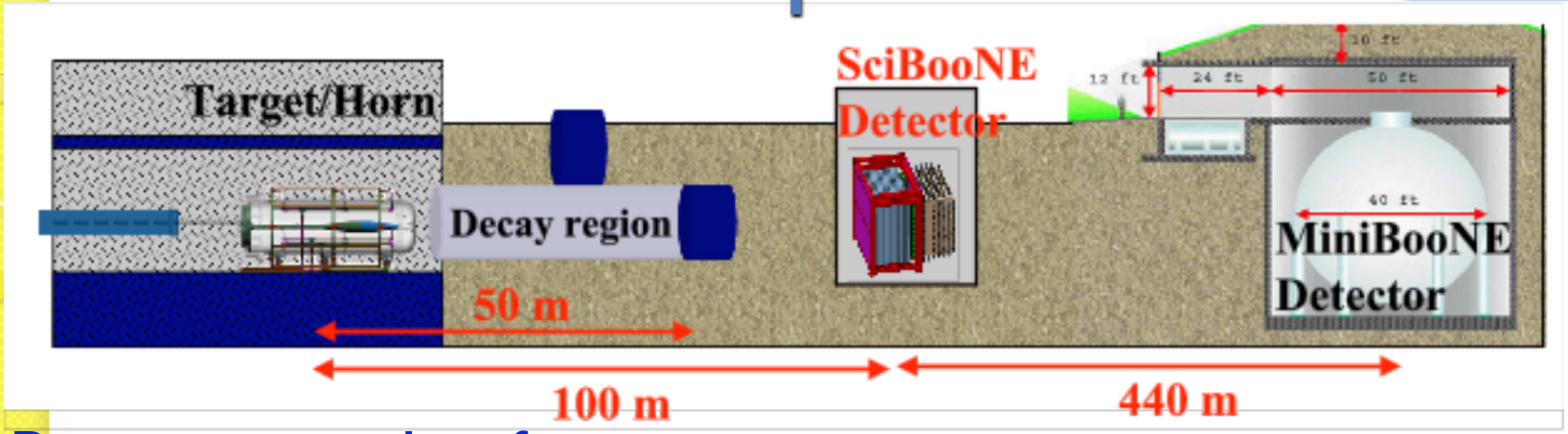
Nov. 19th, 2008
TRIUMF seminar

The SciBooNE neutrino experiment (FNAL E954)

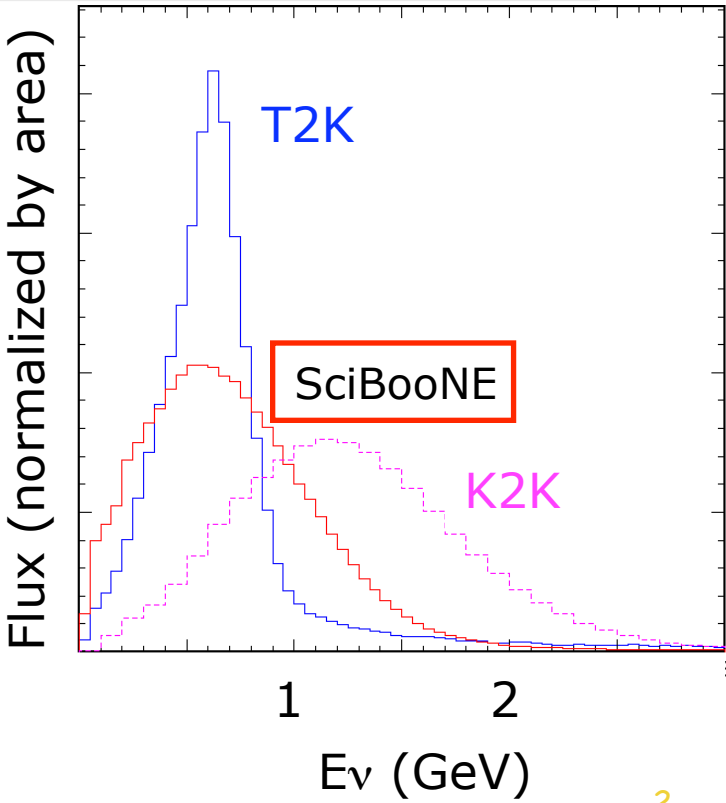
~The First Result and Outlook~

T. Nakaya (Kyoto Univ.)

The SciBooNE Experiment



- Precision study of neutrino cross sections (for T2K).
- Anti-neutrinos
  - Unexplored physics territory and important for CP study in T2K-II.
- MiniBooNE near detector.



K2K-SciBar + FNAL-BNB

- Well developed Detector
- Most intense low energy neutrino beam.

First Result

arXiv:0811.0369v1 [hep-ex] 3 Nov 2008

Search for Charged Current Coherent Pion Production on Carbon in a Few-GeV Neutrino Beam

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(Dated: November 3, 2008)

First Result

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Search for Charged Current Coherent Pion Production on Carbon in a Few-GeV Neutrino Beam

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The SciBooNE Collaboration has performed a search for charged current coherent pion production from muon neutrinos scattering on carbon, $\nu_\mu {}^{12}\mathrm{C} \rightarrow \mu^{-}{}^{12}\mathrm{C}\pi^{+}$, with two distinct data samples. No evidence for coherent pion production is observed. We set 90% confidence level upper limits on the cross section ratio of charged current coherent pion production to the total charged current cross section at 0.67×10^{-2} at mean neutrino energy 1.1 GeV and 1.36×10^{-2} at mean neutrino energy 2.2 GeV.

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(Dated: November 3, 2008)

Outline

1. Introduction
2. Physics background
3. SciBooNE Experiment
4. Analysis and Result
   1. Search for Charged Current Coherent Pion Production
   2. Neutral Current π^0 reconstruction in SciBooNE.
   3. Beam Flux Measurements
5. Conclusion

I. Introduction

SciBooNE

Intense beam

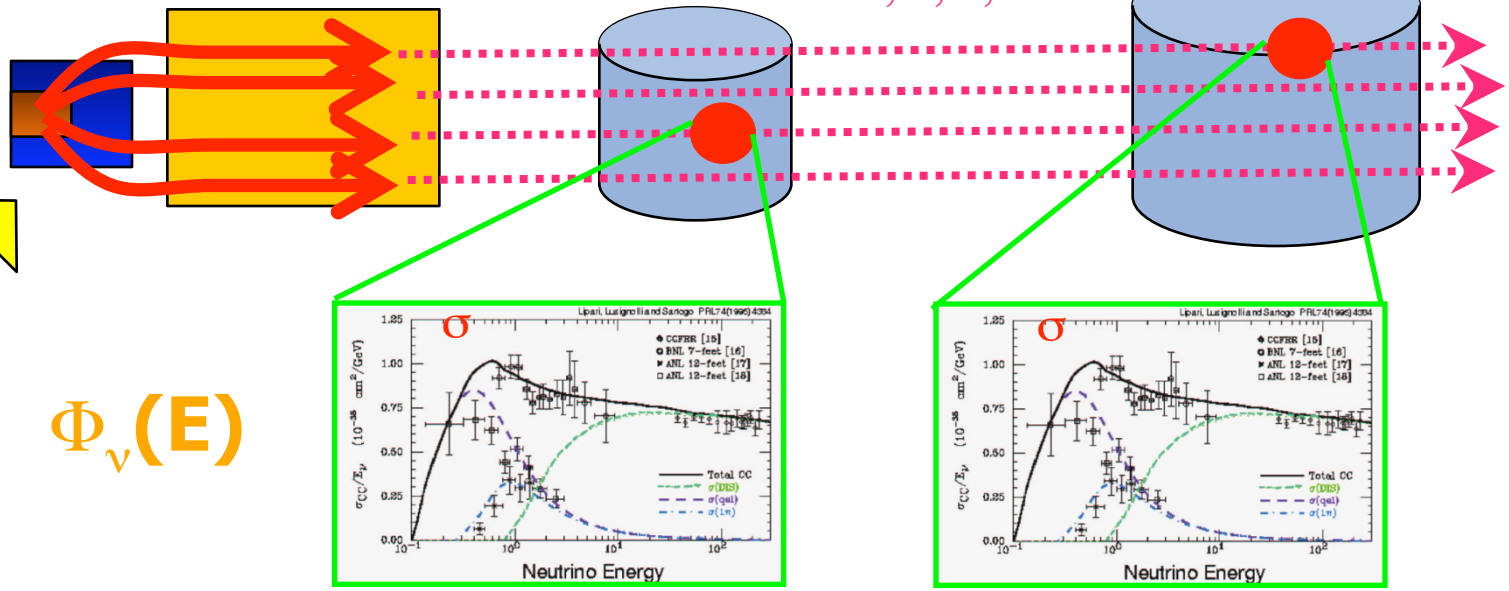
Gigantic detector

oscillation

π, π, π, π, K

ν, ν, ν, ν

protons



HARP

SHINE

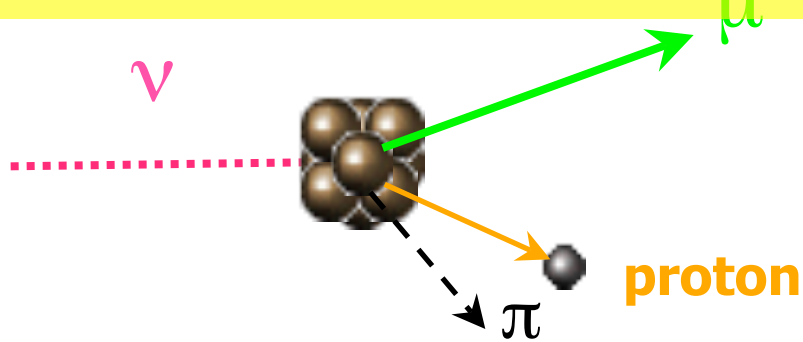
$\Phi_\nu(E)$

$$\sigma(E)\cdot\Phi_\nu^{near}(E) \Leftrightarrow \sigma(E)\cdot\Phi_\nu^{far}(E)$$

MiniBooNE | K2K

SciBooNE | MINERνA

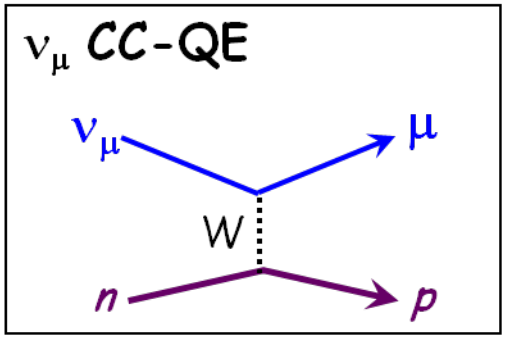
MINOS | T2K



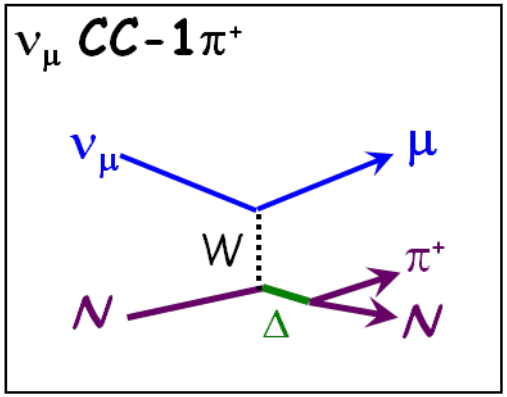
Background processes for oscillation measurements

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

Signal

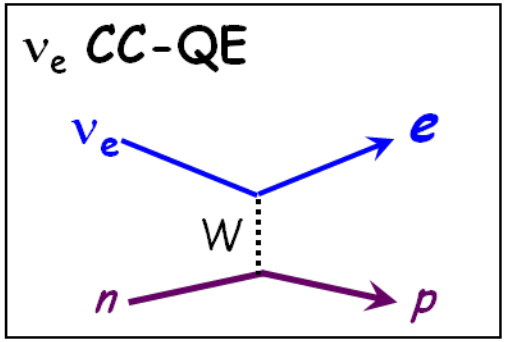


Background

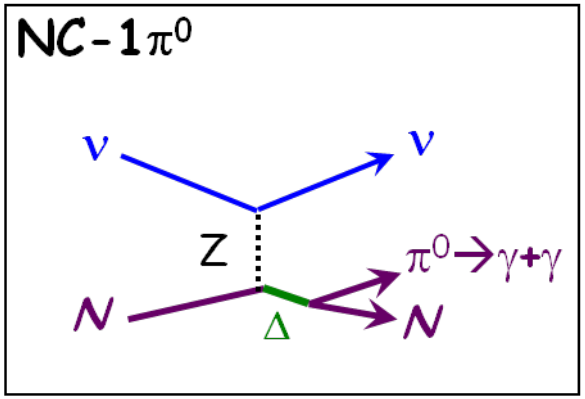


ν_e appearance ($\nu_\mu \rightarrow \nu_e$)

Signal



Background

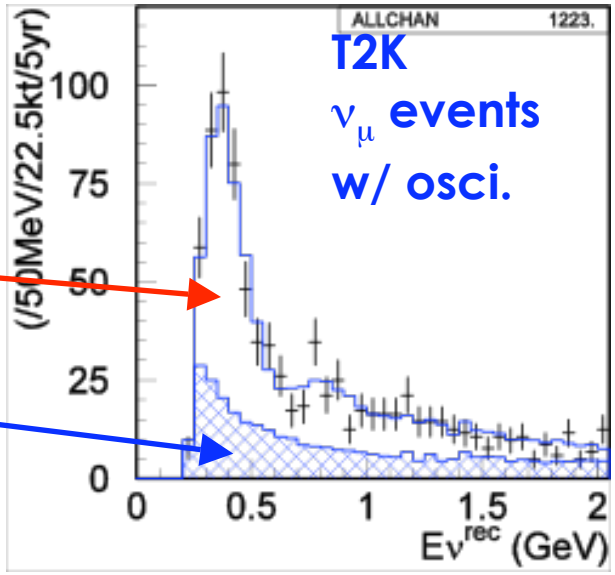


Need to understand these processes as well

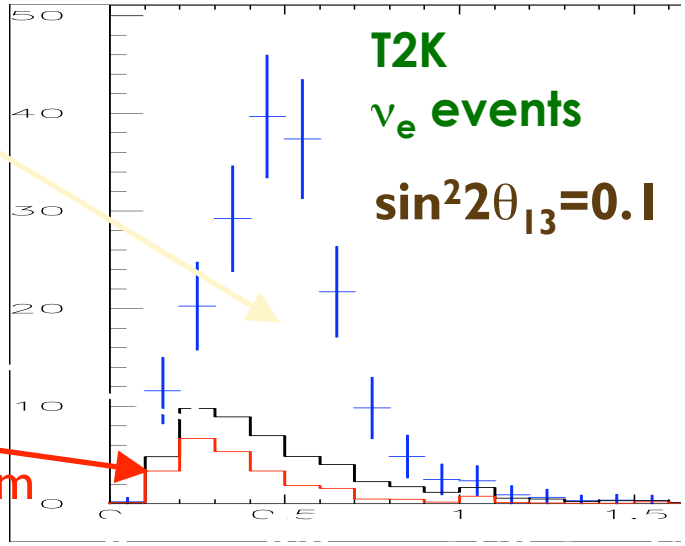
Impact of Neutrino Cross sections on oscillation measurements (T2K case)

SciBooNE

- $\nu_\mu \rightarrow \nu_\mu$: precision measurements (θ_{23} and Δm_{23}^2)
  - Signal: CC-QE ($\nu+n \rightarrow \mu+p$)
    - Energy Reconstruction from μ kinematics
  - Background: Mainly CC-1$\pi^\pm$ ($\nu+N \rightarrow \mu+\pi+N'$)
    - Cross section with **the invisibility of π**



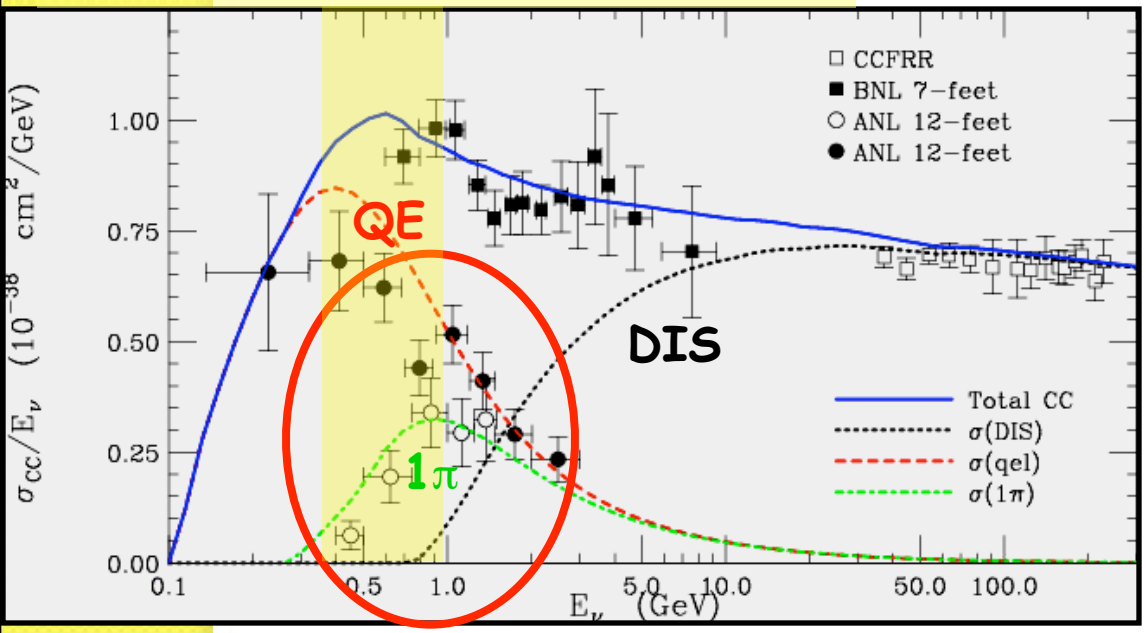
- $\nu_\mu \rightarrow \nu_e$: search for θ_{13}
  - Signal: CC-QE ($\nu+n \rightarrow e+p$)
  - Background
    - Beam ν_e
    - NCπ^0
    - Cross section as a function of the momentum



Anti-ν for CP violation study

Unexplored Areas of Neutrino Physics

σ_ν in this E range of interest:



MINOS, NuMI

K2K, NOvA

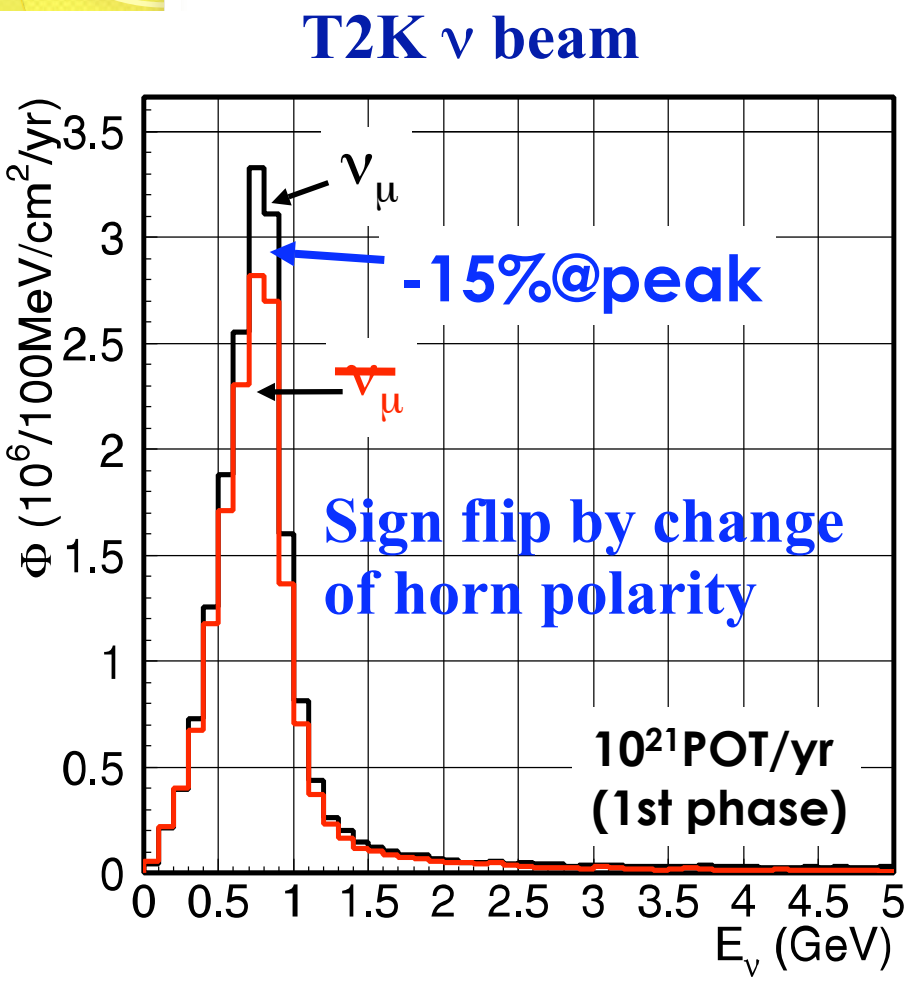
MiniBooNE, T2K, SciBooNE

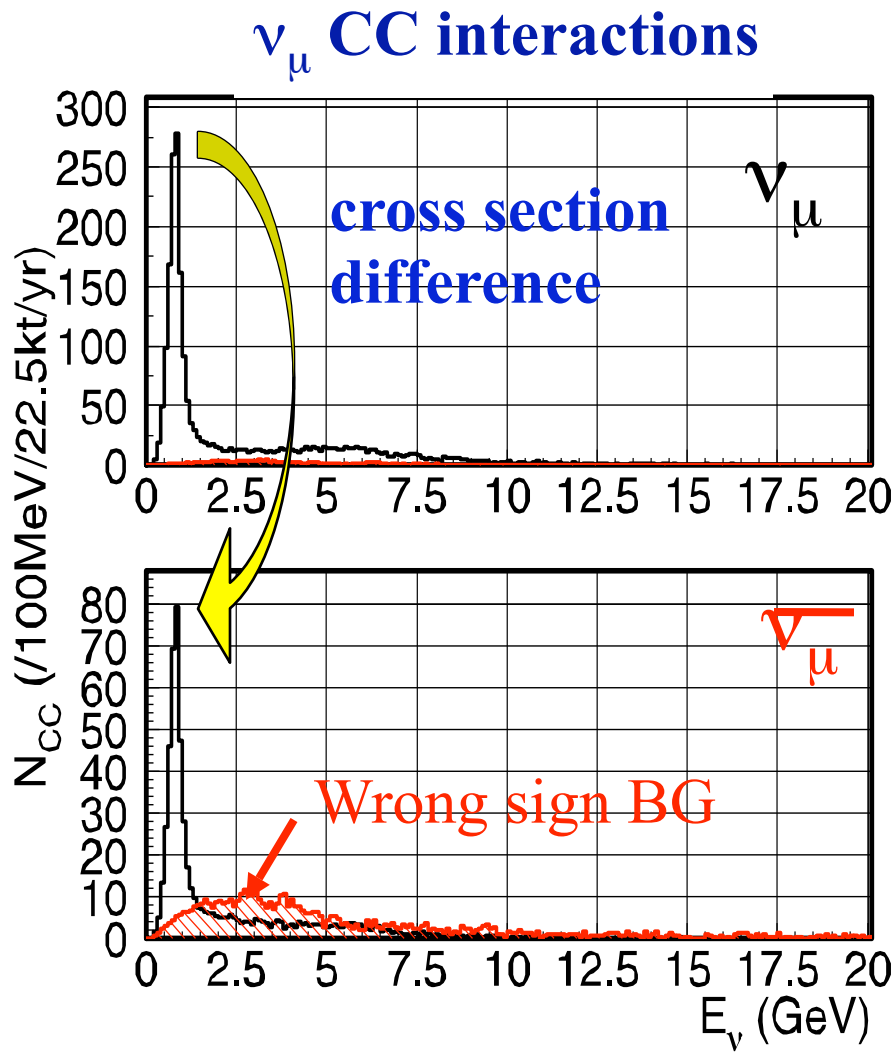
Super-K atmospheric ν

- **Data from old experiments** (1970~1980)
  - Low statistics
  - Systematic Uncertainties
- **Nuclear effects** (π/p/n absorption/scattering, shadowing, low Q^2 region)
  - Not well-modeled
- **New data** from K2K & MiniBooNE revealing surprises
- **More data at 1GeV with fine grained resolution will** [illegible] Physics.

Anti-ν cross sections are in a poor situation.

CP violation search in T2K-II





ν_e appearance in T2K-II

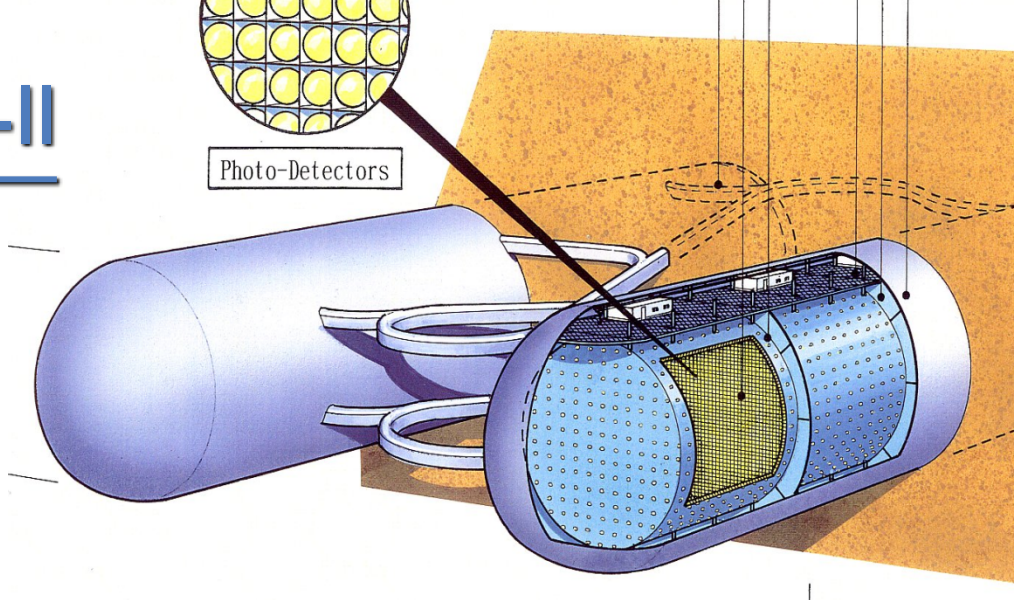
$\Delta m_{21}^2 = 6.9 \times 10^{-5} eV^2$

$\Delta m_{32}^2 = 2.8 \times 10^{-3} eV^2$

$\theta_{12} = 0.594$

$\theta_{23} = \pi/4$

$\theta_{13} = 0.05$ ($\sin^2 2\theta_{13} = 0.01$)



ν_μ:2yr, $\bar{\nu}_\mu$:6.8yr

4MW (J-PARC upgrade)

0.54Mt (Hyper-K)

	signal		background				
	$\delta=0$	$\delta=\pi/2$	total	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
$\nu_\mu \rightarrow \nu_e$	536	229	913	370	66	450	26
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	536	790	1782	399	657	297	430

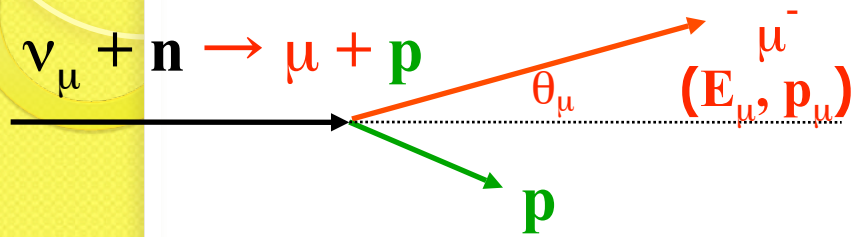
Understanding of Neutrino Interactions with Nucleus is **IMPORTANT**.

2. Physics Background

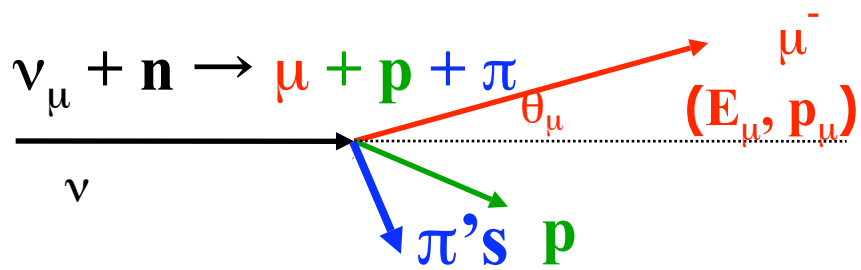
- Quasi-Elastic Scattering
  - M_A
  - Q^2 distribution (Muon angle in SciBooNE)
  - Low Q^2 region
- π production
  - M_A, Q^2 distribution, low Q^2 region.
  - Coherent π production (CC v.s. NC)
  - π^0 Momentum distribution
- (maybe more)

2.1 QE (Quasi-Elastic) scattering

CC quasi elastic (QE)



CC inelastic

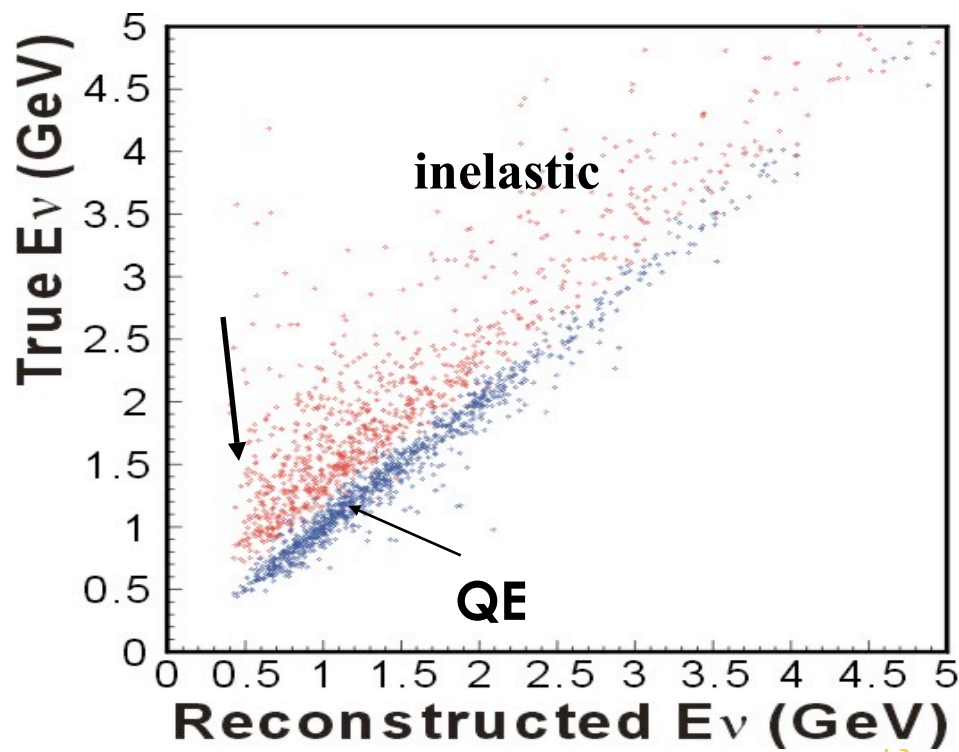


$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

Rate(Eν,Near) → <u>ϕ(Eν,Near)</u>

↑

σ(QE), σ(nonQE)



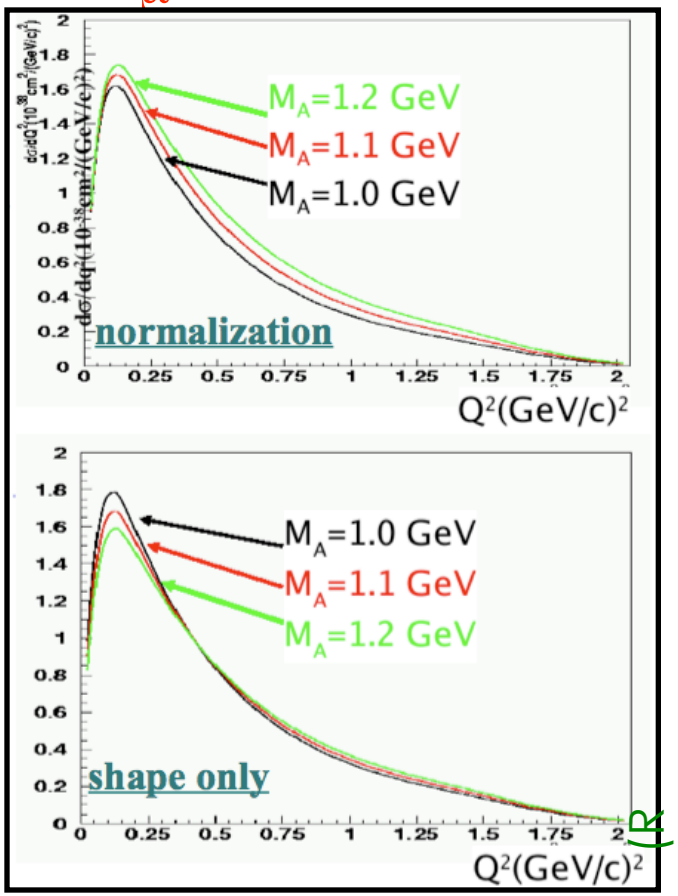
QE Scattering

- It is important to understand
  - Nuclear model
    - Assuming Fermi Gas model
  - Nuclear form factors (FF)
    - Vector FF is known from e^- scattering.
    - Axial Vector FF can be measured by neutrino scattering
    - Dipole form factor

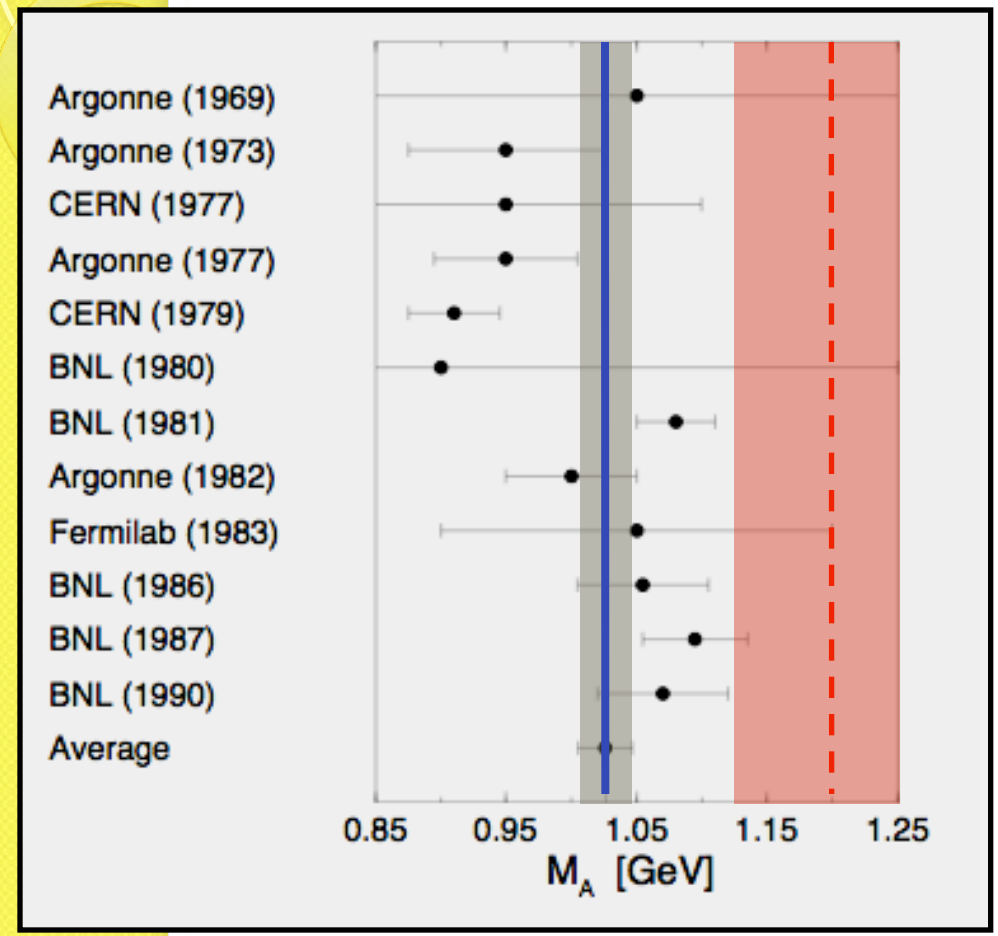
$$F_A(Q^2) = \frac{g_A}{\left(1 + Q^2/M_A^2\right)^2}$$

Single Parameter: **M_A (=1.03 GeV/c^2)** from the past measurements

$\nu_\mu\, n \rightarrow \mu^-\, p$



Recent measurements of M_A



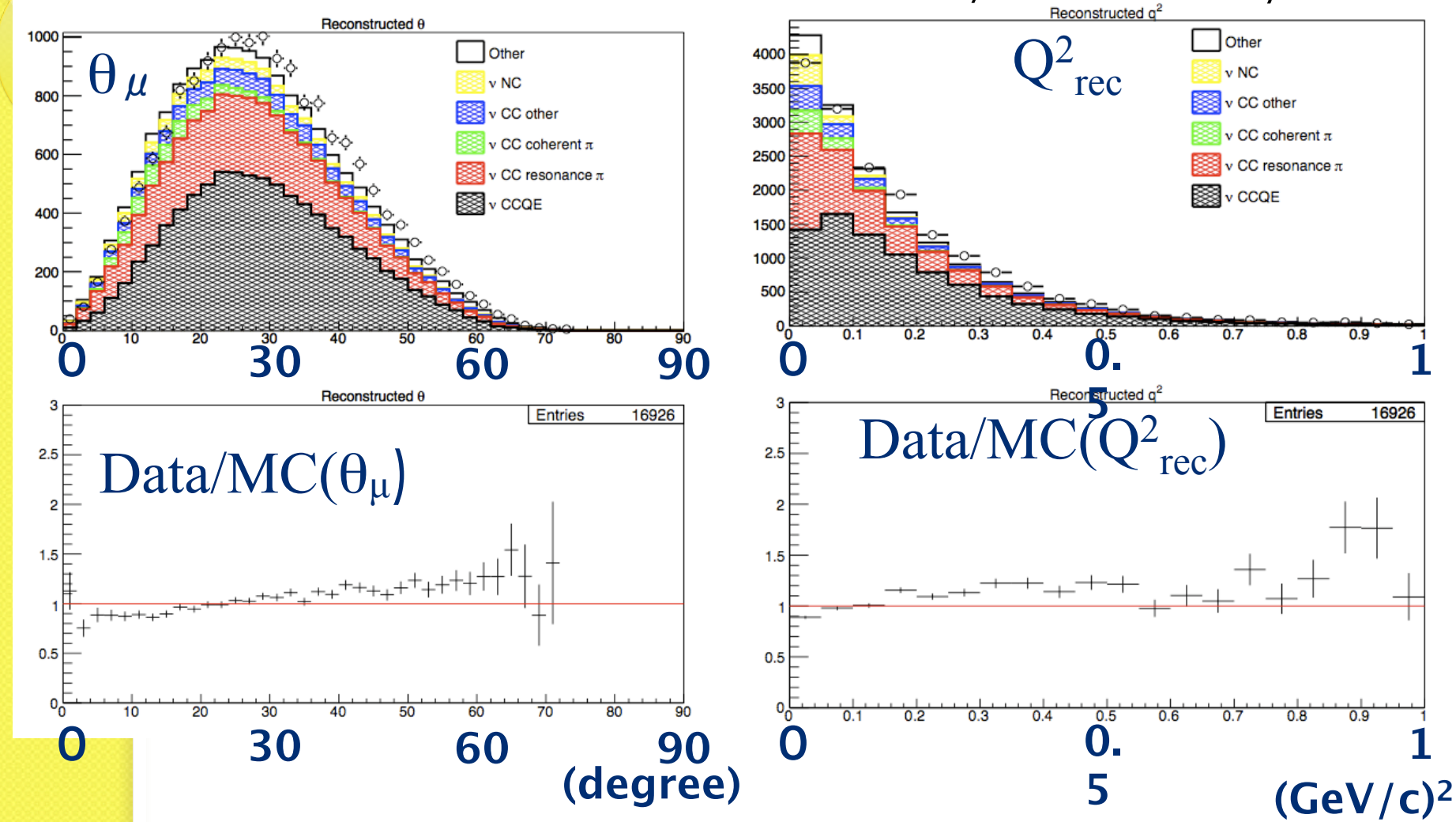
- **K2K SciFi** (^{16}O, $Q^2>0.2$)
  Phys. Rev. **D74**, 052002 (2006)
  $M_A = 1.20 \pm 0.12$ GeV
- **K2K SciBar** (^{12}C, $Q^2>0.2$)
  $M_A = 1.14 \pm 0.11$ GeV
- **MiniBooNE** (^{12}C, $Q^2>0.25$)
  Phys. Rev. Lett. **100**, 032301 (2008)
  $M_A = 1.25 \pm 0.12$ GeV

Systematic Difference?
Effective M_A in nucleus?

past world avg: **M_A = 1.026 ± 0.021** GeV
J. Phys. **G28**, R1 (2002)

θ_μ and Q^2 in SciBooNE

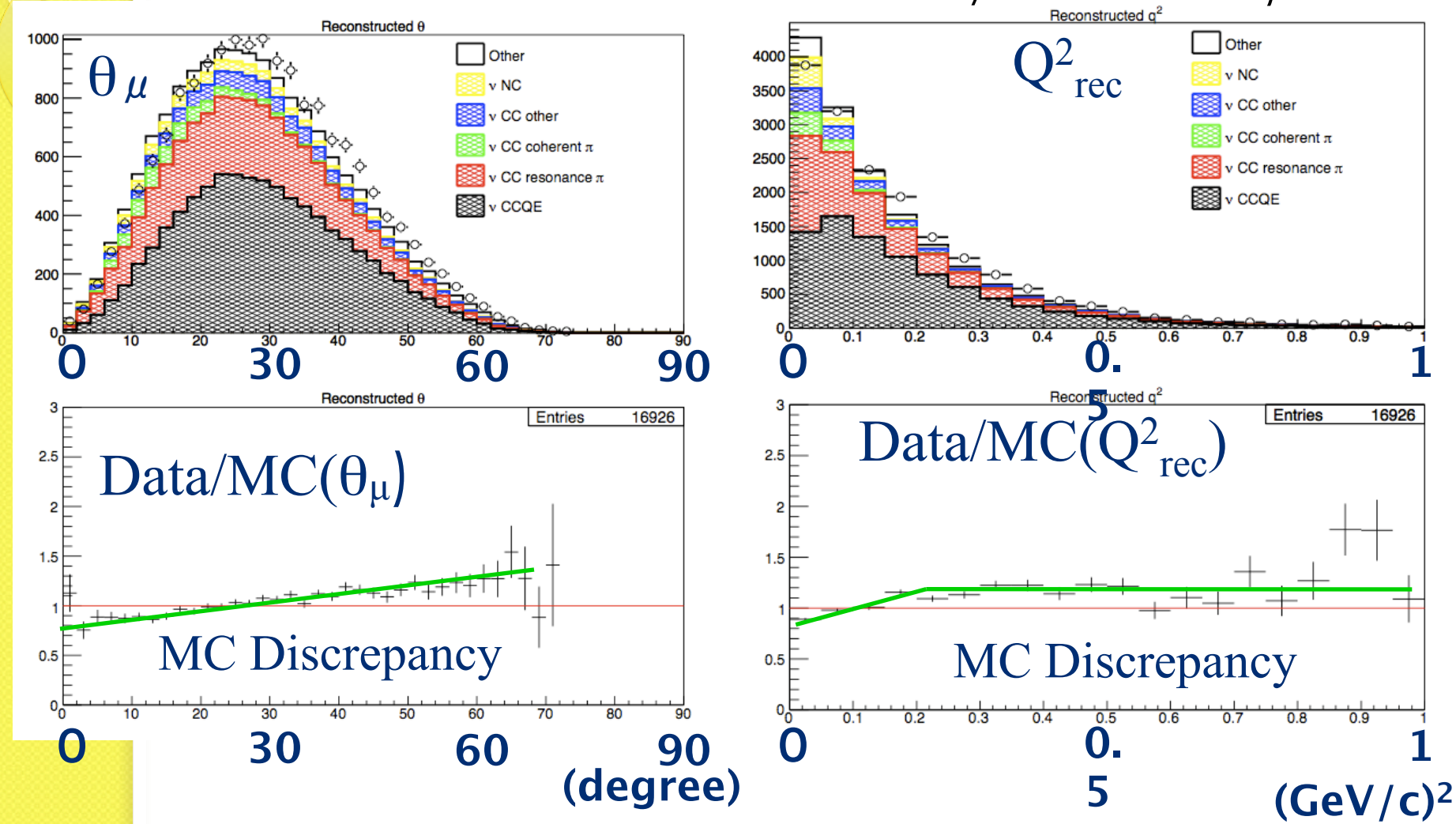
MRD Stopped sample(normalized by muon events)



M_A effect or other sources ?

θ_μ and Q^2 in SciBooNE

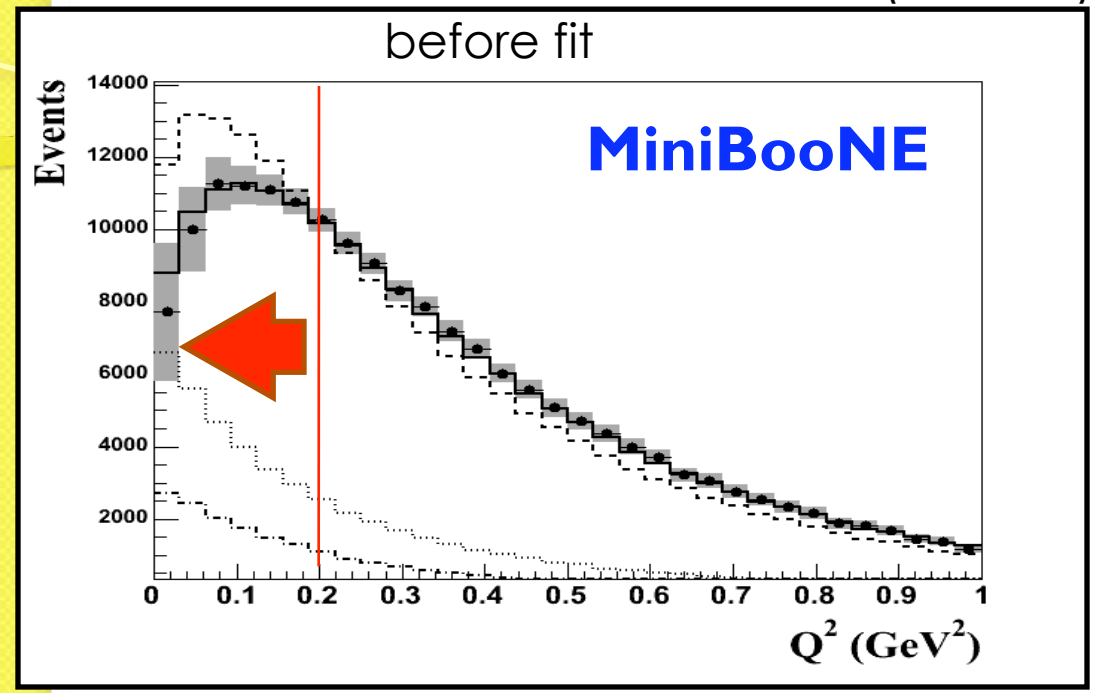
MRD Stopped sample(normalized by muon events)

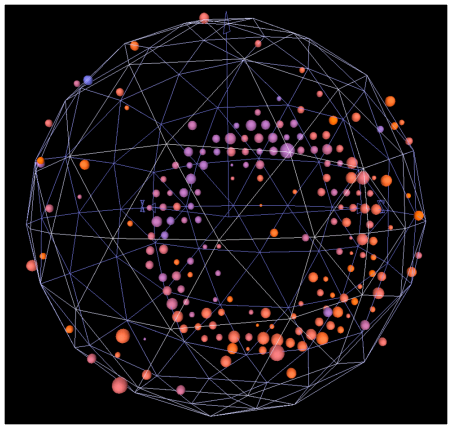


M_A effect or other sources ?

Low Q^2 region in QE

(T. Katori)



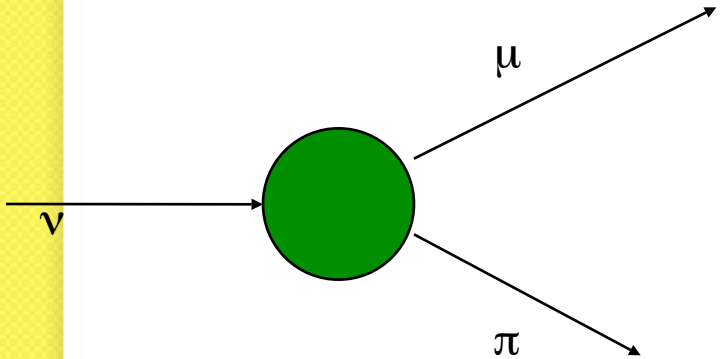


- fit to Q^2 distribution, $Q^2>0$, carbon
  - $M_A = 1.23 \pm 0.20$ GeV → fixes high Q^2
  - $\kappa = 1.019 \pm 0.011$ (Pauli blocking par) → fixes low Q^2

(PRL **100**, 032301 (2008))

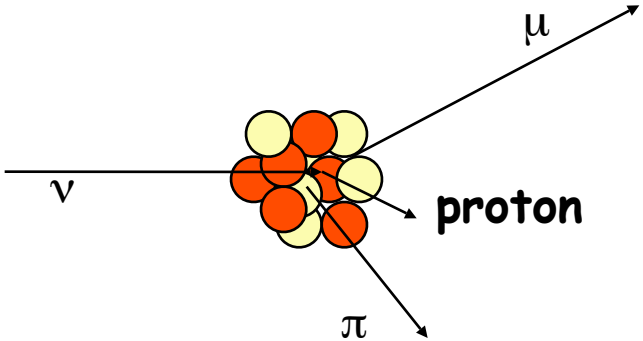
(CC)-ν π production at low energy (~1 GeV)

CC-coherent π (ν+A→μ+A+π)



CC-1π (ν+p→μ+p+π)

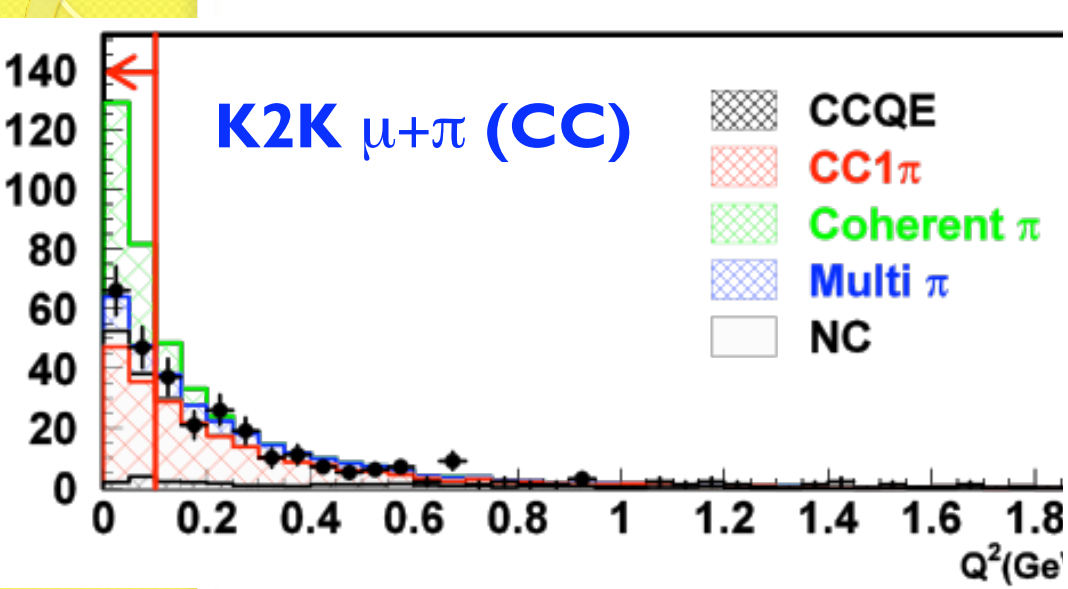
Mainly through Δ resonance.

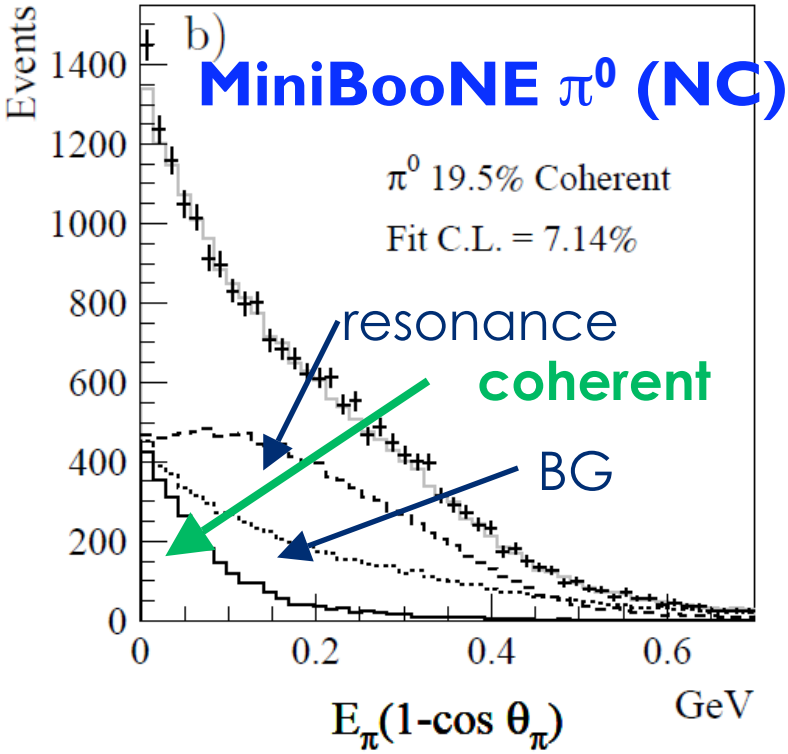


Coherent π signature

- One muon and one pion in the final state
- Low momentum transfer
- No vertex activity due to no proton

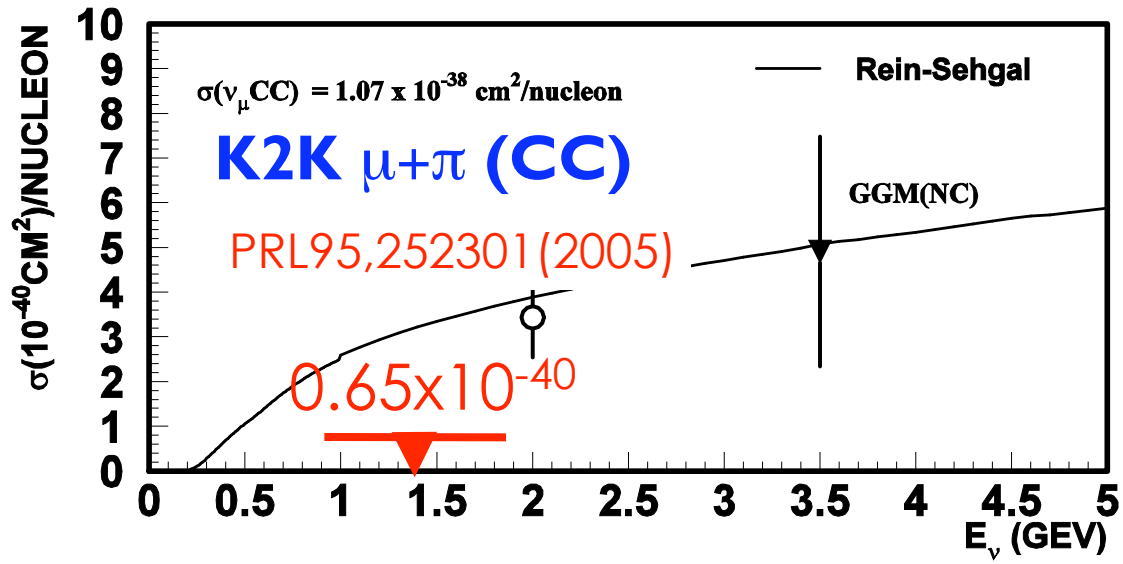
Coherent π production in CC and NC reaction





- CC-coherent π is **NOT** observed.
- NC-coherent π is observed.

MiniBooNE π^0 (NC)

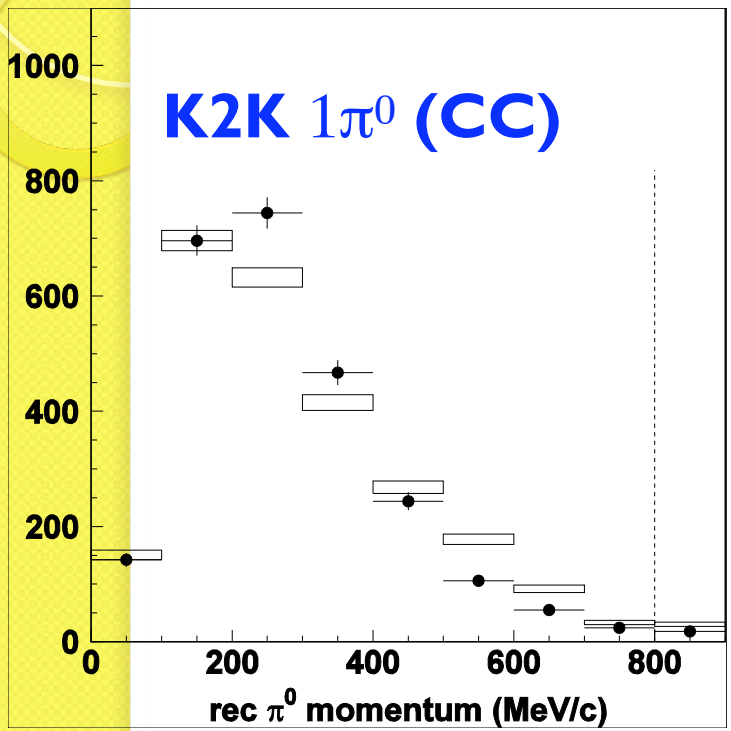


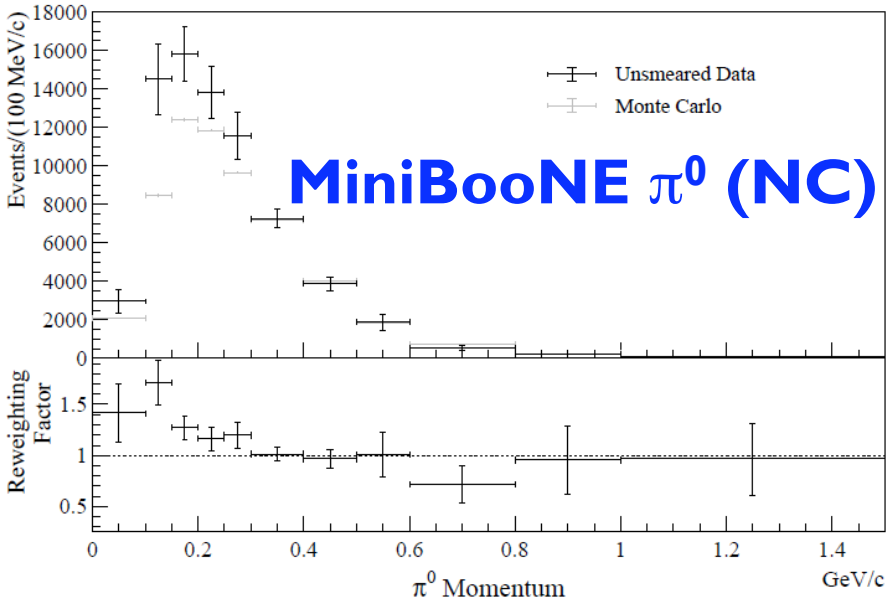
First observation of NC coherent pion production at Eν<2GeV

65% of the model prediction

- Consistent?
  - The new CC result comes from SciBooNE.

π^0 momentum distribution





- More low momentum π^0?
  - Less high momentum π^0?
  - If so, it is a good news for ν osci. Experiments.

(K2K) : $\sigma_{NC1\pi0}/\sigma_{CC\text{-}all}$=0.064±0.001 ±0.007 (MC: 0.065)

New σ_ν Calculations (2006-2008)

SciBooNE

Compiled by Sam Zeller (LANL)

QE

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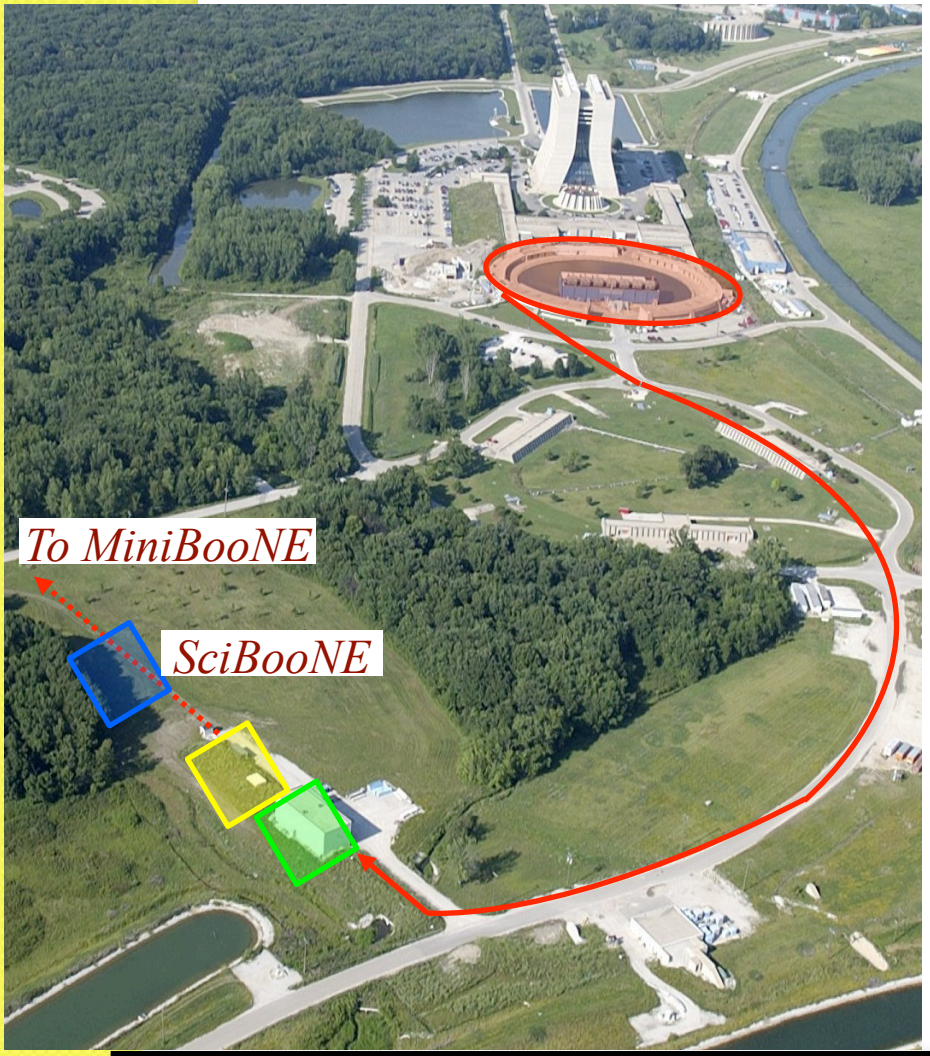
3. SciBooNE experiment



Booster Proton accelerator

- 8 GeV protons sent to target

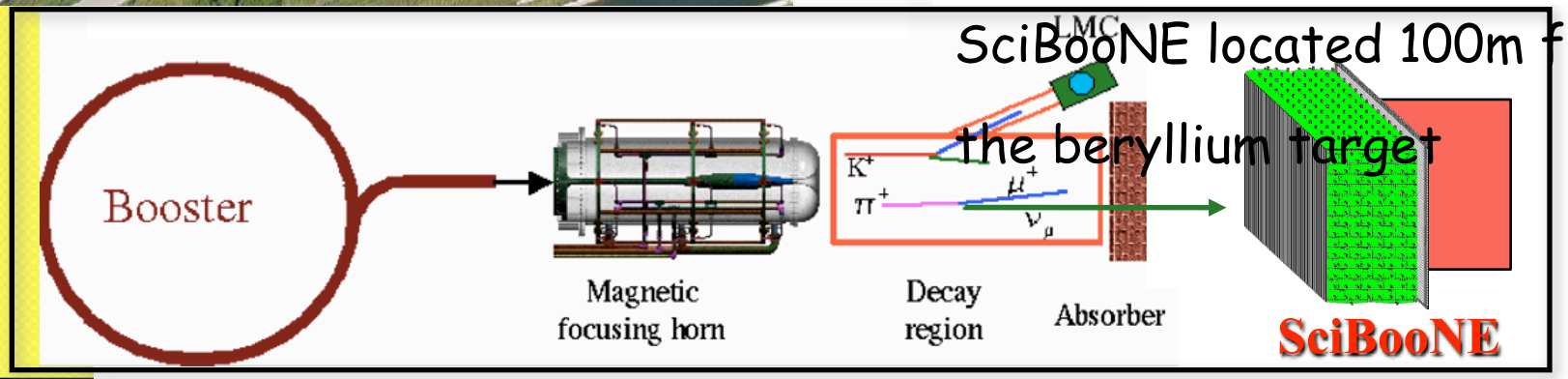
Target Hall

- Beryllium target:
  71cm long 1cm diameter
- Resultant mesons focused with magnetic horn
- Reversible horn polarity

50m decay volume

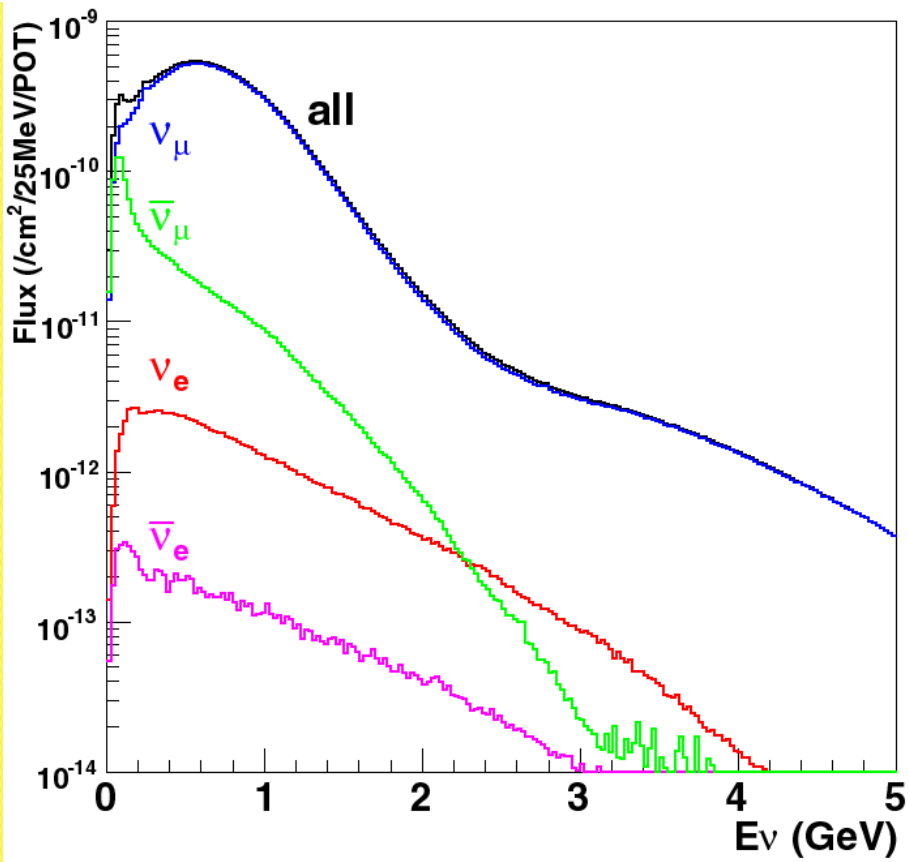
- Mesons decay to μ & ν_μ
- Short decay pipe minimizes $\mu \rightarrow \nu_e$ decay

SciBooNE located 100m from the beryllium target



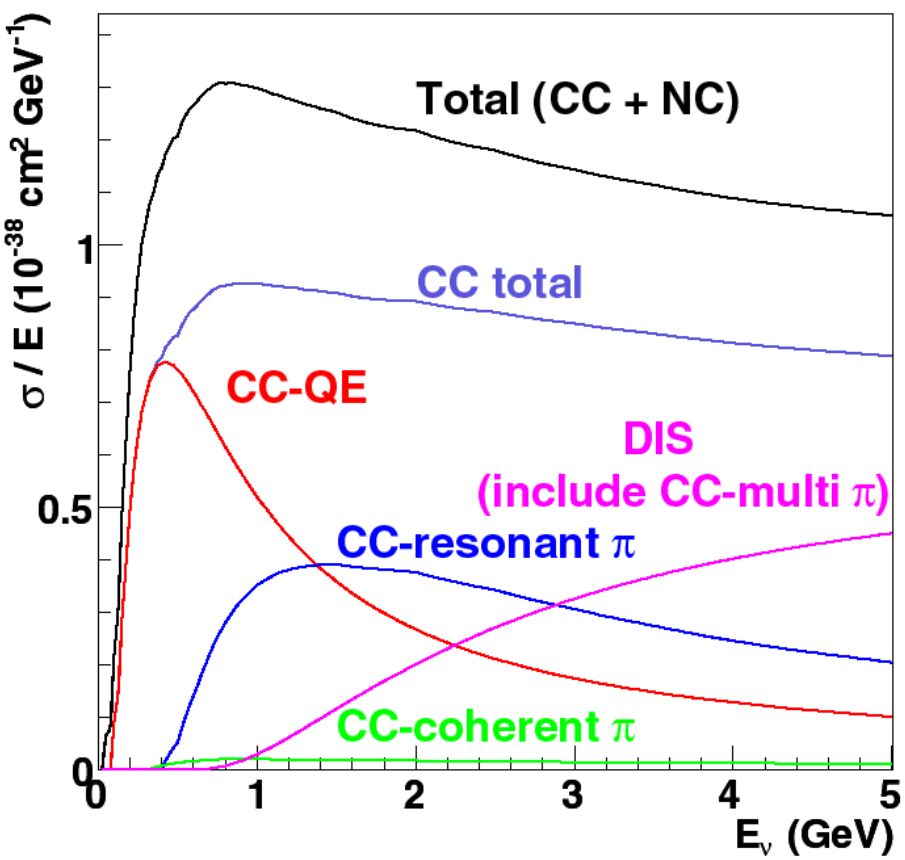
Booster Neutrino Beam (BNB)

Expected neutrino flux at SciBooNE
(neutrino mode)



- mean neutrino energy ~0.7 GeV
- 93% pure 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/c^2
  - P_F=217MeV/c, E_B=27MeV (for Carbon)
- Resonant π
  - Rein-Sehgal (2007)
  - M_A=1.2 GeV/c^2
- Coherent π
  - Rein-Sehgal (2006)
  - M_A=1.0 GeV/c^2
- DIS
  - GRV98 PDF
  - Bodek-Yang correction

SciBooNE detector

SciBar

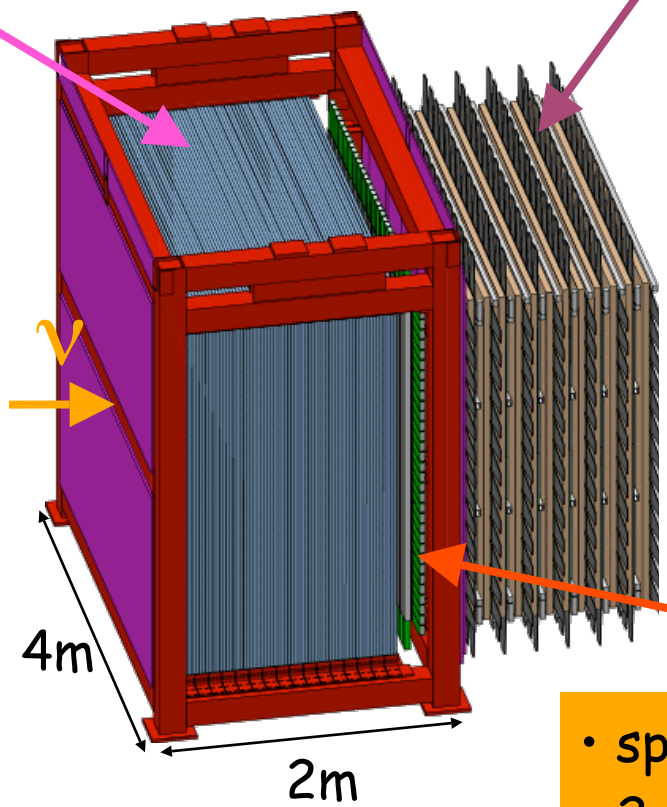
- scintillator tracking detector
- 14,336 scintillator bars (15 tons)
- Neutrino target
- detect all charged particles
- p/π separation using dE/dx

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 experiment



Electron Catcher (EC)

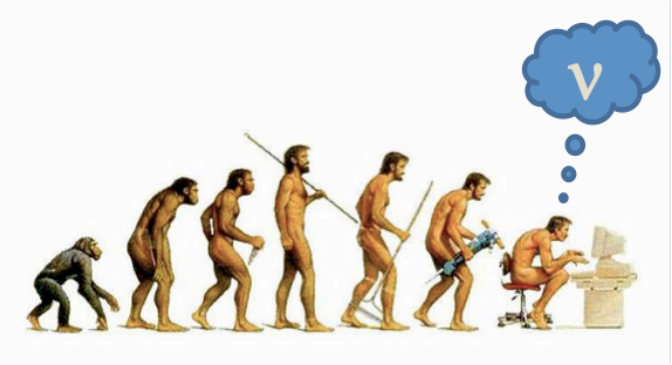
- spaghetti calorimeter
- 2 planes (11 X_0)
- identify π^0 and ν_e

Used in CHORUS, HARP and K2K

DOE-wide Pollution Prevention Star (P2 Star) Award

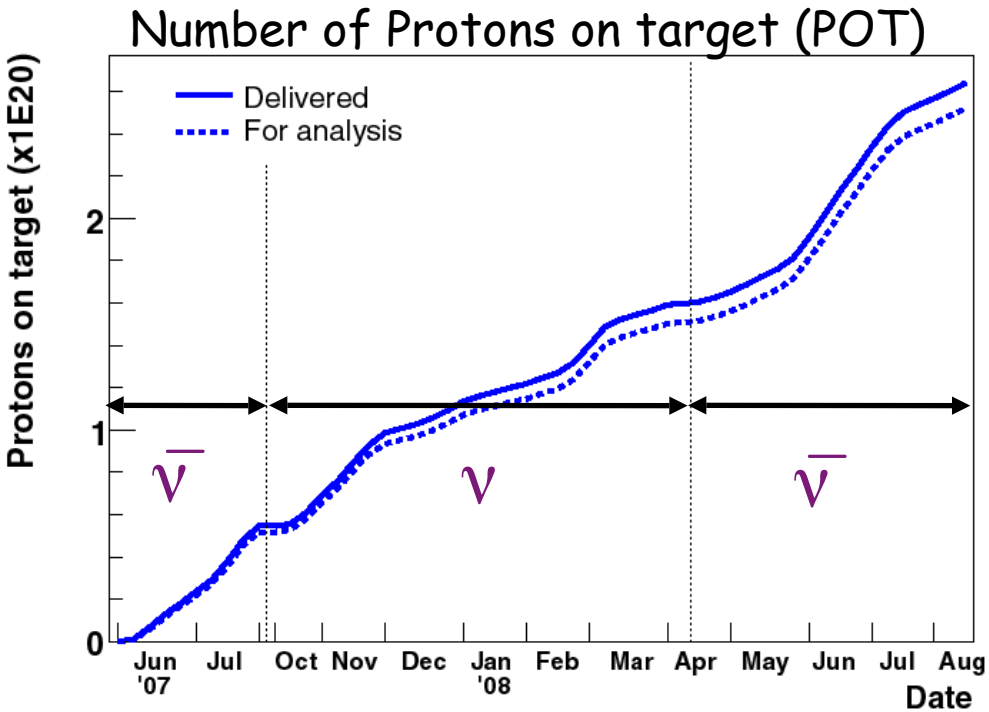
SciBooNE Timeline

- 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 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

We thank support from Accelerator Division

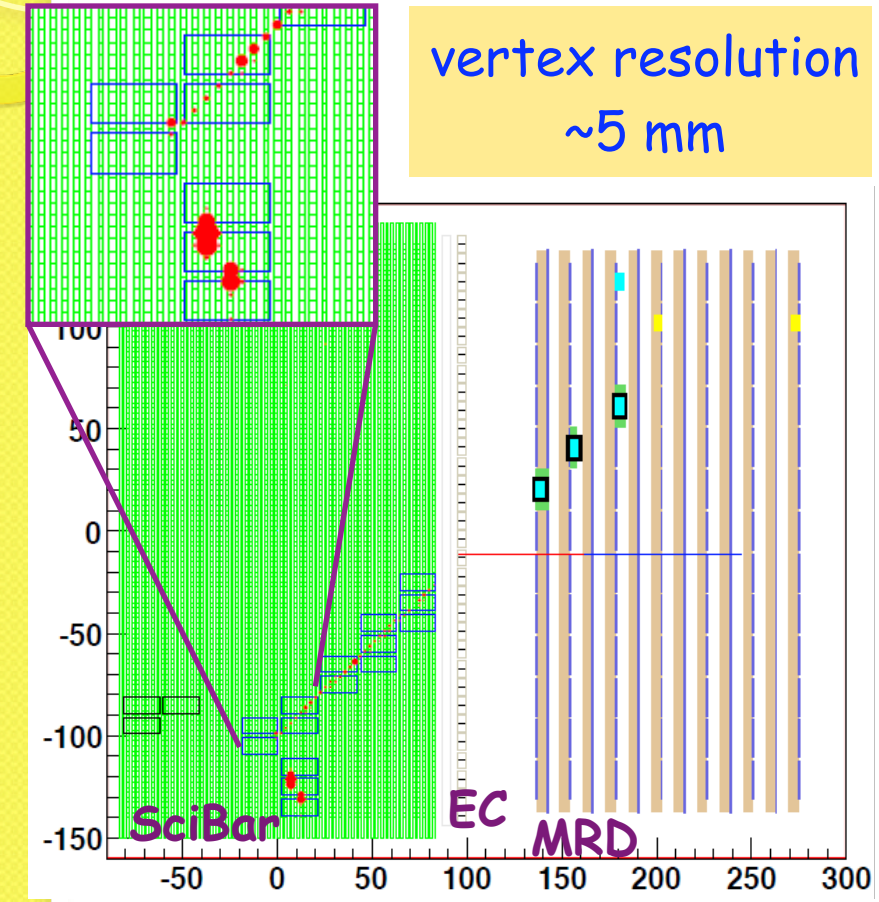
Results from full neutrino data set are presented

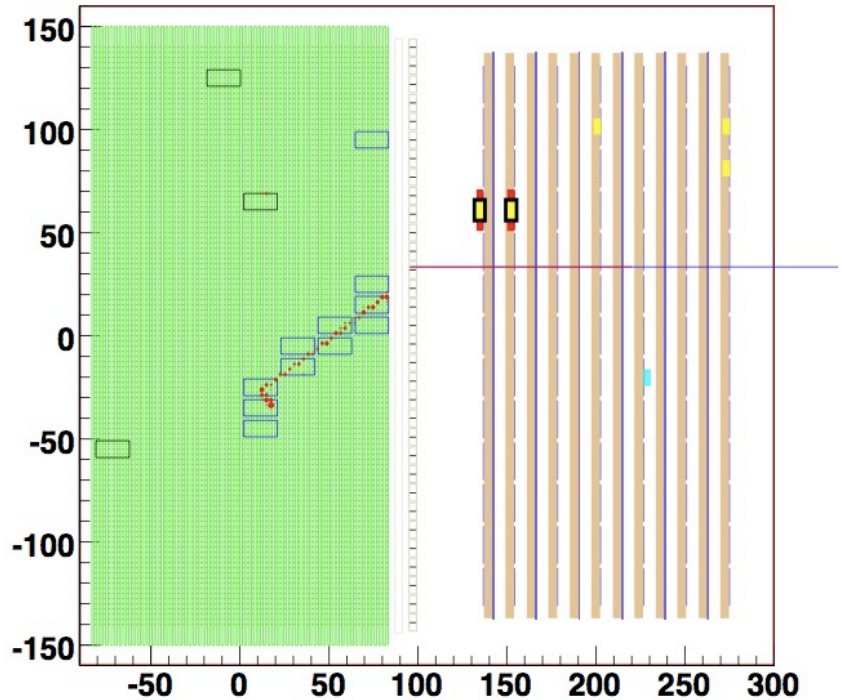
Neutrino event displays

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

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

SciBooNE physics topics

Both ν beam and anti-ν data

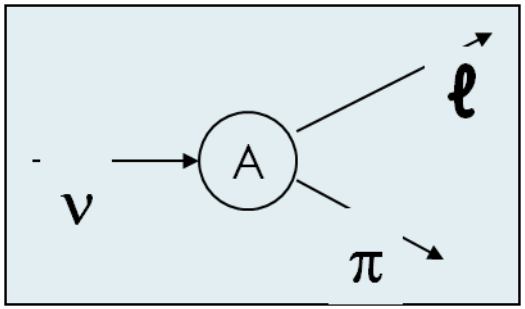
[ν results will come first, and anti-ν results will follow]

- CC-QE study
- CC π^+ production
- CC π^0 production
- NC π^0 production
- NC elastic scattering
- + Short baseline ν_μ disappearance search with MiniBooNE
- ++ ν_e flux? K production??

4.1 Search for Charged Current Coherent Pion Production

Coherent pion production

- 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)

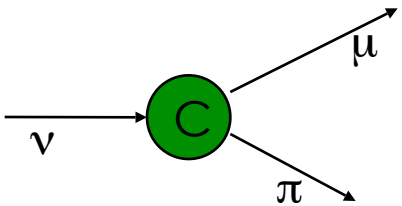
- both NC and CC
- both neutrino and antineutrino
- >2 GeV (NC), >7 GeV (CC) up to ~100 GeV

CC coherent pion production in SciBooNE

Signal

CC-coherent π production

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



Small Q^2

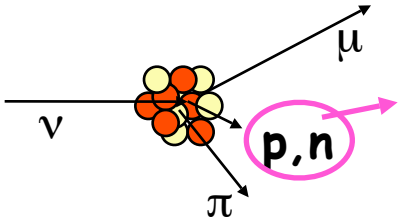
→ 2 MIP-like tracks (a muon and a pion)

→ ~1% of total ν interaction based on Rein-Sehgal model

Background

CC-resonant π production

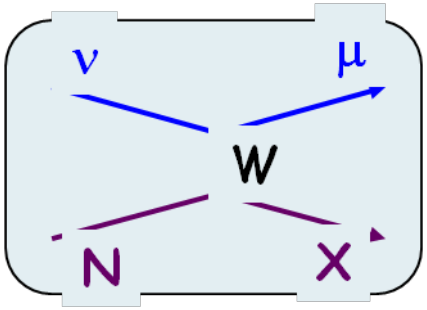
- $\nu + p \rightarrow \mu + p + \pi^+$
- $\nu + n \rightarrow \mu + n + \pi^+$



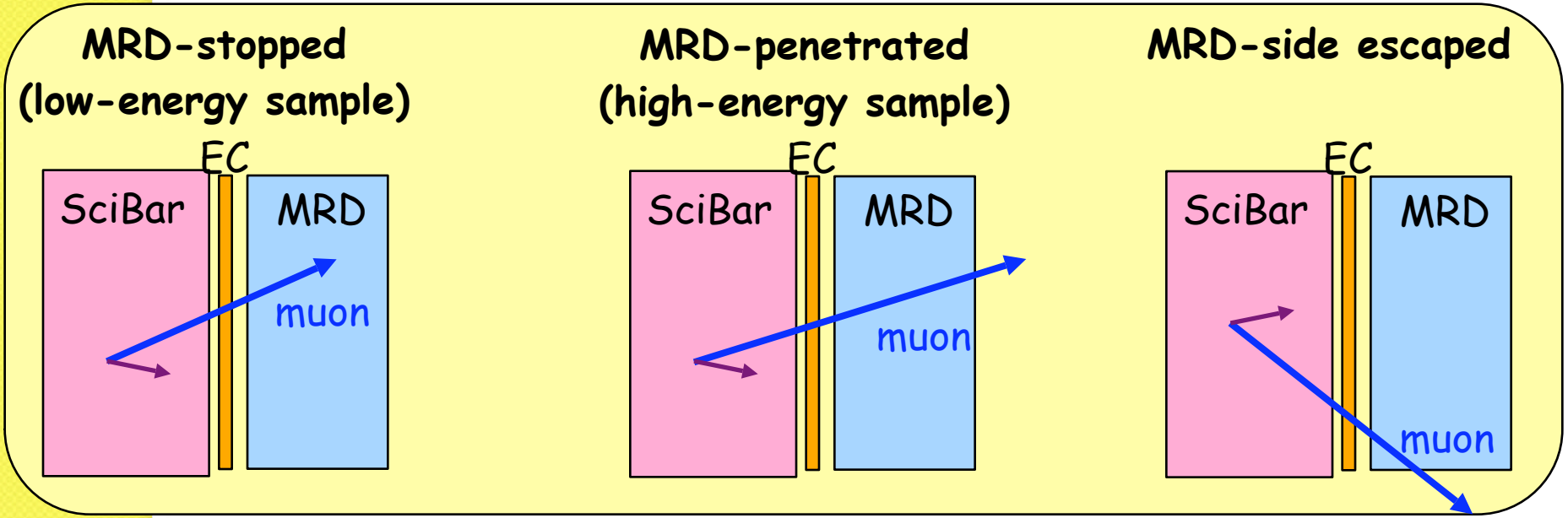
often not reconstructed

Charged Current (CC) event selection

- Muon is identified using MRD
- The track should start from SciBar fiducial volume

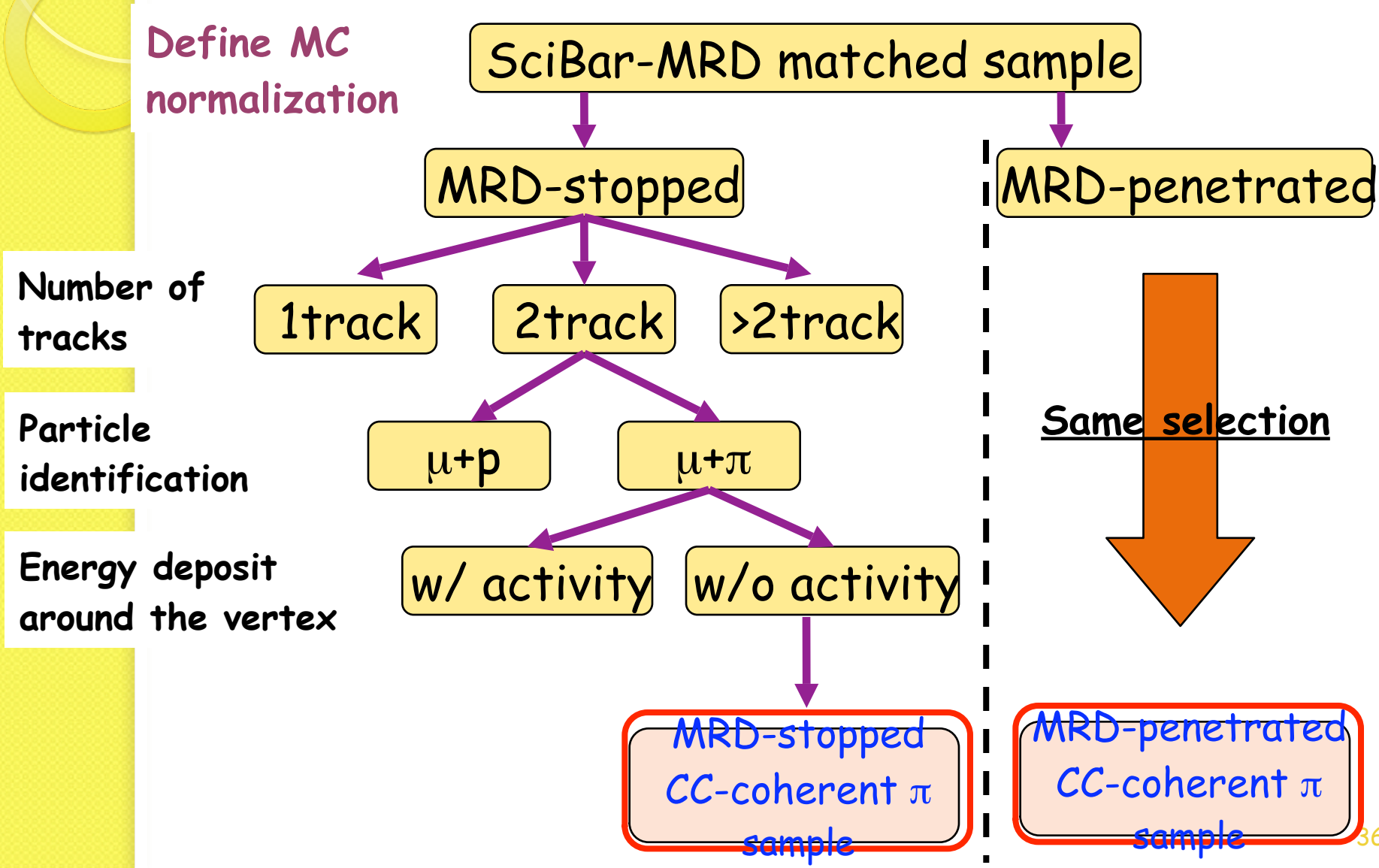


SciBar-MRD matched event (~30k events)



93% pure CC-inclusive ($\nu+N\rightarrow\mu+X$) sample

CC event classification

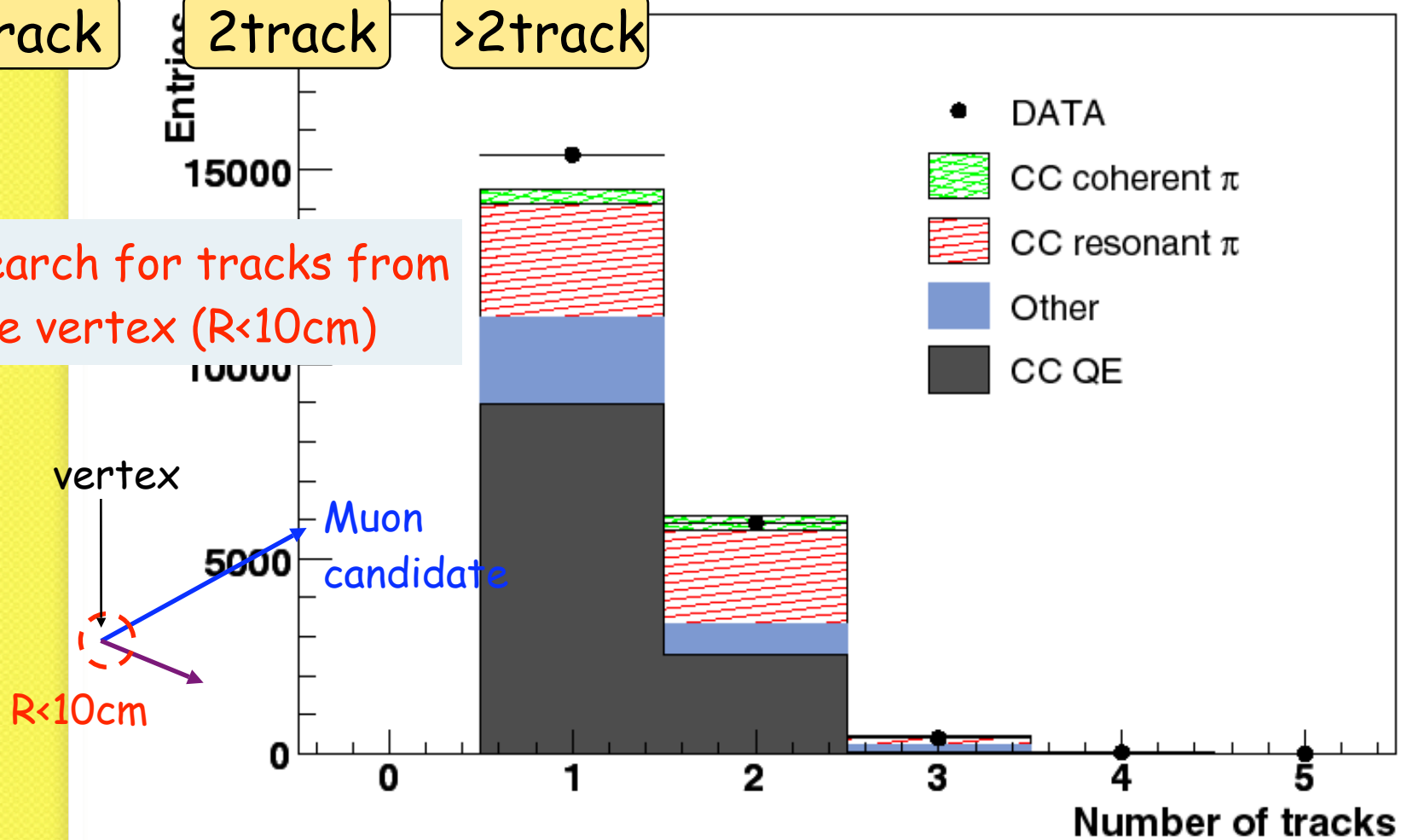


Number of tracks

MRD-stopped

1track | 2track | >2track

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



Particle identification

Using dE/dx in SciBar

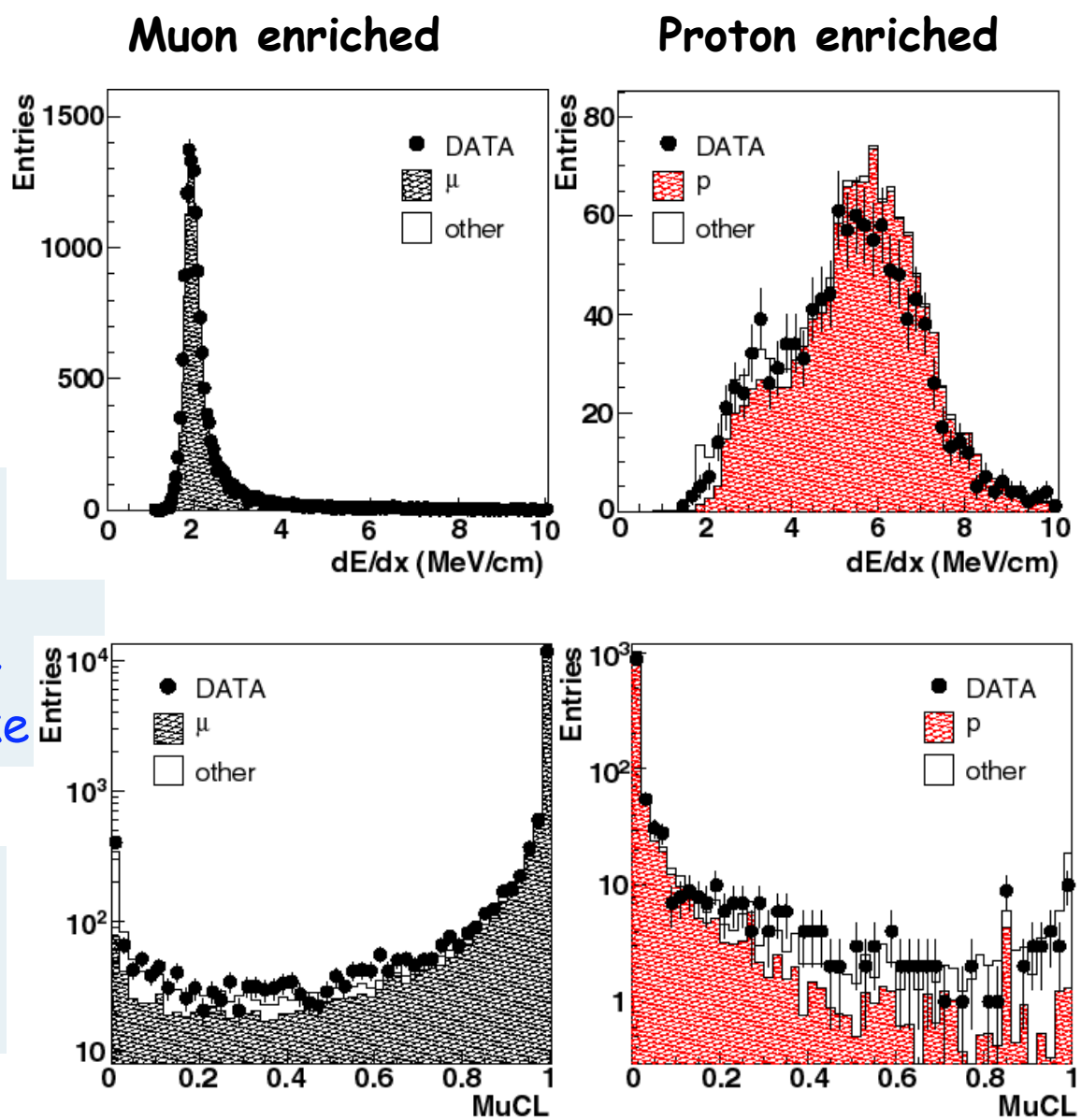
Muon confidence level (MuCL)

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

Mis-ID probability

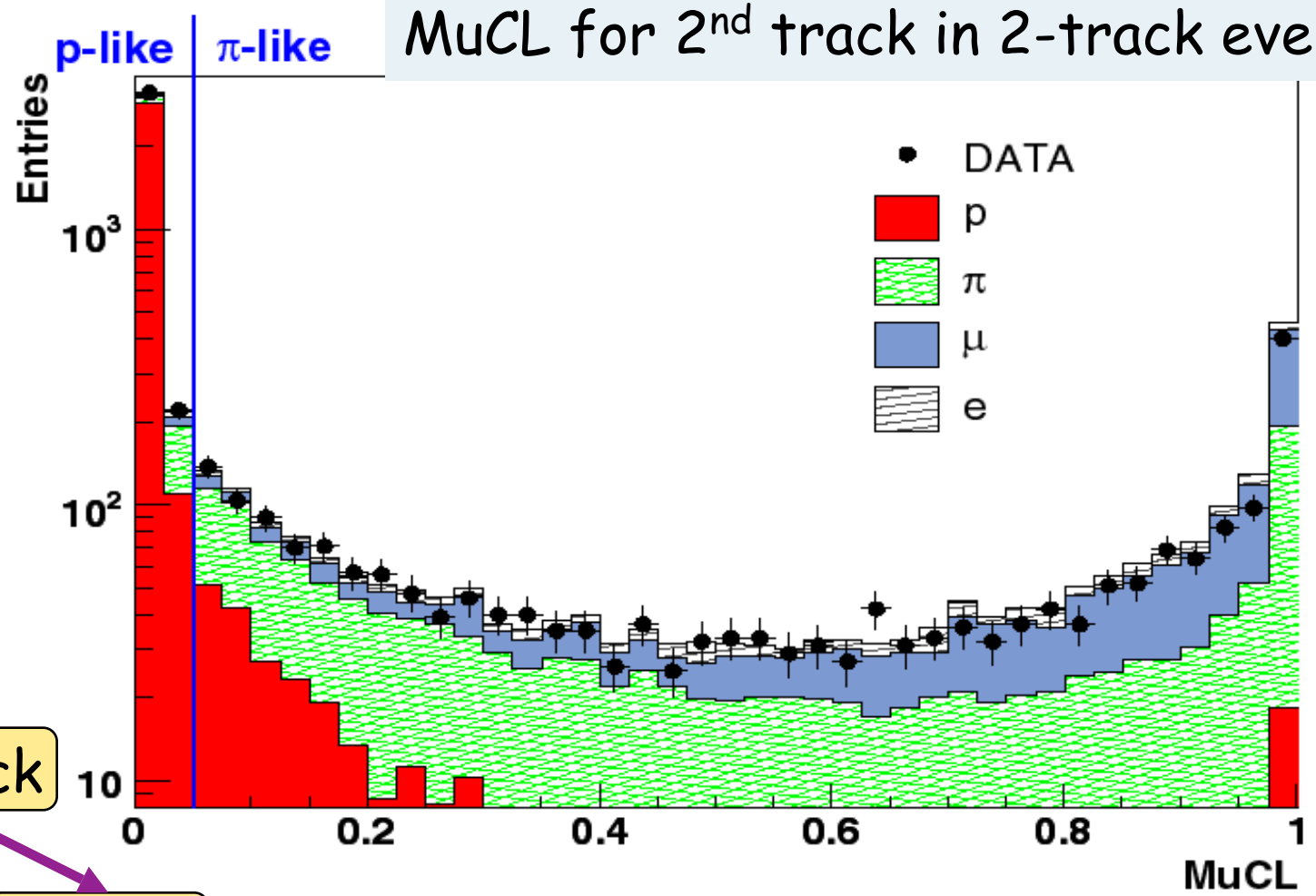
Muon: 1.1%

Proton: 12%



Particle identification (cont'd)

MuCL for 2nd track in 2-track event



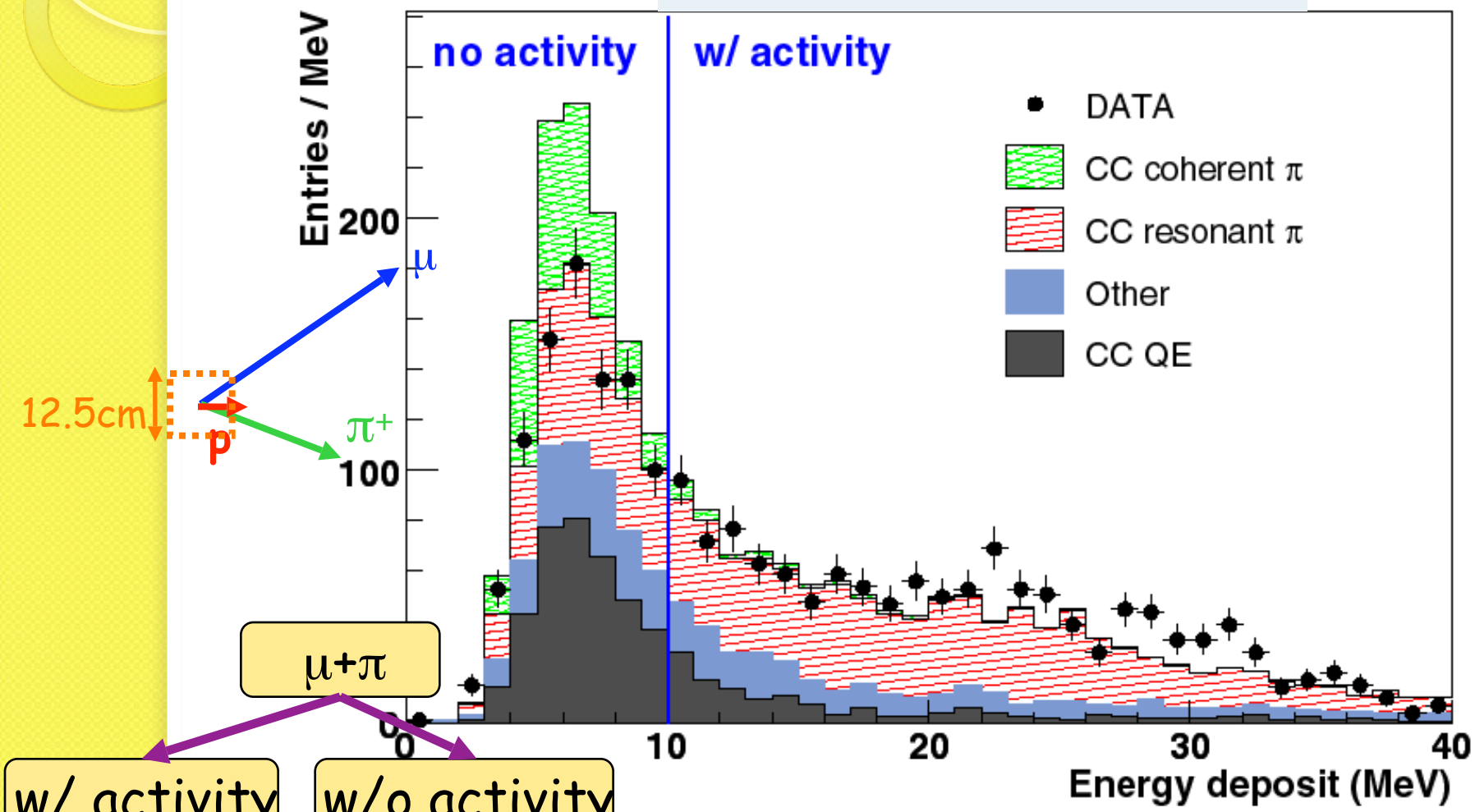
2track

μ+p

μ+π

Vertex activity

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

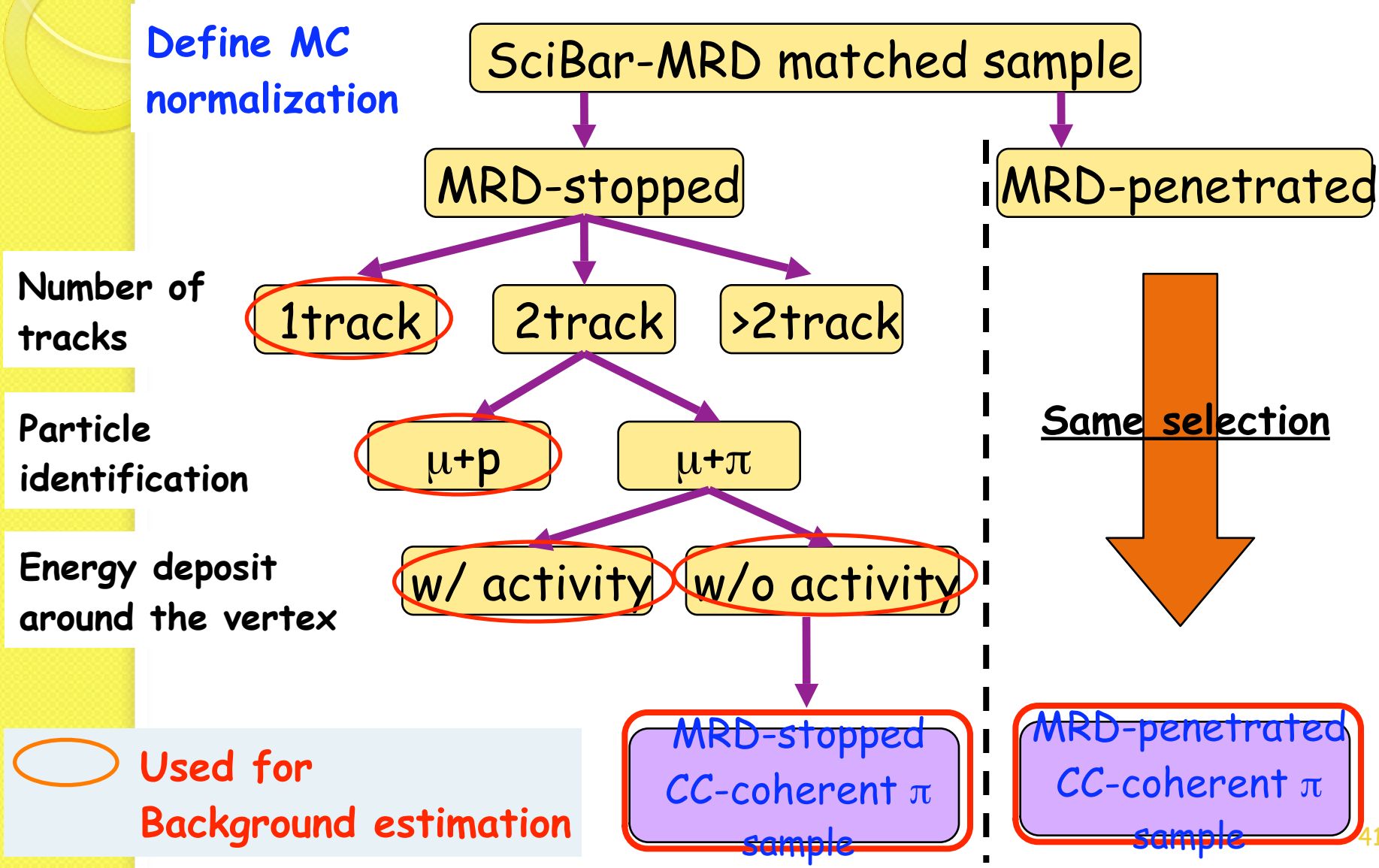


μ+π

w/ activity

w/o activity

CC event classification



Tuning of MC simulation

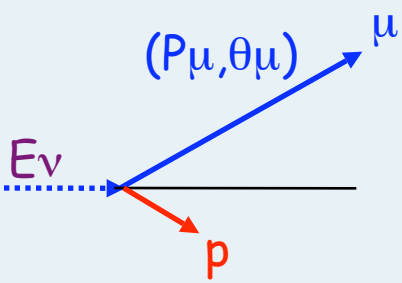
To constrain systematic uncertainties due to

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

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

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

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



CC-QE

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

V: nuclear potential (27MeV)

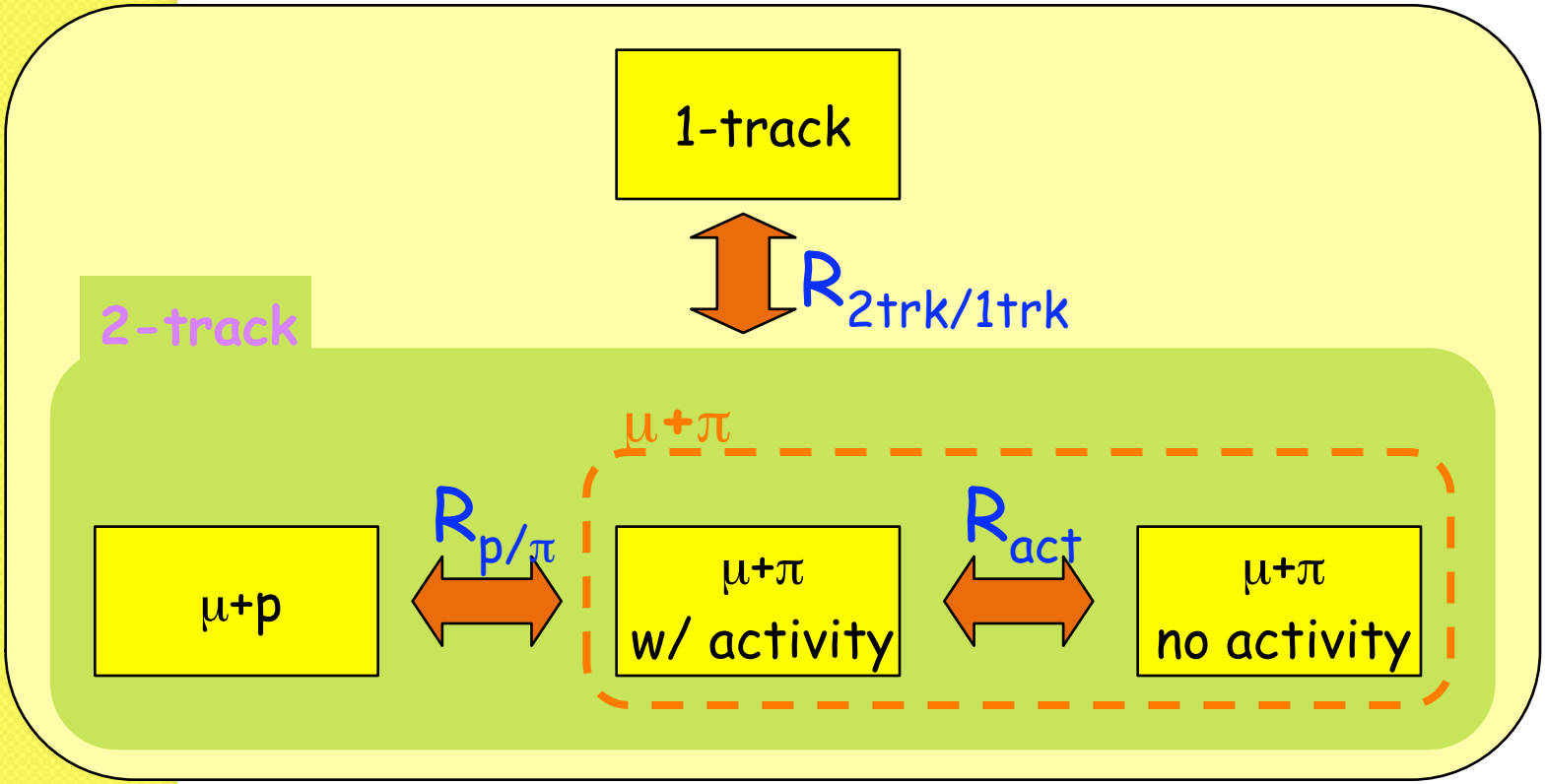
Fitting parameters (I)

Normalization parameter: R_{norm}

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

Muon momentum scale : P_{scale}

MRD-stopped sample



$\times R_{norm}$

Fitting parameters (2)

Parameters related to neutrino interaction models

R_{res}: CC-resonat 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

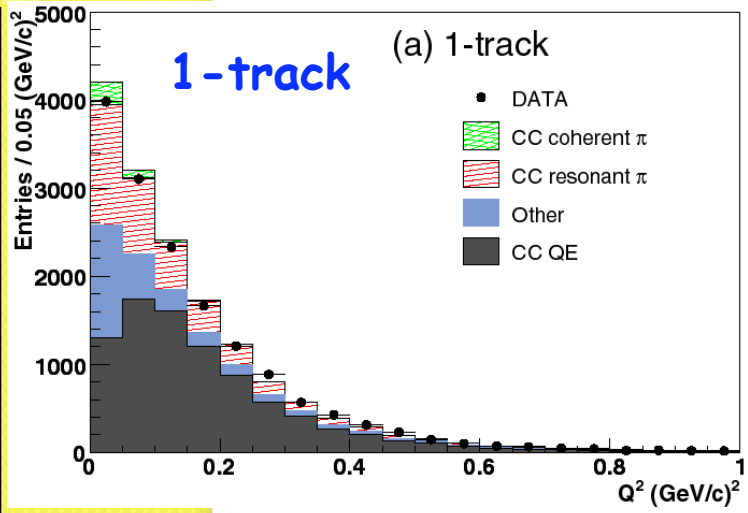
$$E_{lo} = \kappa\left(\sqrt{p_F^2 + m_p^2} - \omega + E_B\right)$$

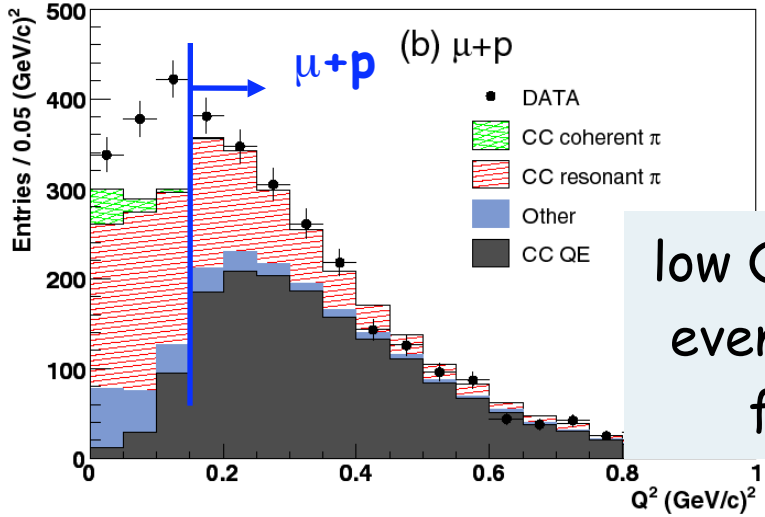
- first introduced by MiniBooNE
- employed because similar data deficit is found in low Q2

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

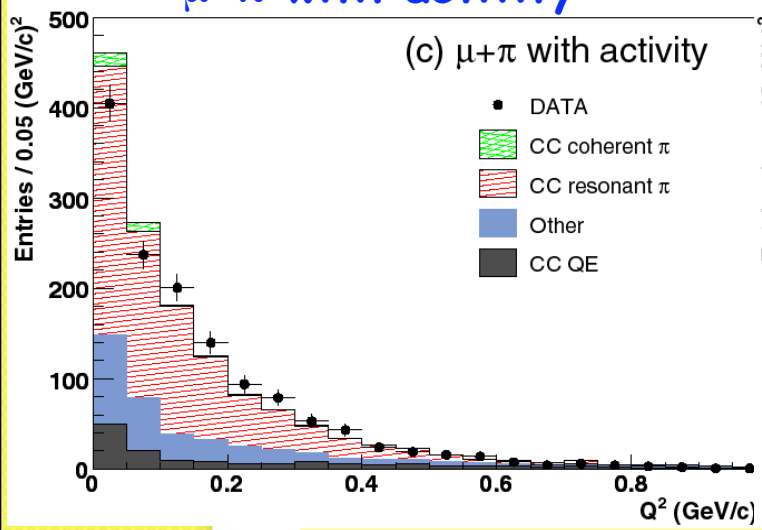
Reconstructed Q^2 distributions after fitting



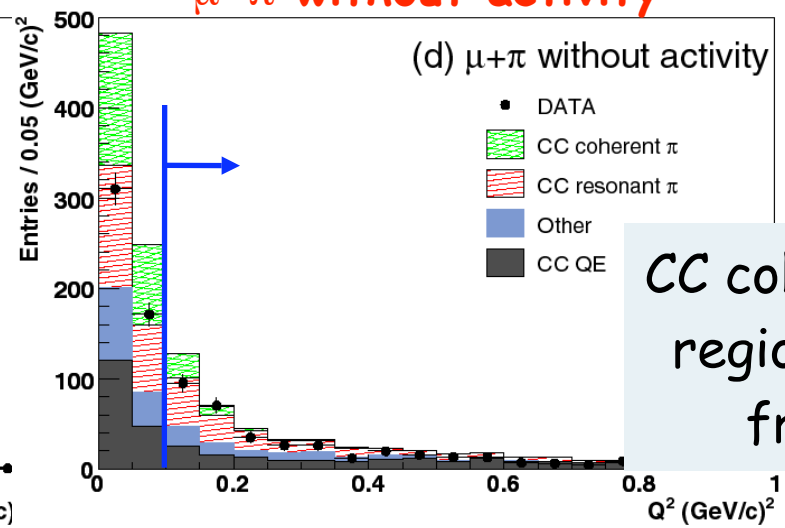


low Q^2 region in μ+p events is excluded from fitting

μ+π with activity



μ+π without activity

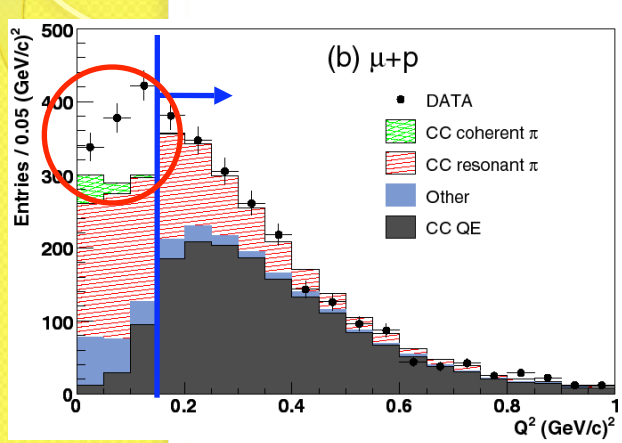


CC coherent π signal region is excluded from fitting

Before fit : χ^2/ndf = 473/75 = 6.31

After fit : χ^2/ndf = 117/67 = 1.75

Data excess in μ+p sample

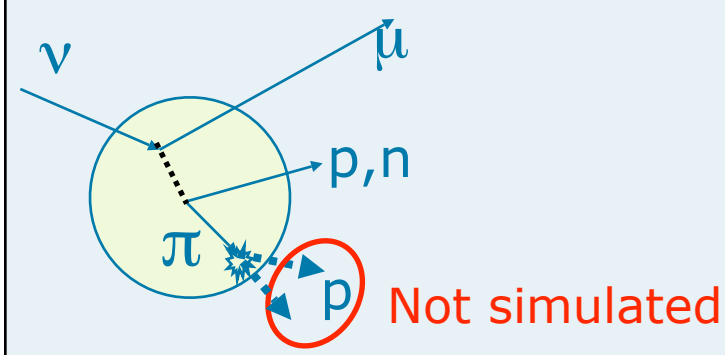


Features of excess events

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

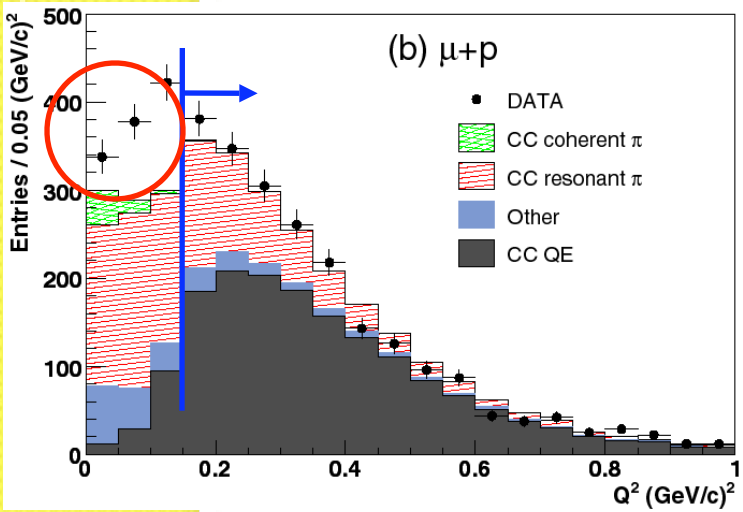
Possible candidate

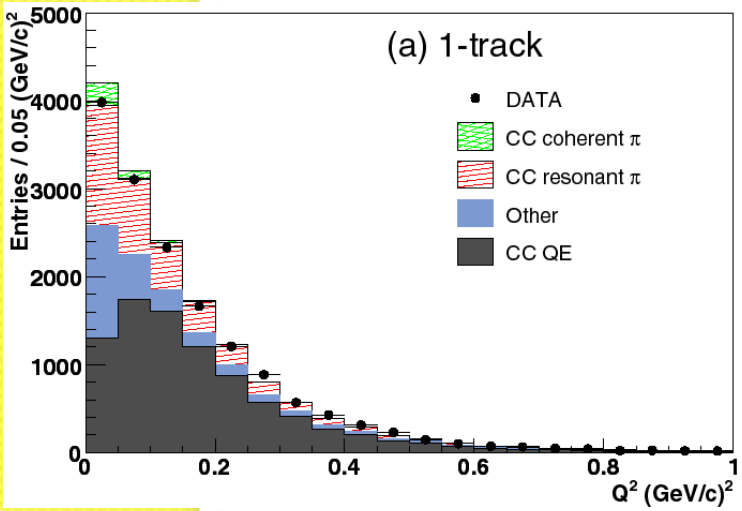
CC resonant pion events in which pion is absorbed in the nucleus



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

Data excess in μ+p sample (cont'd)





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

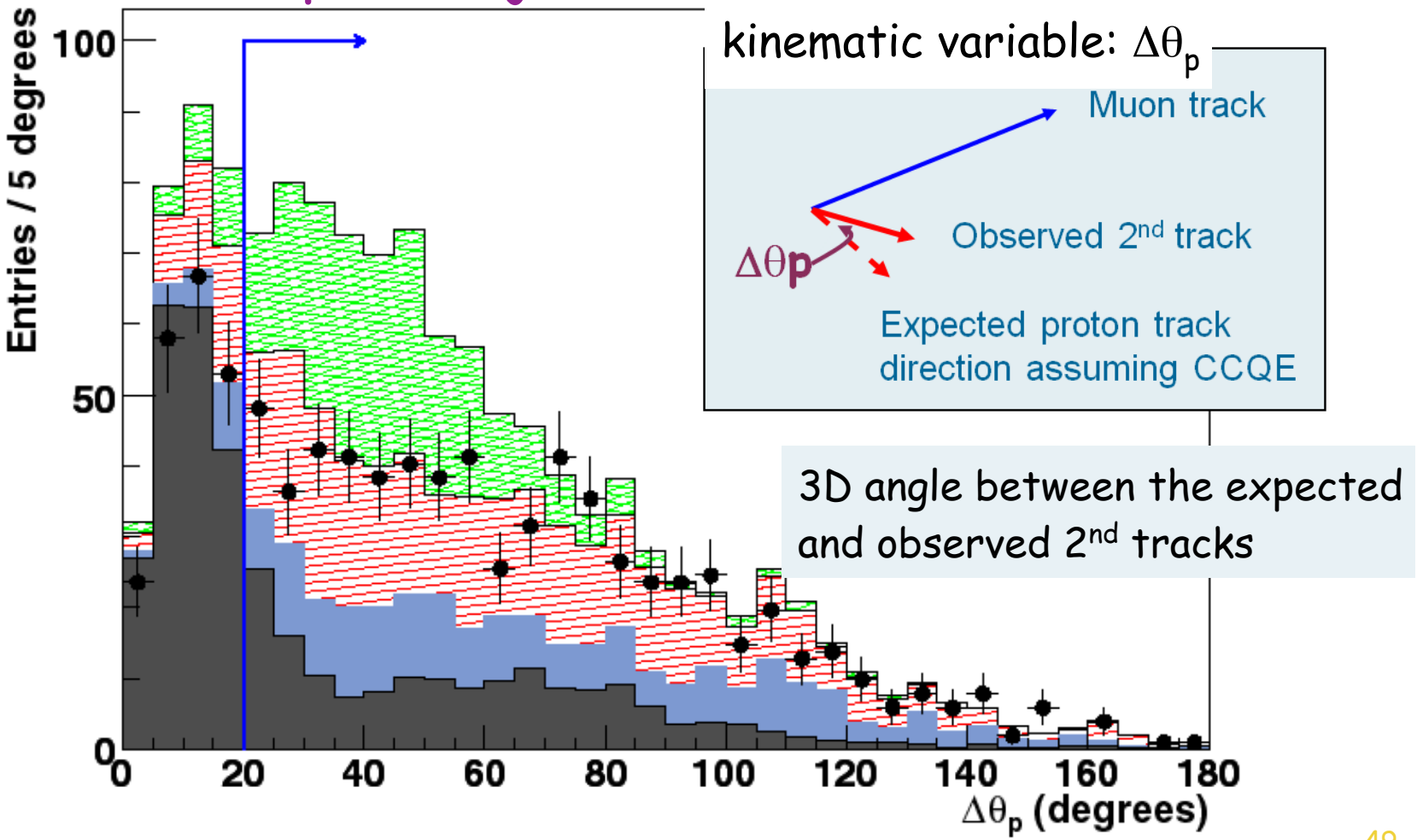
While the excess is ~200 events, there are ~10,000 events in low Q^2 in the 1-track sample

➔hard to see this effect in 1-track sample

This is not expected to affect CC coherent pion measurement

Extracting CC coherent pion events

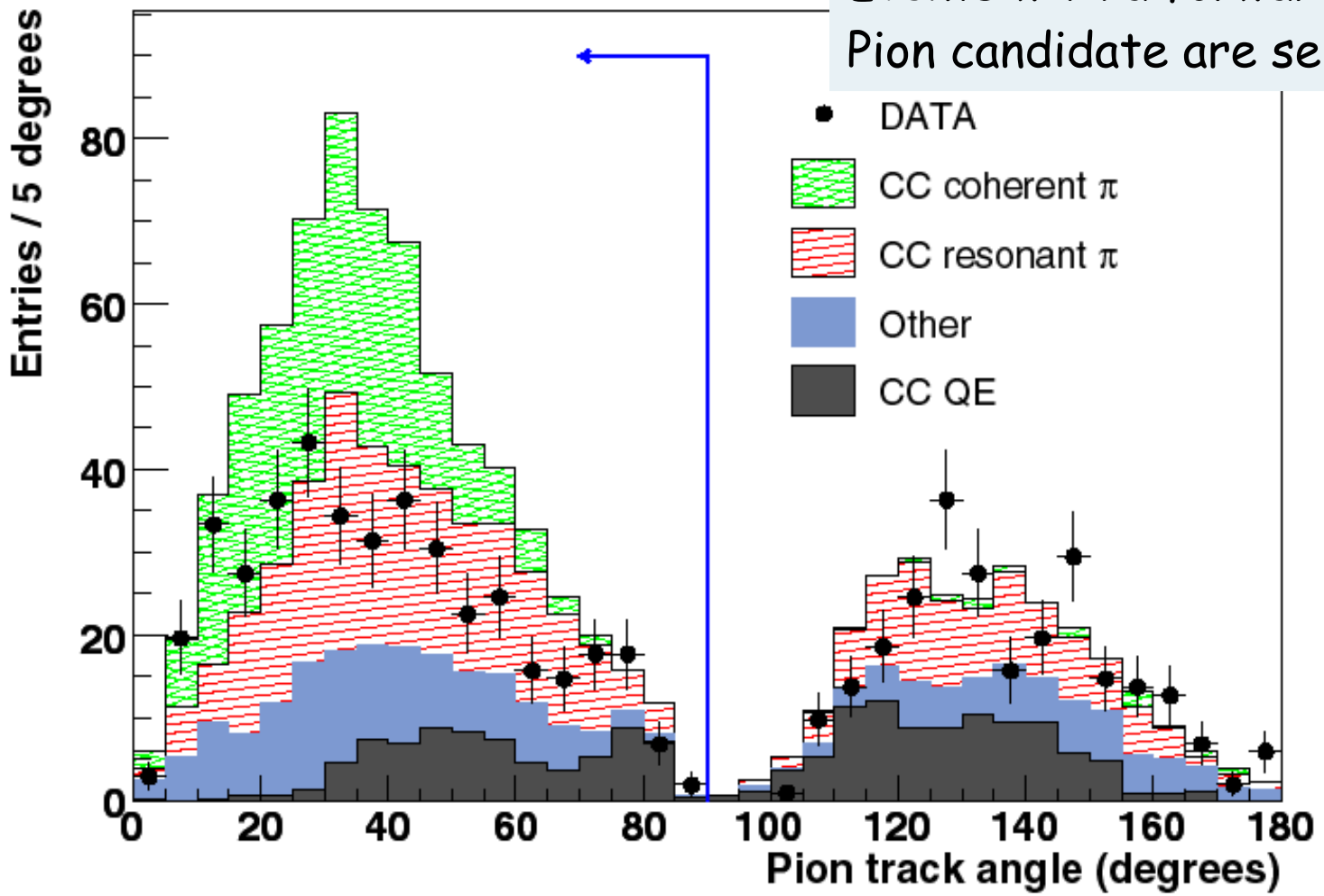
1) CC-QE rejection
2) CC-resonant pion rejection



Extracting CC coherent pion events

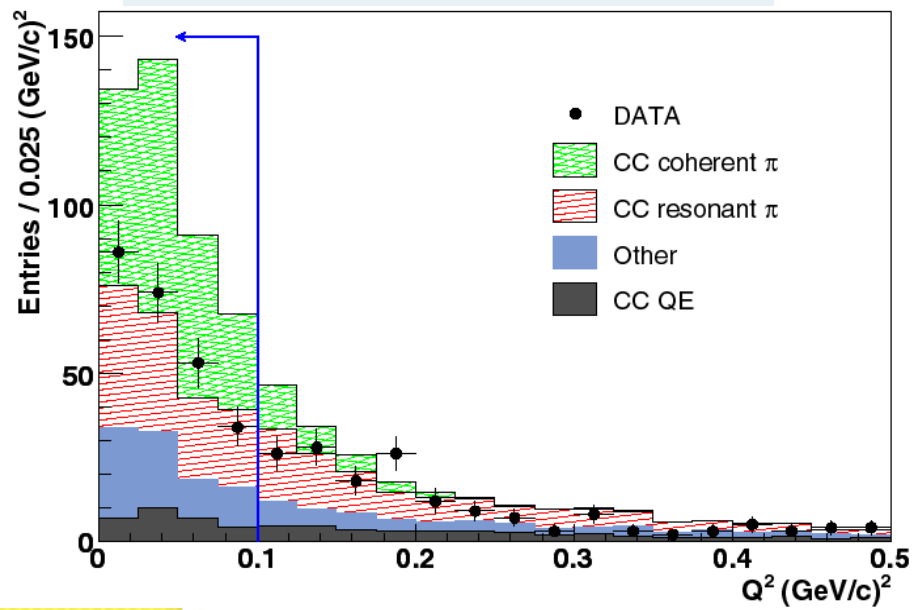
1) CC-QE rejection
2) CC-resonant pion rejection

Events with a forward-going Pion candidate are selected

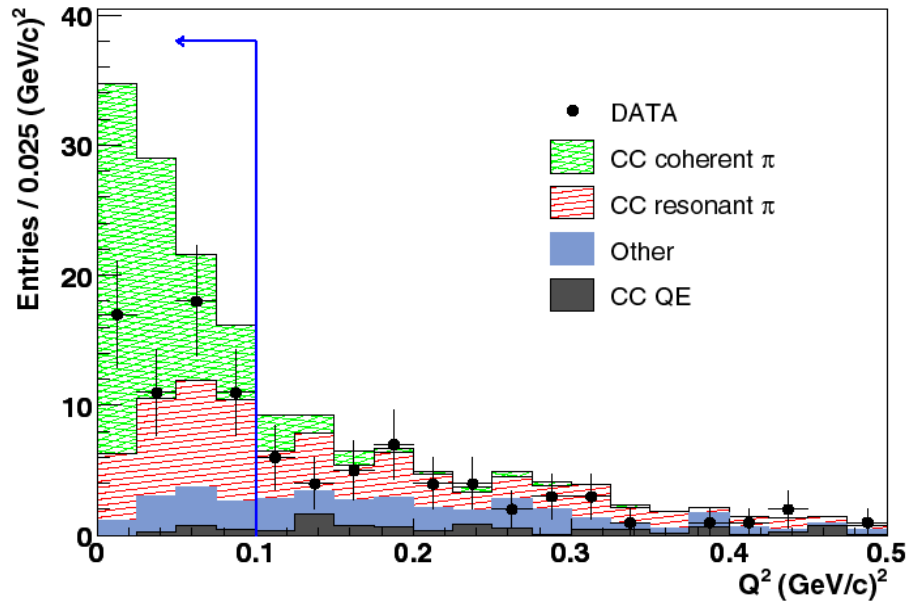


CC coherent pion sample (Q^2<0.1 $(GeV/c)^2$)

MRD stopped sample
<Eν>= 1.1 GeV



MRD penetrated sample
<Eν>= 2.2 GeV



247events selected

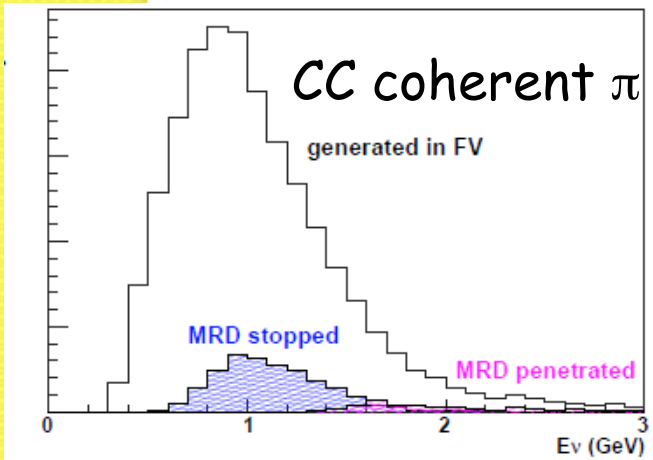
BG expectation
228+/-12 events

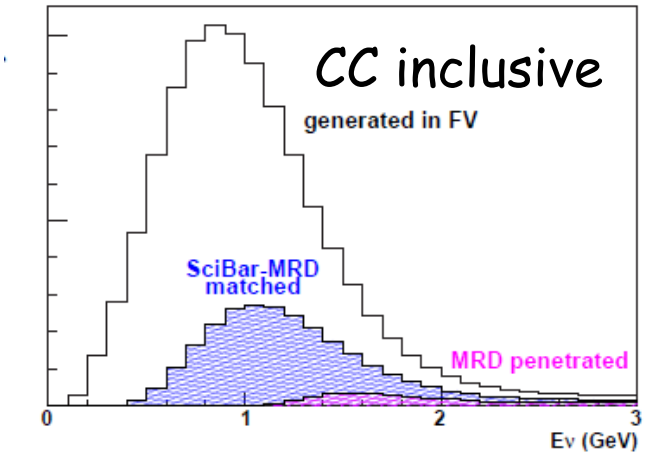
57events selected

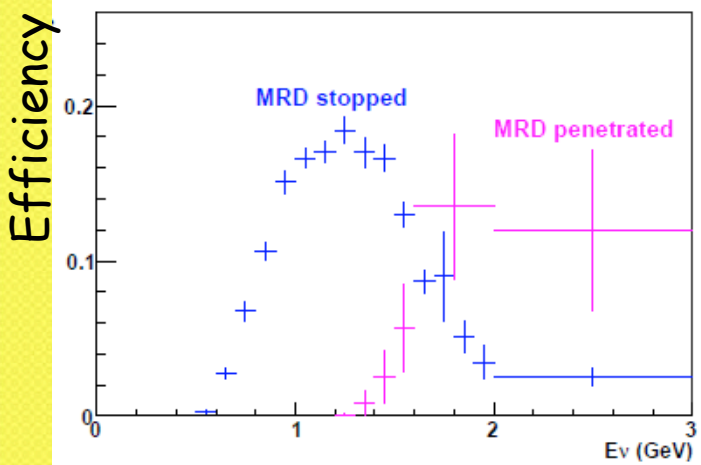
BG expectation
40+/-2.2 events

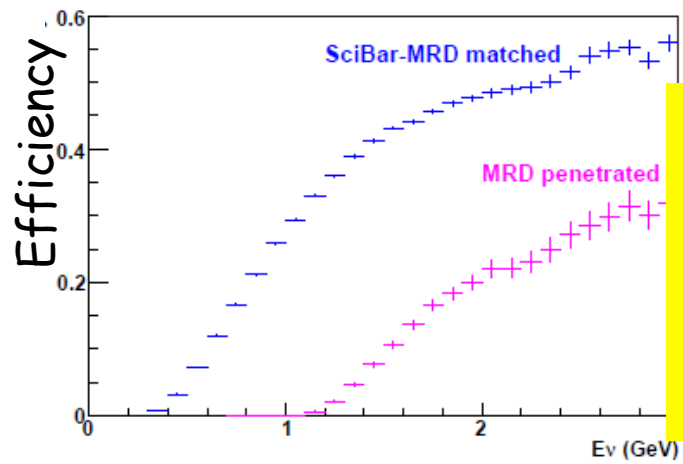
σ(CC coherent π)/σ(CC) cross section ratio

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









CC inclusive samples are used to normalize the cross section of coherent π samples.

Result

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

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

Result (cont'd)

K2K (<Eν>=1.3 GeV)

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

SciBooNE (<Eν>=1.1 GeV)

improved

slightly improved

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

K2K result (90% CL U.L.=m+1.28*σ)

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

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

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

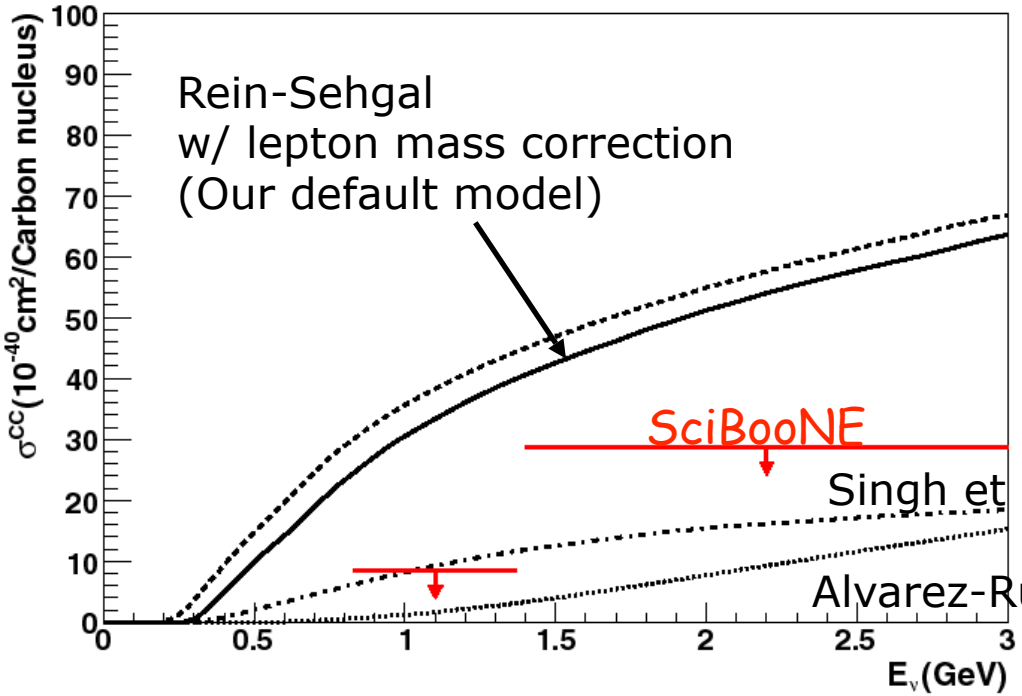
< 1.36×10^{-2} <Eν>=2.2 GeV

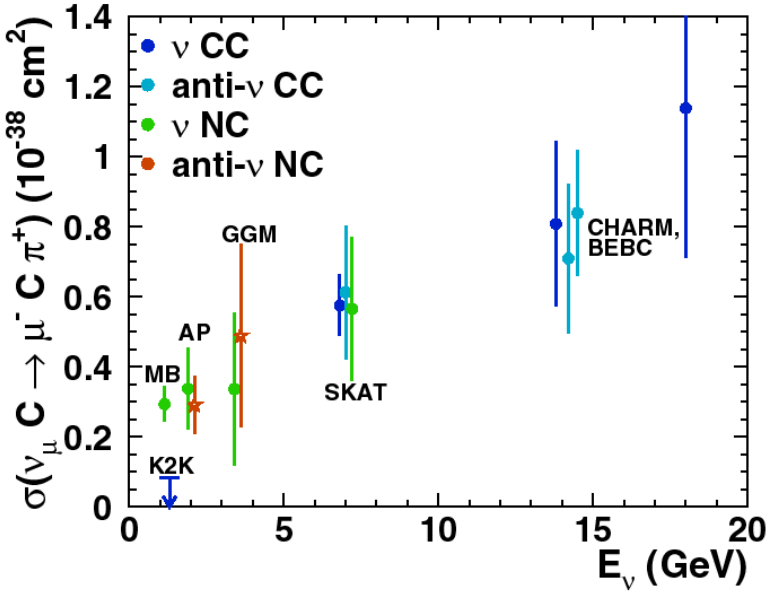
Systematic errors

	MRD stopped Error ($\times 10^{-2}$)	MRD penetrated Error ($\times 10^{-2}$)
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

Result (cont'd)

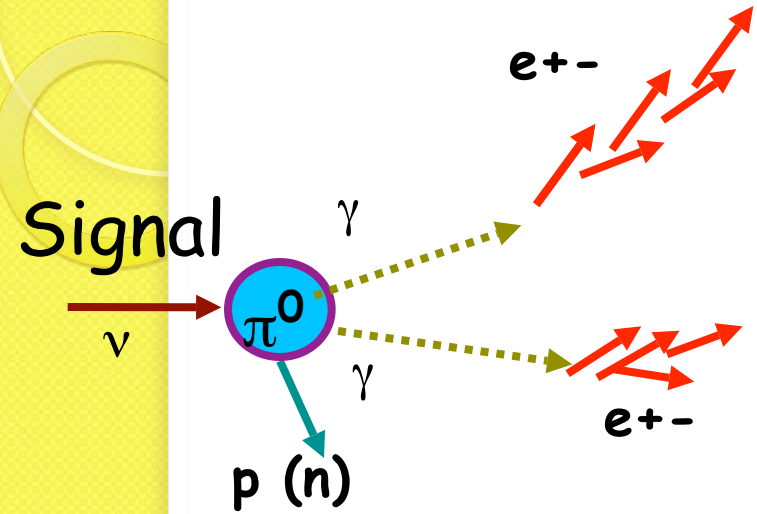
Measured upper limits on σ(CC coherent π)/σ(CC) cross section ratios are converted to upper limits on absolute cross sections by using σ(CC) predicted by MC simulation





4.2 Neutral Current π^0 reconstruction in SciBooNE.

NCπ^0 signal and background

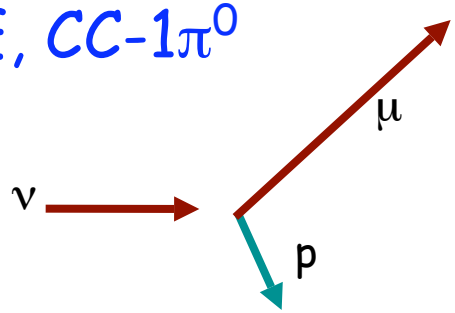


2γ from π^0

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

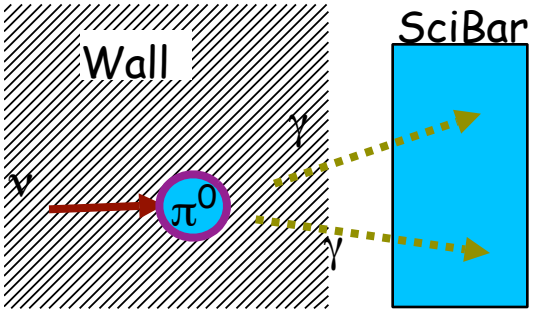
Internal B.G. : ν int. in SciBar

CCQE, CC-1π^0



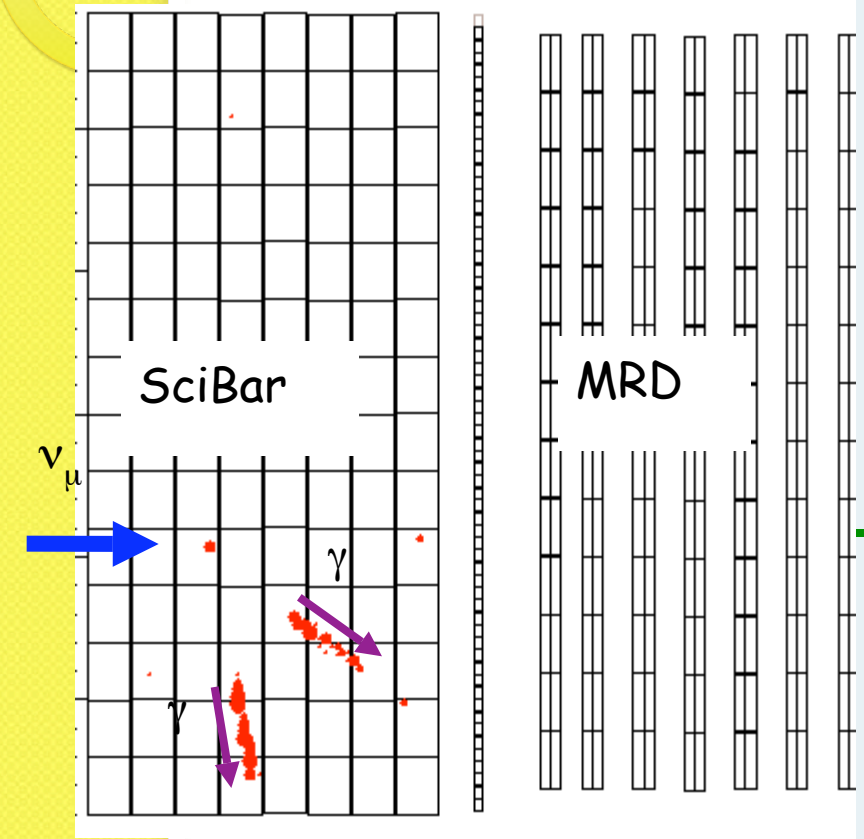
External B.G : from outside

Dirt (wall), cosmic



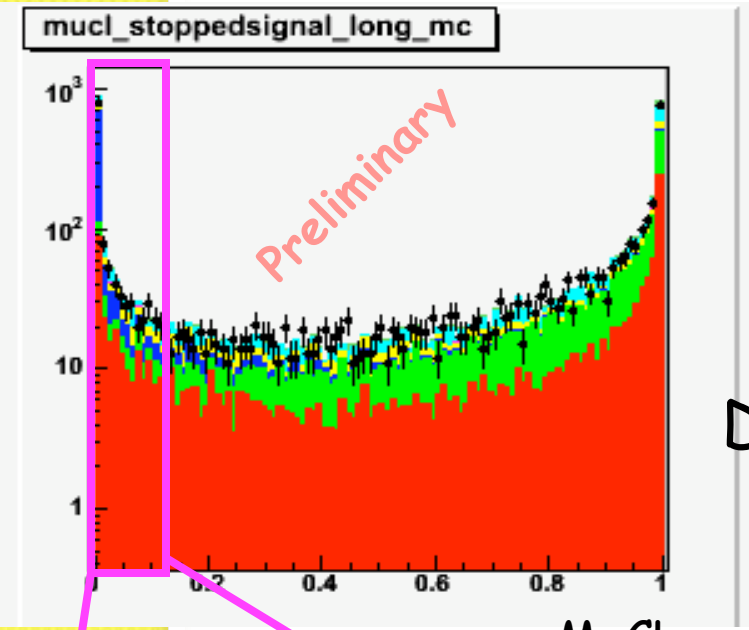
Event Selection

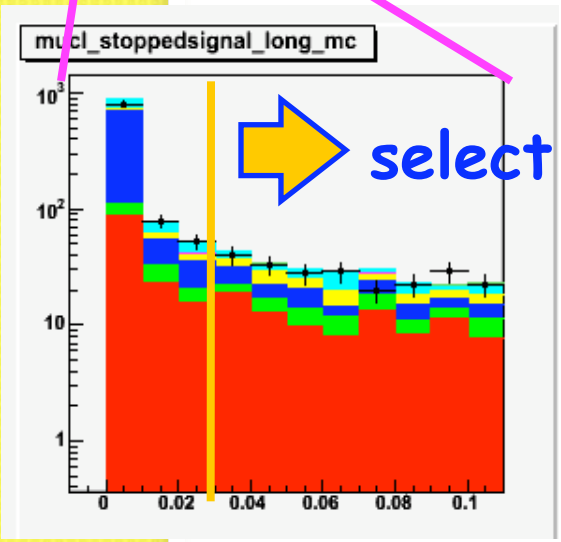
$NC\pi^0$ Candidate



1. Pre-selection
   1. Two tracks or more(2γ)
   2. No 1st
      lay
      e
      r hits (against dir BG)
3. Track information
   1. Stopp
      e
      d in SciBar (against μ BG)
   2. No proton track
      identified by dE/dX

Proton rejection by dE/dx





2contained track sample w/o separation cut

Dot : data

Cosmic

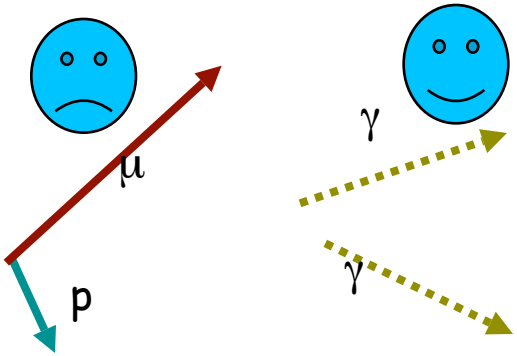
Dirt

Charge π

p

μ

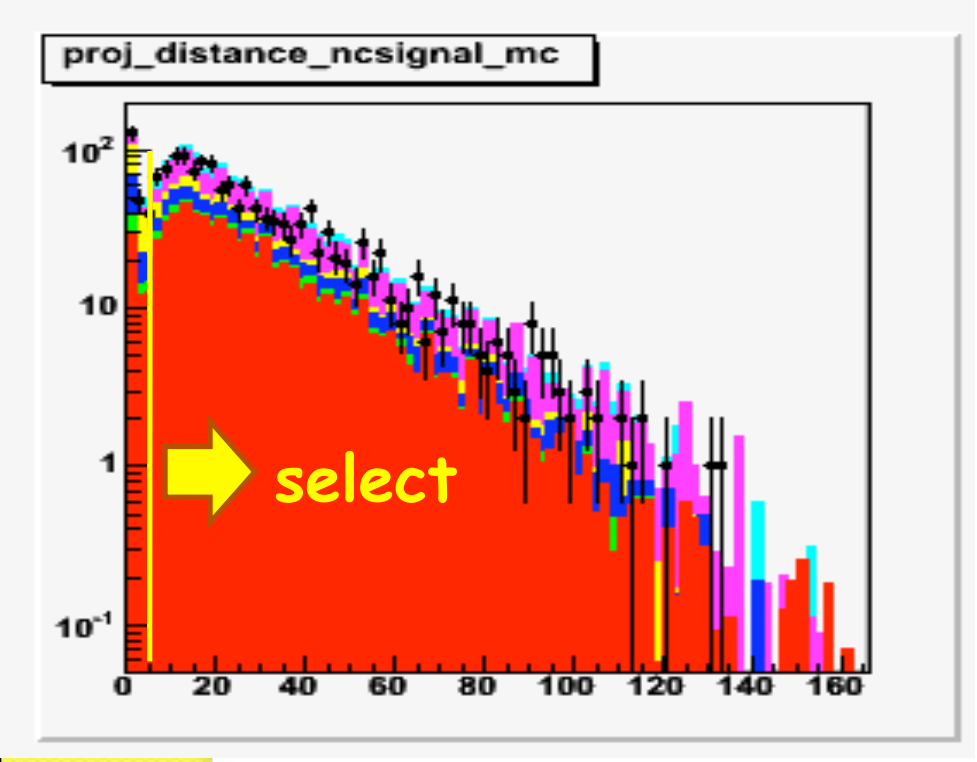
EMShower



MuCL > 0.03

Two track separation

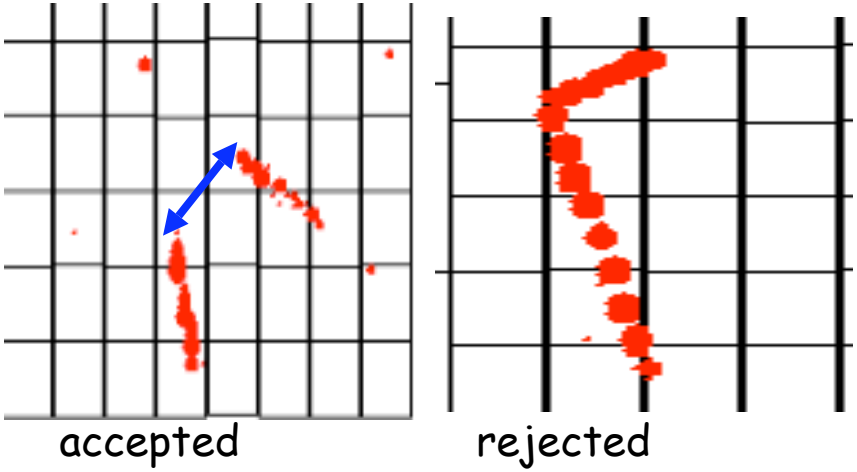
Minimum 2D-distance between track edges



cm

Reject CC events

Distance > 6cm

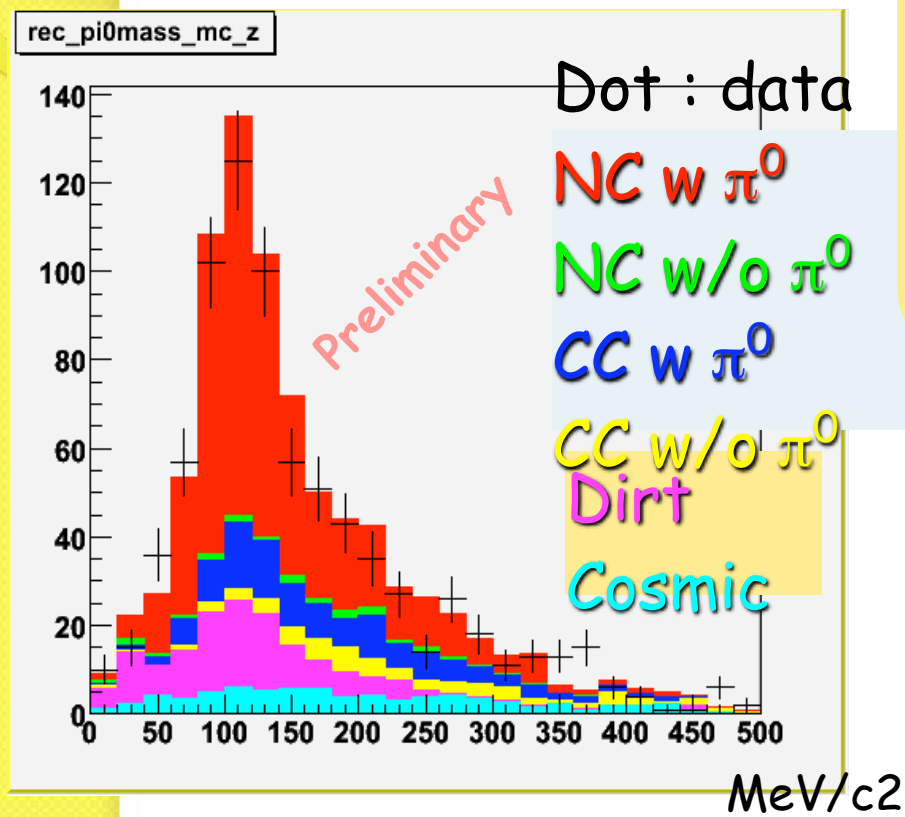


Reject 31 % of CC events

Keep 92 % of π^0 events (NC)

π^0 reconstruction at final sample

Reconstructed 2γ Mass



- Track based γ reconstruction.
- Several separated tracks are connected if they are in the same direction.
- The energy is reconstructed in the sillinder of 20cm radius around the track.

Clear π^0 mass peak !

~850 events

sel

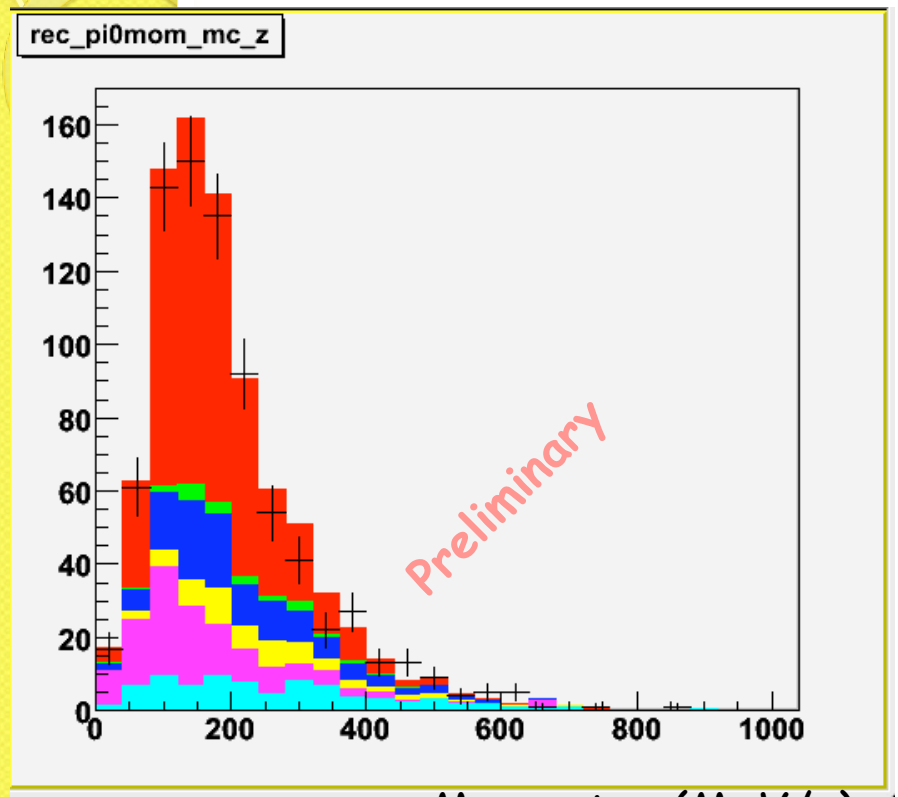
e

cted NC)

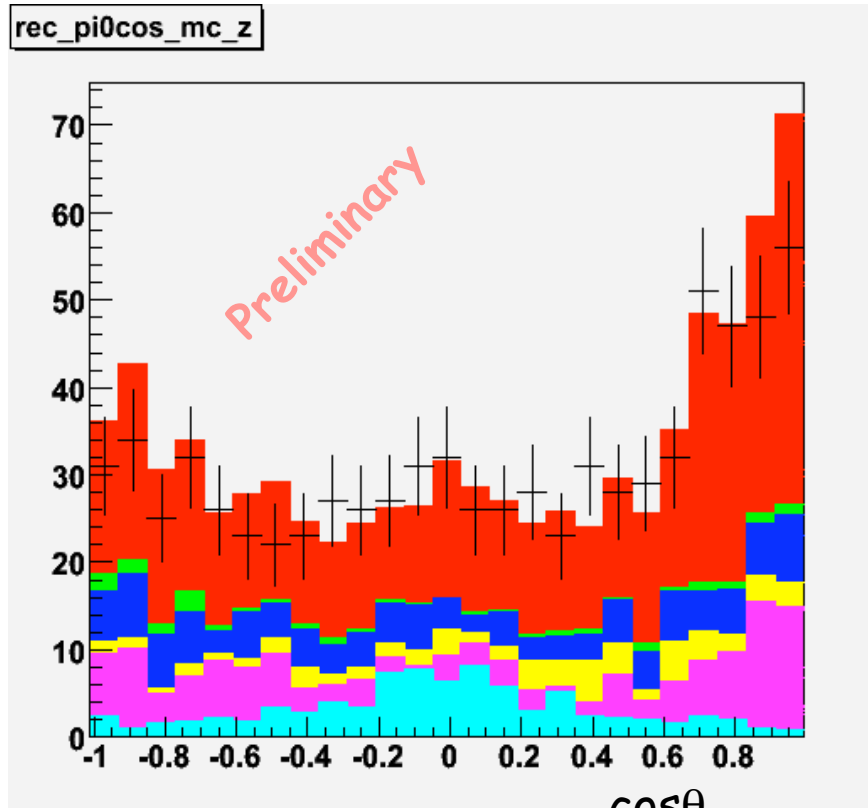
SciBar can reconstruct π^0 !!!

Next Step: Cross Section Measurement

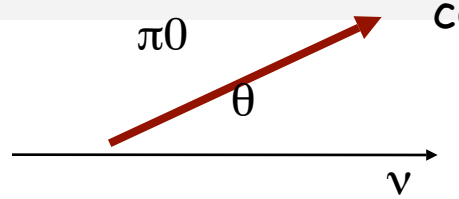
π^0 Kinematics



Momentum(MeV/c)



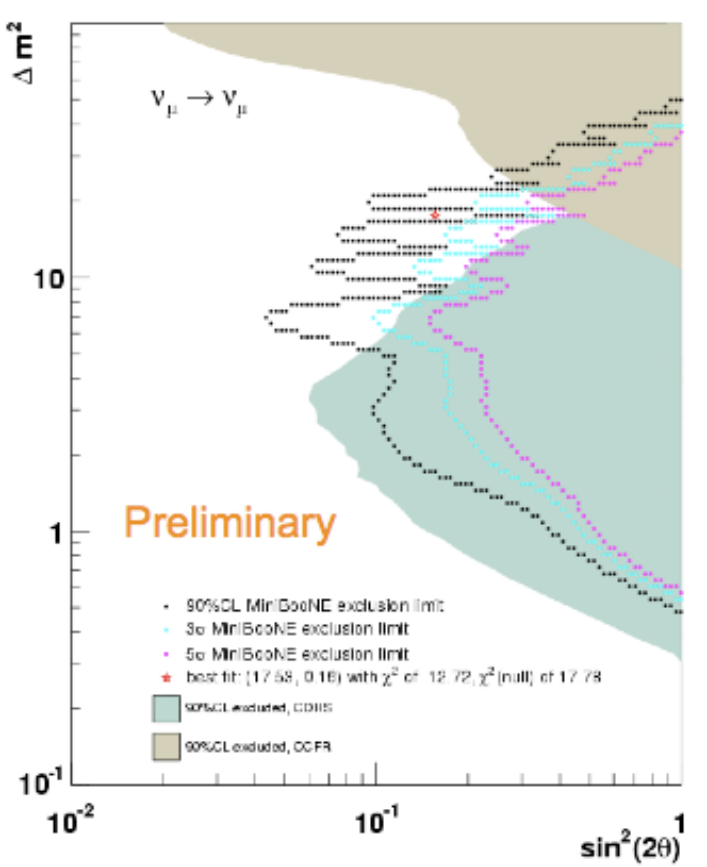
cosθ



4.3 Beam Flux Measurements

ν_μ Spectrum Measurement

Result of MiniBooNE-only ν_μ disappearance search (**shape only** analysis)

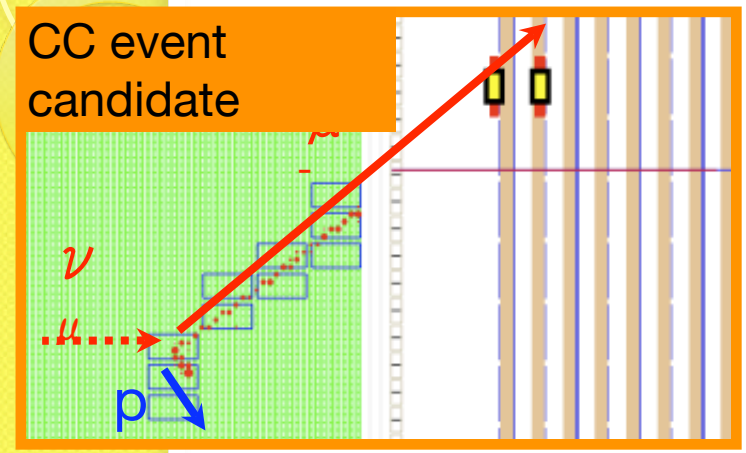


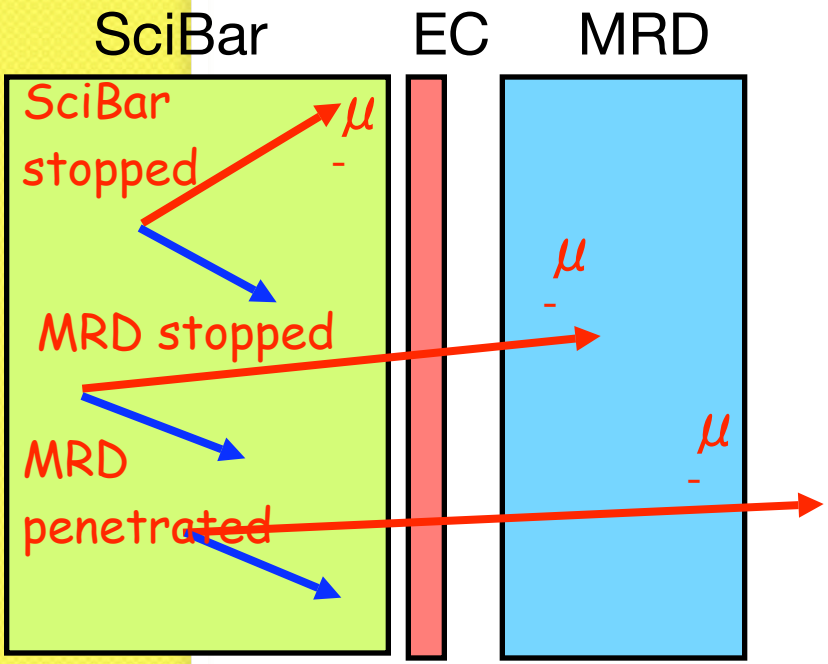
- MiniBooNE/SciBooNE joint ν_μ disappearance search
  - Share beamline
  - Share target material

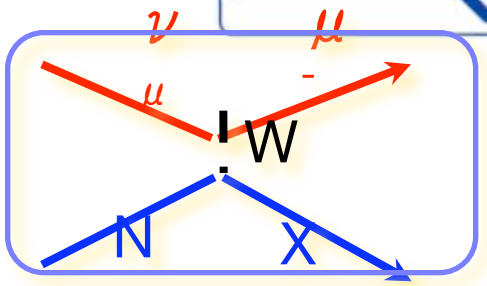
⇒ Strong constraint for flux and cross-sections at MiniBooNE (Shape + Normalization)

- Feed-back to cross section measurements at SciBooNE

Event Selection

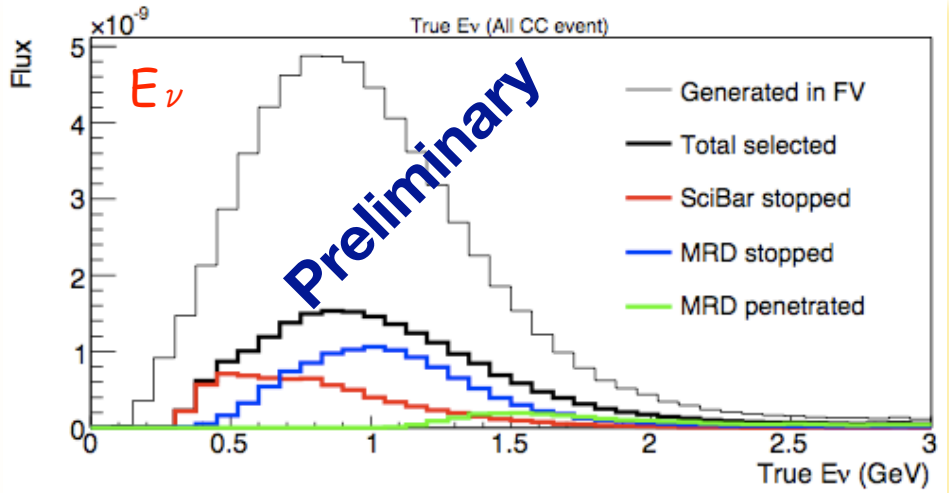






Use charged current inclusive sample

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



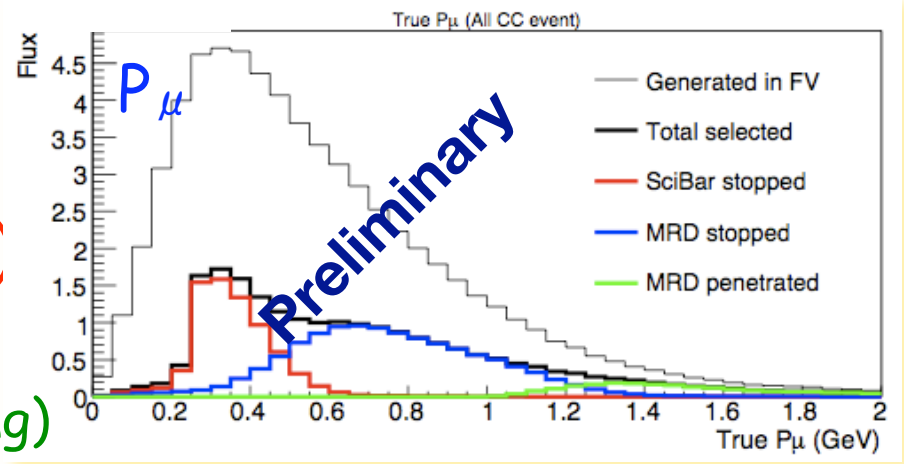
Extracting Eν Spectrum

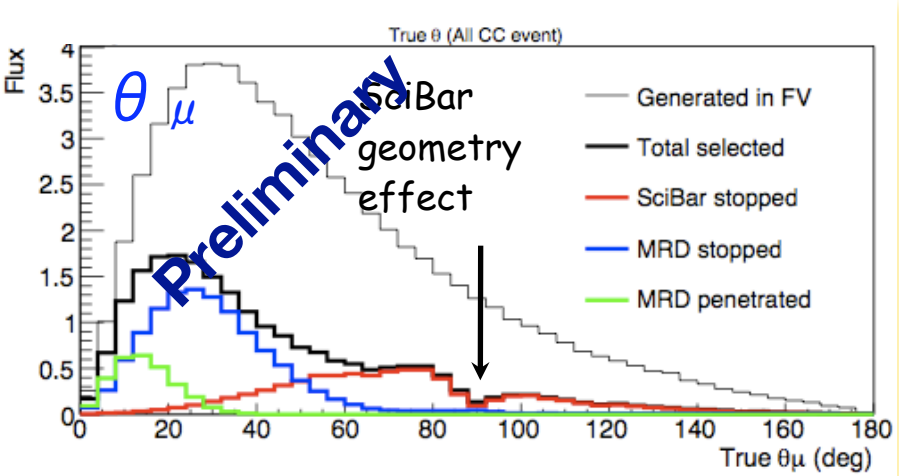
- Use muon kinematics to extract Eν information

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

(Assuming CC-quasi-elastic scattering)

- Good coverage of entire kinematic region with these 3 samples.

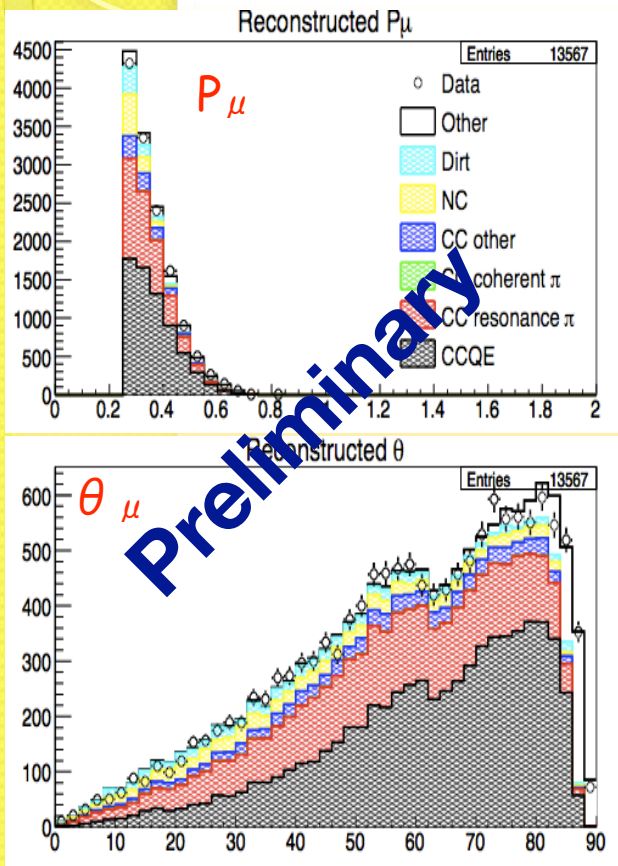




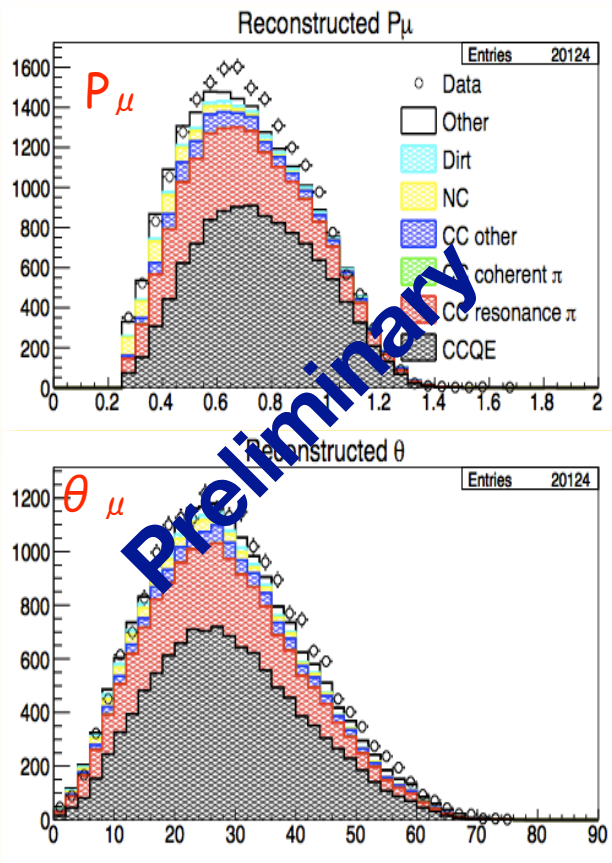
Muon Kinematics

MC are relatively normalized to data by the number of SciBar-MRD matched event.

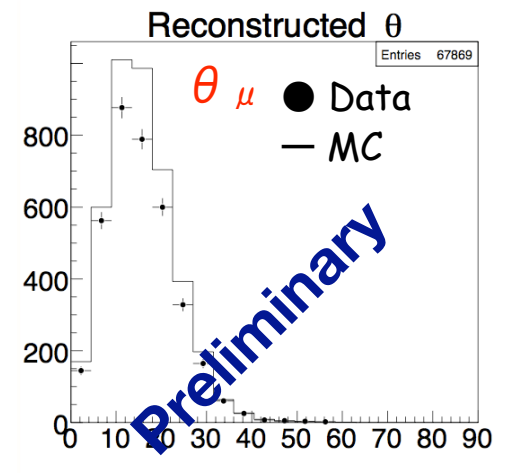
SciBar stopped (P_μ, θ_μ)



MRD stopped (P_μ, θ_μ)



MRD penetrated (θ_μ)

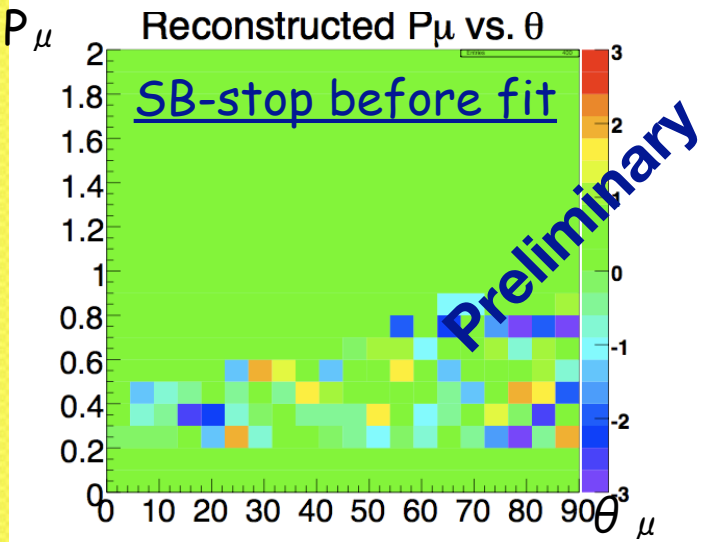


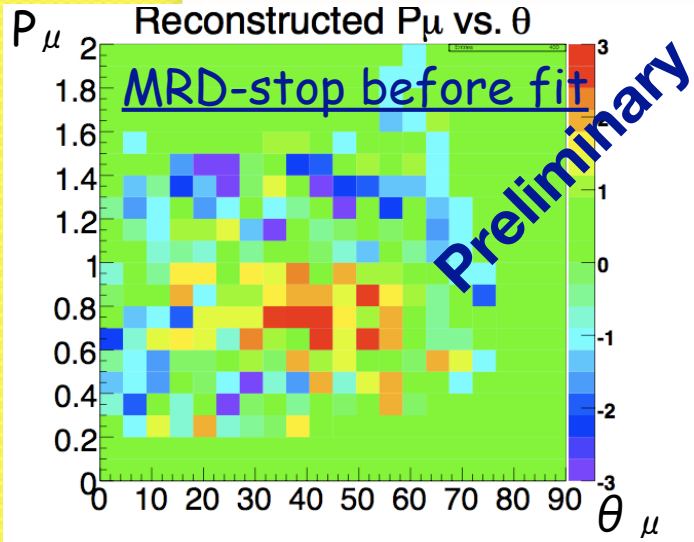
(Unable to reconstruct P_μ since muons are not stopped in the detectors)

Predict neutrino energy spectrum at SciBooNE by fitting P_μ and θ_μ distribution from each sample

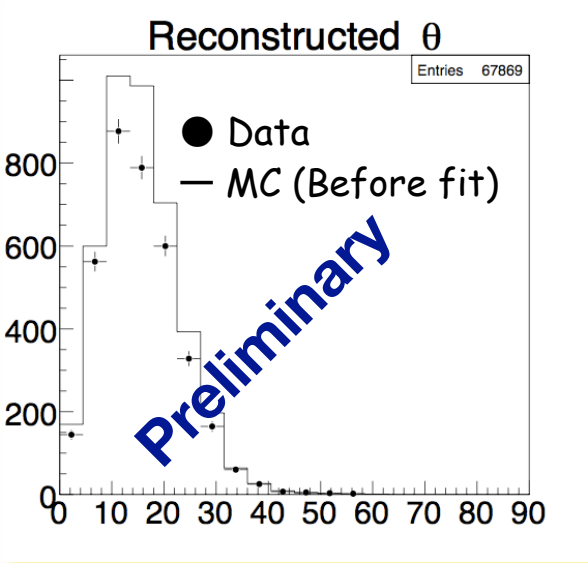
Spectrum Fit Result

(data-MC)/(stat. error)



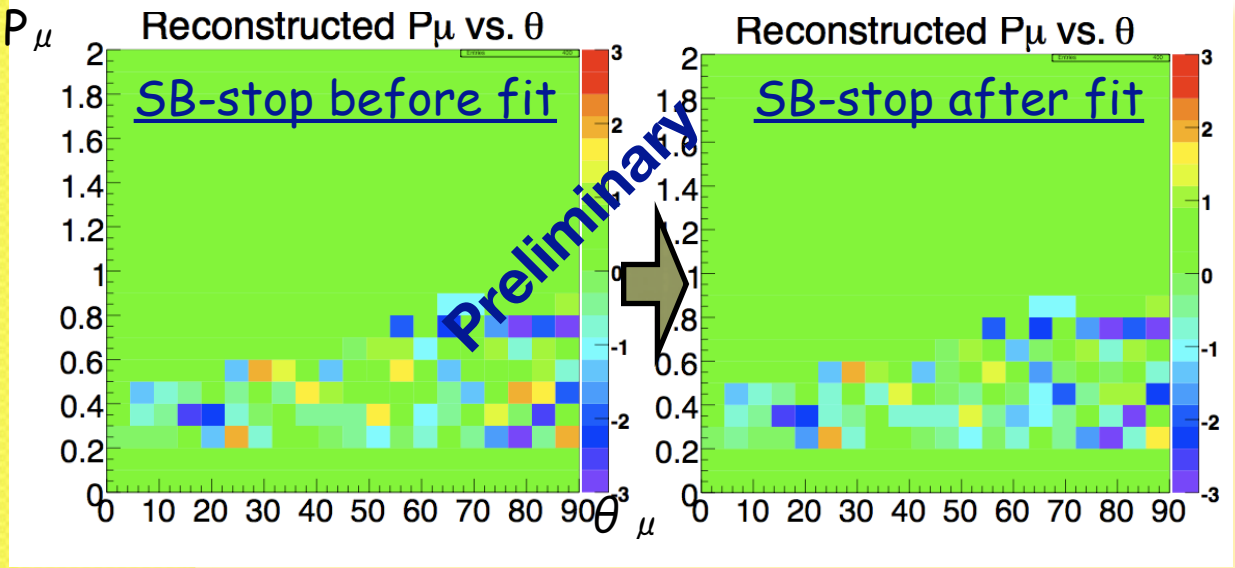


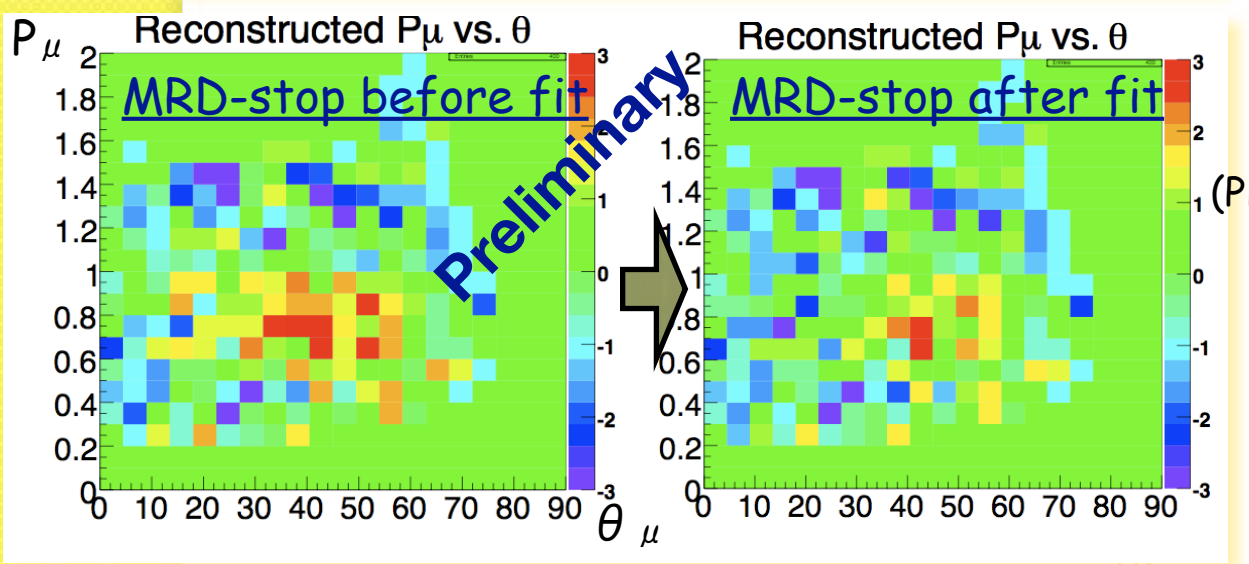
MRD-penetrate



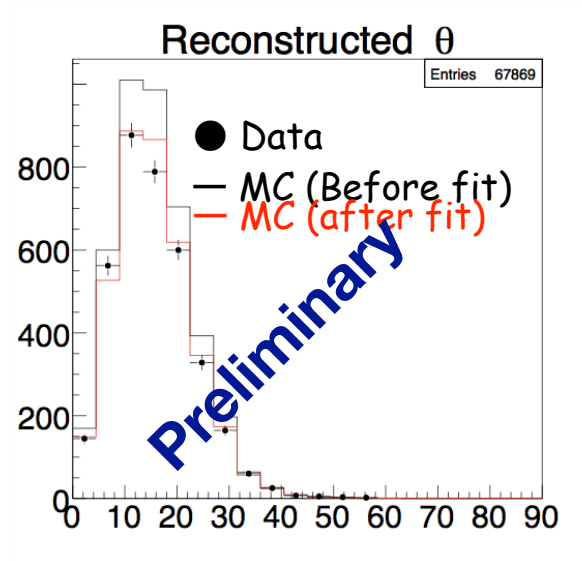
Spectrum Fit Result

(data-MC)/(stat. error)





MRD-penetrate



- Better data/MC agreement after fitting.

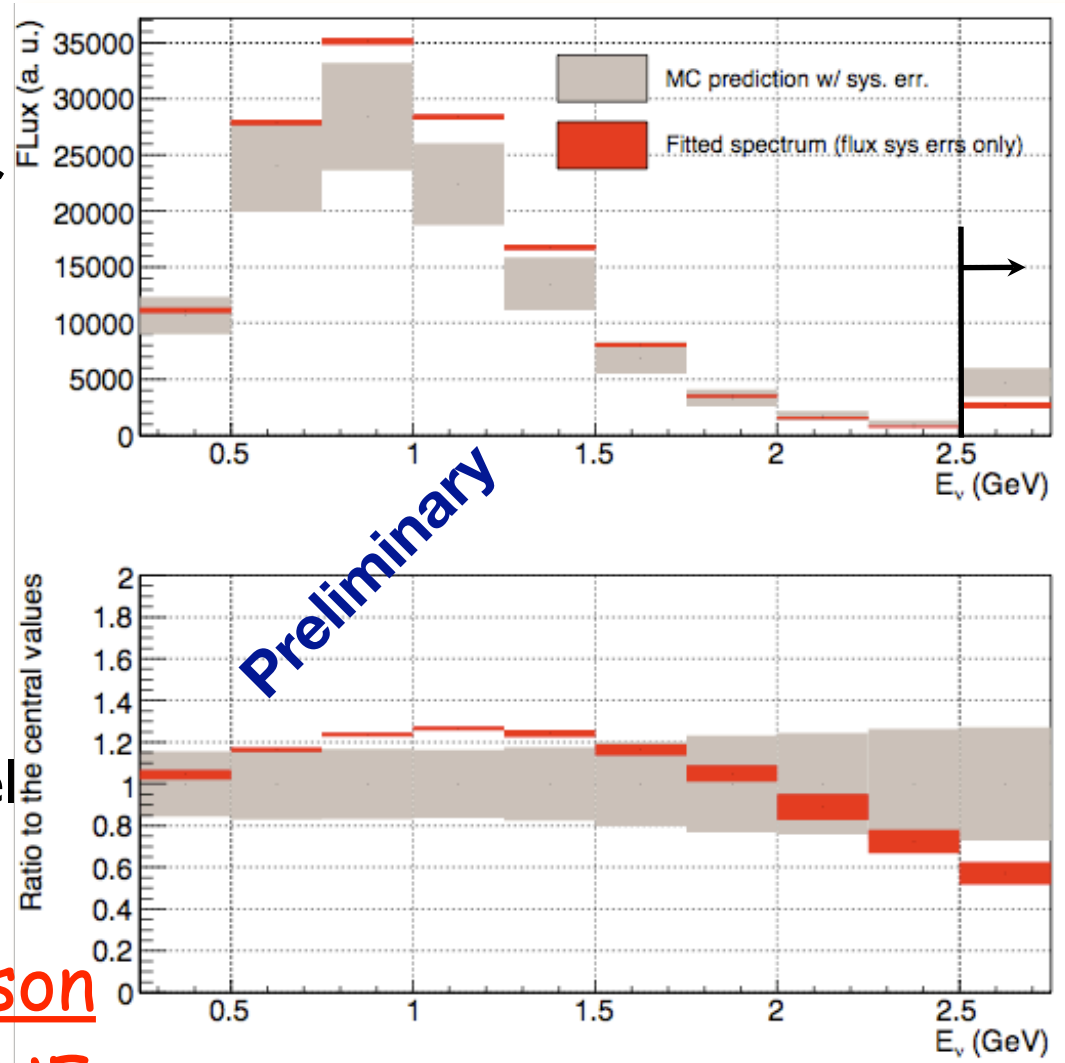
(Plots are relatively normalized)

χ^2/ndf:
1330/ 312 ➜ 505/312

Working on improving MC prediction.

Flux Prediction

- Data prefer higher flux around 1 GeV and lower at high-energy region than MC prediction.
- Next:
  - Take detector/cross-section error into account.
  - Tune cross-section model



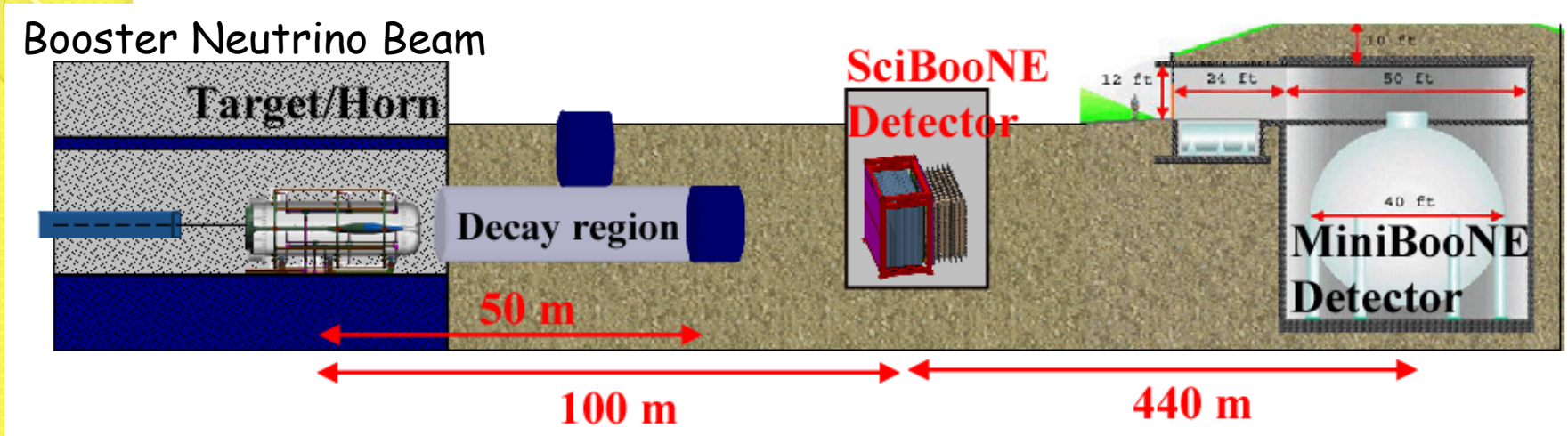
Flux comparison with MiniBooNE

Conclusion

- SciBooNE successfully finished data-taking.
- First physics result from SciBooNE
  - No 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
  - Anti-neutrino cross section measurements will also come soon.

BACKUP

3. 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

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

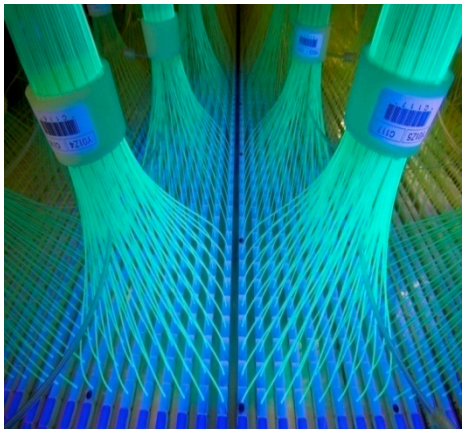
~65 physicists

5 countries 17 institutions

Spokespeople:

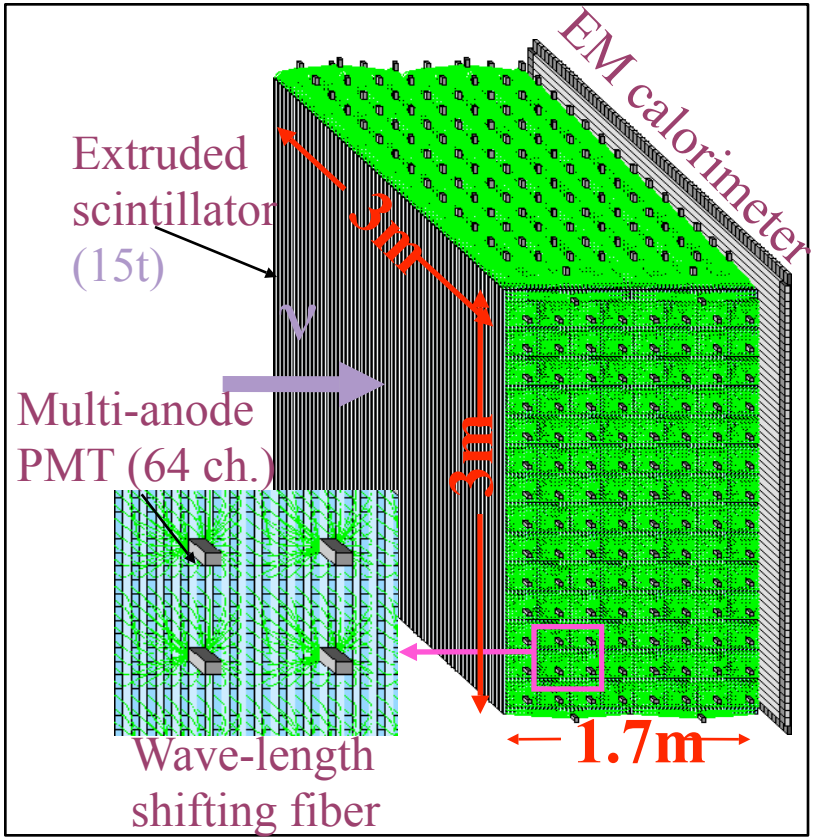
M.O. Wascko (Imperial), T. Nakaya (Kyoto)

SciBar detector

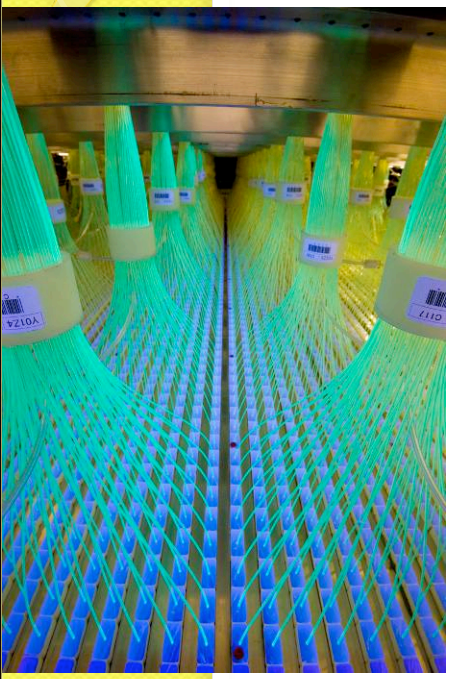


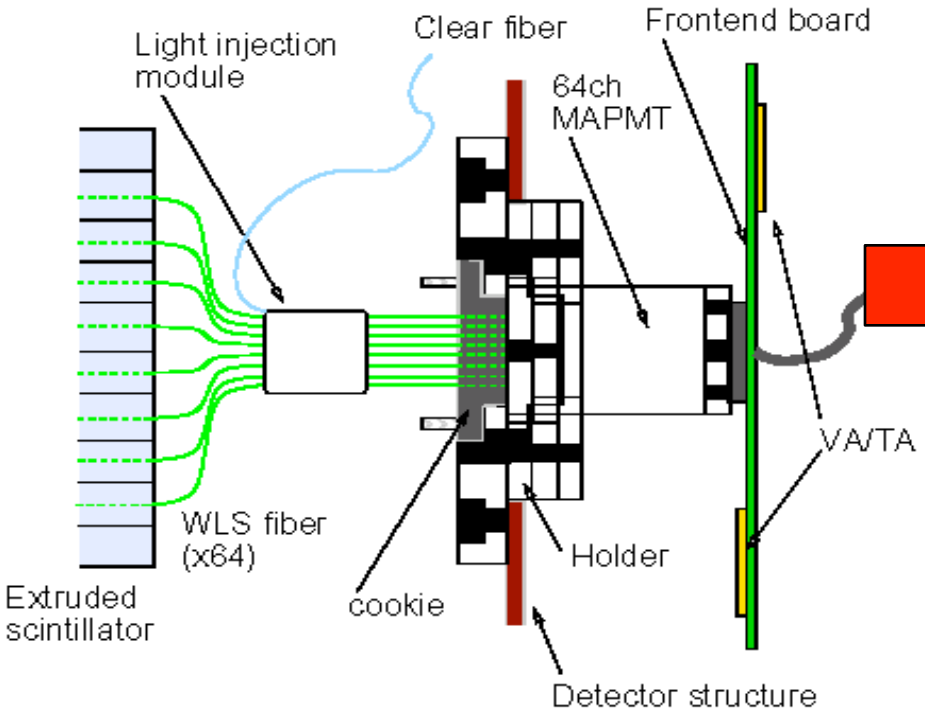
- **Extruded scintillators with WLS fiber readout**
- **Scintillators are the neutrino target**
- **3m x 3m x 1.7m (Total: 15 tons)**
- **14,336 channels**
- **Detect short tracks (>8cm)**
- **Distinguish a proton from a pion by dE/dx**

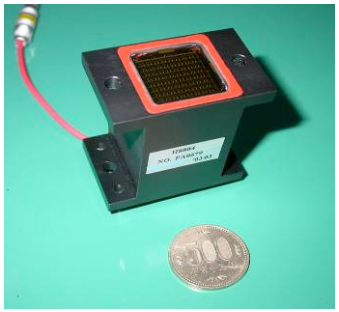
➔Clear identification of ν interaction process



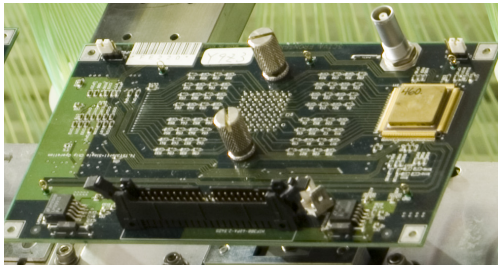
SciBar readout







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

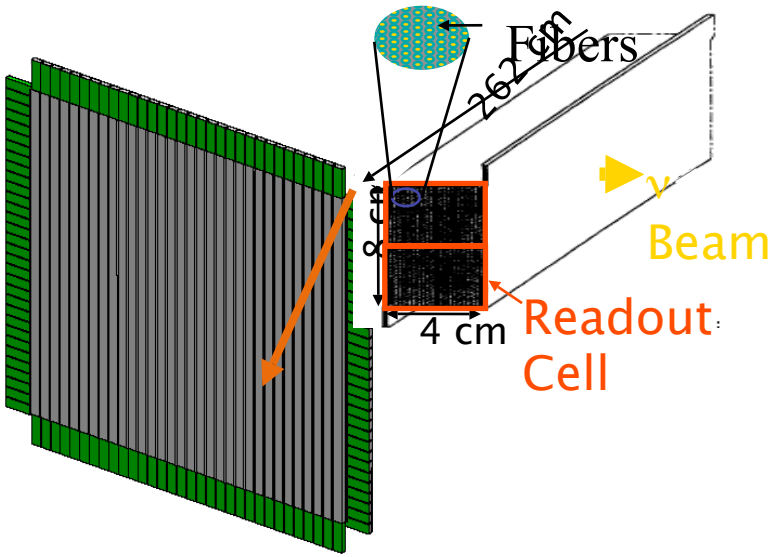
64-channel Multi-Anode PMT
- 2x2mm^2 pixel (3% cross talk@1.5mmΦ)
- Gain Uniformity (20% RMS)
- Good linearity (~200p.e. @6×10^5)

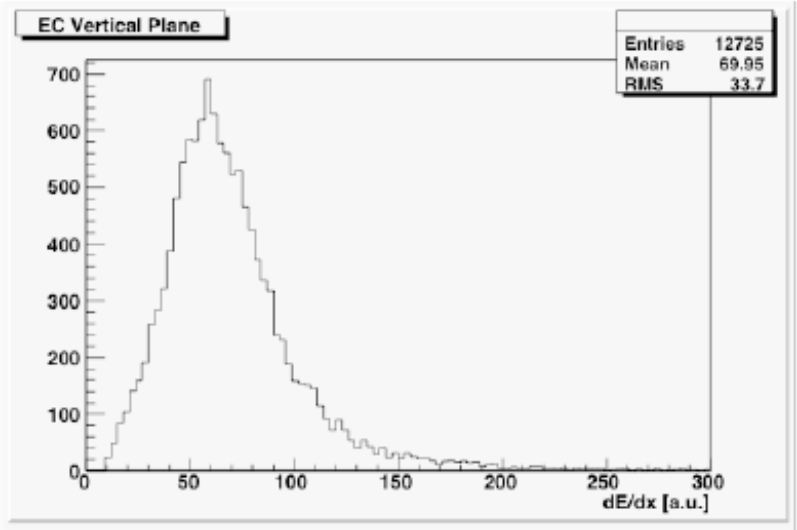
Readout electronics with VA/TA
- ADC for all 14,336 channels
- TDC for 448 sets (32 channels-OR)

Electron Catcher (EC)

- "spaghetti" calorimeter
- 1mm diameter fibers in the grooves of lead foils
- 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%/√E (GeV)
- Linearity: better than 10%

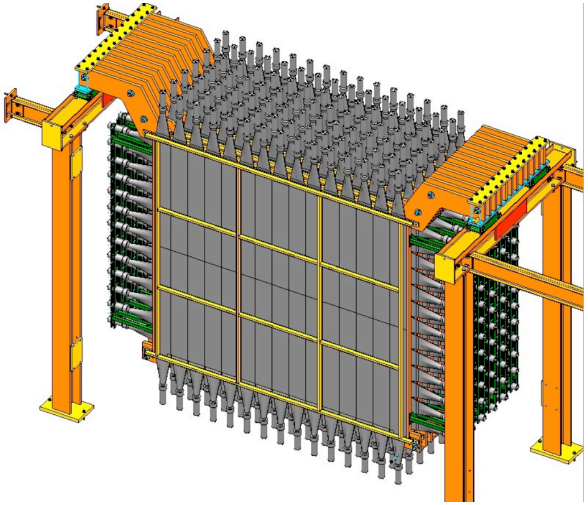




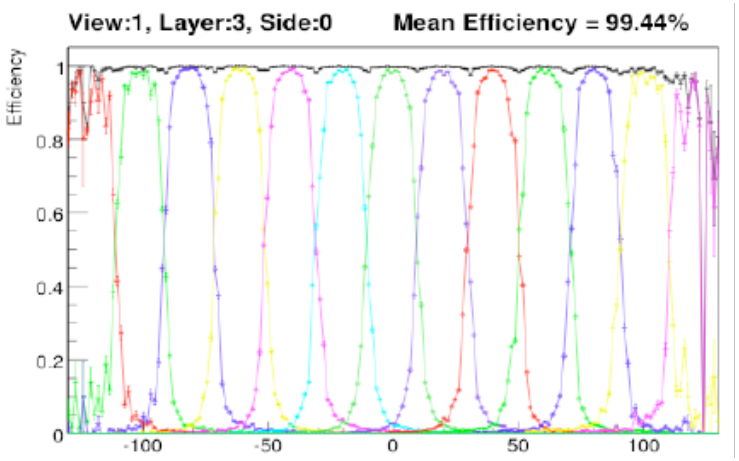
dE/dx distribution of vertical plane for cosmic ray muons

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.



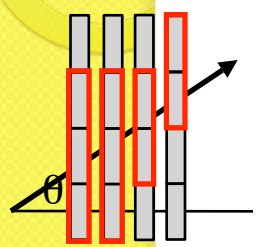
- Iron Plate
  - 305x274x5cm^3
  - Total 12 layers
- Scintillator Plane
  - Alternating horizontal and vertical planes
  - Total 362 channels



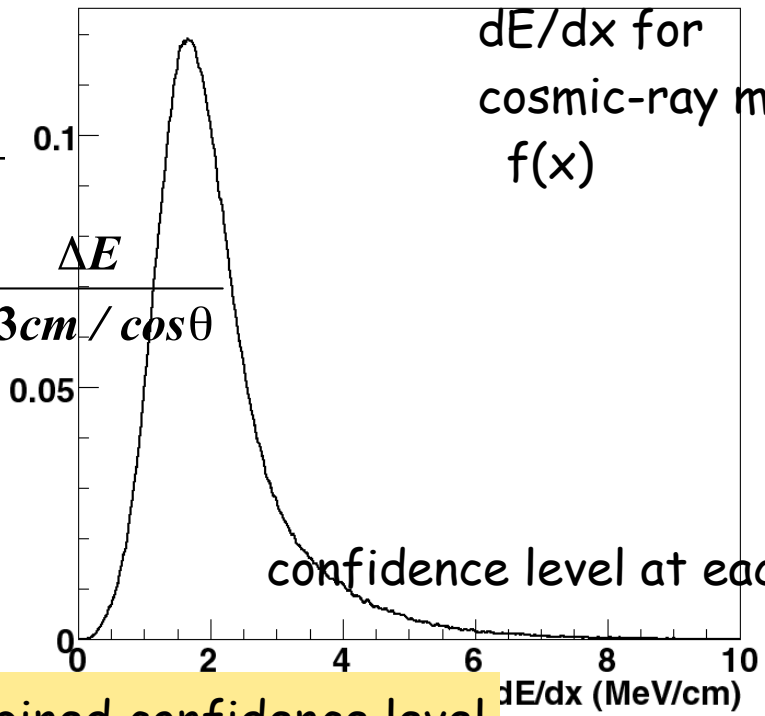
Hit efficiency of a typical horizontal plane

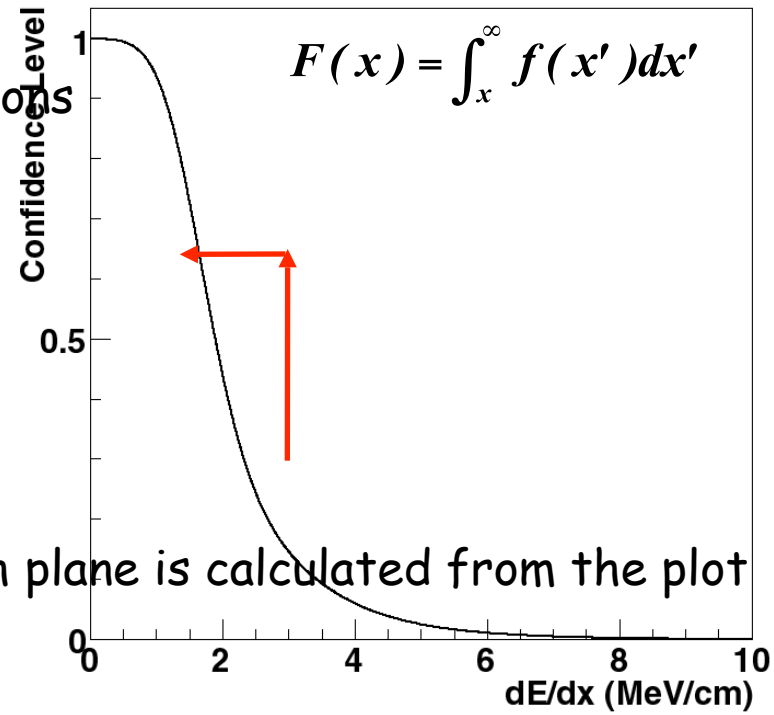
MuCL calculation

plane-by-plane dE/dx measurement



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



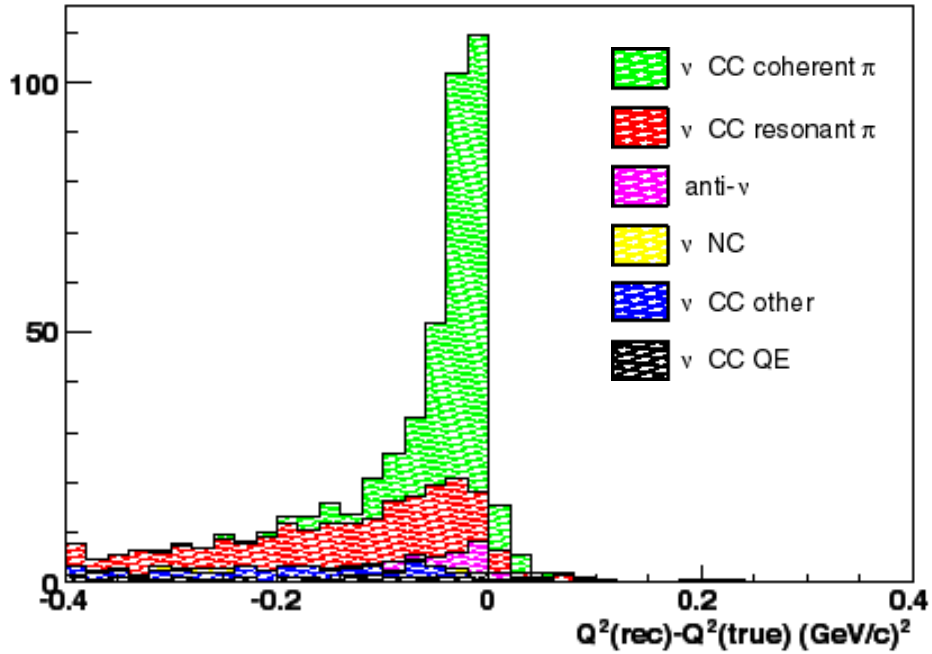


confidence level at each plane is calculated from the plot

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



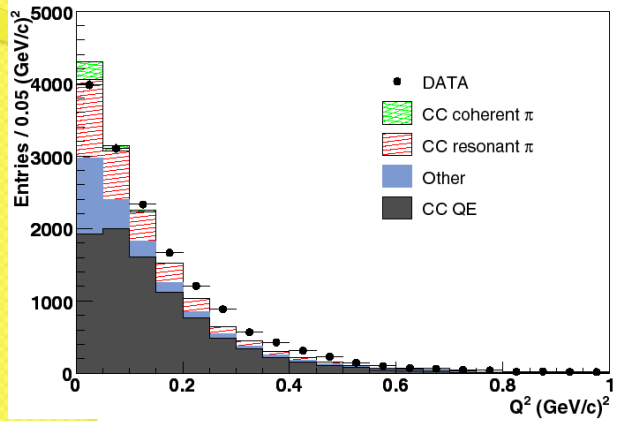
Q2 resolution of CC-coherent π events

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

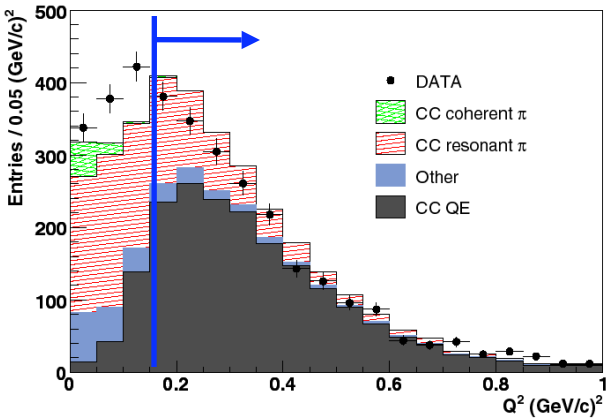
Sigma: 0.016 $(GeV/c)^2$

Q^2 distributions before fitting

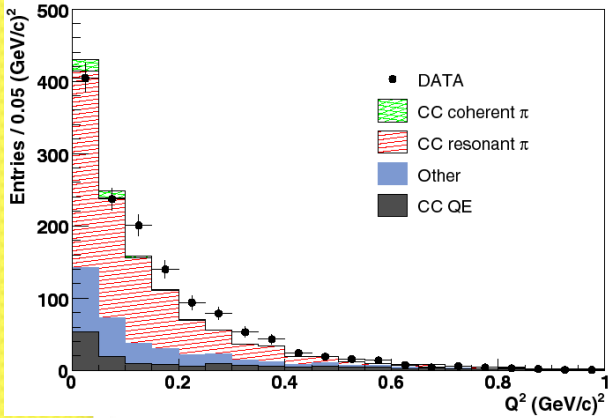
1-track



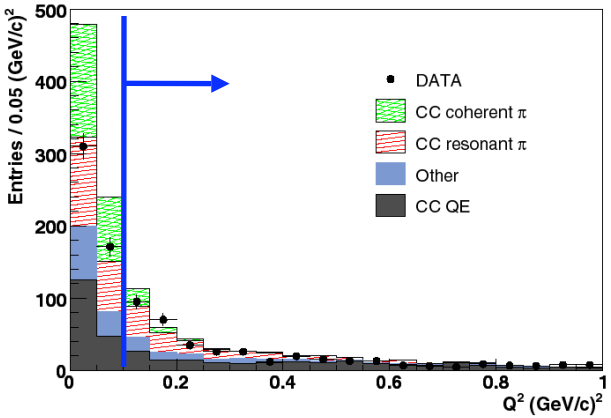
μ+p



μ+π with activity



μ+π without activity



χ^2 definition

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

$$\begin{cases} \chi^2_{\rm dist} = 2\sum_{i,\ j}\left(N^{\rm exp}_{ij} - N^{\rm obs}_{ij} + N^{\rm obs}_{ij} \times \ln\frac{N^{\rm obs}_{ij}}{N^{\rm exp}_{ij}}\right) \\ \chi^2_{\rm sys} = (\boldsymbol{P_{sys}} - \boldsymbol{P_0})\boldsymbol{V}^{-1}(\boldsymbol{P_{sys}} - \boldsymbol{P_0}) \end{cases}$$

Binned likelihood

Constraint on fitting parameters

V: covariance matrix

$$\boldsymbol{P_{sys}} = \begin{pmatrix} R_{\rm res} \\ R_{\rm 2trk/1trk} \\ R_{p/\pi} \\ R_{\rm pscale} \end{pmatrix} \quad , \quad \boldsymbol{P_0} = \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix}$$

Covariance matrix

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

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

$$\begin{array}{cc} & \begin{array}{cccc} R_{res} & R_{2trk/1trk} & R_{p/\pi} & R_{pscale} \end{array} \\ \boldsymbol{V} = & \begin{pmatrix} (0.20)^2 & -(0.09)^2 & +(0.10)^2 & 0 \\ -(0.09)^2 & (0.09)^2 & -(0.07)^2 & 0 \\ +(0.10)^2 & -(0.07)^2 & (0.15)^2 & 0 \\ 0 & 0 & 0 & (0.02)^2 \end{pmatrix} \end{array}$$

Fitting parameters

1-track:

$$N^{\mathrm{exp}}_{i,\ 1\mathrm{trk}} = R_{\mathrm{norm}} \cdot \left[n^{\mathrm{QE}}_{i,1\mathrm{trk}} + R_{\mathrm{res}} n^{\mathrm{res}}_{i,1\mathrm{trk}} + R_{\mathrm{other}} n^{\mathrm{other}}_{i,1\mathrm{trk}} \right]$$

μ+p:

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

μ+π
w/ activity:

$$N^{\mathrm{exp}}_{i,\ \mu\pi\mathrm{H}} = R_{\mathrm{norm}} \cdot R_{2\mathrm{trk}/1\mathrm{trk}} \cdot \left[n^{\mathrm{QE}}_{i,\mu\pi\mathrm{H}} + R_{\mathrm{res}} n^{\mathrm{res}}_{i,\mu\pi\mathrm{H}} + R_{\mathrm{other}} n^{\mathrm{other}}_{i,\mu\pi\mathrm{H}} \right]$$

μ+π
no activity:

$$N^{\mathrm{exp}}_{i,\ \mu\pi\mathrm{L}} = R_{\mathrm{norm}} \cdot R_{2\mathrm{trk}/1\mathrm{trk}} \cdot R_{\mathrm{act}} \cdot \left[n^{\mathrm{QE}}_{i,\mu\pi\mathrm{L}} + R_{\mathrm{res}} n^{\mathrm{res}}_{i,\mu\pi\mathrm{L}} + R_{\mathrm{other}} n^{\mathrm{other}}_{i,\mu\pi\mathrm{L}} \right]$$

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 / $\mu+\pi$ 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

Event selection summary (MRD stopped)

Event selection	DATA	MC		Coherent π
		Signal	B.G.	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 (MRD penetrated)

Event selection	DATA	MC		Coherent π
		Signal	B.G.	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%

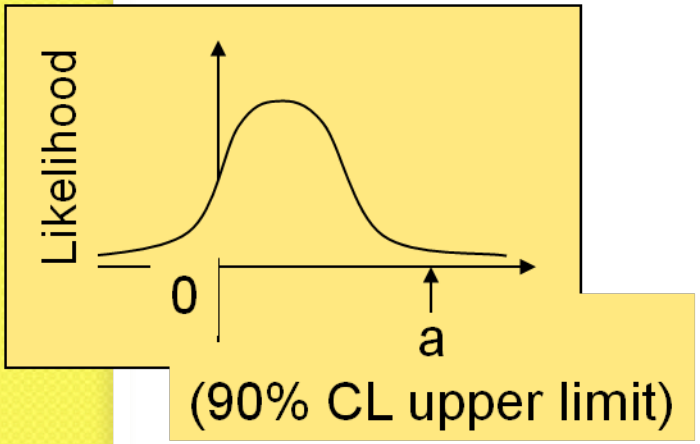
90% CL upper limit

Simple calculation

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

(This is for gaussian statistics without physical boundary)

Bayesian approach



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

$L(x)$ 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

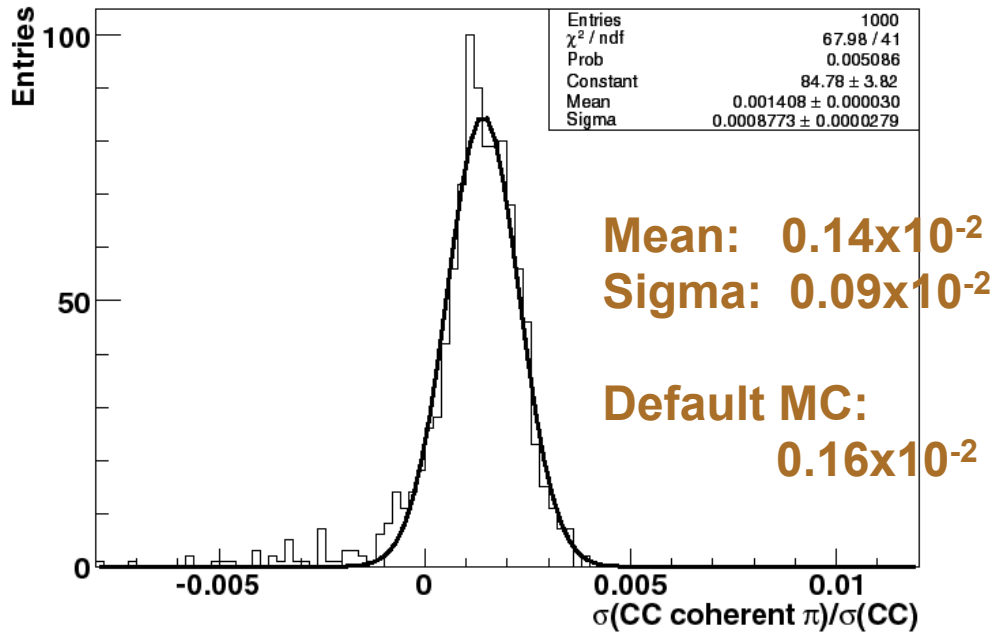
Systematic errors (neutrino interaction model)

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)
- K^0 production (SW)
- Horn skin effect
- Horn current
- Be-nucleon x-section
- Be-pion x-section

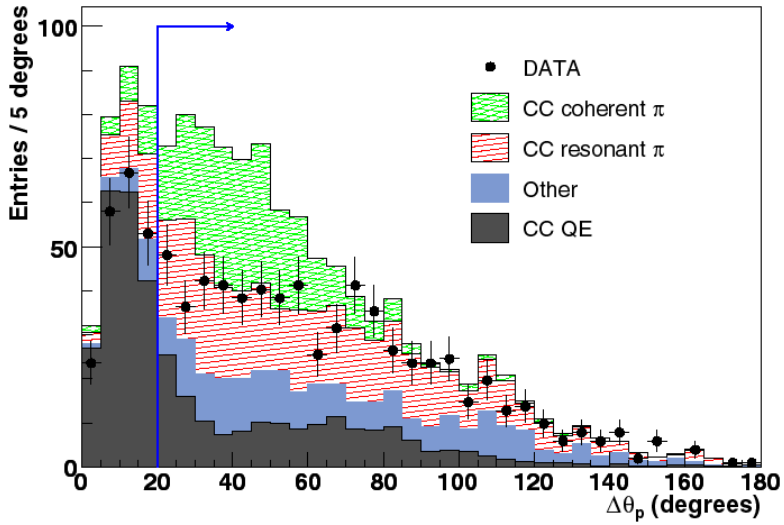
Variation of the cross section ratio using 1,000 multisim parameter sets



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

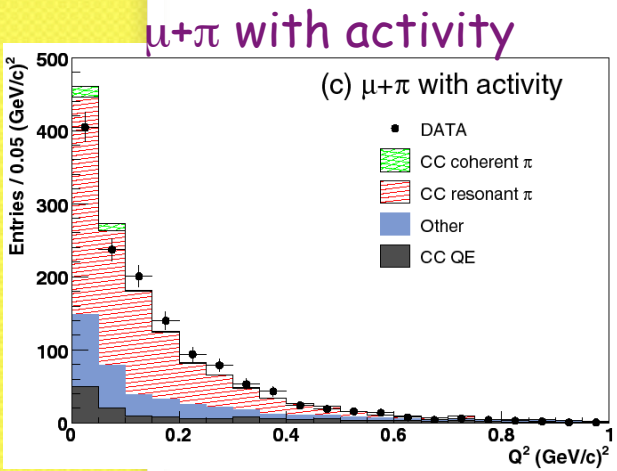
Systematic errors (Event selection)

$\Delta\theta p$ 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

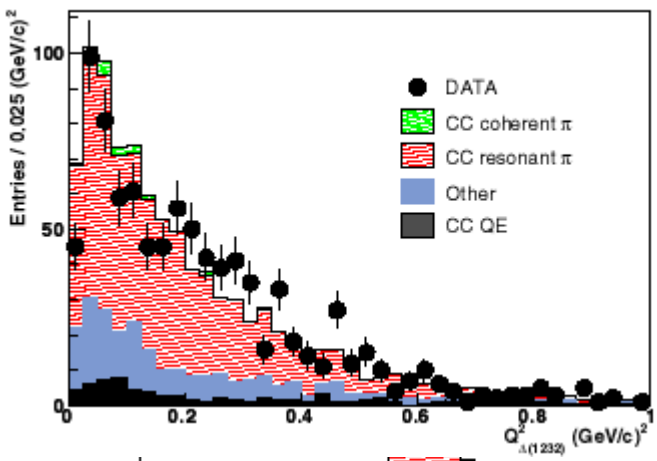


low Q^2 data deficit is observed in CC resonant pion enriched sample

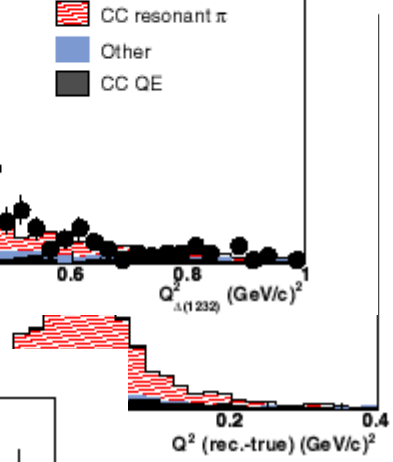
The Q^2 shape uncertainty affects background estimation for CC coherent pion sample

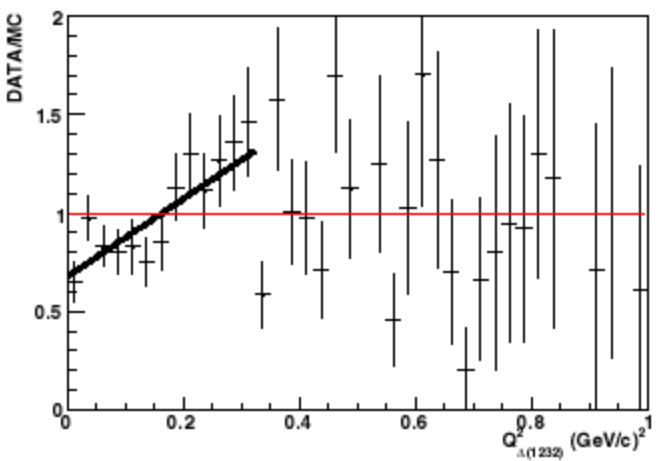
Low Q^2 suppression in CC resonant π

Rec. Q^2 assuming Δ-resonance



Q^2 resolution (rec-true)

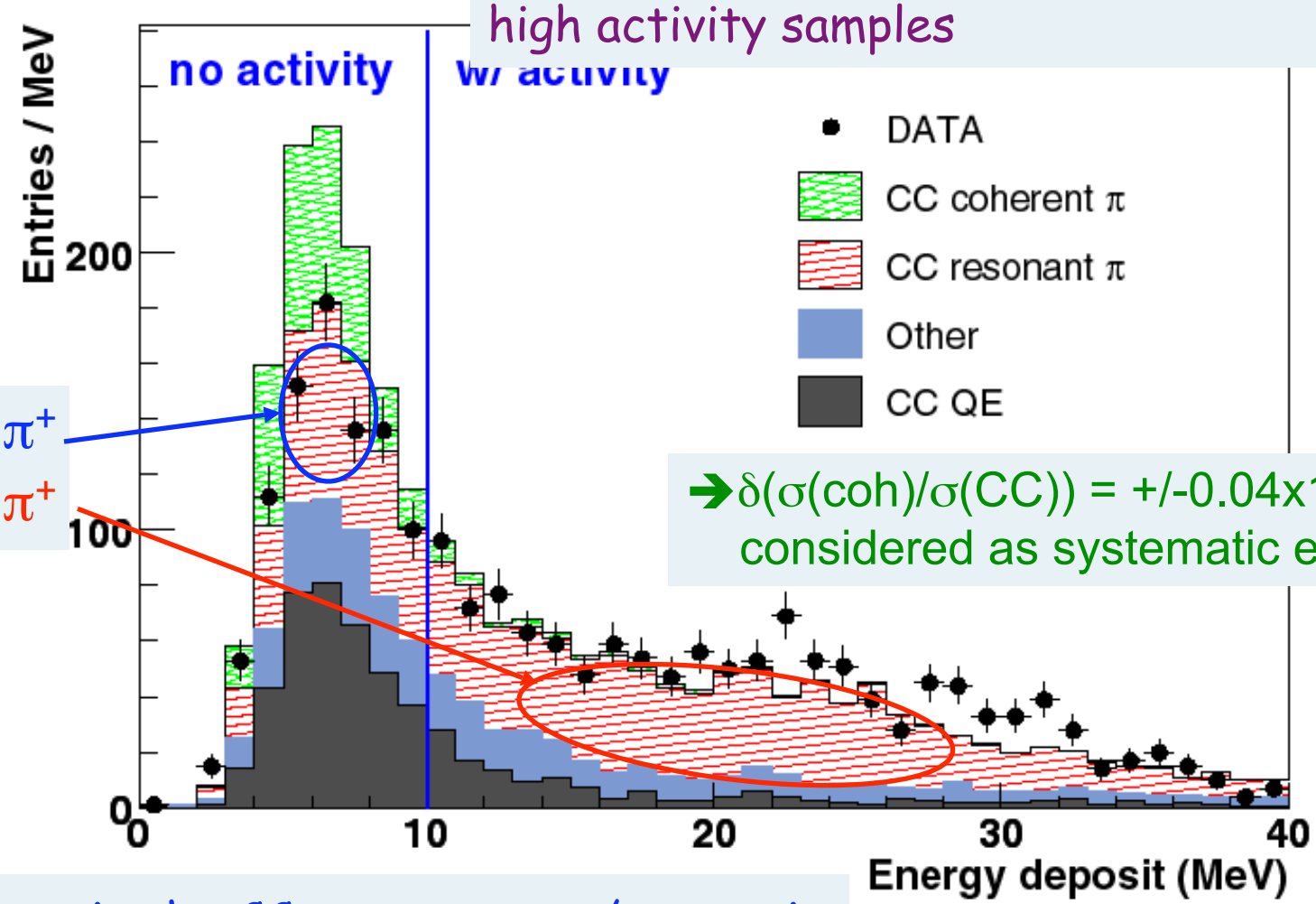




Apply this weighting function to CC coherent π sample in order to estimate systematic error

Uncertainty in CC resonant μnπ/μpπ ratio

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



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

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

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

Discrepancy in the K2K result

MEASUREMENT OF NEUTRINO OSCILLATION BY THE . . . PHYSICAL REVIEW D **74**, 072003 (2006)

TABLE XIV. Results of the spectrum measurement. The best-fit value of each parameter is listed for the fits with all the detectors' data, with the 1KT data, with the SciFi data and with the SciBar data, respectively. The reduced χ^2 (χ^2_{total}/DOF) and the averaged χ^2 of each detector (χ^2/N_{bin}) are also shown.

Parameter	**Combined**	1KT only	SciFi only	SciBar only
f_1 (0.00–0.50 GeV)	**1.657 ± 0.437**	2.372 ± 0.383	≡ 1	≡ 1
f_2 (0.50–0.75 GeV)	**1.107 ± 0.075**	1.169 ± 0.072	0.882 ± 0.317	1.166 ± 0.251
f_3 (0.75–1.00 GeV)	**1.154 ± 0.061**	1.061 ± 0.065	1.157 ± 0.201	1.145 ± 0.134
f_4 (1.00–1.50 GeV)	**≡ 1**	≡ 1	≡ 1	≡ 1
f_5 (1.50–2.00 GeV)	**0.911 ± 0.044**	0.709 ± 0.151	0.980 ± 0.107	0.963 ± 0.070
f_6 (2.00–2.50 GeV)	**1.069 ± 0.059**	≡ 1	1.188 ± 0.096	0.985 ± 0.086
f_7 (2.50–3.00 GeV)	**1.152 ± 0.142**	≡ 1	1.062 ± 0.230	1.291 ± 0.283
f_8 (3.00– GeV)	**1.260 ± 0.184**	≡ 1	1.323 ± 0.203	1.606 ± 0.749
R_{nQE} **±0.2**	**0.964 ± 0.035**	0.589 ± 0.071	1.069 ± 0.060	1.194 ± 0.092

- RnQE ($\equiv\sigma_{\text{non-QE}}/\sigma_{\text{QE}}$)
  - 1KT measurement ⇒ **~0.6**
    - Low energy neutrinos
    - Extracted from the muon angular distributions.
  - SciBar measurement ⇒ **~1.2**
    - Medium-high energy neutrinos.
    - Extracted from both the number of tracks and the muon angle.

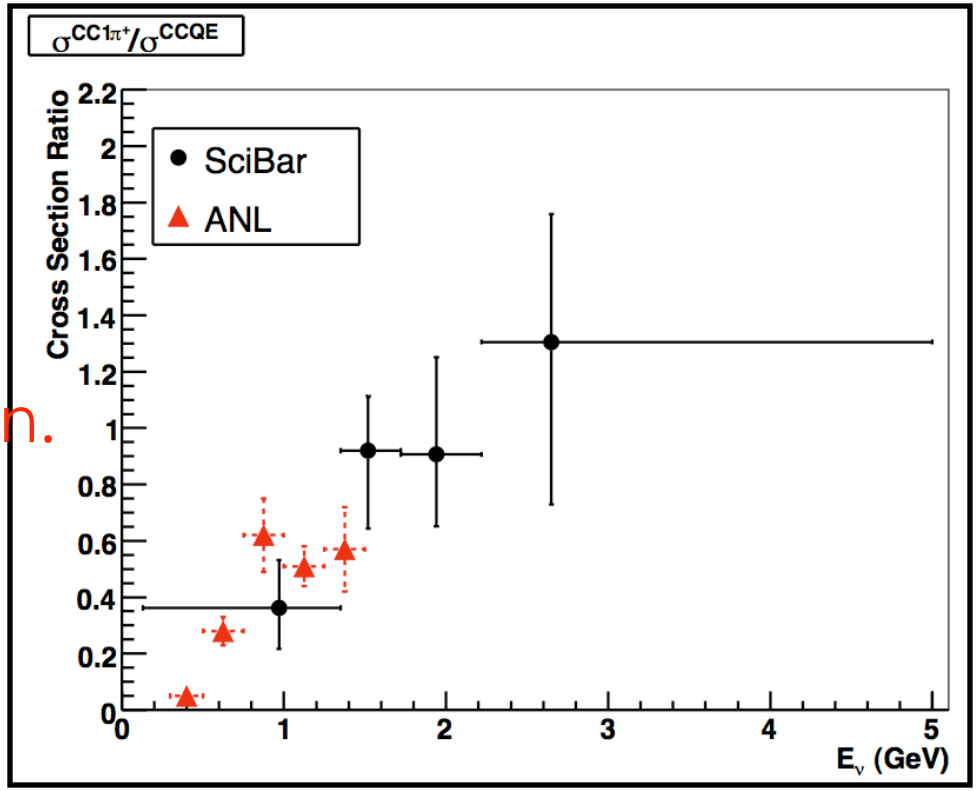
New K2K Result: CC π^+

accepted by PRD

$$\sigma_{CC\ \pi^+}/\sigma_{QE} = 0.734 \pm 0.086\ (\text{fit})^{+\ 0.076}_{-\ 0.103}\ (\text{nucl})^{+\ 0.079}_{-}\ (\text{syst})$$

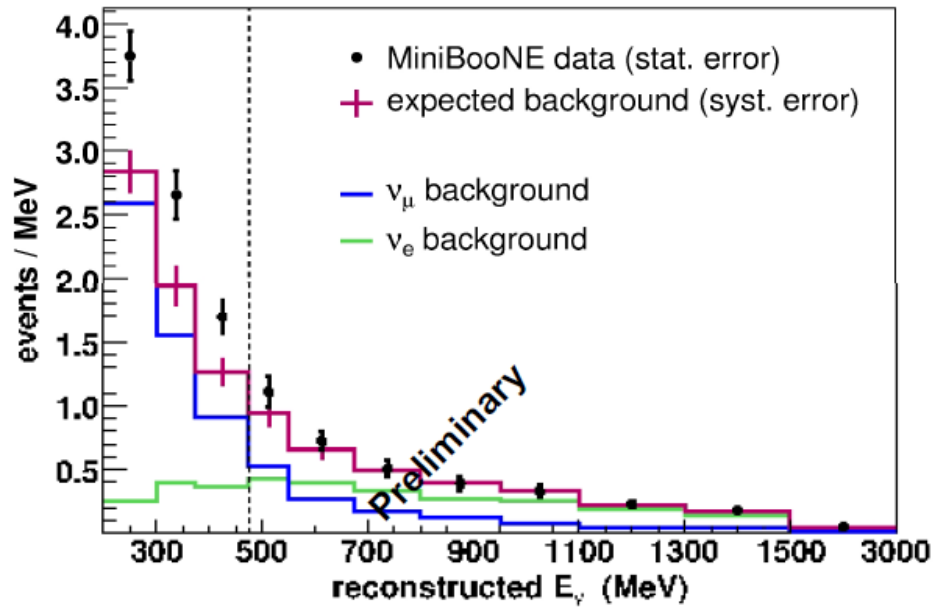
- consistent with ANL (1982, D_2)
- 20% measurement of σ ratio

- T2K requests 5~10% precision.
  - Challenging?



Talk by L. Whitehead at WG2

MiniBooNE low energy e excess

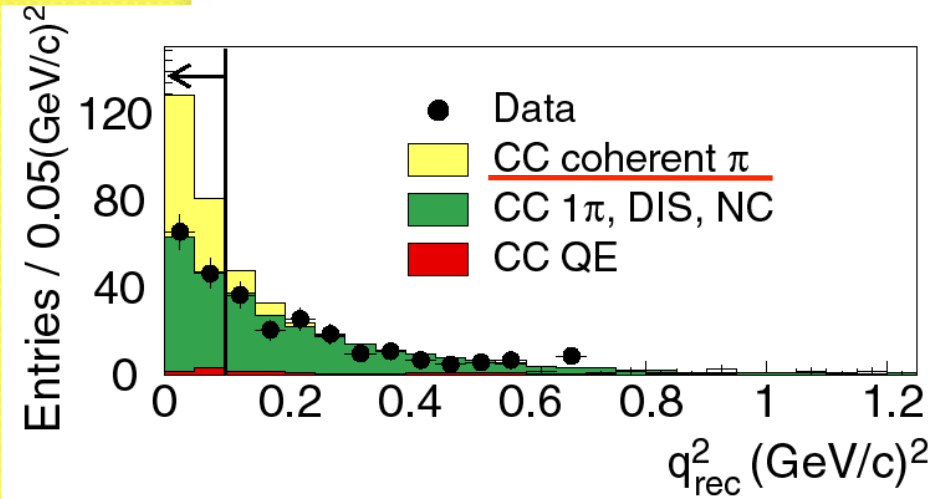


- Needless to say, it is important to understand the source of this effect.
  - However, the effect on T2K may be marginal.
    - T2K: sensitivity of $\sin^2 2\theta_{\mu e}$ ($=0.5\sin^2 2\theta_{13}$)~**0.004** ($0.35<E\nu<0.85$ GeV)
    - MiniBooNE: sensitivity of $\sin^2 2\theta$~**0.001** ($0.475<E\nu$ GeV)

Surprises

CC coherent π^+

K2K, PRL95,252301 (2005)

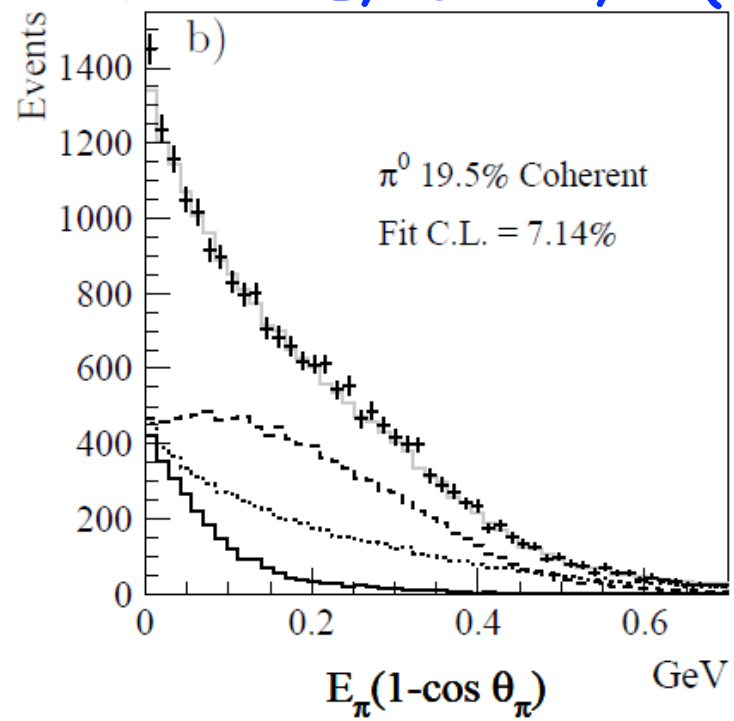


No evidence of CC coherent pion production is found at $\langle E\nu \rangle$=1.3 GeV

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

NC coherent π^0

MiniBooNE, PLB664,41 (2008)



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

65% of the model prediction

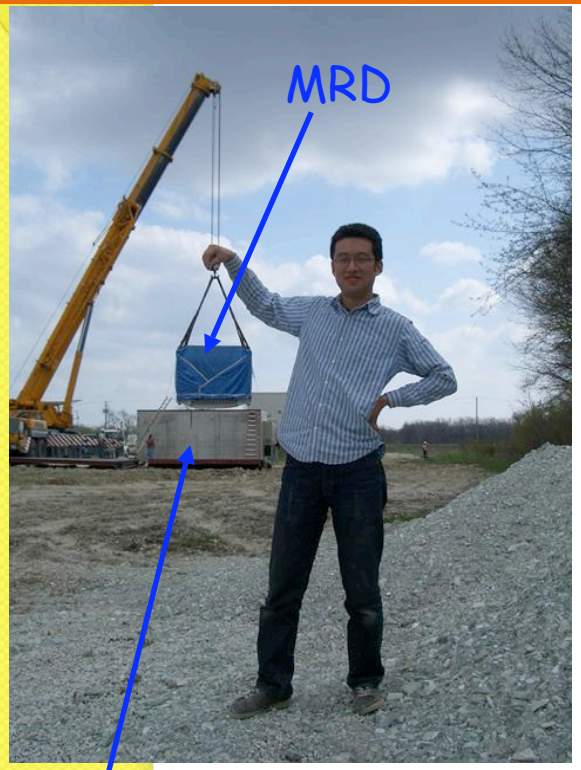
SciBooNE Timeline

Groundbreaking ceremony (Sep. 2006)

Detector Assembly (Nov. 2006 -Mar.2007)

SciBooNE Timeline

Detector installation (Apr. 2007)



End-of-run party
(Aug. 2008)

π^0 Event Summary

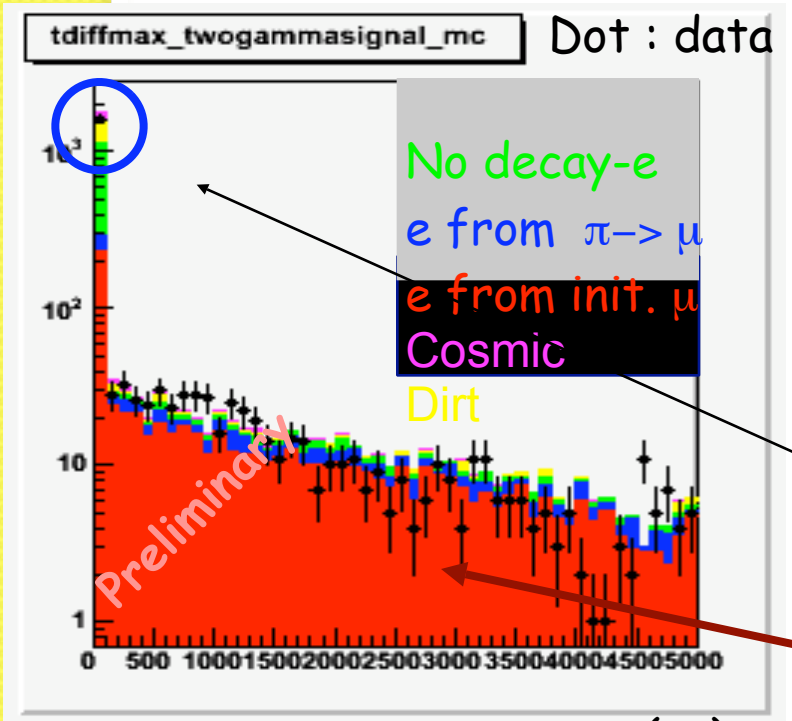
	Data	NC w p0	BG (internal)	Dirt	Cosmic	efficiency(%)
Generated		12064				
Pre-Selection	4228	1221	2389	718	179	10.1
p rejection	2152	781	953	507	154	6.5
μ rejection	1572	719	361	485	137	6.0
disconnection	1357	664	252	463	116	5.5
Trk merge	852	462	220	151	106	3.8

Muon rejection with the decay election

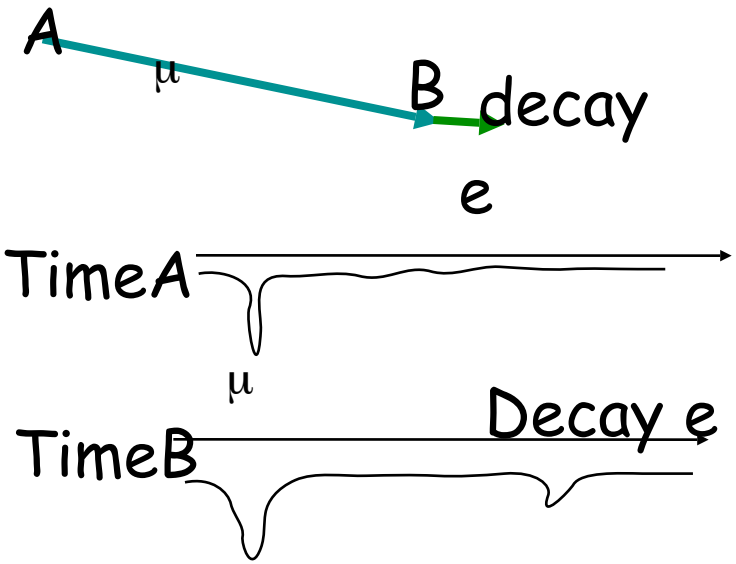
There are muons stopping in SciBar

These muons can be removed using the decay electron

Time difference btw track edges



Internal
External



Δt = (The latest) TimeB - TimeA

Most "no decay"

eve

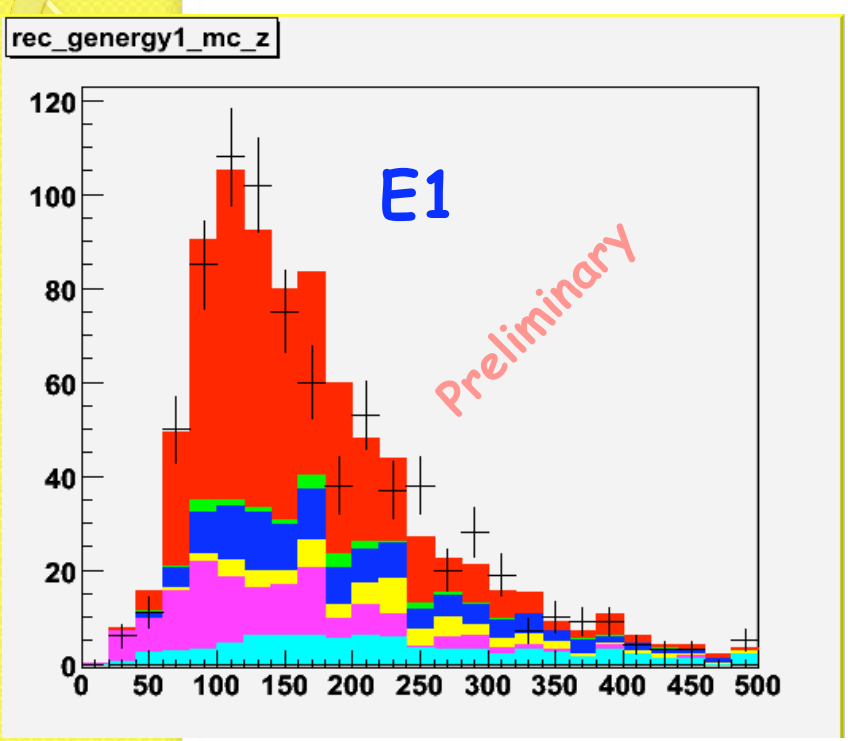
n → Reject " > 100 ns "

ts is in the region < 100 ns (first bin)

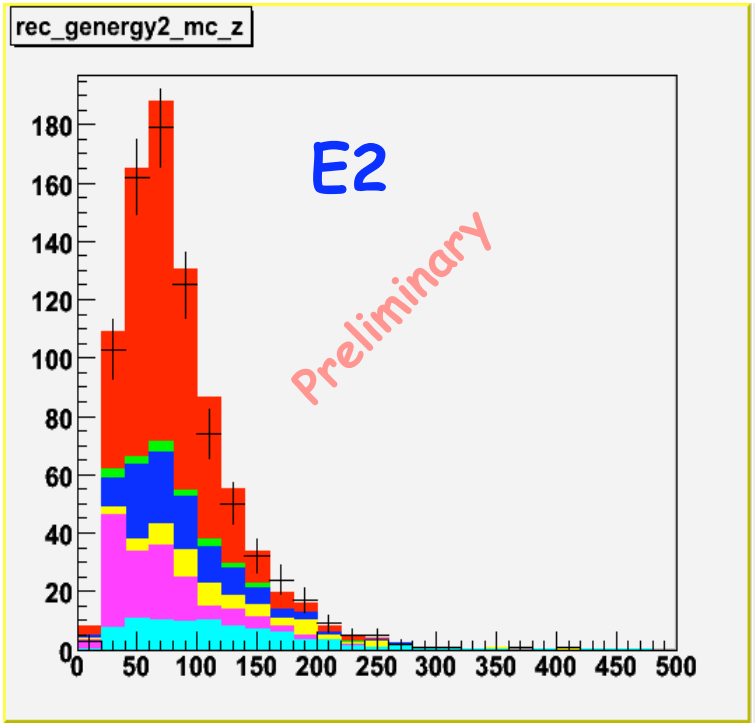
Reject 66 % of decay-e events

Keep 95 % of no decay-e events

Gamma Energy of π^0 sample



MeV



MeV

Energy

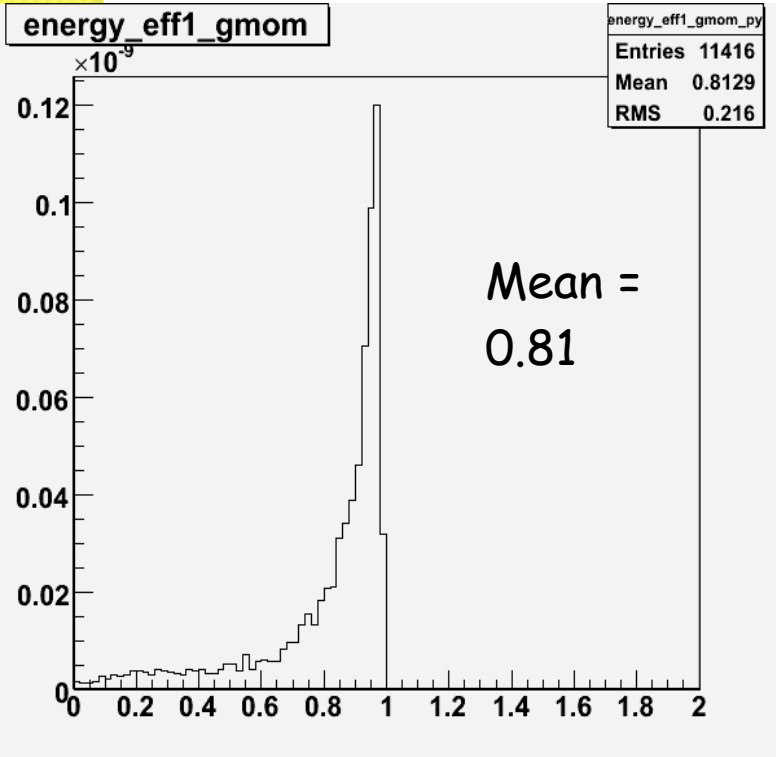
γ reconstruction performance using Extended Track (I)

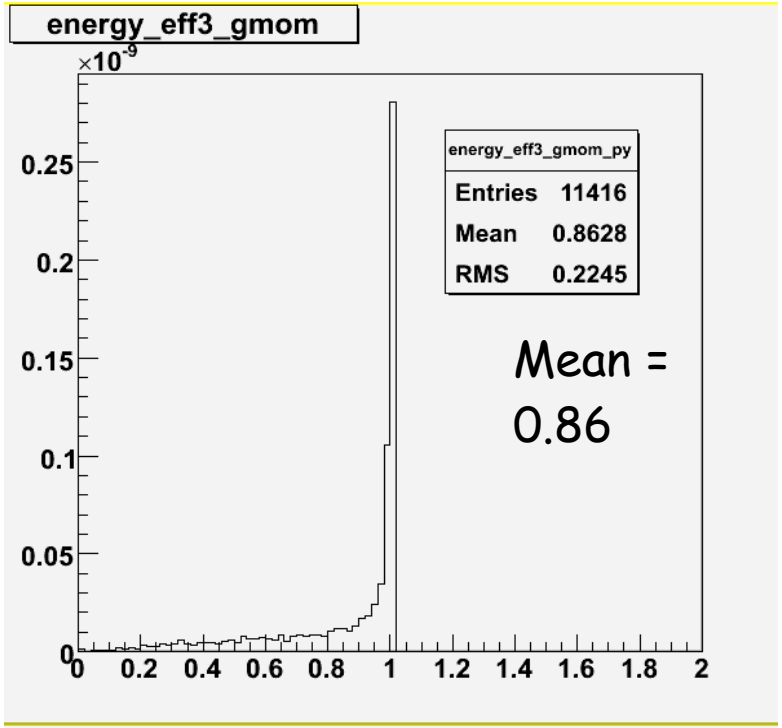
Energy Collection Efficiency

$$= \frac{\text{Energy due to } \gamma \text{ in ETrack}}{\text{Energy loss in SB}}$$

Purity of γ hits

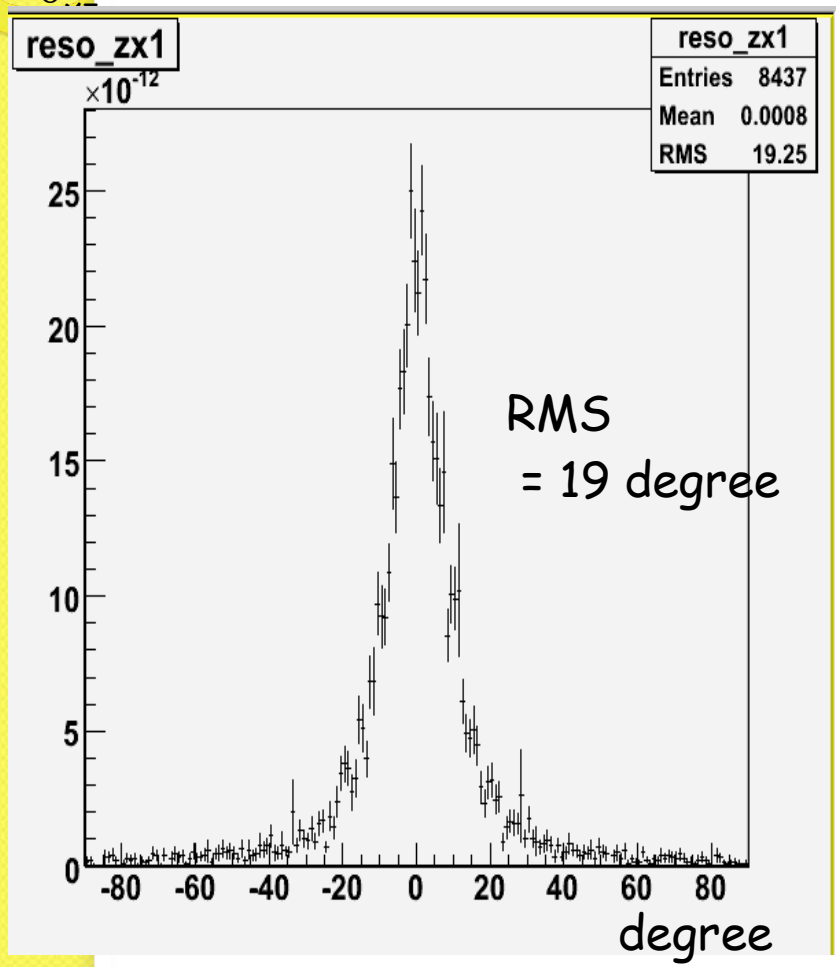
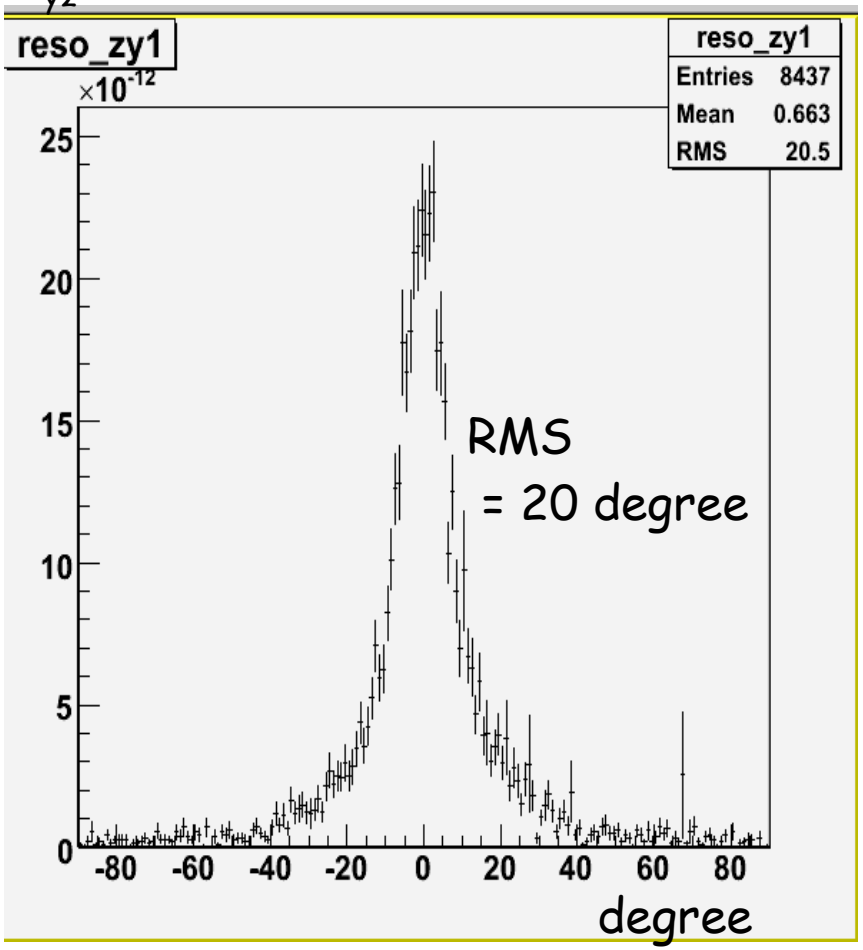
$$= \frac{\text{Energy due to } \gamma \text{ in ETrack}}{\text{Energy in ETrack}}$$





γ reconstruction performance using Extended Track (2)

γ angular resolution (x 2D) θ_{xz}^{rec} - θ_{xz}^{true}



γ angular resolution (x 2D) θ_{yz}^{rec} - θ_{yz}^{true}