Search for Charged Current Coherent Pion Production by Neutrinos at SciBooNE

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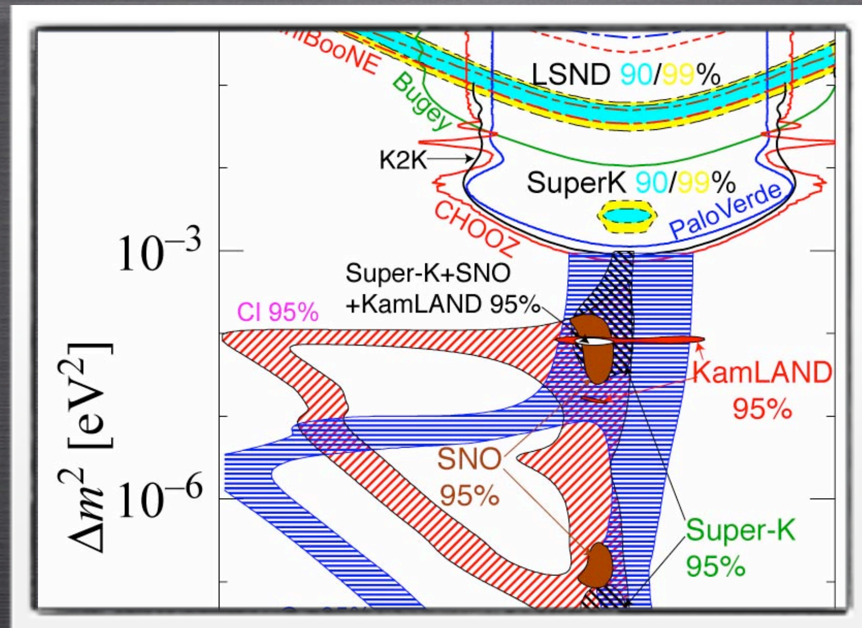


Introduction

Motivation

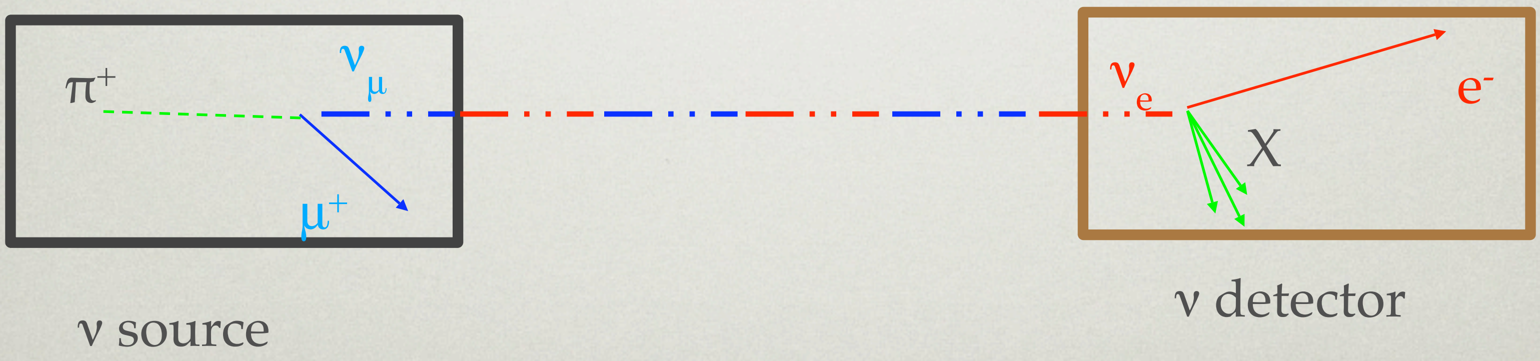
if neutrinos have mass...

a neutrino that is produced as a ν_μ

- (e.g. $\pi^+ \rightarrow \mu^+ \nu_\mu$)

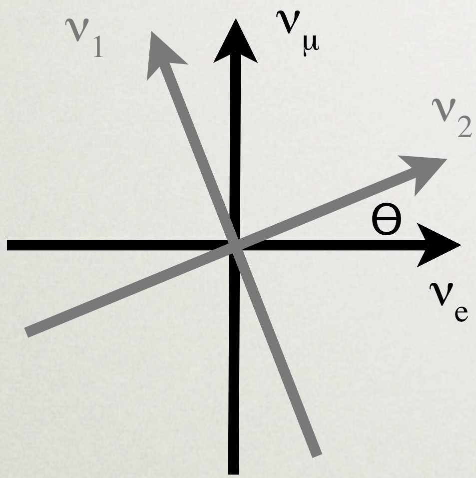
might some time later be observed as a ν_e

- (e.g. $\nu_e\, n \rightarrow e^- p$)



Neutrino Oscillation

$$\begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



- Consider only two types of neutrinos
- If weak states differ from mass states
  - i.e. $(\nu_\mu\ \nu_e) \neq (\nu_1\ \nu_2)$
- Then weak states are mixtures of mass states

$$|\nu_\mu(t)\rangle = -\sin\theta\,|\nu_1\rangle\, e^{-iE_1 t} + \cos\theta\,|\nu_2\rangle\, e^{-iE_2 t}$$

$$P_{osc}(\nu_\mu \to \nu_e) = |\langle \nu_e | \nu_\mu(t)\rangle|^2$$

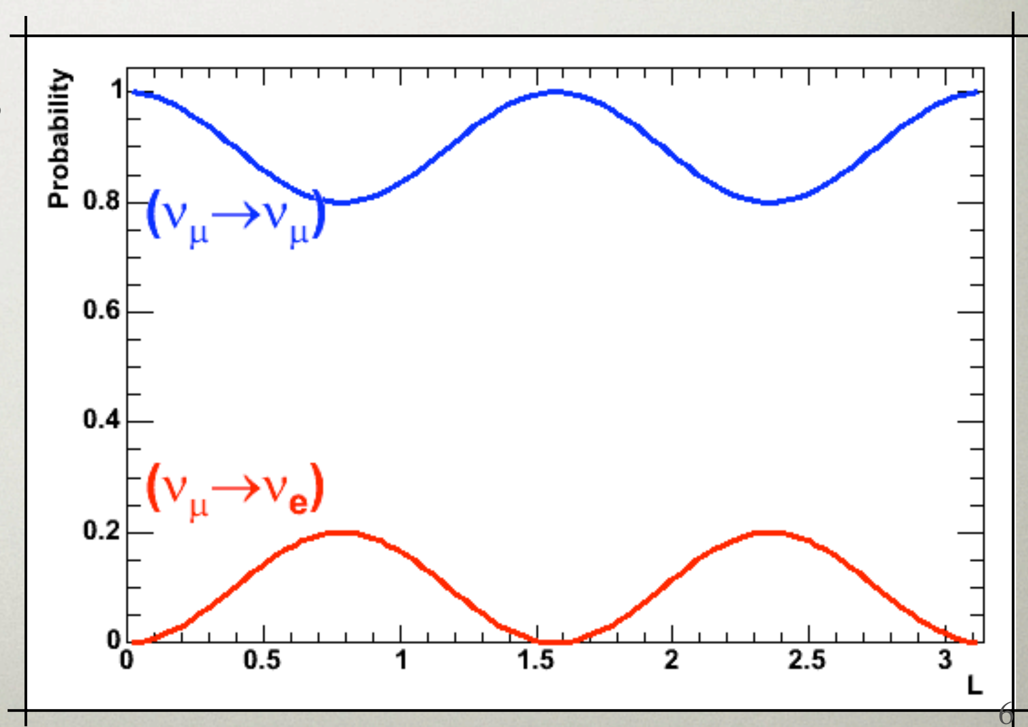
- Probability to find ν_e when you started with ν_μ

Neutrino Oscillation

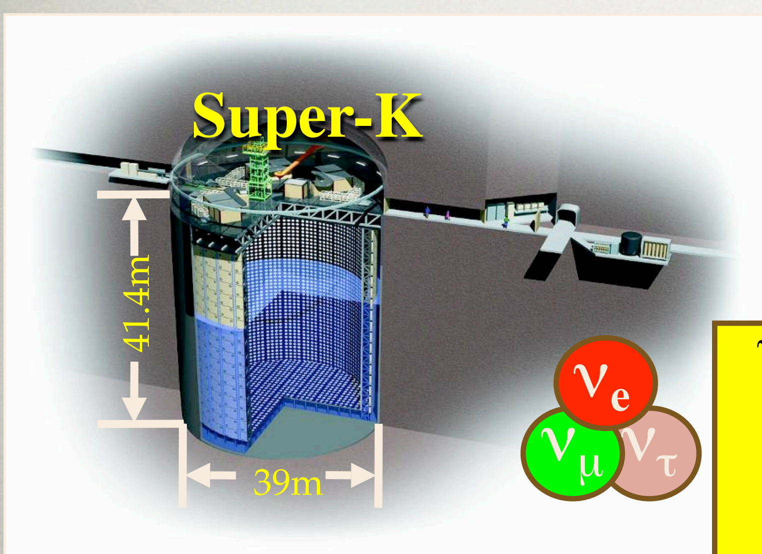
- In units that experimentalists like:

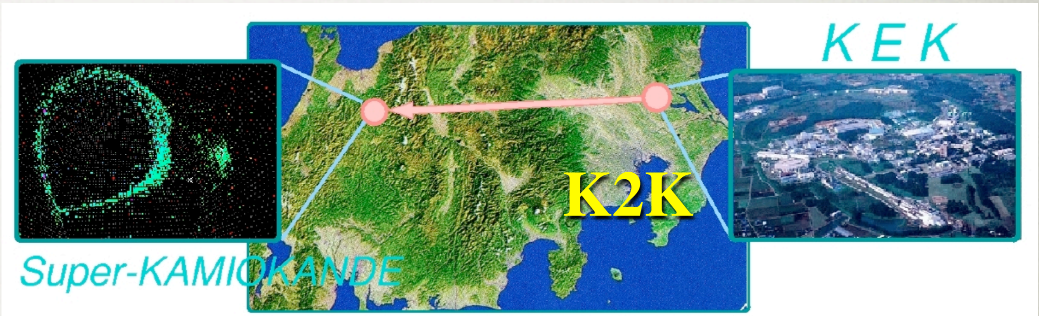
$$P_{osc}(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$

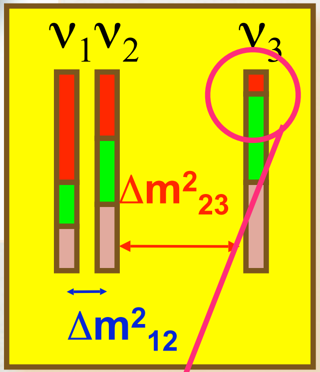
- Fundamental Parameters
  - mass squared differences
  - mixing angle
- Experimental Parameters
  - L = distance from source to detector
  - E = neutrino energy



Neutrino Oscillation Observations



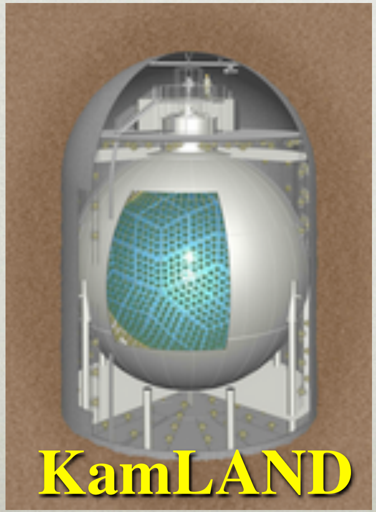


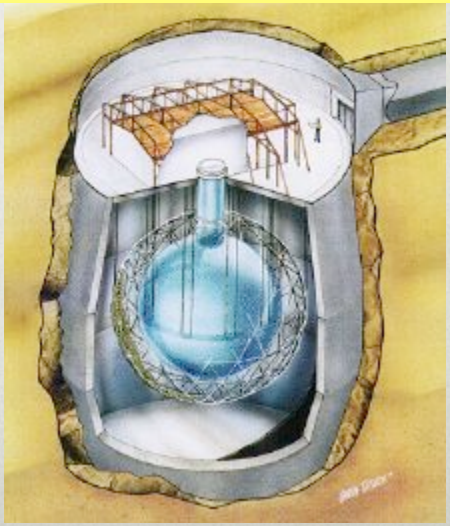


Neutrino masses $(\Delta m_{12}^2, \Delta m_{23}^2)$

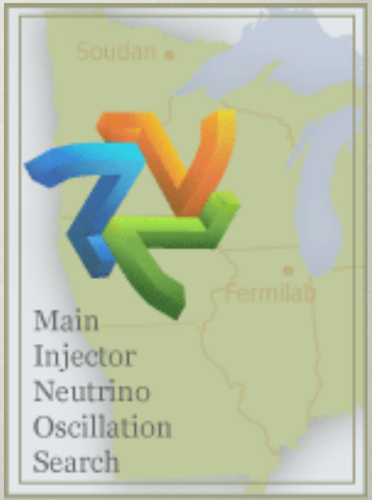
Mixing Angles $(\theta_{12}, \theta_{23})$

$\theta_{13} \rightarrow \delta$



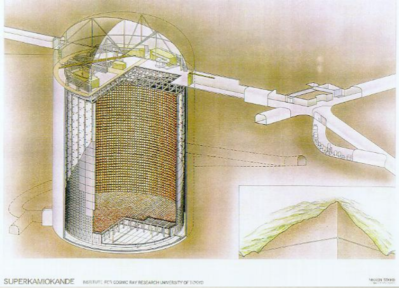


SNO



MINOS

Next Steps



ν_e, ν_μ, ν_τ

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

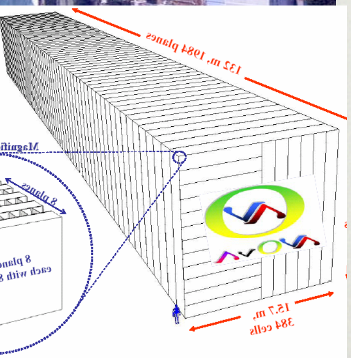
ν_1, ν_2, ν_3

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

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

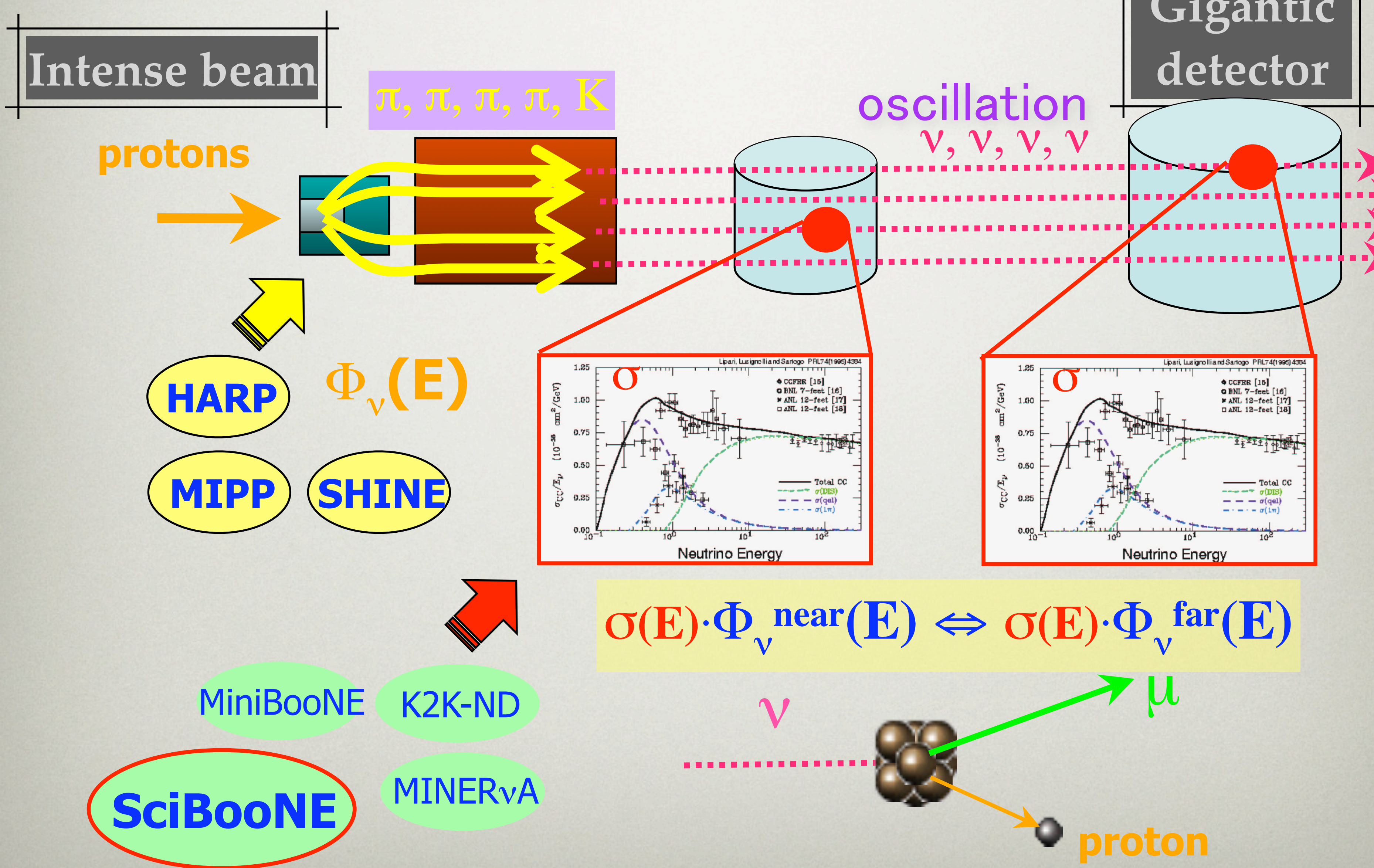
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric | **Cross Mixing** | solar



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

Accelerator Oscillation Experiments

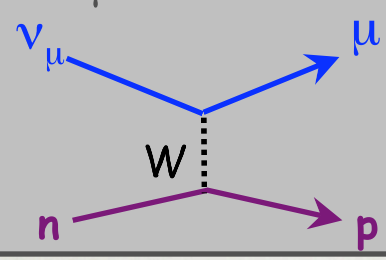


Background Processes

ν_μ disappearance ($\nu_\mu \rightarrow \nu_x$)

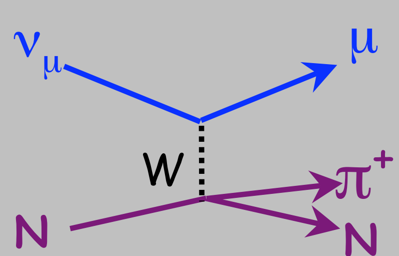
Signal

ν_μ CC-QE



Background

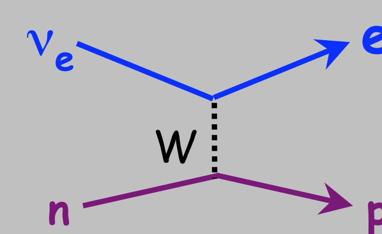
ν_μ CC-1π^+



ν_e appearance ($\nu_\mu \rightarrow \nu_e$)

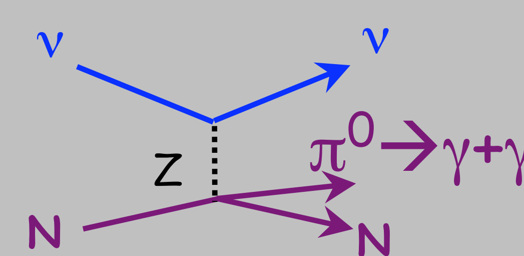
Signal

ν_e CC-QE



Background

NC-1π^0

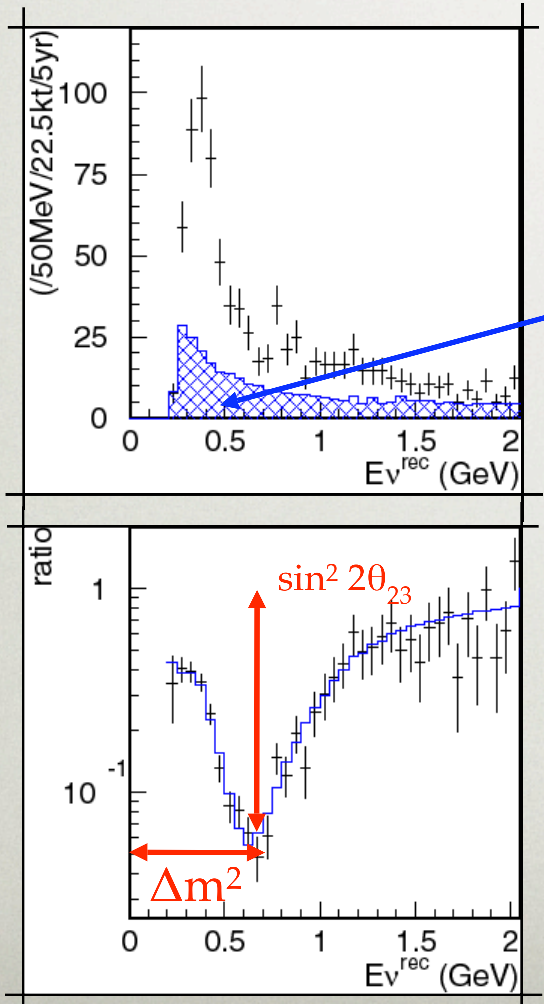


Need to understand these processes as well

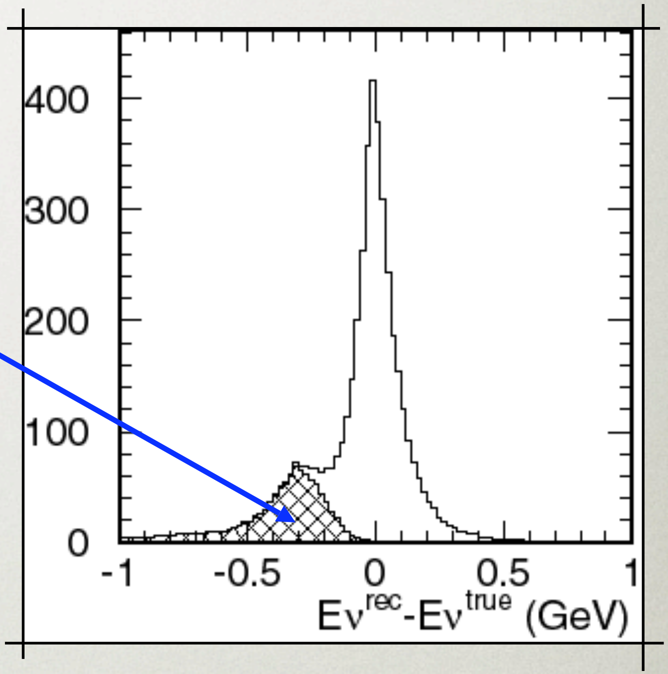
Background Processes

ν_μ disappearance ($\nu_\mu \rightarrow \nu_x$)

T2K (MC) ν_μ events



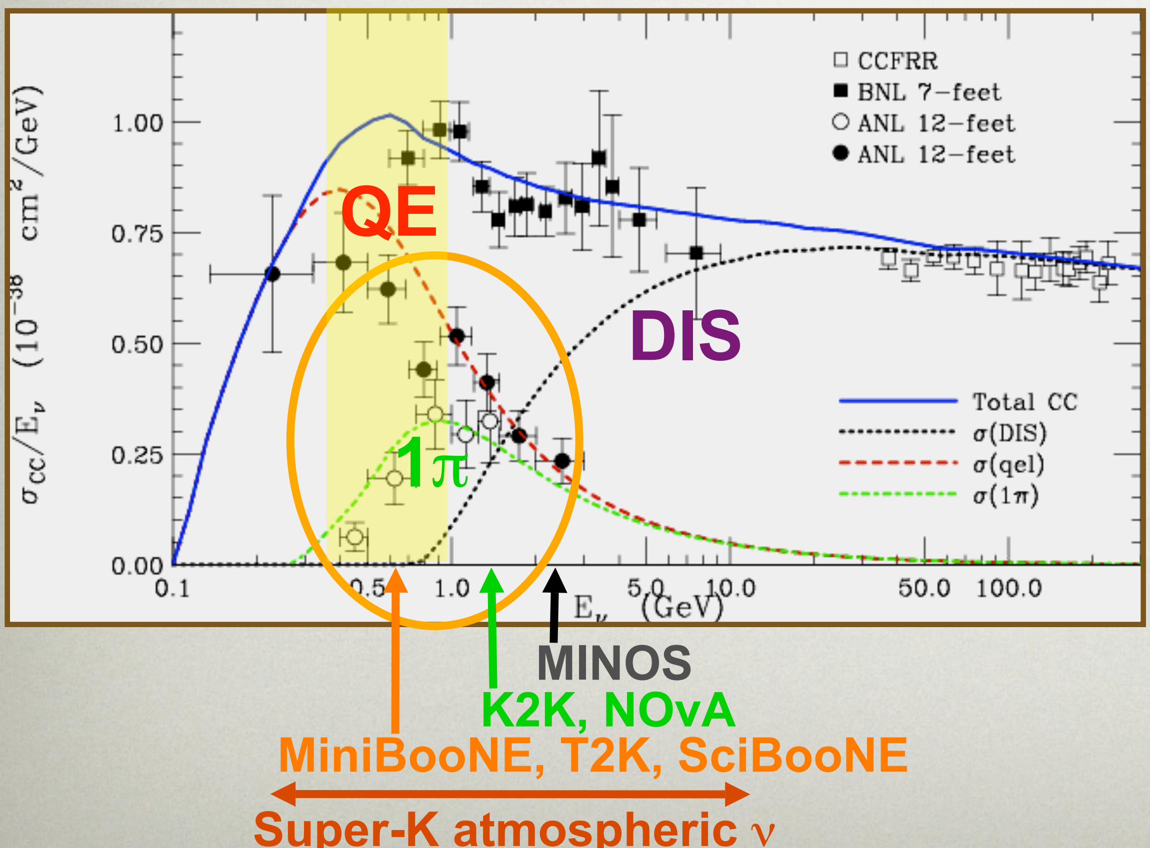
"Non-QE"
mainly CC-1π^+



Uncertainty in the non-QE background affects the measurement of oscillation parameters

ν-NUCLEUS CROSS SECTIONS

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



Data from old experiments (1970~1980)

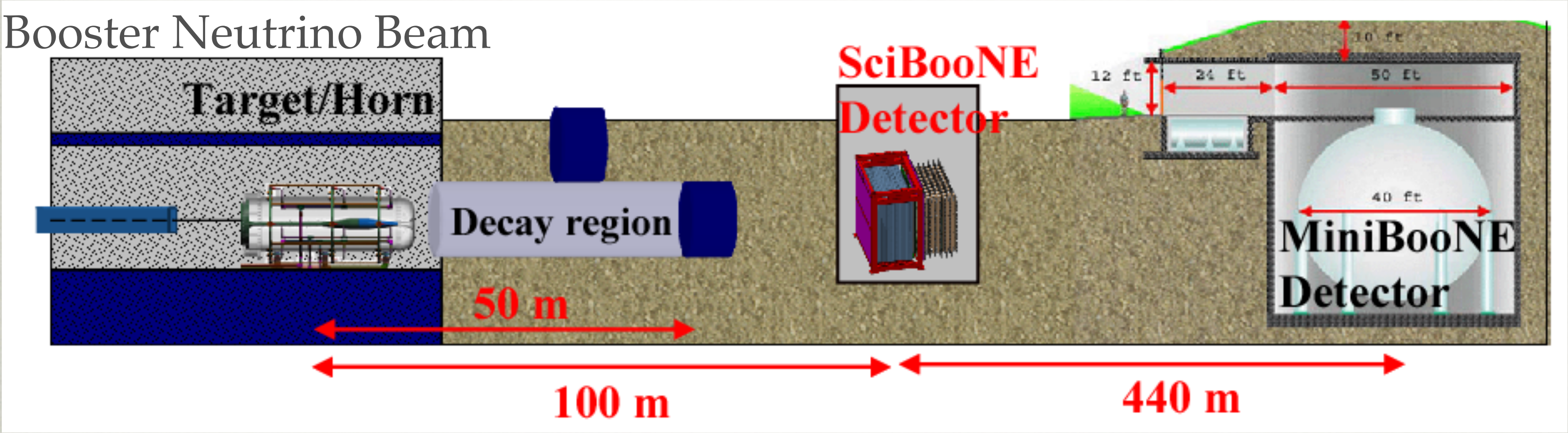
Low statistics

Systematic Uncertainties

New data from K2K & MiniBooNE revealing surprises

SciBooNE Description

SciBooNE Experiment (FNAL E954)



- 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

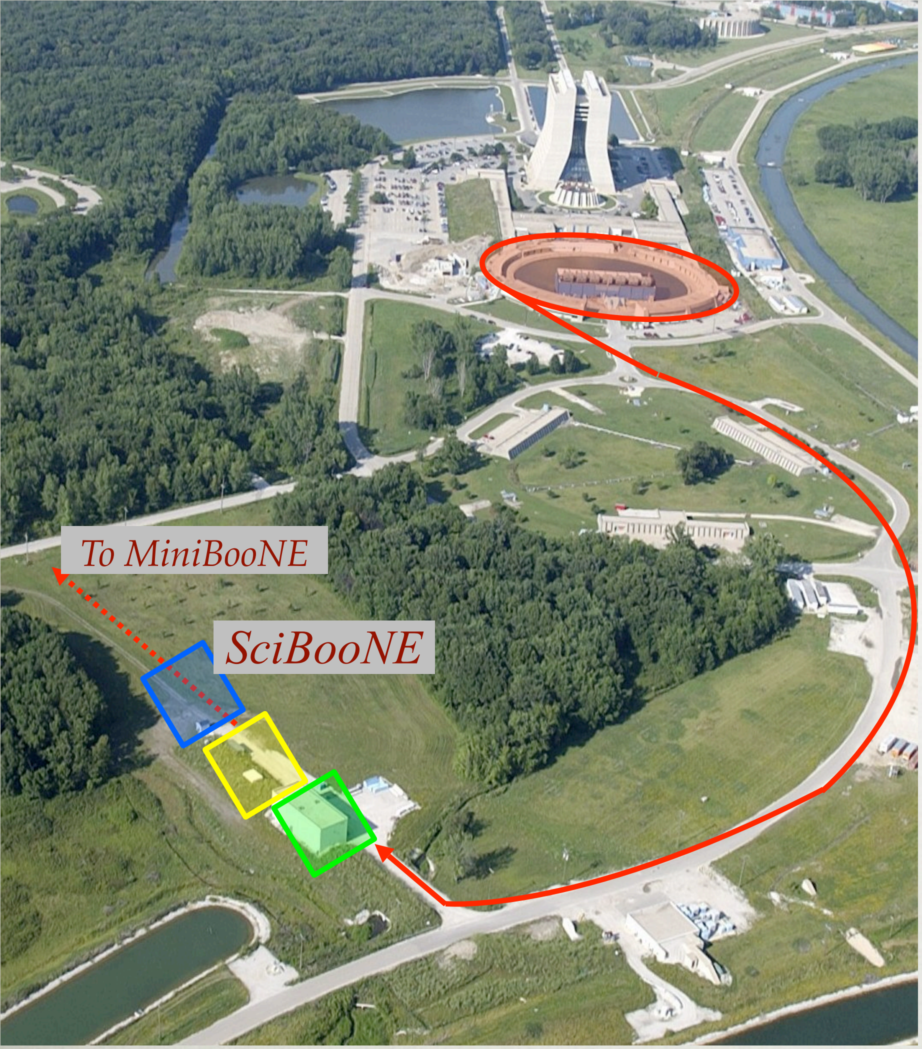
SciBooNE Collaboration

~60 physicists

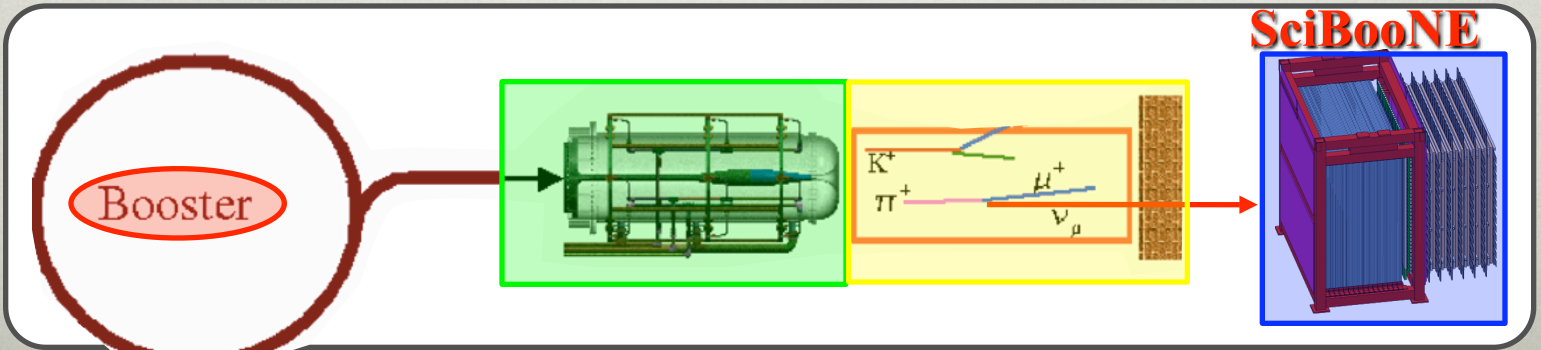
5 countries 17 institutions

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“ and INFN
Saint Mary's University of Minnesota
Tokyo Institute of Technology
Unversidad de Valencia

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

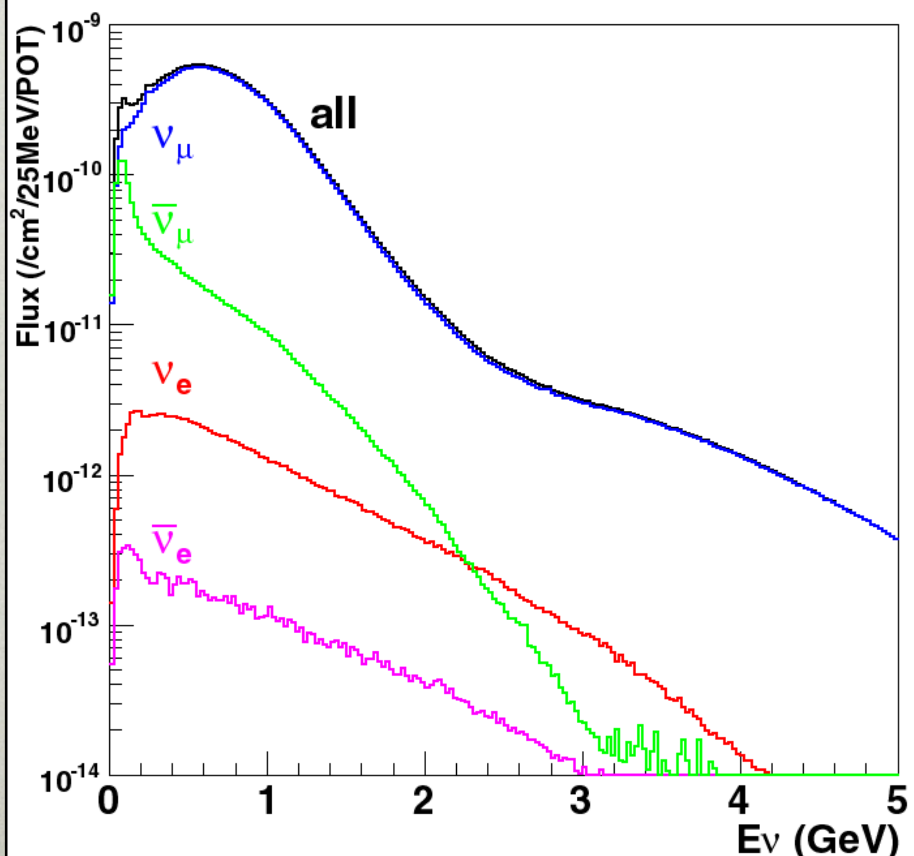


- Booster Proton accelerator
  - 8 GeV protons sent to target
- Target Hall
  - Beryllium target: 71cm long 1cm diameter
  - Resultant mesons focused with magnetic horn
  - Reversible horn polarity
- 50m decay volume
  - Mesons decay to μ & ν_μ
  - Short decay pipe minimizes $\mu \rightarrow \nu_e$ decay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



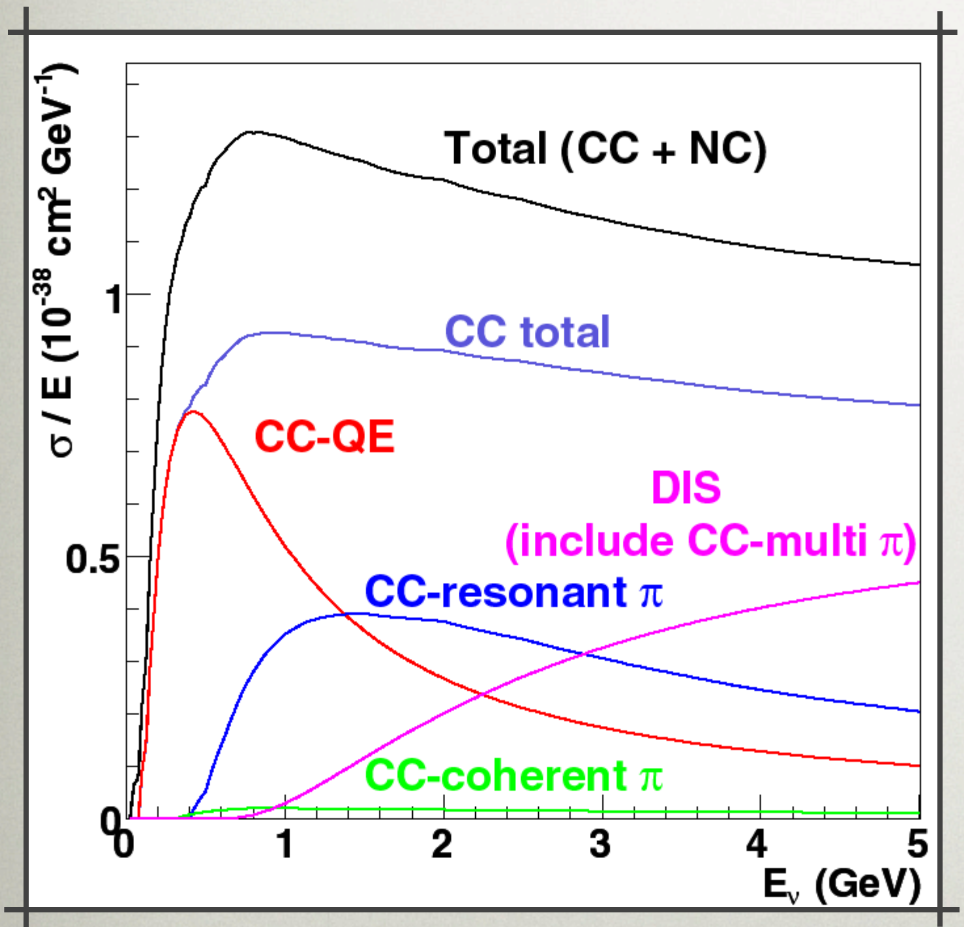
Booster Neutrino Beam

Expected neutrino flux at SciBooNE (neutrino mode)



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

Neutrino Event Generator (NEUT)



- QE
  - Llewellyn Smith, Smith-Moniz
  - M_A=1.2GeV/c²
  - P_F=217MeV/c, E_B=27MeV (for Carbon)
- Resonant π
  - Rein-Sehgal (2007)
  - M_A=1.2 GeV/c²
- Coherent π
  - Rein-Sehgal (2006)
  - M_A=1.0 GeV/c²

CC/NC-1π

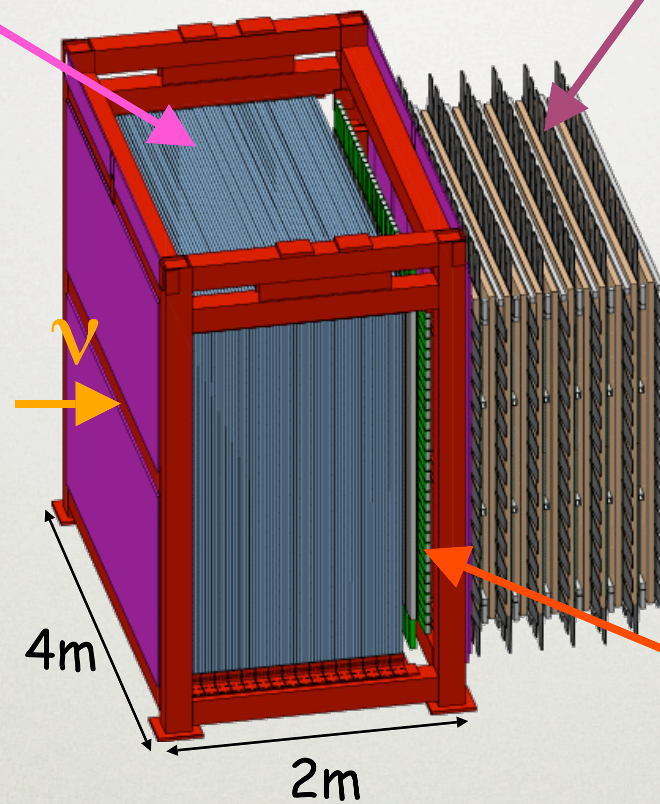
- Deep Inelastic Scattering
  - GRV98 PDF
  - Bodek-Yang correction
- Intra-nucleus interactions

SciBooNE detector

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 experiments

Electron Catcher (EC)

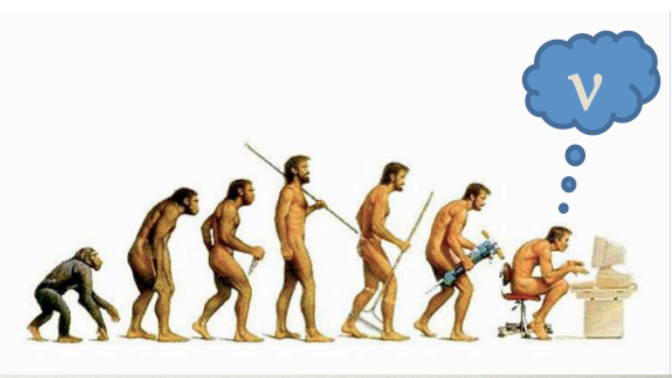
- spaghetti calorimeter
- 2 planes (11 X_0)
- identify π^0 and ν_e

Used in CHORUS, HARP and K2K

DOE-wide Pollution Prevention Star (P2 Star) Award

SciBooNE Timeline

- 2005, Summer - Collaboration formed
- 2005, Dec - Proposal
- 2006, Jul - Detectors move to FNAL
- 2006, Sep - Groundbreaking
- 2006, Nov - Sub-detectors Assembly
- 2007, Apr - Detector Installation
- 2007, May - Commissioning
- 2007, Jun – Started Data-taking
- 2008, Aug – Completed data-taking
- 2008, Nov – 1st physics result



Only 3 years from formation to 1st physics result

SciBooNE Timeline

Groundbreaking ceremony (Sep. 2006)

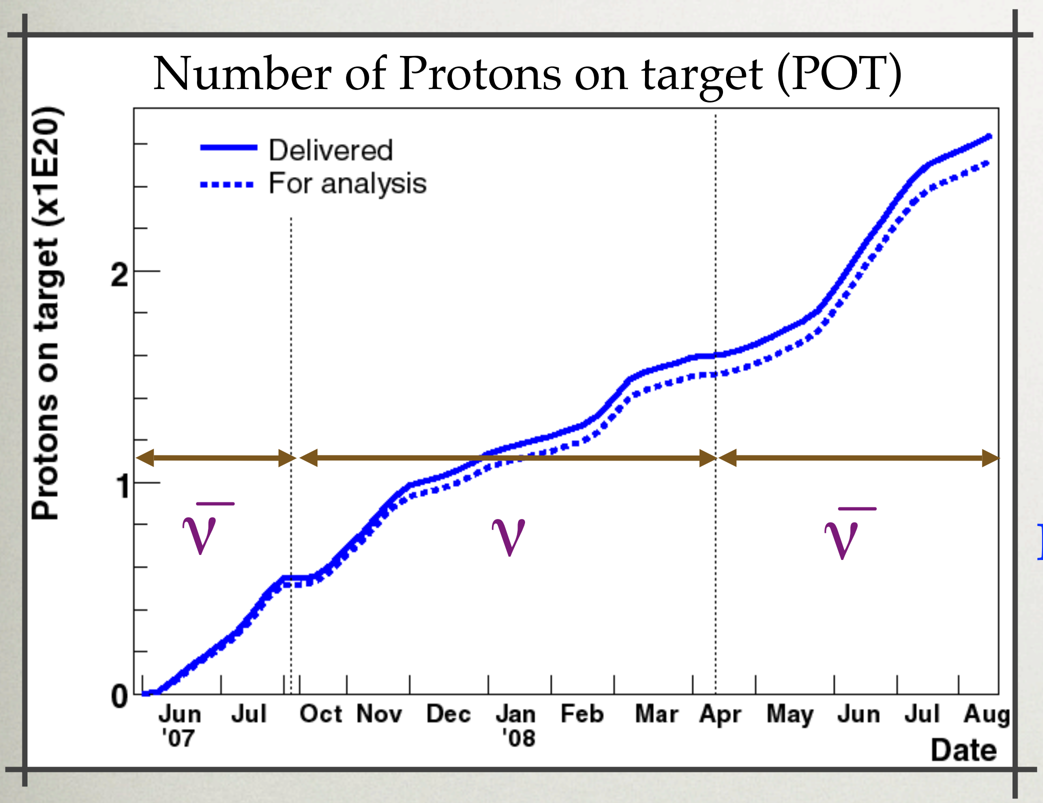
Detector Assembly (Nov. 2006 -Mar.2007)

SciBooNE Timeline

Detector installation
(Apr. 2007)

End-of-run party
(Aug. 2008)

SciBooNE 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

Many thanks to FNAL Accelerator Division!

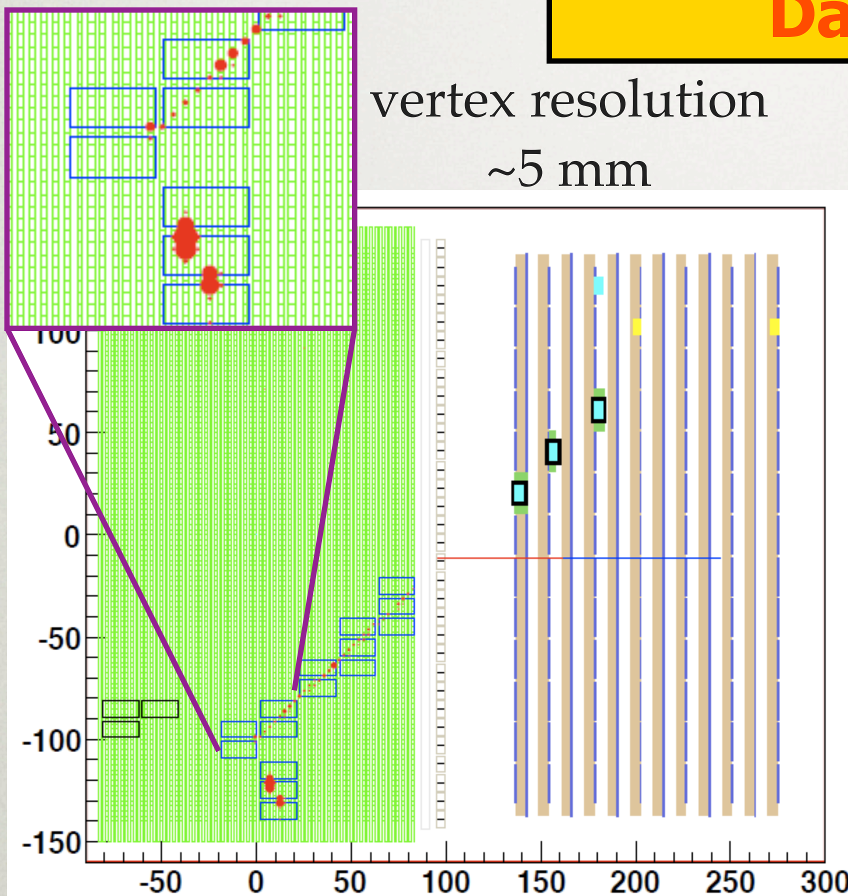
Results from full neutrino data set presented today

Neutrino event displays

Real SciBooNE Data

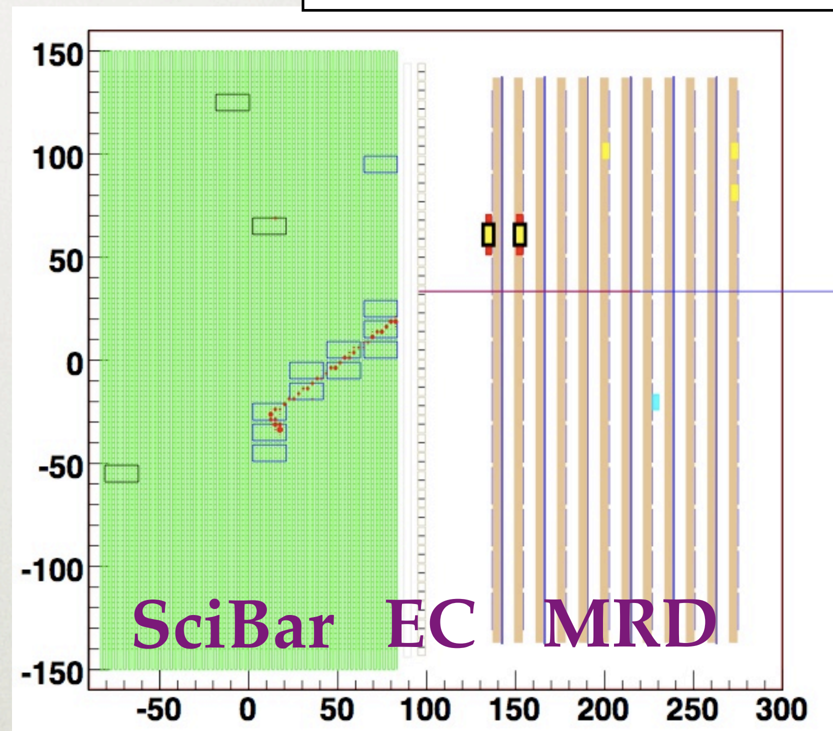
- ADC hits (area ∝ charge)
- TDC hits (32ch "OR")

vertex resolution ~5 mm



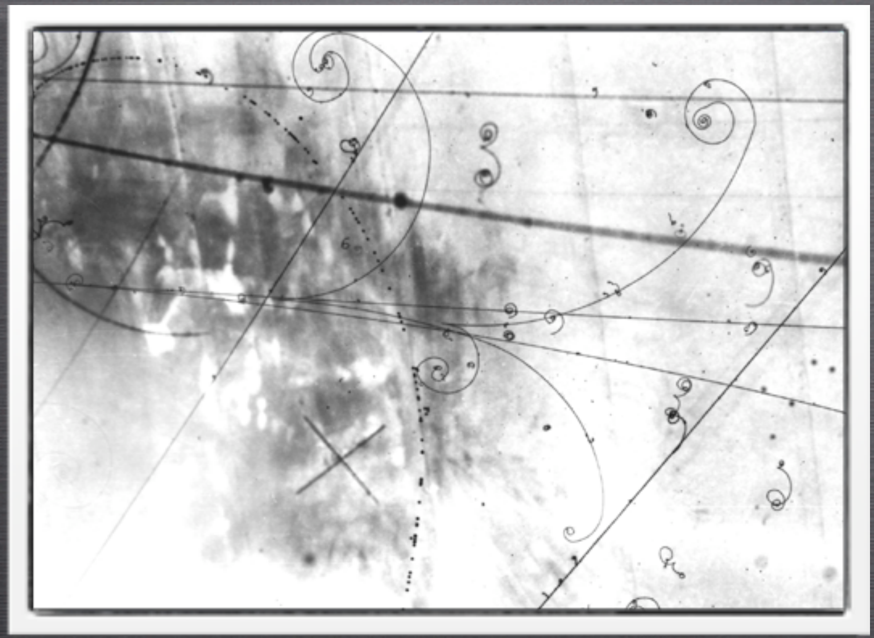
anti-ν_μ CC-QE candidate

$(\bar{\nu}_\mu + p \rightarrow \mu + n)$



ν_μ CC-QE candidate

$(\nu_\mu + n \rightarrow \mu + p)$

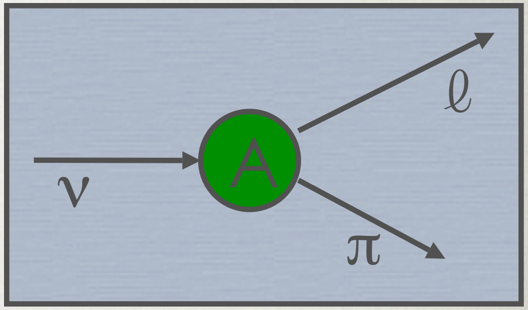


Search for CC Coherent Pion Production

Coherent pion production

The signal for today's search

- Neutrino interacts with nucleons coherently, producing a pion
- No nuclear breakup occurs



Charged Current (CC): $\nu_\mu + A \rightarrow \mu + A + \pi^+$

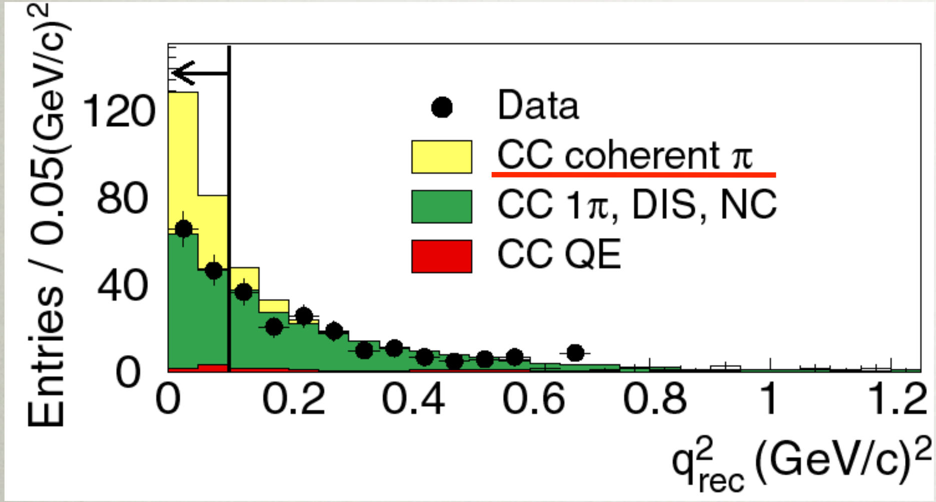
Neutral Current (NC): $\nu_\mu + A \rightarrow \nu_\mu + A + \pi^0$

Several measurements (before K2K and MiniBooNE)

- both NC and CC
- both neutrino and antineutrino
- >2 GeV (NC), >7 GeV (CC) up to ~100 GeV

Surprises

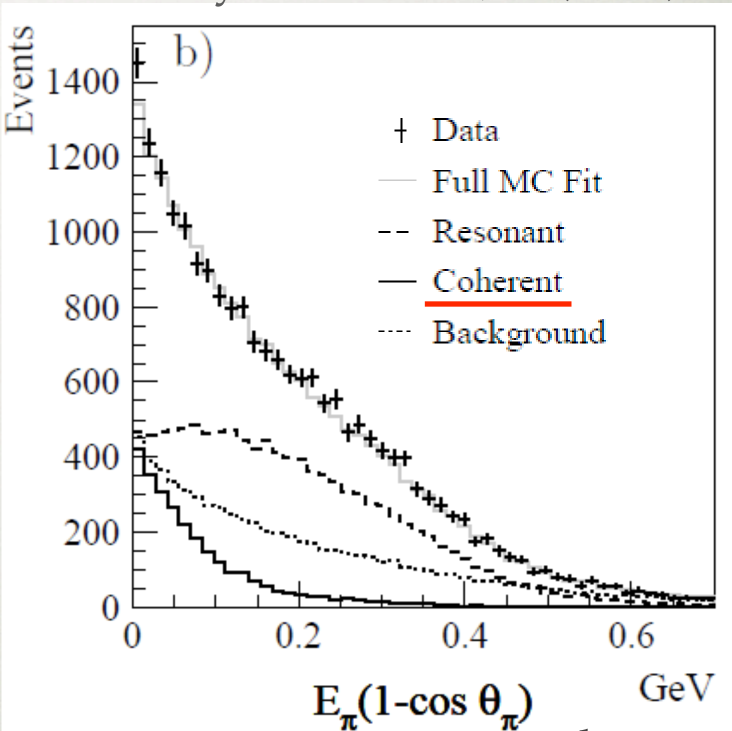
CC coherent π^+
K2K,
Phys.Rev.Lett. 95,252301 (2005)



No evidence of CC coherent pion production is found at <Eν>=1.3 GeV

σ(CC coherent π)/σ(CC)<0.60x10^{-2} (90%CL) (corresponds to 23% of the prediction)

NC coherent π^0
MiniBooNE,
Phys.Lett. B664,41 (2008)



First observation of NC coherent pion production at Eν<2GeV

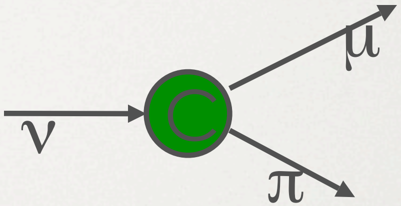
65% of the model prediction

CC Coherent Pion Production

Signal

CC-coherent π production

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



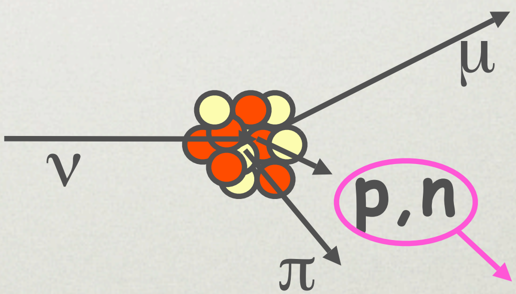
Small Q^2

- 2 MIP-like tracks (a muon and a pion)
- ~1% of total ν interaction based on Rein-Sehgal model

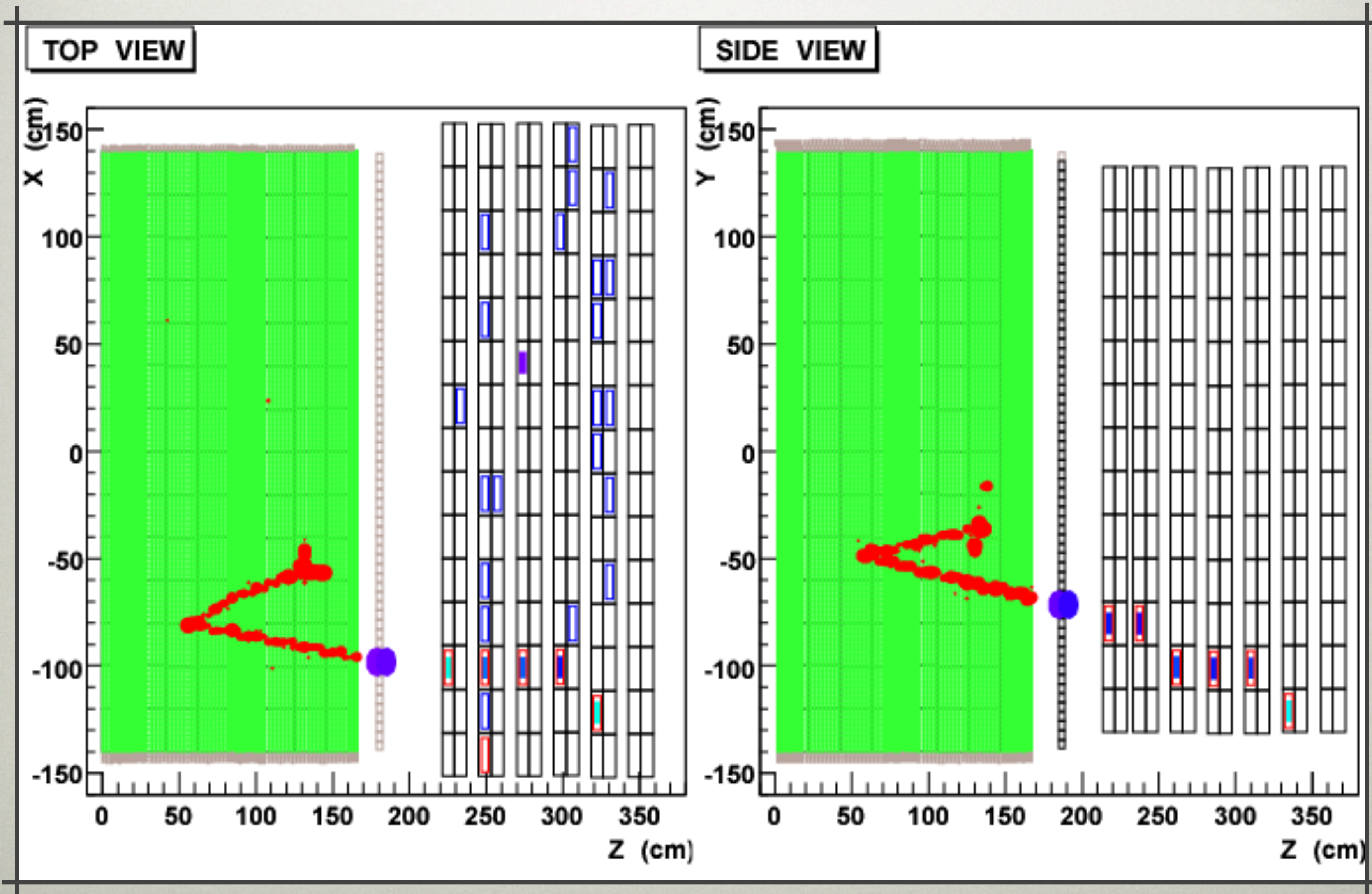
Background

CC-resonant π production

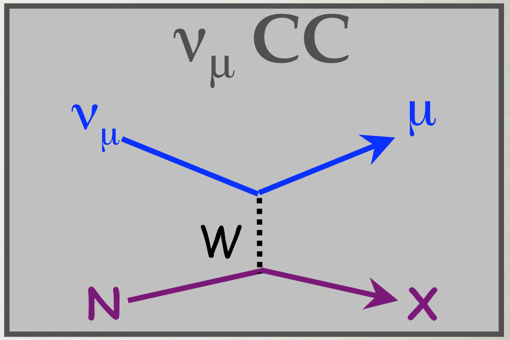
- $\nu + p \rightarrow \mu + p + \pi^+$
- $\nu + n \rightarrow \mu + n + \pi^+$



CC-1π^+ candidate

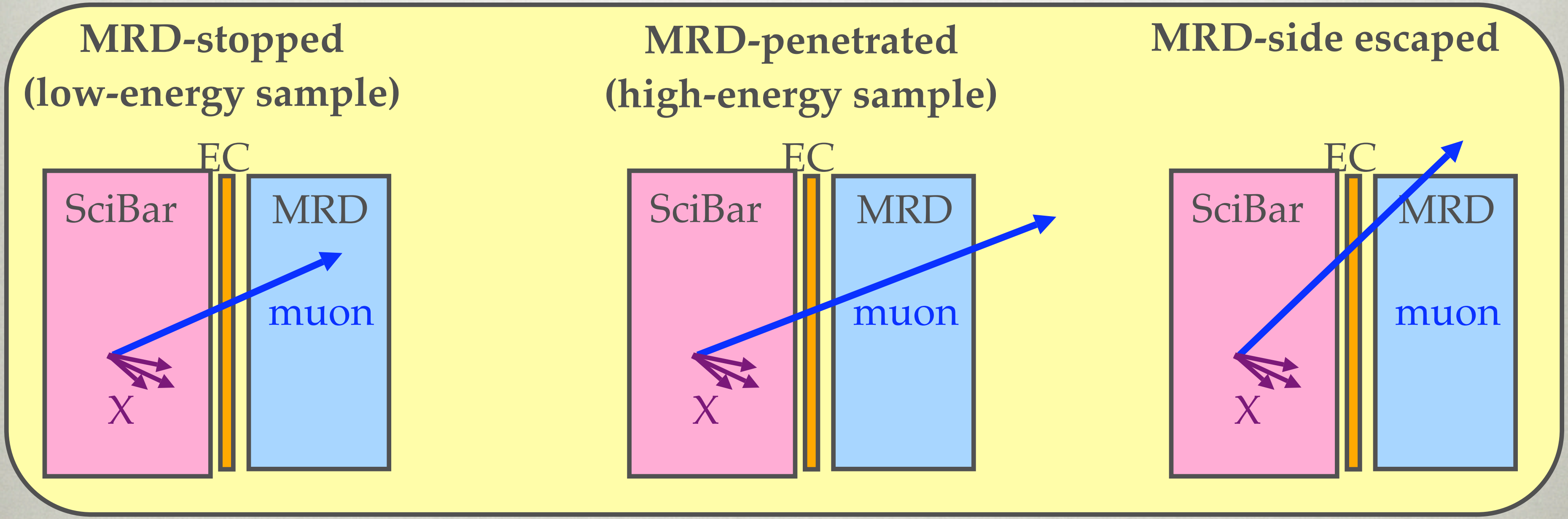


Charged Current (CC) event selection



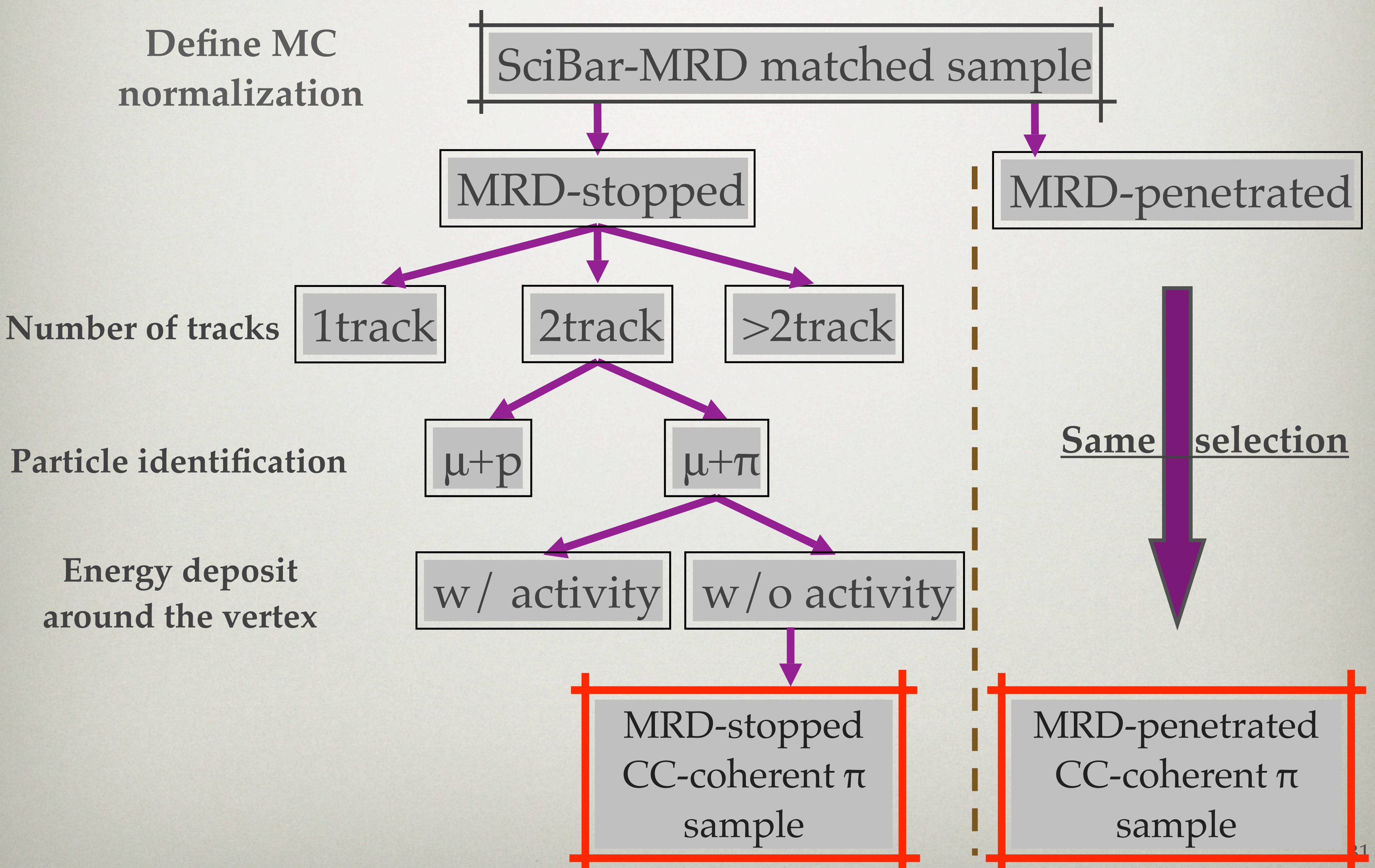
- **Muons identified using MRD**
- **Tracks should start from SciBar fiducial volume**

SciBar-MRD matched event (~30k events)

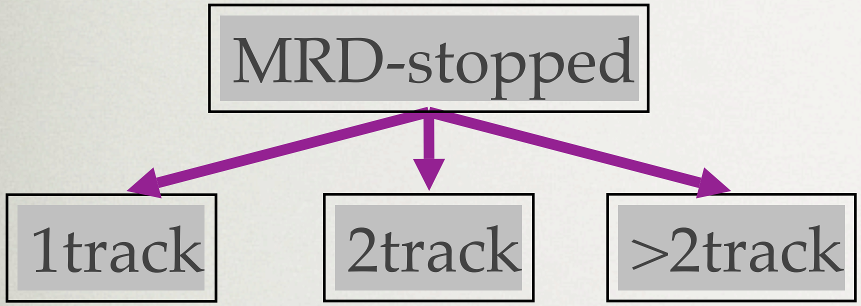


93% pure CC-inclusive (ν+N→μ+X) sample

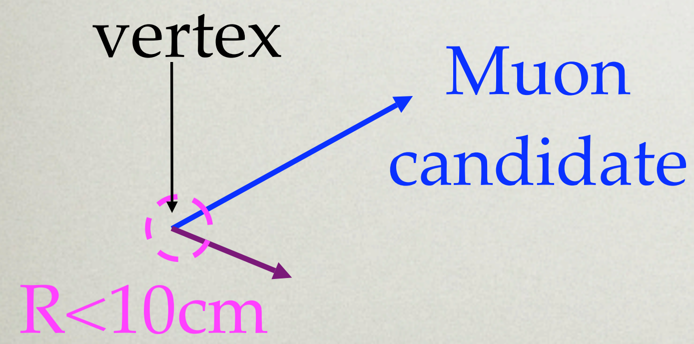
CC event classification

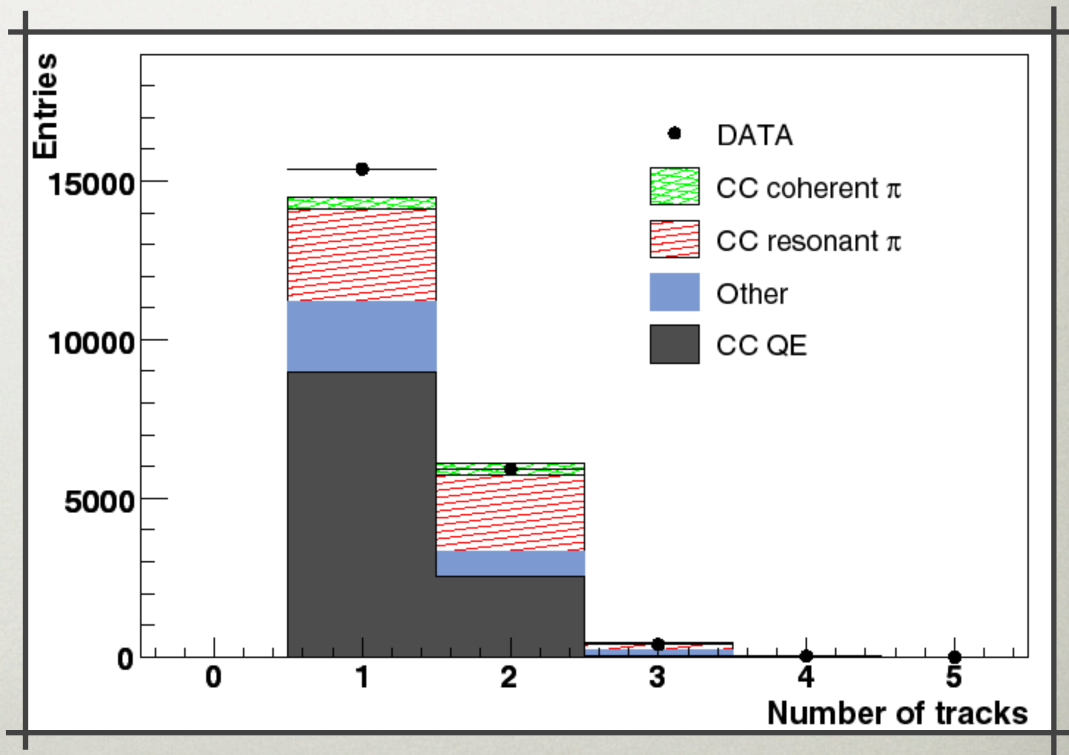


Number of tracks



Search for tracks from the vertex (R<10cm)



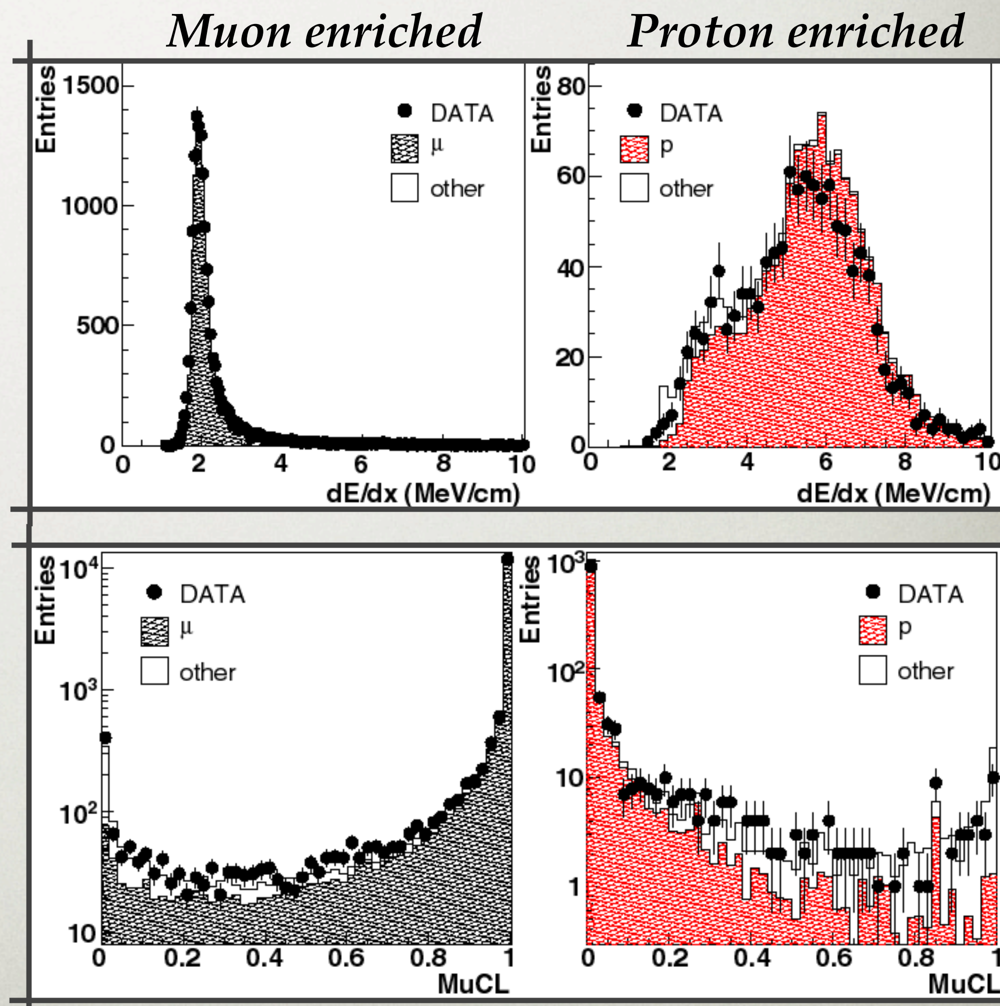


Particle Identification

Particle ID using dE/dx in SciBar

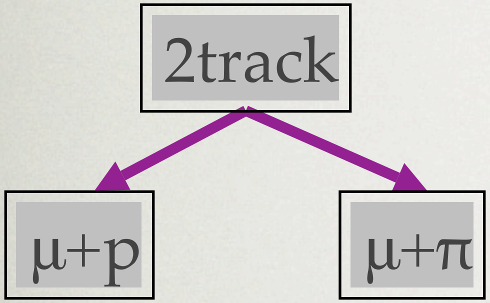
Muon confidence level (MuCL)

MuCL >0.05 → muon-like
<0.05 → proton-like

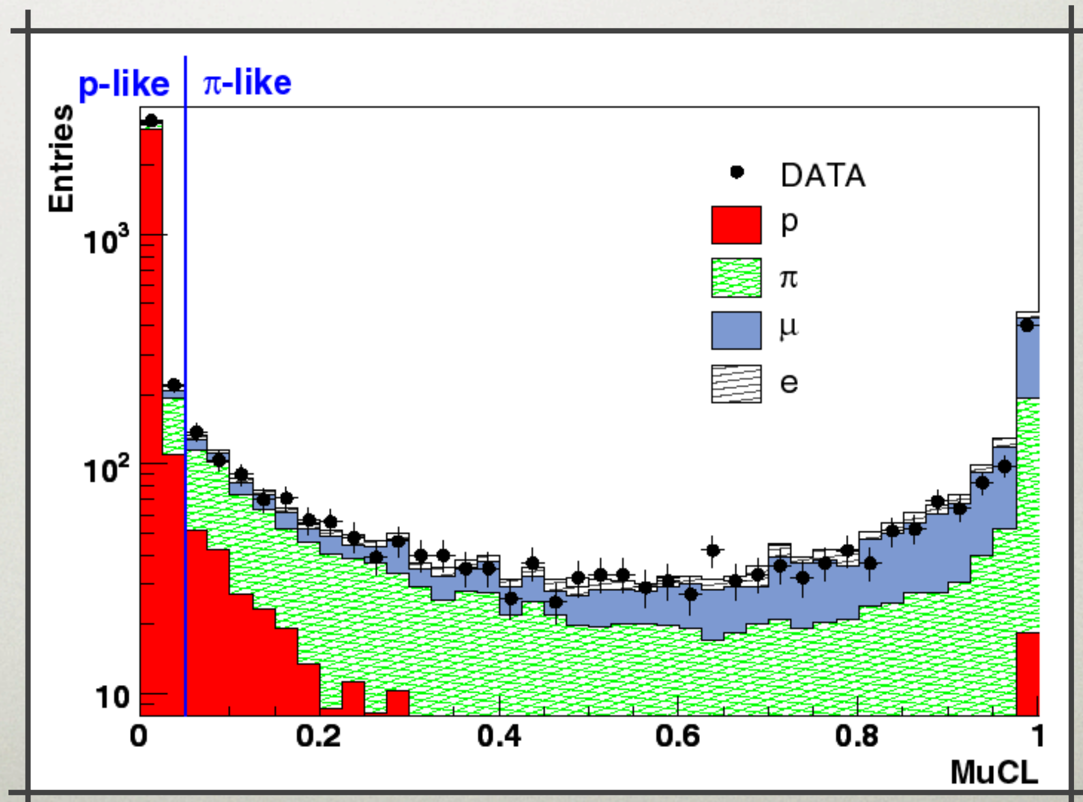


Mis-ID probability
Muon: 1.1%
Proton: 12%

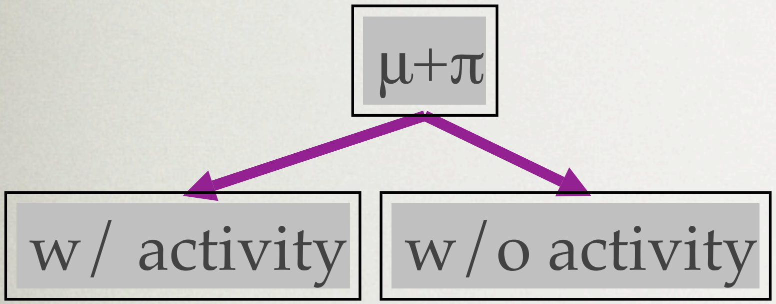
Particle Identification



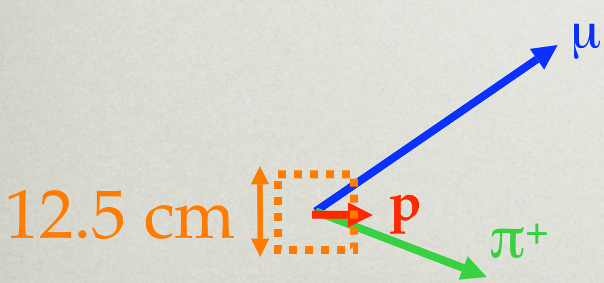
MuCL for 2nd track in 2-track event

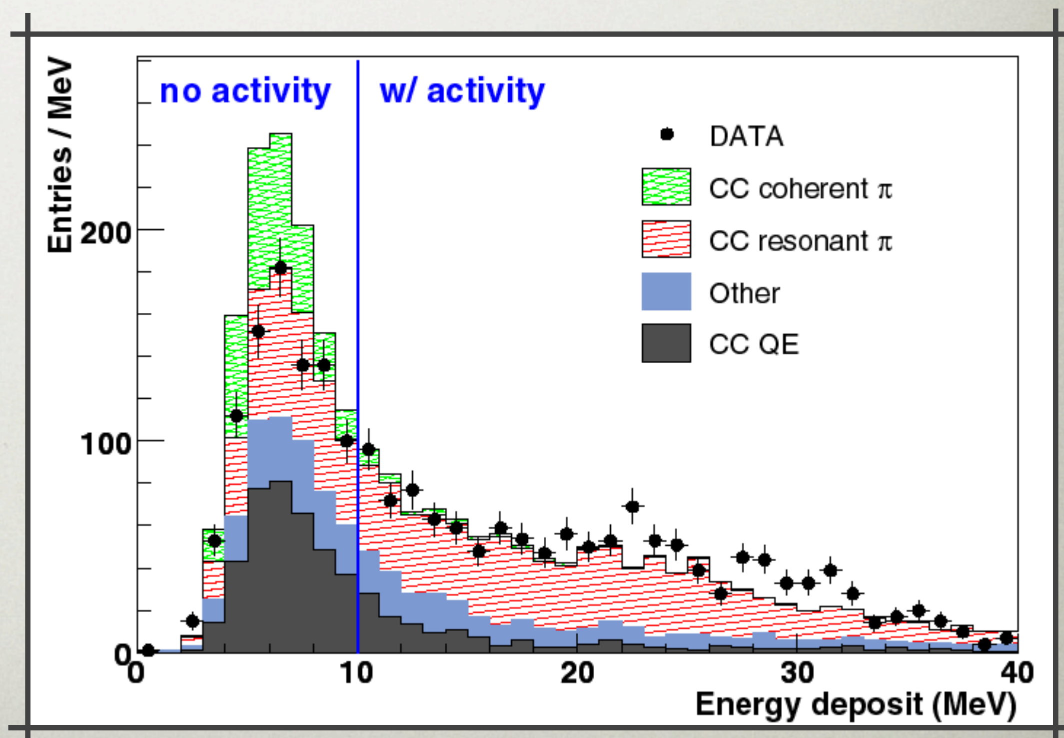


Vertex activity

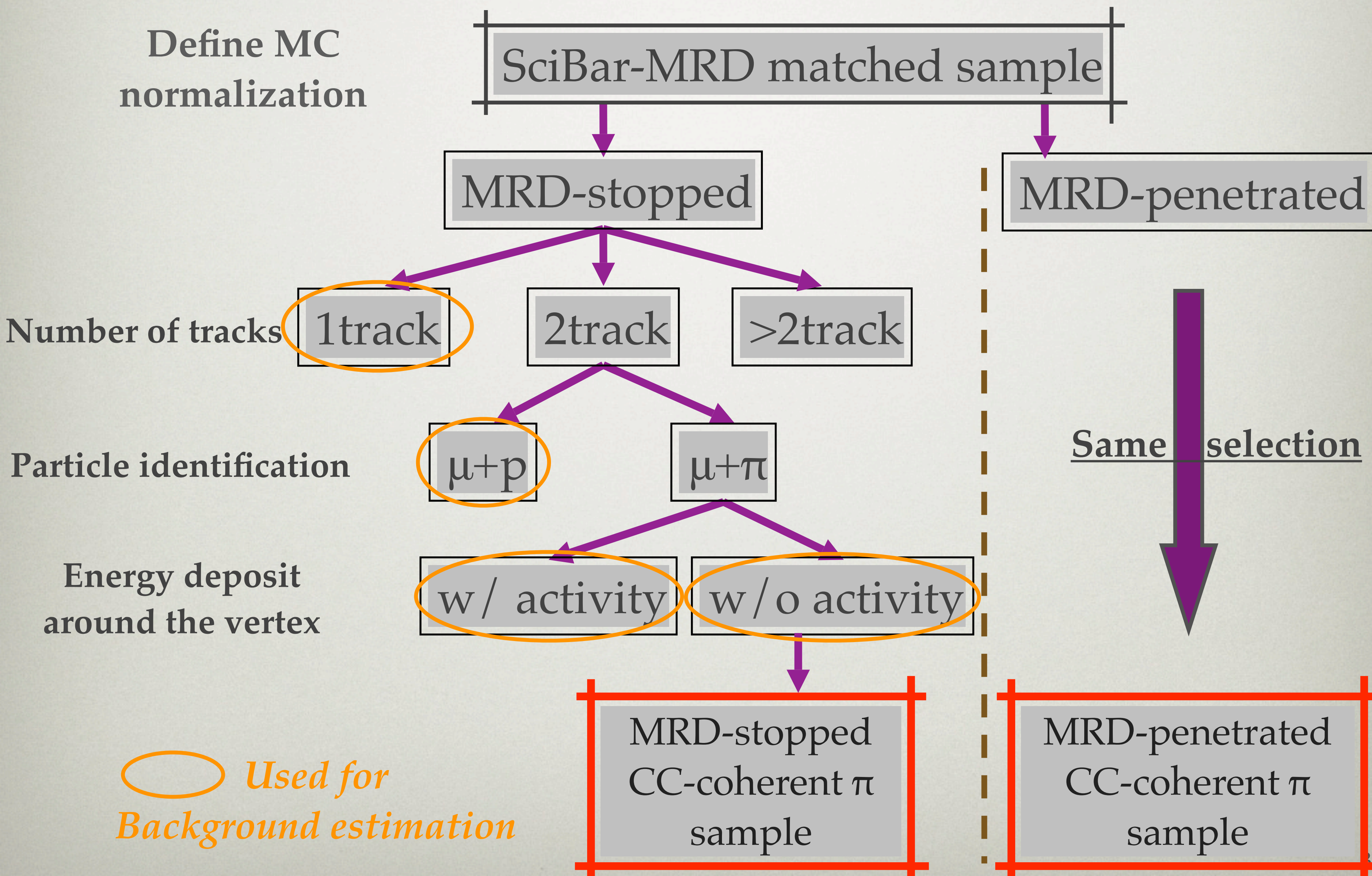


Low energy proton is detected as large energy deposition around the vertex





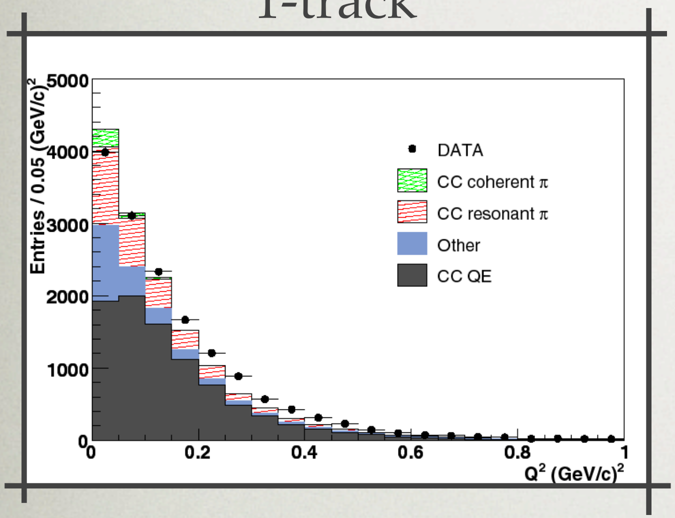
CC event classification



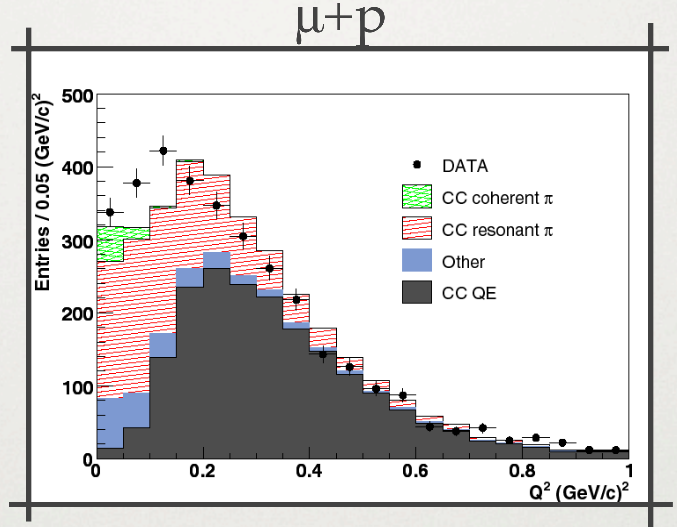
SciBooNE

Q² distributions before tuning MC

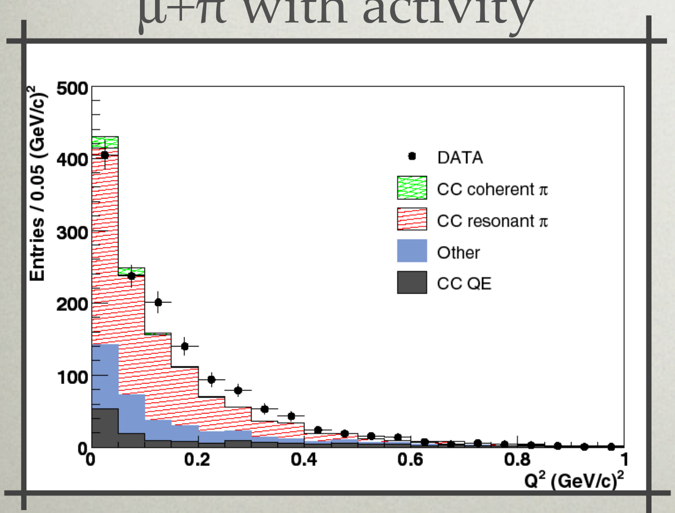
1-track



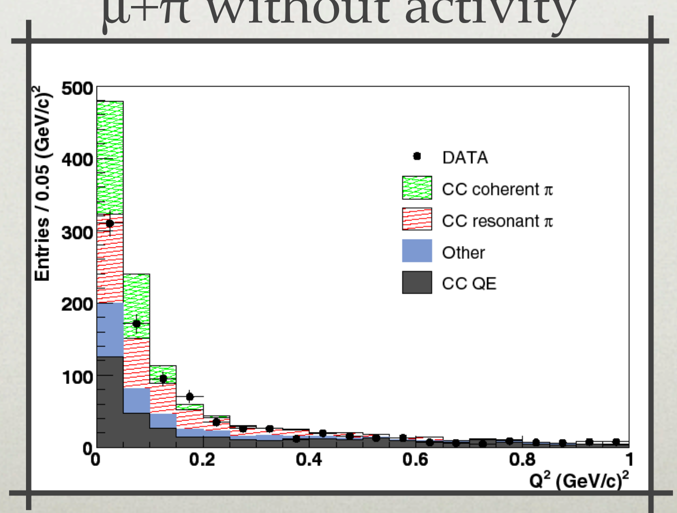
μ+p



μ+π with activity



μ+π without activity



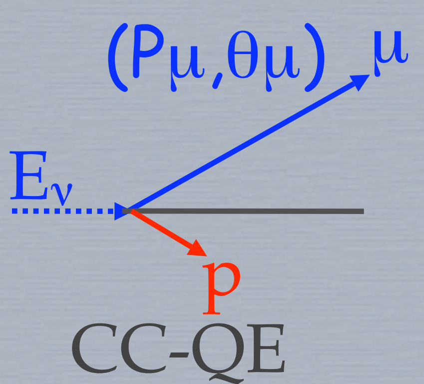
Tuning of MC simulation

To constrain systematic uncertainties due to

- detector responses
- nuclear effects
- neutrino interaction models
- neutrino energy spectrum

Q^2 distributions of sub-samples are fitted to data

Q^2 reconstruction assuming CC-QE ($\nu + n \rightarrow \mu + p$) interaction



$$Q^2_{rec} = 2E_\nu^{rec}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

$$E_\nu^{rec} = \frac{1}{2}\frac{(m_p^2 - m_\mu^2) - (m_n - V)^2 + 2E_\mu(m_n - V)}{(m_n - V) - E_\mu + p_\mu \cos\theta_\mu}$$

V: nuclear potential (27MeV)

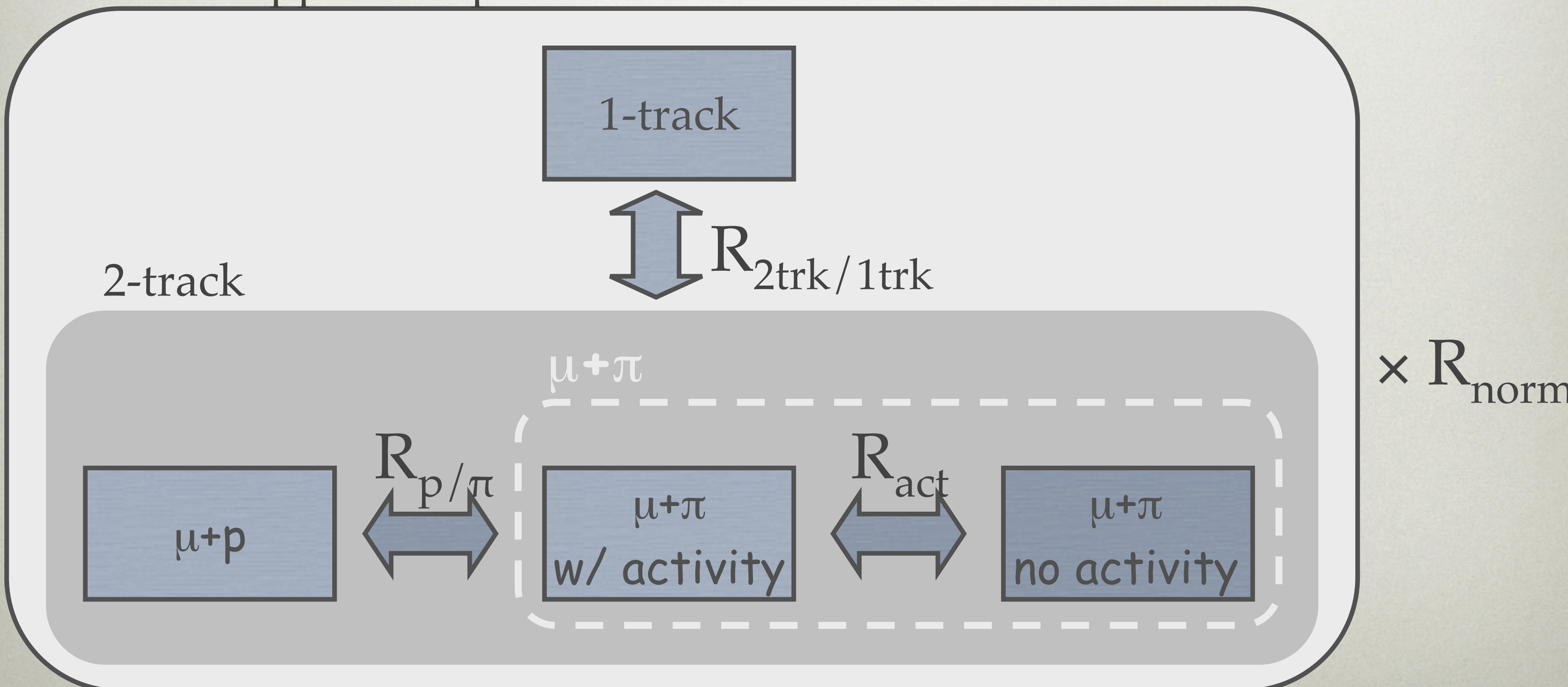
Fitting parameters (1)

Normalization parameter: R_{norm}

Migration parameters : $R_{2trk/1trk}$, $R_{p/\pi}$, R_{act}

Muon momentum scale : P_{scale}

MRD-stopped sample



Fitting parameters (2)

Parameters related to neutrino interaction models

R_{res}: CC-resonant pion production cross section scale factor

R_{other}: other "non-QE" (mainly CC-DIS) cross section scale factor

CC-QE

κ: Pauli suppression parameter (ϰ>1)

Lowest energy of an initial nucleon

$$E_{lo} = \kappa \left(\sqrt{p_F^2 + m_p^2} - \omega + E_B \right)$$

- first introduced by MiniBooNE
- employed because similar data deficit is found in low Q2

SciBooNE

χ^2 DEFINITION

$$\chi^2 = \chi^2_{\mathrm{dist}} + \chi^2_{\mathrm{sys}}$$

$$\begin{cases} \chi^2_{\mathrm{dist}} = 2\sum_{i,\ j}\left(N_{ij}^{\mathrm{exp}} - N_{ij}^{\mathrm{obs}} + N_{ij}^{\mathrm{obs}} \times \ln \frac{N_{ij}^{\mathrm{obs}}}{N_{ij}^{\mathrm{exp}}}\right) \\ \chi^2_{\mathrm{sys}} = (\boldsymbol{P_{sys}} - \boldsymbol{P}_0)\boldsymbol{V}^{-1}(\boldsymbol{P_{sys}} - \boldsymbol{P}_0) \end{cases}$$

Binned likelihood
i: Q^2 bins
j: sub-samples

Constraint on fitting parameters

V: covariance matrix

$$\boldsymbol{P_{sys}} = \begin{pmatrix} R_{\mathrm{res}} \\ R_{\mathrm{2trk/1trk}} \\ R_{p/\pi} \\ R_{\mathrm{pscale}} \end{pmatrix} \quad , \quad \boldsymbol{P}_0 = \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix}$$

SciBooNE

Covariance matrix

$$V_{ij} \equiv \mathrm{cov}[p_i, p_j] = \sum_{\mathrm{source}} \frac{\Delta p_i \Delta p_j|_+ + \Delta p_i \Delta p_j|_-}{2}$$

$\Delta p_i \Delta p_j|_{+(-)}$ the product of variations of two systematic parameters when the underlying physics parameter is increased (decreased) by the size of its uncertainty

Example) CC-resonant pion production cross section

- change the cross section by +/-20%
- take differences of ($R_{2trk/1trk}$, $R_{p/\pi}$) from nominal values

$\Delta(R_{2trk/1trk}) = ^{+4.5\%}_{-3.9\%}$ $\Delta(R_{p/\pi}) = ^{+4.3\%}_{-5.5\%}$

$$\frac{\Delta(R_{2trk/1trk})\Delta(R_{p/\pi})|_+ + \Delta(R_{2trk/1trk})\Delta(R_{p/\pi})|_-}{2} = -21\times10^{-4}$$

Covariance matrix

$$V_{ij} \equiv \mathrm{cov}[p_i, p_j] = \sum_{\mathrm{source}} \frac{\Delta p_i \Delta p_j|_+ + \Delta p_i \Delta p_j|_-}{2}$$

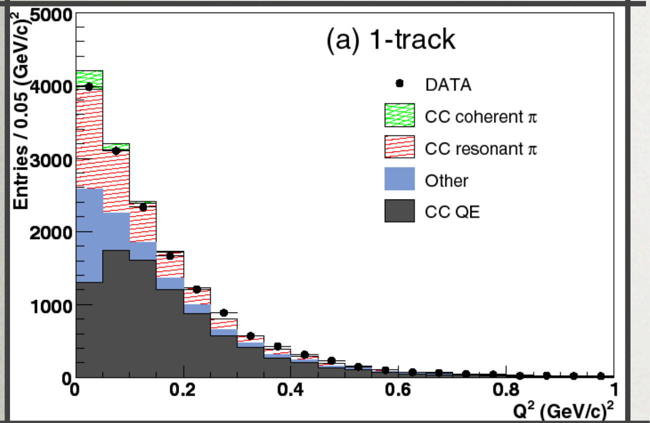
$\Delta p_i \Delta p_j|_{+(-)}$ the product of variations of two systematic parameters when the underlying physics parameter is increased (decreased) by the size of its uncertainty

$$\begin{array}{ccccc} & R_{\mathrm{res}} & R_{\mathrm{2trk/1trk}} & R_{\mathrm{p/\pi}} & R_{\mathrm{pscale}} \end{array}$$

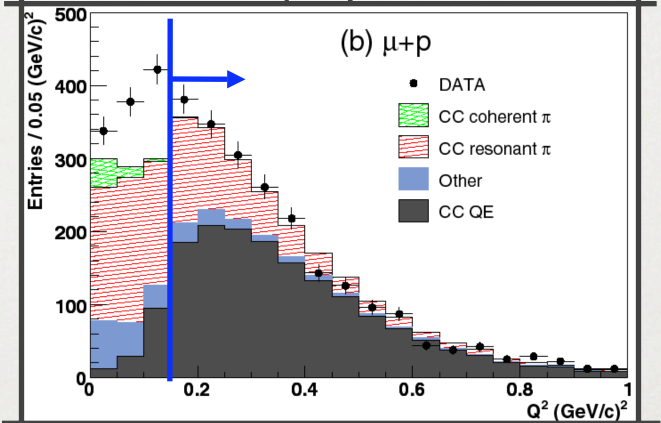
$$\boldsymbol{V} = \begin{pmatrix} (0.20)^2 & -(0.09)^2 & +(0.10)^2 & 0 \\ -(0.09)^2 & (0.09)^2 & -(0.07)^2 & 0 \\ +(0.10)^2 & -(0.07)^2 & (0.15)^2 & 0 \\ 0 & 0 & 0 & (0.02)^2 \end{pmatrix}$$

Reconstructed Q^2 after fitting

1-track

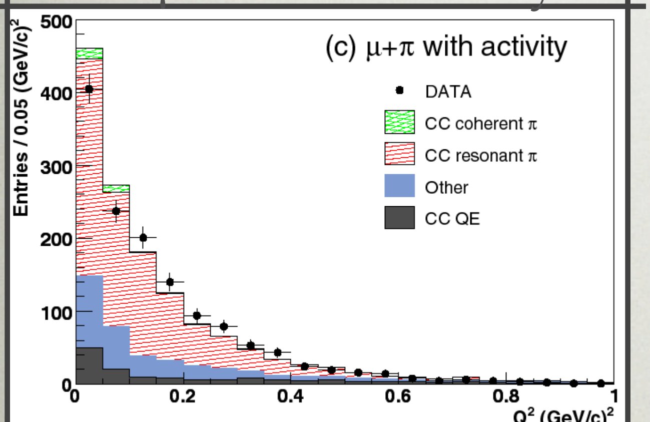


μ+p

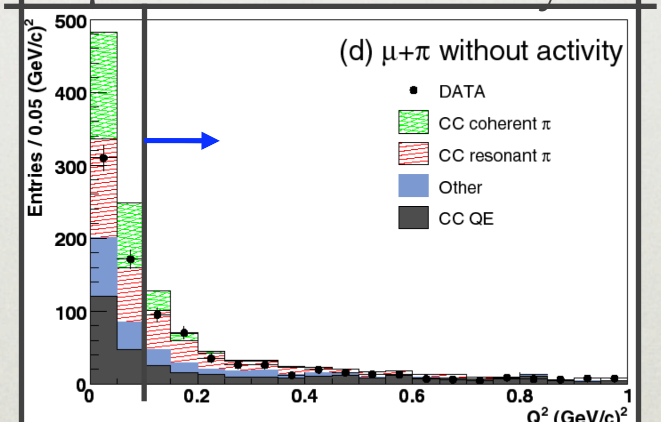


low Q^2 region in μ+p events is excluded from fitting

μ+π with activity



μ+π without activity

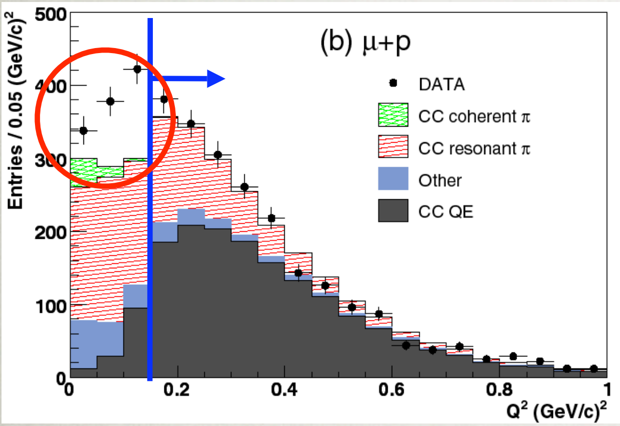


CC coherent π signal region is excluded from fitting

Before fit : $\chi^2/ndf = 473/75 = 6.31$

After fit : $\chi^2/ndf = 117/67 = 1.75$

Data excess in μ+p sample

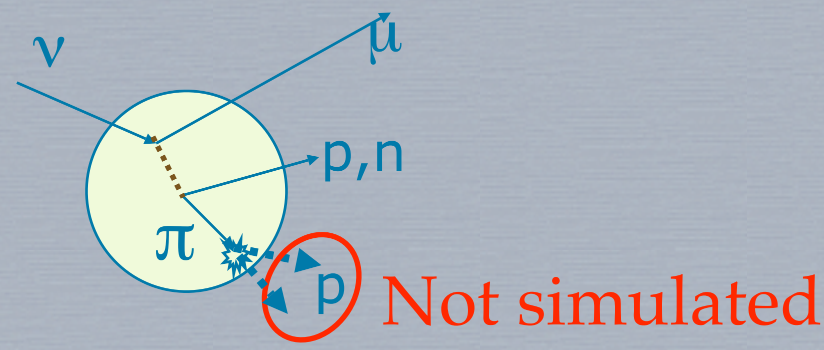


Features of excess events

- proton candidate goes at large angle
- additional activity around the vertex

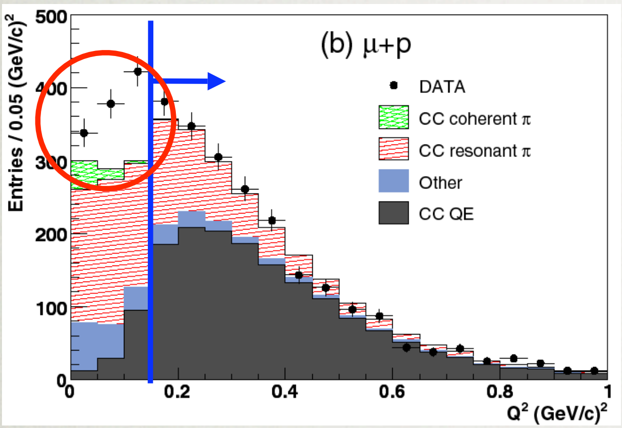
Possible candidate

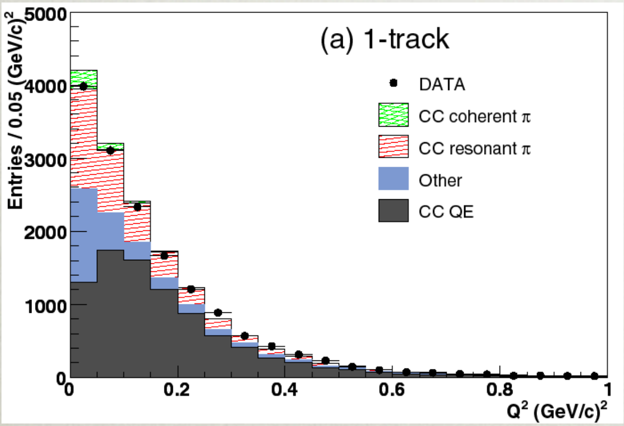
CC resonant pion events in which pion is absorbed in the nucleus



In MC simulation, such events are reconstructed as 1-track events

Data excess in μ+p sample



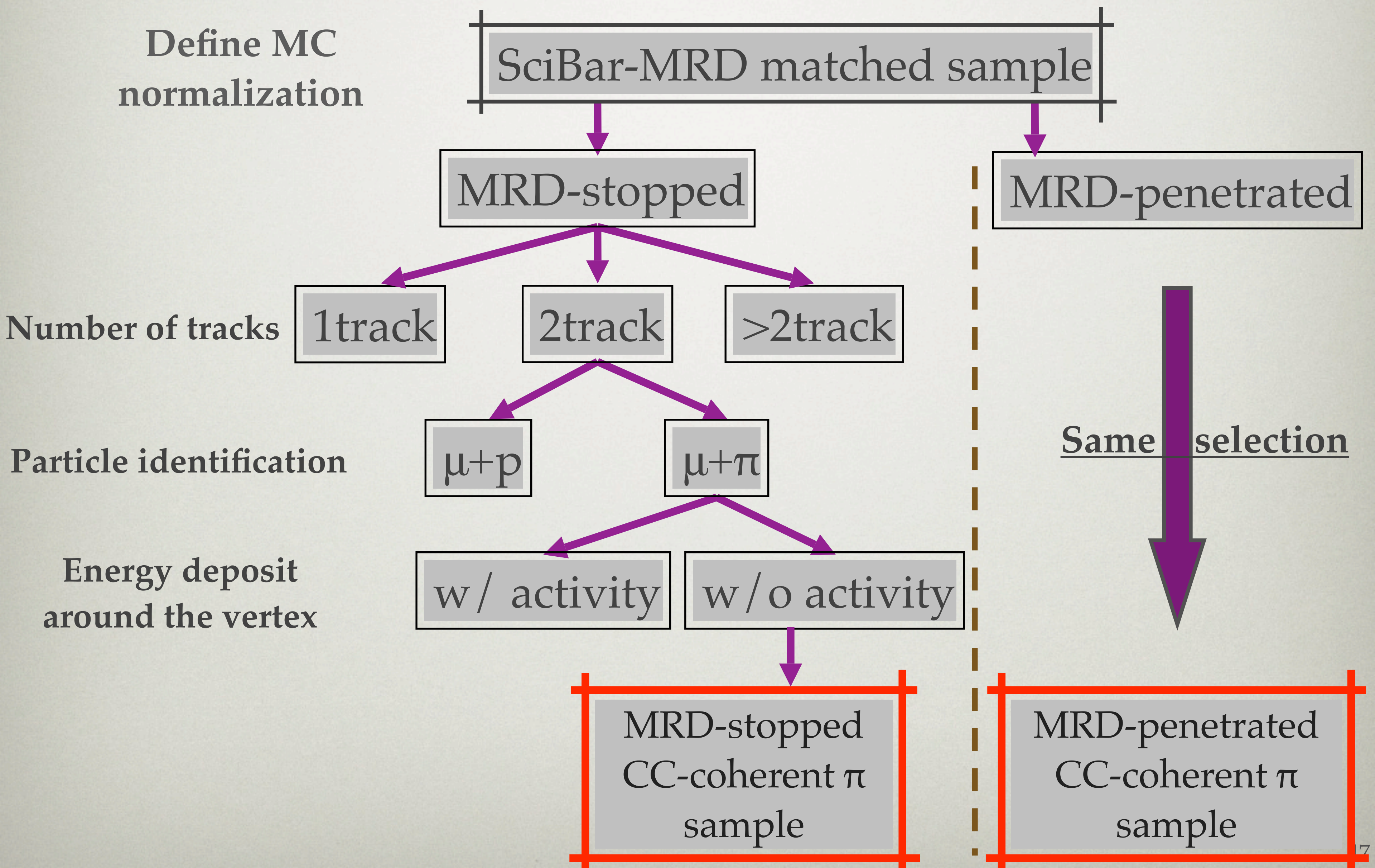


Therefore,
we expect migration between
the μ+p sample and 1-track sample

While the excess is ~200 events,
there are ~10,000 events in low Q^2
1-track sample
⇒hard to see this effect in 1-track sample

Not expected to affect
CC coherent pion measurement

CC event classification

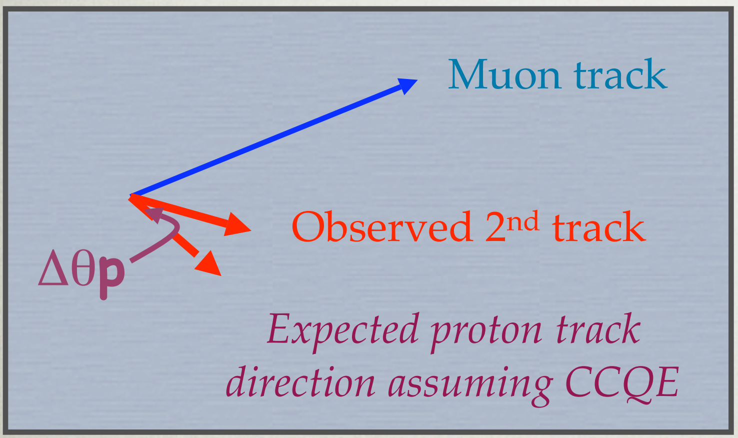


Extracting CC coherent pion events

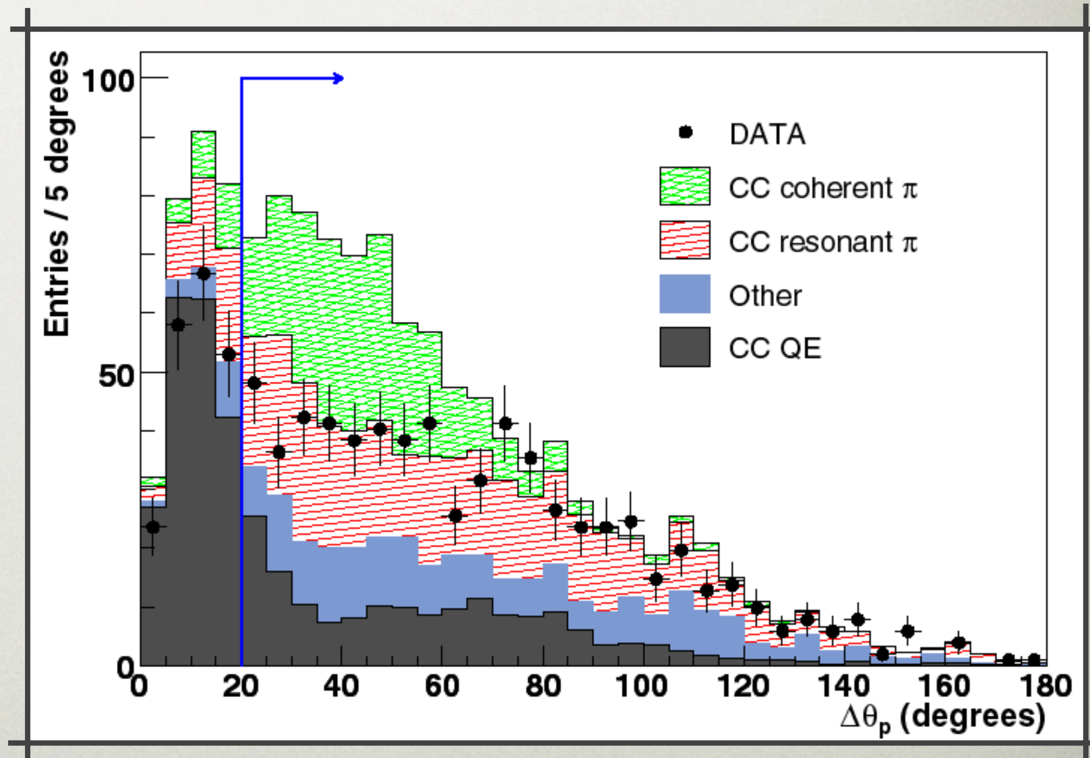
1) CC-QE rejection

2) CC-resonant pion rejection

kinematic variable: $\Delta\theta_p$



3D angle between the expected and observed 2nd tracks

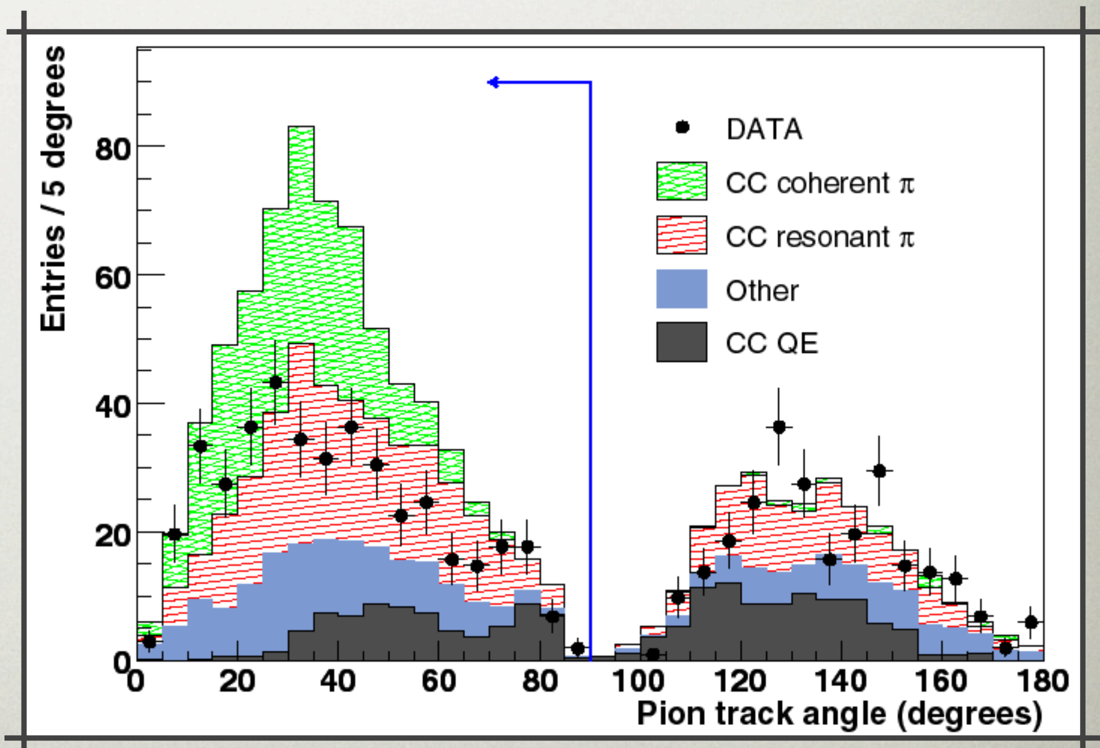


Extracting CC coherent pion events

1) CC-QE rejection

2) CC-resonant pion rejection

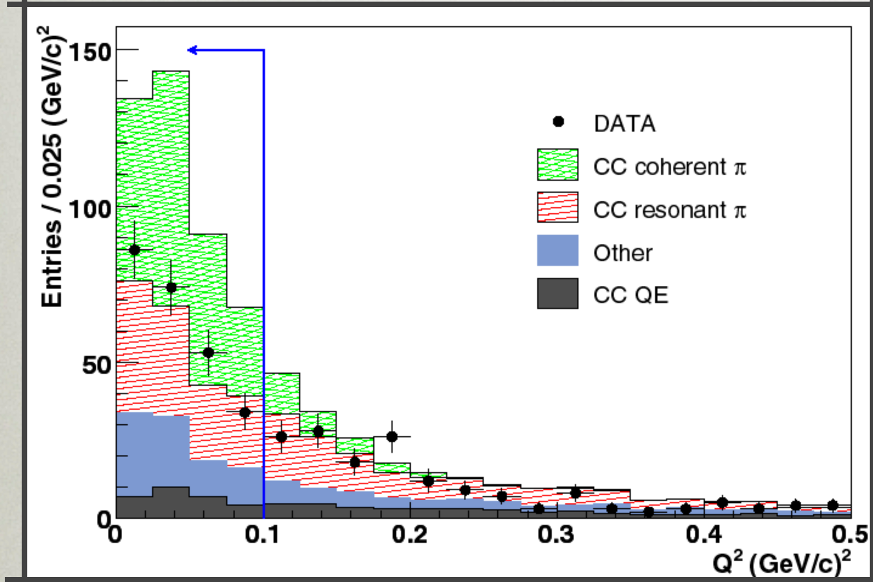
Events with a forward-going Pion candidate are selected



CC coherent pion sample

Q² < 0.1 (GeV/c)²

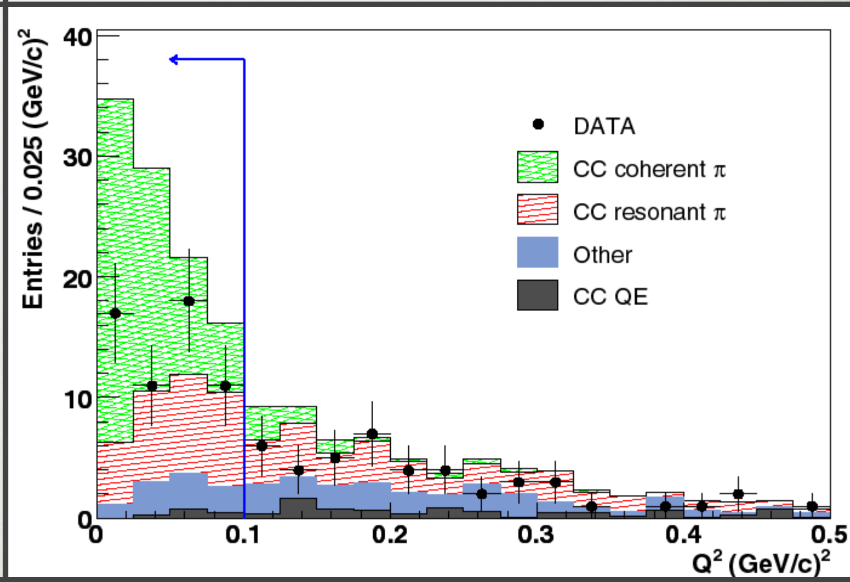
MRD stopped sample
<Eν>= 1.1 GeV



247 events selected

BG expectation
228+/-12 events

MRD penetrated sample
<Eν>= 2.2 GeV



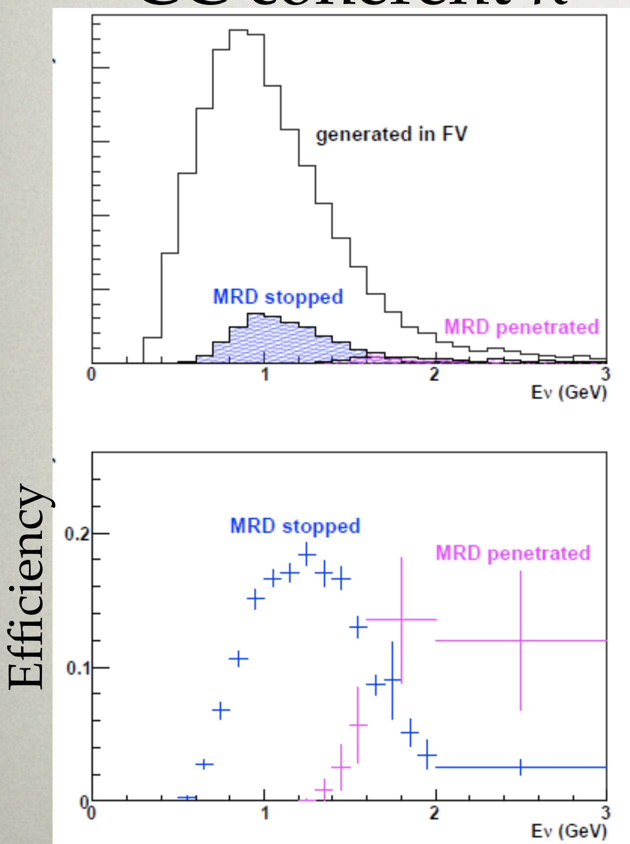
57 events selected

BG expectation
40+/-2.2 events

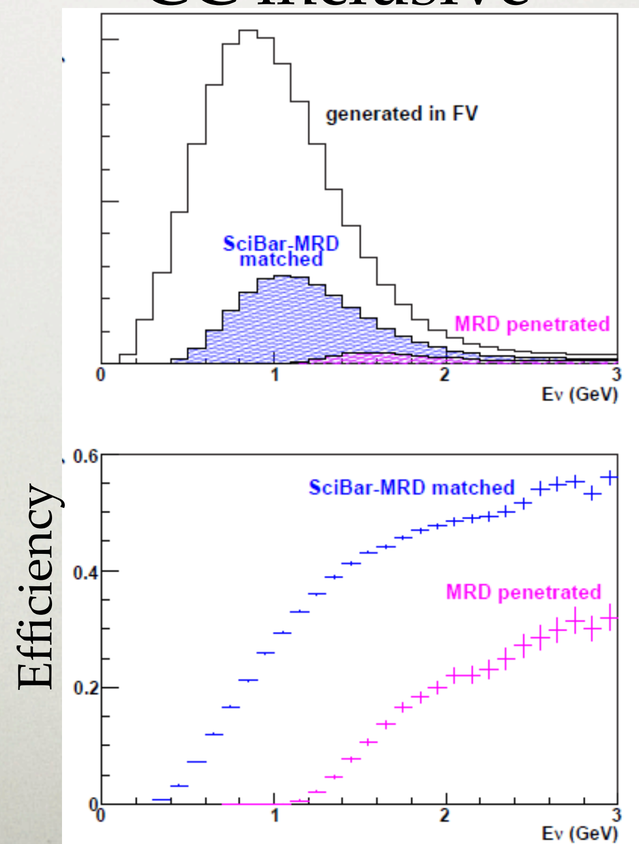
CROSS SECTION RATIO

To reduce neutrino flux uncertainty, we measure σ(CC coherent π) / σ(CC) cross section ratio

CC coherent π



CC inclusive



For denominator, CC inclusive samples are chosen so that they cover similar neutrino energy range as coherent π samples.

Results

MRD stopped sample <Eν>= 1.1 GeV	$\sigma(CC\ coherent\ \pi)/\sigma(CC) = (0.16 \pm 0.17(stat)^{+0.30}_{-0.27}(sys)) \times 10^{-2}$
MRD penetrated sample <Eν>= 2.2 GeV	$\sigma(CC\ coherent\ \pi)/\sigma(CC) = (0.68 \pm 0.32(stat)^{+0.39}_{-0.25}(sys)) \times 10^{-2}$

No evidence of CC coherent pion production is found

90% CL upper limit (Bayesian)

σ(CC coherent π) / σ(CC) < 0.67×10^{-2} for <Eν>=1.1 GeV

< 1.36×10^{-2} <Eν>=2.2 GeV

arXiv:0811.0369, Submitted to PRD

Systematic errors

	MRD stopped Error (x10^{-2})	MRD penetrated Error (x10^{-2})
Detector response	+0.10 / -0.18	+0.18 / -0.18
Nuclear effect	+0.20 / -0.07	+0.19 / -0.09
Neutrino interaction model	+0.17 / -0.04	+0.08 / -0.04
Neutrino beam	+0.07 / -0.11	+0.27 / -0.13
Event selection	+0.07 / -0.14	+0.06 / -0.05
Total	+0.30 / -0.27	+0.39 / -0.25

Discussion

K2K (<Eν>=1.3 GeV)

$$\sigma(CC\ coherent\ \pi)/\sigma(CC) = (0.04 \pm 0.29(stat)^{+0.32}_{-0.35}(sys)) \times 10^{-2}$$

improved

slightly improved

SciBooNE (<Eν>=1.1 GeV)

$$\sigma(CC\ coherent\ \pi)/\sigma(CC) = (0.16 \pm 0.17(stat)^{+0.30}_{-0.27}(sys)) \times 10^{-2}$$

K2K result (90% CL U.L.=m+1.28*σ)

$\sigma(CC\ coherent\ \pi)/\sigma(CC) < 0.60 \times 10^{-2}$ for <Eν>=1.3 GeV

SciBooNE results (Bayesian 90% CL U.L.)

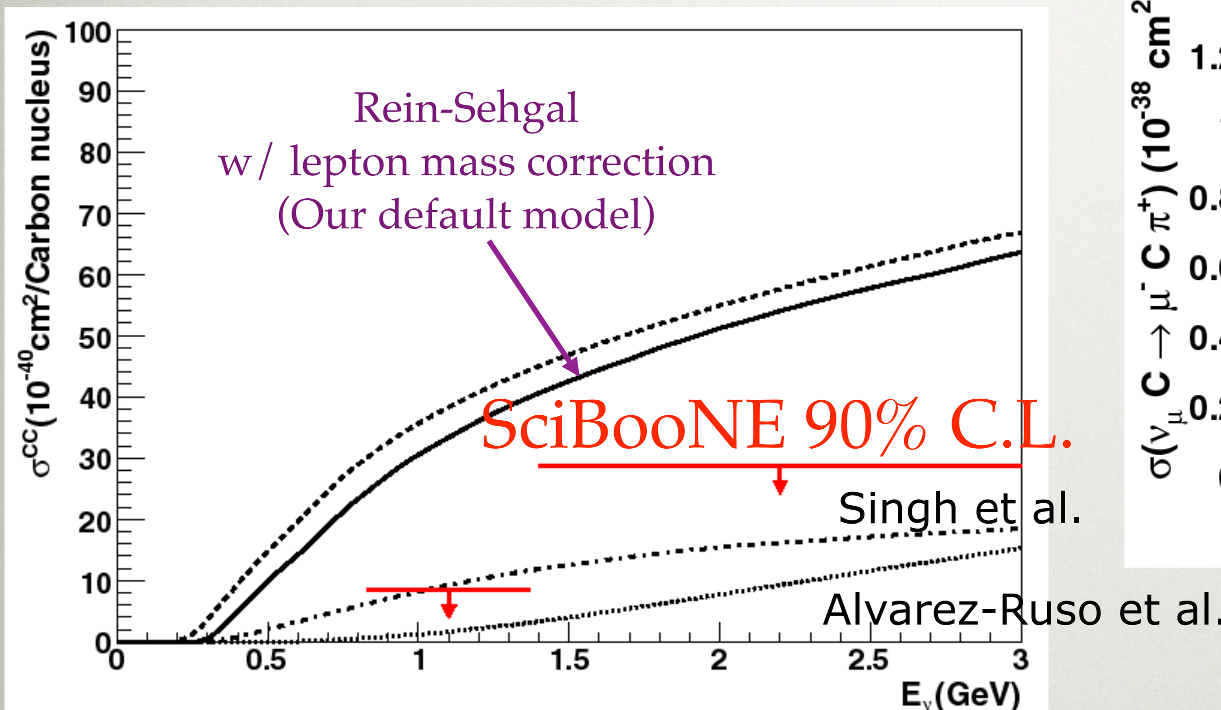
$\sigma(CC\ coherent\ \pi)/\sigma(CC) < 0.67 \times 10^{-2}$ for <Eν>=1.1 GeV

$< 1.36 \times 10^{-2}$ <Eν>=2.2 GeV

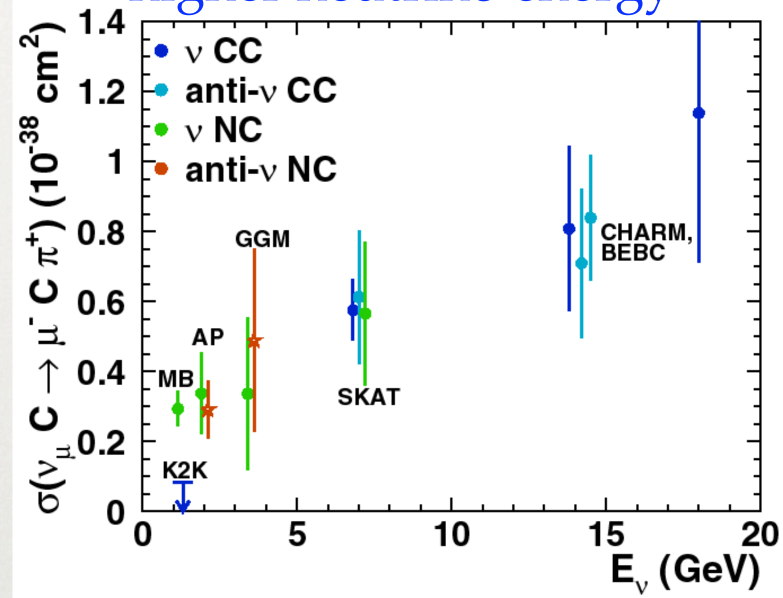
SciBooNE results are consistent with K2K result

Discussion

Comparison with theoretical models



Other measurements at higher neutrino energy



assuming

- $A^{2/3}$ dependence
- σ(CC coh)=2*σ(NC coh)

Measured upper limits on σ(CC coherent π)/σ(CC) ratios are converted to upper limits on absolute cross sections by using σ(CC) predicted by MC simulation

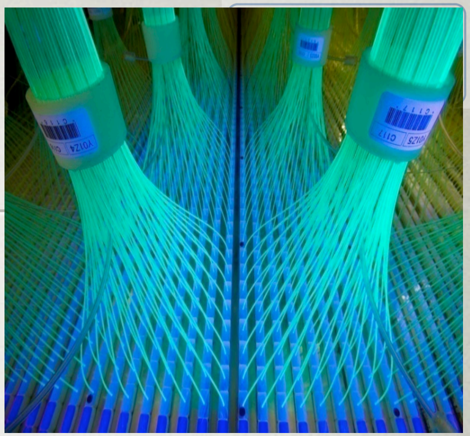
Conclusion

- SciBooNE successfully finished data-taking.
- First physics result from SciBooNE
  - No significant evidence of CC coherent pion production is found
  - arXiv:0811.0369 (Submitted to PRD)
- Many analyses are on-going
  - Neutrino cross section measurements (CC-QE, CC-resonant π^+, CC-π^0, NC-π^0, NC-elastic)
  - Neutrino energy spectrum measurements (oscillation with MiniBooNE)
  - Anti-neutrino cross section measurements

Thank you!

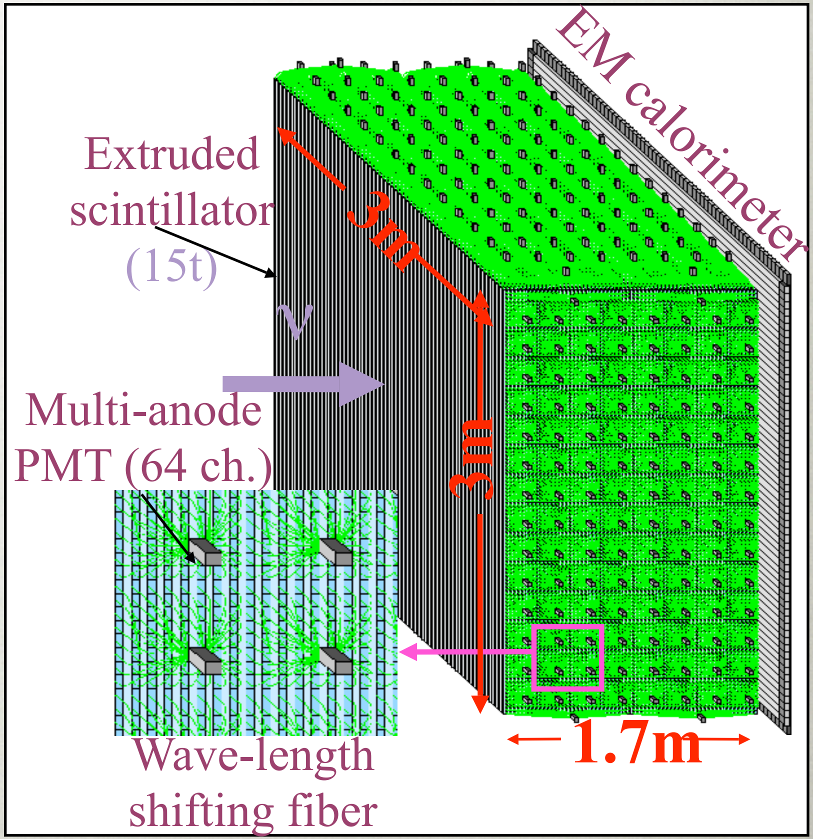
Backup slides

SciBar detector

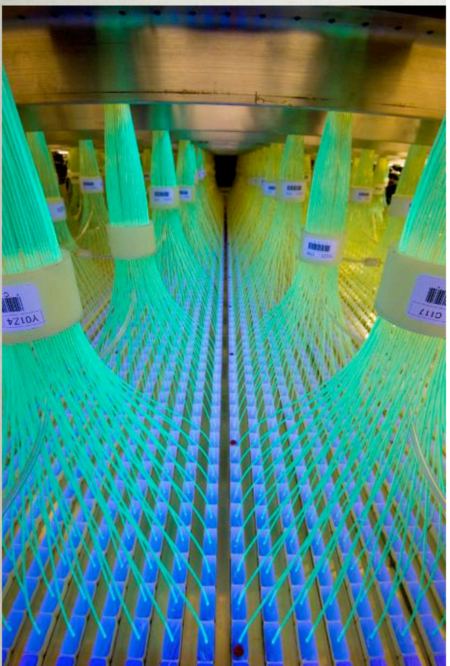


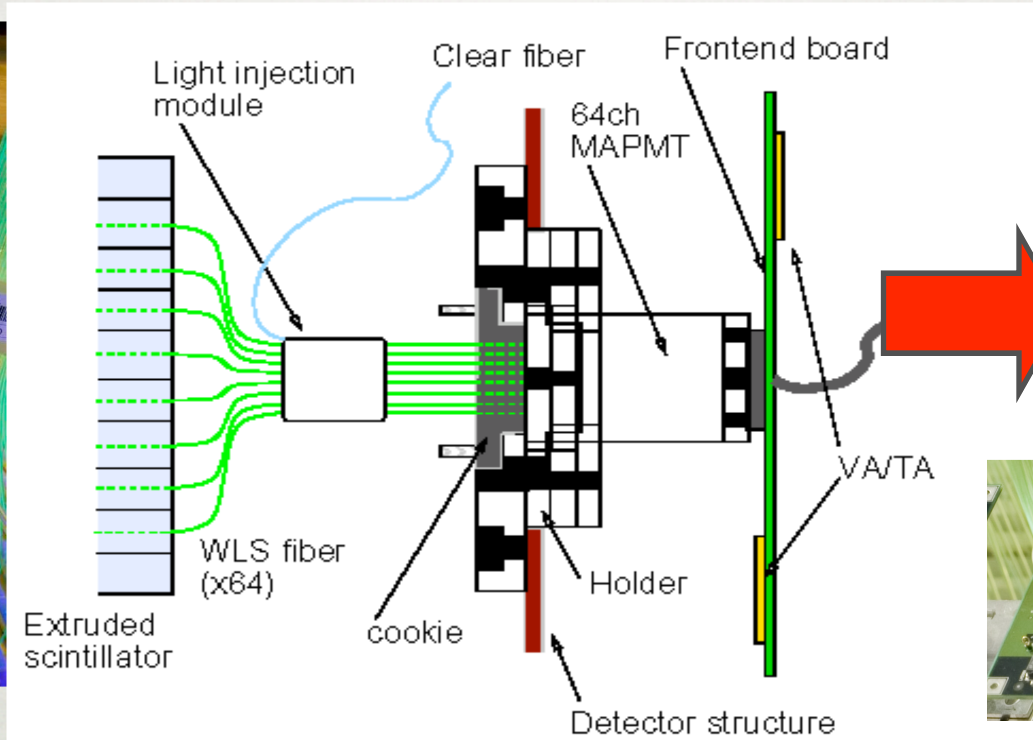
- Extruded scintillators with WLS fiber readout
- Scintillators are the neutrino target
- 3m x 3m x 1.7m (Total: 15 tons)
- 14,336 channels
- Detect short tracks (>8cm)
- Distinguish a proton from a pion by dE/dx

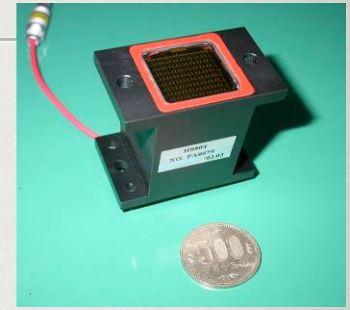
→Clear identification of ν interaction process



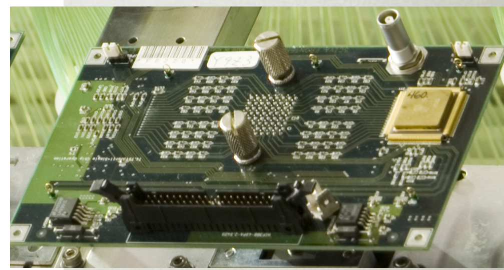
SciBar readout







64 charge info.
2 timing info.



Extruded Scintillator (1.3×2.5×300cm^3)

- 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

- 2x2mm^2 pixel (3% cross talk@1.5mmΦ)
- Gain Uniformity (20% RMS)
- Good linearity (~200p.e. @6×10^5)

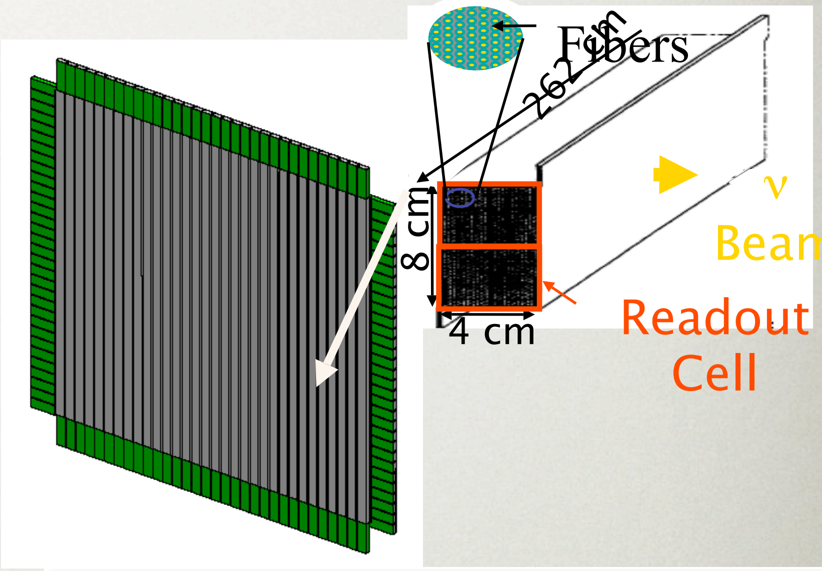
Readout electronics with VA/TA

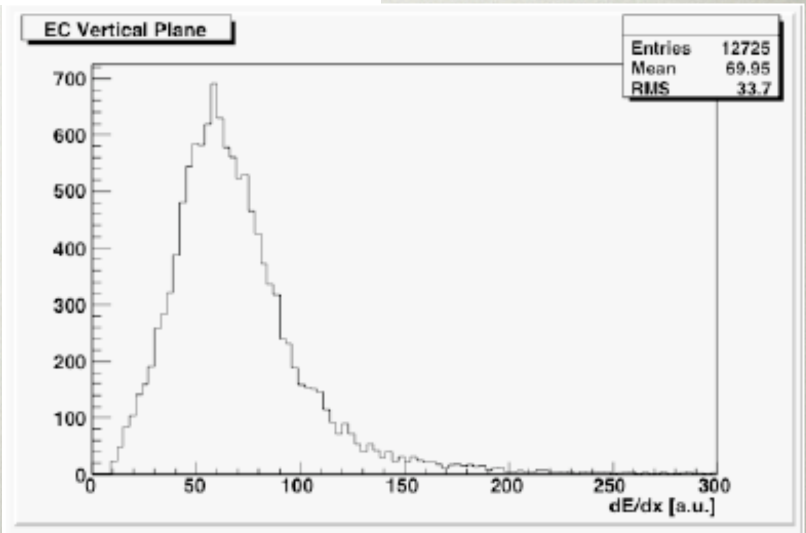
- ADC for all 14,336 channels
- TDC for 448 sets (32 channels-OR)

Electron Catcher (EC)

- "spaghetti" calorimeter
- 1mm diameter fibers in the grooves of lead foils
- 4x4cm² cell read out from both ends
- 2 planes **(11X_0)**

  Horizontal: 32 modules
  Vertical : 32 modules
- Total 256 readout channels
- Expected resolution **14%/√E (GeV)**
- Linearity: **better than 10%**

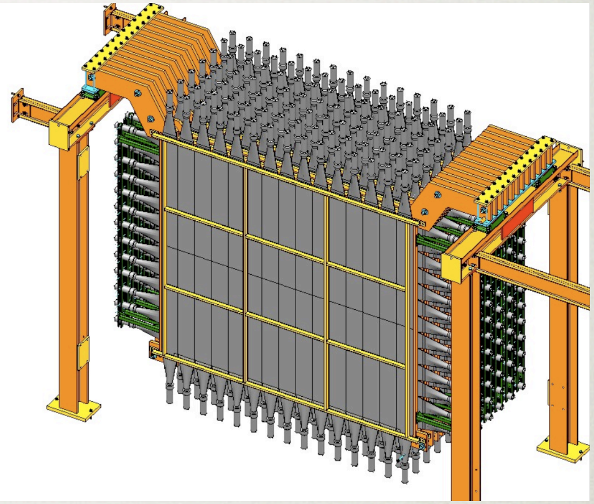




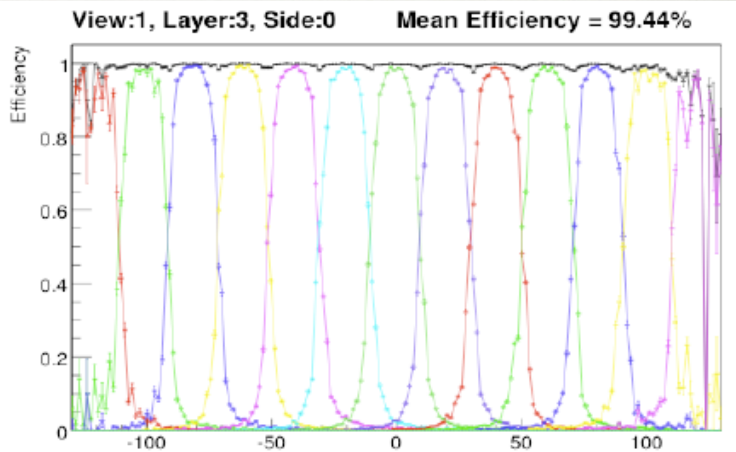
dE/dx distribution of vertical plane for cosmic ray muons

Muon Range Detector

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



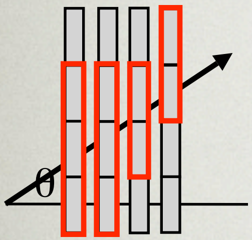
- Iron Plate
  - 305x274x5cm^3
  - Total 12 layers
- Scintillator Plane
  - Alternating horizontal and vertical planes
  - Total 362 channels



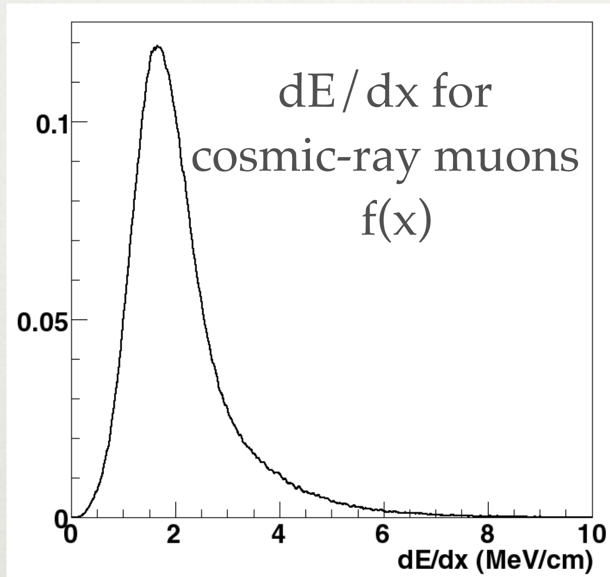
Hit efficiency of a typical horizontal plane

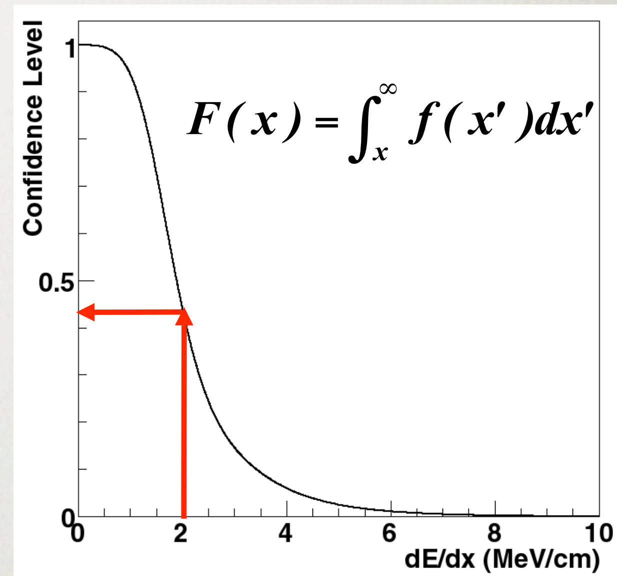
MuCL calculation

plane-by-plane dE/dx measurement



$$dE/dx = \frac{\Delta E}{1.3cm/\cos\theta}$$



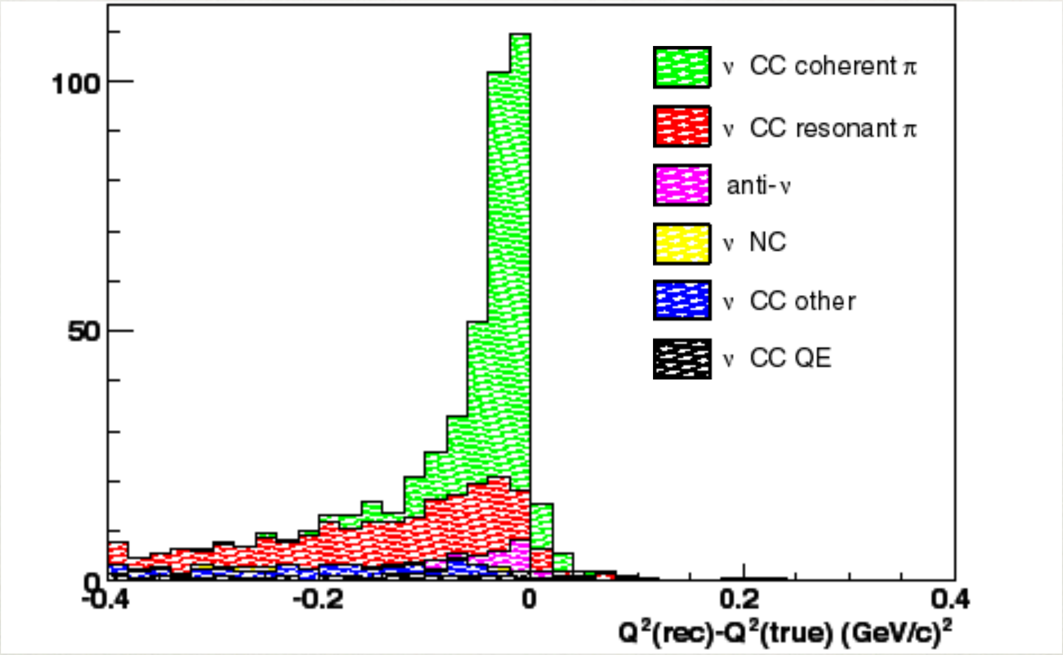


confidence level at each plane is calculated from the plot

MuCL: combined confidence level

$$MuCL = P \times \sum_{i=0}^{n-1} \frac{(-\ln P)^i}{i!} \qquad P = \prod_{i=1}^{n} CL_i$$

Q^2 resolution of CC-coherent π sample

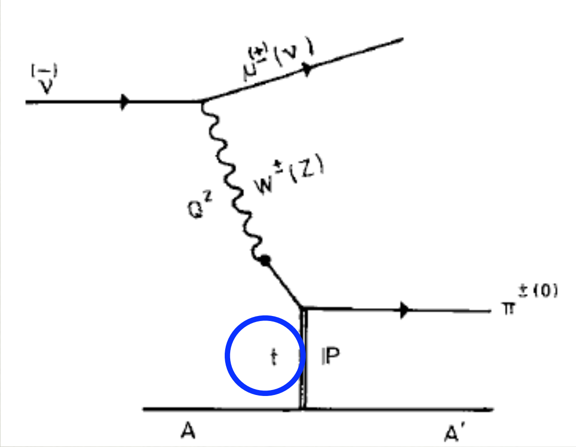


Q2 resolution of CC-coherent π events

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

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

Kinematics variable (1)



Past experiments use kinematic variable ***t*** (4-momentum transfer to nucleus) to extract coherent π production

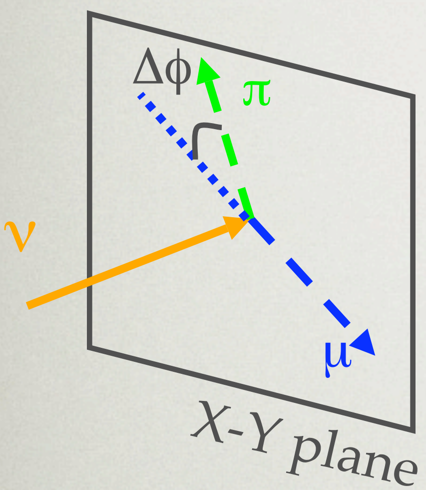
$$|t| = [\sum_{\mu,\pi} \mathbf{p}_i^T]^2 + [\sum_{\mu,\pi} (E_i - p_i^{\parallel})]^2$$

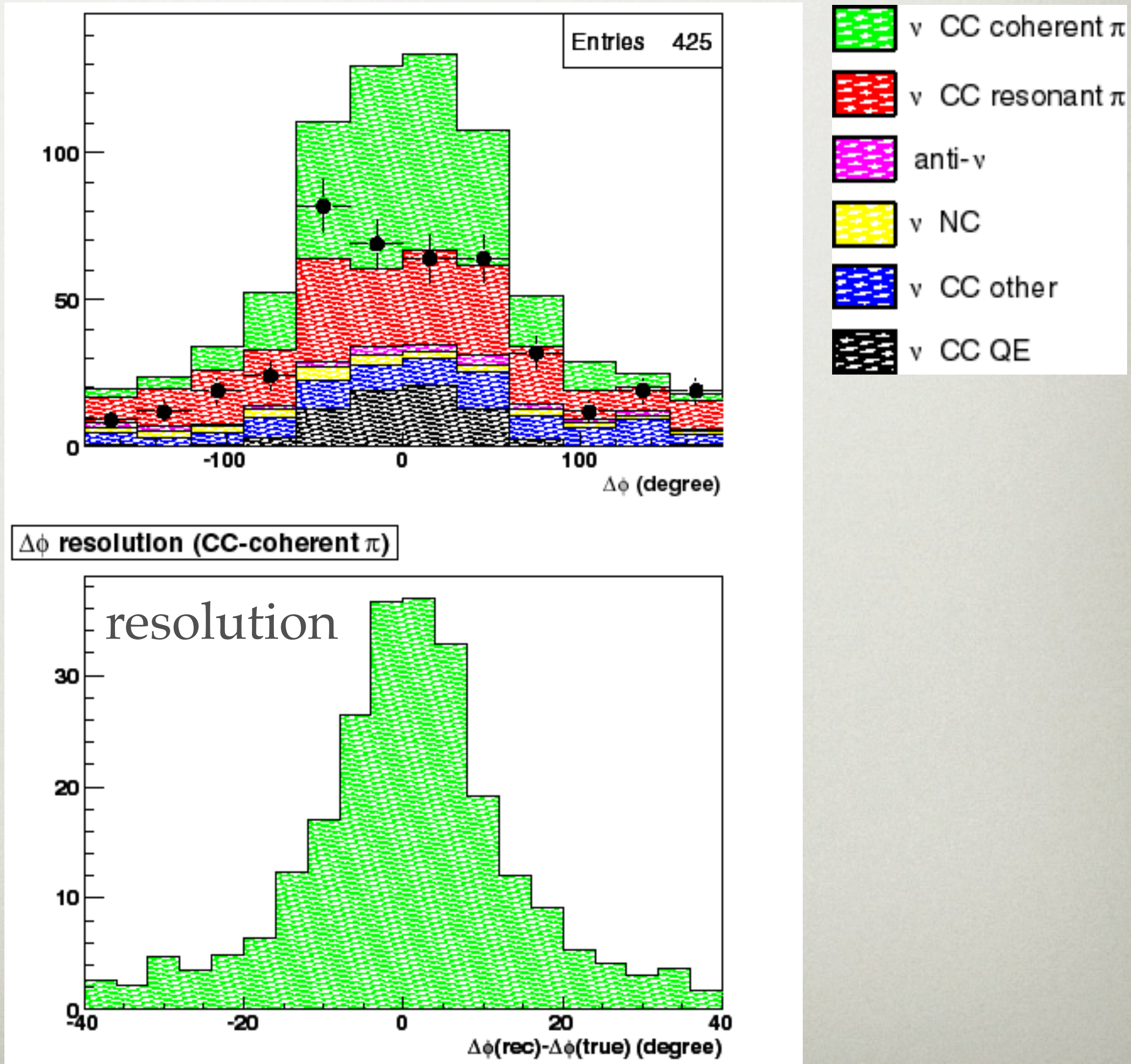
<u>SciBooNE case</u>

Pion is not contained in SciBar with current selection

➔ not easy to reconstruct pion momentum

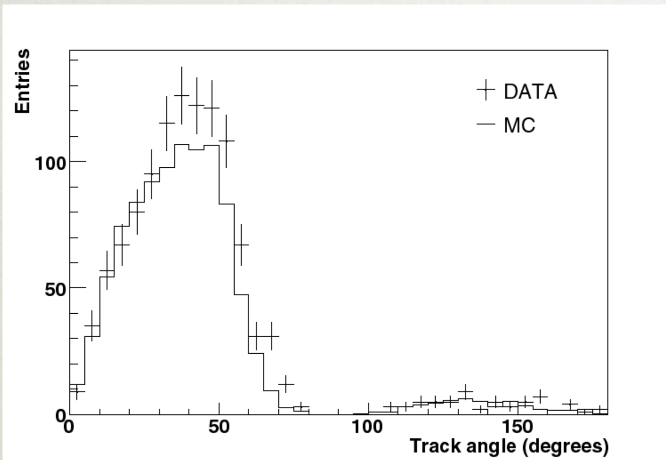
Kinematics variable (2)



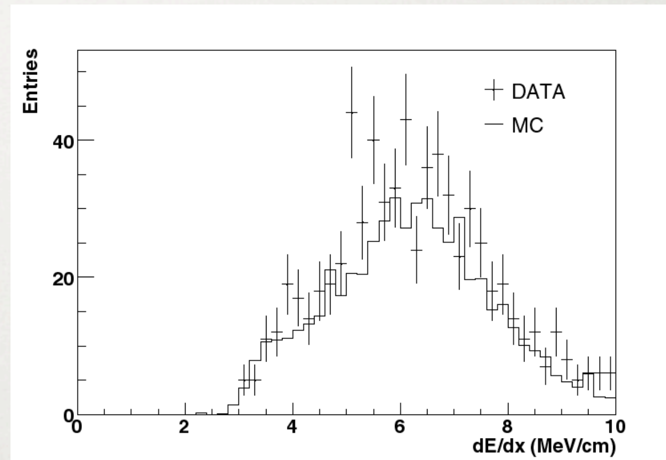


Data excess in μ+p

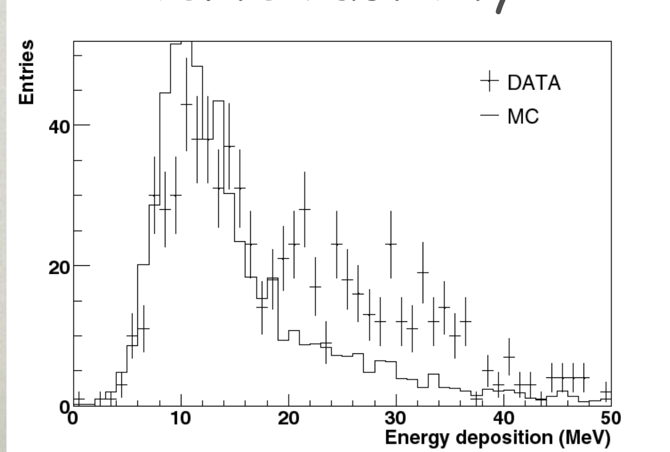
track angle of 2nd track

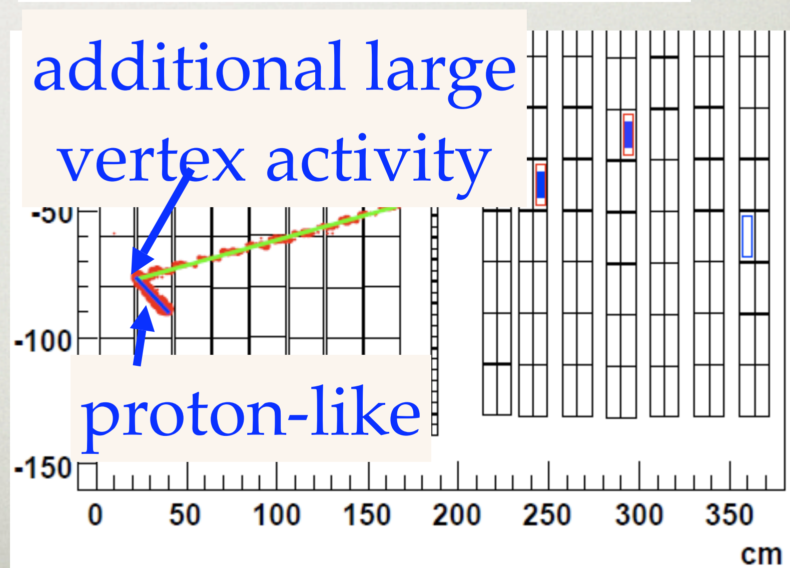


dE/dx of 2nd track



vertex activity





Fitting parameters

1-track: $$N_{i,\ 1\mathrm{trk}}^{\mathrm{exp}} = R_{\mathrm{norm}} \cdot \left[n_{i,1\mathrm{trk}}^{\mathrm{QE}} + R_{\mathrm{res}} n_{i,1\mathrm{trk}}^{\mathrm{res}} + R_{\mathrm{other}} n_{i,1\mathrm{trk}}^{\mathrm{other}}\right]$$

μ+p: $$N_{i,\ \mu p}^{\mathrm{exp}} = R_{\mathrm{norm}} \cdot R_{2\mathrm{trk}/1\mathrm{trk}} \cdot R_{p/\pi} \cdot \left[n_{i,\mu p}^{\mathrm{QE}} + R_{\mathrm{res}} n_{i,\mu p}^{\mathrm{res}} + R_{\mathrm{other}} n_{i,\mu p}^{\mathrm{other}}\right]$$

μ+π w/ activity: $$N_{i,\ \mu\pi\mathrm{H}}^{\mathrm{exp}} = R_{\mathrm{norm}} \cdot R_{2\mathrm{trk}/1\mathrm{trk}} \cdot \left[n_{i,\mu\pi\mathrm{H}}^{\mathrm{QE}} + R_{\mathrm{res}} n_{i,\mu\pi\mathrm{H}}^{\mathrm{res}} + R_{\mathrm{other}} n_{i,\mu\pi\mathrm{H}}^{\mathrm{other}}\right]$$

μ+π no activity: $$N_{i,\ \mu\pi\mathrm{L}}^{\mathrm{exp}} = R_{\mathrm{norm}} \cdot R_{2\mathrm{trk}/1\mathrm{trk}} \cdot R_{\mathrm{act}} \cdot \left[n_{i,\mu\pi\mathrm{L}}^{\mathrm{QE}} + R_{\mathrm{res}} n_{i,\mu\pi\mathrm{L}}^{\mathrm{res}} + R_{\mathrm{other}} n_{i,\mu\pi\mathrm{L}}^{\mathrm{other}}\right]$$

SciBooNE

Fitting parameters

8 fitting parameters

- normalization (1)
- migration parameters (3)
- muon momentum scale (1)
- neutrino interaction model parameters (3)

R_{norm} : MRD stopped sample normalization

$R_{2trk/1trk}$: Migration between 2track / 1track samples

$R_{p/\pi}$: Migration between μ+p / μ+π samples

R_{act} : Migration between low/high vertex activity samples

R_{pscale} : Muon momentum scale

R_{res} : CC-resonant pion cross section scale factor

R_{other} : Other nonQE cross section scale factor

κ : Pauli-suppression parameter for CCQE

Fitting result

Parameter	Value	Error
R_{norm}	1.103	0.029
$R_{2trk/1trk}$	0.865	0.035
$R_{p/\pi}$	0.899	0.038
R_{act}	0.983	0.055
R_{pscale}	1.033	0.002
R_{res}	1.211	0.133
R_{other}	1.270	0.148
kappa	1.019	0.004

SciBooNE

Event selection summary

Event selection	DATA	MC Signal	MC B.G.	Coherent π Efficiency
Generated in SciBar FV		1,939	156,766	100%
SciBar-MRD matched	30,337	978	29,359	50.4%
MRD stopped	21,762	715	20,437	36.9%
2 track	5,939	358	6,073	18.5%
Particle ID ($\mu + \pi$)	2,255	292	2,336	15.1%
Vertex activity cut	887	264	961	13.6%
CC-QE rejection	682	241	709	12.4%
Pion track direction cut	425	233	451	12.0%
Reconstructed Q^2 cut	247	201	228	10.4%

Event selection summary

Event selection	DATA	MC Signal	MC B.G.	Coherent π Efficiency
Generated in SciBar FV		1,939	156,766	100%
SciBar-MRD matched	30,337	978	29,359	50.4%
MRD penetrated	3,712	177	4,375	9.1%
2 track	1,029	92	1,304	4.7%
Particle ID ($\mu + \pi$)	418	78	474	4.0%
Vertex activity cut	167	71	186	3.6%
CC-QE rejection	134	67	135	3.5%
Pion track direction cut	107	66	109	3.4%
Reconstructed Q^2 cut	57	60	40	3.1%

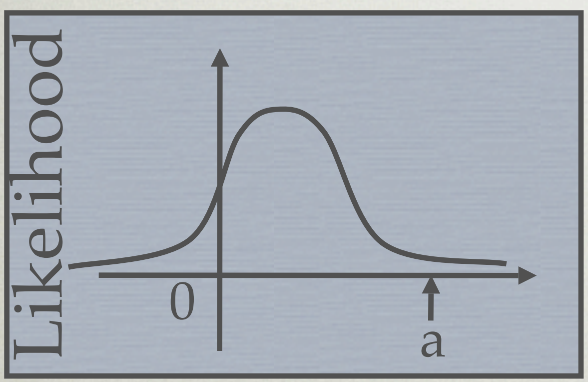
90% CL upper limit

Simple calculation

$$\text{90\% CL upper limit} = mean + 1.28 \times sigma$$

(This is for gaussian statistics without physical boundary)

Bayesian approach



(90% CL upper limit)

$$P(a) = \frac{\int_0^a L(x)dx}{\int_0^\infty L(x)dx} = 0.9$$

$L(x)$ Probability density function
Asymmetric gaussian
(mean, sigma+, sigma-)

Results (cont'd)

90% CL upper limit (Bayesian)

σ(CC coherent π)/σ(CC) < 0.67×10^{-2} for <Eν>=1.1 GeV

< 1.36×10^{-2} <Eν>=2.2 GeV

K2K result (90% CL U.L.=m+1.28*σ)

σ(CC coherent π)/σ(CC) < 0.60×10^{-2} for <Eν>=1.3 GeV

Our results using same definition (90% CL U.L.=m+1.28*σ)

σ(CC coherent π)/σ(CC) < 0.60×10^{-2} for <Eν>=1.1 GeV

< 1.33×10^{-2} <Eν>=2.2 GeV

Systematic errors (detector response)

Source	MRD stopped error ($\times 10^{-2}$)		MRD penetrated error ($\times 10^{-2}$)	
Cross talk	+0.04	−0.05	+0.12	−0.04
1 pe resolution	+0.05	−0.02	+0.07	−0.06
Scintillator quenching	+0.03	−0.17	+0.07	−0.16
Pion interaction in SciBar	+0.01	−0.01	+0.01	−0.00
Hit threshold	+0.07	−0.03	+0.09	−0.02
Subtotal	+0.10	−0.18	+0.18	−0.18

Systematic errors (nuclear effects)

Source	MRD stopped error ($\times 10^{-2}$)		MRD penetrated error ($\times 10^{-2}$)	
Pion absorption cross section	+0.00	−0.05	+0.11	−0.00
Pion inelastic cross section	+0.17	−0.00	+0.04	−0.00
Nucleon re-scattering cross section	+0.11	−0.05	+0.15	−0.08
Fermi momentum	+0.02	−0.02	+0.03	−0.03
Subtotal	+0.20	−0.07	+0.19	−0.09

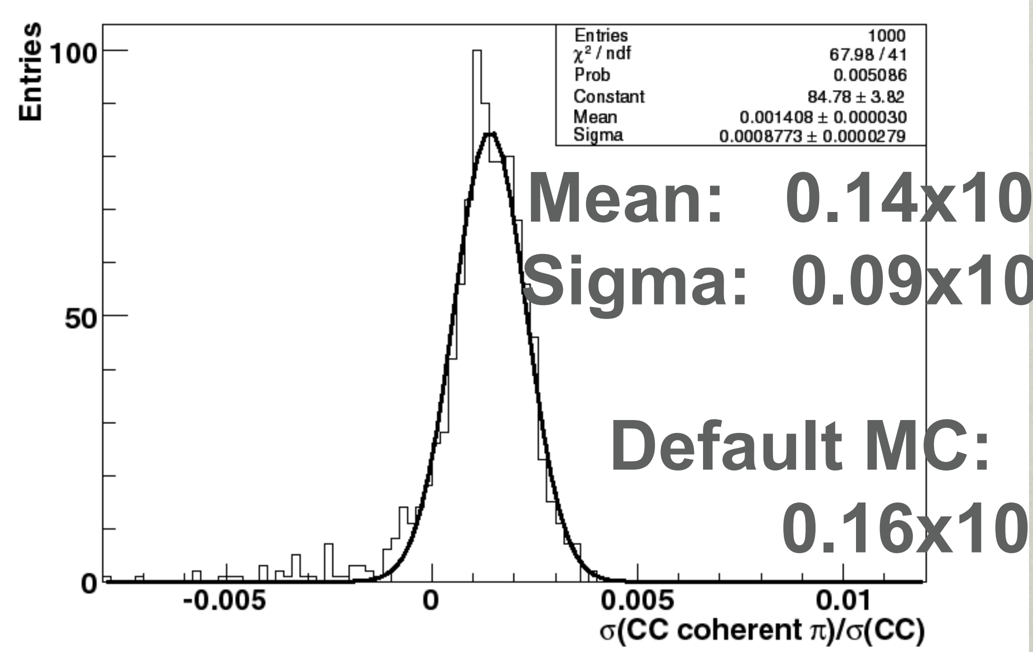
Systematic errors (neutrino interaction model)

Source	MRD stopped error ($\times 10^{-2}$)		MRD penetrated error ($\times 10^{-2}$)	
Axial vector mass	+0.16	$\cdots$	+0.05	$\cdots$
CC resonant $\mu^- n\pi^+/\mu^- p\pi^+$ ratio	+0.04	−0.04	+0.04	−0.04
Low Q^2 suppression in CC resonant pion	+0.04	$\cdots$	+0.04	$\cdots$
Subtotal	+0.17	−0.04	+0.08	−0.04

Systematic errors (Eν spectrum)

- Pi+ production (SW)
- Pi- production (SW)
- K+ production (FS)
- K0 production (SW)
- Horn skin effect
- Horn current
- Be-nucleon x-section
- Be-pion x-section

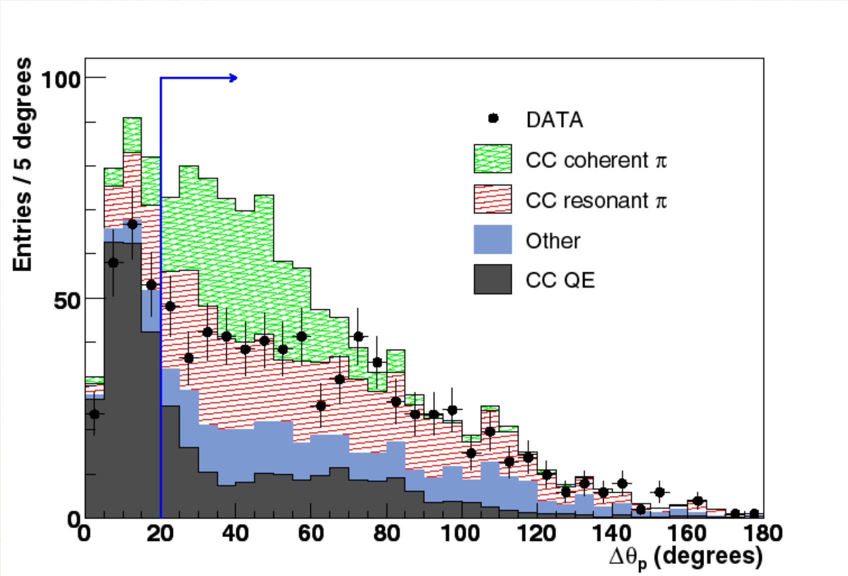
Variation of the cross section ratio using 1,000 multisim parameter sets



➔ (+0.07, -0.11) $\times 10^{-2}$ is assigned for the MRD stopped sample

Systematic errors (Event selection)

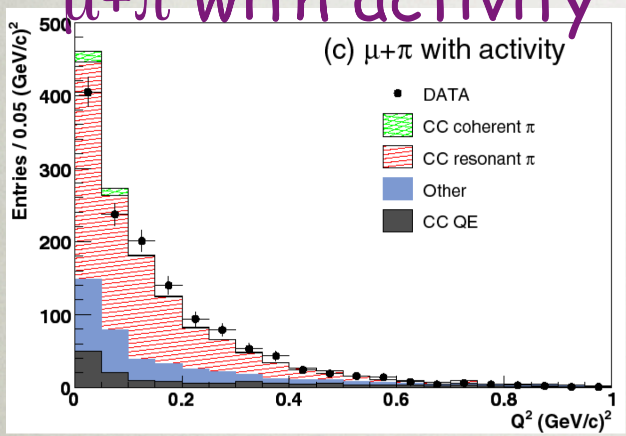
$\Delta\theta p$ for the $\mu+\pi$ events



Vary $\Delta\theta p$ cut by +/-5degrees
Take the change as systematic error

Low Q^2 suppression in CC resonant π

μ+π with activity

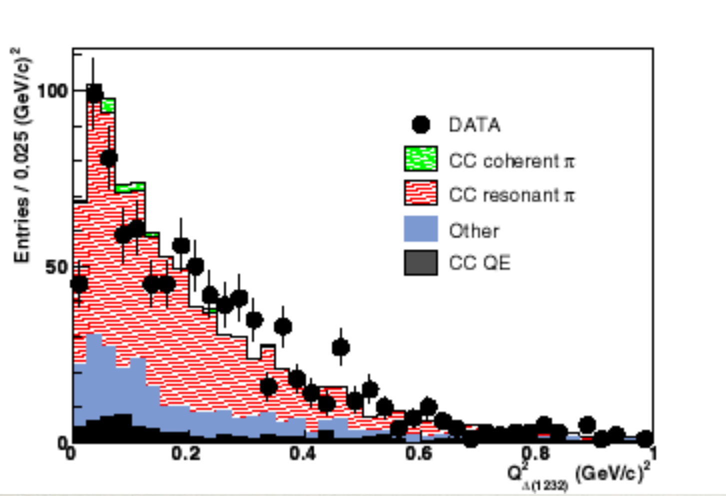


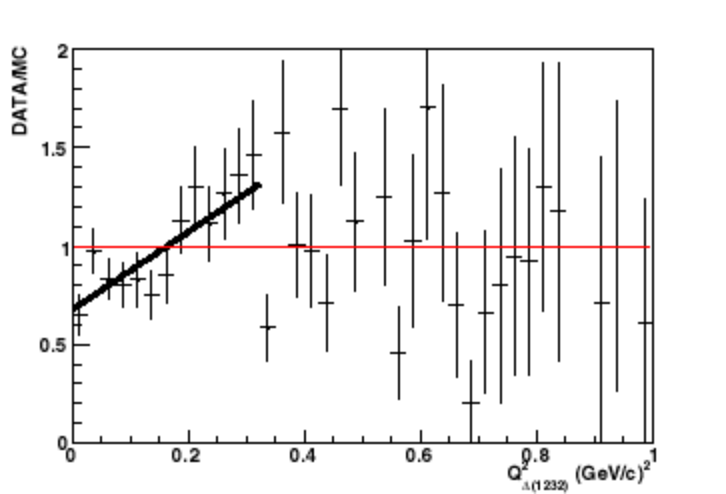
low Q^2 data deficit is observed in CC resonant pion enriched sample

The Q^2 shape uncertainty affects background estimation for CC coherent pion sample

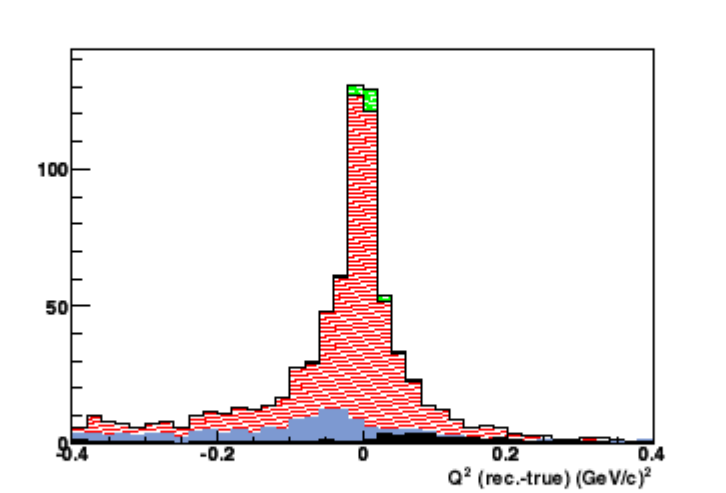
Low Q^2 suppression in CC resonant π

Rec. Q^2 assuming Δ-resonance





Q^2 resolution (rec-true)

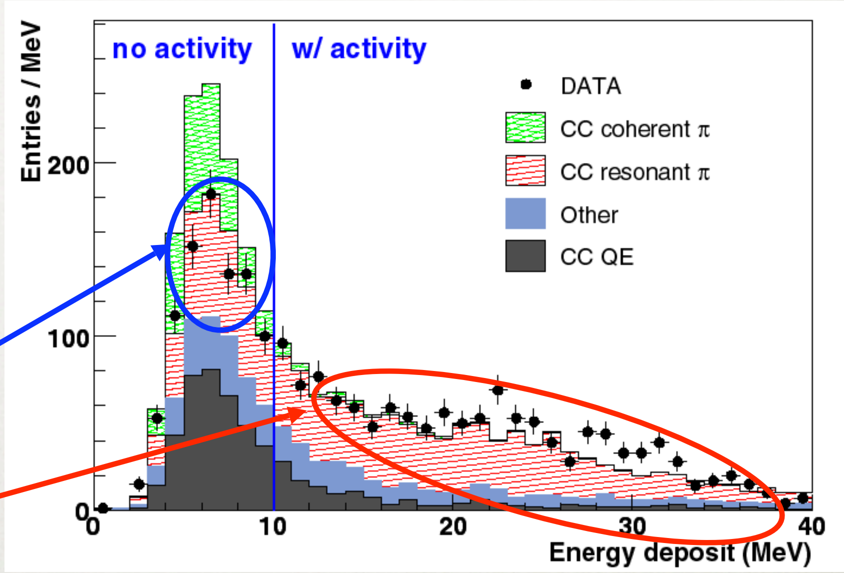


Apply this weighting function to CC coherent π sample in order to estimate systematic error

Uncertainty in CC resonant μnπ/μpπ ratio

The uncertainty in the CC resonant μnπ/μpπ ratio causes migration between low/high activity samples

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



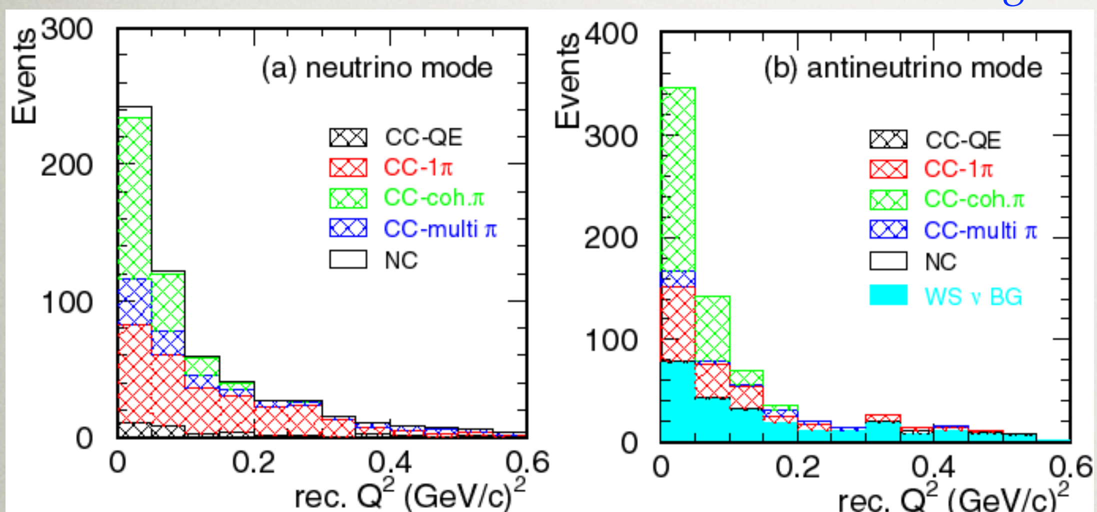
The uncertainty in the CC resonant μnπ/μpπ ratio is ~7%, estimated using SciBooNE sub-samples

→ $\delta(\sigma(coh)/\sigma(CC)) = +/-0.04\times10^{-2}$ considered as systematic error

Future prospects

Antineutrino CC coherent pion production?

K. Hiraide
NuInt05 Proceedings

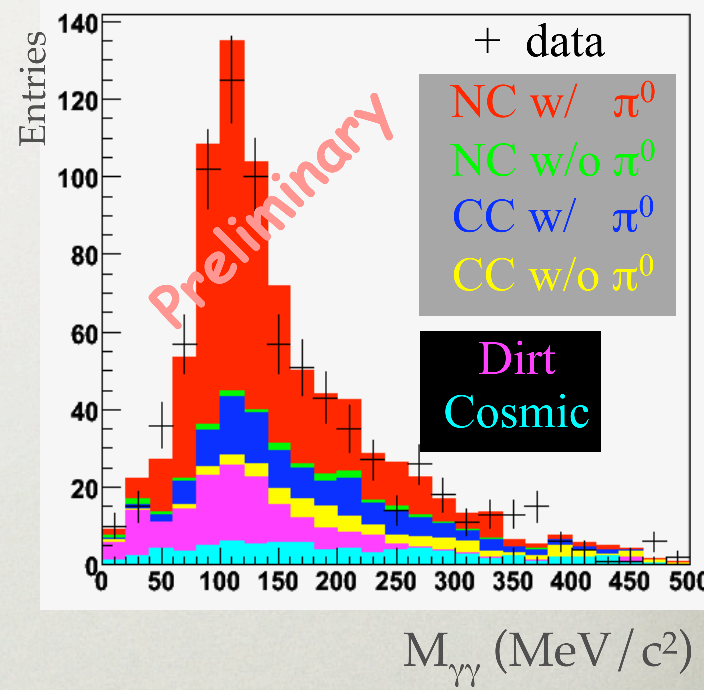


Neutrino mode (assuming 0.5x10[20] POT) antineutrino mode (assuming 1.5x10[20] POT)

MC studies at the time of SciBooNE proposal

Neutrino NC coherent pion production?

Y. Kurimoto



NC-π^0 sample in SciBooNE