Short-baseline Neutrino Oscillations

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Neutrino Oscillation

Sterile neutrinos

ν_e , $\bar{\nu}_e$ appearance results, present and future

ν_μ , $\bar{\nu}_\mu$ disappearance results, present and future

Summary

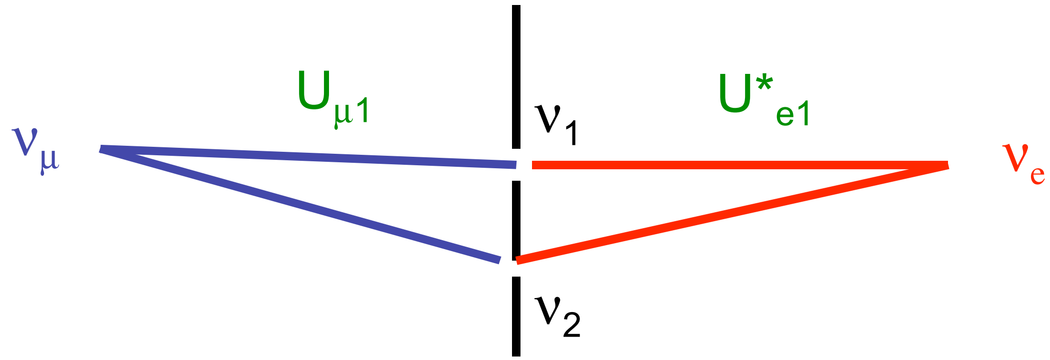
Neutrino Oscillation Intuition

Neutrino oscillation is much like a double slit experiment; the neutrino mass eigenstates propagate differently, and interfere

Given an initial flavor eigenstate of ν_μ, observation some time later will yield a combination which:

1) has maximal ν_e (constructive interference) or
2) has only ν_μ (destructive interference)

The amount of interference is governed by the mixing matrix, U



No mass means no interference is possible

Two-Neutrino Oscillation

If there are just two mass eigenstates, ν_1 and ν_2 and two flavor eigenstates, ν_e and ν_μ, then U is a rotation matrix between mass and flavor:

$$U = \begin{pmatrix} U_{\mu 1} & U_{e1} \\ U_{\mu 2} & U_{e2} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

The probability to observe ν_e with a pure ν_μ sample is:

$$P_{e\to\mu} = |< \nu_e | \nu_\mu(t) >|^2 = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m_{12}^2 L}{E}\right)$$

where L (km) is the distance traveled, E (GeV) is the energy of the neutrino and Δm^2 (eV^2) is the “mass splitting” difference of the masses squared:

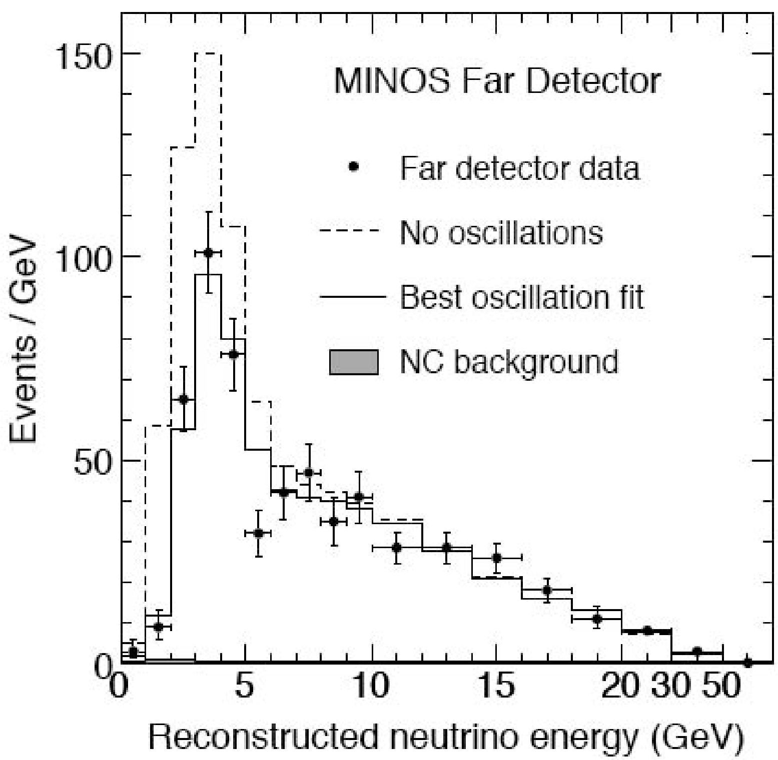
$$\Delta m_{12}^2 = m_1^2 - m_2^2$$

Short baseline (L~1km) vs Long baseline (L~100-1000km) vs Solar (L~1AU)

Disappearance and Appearance Experiments

Neutrino oscillation can be observed via "appearance" or "disappearance"

Disappearance experiment: Detect fewer ν_μ than expected from a ν_μ source
Example: MINOS Experiment (long baseline experiment)
3.6 σ deficit of ν_μ events for $\Delta m^2 \sim 10^{-3} eV^2$, $\theta \sim 45°$



- Signature for neutrino oscillation is a distortion of the neutrino energy spectrum

  Neutrinos at energy E_1 oscillate differently than at E_2 for the same L

- Depends on understanding of ν_μ event rate:

  flux x cross section x efficiency

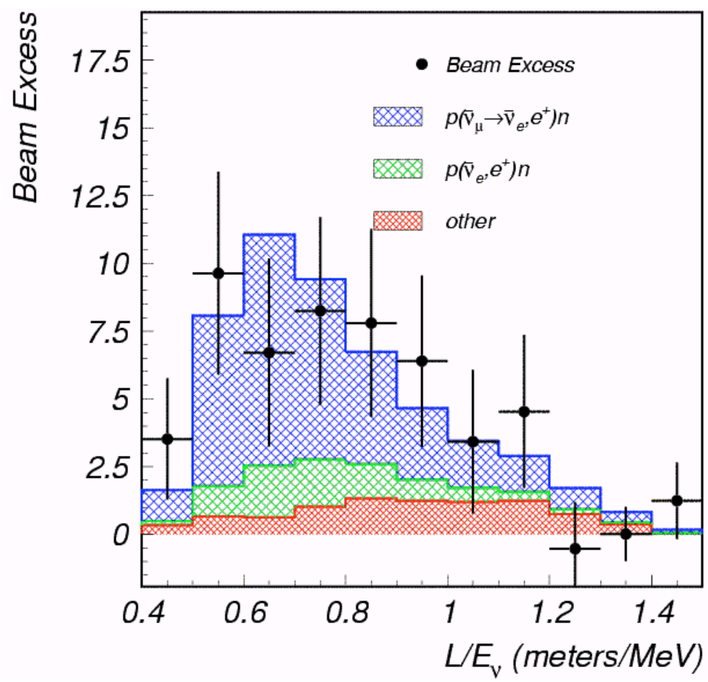
Disappearance and Appearance Experiments

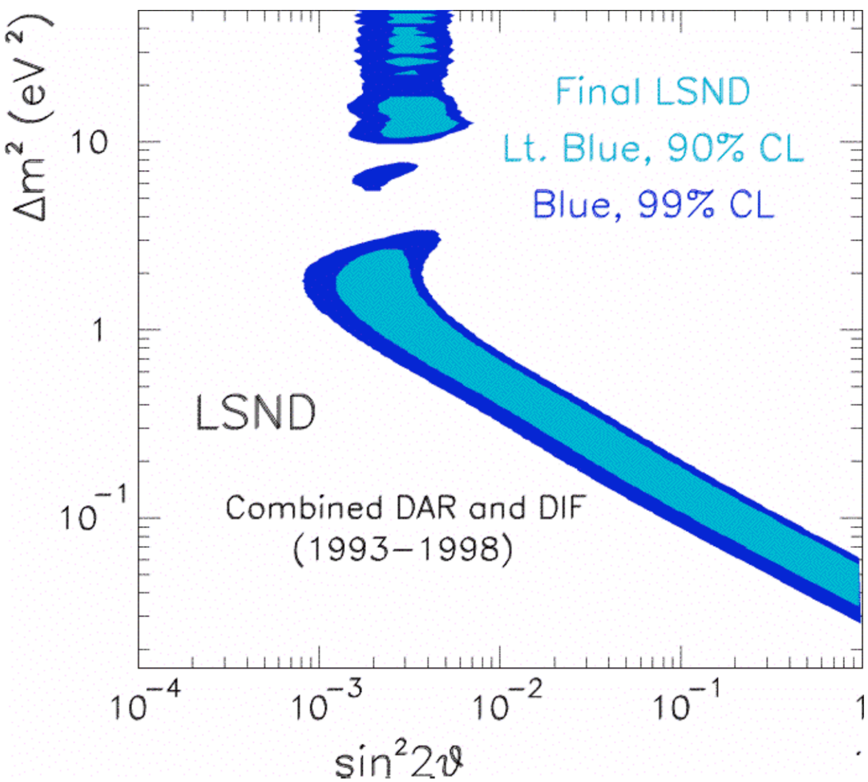
Neutrino oscillation can be observed via "appearance" or "disappearance"

Appearance experiment: Detect more ν_e than expected from a ν_μ source

Example: LSND Experiment

Observation of 3.8 σ excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam, $\Delta m^2 \sim 1 eV^2$, $\theta \sim 1\text{-}10°$





Three-Neutrino Oscillation

Since there are three observed flavors of neutrinos (ν_e, ν_μ, ν_τ), the mixing matrix, U, contains three mixing angles (θ_{12},θ_{23}, θ_{13}) and a CP violating phase δ.

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

$$U_{\alpha i} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

"Atmospheric": $\Delta m^2_{23} \sim 10^{-3} eV^2$, $\theta_{23} \sim 45°$

Observed with atmospheric ν, confirmed with accelerator ν

Recent results (B. Rebel)

"Reactor": $\theta_{13} < 13°$

Not observed yet

Limits from reactors

"Solar": $\Delta m^2_{12} \sim 10^{-5} eV^2$, $\theta_{12} \sim 32°$

Observed with solar ν, confirmed with reactor ν

Recent results (M. Pallavicini)

Three-Neutrino Oscillation

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"Atmospheric": $\Delta m^2_{23} \sim 10^{-3} eV^2$,
$\theta_{23} \sim 45°$

"Solar": $\Delta m^2_{12} \sim 10^{-5} eV^2$,
$\theta_{12} \sim 32°$

There are two independent Δm^2, as $\Delta m^2_{12} + \Delta m^2_{23} = \Delta m^2_{13}$

LSND observed $\Delta m^2 \sim 1 eV^2 >> \Delta m^2_{12} + \Delta m^2_{23}$

Inconsistent with just three mass eigenstates

Sterile Neutrinos

One explanation for the LSND oscillation signal is to add another "sterile" flavor of neutrino (or 2 or N) to the neutrino mixing matrix:

Adding 1 sterile neutrino is 3+1, adding N is 3+N

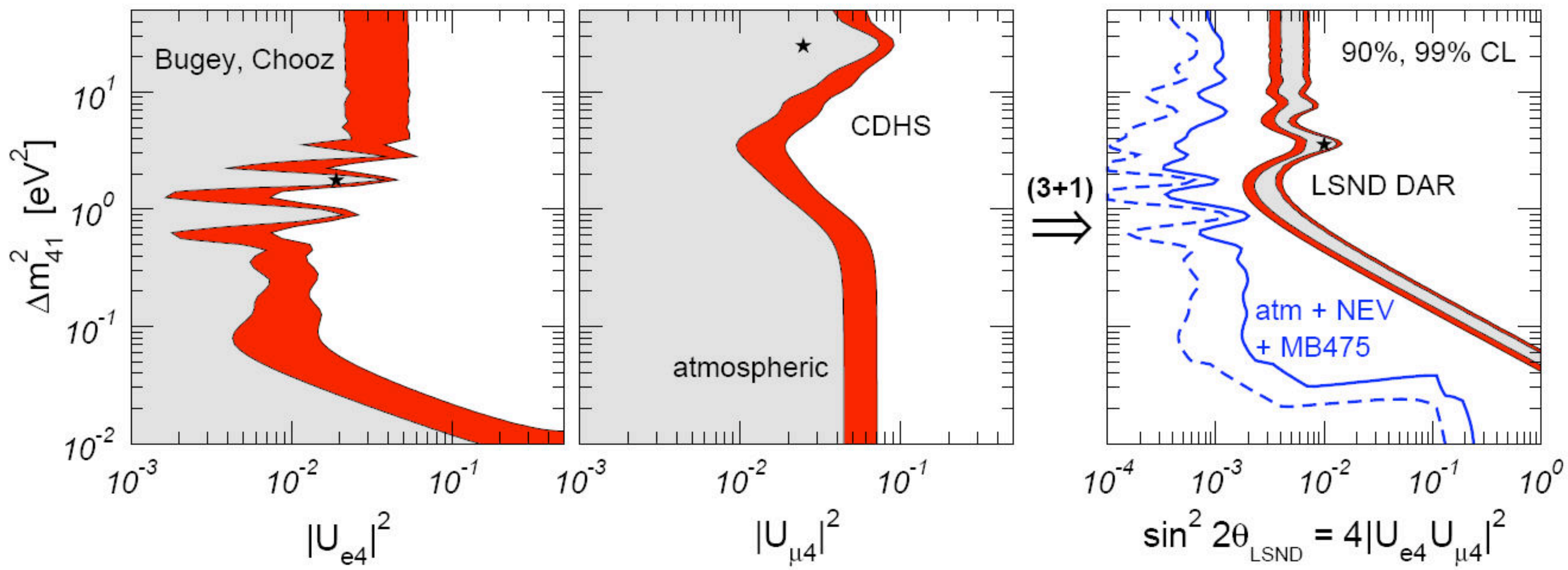
$$U_{\alpha i} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \\ \nu_s \end{pmatrix} \begin{pmatrix} U_{e1} & U_{e2} & \cdots & U_{eN} \\ U_{\mu 1} & U_{\mu 2} & \cdots & U_{\mu N} \\ U_{\tau 1} & U_{\tau 1} & \cdots & U_{\mu N} \\ \vdots & \vdots & \ddots & \vdots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \\ \nu_N \end{pmatrix}$$

Independent of LSND, neutrino oscillation implies non-zero neutrino mass

Most models introduce a right handed neutrino, which by definition would not couple to W, Z and avoid the constraints from LEP

Such neutrinos could interact only via oscillation

Sterile Neutrinos



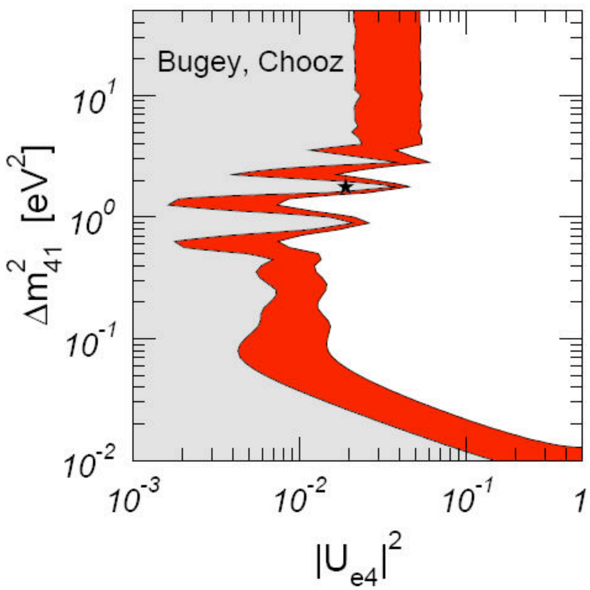
The lack of ν_μ disappearance observed by CDHS and CCFR experiments and the Bugey and Chooz reactor experiments ($\bar{\nu}_e \rightarrow \bar{\nu}_x$) disfavor the addition of 1 sterile neutrino (3+1)

Maltoni, Schwetz, Valle, Phys.Lett.B518:252-260,2001. hep-ph/0107150

Note: $\sin^2 2\theta/4 \sim \sin^2\theta$ for small θ

$\sin^2\theta = |U_{\mu 4}|^2$

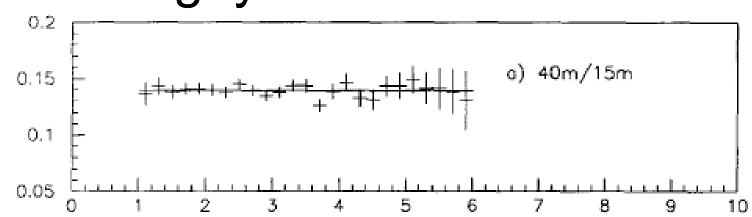
Constraints from Reactors



Previous (single) detector reactor experiments use inverse beta decay to look for energy dependant $\bar{\nu}_e$ disappearance

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$n + p \rightarrow d + \gamma$$

Bugey far/near ratio



E positron (MeV) ~ Eν

Future reactor experiments employ multiple detectors at powerful reactors around the world to measure θ_{13}

RENO (Poster by B.C. Kim) *2 detector sites, 16.4 GW*
Daya Bay (Poster by C.Y. Wang) *3 detector sites, 11.6 GW*
Double Chooz *2 detector sites, 8.5 GW*

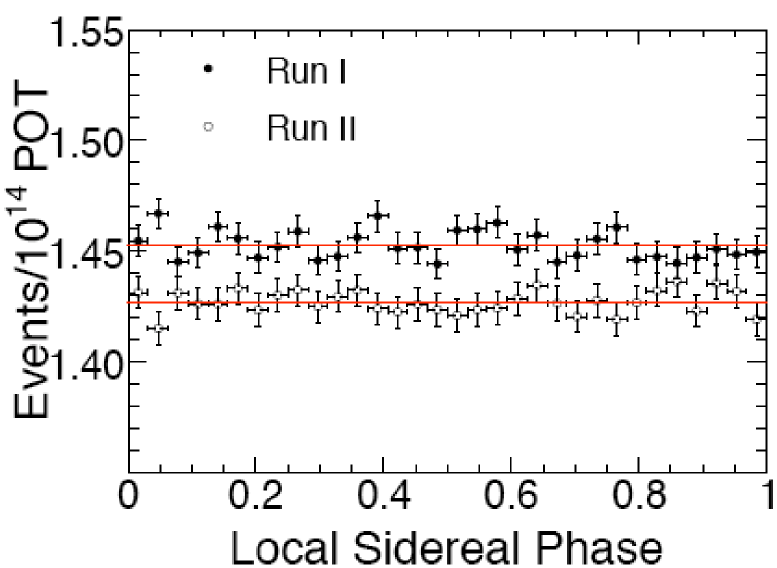
They will also constrain U_{e4}

Constraints from LBL experiments

LBL experiments constrain the sterile content as well

Test of Lorentz Invariance and CPT conservation with Minos near detector

Look for siderial modulation in neutrino rate ⇒ consistent with no modulation



Phys.Rev.Lett.101:151601,2008

Test of active/sterile oscillations at Minos far detector

Check for deficit of NC interactions due to $\nu_\mu \rightarrow \nu_s$ conversion

$$f_s \equiv \frac{P_{\nu_\mu \rightarrow \nu_s}}{1 - P_{\nu_\mu \rightarrow \nu_\mu}} \sim < 50\% \quad (90\%\text{CL})$$

Fraction of sterile neutrinos from ν_μ

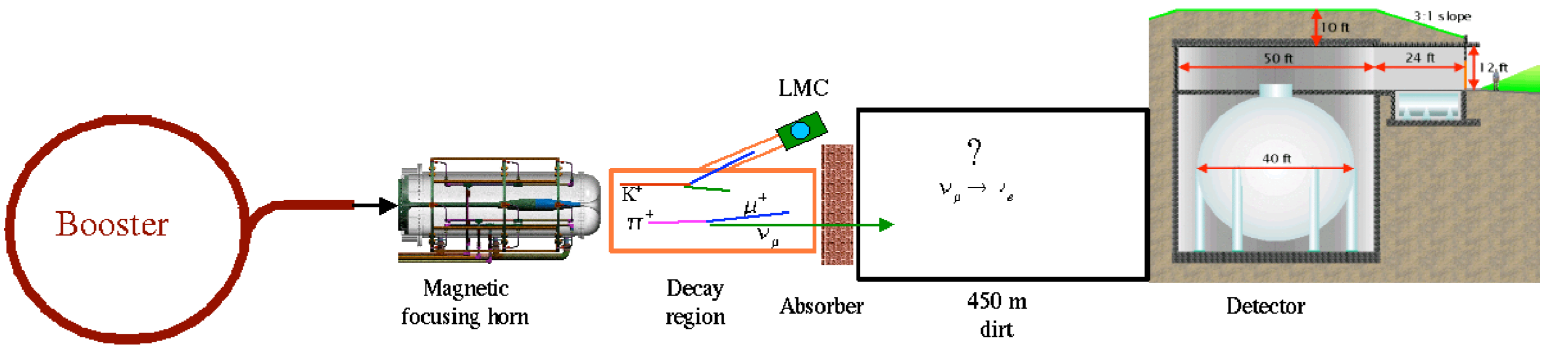
⇒ consistent with no sterile oscillation

Phys.Rev.Lett.101:221804,2008

MiniBooNE Experiment

Similar L/E designed to test LSND-like ν_e appearance

Different event signature and backgrounds than LSND



8.9 GeV/c protons on Be produce mesons which decay to neutrinos (or antineutrinos) detected in a ~1kton mineral oil Cherenkov detector

Changing the polarity of the magnetic horn focuses positive (negative) mesons which decay to produce a beam of neutrinos (antineutrinos)

Since August 2002, MiniBooNE has collected:

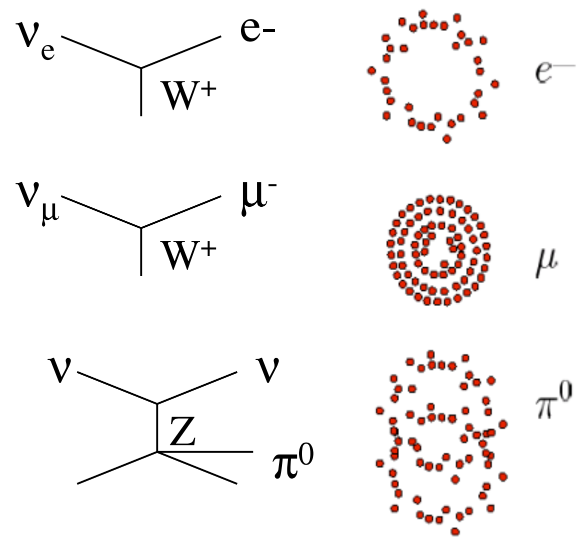
6.5×10^{20} POT (neutrino) fully analyzed

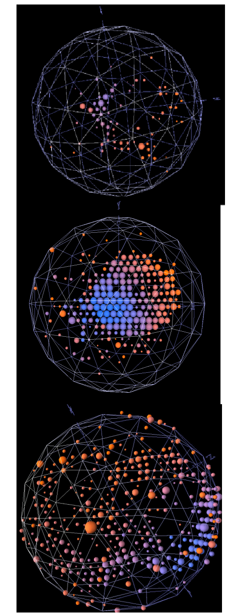
5.1×10^{20} POT (antineutrino) 3.4×10^{20} POT analyzed

Events in MiniBooNE

Use hit topology, timing to determine event type

- Outgoing lepton implies flavor of neutrino for charged current events
- Reconstructed quantities: track length, angle relative to beam direction
- Fundamental: timing, charge of hits, early/late hit fractions
- Geometry: position from wall of tank





Selection of electron-like rings implies electron neutrino candidates, selection of muon-like rings implies muon neutrino candidates

Identical selection for neutrino and antineutrino events

MiniBooNE Oscillation Analyses

Search for ν_e , $\bar{\nu}_e$ appearance

Direct test of LSND observed excess

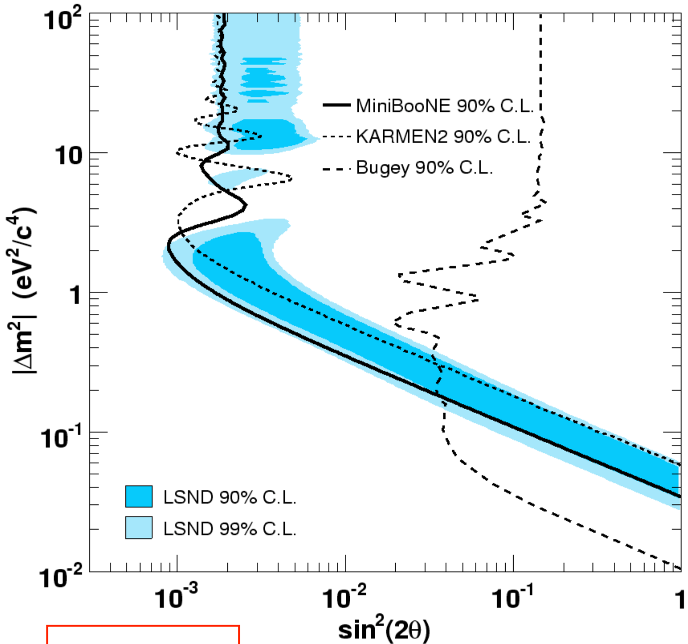
Search for ν_μ , $\bar{\nu}_\mu$ disappearance

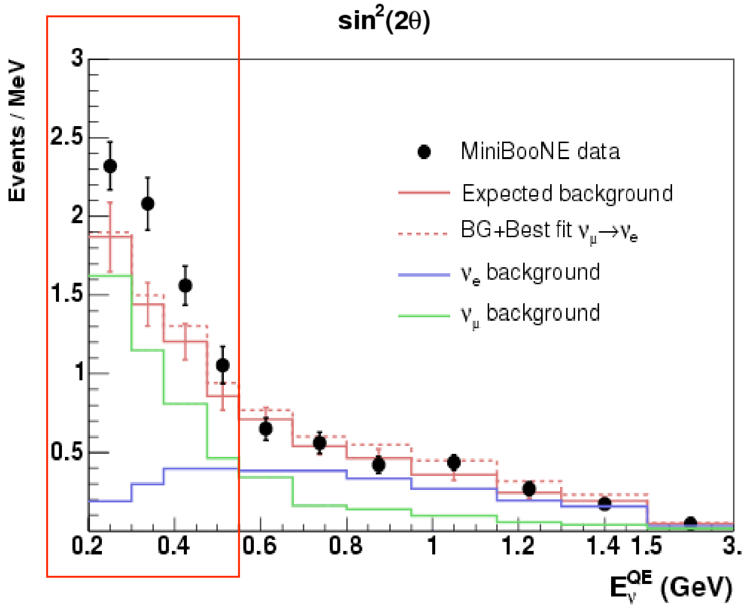
Complementary channel

Constrains sterile neutrino models

The combination of ν and $\bar{\nu}$ results tests unitarity of the mixing matrix, and CPT

MiniBooNE ν_e appearance results





Search for an excess of ν_e events over expected backgrounds

- Beam ν_e from $K^{+/0}$ decay
- Misreconstructed π^0
- Beam ν_e from μ decay

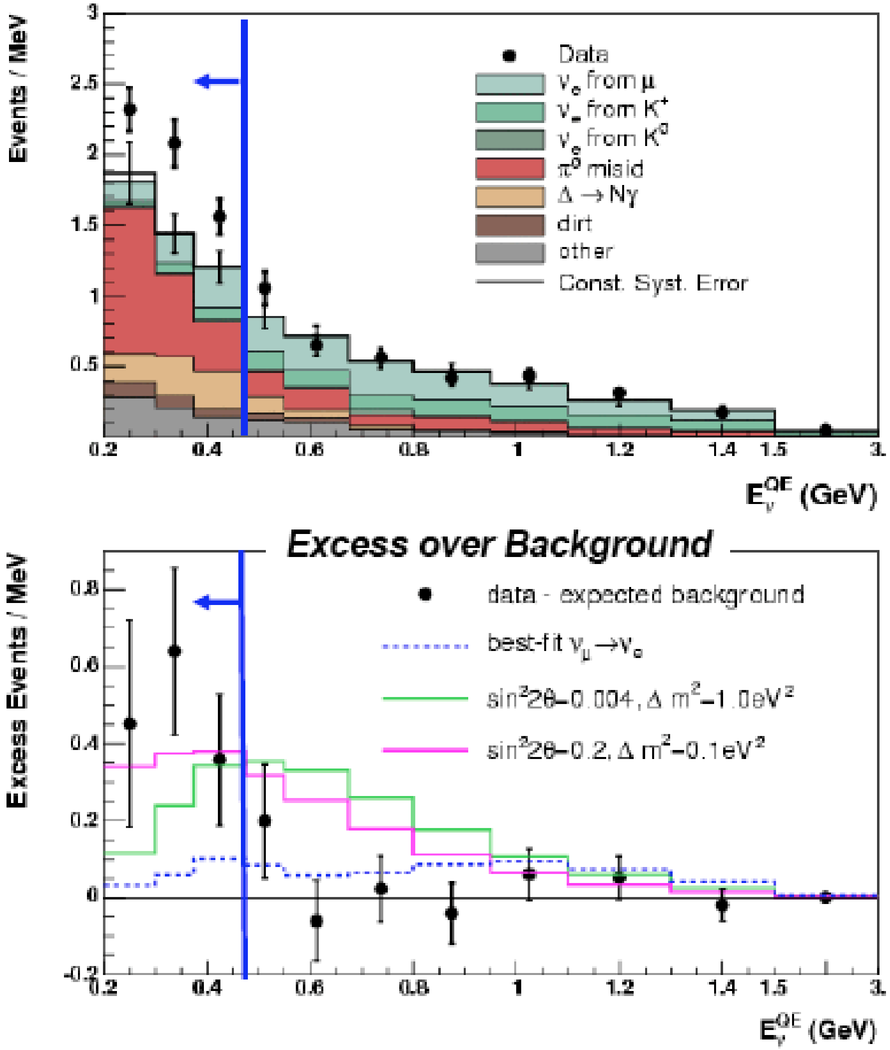
Uncertainties on backgrounds reduced from ν_μ event samples

ν_e sample is consistent with expectation in LSND region E_ν>475 MeV (0.6 σ excess)

- Simple 2 neutrino oscillations excluded at 98% CL *Phys.Rev.Lett.98:231801,2007*

Unexpected excess of events below 475 MeV

Improved ν_e appearance results



For 200-475 MeV:
Excess =128.8+-20.4+-38.3 (3.0σ)

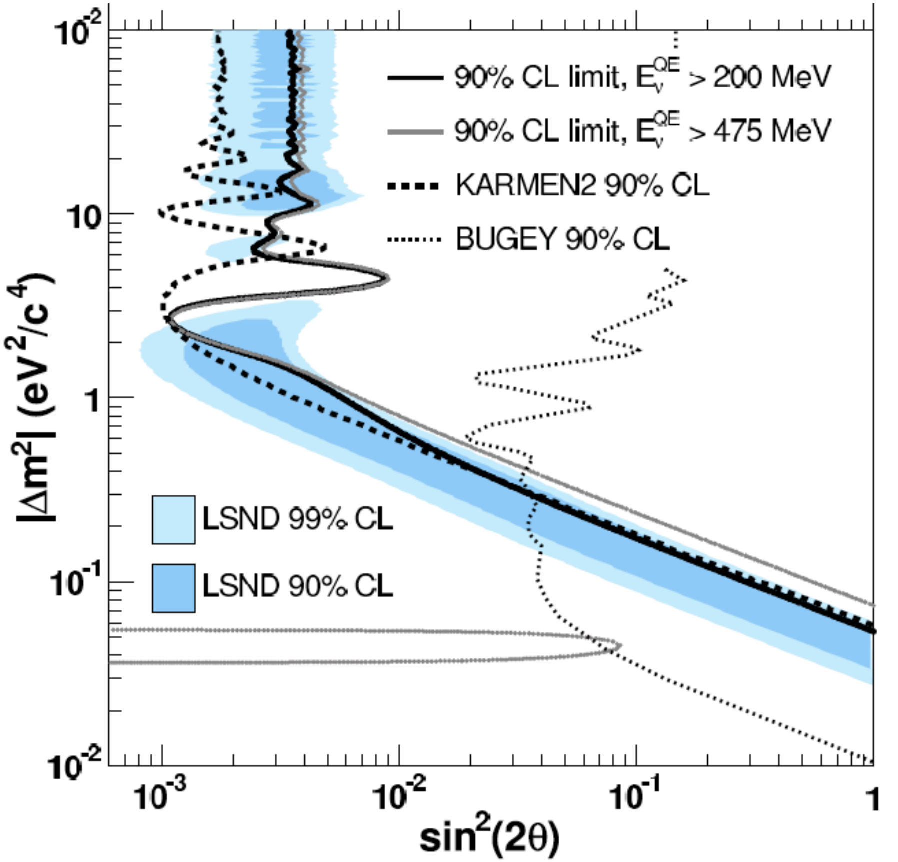
Extensive checks and additions to analysis

1) Improved π^0 prediction
2) Additional "photonuclear" absorption background included
3) Improved analysis cuts to reduce backgrounds further
4) Increased statistics
   5.6 ⇒ 6.5x10^{20} POT

Excess reduced but still present (3.0 σ)

Phys.Rev.Lett.102:101802,2009

MiniBooNE $\bar{\nu}_e$ appearance results



$\bar{\nu}_e$ appearance tests LSND and shares many of the same backgrounds as ν_e appearance at low energy

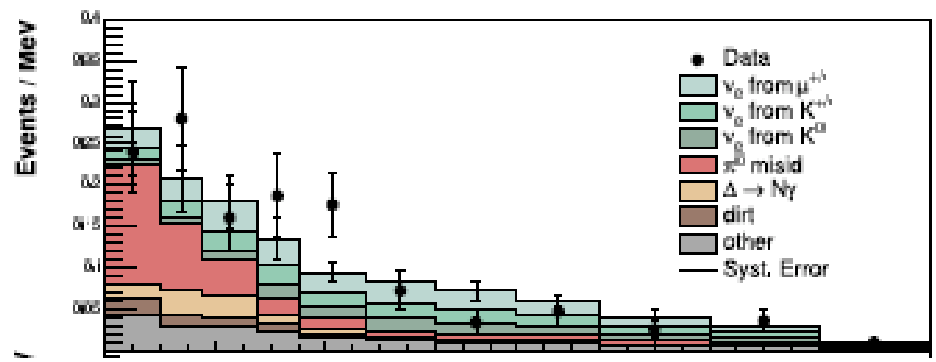
First result (3.4×10^{20} POT) has low statistics

- Both LSND best fit and no-oscillations are allowed ⇒ inconclusive

Additional data will help reduce substantial statistical uncertainties on $\bar{\nu}_e$ sample

But still a surprise, no indication of a low energy excess

arXiv:0904.1958, accepted by PRL



Reconstructed Eν (MeV)

Low energy excess with ν_e / $\bar{\nu}_e$

To explain the low energy excess in neutrino mode, one would need to increase backgrounds substantially

Difficult to do, most backgrounds are constrained and should be the same in neutrino/antineutrino samples

Maximum χ^2 probability from fits to ν and $\bar{\nu}$ excesses in 200-475 MeV range

	Stat Only	Correlated Syst	Uncorrelated Syst
Same $\nu,\bar{\nu}$ NC	0.1%	0.1%	6.7%
NC π^0 scaled	3.6%	6.4%	21.5%
POT scaled	0.0%	0.0%	1.8%
Bkgd scaled	2.7%	4.7%	19.2%
CC scaled	2.9%	5.2%	19.9%
Low-E Kaons	0.1%	0.1%	5.9%
ν scaled	38.4%	51.4%	58.0%

Preliminary

Correlated systematic uncertainties between ν / $\bar{\nu}$ in progress

Most compatible background to match low energy excess is one which scales with neutrinos but not antineutrinos

Low energy excess with ν_e / $\bar{\nu}_e$

Theoretical models are also, similarly, disfavored if they link neutrinos and antineutrinos

Possible explanation	Status
Anomaly Mediated Neutrino-Photon Interactions: *Harvey, Hill, & Hill, arXiv: arXiv:0905.029*	Disfavored
CP-Violation 3+2 Model: *Maltoni & Schwetz, arXiv:0705.0107; T. Goldman, G. J. Stephenson Jr., B. H. J. McKellar, Phys. Rev. D75 (2007) 091301.*	Possible
Lorentz Violation: *Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009*	Possible
CPT Violation 3+1 Model: *Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303*	Possible
VSBL Electron Neutrino Disappearance: *Giunti and Laveder arXiv:0902.1992*	Disfavored
New Gauge Boson with Sterile Neutrinos: *Ann E. Nelson & Jonathan Walsh, arXiv:0711.1363*	Disfavored

Events from NuMI in MiniBooNE

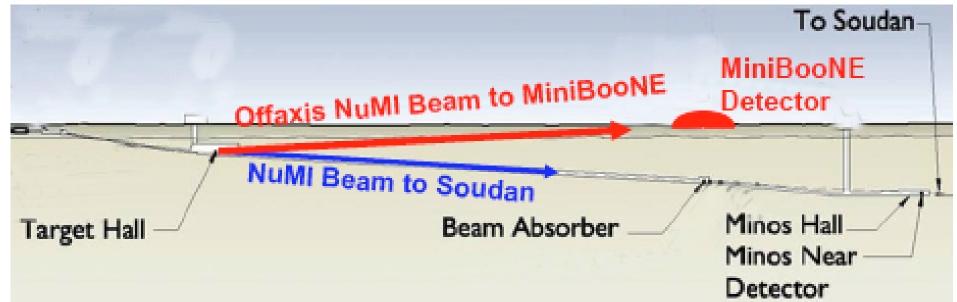
MiniBooNE sees neutrinos from the Minos (NuMI) beam at an angle of 110 mrad off-axis

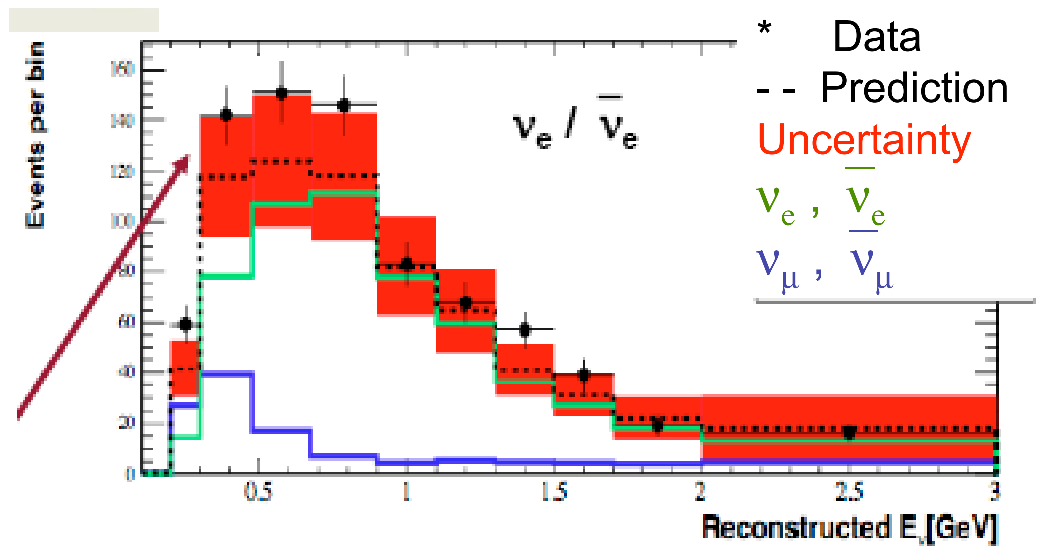
Similar L/E as MiniBooNE from production, different flux

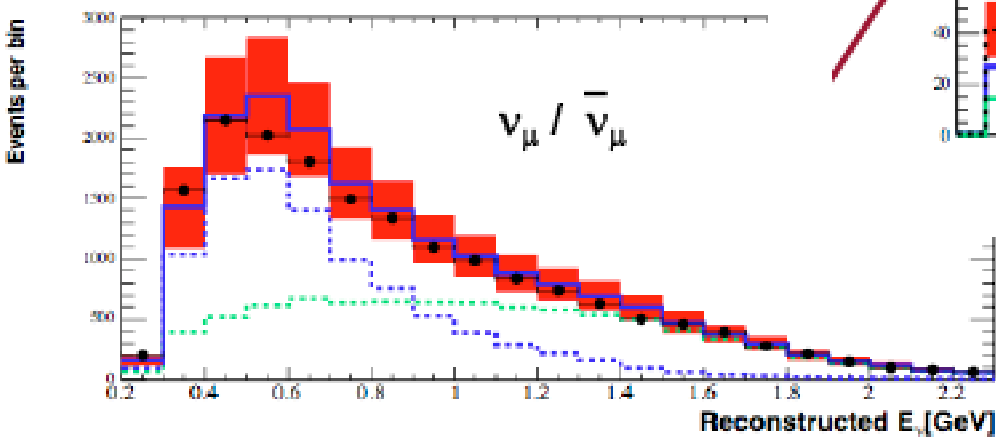
ν_μ events from π, K

ν_e predominantly from $K^{+/0}$

Analysis in progress to constrain uncertainties on ν_e from ν_μ sample







MiniBooNE Oscillation Analyses

Search for ν_e , $\bar{\nu}_e$ appearance

Direct test of LSND observed excess

Search for ν_μ , $\bar{\nu}_\mu$ disappearance

Complementary channel

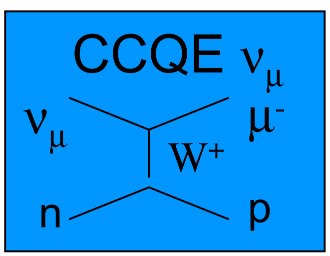
Constrains sterile neutrino models

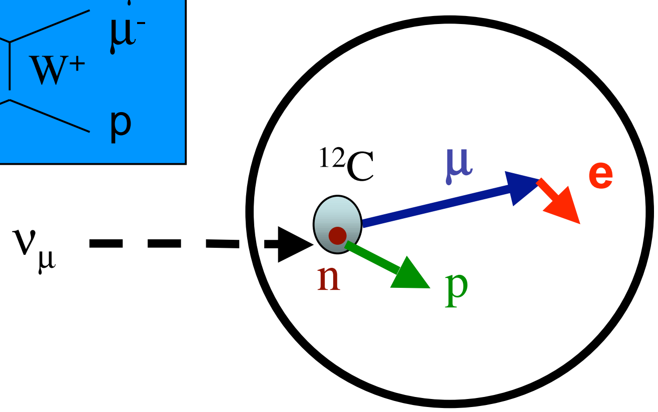
The combination of ν and $\bar{\nu}$ results tests unitarity of the mixing matrix, and CPT

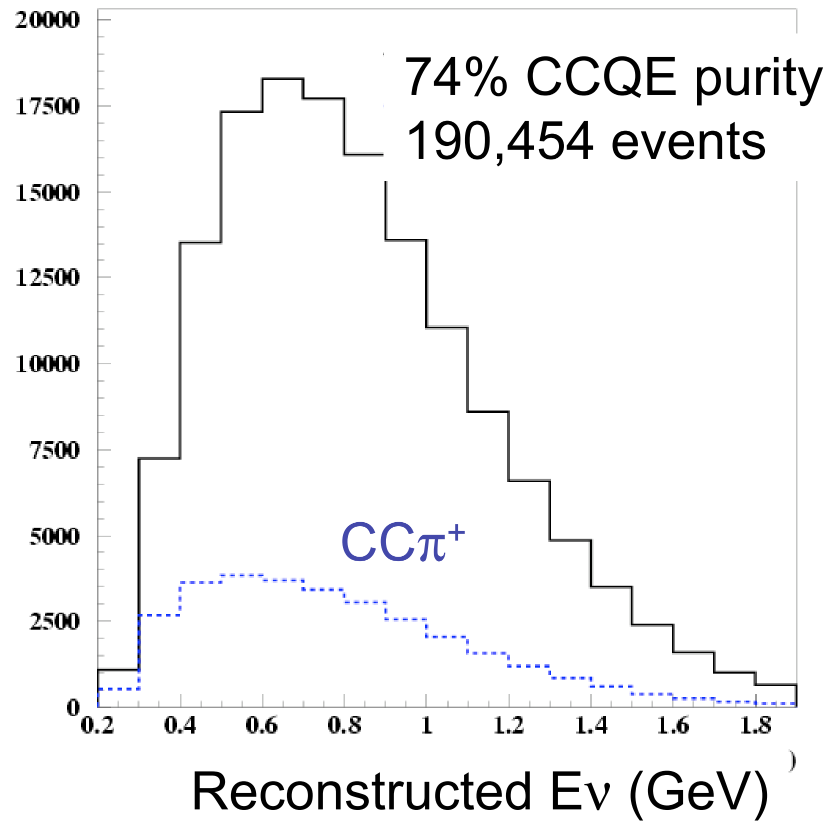
MiniBooNE ν_μ disappearance

Method: Compare for ν_μ / $\bar{\nu}_\mu$ sample to expectation

Selection of ν_μ candidates:
Tag single muon events and their decay electron
Background is $CC\pi^+$ where the pion is absorbed in nucleus or detector







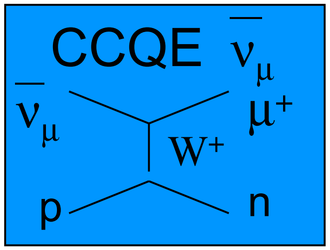
MiniBooNE $\bar{\nu}_\mu$ disappearance

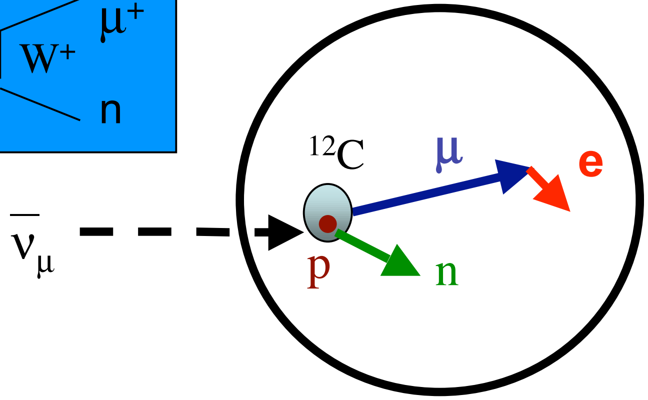
Method: Compare ν_μ / $\bar{\nu}_\mu$ sample to expectation

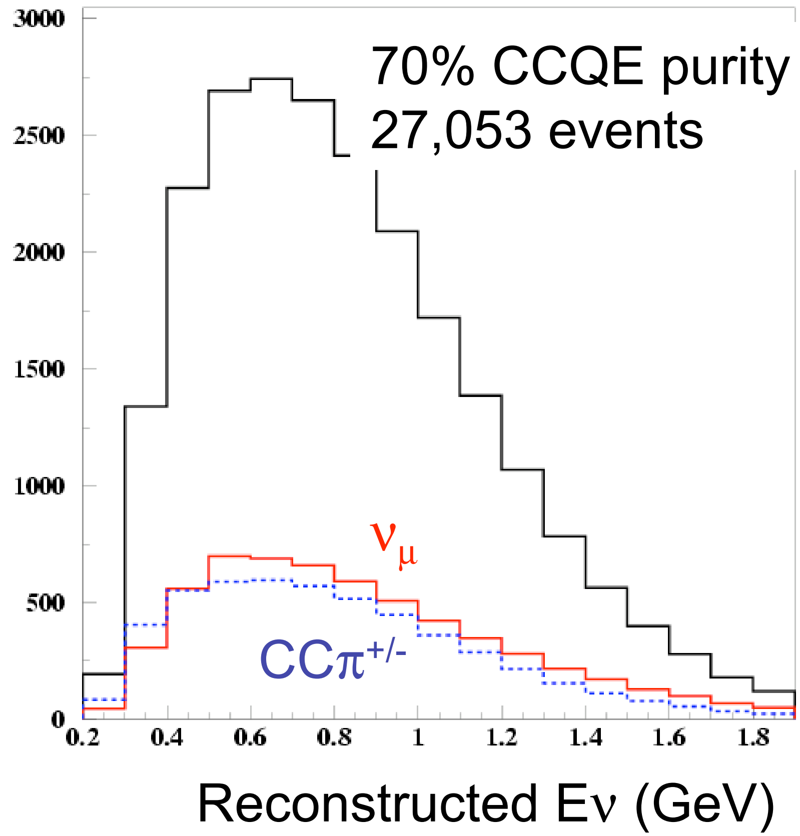
Apply same CCQE selection to antineutrino dataset

Similar $CC\pi^{+/-}$ background, and CCQE purity as in neutrino mode

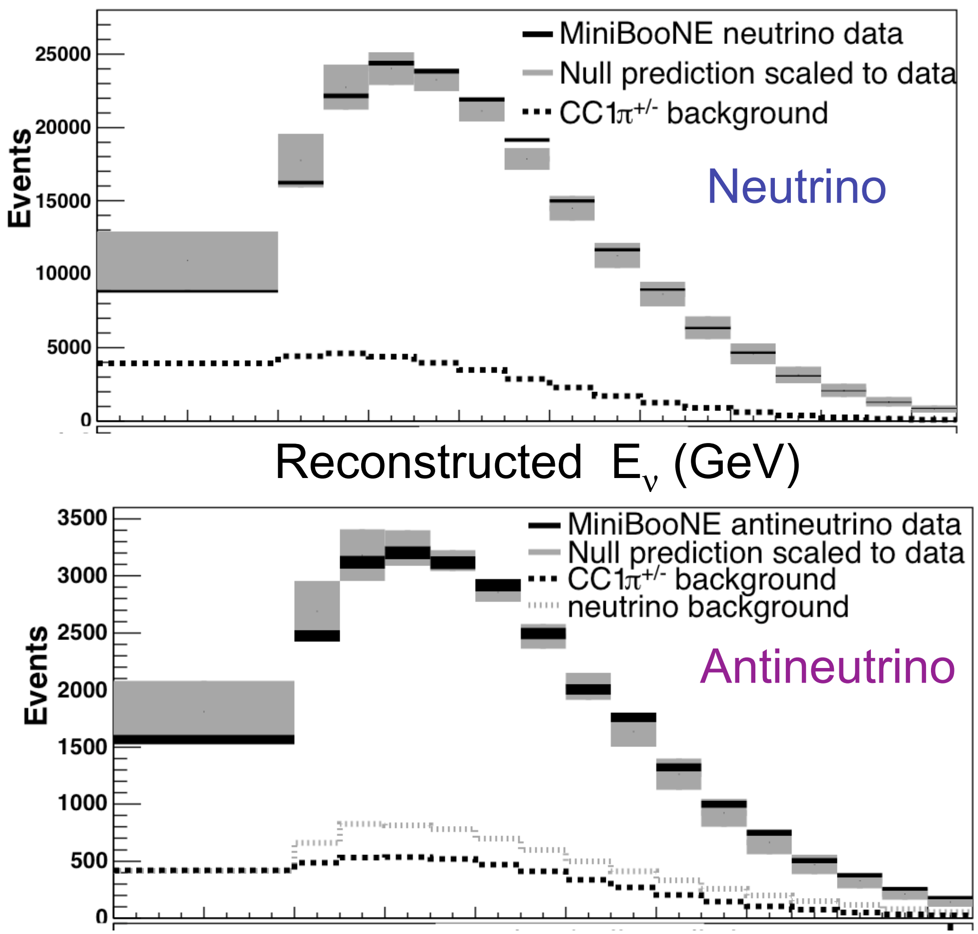
Substantial neutrino events in the antineutrino sample (~25%)

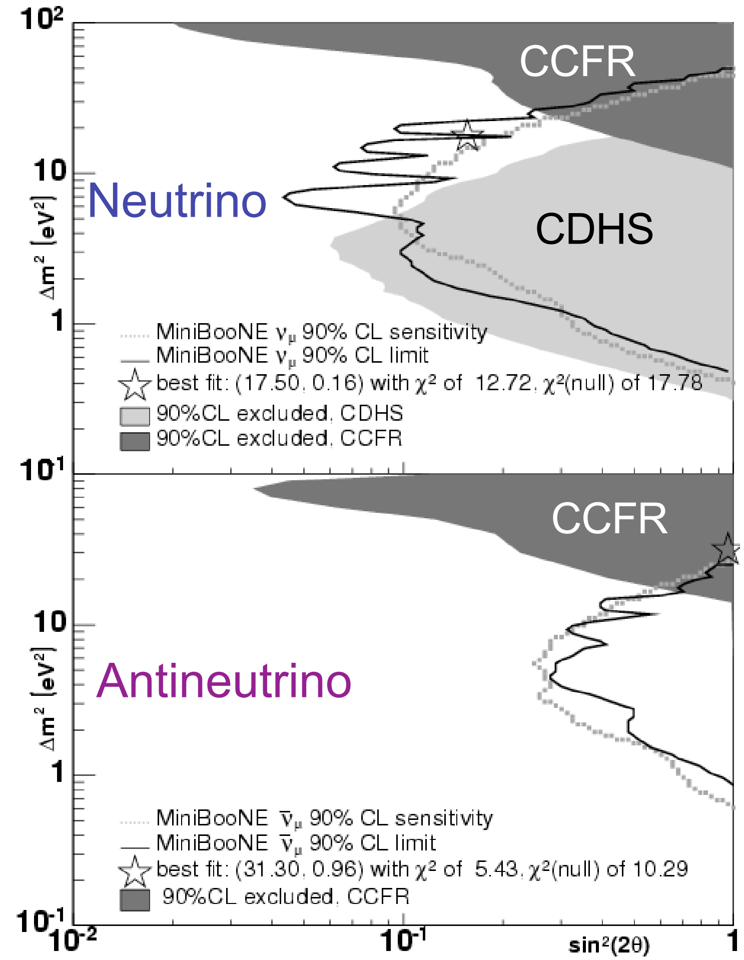






ν_μ and $\bar{\nu}_\mu$ disappearance results





MiniBooNE observes no evidence for neutrino or antineutrino disappearance at 90%CL

Neutrino data excludes some 3+2 models

Phys. Rev. Lett. 103, 061802 (2009)

Future disappearance results

Future work will incorporate data from a second detector, SciBooNE

In 2007, a dedicated cross section experiment, SciBooNE, was put in the MiniBooNE beam

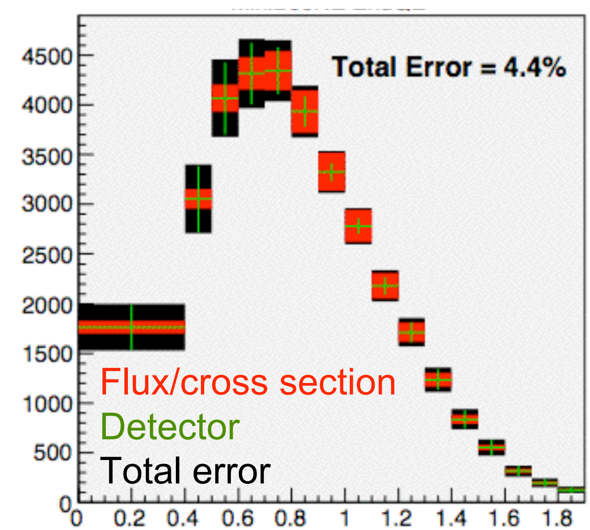
Recent results (M. Yokoyama)

SciBooNE shares the same flux and detector composition as MiniBooNE (carbon)

Use SciBooNE to constrain MiniBooNE rate

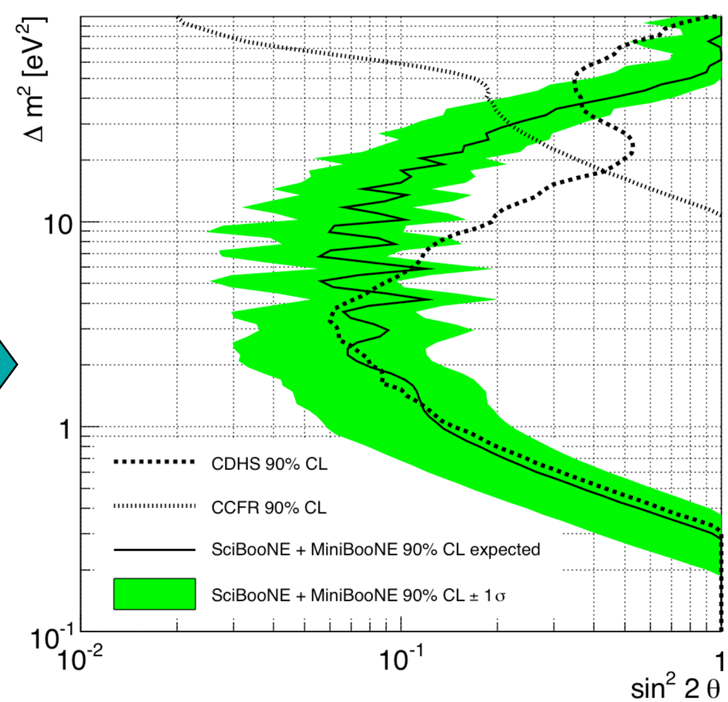
(Poster, Y. Nakajima)

MiniBooNE ν_μ sample w/ SciBooNE constraint



Reconstructed E_ν (GeV)

Preliminary



Summary and Future

Hard to accommodate sterile neutrinos with 3+2 models and existing neutrino/antineutrino disappearance and appearance data

G. Karagiorgi et al, arXiv.org: hep-ph 0906.1997

- Correlated MiniBooNE ν_e , $\bar{\nu}_e$ appearance analysis in progress
- Joint NuMI ν_e analysis with new ν_μ constraint

However, agreement among antineutrino experiments only is high.

Direct tests in both antineutrino appearance and disappearance channels

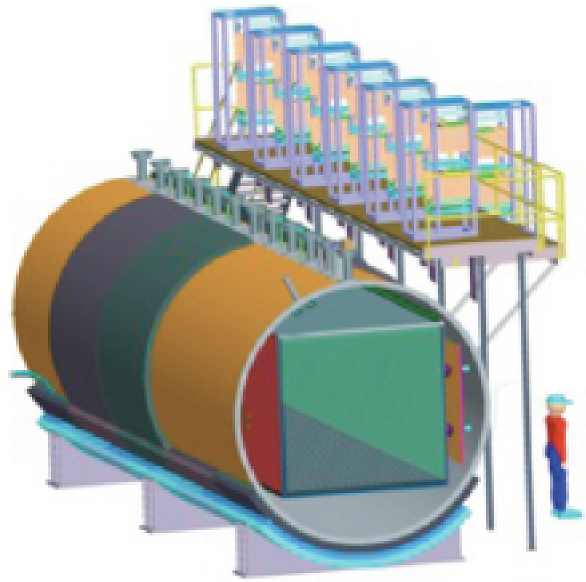
- Joint MiniBooNE/SciBooNE ν_μ , $\bar{\nu}_\mu$ disappearance analysis

- Extended $\bar{\nu}$ running planned for MiniBooNE
  - Approved for ~10x10^{20} POT run with intermediate result with 5x10^{20} POT dataset

Complementary future endeavors

New MicroBooNE experiment approved

- ~70 ton fiducial volume Liquid Argon TPC placed near MiniBooNE
- TPC development combined with physics goal of understanding low energy excess
  - Reduced backgrounds
  - Can distinguish if excess is photon or electron in nature
  - First data ~2012



Far-term future possibilities

Extension of MiniBooNE (BooNE)

Move MiniBooNE to 200 m in beamline (~$4M) or
build a second detector there (~$8M)
Cancel many uncertainties between near, far detectors

Alternate method to study sterile neutrinos:

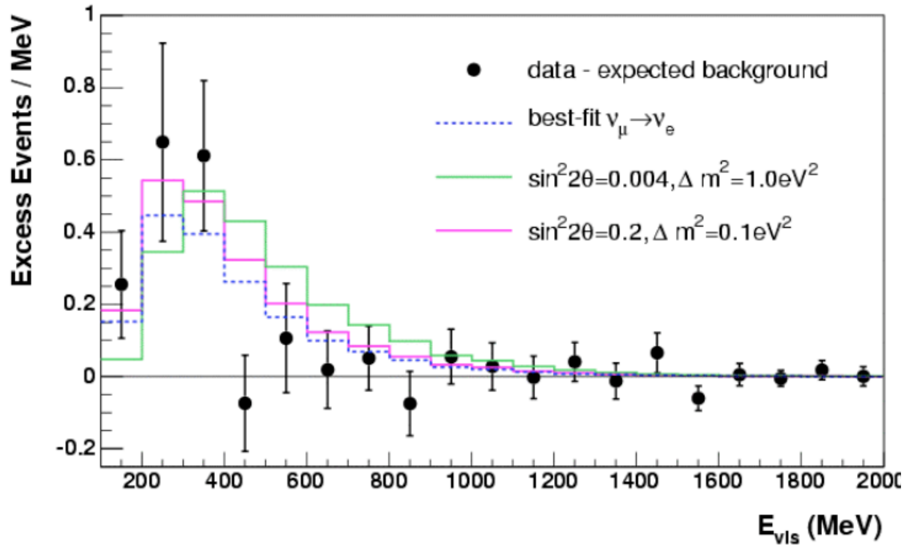
low energy beta beam $\bar{\nu}_e$ disappearance

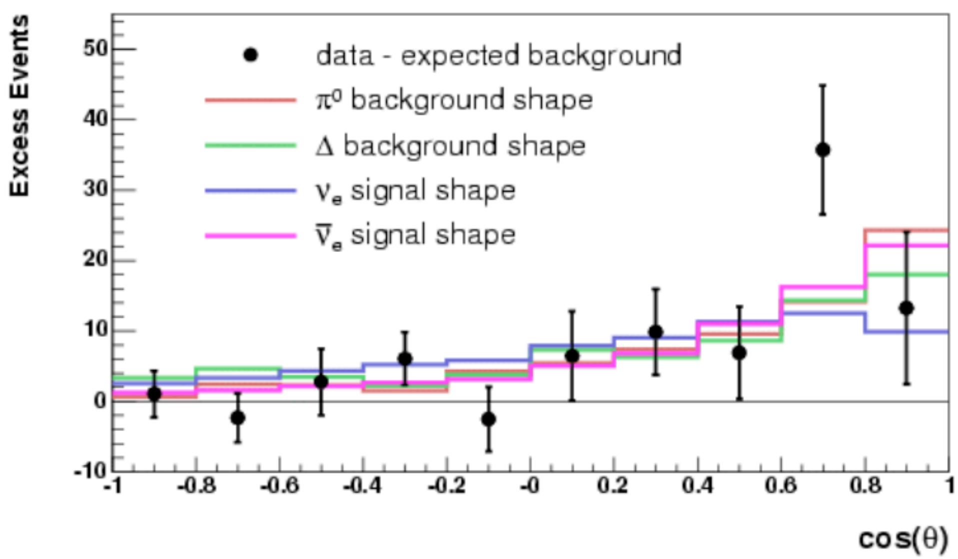
Agarwalla, Huber, Link, arXiv.org: hep-ph 0907.3145

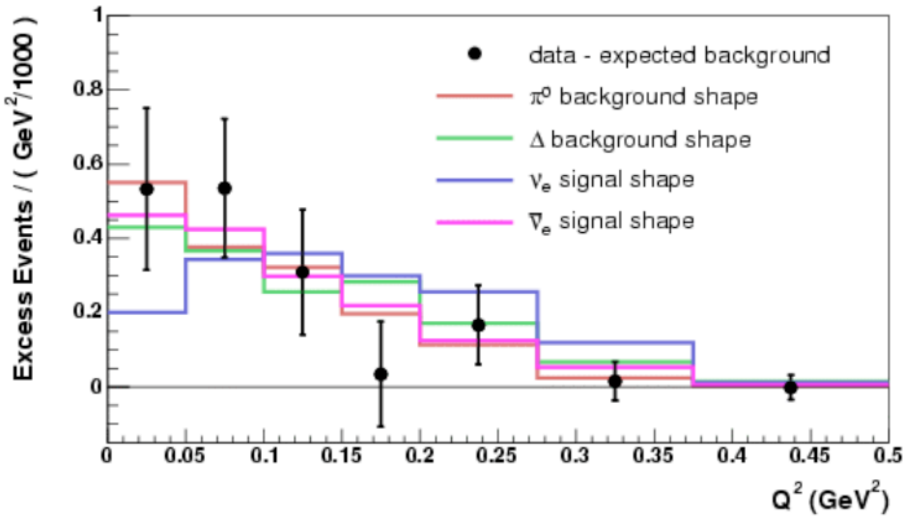
Disappearance channel with inverse beta decay
Different systematics
Would require ~100ton detector and
ion production rates of ~2×10^{13} / s

Thanks to the organizers and local committee for a wonderful conference!

Excess in different kinematic variables







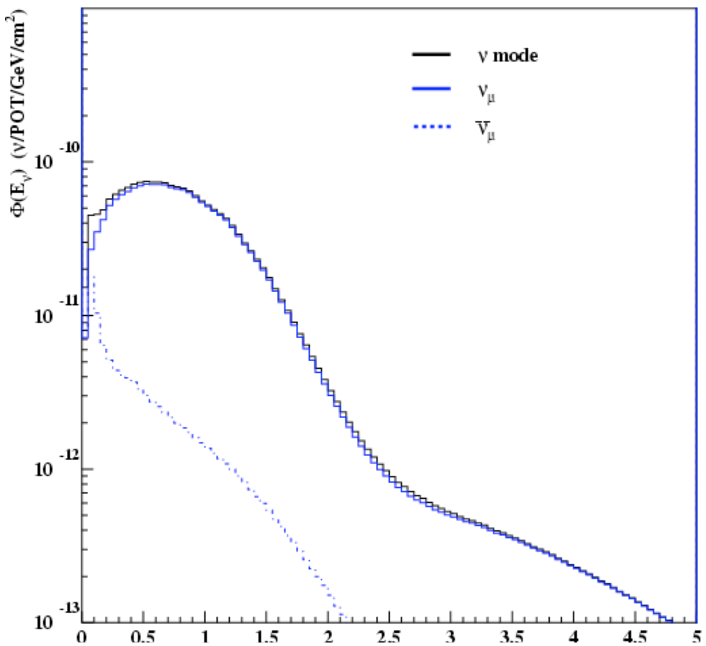
χ^2 Values from Data/MC Comparisons

Process	$\chi^2(\cos\theta)$/9 DF	$\chi^2(Q^2)$/6 DF	Factor Inc.*
NC π^0	13.46	2.18	2.0
$\Delta \to N\gamma$	16.85	4.46	2.7
ν_e C -> e^- X	14.58	8.72	2.4
$\bar{\nu}_e$ C -> e^+ X	10.11	2.44	65.4

* Any background would have to increase by $>5\sigma$!

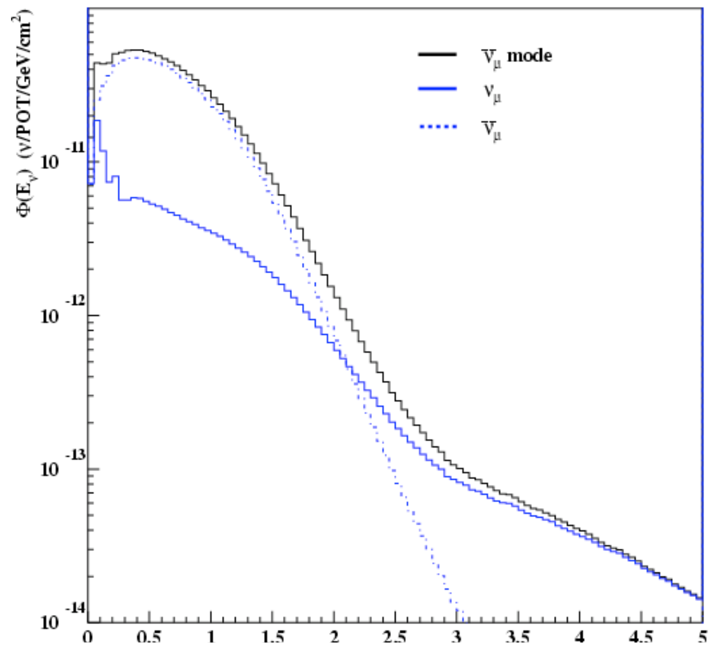
Flux at MiniBooNE

Neutrino mode



neutrino energy (Eν) in GeV

Antineutrino mode



neutrino energy (Eν) in GeV

Predominantly ν_μ

- ~6% $\bar{\nu}_\mu$
- ~0.5% $\nu_e + \bar{\nu}_e$

Substantial ν_μ background

- ~16% ν_μ
- ~0.6% $\nu_e + \bar{\nu}_e$

All details of the beamline geometry are modeled

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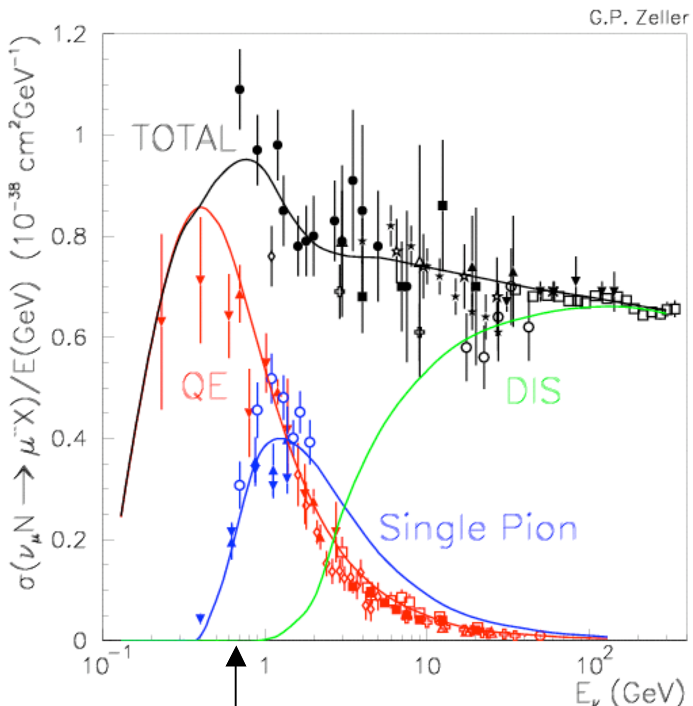
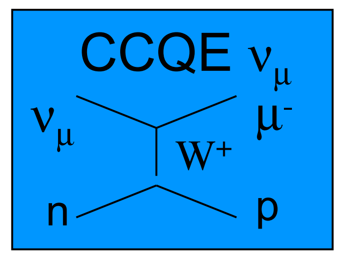
Neutrino Interactions at ~1 GeV

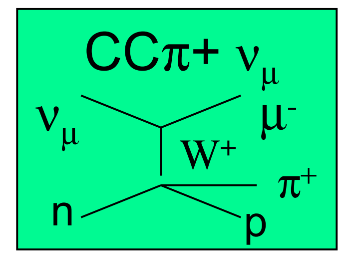
World's data on
GeV neutrino cross sections



mean
flux Eν (0.8 GeV)

At 1 GeV, neutrinos interact via
- CCQE (quasi-elastic scattering)
- CCpi+ (single pion production)





In CCQE interactions, the muon's energy (E_μ), and angle (θ_μ) are sufficient to reconstruct the neutrino energy:

$$E_\nu(QE) = \frac{m_N E_\mu - \frac{1}{2} m_N{}^2}{p_\mu \cos\theta_\mu + m_N - E_\mu}$$

where m_N is the mass of the nucleon