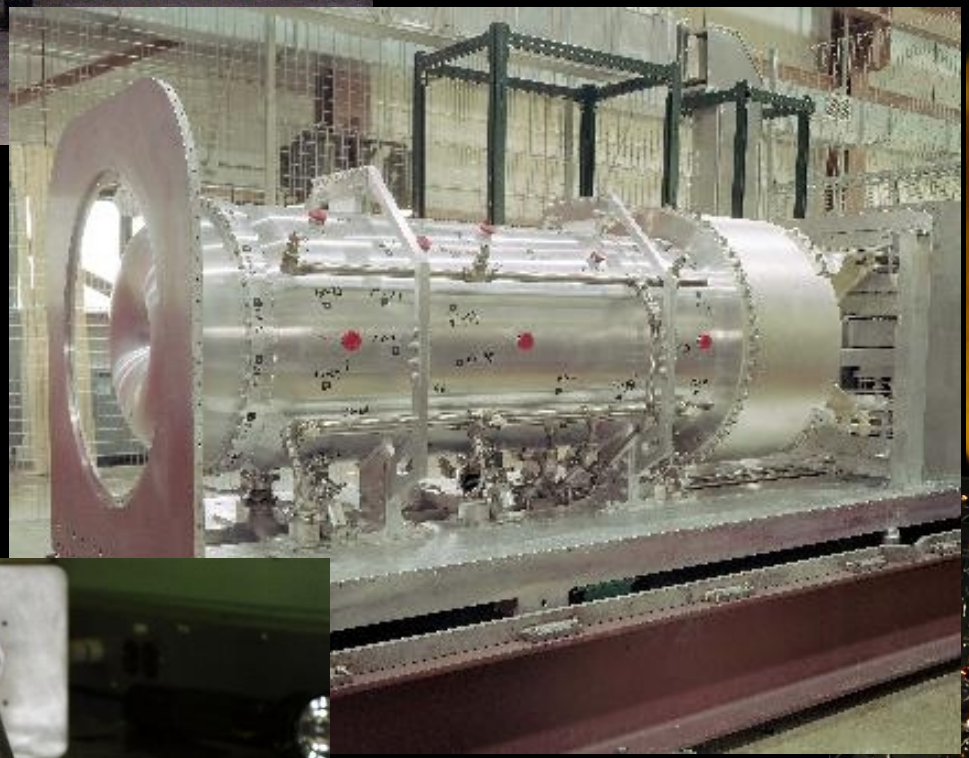
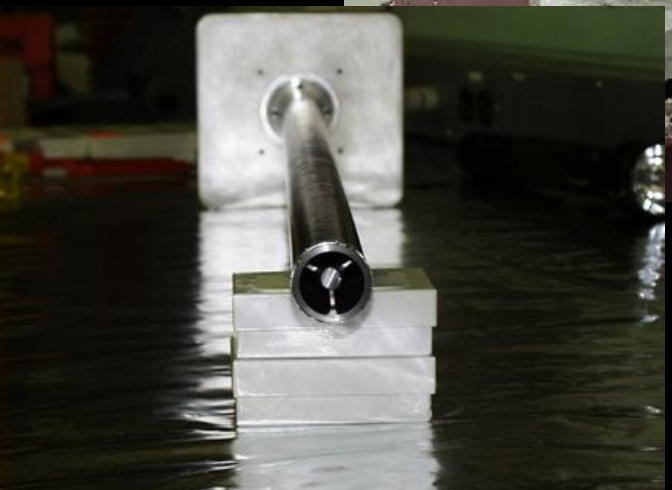
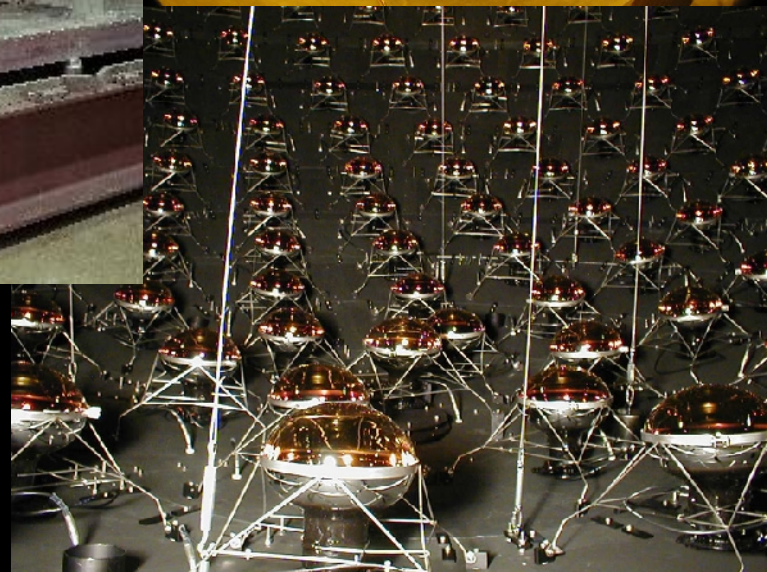
Updated Oscillation Results from MiniBooNE

Chris Polly, Fermilab







MiniBooNE is...

a single-detector (CH_2),
short-baseline (~500m) experiment searching for
υ_e (or anti-υ_e) appearing in
υ_μ (or anti-υ_μ) beam.

Ask some of our colleagues from the field and they might tell you MiniBooNE is...

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the most !#$*@9$ experiment on the planet

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confusing and/or confused

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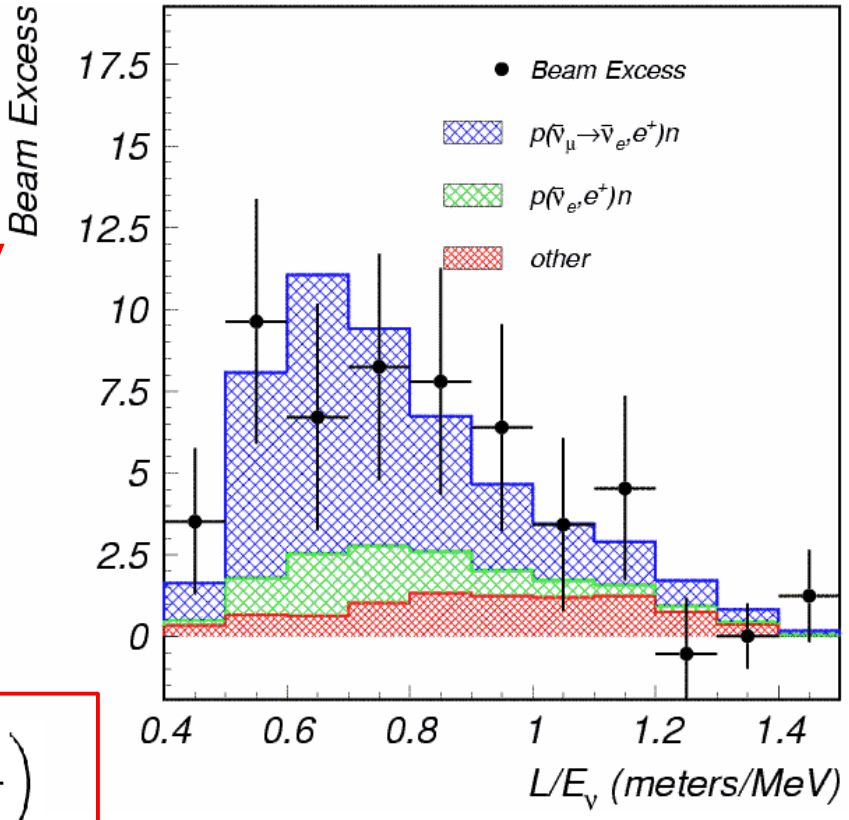
LSND data



...motivated by the LSND anomaly

- LSND found an excess of $\overline{\upsilon}_e$ in $\overline{\upsilon}_\mu$ beam
- Signature: Cerenkov & scin. light from e^+ with delayed n-capture (2.2 MeV)
- Excess: 87.9 ± 22.4 ± 6.0 (3.8σ)
- Under a 2υ mixing hypothesis:

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

MiniBooNE is...

a single-detector (CH_2),
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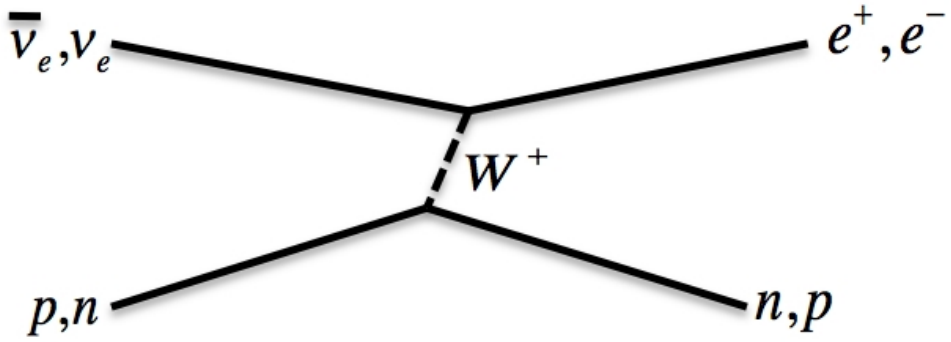
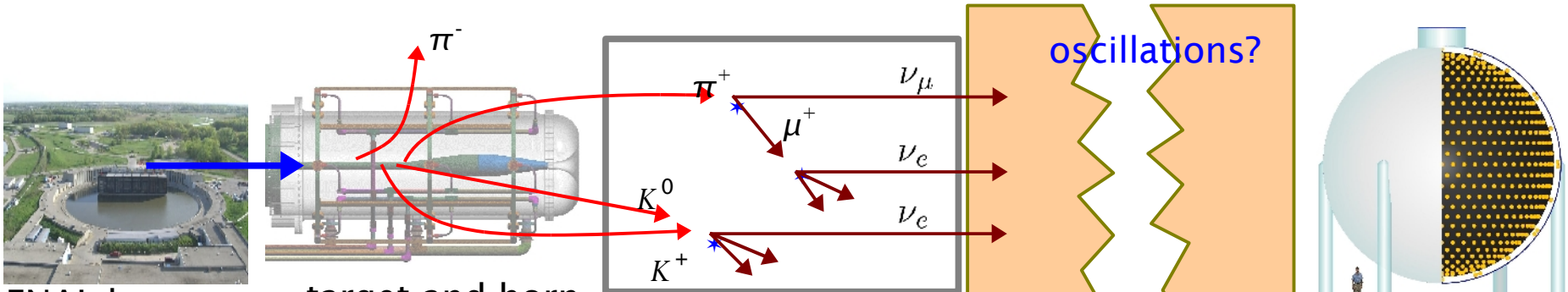
Contrast MiniBooNE signal with LSND...

υ_e Charged-Current Quasi-Elastic

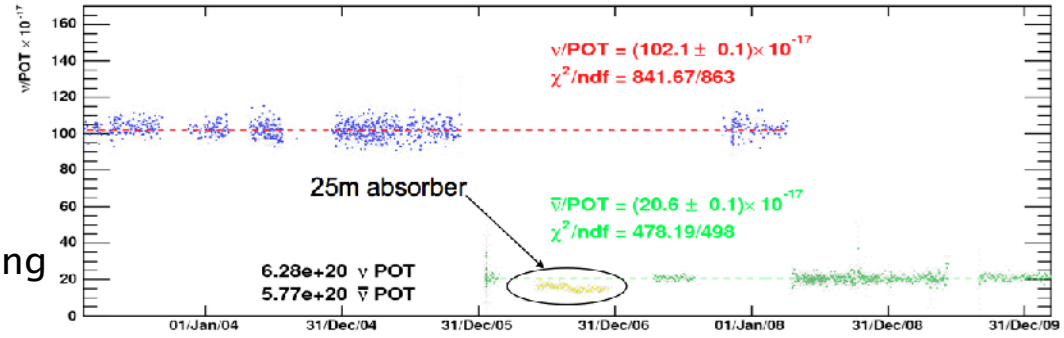


- MiniBooNE runs with υ and anti-υ
  - PID is Cerenkov-based (undoped)
  - scintillation light from n,p small
  - n-capture below threshold

MiniBooNE design strategy...must have protons

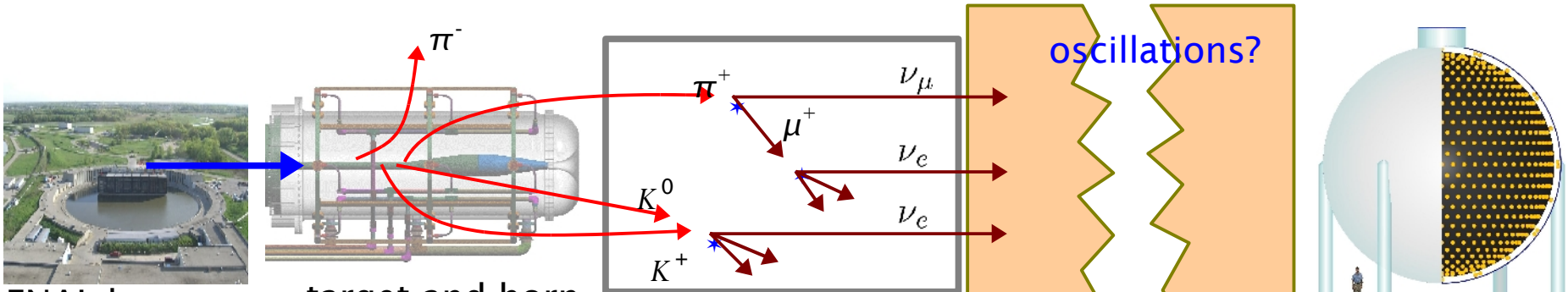


- Early 90s, started looking for source of ν's intense enough to measure $P(\nu_\mu \rightarrow \nu_e)=0.25\%$
- 8 GeV FNAL Booster protons
  - 6.6e20 POT delivered for ν running
  - 5.6e20 POT analyzed for anti-ν running



- Still need a focussing horn to gain x3
  - Switch horn polarity to select π+/π− focus
  - Rate for anti-ν beam reduced by 5 from ν beam

Implications of higher beam energy

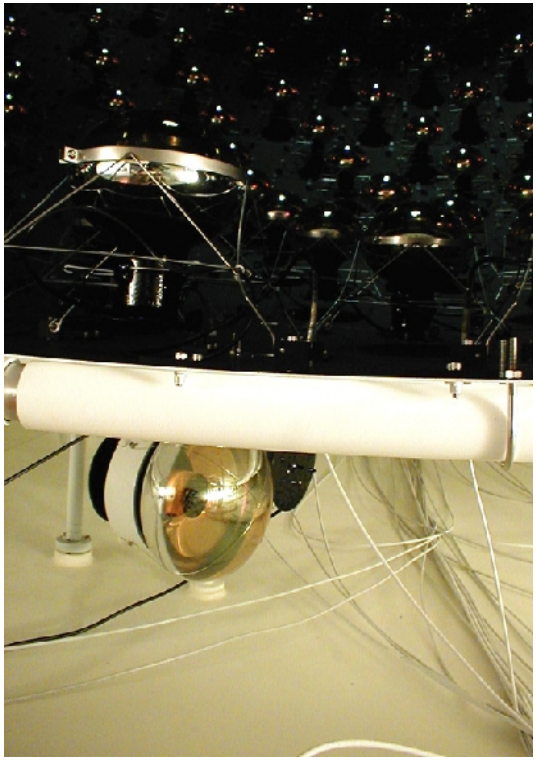


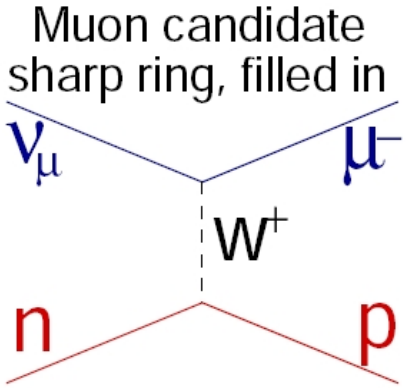
FNAL booster (8 GeV protons) | target and horn (174 kA) | decay region (50 m) | dirt (~500 m) | detector

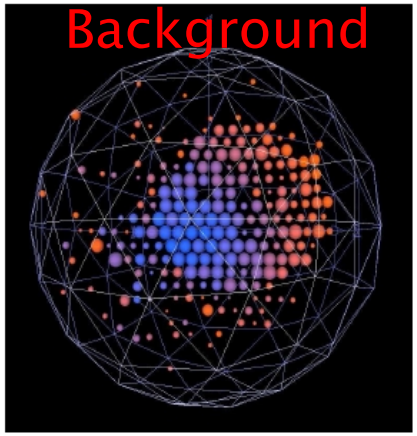
- Average MB E_ν ~800 MeV, LSND ~70 MeV
  - Gains an order of magnitude in cross-section
  - LSND anti-ν_μ's too low in E to make a μ or π
  - New bkgs in MiniBooNE: ν_μ CCQE and NC π^0 mis-id
- Detector placed at 500m to preserve LSND L/E
- Higher energy protons make kaons (0.5%)
  - New bkgs in MiniBooNE: intrinsic ν_e from K

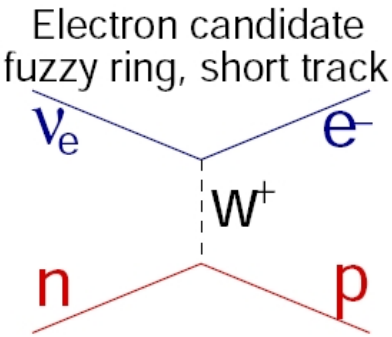
Detector choices

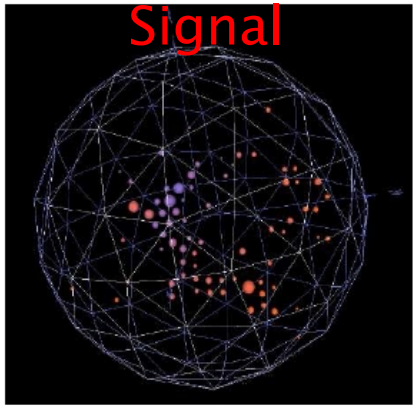
- 800-ton pure mineral oil (520 T fiducial)
  - Ring topology to separate e, μ, and π^0
  - Important Point: Can't distinguish e from γ
- Detector divided into inner/outer region
  - Ensures containment, reduces comic background to negligible level

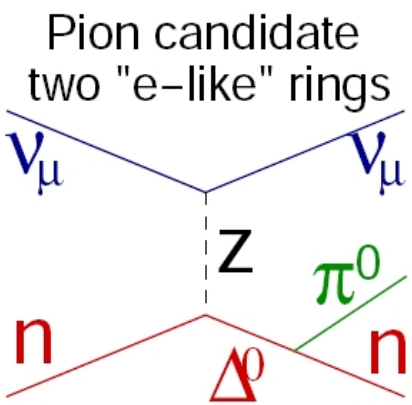


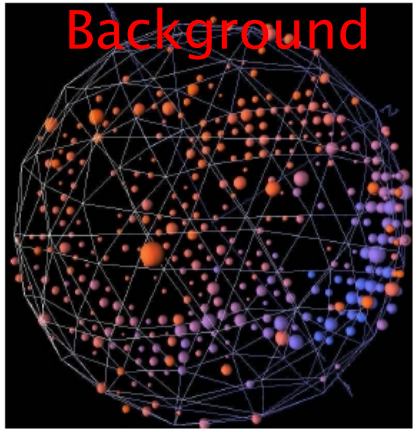






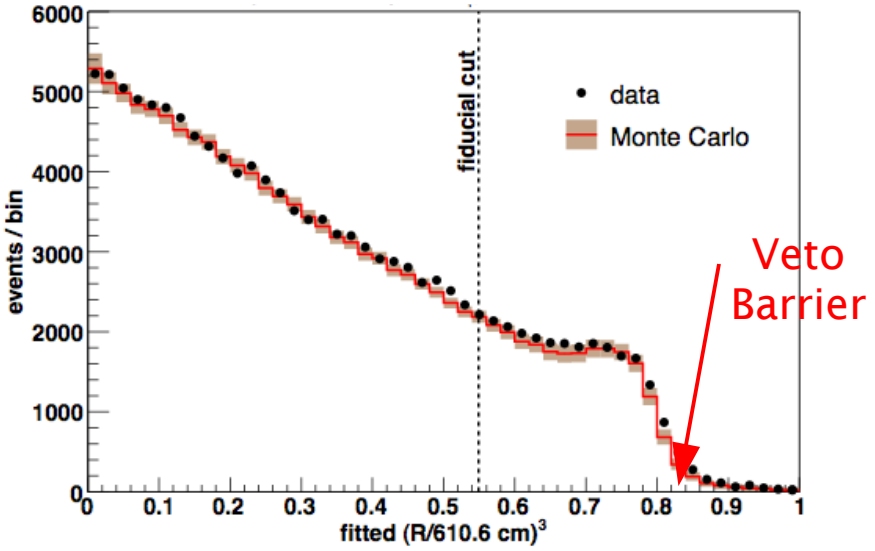


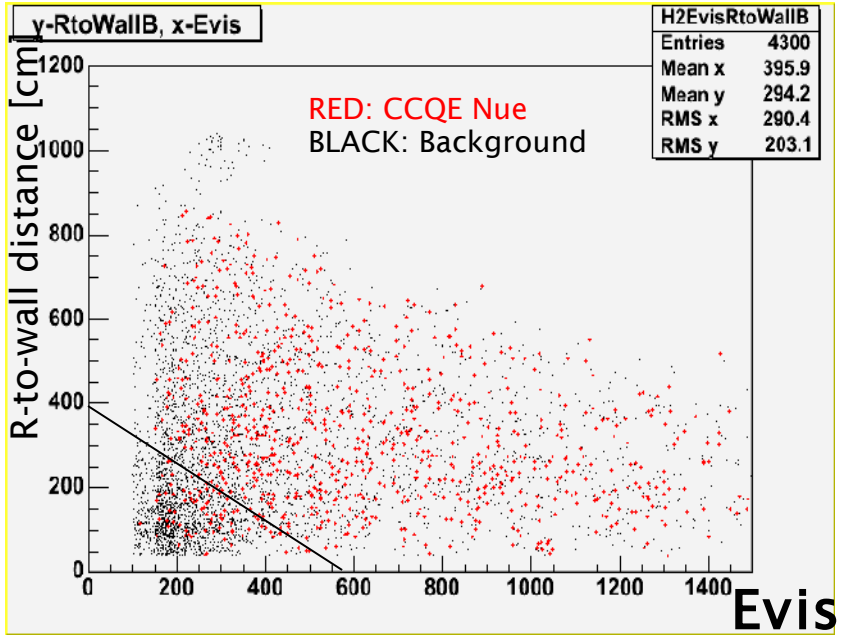




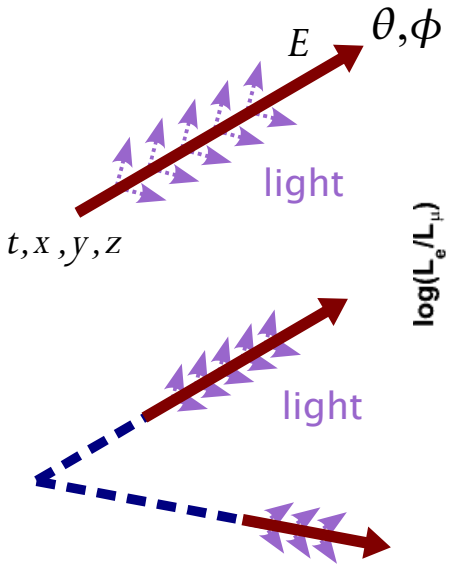
Signal selection in MiniBooNE

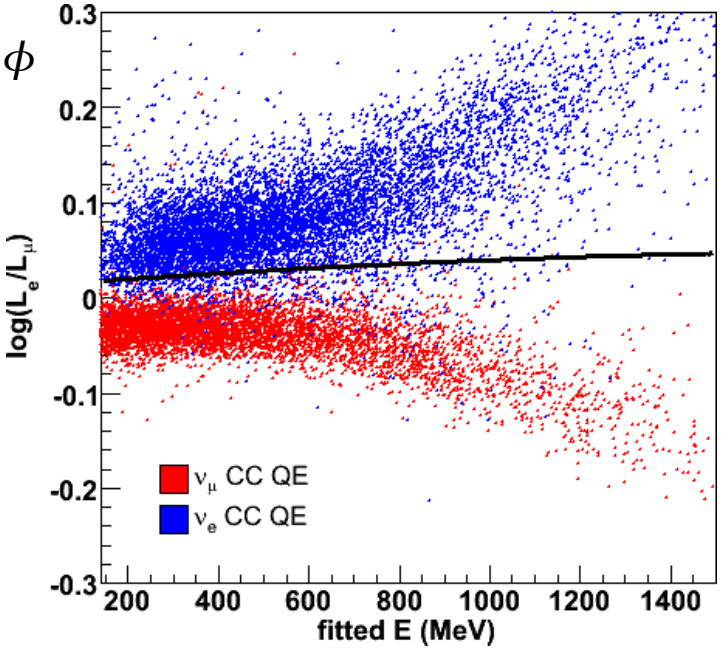
- Neutrino and anti-neutrino analyses are identical
- Start with pre-cuts
  - No late time activity, removes Michel electrons, cuts ~80% of ν_μ CCQE events
  - Veto hits < 6, contained & not a cosmic
  - Tank hits > 200 & visible E >140 MeV, removes NC elastic bkgs
  - Radius < 500 cm, far enough from PMTs to avoid area where light modeling becomes less certain
  - R-to-wall backward cut, removes bkgs (mainly γ's) from beam ν that interact in dirt outside the detector

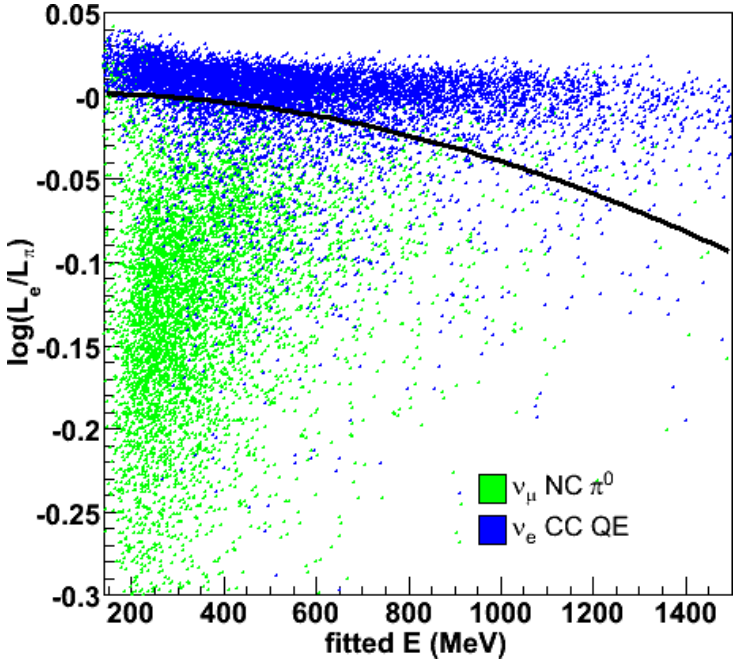


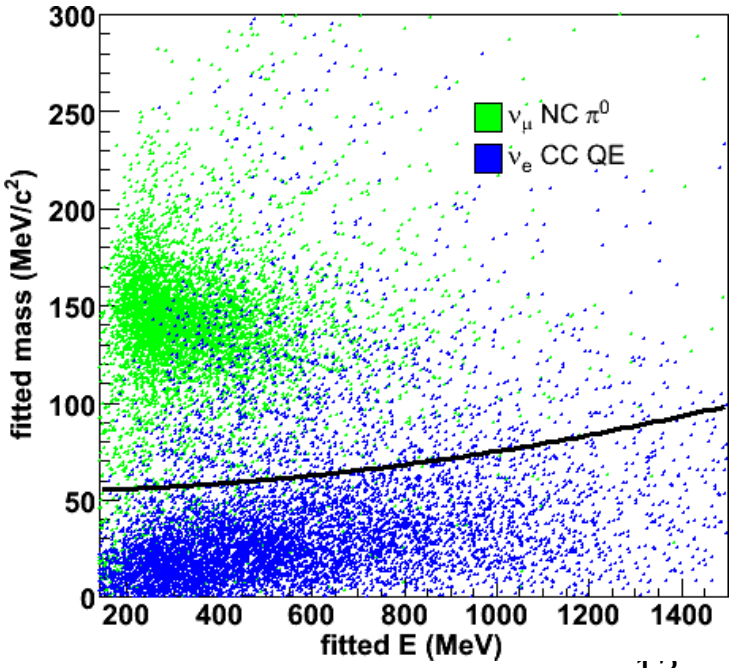


Track-based likelihoods









- Form sophisticated Q and T pdfs, and fit for track parameters under 3 hypotheses
  - The track is due to an electron
  - The track is coming from a muon
  - The "track" is a two-track(ring) π^0 event
- Apply energy-dependent cuts on L(e/μ), L(e/π), and the π^0 mass
- Plot remaining events versus E_ν(QE) and fit

Combined fit of ν_μ and ν_e CCQE spectra

- Maximum likelihood fit:

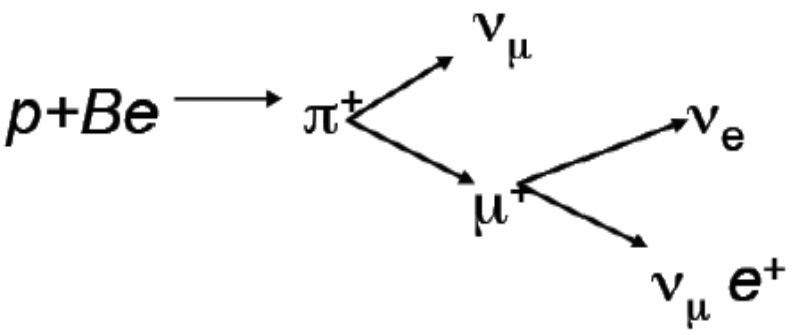
$$-2\ln(L) = (x_1 - \mu_1, \ldots x_n - \mu_n) M^{-1} (x_1 - \mu_1, \ldots x_n - \mu_n)^T + \ln(|M|)$$

$M = M_{om} + M_{xsec} + M_{flux} + M_{\pi^0} + M_{dirt} + M_{K^0} + \ldots$

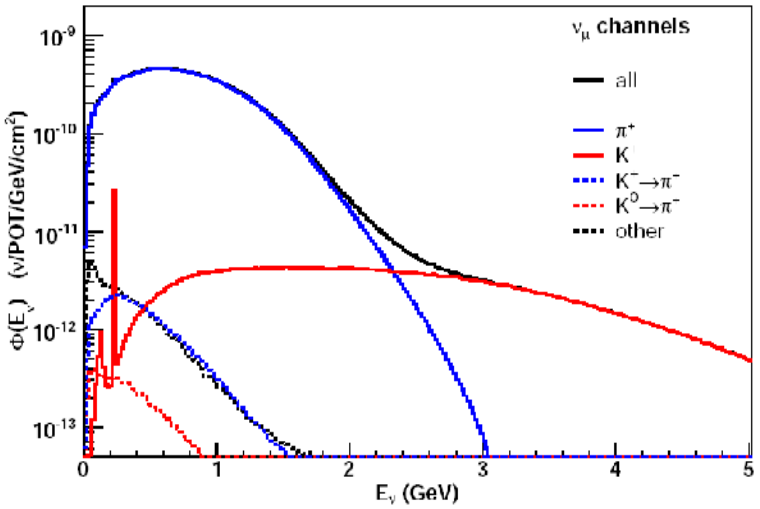
- Simultaneously fit (FC-corrected)
  - ν_e CCQE signal + high E ν_e sample
  - High statistics ν_μ CCQE sample

1000's of MC universes go into forming M

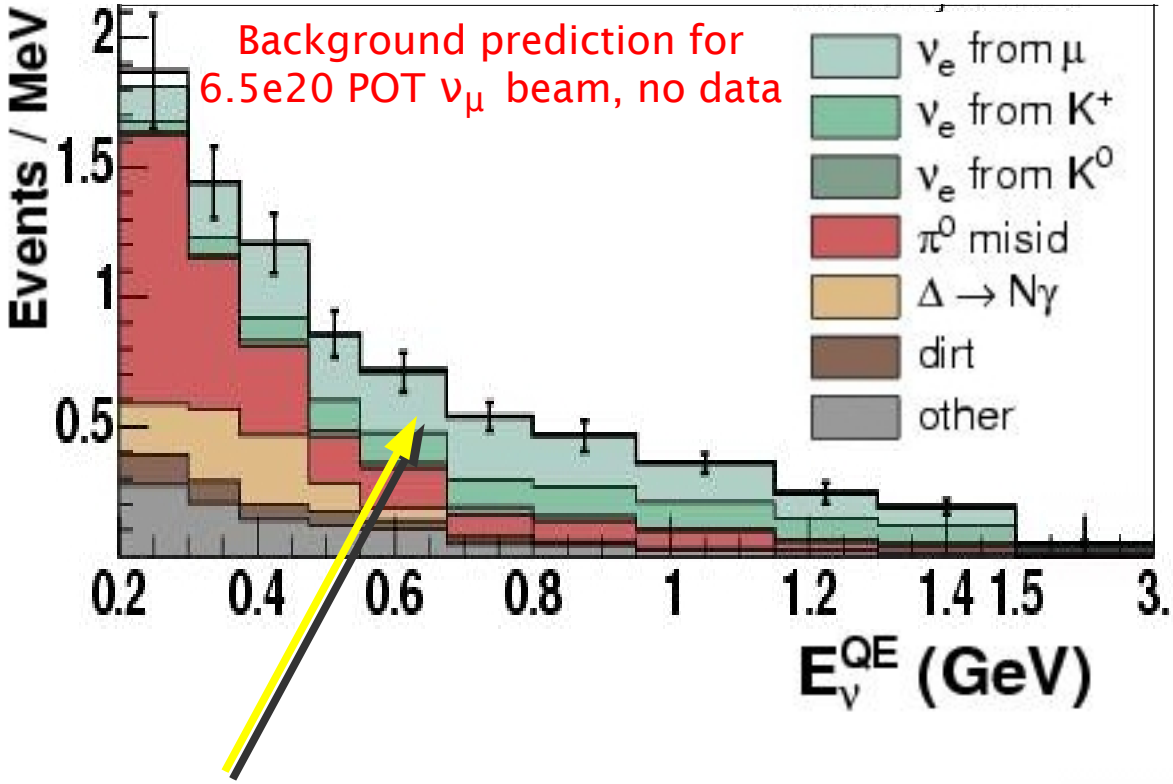
- ν_μ CCQE sample acts like a near detector, i.e. same flux as oscillation ν_e by definition, lepton universality + muon mass corrections fix relative cross-section
  - Low E ν_μ's constrain signal rate
  - Low E ν_μ's constrain ν_e from muons
  - High E ν_μ's constrain ν_e from kaons



ν_μ flux through detector (υ mode)



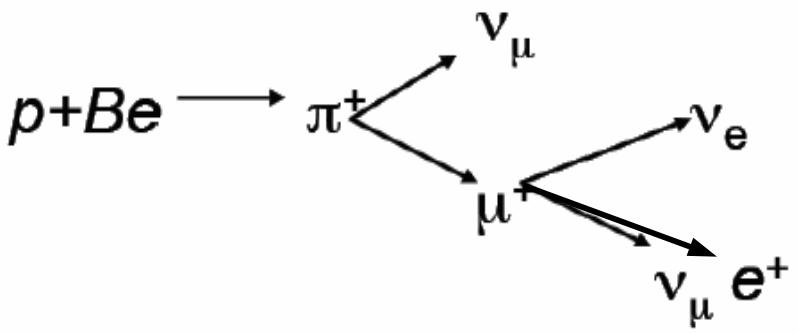
In situ background constraints: Muon ν_e



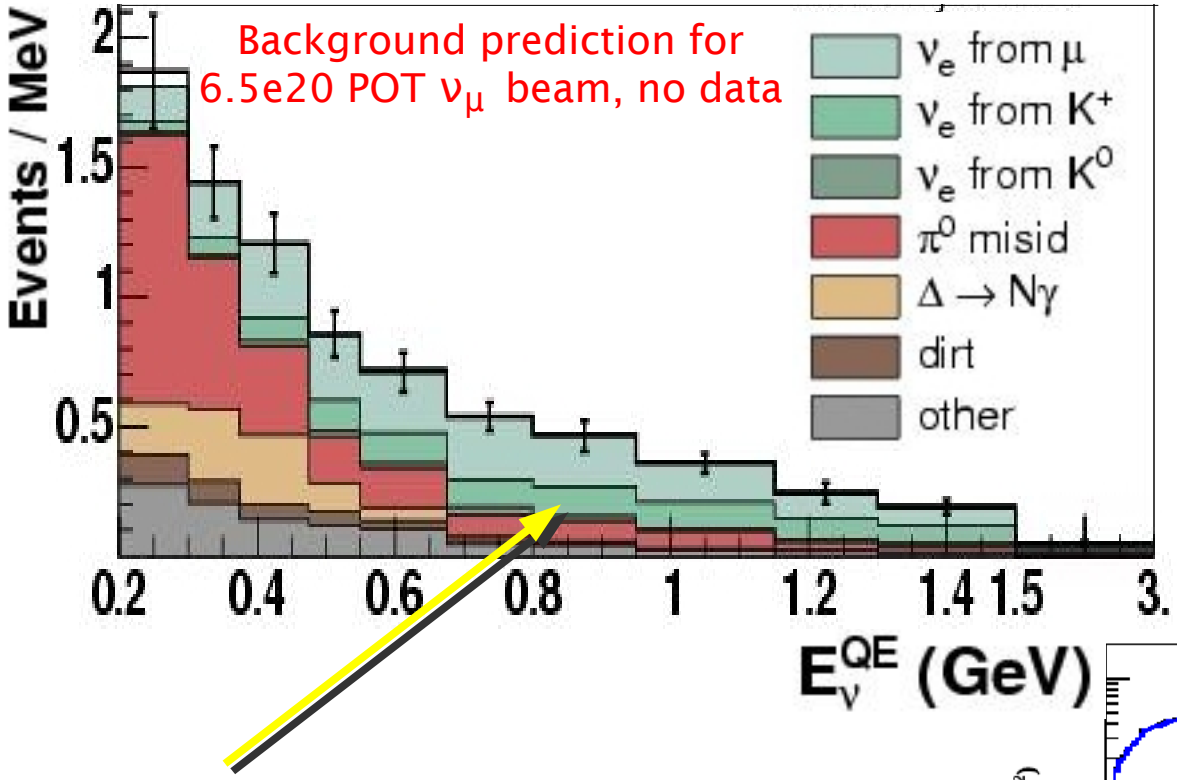
475 MeV – 1250 MeV

ν_e^K	94
ν_e^μ	132
π^0	62
dirt	17
$\Delta \rightarrow N\gamma$	20
other	33
total	358

- Intrinsic ν_e from μ^+ originate from same π^+ as the ν_μ CCQE sample
- Measuring ν_μ CCQE channel constrains intrinsic ν_e from π^+



In situ background constraints: ν_e from K^+



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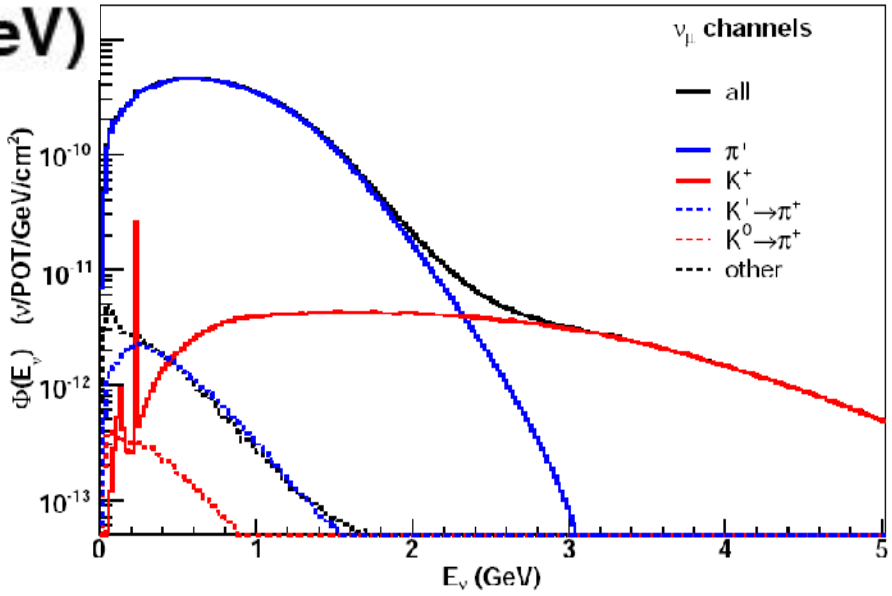
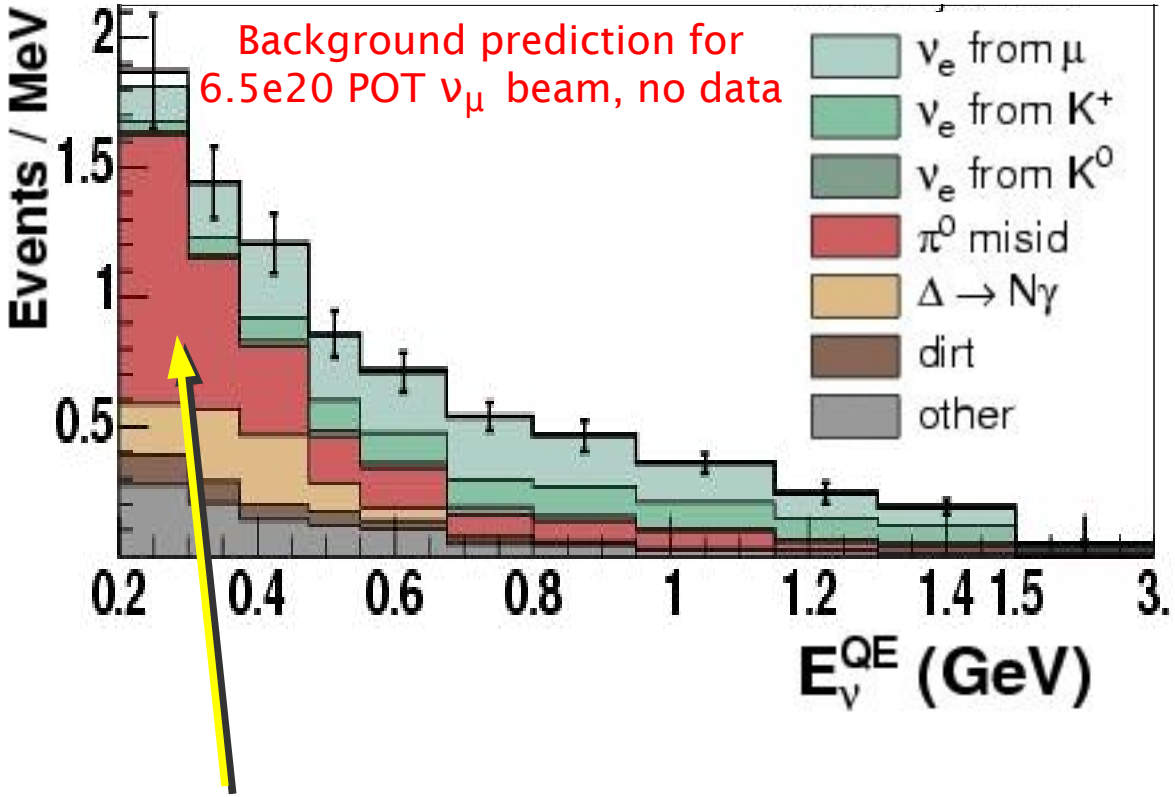
- At high energy, ν_μ flux is dominated by kaon production at the target
- Measuring ν_μ CCQE at high energy constrains kaon production, and thus intrinsic ν_e from K^+



In situ background constraints: NC π^0



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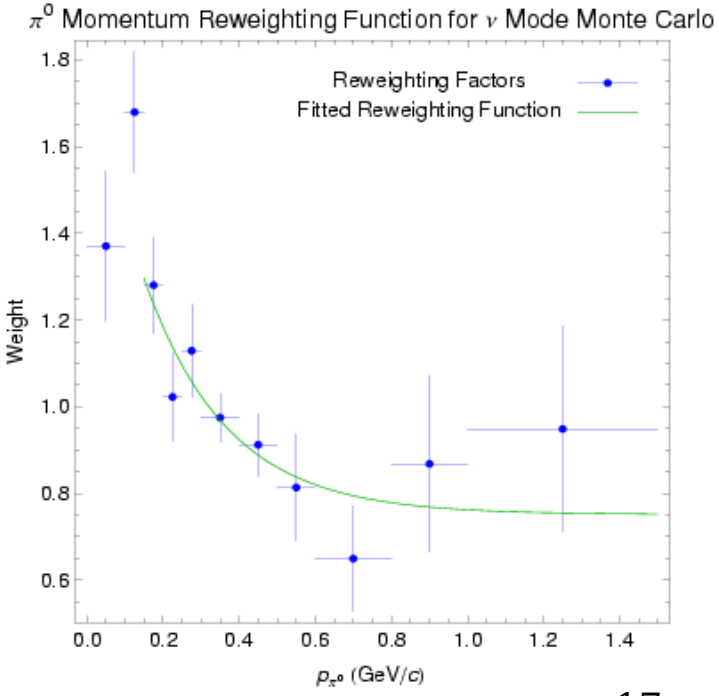
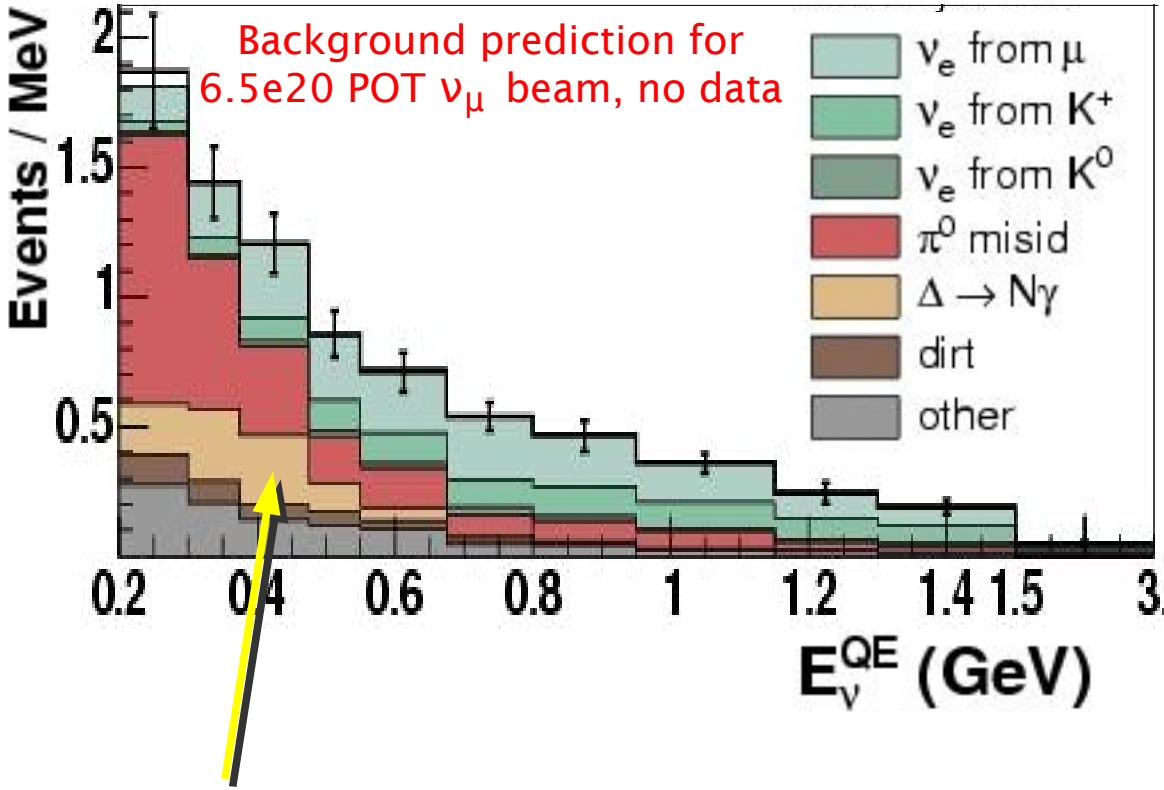


- Reconstruct majority of π^0 events
- Error due to extrapolation uncertainty into kinematic region where 1 γ is missed due to kinematics or escaping the tank

MB, Phys Lett B. 664, 41 (2008)

In situ background constraints: $\Delta \rightarrow N\gamma$



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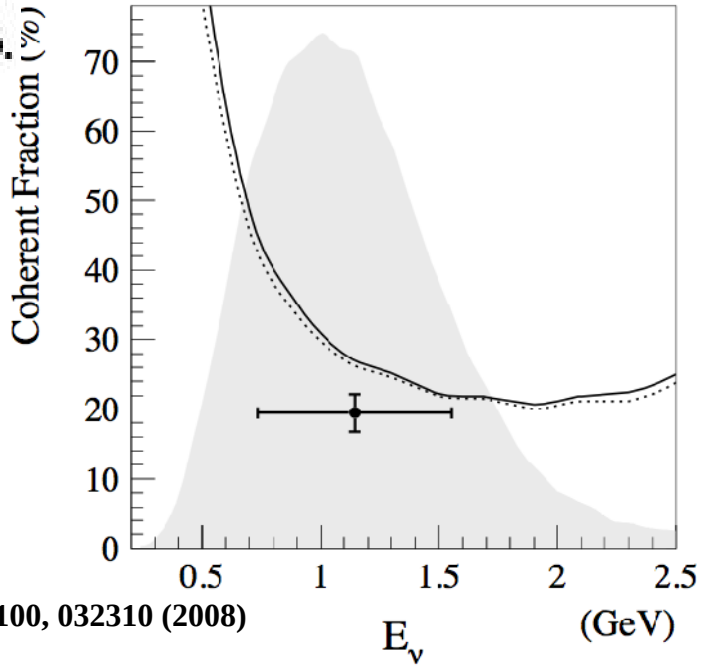
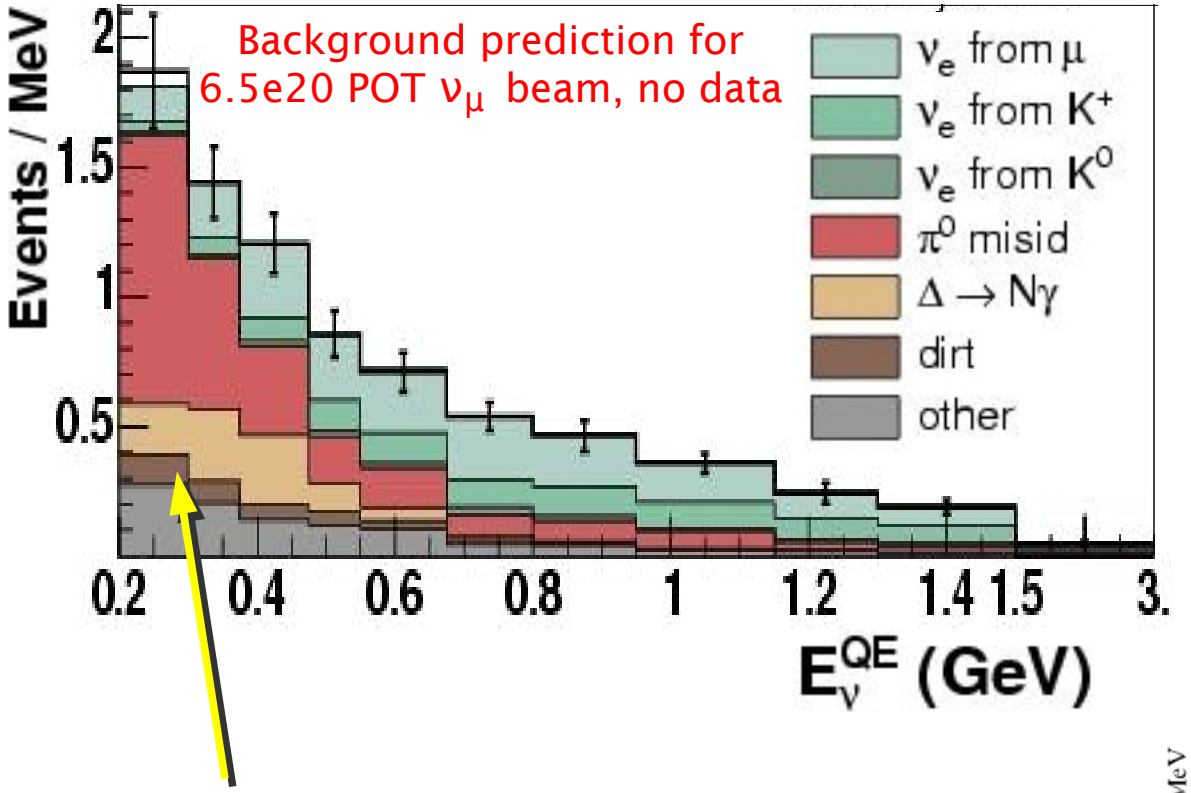
- About 80% of our NC π^0 events come from resonant Δ production
- Constrain $\Delta \rightarrow N\gamma$ by measuring the resonant NC π^0 rate, apply known branching fraction to N, including nuclear corrections



MB, PRL 100, 032310 (2008)

In situ background constraints: Dirt



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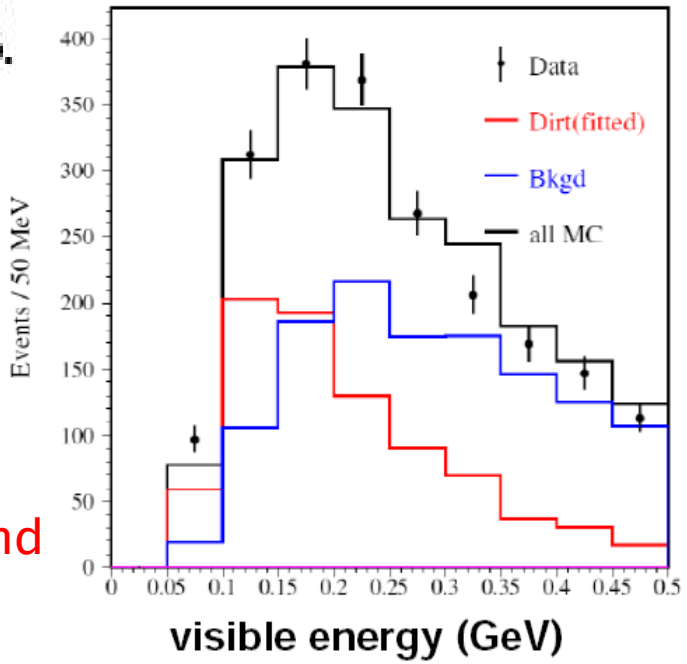
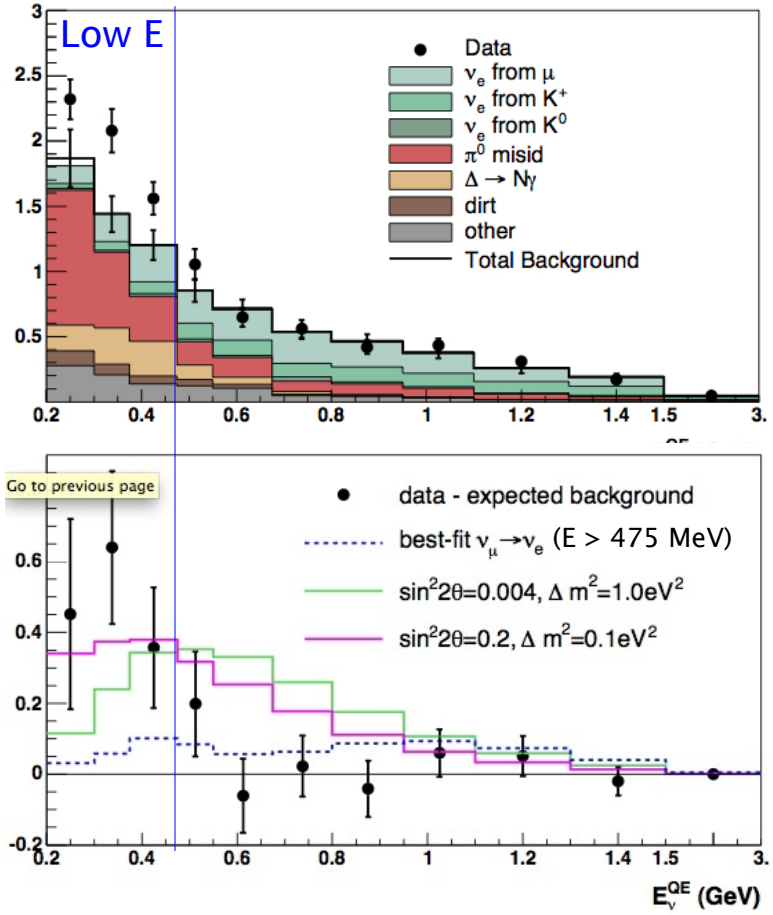


- Come from ν events int. in surrounding dirt
- Pileup at high radius and low E
- Fit dirt-enhanced sample to extract dirt event rate with 10% uncertainty

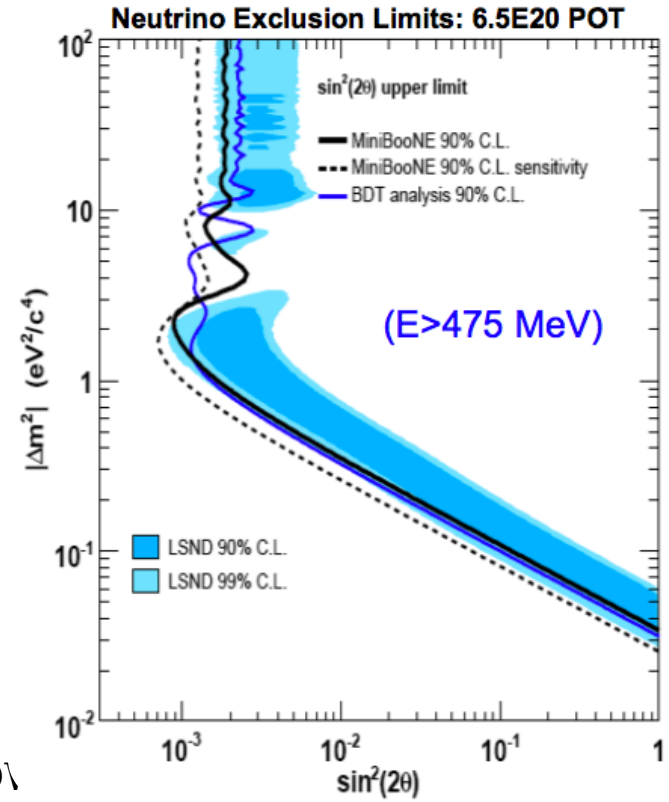
☆ In the end, every major source of background can be internally constrained by MB.

Oscillation Results

Reminder: Neutrino Oscillation Search



- Above 475 MeV...
  - After unblinding, we see amazing agreement with our background predictions
  - Find 408 events, expect 386 ± 20(stat) ± 30(syst)
  - Chi-square probability of 40% in 475-1250 MeV
  - Since this is the region of highest sensitivity to and LSND-like 2 mixing hypothesis, can use it to exclude that model



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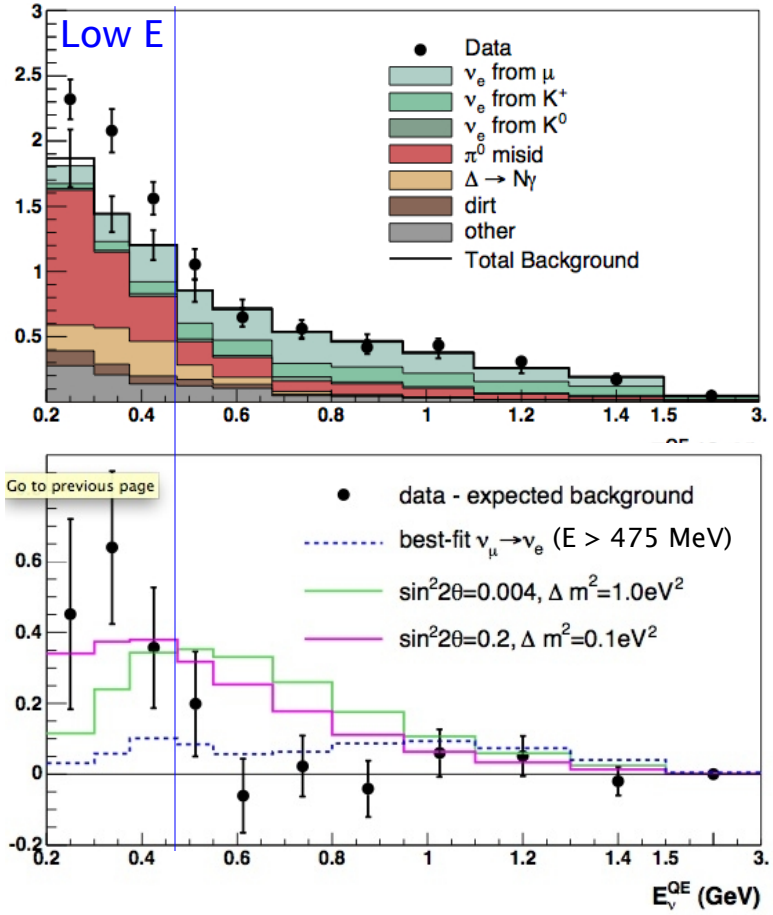


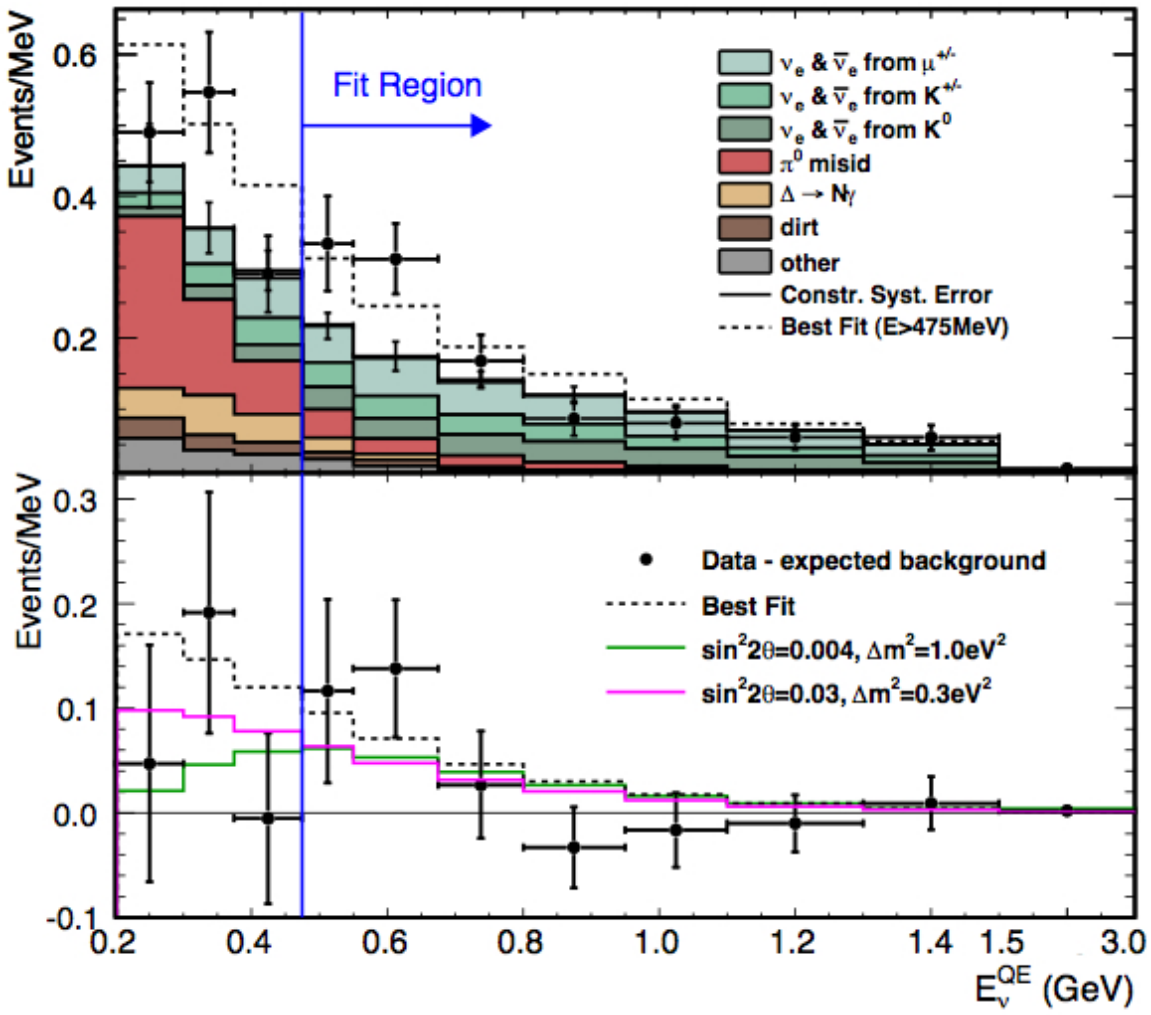
- Below 475 MeV...
  - Find 544 events, expect 415 ± 20(stat) ± 39(syst)
  - Excess is 128 ± 20(stat) ± 39(syst) events
  - 6σ statistical excess, but reduced to 3σ due to falling in region where bkgs are rising

Bkgds and errors in 200-475 MeV region

Bkg Source	Bkg Counts	Inc. Needed	Syst Error*
ν_μ CCQE	26.4	487%	~30%
NC π^0	181.3	71%	~20%
Rad. Δ	67.0	192%	~25%
ν_e from μ	58.1	222%	~25%
ν_e from K	17.4	740%	~40%
dirt	23.8	544%	~15%

*not rigorously correct but withing 5%

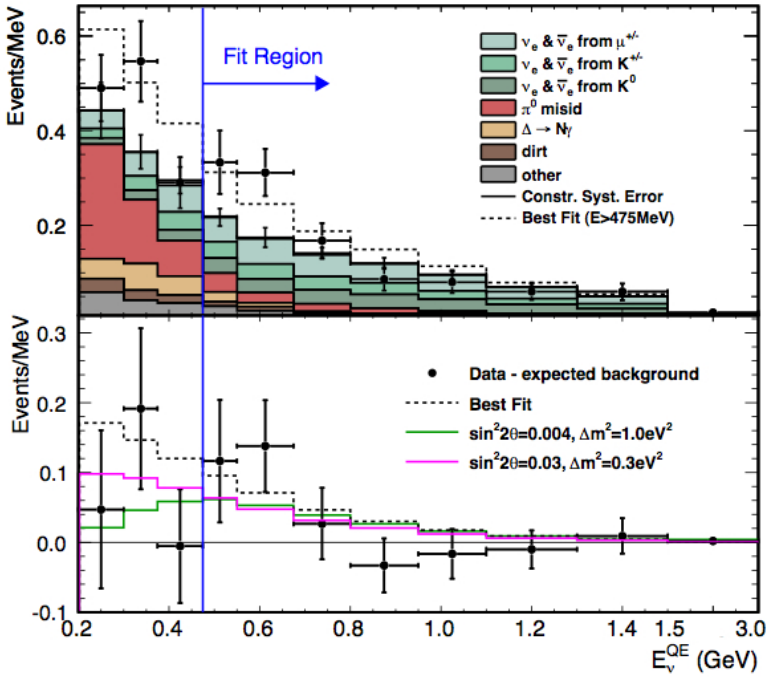
And now for the results you've been waiting for...



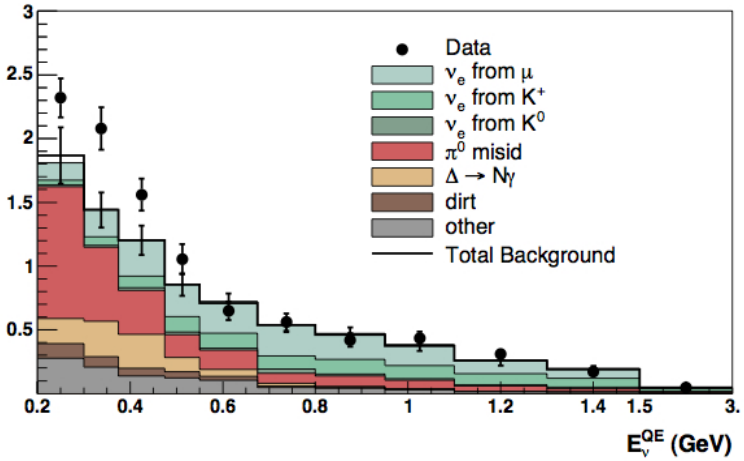
anti-ν results

New Antineutrino Results (below 475 MeV)

anti-ν results



Reminder: ν results

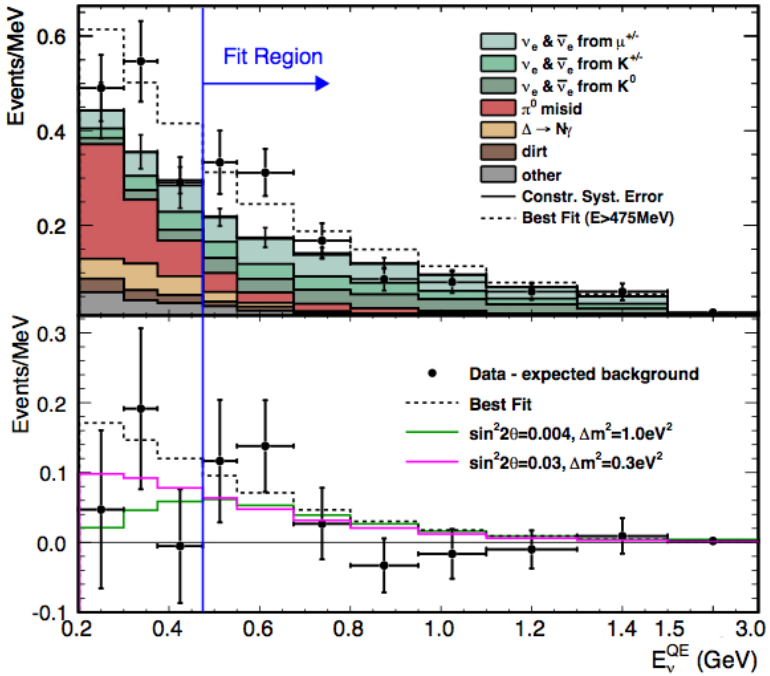


- Below 475 MeV…
  - Find 119 events, expect 100 ± 10(stat) ± 10(syst)
  - Excess is 18.5 ± 10(stat) ± 10(syst) events
  - Starting to become inconsistent with many hypotheses explaining the n mode low E excess

Bkg Source	Nubar Prediction
CC bkgs	38.6
NC π^0	31
Rad Δ	24.9
K^0	114.3
charged K	38
WS neutrinos	12
same xsec	68

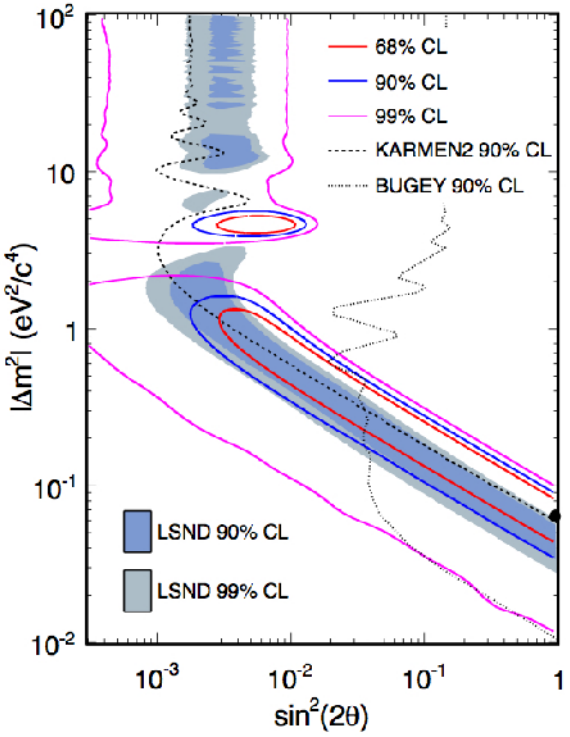
New Antineutrino Results (above 475 MeV)

anti-ν results

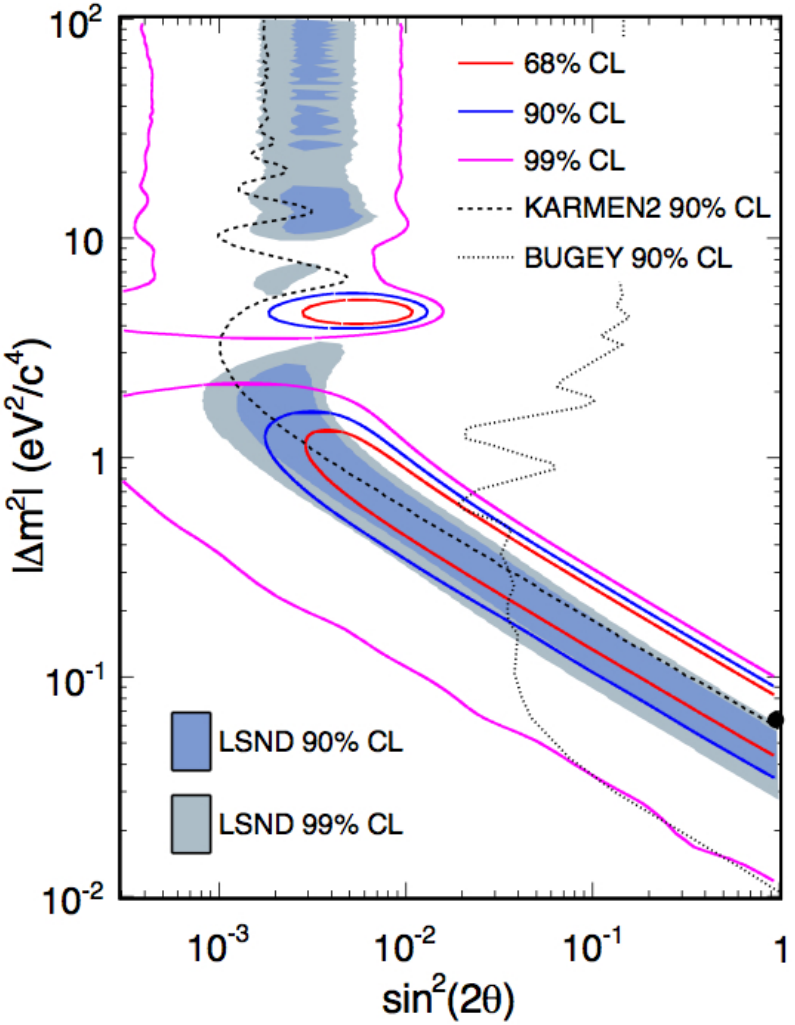


anti-ν results

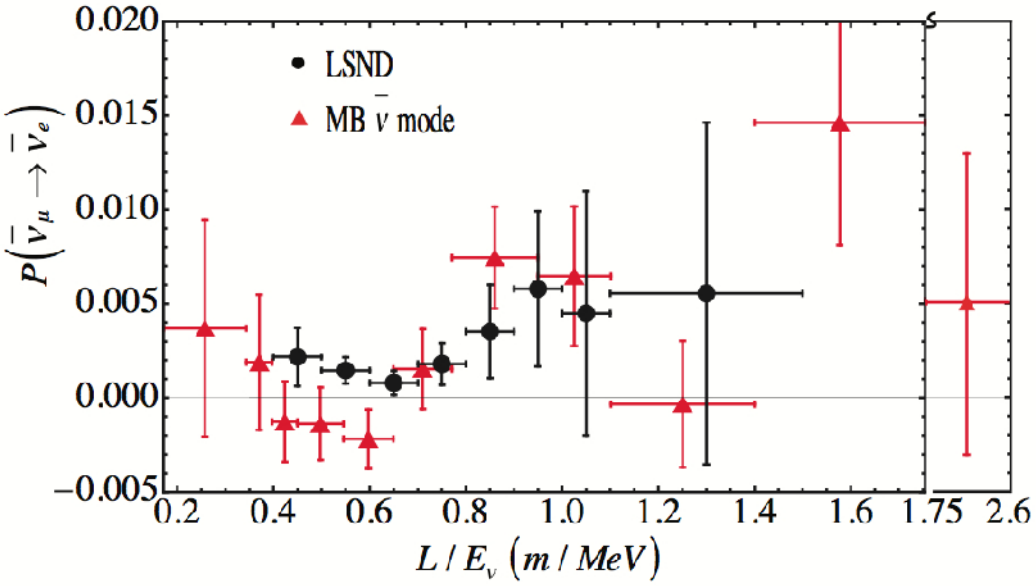
- Above 475 MeV...
  - In 475-1250 MeV, excess 20.9 ± 14 events (1.4σ)
  - In 475-675 MeV, excess is 25.7 ± 7.2 events (3.6σ)
  - True significance comes from fit over entire > 475 MeV energy region + numu constraint
  - Best fit preferred over null at 99.4% CL (2.7σ)
  - Probability of null hypothesis (no model dep.) is 0.5% in 475-1250 MeV signal region



Comparing MiniBooNE anti-ν to LSND



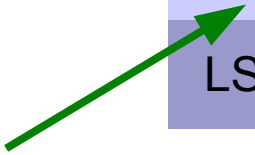
Fit to 2ν mixing model



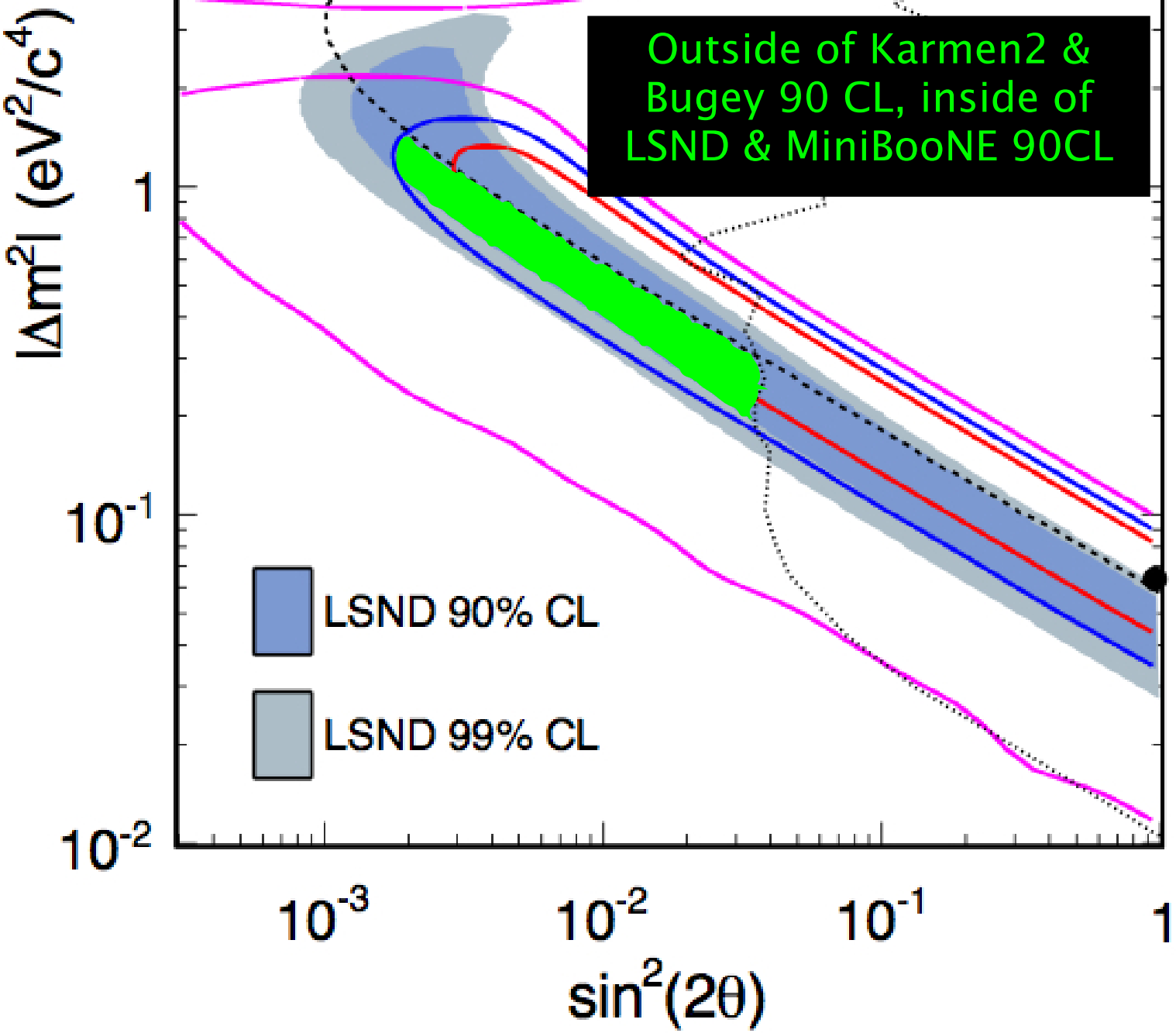
Model-independent plot of inferred oscillation probability

Anoter way to check MB & LSND consistency

	E (QE) [MeV]		
Bkgd	200-475	475-1250	1250-3000
MC	100.5	99.1	34.2
Data	119	120	38
Excess	18.5 ± 10 ± 10	20.9 ± 10 ± 10	3.8 ± 5.8
LSND Best Fit	7.6	22.0	3.5
Low-E excess	11.6	~2	~0
LSND + Low-E	19.2	24.0	3.5



Assumes ν_e excess should be present for WS ν_μ in beam


Outside of Karmen2 & Bugey 90 CL, inside of LSND & MiniBooNE 90CL
LSND 90% CL
LSND 99% CL
$|\Delta m^2|$ (eV^2/c^4)
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2(2\theta)$

Fit

What does MiniBooNE claim?

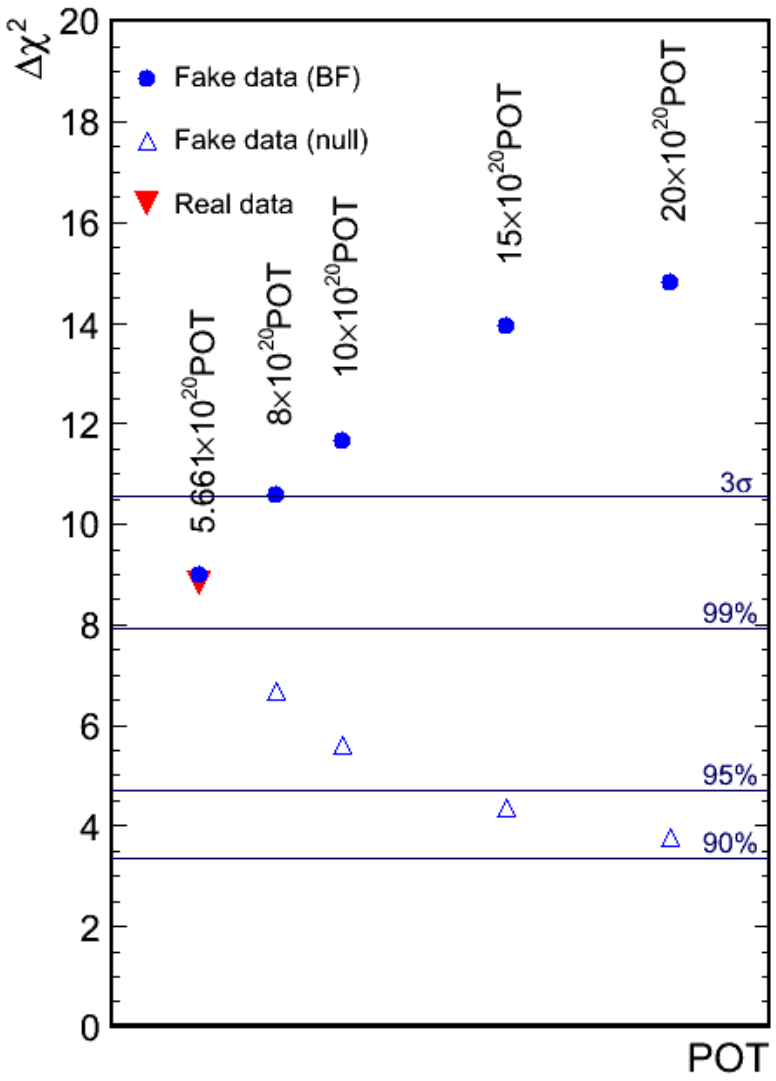
In a ν_μ beam above 475 MeV, we see no evidence for an excess of ν_e-like events. (This is the region of maximal sensitivity if the LSND signal is L/E and CPT invariant.)

In a ν_μ beam below 475 MeV, we see a 3σ excess (128 ± 43) of ν_e signal candidates that don't fit well to a 2ν mixing hypothesis.

In a anti-ν_μ beam below 475 MeV, we see a small excess (18 ± 14). It rules out some explanations of the ν_μ beam low-E excess.

In a anti-ν_μ beam above 475 MeV, we see an excess of events. The null hypothesis in the 475-1250 MeV region is only 0.5% probable. A 2ν fit prefers an LSND-like signal at 99.4% CL.

LSND=3.8σ, MBν=3.0σ, MB$\bar{\nu}$=2.7σ...What now?



2011-2012

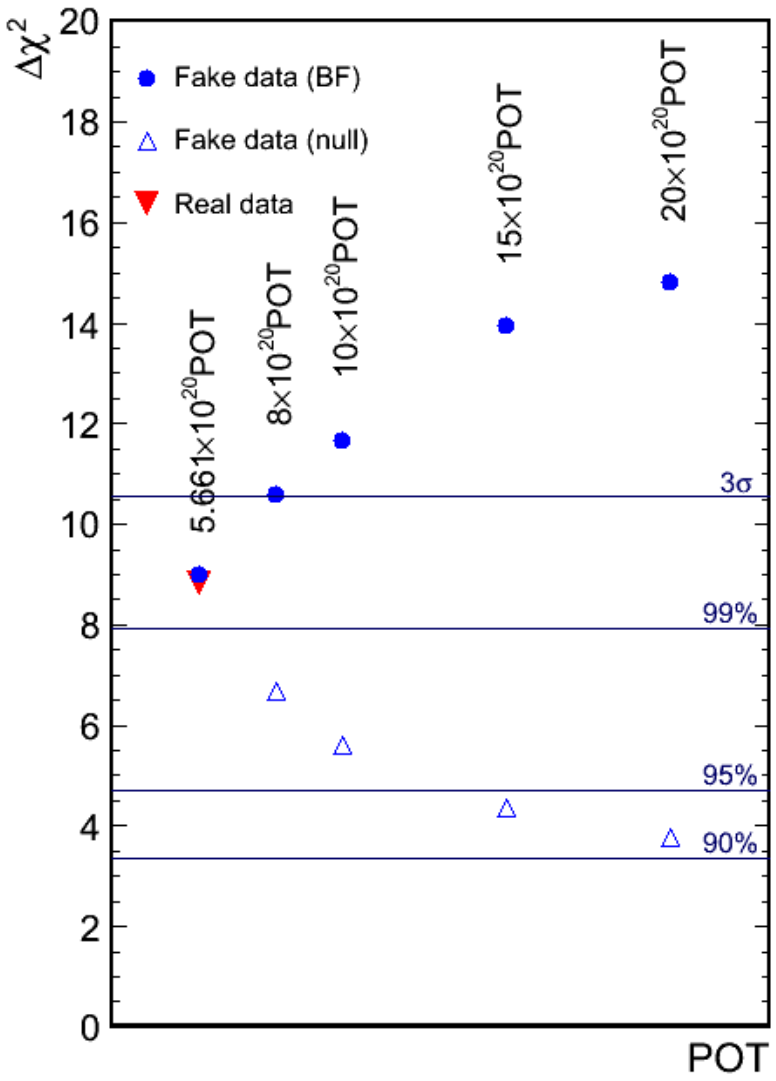
Step 1: anti-ν result is stat limited...need more data

Collaboration is putting in proposal to FNAL to collect 15e20 POT a prior to March 2012 shutdown

From stats only at 15e20, the anti-ν significance could grow to 3.7σ or fall back to including the null at 95%

Possibility for ~20% analysis gain during this time

LSND=3.8σ, MBν=3.0σ, MB$\bar{\nu}$=2.7σ...What now?



2013-2015

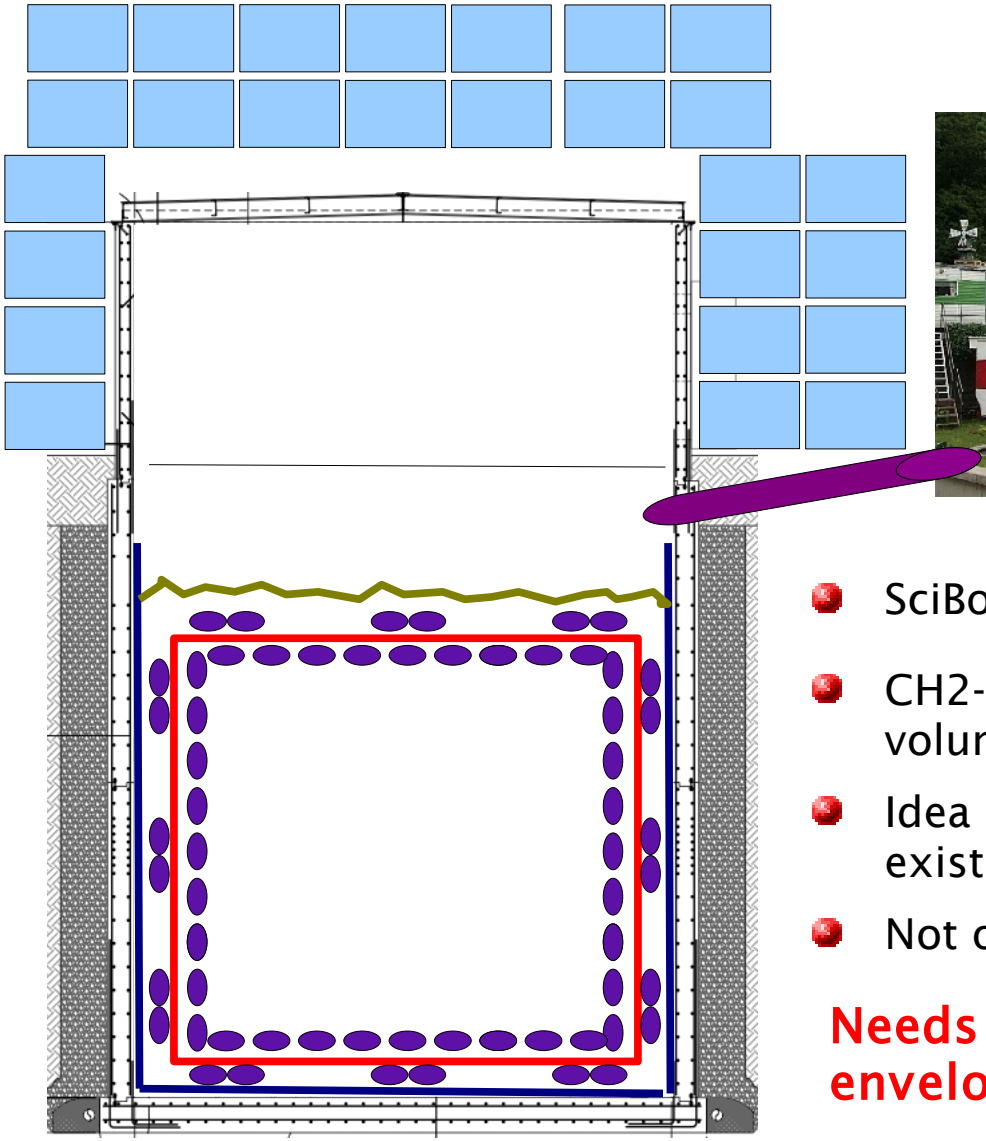
The MicroBooNE era

MicroBooNE experiment to advance liquid Ar R&D, resolve if the MiniBooNE low-E excess is ν_e CCQE at 5σ

6.7e20 POT delivered with ν beam during this time

Would double stats in MiniBooNE during this time making low-E excess 9σ statistically significant...but need a near detector to reduce systematics

Need a low-cost near detector...one idea



- SciBooNE enclosure still exists at 200m
- CH2-based near-detector could have fiducial volume 8x smaller than MB, but x25 gain in r^2
- Idea here is for a tank-like design, but using existing NOvA prototype could be better sol'n
- Not on the roadmap...yet

Needs detailed simulation, back-of-the-envelope shows 5 sigma a possibility

Backup Slides....

What happens if you extend the fit down to 200 MeV?

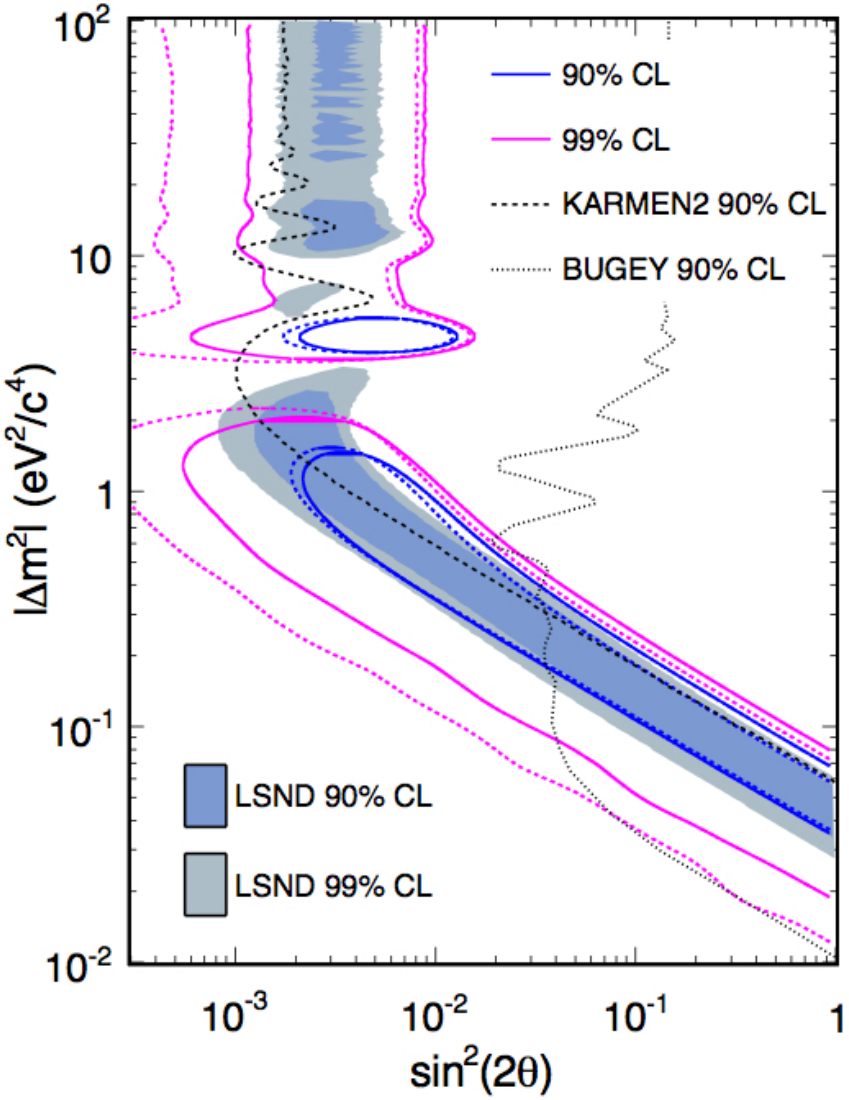
Is there tension with LSND's ν_μ result?

What if the anti-ν BF had been found in ν beam, signifcance?

How does this compare to first anti-ν result?

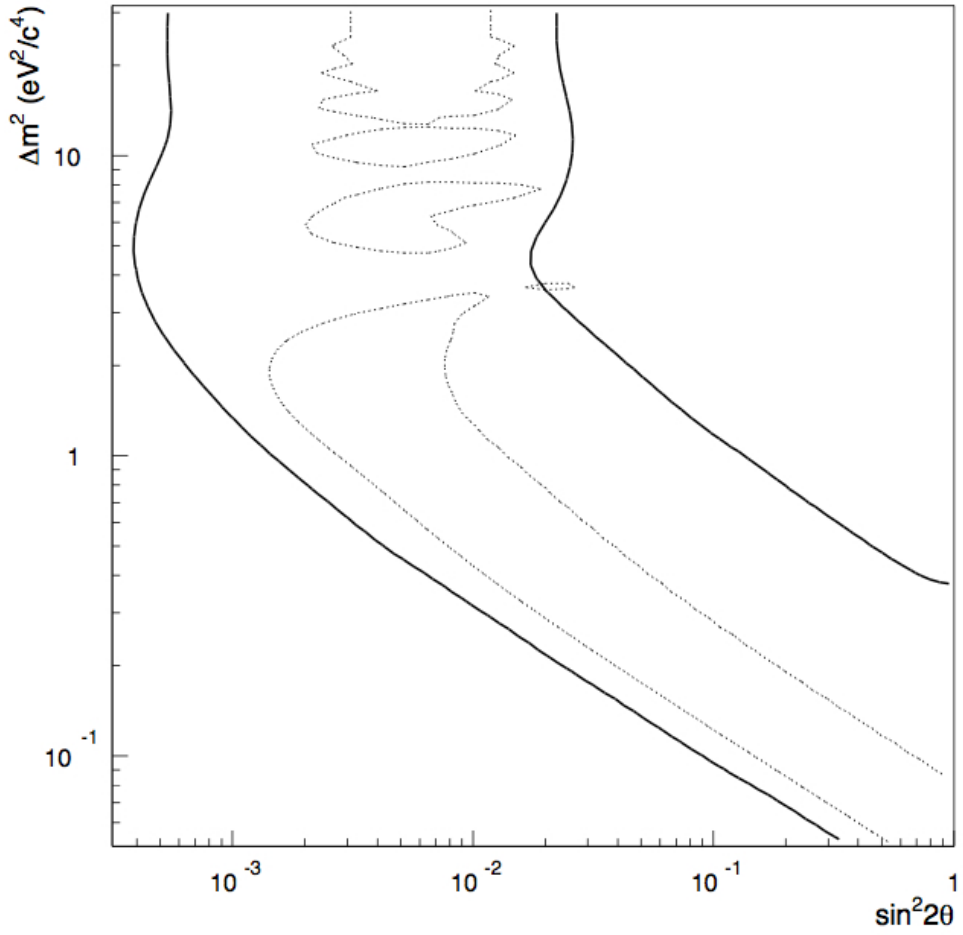
What's the latest news from cross-sections?

Fitting down to 200 MeV

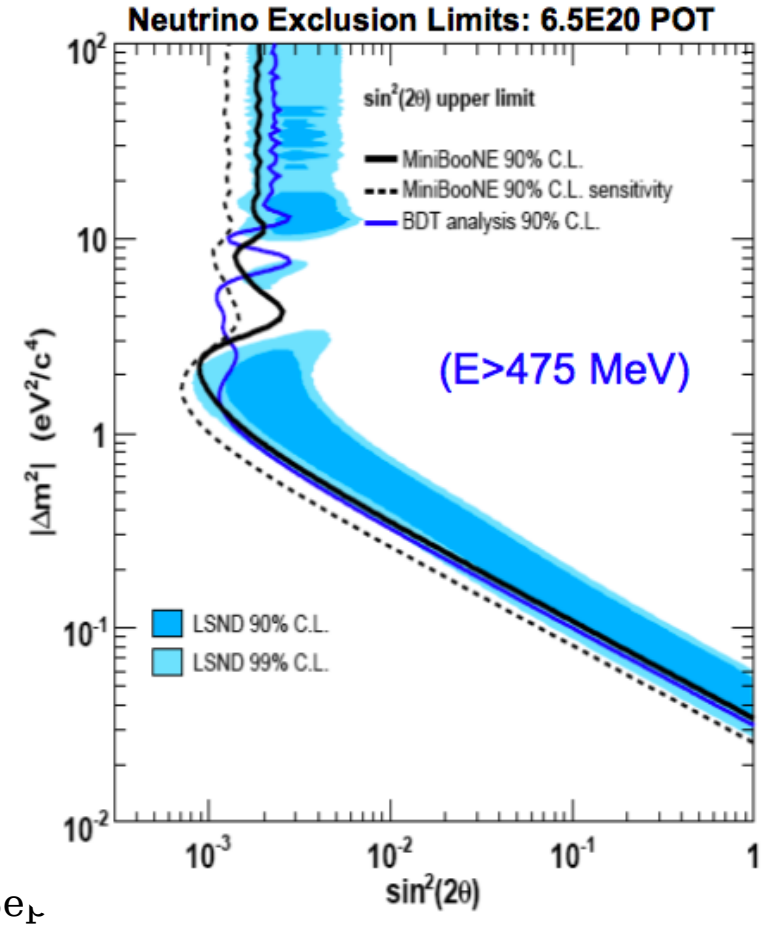


- Dashed pink and blue lines show fit result down to 475 MeV, solid lines extend fit down to 200 MeV
  - Only nubar are assumed to oscillate
  - No inclusion of low-E expectation
  - Large backgrounds in 200-475 means the region carries little weight in the fit
  - Get same result if 12 low E bkg events are added to low E region.

LSND ν_μ result

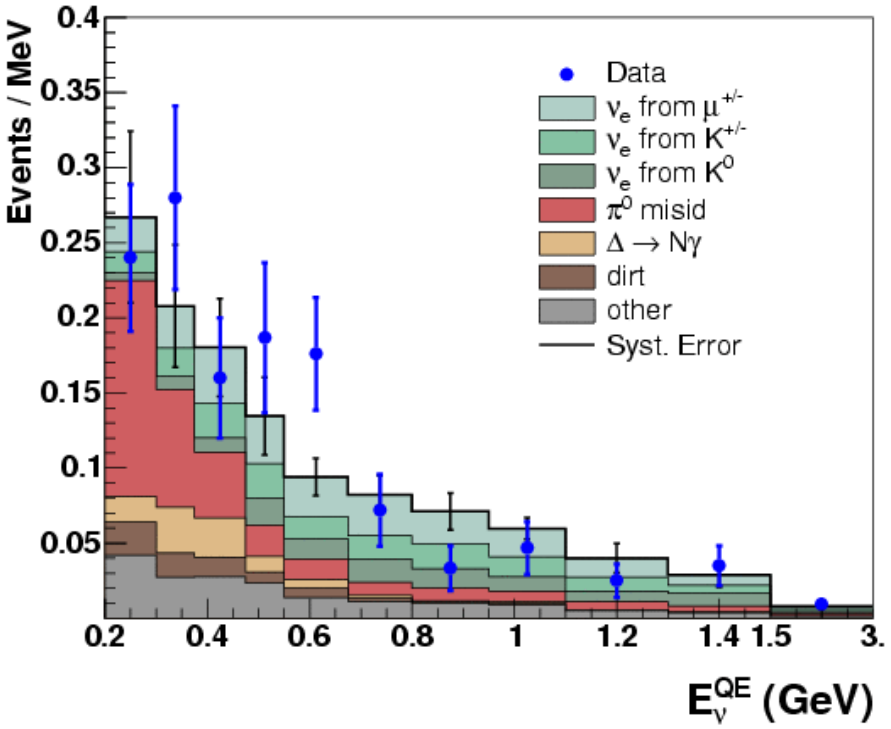


- LSND Found 40 events on a bkg of 21
- Excluded null at just > 2σ
- MB 90CL well within LSND 95CL
- Conclusion…some tension but it will be < 2σ

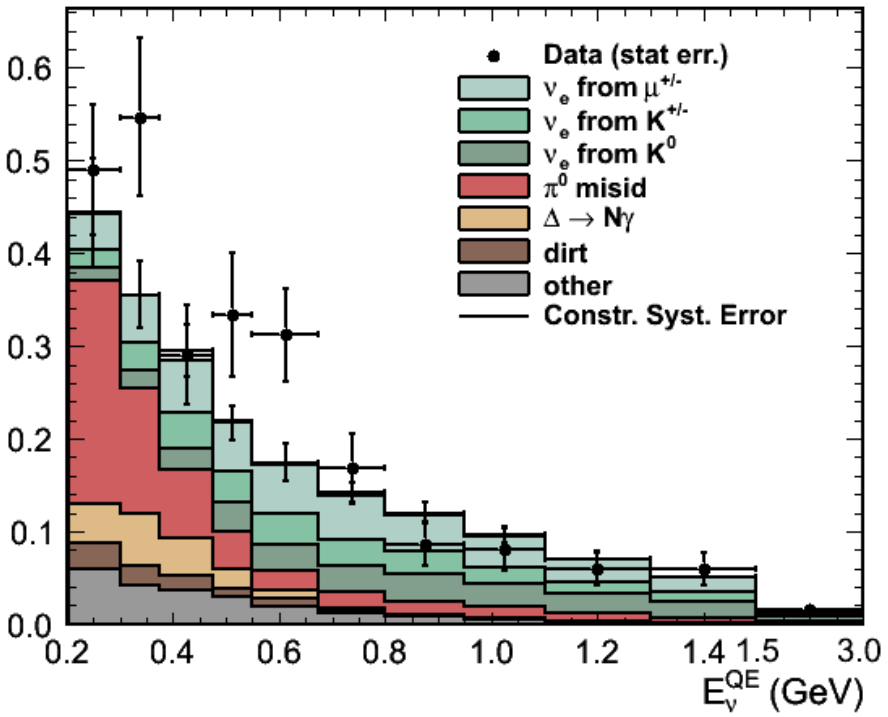


Anti-ν results from 2009 PRL

$\bar{\nu}$ mode 3.4e20 POT

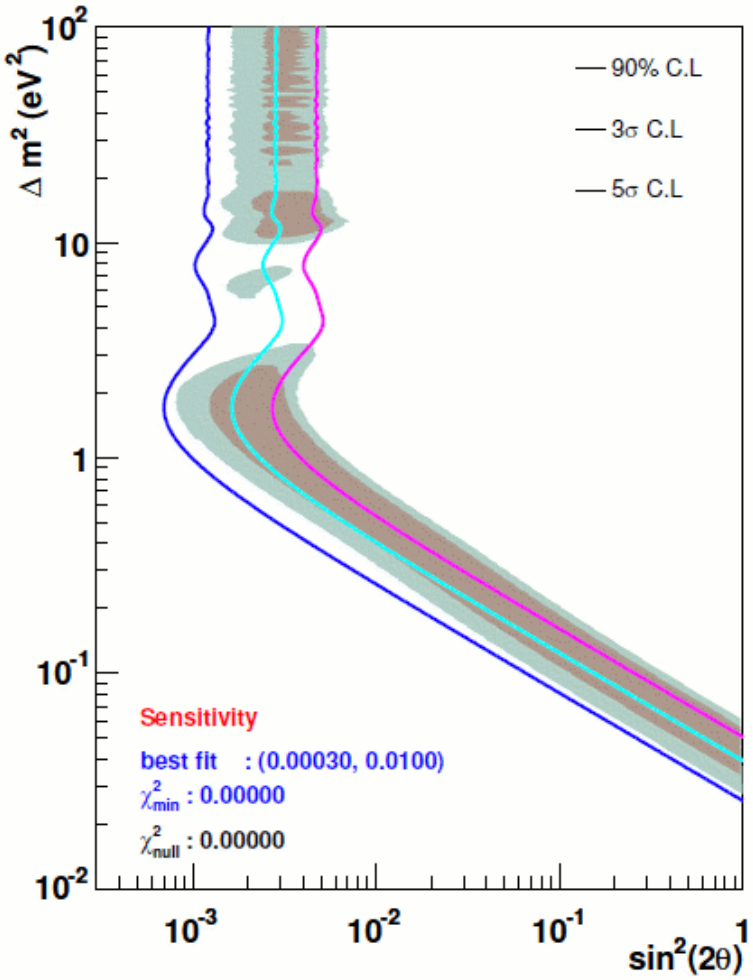


$\bar{\nu}$ mode 5.6e20 POT



- Contrasting neutrino to anti-neutrino
  - Anti-neutrino beam contains a 20% WS background, fits (above 475 MeV) assume only nubar are allowed to oscillate
  - Background composition fairly similar, bkg constraints re-extracted
  - Consistent at 1.5σ level

What if anti-ν best fit was found in ν beam?



BF point would have been 7 sigma signal

2009-2010 MiniBooNE Graduates

- Dissertations
  - Michael Wilking
    "Measurement of Neutrino Induced, Charged Current, Charged Pion Production"
    PhD Thesis, Colorado University, 2009
  - Kendall Mahn
    "A Search for Muon Neutrino and Antineutrino Disappearance with the Booster Neutrino Beam"
    PhD Thesis, Columbia University, 2009
  - Denis Perevalov
    "Neutrino-Nucleus Neutral Current Elastis Interaction Measurement in MiniBooNE"
    PhD Thesis, University of Alabama, 2009
  - Bob Nelson
    "A Measurement of Neutrino-Induced Charged-Current Neutral Pion Production"
    PhD Thesis, University of Colorado, 2010
  - Georgia Karagiorgi
    "Searches for New Physics at MiniBooNE: Sterile Neutrinos and Mixing Freedom"
    PhD Thesis, Massachusetts Institute of Technology, 2010
- Still have 2-3 PhD students finishing anti-neutrino analyses

2009-2010 MiniBooNE Publications

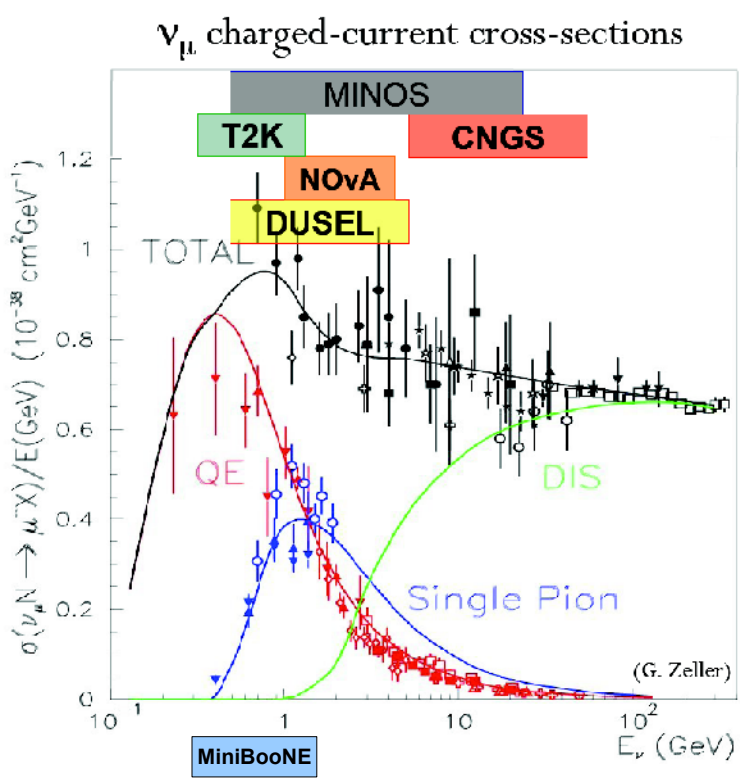
- A.A. Agular-Arevalo et al., Measurement of the Neutrino Neutral-Current Elastic Differential Cross Section, arXiv:1007.4730 [hep-ex], submitted to Phys. Rev. D.
- A.A. Agular-Arevalo et al., Observed Event Excess in the MiniBooNE Search for Muon Antineutrino to Electron Antineutrino Oscillations, arXiv:1007.1150 [hep-ex], submitted to Phys. Rev. Lett., Result of the Week, Press
- A.A. Aguilar-Arevalo et al., First Measurement of the Muon Neutrino Charged Current Quasielastic Double Differential Cross Section, arXiv:1002:2680 [hep-ex], Phys. Rev. D81, 092005 (2010), Result of the Week, Data release
- A.A. Aguilar-Arevalo et al., "Measurement of ν_μ and $\bar{\nu}_\mu$ induced neutral current single π^0 production cross sections on mineral oil at E_ν~O(1 GeV)", arXiv:0911.2063 [hep-ex], Phys. Rev. D81, 013005 (2010), Result of the Week, Data release
- A.A. Aguilar-Arevalo et al., "A Search for Core-Collapse Supernovae using the MiniBooNE Neutrino Detector", arXiv:0910.3182 [hep-ex], Phys. Rev. D81, 032001 (2010), Result of the Week
- A.A. Aguilar-Arevalo et al., "Measurement of the ν_μ CC pi+/QE Cross Section Ratio on Mineral Oil in a 0.8 GeV Neutrino Beam", arXiv:0904.3159 [hep-ex], Phys. Rev. Lett. 103, 081801 (2009)
- A.A. Aguilar-Arevalo et al., "A Search for Electron Anti-Neutrino Appearance at the Δm^2 ~1 eV^2 Scale", arXiv:0904.1958 [hep-ex], Phys. Rev. Lett. 103, 111801 (2009), Result of the Week, Data release
- A.A. Aguilar-Arevalo et al., "A Search for Muon Neutrino and Anti-Neutrino Disappearance in MiniBooNE", arXiv:0903.2465 [hep-ex], Phys. Rev. Lett. 103, 061802 (2009), Data release
- A.A. Aguilar-Arevalo et al., "Unexplained Excess of Electron-Like Events From a 1 GeV Neutrino Beam", arXiv:0812.2243 [hep-ex], Phys. Rev. Lett. 102, 101802 (2009), Data release
- P. Adamson et al., "First Measurement of ν_μ and ν_e Events in an Off-Axis Horn-Focused Neutrino Beam", arXiv:0809.2447 [hep-ex], Phys. Rev. Lett. 102, 211801 (2009)
- A.A. Aguilar-Arevalo et al., "The MiniBooNE Detector", arXiv:0806.4201 [hep-ex], Nucl. Instr. Meth. A599 (2009) 28-46
- A.A. Aguilar-Arevalo et al., "The Neutrino Flux Prediction at MiniBooNE", arXiv:0806.1449 [hep-ex], Phys. Rev. D79, 072002 (2009), Data release

- 12 publications
  - 6 PRL's
  - 5 PRD's
  - 1 NIM

Despite being a small collaboration we continue to maximize the physics potential of the data!

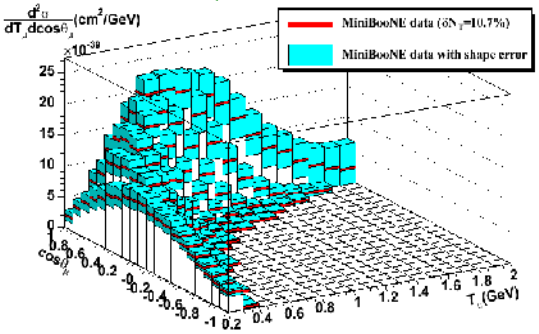
MiniBooNE Cross-Sections

- Two crucial items that make MiniBooNE cross-sections unprecedented
  - Flux determined to 9%, due to dedicated HARP measurement
  - Immense statistics, 500 ton mineral oil target at 500 m

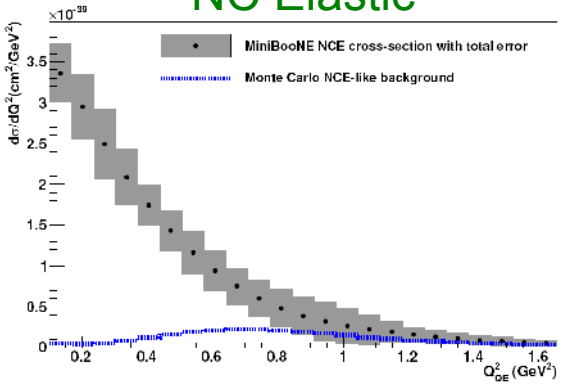


MiniBooNE spans transition region from QE to single-pion, important for osc expts

CC Quasi-Elastic



NC Elastic



CC $^+$/CCQE

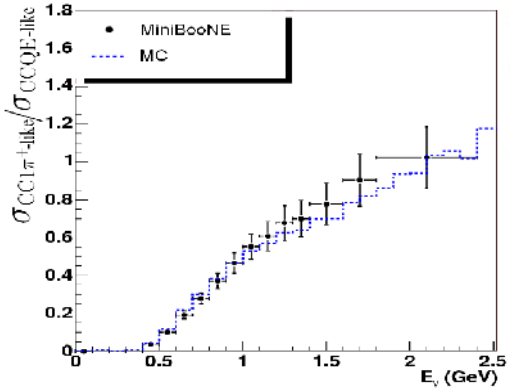
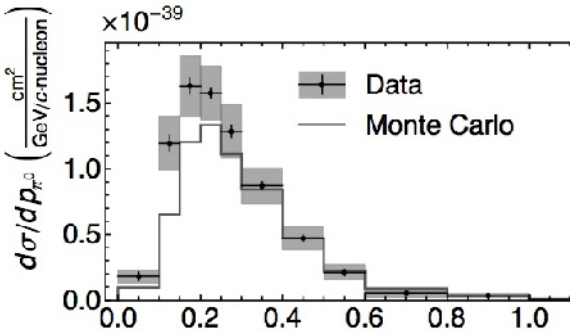


FIG. 1: Observed CC1π^+-like/CCQE-like cross section ratio on CH_2, including both statistical and systematic uncertainties, compared with the MC prediction [6]. The data have not been corrected for hadronic re-interactions.

NC ^{0}



Paper references on pg 4.
Other cross-sections nearing publication CC ^{0}, CC $^+$, and antineutrinos equiv.