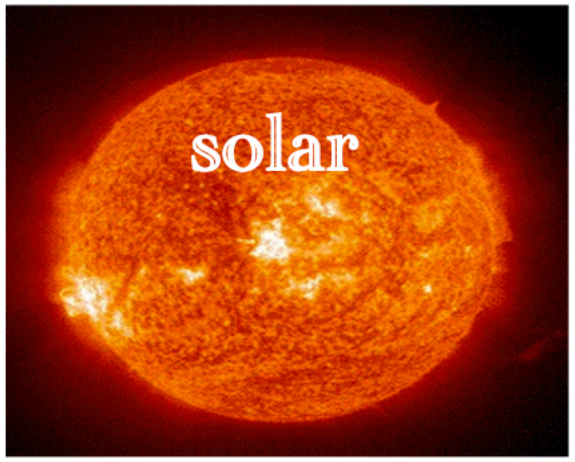
Overview of the sterile neutrino searches and status of SBN/ICARUS experiment

Animesh Chatterjee, CERN/PRL, for the ICARUS Collaboration

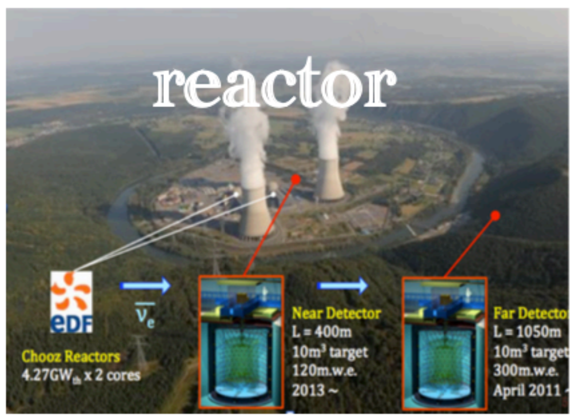
43rd International Symposium on Physics in Collision PIC2024

22-25 October, 2024, Athens, Greece

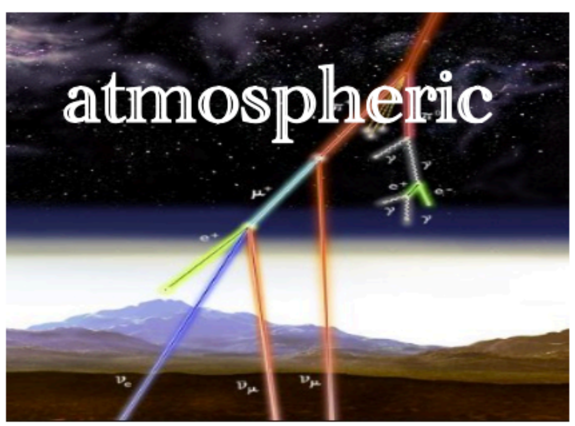
Status of Neutrino Physics



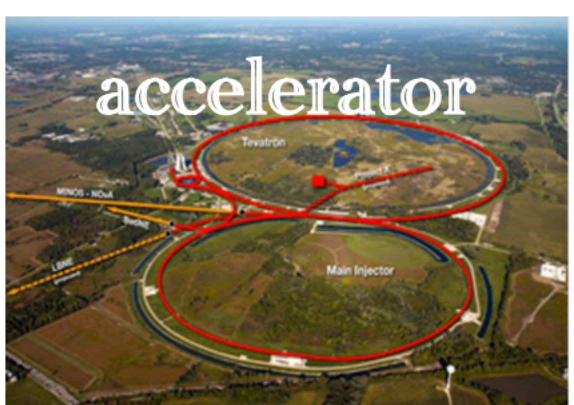
Super-Kamiokande, Borexino, SNO



MBL: Daya Bay, RENO, Double Chooz
LBL: KamLAND



IceCube, Super-Kamiokande



T2K, MINOS, NOvA

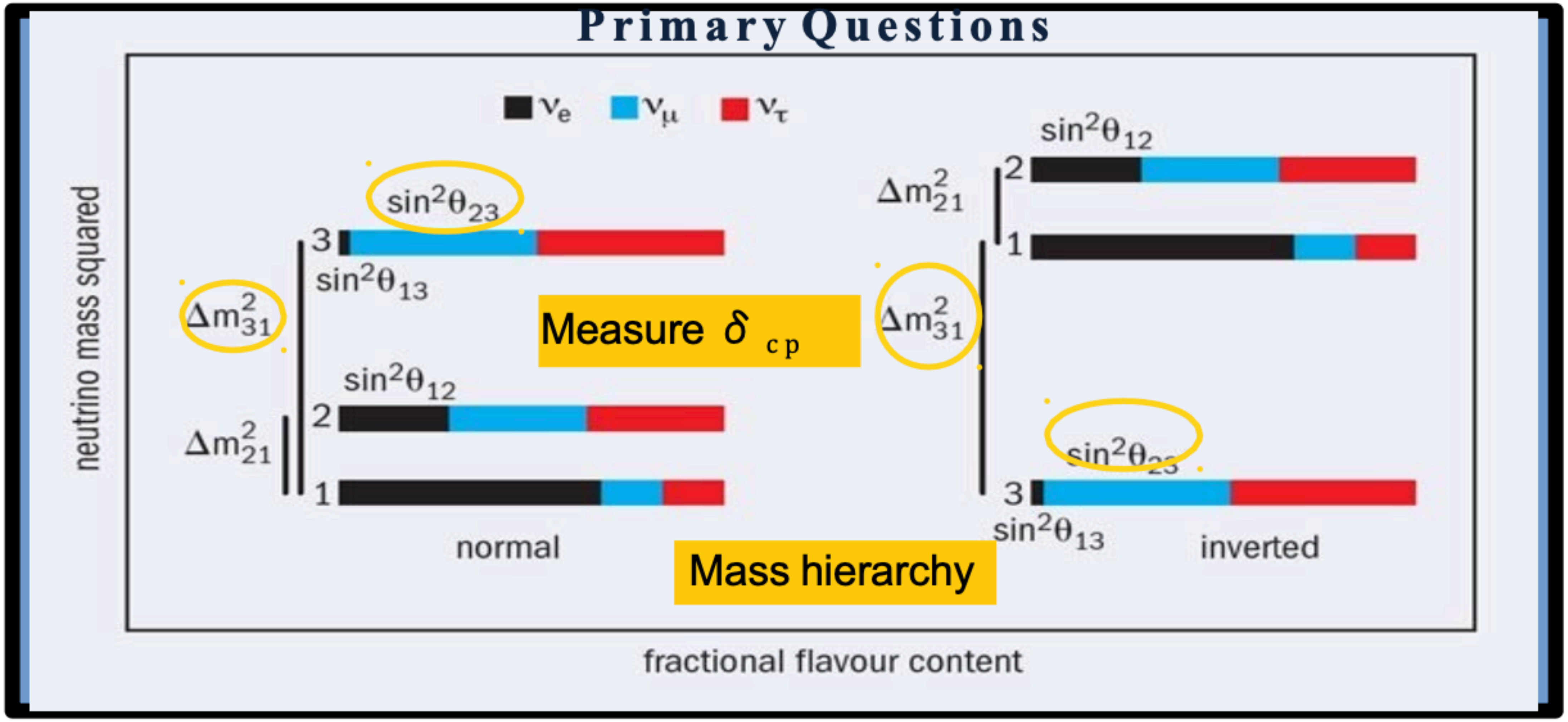
mixing angles:

$$sin^2\theta_{12} @ 4\%$$
$$sin^2\theta_{13} @ 3\%$$
$$sin^2\theta_{23} @ 3\%$$

mass squared differences:

$$\Delta m^2_{21} @ 3\%$$
$$|\Delta m^2_{31}| @ 1\%$$

Status of Neutrino Physics



Neutrino mixing matrix :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$|U_{e3}|$ **(recent discovery)**

Several decades of a rich program of experimental neutrino measurements have provided the resolution to decades-long experimental anomalies associated with solar and atmospheric neutrino measurement

Why BSM ?

WHITE PAPER ON NEW OPPORTUNITIES AT THE NEXT-GENERATION NEUTRINO EXPERIMENTS
(PART 1: BSM NEUTRINO PHYSICS AND DARK MATTER)

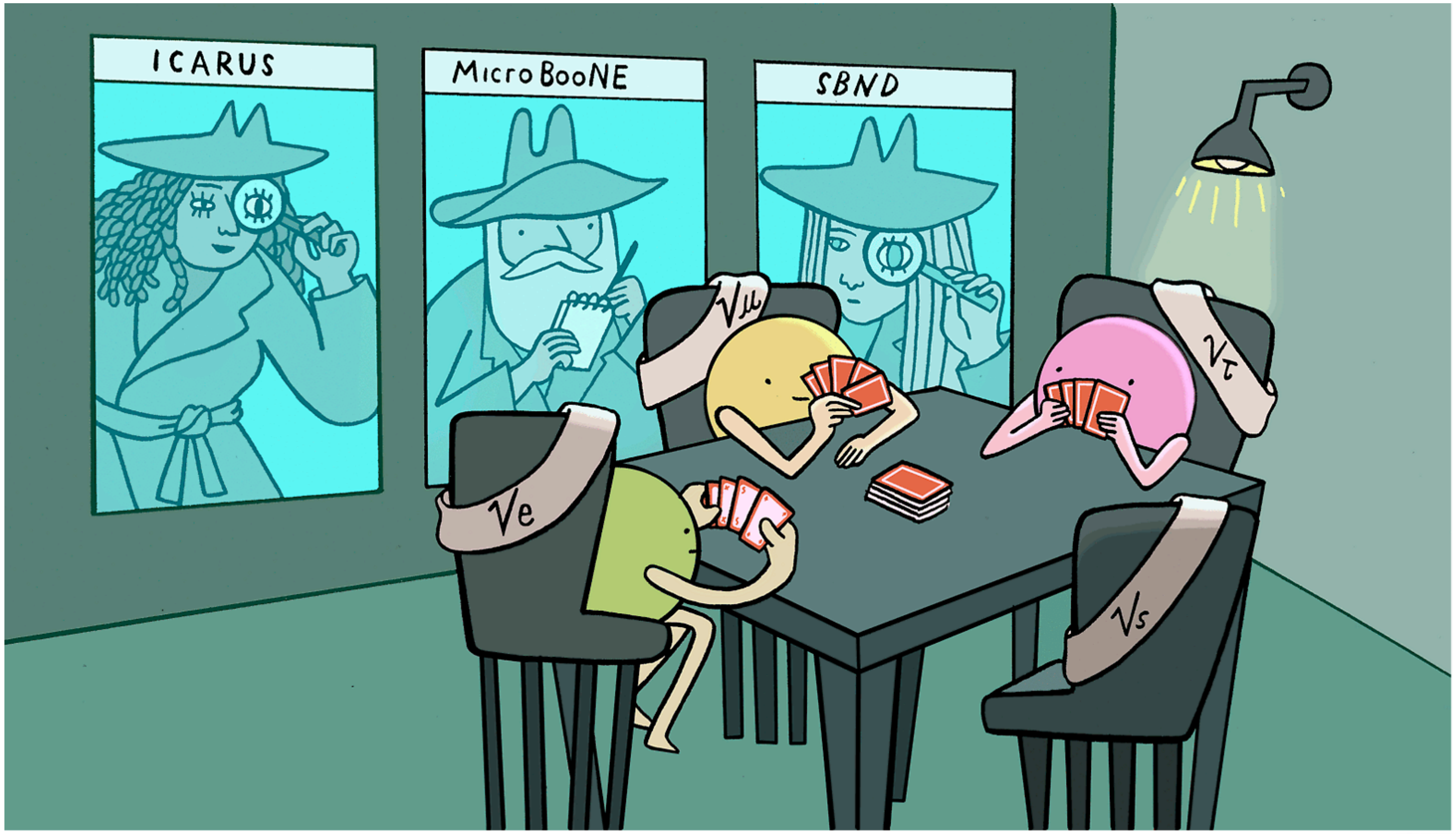
C.A. ARGÜELLES[1], A.J. AURISANO[2], B. BATELL[3], J. BERGER[3], M. BISHAI[4], T. BOSCHI[5], N. BYRNES[6], A. CHATTERJEE[6], A. CHODOS[6], T. COAN[7], Y. CUI[8], A. DE GOUVÊA[* 9], P.B. DENTON[4], A. DE ROECK[* 10], W. FLANAGAN[11], D.V. FORERO[12], R.P. GANDRAJULA[13], A. HATZIKOUTELIS[14], M. HOSTERT[15], B. JONES[6], B.J. KAYSER[16], K.J. KELLY[16], D. KIM[17], J. KOPP[10,18], A. KUBIK[19], K. LANG[20], I. LEPETIC[21], P.A.N. MACHADO[16], C.A. MOURA[22], F. OLNESS[6], J.C. PARK[23], S. PASCOLI[15], S. PRAKASH[12], L. ROGERS[6], I. SAFA[24], A. SCHNEIDER[24], K. SCHOLBERG[25], S. SHIN[26,27], I.M. SHOEMAKER[28], G. SINEV[25], B. SMITHERS[6], A. SOUSA[* 2], Y. SUI[29], V. TAKHISTOV[30], J. THOMAS[31], J. TODD[2], Y.-D. TSAI[16,32], Y.-T. TSAI[33], J. YU[* 6], AND C. ZHANG[4]

[1907.08311]

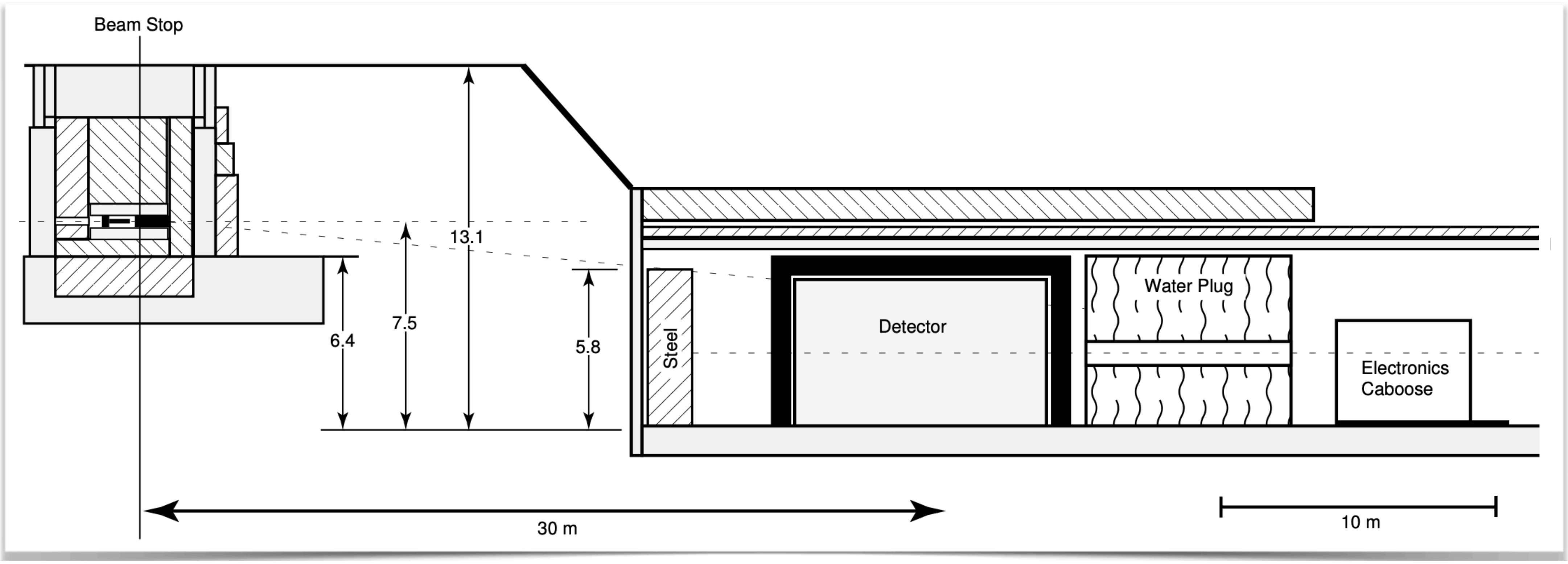
* **Experimental evidence :**
  - ☑ Dark matter
  - ☑ Neutrino masses
  - ☑ Short-baseline anomalies
  - ☑ Matter-antimatter asymmetry
  - ☑ Gravitational interaction e.t.c.

* **Theoretical motivation :**
  - ☑ Hierarchy problem
  - ☑ Flavor puzzle
  - ☑ Nature of neutrinos (Dirac or Majorana)
  - ☑ Strong CP Problem
  - ☑ Dark sector e.t.c.

Short Baseline Anomaly

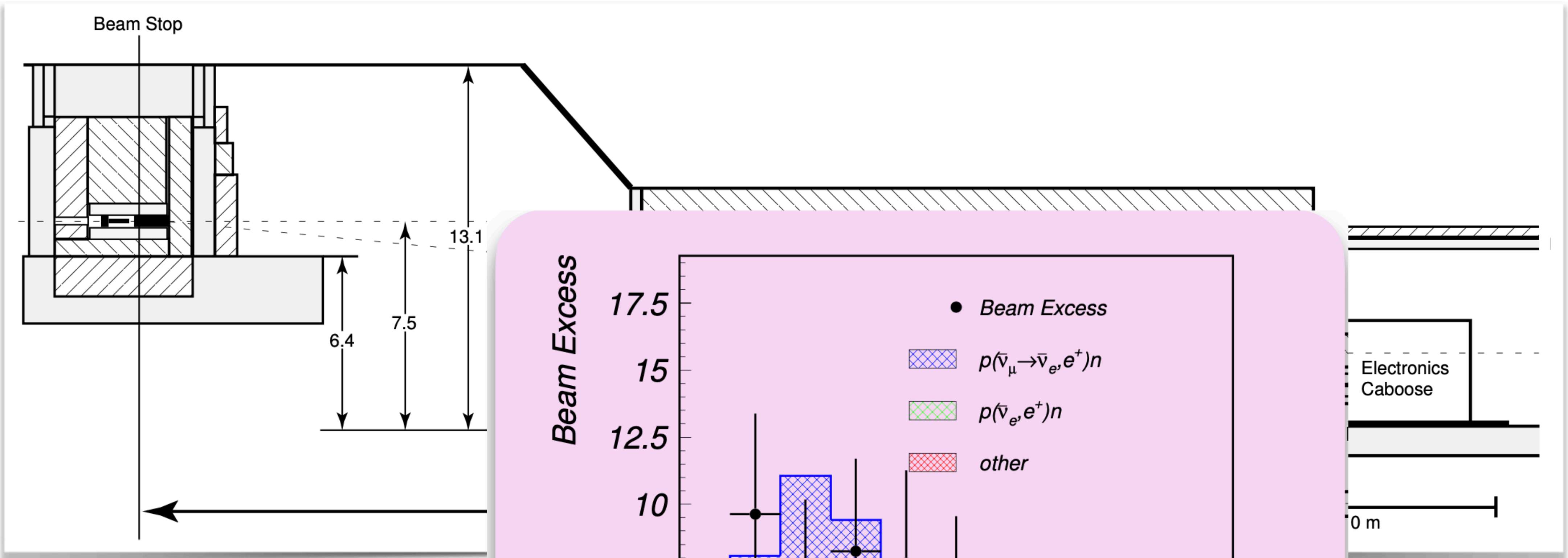


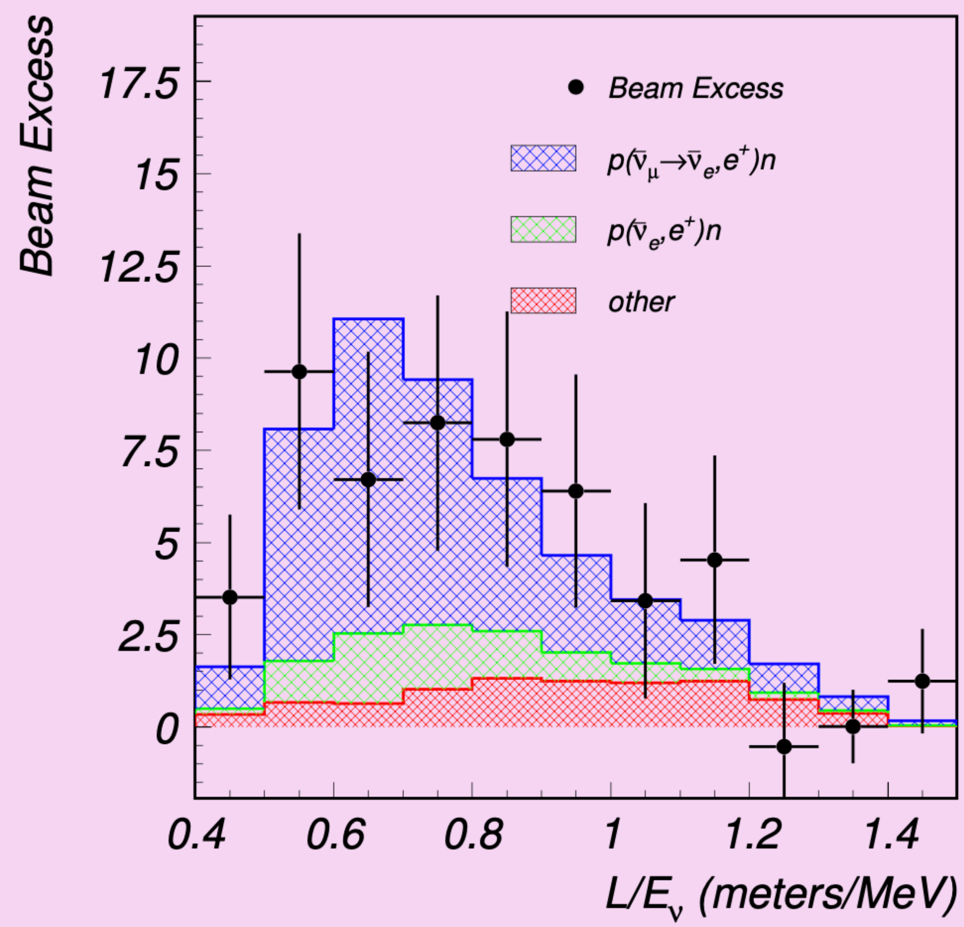
Anomaly #1 : LSND



- ☑ $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam(~3σ)
- ☑ Source—detector distance (“baseline”) ~ 30 m
- ☑ $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ oscillations

Anomaly #1 : LSND

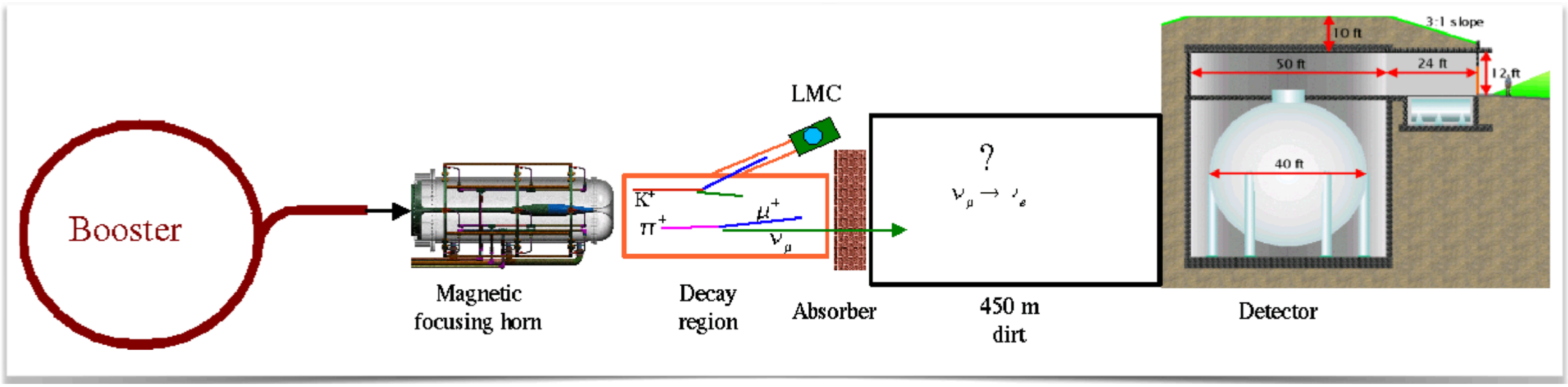




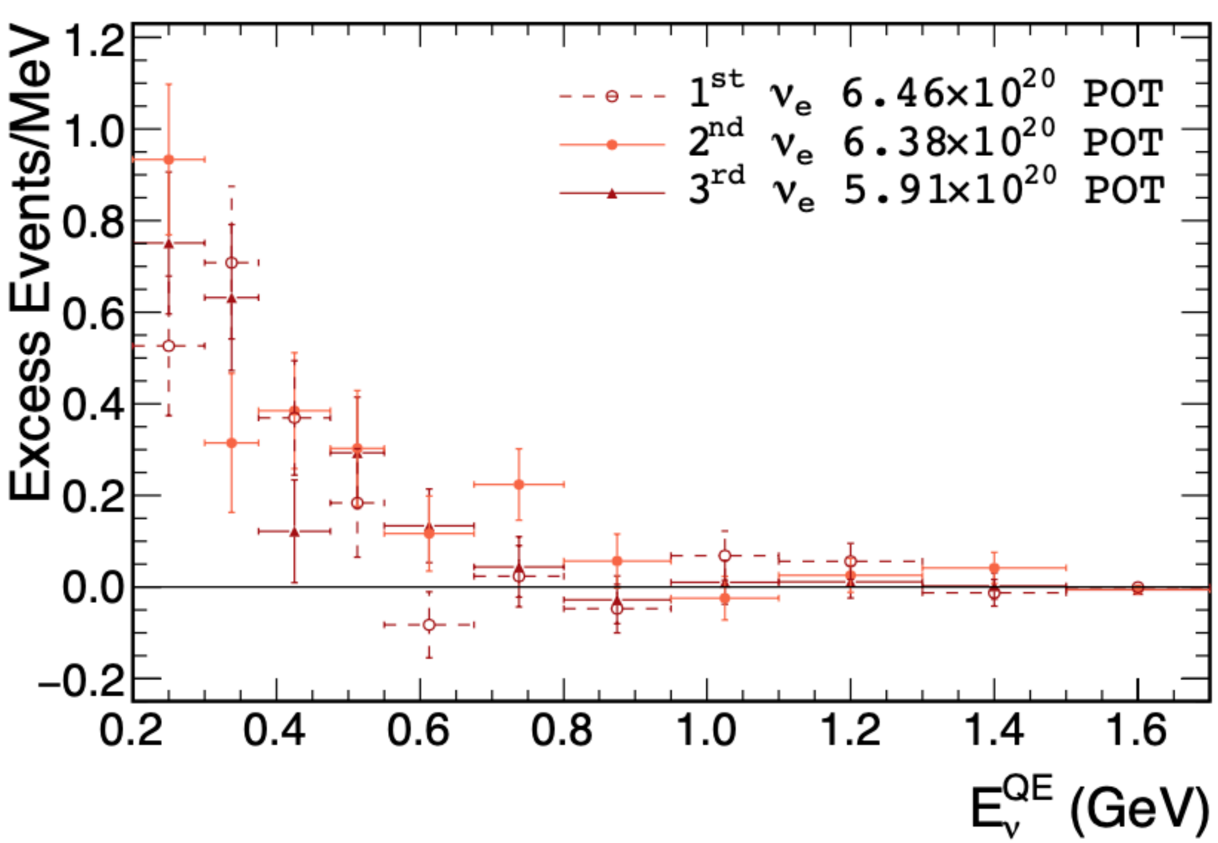
LSND Collaboration, hep-ex/0104049

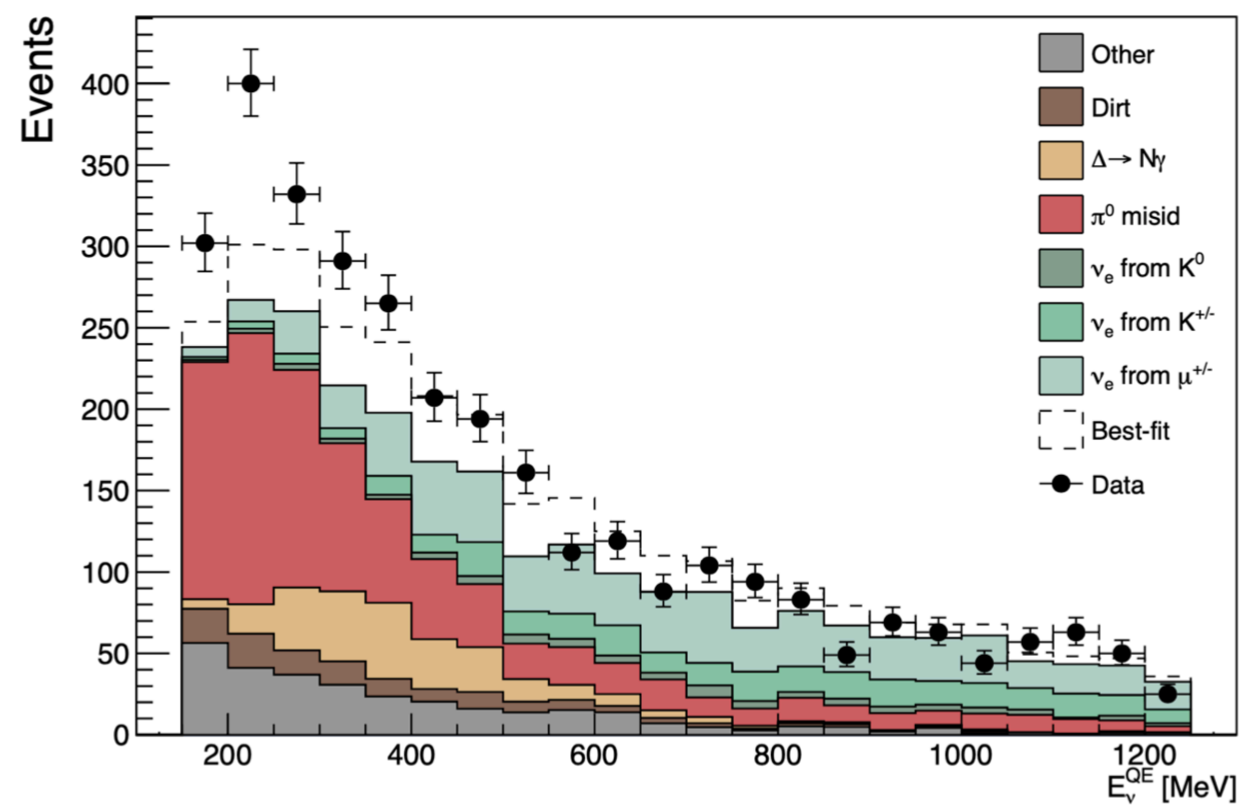
- ☑ $\bar{\nu}_e$ appearance in
- ☑ Source—detect
- ☑ $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations?

Anomaly #2: MiniBooNE

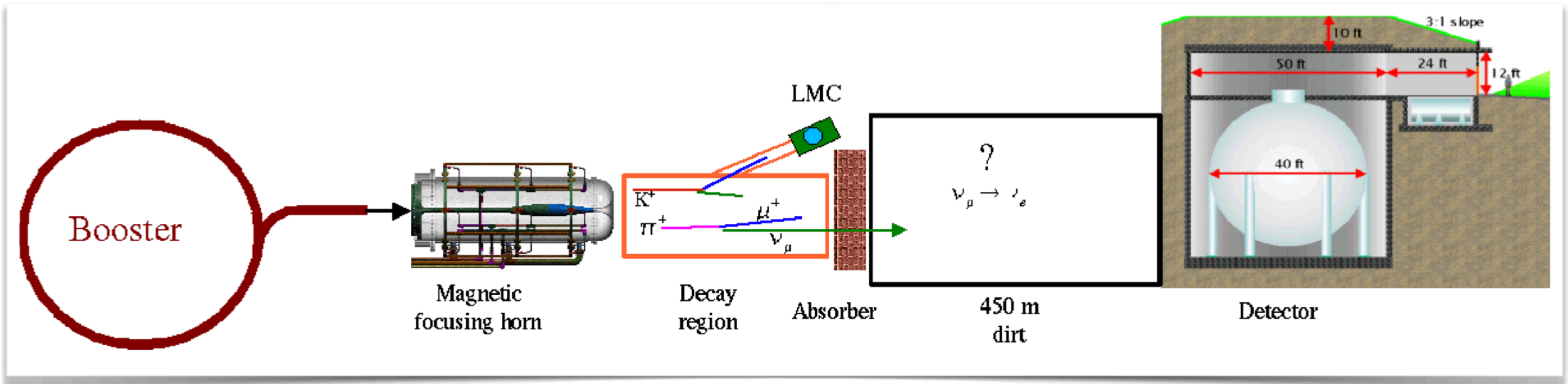


Phys. Rev. D 103, 052002 (2021)





Anomaly #2: MiniBooNE



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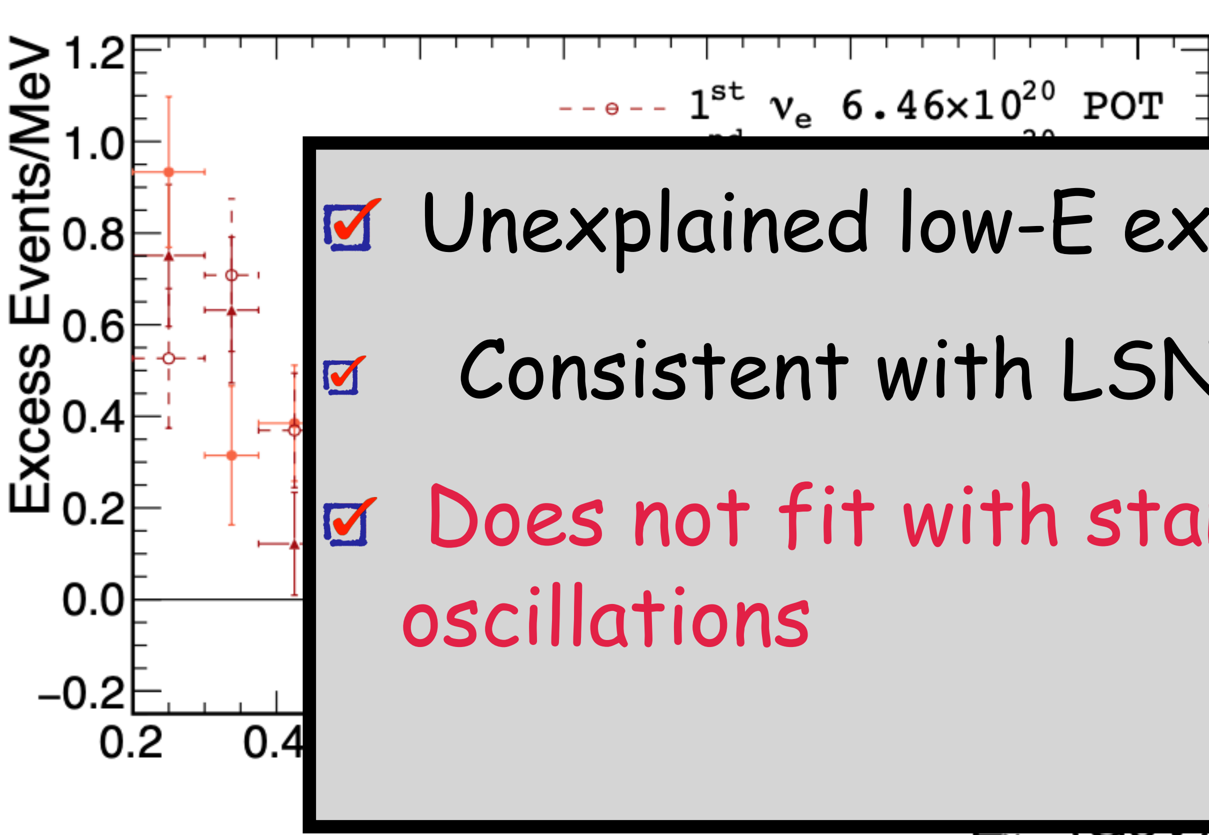
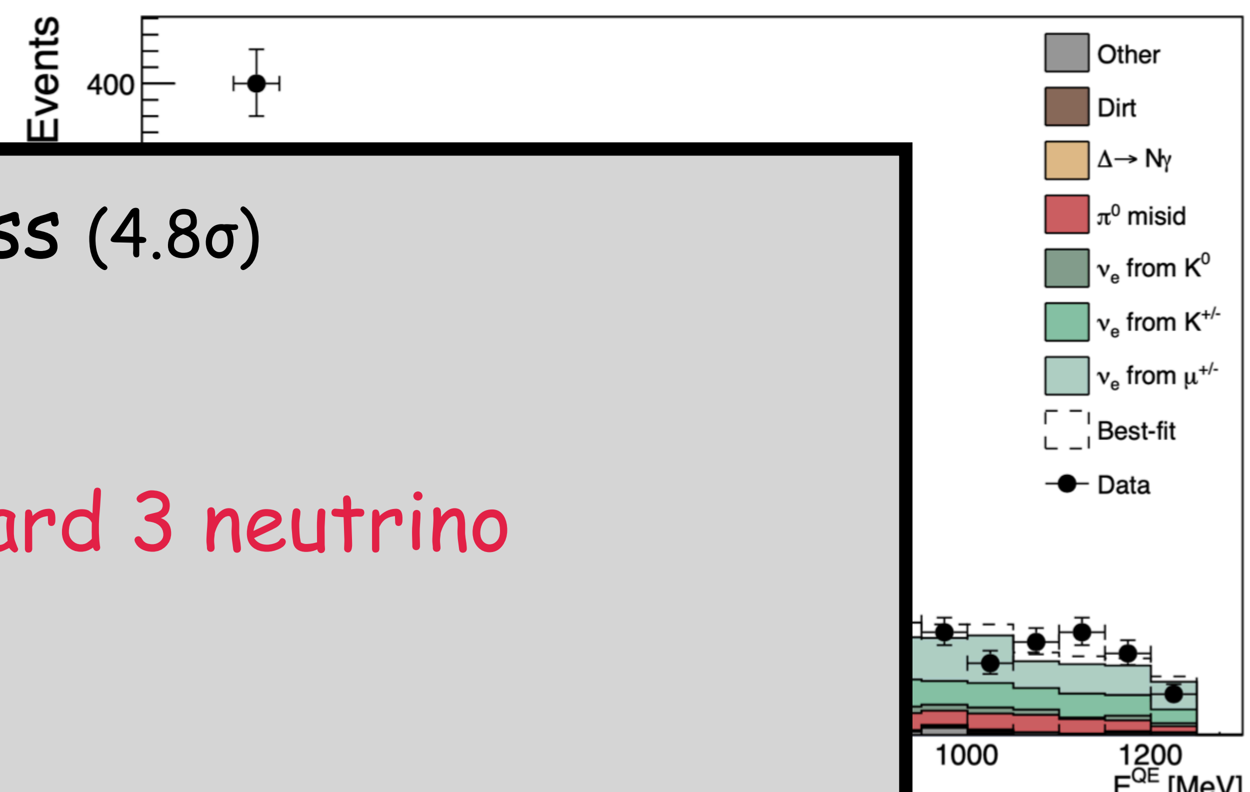
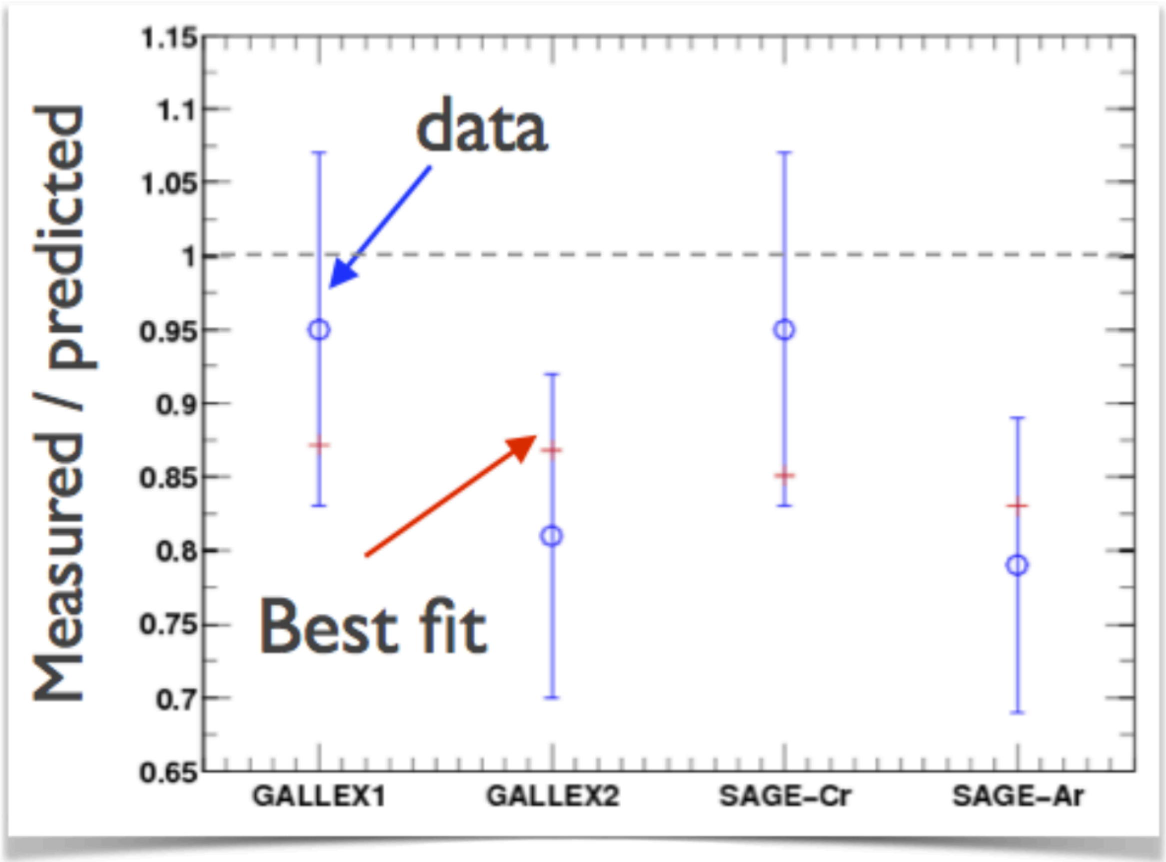


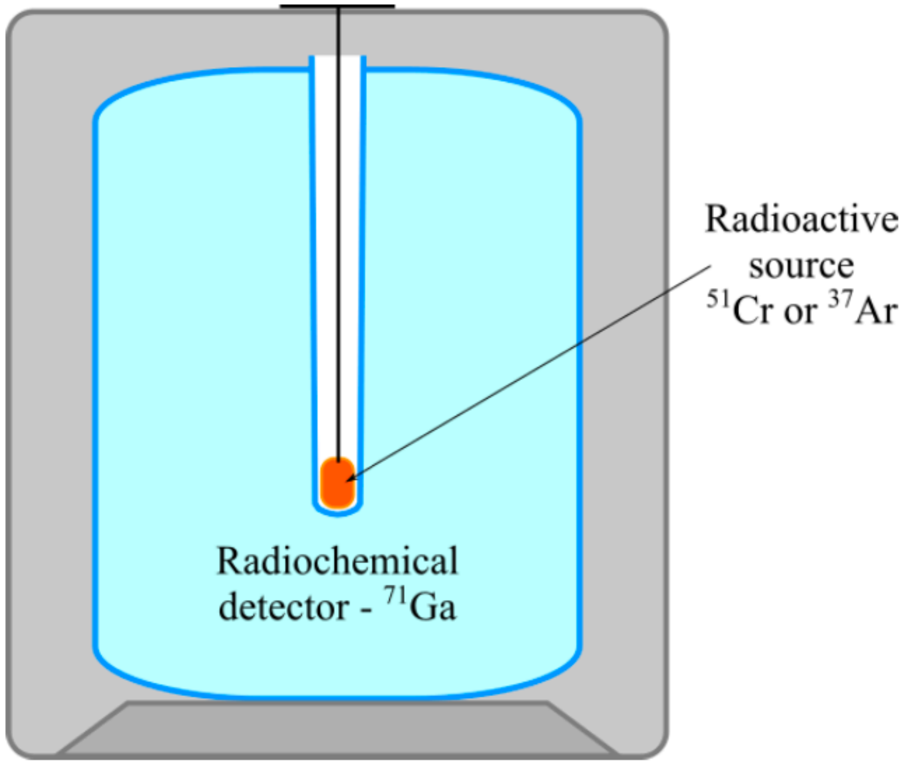


- ☑ Unexplained low-E excess (4.8σ)
- ☑ Consistent with LSND
- ☑ Does not fit with standard 3 neutrino oscillations

Anomaly #3 : the Gallium Anomaly

- The SAGE and GALLEX experiments designed to confirm neutrino oscillation from SUN
- Neutrino detection via
- $^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$
- The ratio of observed over expected ~ 0.86 ± 0.05 (~ 3σ deficit)
- ν_e disappearance into sterile state?
- Recently confirmed by BEST experiment (~4σ) BEST arXiv:2109.11482 , Barinov Gorbunov arXiv:2109.14654
- They found the ratio to be ~0.8, consistent with the SAGE and GALLEX

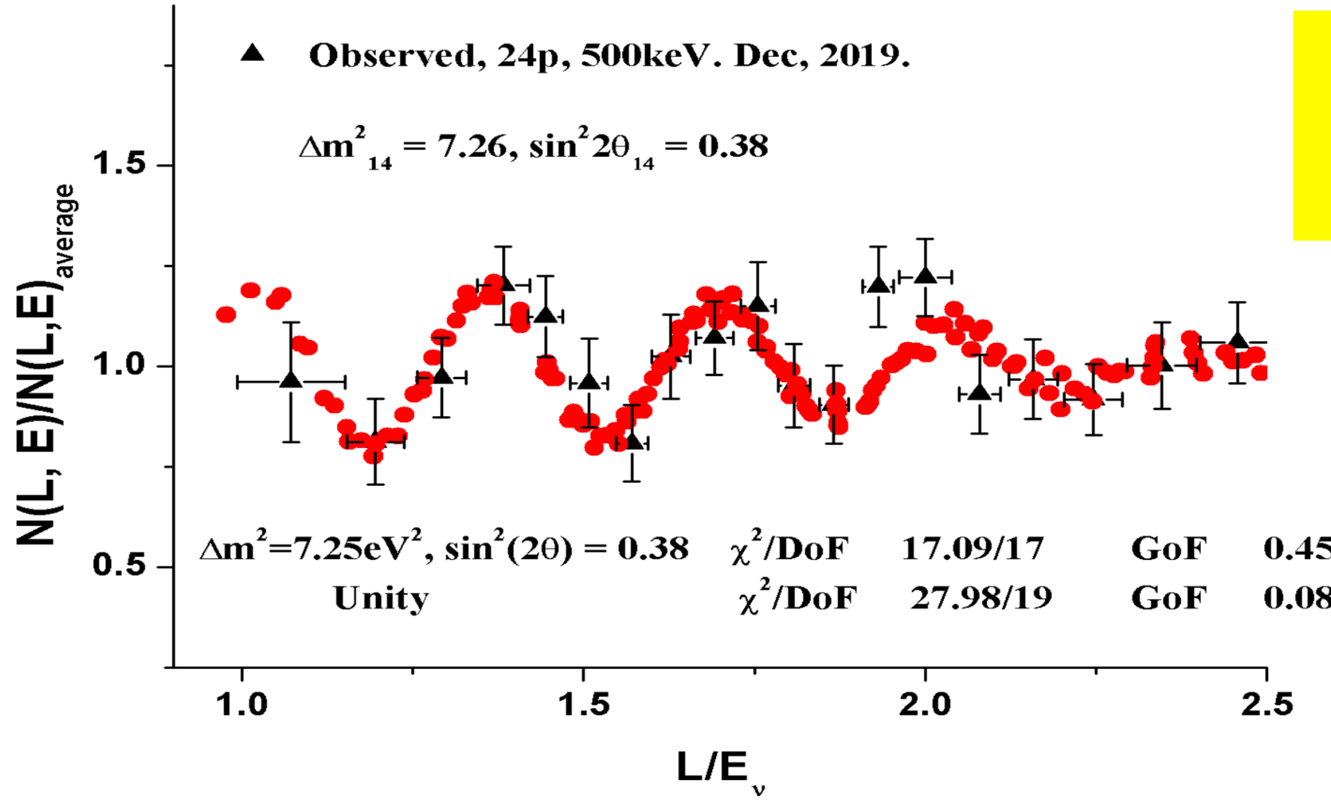




Anomaly #4 : the Neutrino 4 experiment

- 100 MW thermal power SM-3 reactor
- Anti-neutrino detector (liquid scintillator) located at a distance of 5m from the reactor
- Measurement performed with the reactor ON/OFF condition, which provides antineutrino spectrum.

All data 2016 -2019 + background 20119



The period of oscillation for neutrino energy 4 MeV is 1.4 m

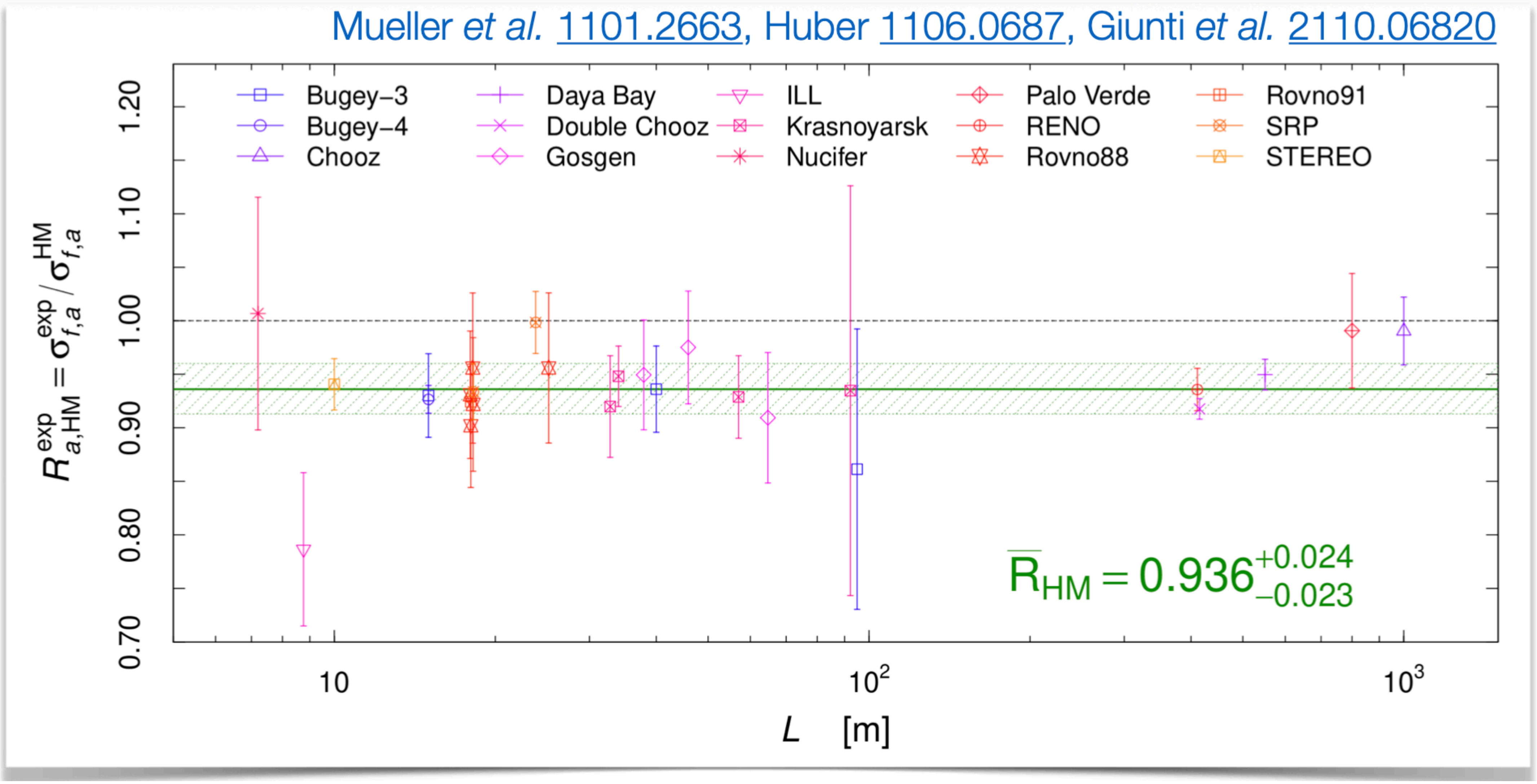
A.P.Serebrov, et al.
JETP Letters, Volume 109, Issue 4, pp 213–221.

arxiv:1809.10561

* No contradiction with Gallium Anomaly, the combined result of the Neutrino-4 and gallium anomaly gives

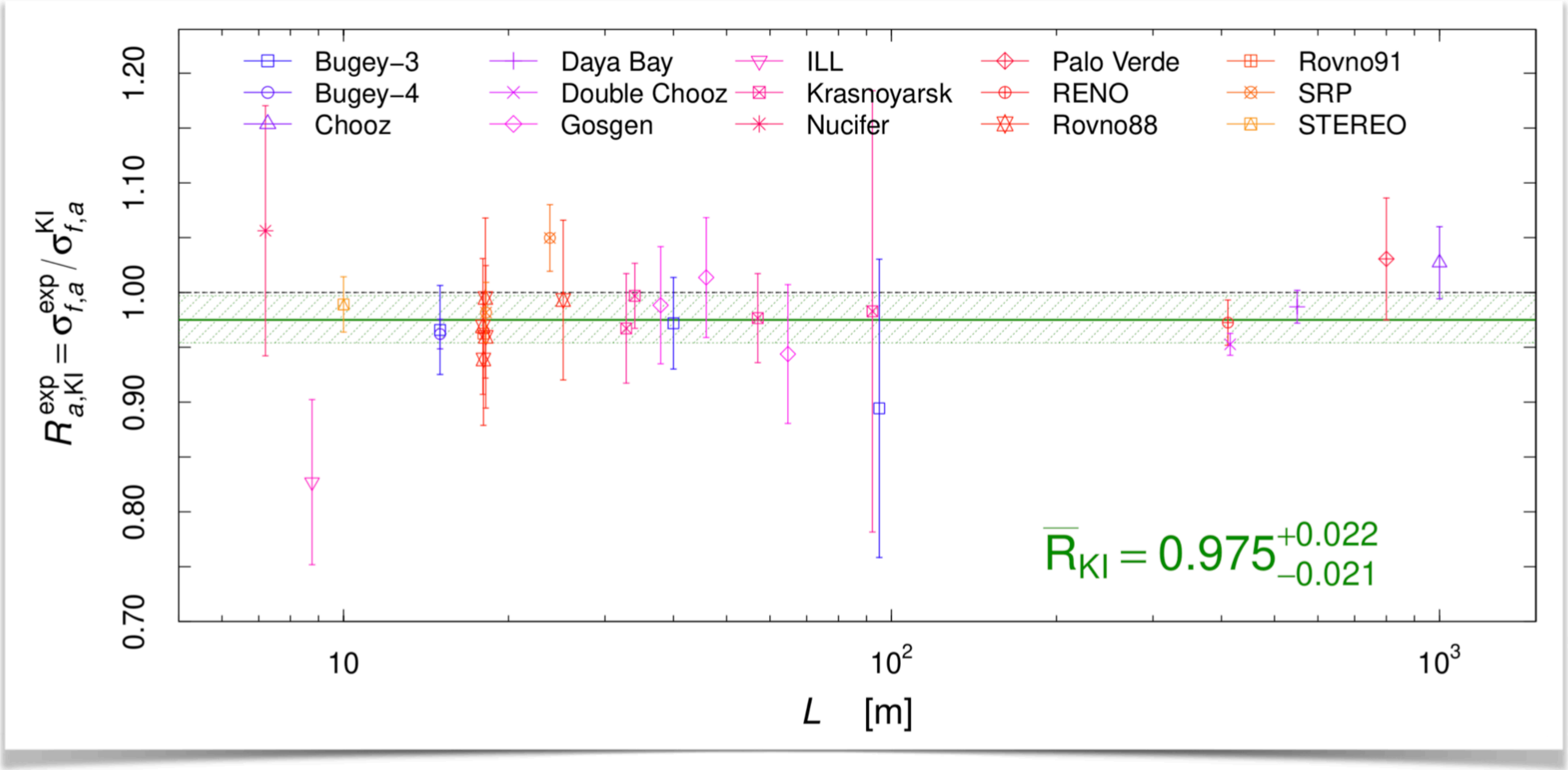
$$\sin^2 2\theta_{14} \approx 0.35 \pm 0.07\ (5.0\sigma)$$

Anomaly #5 : Reactor Neutrino Fluxes



- $\bar{\nu}_e$ flux from nuclear reactors ~ 3.5% (~ 3σ) below prediction
- Oscillation of $\bar{\nu}_e$ into sterile neutrino $\bar{\nu}_s$? (L/E too small for standard oscillations)

Anomaly #5 : Reactor Neutrino Fluxes

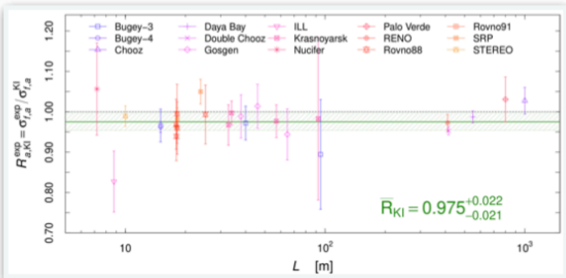


Kopeikin Skorokhvatov Titov arXiv:2103.01684, Berryman Huber arXiv:2005.01756, Giunti Li Ternes Xin arXiv:2110.06820

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

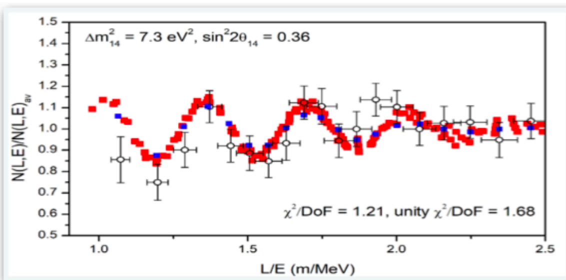
reactor flux anomaly, resolved with new input data to flux calculation

Short Baseline Anomaly



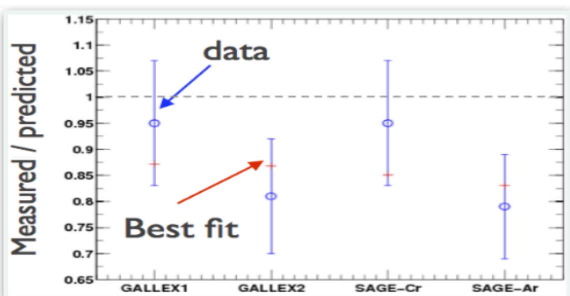
reactor flux anomaly
resolved with new input data
to flux calculation

✓



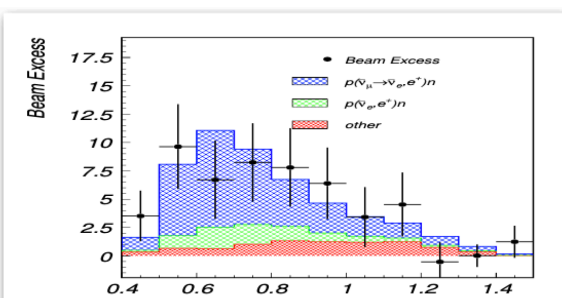
reactor spectra
is there really an anomaly?

?



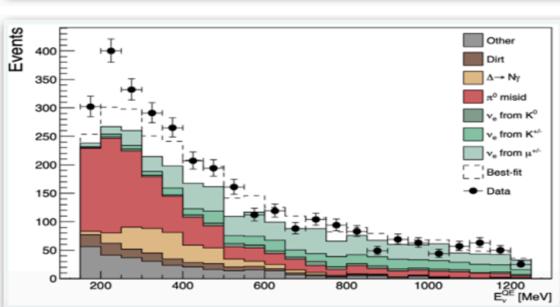
gallium anomaly
unresolved, recently reinforced

?



LSND
unresolved

?



MiniBooNE
unresolved

?

Is there a common explanation for all the anomalies ?

- ☑ Flavor conversion : Inclusion of a new light sterile neutrino

- ☑ Inclusion of dark sectors: Dark matter particles, dark neutrinos, Long lived Heavy Neutrinos etc.

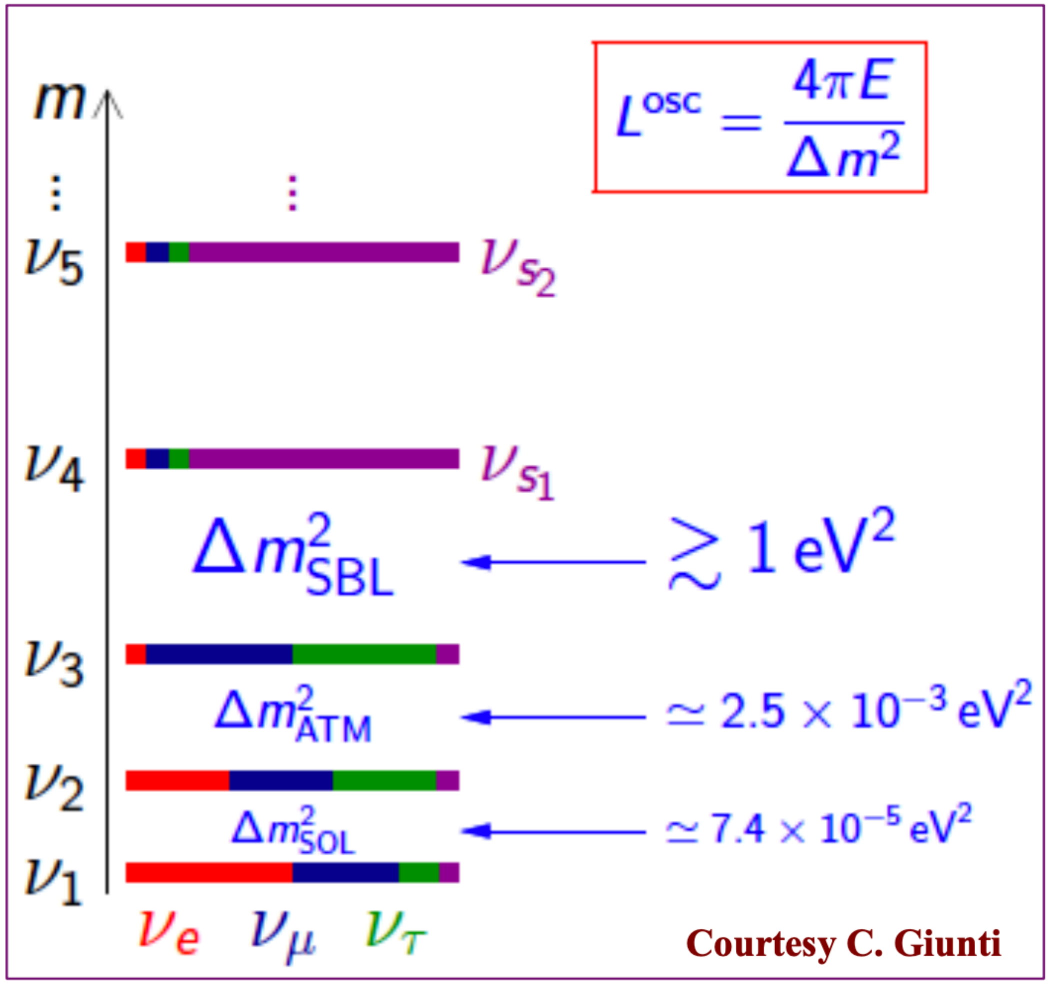
- ☑ Conventional explanation : Single photon production, reactor flux modeling etc.

And many more theoretical models …

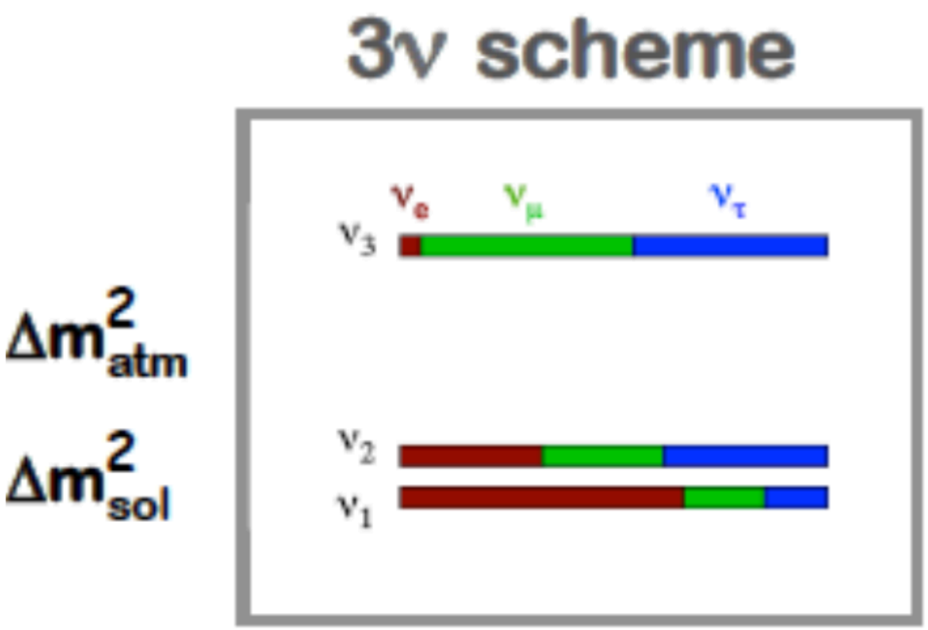
Anomalies hint towards a eV-Scale Sterile neutrino

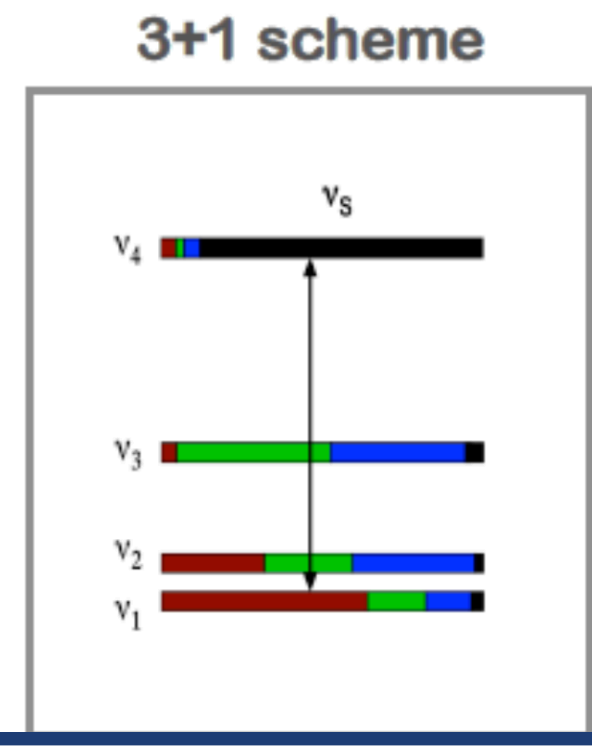
Require additional neutrinos with masses at eV scale

- ν_S : Sterile States (no weak interactions)
- singlets of SU(2) × U(1) gauge group
- Can affect oscillations through mixing
- The right-handed neutrinos are, by definition, sterile.
- To generate neutrino masses, we need to couple the (active) left-handed neutrinos to right-handed neutrinos.
- Hence, sterile neutrino has a great motivation both from theory and experiments



3+1 Sterile-Active Neutrino Oscillations





$\Delta m^2_{41} \sim 1\ \mathrm{eV}^2$

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

SBL

Small perturbation of 3ν mixing

$|U_{e4}|^2 << 1, |U_{\mu4}|^2 << 1, |U_{\tau4}|^2 << 1, |U_{s4}|^2 \approx 1$

3+1 Short Baseline Oscillation

Appearance ($\alpha \neq \beta$)

$$P^{SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

Disappearance

$$P^{SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases

- Amplitude of ν_e disappearance:

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \simeq 4|U_{e4}|^2$$

- Amplitude of ν_μ disappearance:

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right) \simeq 4|U_{\mu 4}|^2$$

- Amplitude of $\nu_\mu \to \nu_e$ transitions:

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

quadratically suppressed for small $|U_{e4}|^2$ and $|U_{\mu 4}|^2$

$\Downarrow$

Appearance-Disappearance Tension

See reviews by C. Giunti

Current Status and future of the Sterile neutrino Experiments

- Short-Baseline means : L/E ~ 1 (m/MeV or km/GeV)
- It covers a wide range of experiments
- Reactor based ν experiments (L/E ~ m/MeV)
- Atmospheric Neutrinos in IceCube (L/E ~ 1000km/TeV)
- Accelerator produced ν experiments (L/E ~ 1 km/GeV)
- … and many more ….

Reactor based ν experiments : Status and future

Key aspect : **distance to reactor** (L) $\Delta m^2_{41} \simeq 2 - 10\ \mathrm{eV}^2 \times \left(\frac{10\ m}{L}\right)$

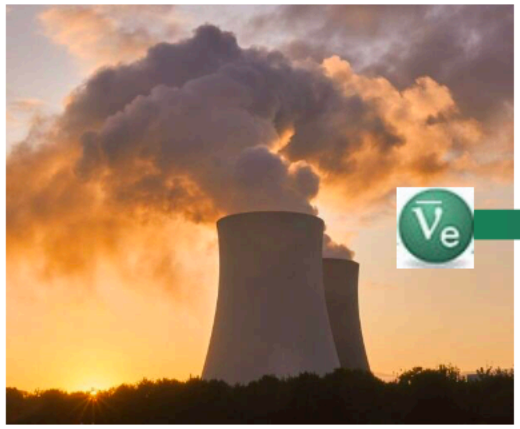
Very short baseline (VSBL)
- L ~ O(10 m)
- access to large Δm^2
- restricted space available, high background environnement

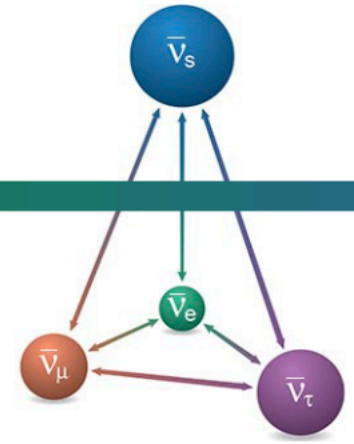
← Complementary Δm^2 coverage →

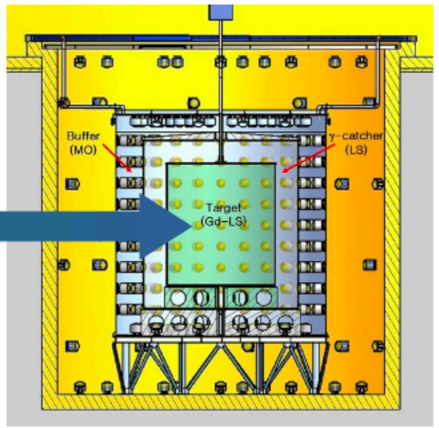
Short baseline (SBL)
- L ~ O(1 km)
- restricted to smaller Δm^2
- larger detectors possible
- no reactor background

Research reactors (HEU)
- lower power, lower stat
- compact core (Ø ≈ 0.5m)
- *pure ^{235}U (irrelevant)*

Commercial reactors (LEU)
- high power, high stat
- extended core (Ø ≈ few m)
- *mixed isotopes (irrelevant)*

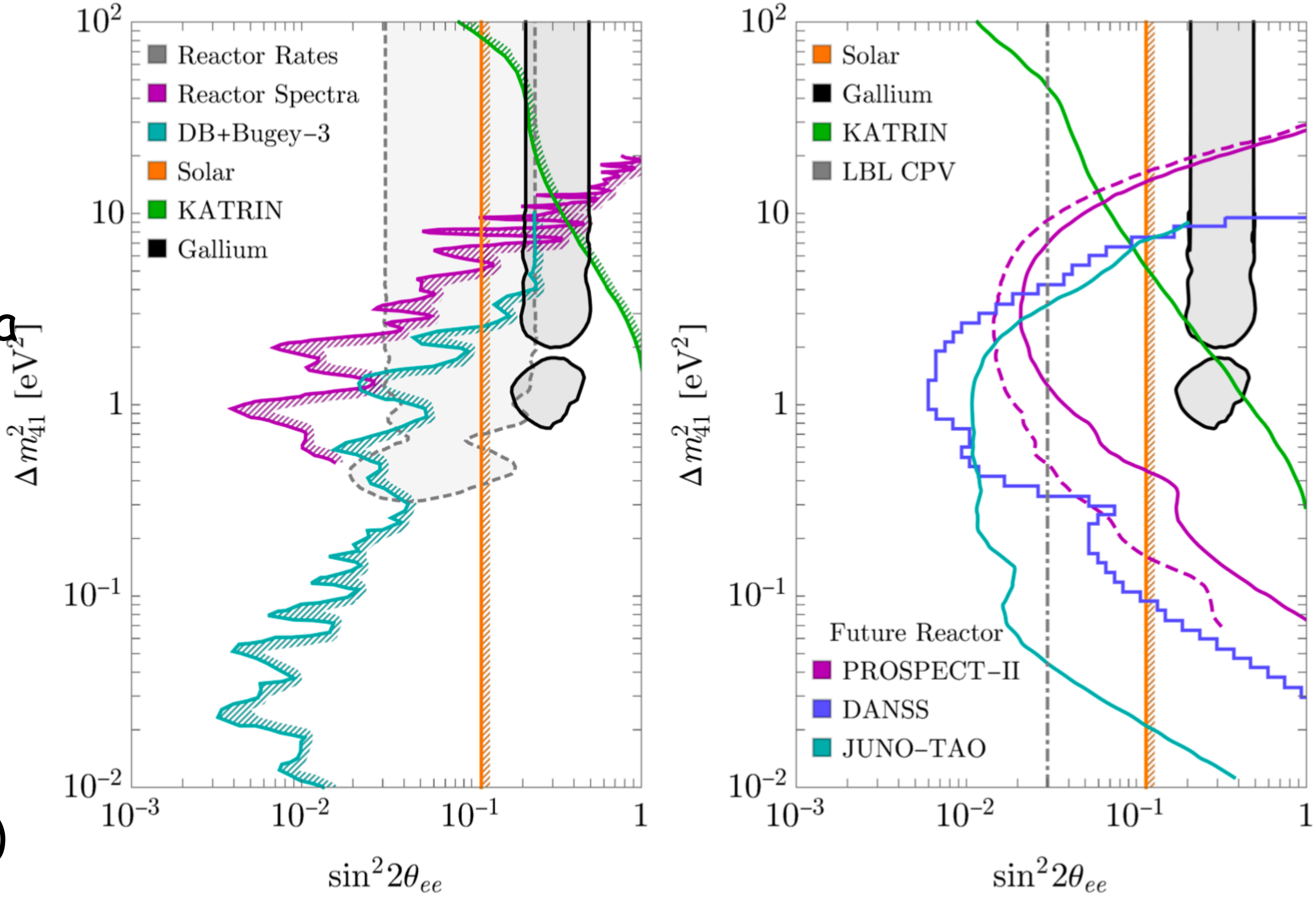






Reactor based ν experiments : Status and future

- ☑ Complementary constraints from different reactor experiments (SBL + VSBL) allow to probe a large range of Δm^2
- ☑ KATRIN + Reactor constraints already cover most of Gallium Anomaly parameters
- ☑ Reactor Anomaly strength ($\leftrightarrow \sin 2\theta_{ee}$) still depends on flux modeling: not fully solved yet



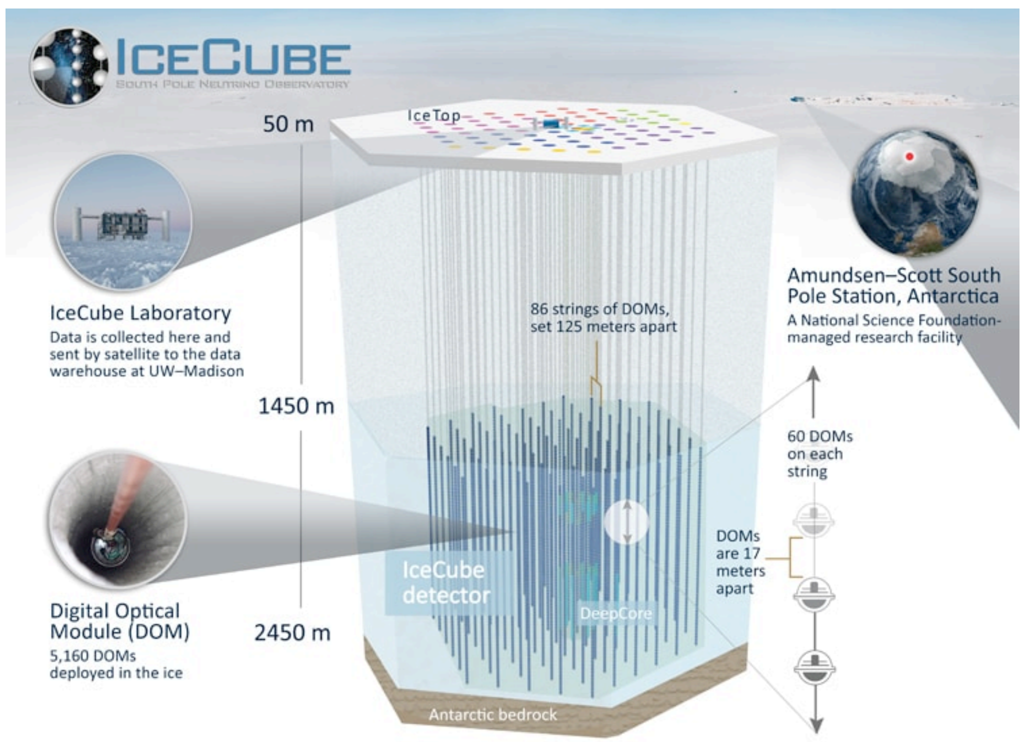
Snowmass 2021 white paper 2203.07214

Positive observations (BEST, Neutrino-4, RENO-NEOS) **in (strong) tension** with other experiments, to be confirmed in the next few years

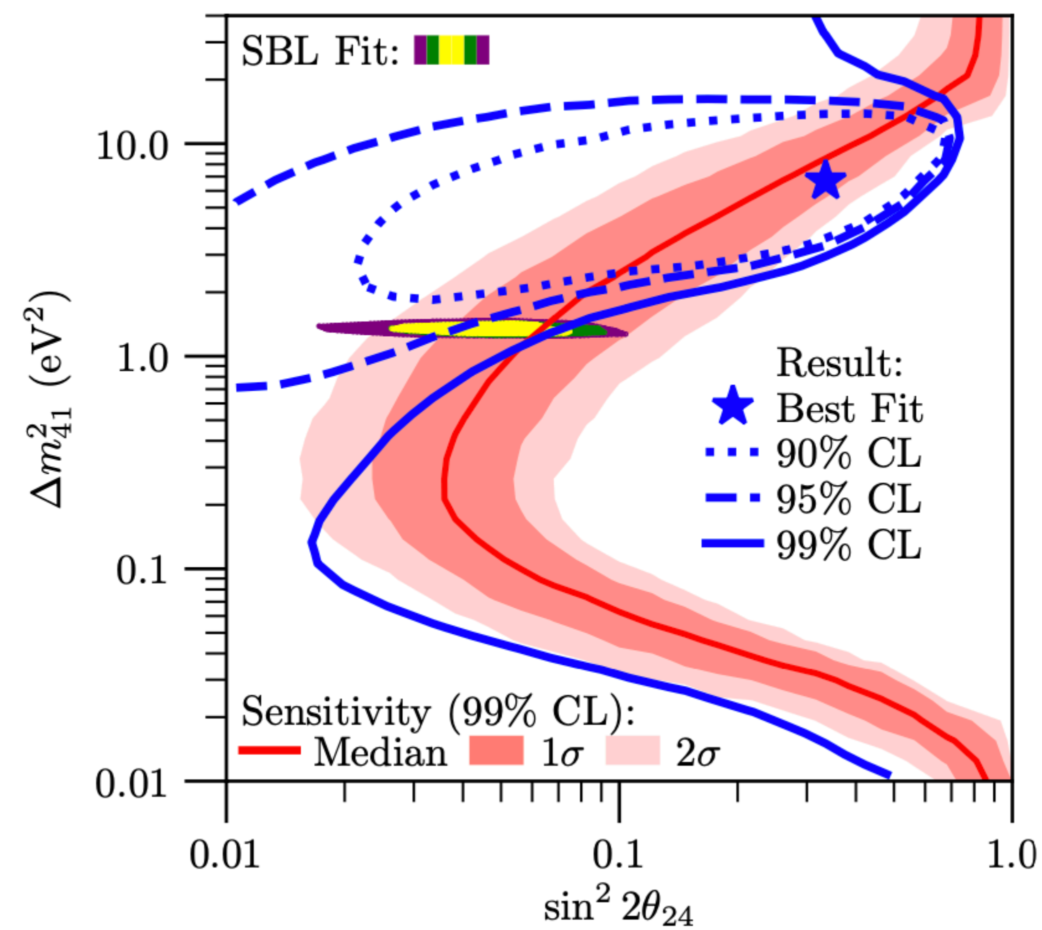
Atmospheric Neutrinos in ICECUBE

- IceCube is a cubic- kilometer neutrino detector buried 1.5km–2.5km beneath the surface of the Antarctic glacier at the South Pole

- IceCube has made powerful sterile neutrino searches in both high (≳ 400 GeV) and low (≲ 60 GeV) energy ranges



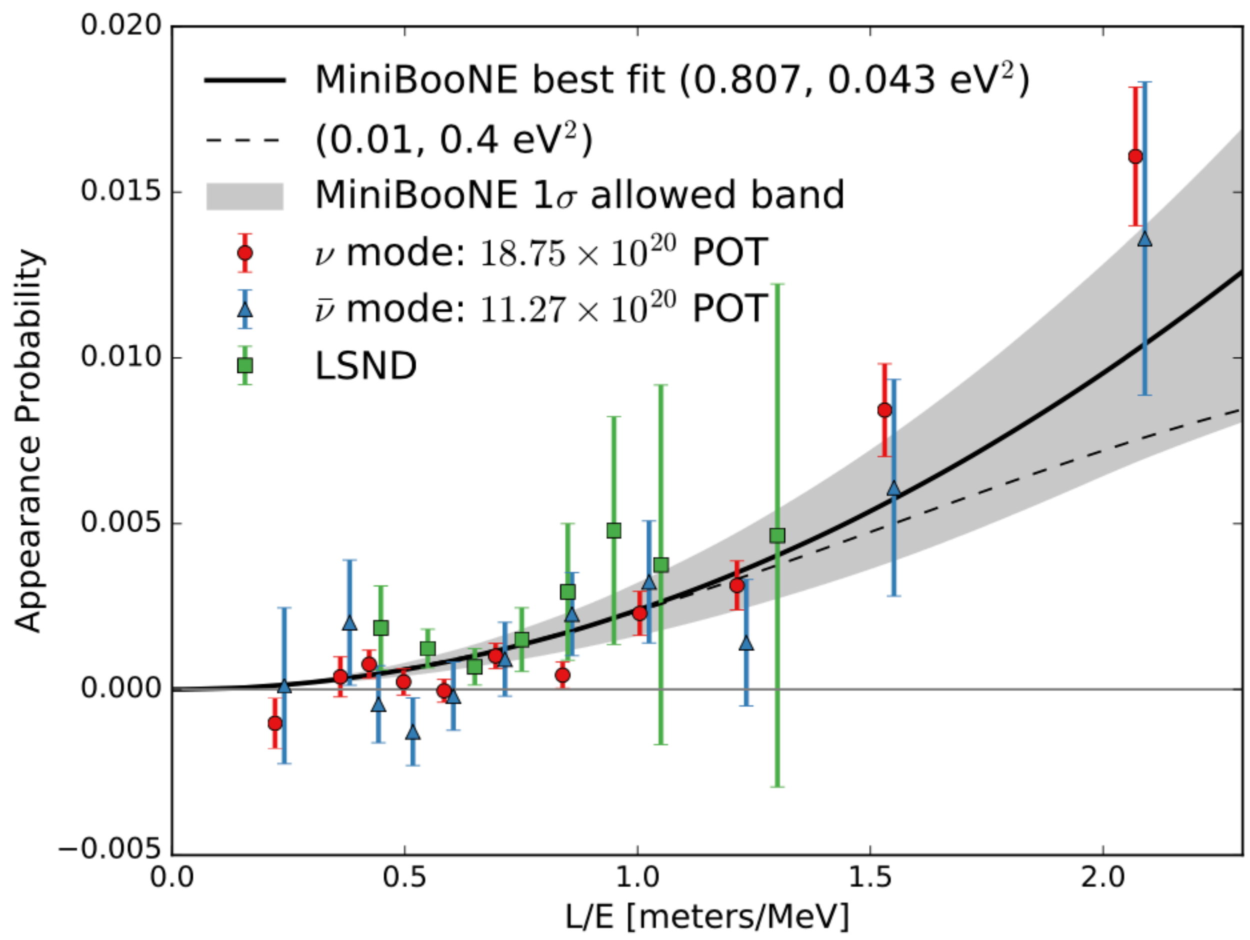
• Phys.Rev.Lett. 129 (2022) 15, 15

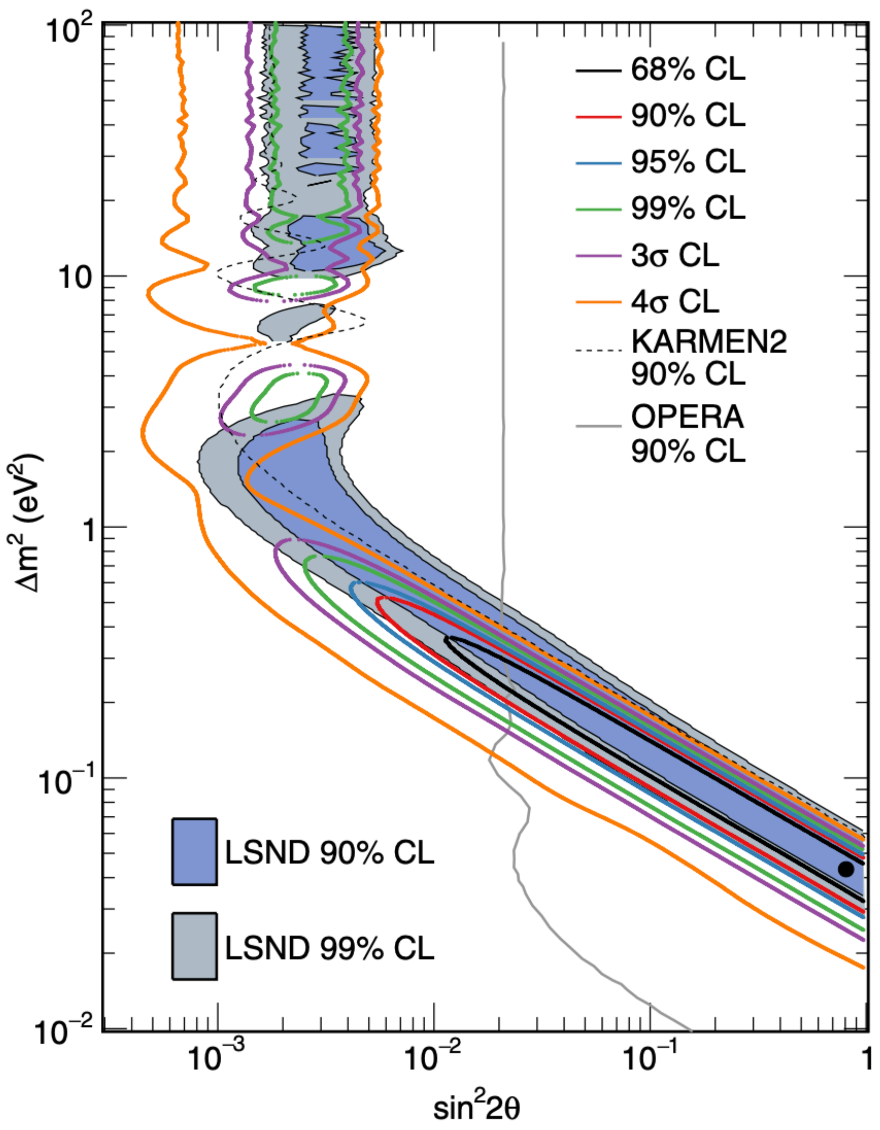


- This result is one of the world's most sensitive in the ν_μ disappearance channel at eV^2-scale mass splittings

- The expected sensitivity of the combined high energy ν_μ disappearance and cascade appearance signatures

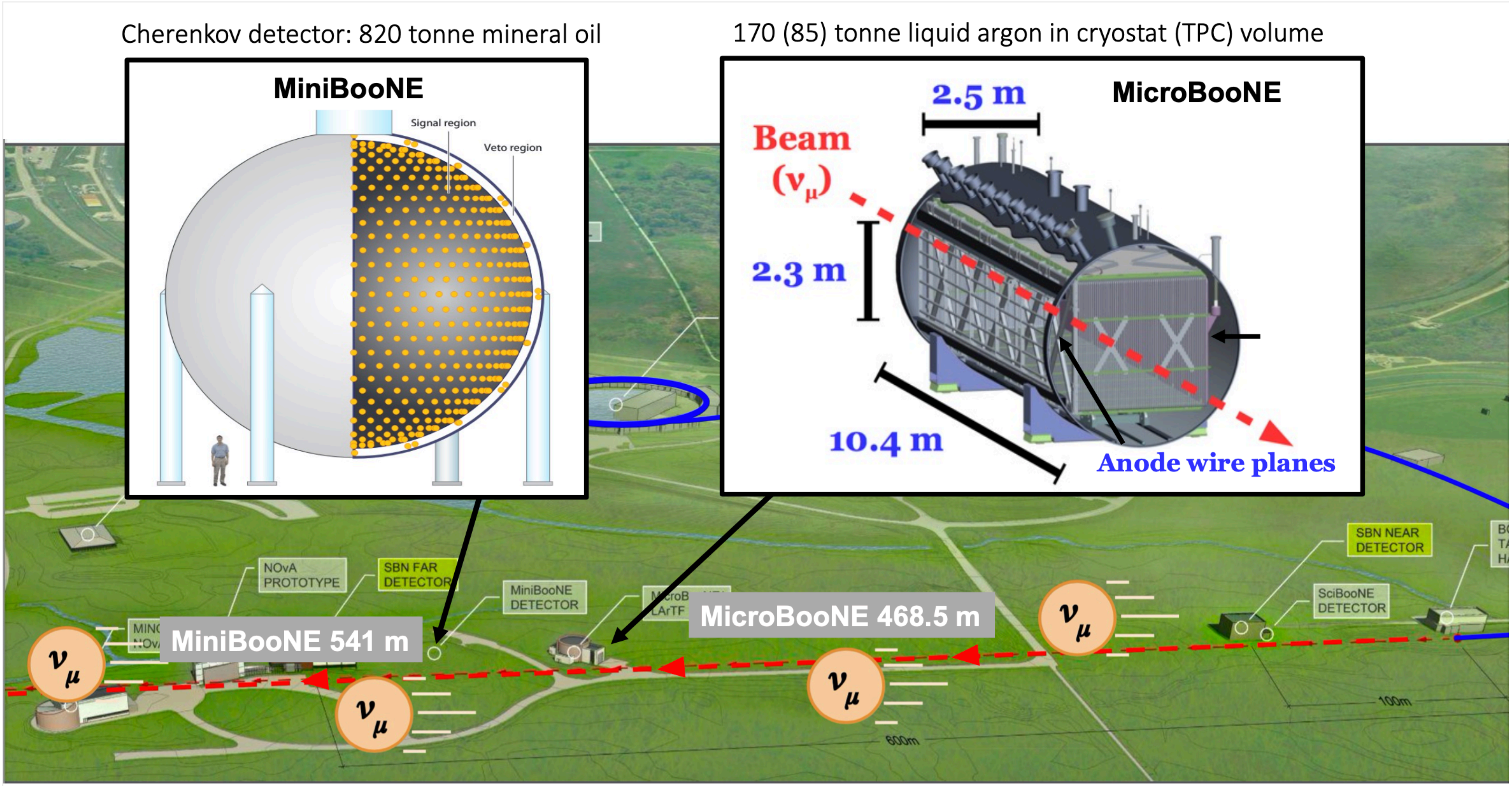
Accelerator based ν experiments : LSND & MiniBooNE





- The MiniBooNE experiment observes a total excess of 638.0 +/ 52.1 (stat) +/132.8 (syst)
- The overall significance of the excess, 4.8σ, is limited by systematic uncertainties, assumed to be Gaussian, as the statistical significance of the excess is 12.2σ.

MicroBooNE

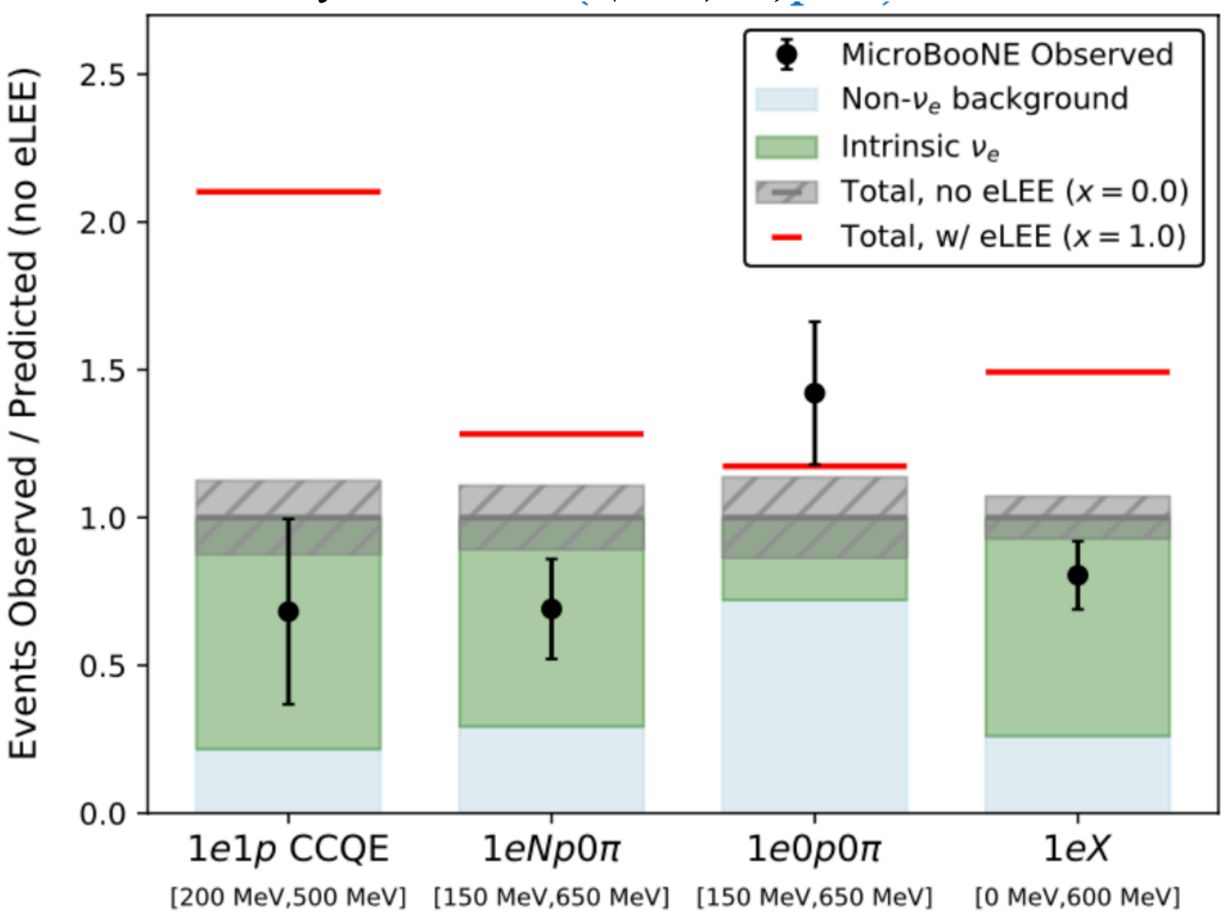


MicroBooNE experiment is designed to understand the MiniBooNE LEE region (same L/E) with LArTPC detector

Examination of MiniBooNE LEE

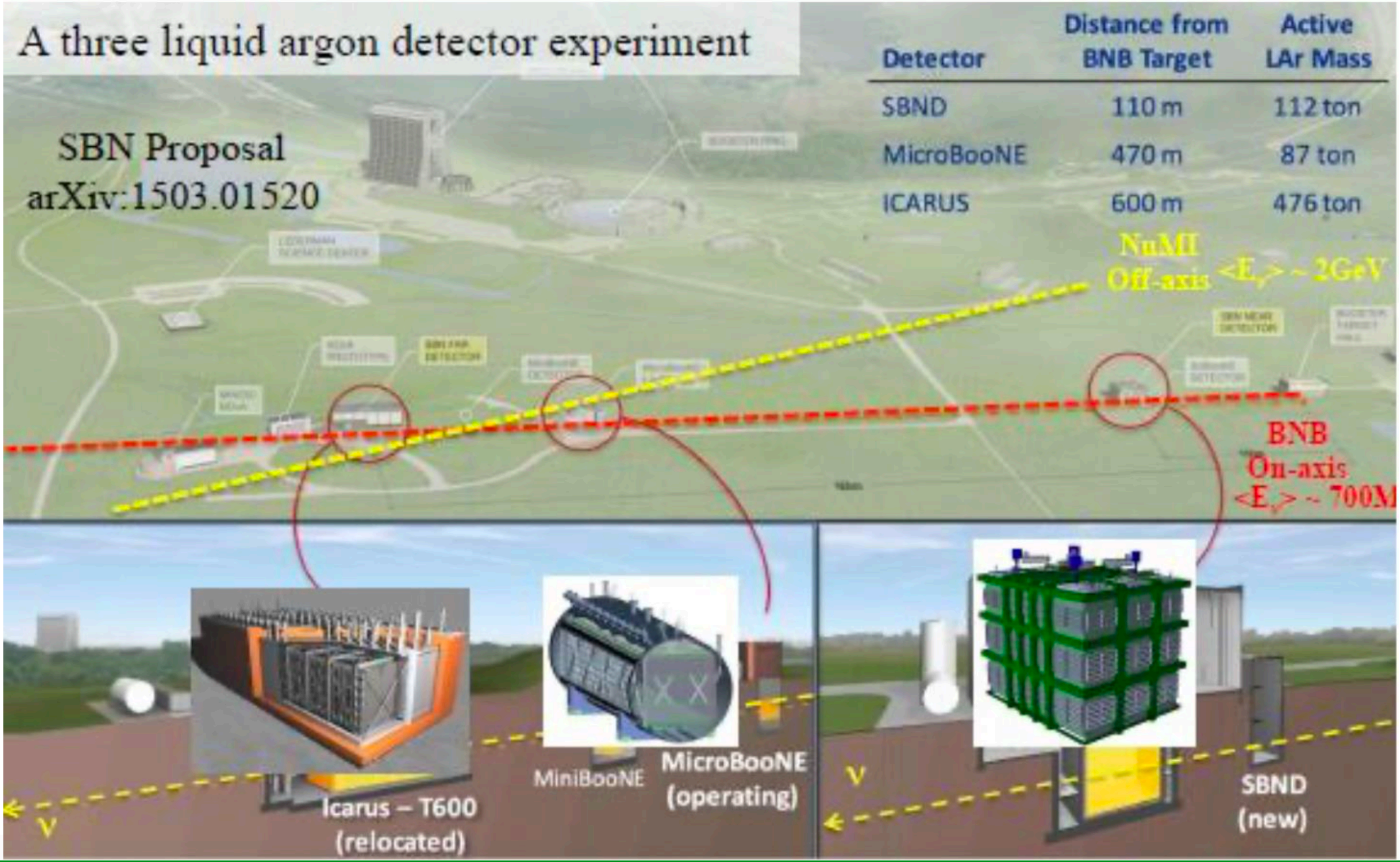
- Electron-like excess (ν_e excess)
  - Mismodeled/ unknown process?
  - Oscillation-driven excess ?
- Photon-like excess
  - Mismodeled/unknown process producing photons, e.g. NC Δ resonance radiative decay?

Phys.Rev.Lett. 128 (2022) 24, 241801



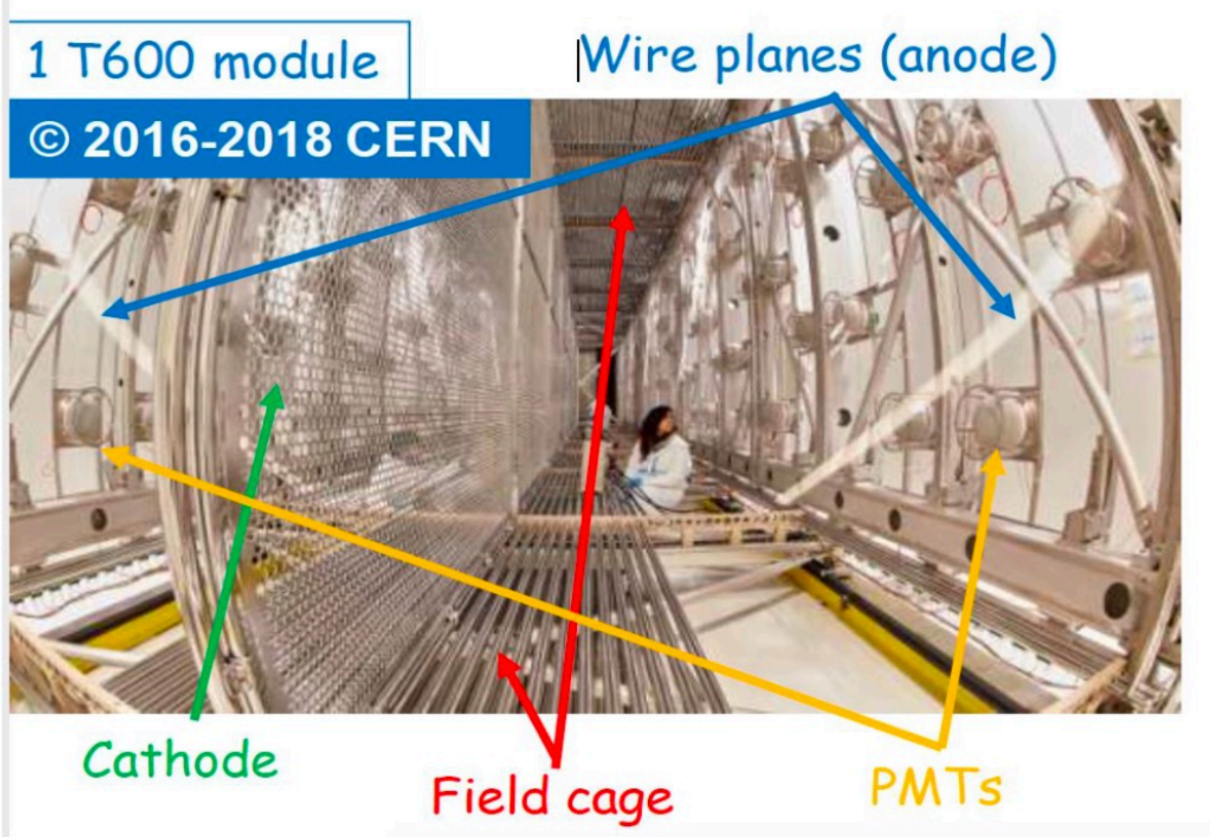
- Observed ν_e candidate rates are statistically consistent with the predicted background rates in the LEE region
- The MicroBooNE eLEE result disfavors the MiniBooNE anomaly originating from a pure ν_e excess
- Hence, it is ideal to have Short-Baseline Neutrino Program: a combination of ν_e appearance and ν_μ disappearance with Near and Far detector.

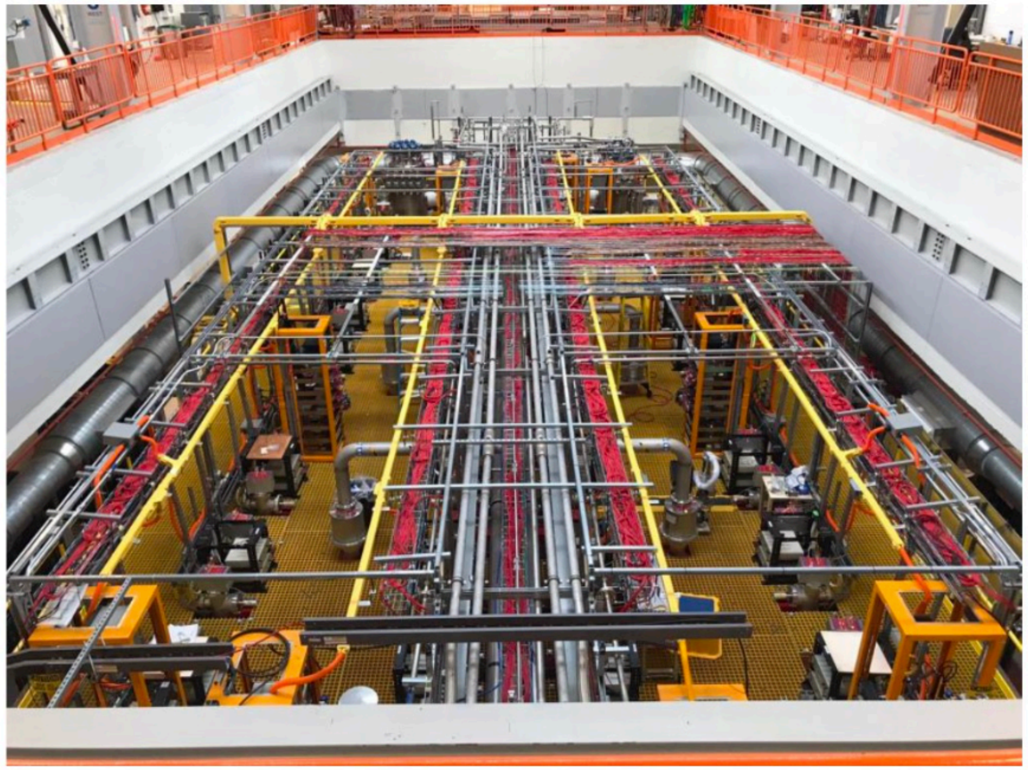
Short Baseline Neutrino Program (SBN)



☑ The SBN Program is composed of three LArTPC detectors with the goal of definitively addressing the hints of eV-scale sterile neutrinos

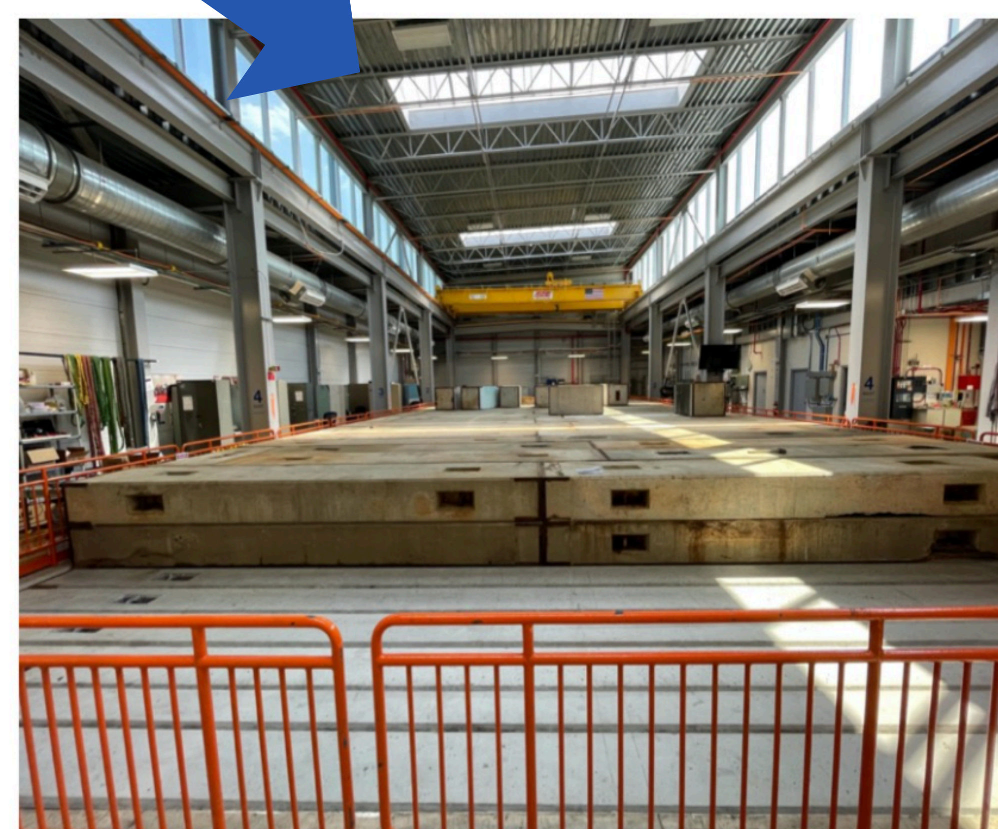
Imaging Cosmic And Rare Underground Signals (ICARUS) in a nutshell

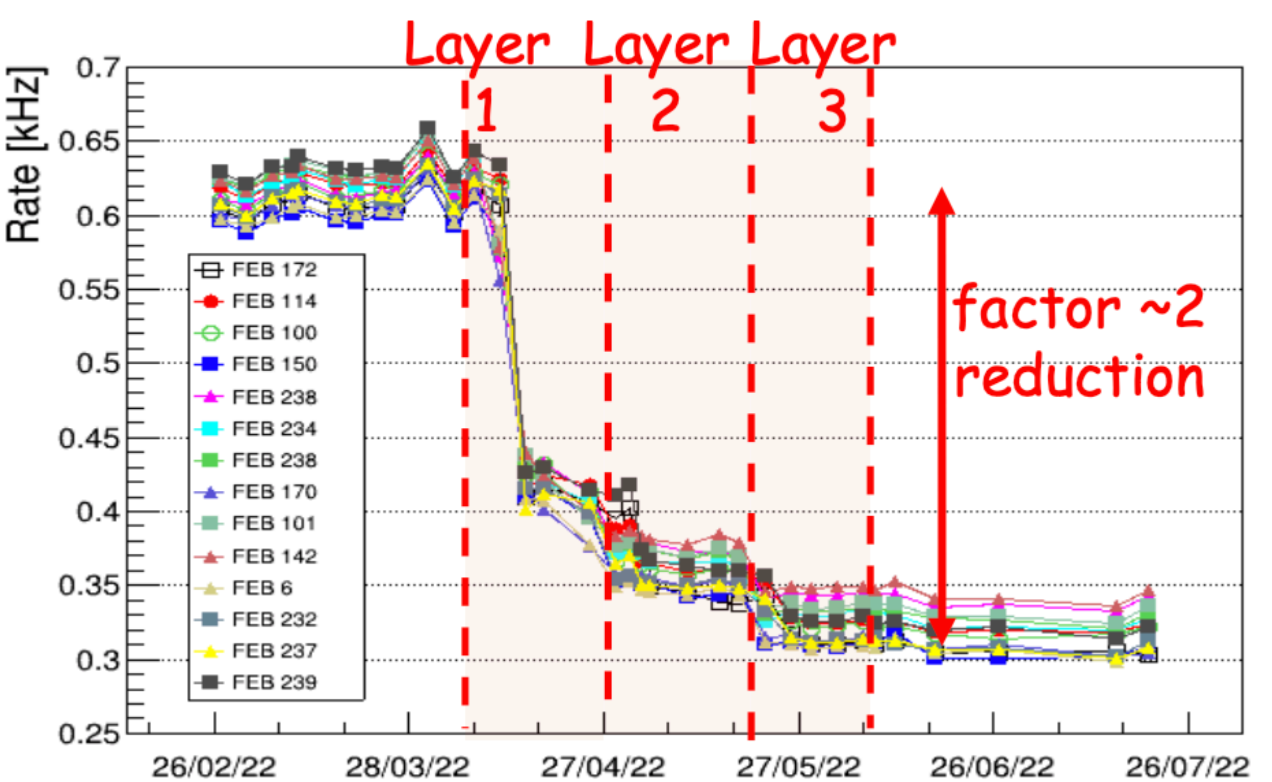




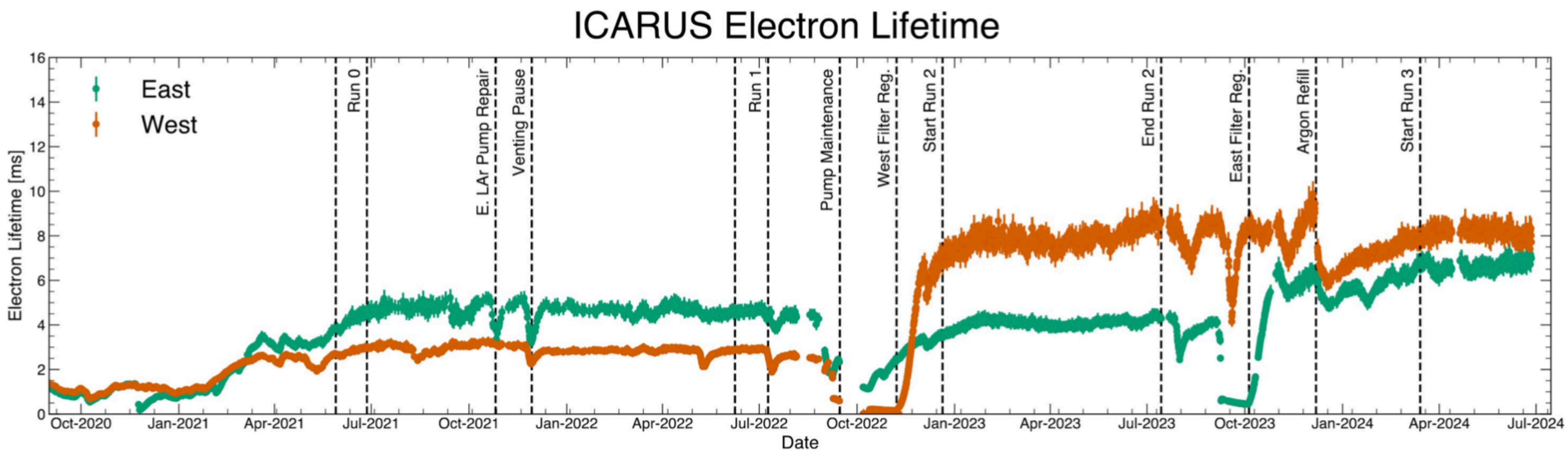
- ICARUS-T600 was the first large LArTPC detector
- Two identical modules (T300) each 19.6 x 3.6 x 3.9 m^3
- ICARUS-T600 Liquid argon mass: total 760 t; active 476 t
- Drift distance 1.5 m. Electric field 500 V/cm (75 kV) -> drift time ~1ms
- 3 signal wire planes (2 induction + 1 collection)
- Pitch : 3 mm; 400 ns sampling time, ~54,000 channels

Installation of the ICARUS Detector at the SBN program



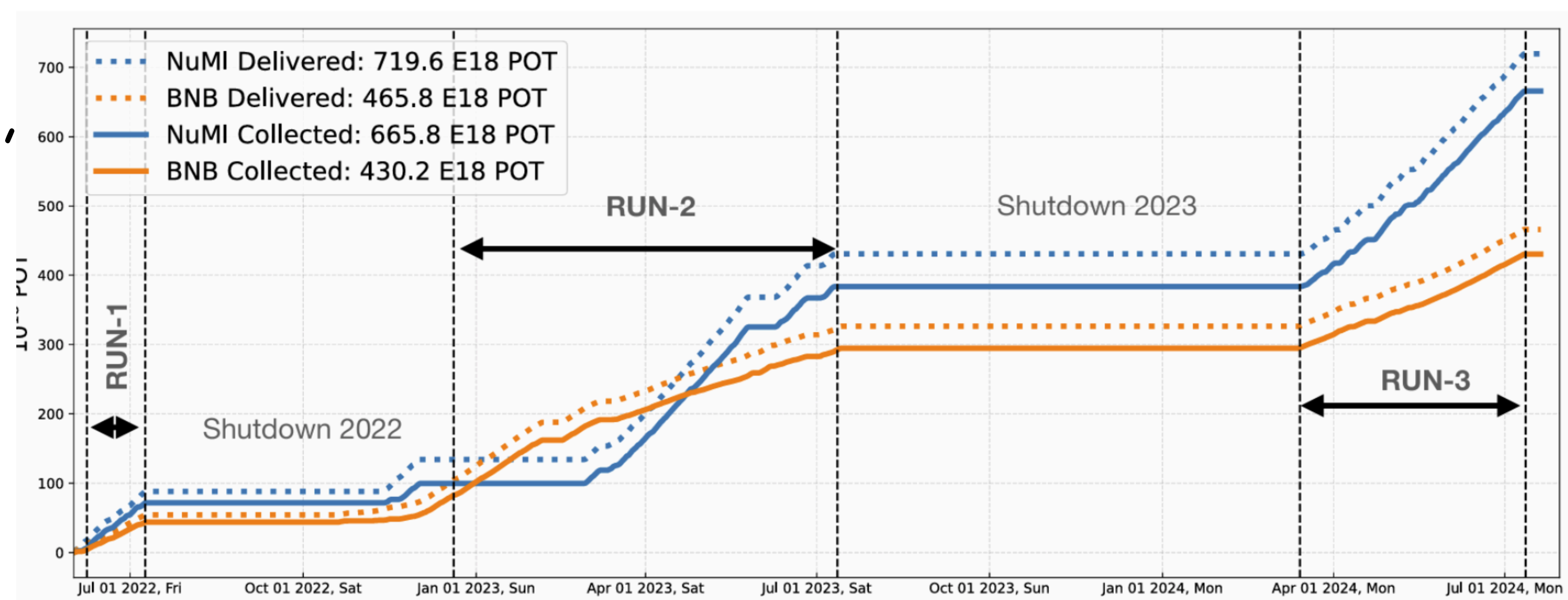


Operation and data taking of the ICARUS Detector at SBN



* Detector filled in April 2020, fully operational from August 2020.

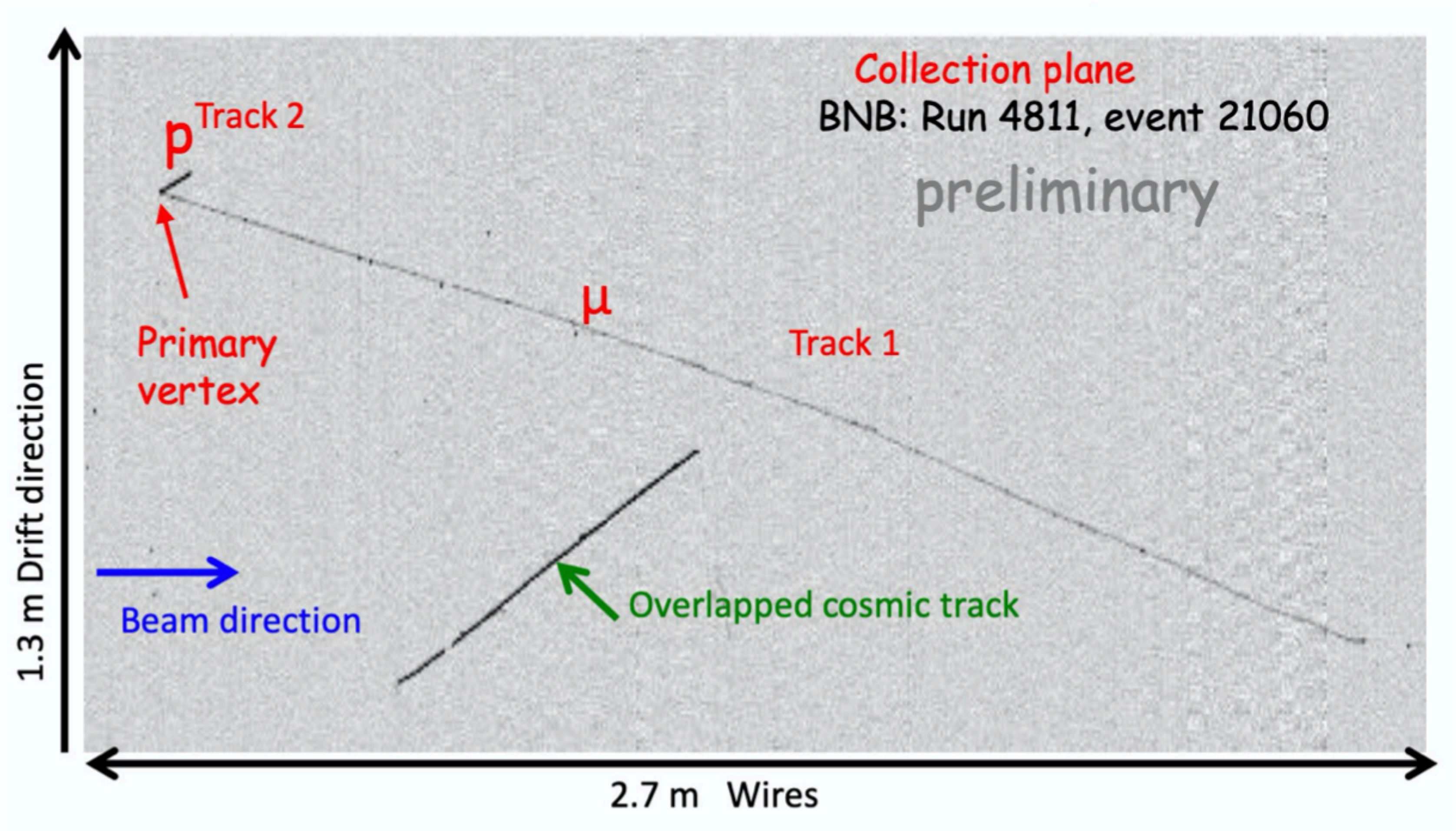
* Commissioning completed in 2022, physics data taking started

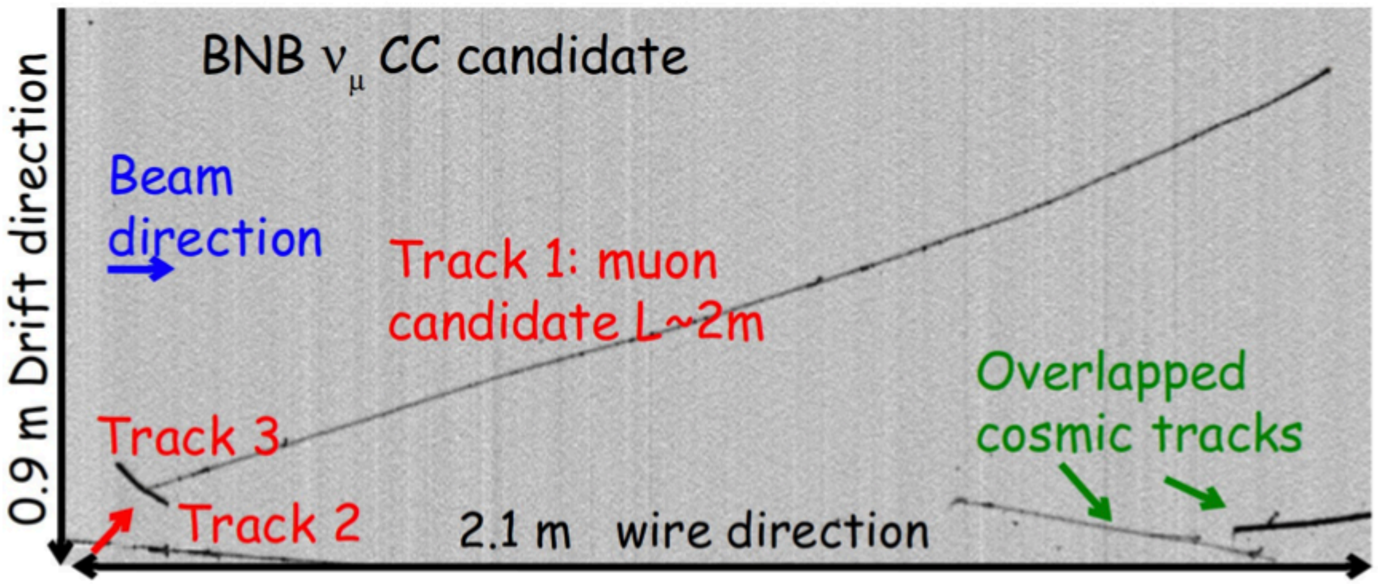


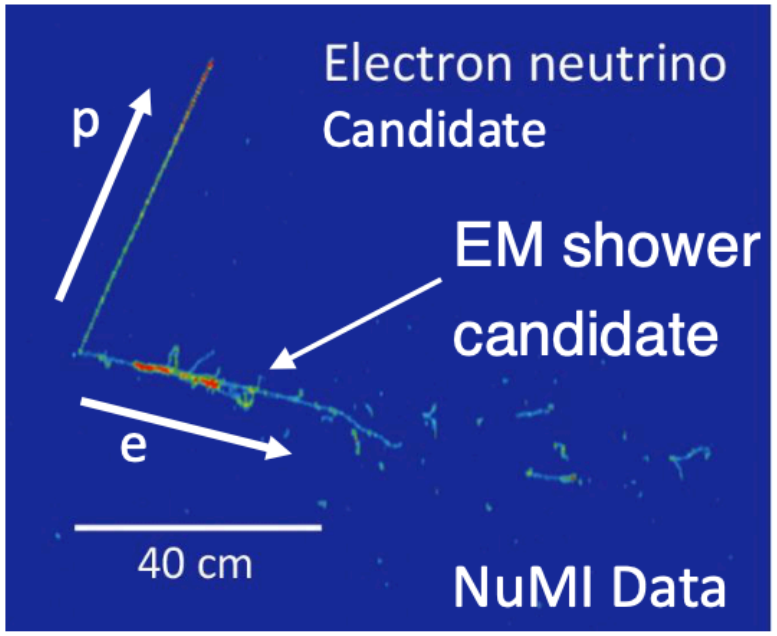
* Electron lifetime reached >3ms target for quality physics data taking

* Detector operates with a light based trigger system in coincidence with beam spill, trigger efficiency >90% for BNB events for energies >200 MeV

Neutrino events inside the detector



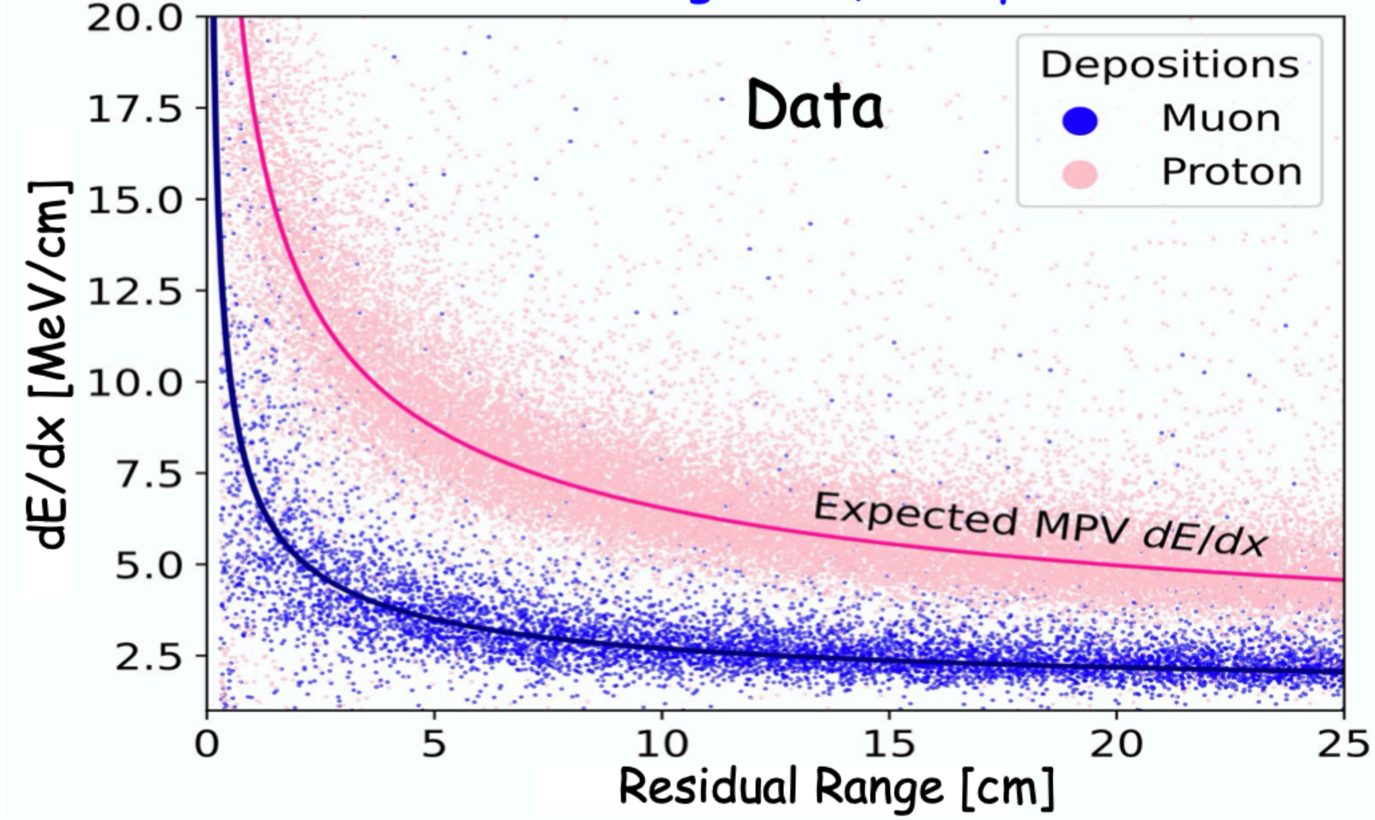




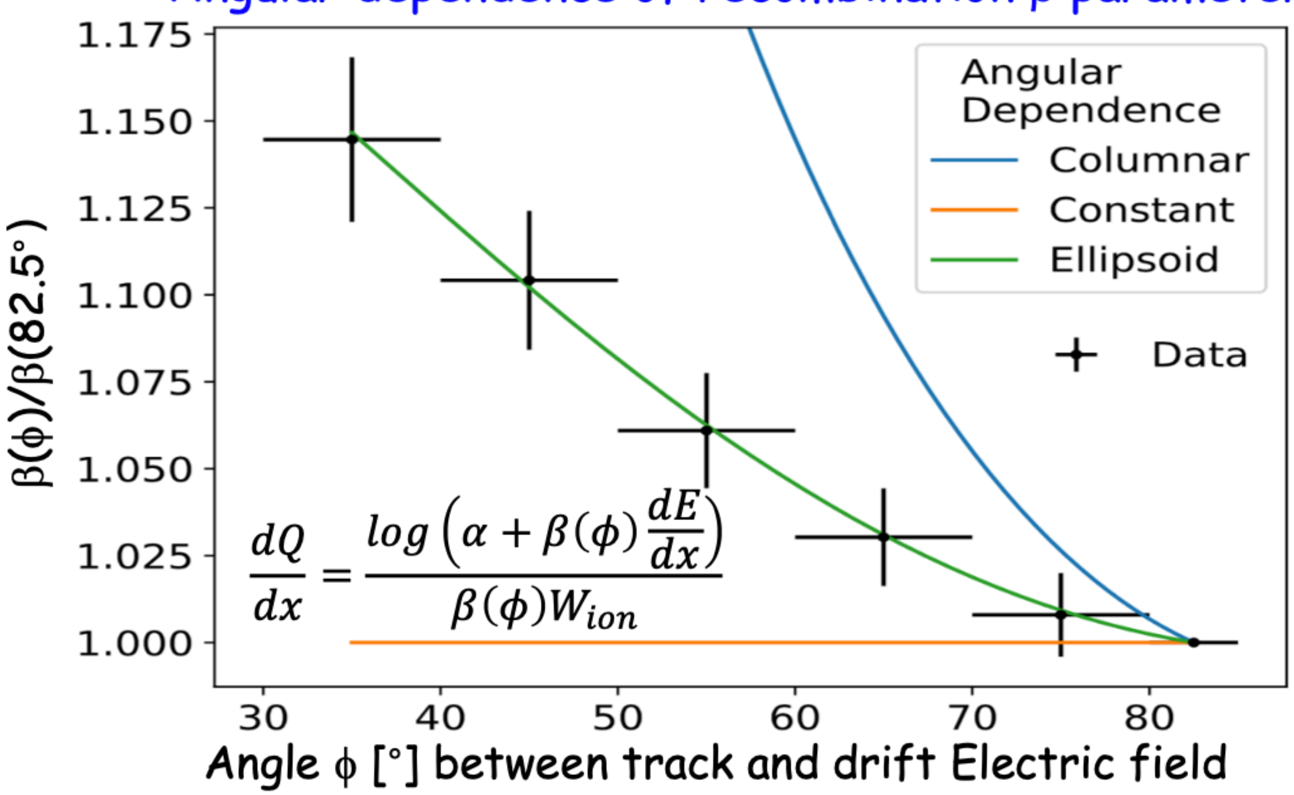
Detector calibration and performance

* Detector response is calibrated with cosmic muons and protons from n events, including a new angular dependent recombination model

dE/dx vs residual range for μ and p used for PID



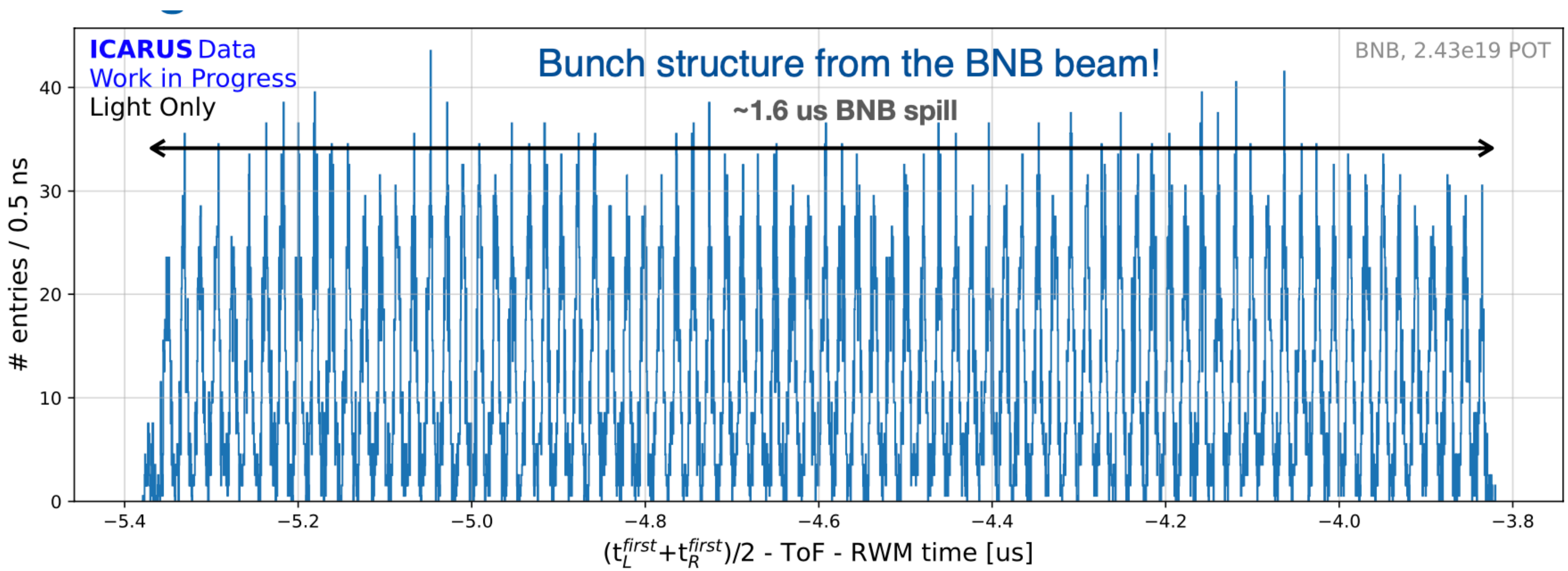
Angular dependence of recombination β parameter



* Particle identification using calorimetric measurements

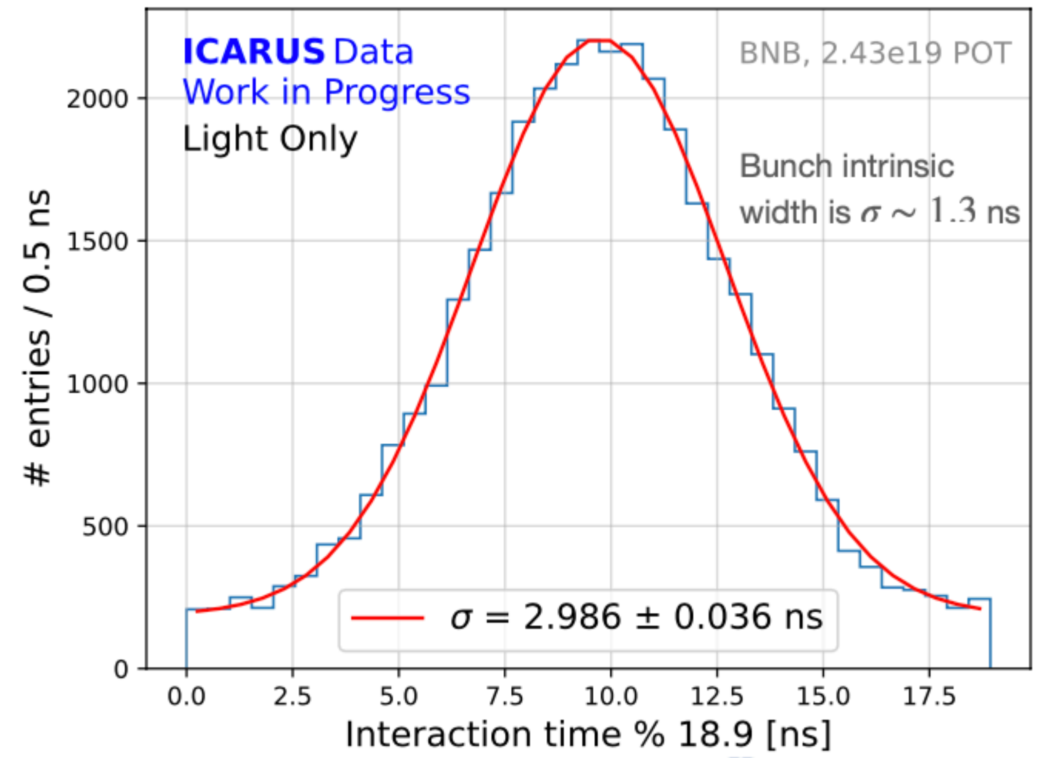
arXiv:2407.12969, submitted to JINST

Beam bunch structure from the data using PMTs



* BNB and NuMI bunch structure reconstructed using PMT system.

Individual bunch structure of the BNB



Physics @ICARUS : Neutrino Oscillation measurements

- The SBN program is searching sterile neutrinos with the BNB beam by looking at the ν_μ disappearance and ν_e appearance using the ICARUS (Far-detector) and SBND (Near-detector) LAr-TPCs.

- ICARUS detector is also exposed to ν_μ/ν_e events from NuMI beam.

- Before the start of joint operation and in preparation for the SBN oscillation analyses, ICARUS is focusing on ν_μ disappearance channel:

  - Focus is on $1\mu\mathrm{Np}0\pi$ final states from events in coincidence with the BNB for the ICARUS single-detector oscillation measurement with two reconstruction approaches

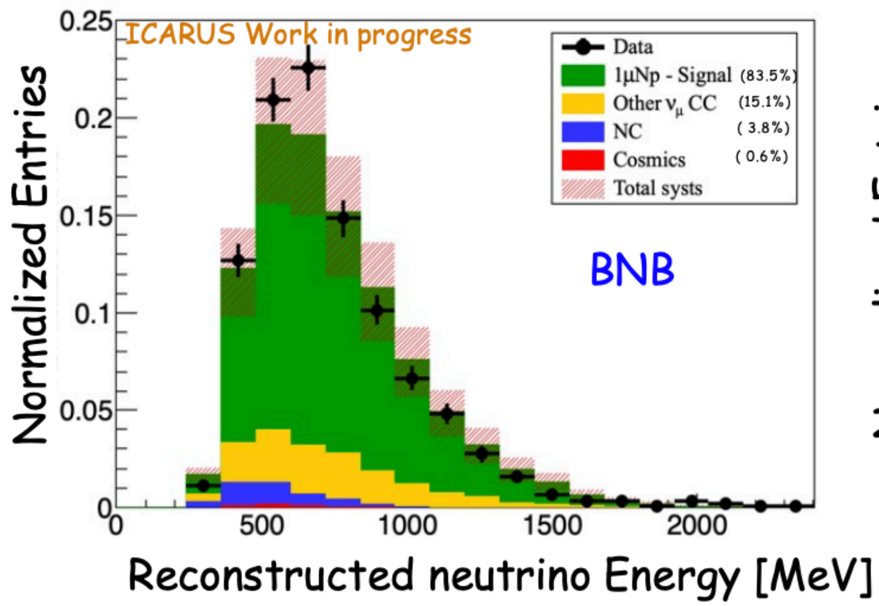
  - Pandora - pattern recognition based software used in previous LArTPC experiments

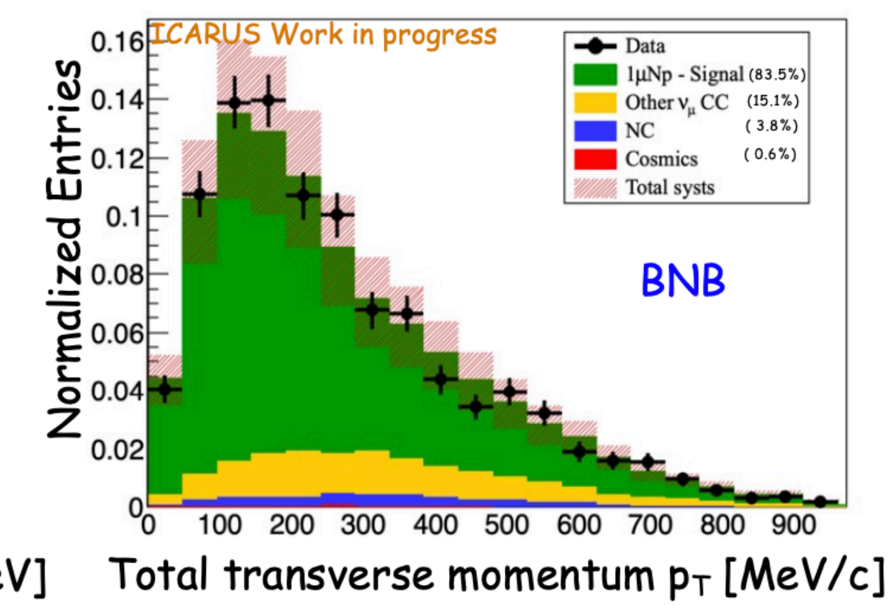
  - SPINE - machine learning based reconstruction chain

Physics @ICARUS : Event Selections for Neutrino Oscillation Physics

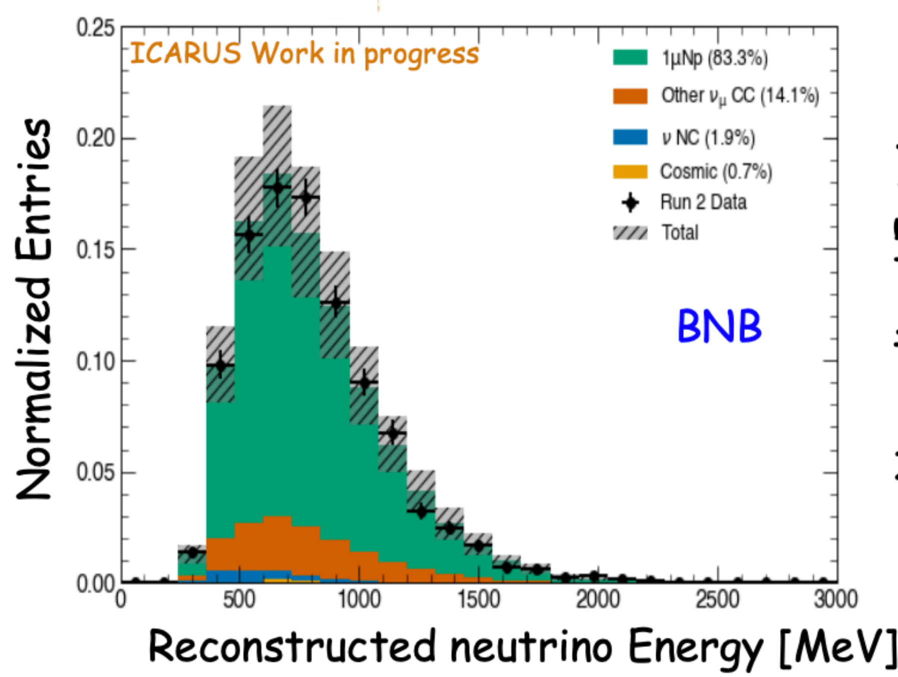
- Advanced event selections are in place looking at $1\mu Np0\pi$ final states
- Good data/MC agreement seen in 10% subset of the Run 2 (2023) data

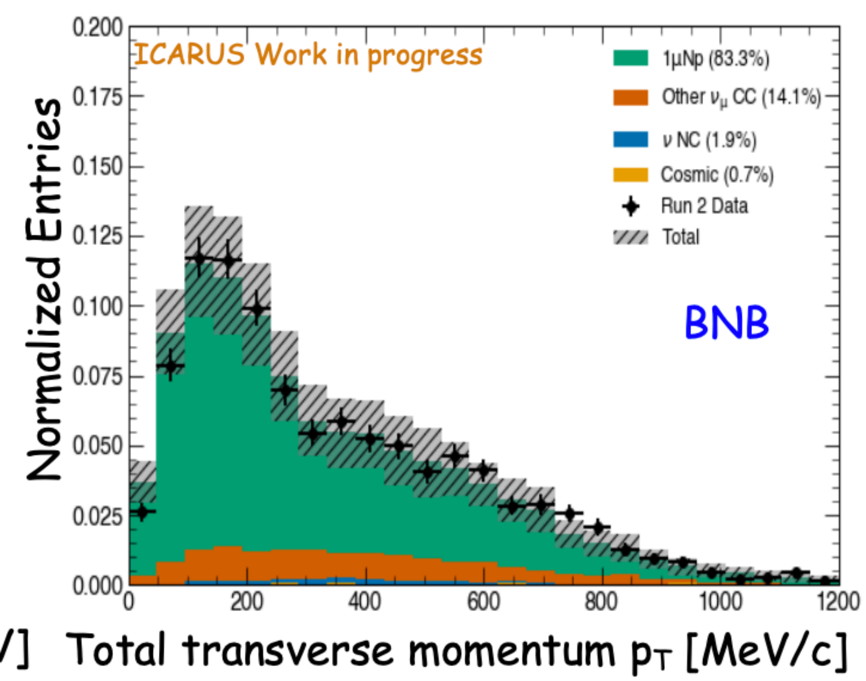
Pandora Selection





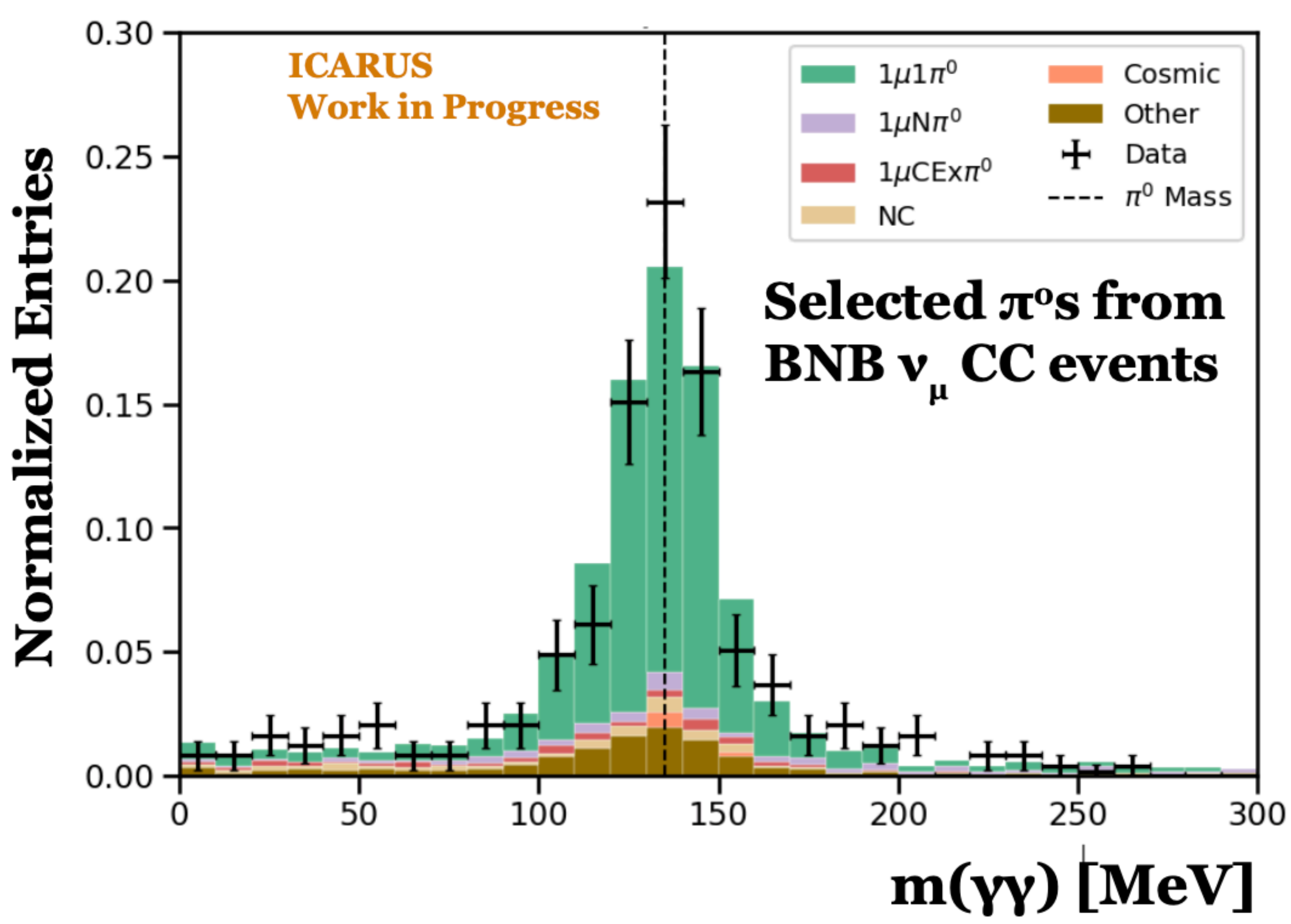
SPINE Selection





Physics @ICARUS : ν_e appearance event selections

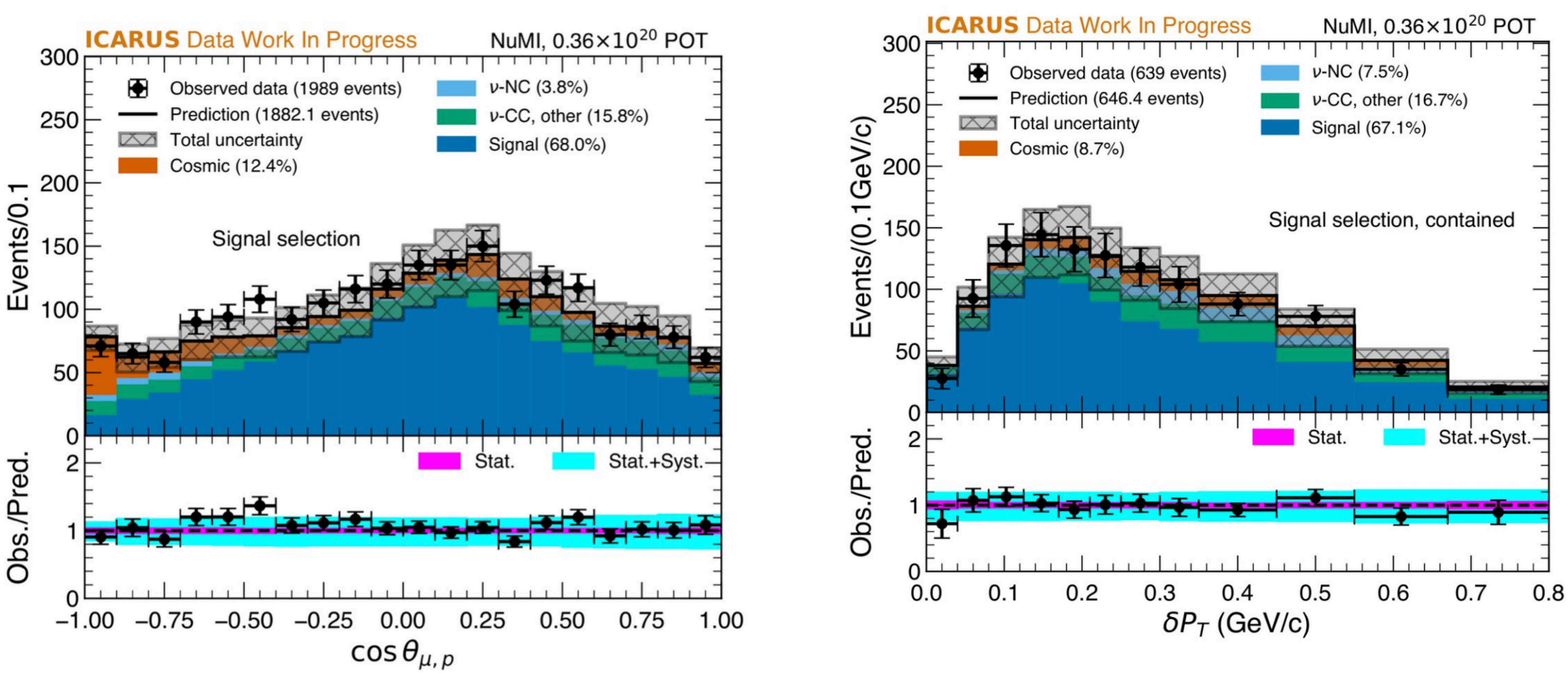
- EM Shower reconstruction is the key for electron neutrino event selection
- Studies using the SPINE reconstruction show promising ability to reconstruct π^0 events which are used to calibrate the shower reconstruction



- Good data/MC agreement!
- Ready for the next analysis steps: enlarge the control sample size to confirm the analysis robustness and then proceed to full dataset unblinding and oscillation fit.

Physics @ICARUS : Neutrino-Argon Cross-section measurements

- ICARUS is located at 6 degrees off-axis to the 120 GeV NuMI neutrino beam.
- Provides high statistics for neutrino-argon cross section measurements: expect ~330k muon neutrinos and ~17k electron neutrinos in 6 x 10^{20} POT

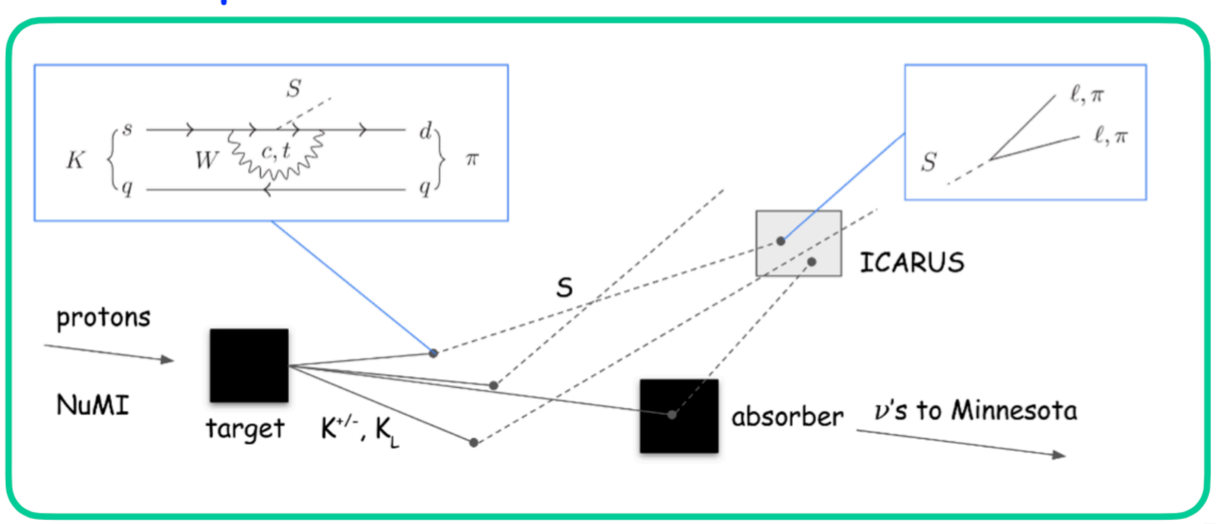


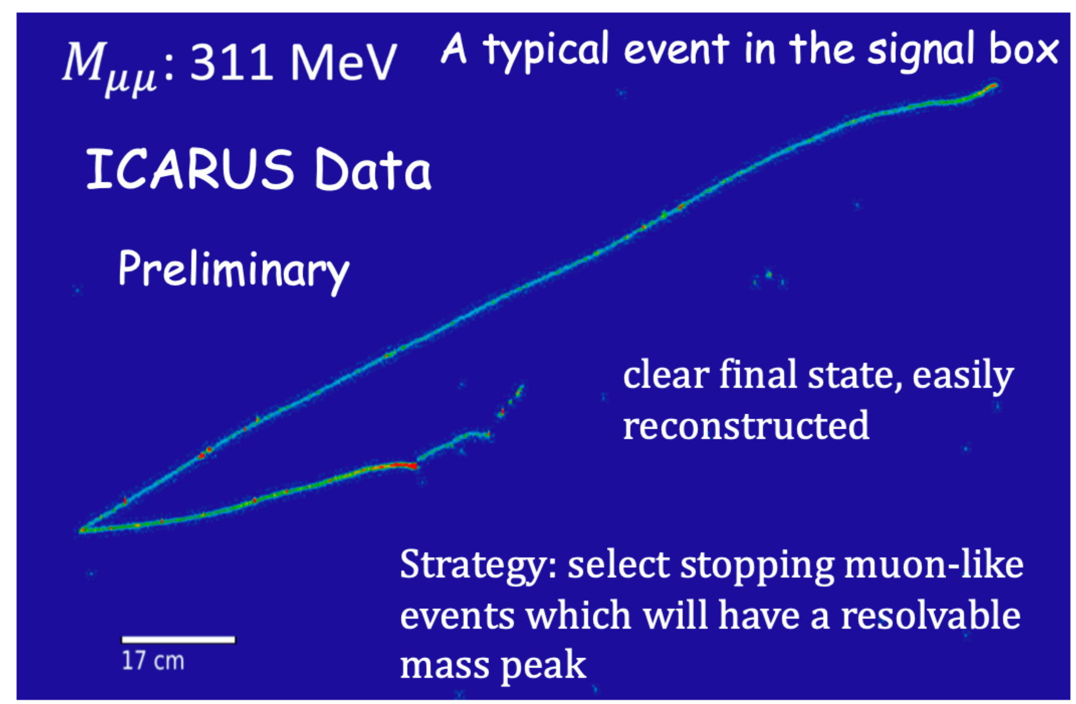
- First cross-section measurement also focuses on $1\mu Np0\pi$ final state.
- Good data/MC agreement with 15% subset of Run1+Run2 (2022+2023) data

Physics @ICARUS :Beyond the Standard Model (BSM) searches

- ICARUS can probe Beyond the Standard Model signatures with the significant sensitivity originating from the NuMI off-axis beam.
- First BSM analysis involve kaon decay and looking at the dimuon final state signature
  - ☑ Higgs portal Scalar (HPS) : Scalar dark sector particles - interactions by mixing with the Higgs boson
  - ☑ Heavy QCD axion (ALP) : Pseudoscalar particles - interactions by mixing with pseudo-scalar mesons
- Other search possibilities include i.e. light dark matter and heavy neutral leptons

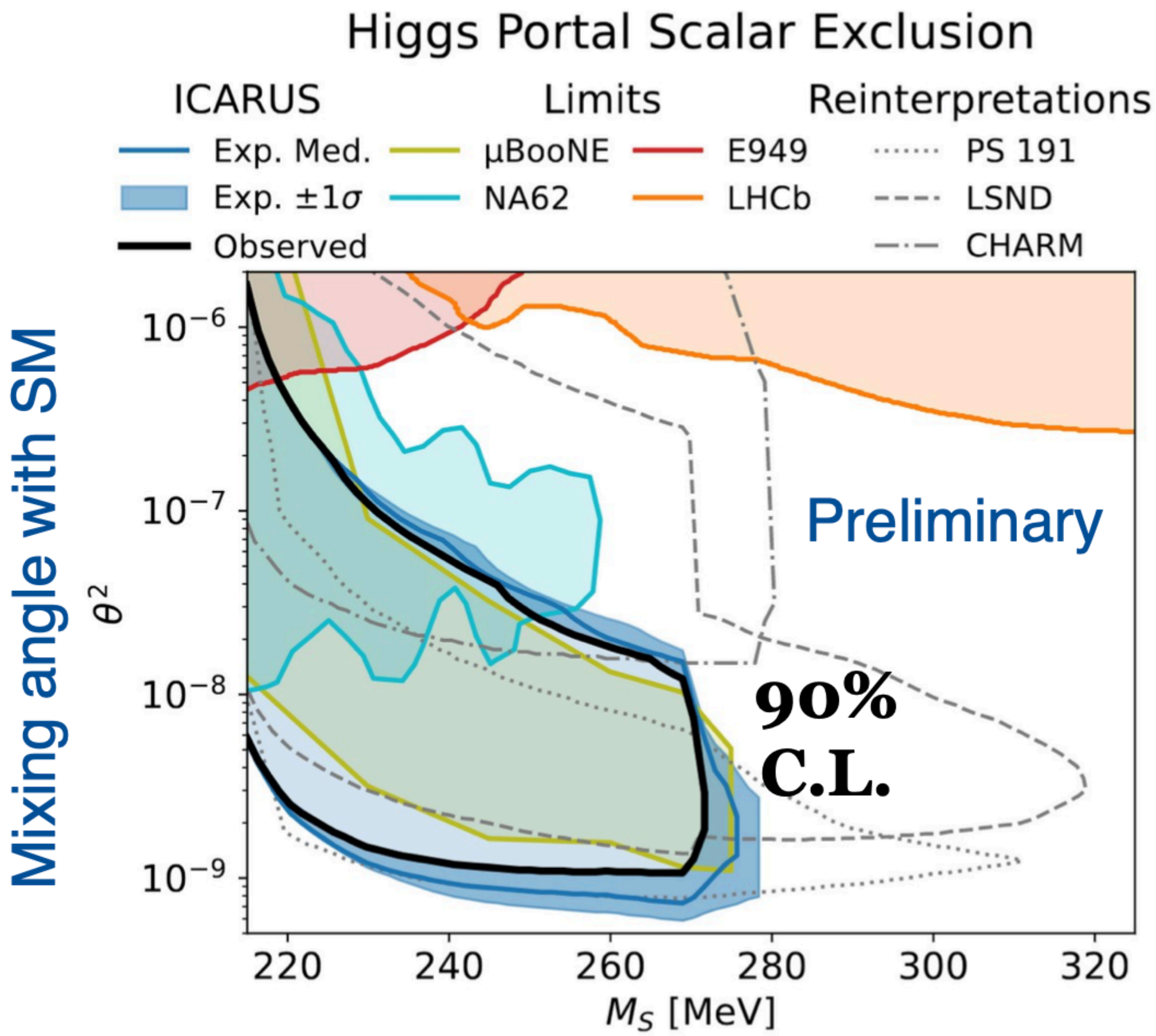
HPS production and detection @ICARUS

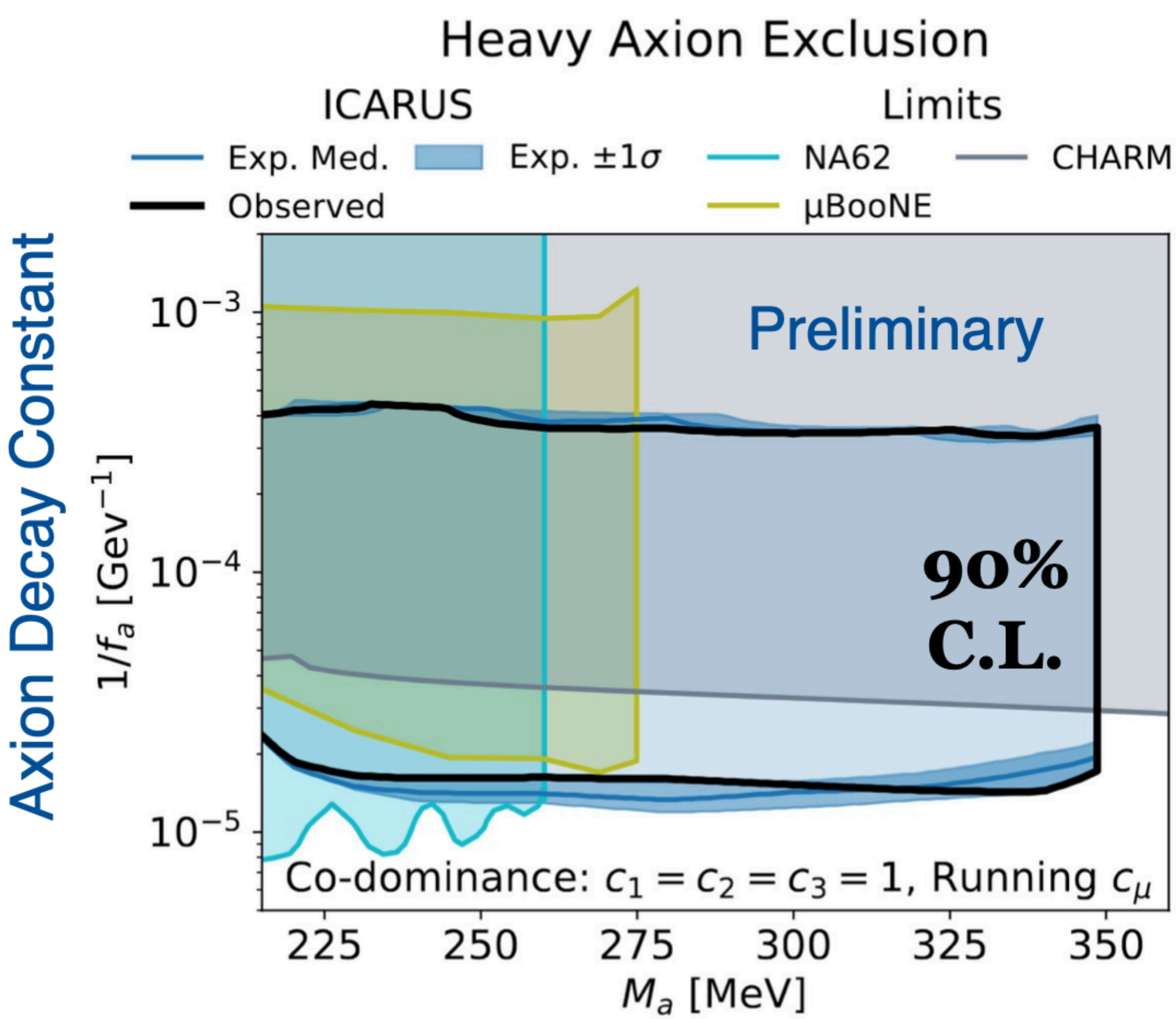




Physics @ICARUS :Beyond the Standard Model (BSM) searches

- The idea to probe HPS/ALP is to look for a resonance ("bump" above the background) at a specific value of the di-muon invariant mass.
- Analysis performed using the ICARUS Run1+Run2 NuMI data, there is no new physics signal observed and the observed events are consistent with the expected background.

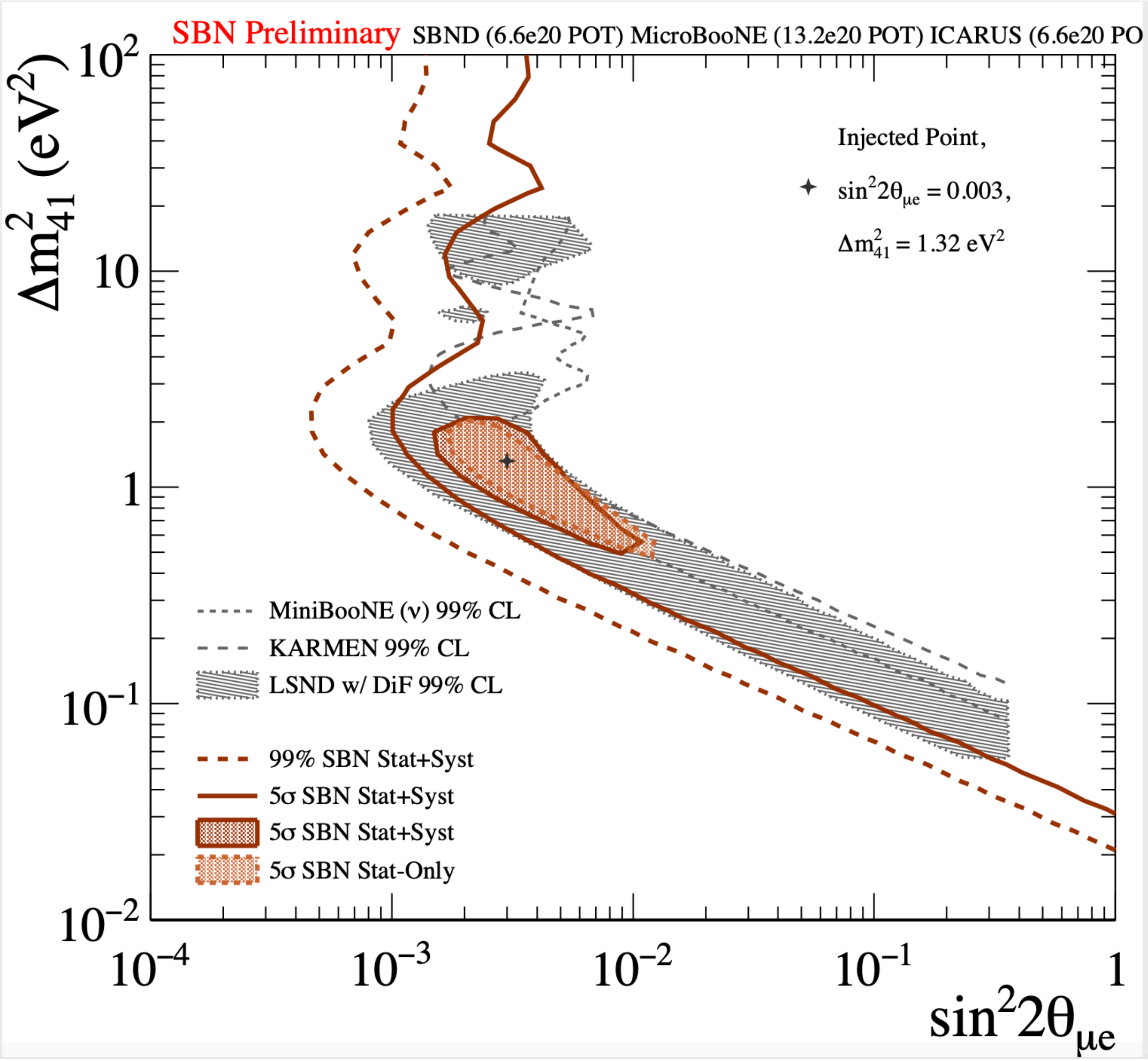




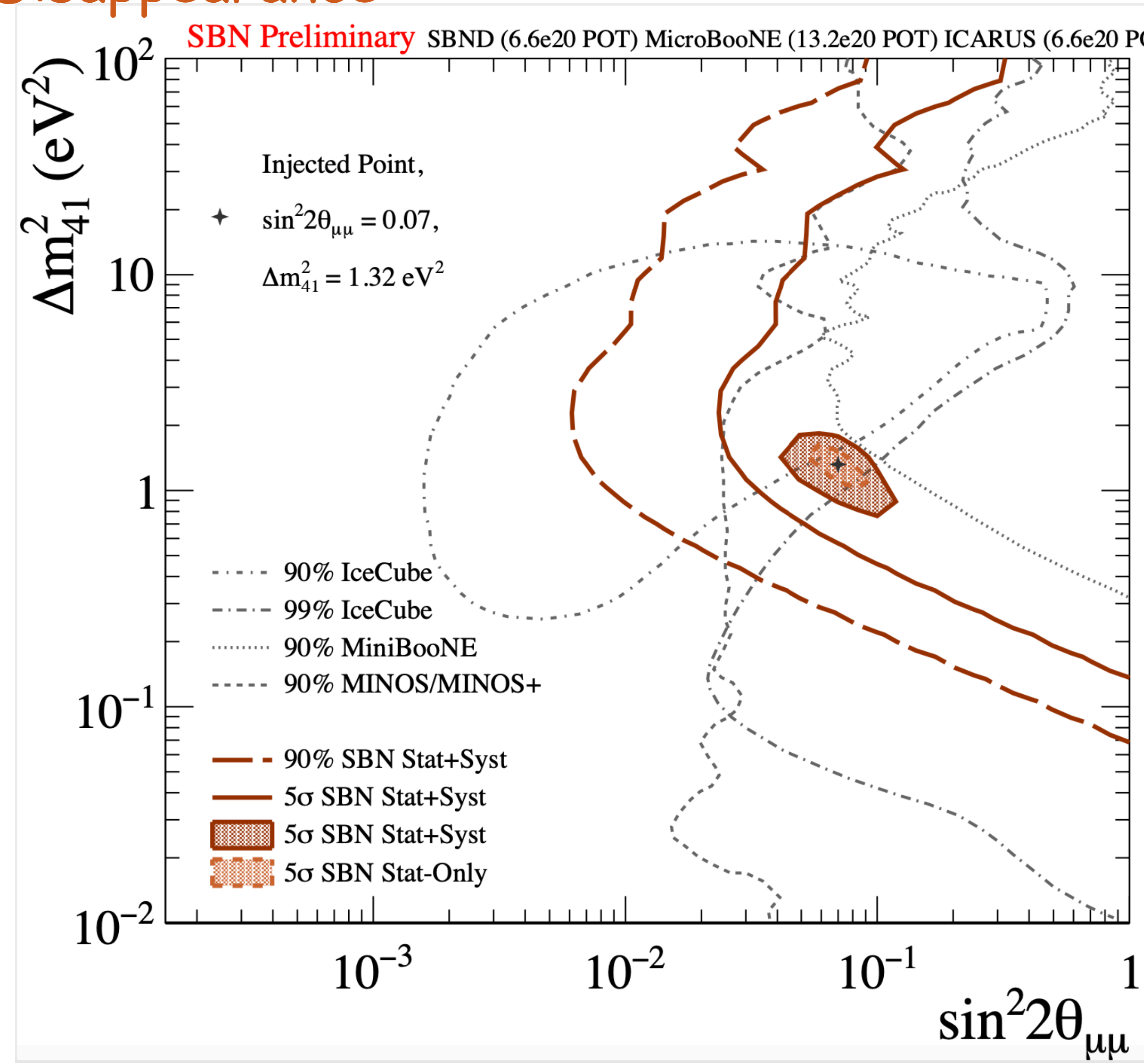
Paper in preparation!

Sterile sensitivity: SBN

Appearance



Disappearance



- ☑ The LSND 99% C.L. will be covered at 5 σ C.L. with just 3 years of data
- ☑ Observations of ν_μ disappearance and ν_e appearance signal will confirm any excess due to sterile neutrino or not
- ☑ SBND experiment at SBN started taking data recently, stay tuned!

Outlook

- The simplest theoretical interpretation of the outstanding short-baseline anomalies in neutrino physics, namely, the light sterile neutrino within the context of a 3+1 model
- Despite significant progress in the form of new experimental measurements and theoretical development, the short-baseline experimental neutrino anomalies remain unresolved
- Different experimental efforts (accelerator-based short/long-baseline, reactor- based short-baseline, atmospheric neutrinos, and radioactive source) will provide solution of the anomalies

Outlook

* The ICARUS experiment is currently operating at Fermilab as part of the SBN program and is currently taking physics data after completing its commissioning period in June 2022
* ICARUS can take advantage of both the BNB beam on-axis and the NuMI beam off-axis
* The ICARUS data can be used for neutrino oscillation searches, cross section measurements, and BSM physics
* Event selections for neutrino oscillations and neutrino-argon cross sections are in advance state with good data/MC agreement
* ICARUS has completed its first physics search looking for Higgs Portal Scalar and Axion-Like Particle BSM signatures
* Stay tuned for more exciting physics results from ICARUS!

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Thank you

Sterile Neutrinos in Cosmology

- 1 eV-mass light sterile neutrino motivated by the short baseline anomalies is in strong tension with cosmological measurements primarily because of the non-detection of a non-standard Neff ~ 4

- $$N_{\rm eff} = 3.11^{+0.37}_{-0.36} \quad (95\%\ {\rm CL})$$ $$\sum m_\nu < 0.16\ {\rm eV}$$

measure for the energy density in relativistic particles

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

- Given the large number of unknowns in cosmology, e.g., the nature of dark energy, inflation, etc., and with different extended models can explain the short-baseline neutrino anomalies with light sterile neutrino hypothesis