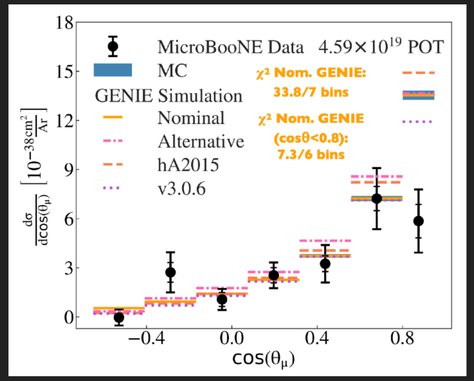
Neutrino Theory Post-Nu2020

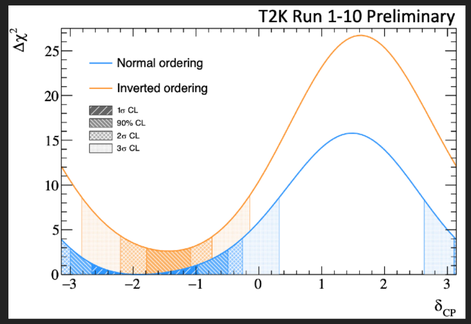
Kevin J. Kelly, Fermilab

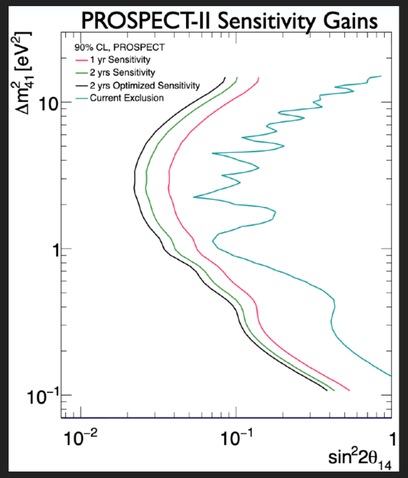
Users Meeting, 13 August 2020

Outline

- Neutrino Cross Sections
- Three-flavor Oscillations
- Sterile Neutrinos



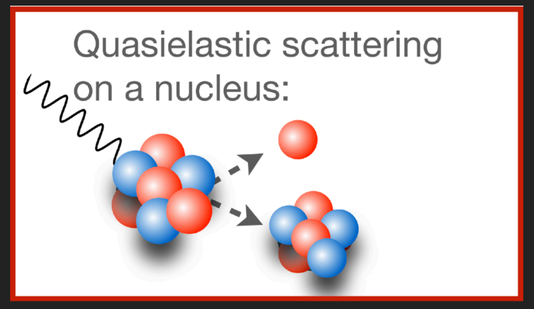


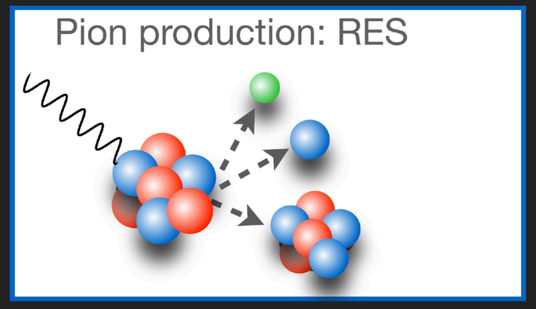


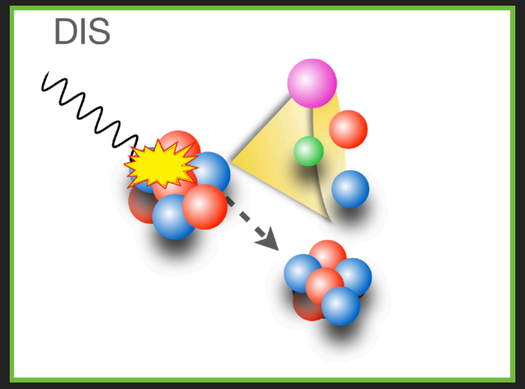
Neutrino Cross Sections

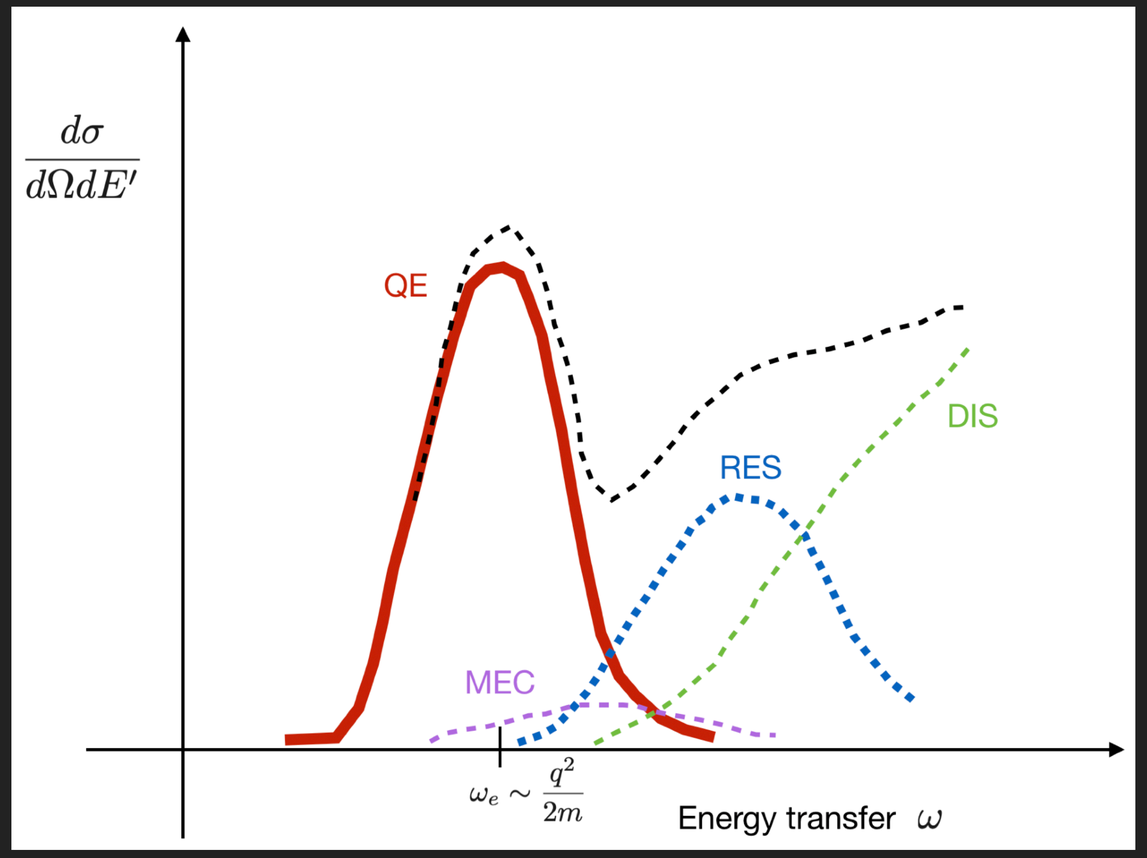
Neutrino Cross Section Difficulties

- When leptons (neutrinos *or* electrons) scatter off nuclei, several processes contribute





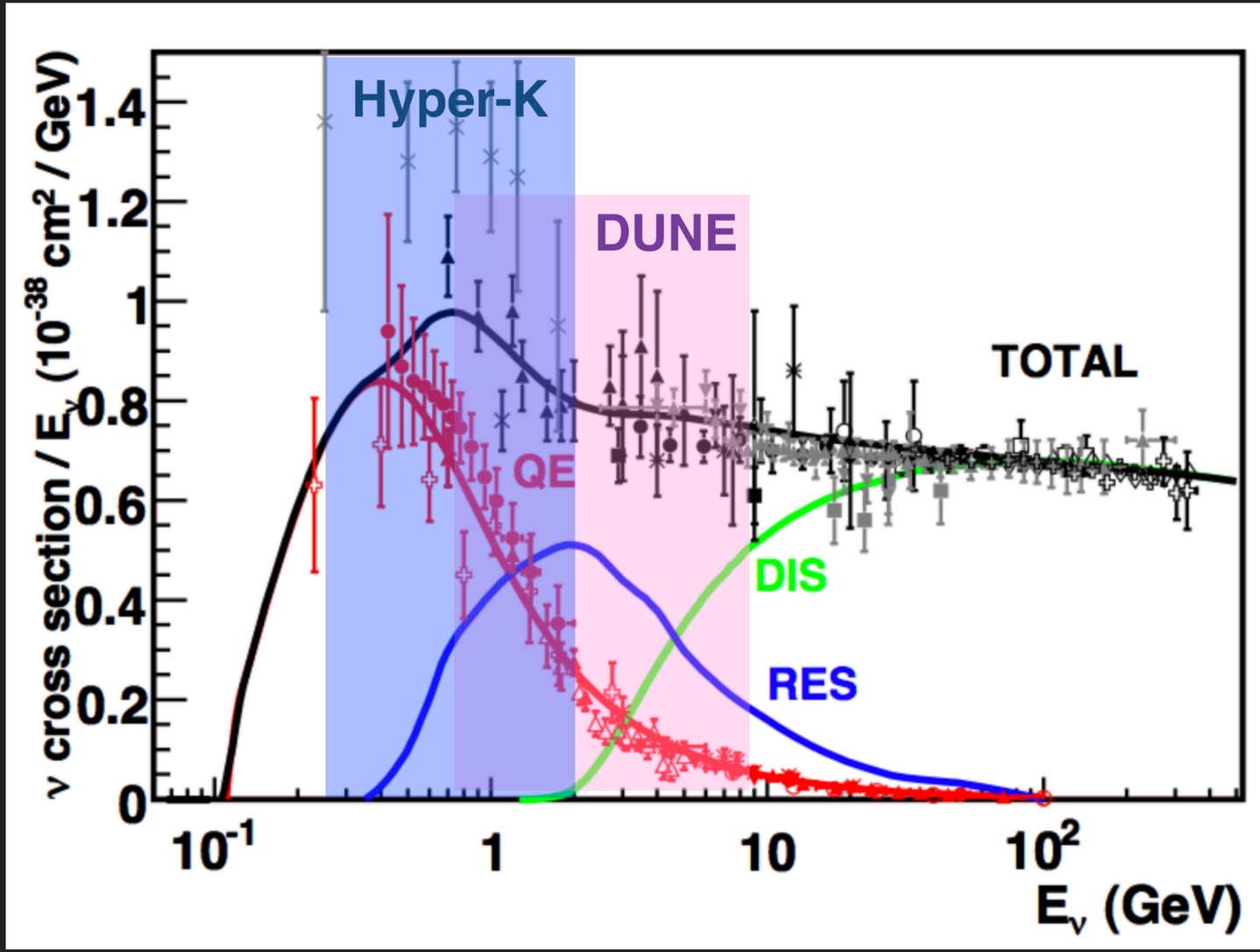




- A better understanding of all of these processes (and where they overlap) is crucial for current and future neutrino experiments.

Noemi Rocco @ Neutrino2020
https://zenodo.org/record/3959664

Cross Sections across different Energies



- Current and future experiments (DUNE & Hyper-Kamiokande) will operate in regions of overlap between different processes.

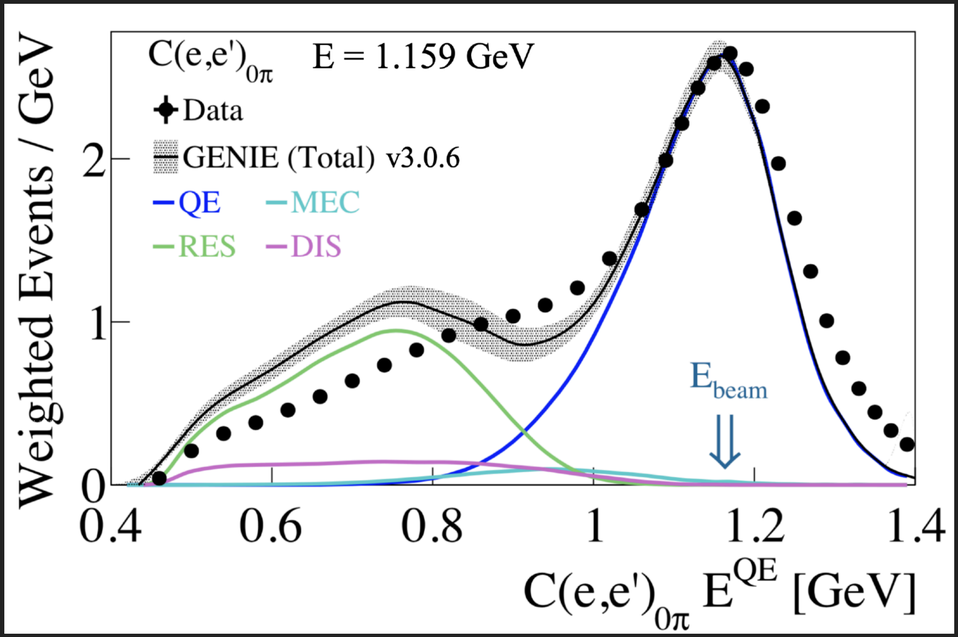
Noemi Rocco @ Neutrino2020
https://zenodo.org/record/3959664

and

Formaggio and Zeller, [1305.7513]

Using Electrons to Learn about Neutrino Scattering

- Even though they interact electromagnetically (unlike neutrinos), electron/nuclei interactions can inform us about these scattering processes.
- The “Electrons for Neutrinos” collaboration aims to use existing (or proposed) electron scattering data to reduce uncertainties for neutrino scattering.

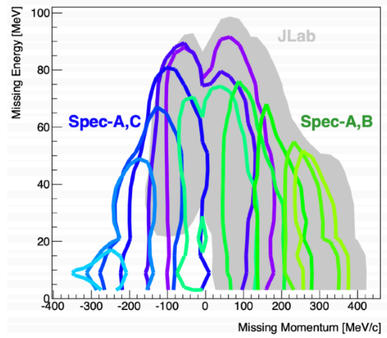


Possible electron facilities

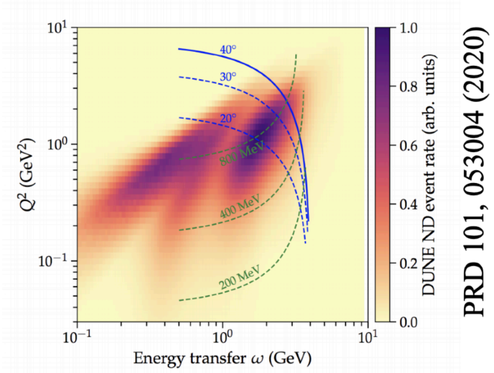
CEBAF Large Acceptance Spectrometer

Jefferson Lab

Mainz MAMI accelerator testing their sensitivity



Lepton-Nucleus σ Measurements with LDMX



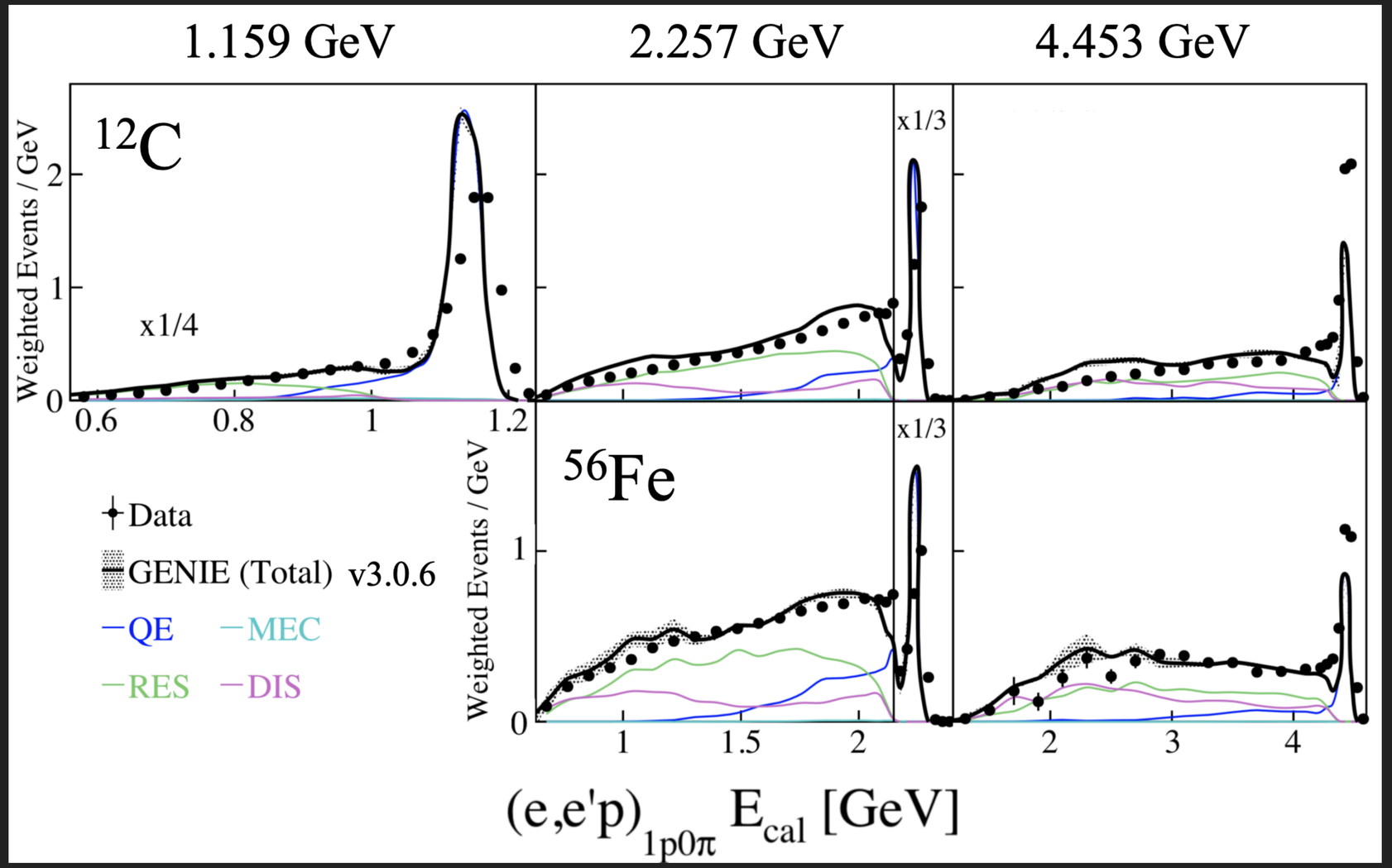
PRD 101, 053004 (2020)

SLAC

Adi Ashkenazi @ Neutrino2020

https://zenodo.org/record/3959538

Electrons for Neutrinos — Progressing to Heavier Nuclei

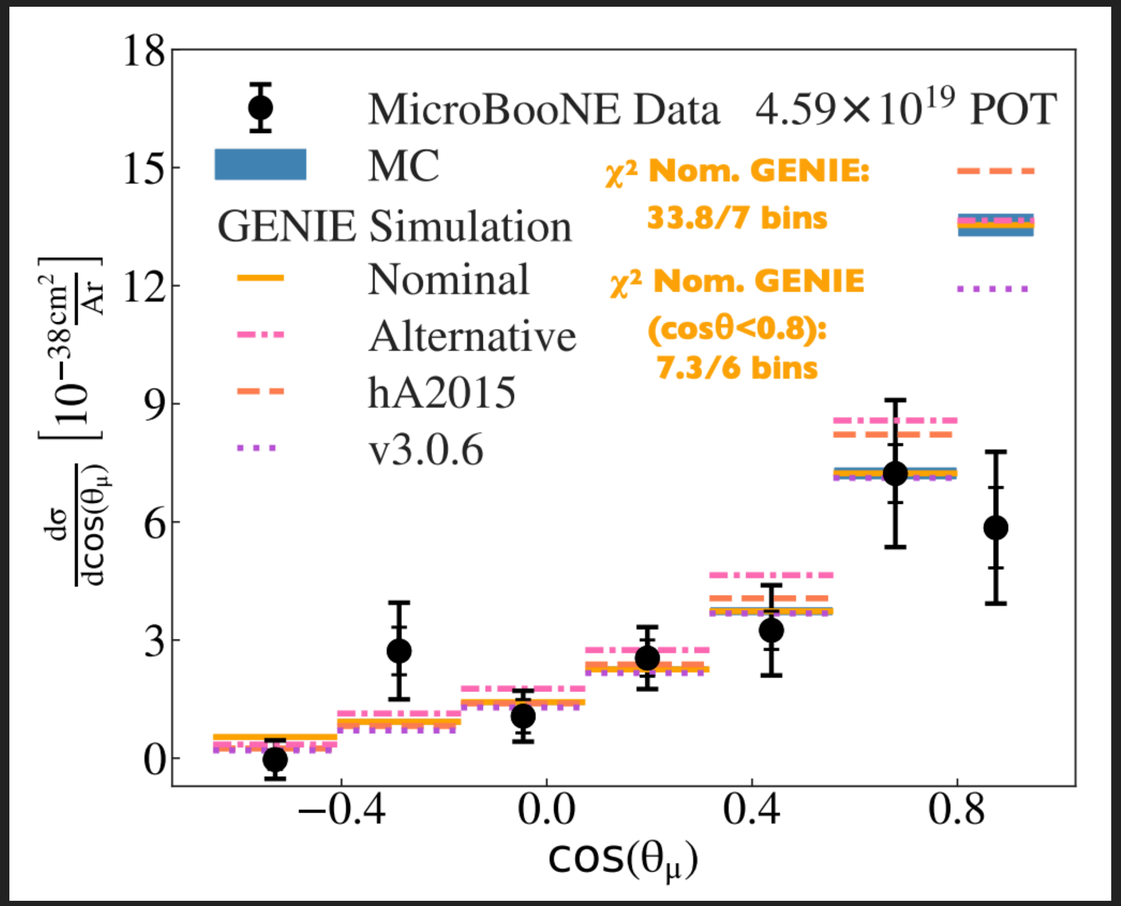


Adi Ashkenazi @ Neutrino2020

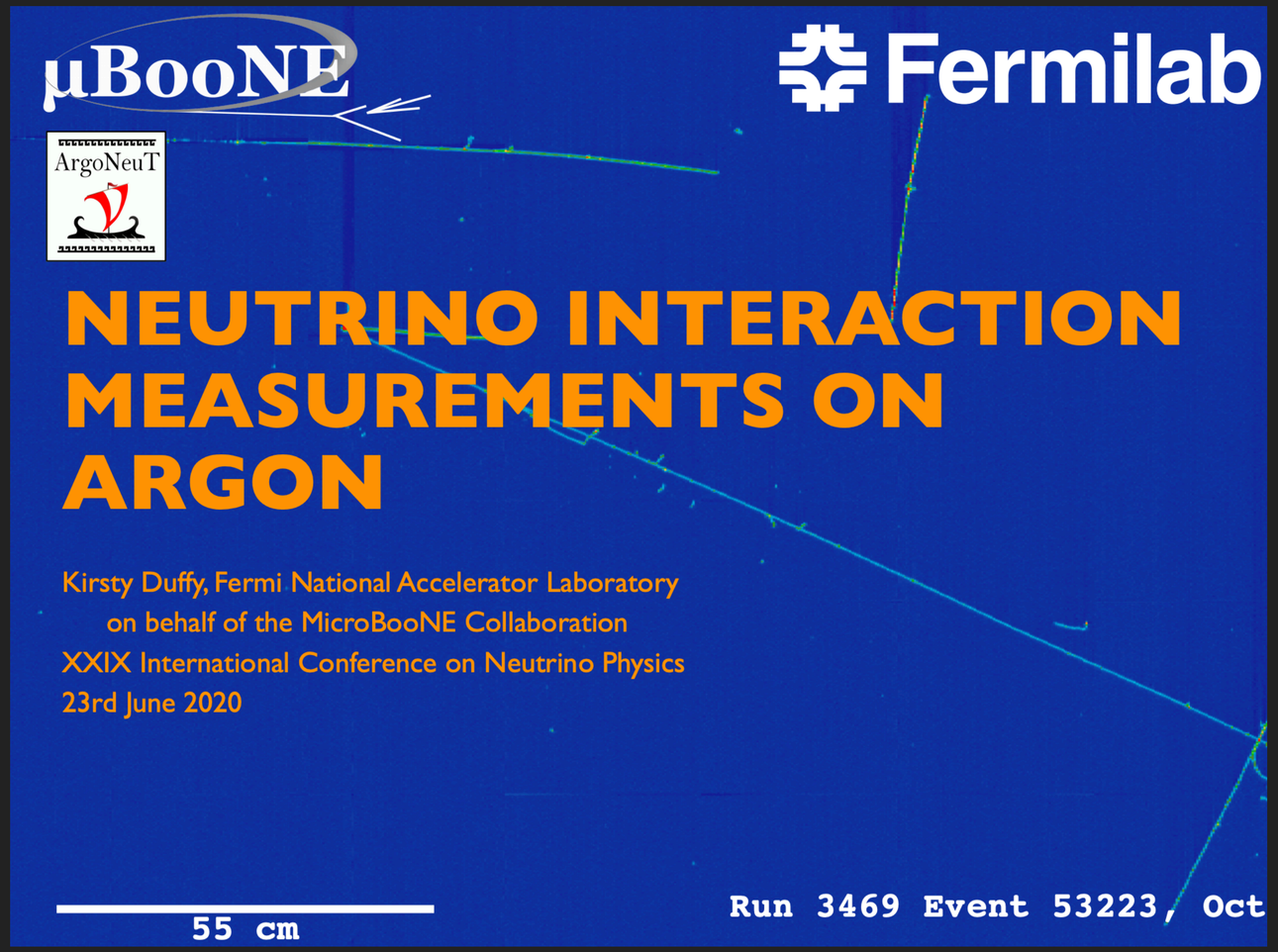
https://zenodo.org/record/3959538

Precision Measurements of Neutrino/Argon Scattering

- Liquid Argon Time-Projection Chambers (MicroBooNE, ArgoNeuT, etc.) are allowing for precision measurements today that will feed forward to the future neutrino program.



MicroBooNE Collaboration, [2006.00108]

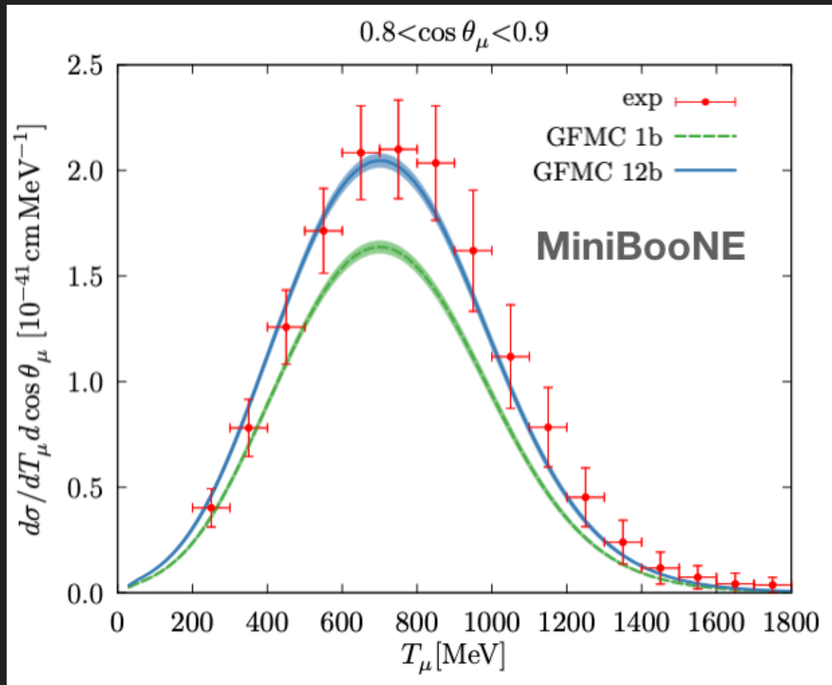


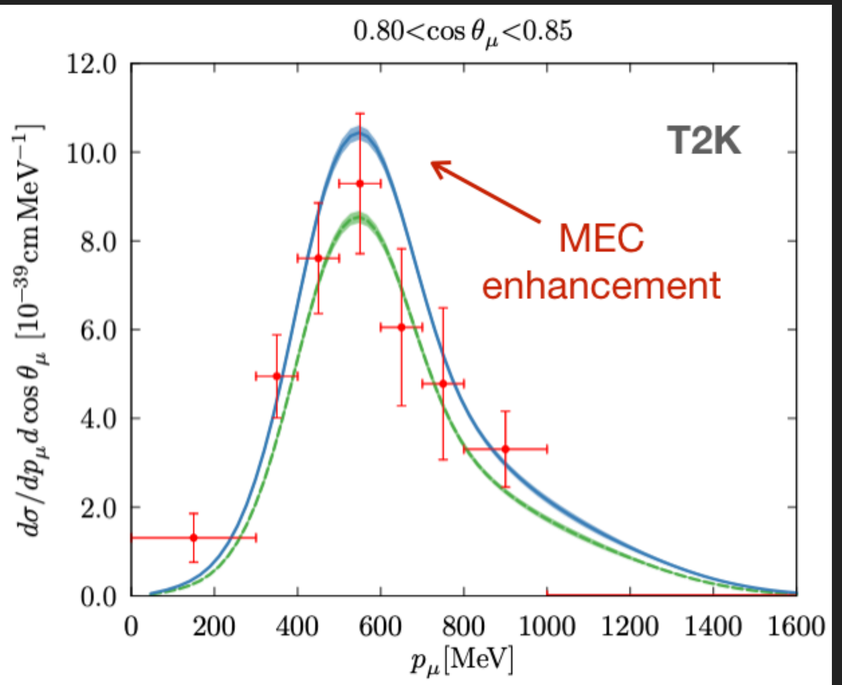
Many more results – Kirsty Duffy's talk @ Neutrino2020
https://zenodo.org/record/3959556

How these measurements inform Theoretical Work

- New techniques under exploration/development now to address cross sections across different energy scales and for neutrino scattering on heavier nuclei.
- Quantum Monte Carlo, which determines the nuclear states for neutrino scattering, is quickly expanding over recent years.
  - Example: using these techniques to estimate neutrino scattering off Carbon in the MiniBooNE/T2K experiments:

Lovato et. al., [2003.07710]





For much more perspective on theoretical developments/future projections,

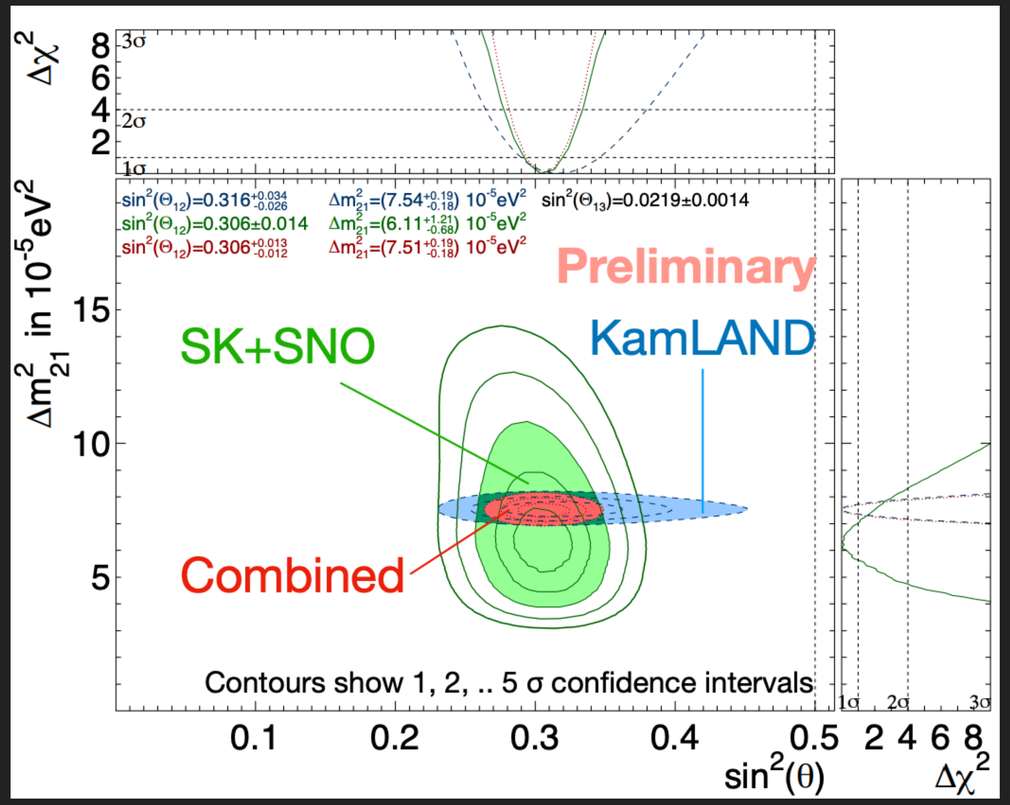
Noemi Rocco @ Neutrino2020
https://zenodo.org/record/3959664

Three-Flavor Oscillations*

*Emphasis on new results reported at Neutrino2020
Won't have time to discuss everything, see links for more details

New Solar Neutrino Results

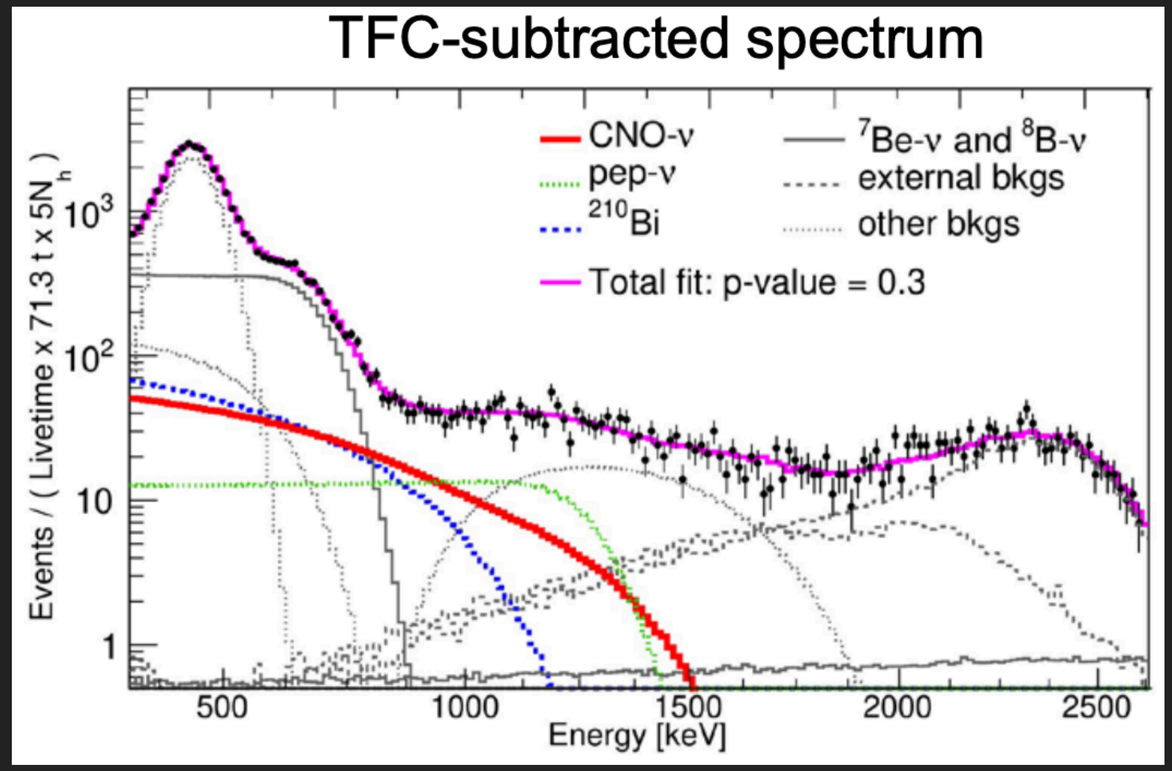
Super-Kamiokande Collaboration: New combination with SNO



Yasuhiro Nakajima @ Neutrino2020,
https://zenodo.org/record/3959640

Updated results point towards consistency between Solar Neutrino and Reactor Antineutrino measurements of the “solar” mass-squared splitting, resolving a long-standing tension.

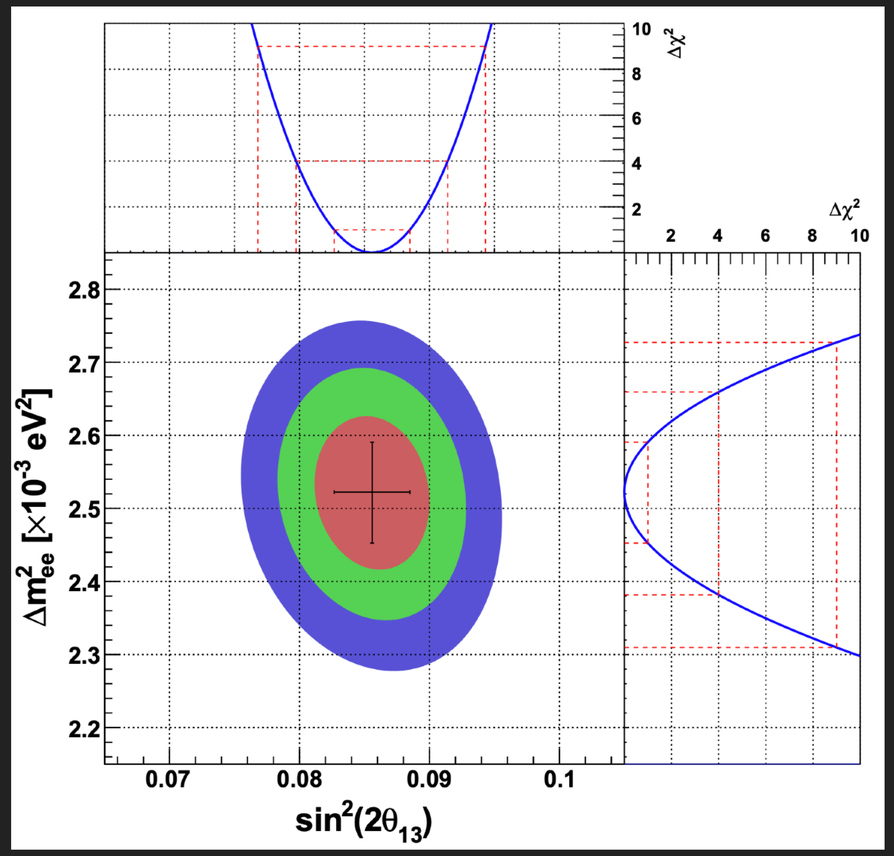
Borexino Experiment: First-ever detection of neutrinos from CNO cycle



Gioacchino Ranucci @ Neutrino2020,
https://zenodo.org/record/3959662

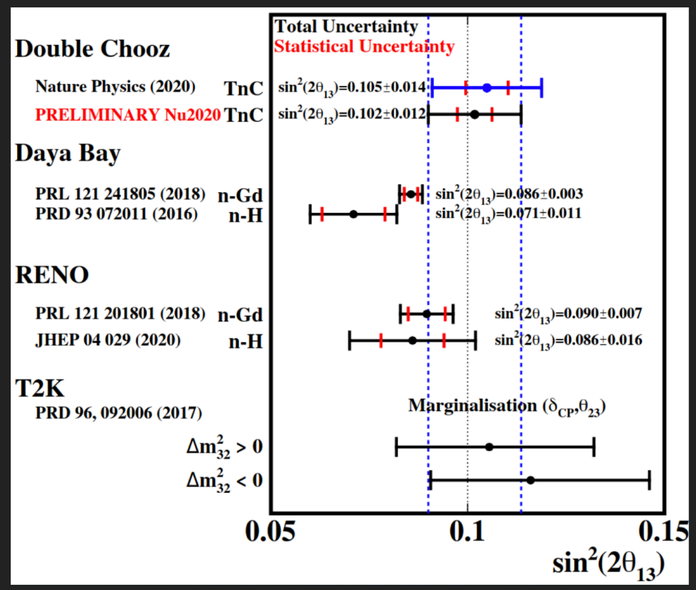
First detection of a new production mechanism of solar neutrinos. Precision measurement of CNO neutrinos can allow us to understand the Sun’s metallicity.

Reactor Antineutrino Updates (three-flavor)

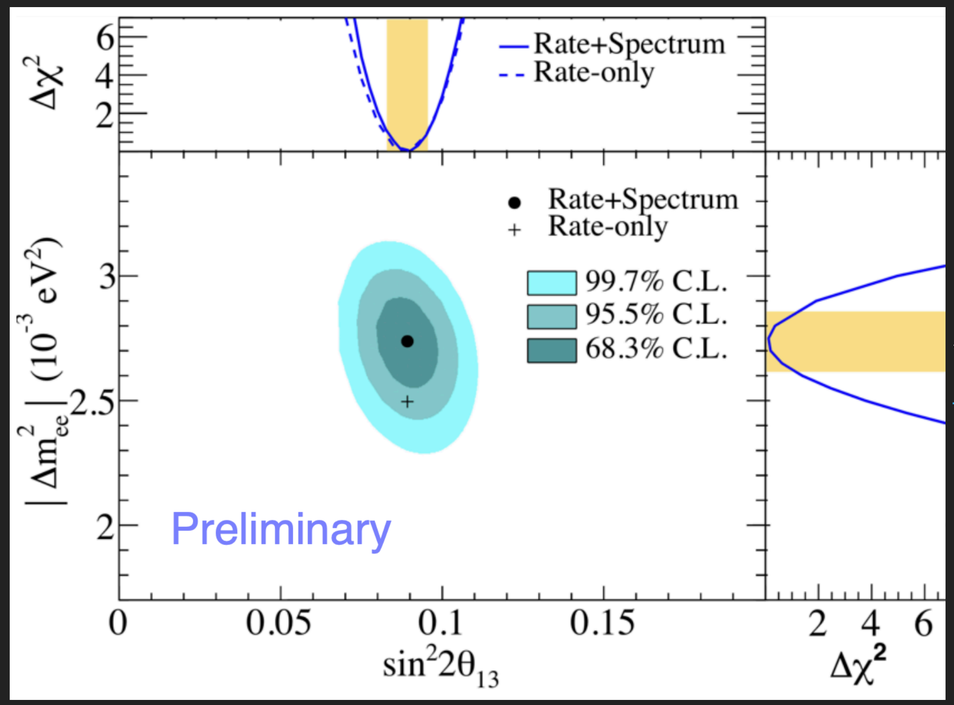


Daya Bay Collaboration, [1809.02261]
Jiajie Ling @ Neutrino2020,
https://zenodo.org/record/3959601

General consensus regarding the reactor mixing angle and the mass-squared splitting (combination) that these experiments measure.

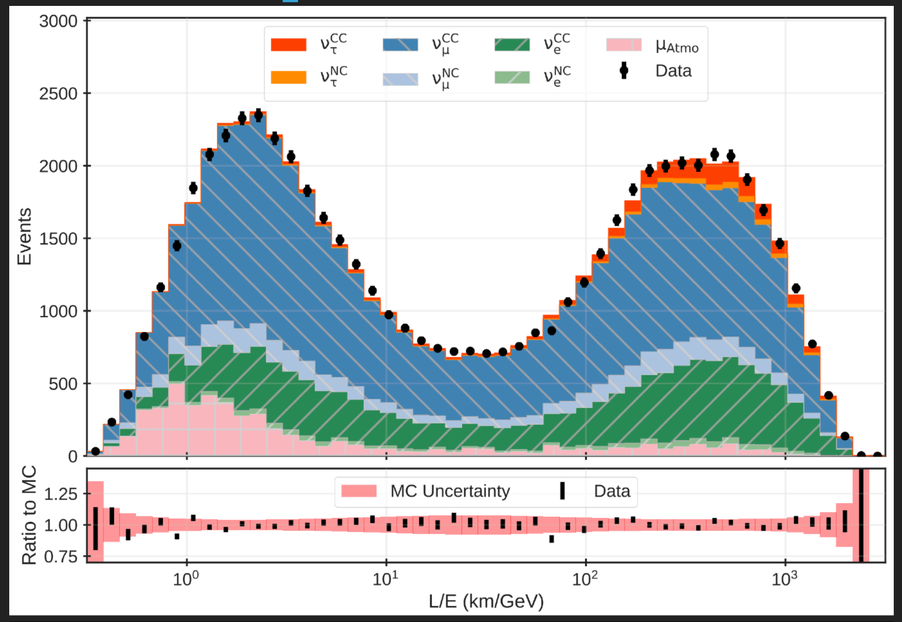


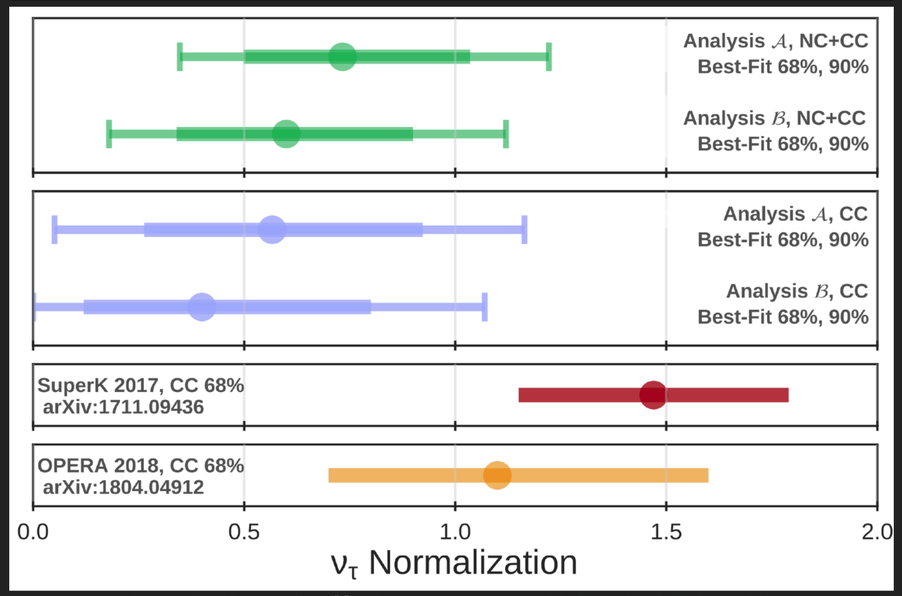
Double Chooz Collaboration,
Thiago Bezerra @ Neutrino2020
https://zenodo.org/record/3959542



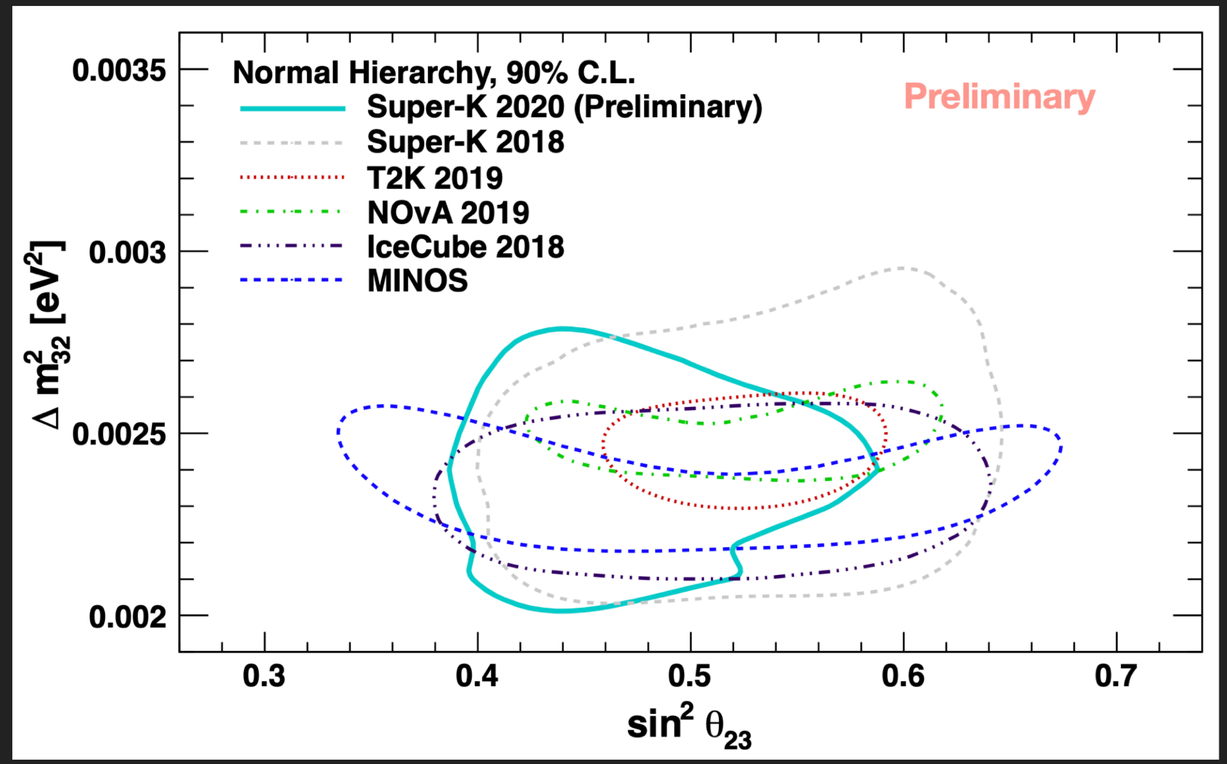
RENO Collaboration,
Jonghee Yoo @ Neutrino2020,
https://zenodo.org/record/3959698

Atmospheric Neutrinos





IceCube Collaboration, [1901.05366]
Summer Blot @ Neutrino2020, https://zenodo.org/record/3959546

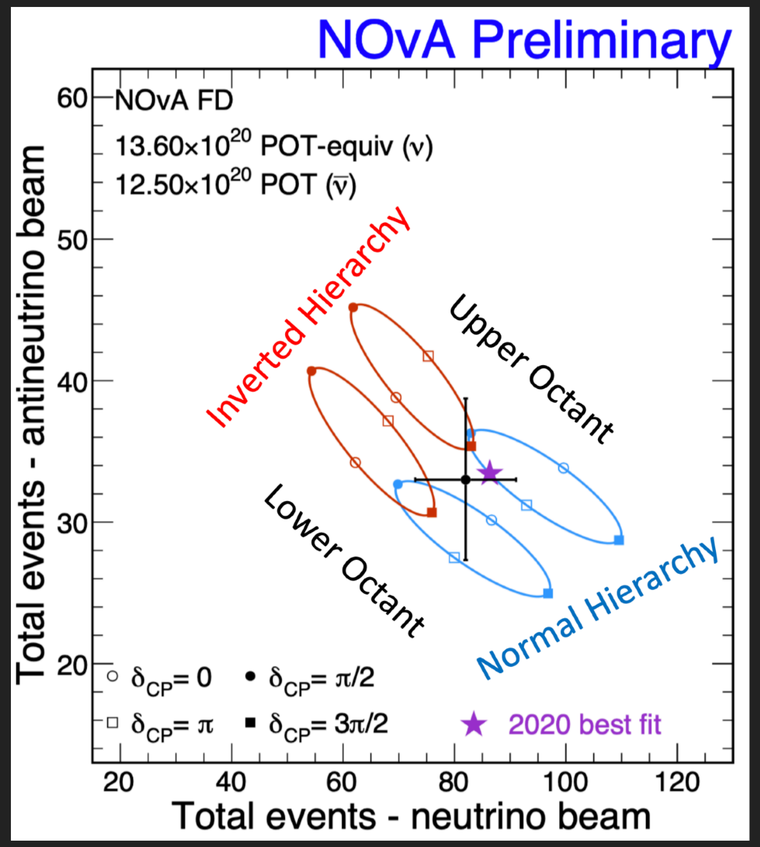


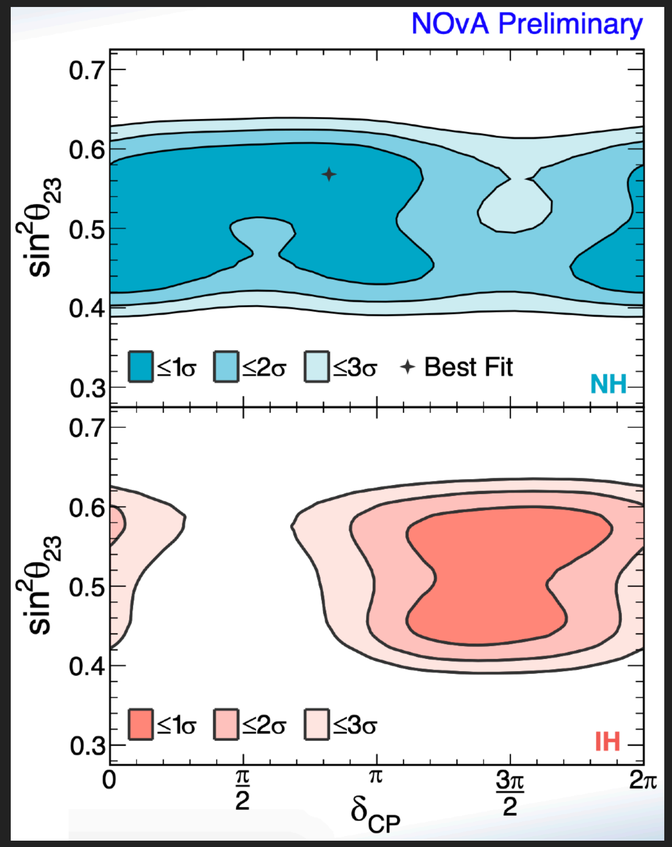
Super-Kamiokande Collaboration
Yasuhiro Nakajima @ Neutrino2020, https://zenodo.org/record/3959640

Very different experiments converging on agreement in terms of the atmospheric mixing angle and mass-squared splitting.

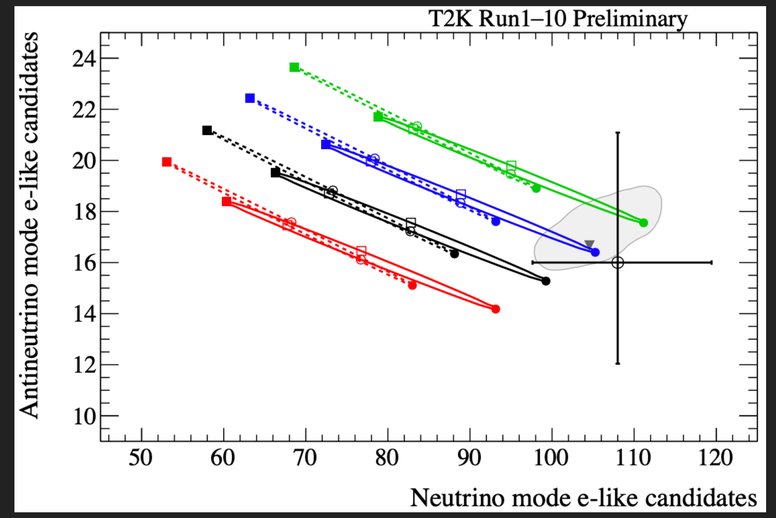
IceCube's ability to identify tau neutrinos is competitive with existing beam-based measurements and will only improve with time – 10% measurement with data currently collected.

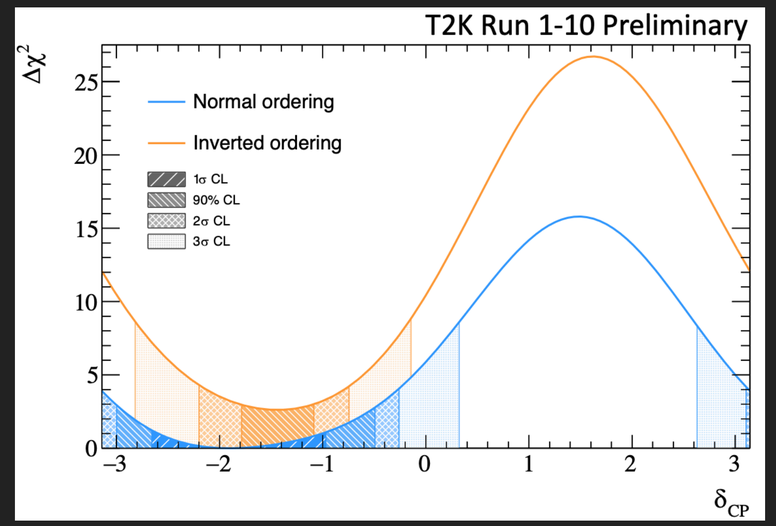
Long-Baseline Accelerator Neutrinos





NOvA Collaboration,
Alex Himmel @ Neutrino2020, https://zenodo.org/record/3959581



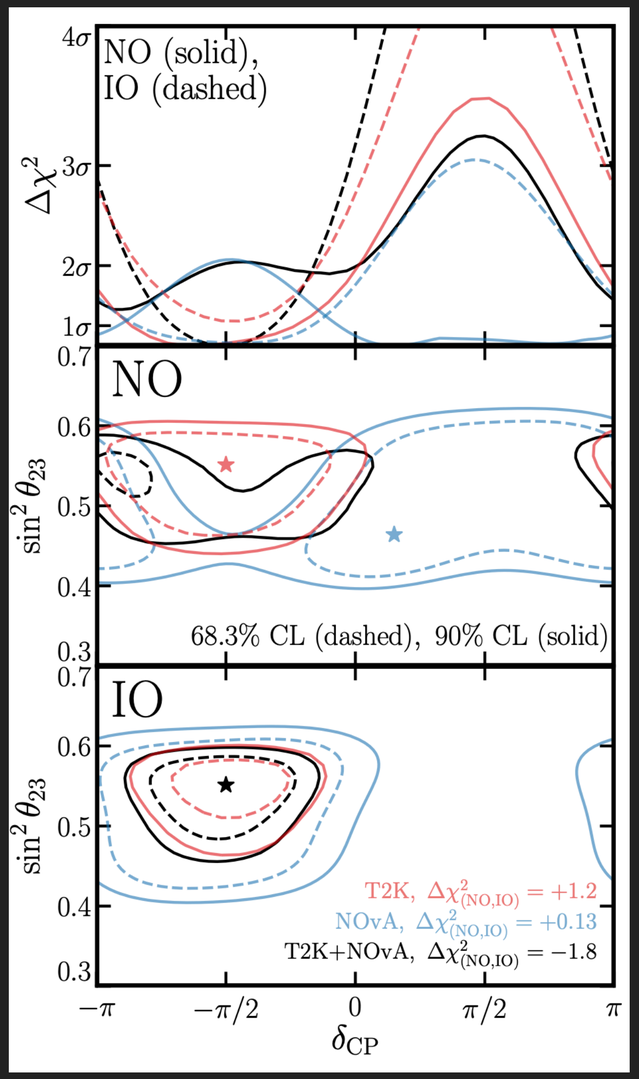


T2K Collaboration,
Patrick Dunne @ Neutrino2020,
https://zenodo.org/record/3959558

Still no consensus from T2K and NOvA regarding the neutrino mass ordering, CP violation, or the atmospheric mixing angle octant. More data/new experiments are needed!

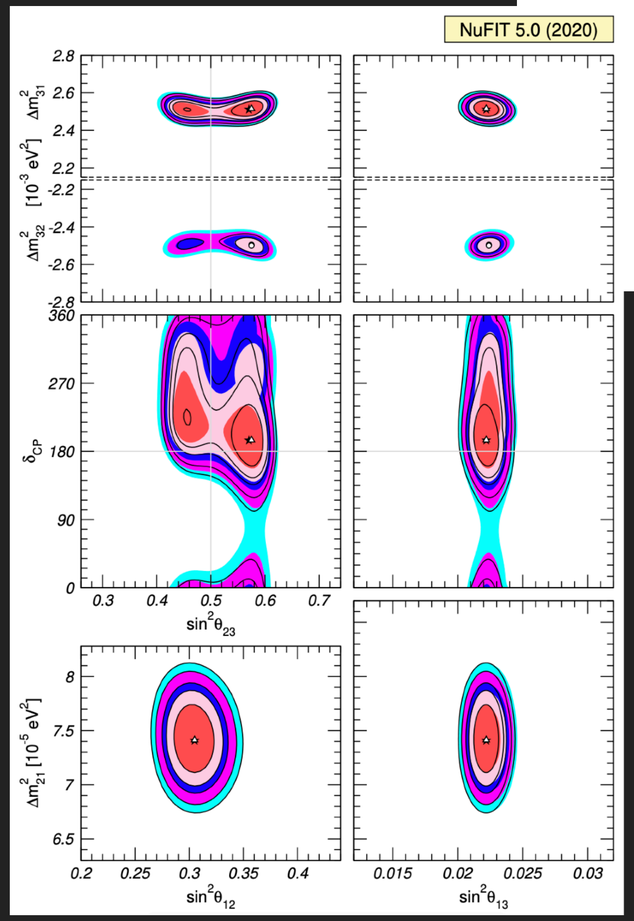
Three-neutrino Takeaways

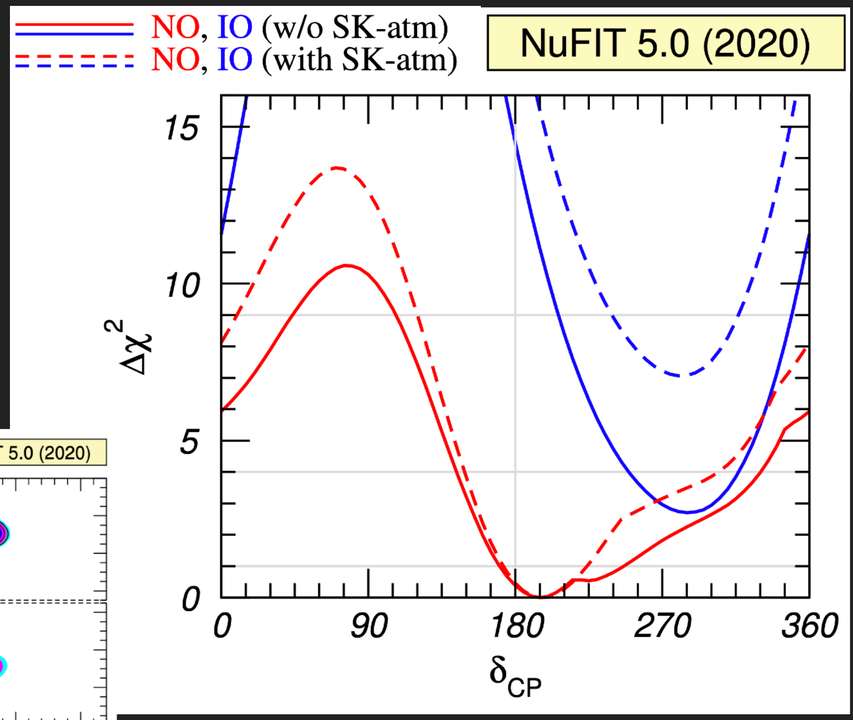
"New" Knowledge Post Nu2020



- T2K and NOvA each prefer the normal mass ordering, but their combination prefers the inverted ordering…

  Kelly et. al., [2007.08526]



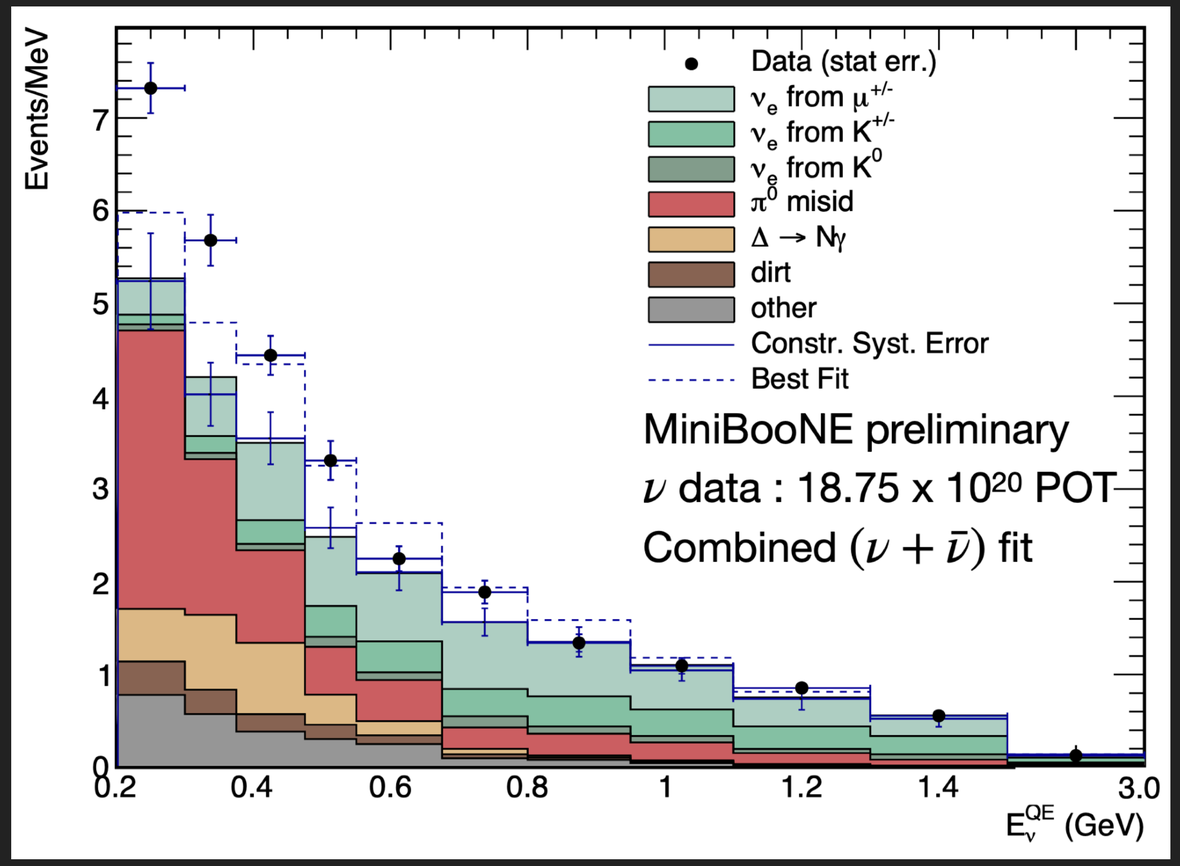


- Nu-Fit Updates, Esteban et. al., [2007.14792]
- Prior preference for CP violation (mostly from T2K) vanished.
- Could beyond-the-Standard-Model physics be responsible for T2K/NOvA discrepancies? See [2008.01110] and [2008.04161]

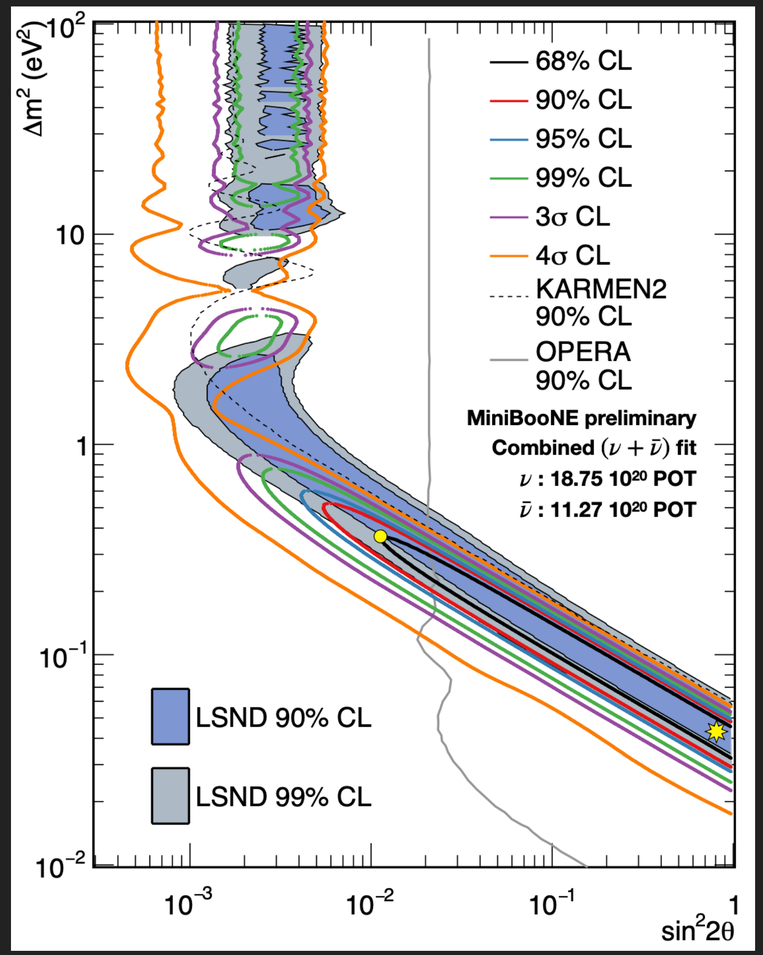
Sterile Neutrinos

Long-standing hints from LSND & MiniBooNE

- Simplest explanation: fourth, "sterile" neutrino that mixes with the other three



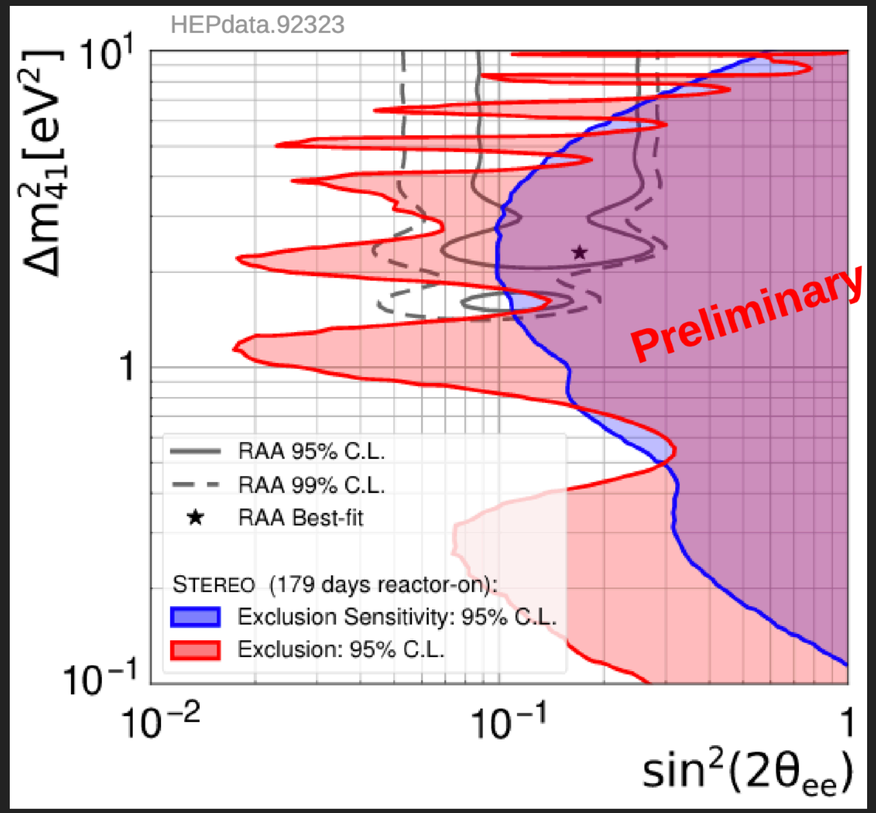
MiniBooNE Collaboration
Adrien Hourlier @ Neutrino2020, https://zenodo.org/record/3959583



- Probing this? The Fermilab SBN Program. See Georgia Karagiorgi's Neutrino2020 Talk (https://zenodo.org/record/3959589) or Gianluca Petrillo @ Users Meeting (later today)

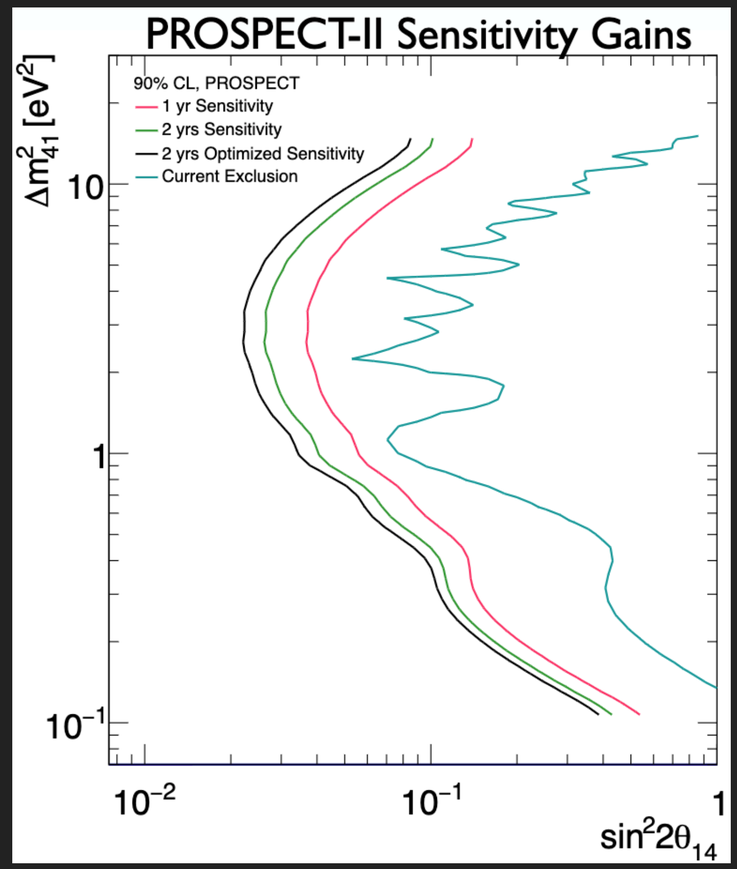
Anomalous Appearance requires Anomalous Disappearance…

- If sterile neutrino(s) are responsible for the MiniBooNE/LSND excesses, then there must be similar disappearance of electron- and muon-neutrinos at short baselines.
- Reactor antineutrinos ($\bar{\nu}_e$) are well-suited to search for this.



STEREO Collaboration

Stefan Schoppmann @ Neutrino2020, https://zenodo.org/record/3959676



PROSPECT Collaboration

Bryce Littlejohn @ Neutrino2020, https://zenodo.org/record/3959603

Theory Takeaways Regarding Sterile Neutrinos

- Simple, "3+N" sterile neutrino solutions to LSND/MiniBooNE are incompatible with observations searching for electron- and muon-neutrino disappearance.

- Nevertheless, existing anomalous results are exciting and worthy of testing. Could point towards more complicated new "fundamental" physics or interesting neutrino/ nuclear physics properties we didn't expect.

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

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

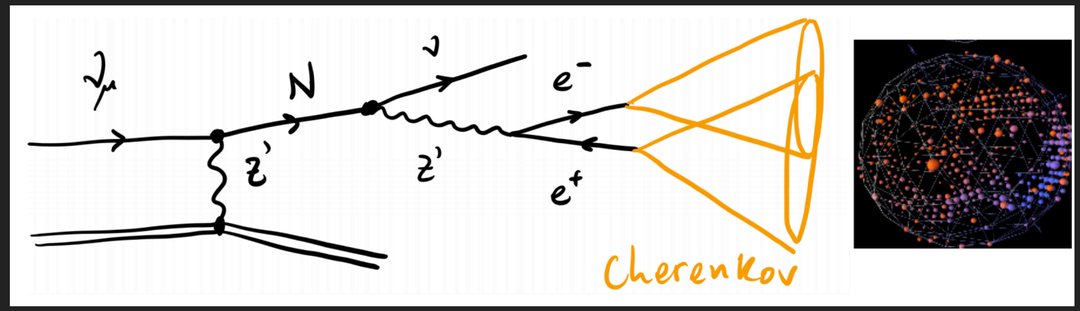
Oscillations+:
Asaadi et al 1712.08019
Resonant matter effect UV challenge

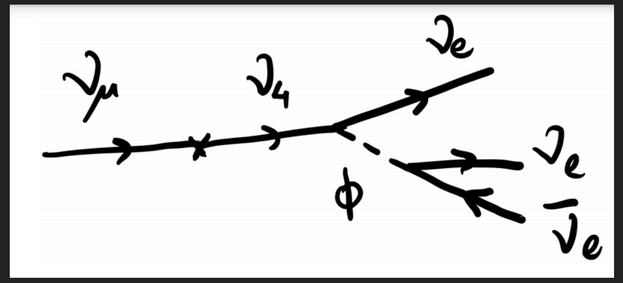
Doring et al 1808.07460, Barenboim et al 1911.02329
eV steriles and extra dimensional shortcuts not clear

Liao et al 1810.01000
Steriles + NCNSI + CCNSI Baroque

Decay:
Bai et al 1512.05357, Dentler et al 1911.01427, de Gouvêa et al 1911.01447
Heavy sterile O(keV-MeV) decay to ν_e May work

Pedro Machado @ Neutrino2020
https://zenodo.org/record/3959609





Summary

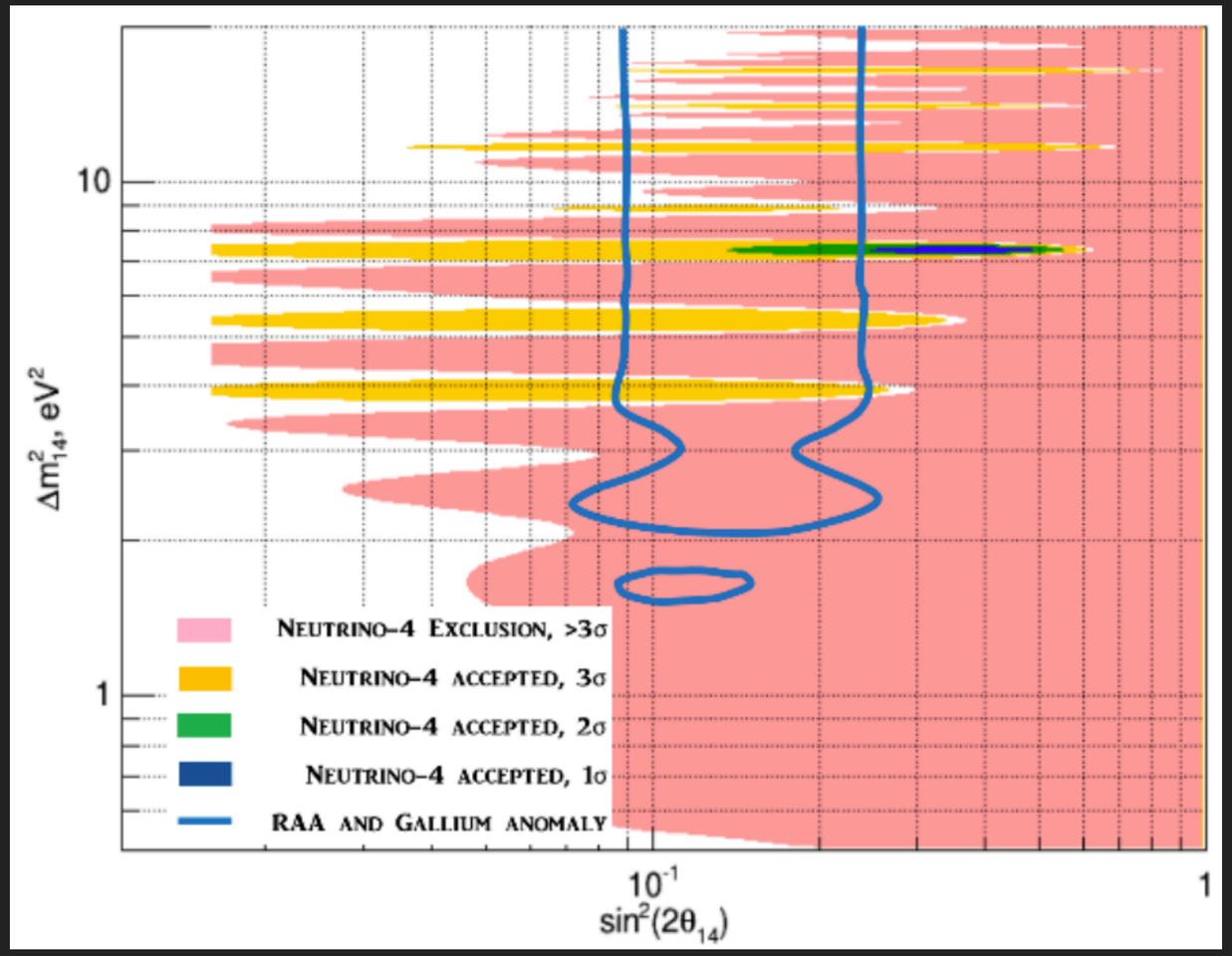
- The future is bright, both for neutrino experiments and the theoretical work that is intertwined with them.
- Exciting challenges are ahead in the form of understanding neutrino cross sections from a theoretical perspective and applying that knowledge to future experiments.
- Many unknowns abound currently in neutrino physics – both in the “three-neutrino-mixing” picture and in beyond-the-Standard Model contexts. Upcoming and future experiments will probe these questions precisely!

Thank you!

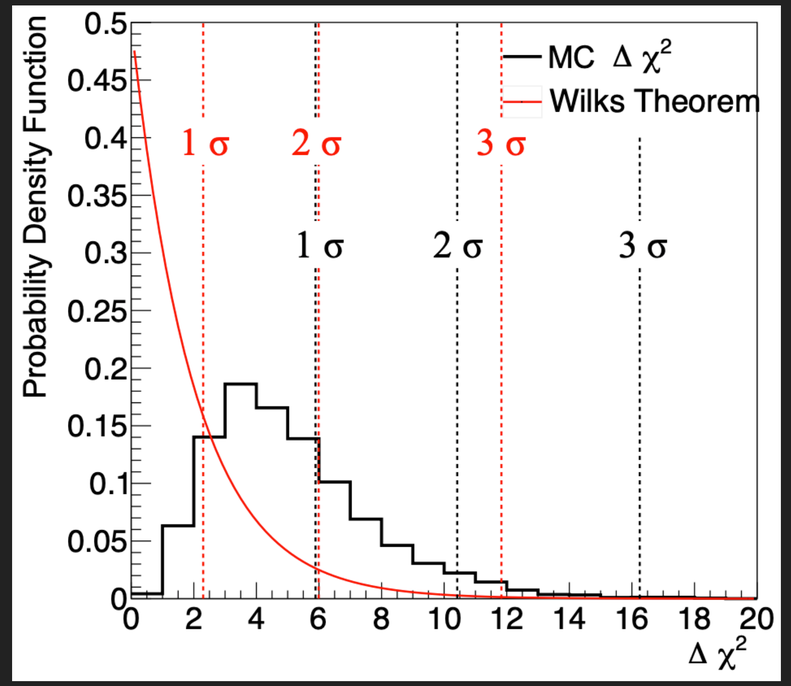
Backup

Reactor Antineutrinos: Neutrino-4

- Neutrino-4, a reactor antineutrino experiment (similar in spirit to STEREO and PROSPECT) reports a detection of a sterile neutrino at high significance.



Neutrino-4 Collaboration, [2005.05301]
https://zenodo.org/record/3959680



- However, statistics must be taken into consideration carefully – when MC distributions don't follow the "standard" chi-squared distribution, confidence levels must be adjusted. Neutrino-4 has *not* done this.
- Recent back-and-forth between PROSPECT/STEREO and Neutrino-4:
  - PROSPECT/STEREO: [2006.13147]
  - Neutrino-4 response: [2006.13639]