Sci/Mini/Micro-BooNE

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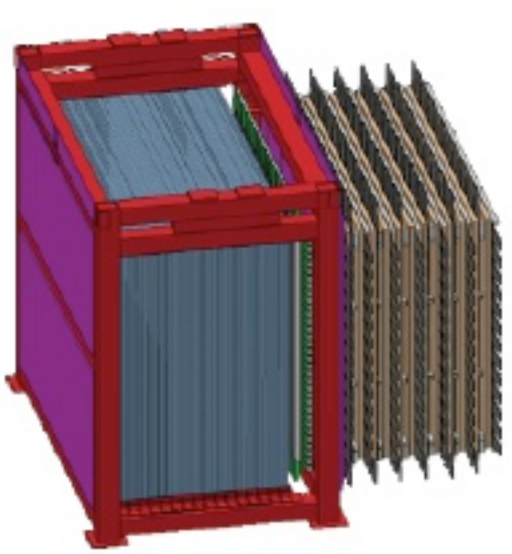
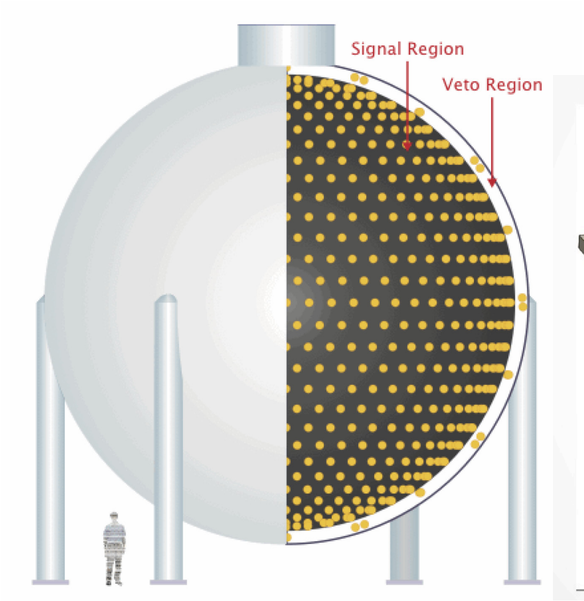
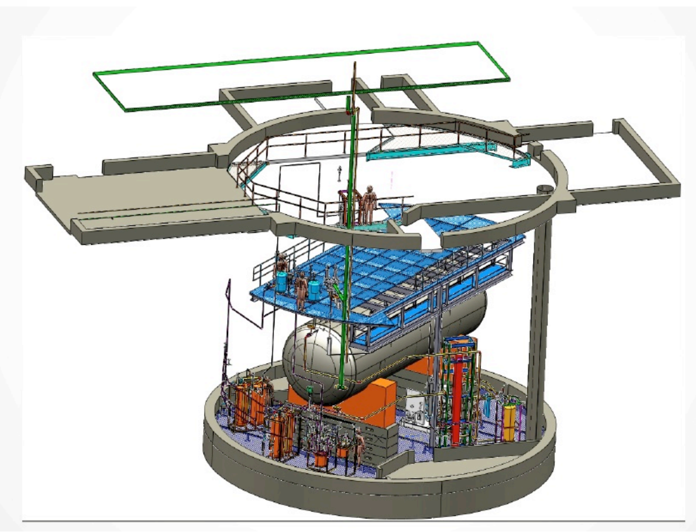
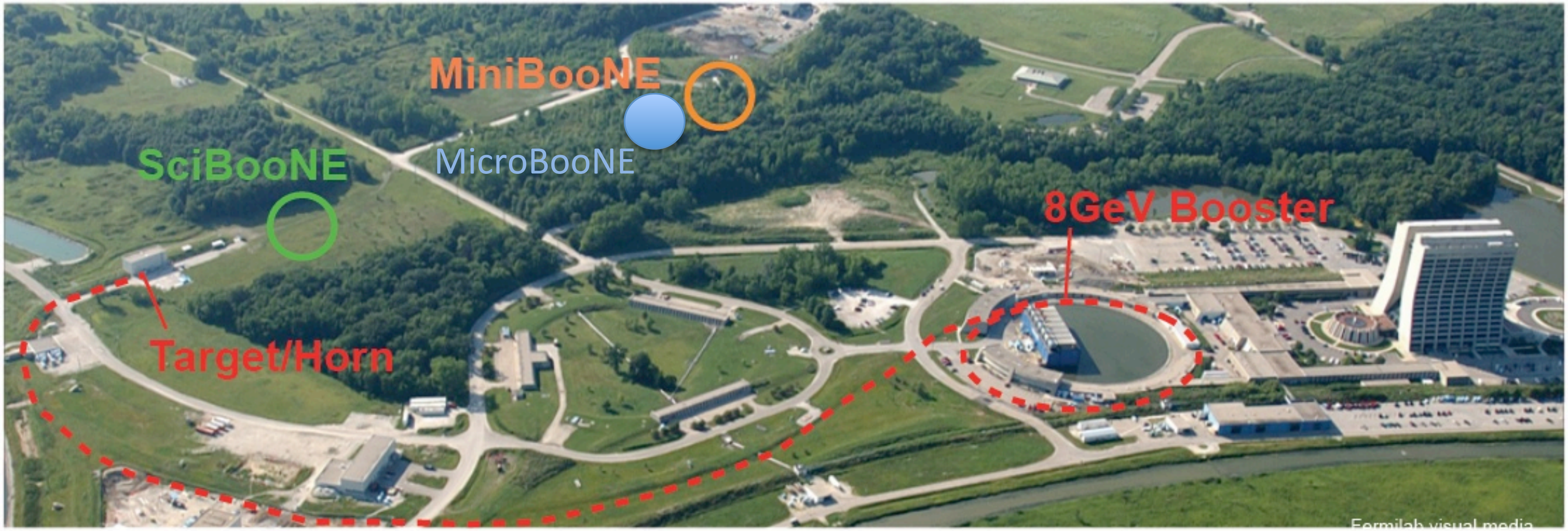


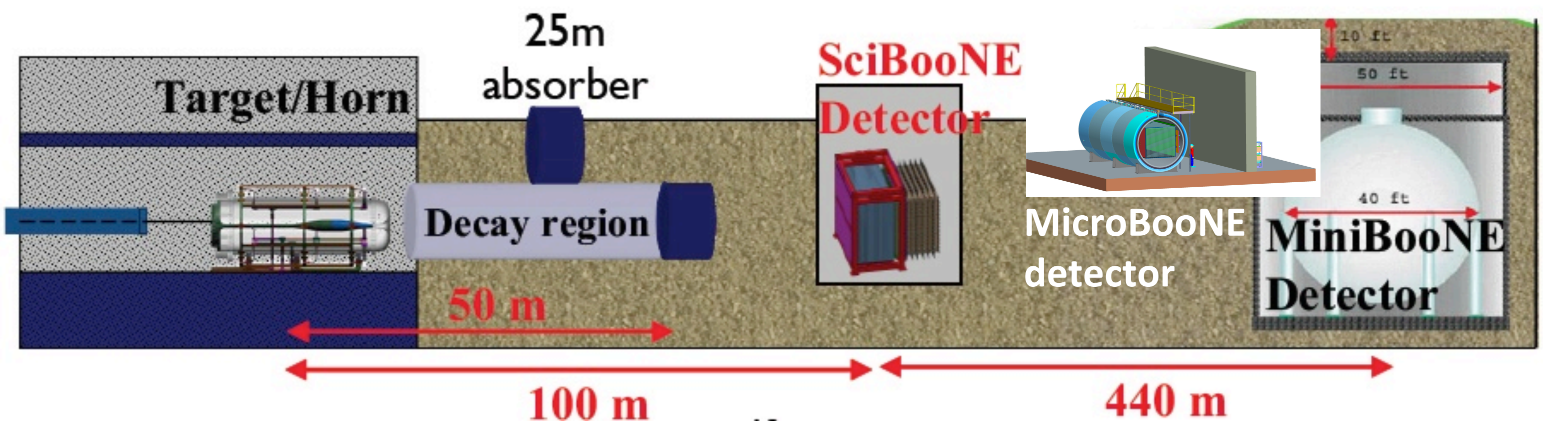




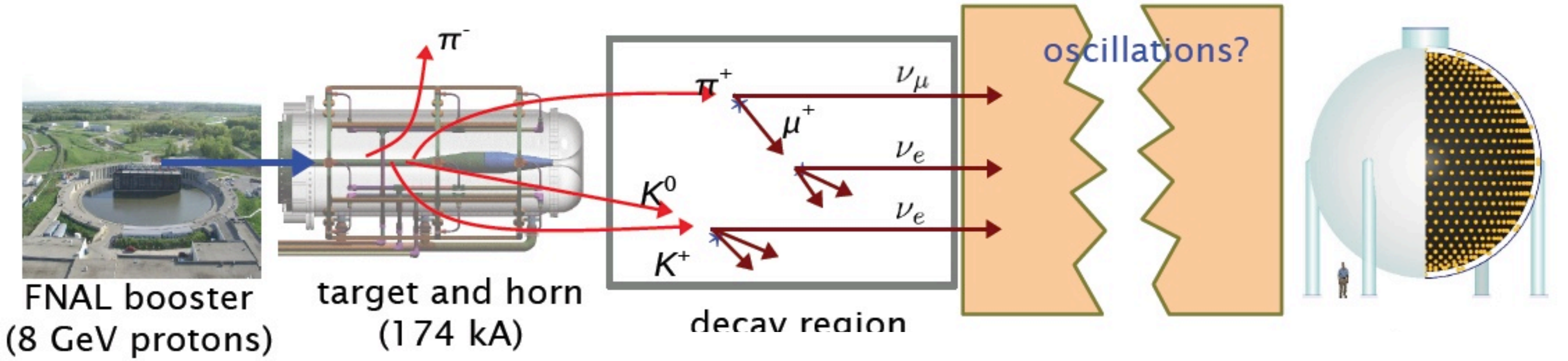
Beamline Overview



Fermilab visual media services



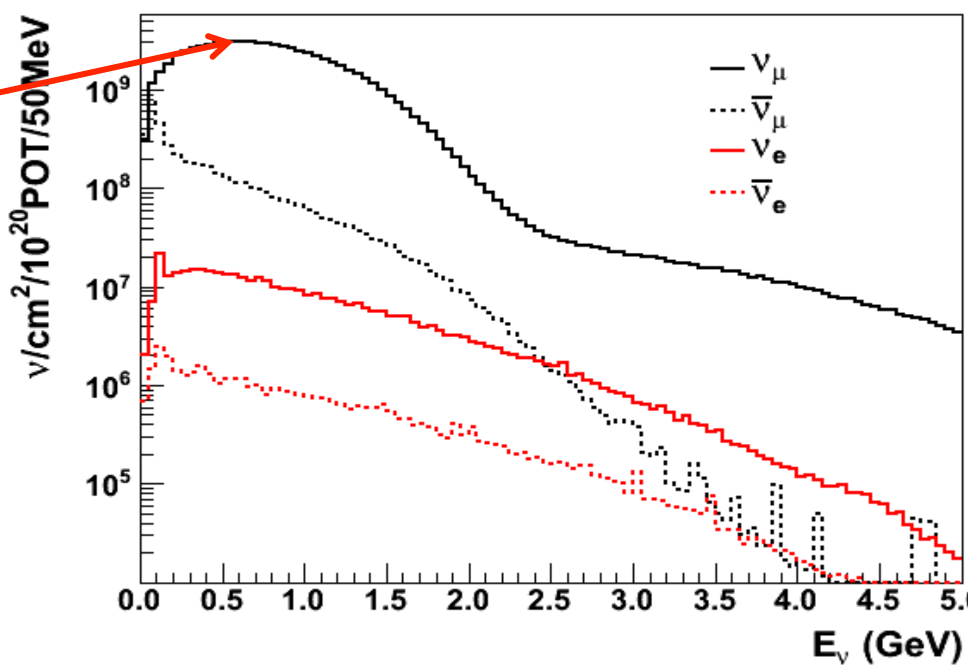
Booster Neutrino Beam (few details)



- Similar L/E as LSND
- 30m/40MeV ~ 475m/600MeV
- → Same oscillation Prob → ν_e Excess

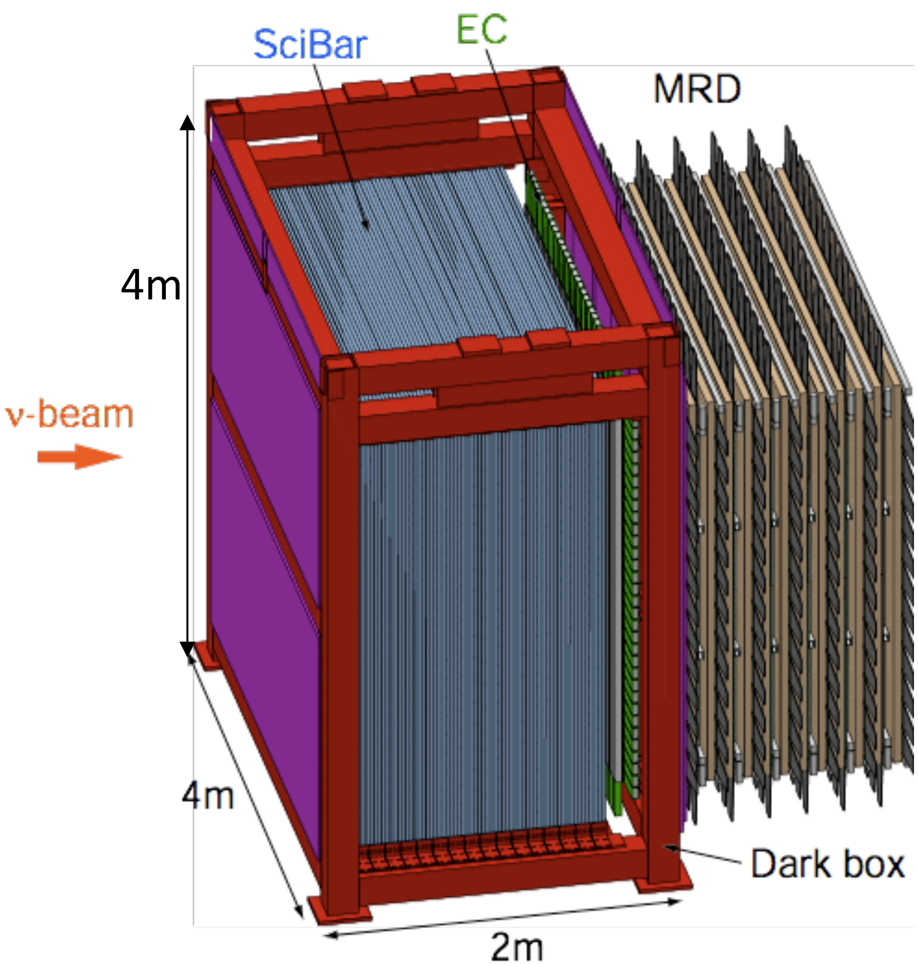
- Similar to MiniBooNE → Low energy Excess

- Different systematics
  - Event signatures
  - Backgrounds



SciBooNE detector (100 m from target)

- Precise measurement of neutrino cross sections
- for future oscillation experiments
- MiniBooNE near detector



SciBar:

Full active scintillator tracker (~14000 strips - X&Y planes)

Neutrino Target

Fiducial volume: ~10 tons

Main component: CH

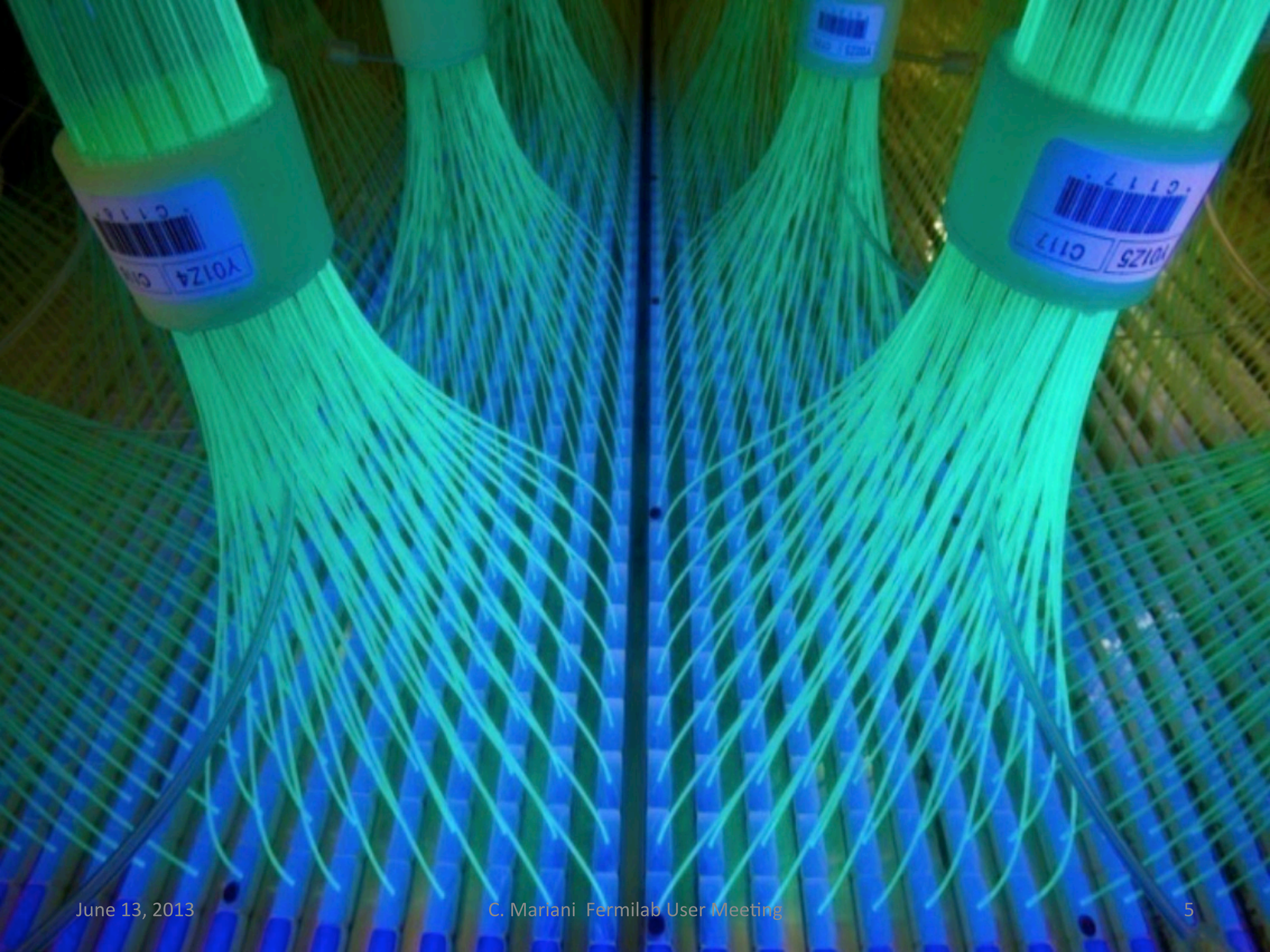
Electron Catcher (EC)

"Spaghetti" type calorimeter

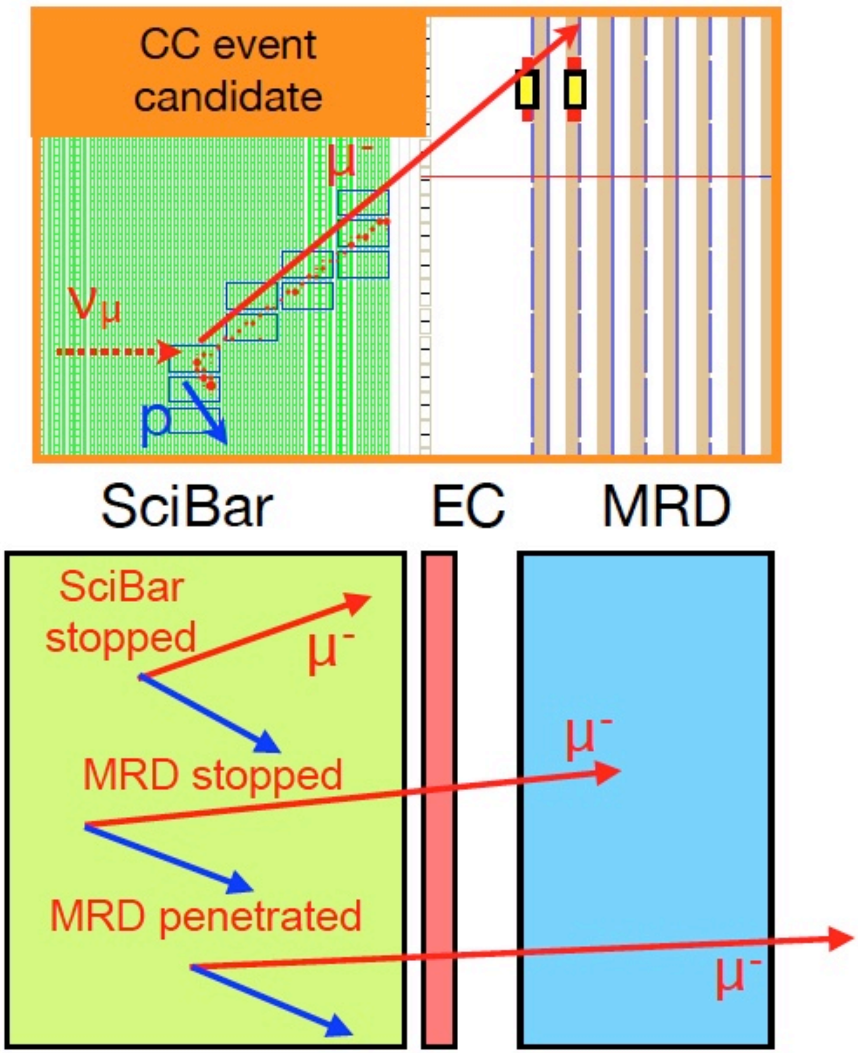
Muon Range Detector (MRD)

Steel and scintillator sandwich

Measure muon momentum from its range



Particle ID in SciBooNE (fine grained det.)



- Reject escaping muons
- Sample used:
  - SciBar-stopped
  - MRD-stopped
- Both SciBooNE and MiniBooNE rely on muon for event and energy estimation
- Muon momentum reconstructed by its range

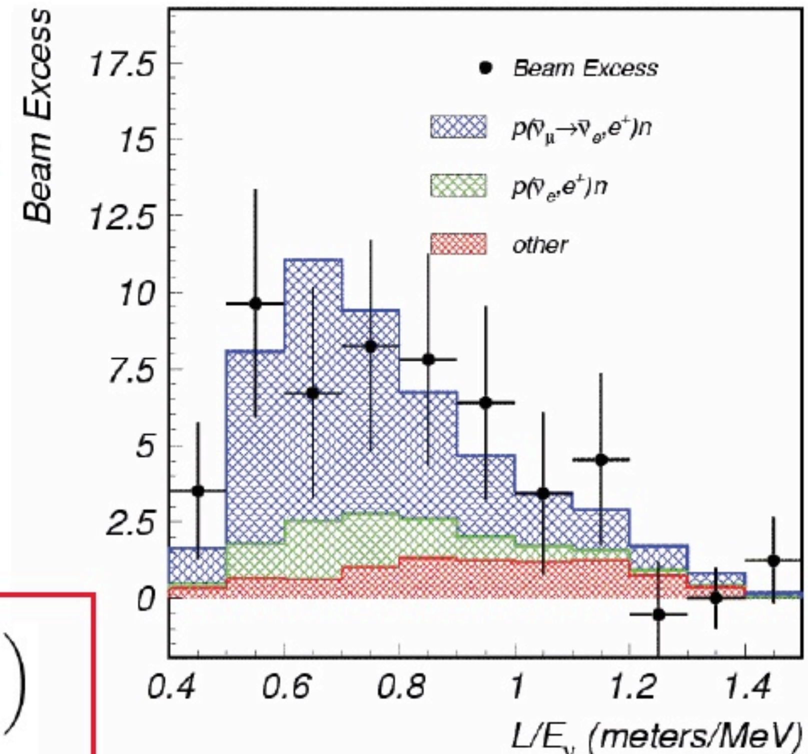
Reconstruct neutrino energy assuming CCQE:

$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

MiniBooNE is...

a single-detector experiment (CH_2) at Fermilab, short-baseline (500 m) experiment searching for ν_e (or anti-ν_e) appearing in ν_μ (or anti-ν_μ) beam.

LSND data



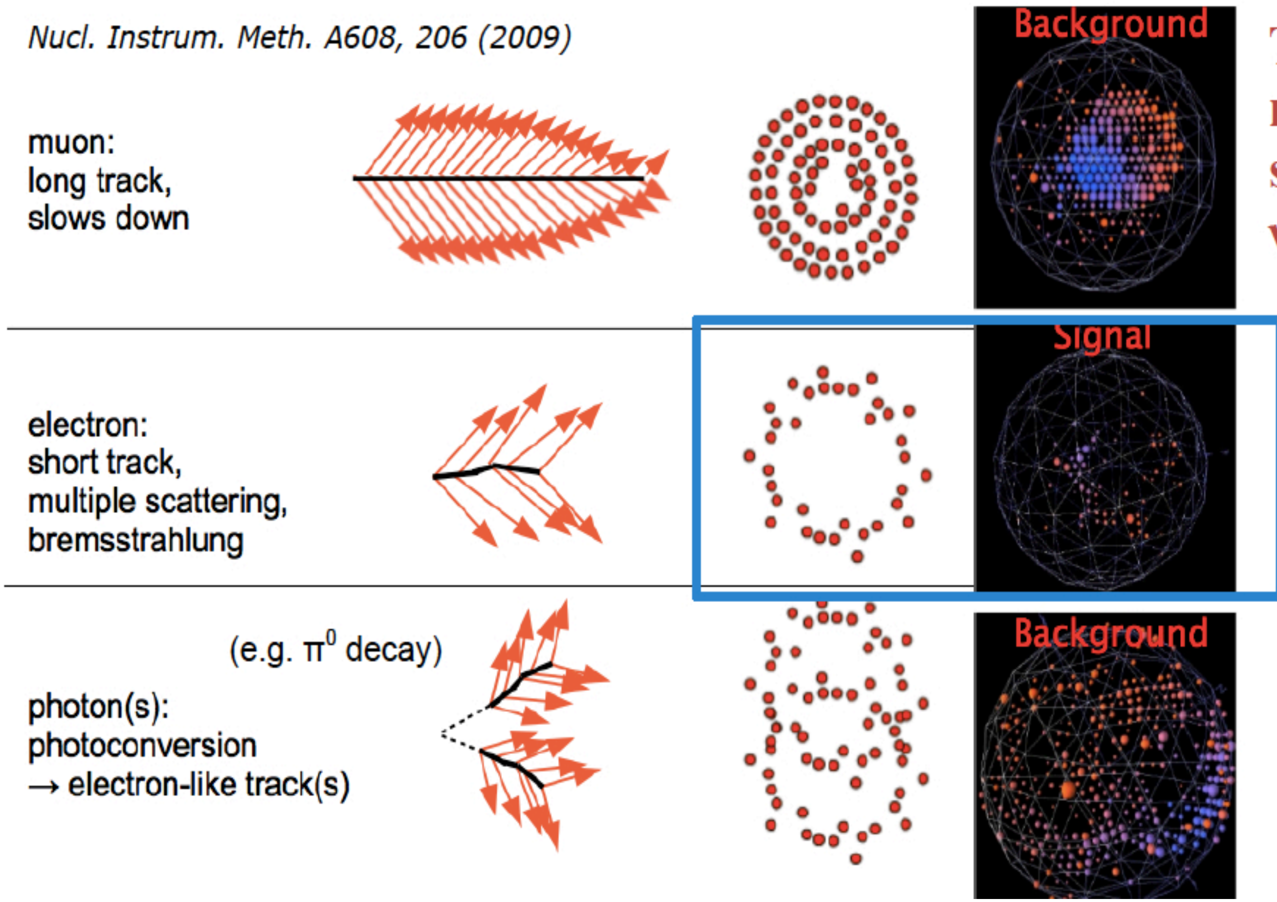
...motivated by the LSND anomaly

- LSND found an excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ 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 2ν mixing hypothesis:

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

Particle ID in MiniBooNE (mineral oil det.)

Cherenkov ring topology is used to differentiate between electrons and muons:



Track-Based-Likelihood reconstruction and event selection →

ν_e CCQE event selection cuts:

- 99% background rejection
- 20% signal efficiency

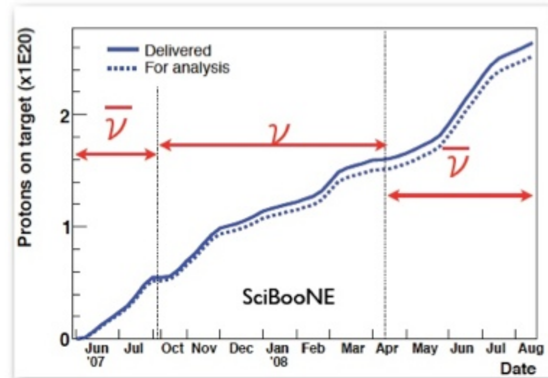
ν_e (or $\bar{\nu}_e$) signal

SciBooNE vs MiniBooNE

- different geometries
  - distance from target 100m vs 400m -> angular acceptance
- different nuclear target
  - plastic scintillator vs mineral oil -> C-H ratio is different
- different event selection, different event content in final sample
- different energy and spatial resolution
- different detector systematics
- SciBooNE as near detector for MiniBooNE: flux and cross section uncertainties do not fully cancel

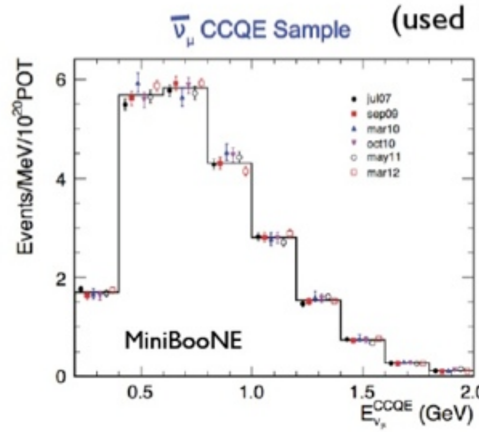
SciBooNE

- Data taking: Jun 2007-Aug 2008
- Total POT: 2.53×10^{20}
- Neutrino mode: 0.99×10^{20} POT
- Antineutrino mode: 1.53×10^{20} POT



MiniBooNE

- Data taking: 2002-2012
- Total POT: 19.8×10^{20}
- Neutrino mode: 6.5×10^{20} POT
- Antineutrino mode: 11.3×10^{20} POT (used 10.1×10^{20} POT)



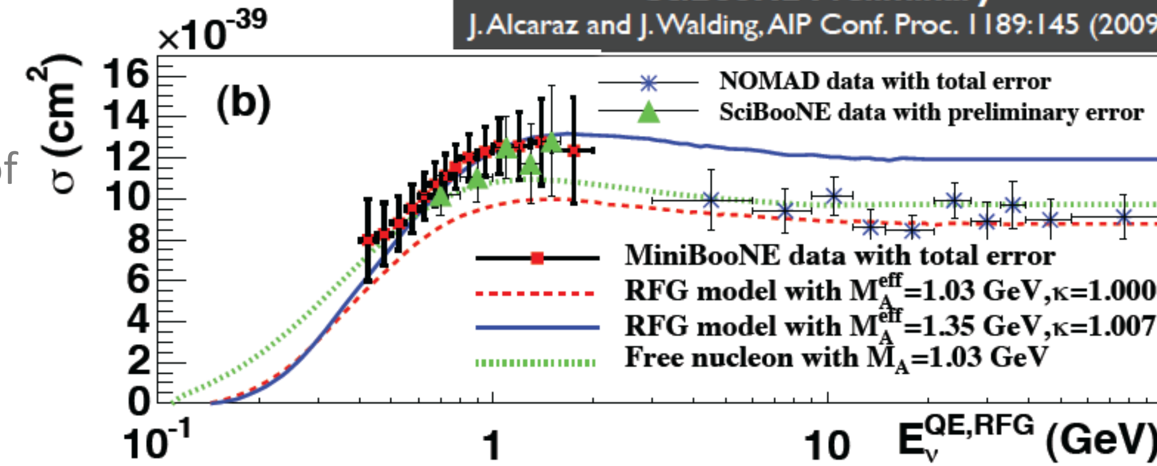
SciBooNE Results

- ν CC coh-π: Phys.Rev.D78, 112004 (2008)
  - No evidence of CC coh-π
- ν NC-π^0: Phys.Rev.D81, 033004 (2010)
  - Cross section and π^0 kinematics, MC agree with data
- ν NC coh-π^0: Phys.Rev.D81, 111102 (2011)
  - Clear evidence of coh-π, R-S model agrees with data
- $\bar{\nu}$ CC coh-π: preliminary results
  - Cross section ratio ~2σ away from zero
  - Data hint that non-zero CC coh-π events in very forward region (than R-S model)
- ν CC-π^0: preliminary results
  - Absolute cross section, working on syst. uncertainties
- K^+ production measurement at the BNB: Phys. Rev. D84, 012009
- CC inclusive production measurement: Phys. Rev. D83, 012005

CCQE

SciBooNE Preliminary
J. Alcaraz and J. Walding, AIP Conf. Proc. 1189:145 (2009)

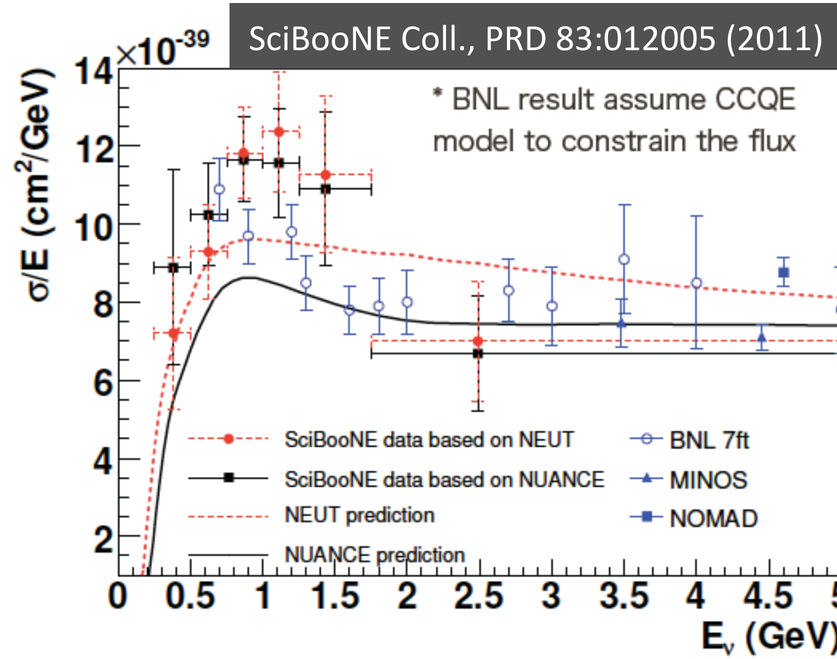
- Neutrino energy from kinematics of MRD-stopped muons
- fit μ, μ+p, μ+π samples to extract $\sigma^{QE}(E_\nu)$ along with data-driven constraint on inelastic backgrounds



CC inclusive

SciBooNE Coll., PRD 83:012005 (2011)

- Select MIP-like energetic track (P_μ>0.25GeV)
- Reject side-escaping muons.
- 3 samples:
  - SciBar-stopped (P_μ,θ_μ)
  - MRD-stopped (P_μ,θ_μ) - CCQE sample
  - MRD-penetrated (θ_μ)

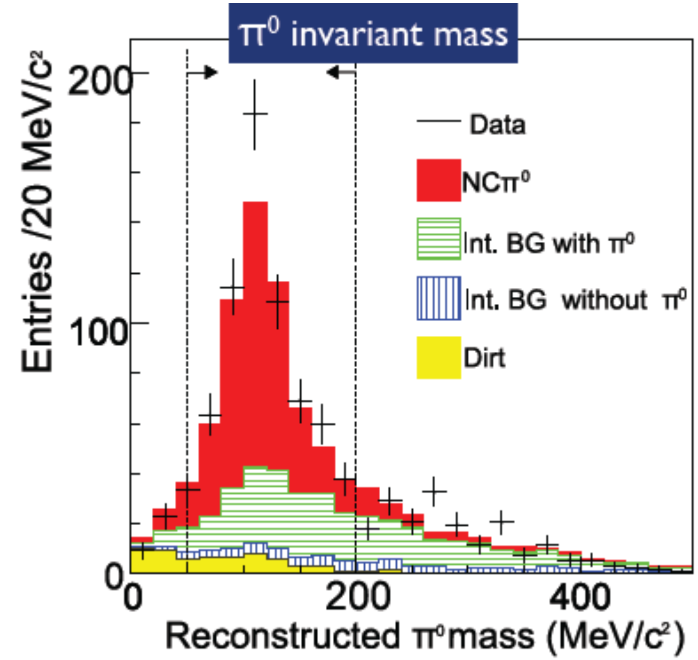


NC-1π^0

- Select events with 2 γ-like tracks converting in SciBar and pointing to common vertex
- EC/MRD for energy leakage, CC background suppression
- π^0 vertex, mass and kinematics from γ candidates
- NC-1π^0 cross section relative to CC inclusive:

SciBooNE Coll., PRD 81:033004 (2010)

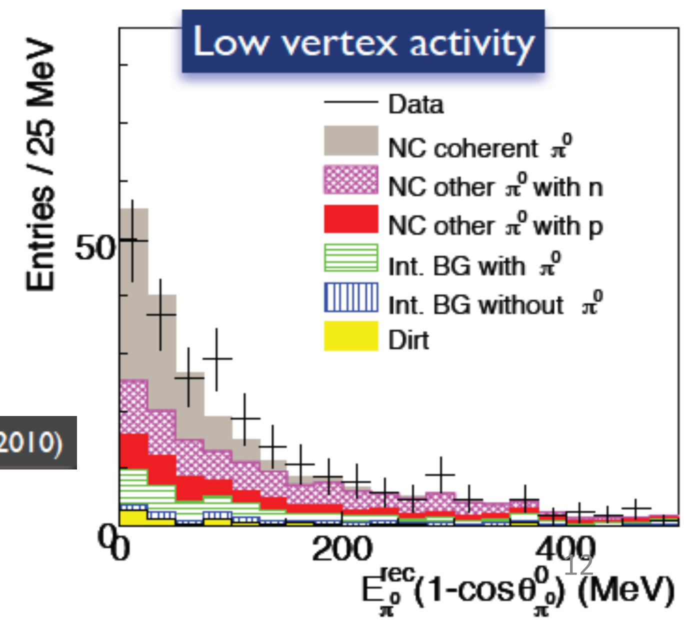
$\sigma(\text{NC-1}\pi^0) / \sigma(\text{CC}) = (7.7 \pm 0.5\ (\text{stat}) \pm 0.5\ (\text{syst}))\times 10^{-2}$



- Separate π^0 selection in two sub-samples:
- Low vertex activity: signal sample
- High vertex activity: background sample
- Fit the two $E_{\pi 0}(1\text{-}\cos\theta_{\pi 0})$ distributions
- Coherent π^0 production ⇔ low momentum transfer to nucleus ⇔ low values for $E_{\pi 0}(1\text{-}\cos\theta_{\pi 0})$

SciBooNE Coll., PRD 81:111102 (2010)

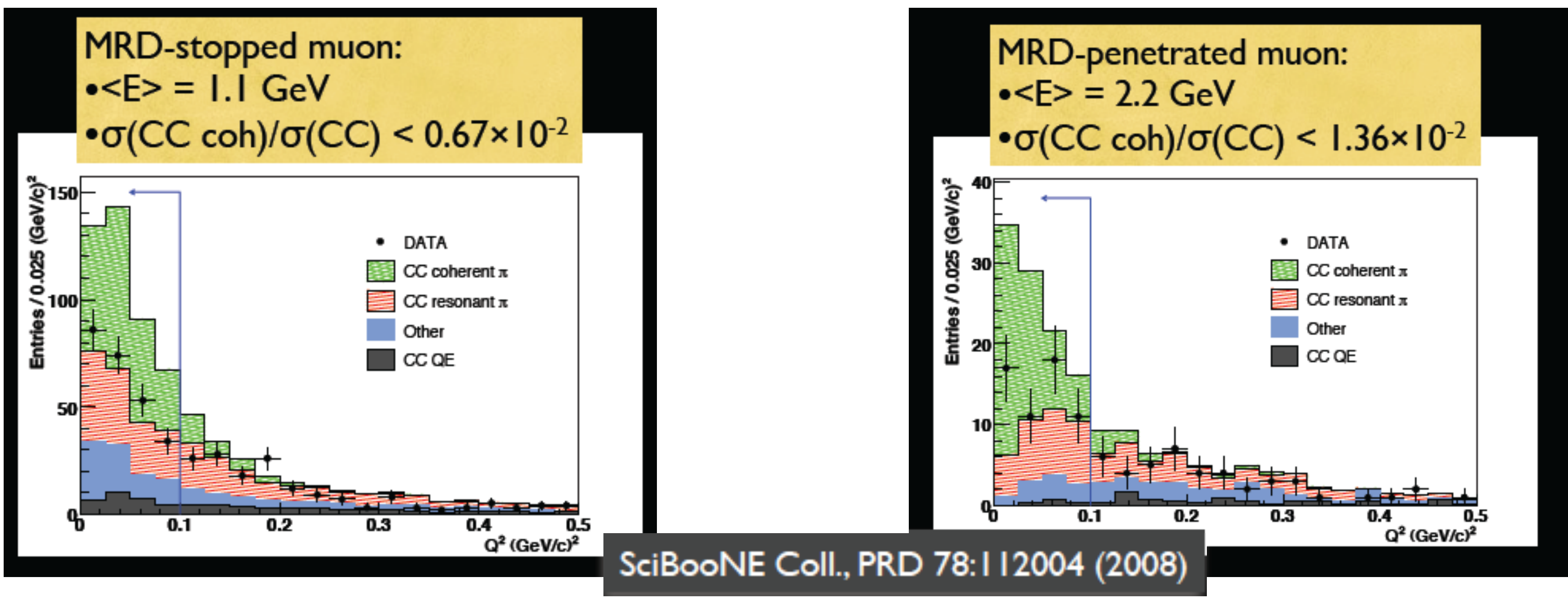
$\sigma(\text{NC coh})/\sigma(\text{CC}) = (1.16 \pm 0.24)\times 10^{-2}$



Coherent π^+ Production @ SciBooNE

- Select μ+π events with low vertex activity, forward pion, low Q2
- Additional CC samples to constrain backgrounds
- Two coherent π+ samples depending on muon range

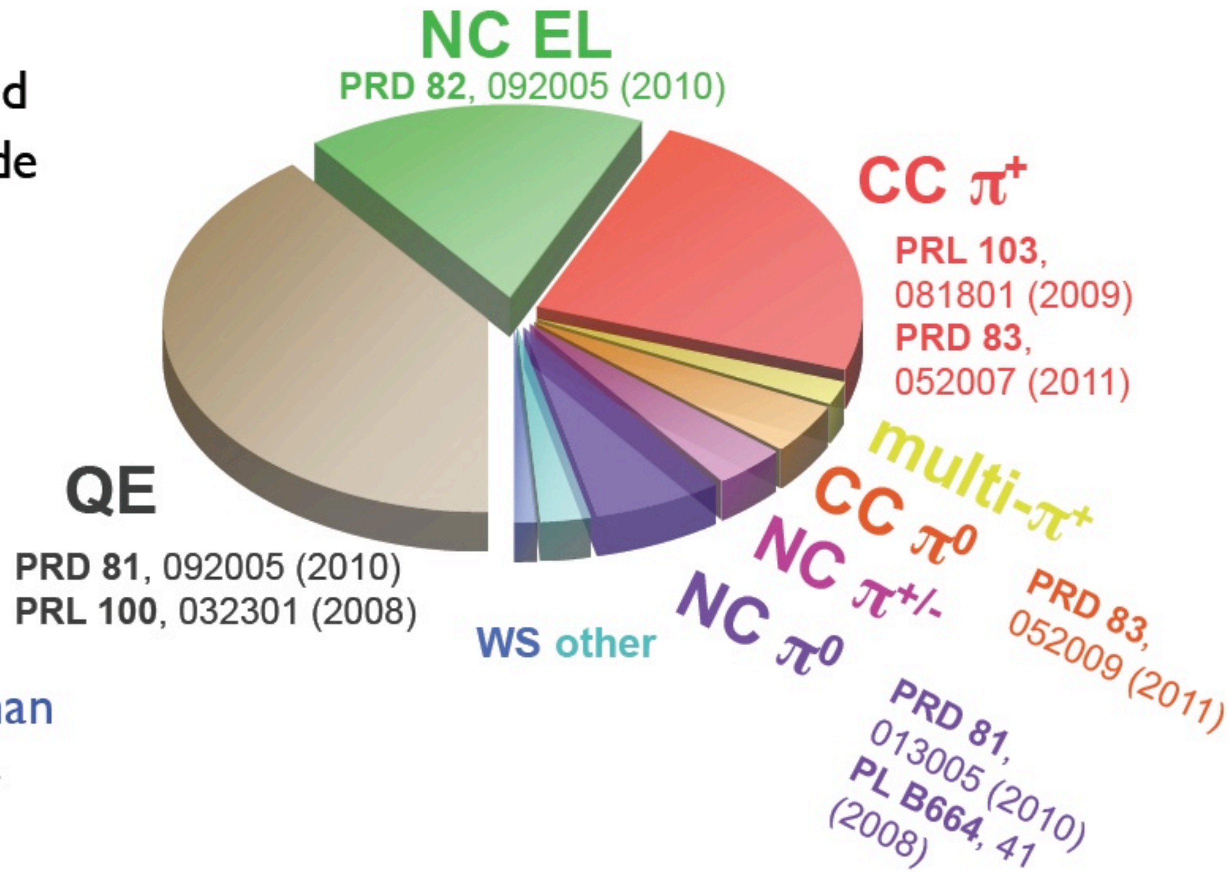
- No evidence for CC coherent π production at SciBooNE
- Compatible with K2K data, incompatible with Rein-Sehgal model (2.04x 10^{-2})



MiniBooNE results

- MiniBooNE has published ~90% of the total ν-mode rate

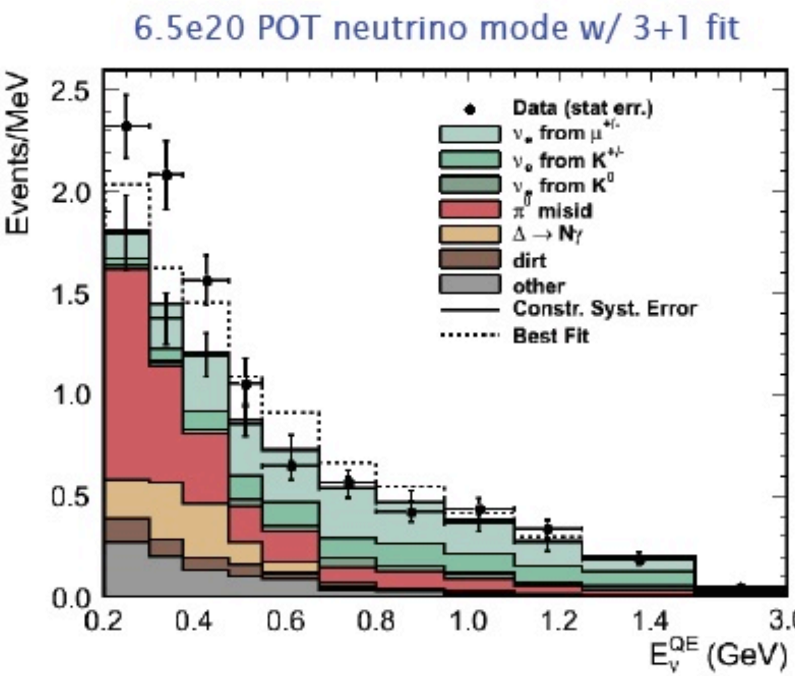
- Lots of interest: more than 500 citations from these papers in < 4 yrs!

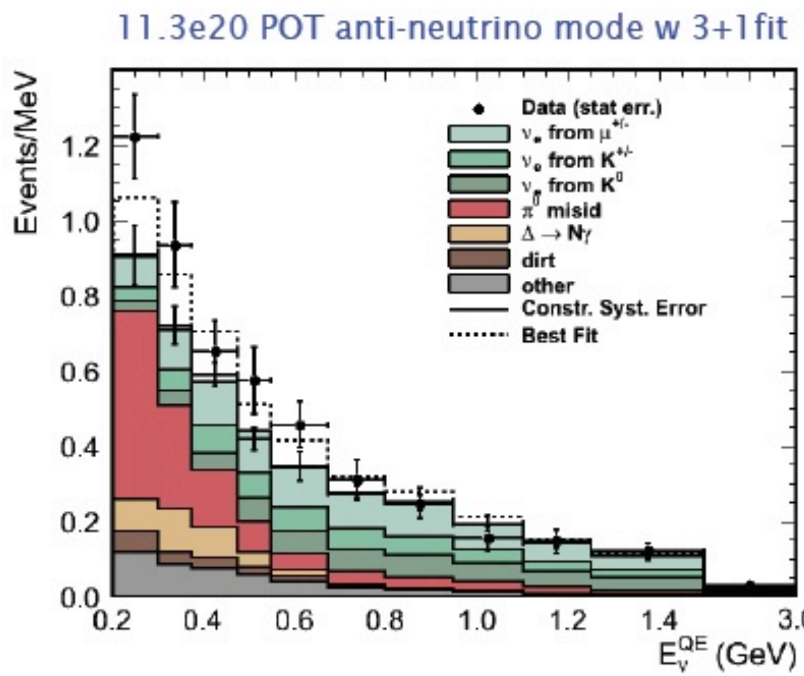


- MiniBoone observes an excess of n_e candidates in the 200-1500 MeV energy range in neutrino mode (3.4σ) and in anti-neutrino mode (2.5σ). The combined excess is 240.3±34.5±52.6 events (3.8σ) consistent with LSND excess -> >3 neutrinos ?

- The event excess is concentrated in the 200-475 MeV region where NC π^0 and other processes leading to a single γ dominates

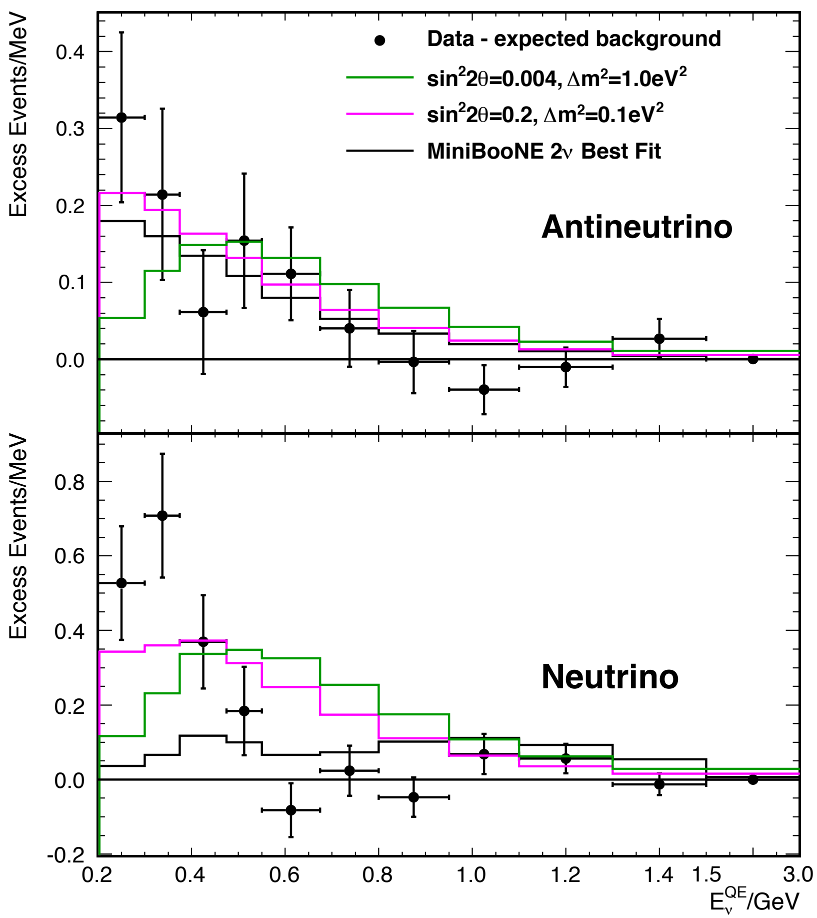
- It is not yet known whether the MiniBooNE excesses are due to oscillations, some unrecognized NC γ background, or something else MicroBooNE





Phys. Rev. Lett. 110, 161801 (2013)

Neutrino Event Excess from 200-1250 MeV	Antineutrino Event Excess from 200-1250 MeV
162.0±28.1±38.7 (3.4σ)	78.4±20.0±20.3 (2.8σ)

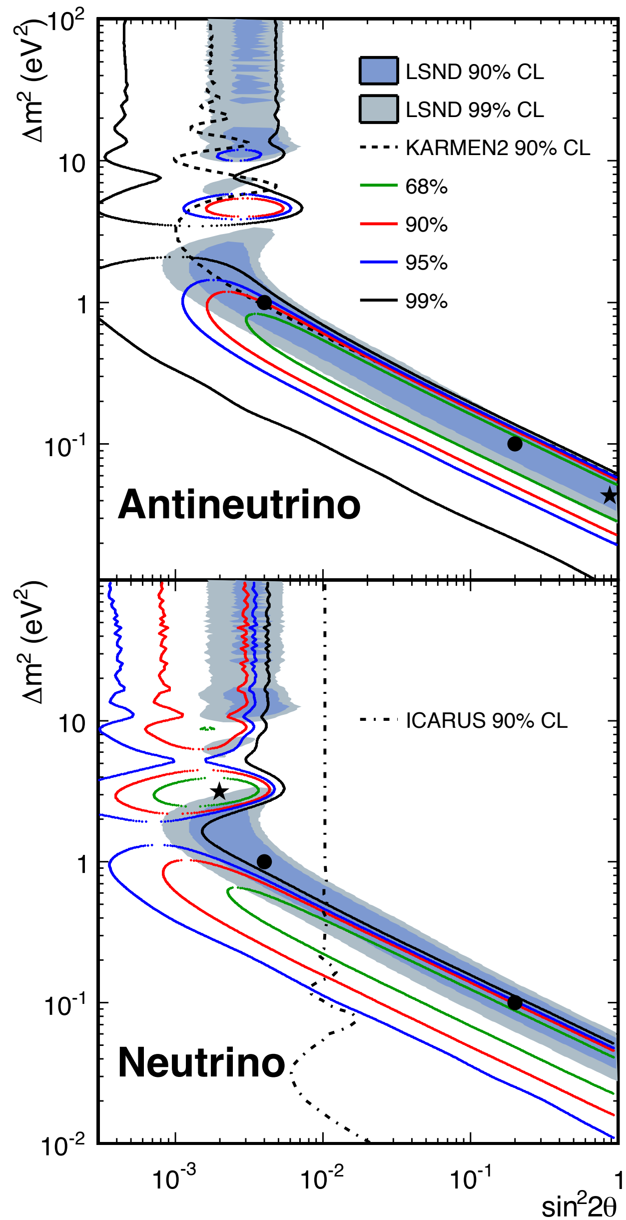


P_{bf} = 66% ,
P_{null} = 5.4%

P_{null} relative to P_{bf} = 0.5%

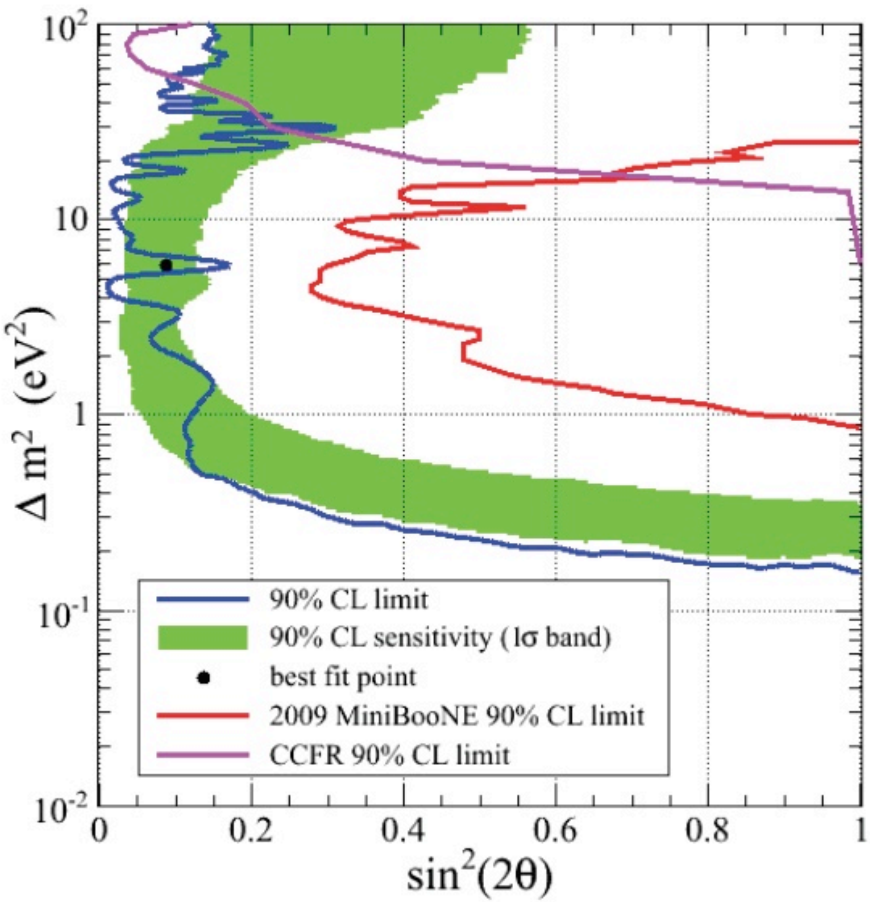
P_{bf} = 6.1%
P_{null} = 0.5%\

P_{null} relative to P_{bf} = 2.0%



Sci+Mini-BooNE combined fits result

SciBooNE+MiniBooNE Coll., PRD 86:052009 (2012)



- MiniBooNE results are very interesting

- LEP says that we have 3 active neutrinos
- LSND says that maybe we have >3 neutrinos (3 active + 1 sterile or ν_1, ν_2, ν_3, ν_4)

MiniBooNE sees excess.

If MiniBooNE and LSND excess are explained by sterile then

ν_μ - ν_e they observe must go through ν_μ -> ν_4 and then ν_4 -> ν_e

then no more tension.

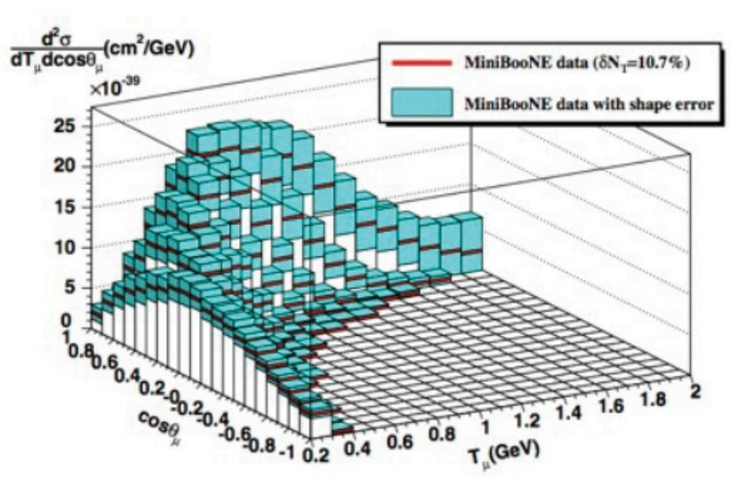
But the combined fit Mini+Sci-BooNE exclude a lot of the parameter region.

$\bar{\nu}_\mu$ CCQE σ's on ^{12}C only

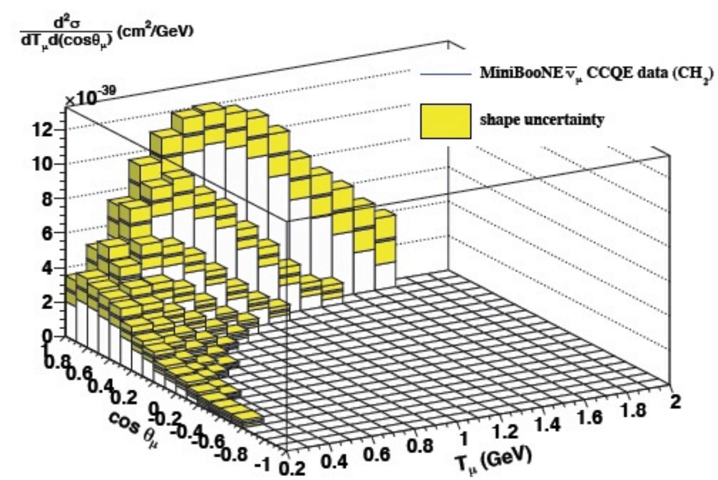
why is it important ?

- Found a big surprise in the ν_μ CCQE channel – studied a lot
  - important because CCQE is crucial for the ν_e appearance analysis.
  - Muon kinematics measured directly from the data
  - possible due to nuclear models

New analysis done using anti-ν sample help constraining various nuclear model predictions and it is “independent” from ν analysis. MicroBooNE will investigate this.



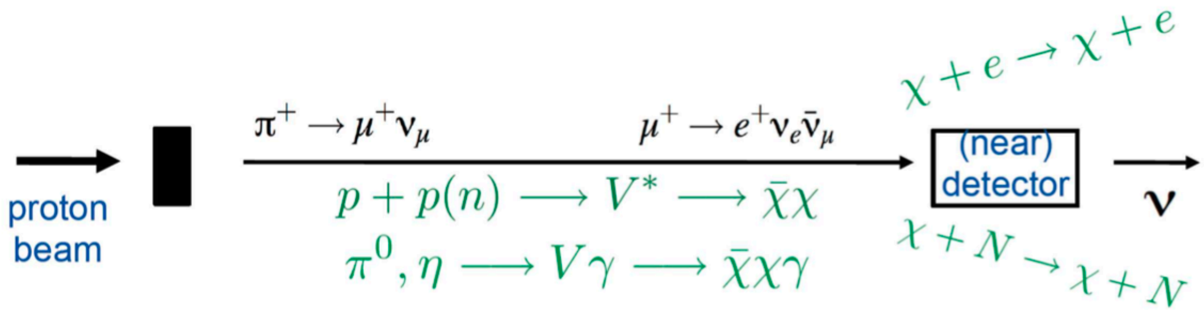
ν_μ CCQE



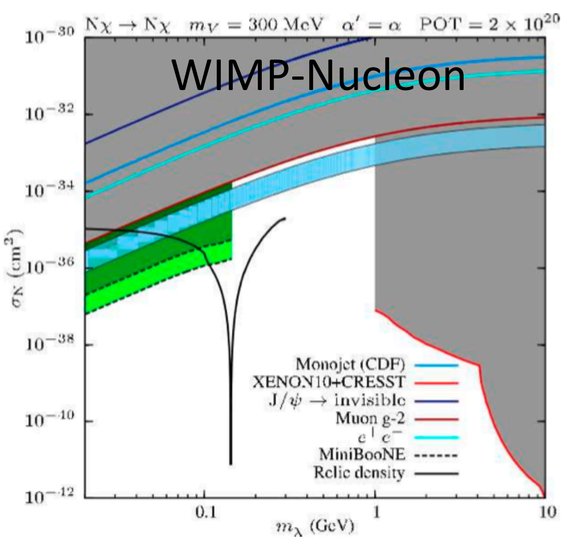
$\bar{\nu}_\mu$ CCQE

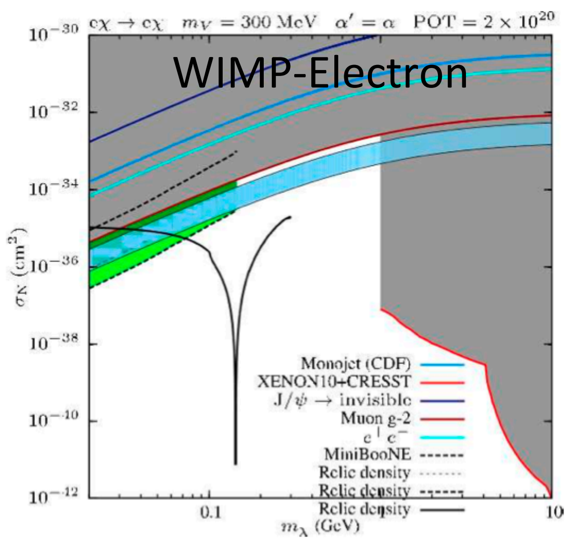
MiniBooNE Search for Dark Matter:

Test U(1) Dark Sector/light Models which are motivated by low mass (sub GeV) WIMPs and the muon g-2 anomaly.



- Dark light (V) couples to photons from beam π^0 decay.
- WIMPs (χ) travel to detector and scatter off nucleons or electrons. (for details see **arXiv:1211.2258)**





- Analyzing current data sets (1.8E21 POT), proposing short summer beam off target run which significantly reduces neutrino backgrounds. First results later this year!
- Overlaps muon g-2 region.

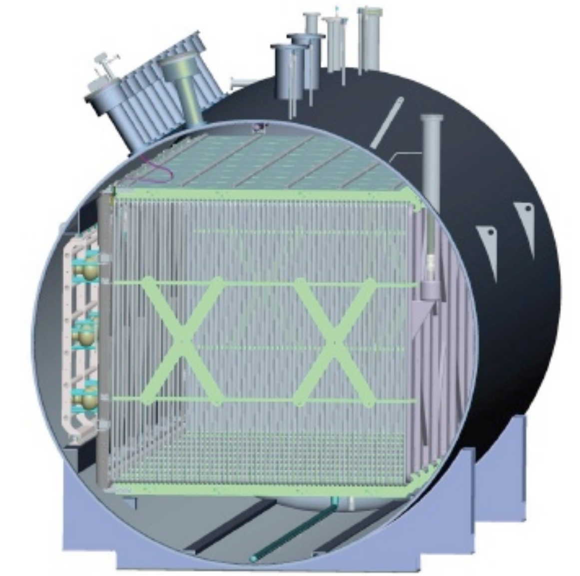
MicroBooNE

- Liquid Argon Time Projection Chamber (LAr TPC)
  - 170 tons LAr (~84t active)
  - located on the BNB
- Major advance in neutrino detector technology
  - Achieve Ar purity without evacuation
  - Foam insulation
  - Cold electronics
  - 2.5 m drift distance (1.6ms)

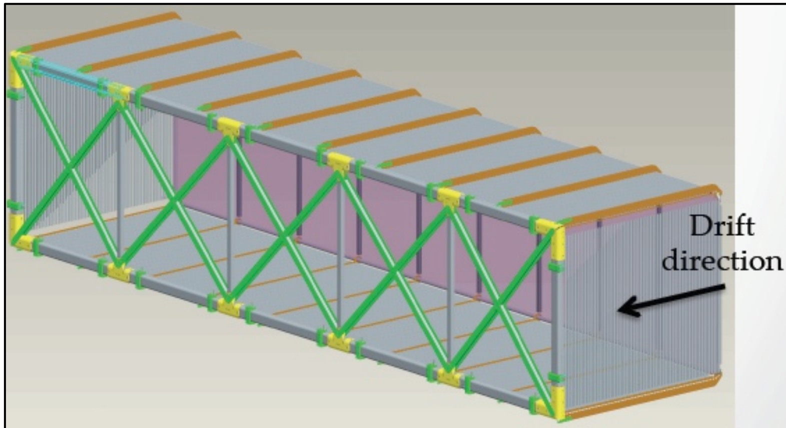
Simplify det. construction, make possible to build bigger detectors

Low noise

- TPC active volume
  - Length: 10.4m
  - Height: 2.3m
  - Width: 2.5m
  - 3mm wire pitch
  - 3wire planes
    - 2 induction planes
    - 1 collection plane
- Scintillation light detection by PMTs viewing LAr volume through wire plane



TPC in cryostat



TPC field cage, cathode, & anode planes

MicroBooNE Goals

- Investigate the source of low energy excess observed by MiniBooNE by using the unique capability of LAr TPC in distinguish between electron and photons - MiniBooNE excess due to electrons = confirm sterile neutrino

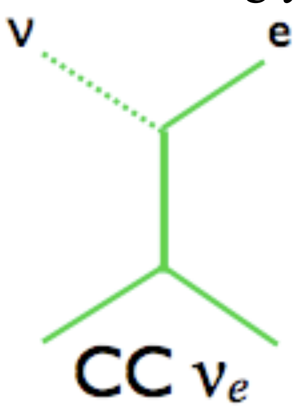
- Make the first high-statistics measurements of neutrino interactions in Argon

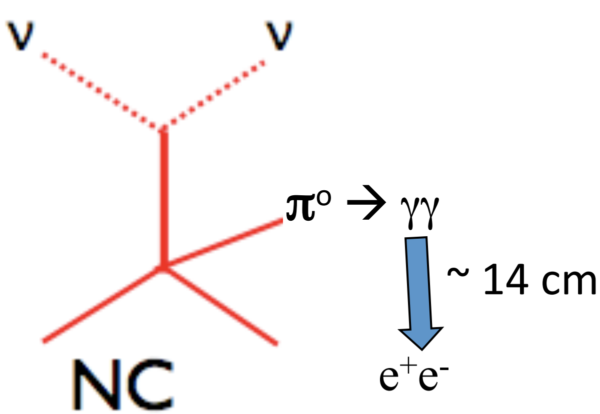
- Fully test LAr TPC technology at large scale that will serve as a R&D work for design and operation of multi-kiloton LAr detector (LBNE)

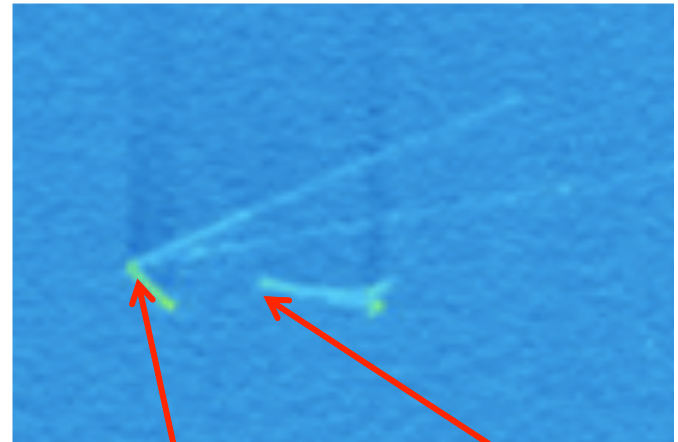
- Development a full reconstruction of neutrino interactions in LAr

What is the MiniBooNE excess due to? Electrons or Photons?

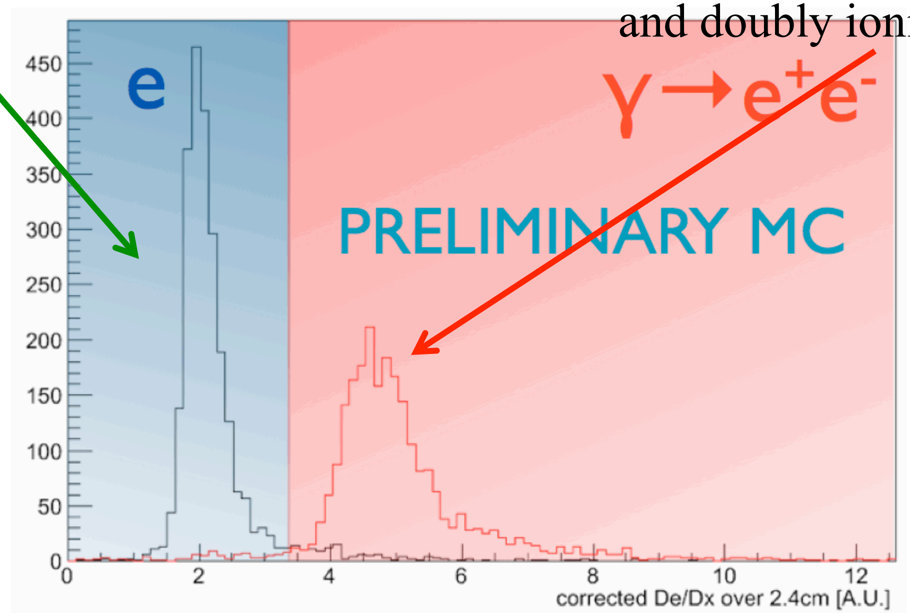
Electron : Connected to primary vertex
And singly ionizing track







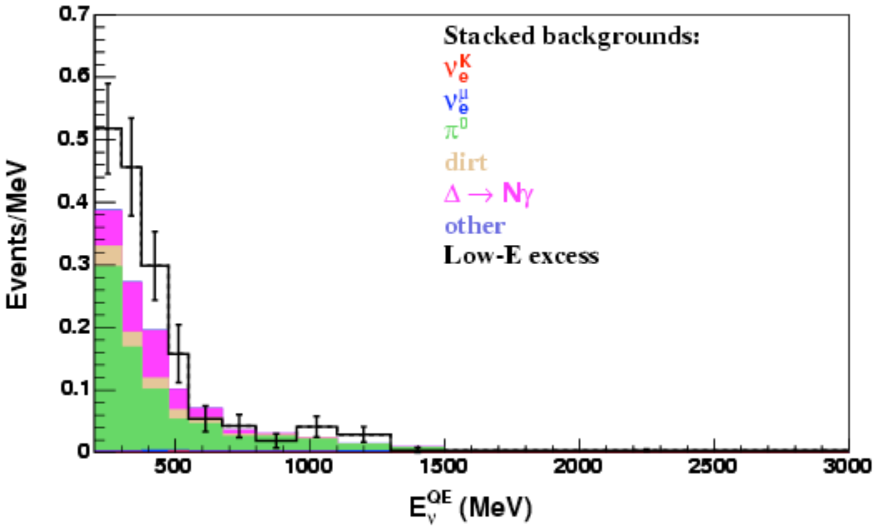
Photon: Gap between primary vertex and conversion point and doubly ionizing track



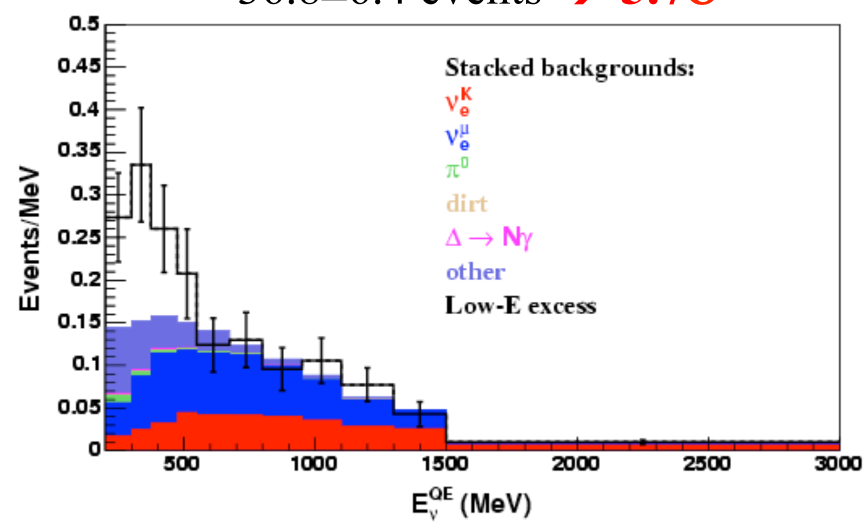
Physics Motivation I. Excess due to Electrons.

Cuts to Select Electrons, Reject γ's

Excess NOT due to electrons



Excess IS due to electrons
36.8±6.4 events → 5.7σ

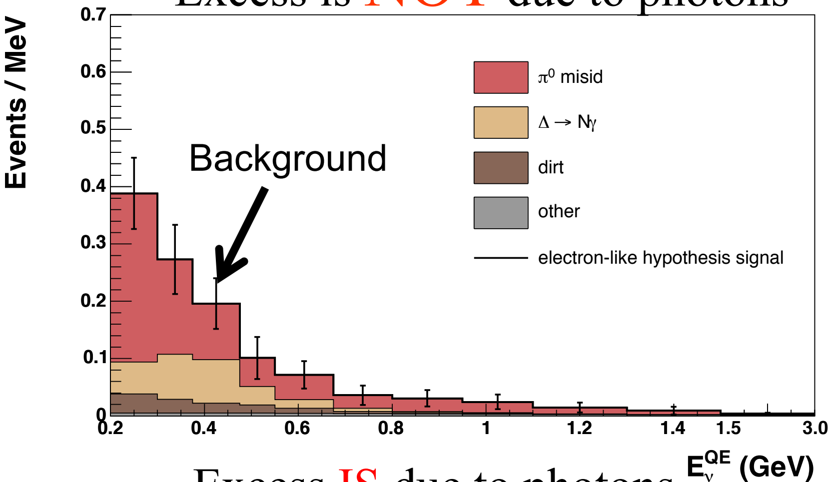


(Estimated from MiniBooNE rates)

Physics Motivation. Excess due to: Photons.

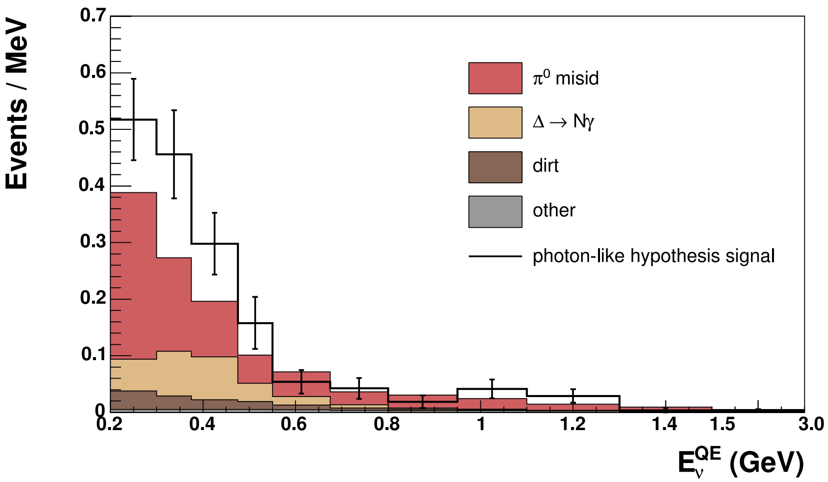
Cuts to Select Photons, Reject e’ s

Excess is NOT due to photons



Excess IS due to photons

36.8±8.9 events → 4.1σ



(Estimated from MiniBooNE rates)

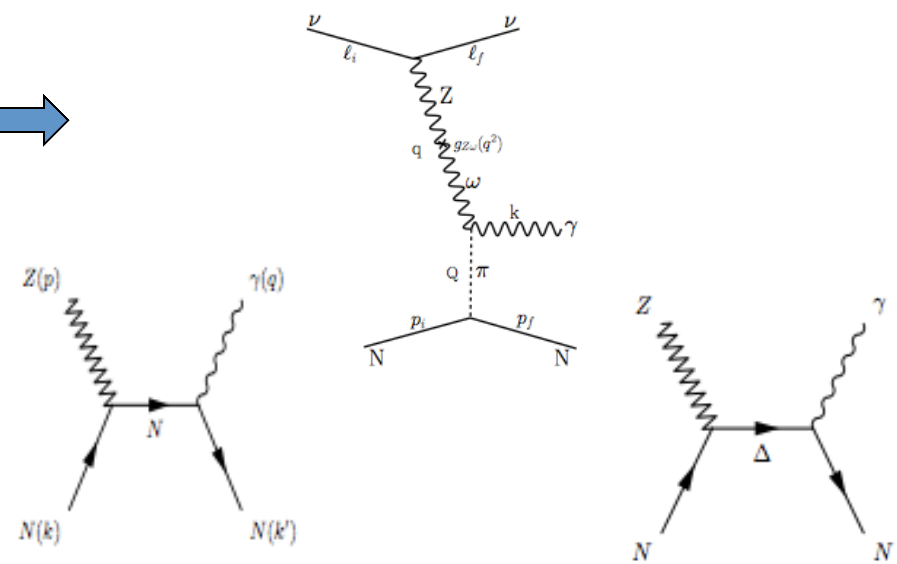
- Background: γ or π^0

  OR

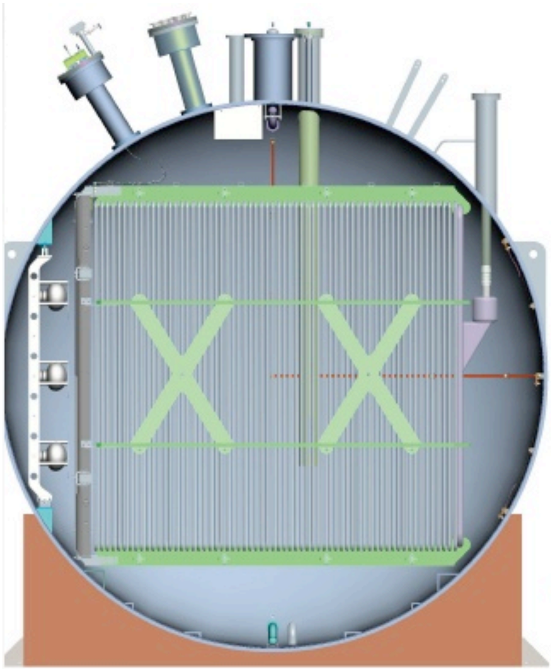
- Radiative ν interaction

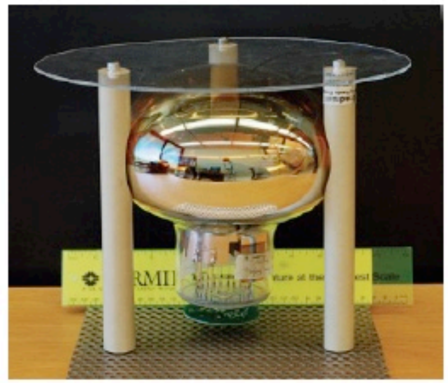
  Examples:

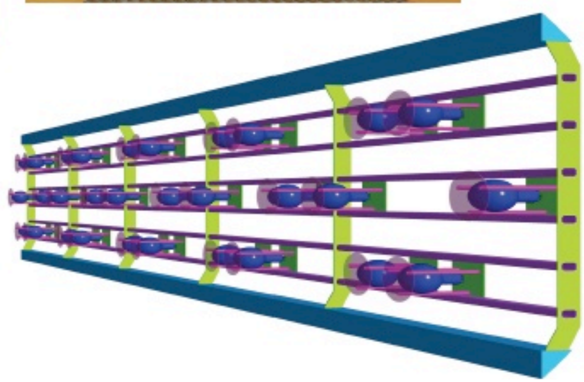
- R. Hill arXiv: 0905.0291
- Jenkins et al arXiv:0906.0984
- Serot et al arXiv: 1011.5913

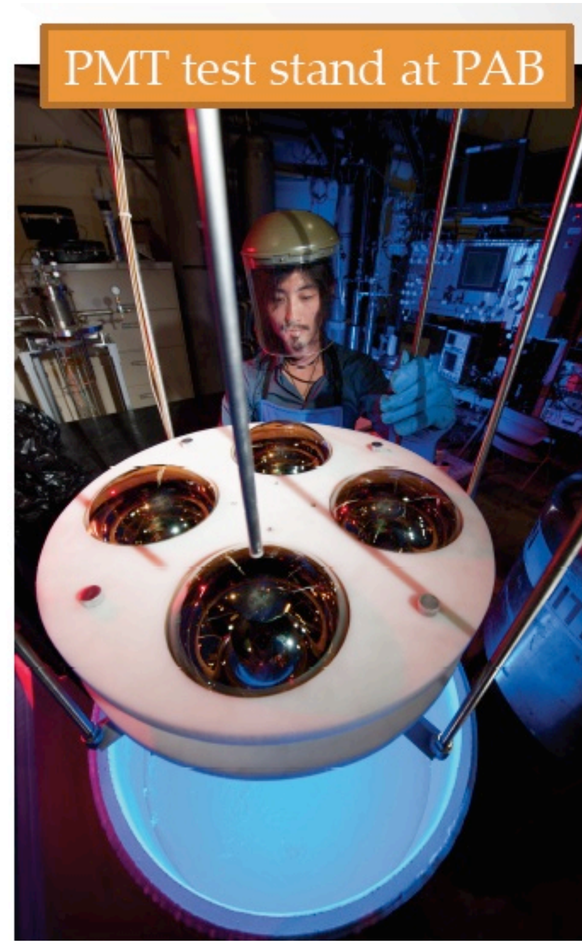


PMT system





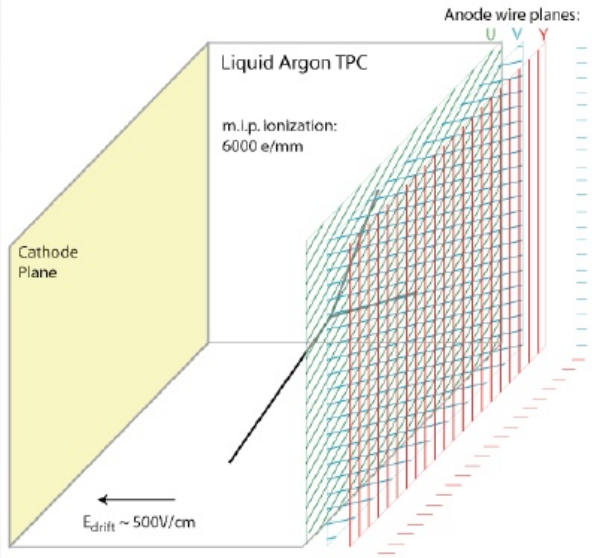




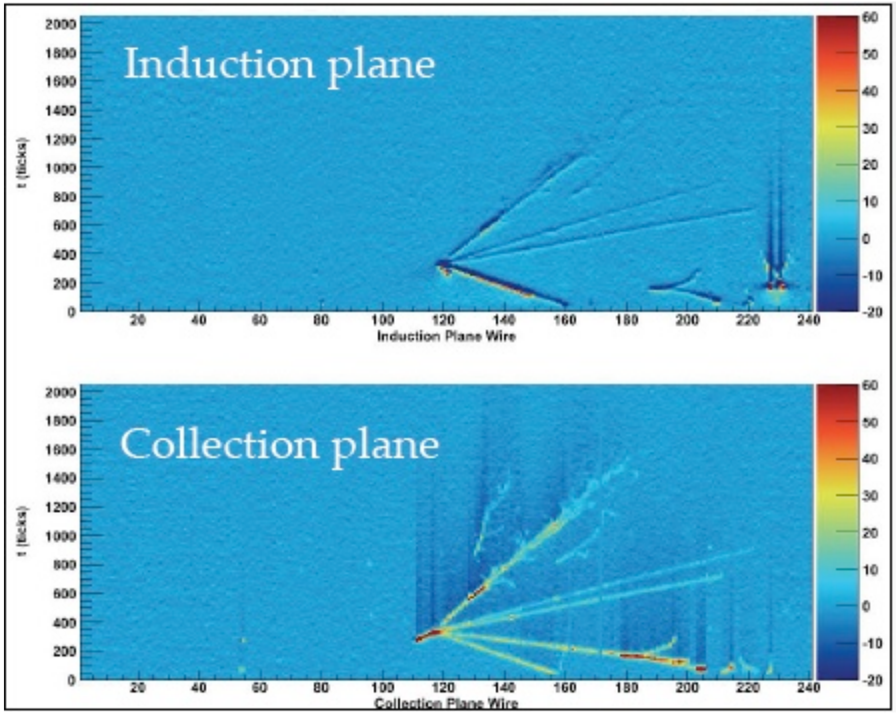
32 PMTs mounted on a support rack outside the region of E-field that will detect Ar scintillation light

Ongoing tests By MIT and St. Mary's University of Minn. to study properties of wavelength shifter plates and PMTs

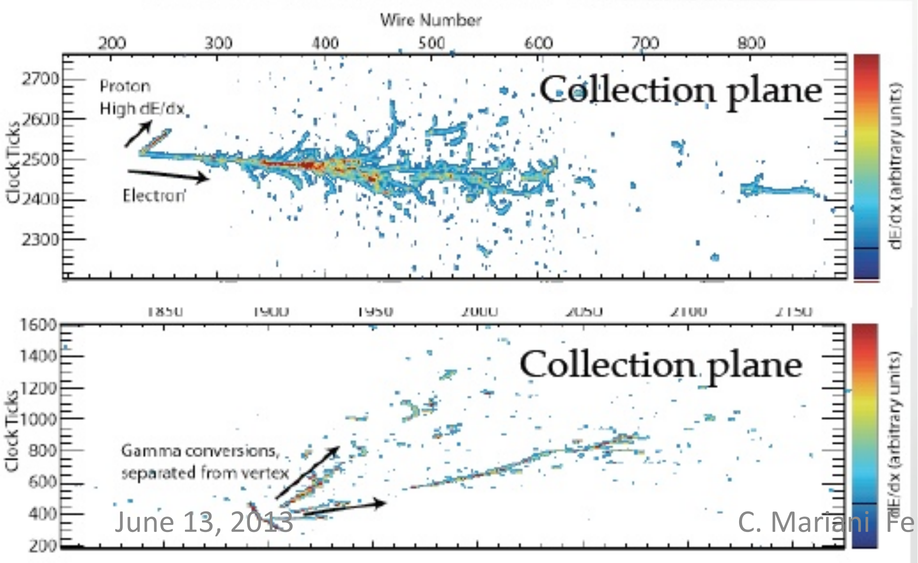
LAr TPC Operation



ArgoNeut neutrino candidate



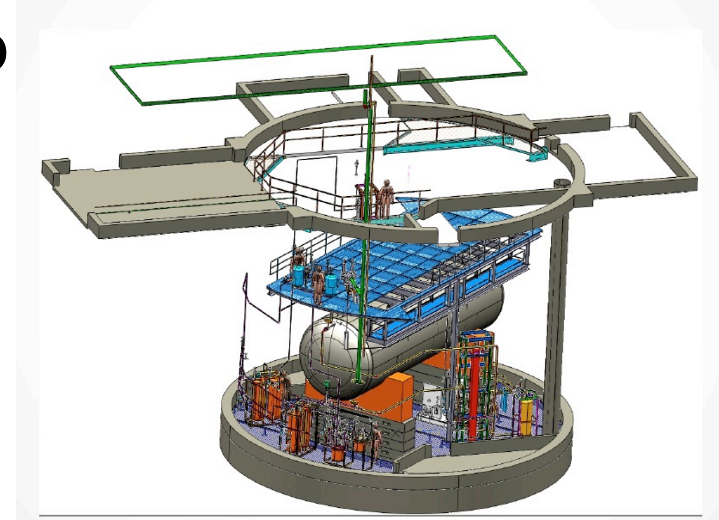
Geant 4 MicroBooNE simulation



What data we can expect ?

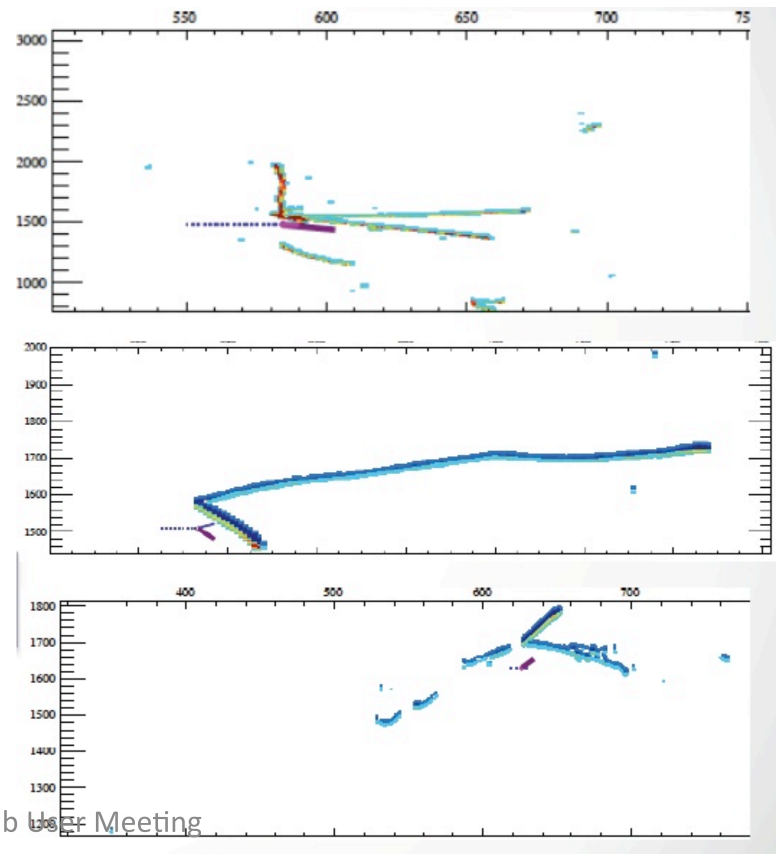
MicroBooNE will start the data taking in 2014

Expected 6.6x10^{20} POT in 3 years



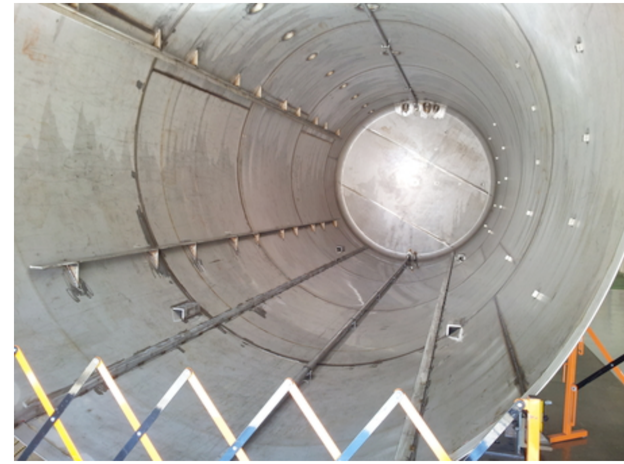
Expected event rates for 6.6 x 10^{20} POT

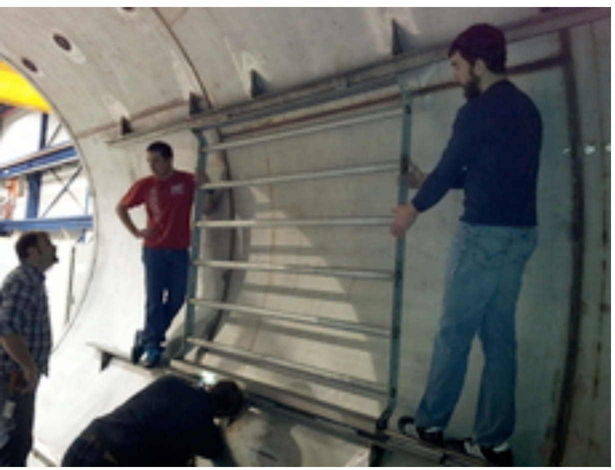
production mode	# events
CC QE ($\nu_\mu n \to \mu^- p$)	60,161
NC elastic ($\nu_\mu N \to \nu_\mu N$)	19,409
CC resonant π^+ ($\nu_\mu N \to \mu^- N \pi^+$)	25,149
CC resonant π^0 ($\nu_\mu n \to \mu^- p \pi^0$)	6,994
NC resonant π^0 ($\nu_\mu N \to \nu_\mu N \pi^0$)	7,388
NC resonant $\pi^\pm$ ($\nu_\mu N \to \nu_\mu N' \pi^\pm$)	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

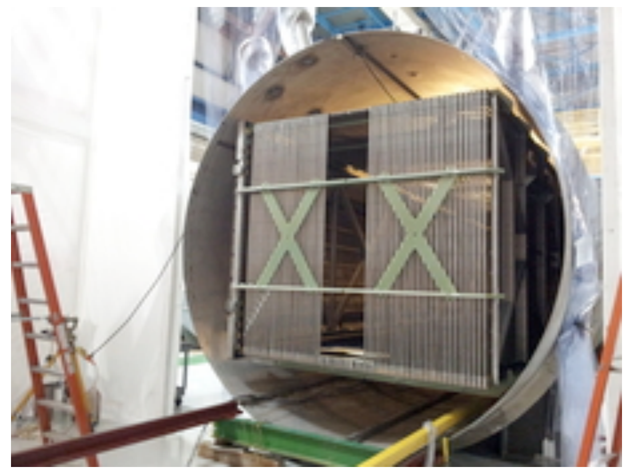


MicroBooNE Progress

Cryostat delivered, installed and cleaned at DAB







TPC inserted into the cryostat

MicroBooNE Progress

Building ready

MicroBooNE Progress

Wire installed into the TPC

Conclusions

SciBooNE and MiniBooNE have and continue to produce important neutrino cross-section and oscillation results

MiniBooNE observe an excess of 240±34.5±52.6 (3.8σ) events in electron neutrino samples with combined neutrino and anti-neutrino data but no anti-ν disappearance observed in SciBooNE/MiniBooNE disappearance analysis

MiniBooNE has reached 10 years of running period, great success for the experiment and the BNB – New proposal MB+

New analysis and search for Dark Matter in MiniBooNE data

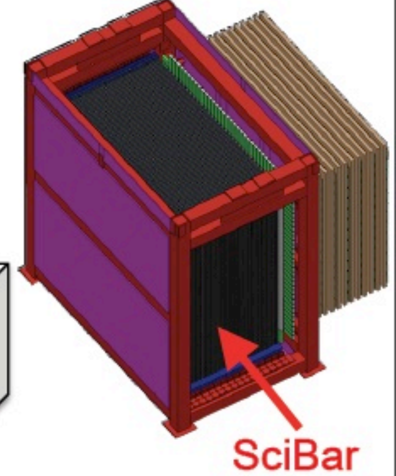
Neutrino and anti-neutrino cross-sections are beginning to tightly constrain models for proposed for nuclear interactions

Oscillation results depend upon nuclear effects, experimental resolution will be crucial to understand future oscillation experiments

MicroBooNE will be soon starting taking data, LAr promises very good spatial and energy resolution – great separation between electron and photons

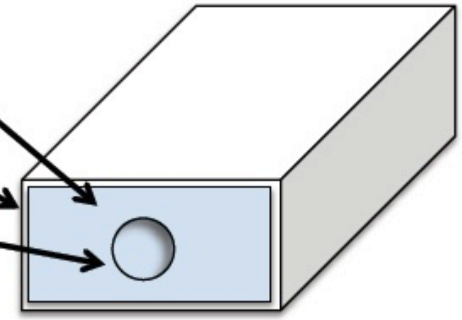
Backup

SciBooNE: how it works

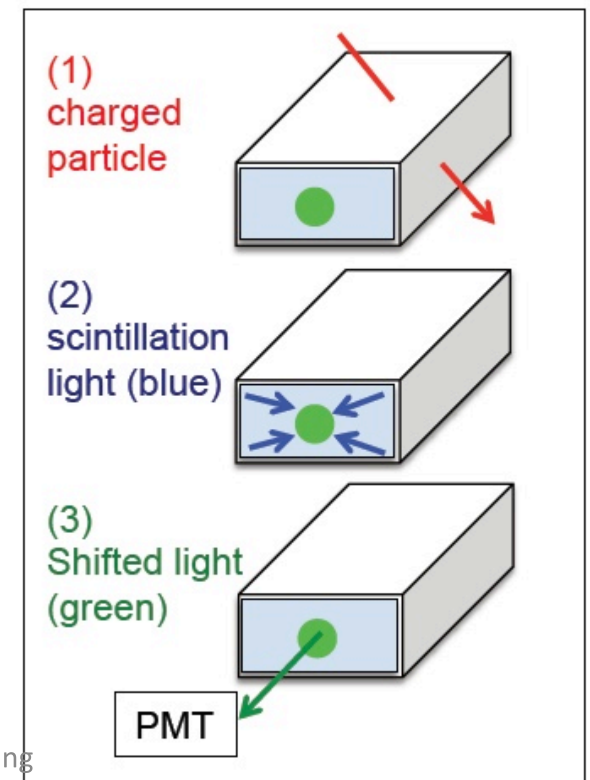


Extruded scintillation bar
- Polystyrene (PS), 1% PPO and 0.03% POPOP
- TiO_2 is merged in outer layer as a reflector
- hole for WLS fiber
- ~20 p.e. for MIP particle
- K2K, MINOS, SciBooNE, MINERvA, T2K...

Wave length shifting (WLS) fiber
- Absorb blue light, emit green light




Extruded scintillator production machine (Fermilab)



SciBooNE+MiniBooNE combined fits

- Simultaneous fit to MiniBooNE and SciBooNE Reconstructed Energy Distributions
- Only antineutrino events are oscillated in the fits (includes CCQE, CC1pi, etc.); neutrino events are constrained
- Model is simple, 2-neutrino oscillation model:

$$P_{\bar{\nu}_\mu \to \bar{\nu}_\mu} = 1 - \sin^2 2\theta \sin^2 1.27 \frac{\Delta m^2 L}{E}$$

Test Statistic: $\Delta\chi^2 = \chi^2\left(X(\Theta_{\text{phys}}), M(\Theta_{\text{phys}})\right) - \chi^2\left(X(\Theta_{\text{BF}}), M(\Theta_{\text{BF}})\right)$

$$\Theta : \Delta m^2, \sin^2 2\theta$$

$$\chi^2 = \sum_{i,j=1}^{n} \left(D_i - X_i\right)\left(M^{-1}\right)_{ij}\left(D_j - X_j\right)$$

D_i = data; 21-bin reconstructed energy distributions from MiniBooNE and SciBooNE

X_i = Monte Carlo predictions for MiniBooNE and SciBooNE = $X_i^{RS}\left(\Delta m^2, \sin^2 2\theta\right) + X_i^{WS}$

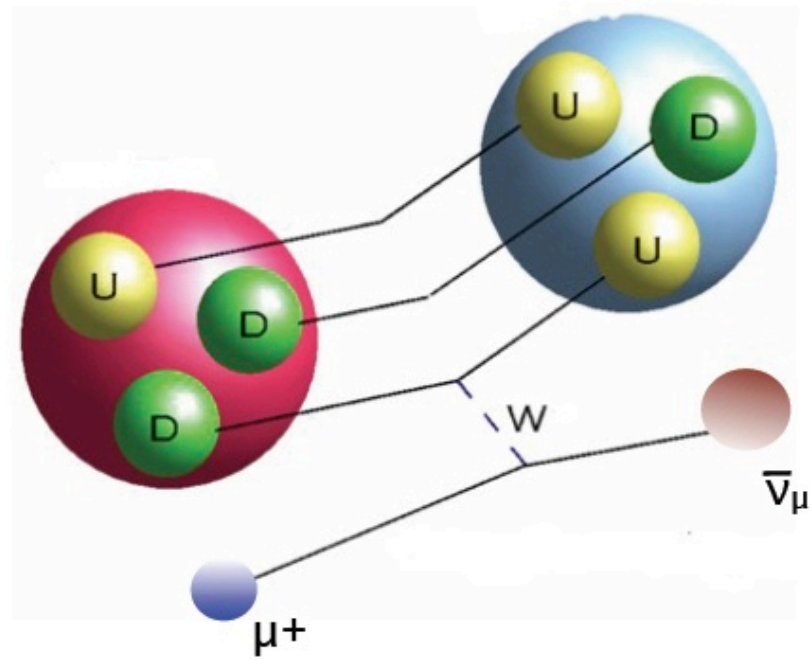
M = covariance matrix for uncertainties in total event rate (RS+WS)

21 bins in E_ν^{QE} from 300 MeV to 1.9 GeV, for SB and MB (n = 42)

RS: antineutrinos
WS: neutrinos

$\bar{\nu}_\mu$ CCQE σ's on ^{12}C only

1. Two subevents
   - consistent with prompt μ + decay e
2. In time with ν beam
3. T_μ > 200 MeV
   - removes beam-unrelated e's
4. 2nd subevent vertex consistent prompt particle
   - based on observed μ kinematics
5. μ/e separation PID
   - single-pion bkgs look more e-like
6. 5m fiducial volume
7. Low veto activity
   - containment + nothing coming in



Identical selection to ν_μ CCQE analysis:
single μ, 0 π, any # nucleons