The SciBooNE Experiment

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HEP Seminar @ Northwestern University

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Introduction

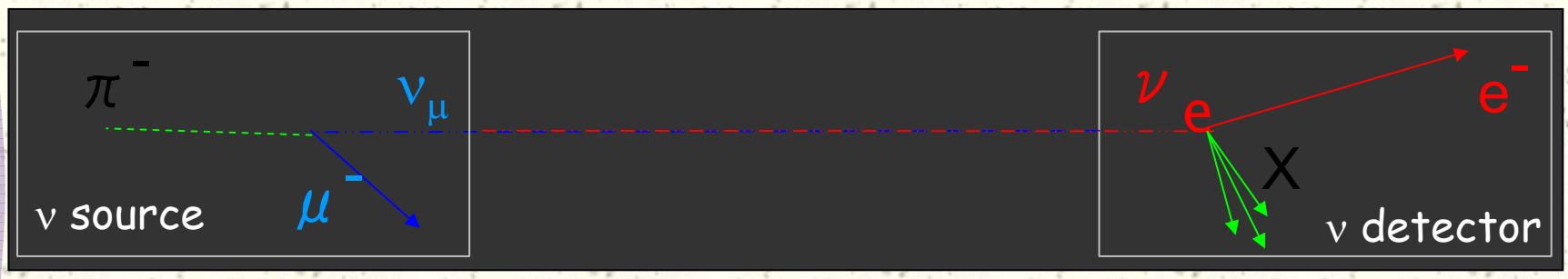
Neutrino oscillation

IF neutrinos have (different) mass, states are a mixture of the mass states

Flavor eigenstates

Mass eigenstates

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \begin{matrix} \cdots m_1 \\ \cdots m_2 \end{matrix}$$

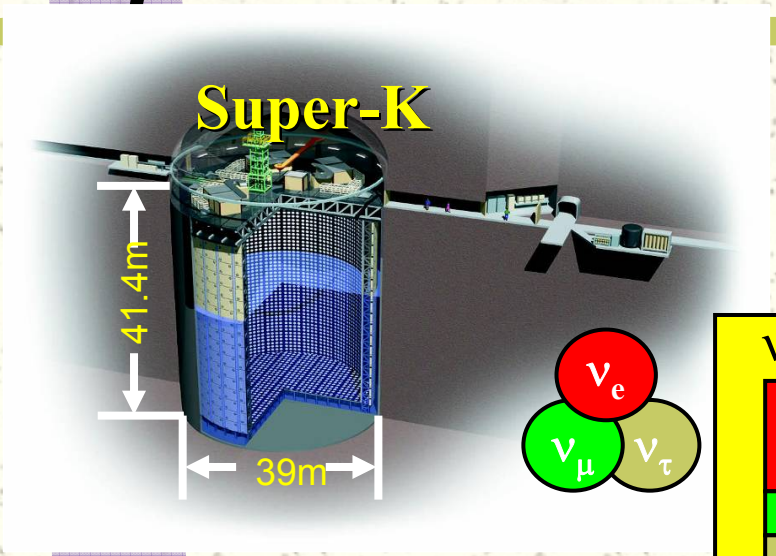


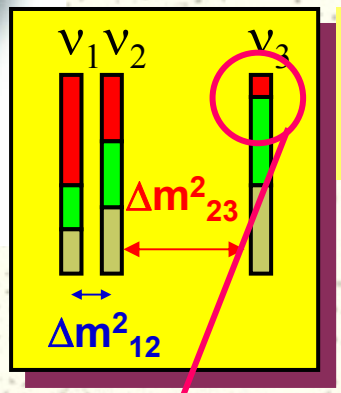
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \cdot \sin^2 \frac{1.27 \cdot \Delta m^2 \cdot L}{E_\nu}$$

2 fundamental parameters
- $\Delta m^2 \leftrightarrow$ period
- $\theta \leftrightarrow$ magnitude

2 experimental parameters
- L = distance travelled
- E = neutrino energy

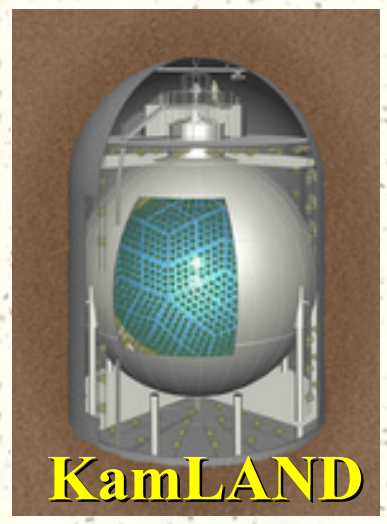
Neutrino Oscillation experiments (1998~)

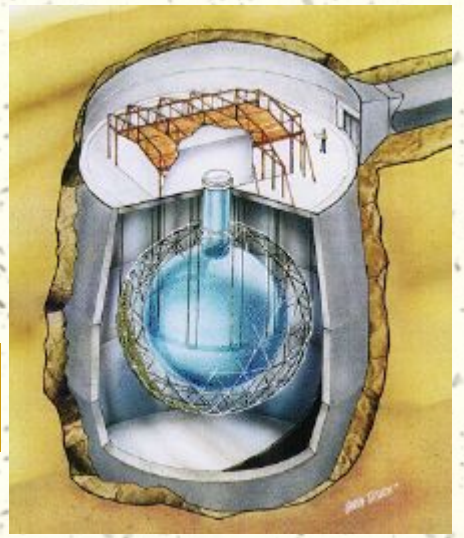




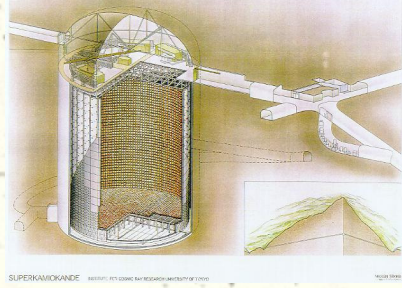
Neutrino masses (Δm_{12}^2, Δm_{23}^2)
Mixing Angles (θ_{12}, θ_{23})

$\theta_{13} \rightarrow \delta$





Next step…



ν_e ν_μ ν_τ

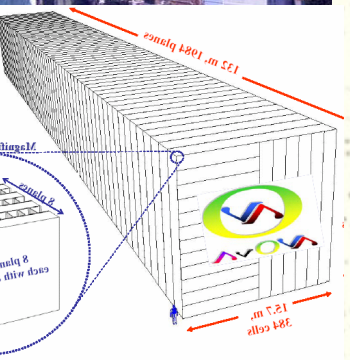
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{MNS}\, V_M^{CP} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

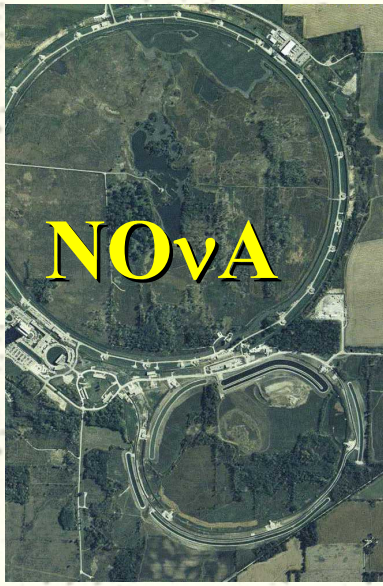
$$c_{ij} = \cos\theta_{ij}$$

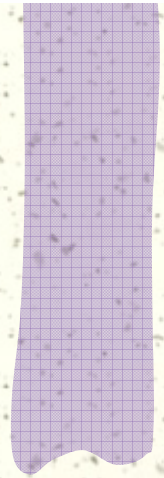
$$s_{ij} = \sin\theta_{ij}$$

ν_1 ν_2 ν_3

$$U_{MNS} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric}} \times \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Cross Mixing}} \times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}}$$

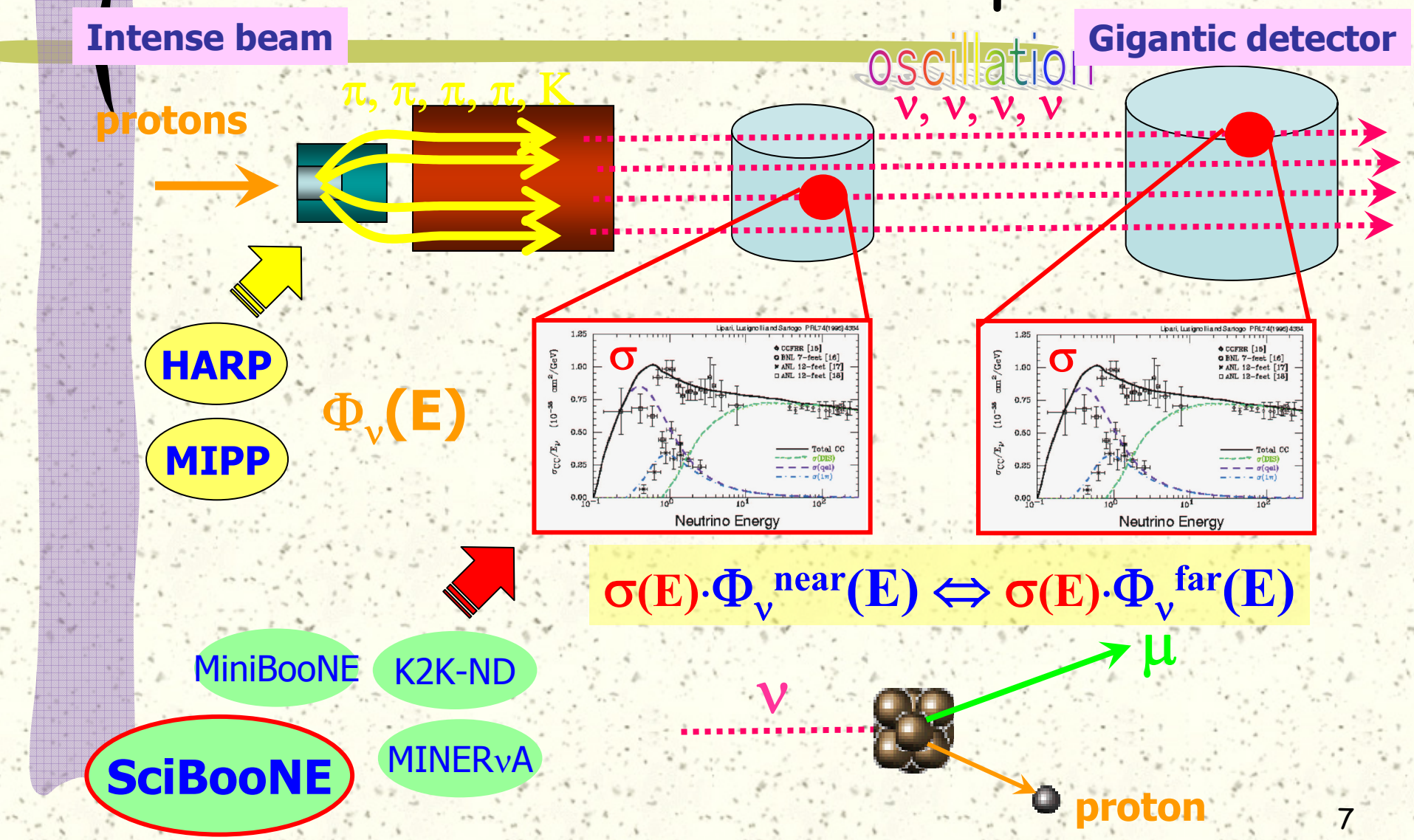






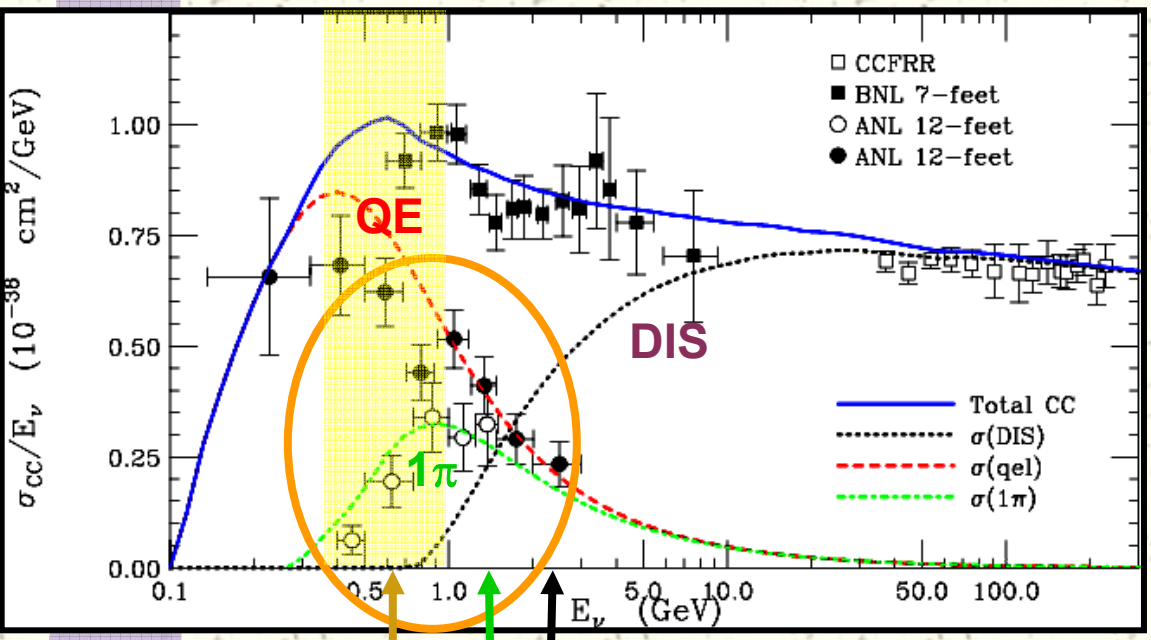
- Discover the last oscillation channel
  - θ_{13}
- CP violation in the lepton sector $(\nu, \bar{\nu})$
  - δ
- Mass hierarchy
  - **The sign of Δm_{23}^2**
- Test of the standard ν oscillation scenario (U_{MNS})
  - Precise measurements of ν oscillations ($\pm\Delta m_{23}^2$, θ_{23})

Principle of accelerator neutrino oscillation experiment



Neutrino-nucleus cross sections

Future neutrino oscillation experiments need precise knowledge of neutrino cross sections near 1GeV



MINOS, NuMI

K2K, NOvA

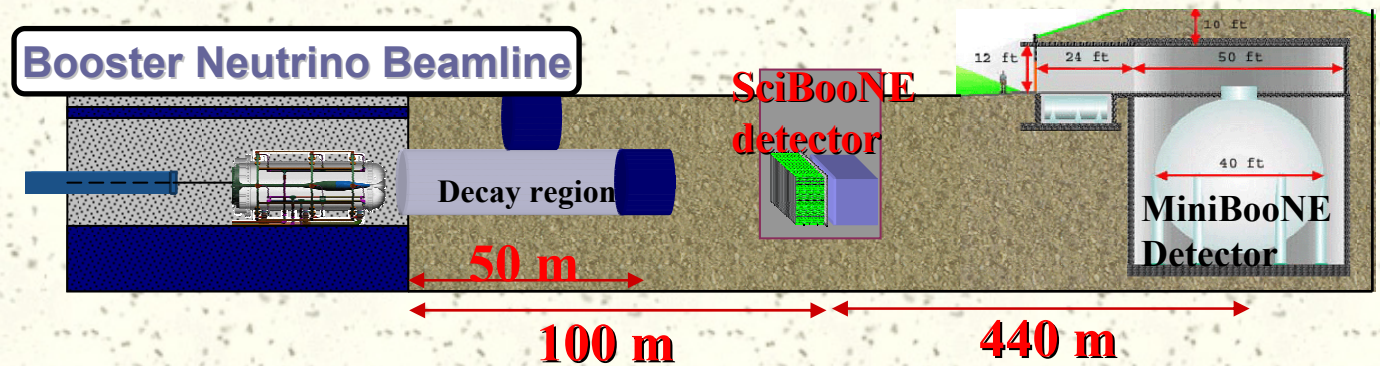
MiniBooNE, T2K, SciBooNE

Super-K atmospheric ν

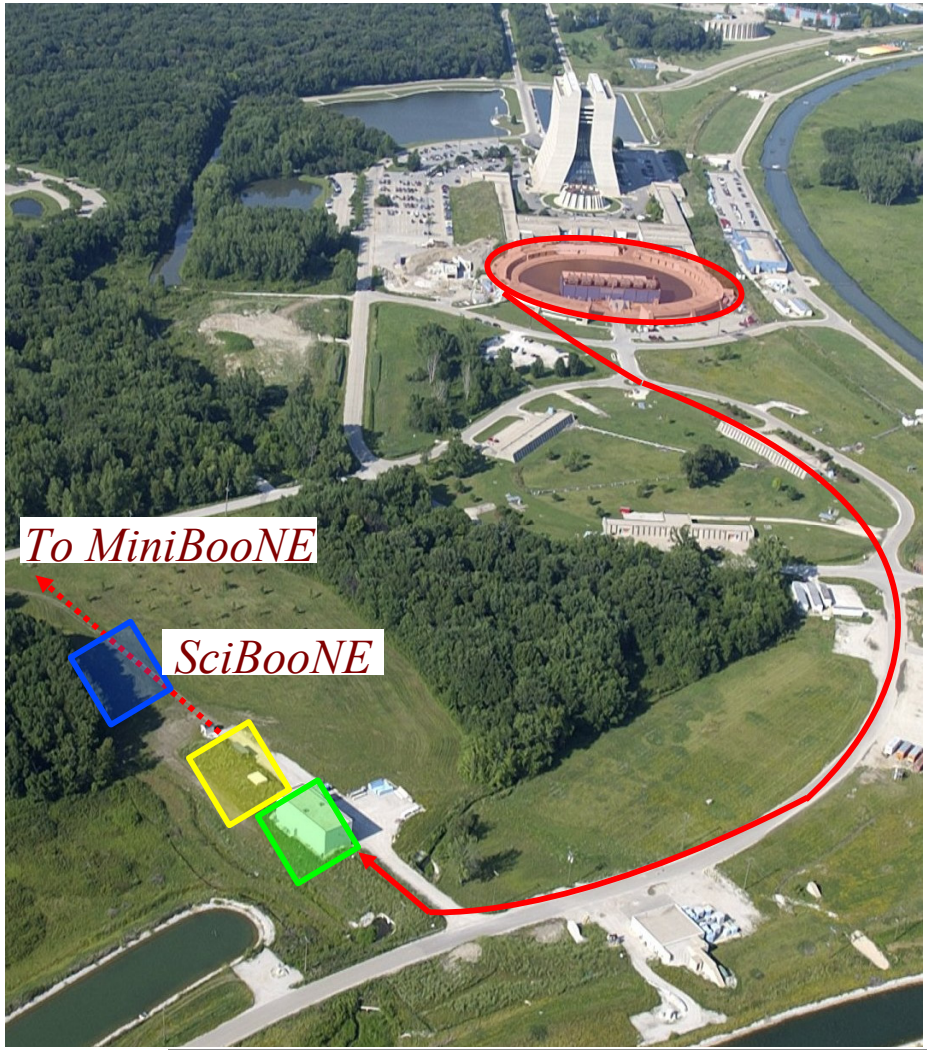
- **Data from old experiments (1970~1980)**
  - Low statistics
  - Systematic Uncertainties
- **New data** from K2K & MiniBooNE revealing surprises

SciBooNE experiment

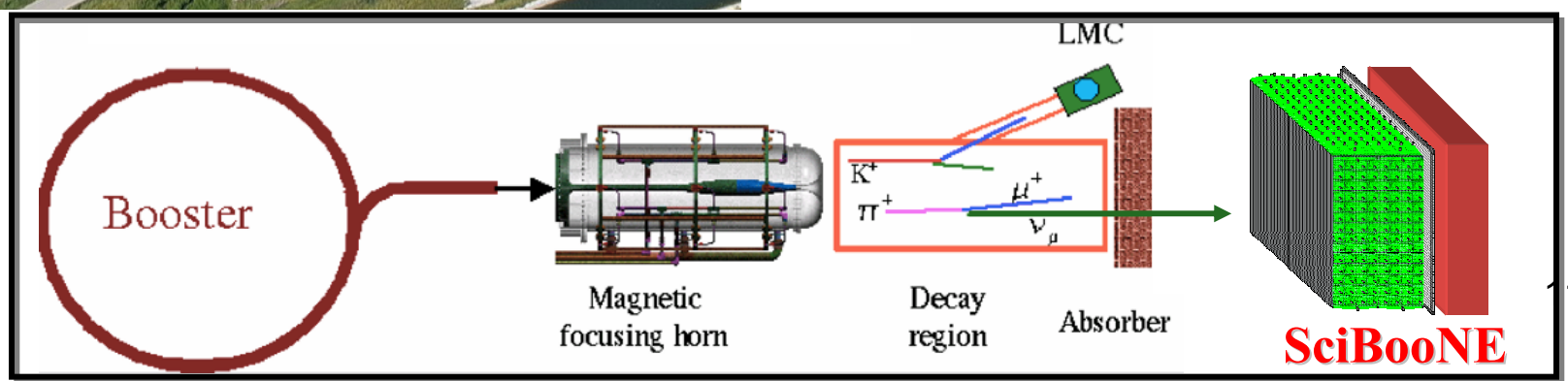
SciBooNE (FNAL E954) experiment



- Precise measurements of neutrino- and antineutrino-nucleus cross sections near 1 GeV
  - Essential for future neutrino oscillation experiments
- Neutrino energy spectrum measurements
  - MiniBooNE/SciBooNE joint ν_μ disappearance
  - ν_e constraint for MiniBooNE

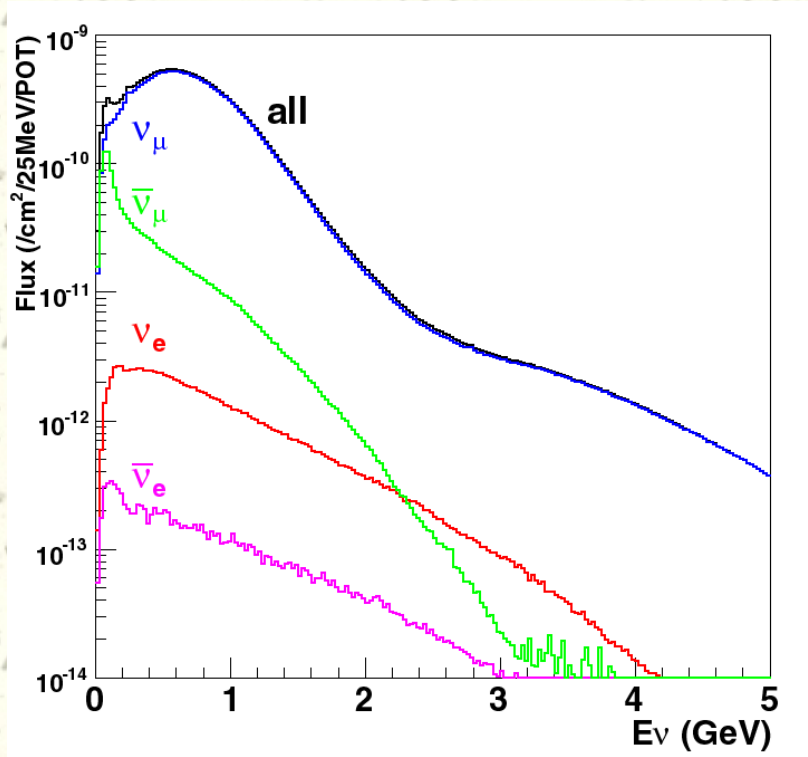


- Booster Proton accelerator
  - 8 GeV protons sent to target
- Target Hall
  - Beryllium target: 71cm long 1cm diameter
  - Resultant mesons focused with magnetic horn
  - Reversible horn polarity
- 50m decay volume
  - Mesons decay to μ & ν_μ
  - Short decay pipe minimizes $\mu \rightarrow \nu_e$ decay
- SciBooNE located 100m from the beryllium target



Booster Neutrino Beam (BNB)

Expected neutrino flux at SciBooNE
(neutrino mode)



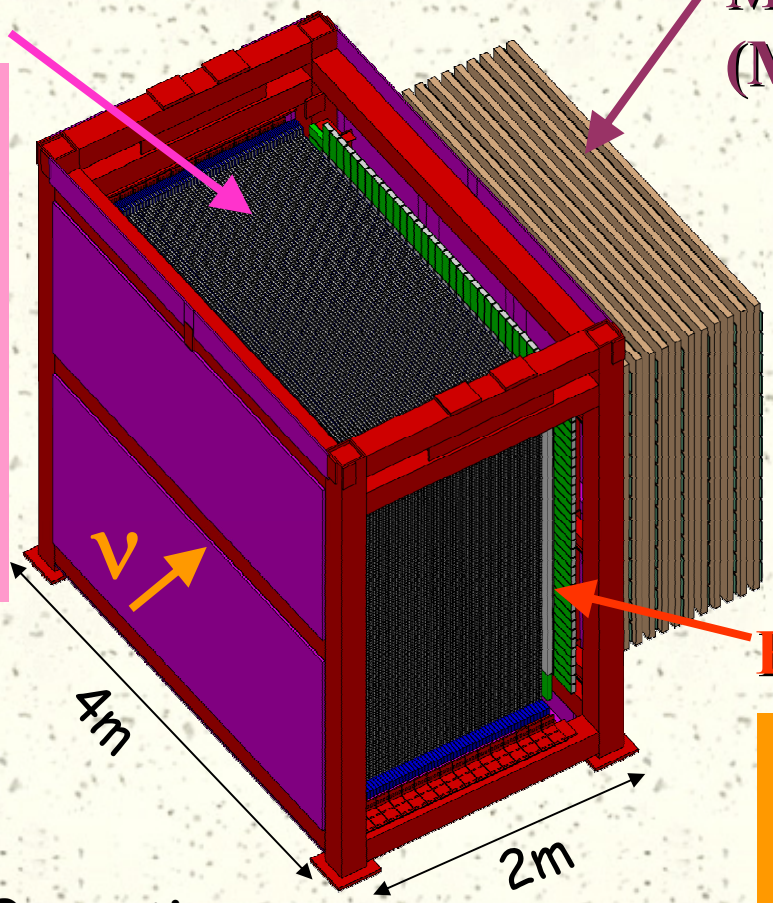
- mean neutrino energy ~0.7 GeV
- 93% pure $\nu\mu$ beam
  - anti-ν_μ (6.4%)
  - ν_e + anti-ν_e (0.6%)
- antineutrino beam is obtained by reversing horn polarity

SciBooNE detectors

SciBar

- scintillator tracking detector
- 14,336 scintillator bars (15 tons)
- Neutrino target
- detect all charged particles
- p/π separation using dE/dx

Used in K2K experiment



Muon Range Detector (MRD)

- 12 2"-thick steel + scintillator planes
- measure muon momentum with range up to 1.2 GeV/c

Parts recycled from Past experiment

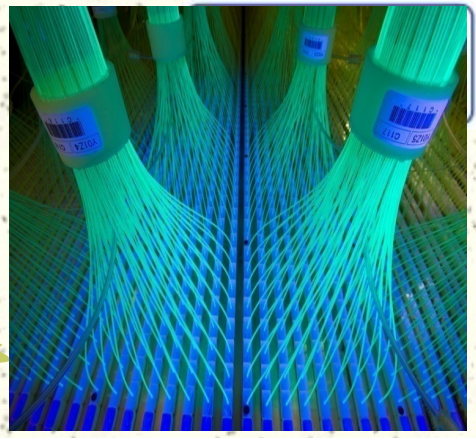
Electron Catcher (EC)

- spaghetti calorimeter
- 2 planes (11 X_0)
- identify π^0 and ν_e

Used in CHORUS, HARP and K2K

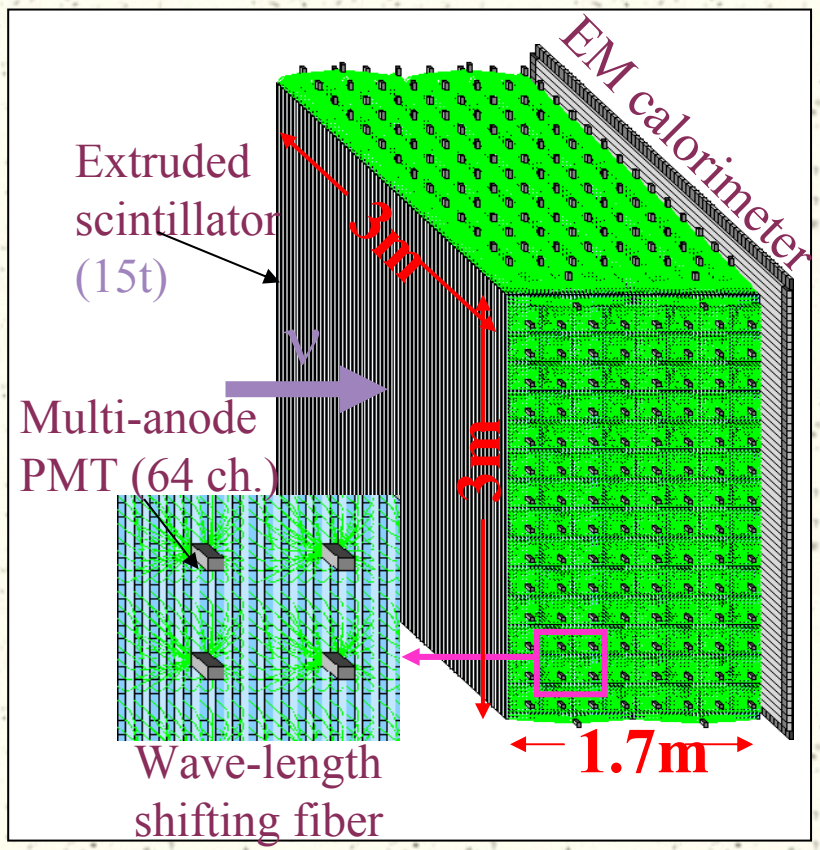
DOE-wide Pollution Prevention Star (P2 Star) Award

SciBar Detector

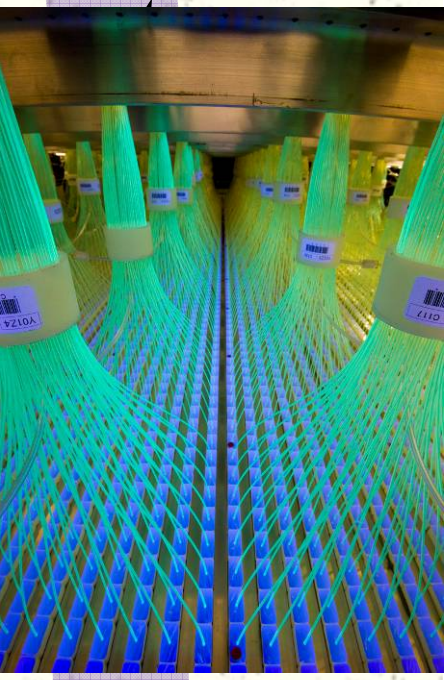


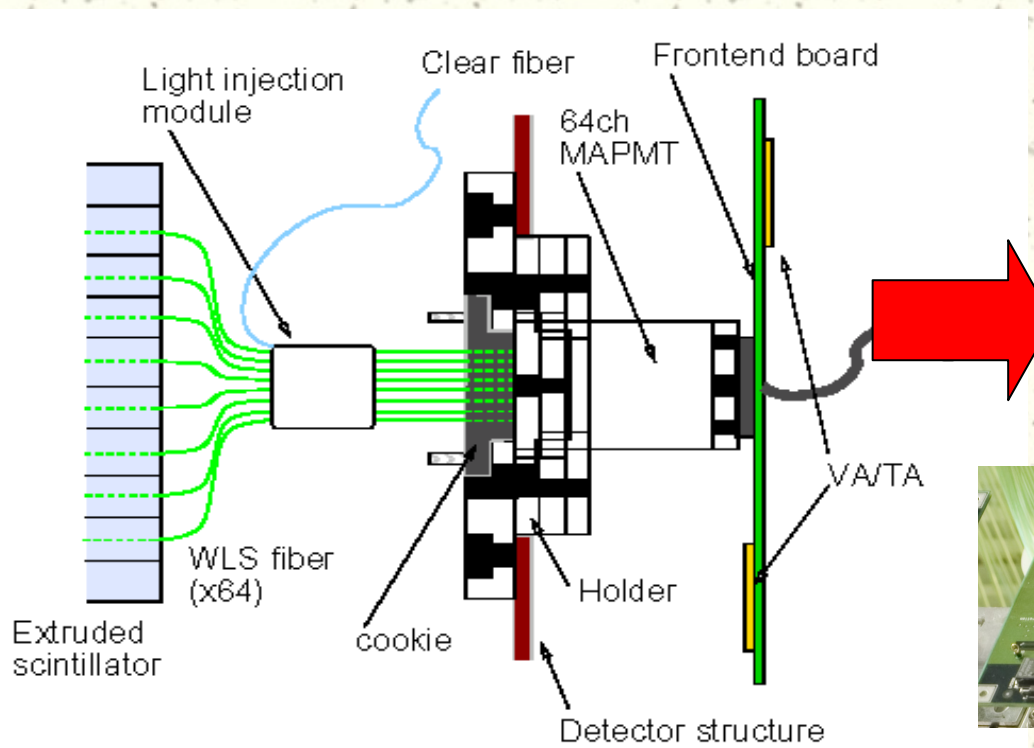
- Extruded scintillators with WLS fiber readout
- Scintillators are the neutrino target
- 3m x 3m x 1.7m (Total: 15 tons)
- 14,336 channels
- Detect short tracks (>8cm)
- Distinguish a proton from a pion by dE/dx

➔Clear identification of ν interaction process

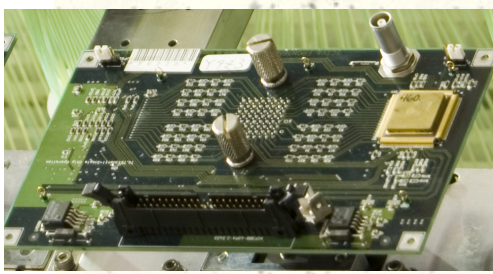


SciBar Readout





64 charge info.
2 timing info.



Extruded Scintillator (1.3×2.5×300cm³)
- made by FNAL (same as MINOS)

Wave length shifting fiber (1.5mmΦ)
- Long attenuation length (~350cm)
  → Light Yield : ~20p.e./1.3cm/MIP

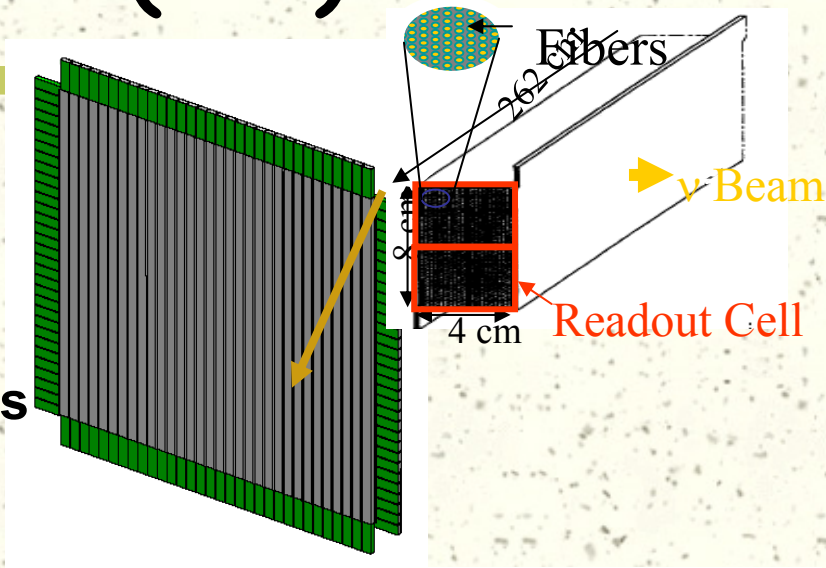
64-channel Multi-Anode PMT
- 2x2mm² pixel (3% cross talk@1.5mmΦ)
- Gain Uniformity (20% RMS)
- Good linearity (~200p.e. @6×10⁵)

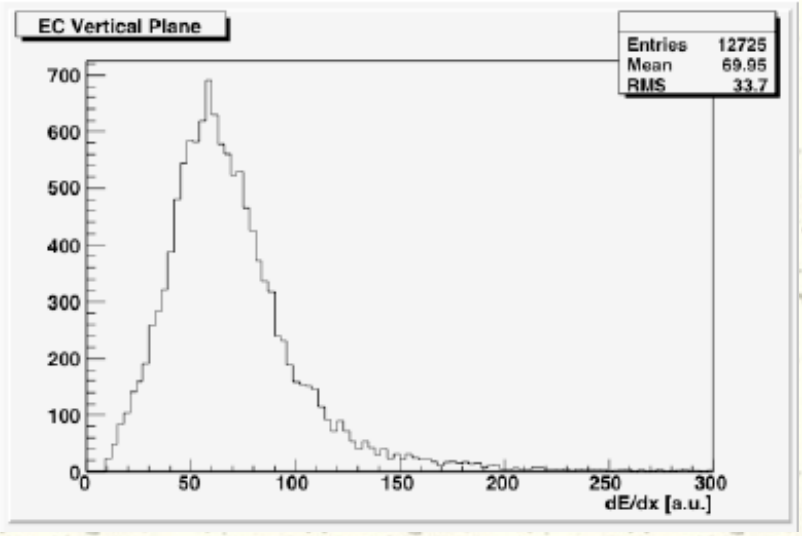
Readout electronics with VA/TA
- ADC for all 14,336 channels
- TDC for 448 sets (32 channels-OR)

Electron Catcher (EC)

- "spaghetti" calorimeter
- 1mm diameter fibers in the grooves of lead foils
- 4x4cm^2 cell read out from both ends
- 2 planes (11X_0)

  Horizontal: 32 modules
  Vertical : 32 modules
- Total 256 readout channels
- Expected resolution 14%/$\sqrt{E}$
- Linearity: better than 10%

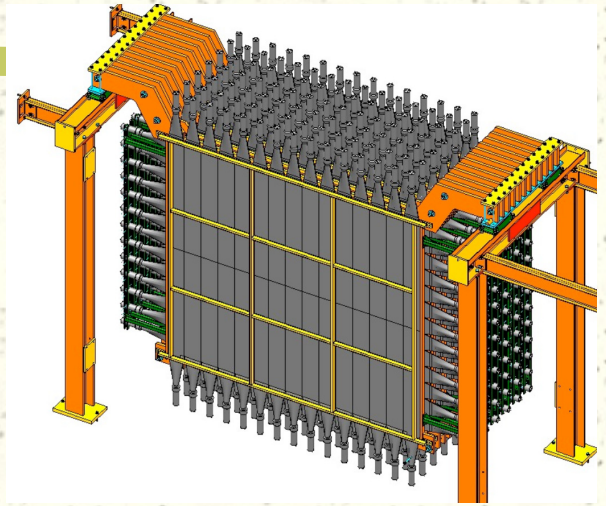




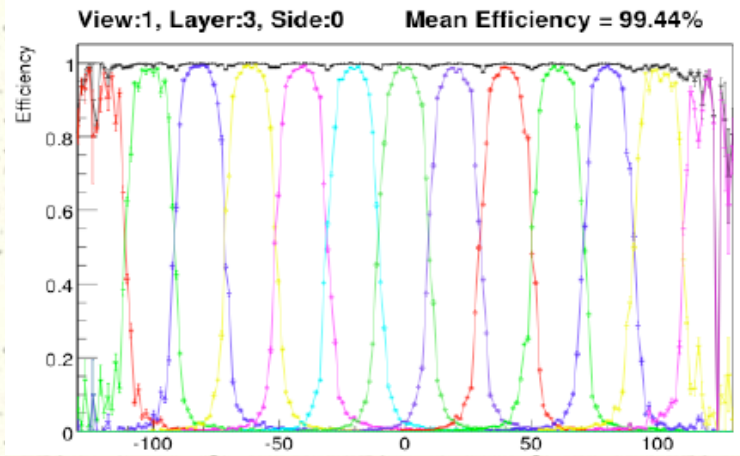
dE/dx distribution of vertical plane for cosmic ray muons

Muon Range Detector (MRD)

A new detector built with the used scintillators, iron plates and PMTs to measure the muon momentum up to 1.2 GeV/c.



- Iron Plate
  - 305x274x5cm^3
  - Total 12 layers
- Scintillator Plane
  - Alternating horizontal and vertical planes
  - Total 362 channels



Hit efficiency of a typical horizontal plane

SciBooNE Collaboration

Mar 18, 2008

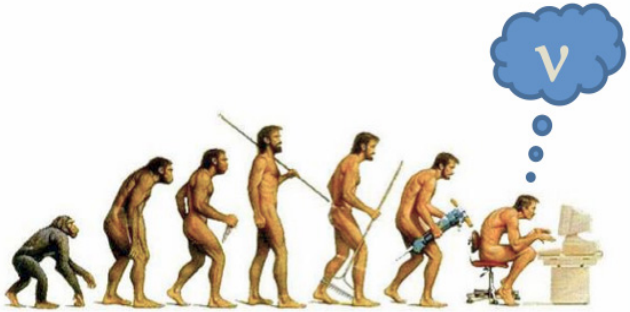
- Universitat Autonoma de Barcelona
- University of Cincinnati
- University of Colorado, Boulder
- Columbia University
- Fermi National Accelerator Laboratory
- High Energy Accelerator Research Organization (KEK)
- Imperial College London
- Indiana University
- Institute for Cosmic Ray Research (ICRR)
- Kyoto University
- Los Alamos National Laboratory
- Louisiana State University
- Purdue University Calumet
- Universita degli Studi di Roma "La Sapienza"
- Saint Mary's University of Minnesota
- Tokyo Institute of Technology
- Unversidad de Valencia

5 countries 17 institutions
~70 physicists

Spokespeople:
M.O. Wascko (Imperial), T. Nakaya (Kyoto)

SciBooNE History

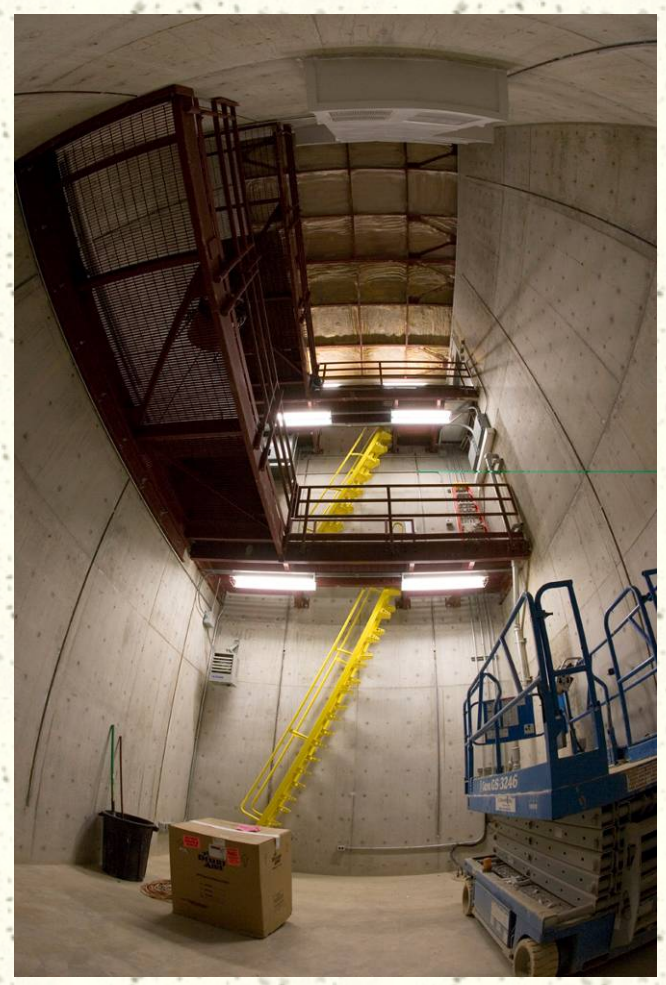
- 2005, Summer - Collaboration formed
- 2005, Dec - Proposal
- 2006, Jul - Detectors move to FNAL
- 2006, Sep - Groundbreaking
- 2006, Nov - Sub-detectors Assembly
- 2007, Mar - Cosmic Ray Data-taking
- 2007, Apr - Detector Installation
- 2007, May - Commissioning
- 2007, Jun - Anti-Neutrino Data Run
- 2007, Oct - Neutrino Data Run
- 2008, Apr – Anti-neutrino Data Run
- 2008, Aug – Run-end



Only 3 years from formation to end-of-run

SciBooNE History

Ground breaking ceremony (Sep. 2006)



Detector hall constructed (Feb. 2007)

SciBooNE History

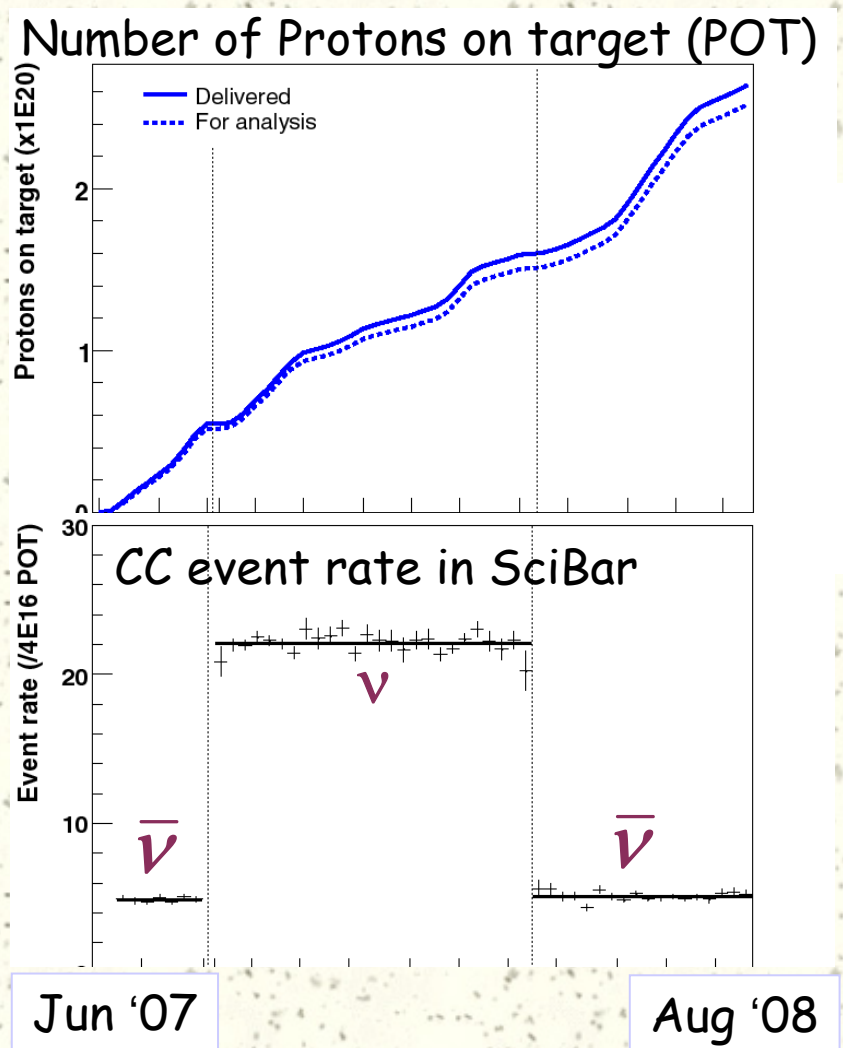
Detector assembly (Nov. 2006- Mar. 2007)

SciBooNE History

Detector installation (Apr. 2007)

End-of-run (Aug. 2008)

Data-taking



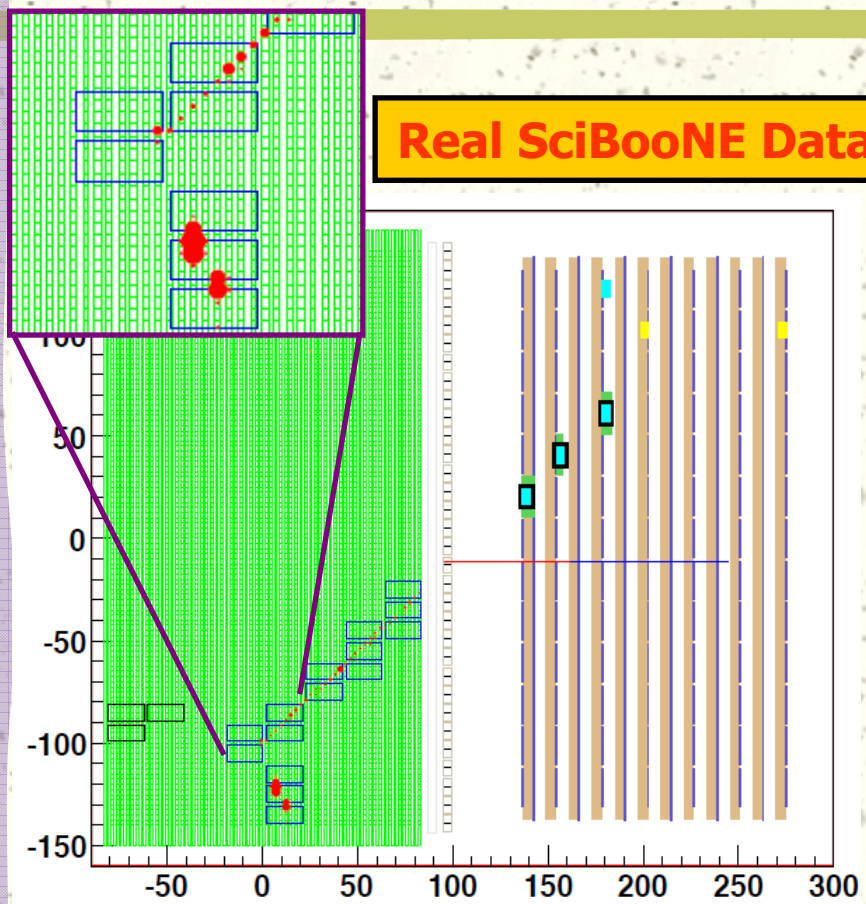
- Jun. 2007 – Aug. 2008
- 95% data efficiency
- 2.52×10^{20} POT in total
  - neutrino : 0.99×10^{20} POT
  - antineutrino: 1.53×10^{20} POT

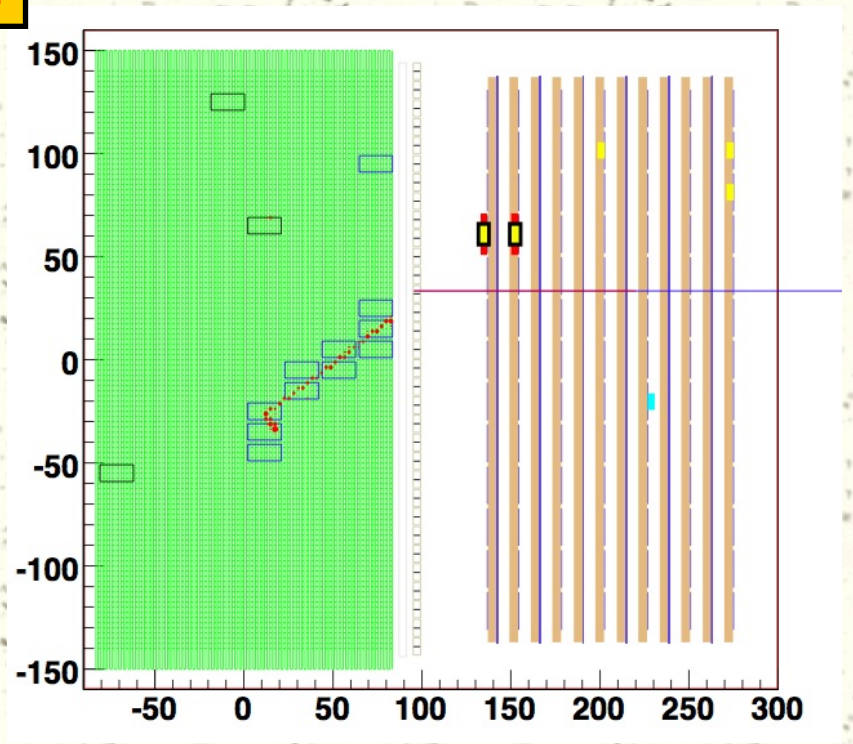
Preliminary results from full neutrino data set are presented

Event displays

ADC hits (area→charge)
TDC hits (32ch OR)

Real SciBooNE Data





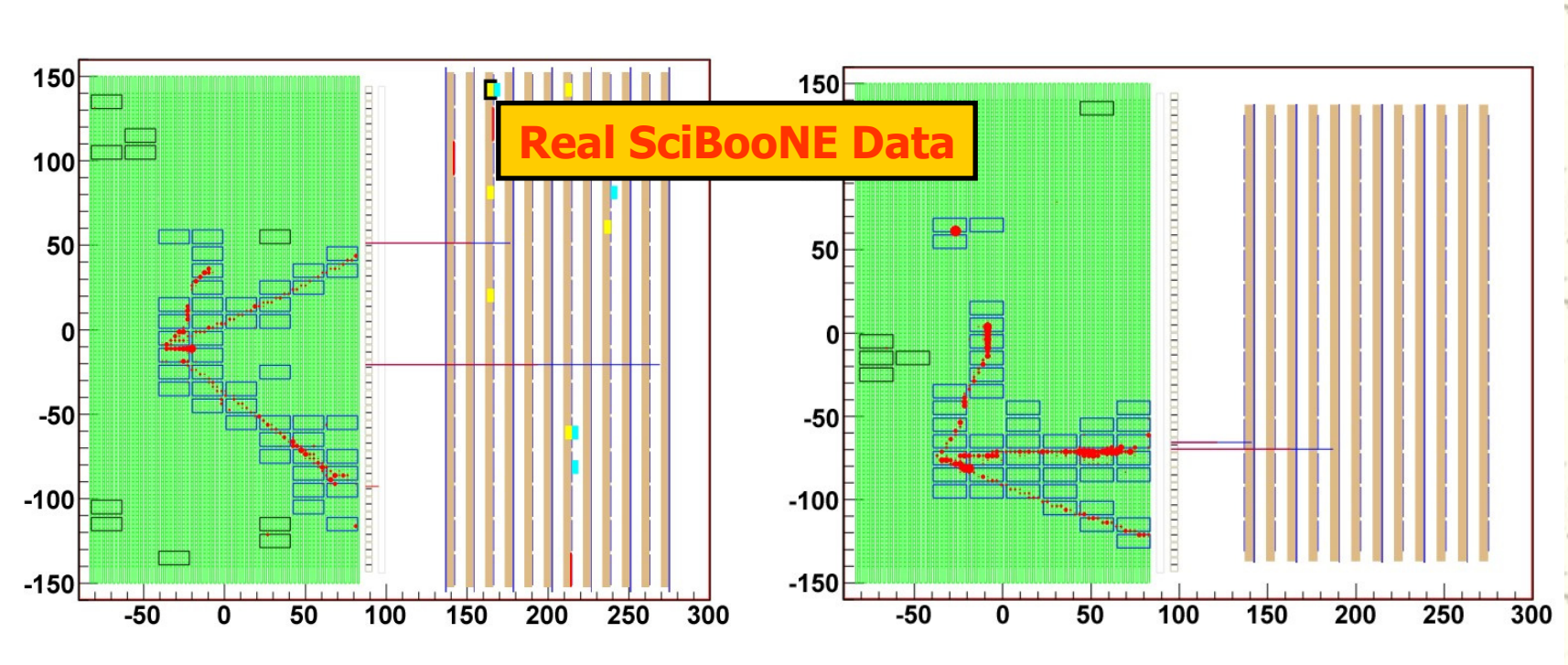
anti-$\nu\mu$ CC-QE candidate
($\bar{\nu}_\mu + p \rightarrow \mu + n$)

ν_μ CC-QE candidate
($\nu_\mu + n \rightarrow \mu + p$)

Event displays

TOP view

SIDE view



Many tracks

Preliminary results

SciBooNE Analyses

- Cross section measurements
  - **CC-1π^+ production**
  - **NC-π^0 production**

    → Will be covered in today's talk
  - CC-π^0 production
  - CC-QE scattering
  - NC-elastic scattering
  - Anti-neutrino cross sections
- Neutrino energy spectrum measurements
  - SciBooNE/MiniBooNE joint ν_μ disappearance
  - Beam νe measurement for MiniBooNE

CC-1π^+ measurement in SciBooNE

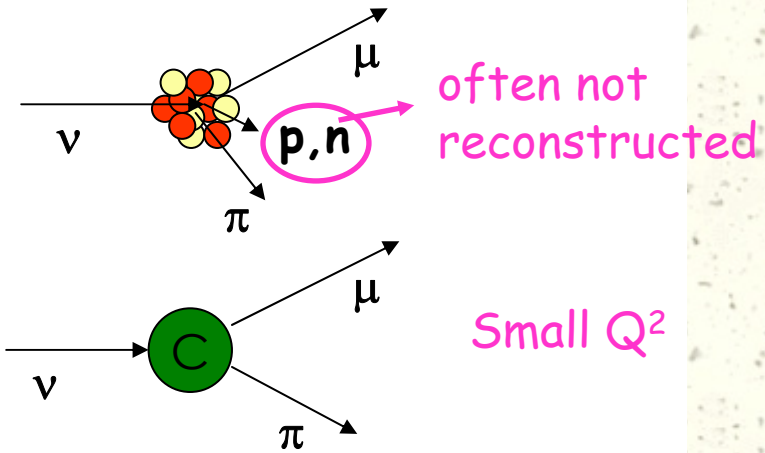
Charged current single charged pion (CC-1π^+) production

CC-resonant π production

- $\nu + p \rightarrow \mu + p + \pi^+$
- $\nu + n \rightarrow \mu + n + \pi^+$

CC-coherent π production

$\nu + C \rightarrow \mu + C + \pi^+$

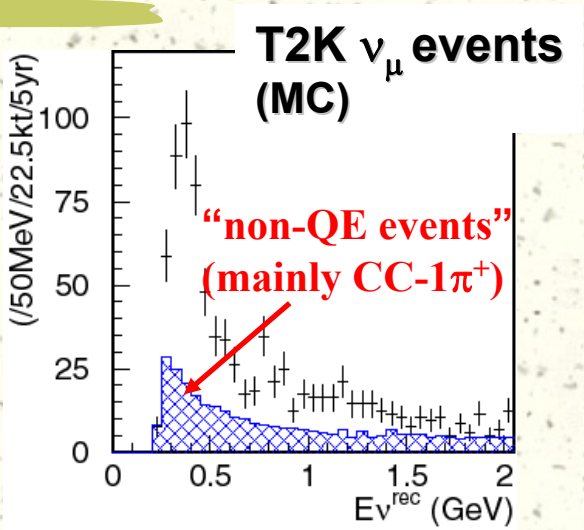


signal

2 MIP-like tracks (a muon and a pion)

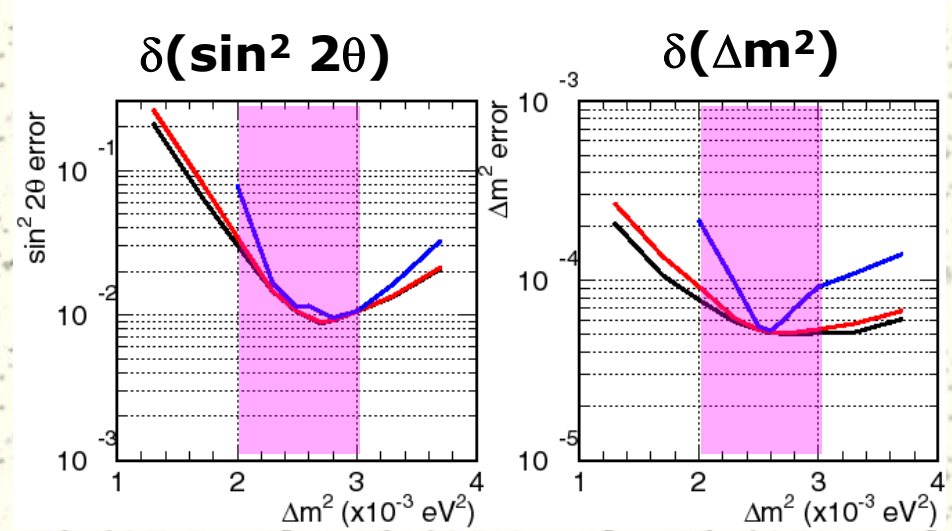
Why we measure CC-1π^+

- dominant background interaction for ν_μ disappearance
- T2K needs to reduce uncertainty of nonQE/QE to ~5%



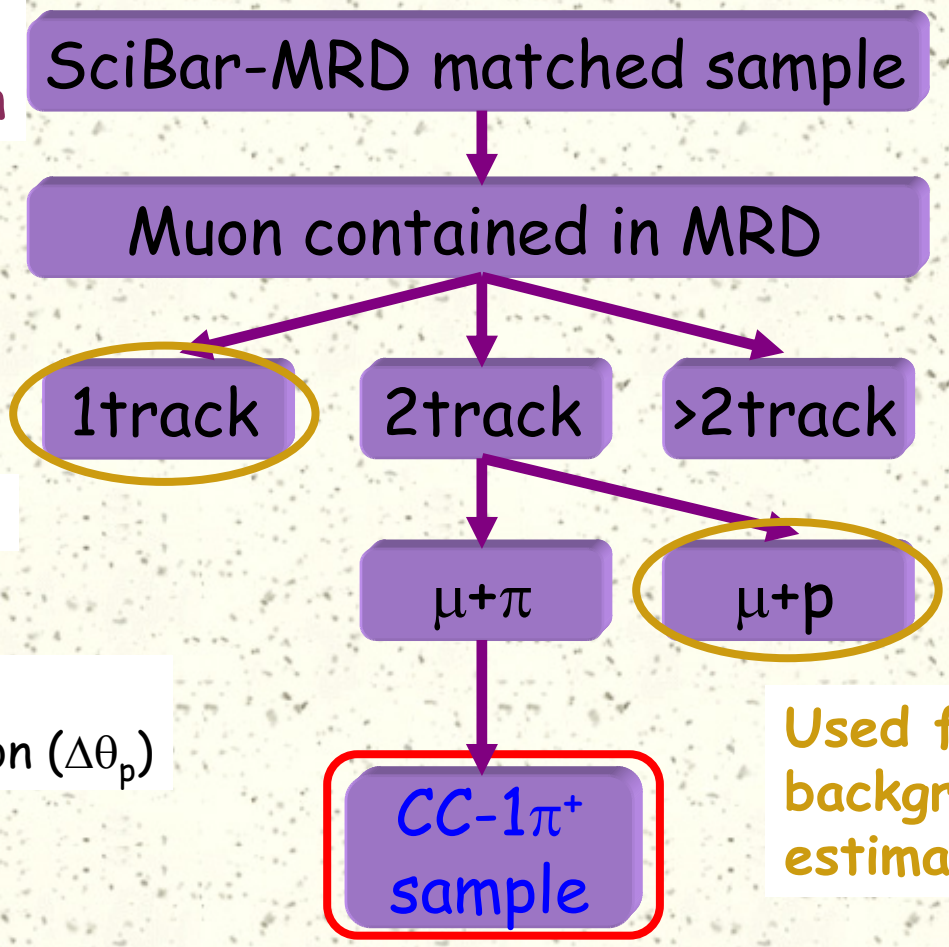
ν_μ disappearance measurement error (90%CL)

— stat. only
— δ(nQE/QE)= 5%
— δ(nQE/QE)=20%



CC-1π^+ event selection

Define MC normalization



Number of tracks from a common vertex

Particle ID using dE/dx

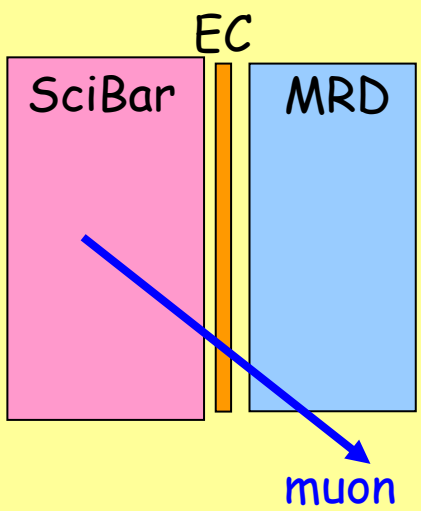
CCQE rejection using non-muon track direction ($\Delta\theta_p$)

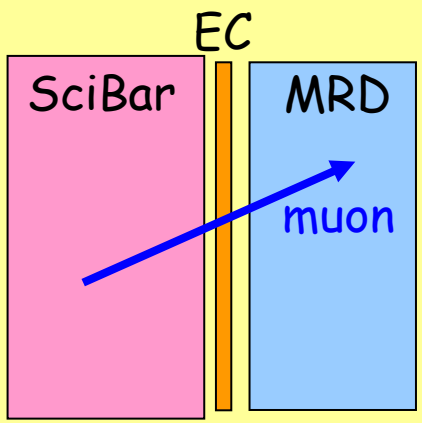
Used for background estimation

CC-inclusive sample

Neutrino energy spectrum measurement using CC-inclusive sample

<u>SciBar-MRD matched event</u> (~30k events)



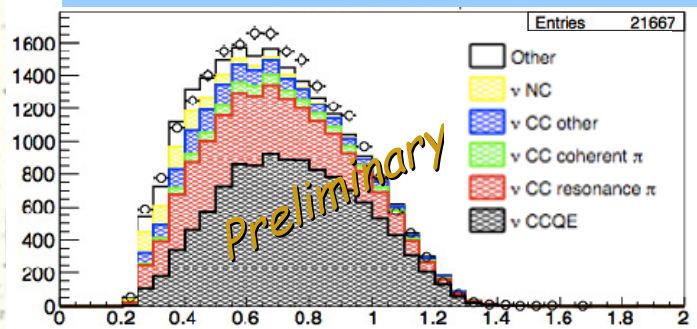


MRD stopped event (~22k events)
(muon contained in MRD)

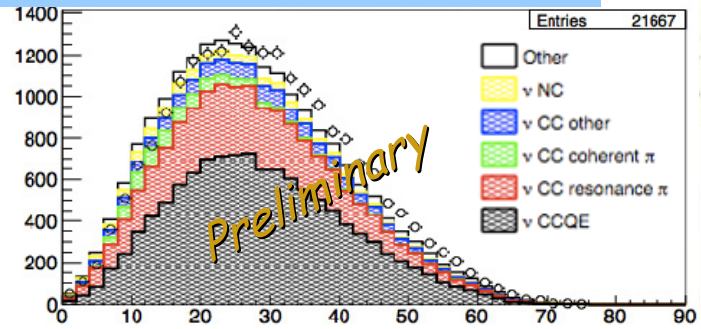
93% pure CC-inclusive sample

CC-inclusive sample

Muon kinematics of MRD stopped sample



Pμ (GeV/c)

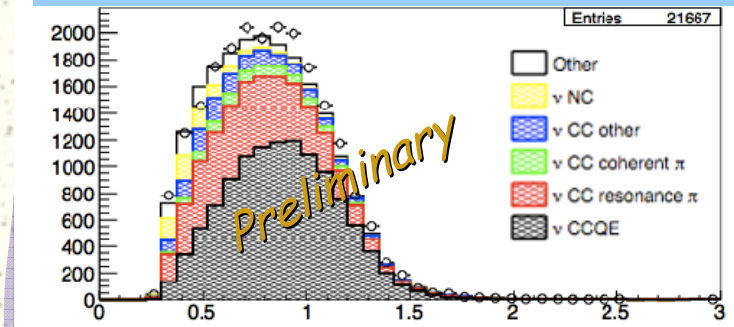


θμ (degree)

Y.Nakajima

$\sigma(P\mu)$~50MeV/c
$\sigma(\theta\mu)$~0.9degree
M_A=1.1 GeV/c^2

Reconstructed Eν assuming CC-QE



$E\nu^{rec}$ (GeV)

MC is normalized to SciBar-MRD matched sample

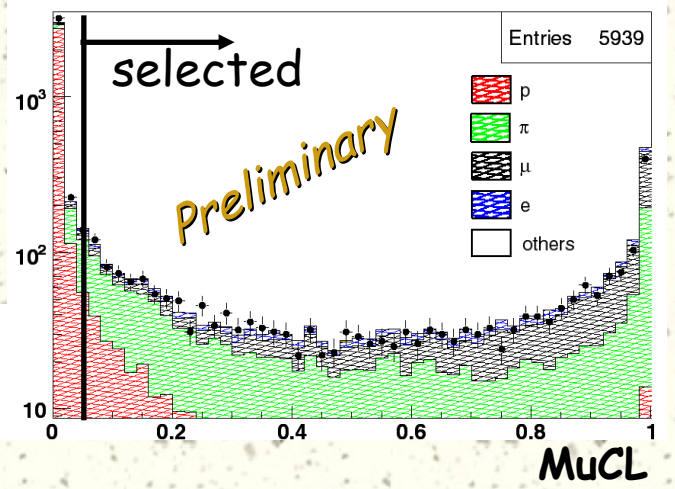
The sample is used to get neutrino spectrum for ν_μ disappearance search

CC-1π^+ event selection (cont'd)

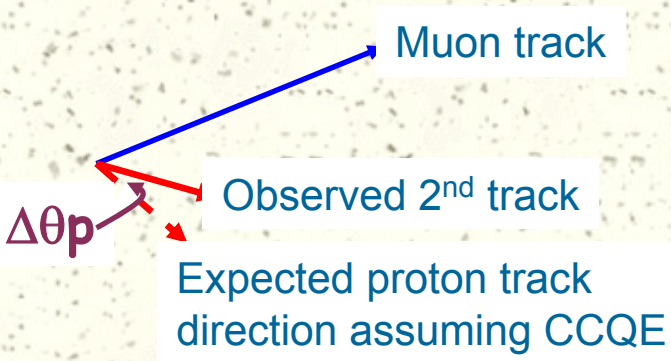
Particle ID using dE/dx

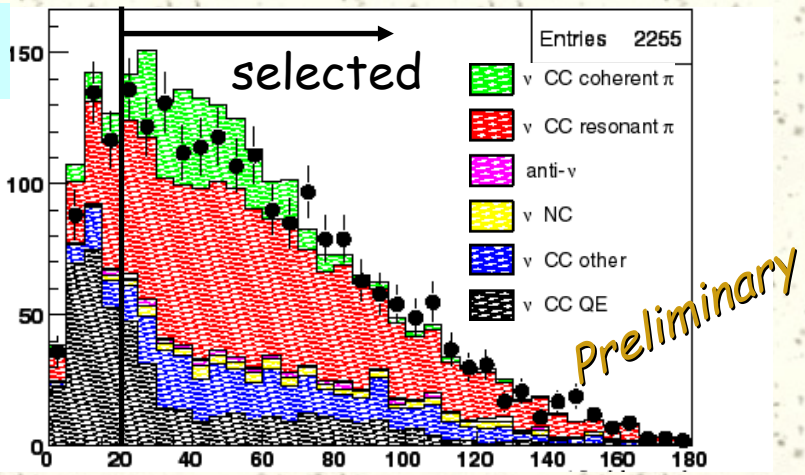
Construct "Muon Confidence Level" to separate proton from muon/pion

MuCL distribution of 2nd track



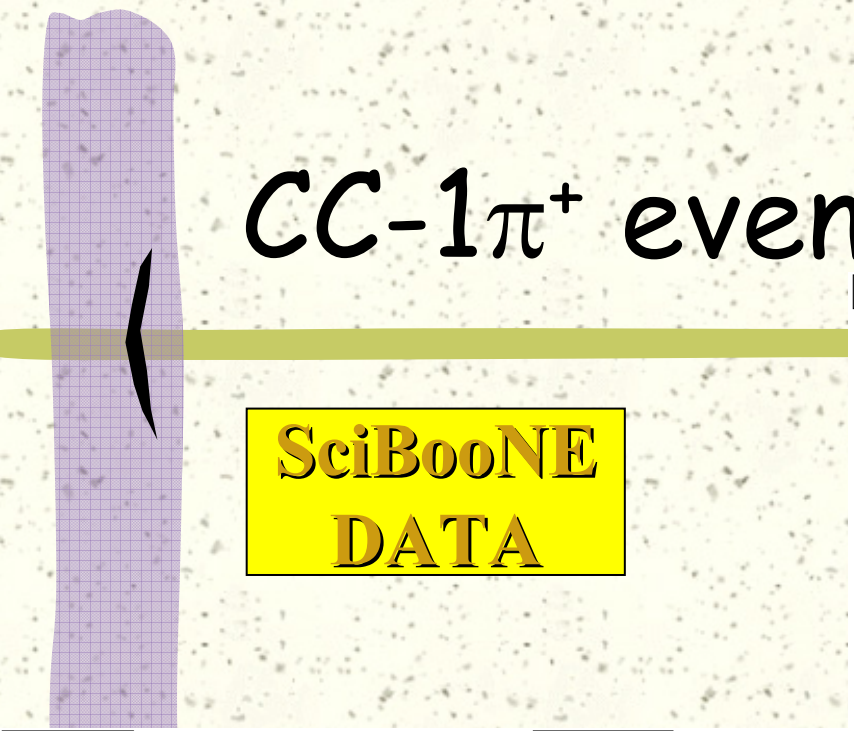
CCQE rejection based on $\Delta\theta p$



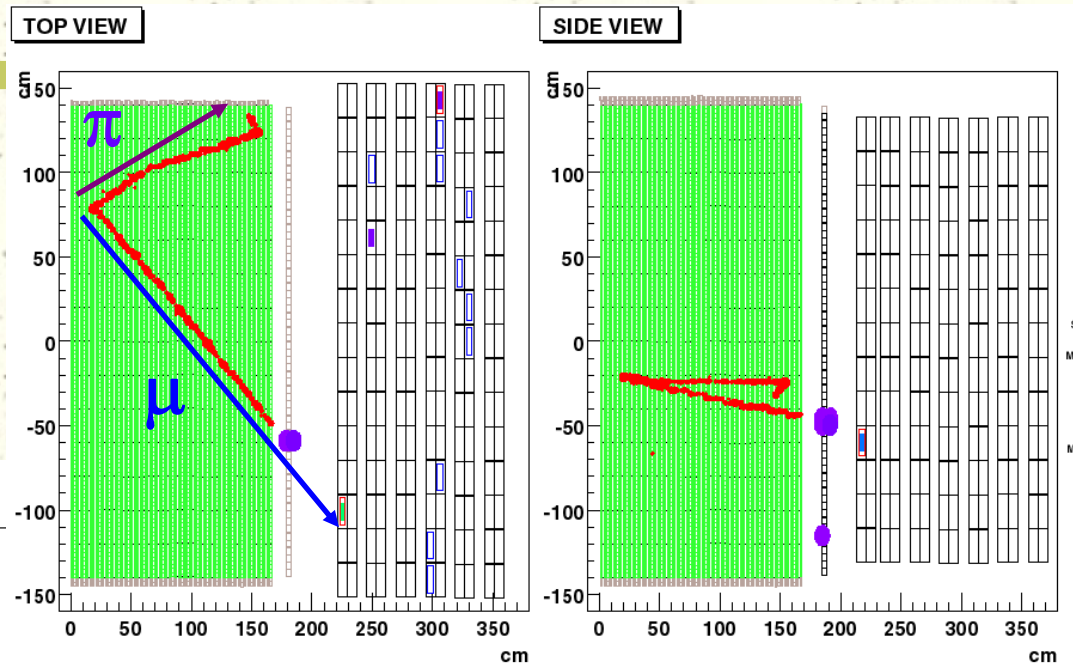


CCQE contamination 20%→13%

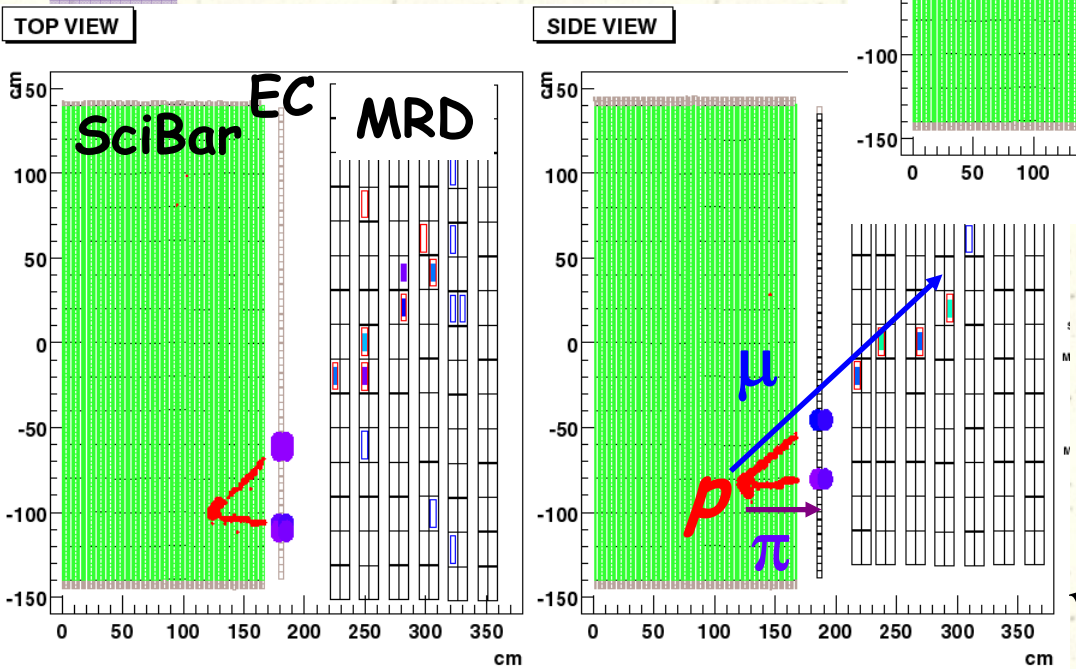
CC-1π^+ event candidates



SciBooNE DATA

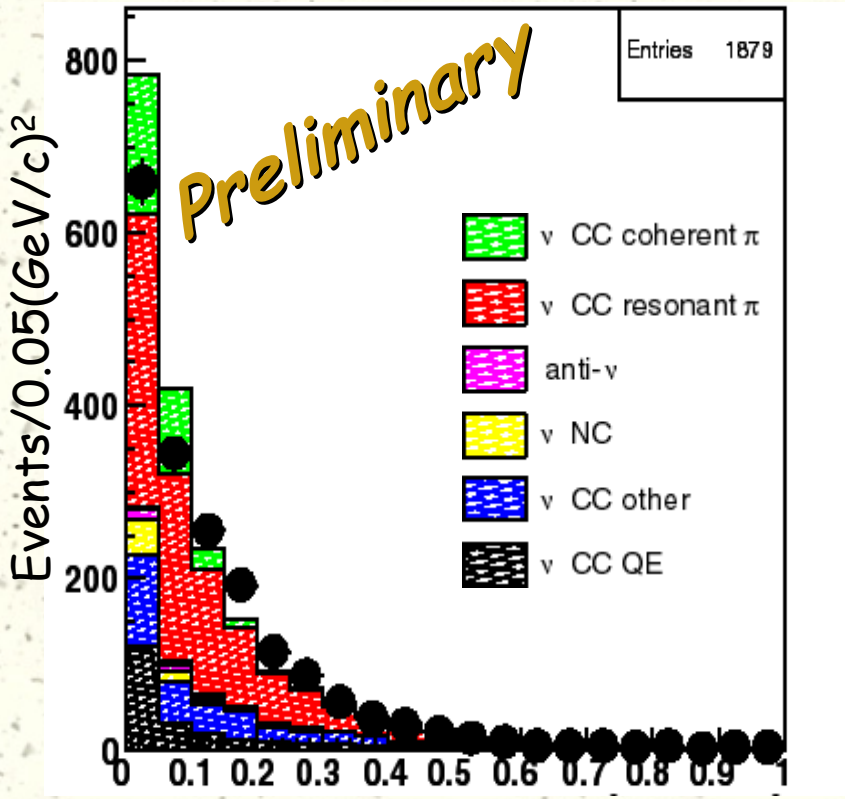


$\nu n \rightarrow \mu n \pi$ candidate



$\nu p \rightarrow \mu p \pi$ candidate

CC-1π^+ sample



Reconstructed Q^2 $(GeV/c)^2$ assuming CC-QE

~80% pure $\mu+\pi$ sample

CC-1π^+ fraction in the sample

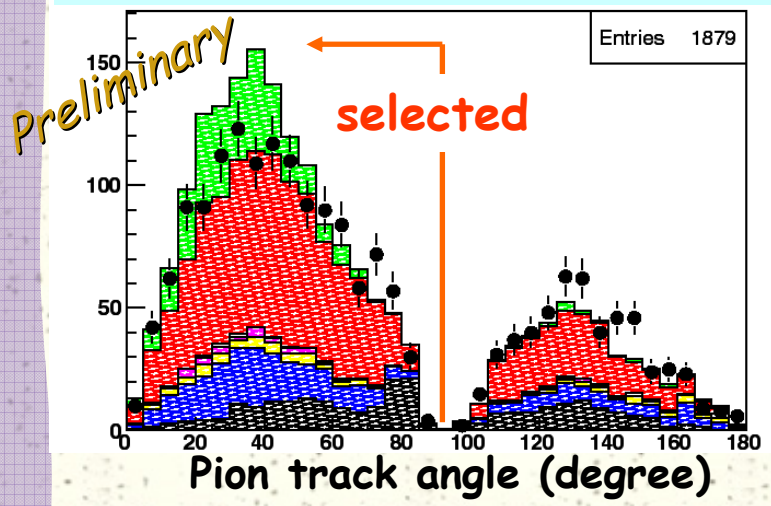
$\nu p \rightarrow \mu p \pi$	34%
$\nu n \rightarrow \mu n \pi$	11%
CC-coherent π	15%

Observed DATA deficit in low Q^2 region

Separate CC-coherent π from CC-resonant π using its characteristic kinematics

Extracting CC-coherent π

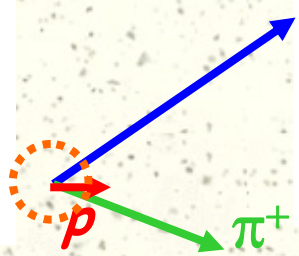
Direction of the pion track

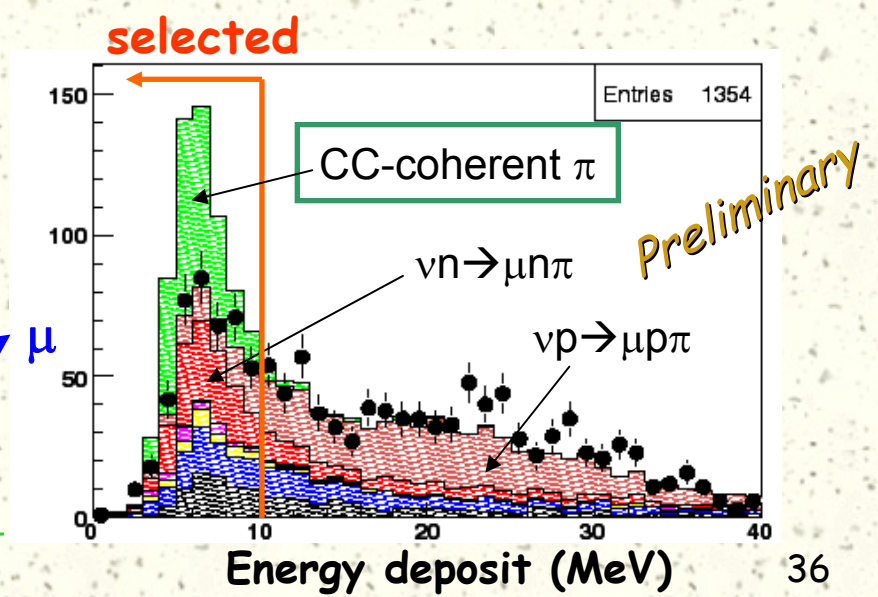


Events with a forward-going Pion track are selected

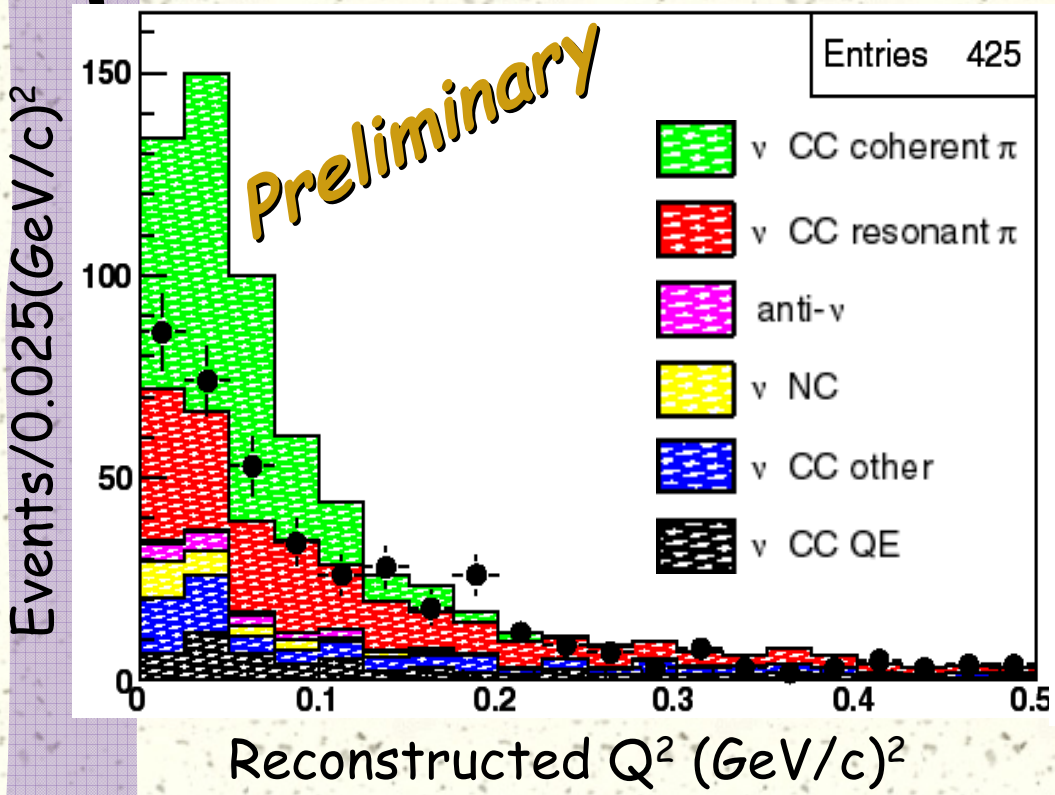
Vertex activity

Low energy proton is identified as a large energy deposit around the vertex





Final CC-coherent π sample



* Systematic error on background estimation is not included yet

Observed CC-coherent π sample in SciBooNE contains fewer events than our MC simulation, which is based on the Rein&Sehgal model (2007)

CC-coherent π

Efficiency 13%

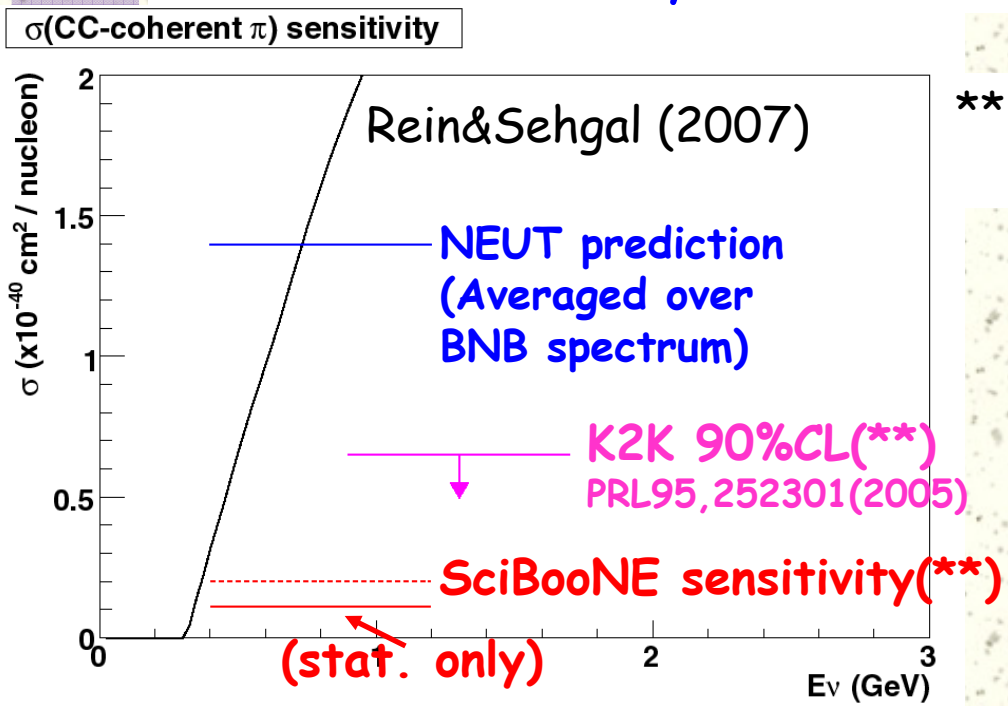
Purity 40%

SciBooNE sensitivity to σ(CC-coherent π)/σ(CC) ratio

SciBooNE sensitivity

σ(CC-coherent π)/σ(CC)~0.3x10^{-2} (*)
(sensitive down to ~10% level of the MC prediction)

*Included only detector systematic error



** Interpreted from cross section ratio using σ(CC) prediction

MiniBooNE NC-coherent π^0 (<Eν>~0.8GeV)
Phys.Lett.B664,41(2008)
(NC-coherent π)/(NC exclusive π^0)
=(19.5+/-1.1+/-2.5) %
65% of the Rein&Sehgal model

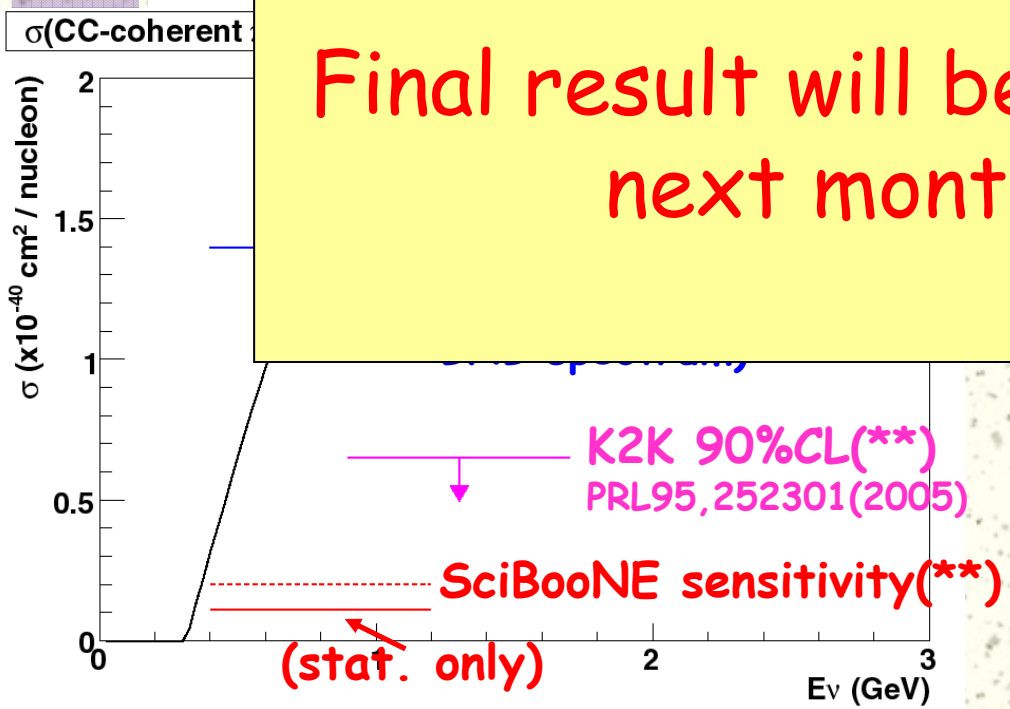
SciBooNE sensitivity to σ(CC-coherent π)/σ(CC) ratio

SciBooNE sensitivity

σ(CC-coherent π)/σ(CC)~0.3x10^{-2} (*)

(sensitive down to ~10% level of the MC prediction)

Final result will be published next month !!!



oss section ratio

erent π^0

(<Eν>~0.8GeV)

Phys.Lett.B664,41(2008)

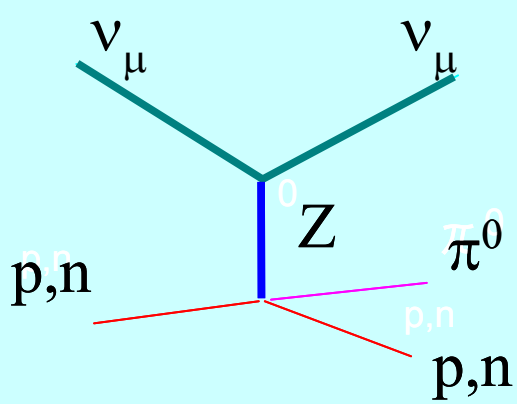
(NC-coherent π)/(NC exclusive π^0)

=(19.5+/-1.1+/-2.5) %

65% of the Rein&Sehgal model

NC-π^0 measurements in SciBooNE

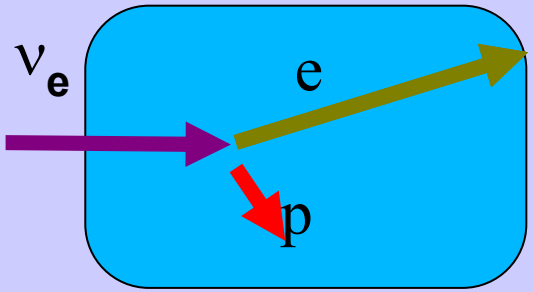
Neutral Current π^0 (NCπ^0)



NC π^0 is the main background for ν_μ to ν_e oscillation searches

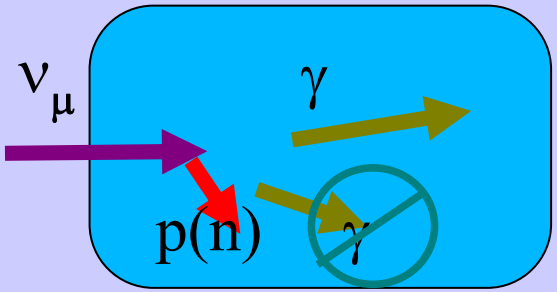
ν_e signal

electron



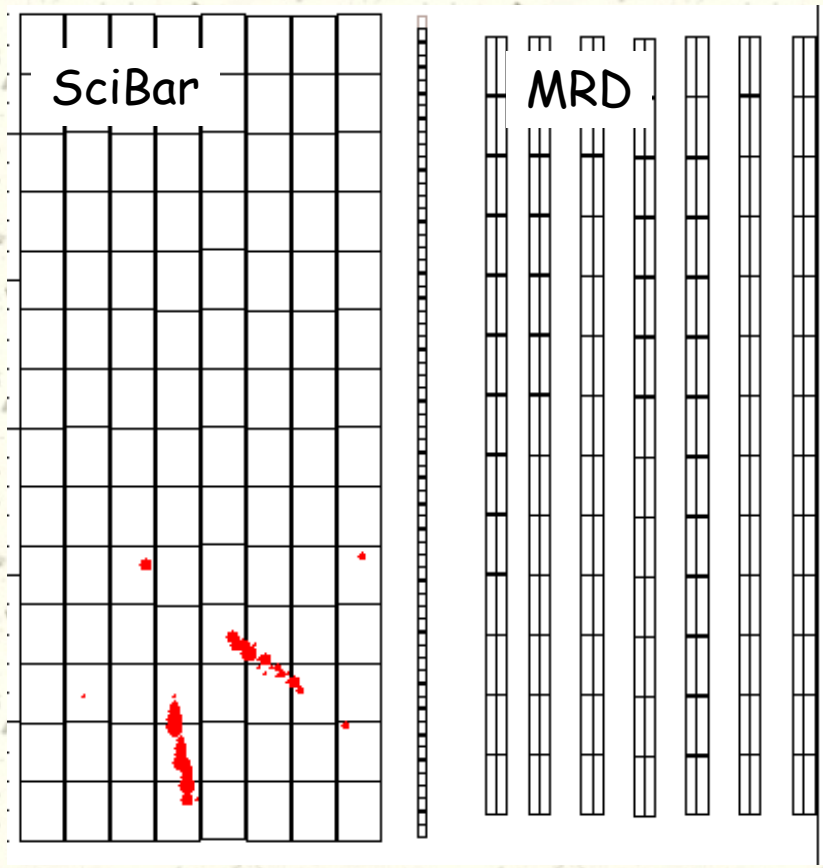
Background:

Gamma from π^0 mimics ν_e signal



NC-π^0 signal & background

NC-π^0 candidate



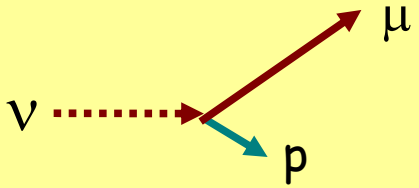
Experimental signature

2γ from π^0

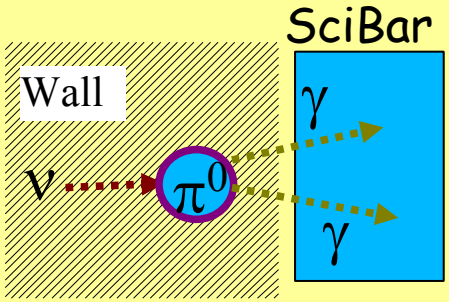
- 2 tracks in Fiducial Volume
- Disconnected
- Both tracks are not μ, p

Backgrounds

Internal BG
ex. CC-QE



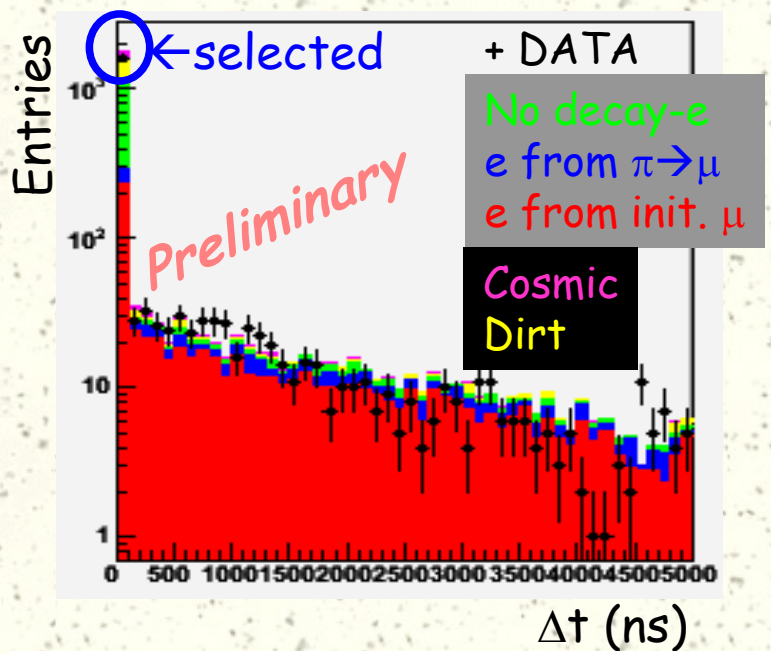
External BG
ex. Dirt

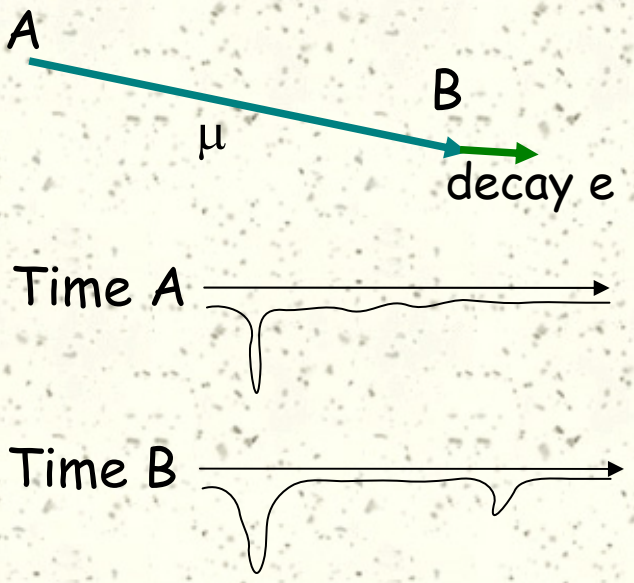


Muon rejection with decay electron

Time difference between track edges

Y. Kurimoto





Δt = (The latest) TimeB - TimeA

Most "no decay" events are in the region <100 ns (first bin)

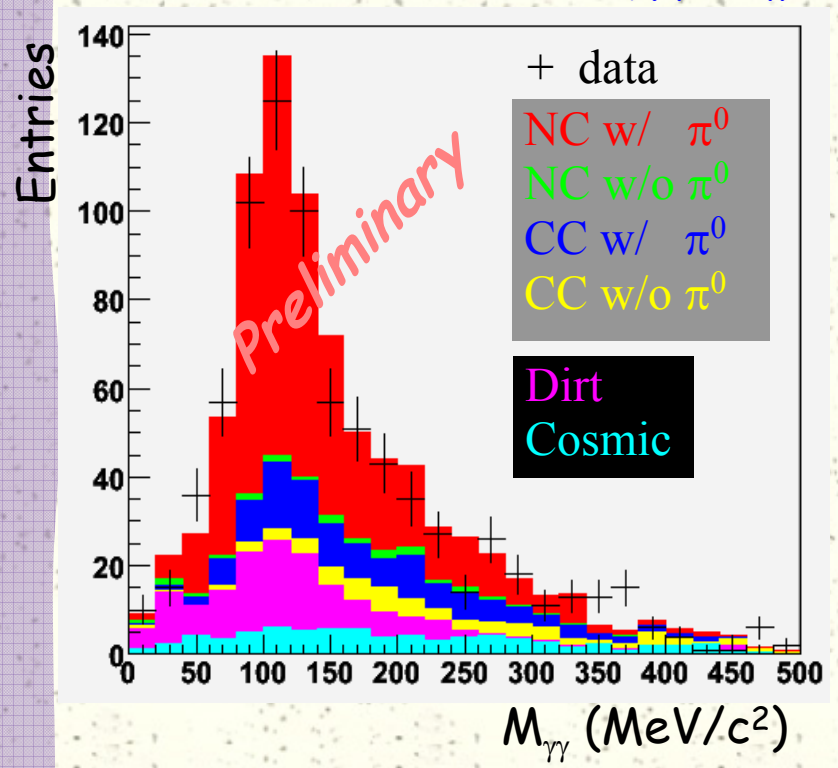
Reject 66 % of decay-e events

Keep 95 % of no decay-e events

π^0 reconstruction at final sample

Reconstructed mass

Y. Kurimoto



Reconstructing invariant mass using 2 tracks in SciBar after all event selection

Clear π^0 mass peak !
~850 events selected
~460 π^0 events (NC)

SciBar can reconstruct π^0 !!!

➔ Cross section measurement

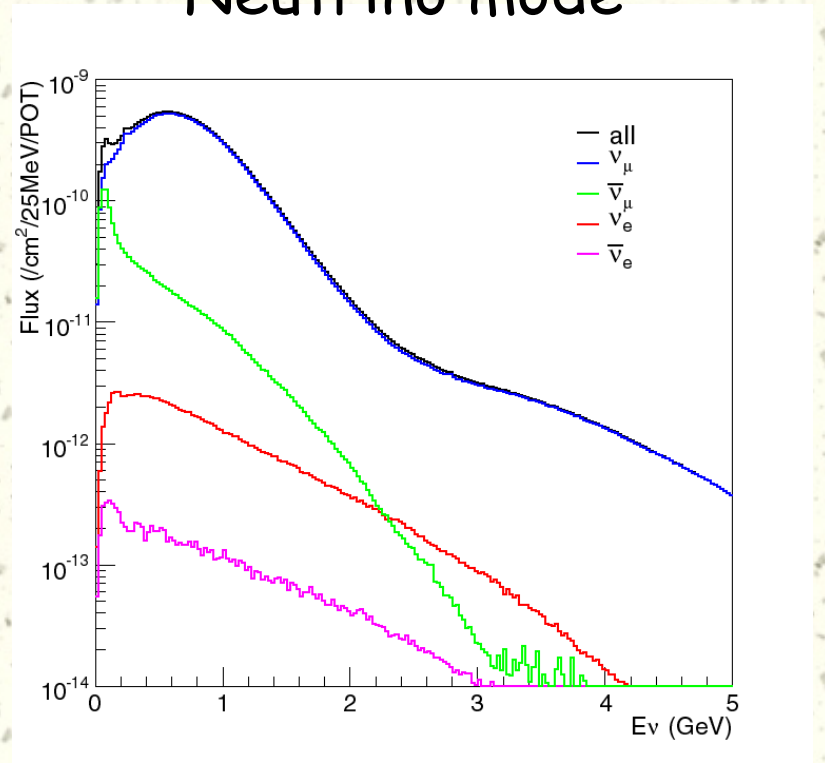
Summary

- SciBooNE measures neutrino and antineutrino cross sections near 1 GeV
- CC-1π^+ measurement in SciBooNE
  - Essential for future neutrino oscillation experiment
  - Observed fewer events in CC-coherent π sample than prediction
    - The result on CC-coherent pion production will be published next month
- Results will come soon
  - Many analyses (CCQE, CCπ^0, NCπ^0, NCelastic, ν_μ disappearance, ν_e measurement etc.) are on-going
  - Antineutrino measurements

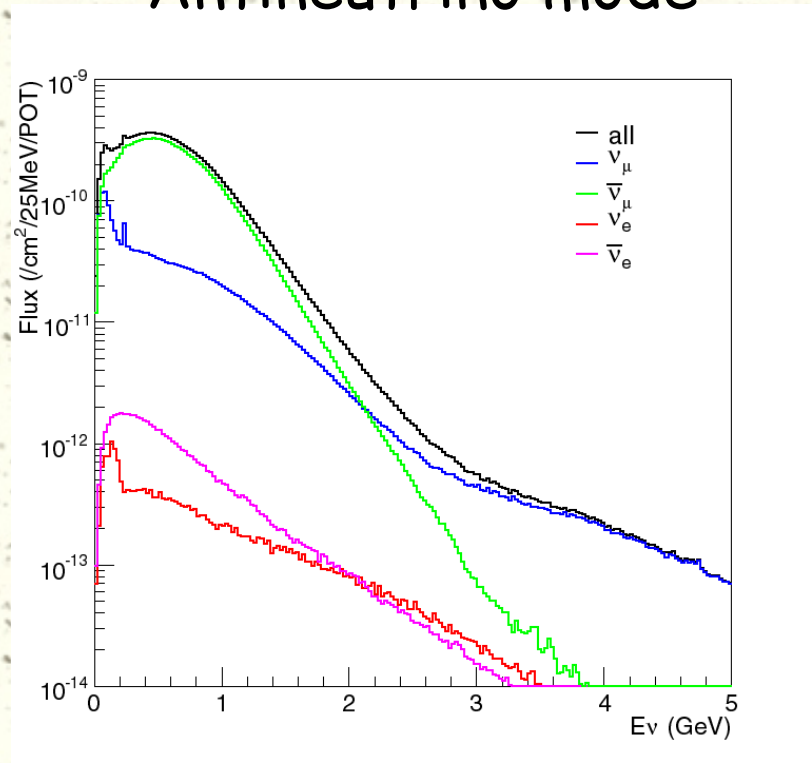
Backup slides

Booster neutrino beam

Neutrino mode

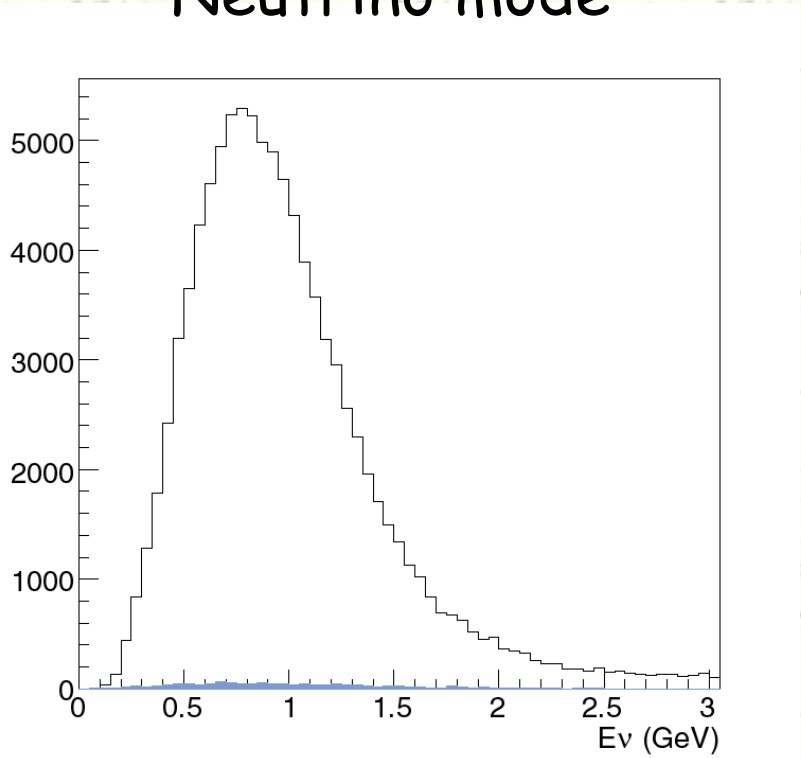


Antineutrino mode

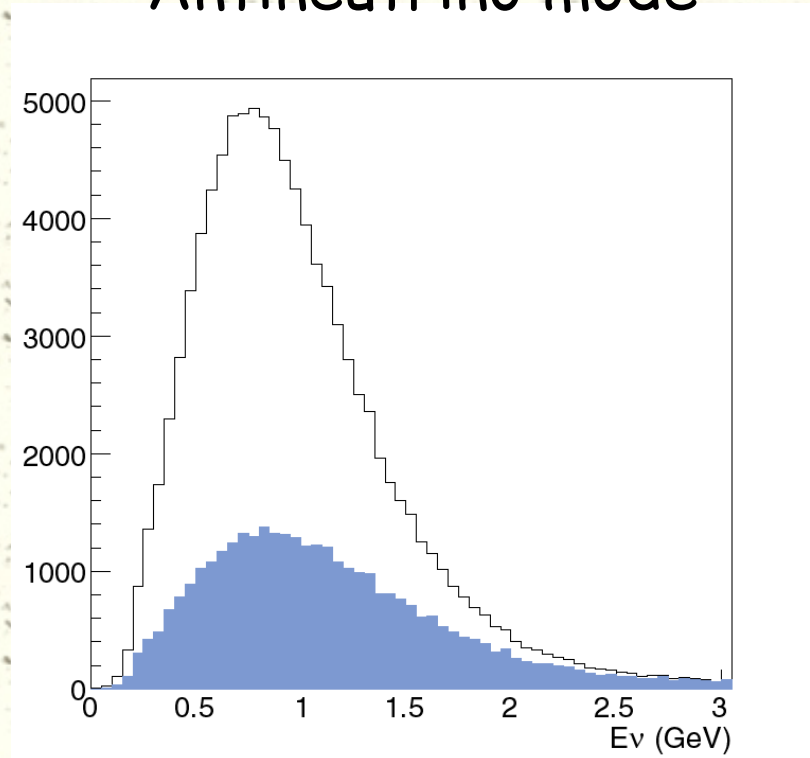


Neutrino energy distribution (cross section weighted)

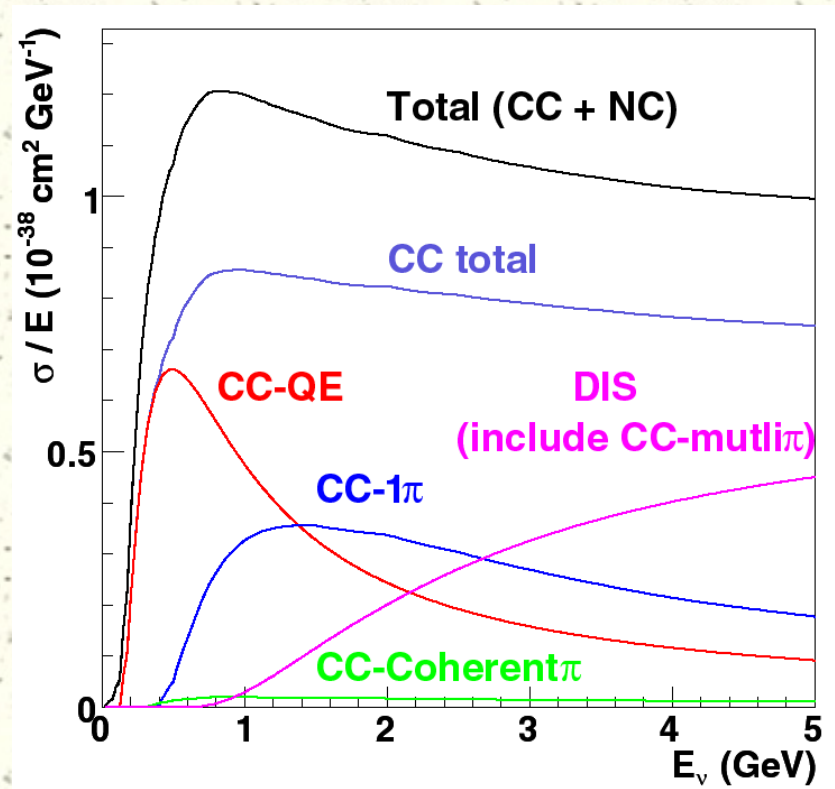
Neutrino mode



Antineutrino mode



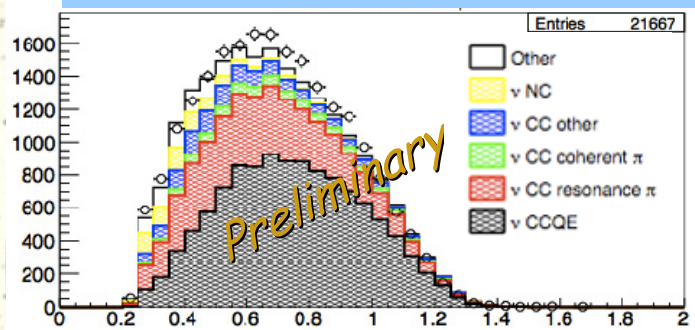
NEUT simulation



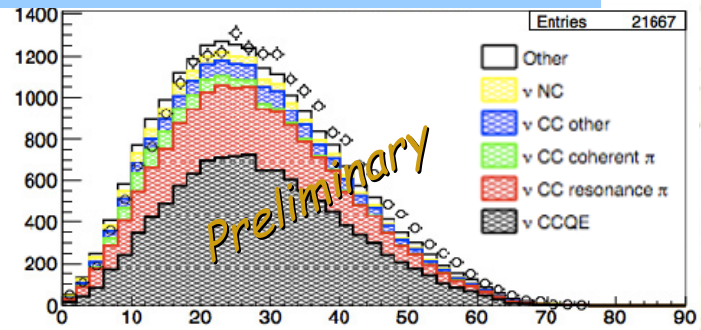
- QE
  - Llewellyn Smith
  - Smith & Moniz
  - M_A=1.1GeV/c^2
  - P_F=217MeV/c, E_B=27MeV
- 1π
  - Rein & Sehgal w/ lepton mass corr.
  - M_A=1.1 GeV/c^2
- DIS
  - GRV98
  - Bodek & Yang corr.
- Nuclear effects

CC-inclusive measurement

Muon kinematics of MRD stopped sample



Pμ (GeV/c)

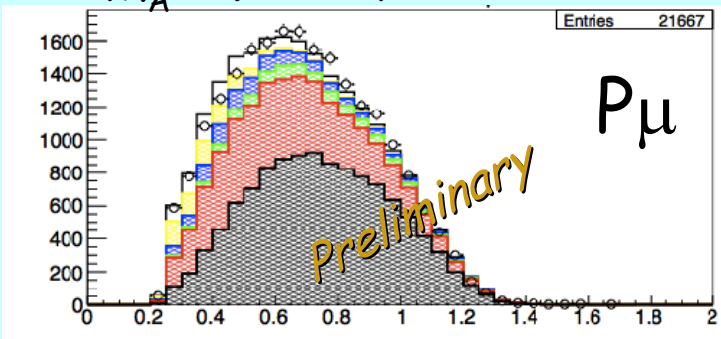


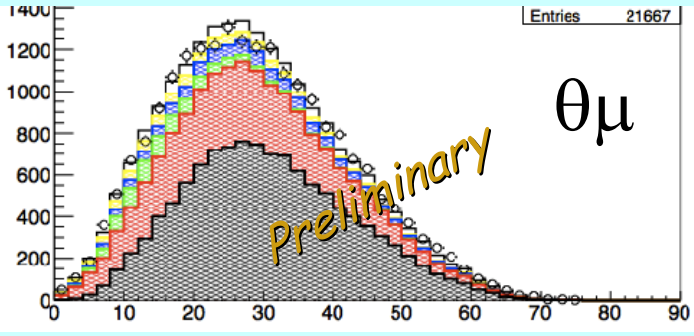
θμ (degree)

Y.Nakajima

σ(Pμ)~50MeV/c
σ(θμ)~0.9degree

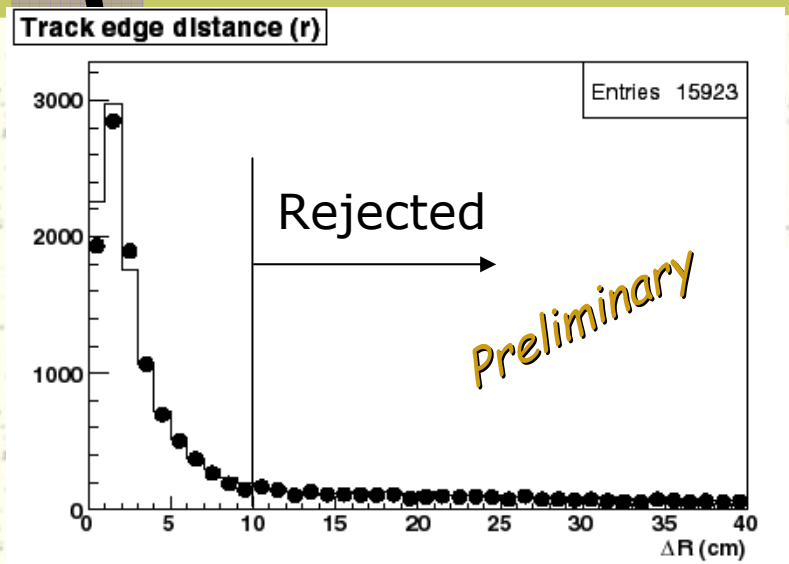
MiniBooNE Pauli blocking parameter κ=1.019
M_A= 1.2 GeV/c^2

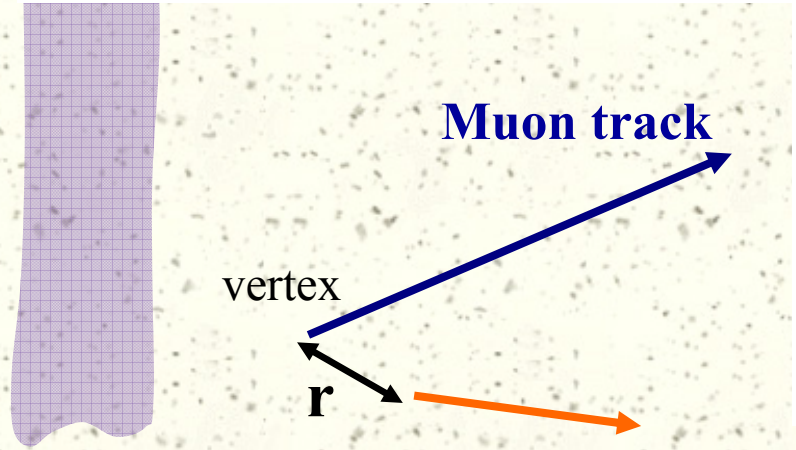


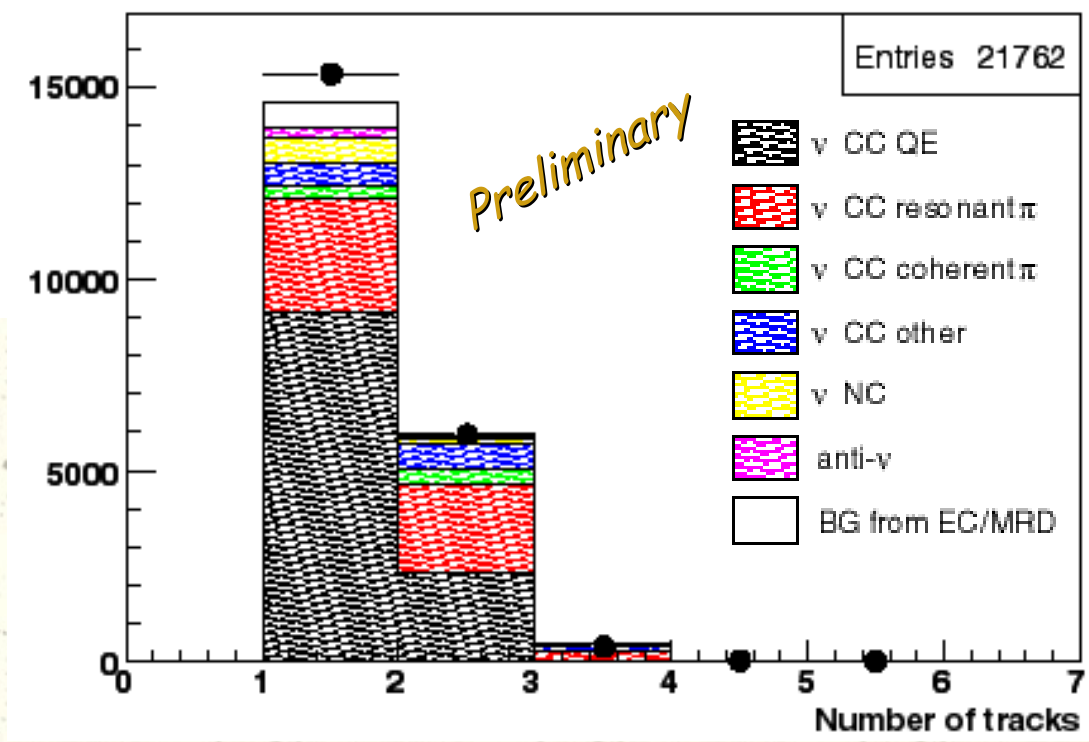


Better agreement!

of tracks from the vertex (MRD stopped sample)

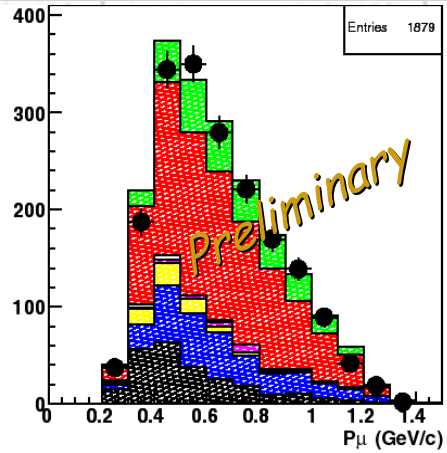




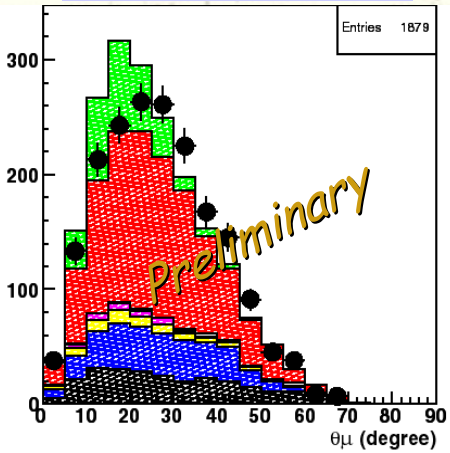


CC-1π^+ distributions

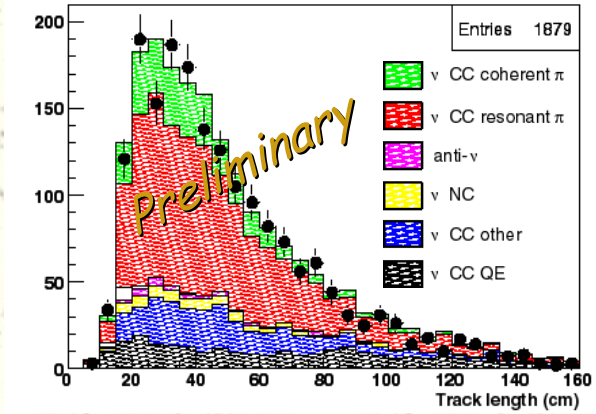
Muon momentum



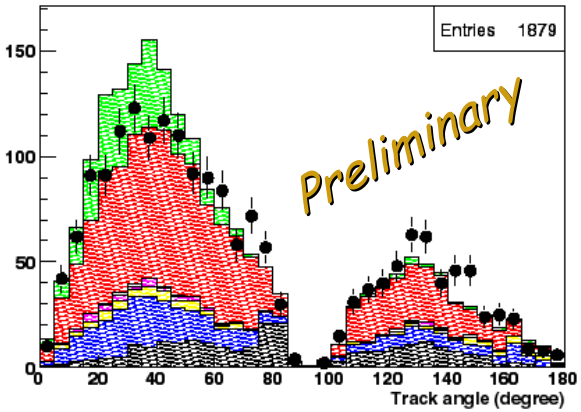
Muon angle



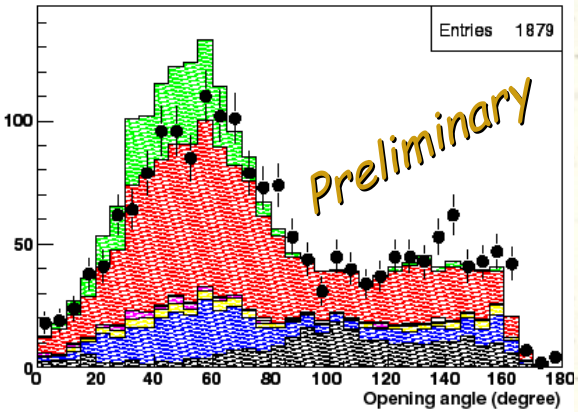
2nd track length



2nd track angle

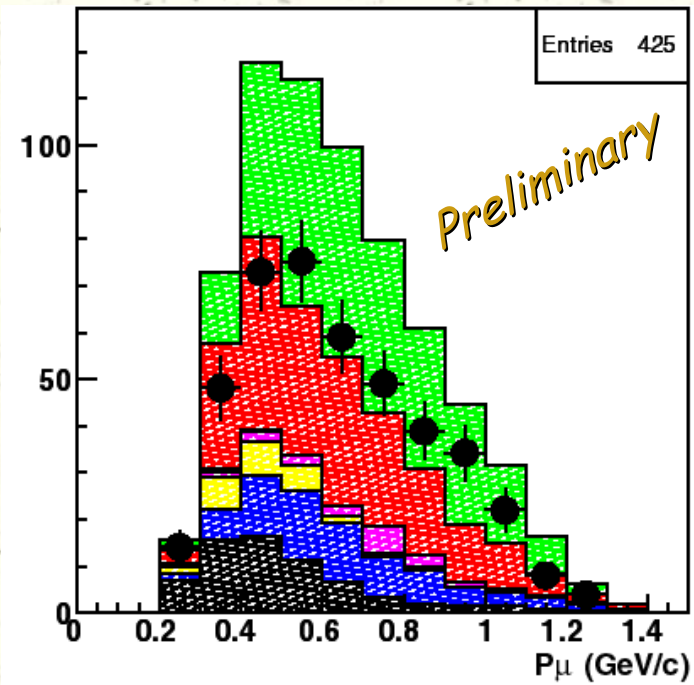


Opening angle

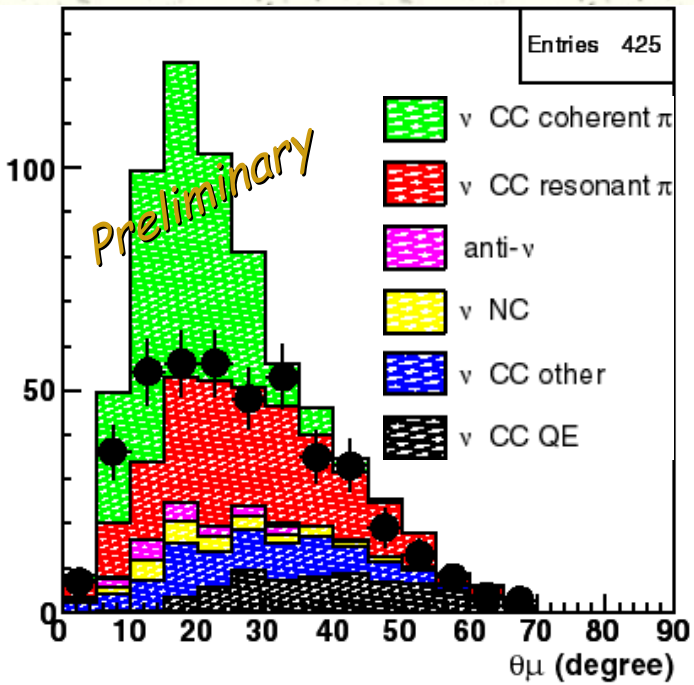


CC-coherent π sample

Muon momentum



Muon angle



CC-1π^+ event selection summary

Preliminary

	DATA	MC	$\nu p \rightarrow \mu p \pi$ efficiency	$\nu n \rightarrow \mu n \pi$ efficiency	Coherent π efficiency
Generated in FV		140,033	100%	100%	100%
MRD matched	30,337	30,337	25.4%	24.2%	49.4%
MRD stopped	21,762	21,041	18.5%	16.7%	36.7%
2 track	5,939	5,898	8.2%	5.8%	19.0%
$\mu+\pi$ (MuCL>0.05)	2,255	2,388	3.8%	4.8%	15.8%
$\Delta\theta_p$>20 degree	1,879	1,972	3.4%	4.3%	14.1%

CC-resonant π
- $\nu p \rightarrow \mu p \pi$ 34%
- $\nu n \rightarrow \mu n \pi$ 11%

CC-coherent π 15%

Backgrounds
CC-QE 13%
CC-multi π 12%

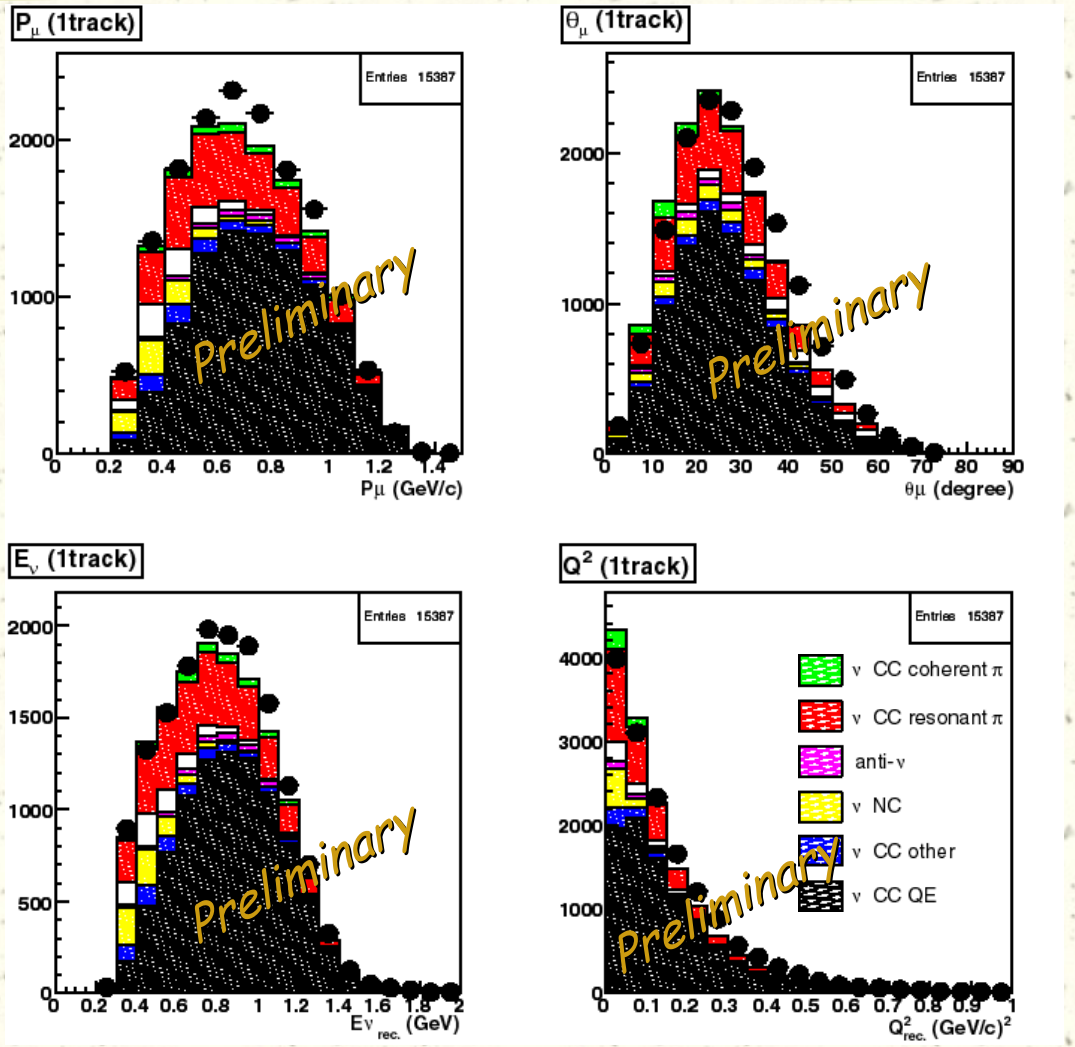
CC-coherent π event selection summary

CC-1π+ selection

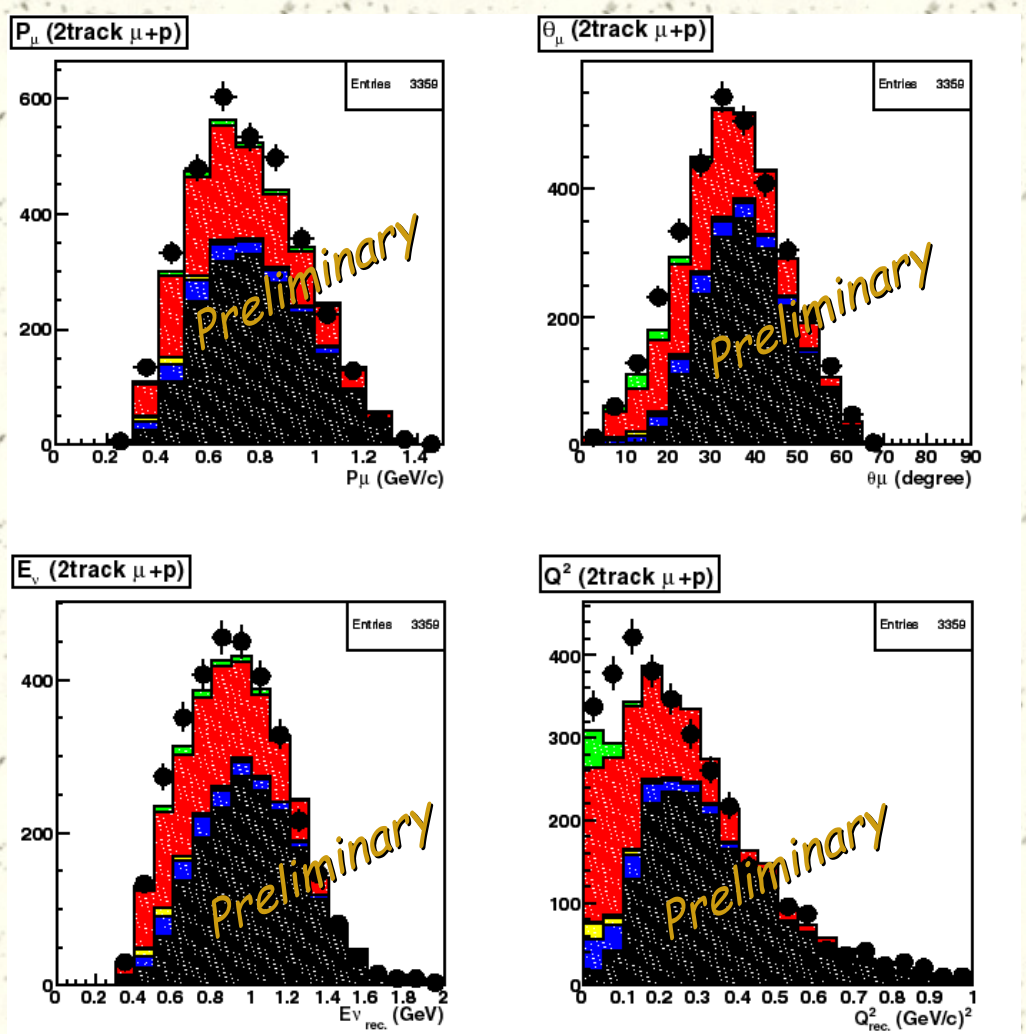
Coherent π

Preliminary	DATA	MC		Coherent π efficiency	Coherent π purity
		coherent	Others		
Generated in FV		2,119	137,914	100%	1.5%
MRD matched	30,337	1,047	29,290	49.4%	3.5%
MRD stopped	21,762	777	20,264	36.7%	3.7%
2 track	5,939	402	5,496	19.0%	6.8%
$\mu+\pi$ (MuCL<0.05)	2,255	334	2,054	15.8%	14%
$\Delta\theta_p$>20 degree	1,879	300	1,672	14.1%	15%
θ_π<90 degree	1,354	284	1,229	13.4%	19%
No vertex activity	425	266	395	12.6%	40%

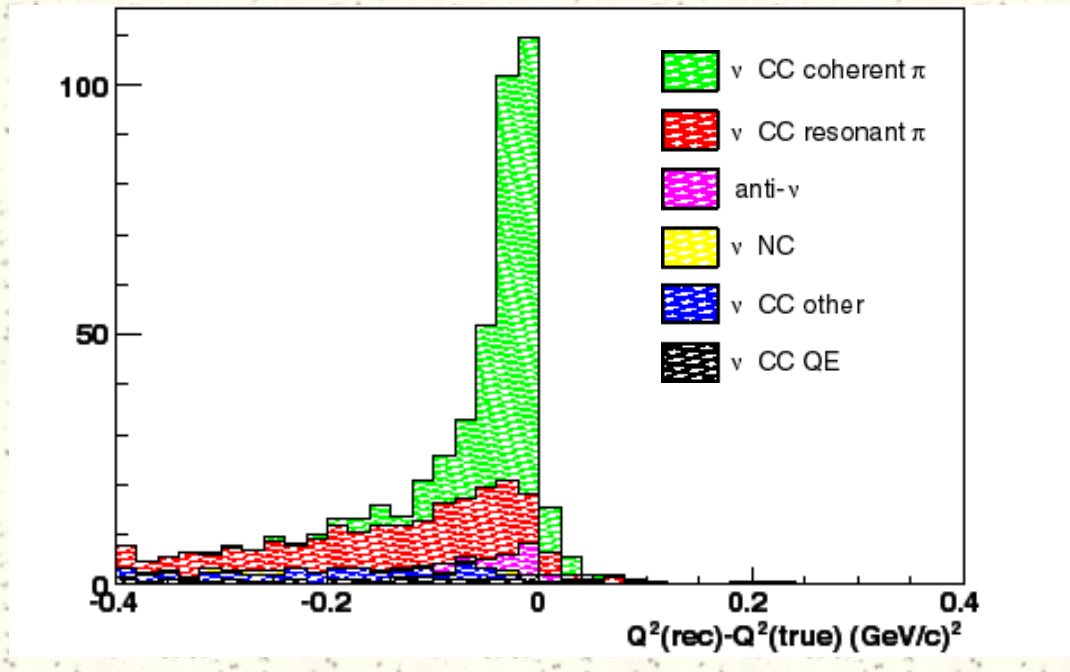
1track sample



2track μ+p sample



Q^2 resolution of CC-coherent π sample

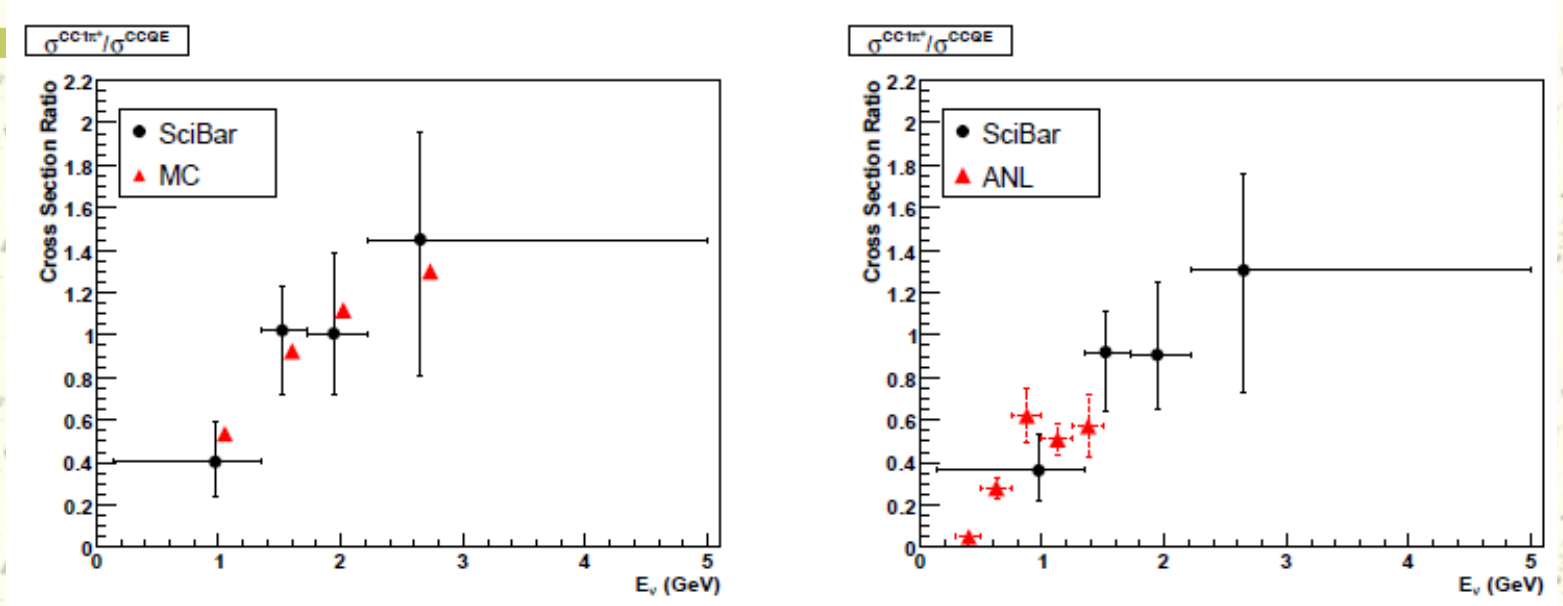


Q2 resolution of CC-coherent π events

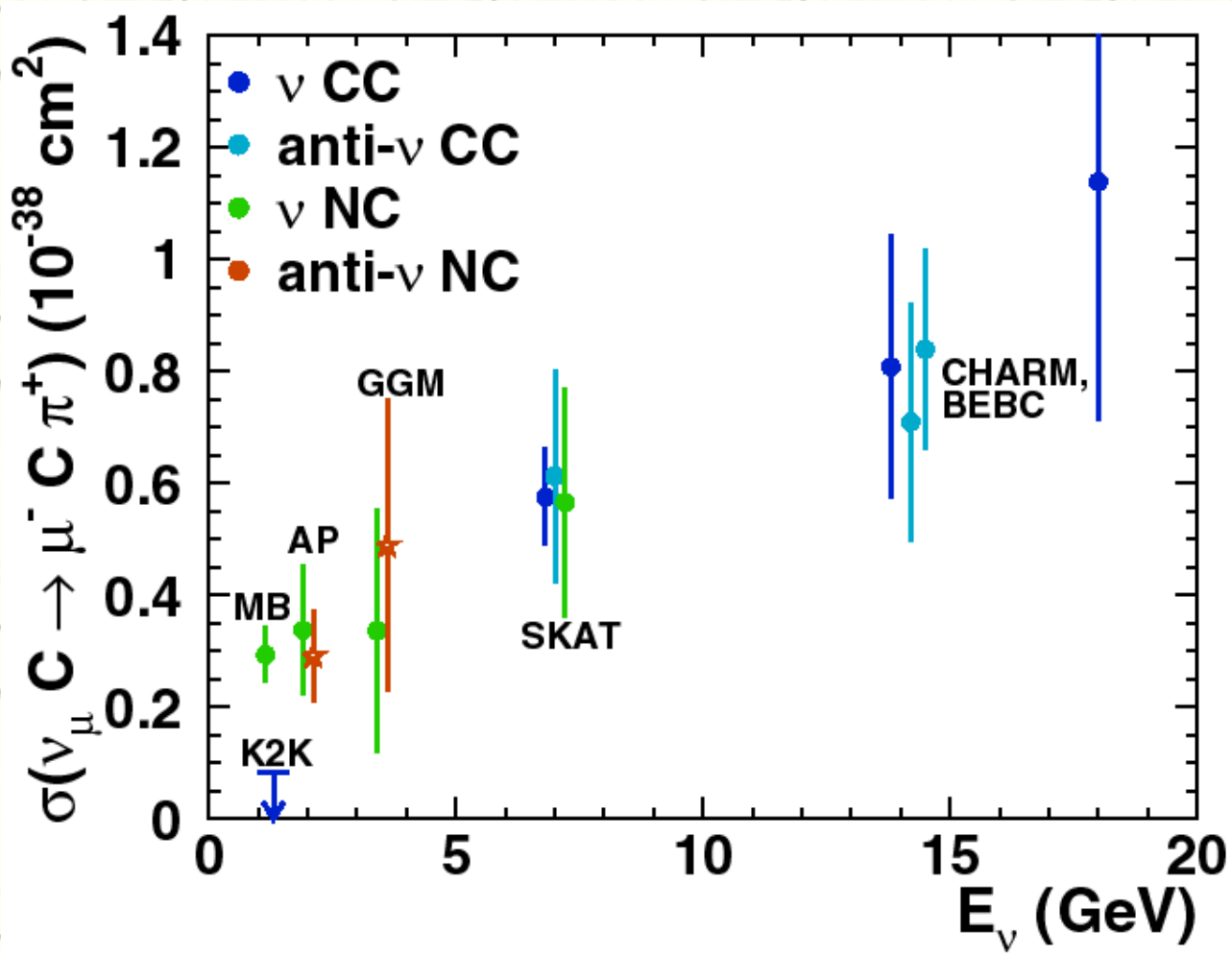
Mean: -0.024 $(GeV/c)^2$

Sigma: 0.016 $(GeV/c)^2$

K2K result on CC-resonant π^+



Energy Range (GeV)	Cross Section Ratio $R_e = \frac{\sigma_e^{CC1\pi^+}}{\sigma_e^{CCQE}}$
>0.00	$0.734 \pm 0.086(\text{fit})^{+0.076}_{-0.103}(\text{nucl})^{+0.079}_{-0.073}(\text{syst})$
0.00-1.35	$0.402 \pm 0.111(\text{fit})^{+0.079}_{-0.071}(\text{nucl})^{+0.131}_{-0.092}(\text{syst})$
1.35-1.72	$1.022 \pm 0.167(\text{fit})^{+0.072}_{-0.217}(\text{nucl})^{+0.107}_{-0.139}(\text{syst})$
1.72-2.22	$1.007 \pm 0.214(\text{fit})^{+0.209}_{-0.065}(\text{nucl})^{+0.241}_{-0.173}(\text{syst})$
>2.22	$1.450 \pm 0.324(\text{fit})^{+0.200}_{-0.272}(\text{nucl})^{+0.330}_{-0.480}(\text{syst})$

arXiv:0805.0186

Other coherent π measurements