SBN physics case
(A short review)

Sandro Palestini

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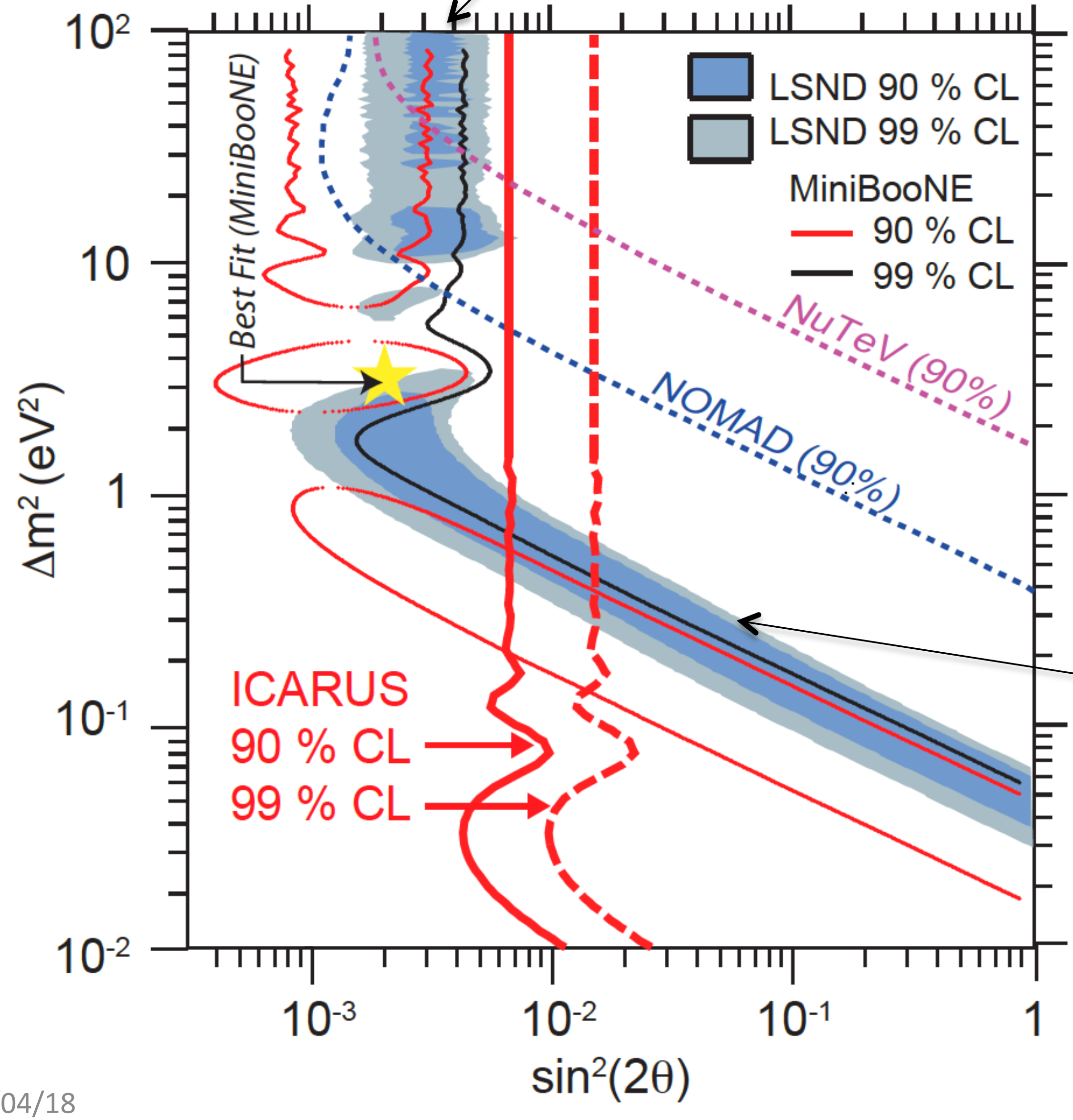
Situation (to be confirmed): more than 3 neutrinos

- LSND oscillations (anti-υ_μ -> anti-υ_e from muons at rest, Los Alamos, at ≈0.25% fraction) 3.8 σ evidence of appearance
- Confirmed by MiniBooNE (BNB beam at Fermilab) with 3.4 (2.8) σ for (anti)neutrinos

- Low energy anomalies: ν_e flux deficit ≈7% observed at ≈3 σ with nearby detectors at reactors, and with calibration sources at solar neutrino experiments SAGE and Gallex.

- Phenomena at $L/E \approx 1$ m/MeV, or $\Delta m^2 \approx 1$ eV^2, far from the scale of oscillations established at $\Delta m^2 = 2.5\times10^{-3}$, 0.76×10^{-4} eV^2 for atmospheric and solar neutrinos.
- An additional mass difference implies at least one additional neutrino, which does not take part in SM weak interactions.

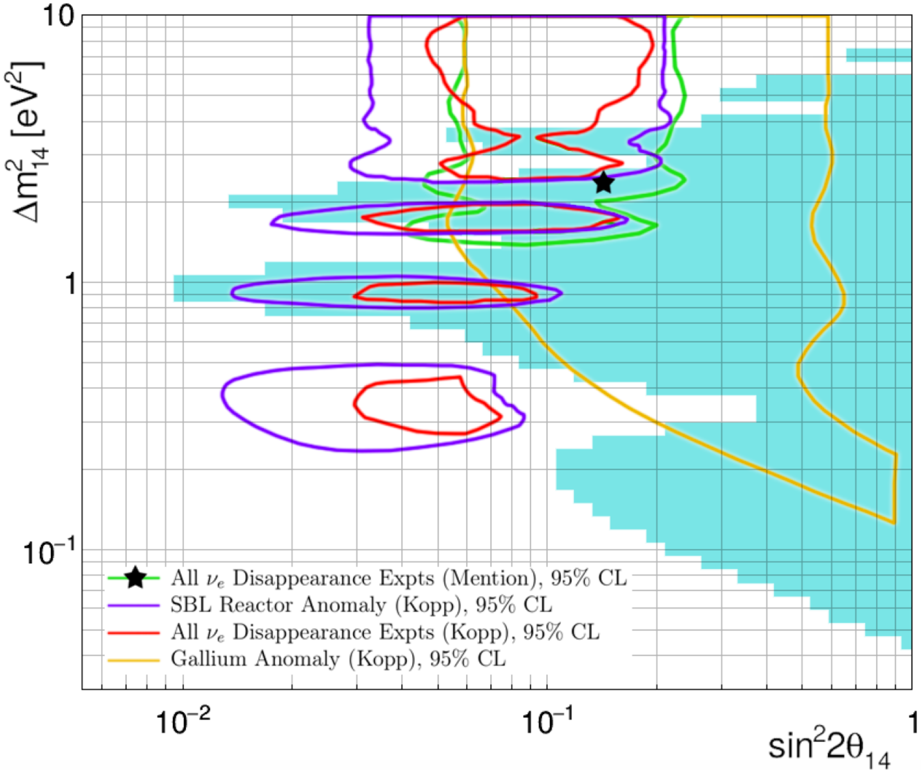
Band of solution with many oscillations, averaging ½, with $\sin^2(2\theta) \approx 0.5\%$ for LSND.



LSND and MiniBooNE have observed an excess of υ_e equal to ≈0.25% of υ_μ, after subtraction of other sources and bkg.

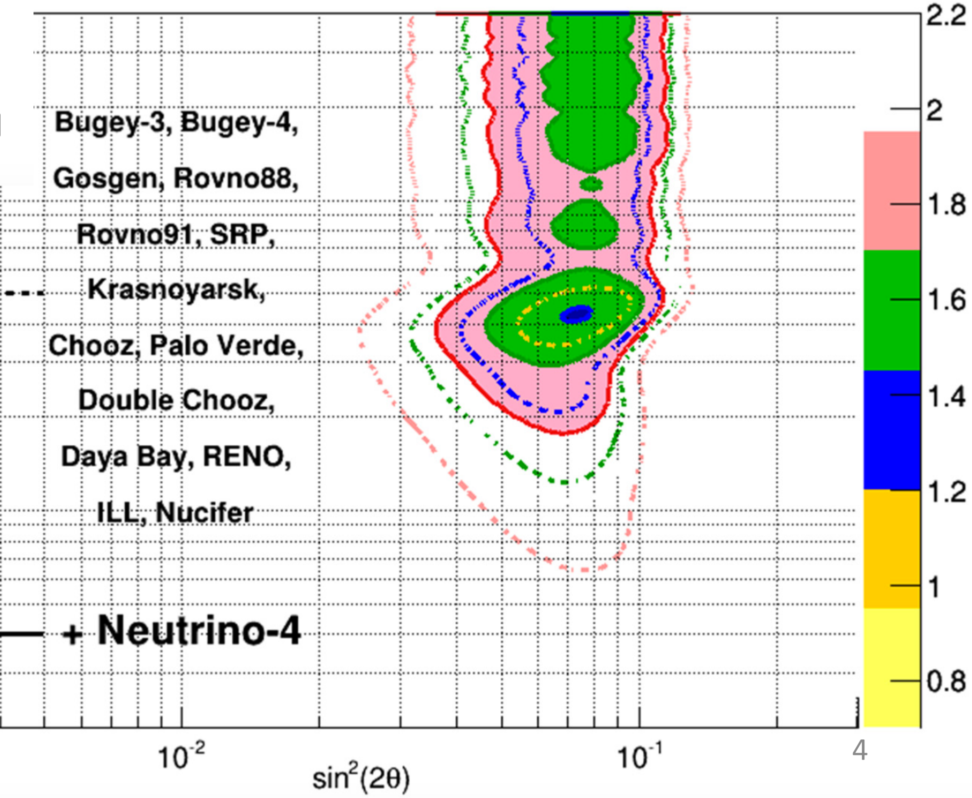
Band of solution for initial oscillation with $(\Delta m^2)^2 \times \sin^2(2\theta) \approx \text{constant}$

Low energy anomaly current status



DANSS – arXiv:1804.04046

Nutrino4 – arXiv:1702.00941

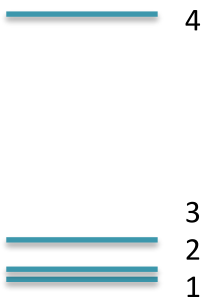


Note that the amplitude explored is at the level of some %.

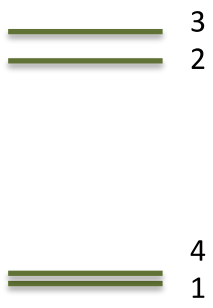
Better sensitivity for future experiment(s) with ^{144}Ce-^{144}Pr source (usual Inverse Beta Decay, e+ annihilation and n capture in scintillator).

Phenomenology

- New mass difference: at least one new sterile υ
- Schemes:
    - 3+1 : 3 υ's in the usual mass pattern plus a fourth one (which does not interact with leptons, Z …) well separated from the others.



    - 2+2 : doublet internally separated by dm^2_{solar}, $dm^2_{atmospheric}$, and globally separated by $\approx 1eV^2$



    - >1 sterile neutrinos

Phenomenology of 3+1 ν’s

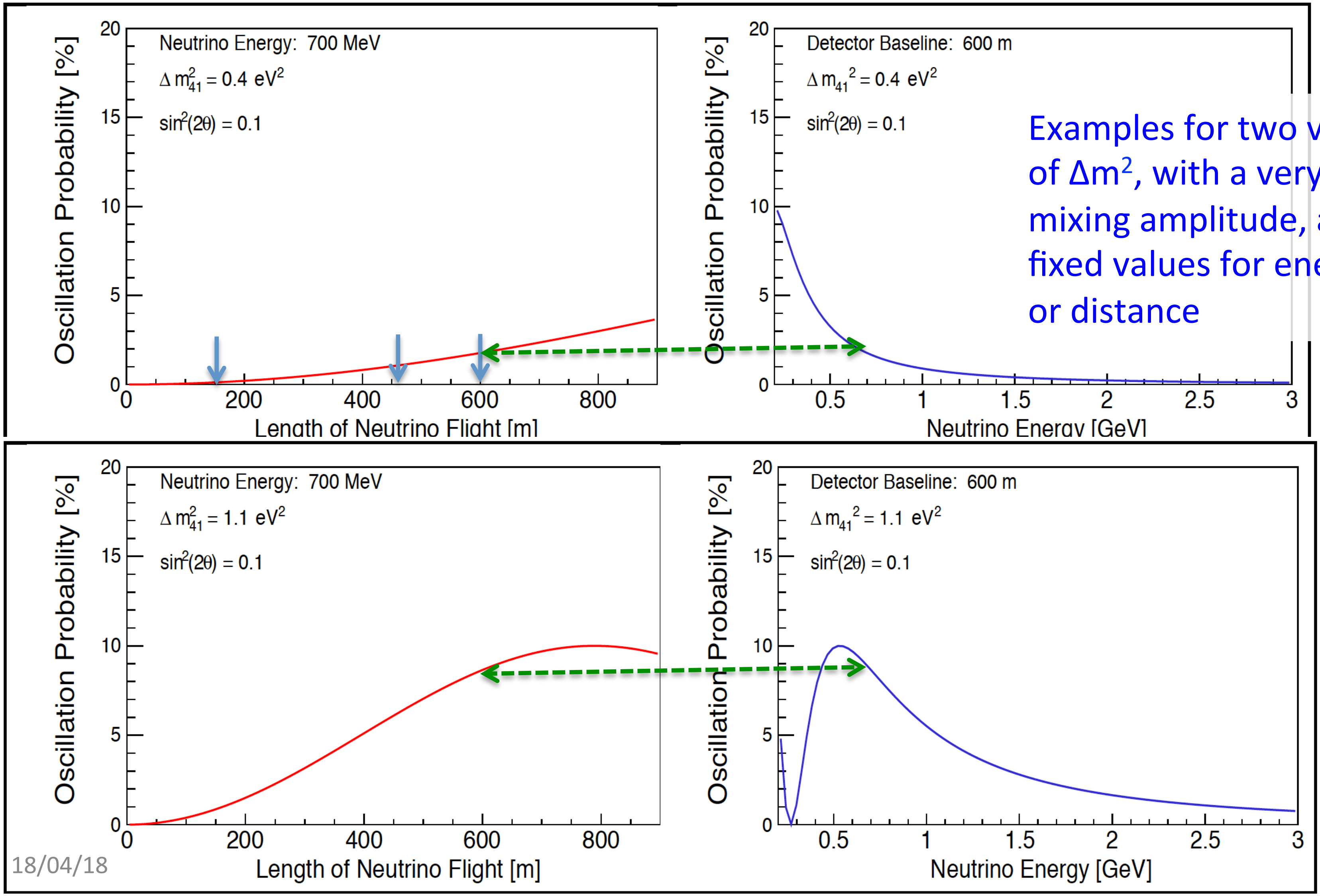
- 3+1 is more frequently taken as paradigm:
  - In the regime of oscillations driven by Δm^2_{4i} :
    - $Prob^{3+1}(\upsilon_\mu\text{->}\upsilon_e) = \sin^2(2\theta_{\mu e})\,\sin^2(\Delta m^2_{4i}L/4E)$
    - $Prob^{3+1}(\upsilon_\mu\text{->}\upsilon_\mu) = 1 - \sin^2(2\theta_{\mu\mu})\,\sin^2(\Delta m^2_{4i}L/4E)$
    - $\sin^2(2\theta_{\mu e}) = 4\,|U_{\mu 4}U_{e4}|^2$
    - $\sin^2(2\theta_{\mu e}) = 4\,|U_{\mu 4}|^2\,(1-|U_{\mu 4}|^2\,)$
  - Similar equations can be written in the regimes of oscillation driven by Δm^2_{21} and $\Delta m^2_{32} \cong \Delta m^2_{31}$.
  - Observed amplitude of the oscillations in the 2-neutrinos scheme implies $|U_{\mu 4}|^2 \approx |U_{e4}|^2 << 1$.

SBN concept in few words

- Improve on MiniBooNE with better detector(s) (better ID, less background)
- Expand the L/E range using three similar detectors
  - SBND, MicroBooNE, Icarus (T600) at 150m, 470m, 600m and 80t, 90t, 480 t fiducial volume respectively
  - Similar (LArTPC) technology to improve performance and systematics
  - Reduction of beam systematics due to knowledge of BNB and flux scaling properties (in particular between 470 and 600 m)
- Experiments at surface, cosmic-ray induced background is relevant.

Measurement main target: υ_e appearance

To be obtained measuring the *E, L* dependence of Charged-Current events in excess of non-oscillating υ_e in the beam (from K, μ decays) and of backgrounds



Examples for two values of Δm^2, with a very large mixing amplitude, and fixed values for energy or distance

Measurement target: mainly υ_e appearance

- Detectors:
  - Charged particle reconstruction in LAr TPC , with collection time 1.3 ms, 1.6 ms , 1.0 ms respectively, with 3 layers read-out wires, 3 mm spacing (read out in Lar).
  - E_υ from energy of electron (CC interaction)
  - Scintillation light signal to enforce coincidence with beam spill

- Beam: Fermilab Booster Neutrino Beam (8 GeV p)

  5E12 p per spill, 1.6 micros spill, 2ns/19ns substructure

  5 Hz cycle, 6.6E20 p on target, 3 years run

  (211 s total *beam time*)

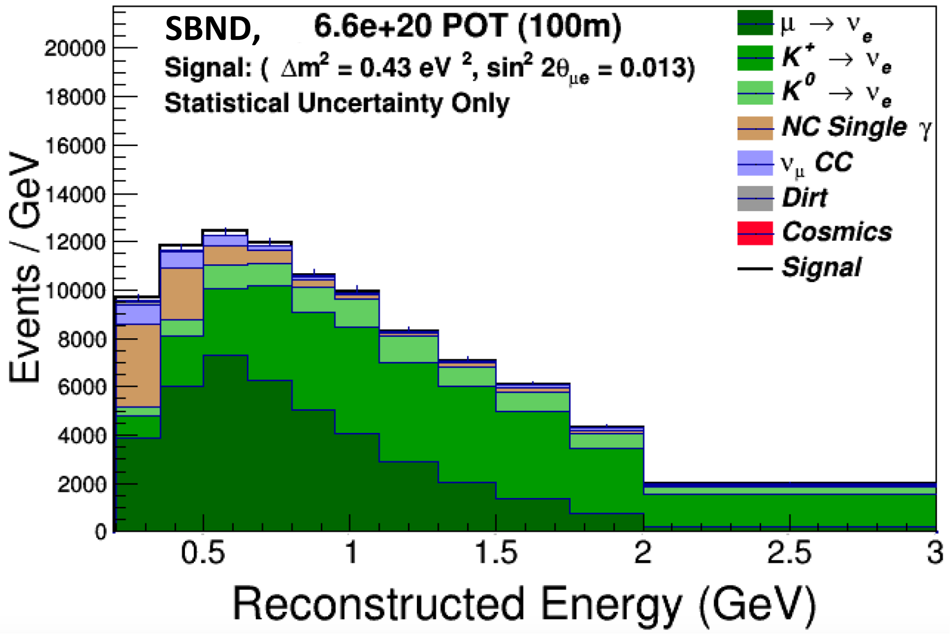
Backgrounds

- Beam interaction in detectors:
  - NC gamma misidentified as electron events (reject with local energy deposition) (E > 200 MeV taken as selection criteria, with 80% reconstruction efficiency)
  - υ_μ CC with π^0-> γ's mistaken as $e^\pm$ and μ misidentified
  - υ_e e- elastic scattering, but the cross section is small
- Beam interactions near detector (*dirt events*):
  - Fake $e^\pm$ mostly near detector front and side walls, mitigated with fiducial volume < LAr volume
- Background related to cosmic rays (*cosmogenic bkg.*):
  - gamma conversion taken as υ_e CC

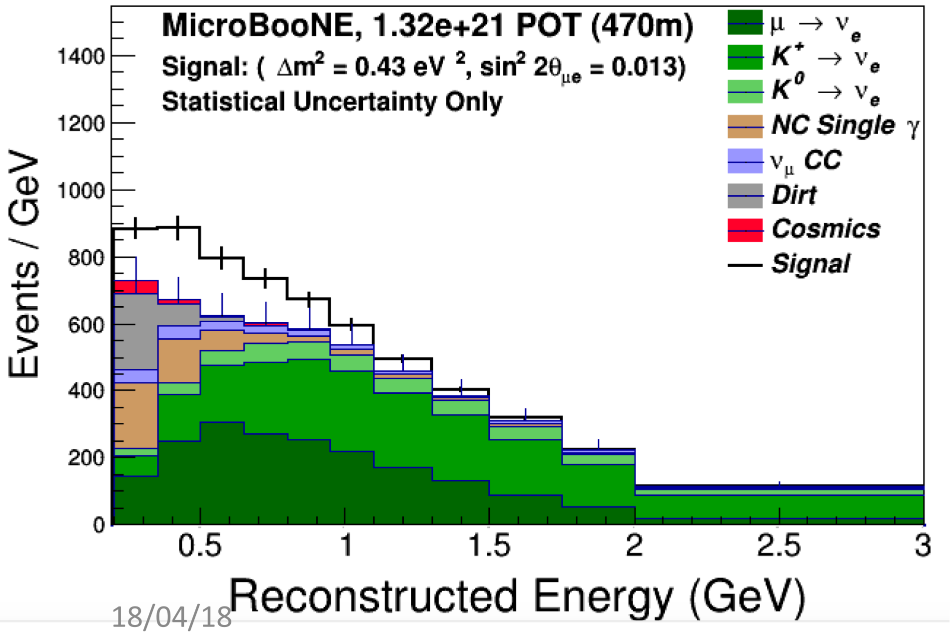
Cosmogenic bkg. continued

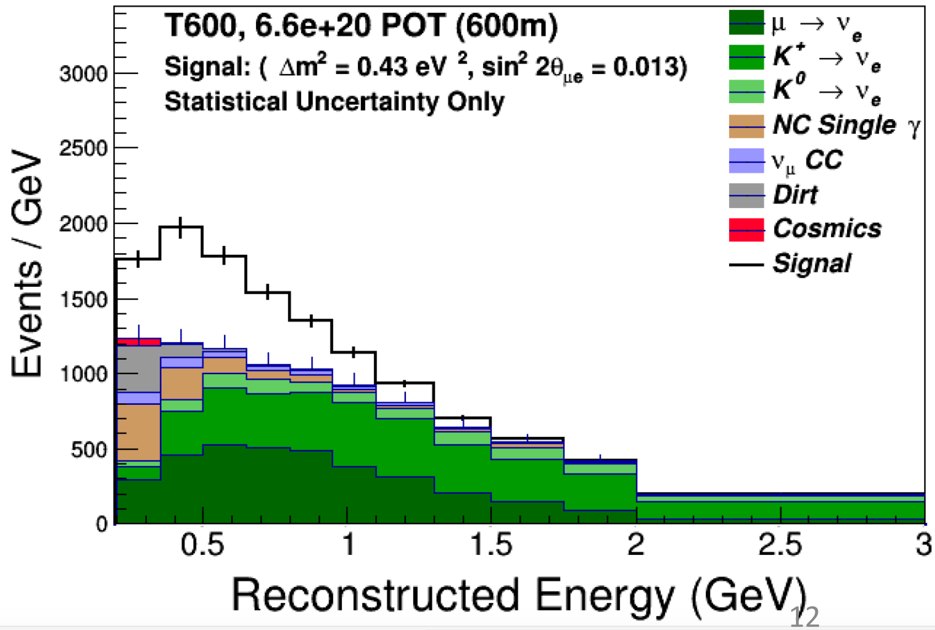
- Needs to be in time with beam spill
- Better, in time with spill substructure (2 ns ≈ σ_{time} << 19 ns)
- Tends to come together with a muon entering/crossing the detector
  - Reject if υ_e CC candidate near a muon (or near wall)
- Can be present also if in time only with the detector collection time (≅1 ms)
  - if a second cosmogenic background event occurs in a triple coincidence with the spill (1.4 µs) (triple coincidence)
  - or if a beam interaction (e.g. υ_μ CC) takes place in the same spill.
- Mitigate with:
  - association of υ_e CC candidate with scintillating signal to enforce timing to 1.4 µs
  - External veto tagging (position and time for 1.4 µs coincidence)

Example of expected dN_{υ_e}/dE



Note the large value of the oscillation amplitude chosen here,
and the differences in event yield, related to position and volume.
The muon tagger reduces the cosmogenic bkg. by a factor > 100.



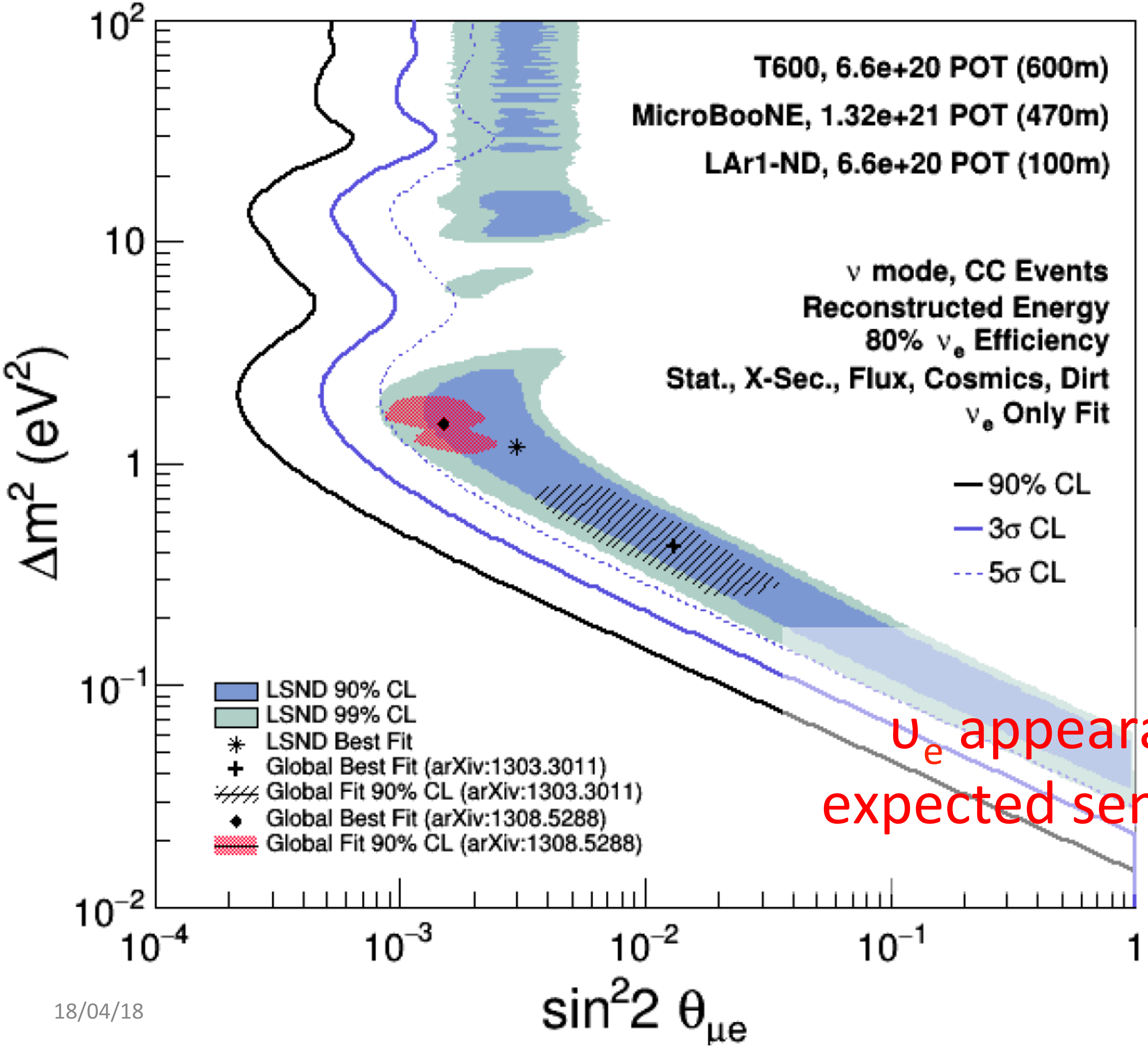


Beam related systematics

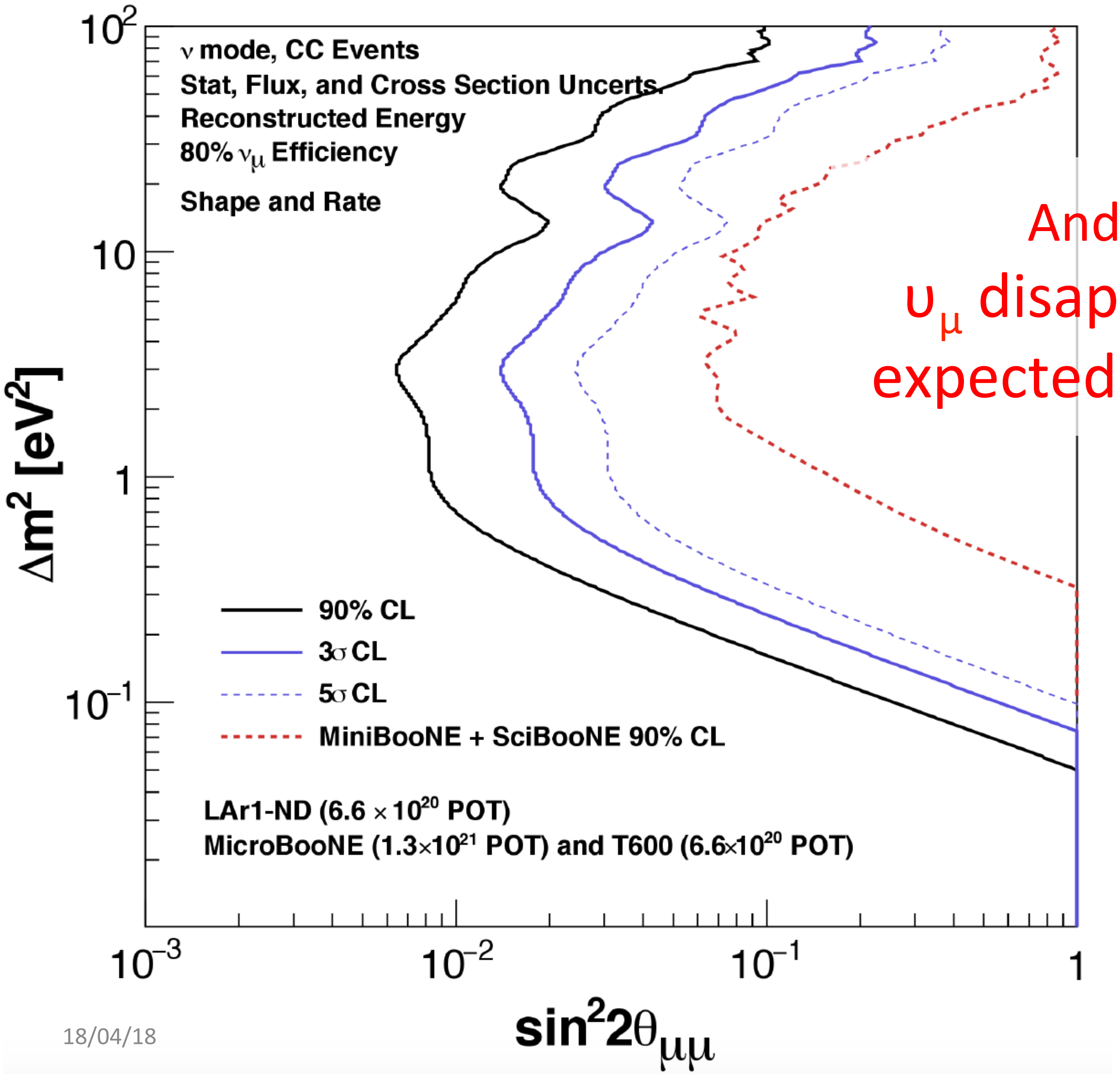
- Normalization uncertainties in the total flux are at the level of 10-15% in both neutrino flux and the neutrino interaction uncertainties.

- However the effect of these uncertainties cancel to large extent:
  - Relative rates in the three detectors are used in the measurement
  - Very similar detector response, and use of the same beam result in largely coherent systematic errors (hence favorable) in reconstructed energy spectra among the different detectors and the between υ_e and υ_μ CC events.

Coming to the conclusion:



υ_e appearance expected sensitivity



And also:
υ_μ disappearance
expected sensitivity