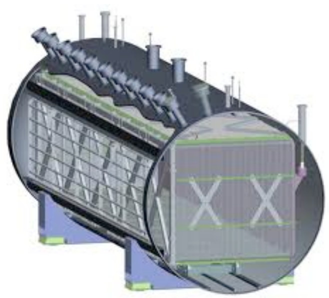
MicroBooNE: Neutrino Physics at the Dawn of the Liquid Argon TPC Era

Georgia Karagiorgi
Columbia University

Weak Interactions Discussion Group Seminar @ Yale
November 11, 2013

Sterile neutrinos? **Mass hierarchy?** **CP violation?**

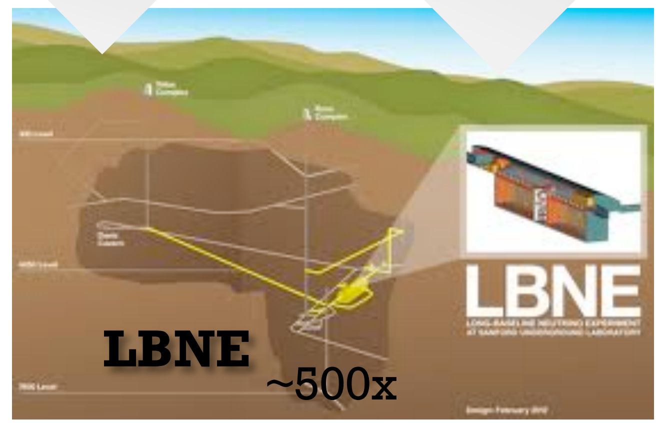
MicroBooNE



~1x

...MicroBooNE
+LAr1

~15x



LBNE ~500x

No sterile neutrinos in the Standard Model*

**Minimally* extended to account for neutrino mass

Three-Neutrino Oscillation Parameters

Ingredients for neutrino oscillation:

neutrinos have non-zero masses
+
(neutral) leptons mix

weak ("flavor") states "mass" states

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

3×3 unitary mixing matrix *U*

Three-Neutrino Oscillation Parameters

1. **Why 3 "flavor" states?**
2. **Why 3 "mass" states?**

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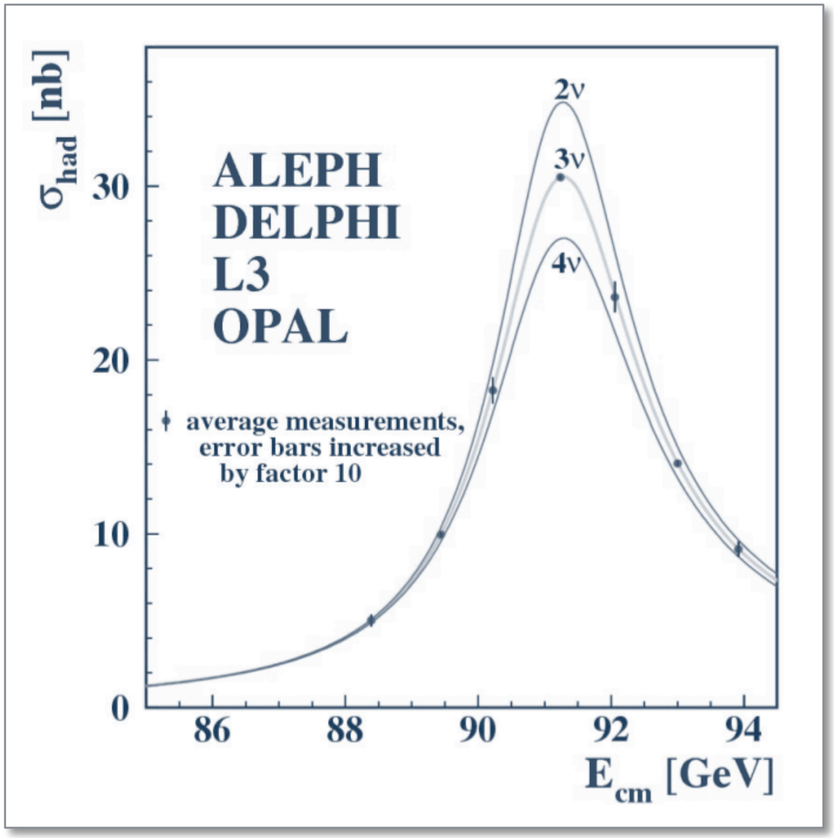

$$N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_\ell}\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\rm SM}$$

$$= 2.984 \pm 0.008$$

[Phys. Reports 427, 257 (2006)]

Measurement of the invisible Z width: $Z \rightarrow \nu\bar{\nu}$

Three-Neutrino Oscillation Parameters

2. Why 3 "mass" states?

1. Theoretical prejudice
2. Limits on number of light neutrino species from cosmology*

Model	Data	N_{eff}
N_{eff}	W-5+BAO+SN+H_0	$4.13^{+0.87(+1.76)}_{-0.85(-1.63)}$
	W-5+LRG+H_0	$4.16^{+0.76(+1.60)}_{-0.77(-1.43)}$
	W-5+CMB+BAO+XLF+f_{gas}+H_0	$3.4^{+0.6}_{-0.5}$
	W-5+LRG+maxBCG+H_0	$3.77^{+0.67(+1.37)}_{-0.67(-1.24)}$
	W-7+BAO+H_0	$4.34^{+0.86}_{-0.88}$
	W-7+LRG+H_0	$4.25^{+0.76}_{-0.80}$
	W-7+ACT	5.3 ± 1.3
	W-7+ACT+BAO+H_0	4.56 ± 0.75
	W-7+SPT	3.85 ± 0.62
	W-7+SPT+BAO+H_0	3.85 ± 0.42
	W-7+ACT+SPT+LRG+H_0	$4.08^{(+0.71)}_{(-0.68)}$
	W-7+ACT+SPT+BAO+H_0	3.89 ± 0.41
$N_{eff}+f_\nu$	W-7+CMB+BAO+H_0	$4.47^{(+1.82)}_{(-1.74)}$
	W-7+CMB+LRG+H_0	$4.87^{(+1.86)}_{(-1.75)}$
$N_{eff}+\Omega_k$	W-7+BAO+H_0	4.61 ± 0.96
	W-7+ACT+SPT+BAO+H_0	4.03 ± 0.45
$N_{eff}+\Omega_k+f_\nu$	W-7+ACT+SPT+BAO+H_0	4.00 ± 0.43
$N_{eff}+f_\nu+w$	W-7+CMB+BAO+H_0	$3.68^{(+1.90)}_{(-1.84)}$
	W-7+CMB+LRG+H_0	$4.87^{(+2.02)}_{(-2.02)}$
$N_{eff}+\Omega_k+f_\nu+w$	W-7+CMB+BAO+SN+H_0	$4.2^{+1.10(+2.00)}_{-0.61(-1.14)}$
	W-7+CMB+LRG+SN+H_0	$4.3^{+1.40(+2.30)}_{-0.54(-1.09)}$

[pre-Planck data: arXiv:1204.5379]

Three-Neutrino Oscillation Parameters

Mixing matrix parameterization for two-mass-scale dominance scenario:

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

three mixing angles:

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

"solar" $\theta_{12} \approx 34°$

"reactor" $\theta_{13}=9°$

"atmospheric" $\theta_{23} \approx 45°$

and a CP-violating phase:

If $\delta \neq 0$, then have CP violation $\Rightarrow P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

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three mixing angles:

As of 2012, the only unknown mixing parameter!

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

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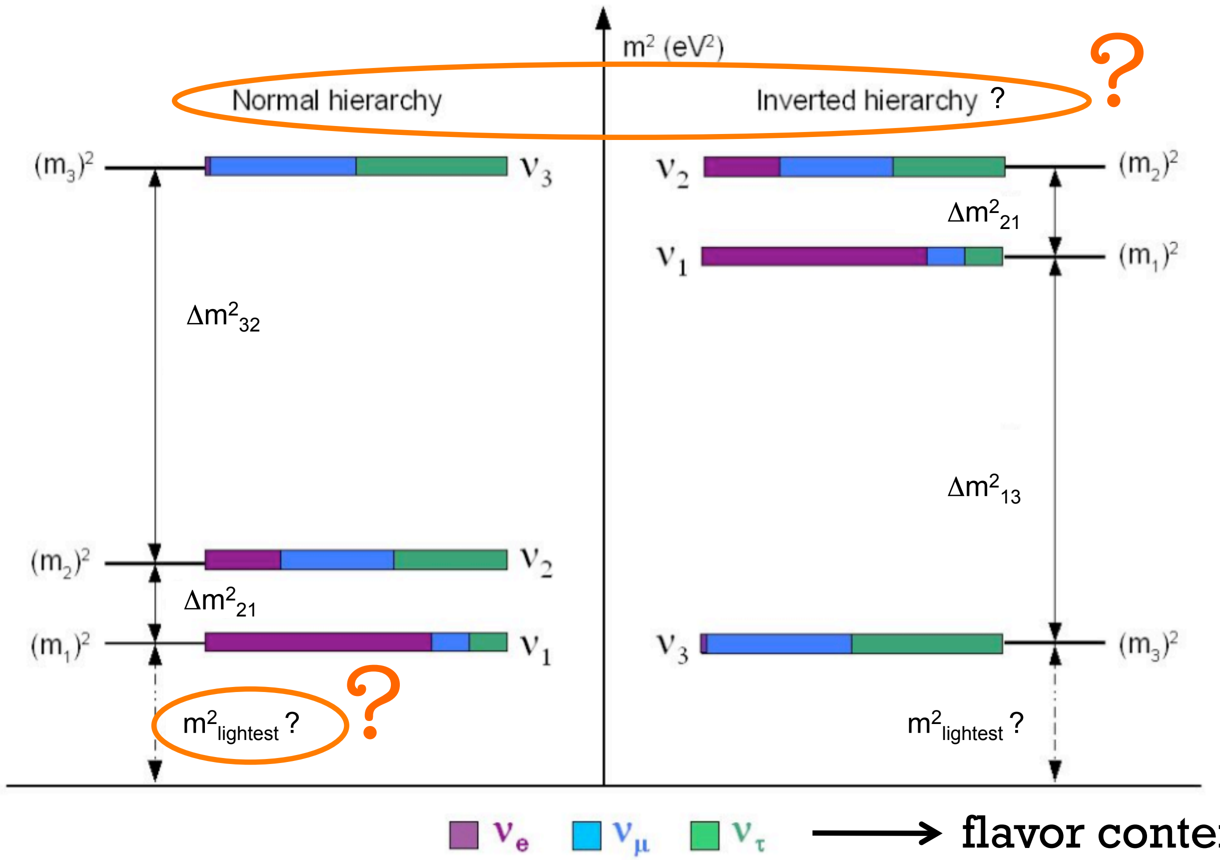


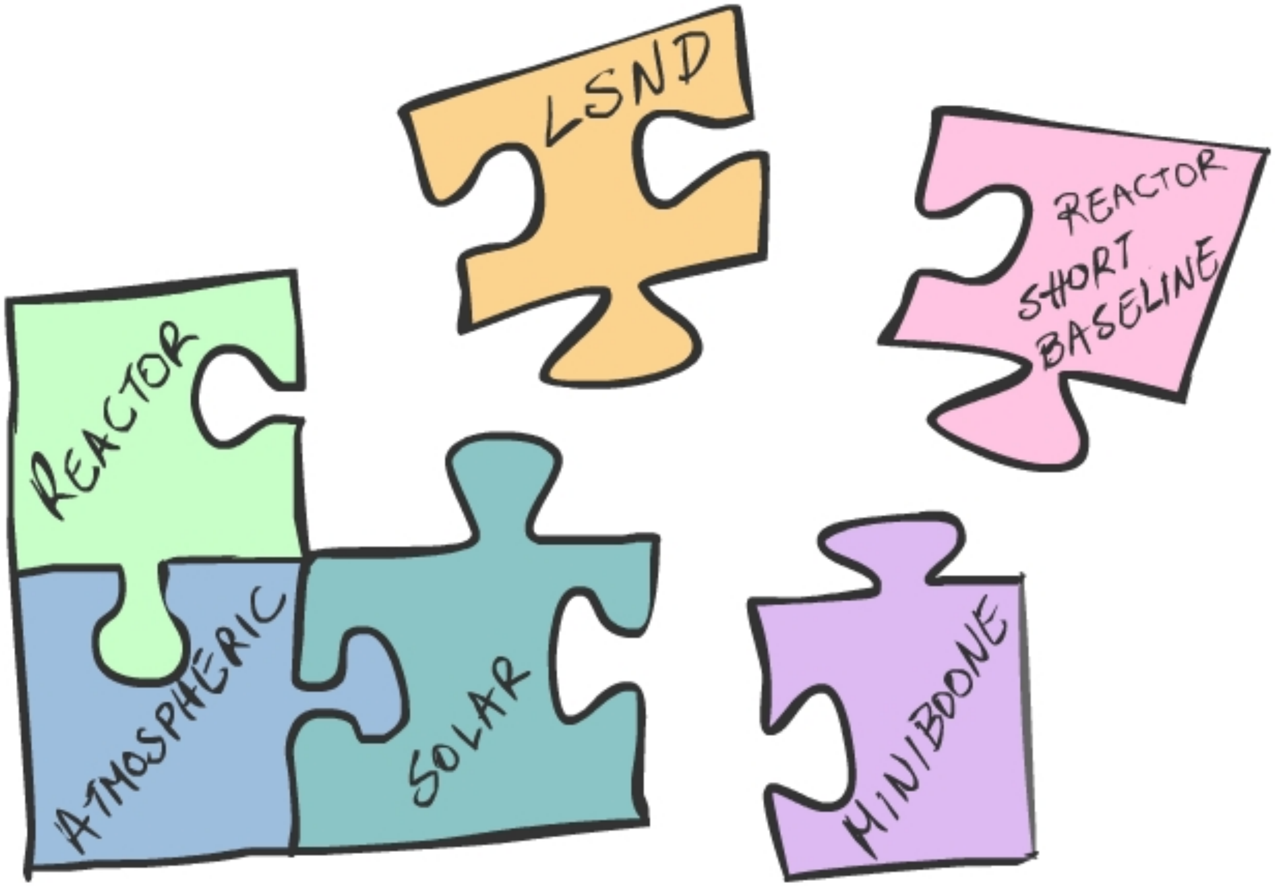
→ flavor content depends on mixing elements (angles)

Three mass splittings:

$$\Delta m_{21}^2 = m_2^2 - m_1^2 \qquad \Delta m_{32}^2 = m_3^2 - m_2^2 \qquad \Delta m_{31}^2 = m_3^2 - m_1^2$$

but only two are independent since the framework assumes only three mass states.

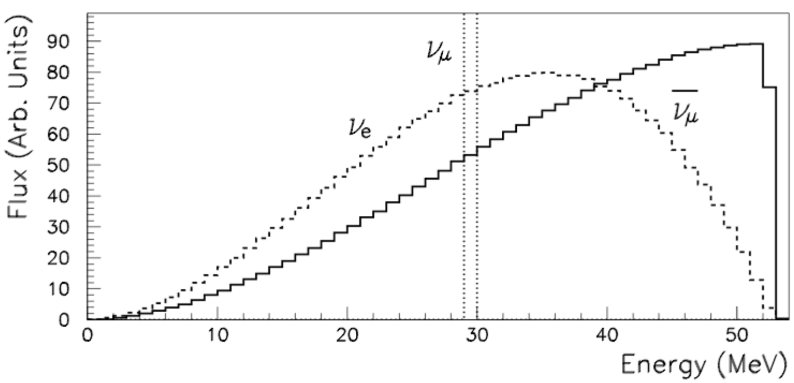
Why or why not sterile neutrinos?

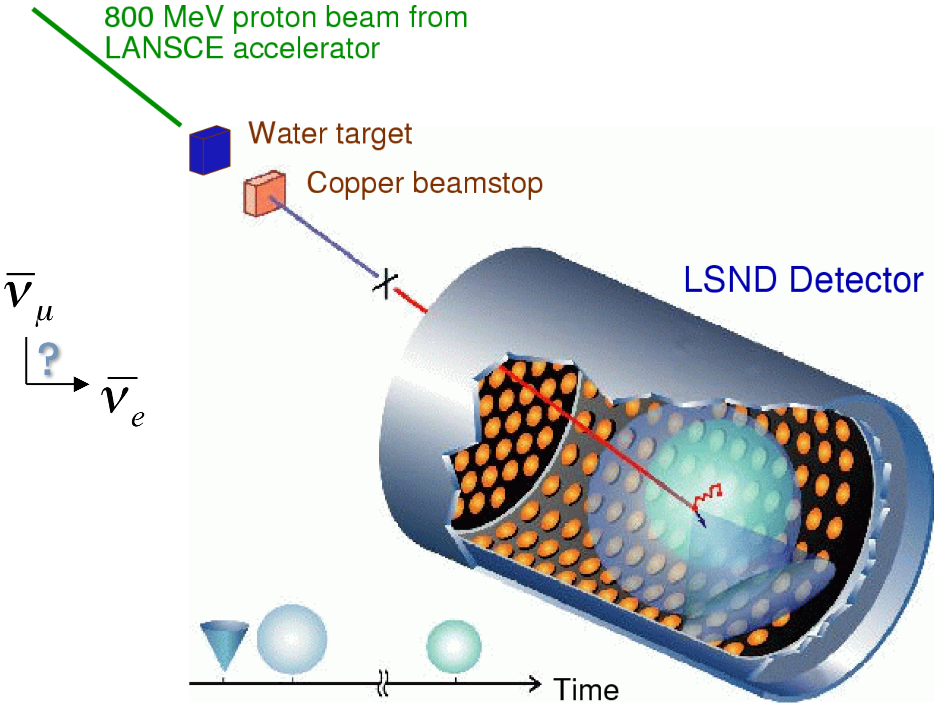


Puzzle piece #1: LSND Experiment

μ^+ decay-at-rest experiment:

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\overset{?}{\hookrightarrow} \bar{\nu}_e$$





Well-predicted neutrino flux and cross-section.
Very low $\bar{\nu}_e$ backgrounds.

$\bar{\nu}_e$ detection via inverse-beta-decay: $\bar{\nu}_e + p \rightarrow e^+ + n$
(coincidence signal)

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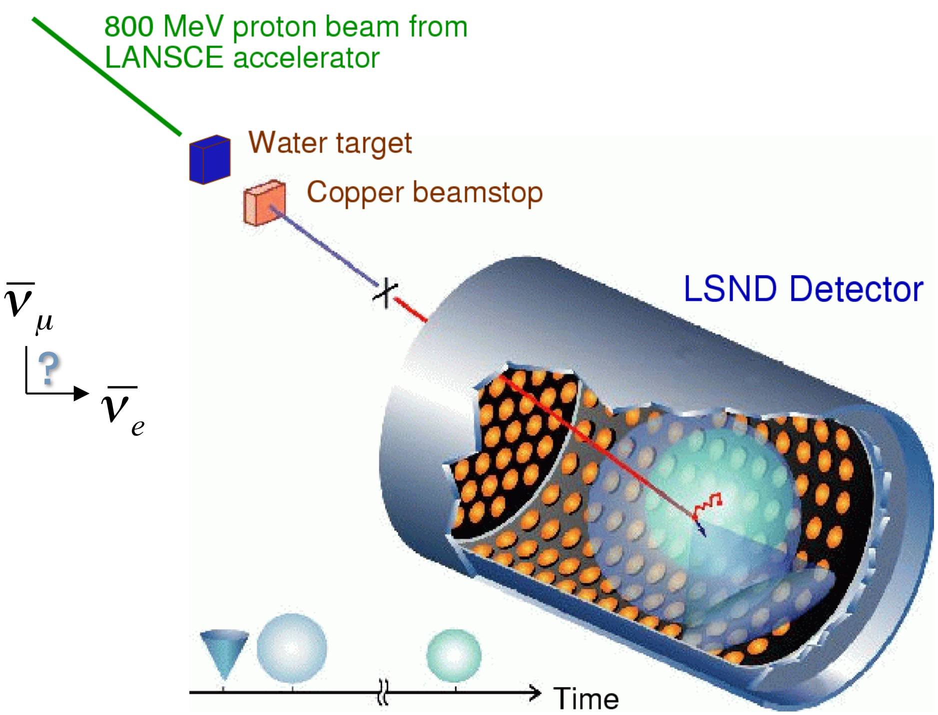
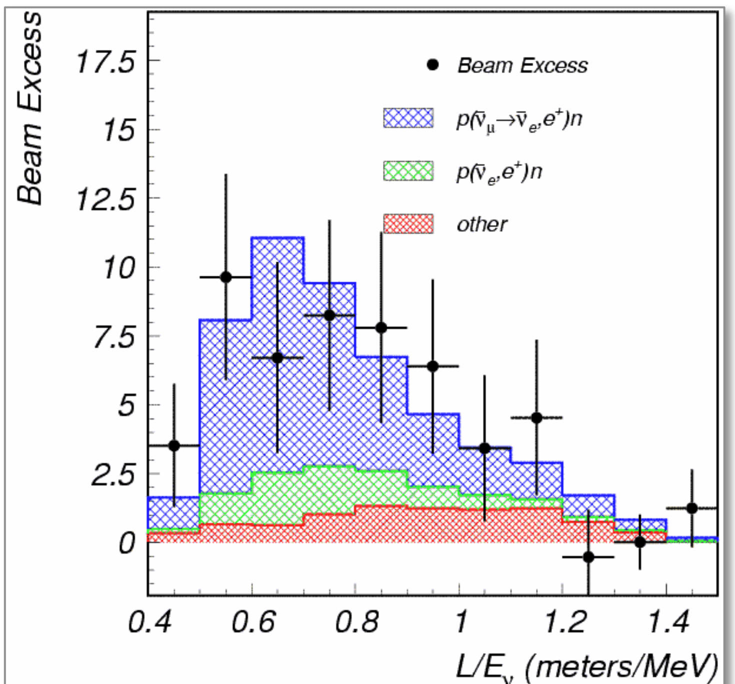




Observed excess of $\bar{\nu}_e$ described by oscillation probability:
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)$ %

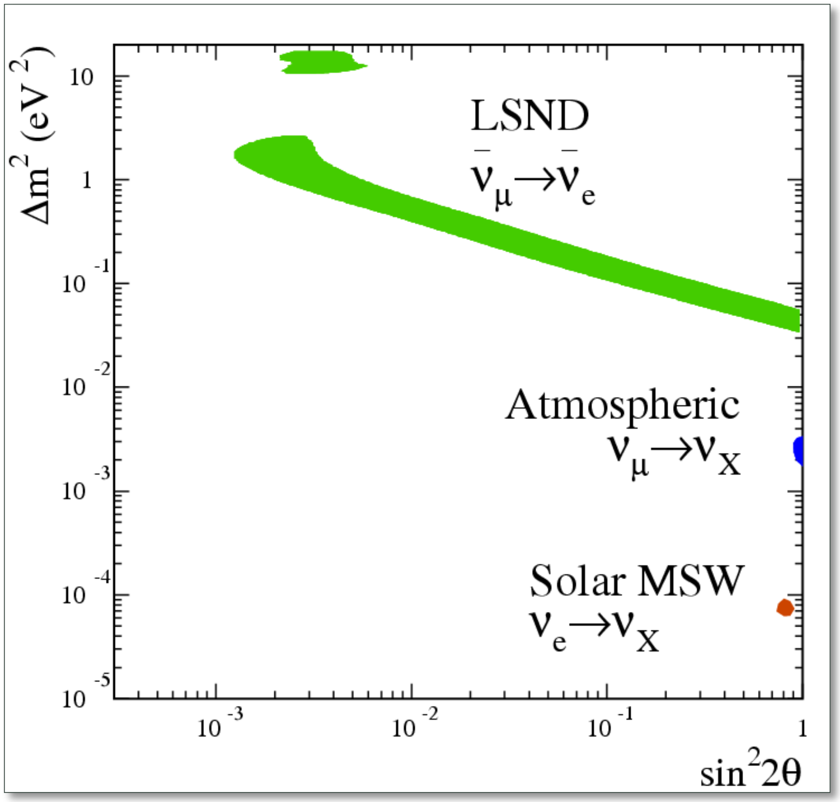
(3.8σ evidence)

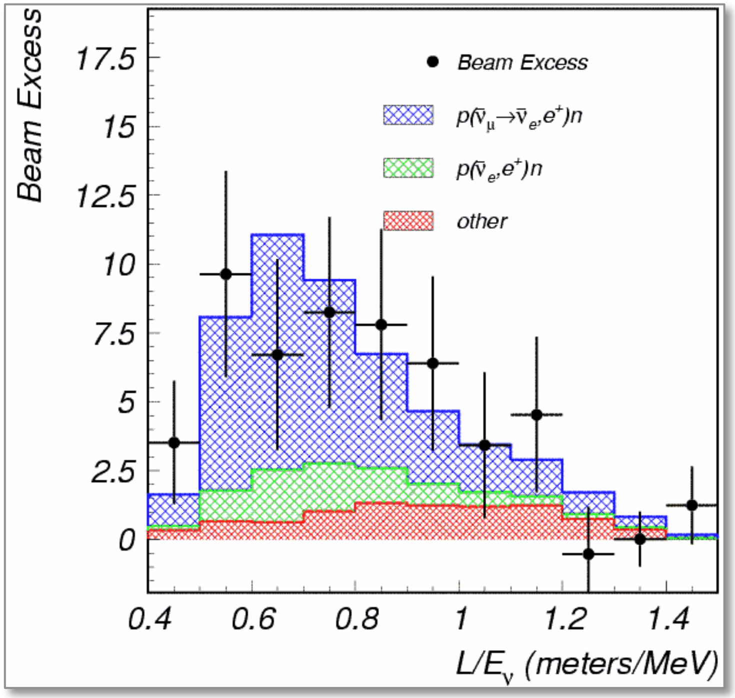
[C. Athanassopoulos et al., Phys. Rev. Lett. 75, 2650 (1995); 81,1774(1998); A.Aguilaretal., Phys. Rev. D64, 112007(2001).]

Puzzle piece #1: LSND Experiment

Points to large Δm^2
if interpreted as
two-neutrino oscillations:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27 \Delta m^2 L/E)$$





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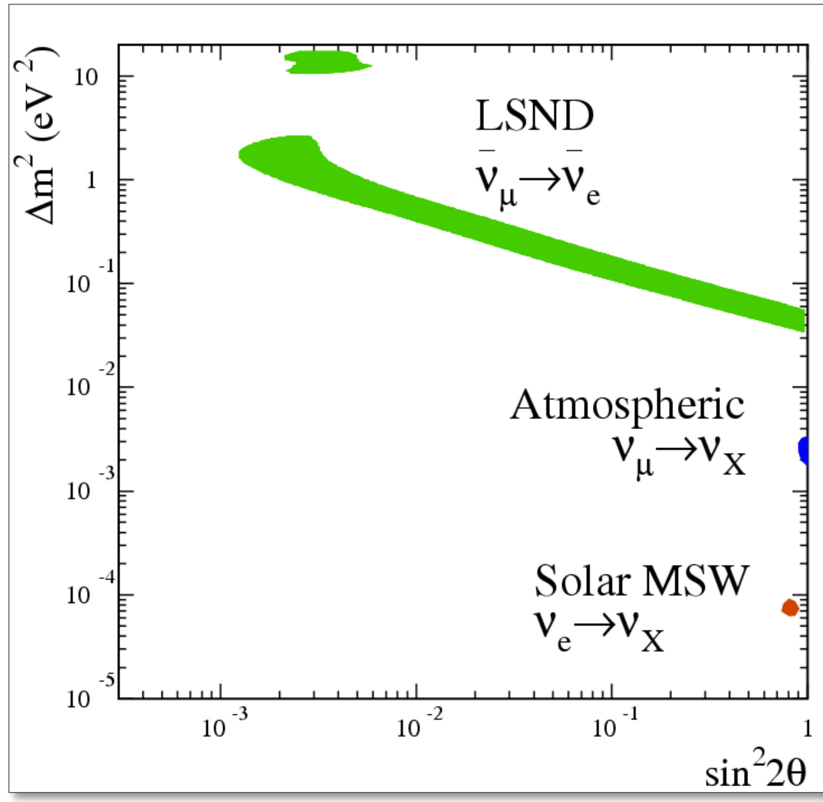
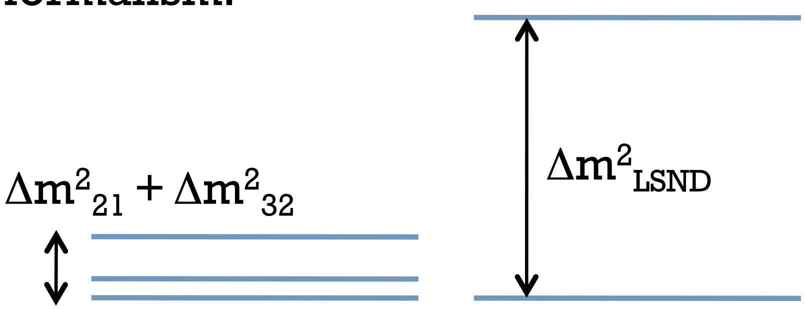


In conflict with three-neutrino formalism!



$\Delta m^2_{LSND} >> \Delta m^2_{21} + \Delta m^2_{32}$

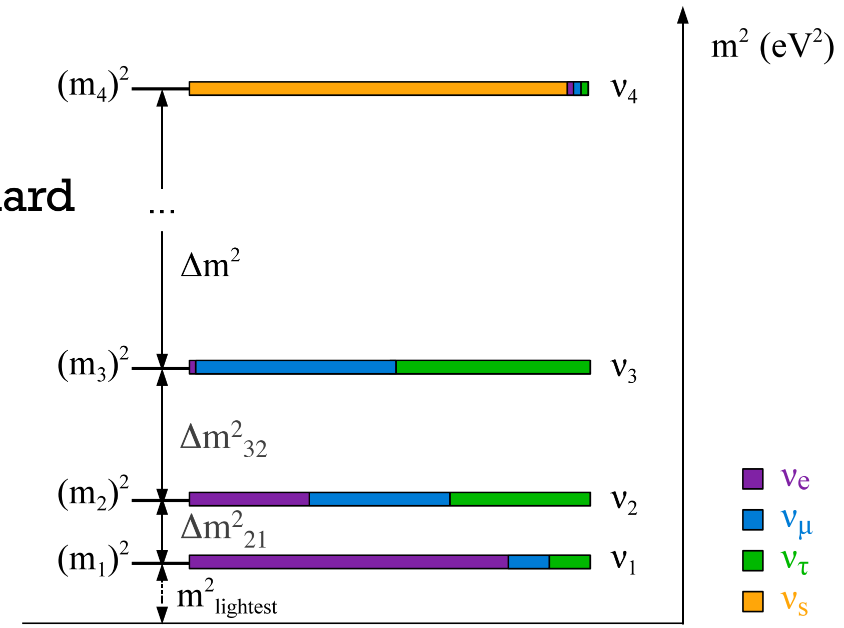
Needs more than 3 neutrinos!

Possible interpretation: sterile neutrino

Additional neutrino "flavor" (and mass) state which has **no weak interactions** (through the standard W/Z bosons)

Additional mass state is assumed to be produced through mixing with the standard model neutrinos

→ Can affect neutrino oscillations through mixing



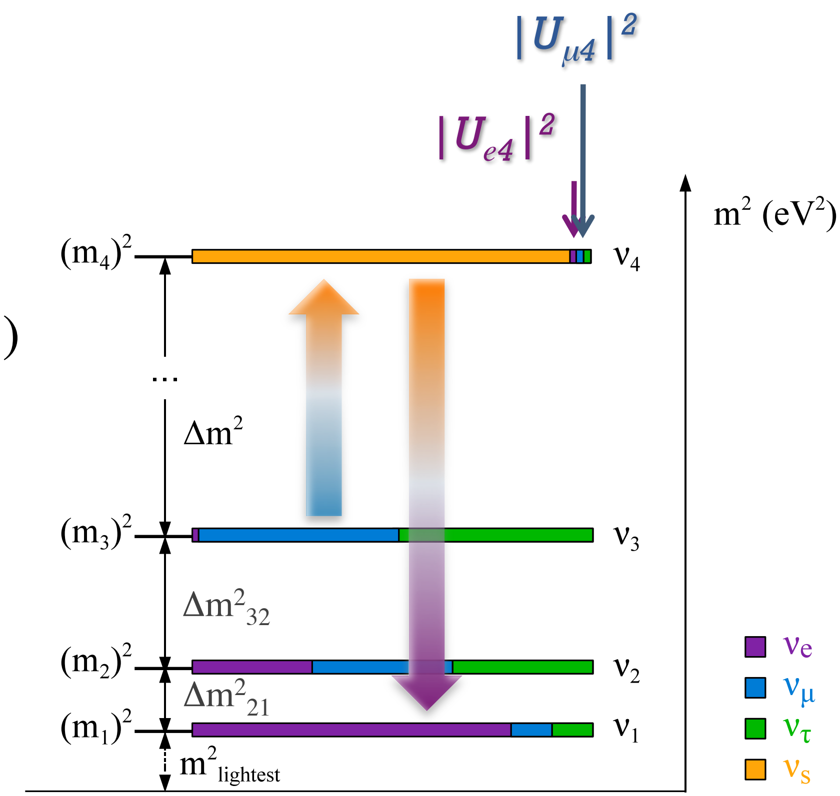
Sterile Neutrino Oscillation Formalism

Oscillation effects:

$\nu_\mu \rightarrow \nu_e$ appearance*:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27\Delta m^2 L/E)$$

$$\hookrightarrow \quad 4|U_{e4}|^2|U_{\mu4}|^2$$



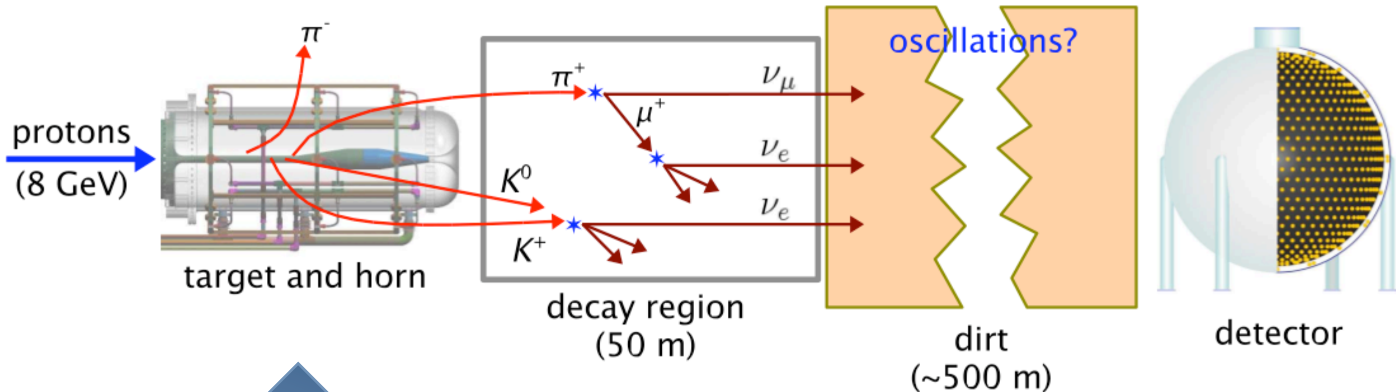
Explains LSND result but needs independent confirmation!

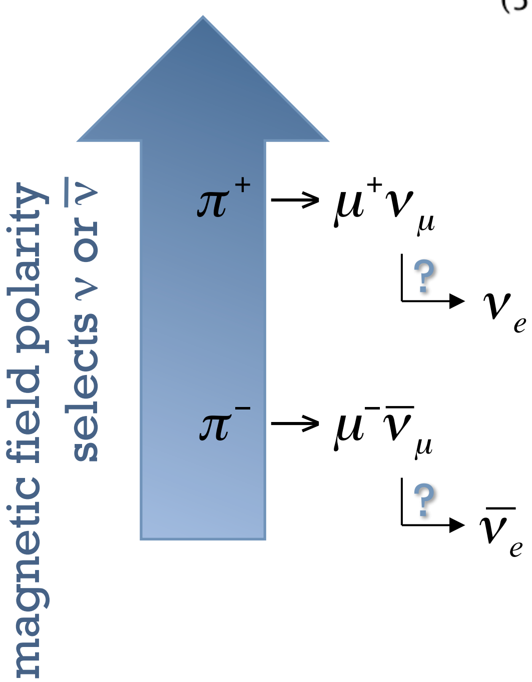
(3+1)

*Approximation: $m_1, m_2, m_3 << m_4 \rightarrow \quad m_1, m_2, m_3 = 0$

Puzzle piece #2: MiniBooNE

MiniBooNE was proposed to test the LSND result:



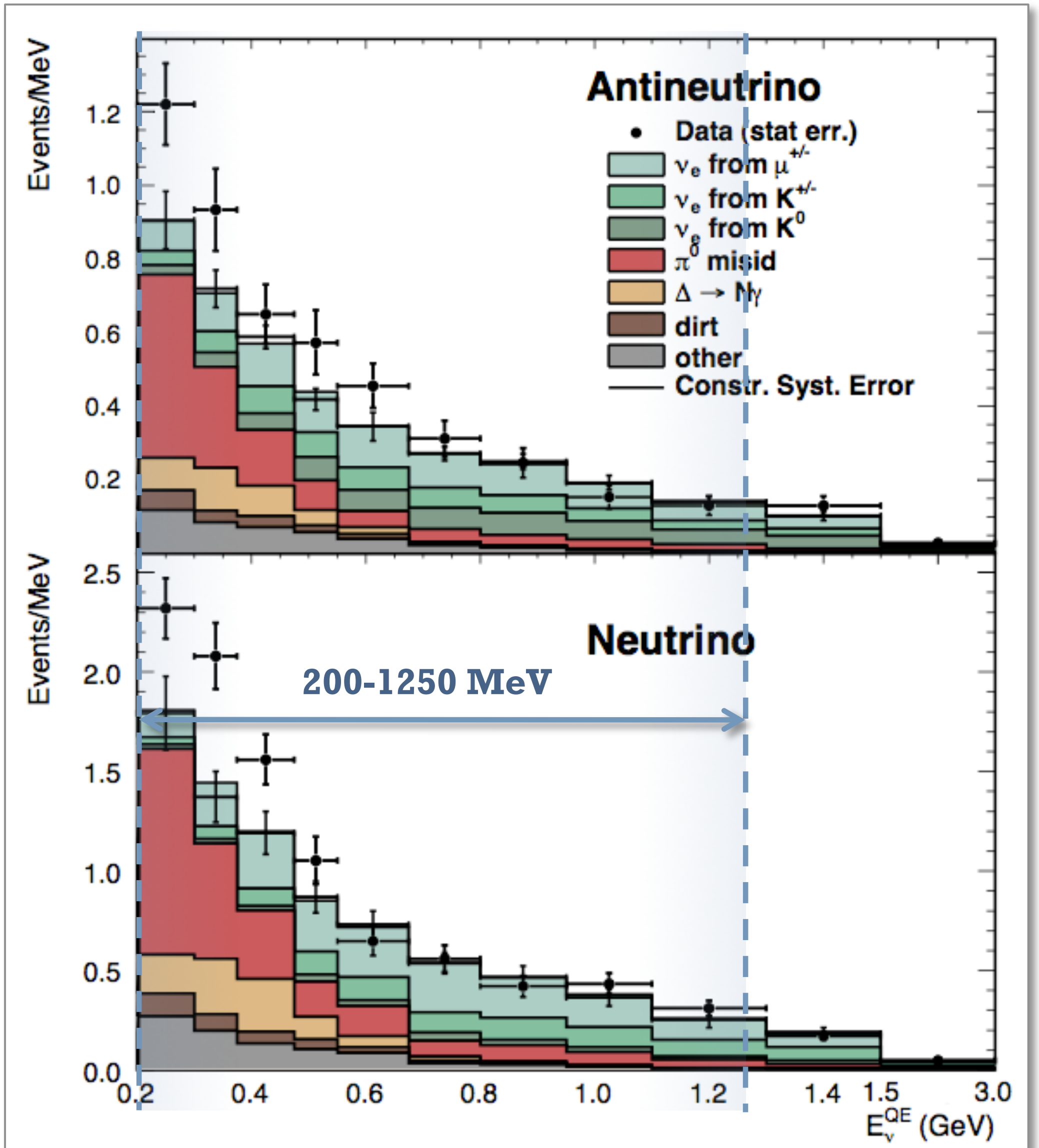


Similar L/E as LSND

but

- Different energy, beam and detector systematics
- Different event signatures and backgrounds (cherenkov detector)

Puzzle piece #2: MiniBooNE



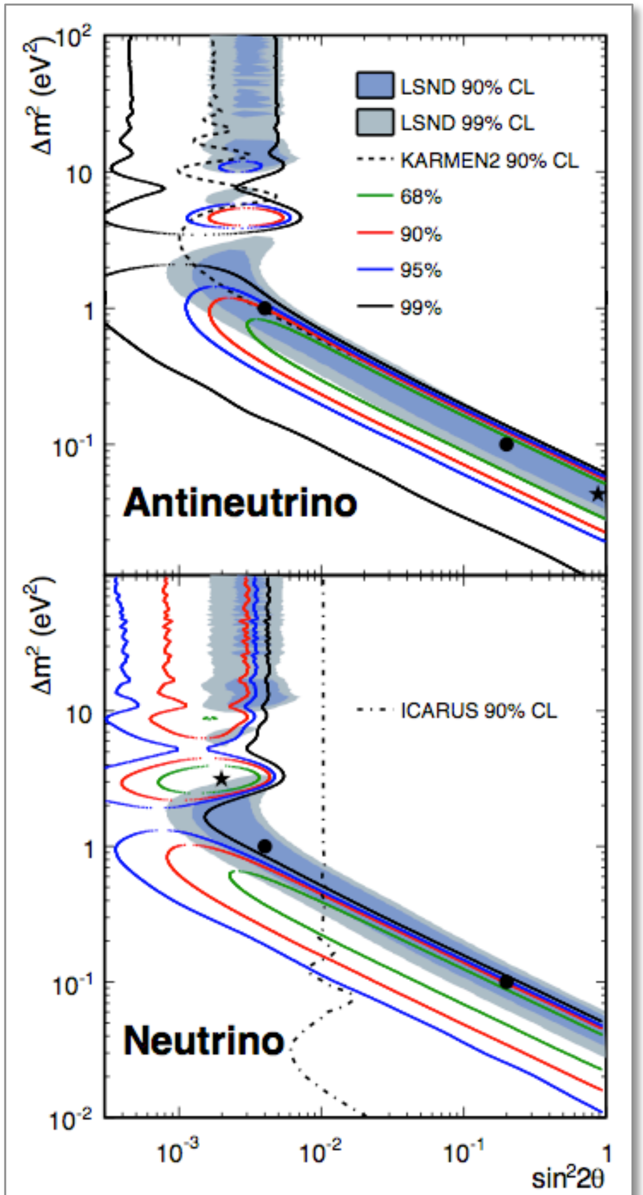
[arXiv:1303.2588, accepted by Phys. Rev. Let.; see also:
Phys.Rev.Lett.110.161801,2012
Phys.Rev.Lett.98.231801,2007,
Phys.Rev.Lett.102.101802,2009,
Phys.Rev.Lett.103:111801,2009,
Phys.Rev.Lett.105:181801,2010]

Oscillation signal region: 200-1250 MeV

Antineutrino search:
2.8σ excess
Excess of events is at both high and "low energy."

Neutrino search:
3.4σ excess
Excess of events is at "low energy," E < 475 MeV.

Puzzle piece #2: MiniBooNE



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Phys.Rev.Lett.98.231801,2007,
Phys.Rev.Lett.102.101802,2009,
Phys.Rev.Lett.103:111801,2009,
Phys.Rev.Lett.105:181801,2010]

Antineutrino (3+1) best fit:
χ^2-probability = 66%
$(\Delta m^2, \sin^2 2\theta) = (0.04\ eV^2, 0.88)$

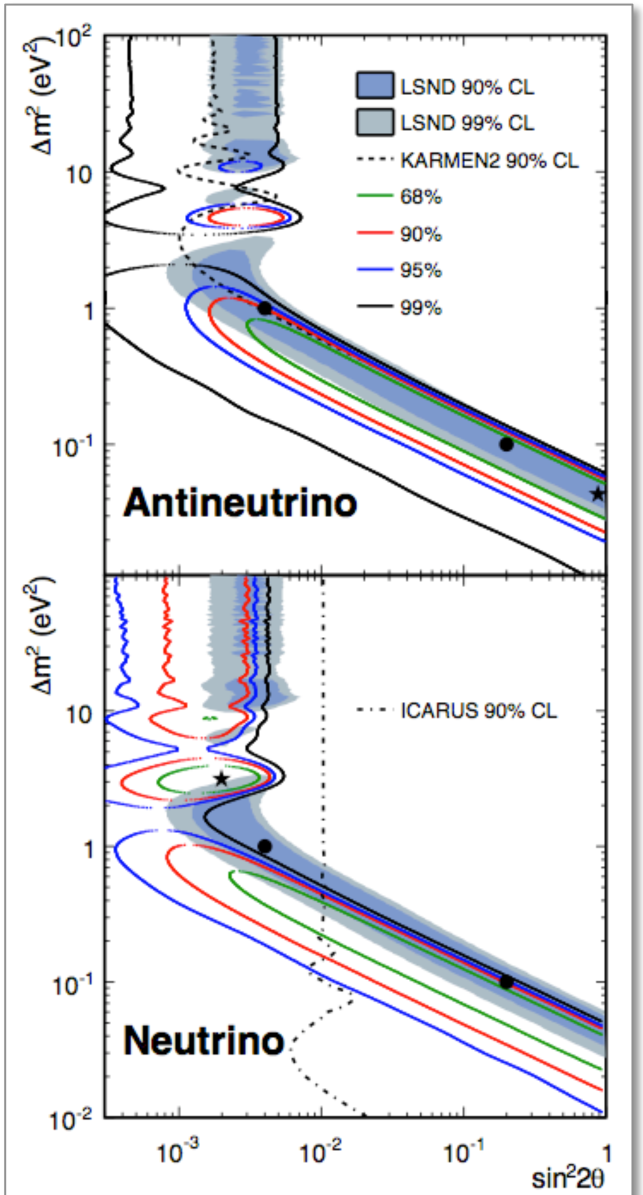
Background-only relative to best fit: 0.5%

Neutrino (3+1) best fit:
χ^2-probability = 6.1%
$(\Delta m^2, \sin^2 2\theta) = (3.14\ eV^2, 0.002)$

Background-only relative to best fit: 2%

Both are consistent with (3+1) oscillations in general, but MiniBooNE antineutrino allowed parameters are in better agreement with LSND parameters.

Puzzle piece #2: MiniBooNE



Barring CP violation,

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

(3+1) approximation
does not allow for CP violation

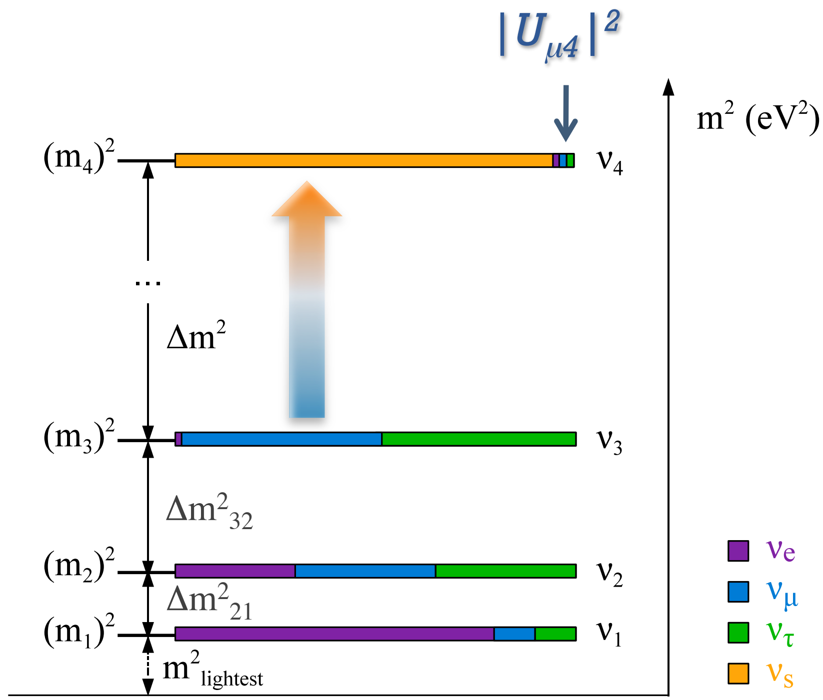
Sterile Neutrino Oscillation Formalism

$\nu_\mu \rightarrow \nu_e$ appearance implies ν_μ and ν_e disappearance!

ν_μ disappearance*:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\vartheta_{\mu\mu} \sin^2(1.27\Delta m^2 L/E)$$

$$\hookrightarrow 4|U_{\mu 4}|^2\left(1-|U_{\mu 4}|^2\right)$$



(3+1)

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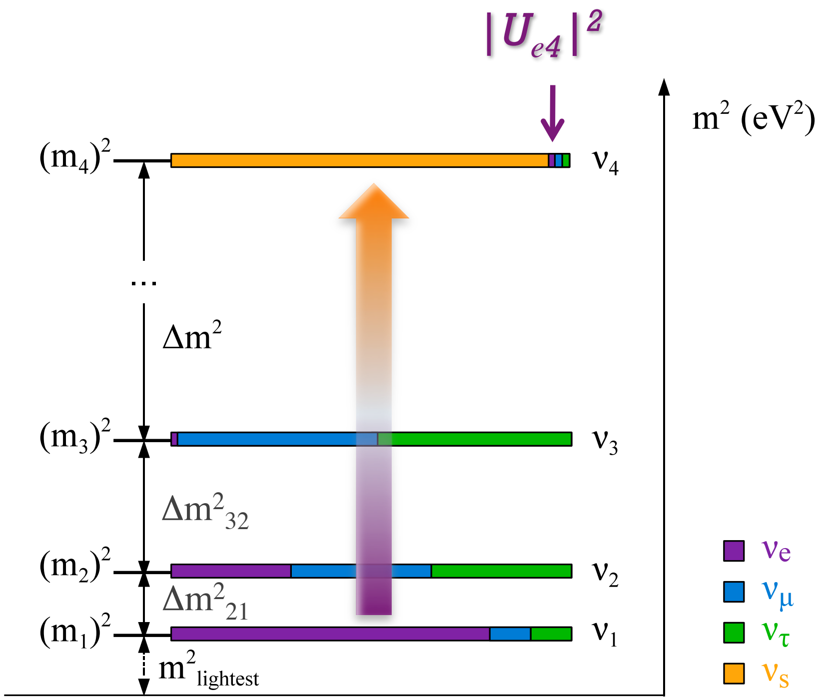

(3+1)

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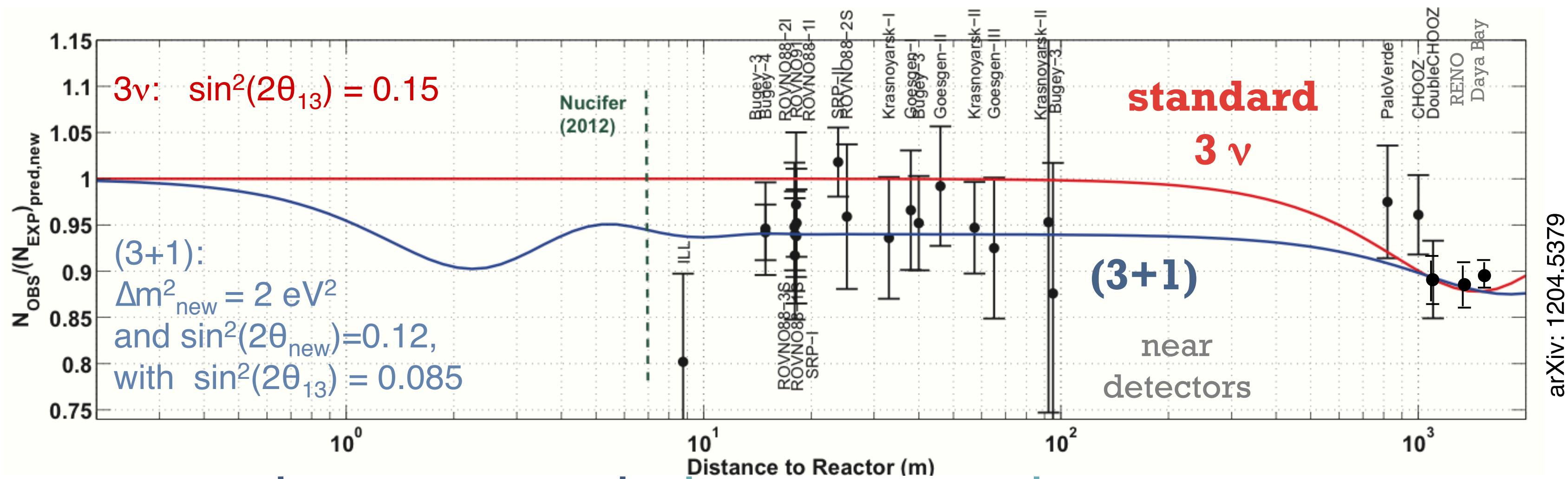
Puzzle piece #3: Reactor Anomaly

$\bar{\nu}_e \rightarrow \bar{\nu}_s$ disappearance?



region to explore for sterile neutrinos

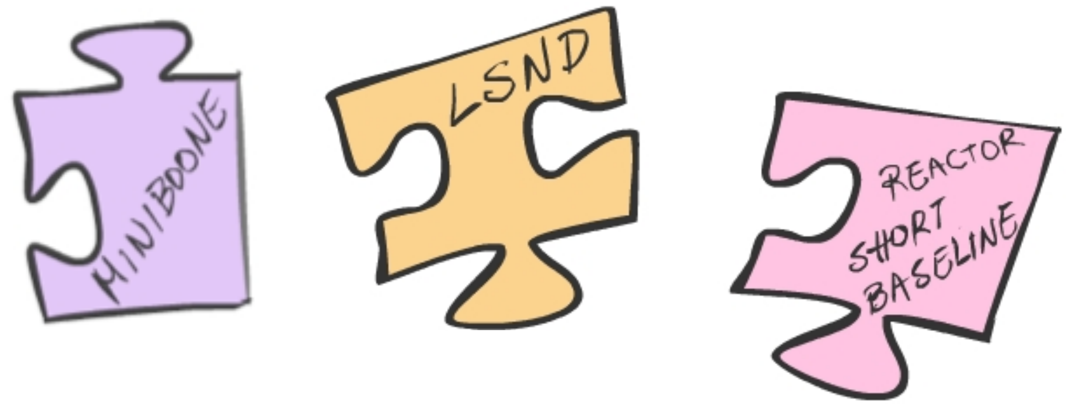
older reactor exps at close distances
R = 0.927 ± 0.023 (3.0σ)
1.4σ when θ_{13} included
[arXiv:1303.0900]

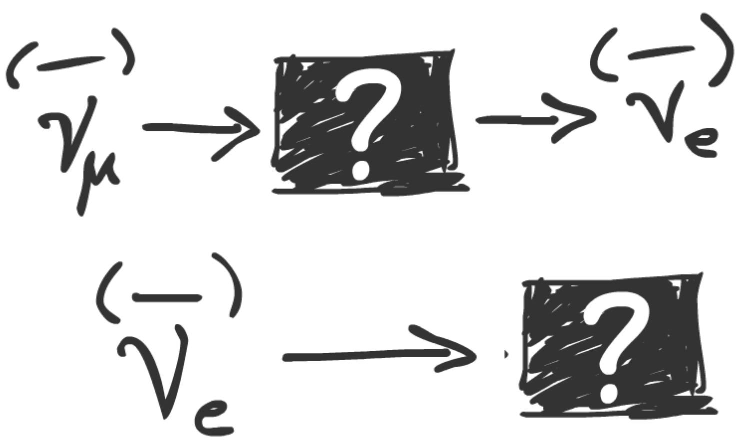
current reactor experiments

Fewer reactor neutrinos than expected at short baselines

→ **A possible interpretation: sterile neutrino osc. with $\Delta m^2 \sim 1 eV^2$ and $\sin^2 2\theta \sim 0.1$**

1. Can all three signatures be explained by (3+1) sterile neutrino hypothesis?





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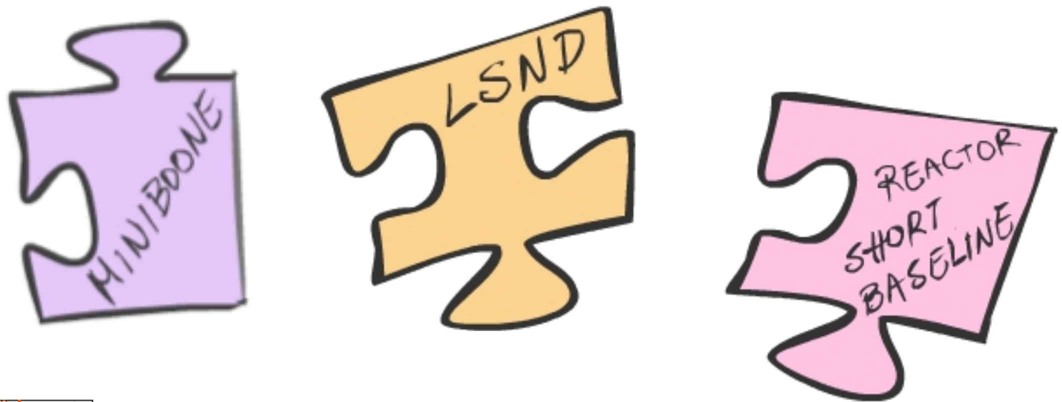

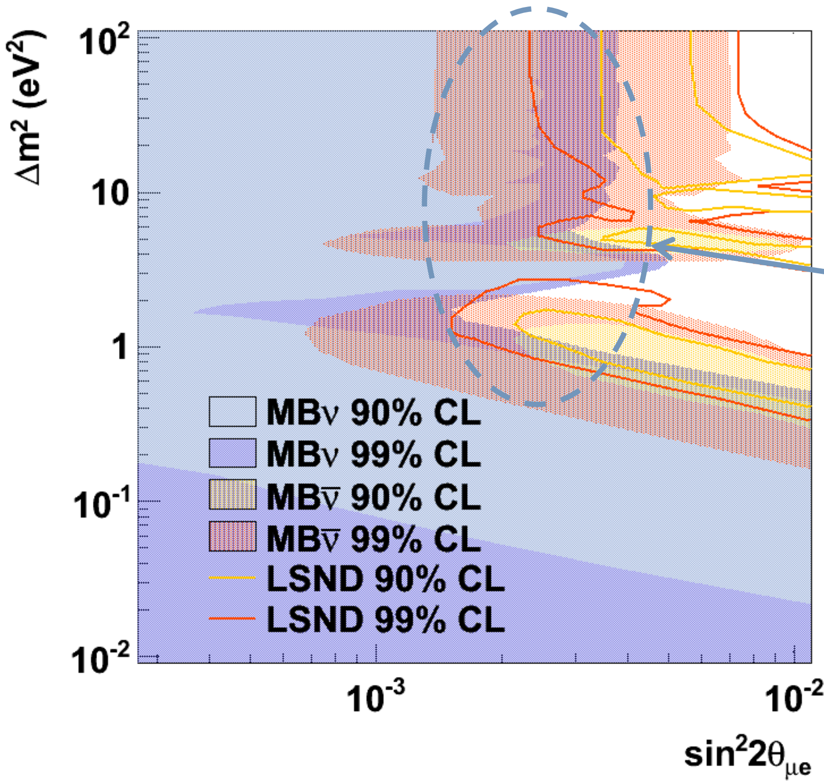

Reactor short-baseline consistent with these values

A: Yes!

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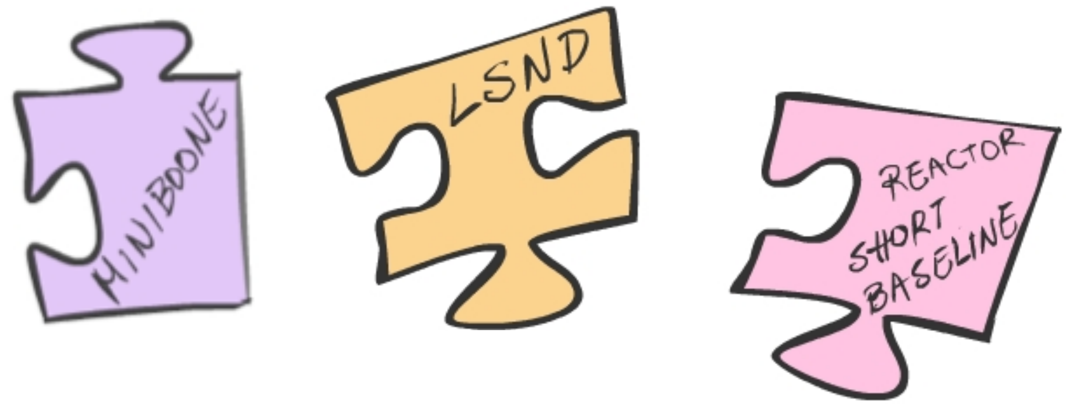
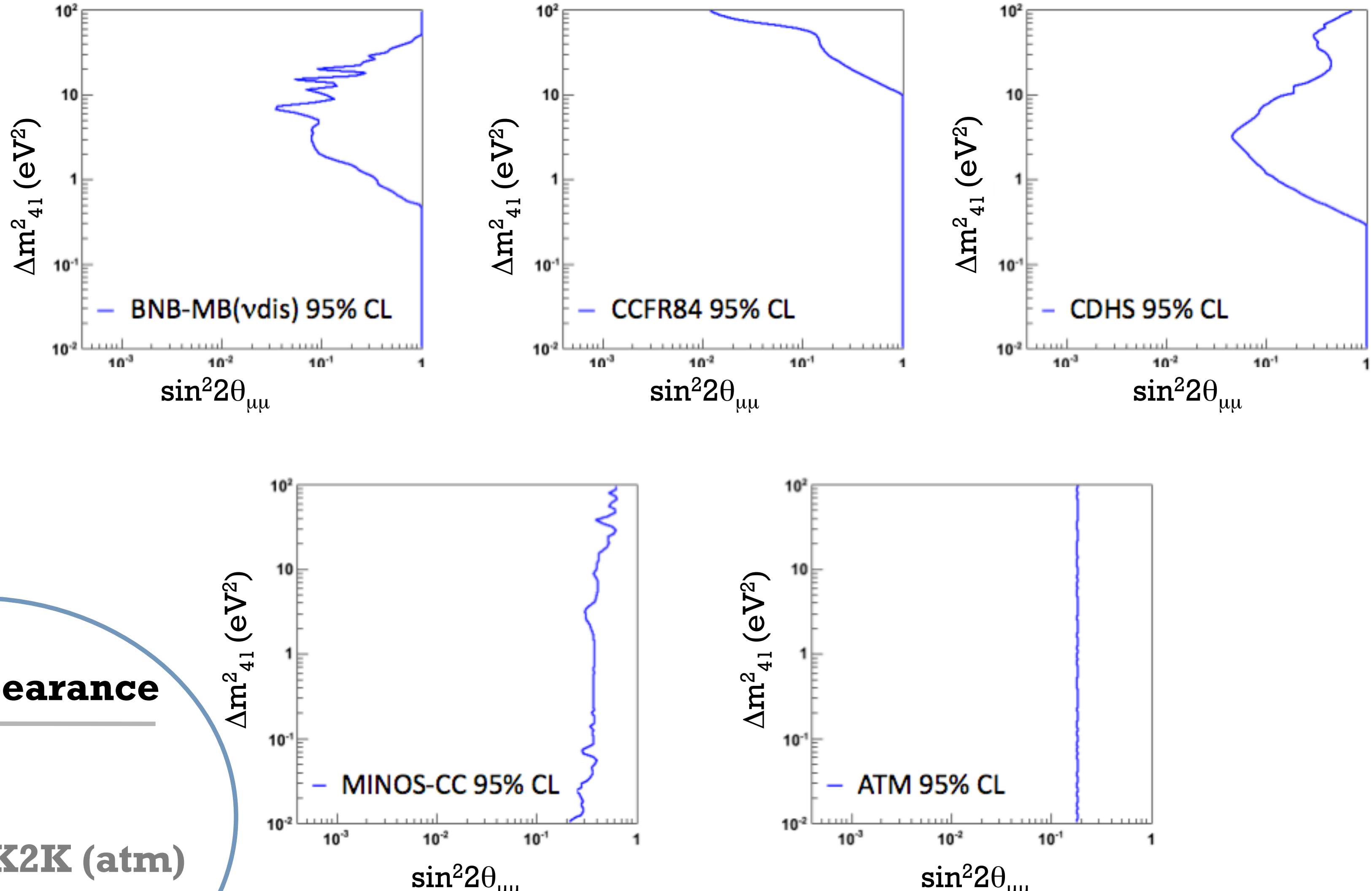


2. What about information from other experiments sensitive to high-Δm^2 oscillations?

$\overset{(-)}{\nu}_\mu$ disappearance	$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ appearance	$\overset{(-)}{\nu}_e$ disappearance
CDHS	MiniBooNE ν	Bugey
CCFR84	MiniBooNE $\bar{\nu}$	KARMEN/LSND (xsec)
SuperK/K2K (atm)	LSND	Gallium
MiniBooNE (dis)	KARMEN	
MINOS CC	NOMAD	
	NuMI-MB	

[Conrad, Ignarra, GK, Shaevitz, Spitz, arXiv:1207.4765, accepted by Advances in HEP; see also: GK et al, Phys.Rev. D80 (2009) 073001, GK et al, Phys.Rev. D75 (2007) 013011]

Other experimental constraints



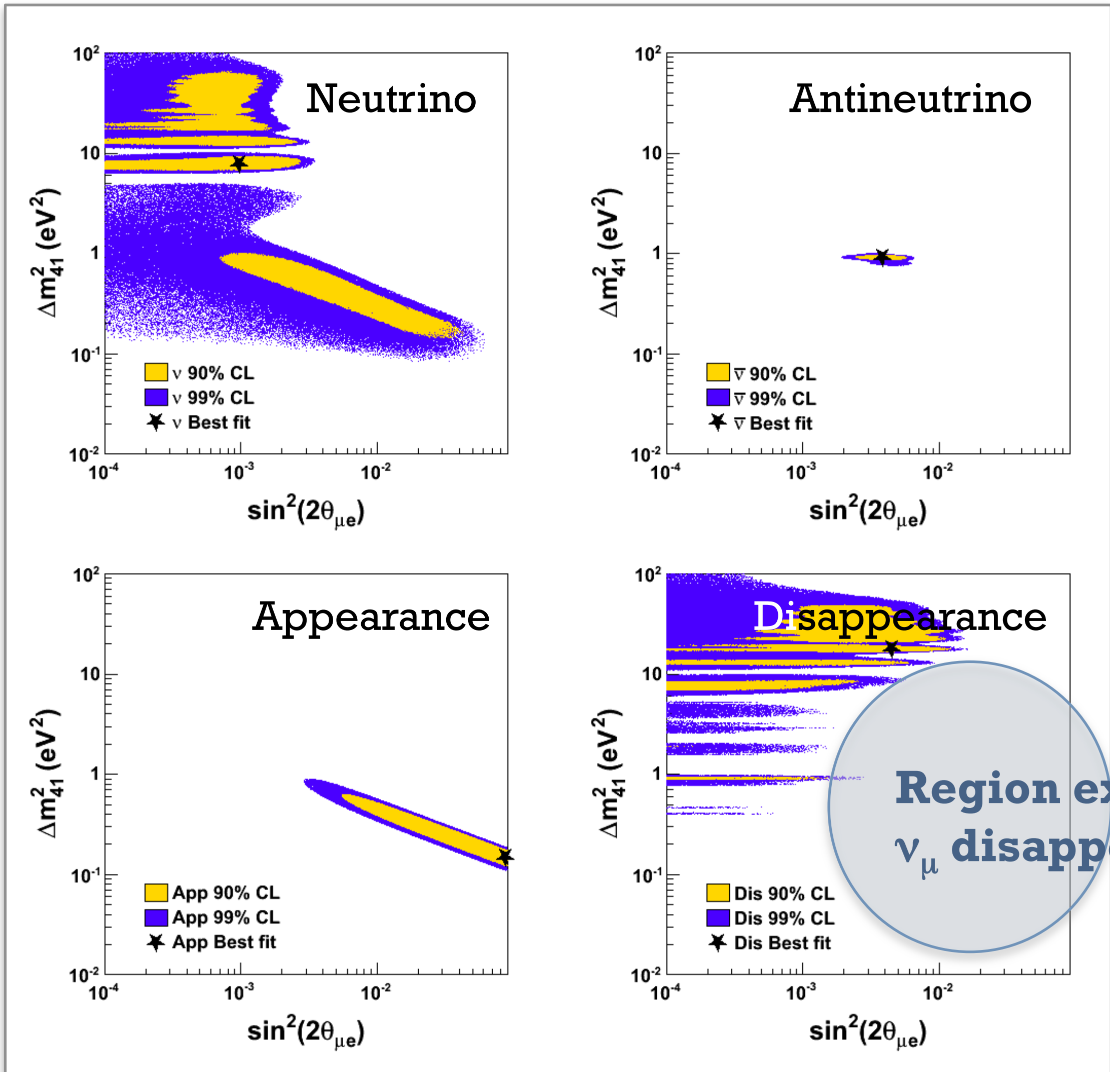
$\overset{(-)}{\nu}_\mu$ disappearance

CDHS
CCFR84
SuperK/K2K (atm)
MiniBooNE (dis)
MINOS CC

[arXiv:1207.4765]

(3+1) Global Fits to Sterile Neutrino Oscillations

Incompatibilities!



Compatibility $(\nu,\bar{\nu})$ = 0.14%

Compatibility (app,dis) = 0.013%

[Conrad, Ignarra, GK, Shaevitz, Spitz, arXiv:1207.4765, accepted by Advances in HEP]

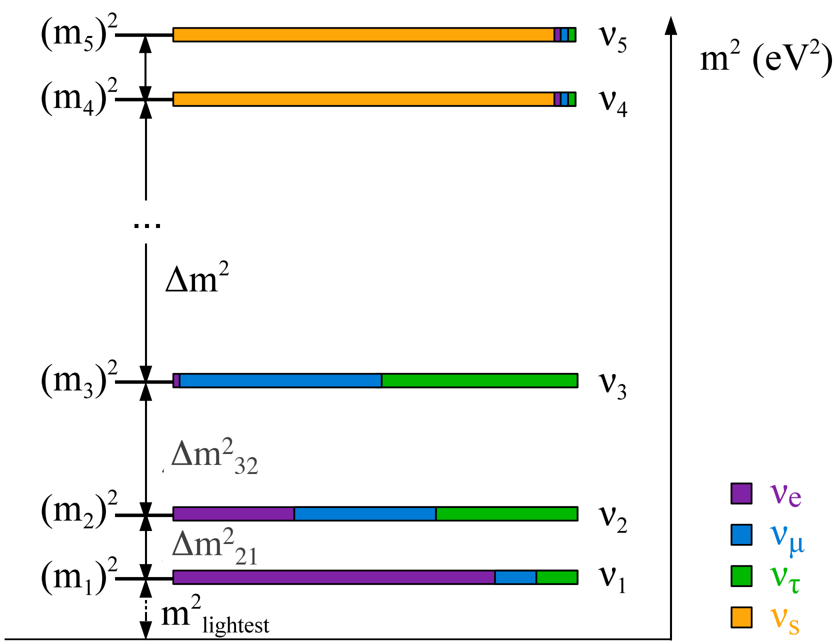
(3+1) is not enough!

Theoretical developments attempting to address inconsistencies:

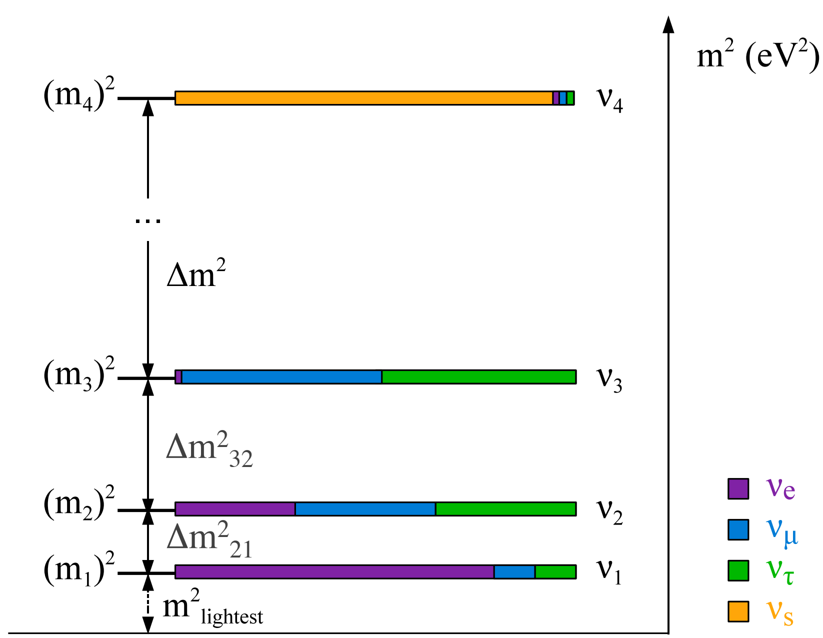
- Fact #1: ν vs $\bar{\nu}$ differences
  Extended sterile neutrino models with CP violation?
- Fact #2: appearance vs disappearance differences
  "Non-standard" oscillations?

Extended models: (1) CP violation

Can have more than one new state…



(3+2)



(3+1)

Extended models: (1) CP violation

Disappearance:

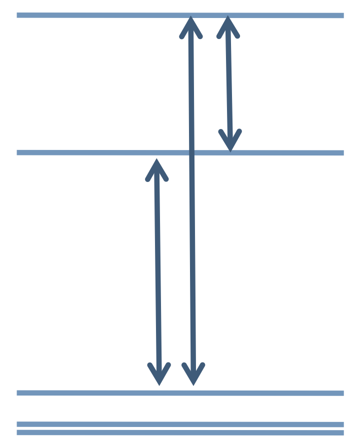
$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4[(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2) \cdot (|U_{\alpha 4}|^2 \sin^2 x_{41} + |U_{\alpha 5}|^2 \sin^2 x_{51}) + |U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 x_{54}]$$

Appearance:

$$P(\nu_\alpha \to \nu_{\beta \neq \alpha}) = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2 x_{41} + 4|U_{\alpha 5}|^2 |U_{\beta 5}|^2 \sin^2 x_{51} + 8|U_{\alpha 5}||U_{\beta 5}||U_{\alpha 4}||U_{\beta 4}| \sin x_{41} \sin x_{51} \cos(x_{54} - \phi_{45})$$

$$x_{ji} \equiv 1.27 \Delta m^2_{ji} L/E$$

CPV phase



assumed degenerate

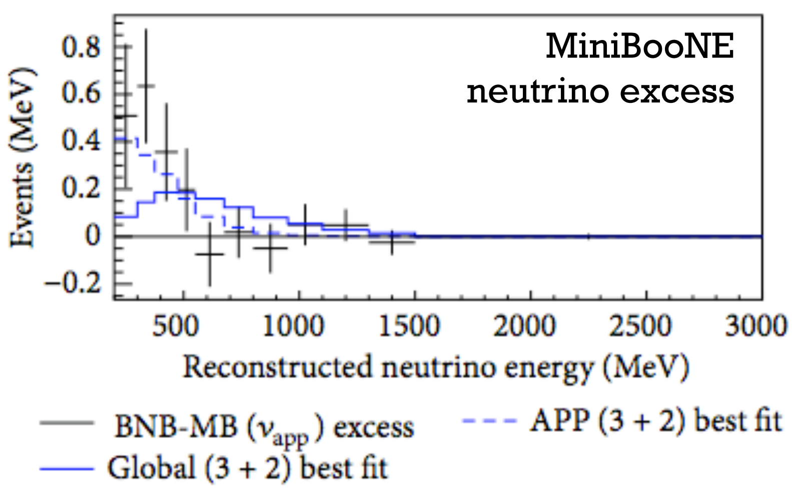
→ 2 effective Δm^2

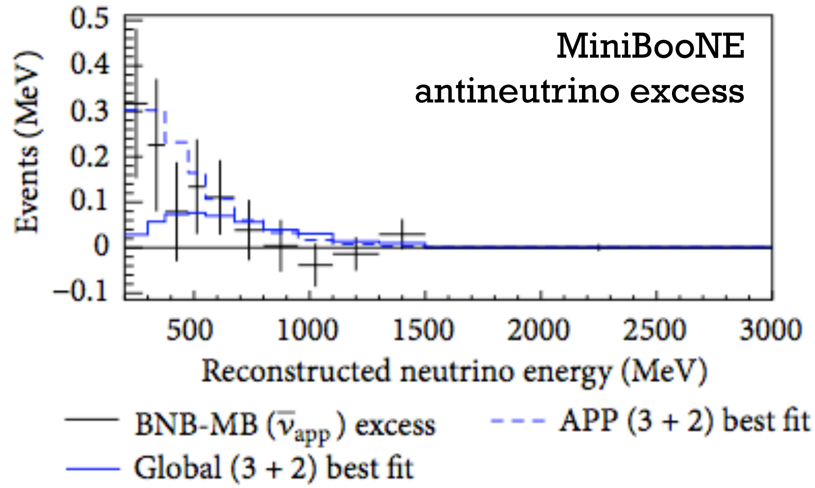
(3+2) is attractive because of **CP violation**

Extended models: (1) CP violation

[Conrad, Ignarra, GK, Shaevitz, Spitz,
arXiv:1207.4765, accepted by Advances in HEP]

(3+2) global best fit





(3+2) with CP violation cannot explain MiniBooNE low E excess, unless we throw out disappearance constraints!

Global Fits: Caveats and Limitations

- Appearance searches assume no disappearance
  - This is an incorrect assumption, given best fit parameters extracted in global fits
  - This may resolve some tension seen in the MiniBooNE appearance data sets, if one allows for ν_e background disappearance

- Need a more advanced statistical and systematic treatment of data sets
  - Compatibility measure needs to be verified with fake data and frequentist studies
  - Need better treatment of systematic correlations between data sets.

  This is a challenging step, but necessary for meaningful quantitative statements on these models

Theoretical developments attempting to address inconsistencies:

Does not explain MiniBooNE low E excess

- ~~Fact #1: ν vs $\bar{\nu}$ differences~~
  ~~Extended sterile neutrino models with CP violation?~~

- Fact #2: appearance vs disappearance differences
  "Non-standard" oscillations?

Theoretical developments attempting to address inconsistencies:

- ~~Fact #1: ν vs $\bar{\nu}$ differences~~
  ~~Extended sterile neutrino models with CP violation?~~

Does not explain MiniBooNE low E excess

- ~~Fact #2: appearance vs disappearance differences~~
  ~~"Non-standard" oscillations?~~

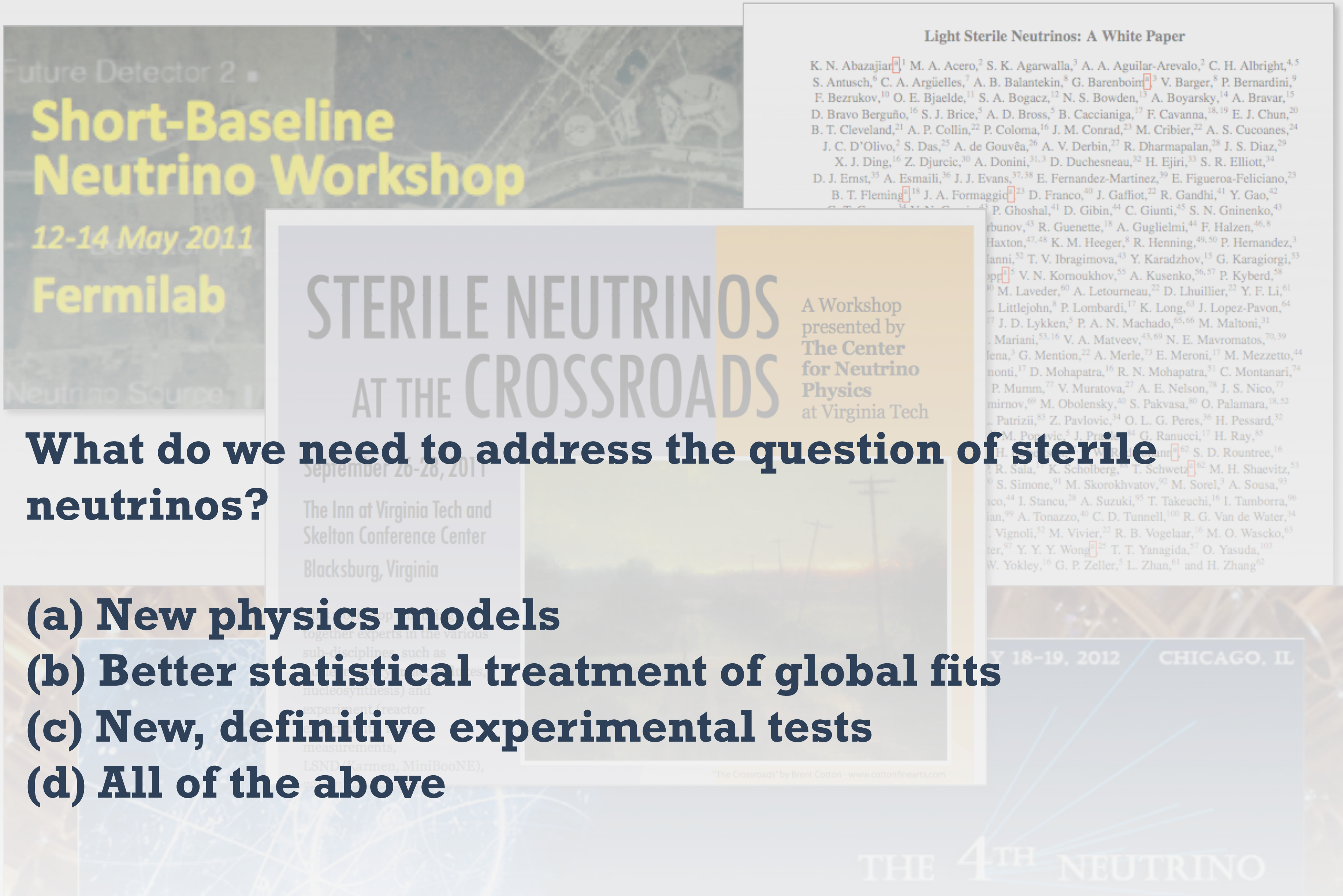
MiniBooNE low E excess?? difficult to interpret...

Other theoretical interpretations:

- CPT violation
- Heavy (sterile) neutrino decay
- Extra dimensions
- New interactions
- Altered neutrino dispersion relations

None of these work that great

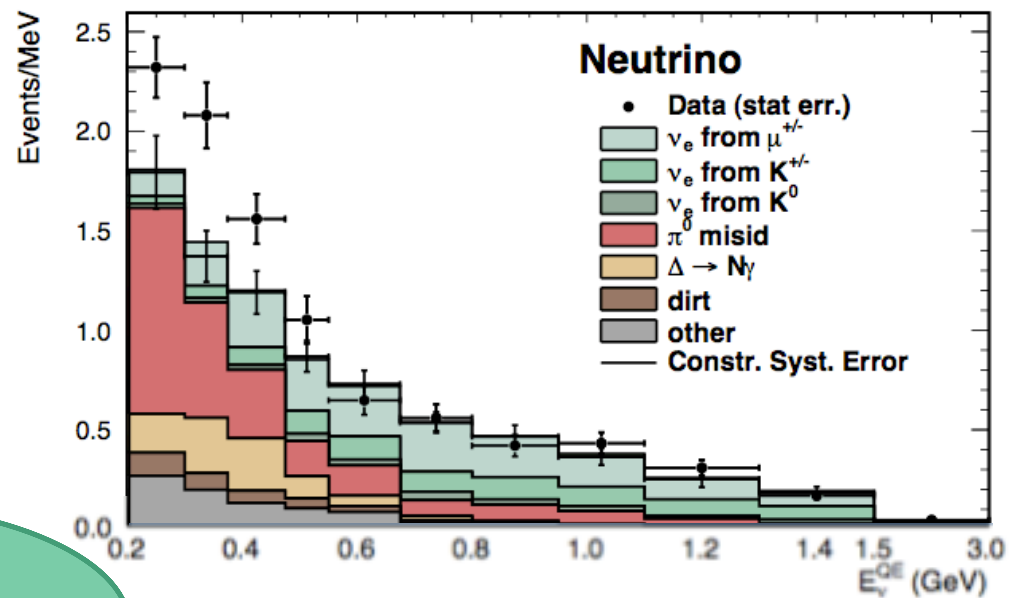
Currently a puzzle in neutrino physics!



What do we need to address the question of sterile neutrinos?

(a) New physics models
(b) Better statistical treatment of global fits
(c) New, definitive experimental tests
(d) All of the above

Low E excess: Are we missing something?



Unaccounted ν_e/ν_μ disappearance?

Energy reconstruction? Cross-section/ nuclear effects?

Electron-like misestimated or new background?

Single-photon mis-estimated or new background?

Big Questions in Neutrino Physics

Fundamental questions

What is the value of δ_{CP}?

Is the neutrino mass spectrum normal, or inverted?

What are the absolute neutrino masses?

Are neutrinos dirac or majorana fields?

Are there additional, "sterile" neutrino states?

Do we understand exclusive and inclusive neutrino cross sections on nuclear targets?

Pressing experimental questions

Big Questions in Neutrino Physics

Directly addressed by LArTPC oscillation experiments?

Fundamental questions

✓ What is the value of δ_{CP}?

✓ Is the neutrino mass spectrum normal, or inverted?

What are the absolute neutrino masses?

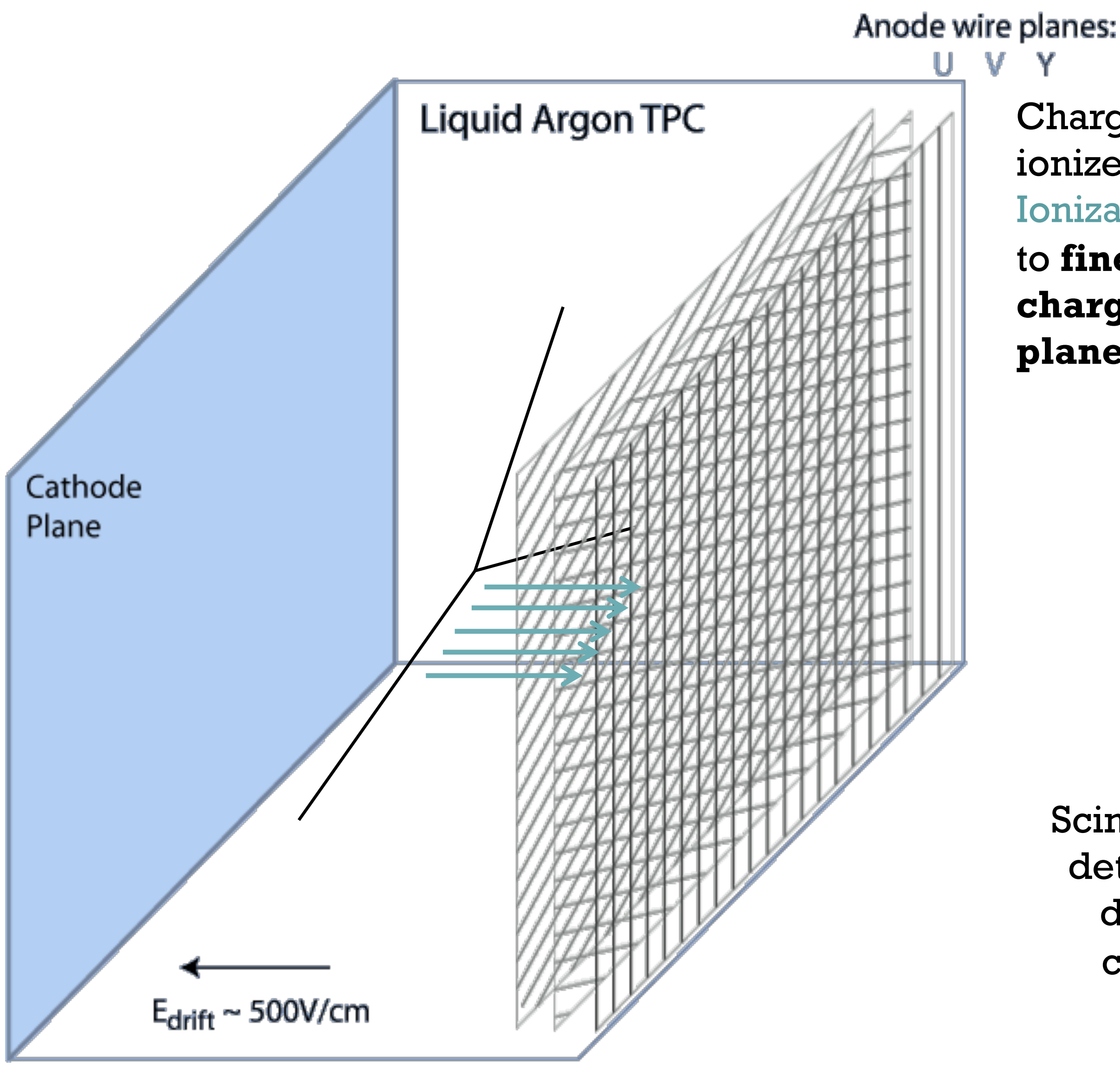
Are neutrinos dirac or majorana fields?

✓ **Are there additional, "sterile" neutrino states?**

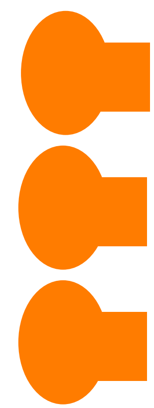
✓ Do we understand exclusive and inclusive neutrino cross sections on nuclear targets?

Pressing experimental questions

LArTPC detector concept



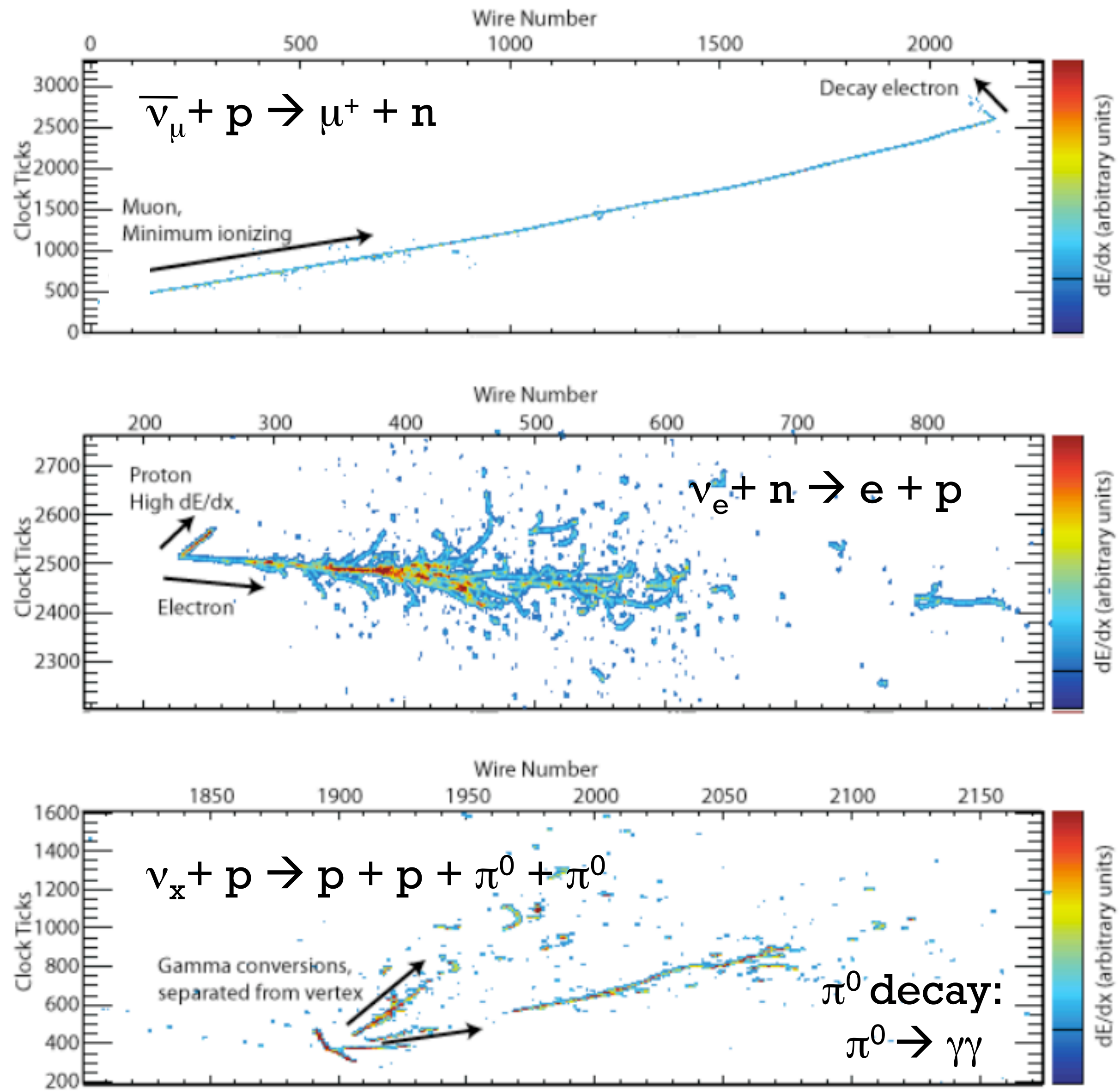
Charged particle tracks ionize argon atoms; Ionization charge drifts to **finely segmented charge collection planes** over ~1-few ms.



Scintillation light (~few ns) is detected by photo-sensitive detectors for event t_0, drift coordinate and triggering

Exquisite event topology!

High event selection efficiency and excellent background rejection!

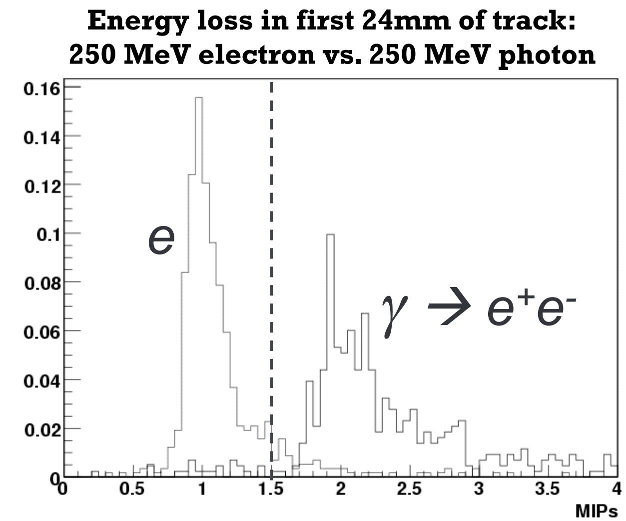


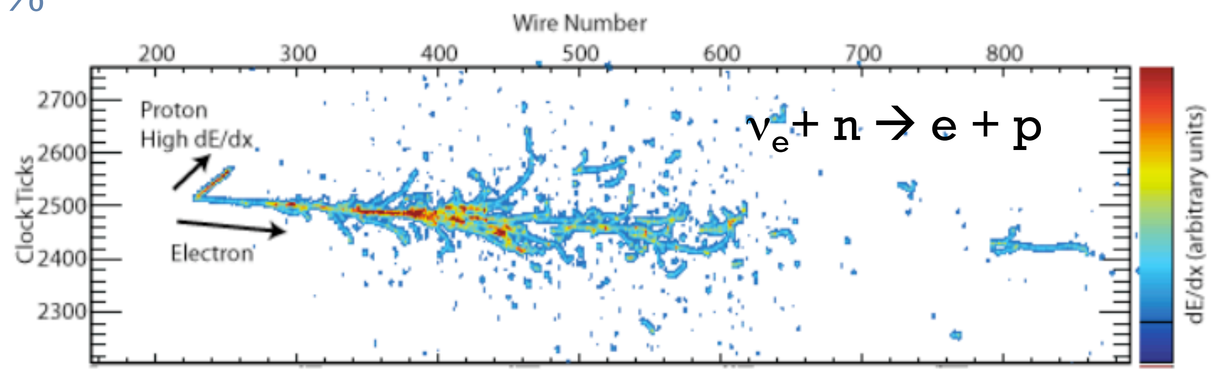
e/γ differentiation

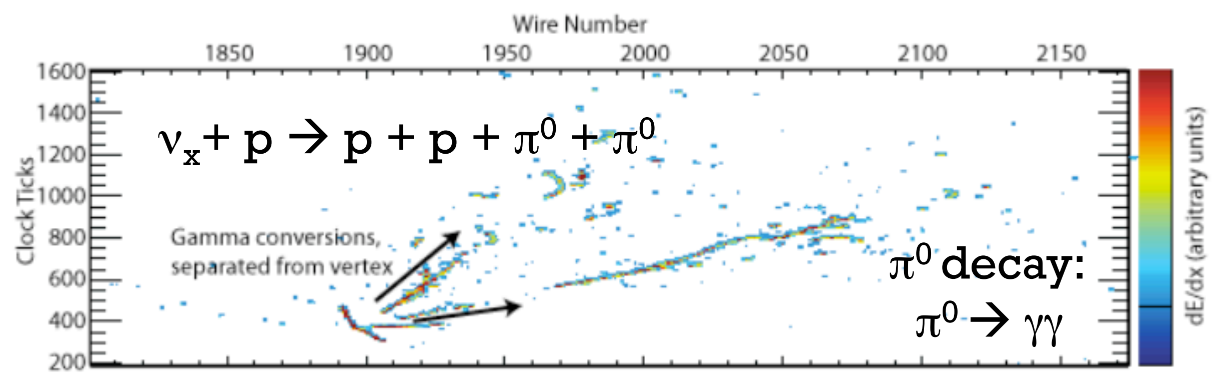
γ's rejected on the basis of

1. detached shower vertex
2. larger dE/dx at the beginning of shower

Typical e/γ separation: ~90%
→ Ideal technology for
ν_e measurements!



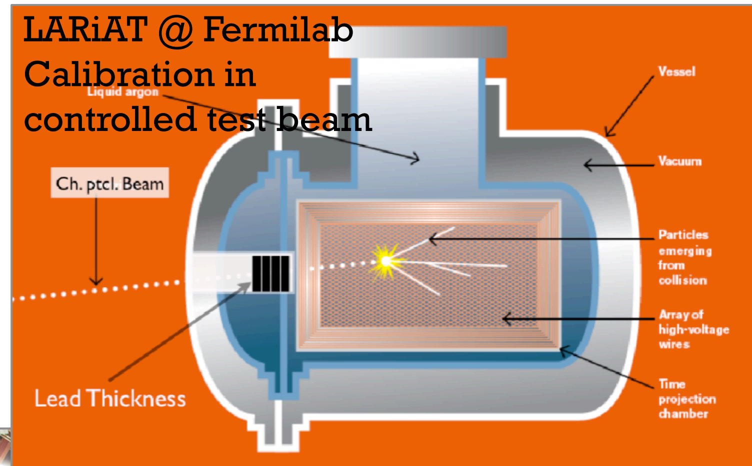




Scalability is challenging!

[Being addressed by ongoing and planned R&D projects]

- Large cryogenic system
- Long drift distances
  - Requires ultra high purity and evacuation is impractical
  - Implies high voltage on cathode
- Large number of readout channels with high data volume/channel (data storage, data processing, …)
- Cold electronics
- Reconstruction tools



LARiAT @ Fermilab
Calibration in controlled test beam

LAPD @ Fermilab
Establishing high purity without evacuation

ArgonTube
5m drift demonstration

LArTPC's: Test Facilities & Experiments

Updated from M. Soderberg

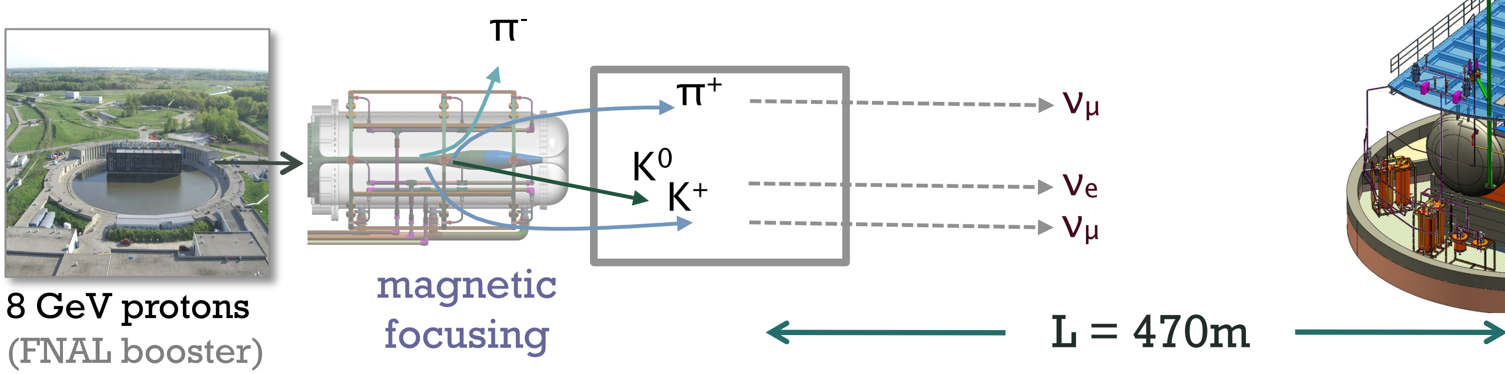
MicroBooNE

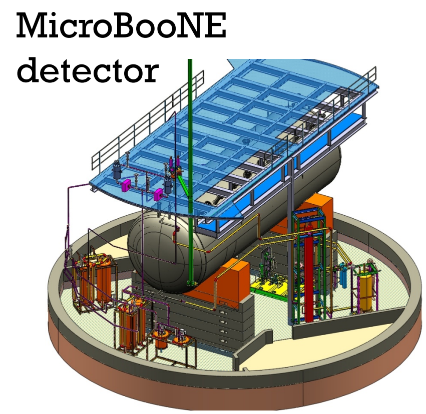
First large-scale LArTPC in the US!

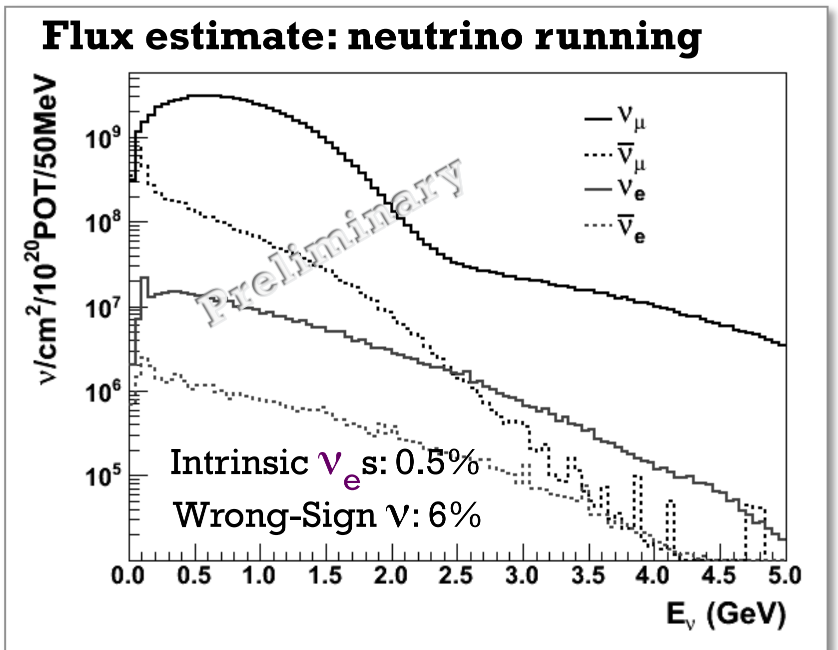
MicroBooNE cryostat at Fermilab on March 8, 2013

MicroBooNE

Located in the Fermilab Booster Neutrino Beamline:

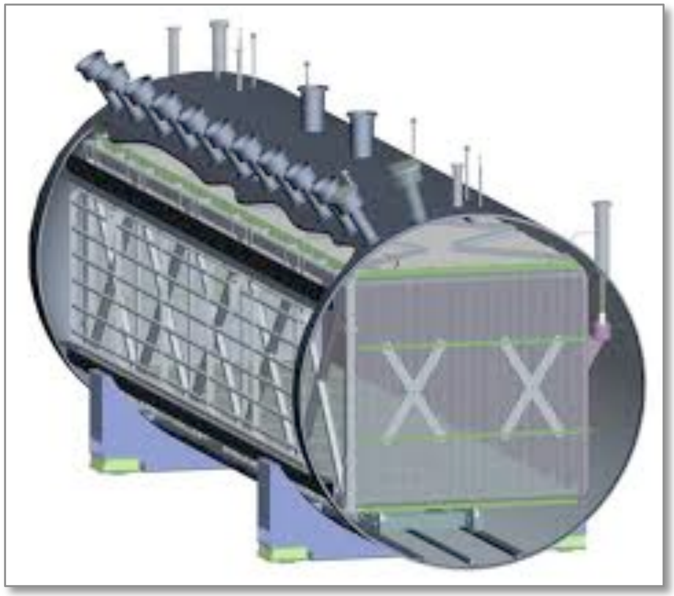




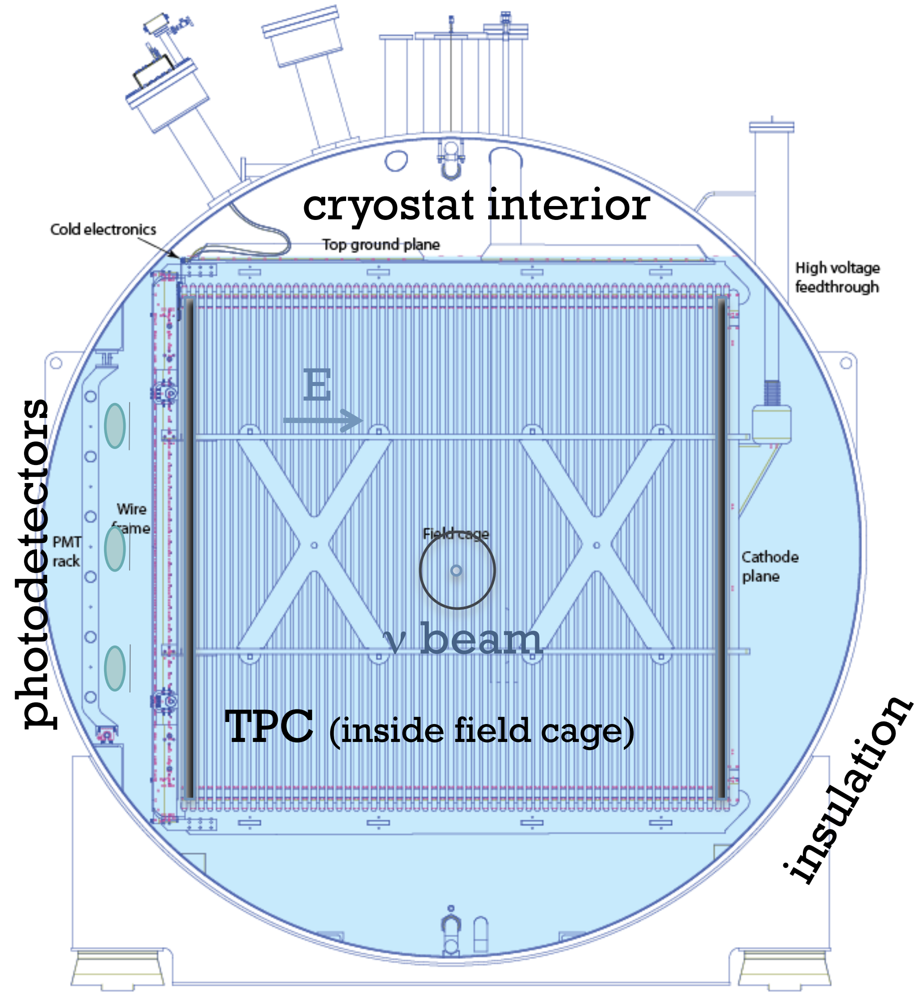


Current run plan (approved):
Neutrino mode running, 6.6e20 POT

MicroBooNE



Cross section of detector:



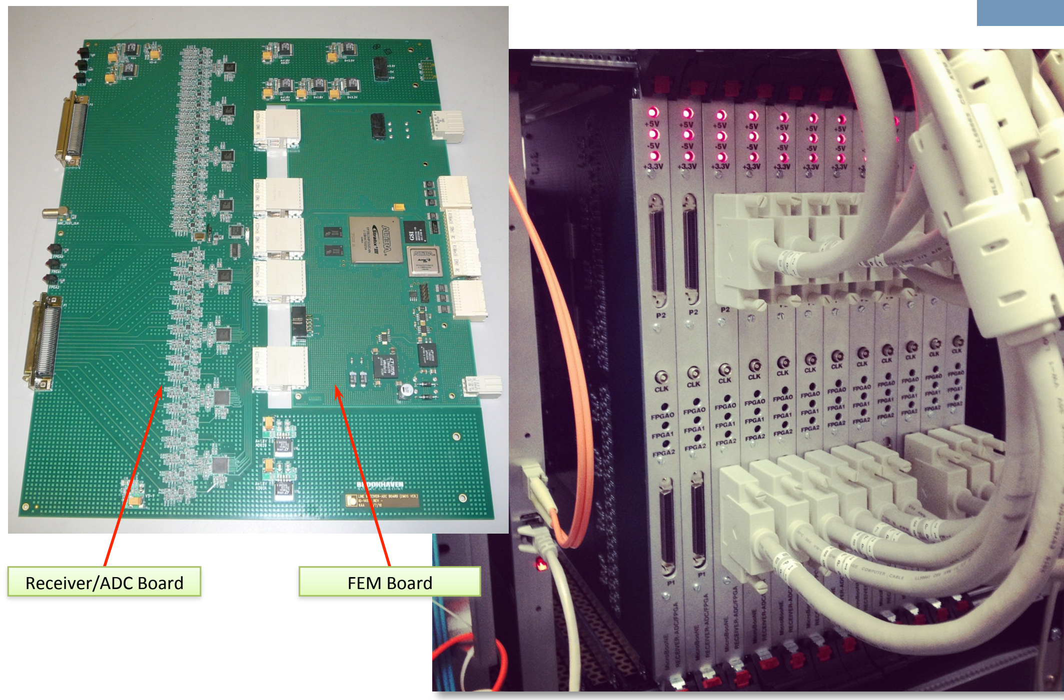
- Detector parameters:
  - 2.5 m x 2.3 m x 10.2 m TPC
  - 2.5 m drift length
  - 170 (60) tons total (fiducial) mass
  - 3 wire planes, 0,±60° from vertical, 3 mm wire separation
  - 8256 wires
  - 32 PMT's for t_0, drift coordinate, and triggering for empty beam spill rejection

MicroBooNE

A lot of data!

Each event: 160 MB

8256 wires
read over 4.8 ms
digitized at 2 MHz
12-bit ADC (16-bit packets)



MicroBooNE readout electronics
developed at Nevis Labs

Event rate of ~0.1-10 Hz
→ need compression:
Huffman (lossless) compression provides up to x15 reduction

100% live for SuperNova neutrino search: >30 GB/s !

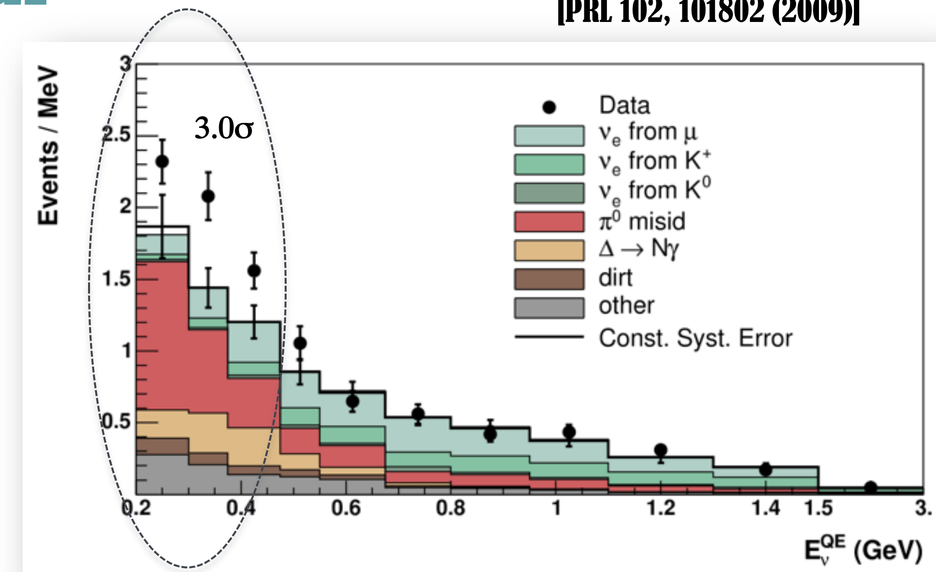
Solution:
Implement zero suppression, Huffman compression,
and only retain ~few hrs of data at any time

MicroBooNE

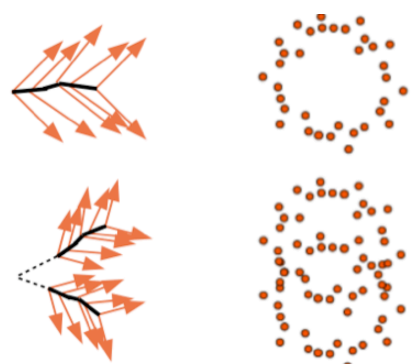
Primary physics goal

- Investigate the nature of the MiniBooNE low energy excess
- Is the excess due to e or γ?

MiniBooNE unexplained "low energy excess"
[PRL 102, 101802 (2009)]

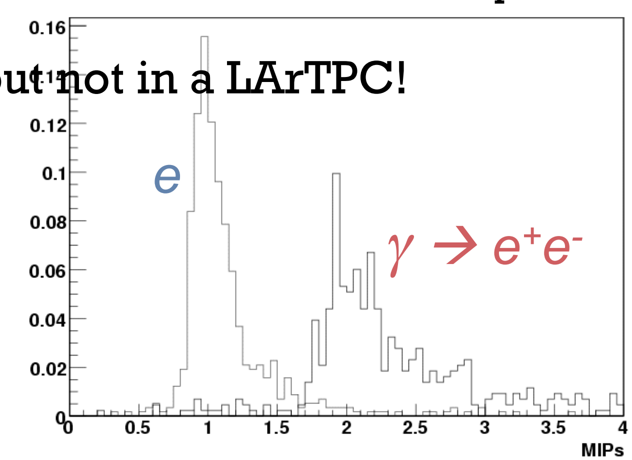


Single e and single γ are indistinguishable in a cherenkov detector…



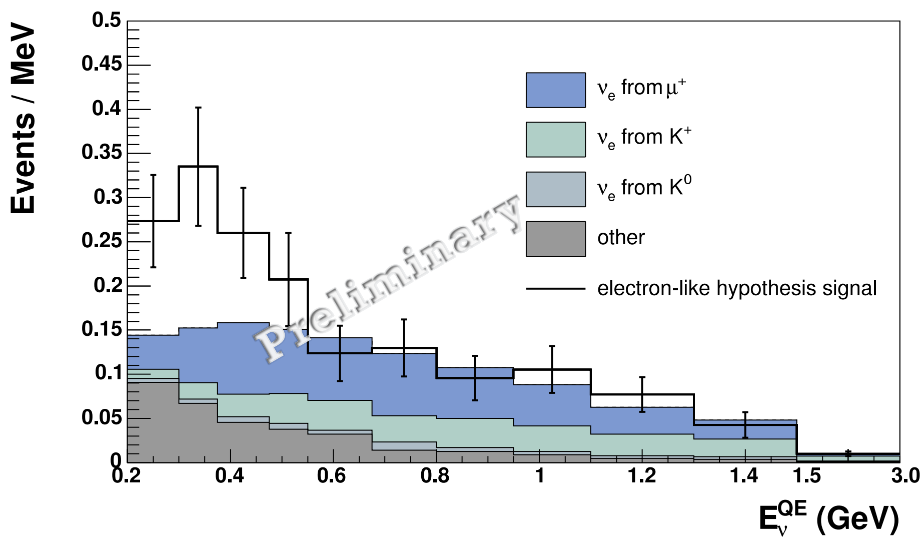
…but not in a LArTPC!

Energy loss in first 24mm of track:
250 MeV electron vs. 250 MeV photon



Primary physics goal

What MicroBooNE expects to see if excess is due to single e

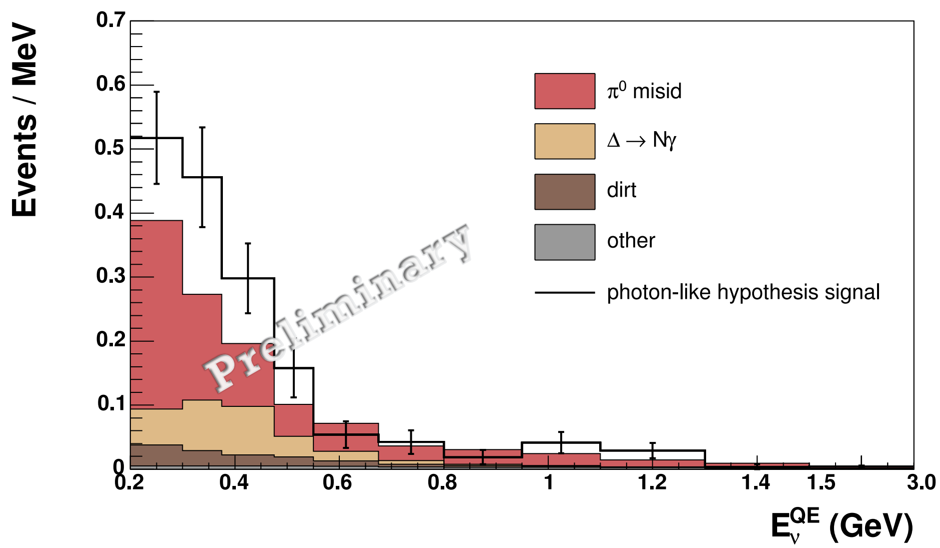


Possible explanation:
$\nu_\mu \rightarrow \nu_e$ nonstandard oscillations
(sterile neutrinos, extra dimensions, NSI,…)

About **37 excess events** above a background of 45 events
→ **5.7σ statistical** significance

Primary physics goal

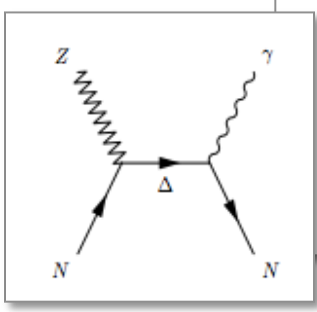
What MicroBooNE expects to see if excess is due to single γ

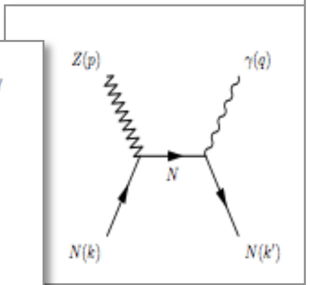


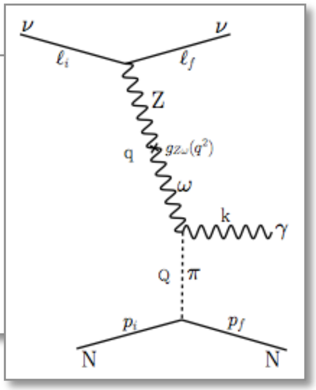
Possible explanation:
background γ or π^0 or
"new" single photon
production

e.g.
R. Hill arXiv: 0905.0291
Jenkins et al arXiv:0906.0984
Serot et al arXiv: 1011.5913

About **37 excess events** above a background of 79 events
→ **4.1σ statistical** significance





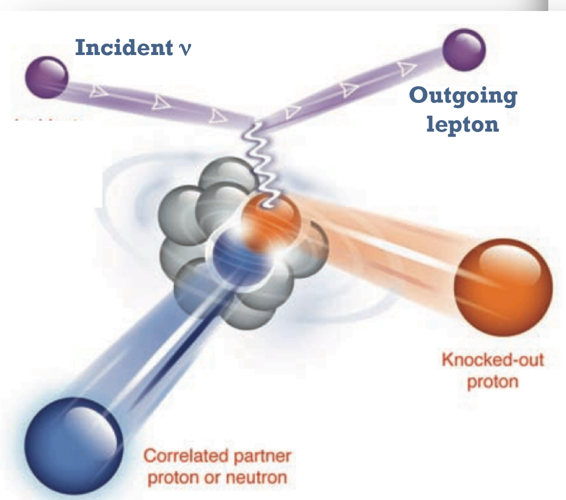


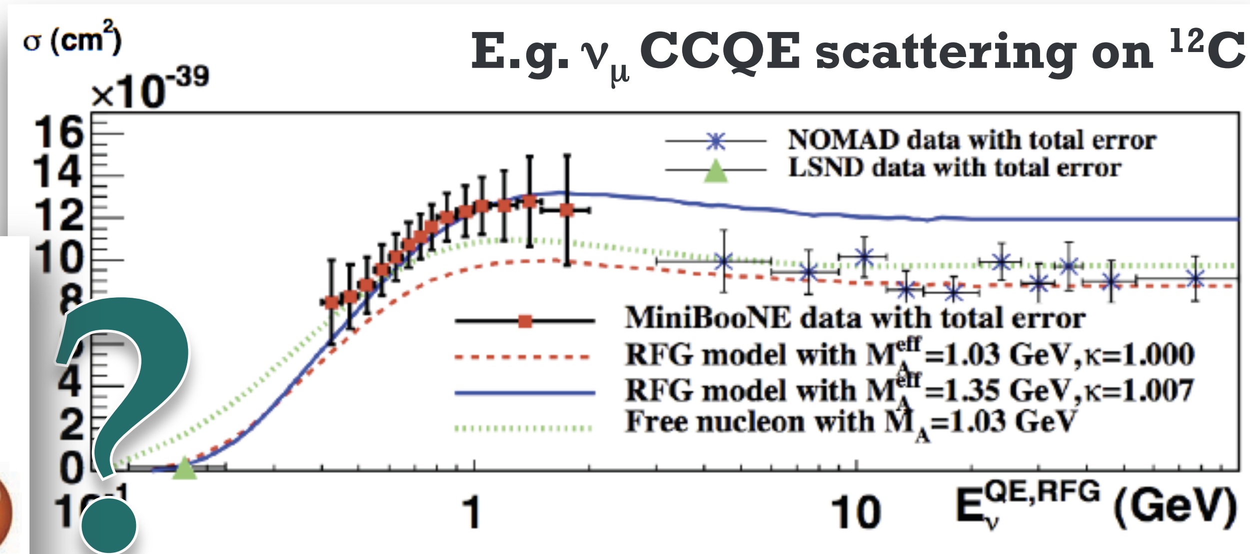
Additional physics goal

measure neutrino cross sections around 1 GeV

- Past cross section measurements (from K2K, MiniBooNE, SciBooNE, MINOS, NOMAD) have revealed limitations in our understanding of neutrino interactions

Hadronic effects must play a critical role!



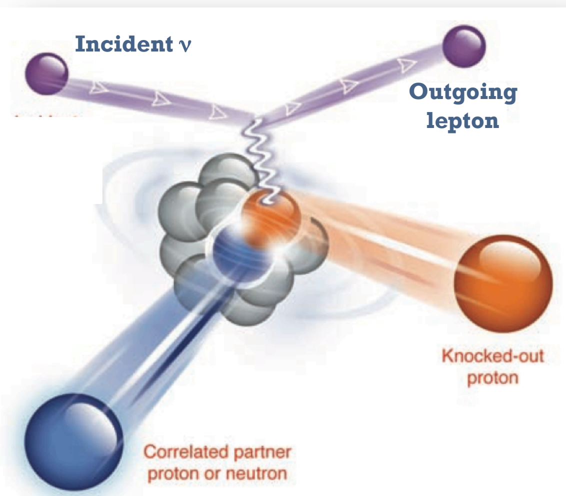


Phys. Rev. D81, 092005 (2010)

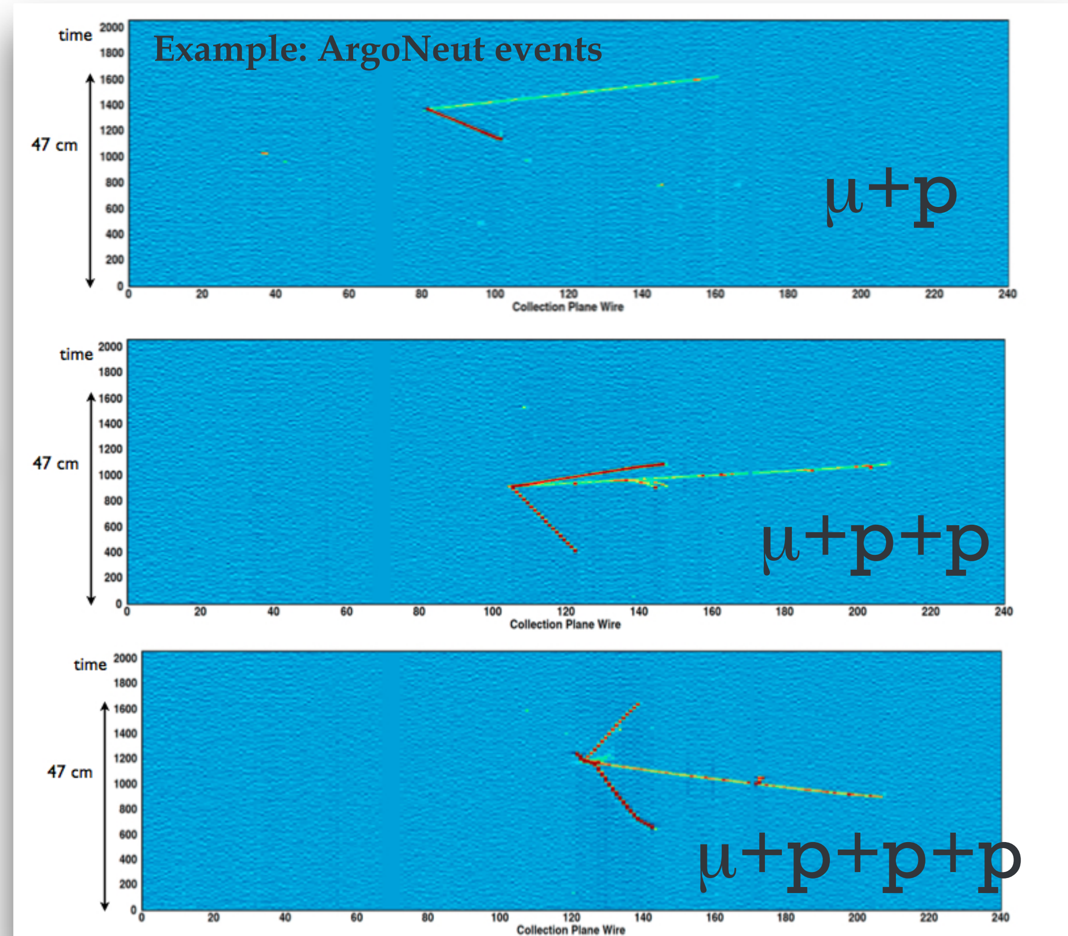
Additional physics goal

measure neutrino cross sections around 1 GeV

- **Event topology and final state information** (proton multiplicity, momenta) provides information for nuclear effects modeling



?



Additional physics goal

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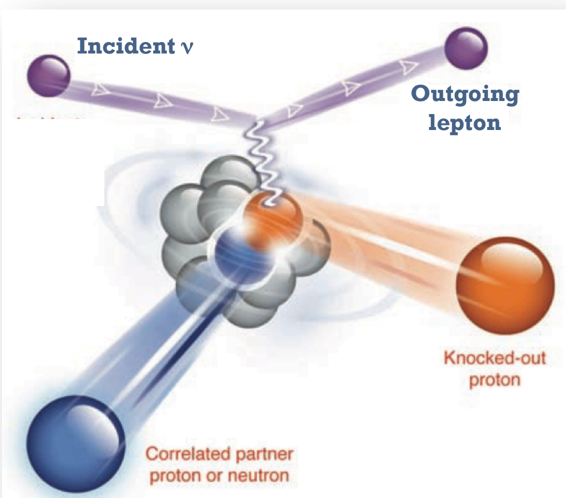
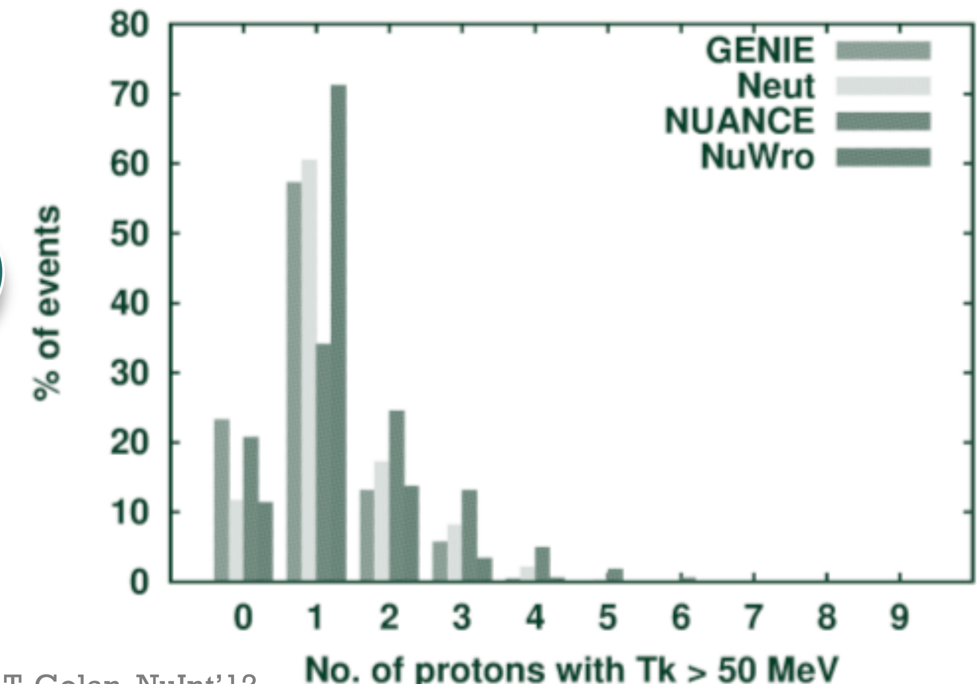


Cross-section and nuclear effects modeling: Vastly different predictions from different neutrino event generators



T. Golan, NuInt'12

Additional physics goal

measure neutrino cross sections around 1 GeV

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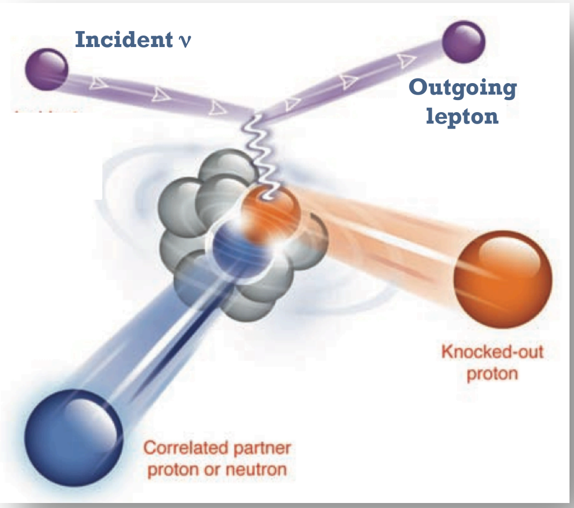
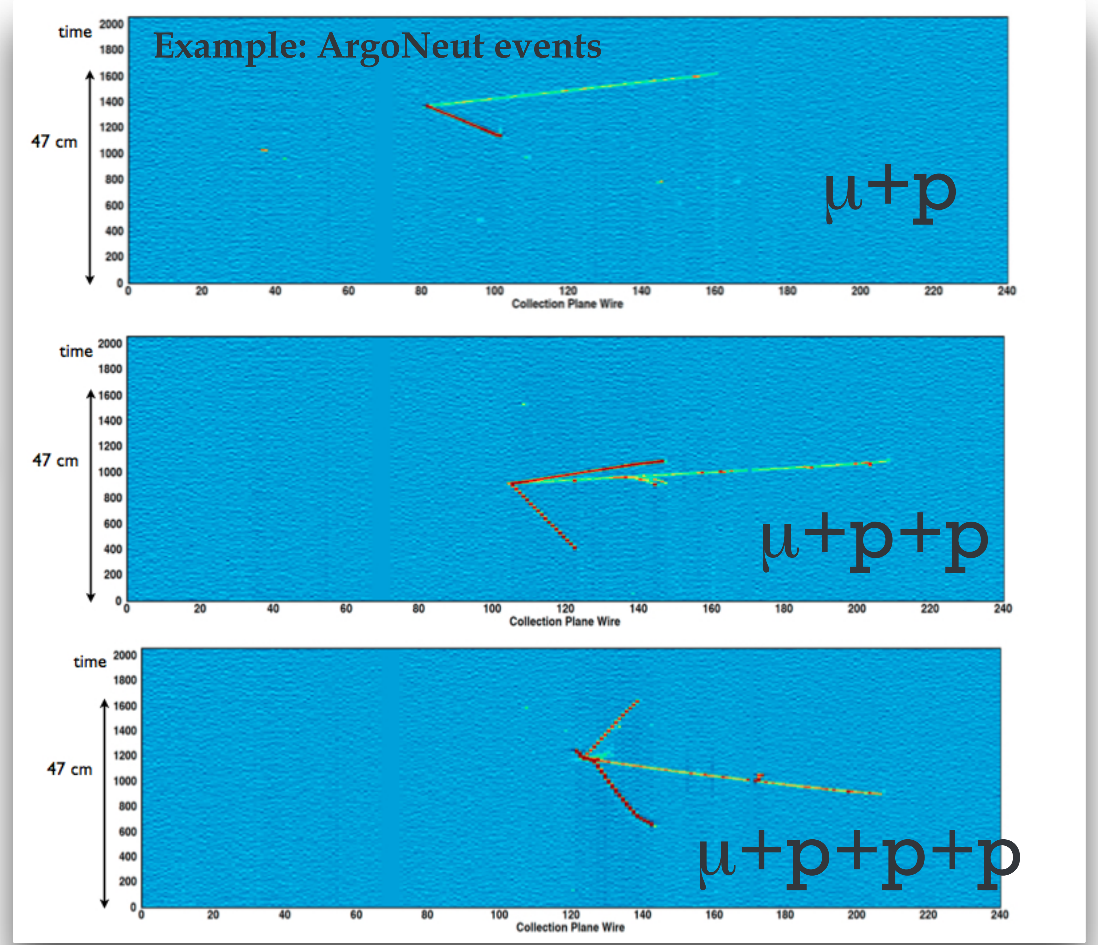




Additional physics goal

measure neutrino cross sections around 1 GeV

- First LArTPC with high-statistics event samples in 1 GeV range

Expected MicroBooNE event rates

production mode	# events
CC QE ($\nu_\mu n \to \mu^- p$)	60,161
NC elastic ($\nu_\mu N \to \nu_\mu N$)	19,409
CC resonant π^+ ($\nu_\mu N \to \mu^- N \pi^+$)	25,149
CC resonant π^0 ($\nu_\mu n \to \mu^- p \pi^0$)	6,994
NC resonant π^0 ($\nu_\mu N \to \nu_\mu N \pi^0$)	7,388
NC resonant $\pi^\pm$ ($\nu_\mu N \to \nu_\mu N' \pi^\pm$)	4,796
CC DIS ($\nu_\mu N \to \mu^- X$, $W > 2$ GeV)	1,229
NC DIS ($\nu_\mu N \to \nu_\mu X$, $W > 2$ GeV)	456
NC coherent π^0 ($\nu_\mu A \to \nu_\mu A \pi^0$)	1,694
CC coherent π^+ ($\nu_\mu A \to \mu^- A \pi^+$)	2,626
NC kaon ($\nu_\mu N \to \nu_\mu K X$)	39
CC kaon ($\nu_\mu N \to \mu^- K X$)	117
other ν_μ	3,678
total ν_μ CC	98,849
total ν_μ NC+CC	133,580
ν_e QE	326
ν_e CC	657

Nuance-generated events on LAr, MicroBooNE Collaboration

Preliminary

Additional physics opportunities

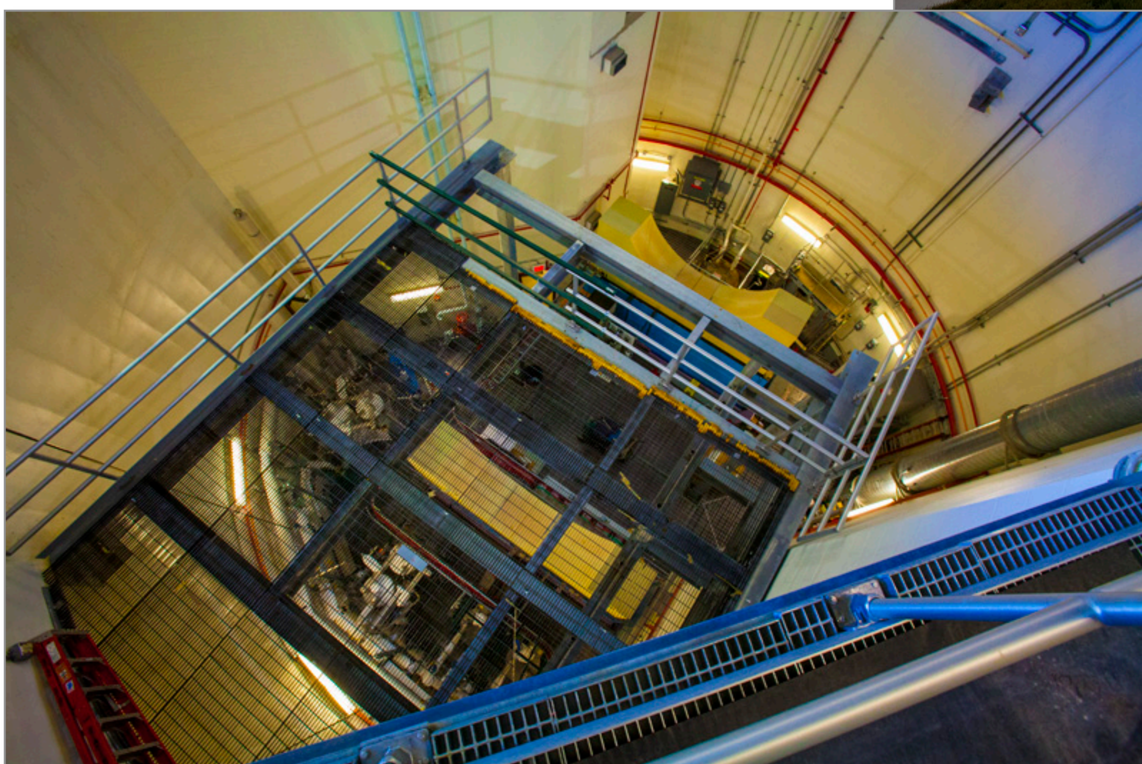
- Backgrounds to proton decay & baryon number violating processes for larger (underground) detectors
- Supernova core collapse neutrinos

MicroBooNE

Current status

Experiment is well under construction

- LArTF building construction complete, being outfitted for detector for installation



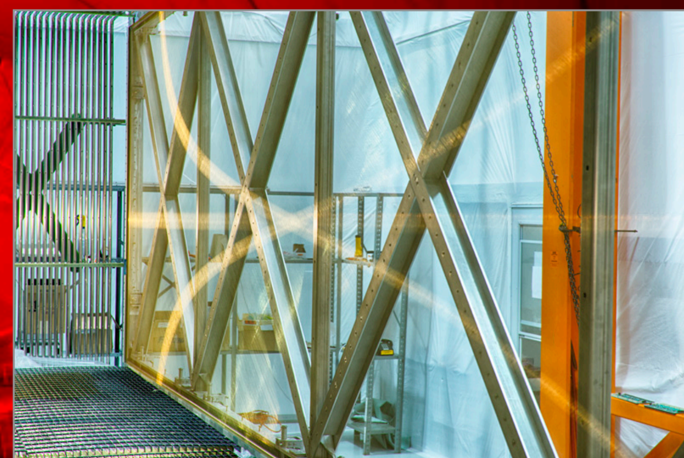
LArTF (Sep. 2013)

MicroBooNE

Current status

Experiment is well under construction

- LArTF building construction complete, being outfitted for detector for installation
- PMT's installed in cryostat
- TPC field cage and wire planes constructed
- Cold electronics installed on TPC
- Electronics fully tested and ready for commissioning



- Expected start of data taking: 2014
- Current MicroBooNE run plan: neutrino mode running, 6.6e20 POT (2-3 years to complete)

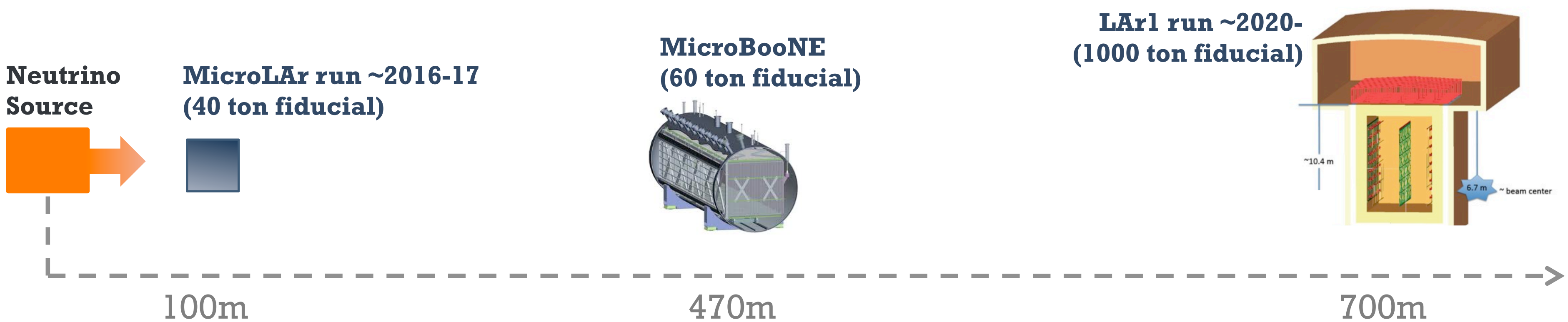
Beyond MicroBooNE: LAr1

- **New idea:** A second (Phase I) and third (Phase II) LArTPC placed in the Booster Neutrino Beam at Fermilab, in line with MicroBooNE

- Near/far comparison for short-baseline oscillation search

- **Definitive test of MiniBooNE/LSND sterile neutrino interpretation**

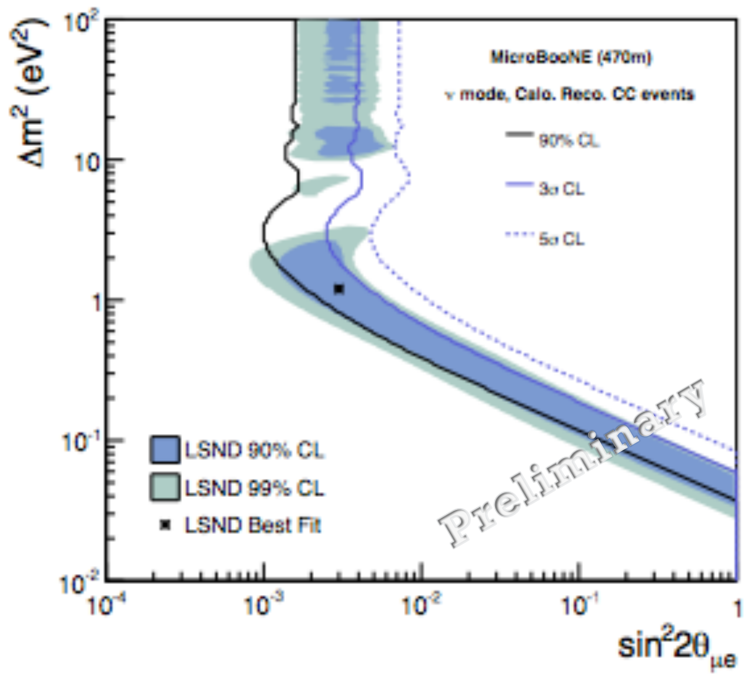
- Design philosophy: serve as a development step toward LBNE while functioning as a physics experiment



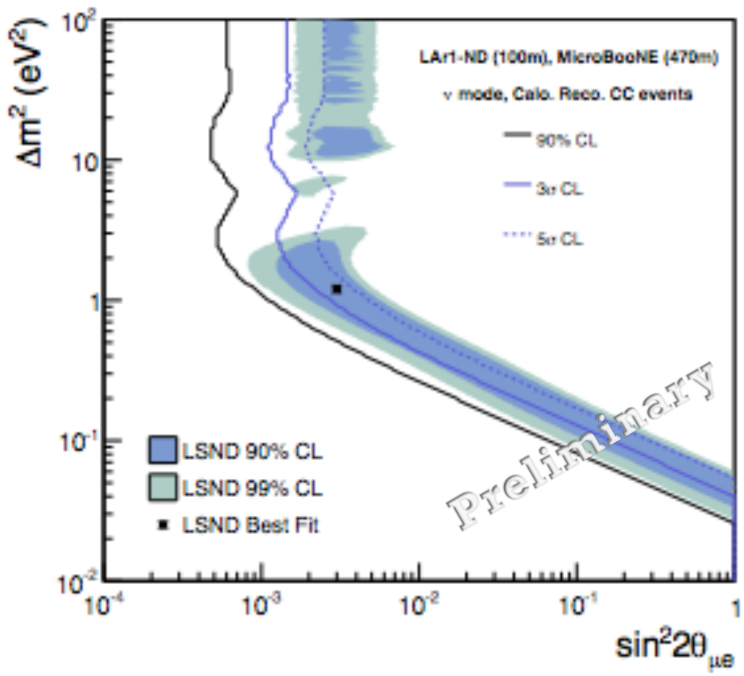
Beyond MicroBooNE: LAr1(ND)

The high-statistics event sample in LAr1-ND constrains the expected background event rate in MicroBooNE, reducing the systematic uncertainties.

6.6×10^{20} POT exposure for MicroBooNE alone, assuming 20% systematic uncertainties on ν_e backgrounds



Same MicroBooNE exposure + 2.2×10^{20} POT exposure for LAr1-ND



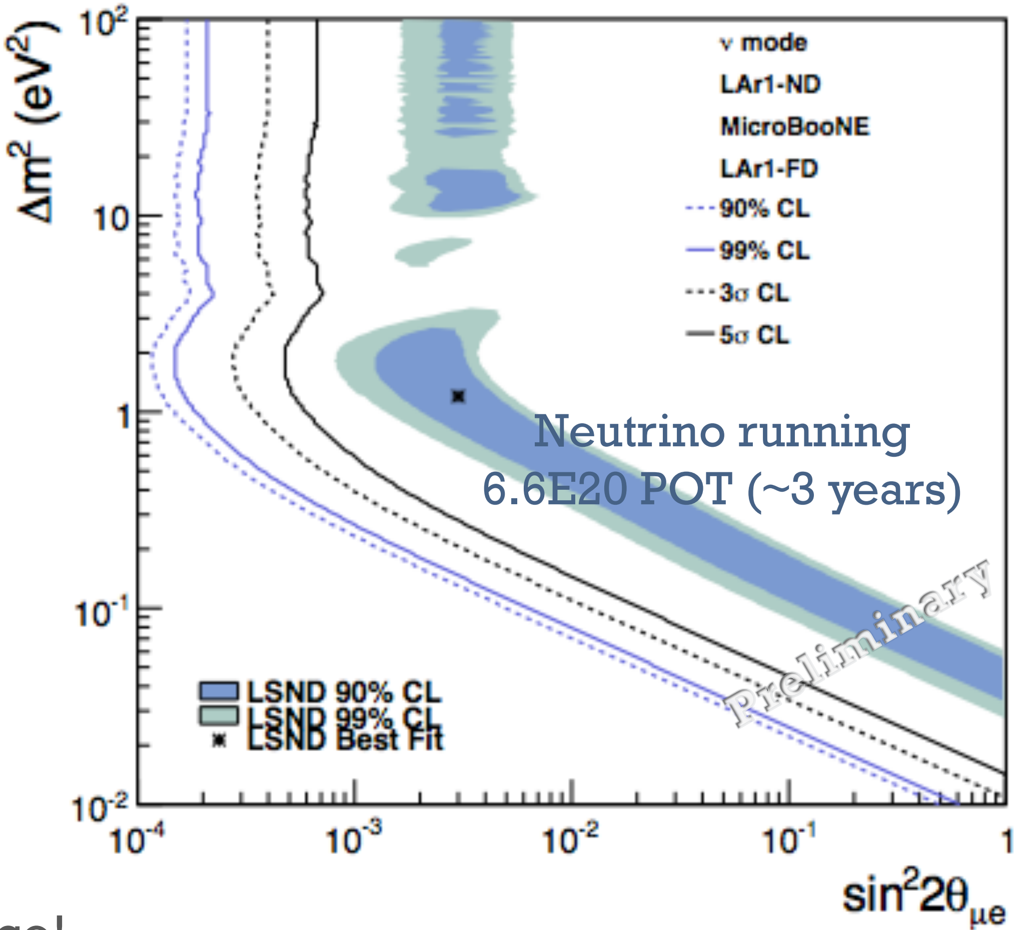
The sensitivity is strengthened through the reduction of systematic errors, covering the LSND best-fit point at ~4 σ .

Beyond MicroBooNE: LAr1

- Physics reach: Definitive (5σ) test of LSND and MiniBooNE in both neutrino and antineutrino modes

While MicroBooNE will definitively address the MiniBooNE excess as electrons or photons in neutrino mode,

the combination of LAr1(ND) and MicroBooNE will allow for its interpretation as new physics.



- Also $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$ disappearance!

Beyond MicroBooNE: LAr1

Current status

- Letter of Intent submitted to Fermilab Directorate in 2012
- Snowmass White Paper in Sep. 2013, focused on LAr1-ND and potential to expand into LAr1-ND (arXiv:1309.7987)
- Strong ongoing effort to develop full LAr1-ND proposal by Dec. 2013

A Letter of Intent for a Neutrino Oscillation Experiment on the Booster Neutrino Beamline: LAr1

June 13, 2012

H. Chen, C. Thorn, D. Lissauer, V. Radeka, B. Yu, G. Mahler, S. Rescia, S. Duffin, Y. Li
Brookhaven National Laboratory, Upton, NY

L. Bartoszek
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F. Cavanna, E. Church, B. Fleming, R. Guenette, O. Palamara, K. Partyka, A. Szelc
Yale University, New Haven, CT 06520

Summary

We are entering an era of high-precision neutrino physics measurements, enabled by the LArTPC technology:

- Increased detection efficiency (>x2 conventional detectors)
- Increased background rejection from detailed event topology and dE/dx

MicroBooNE is first in the line of ton-scale LArTPC detectors in the US.

- Important R&D stepping stone for LBNE (mass hierarchy, CP violation,…)
- Extremely rich physics on its own:
  - MiniBooNE low energy excess
  - Neutrino cross sections on Ar
  - Sterile neutrino oscillations with the addition of second/third detector
  - …

- MicroBooNE data taking begins in less than a year!

End remarks

Theoretical motivation for light (~1 eV) sterile neutrinos is perhaps not so strong, though sterile neutrinos with sizable mixing emerge in several models of neutrino mass (heavy sterile neutrinos…).

Their discovery would point towards new physics.

"…their role is relevant enough to justify an open mind attitude and a close look for any, yet tiny, evidence for new effects beyond the *too much* successful Standard Model." [Theorist Anonymous]

Experimental hints may be right in front of us, albeit not completely understood. Need new, definitive experiments. Model-independent searches should be given highest priority.

Thank you!