Short-baseline neutrinos

Recent results and future prospects

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XXVIII Physics In Collision
June 2008

Neutrino Oscillations

- non-zero neutrino mass allows for lepton flavor changing physics
- mass eigenstates ≠ flavor eigenstates: $$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$ $\alpha = (e, \mu, \tau)$
- flavor composition of the neutrino can change as it propagates:

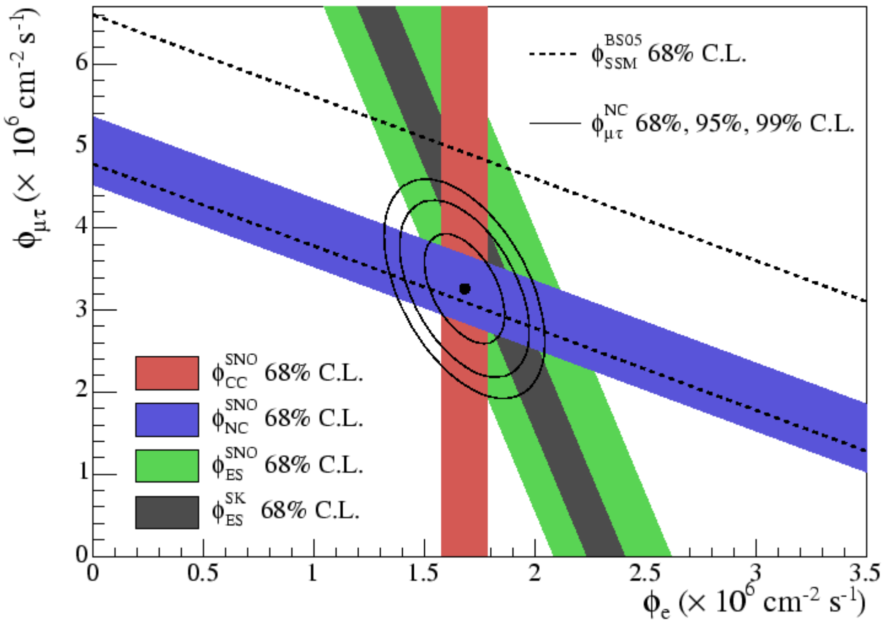
$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(L)\rangle|^2$$

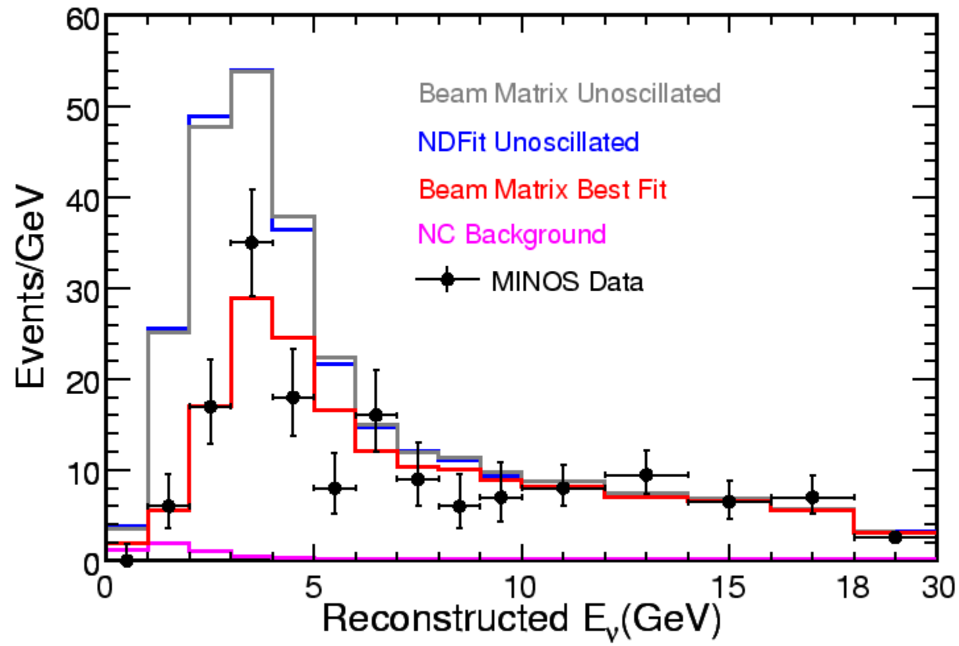
$$= \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin^2[1.27\Delta m^2_{ij} L/E]$$

$$+2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin^2[2.54\Delta m^2_{ij} L/E]$$

- two neutrino case: $P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$

$$\left(1.27,\ 2.54 \text{ in units of } \frac{\text{GeV}\cancel{c^4}}{\text{eV}^2\text{km}}\right)$$





- solar, reactor experiments:
  $\Delta m_{12}^2 \sim 8\times10^{-5}$ eV^2
- atmospheric, accelerator experiments:
  $\Delta m_{23}^2 \sim 2\times10^{-3}$ eV^2

well established

- LSND:
  $\Delta m^2 \sim 1$ eV^2 $(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

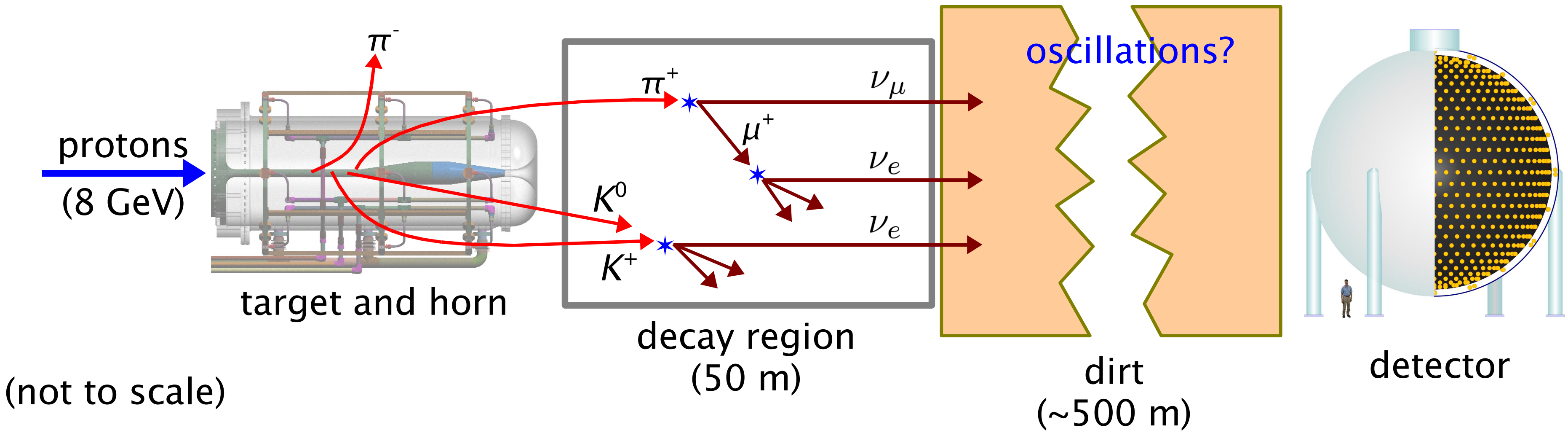
3.8σ signal, unconfirmed
(enter MiniBooNE)

Incompatible with three-neutrino picture

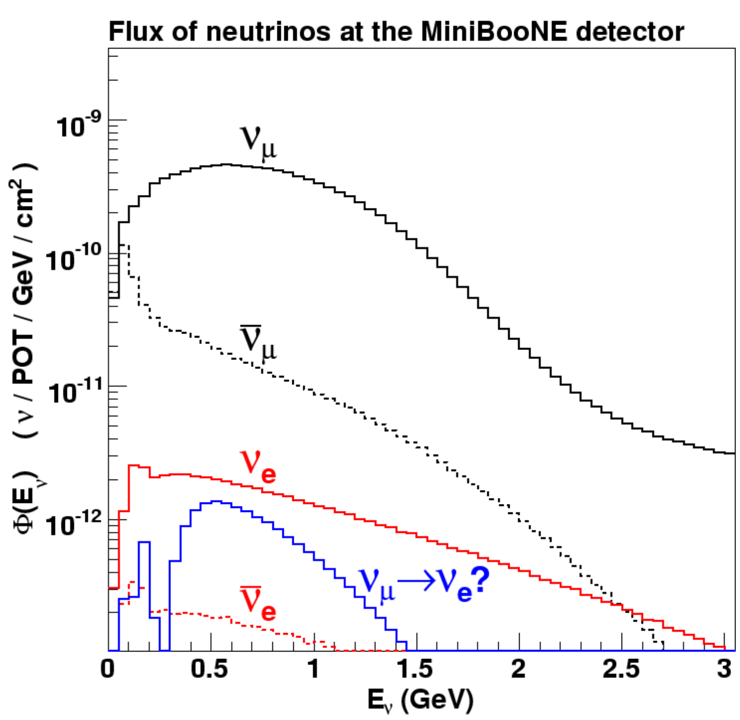
⇒ new physics needed to accommodate LSND (sterile states, CPT violation?)

⇒ active theoretical topic: ~400 abstracts at arXiv.org mention LSND

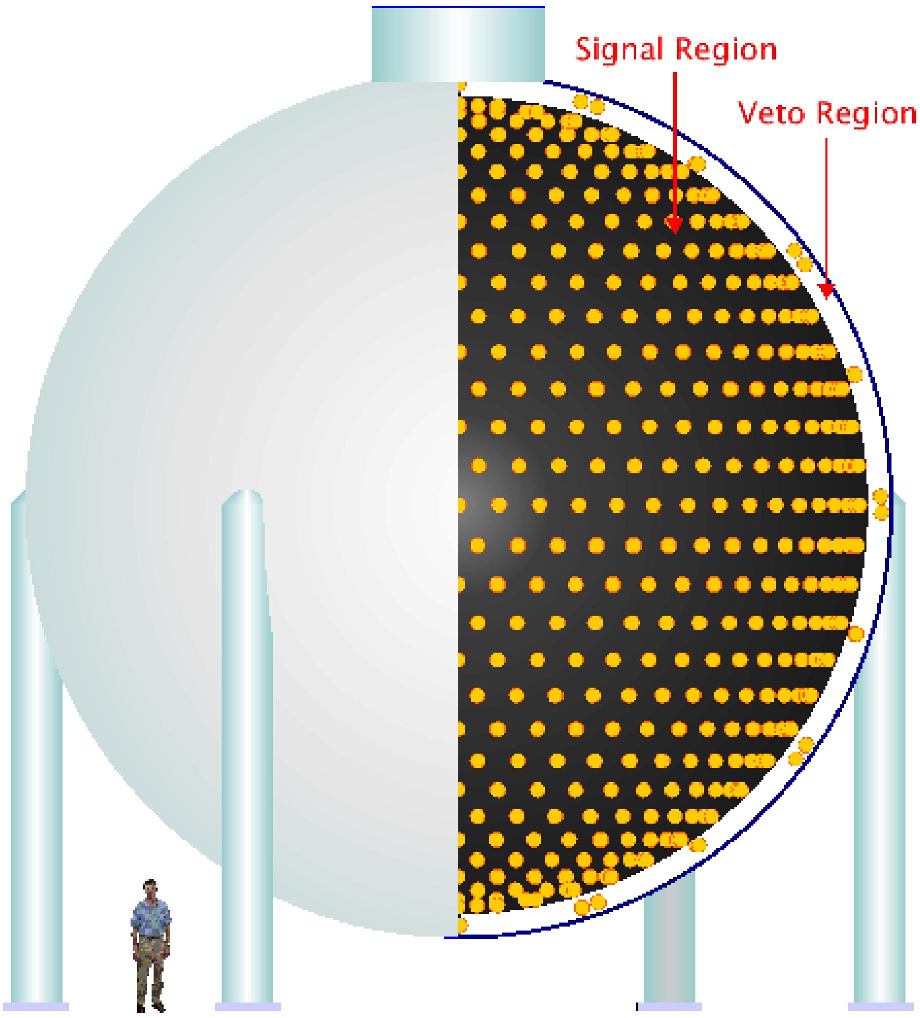
MiniBooNE: $\nu_\mu \rightarrow \nu_e$ at large Δm^2

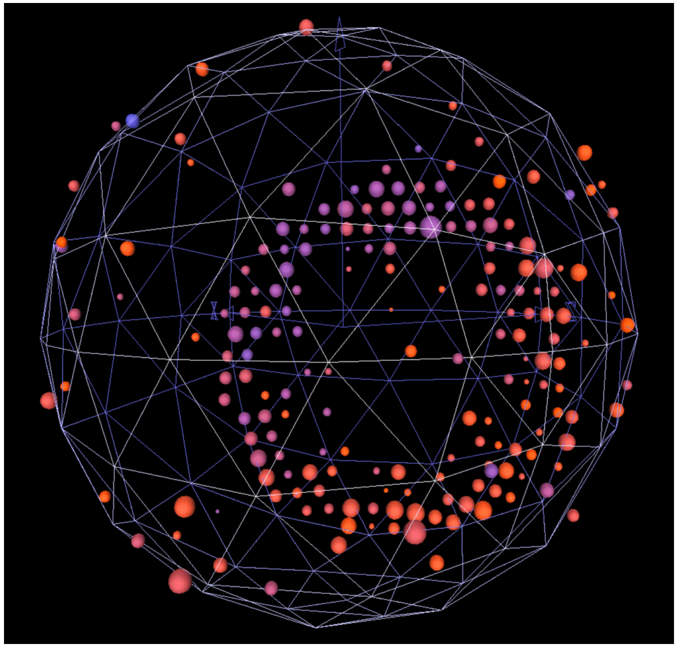


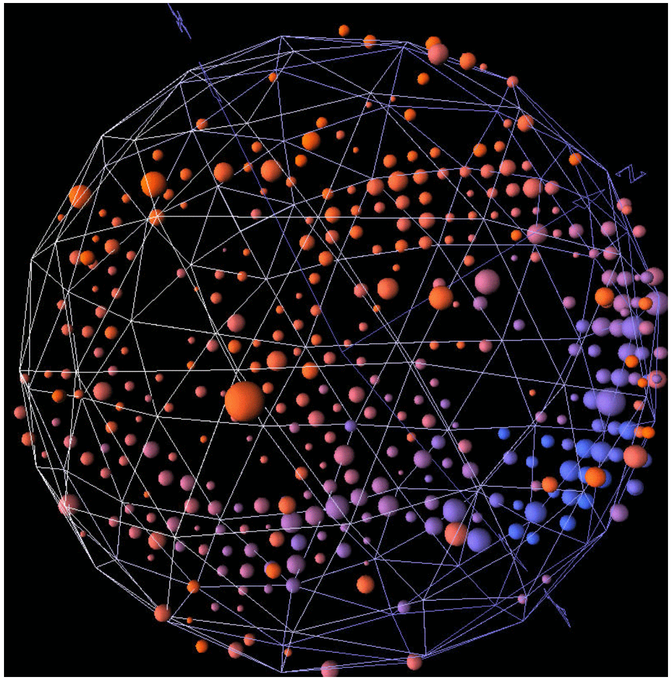
- ~0.8 GeV ν_μ beam (0.6% intrinsic ν_e)
- L/E:
  MiniBooNE: (0.5 km) / (0.8 GeV)
  LSND: (0.03 km) / (0.05 GeV)
- 1.7M neutrino events collected during run
- Looking for a few hundred excess ν_e CC events

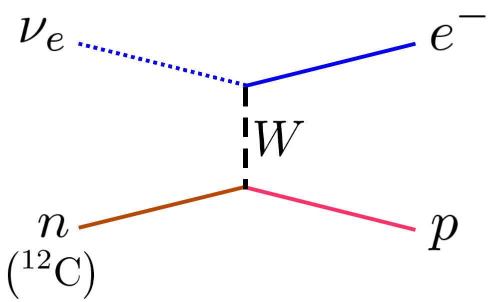


- 0.8 kton mineral oil Cherenkov detector
- 1280 8-inch PMTs facing inward
- 240 PMTs in thin veto region

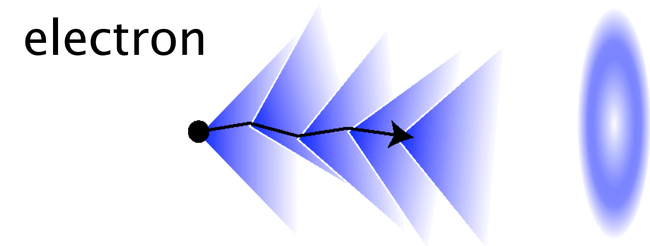


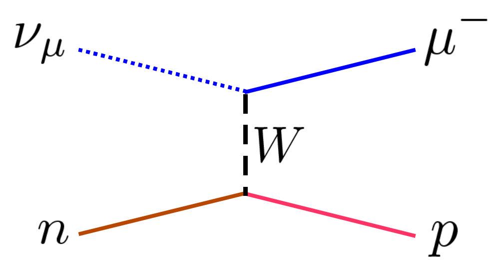




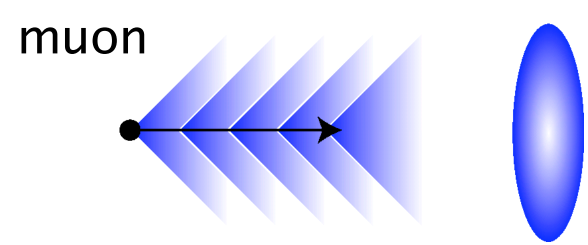


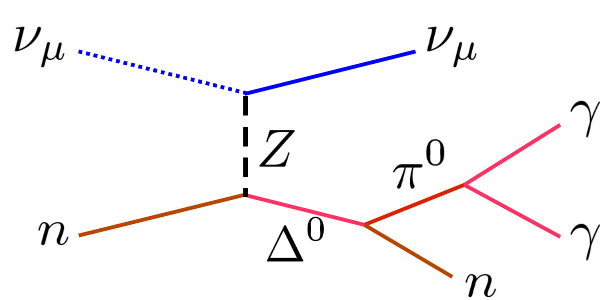
signal and
intrinsic ν_e background



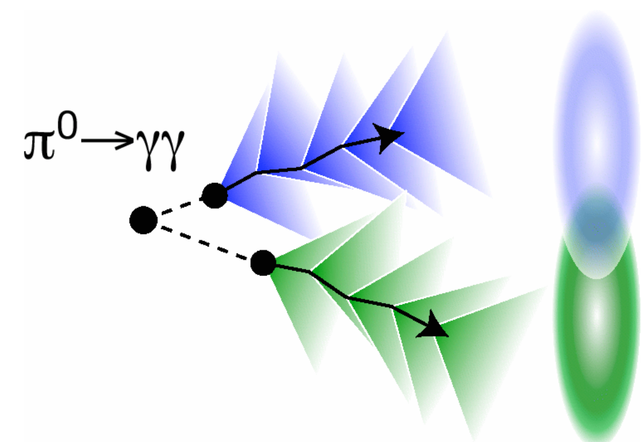


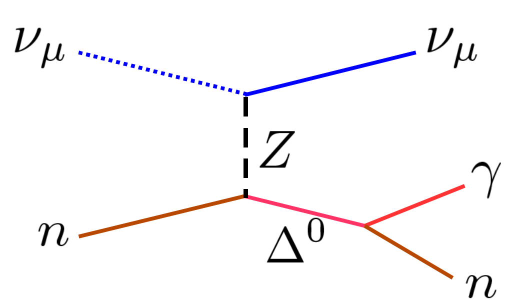
single muon ring
(μ decay-at-rest tags
~80% of these)





NC $\pi^0 \to \gamma\gamma$
(can look like one ring)





NC $\Delta \to N\gamma$
(approximately irreducible)

Counting result
(E$_\nu$ from 475–1250 MeV)

Expected: 358 ± 19(stat) ± 35(syst) events

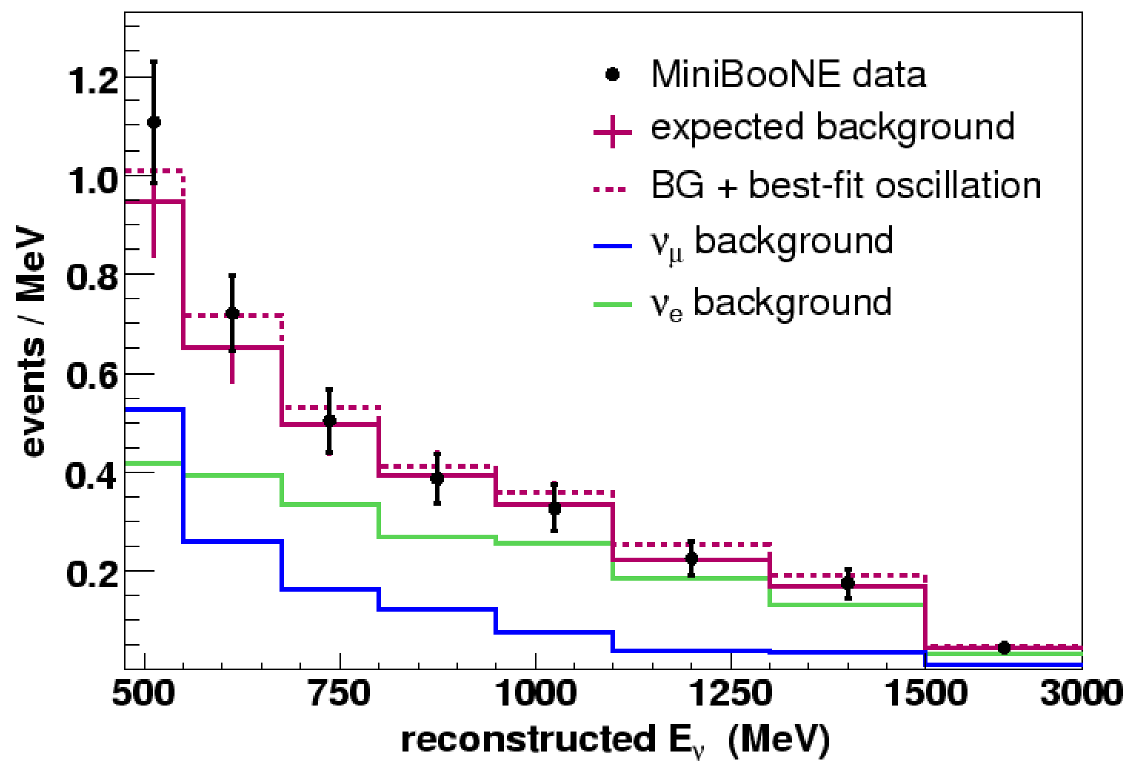
Observed: 380 events

Deviation: 0.55σ

Energy fit result

Best fit:

- $\sin^2 2\theta = 1.1\text{x}10^{-3}$
- $\Delta m^2 = 4.1\ \text{eV}^2/\text{c}^4$
- $\chi^2_{null} - \chi^2_{best} = 0.83$



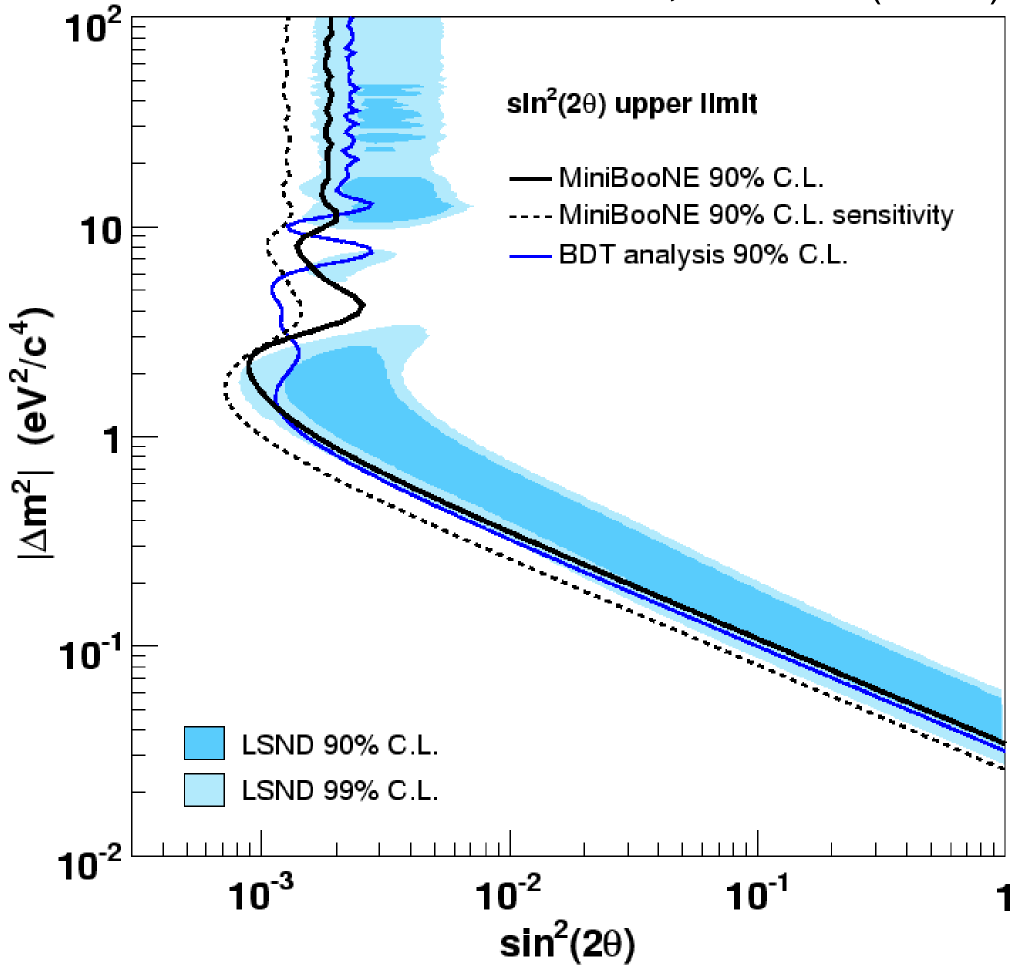
- Most of LSND allowed region excluded at 90% C.L.

- Two quasi-independent analyses give compatible results

- *New combined fit:*
  Bugey + KARMEN2 + LSND + MiniBooNE
  → **3.9% compatibility**

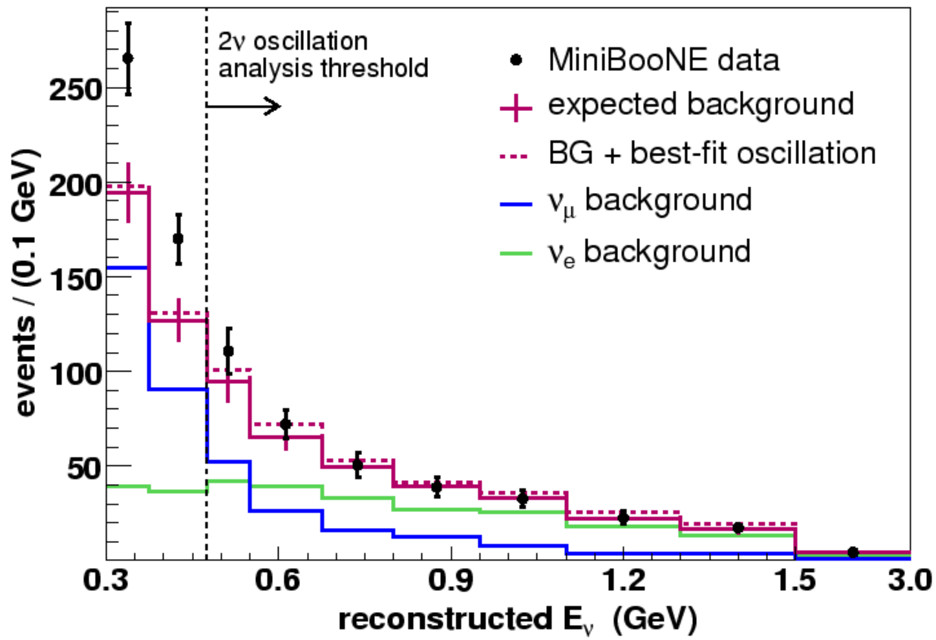
  arXiv:0805.1764

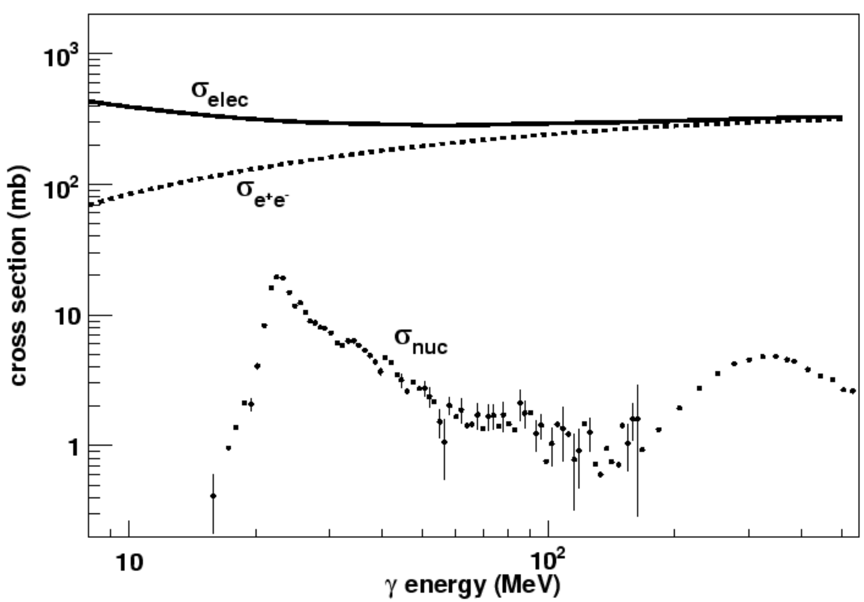
PRL **98**, 231801 (2007)



Below the E_ν=475 MeV threshold

- A discrepancy at low energy
- Does not follow a two-neutrino oscillation shape
- Photonuclear absorption explains ~25% of the excess
- ν-γ interaction at finite baryon density
  Harvey, Hill, and Hill, PRL **99** 261601 (2007)



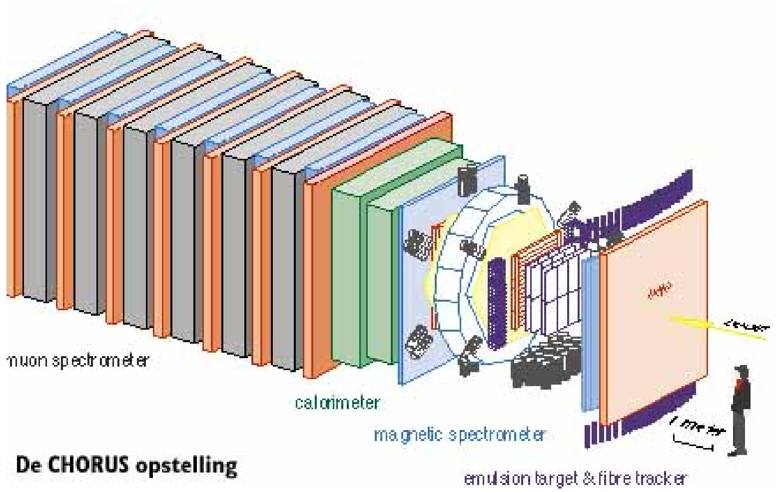


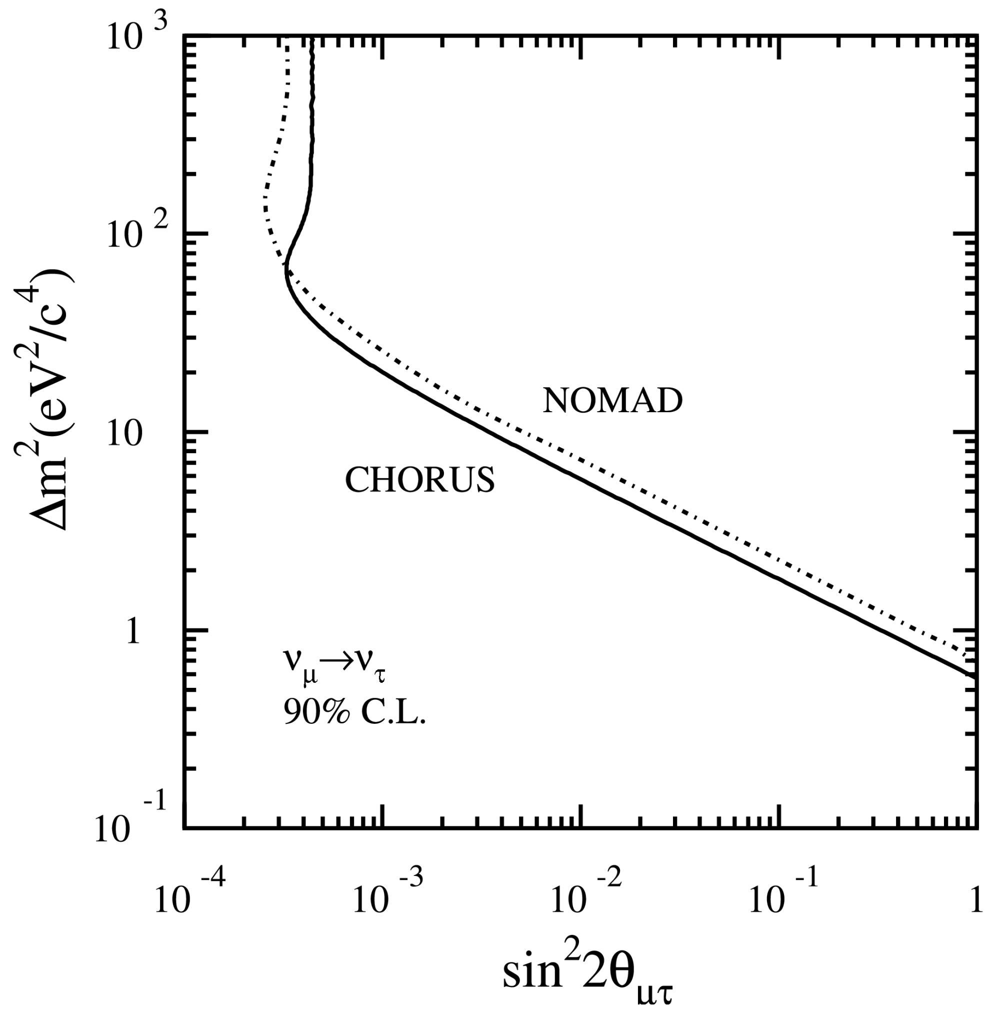
MiniBooNE will soon release results of a complete review of low energy event predictions and systematic errors

(expected this summer...)

Improved CHORUS $\nu_\mu \to \nu_\tau$ analysis (high Δm^2)

- Updated analysis of 1994-1997 data set
- New automated emulsion scanning
- Improved reconstruction
- ~30% better limit than previous CHORUS analysis





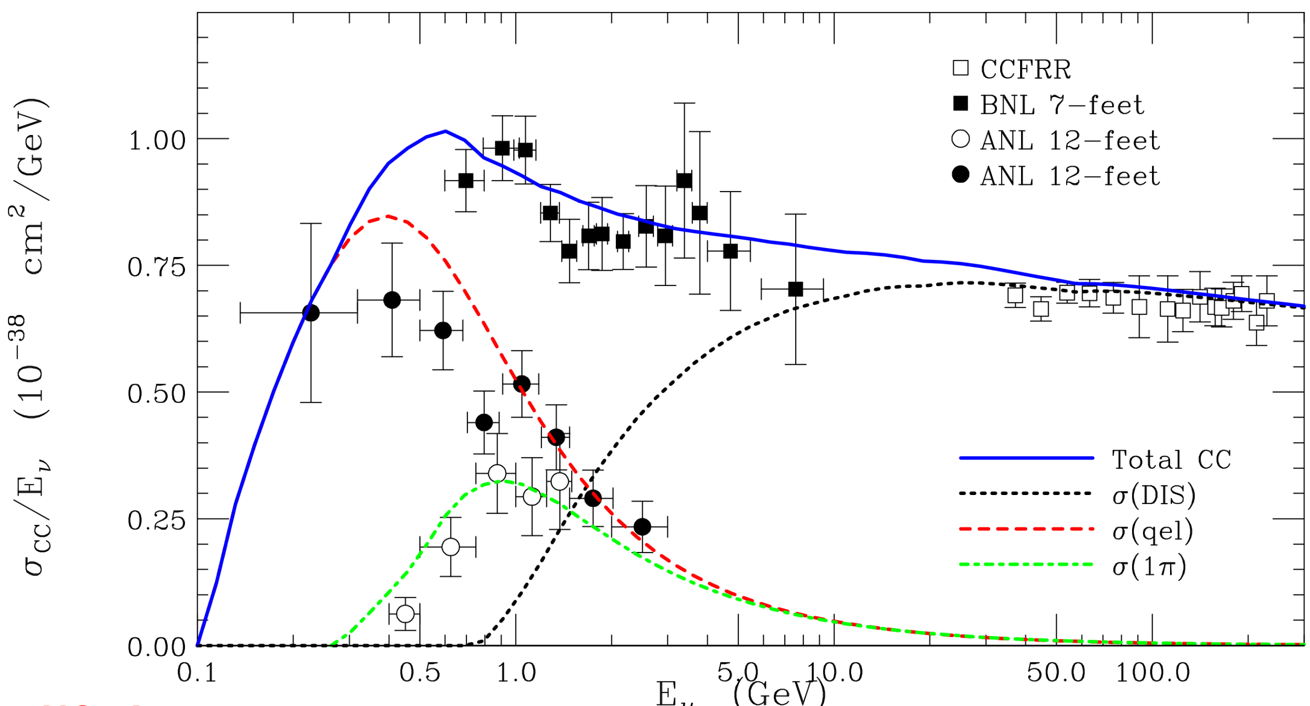
Nucl. Phys. **B793** 326 (2008)

Neutrino cross sections

- Surge in oscillation experiments ⇒ increase in need for precise ν cross sections
- Many relevant channels/energies have never been measured
- Others not addressed for decades
- Data on *nuclear targets* needed

Lipari, Lusignoli and Sartogo, PRL **74**, 4384 (1995)

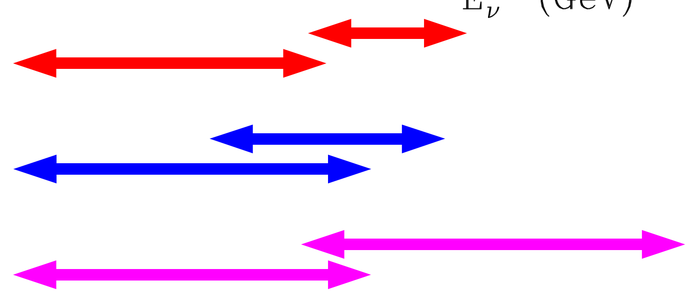
(ν charged current cross sections shown)



upcoming LBL expts.: NOνA, T2K

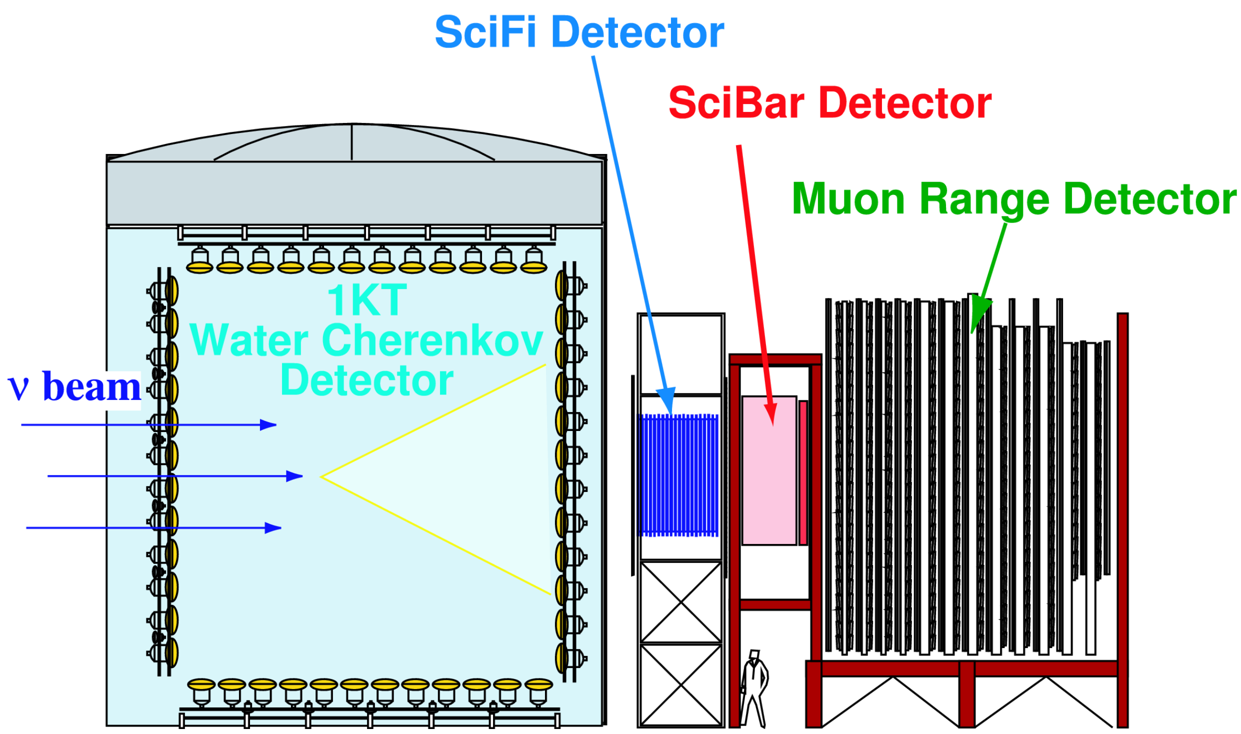
existing osc./σ_ν expts.: K2K, MiniBooNE

new σ_ν expts.: MINERνA, SciBooNE



K2K Near Detector

- Sees KEK neutrino beam (Tsukuba, Japan)
- 1.3 GeV wide-band, 97% ν_μ
- Multiple detectors/targets
  - Cherenkov (H_2O)
  - scintillating fibers (H_2O)
  - scintillating bars (C_8H_8)
  - muon range stack (Fe)



- Measured cross sections reported as ratios with inclusive or quasi-elastic CC channels
  - absolute ν flux is poorly known *(a generic feature of ~GeV ν beams)*

(For oscillation physics at K2K, see M. Thomson's talk later in the symposium)

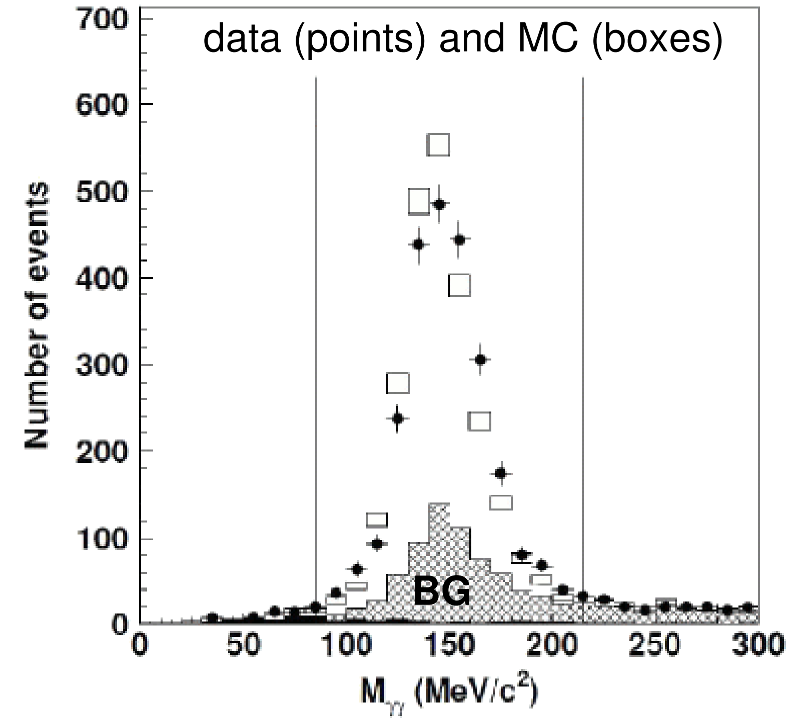
Neutral current π^0 production →

- Significant bkgnd. to ν_e appearance searches
- Using water Cherenkov data:

$$\sigma_{NC1\pi0}/\sigma_{CC} = 0.063 \pm 0.001_{stat} \pm 0.006_{syst}$$

[MC prediction: 0.064]

K2K π^0 mass peak



AIP Conf. Proc. **967** 174 (2007)

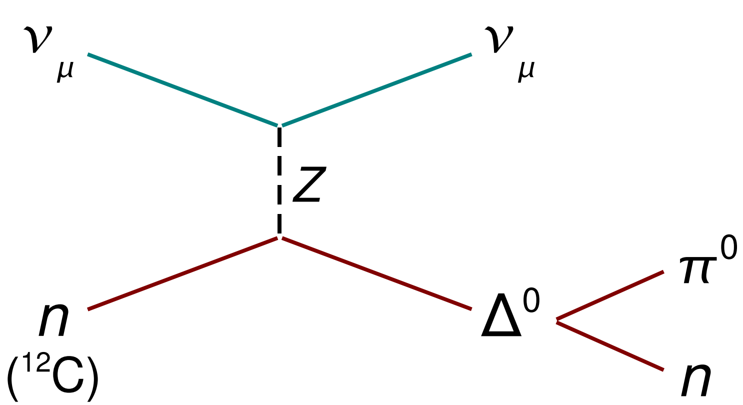
Charged current π^0 production

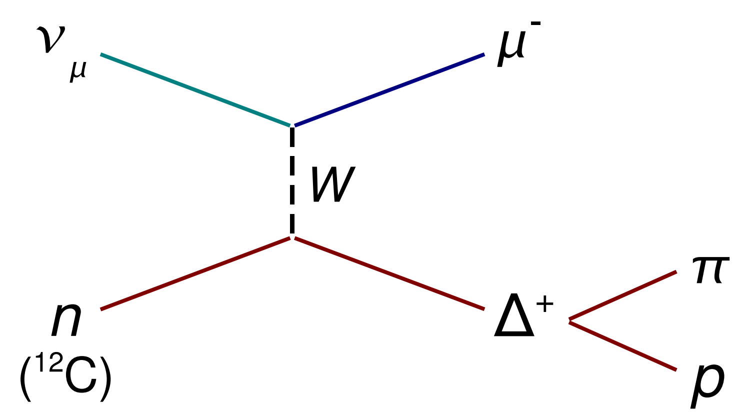
- Using SciBar (carbon) data:

$$\sigma_{CC1\pi0}/\sigma_{CCQE} = 0.306 \pm 0.023_{stat} \pm 0.025_{syst}$$

[40% above MC prediction!]

(resonant channel is dominant)





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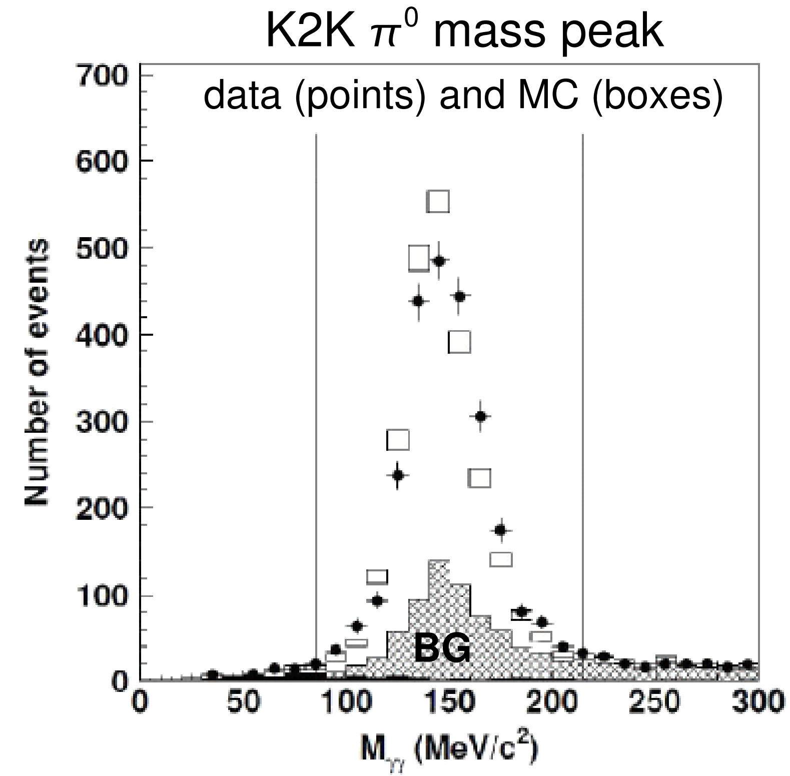
[MC prediction: 0.064]



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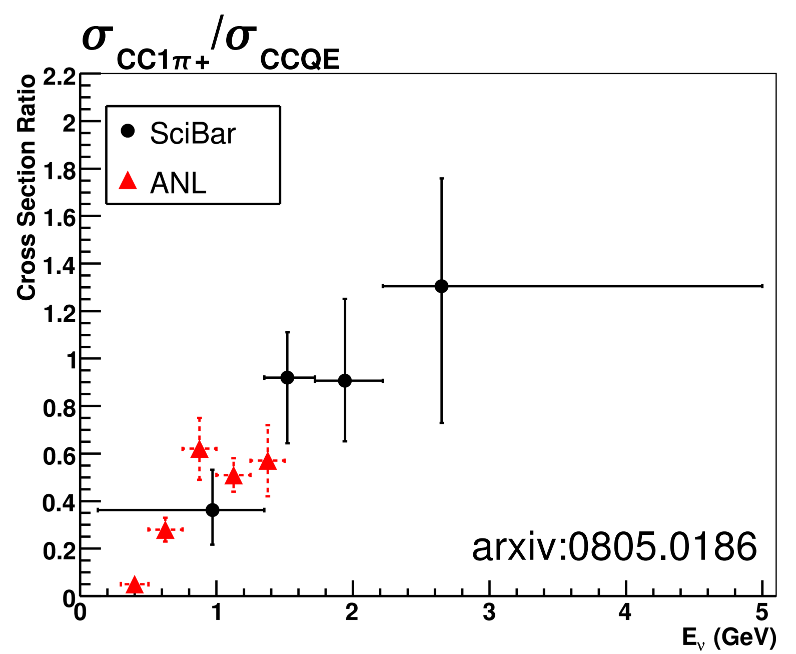
[40% above MC prediction!]

Charged current π^+ production

- Using SciBar (carbon) data: $\sigma_{CC1\pi+}/\sigma_{CCQE}$ →
- **Consistent with Monte Carlo**

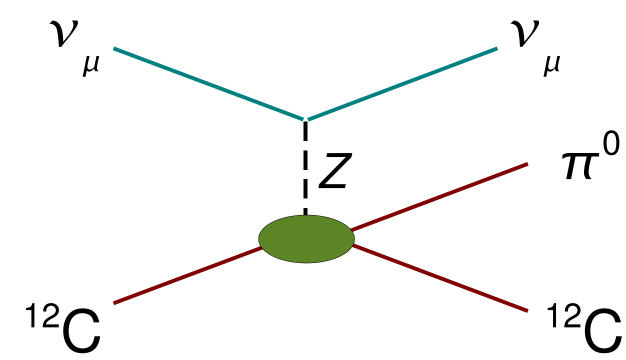
  and ANL bubble chamber data

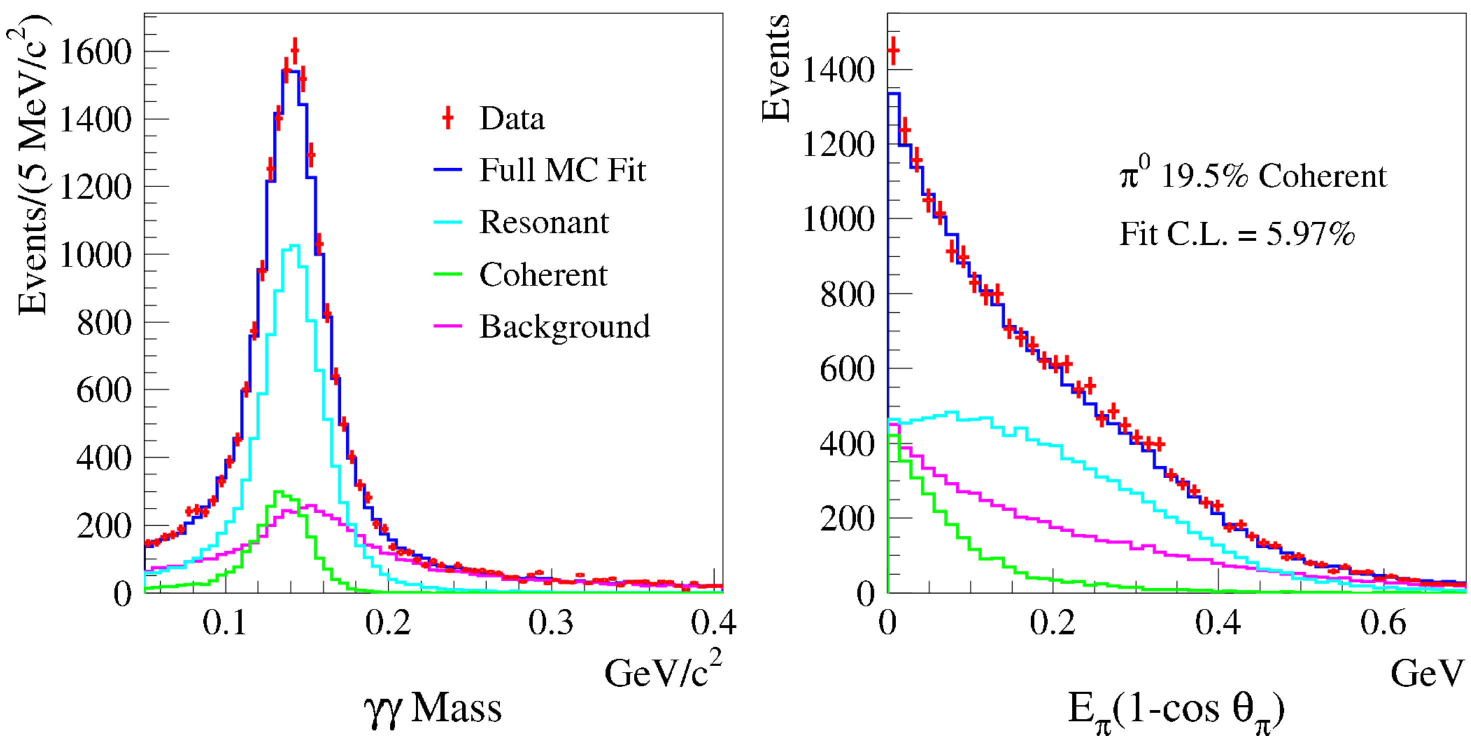
  (though errors are large)



MiniBooNE: Coherent pion production

- Alongside resonant production is **coherent production**
- Nucleus stays intact; pion momentum more forward
- MiniBooNE has made first ever measurement of coherent π^0 production below E_ν = 2 GeV

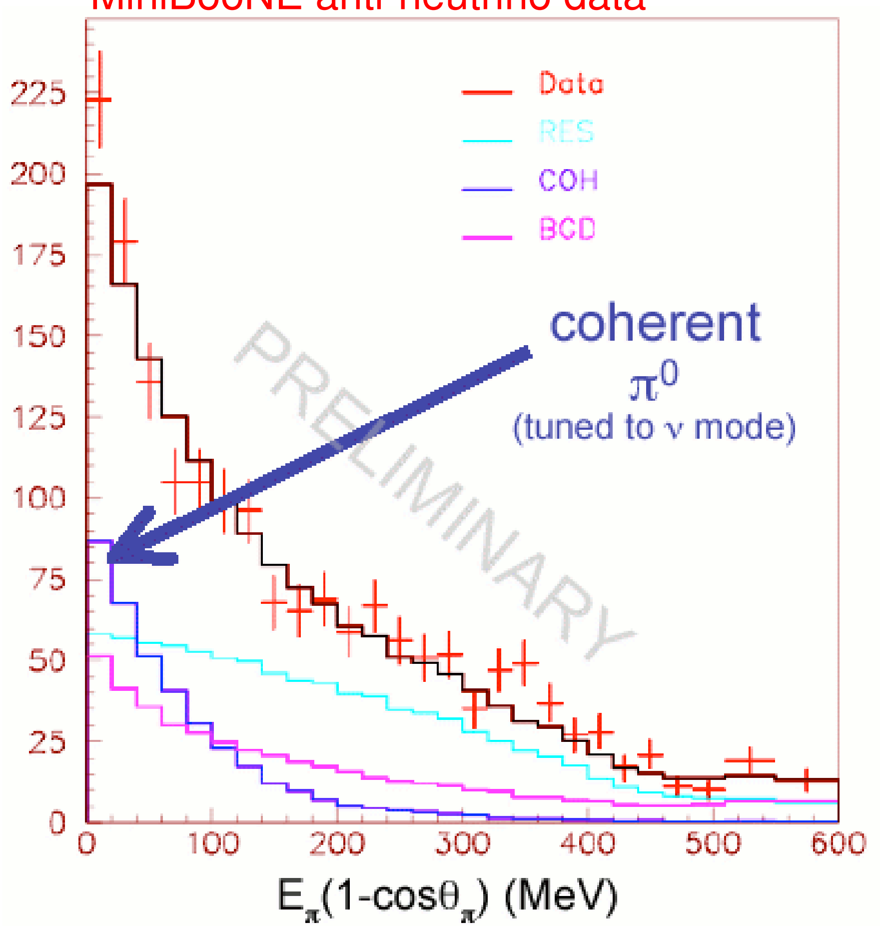




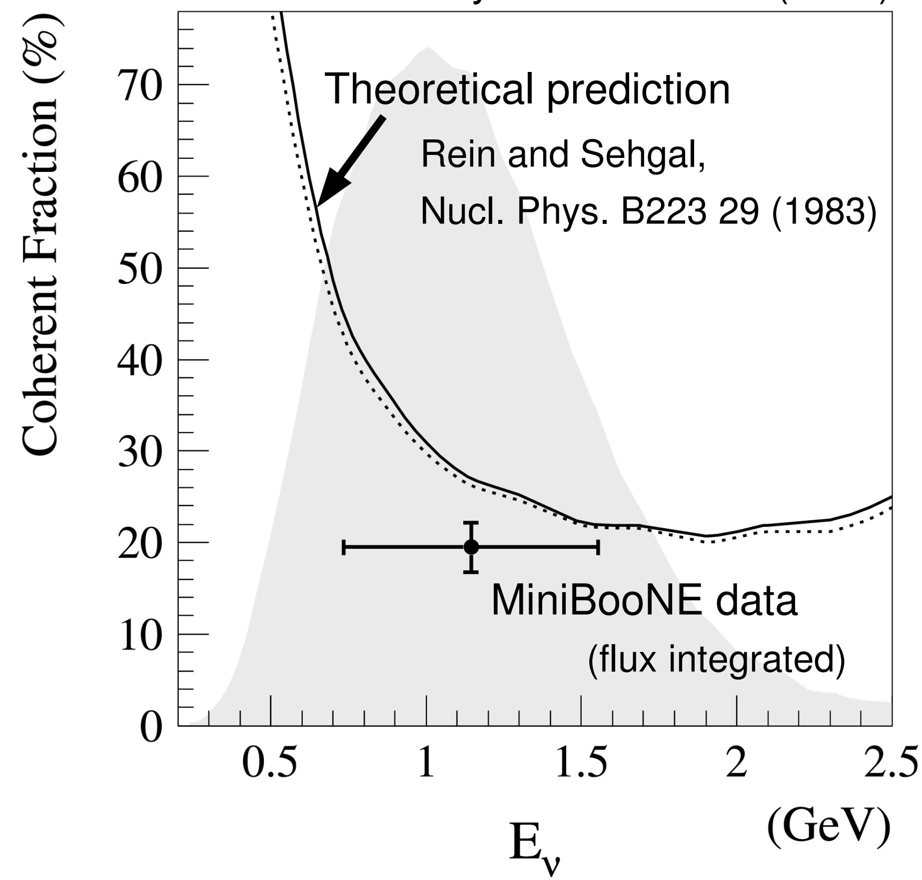
- MiniBooNE finds **(19.5 ± 1.1$_{stat}$ ± 2.5$_{syst}$)%** of its π^0 production is coherent

- Monte Carlo expectation: **30%**

MiniBooNE anti-neutrino data



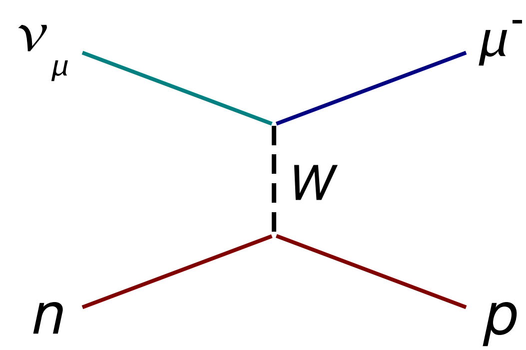
Phys. Lett. **B664** 41(2008)



- Preliminary MiniBooNE anti-neutrino data is consistent *(figure at left)*

- MINOS is investigating coherent π^0 measurement possibilities

Charged current quasi-elastic scattering



- Golden channel for neutrino flavor oscillations
  - flavor tagging via charged lepton
  - two-body kinematics (E_ν determination)

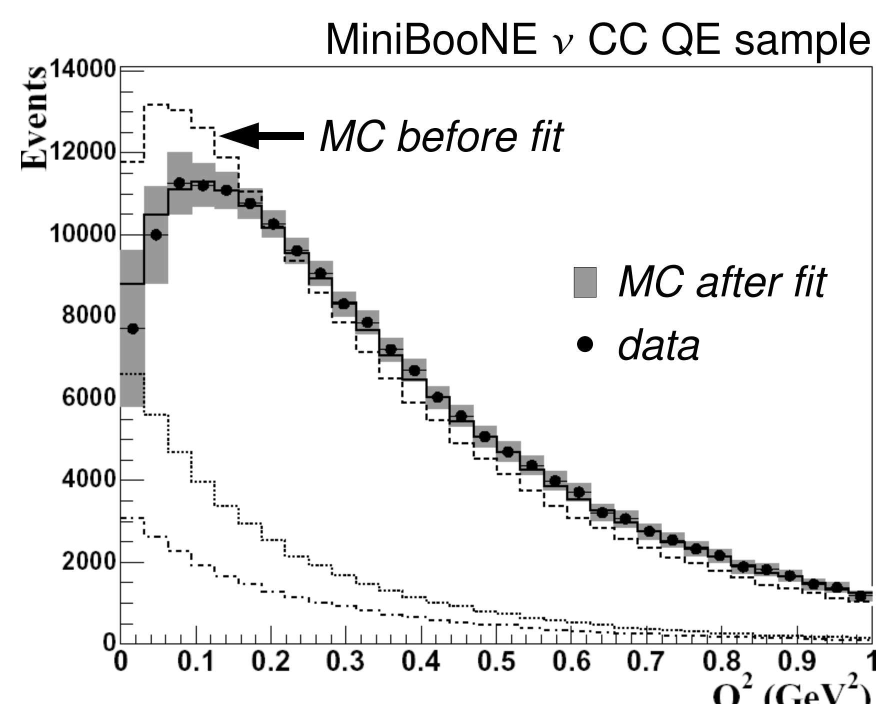
- Rate and Q^2 dependence of cross section depends on nucleon axial-vector form factor:

$$F_A(Q^2) = \frac{F_A(0)}{(1 + Q^2/M_A^{\,2})^2}$$

free parameter:
axial mass M_A

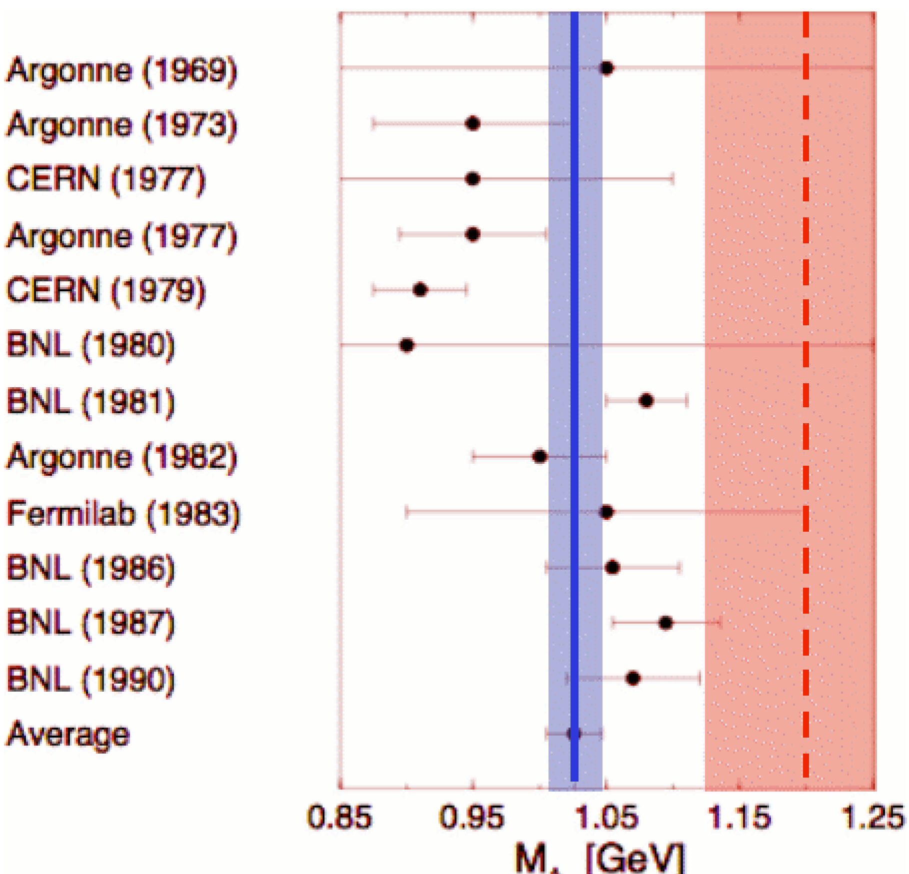
- **K2K, MiniBooNE extract M_A**

- Complications (beyond backgrounds):
  - normalization poorly known
    - *do shape-only fit*
  - nuclear effects poorly modeled
    - *remove lowest Q^2 data, or*
    - *include nuclear model parameters*



M_A results:

K2K SciFi	**1.20 ± 0.12 GeV**	Phys. Rev. **D74** 052002 (2006)
K2K SciBar	**1.14 ± 0.11 GeV**	(in preparation)
MiniBooNE	**1.23 ± 0.12 GeV**	Phys. Rev. Lett. **100** 032301 (2008)



J. Phys. **G28** R1 (2002)

Prior world average (from bubble chamber experiments) markedly lower

1.026 ± 0.021 GeV

Measuring "effective" M_A?

Nuclear effects exhibiting at high Q^2?

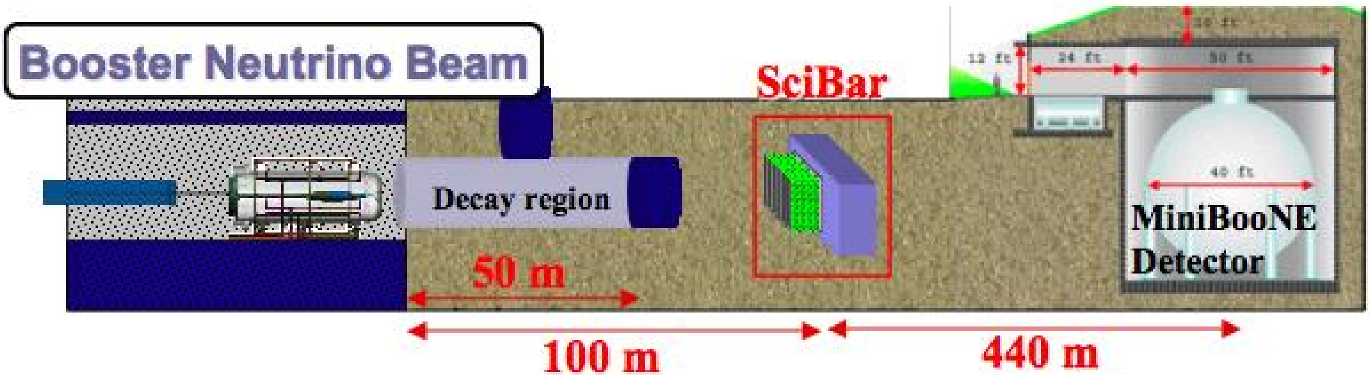
MINOS will soon provide another data point (with heavier Fe target)

Dedicated cross section experiments

(SciBooNE and MINERνA)

SciBooNE

- Place K2K's SciBar detector in the Booster Neutrino Beam
- Beam already characterized (MiniBooNE)
- Detector already proven (K2K)
- 100k events (neutrino and anti-neutrino)
  - precision cross sections
  - CC quasi-elastic, NC elastic, pion production (charged and neutral)
  - ~800 ν_e events ⇒ *measure largest MiniBooNE oscillation background*
  - SciBooNE/MiniBooNE ν_μ disappearance measurement
- Initial runs complete; results expected over the coming year



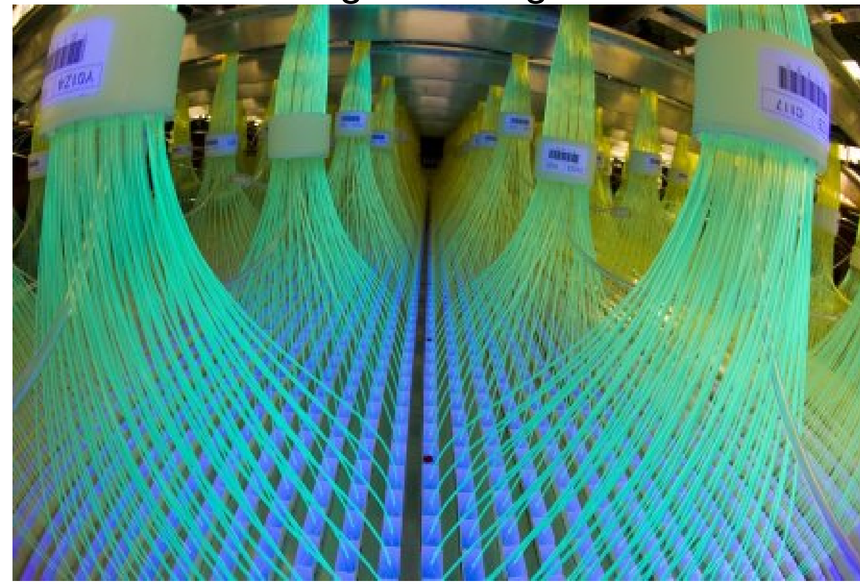
SciBar detector

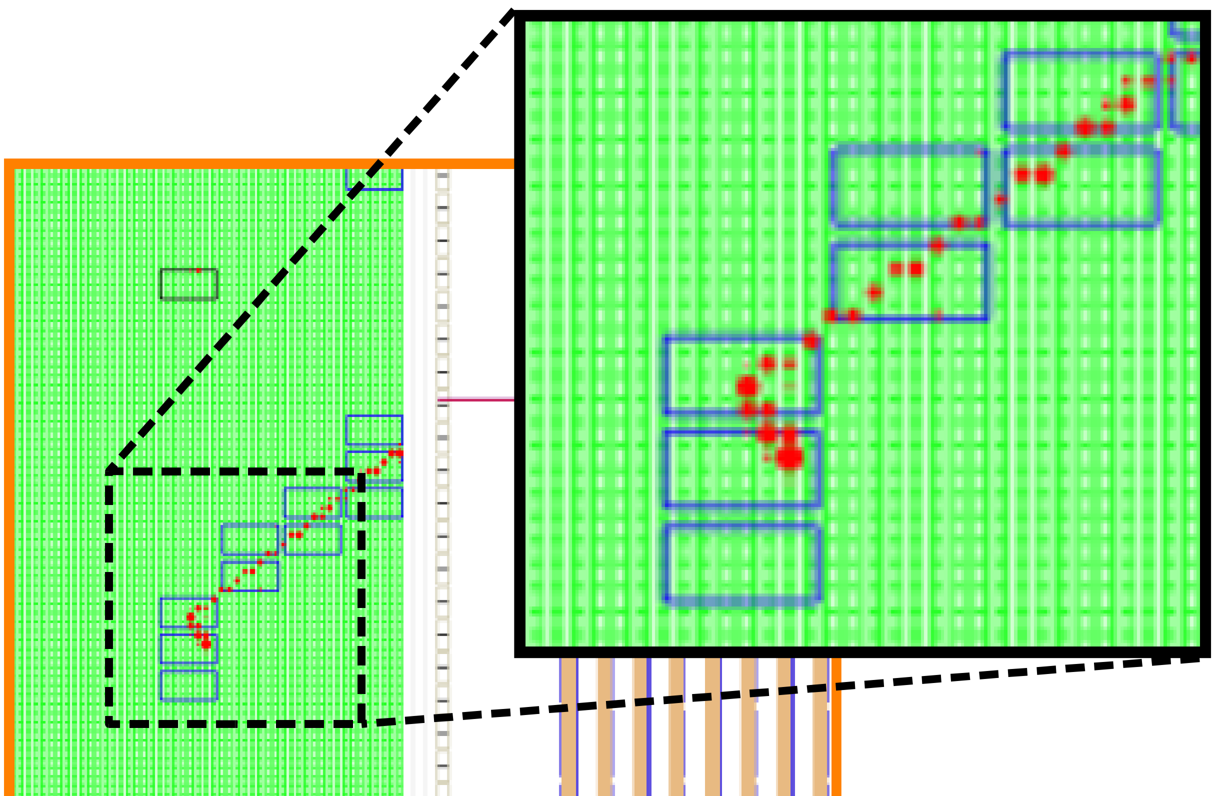
- 10 kton fiducial mass
- 14,000 channels
- fine-grain tracking
- downstream:

  electromagnetic calorimeter

  muon range stack

SciBar's wavelength-shifting readout fibers



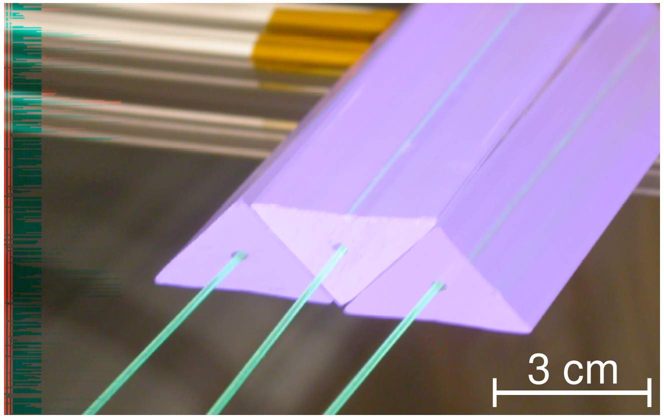


ν_μ CC quasi-elastic event

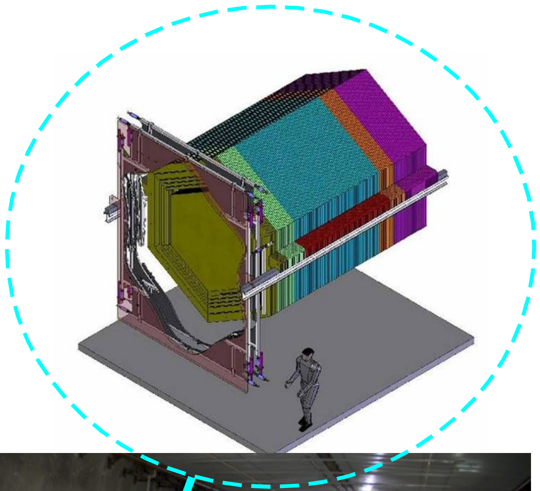
($p + \mu^-$ final state)

Can distinguish ν and $\bar{\nu}$ CC events according to recoil track (attached *vs.* displaced)

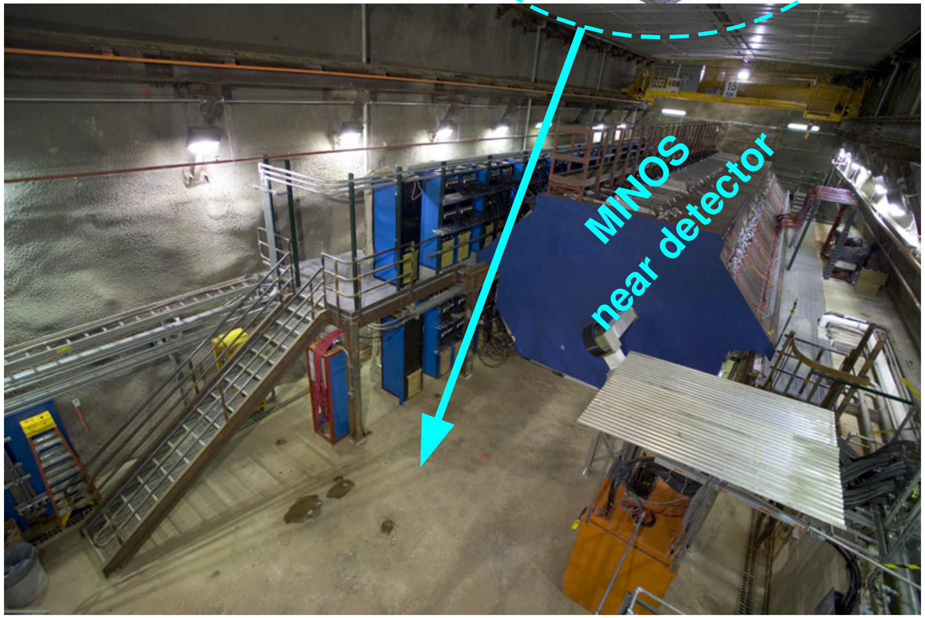
MINERνA



- Highly segmented detector – 31,000 channels
- 2.5 mm resolution (through charge sharing)
- Place in existing beamline (NuMI)
  - *Well-characterized beam*
  - *Tunable neutrino spectrum*



- Multiple nuclear targets; *A*-scaling of cross sections
  - Fe, Pb, C, He
- π production *(resonant, DIS, coherent)*
- quasi-elastic
  - *Access to much higher Q^2*
  - *Test dipole form*
- Data taking to start in 2009



Short baseline: Longer term

- Neutrino scattering on glass ("NuSOnG", Fermilab)
  - Use upgraded Tevatron, 100 GeV neutrino beam
  - Look for TeV-scale modifications to SM processes
  - LHC complementarity

- Oak Ridge National Laboratory (Tennessee, USA)
  - Spallation neutron source under construction
  - *By-product:* 10^{15} ν/second, pulsed source
  - Decay-at-rest spectra
  - under consideration (abridged):
    - low energy cross section measurements
    - better sensitivity to LSND-type oscillations
    - BSM components of weak interaction (ν_e spectrum from μ decay)

Summary

- Short baseline neutrino experiments trending...

  ...from oscillation searches

  ...to precision measurements

- The LSND anomaly was *not* confirmed by MiniBooNE –

  90% C.L. excluded region includes bulk of LSND allowed region

- K2K, MiniBooNE cross section results –

  Predictions and observations data are very different in some channels

- Precision efforts are critical to upcoming LBL measurements –

  MINERνA, SciBooNE