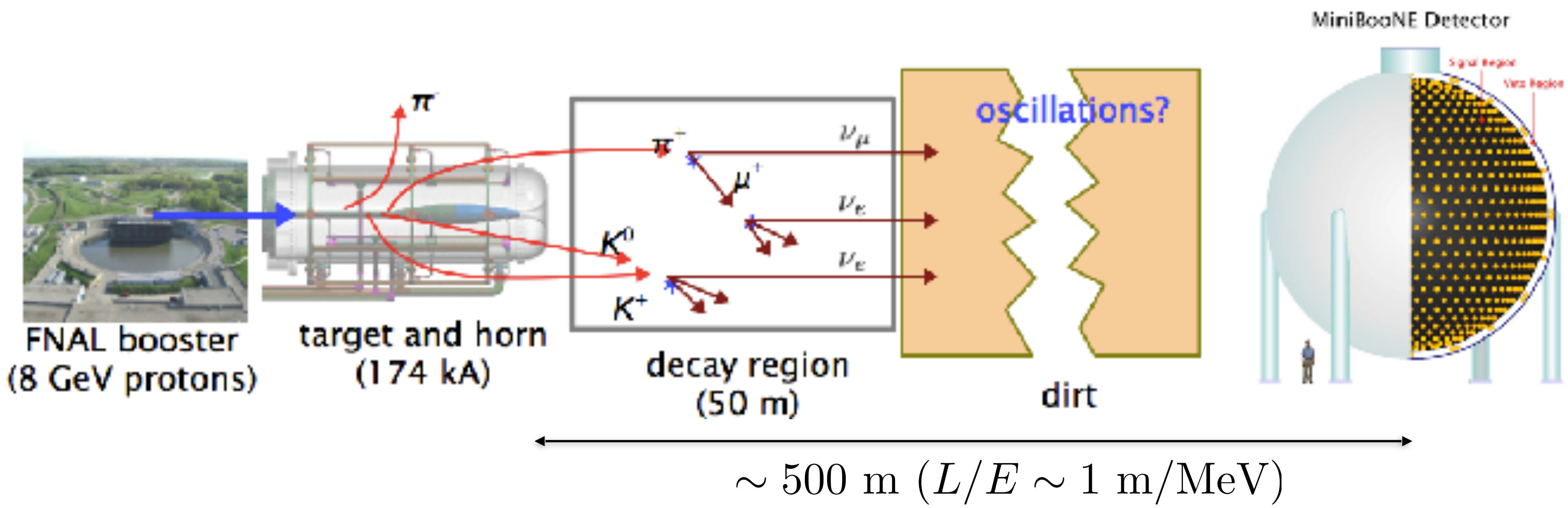
arXiv:1710.06488

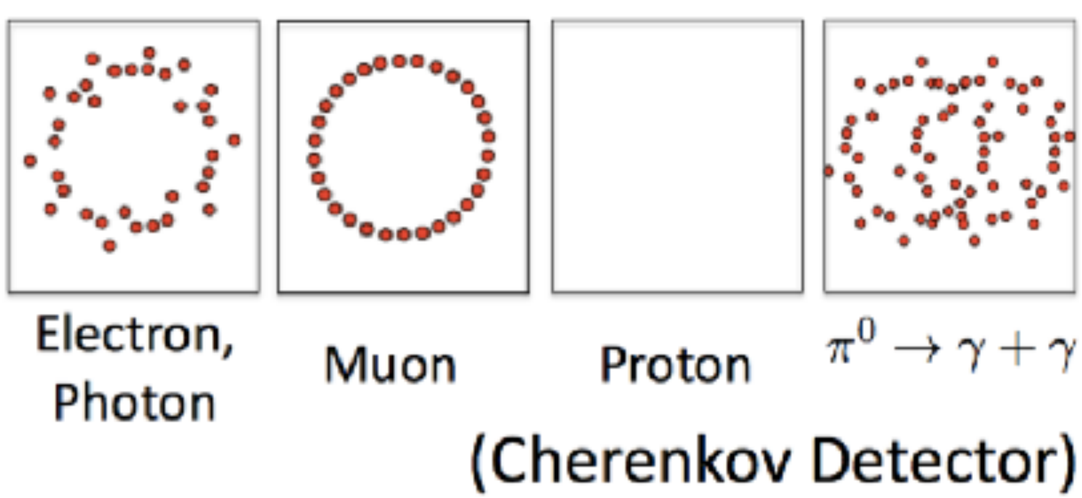
Bottom Line for 3+1 Models



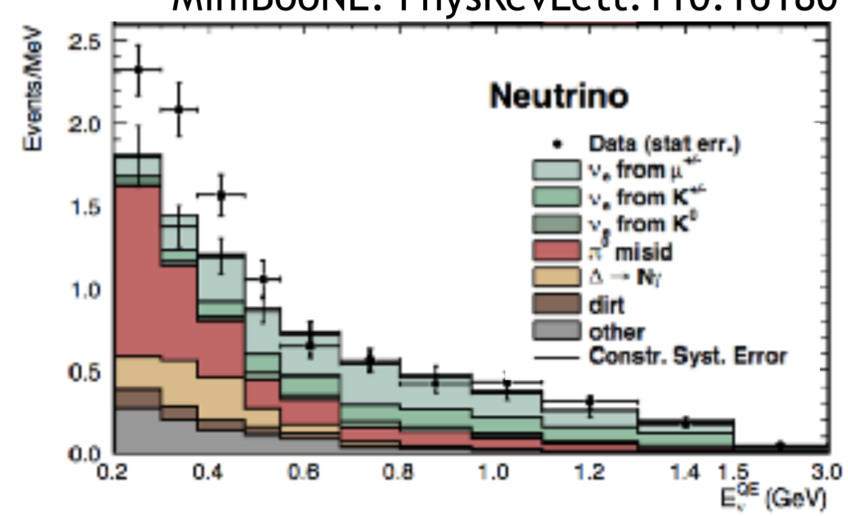
arXiv:1803.10661

MiniBooNE Experiment

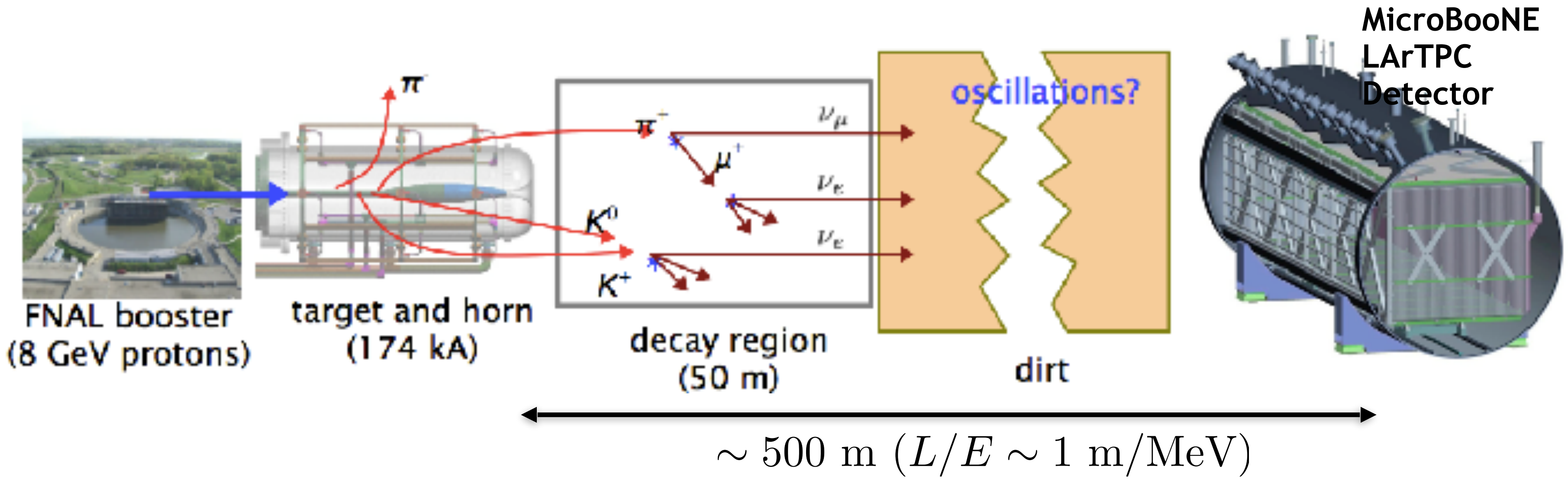


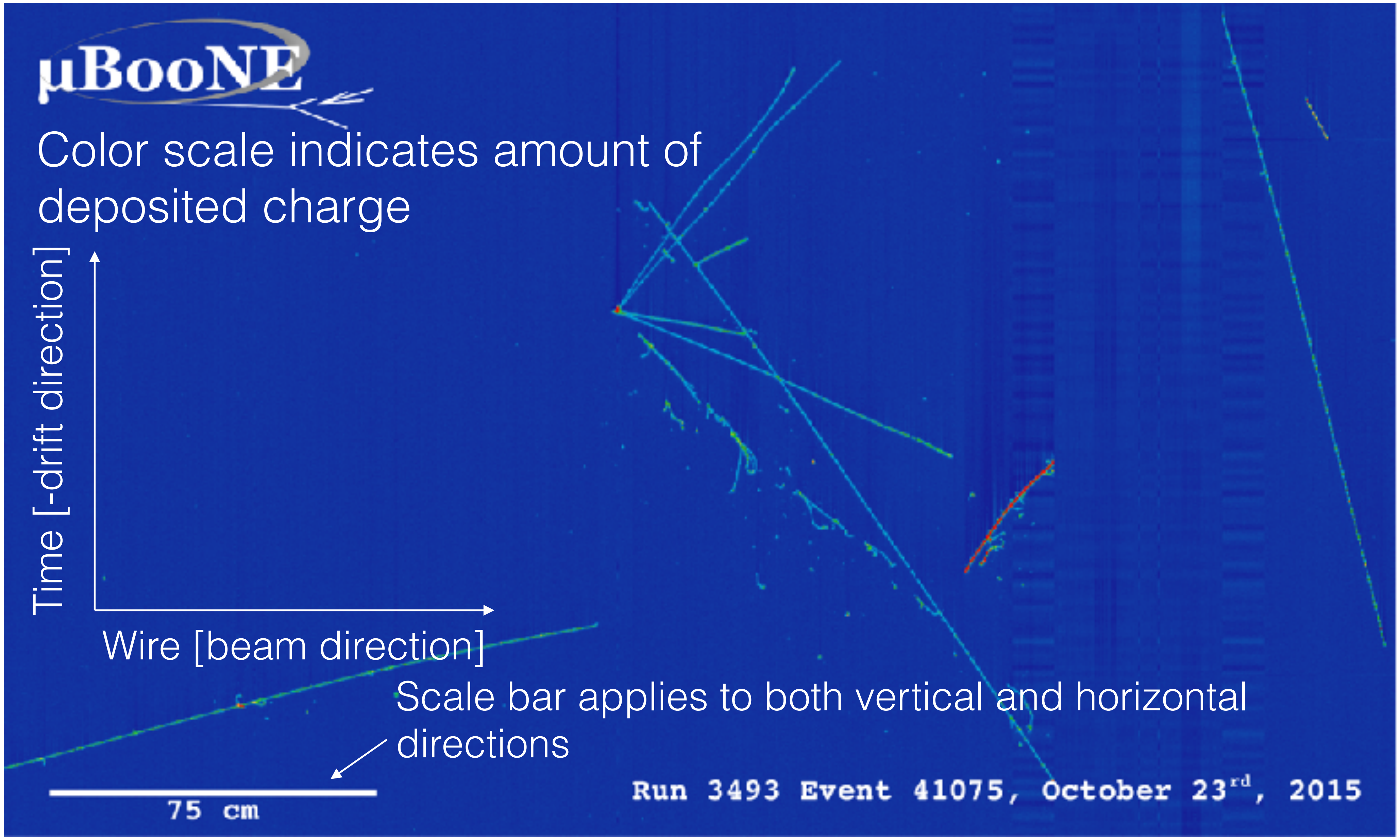


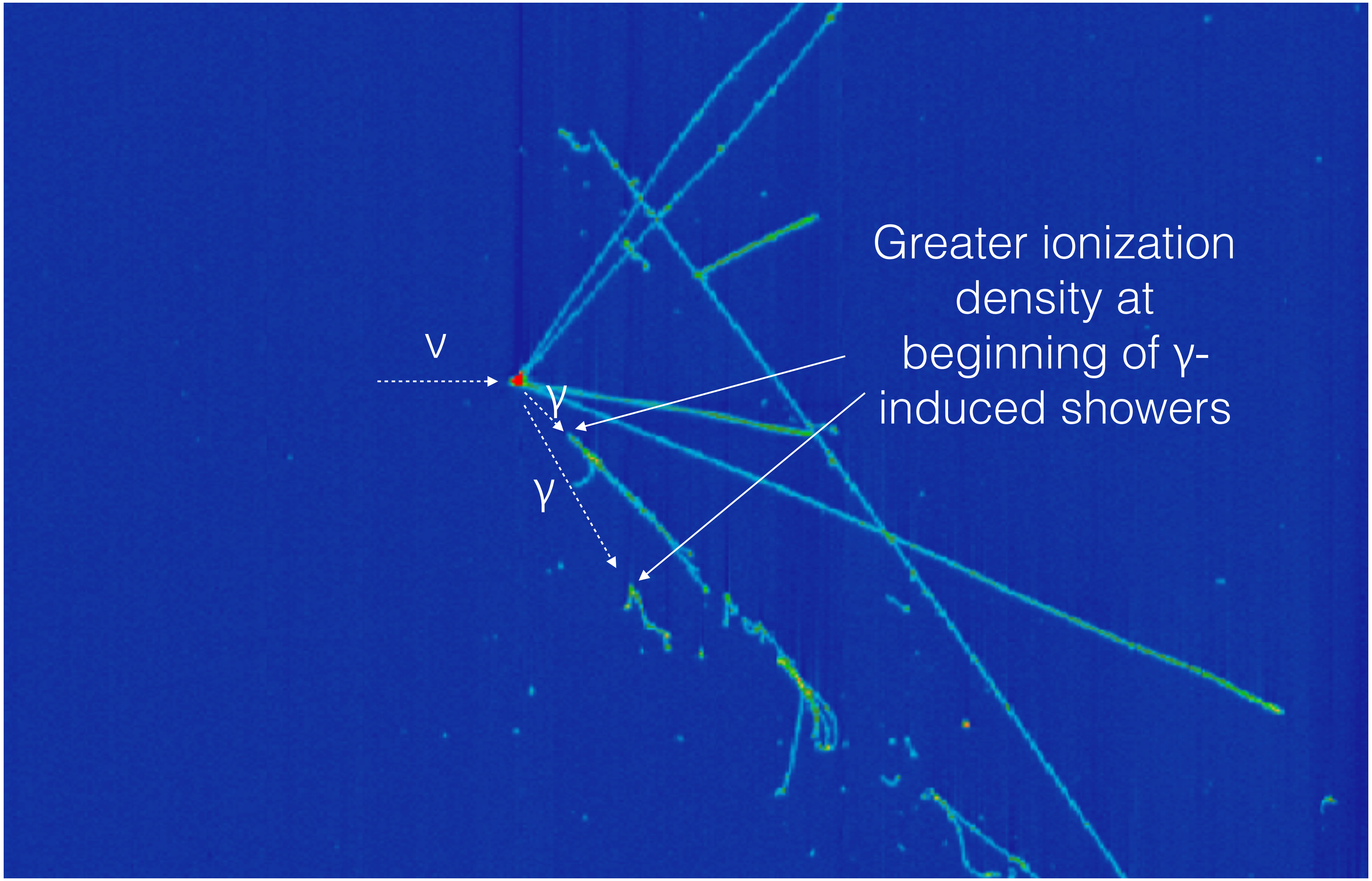
MiniBooNE: PhysRevLett.110.161801



Addressing the MiniBooNE "Low-Energy Excess"



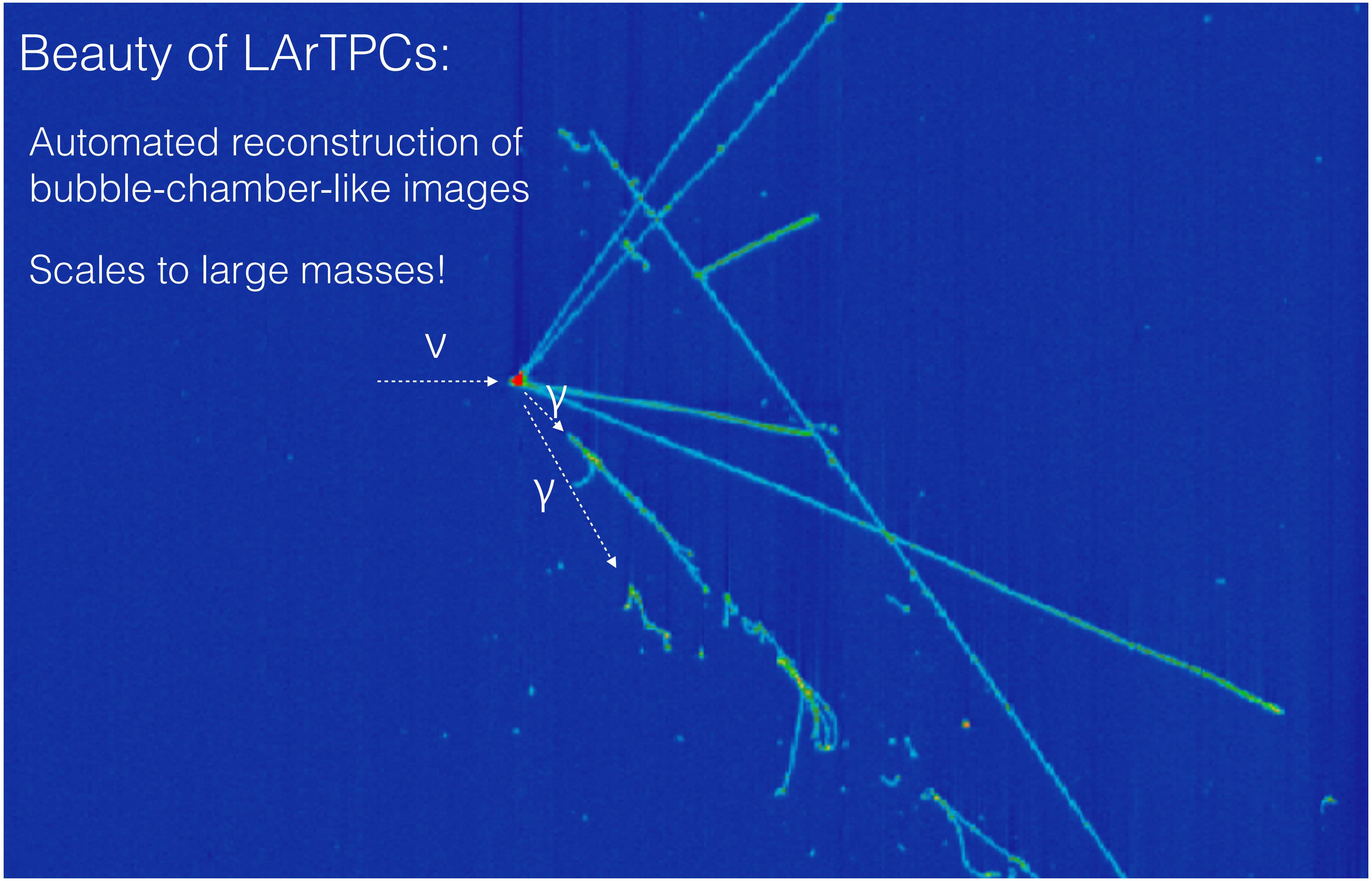

μBooNE
Color scale indicates amount of deposited charge
Time [-drift direction]
Wire [beam direction]
Scale bar applies to both vertical and horizontal directions
75 cm
Run 3493 Event 41075, October 23rd, 2015


ν
γ
γ
Greater ionization density at beginning of γ-induced showers

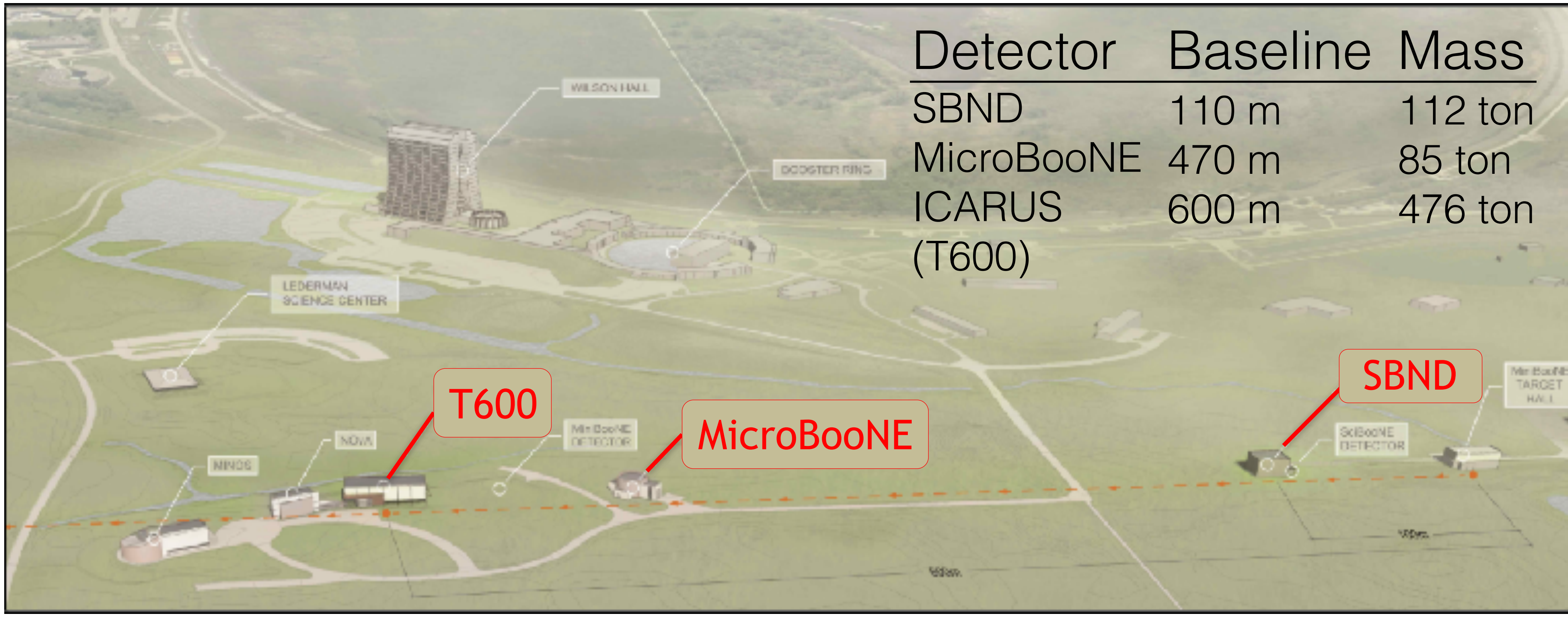
Beauty of LArTPCs:

Automated reconstruction of bubble-chamber-like images

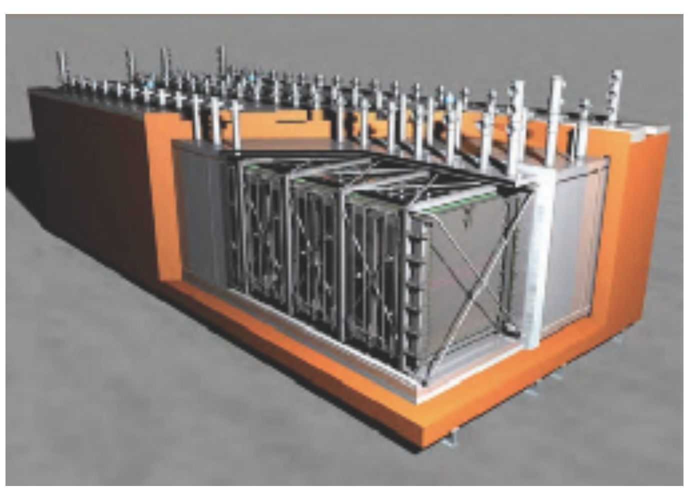
Scales to large masses!



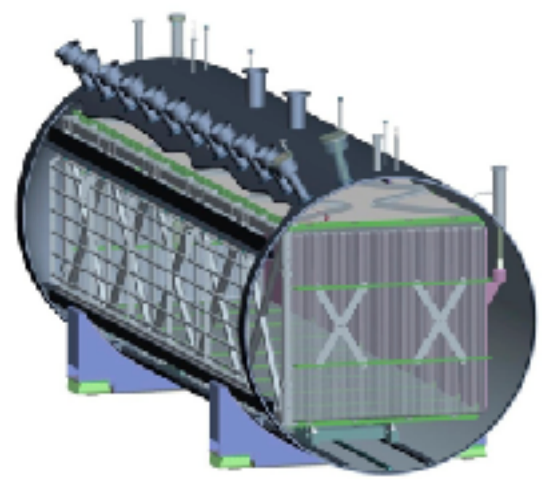
Trio of LArTPCs on the Booster Neutrino Beam (BNB)



Detector	Baseline	Mass
SBND	110 m	112 ton
MicroBooNE	470 m	85 ton
ICARUS (T600)	600 m	476 ton



M. Toups



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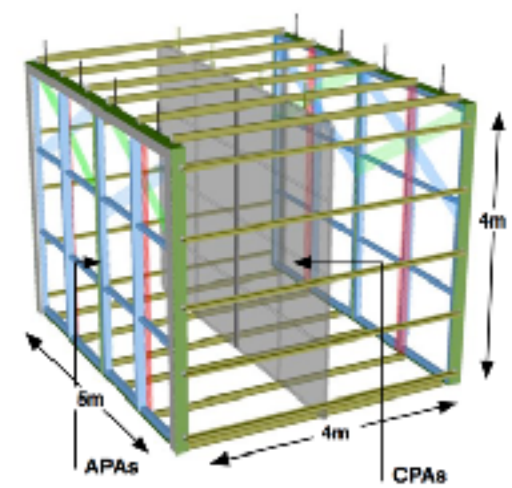

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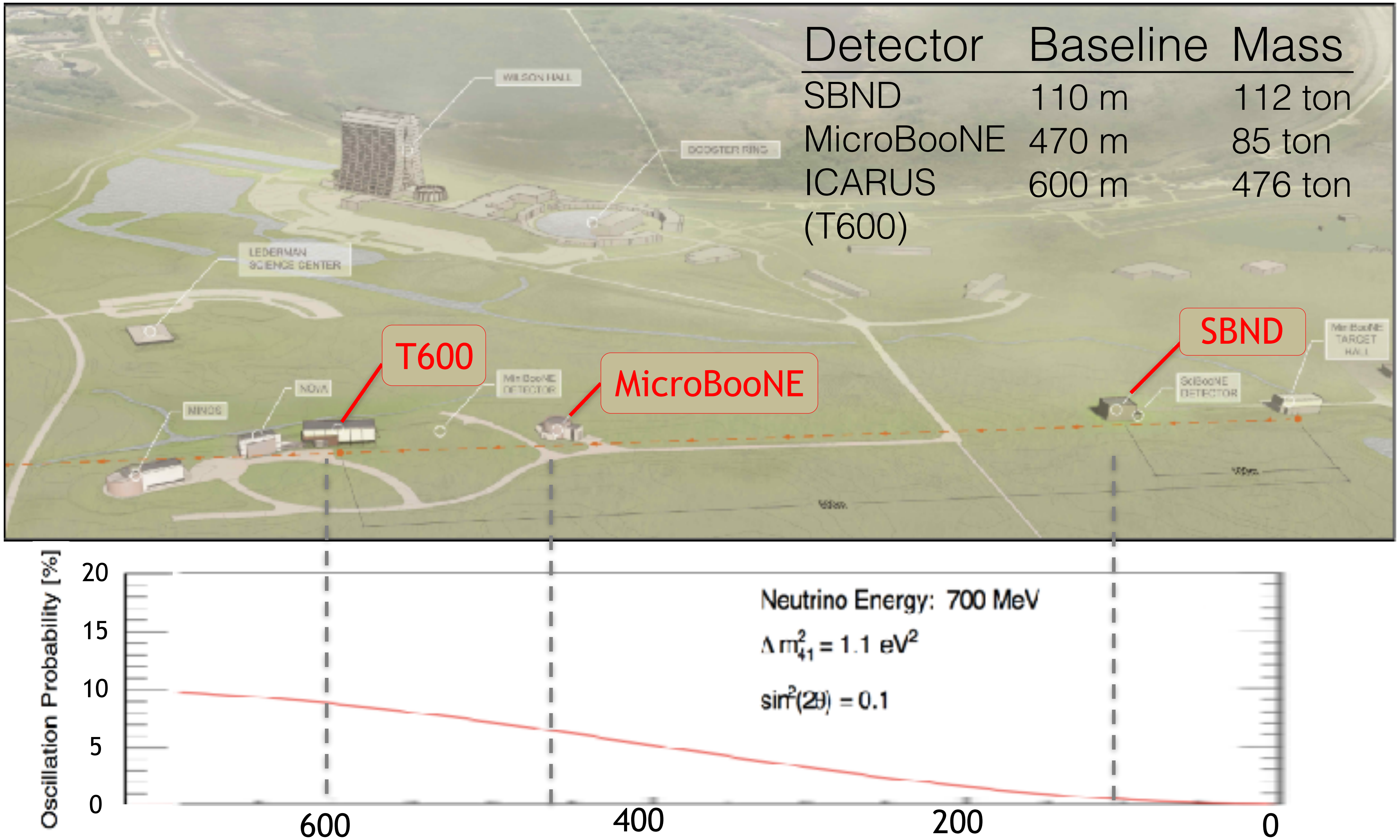
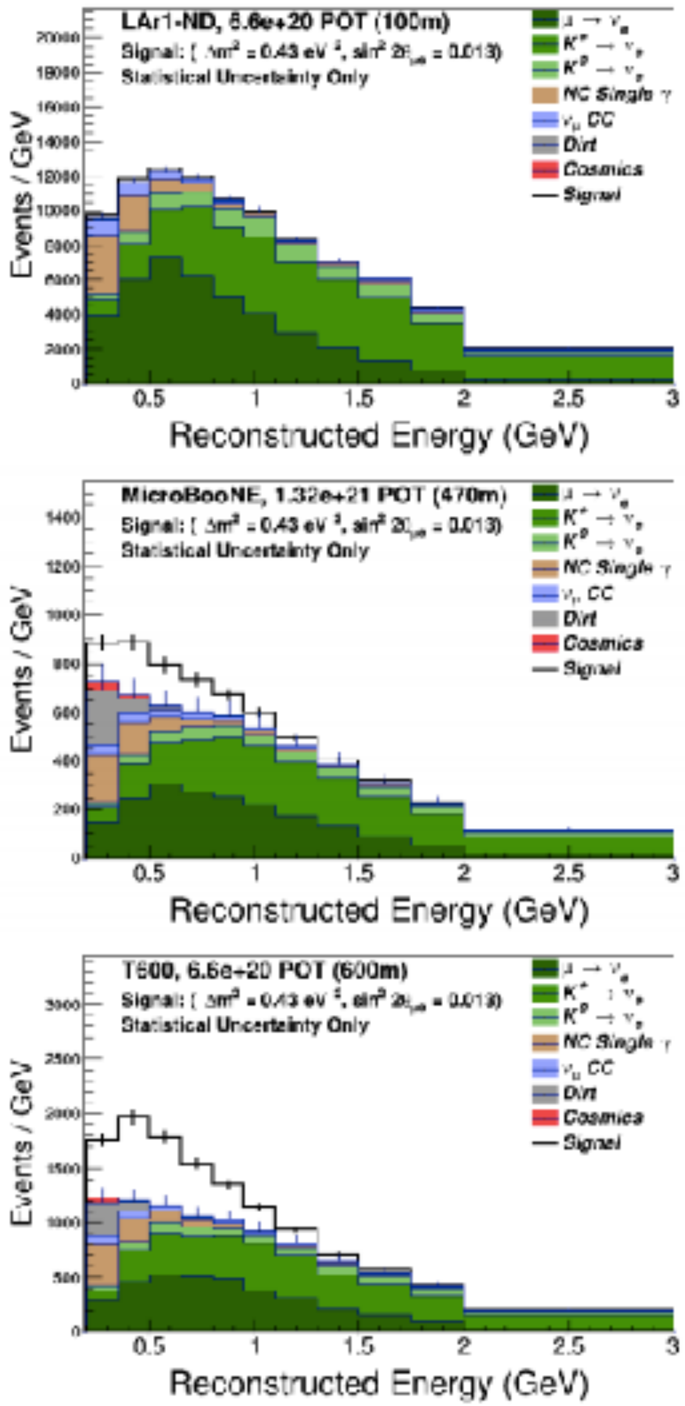
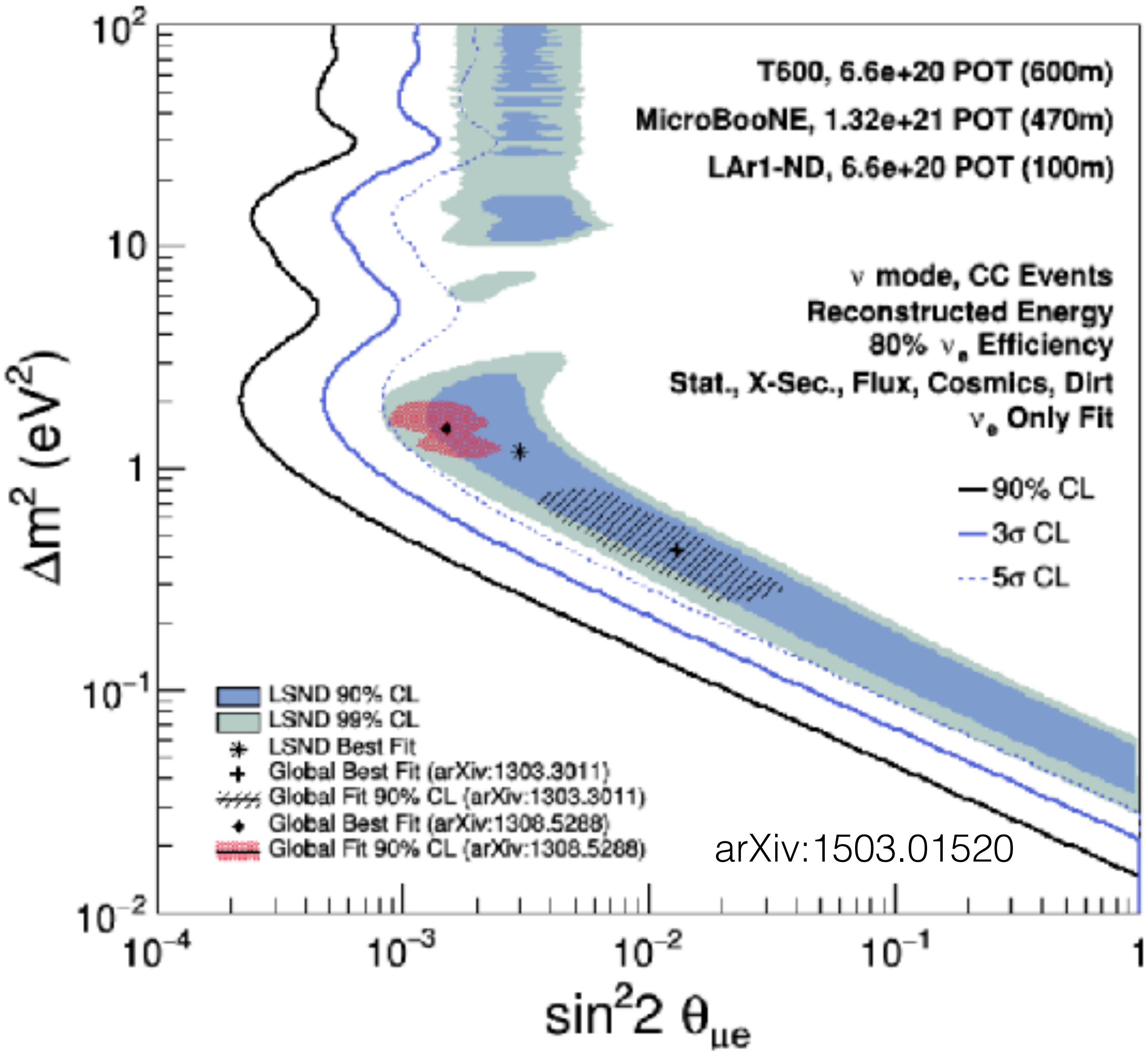
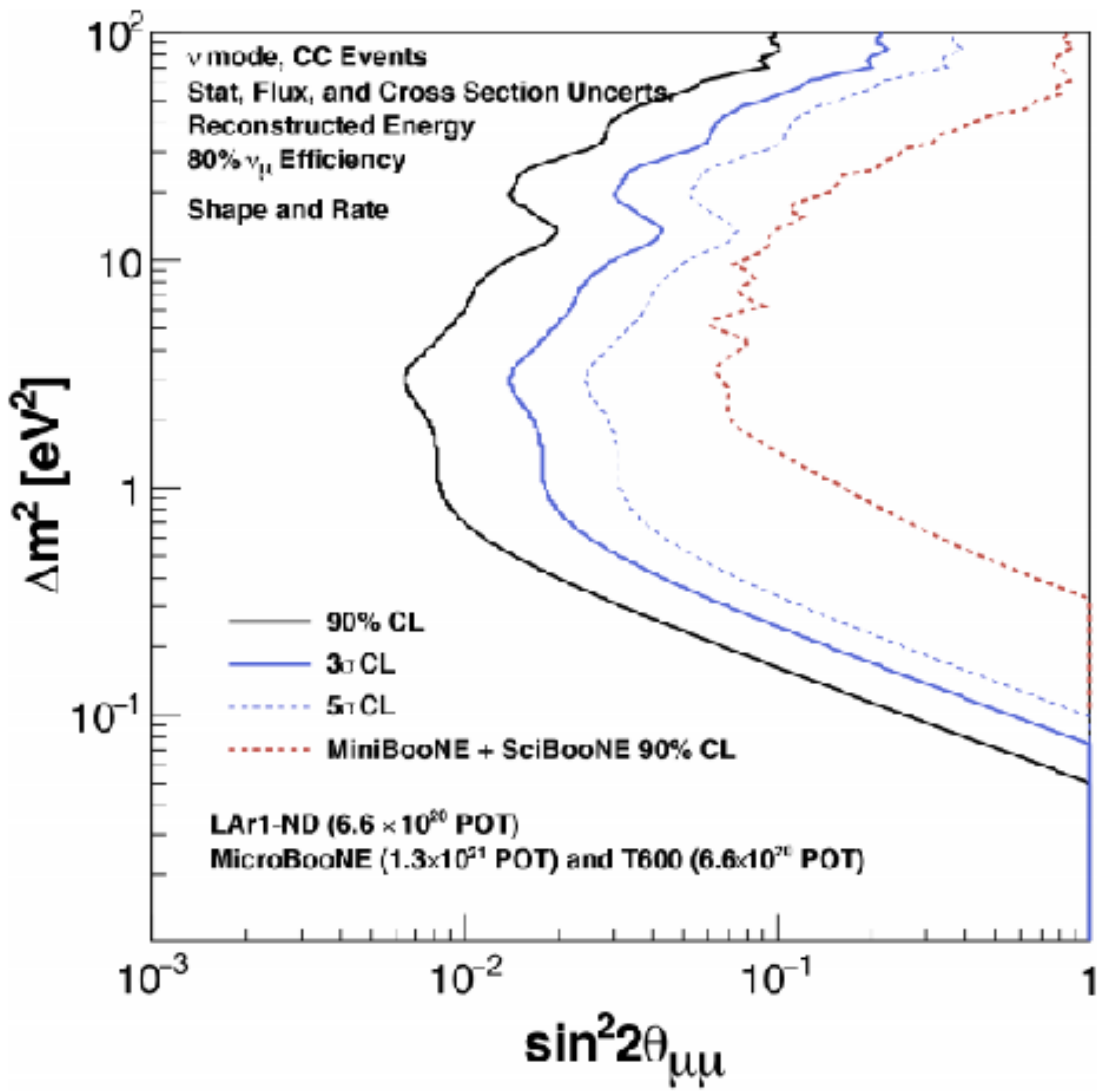



LAr1-ND, 6.6e+20 POT (100m)
Statistical Uncertainty Only
NC Single γ
ν_μ CC
Dirt
Cosmics
Signal
Events / GeV
Reconstructed Energy (GeV)
MicroBooNE, 1.32e+21 POT (470m)
Statistical Uncertainty Only
T600, 6.6e+20 POT (600m)
Statistical Uncertainty Only


T600, 6.6e+20 POT (600m)
MicroBooNE, 1.32e+21 POT (470m)
LAr1-ND, 6.6e+20 POT (100m)
ν mode, CC Events
Reconstructed Energy
80% ν_e Efficiency
Stat., X-Sec., Flux, Cosmics, Dirt
ν_e Only Fit
90% CL
3σ CL
5σ CL
LSND 90% CL
LSND 99% CL
LSND Best Fit
Global Best Fit (arXiv:1303.3011)
Global Fit 90% CL (arXiv:1303.3011)
Global Best Fit (arXiv:1308.5288)
Global Fit 90% CL (arXiv:1308.5288)
arXiv:1503.01520
Δm^2 (eV^2)
$\sin^2 2\theta_{\mu e}$

SBN ν_μ Disappearance Sensitivity

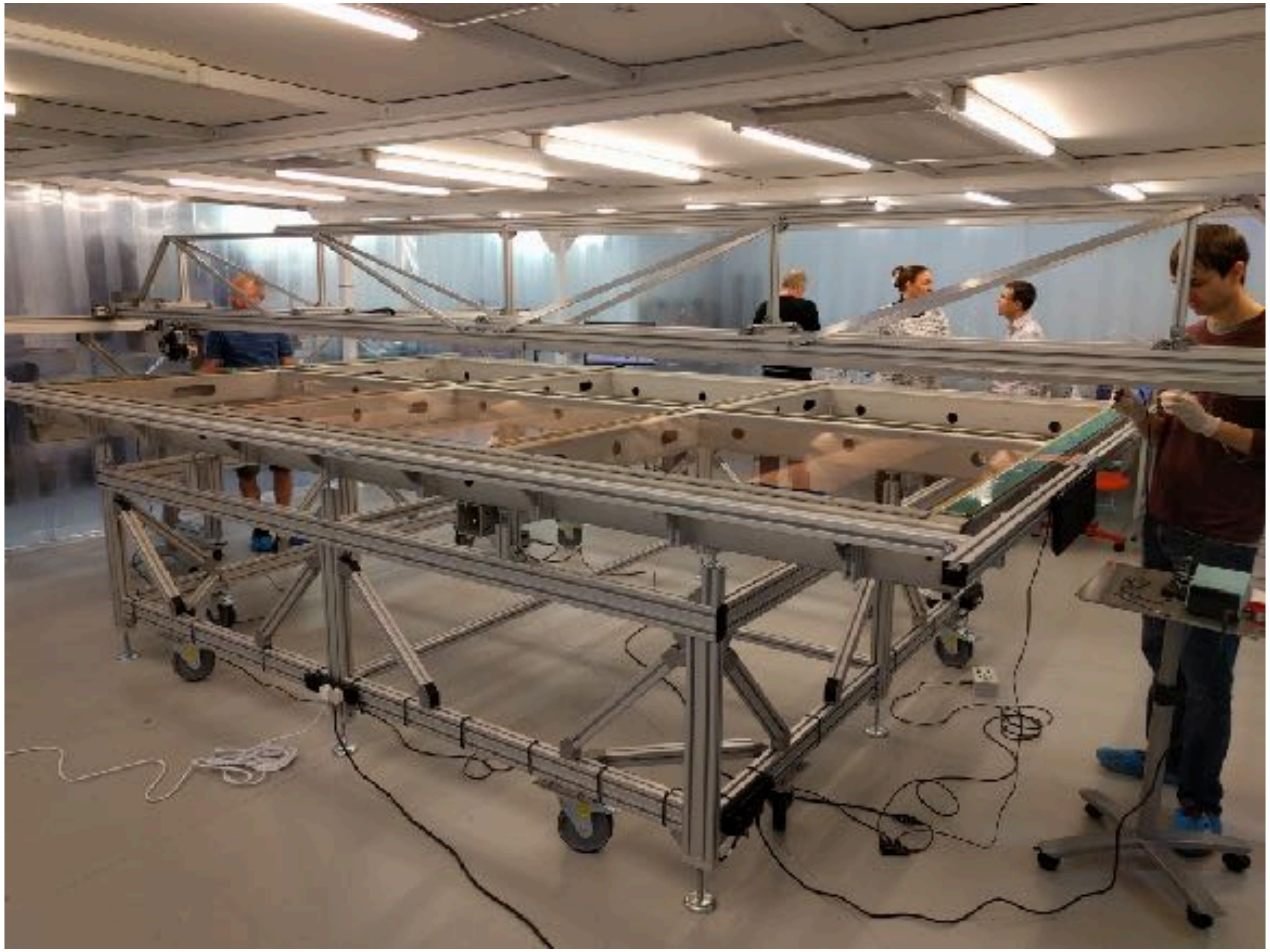


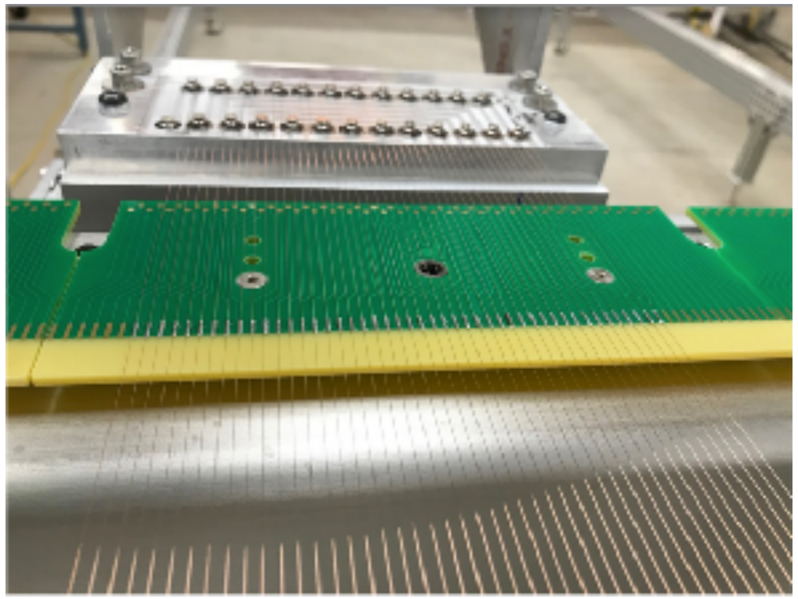
ICARUS

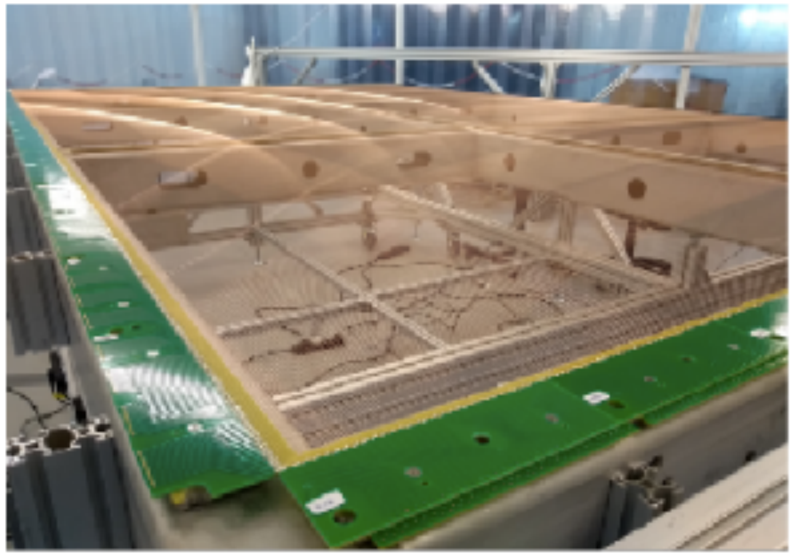
Detector installation underway
Planned data-taking 2019

SBND

Detector construction underway
Planned data-taking 2020

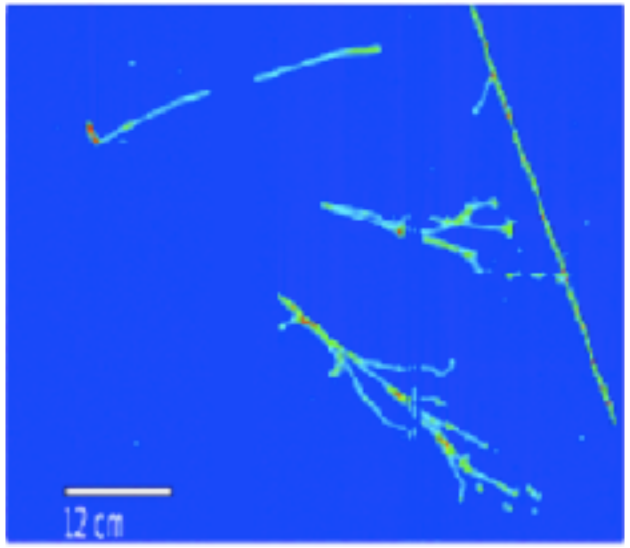




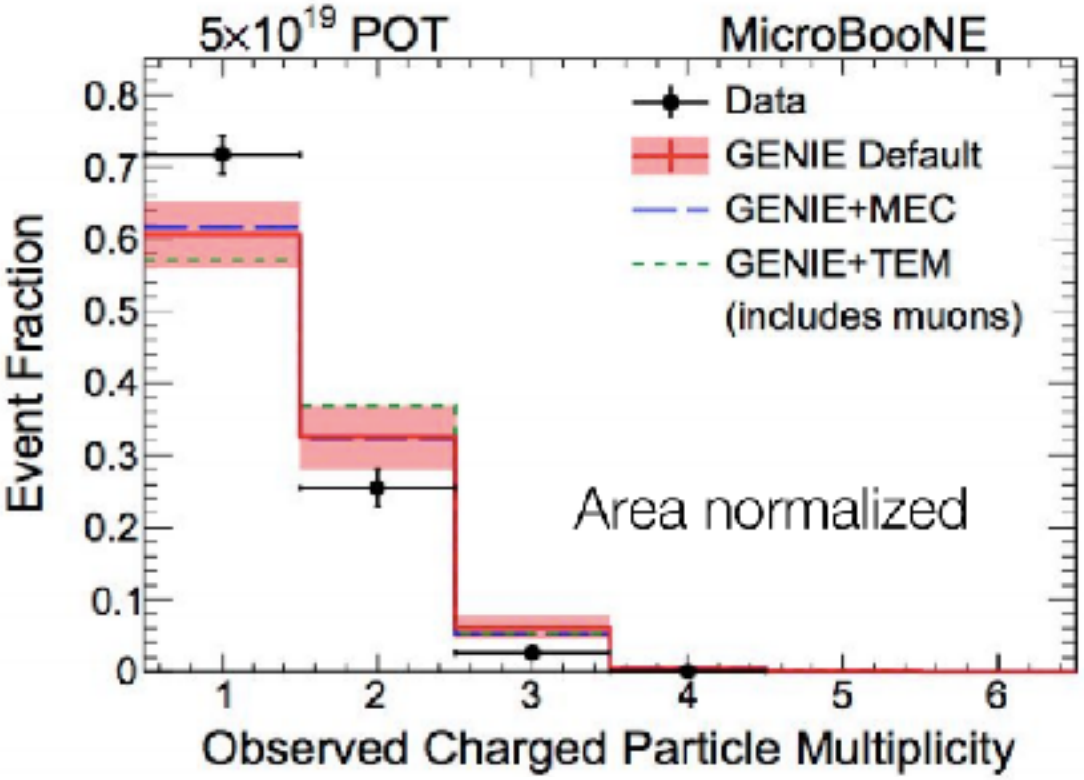


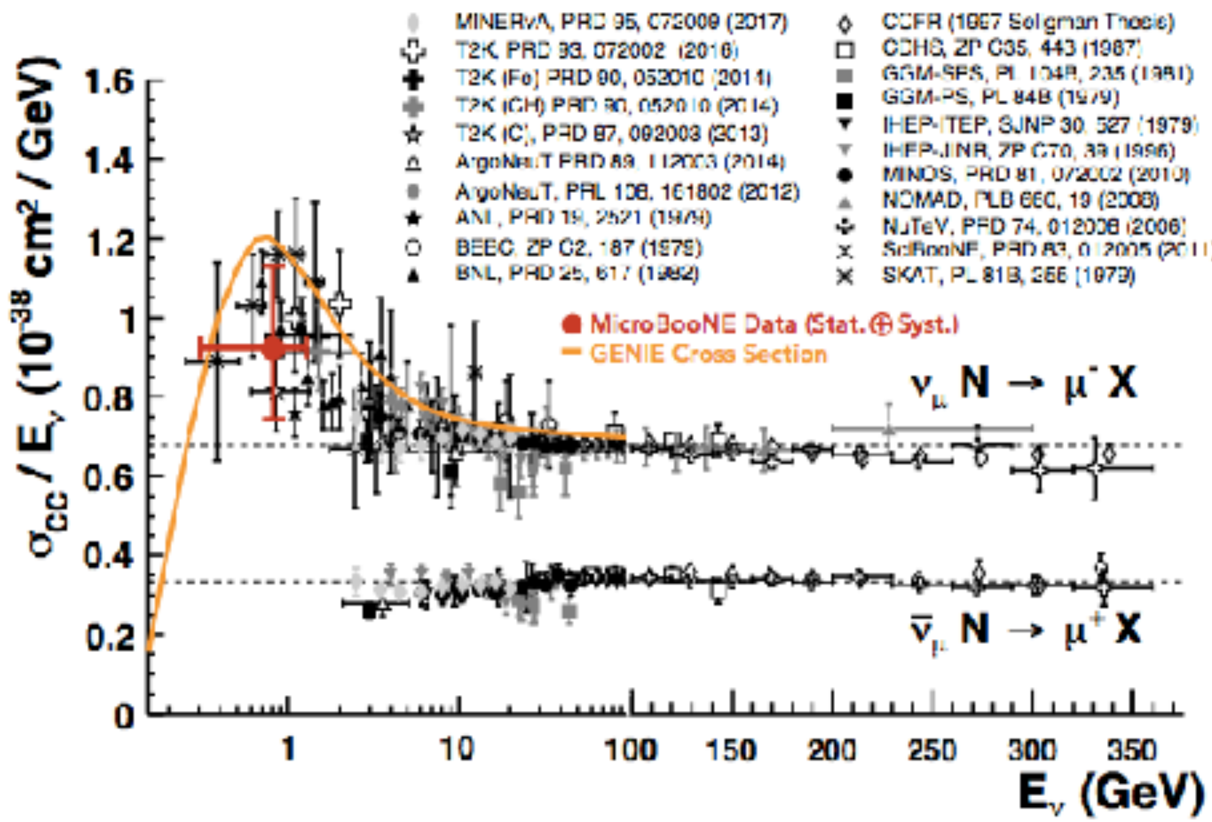
MicroBooNE Status

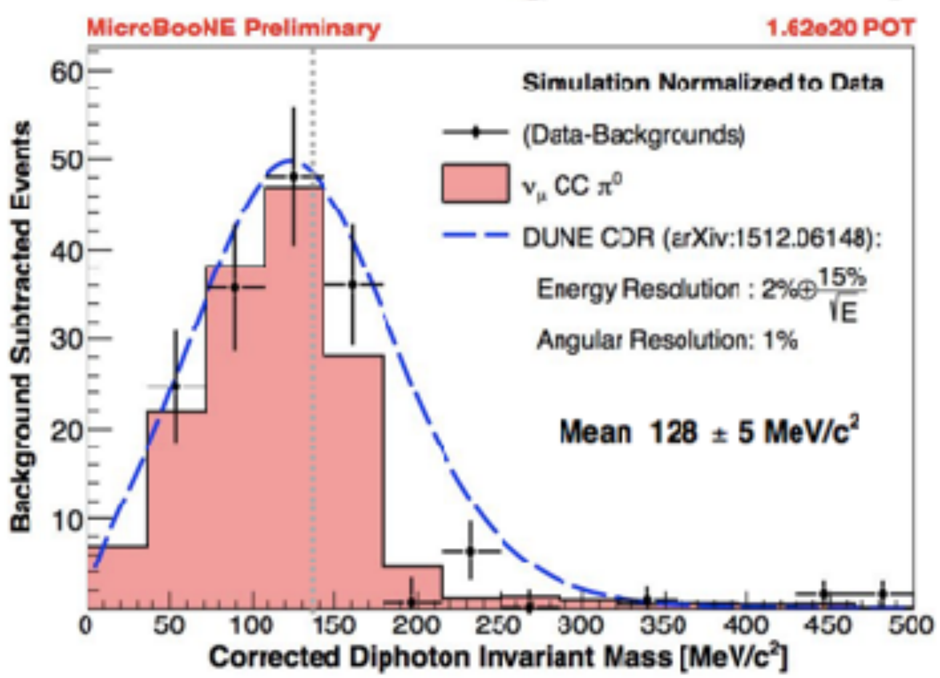
- LArTPCs are still a relatively new technology for neutrino physics
    - Building a robust foundation before releasing low energy excess results (see http://microboone.fnal.gov/documents-publications/)
- Understand our detector
- Understand neutrino interactions on argon
    - Identify neutrino vertices and study track multiplicities
    - Develop an inclusive ν_μ CC cross section measurement as a basis for further exclusive channel measurements
        - ν_μ CCπ^0
        - ν_μ CCπ^+
        - ν_μ CC + N protons
        - etc

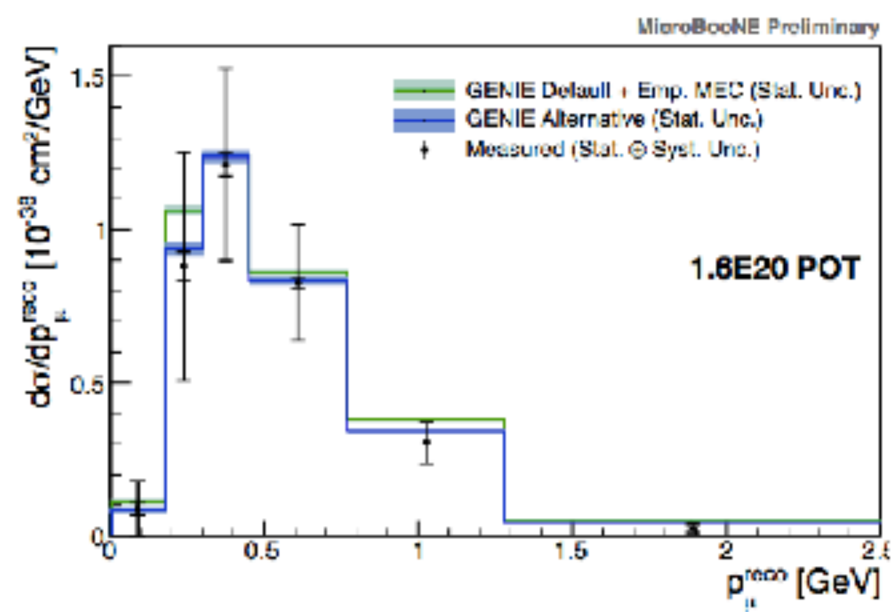


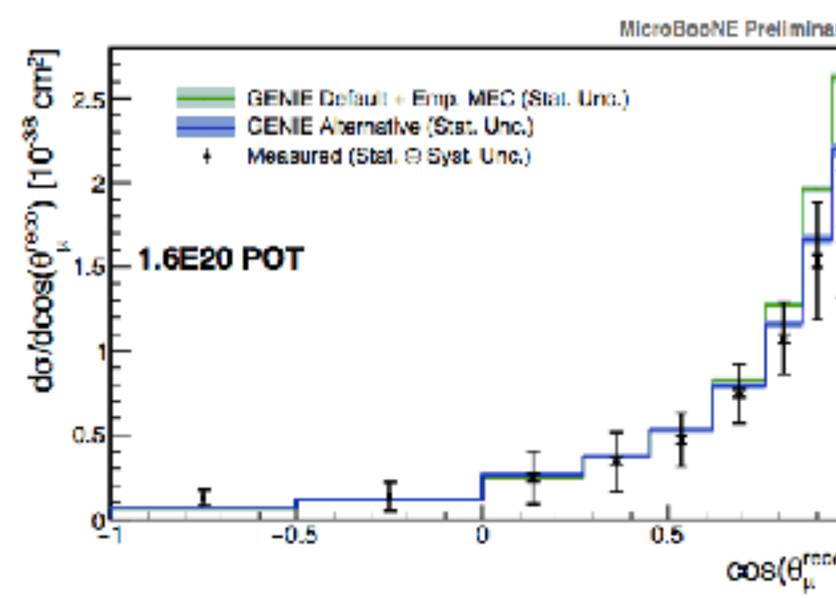
MicroBooNE: First Physics Results









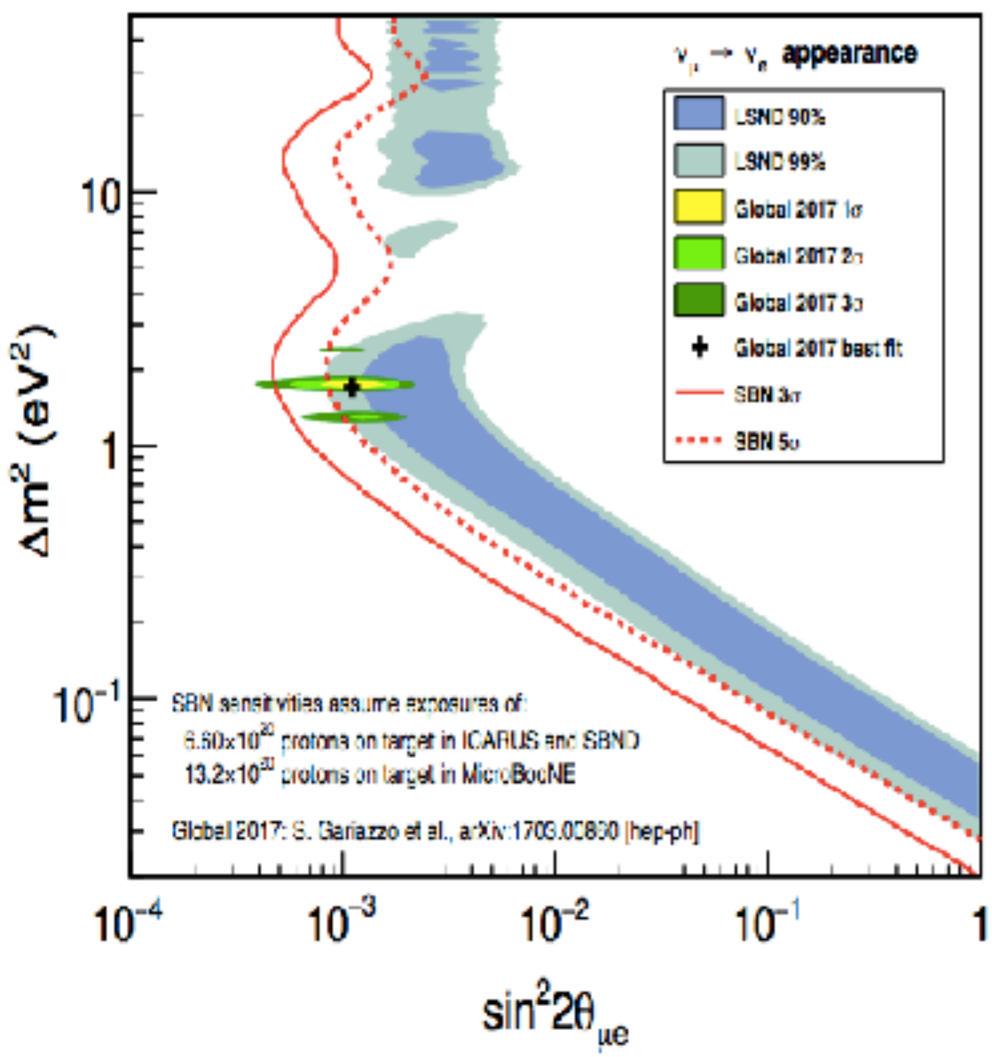


M. Toups LPC Physics Forum

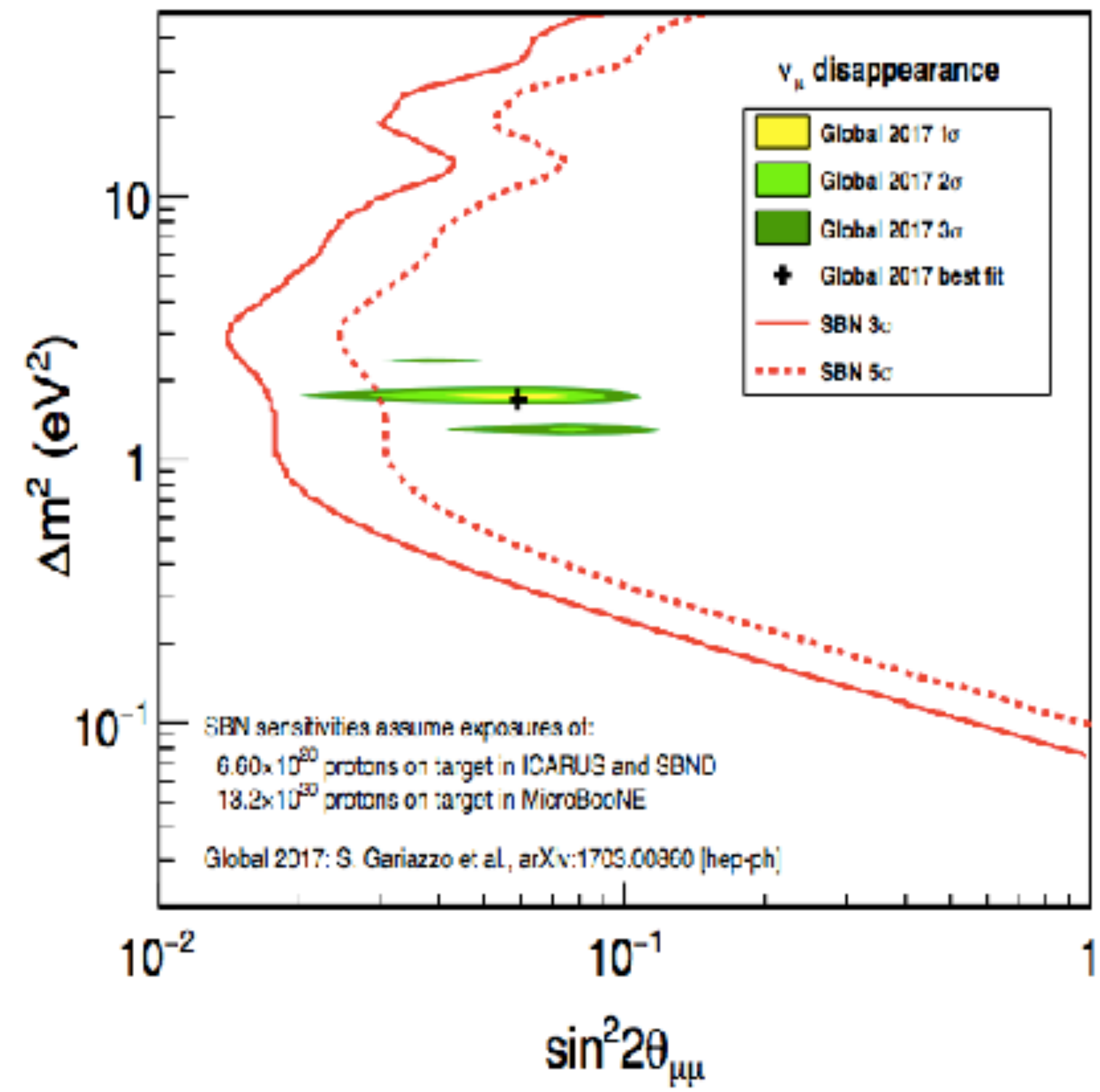
Conclusions

- The search for light sterile neutrinos in accelerator-based short baseline neutrino experiments are driven by experimental “anomalies”
- Fundamentally, these are an excess of candidate ν_e and $\bar{\nu}_e$ events seen in decay-at-rest and decay-in-flight neutrino beams over short baselines
    - ν_e appearance measurements are essential to understanding the nature of these excesses
- Searches for other oscillation modes play a key role in constraining sterile neutrino and other types of exotic models
- Ongoing and upcoming efforts such as the short baseline neutrino program at Fermilab will provide definitive statements on the existence of a light sterile neutrino in the coming years

End



$\nu_\mu \rightarrow \nu_e$ appearance
LSND 90%
LSND 99%
Global 2017 1σ
Global 2017 2σ
Global 2017 3σ
Global 2017 best fit
SBN 3σ
SBN 5σ
SBN sensitivities assume exposures of:
6.60×10^{20} protons on target in ICARUS and SBND
13.2×10^{20} protons on target in MicroBooNE
Global 2017: S. Gariazzo et al., arXiv:1703.00860 [hep-ph]
Δm^2 (eV^2)
$\sin^2 2\theta_{\mu e}$



ν_μ disappearance
Global 2017 1σ
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