Short-baseline neutrino experiments

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Fermilab, November 7 2013

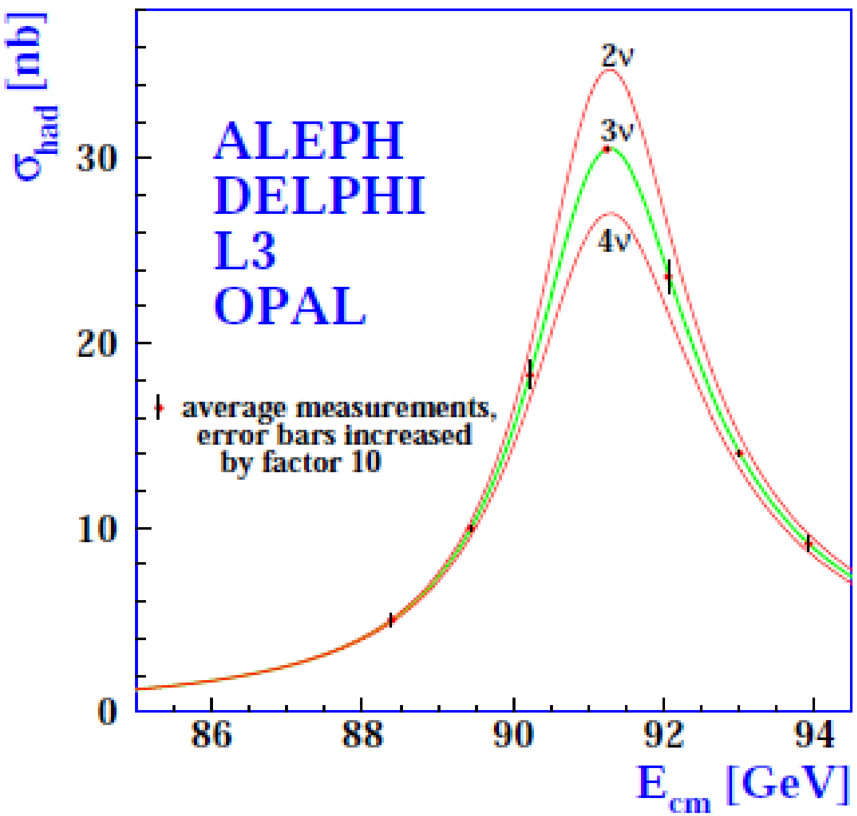
Outline

- Sterile neutrinos
  - Theory
  - Experiment
- Future outlook
- Light Dark Matter

Standard Model neutrinos

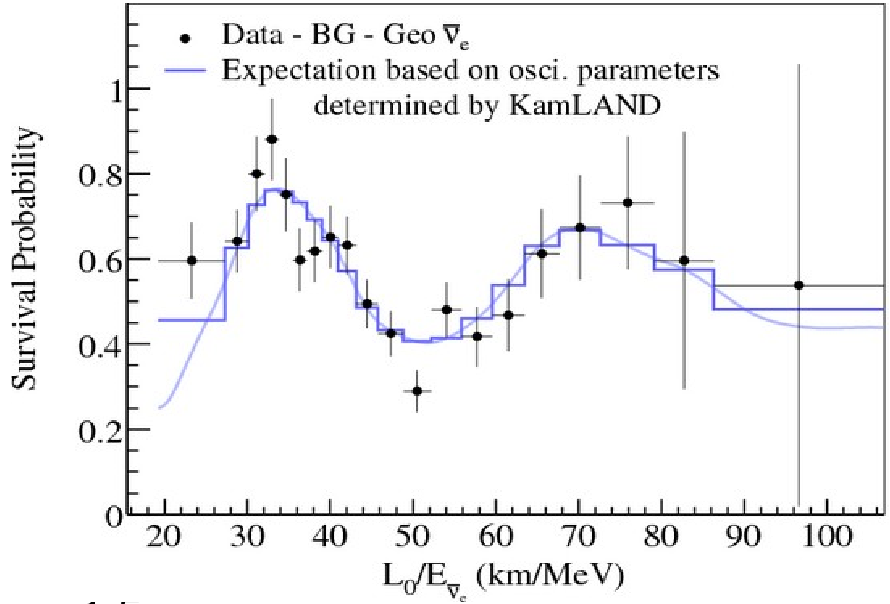
- 3 active neutrinos in Standard Model: ν_e, ν_μ and ν_τ
- Invisible Z^0 width

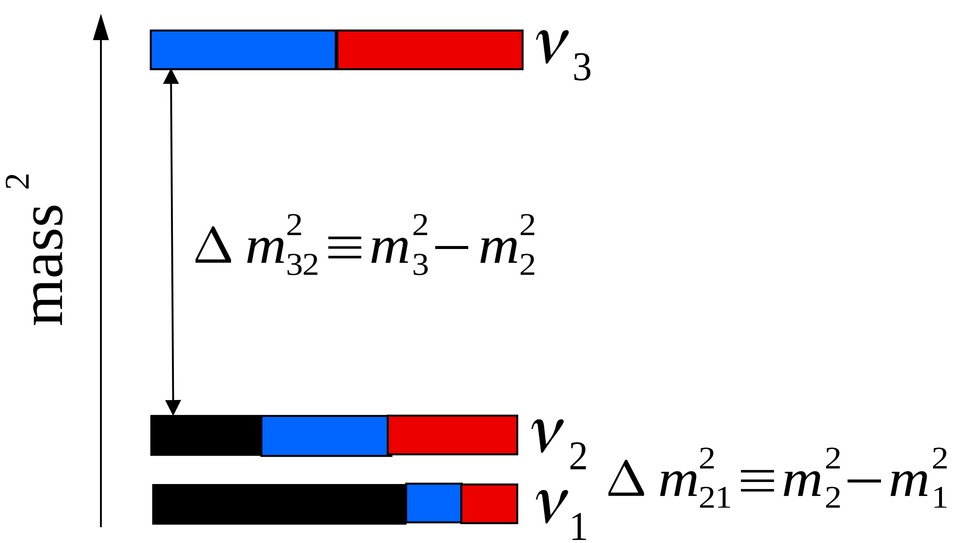
N=2.9841 ± 0.0083

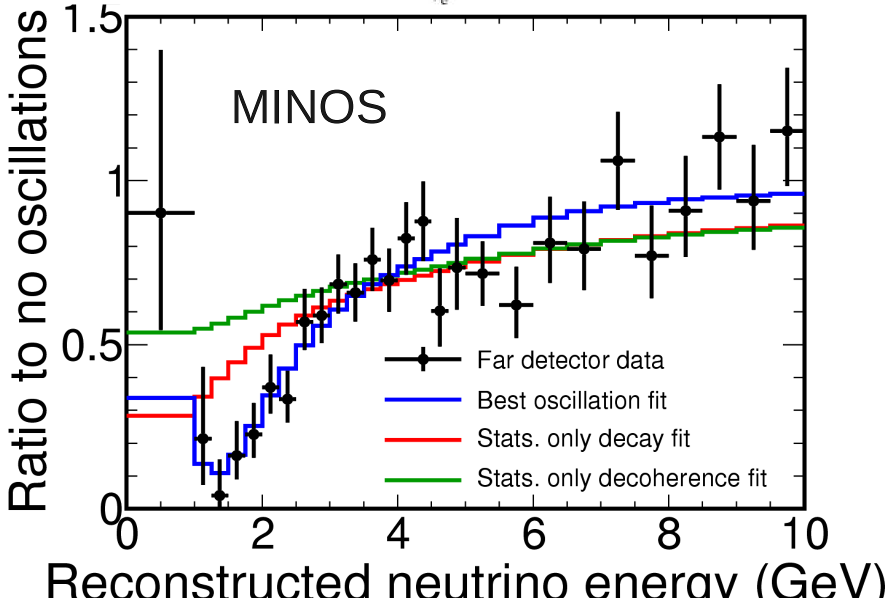


Neutrinos oscillate

- Lot of experimental evidence
- L/E dependence
- Precise measurement of atmospheric and solar Δm^2
- Neutrinos have mass



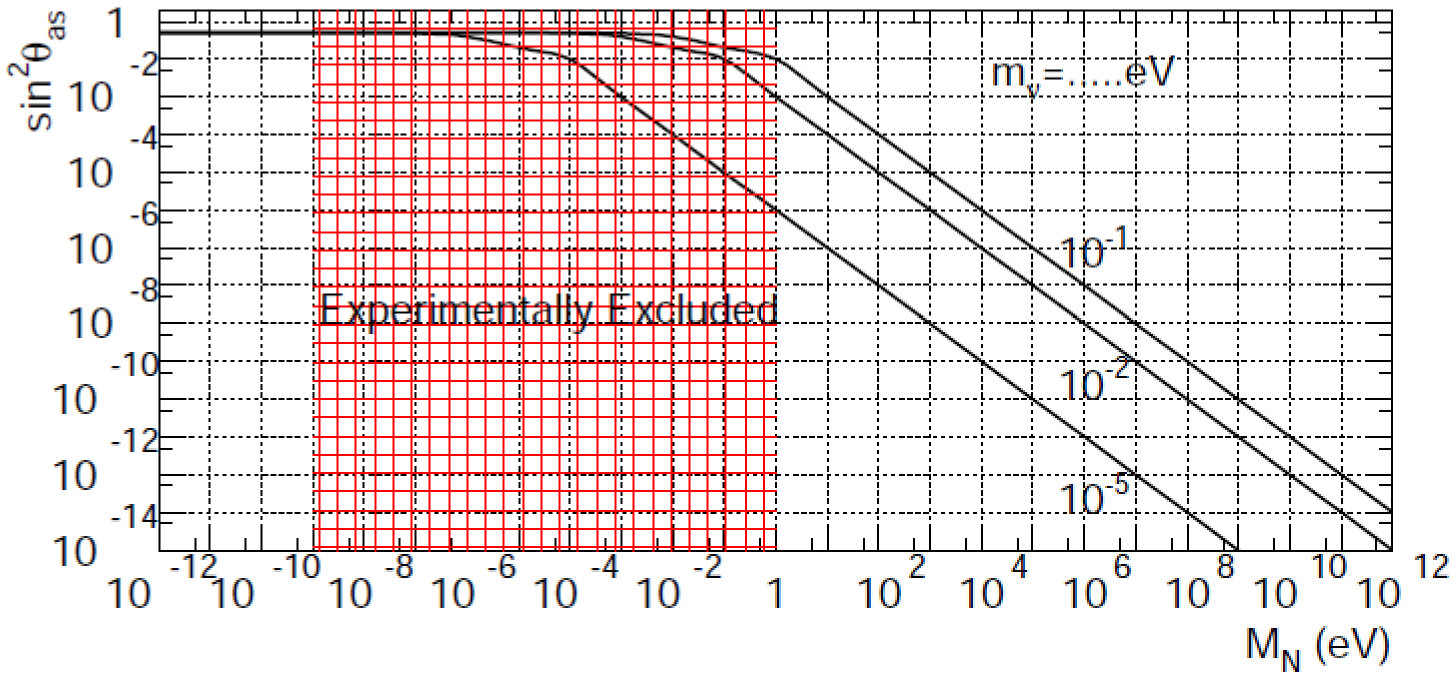




Neutrinos have mass

- Neutrino masses much smaller compared to other leptons
- Oscillations probe physics beyond Standard Model
- Origin of neutrino masses is unknown
- Many models predict additional, sterile neutrino states – right handed neutrinos

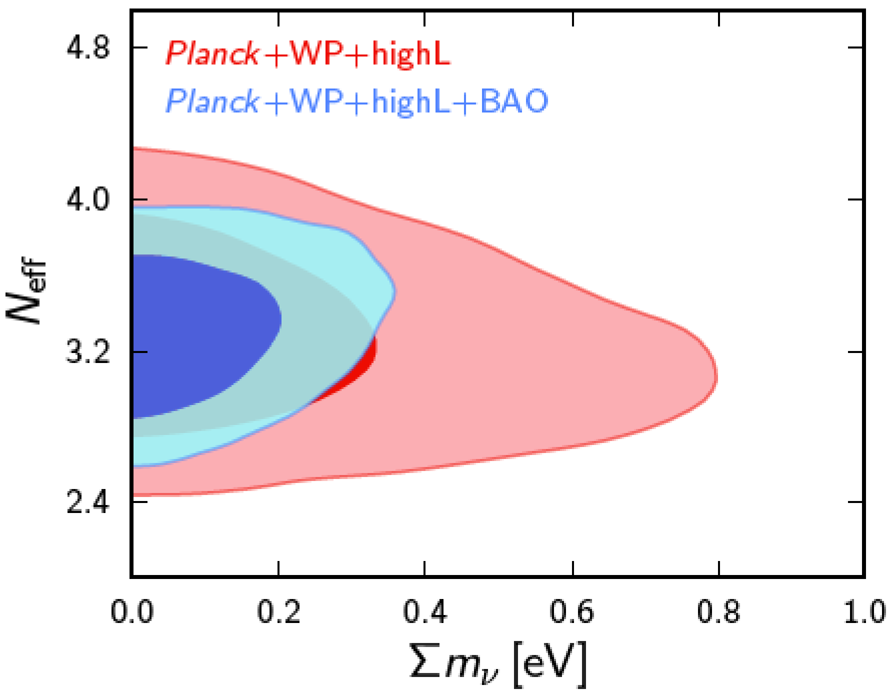
ν_R mass



- Large parameter space
- See saw limit M>1eV

A. de Gouvea et al. 0906.1611v2

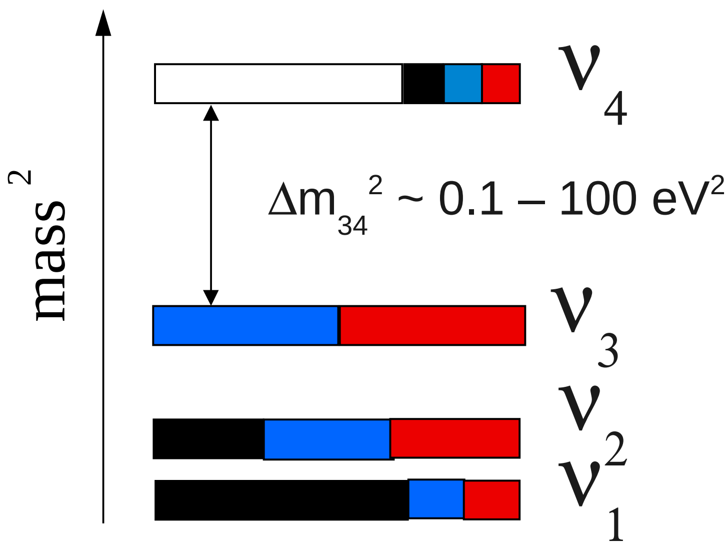
Cosmology



Planck Collaboration, 1303.5076v1

- Sensitive to sterile neutrinos
- Consistent with extra sterile neutrino
- Limits depend on datasets included in the fit and model
- Many open questions
  - More than trivial cosmology
  - Models with N_{eff} different at CMB and BBN (neutrino recoupling)
  - Light dark matter
  - ...
  - All can affect how sterile neutrino enters this picture

Sterile neutrinos



- Sterile neutrinos have no Standard Model interactions but can oscillate into active neutrinos
- 3+N models (N=1, 2, …) (short baseline CP violation for N>1)

  $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

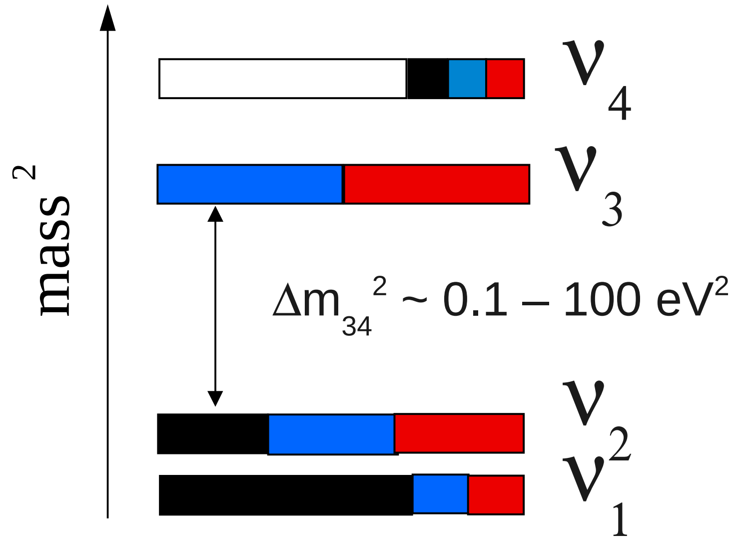
- In 3+1 model 3 parameters relevant for short baseline exp.: Δm_{41}^2, $|U_{e4}|$ and $|U_{\mu 4}|$

$$P(\nu_\mu \rightarrow \nu_e) = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2(1.27\,\Delta m_{41}^2\, L/E)$$

$$P(\nu_e \rightarrow \nu_e) = 1 - 4|U_{e4}|^2 (1 - |U_{e4}|^2) \sin^2(1.27\,\Delta m_{41}^2\, L/E)$$

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - 4|U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2) \sin^2(1.27\,\Delta m_{41}^2\, L/E)$$

2+2?



- Within 2+2 model Sterile neutrino participates in either solar or atmospheric neutrino oscillations (or both)
- Experiments measuring solar and atmospheric dm2 disfavor oscillations to pure sterile neutrinos

=> 2+2 is strongly disfavored

Parameters

- In general, oscillation probability:

$$P_{\alpha\beta} = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \delta_{\alpha\beta} - 4 \sum_{i<j}^{n} \mathrm{Re}[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}] \sin^2 X_{ij}$$

$$+ 2 \sum_{i<j}^{n} \mathrm{Im}[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}] \sin 2X_{ij}$$

$$X_{ij} = \frac{(m_i^2 - m_j^2)L}{4E} = 1.27 \frac{\Delta m_{ij}^2}{\mathrm{eV}^2} \frac{L/E}{\mathrm{m/MeV}}$$

- Formalism gets complicated with more neutrinos

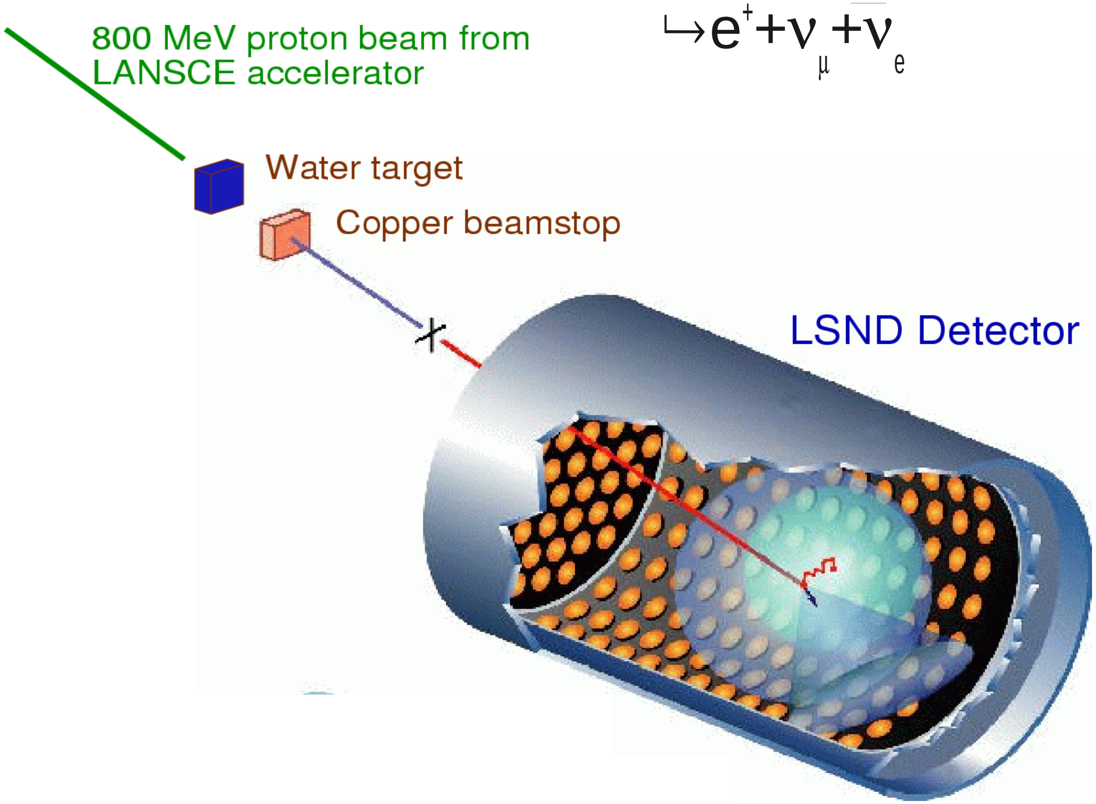
Neutrinos	$\#\Delta m_{ij}^2$	$\#\theta_{ij}$	#CP Phases
2	1	1	0
3	2	3	1
6	5	15	10

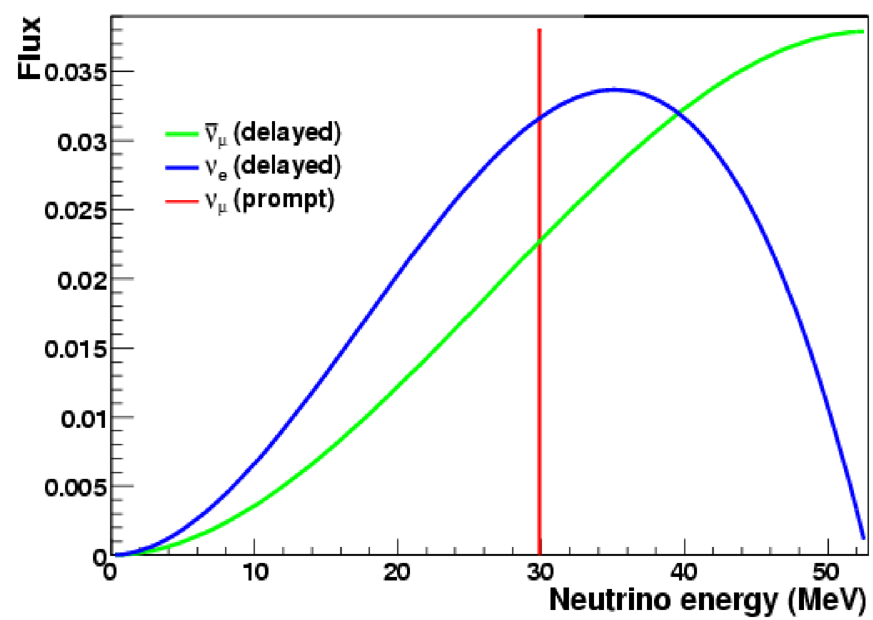
LSND

- Liquid Scintillator Neutrino Detector at Los Alamos
- Evidence for oscillations at higher Δm^2 than atmospheric and solar
- Excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam: 87.9 ± 22.4 ± 6 (3.8σ)
- Stopped pion source:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\hookrightarrow e^+ + \nu_\mu + \bar{\nu}_e$$





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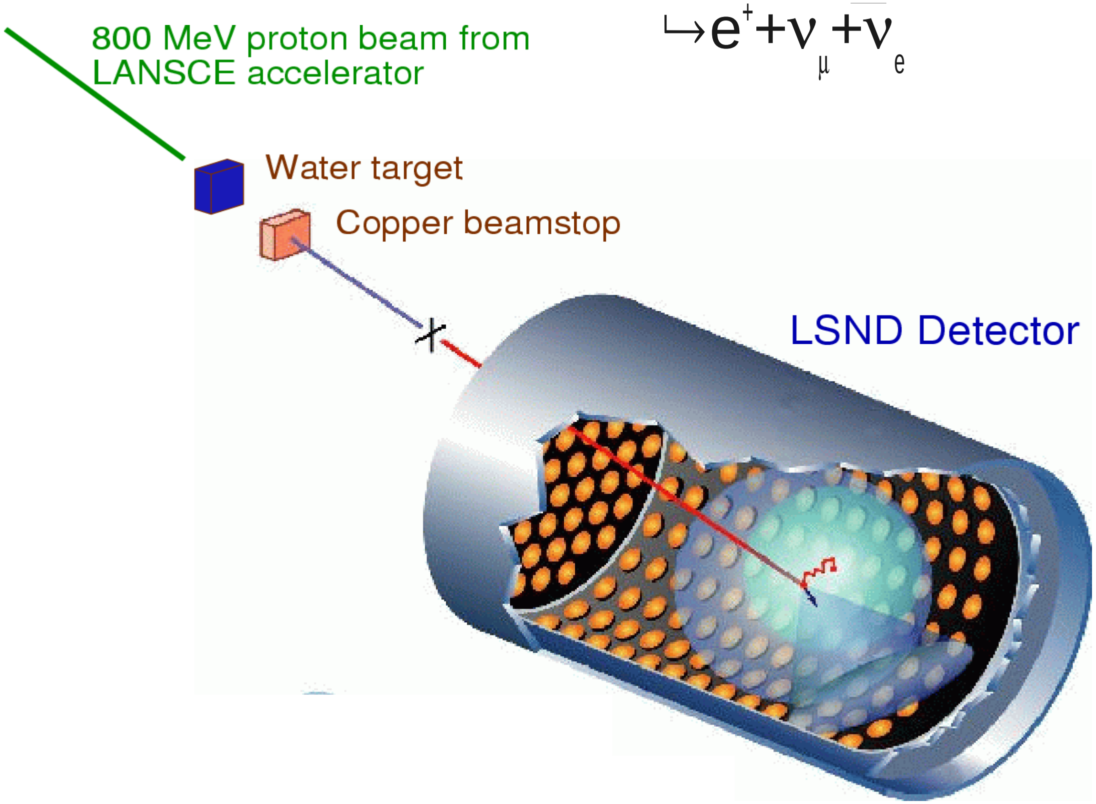
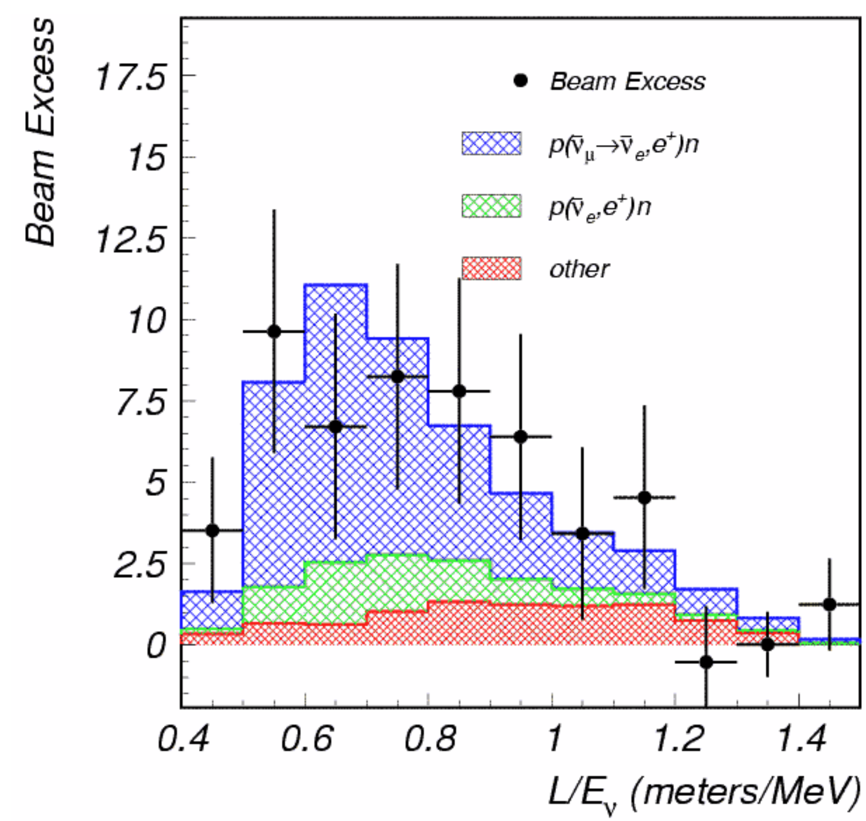


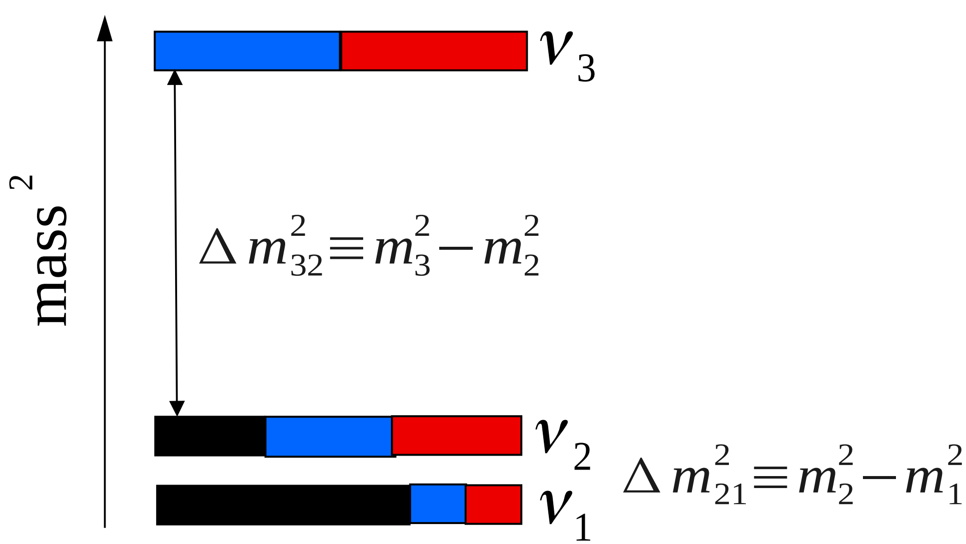


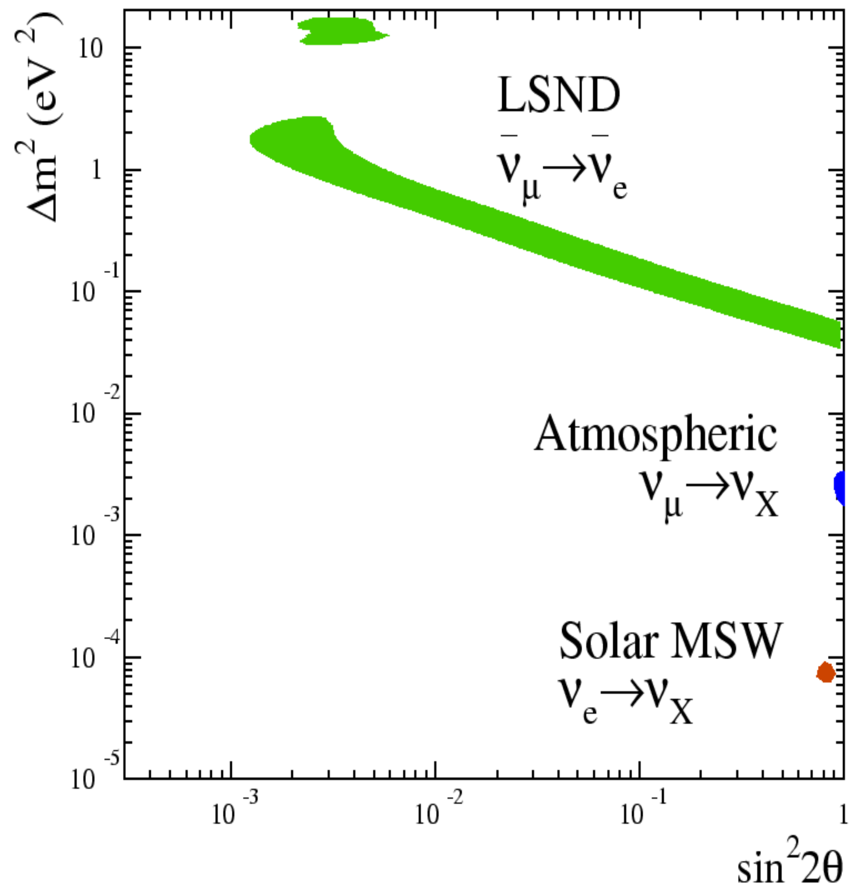
LSND signal

- Assuming two neutrino oscillations

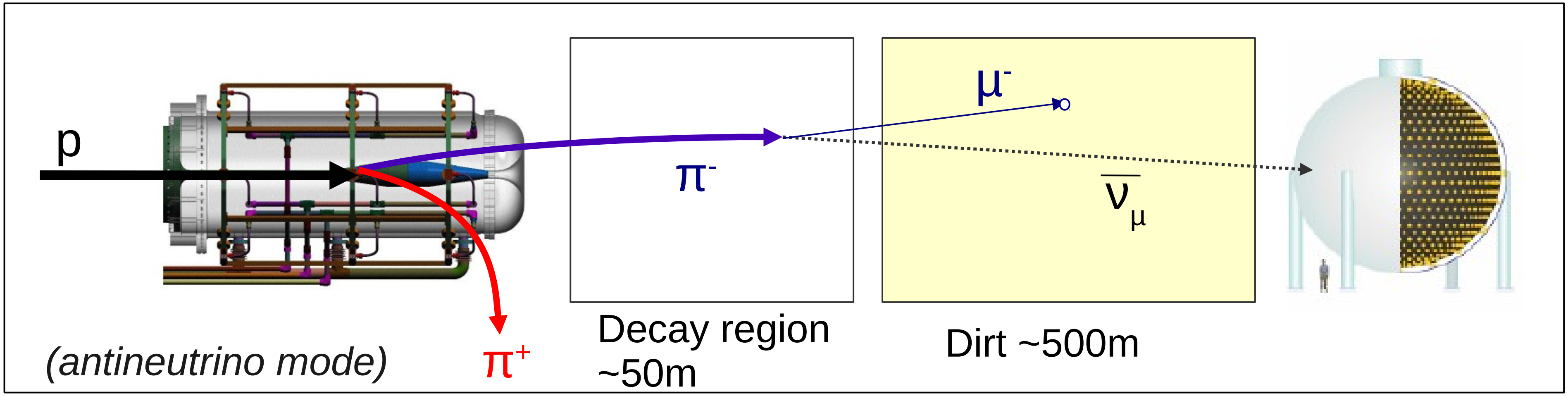
$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\,L\,\Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$

- Can't reconcile LSND result with atmospheric and solar neutrino using only 3 Standard Model neutrinos – only two independent mass splittings





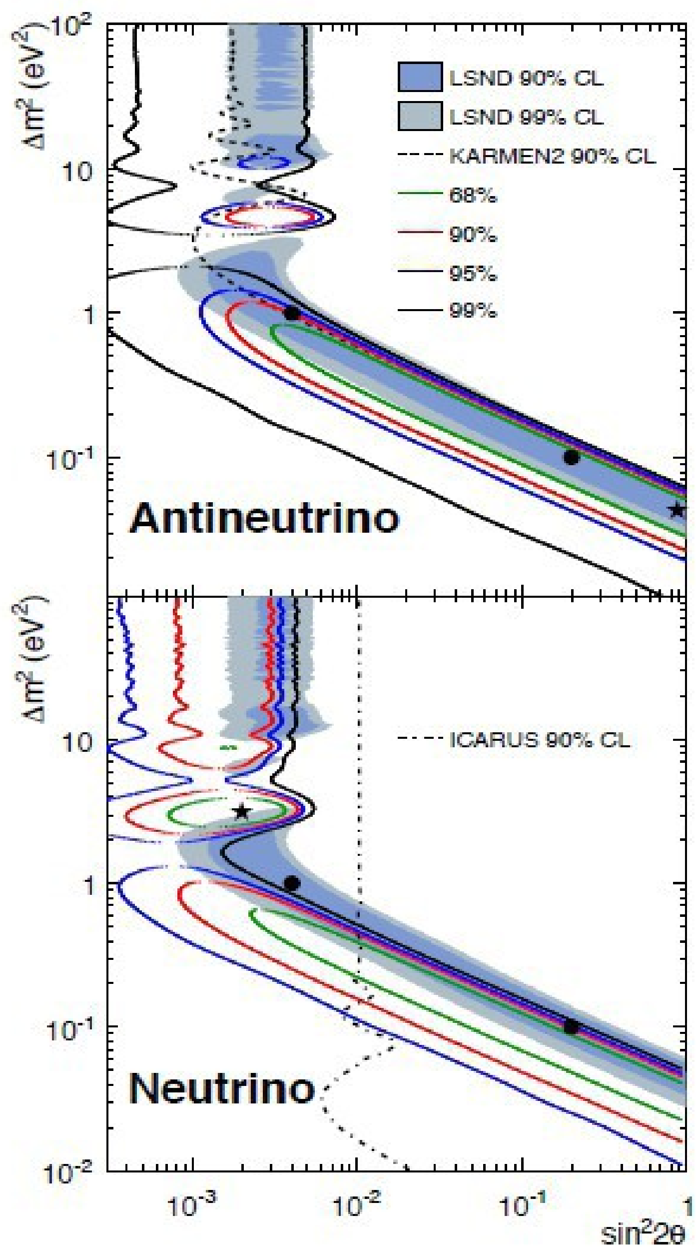
MiniBooNE experiment



- Similar L/E as LSND
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p+Be)
  - Horn polarity → neutrino or anti-neutrino mode
- Mineral oil Cherenkov detector

MiniBooNE result

- Last year concluded 10 year run
- Observed excess:
  - Neutrino: 162 ± 47.8 (3.4σ)
  - Antineutrino 78.4 ± 28.5 (2.8σ)



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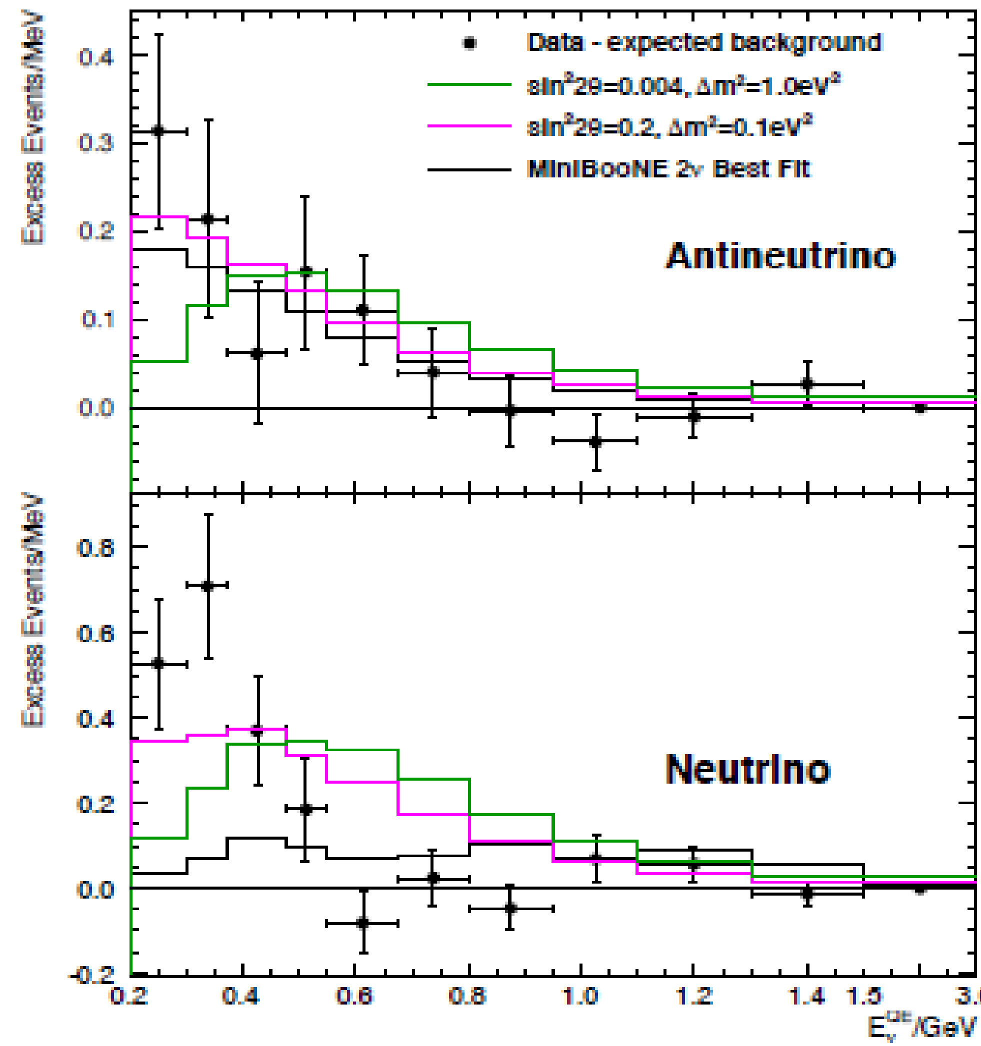
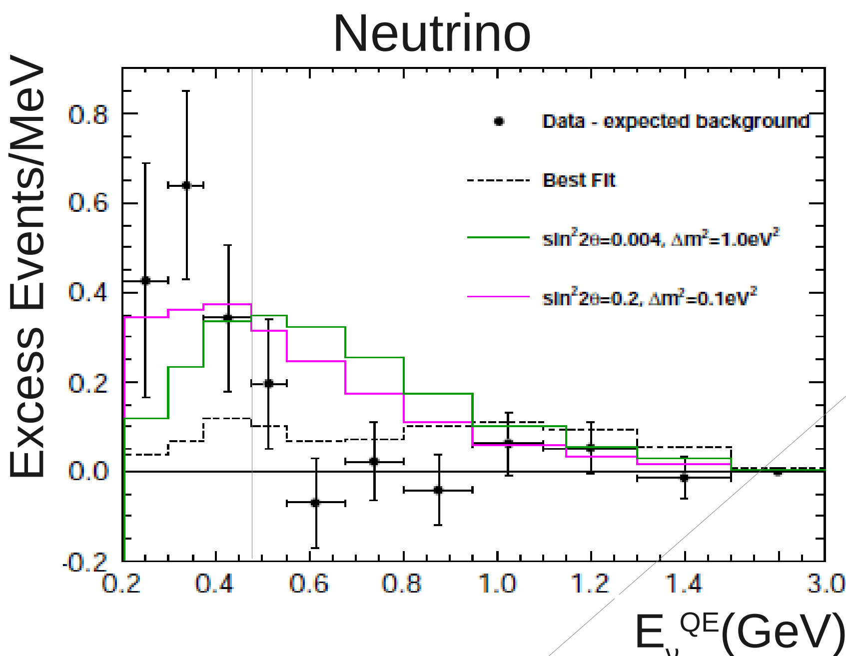
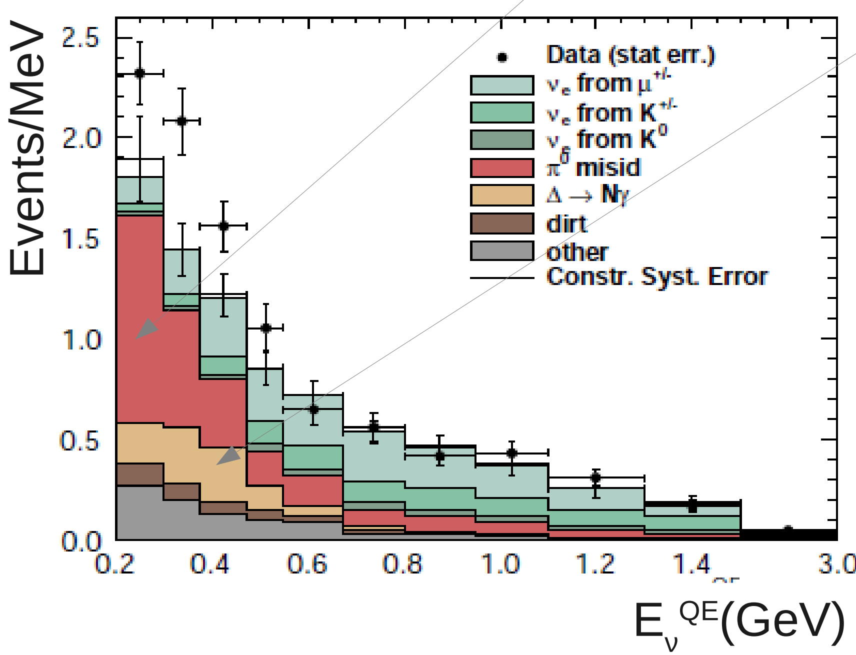


What can we say about low-E excess





- Not a stat fluctuation, statistically 7σ
- Unlikely to be intrinsic ν_e, small bkg at low E
- NC π^0 background dominates
  - Reduces significance to 3.7σ
  - Heavily constrained by NC π^0 *in situ* measurement
- Region where single γ can contribute
- MB ties $\Delta \rightarrow N\gamma$ expected rate to be 1% of measured NC π^0 rate
  - Number of theory calculations for various single γ processes
  - All find total cross section within 30% of MB ~5×10^{-42} cm^2/N
  - Would need nearly 200% change

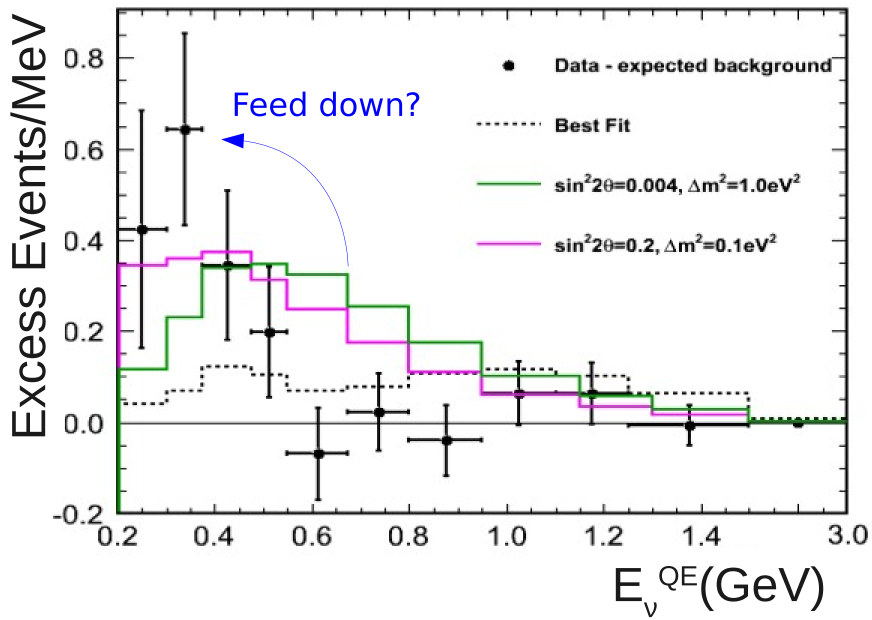
R. Hill, arxiv:0905.0291
Jenkins & Goldman, arxiv:0906.0984
Serot & Zhang, arxiv:1011.5913, 1210.3610

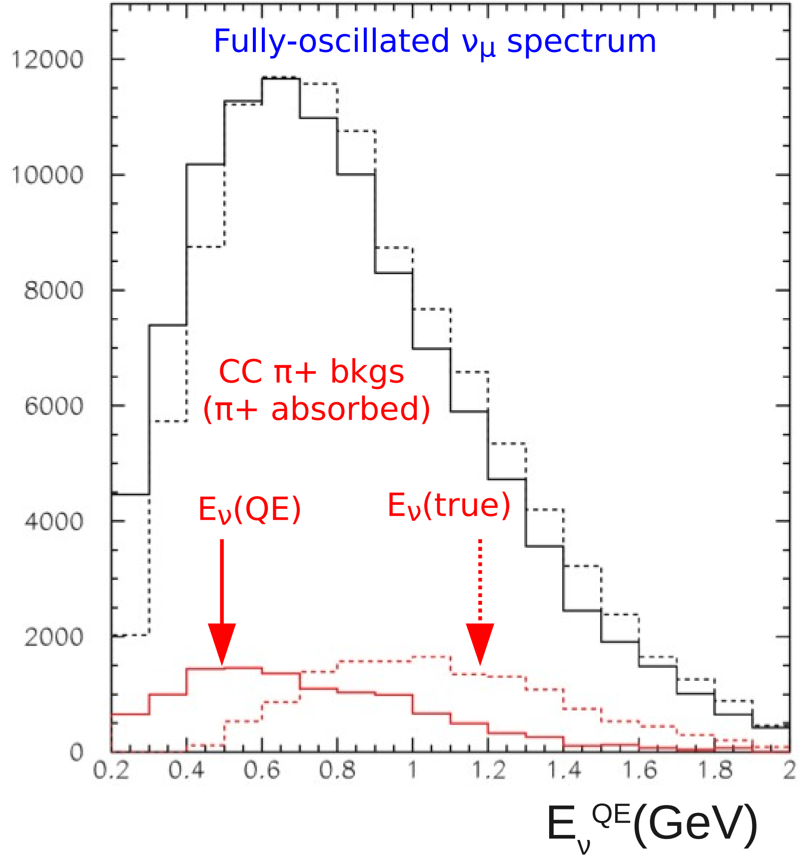
Nuclear effects & Reconstructed E_ν

- This plot assumes CCQE-like reconstruction

$$E_\nu = \frac{2(M_n - E_B)E_\mu - (E_B^2 - 2M_nE_B + m_\mu^2 + \Delta M^2)}{2\left[(M_n - E_B) - E_\mu + p_\mu \cos\theta_\mu\right]}$$

- Additional participants other than the outgoing lepton and struck nucleon will cause events to reconstruct at lower E_ν(QE)

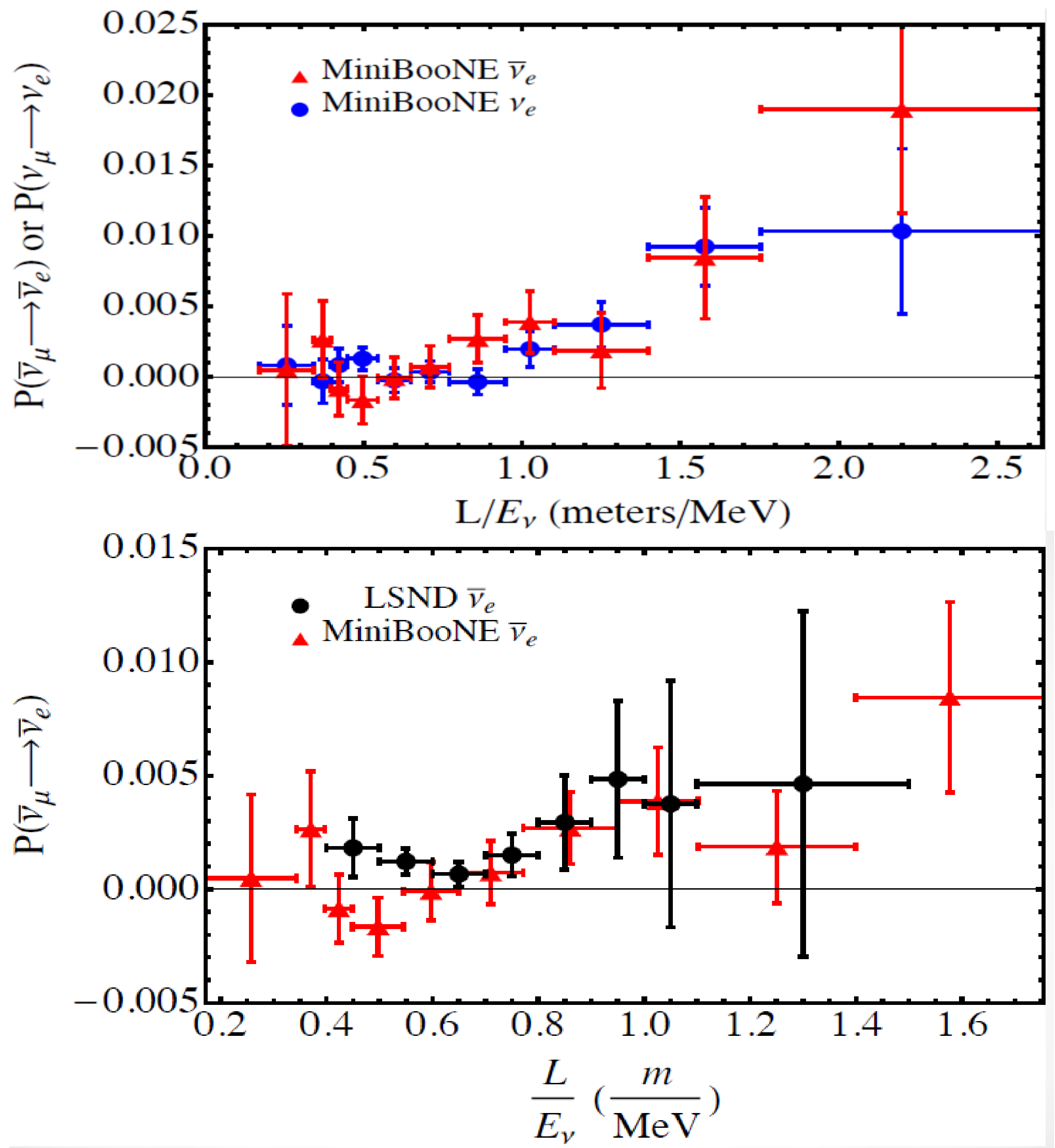




- MiniBooNE find a cross-section for CCQE that is 20-30% high
- Number of theorists suggesting this could arise from multi-nucleon correlations
- Fraction of oscillated ν_e could be misreconstructed (similar to CCπ+ case)
- MiniBooNE corrects signal prediction based on the measured ν_μ spectrum

Probability vs L/E

- Fixed baseline L, vary energy E_ν
- Model independent look at the data
- The excess as a function of L/E in MiniBooNE neutrino, antineutrino and LSND data consistent

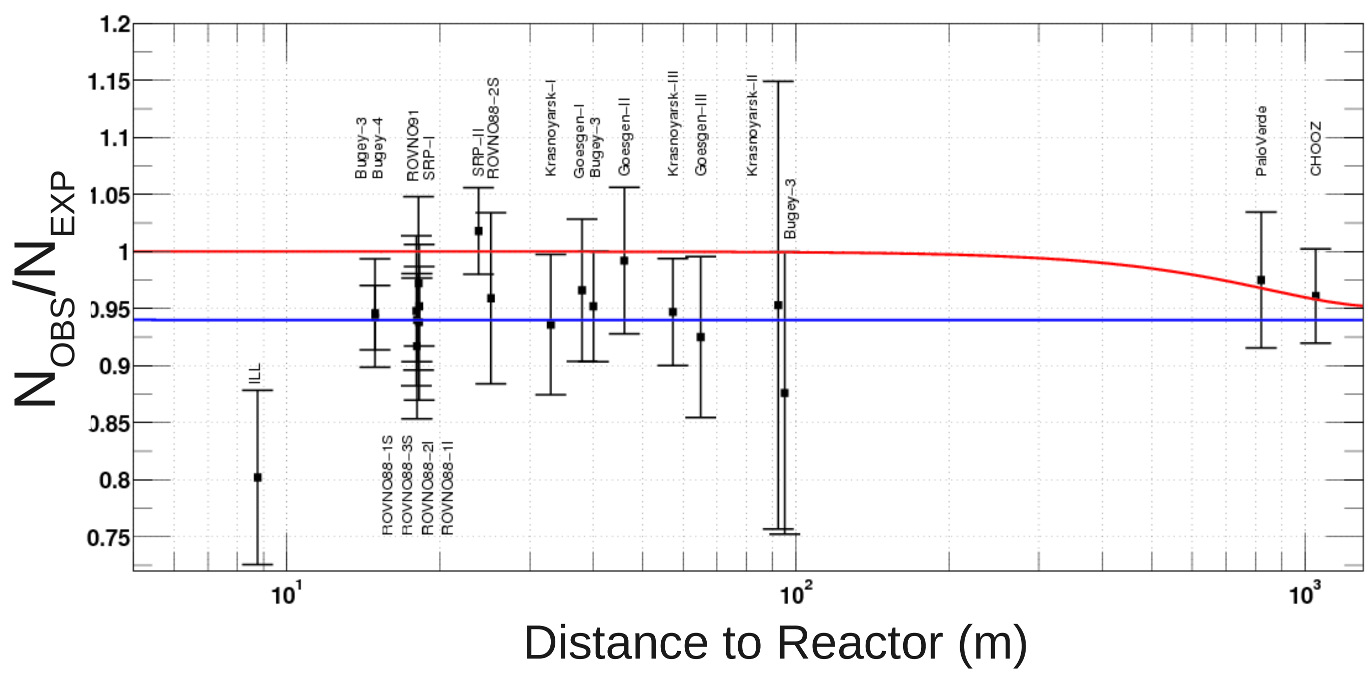


Other short baseline anomalies?

- Reactor neutrino anomaly
- Gallium anomaly

Reactor anti-neutrino anomaly

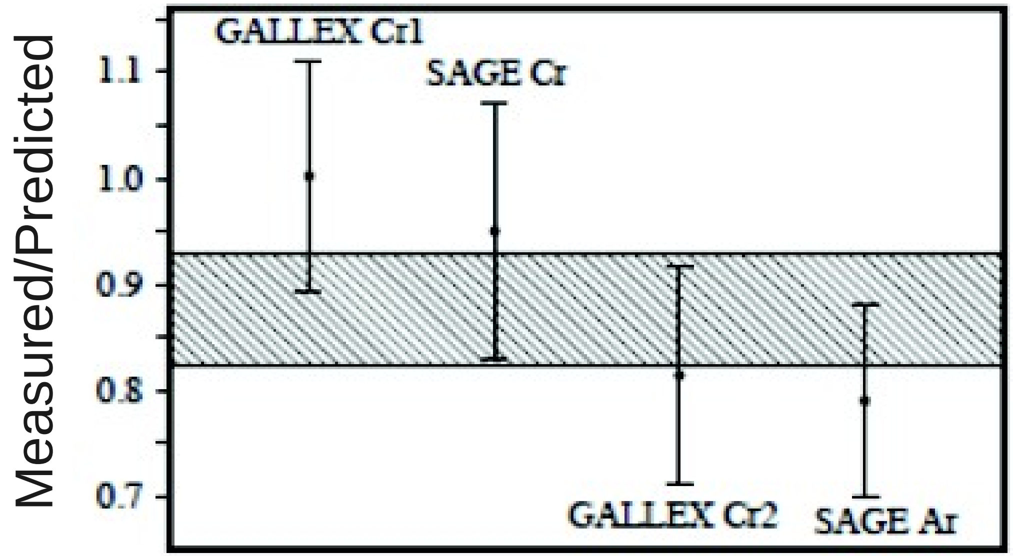
- Recent re-evaluation of reactor fluxes → +3%
- 7% deficit in observed flux from reactors
- Deviation from unity at 98.6% CL



Phys.Rev.D 83, 073006 (2011)

Gallium Anomaly

- GALLEX (LNGS) and SAGE (Baksan) looked at solar neutrinos
- Observed deficit during calibration runs with intense MCi sources (ν_e)



- R=measured/predicted = 0.86+-0.06

Phys.Rev.D 83, 073006 (2011)

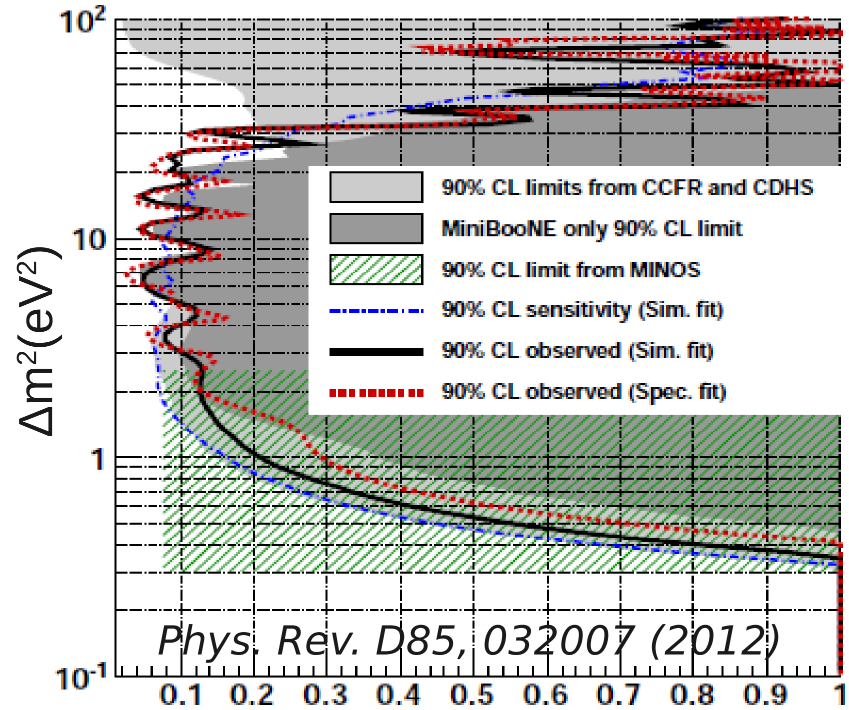
3+N models require large $\bar{\nu}_\mu$ disappearance

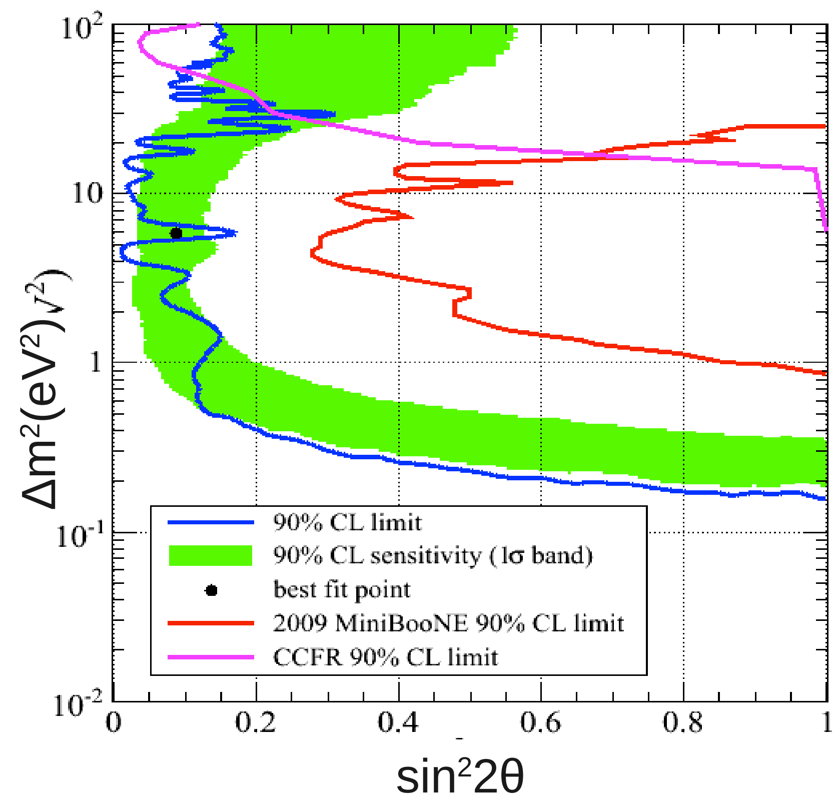
- In general: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) < \frac{1}{4} P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) P(\bar{\nu}_e \rightarrow \bar{\nu}_x)$
- From reactor experiments: $P(\bar{\nu}_e \rightarrow \bar{\nu}_x) \sim 15\,\%$
- From LSND/MiniBooNE: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \sim 0.25\,\%$
- Therefore: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) > 5\,\%$

**Assuming light neutrinos are mostly active and sterile neutrinos are heavy*

ν_μ disappearance

- Neutrino (top) and Antineutrino (bottom)
- Limits from CCFR, CDHS, MiniBooNE & MINOS
- MiniBooNE used SciBooNE as near detector
- Under CPT ν_μ and $\bar{\nu}_\mu$ disappearance probability is the same
- No disappearance observed yet

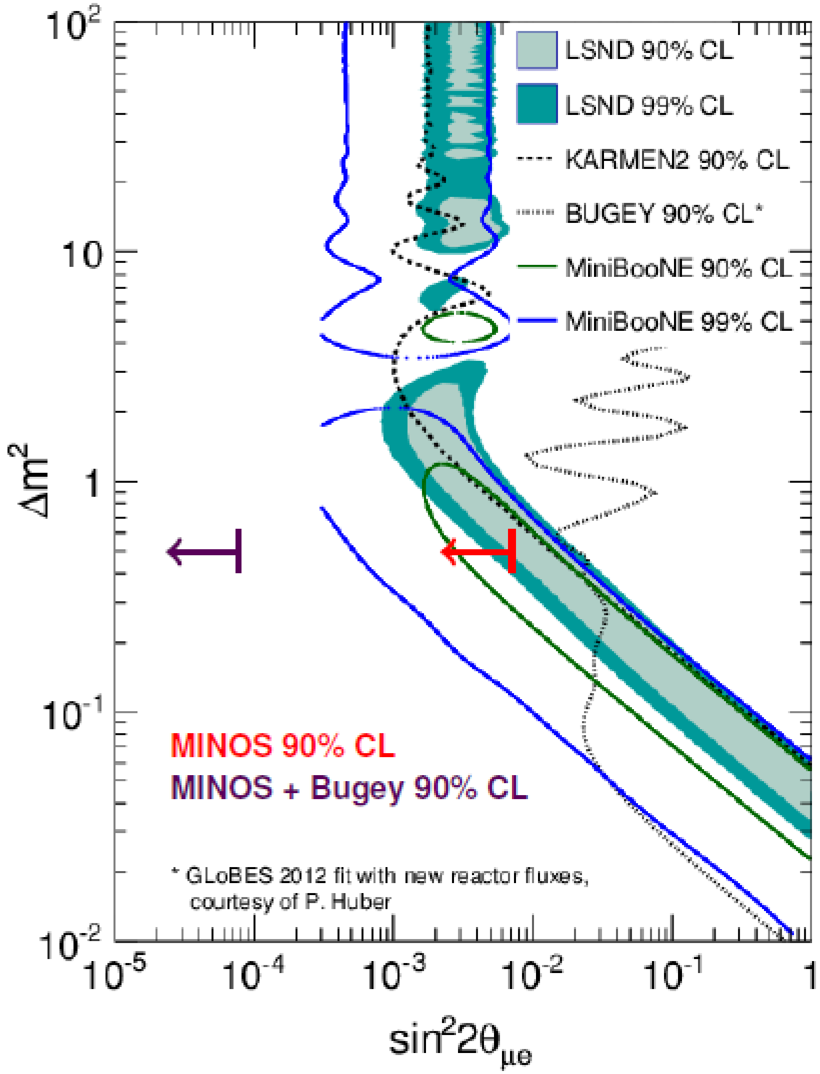




Phys. Rev. D86, 052009 (2012)

MINOS

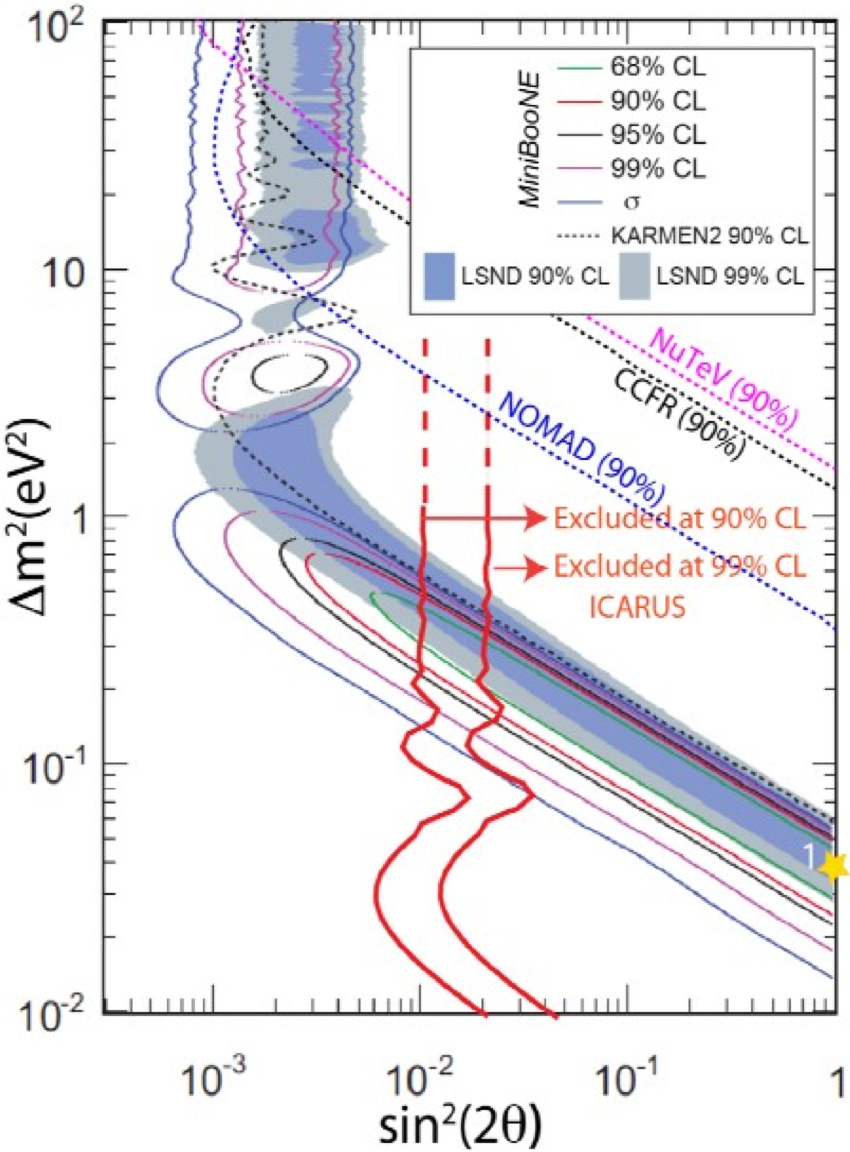
- 4 flavor analysis
- NC and $(\nu_\mu + \bar{\nu}_\mu)$ CC
- Preliminary result at $\Delta m^2_{43} = 0.5\ eV^2$



Coelho, J.A.B. Fermilab W&C, August 14 2013

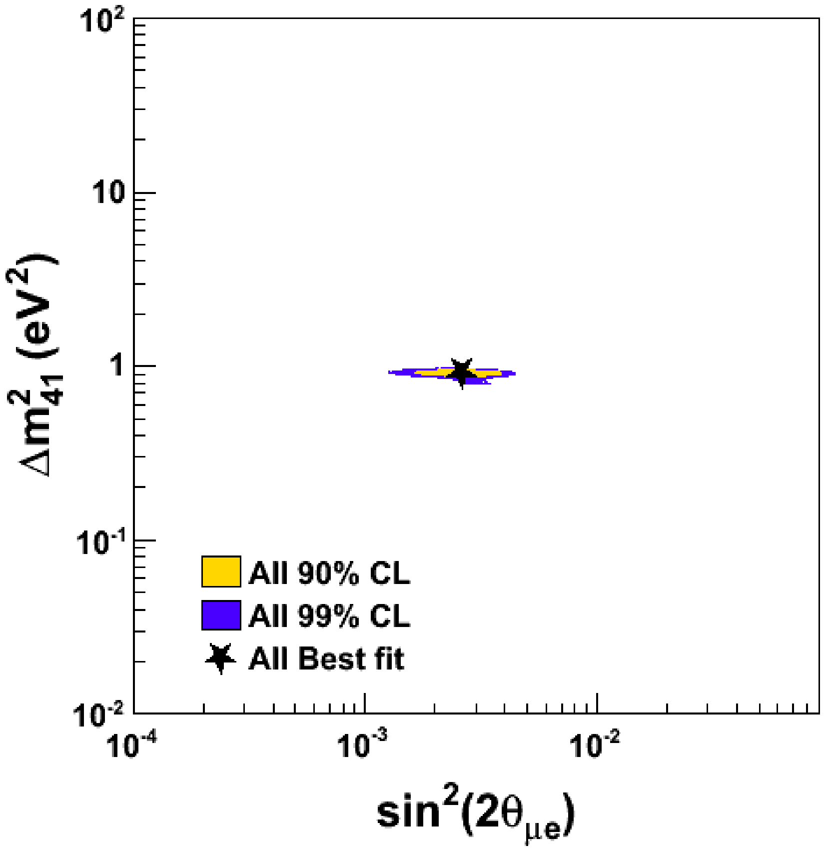
Null results

- KARMEN
  - Rutherford lab
  - Stopped π source like LSND
  - Detector at 17.7m
  - Looked for $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$
  - Saw no evidence of oscillations
- ICARUS
  - CERN to Gran Sasso neutrino beamline (730km)
  - Looked for $\nu_{\mu} \rightarrow \nu_{e}$
  - Observed 2 events with expected background of 3.7



arxiv:1209.0122

Global fits with 3+1 model



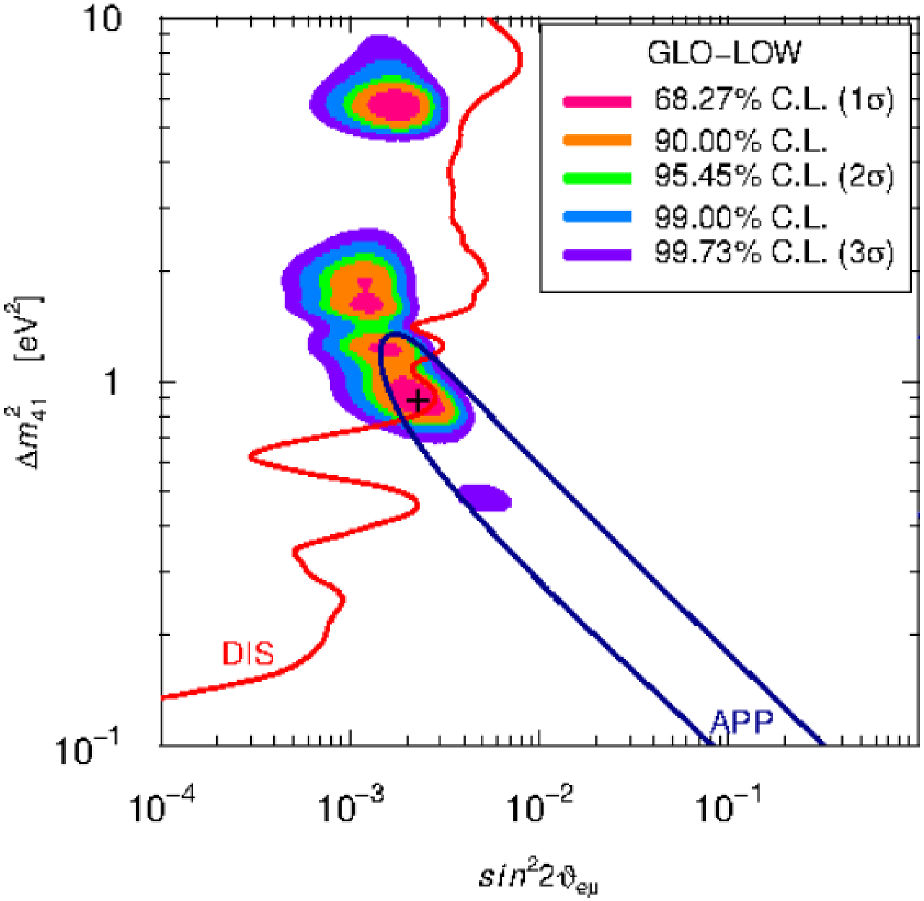
- Fit to all data
- 3 fit parameters
- Good χ^2 probability, however low parameter of goodness of fit (PG) indicates tensions in the data

χ^2(dof)	χ^2_{null} (dof)	gof	null gof	χ^2_{PG} (dof)	PG
233.9 (237)	286.5 (240)	55%	2.1%	54 (24)	0.043%

$$X^2_{PG} = X^2_{min;combined} - \sum_{Experiments} X^2_{min}$$

Conrad, Ignarra, Karagiorgi, Shaevitz & Spitz
arxiv:1207.4765

Global fits with 3+1 model (cont'd)

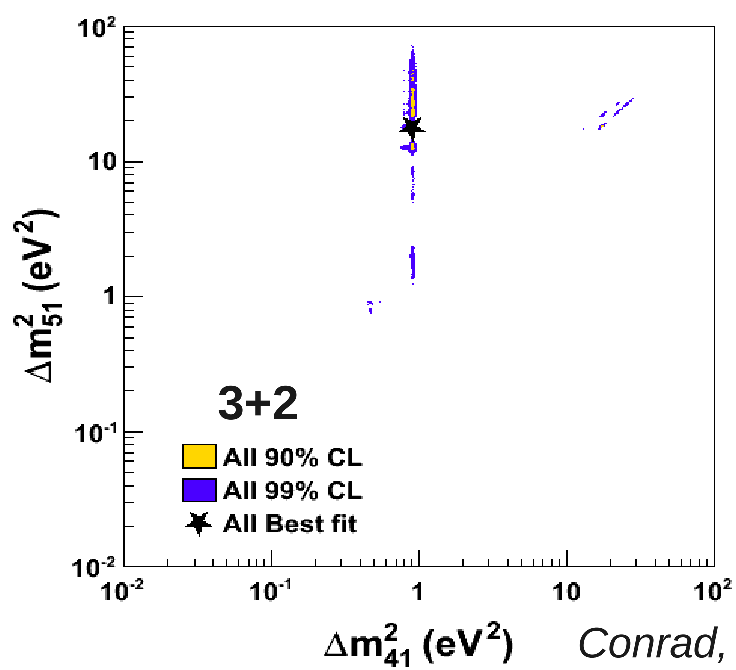


- Tension between neutrino mode and antineutrino mode appearance experiments
- Tension between disappearance and appearance experiments
- All of the data cannot be fit simultaneously with 3+1 model

Giunti, Laveder, arxiv:1111.1069
Giunti et al. Phys. Rev. D 88, 073008 (2013)

3+N fits (N>1)

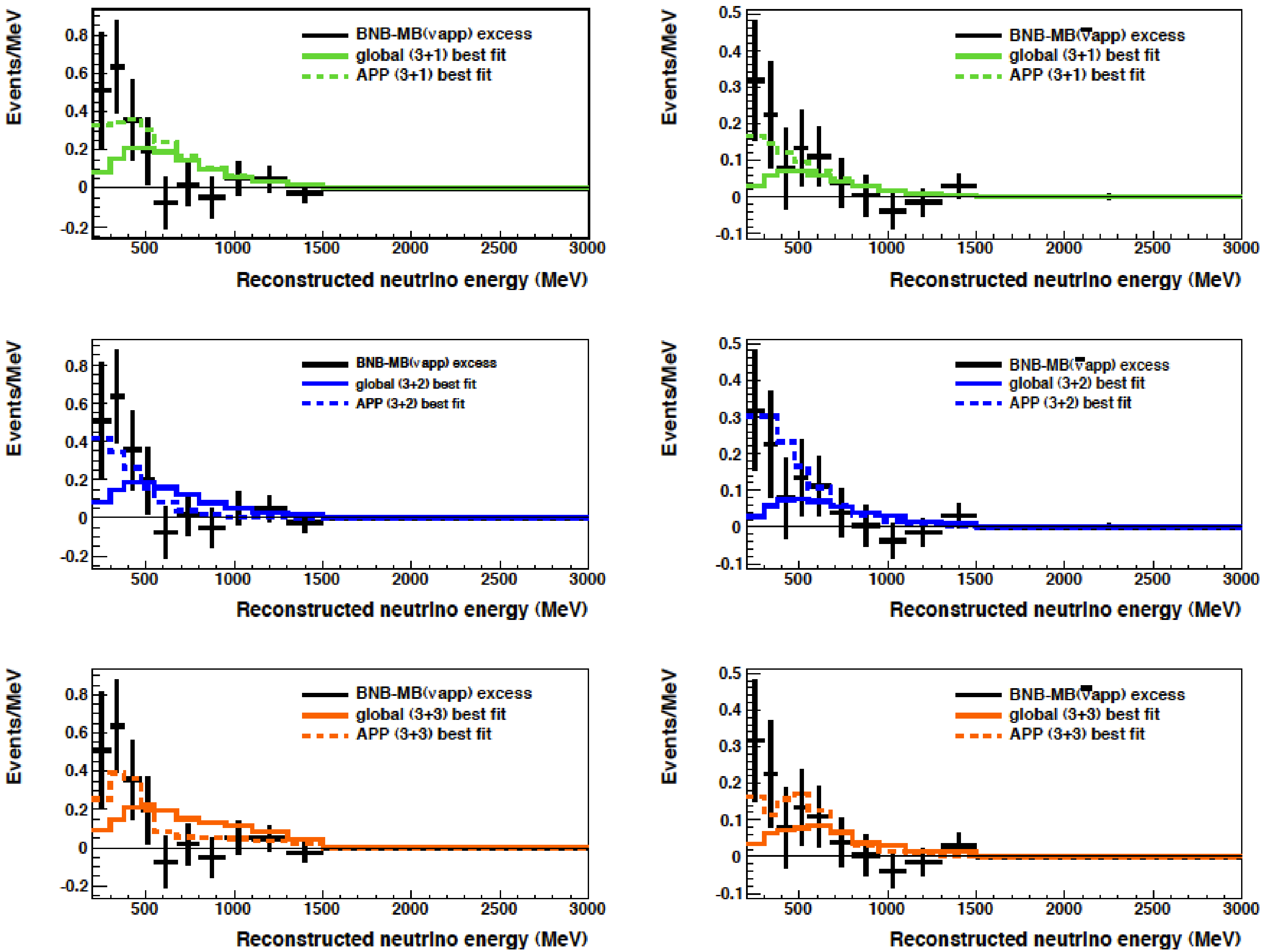
- 3+2 fits allow for CP violation – neutrino vs anti-neutrino appearance
- Tension relaxed with 3+2 fits and even more in 3+3 fits
- However, still some tension between appearance and disappearance even in 3+3 fits



Conrad, Ignarra, Karagiorgi, Shaevitz & Spitz arxiv:1207.4765

MiniBooNE low energy excess

Neutrino | Antineutrino



3+1

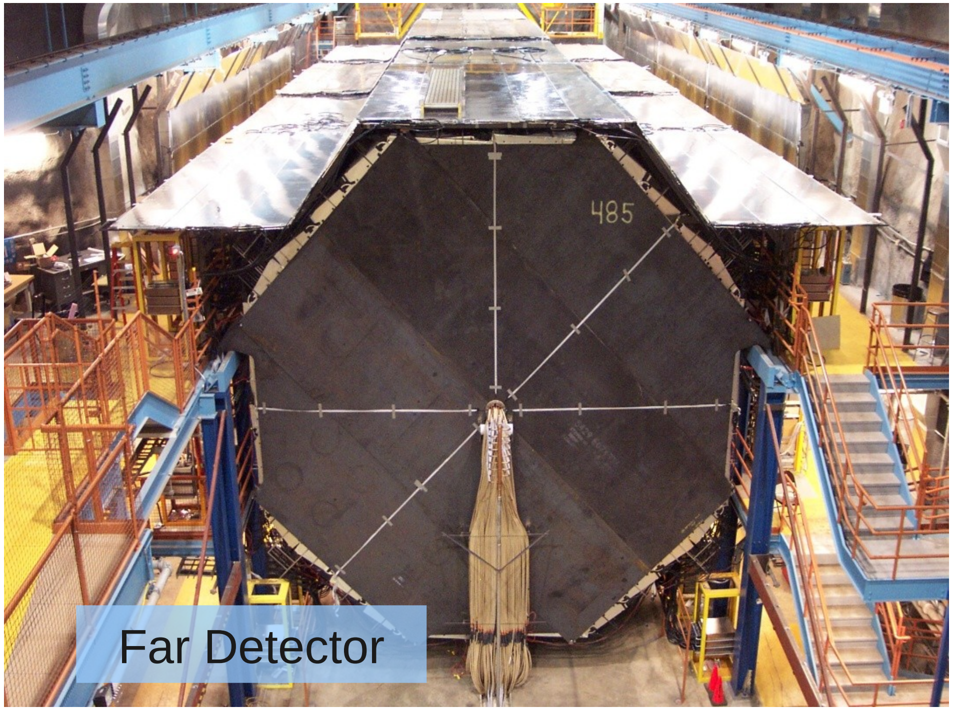
3+2

3+3

Conrad, Ignarra, Karagiorgi, Shaevitz & Spitz
arxiv:1207.4765

Future outlook

- Many proposals:
  - Radioactive sources
  - Reactor neutrinos
  - Stopped π beam
  - Decay in flight beams
- Goal is to:
  - test the anomalies
  - test L/E dependence
- Focus next on experiments at Fermilab

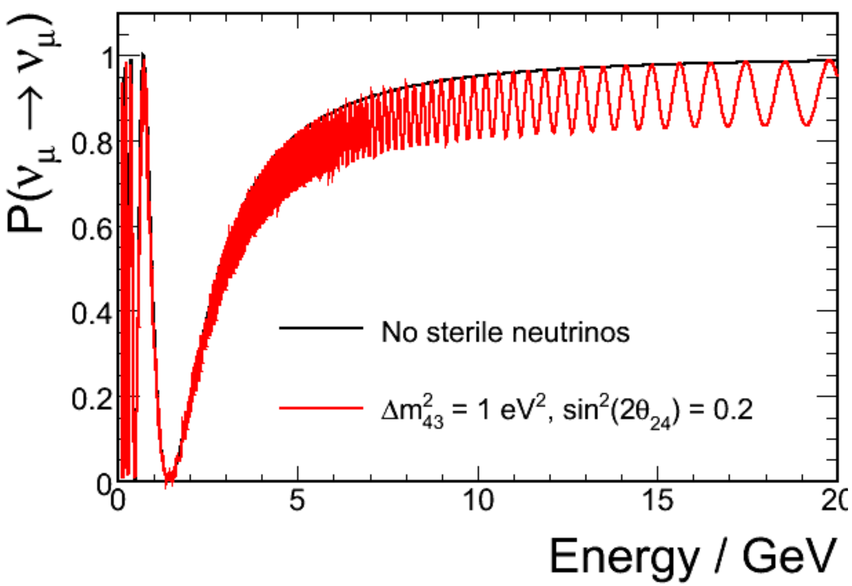


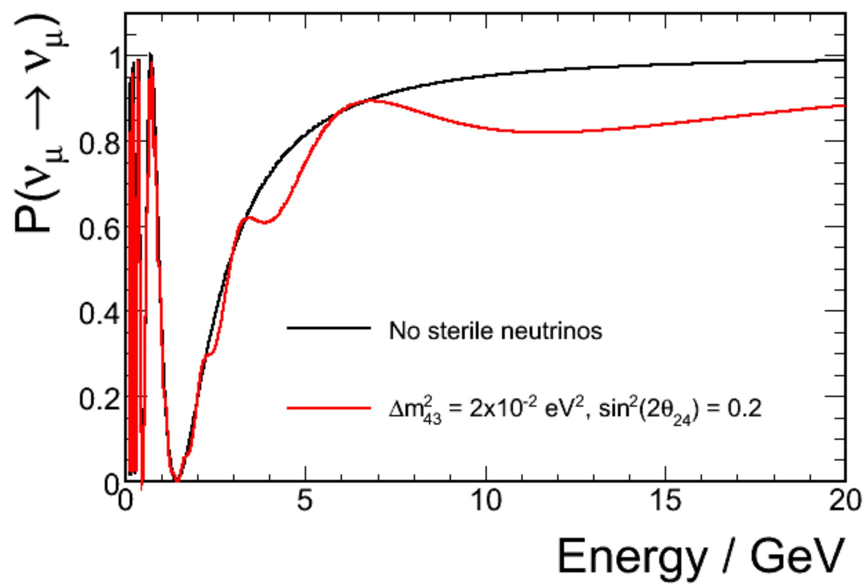
MINOS+

- NuMI beamline
- Two functionally identical detectors
- 1kton Near and 5.4kton Far

MINOS+

- Use high energy neutrino beam with MINOS detectors
- Lot of events - ~4000 events/year in FD
- Sensitive to oscillations with high Δm^2
- Also look for non-standard neutrino interactions, extra-dimensions





MicroBooNE Experiment

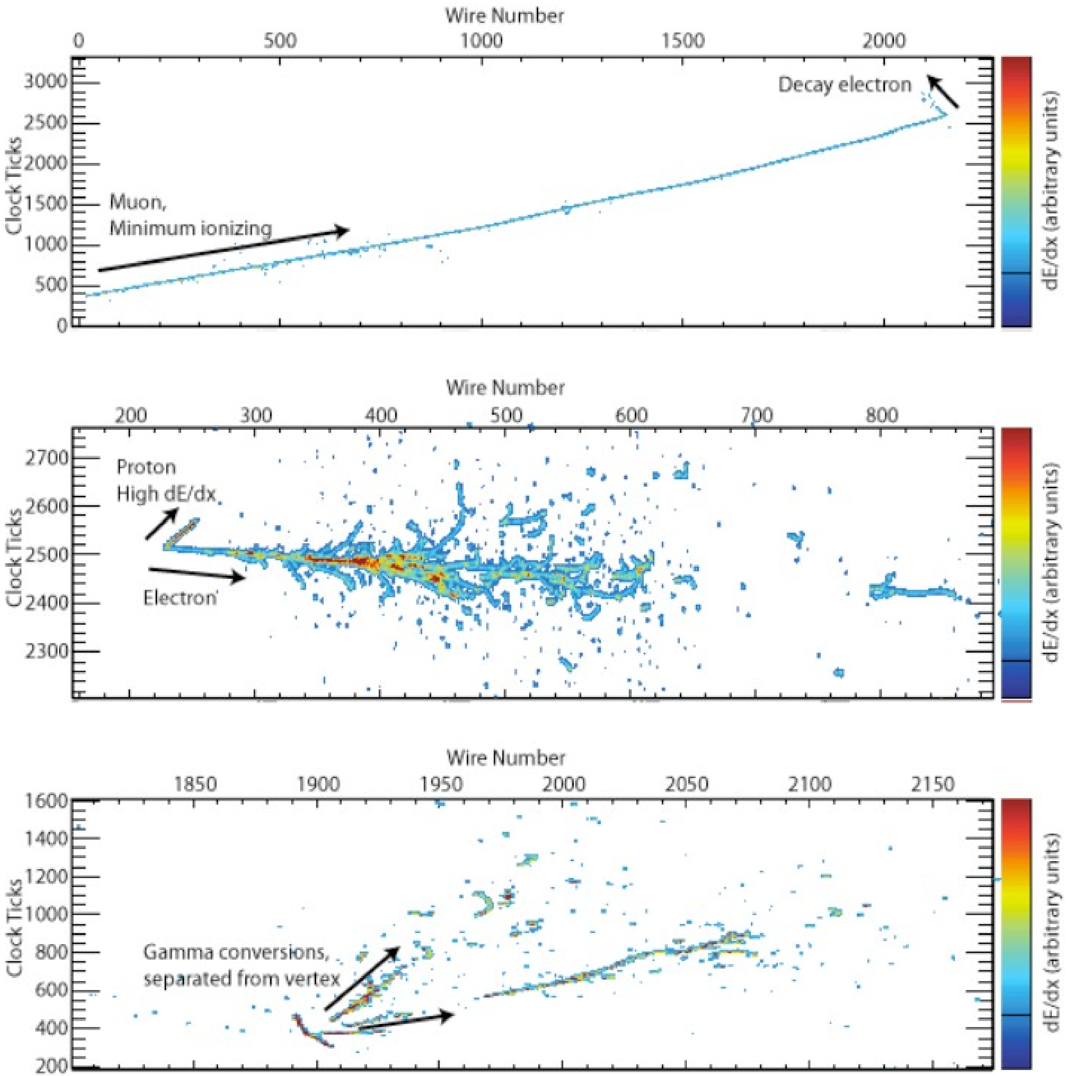
- Liquid Argon Time Projection Chamber (LArTPC)
  - 170t LAr (~84t active)
  - Fermilab's Booster Neutrino Beamline
- Start data taking in 2014

MicroBooNE goals

- Physics goals
  - MiniBooNE low energy excess
    - MicroBooNE can distinguish between e and gamma
  - Cross sections
- R&D goals
  - Serve as a step toward multi-kton detectors
  - Test LArTPC technology
  - Development of full reconstruction of neutrino interactions in LArTPC

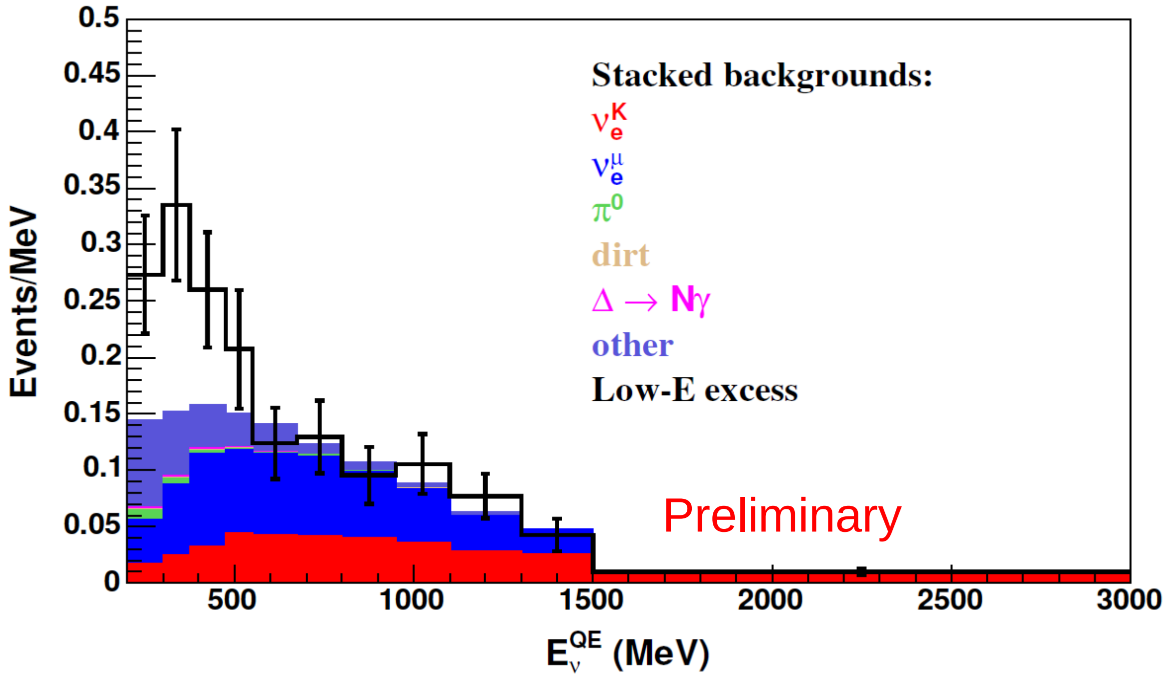
Events in LArTPC

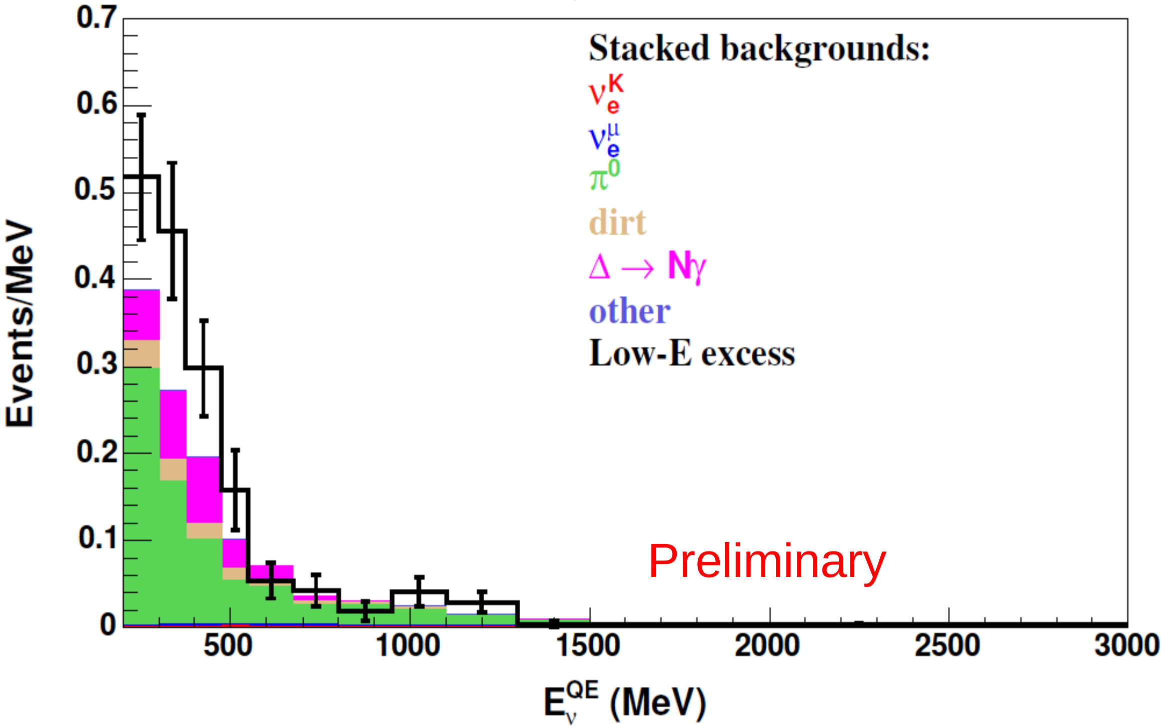
- mm scale resolution
- dE/dx information
- Excellent PID and e/γ separation



e vs gamma

- In MicroBooNE low Energy excess will show in either electron like sample (top) or gamma like sample (bottom)
- If excess is due to electrons expect 36.8±6.4 (5.7σ)
- If excess is due to photons expect 36.8±8.9 (4.1σ)



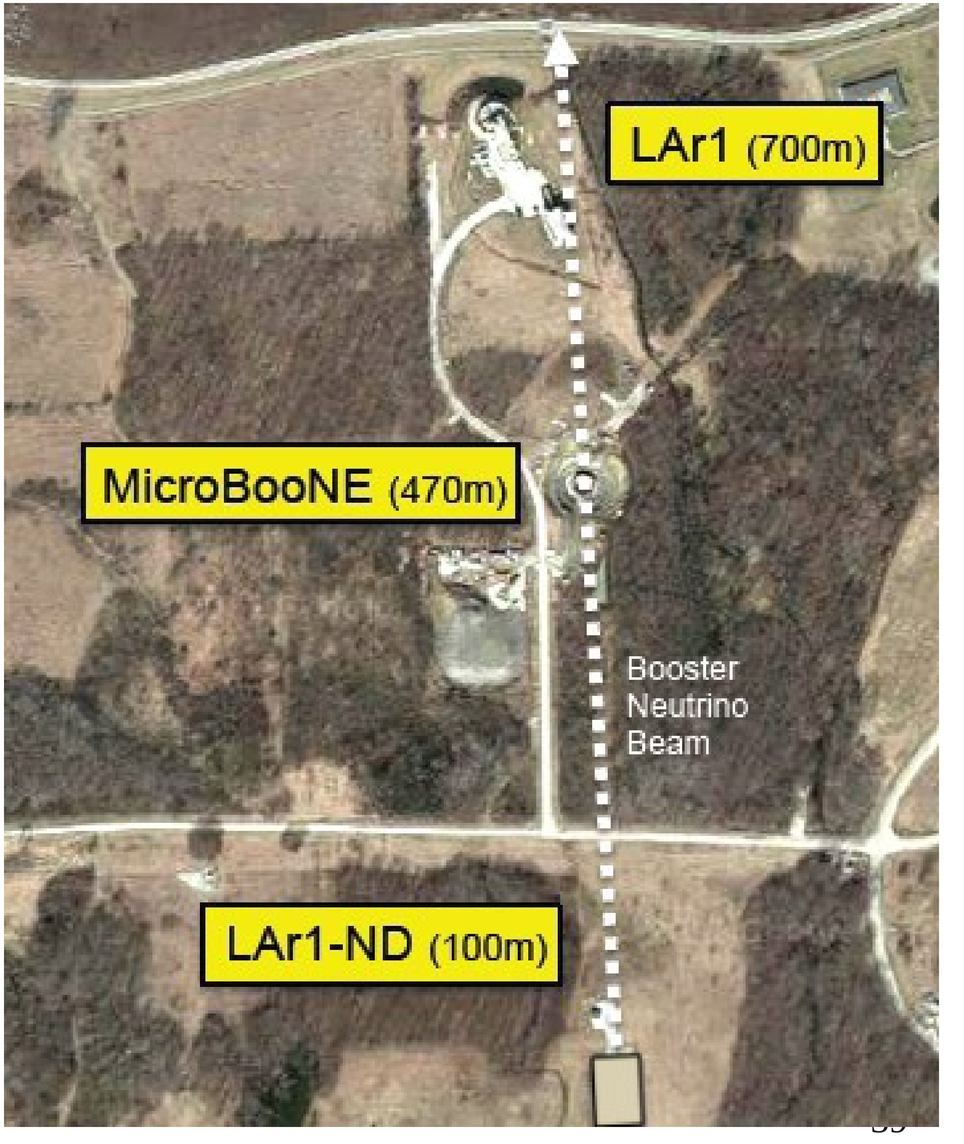


Few more ideas

- Proposals under construction:
  - LAr1
  - MiniBooNE+

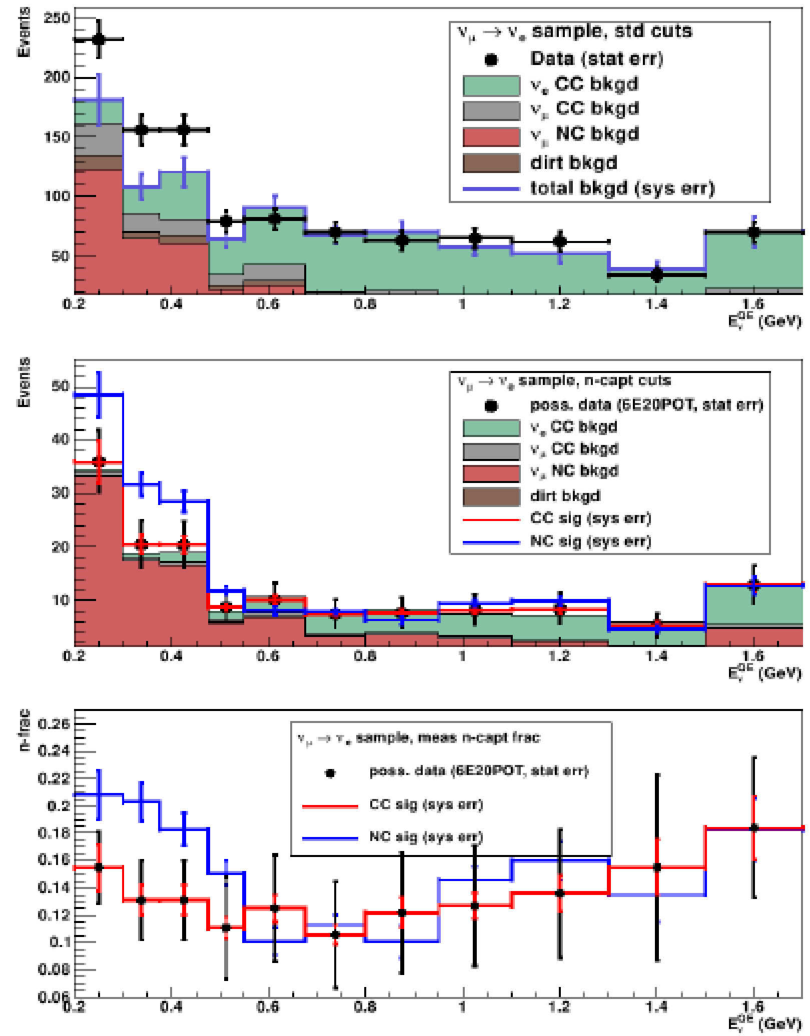
LAr1

- Run along MicroBooNE
- Definitive test of LSND and MiniBooNE both in neutrino and antineutrino mode
- Staged program
- Phase 1 detector@100m (40t fiducial)
  - Study L/E dependence and nm disappearance
- Phase 2 detector@700m (1kt)
  - test antineutrinos



MiniBooNE+

- Add scintillator to MiniBooNE to enable reconstruction of 2.2MeV gamma from n capture
  - Determine if low energy excess is CC like or NC like
  - Test QE assumpition in neutrino energy reconstruction
  - Measure flux using known cross section $\nu_\mu C \rightarrow \mu^- N_{gs}$



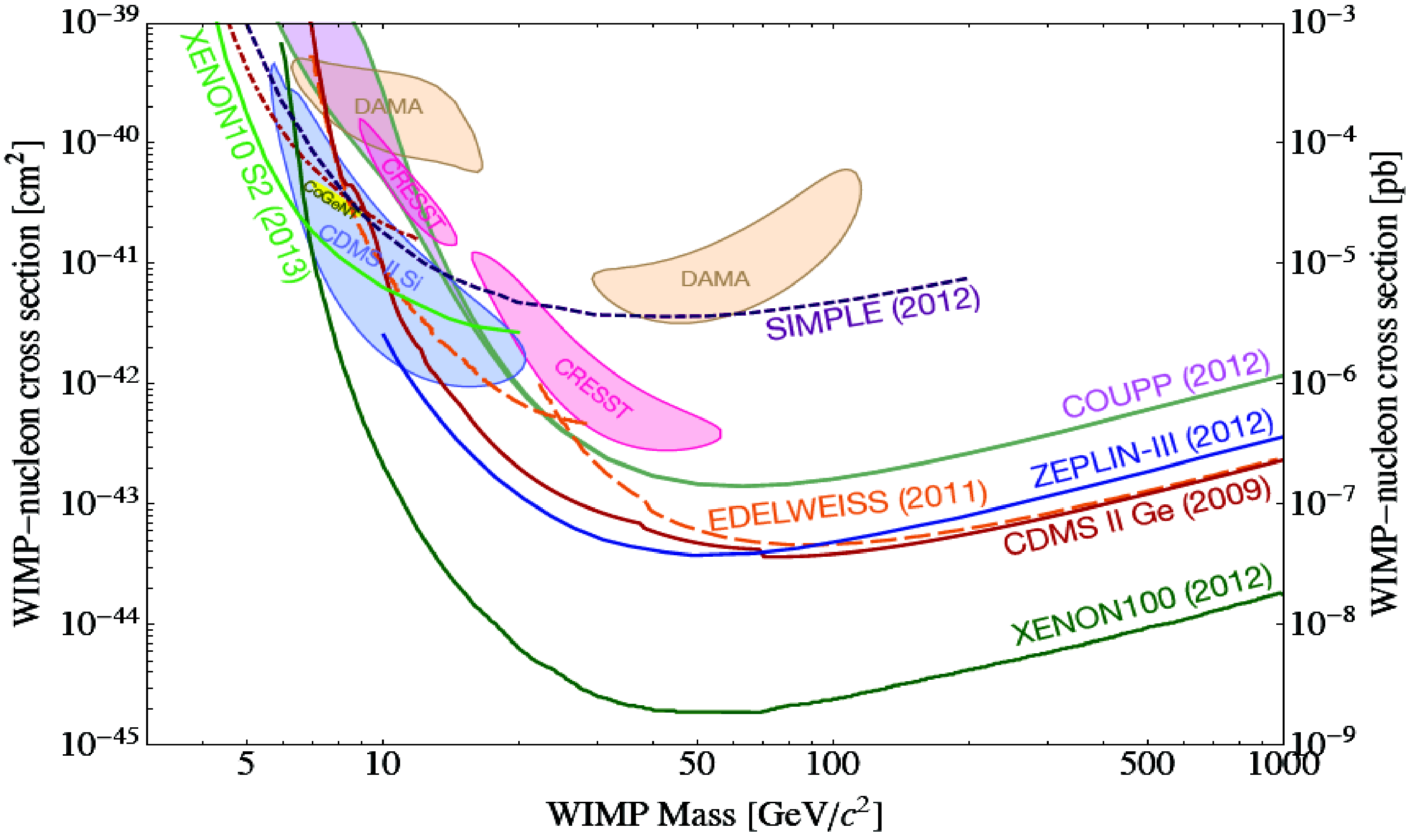
Conclusion 1

- Increasing evidence for short baseline anomalies and existence of light sterile neutrinos, however not definite proof
- Important to find physics behind these anomalies
- Follow-up experiments being proposed and under construction
- In near future probe physics behind short baseline anomalies with high significance

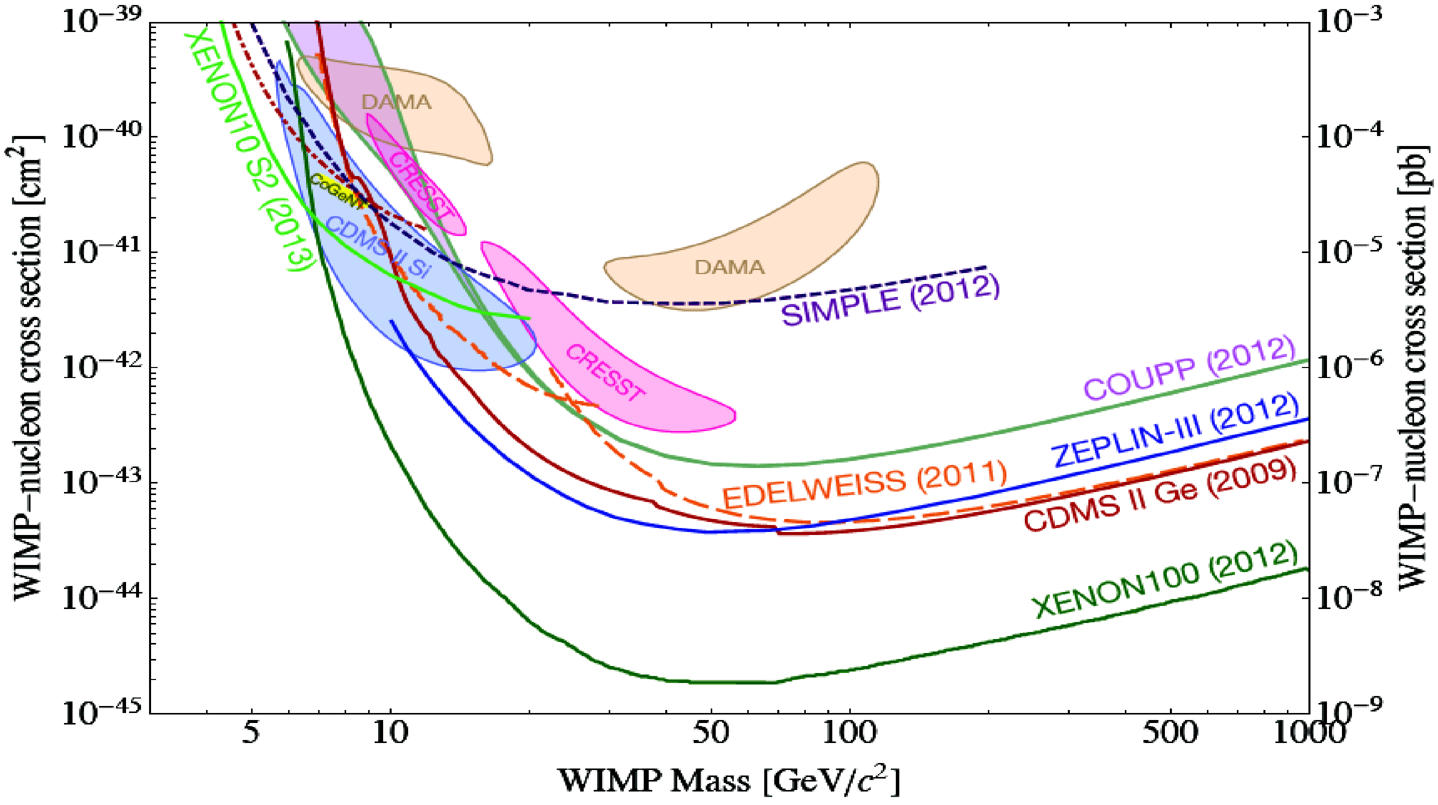
Direct dark matter search with short-baseline neutrino experiments

Direct Dark Matter Searches

- Most direct searches focus on M > few GeV



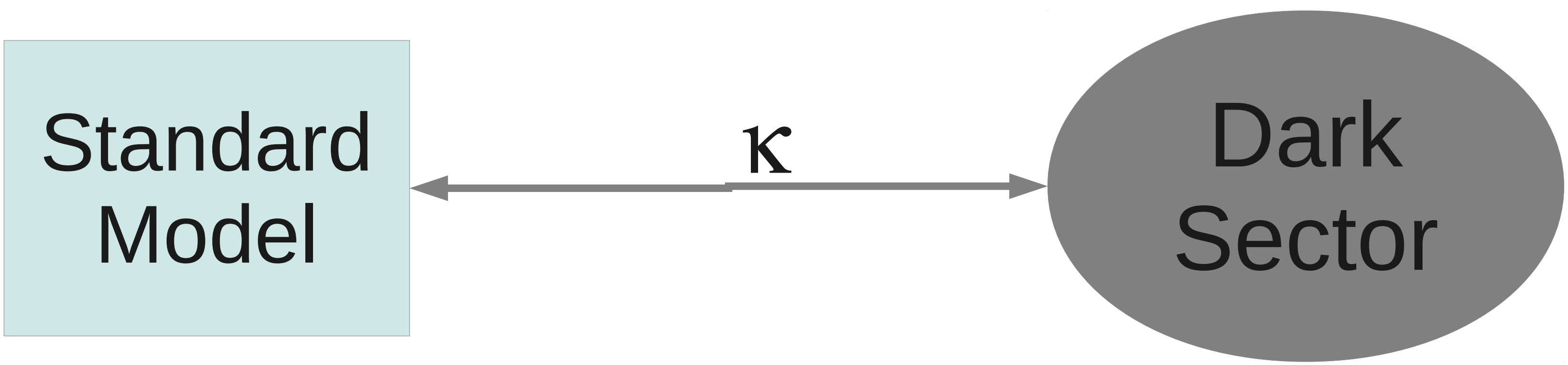
Direct Dark Matter Searches



- What about WIMP Mass below GeV?
- Lee-Weinberg bound – need new light mediators
- Recoil energy detection threshold – need relativistic DM beam

Minimal Standard Model extension

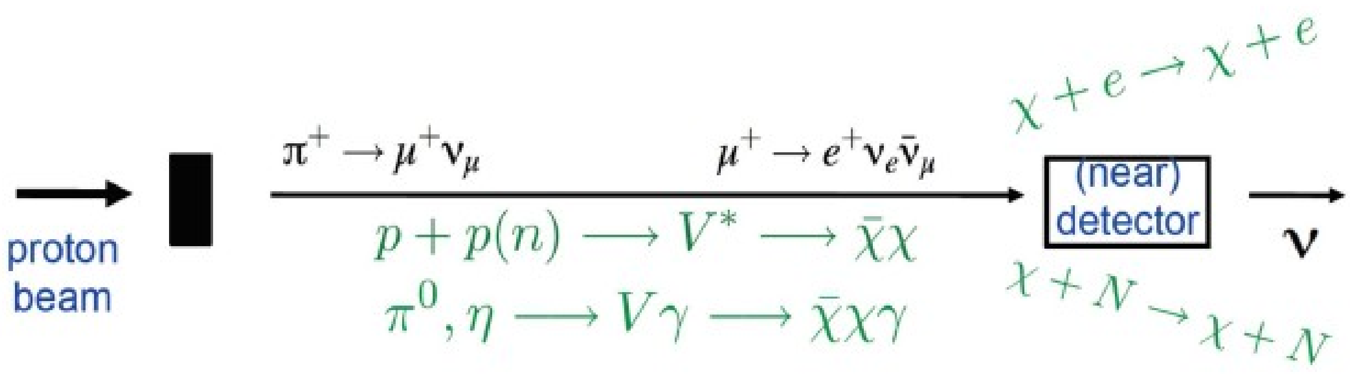
- New vector mediator *V* and dark matter particle χ
- 4 new parameters: m_χ, m_V, κ, α'
- Interestingly, *V* could explain g-2 anomaly (*M. Pospelov Phys.Rev.D80, 095002 (2009)*)



P. deNiverville, D. McKeen, A. Ritz Phys.Rev.D86:035022 (2012)

Relativistic dark matter beam

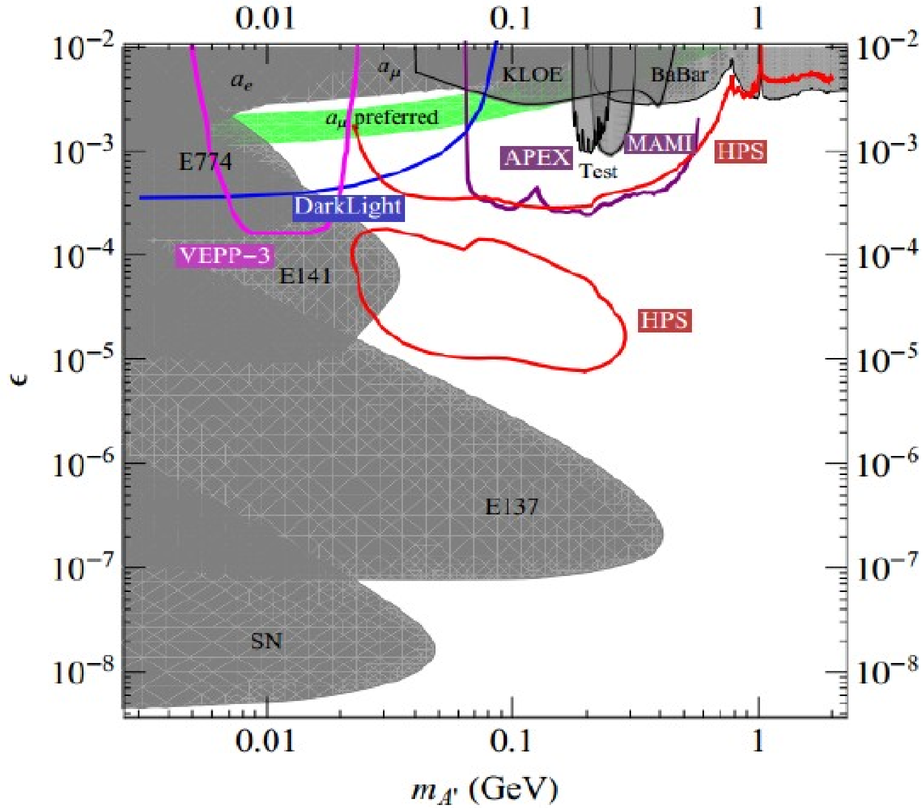
- Production:
  - Intense proton beam
  - Direct parton-level processes p+p(n) $\rightarrow V^* \rightarrow \chi + \chi$
  - Through decays of mesons with large radiative branching



- Detection
  - Assumption: $M_V > 2M_\chi$
  - Scattering on nucleons and electrons

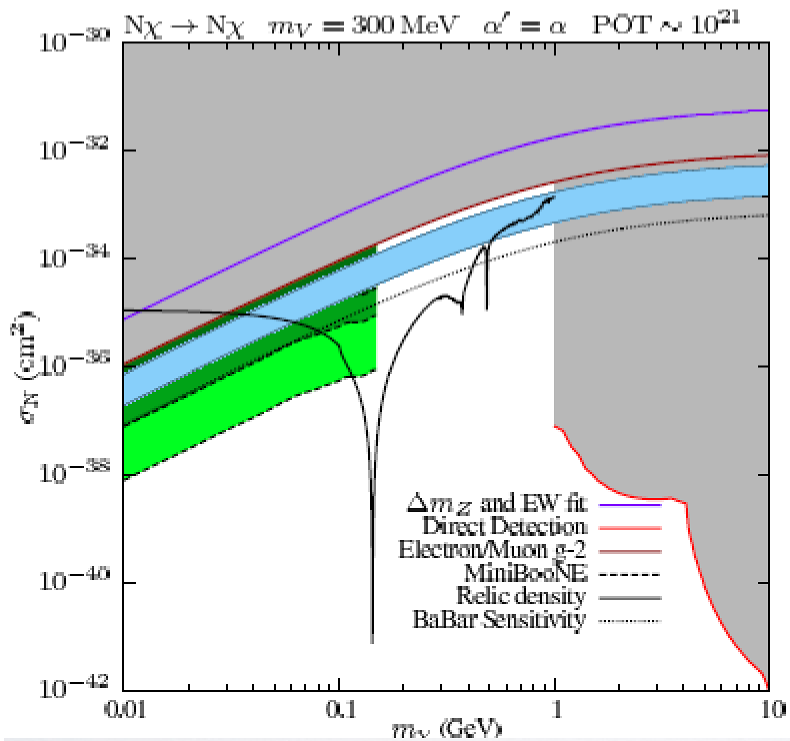
Complementary to dark force searches

- Heavy photon search at Jlab
- Looking for visible V decays ($M_V < 2M_\chi$)



Proof of concept

- Search for Dark Matter with MiniBooNE
- Dark matter scattering mimics neutrino neutral current elastic events
- Look for excess in NC elastic sample

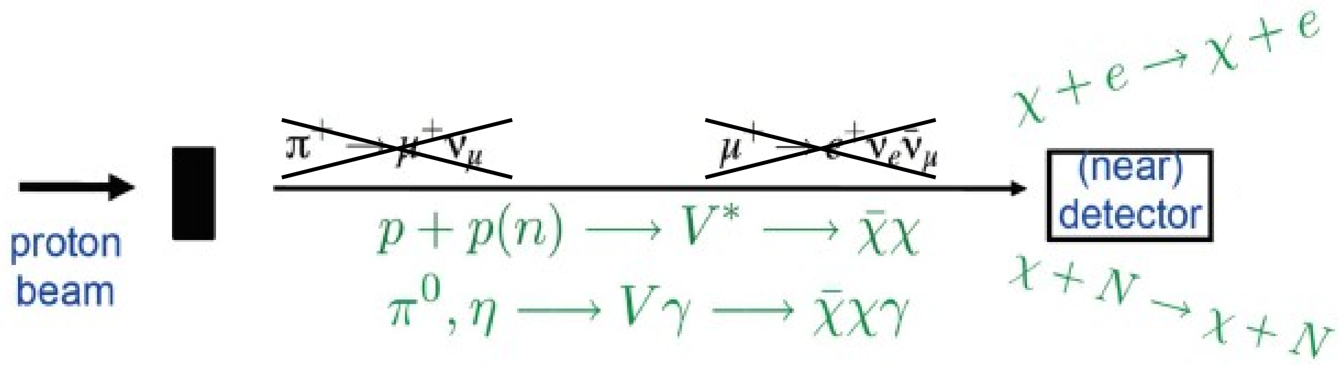


- light green: 1 – 10 events
- green: 10 – 1000 events
- dark green: more than 1000 events

arxiv: 1211.2258

Boosting sensitivity

- Cover whole g-2 region
- Beam off-target run
  - Steer protons directly to beam absorber
  - Reduce dominant background due to neutrinos by ~40 times



Conclusion 2

- Intense proton beam great source of dark matter particles
- Unique opportunity to search for low mass Dark Matter at Fermilab
- Short baseline neutrino experiments can search for dark matter

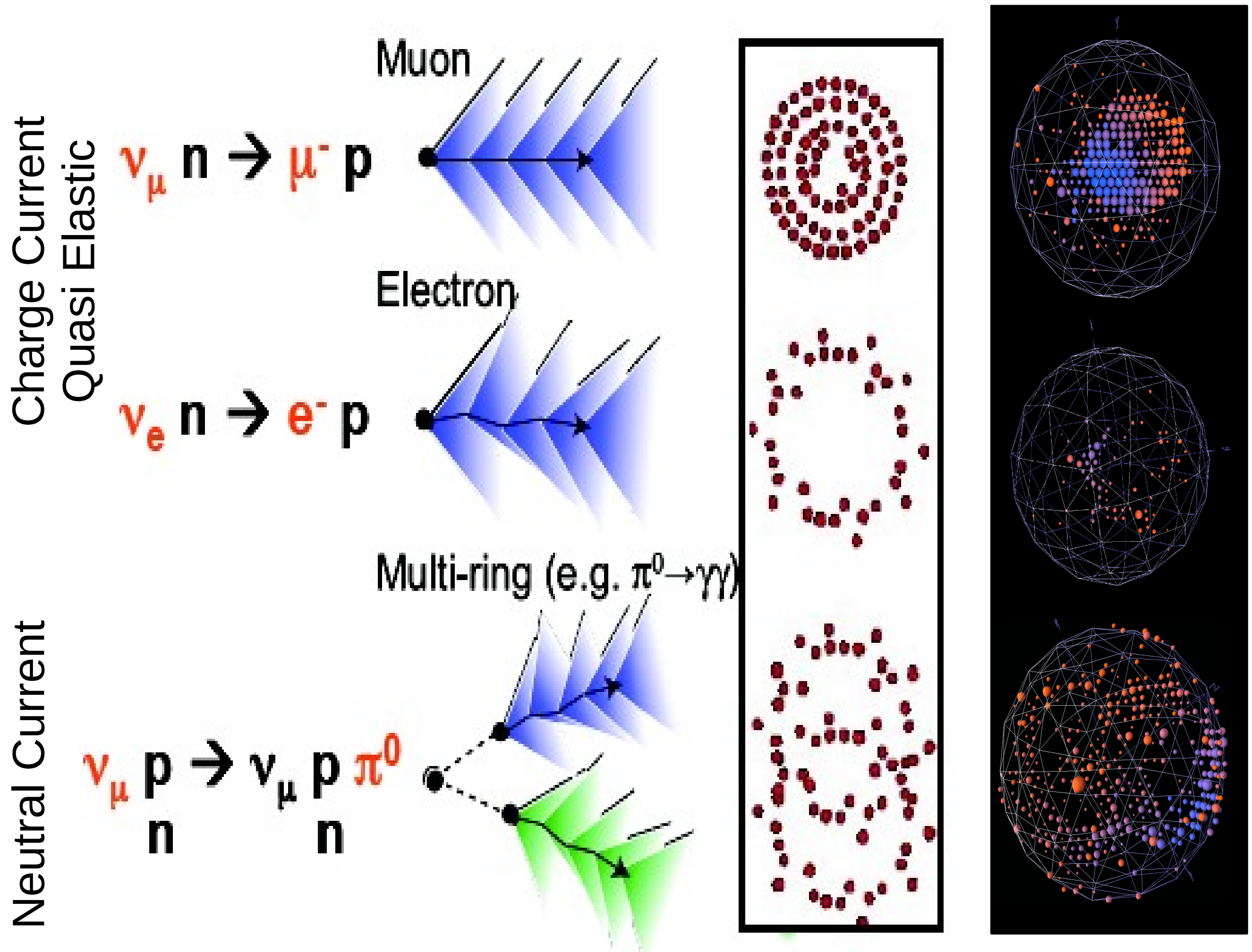
Backup

MiniBooNE detector

- Sphere 12m in diameter
- 800t mineral oil
- 1280 inner PMTs + 240 veto PMT

Events in MiniBooNE

- Identify events using timing and hit topology
- Use primarily Cherenkov light



Filled ring with sharp boundary

One fuzzy ring

Two fuzzy rings

Background events

- Backgrounds similar in neutrino (left) and antineutrino (right) mode
- Use MiniBooNE data to constrain backgrounds