Recent Results from SciBooNE:

~ Search for Neutrino Charged Current Coherent Pion Production ~

- SciBooNE Experiment
- SciBooNE 1st Result
  - Phys. Rev. D78, 112004 (2008)
- Summary

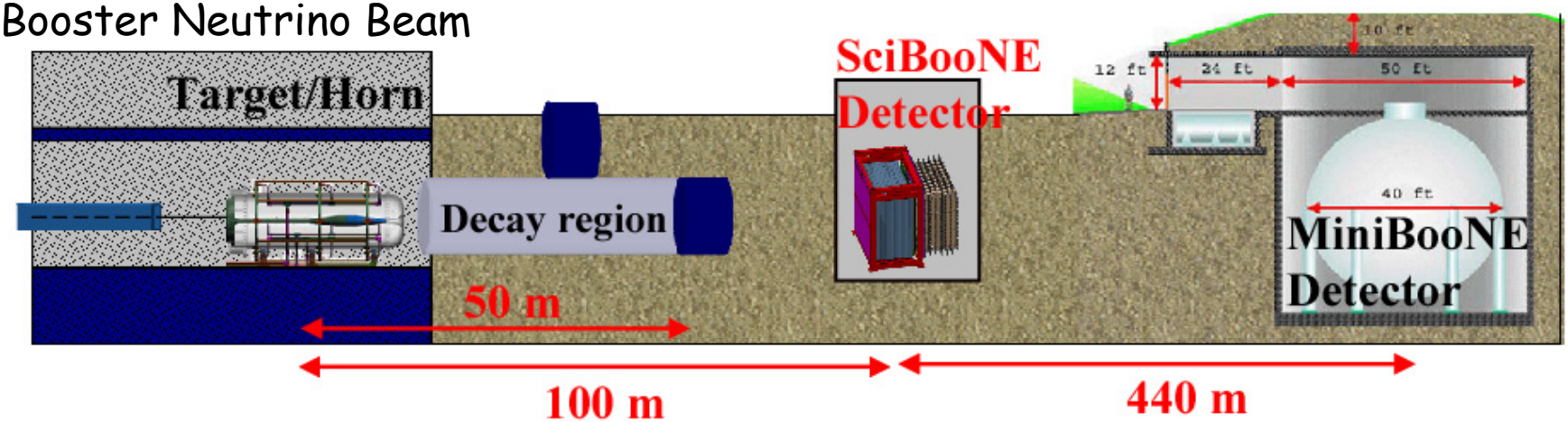
Katsuki Hiraide (Kyoto Univ.)

March 3, 2009

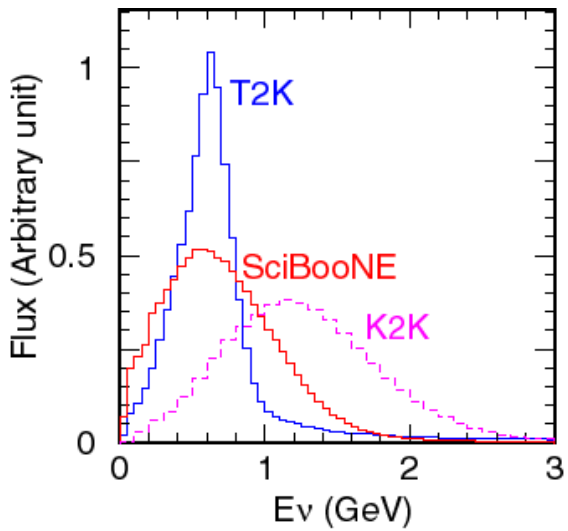
La Thuile 2009

SciBooNE experiment (FNAL E954)

Booster Neutrino Beam

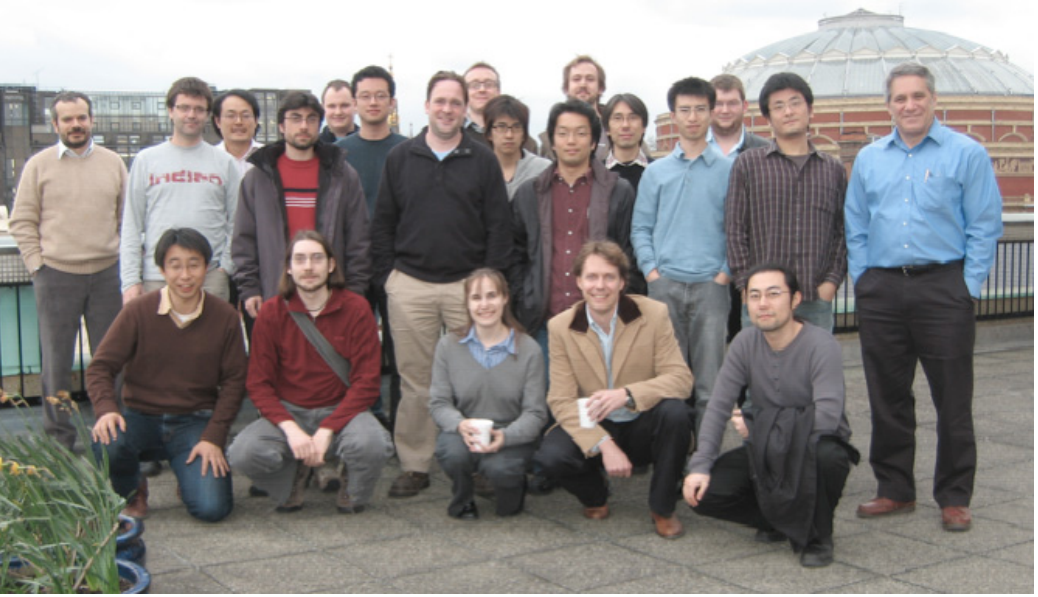


- Precise measurements of neutrino- and antineutrino-nucleus cross sections near 1 GeV
  - Essential for future neutrino oscillation experiments
- Neutrino energy spectrum measurements
  - MiniBooNE/SciBooNE joint ν_μ disappearance
  - ν_e constraint for MiniBooNE



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

~60 physicists
5 countries 17 institutions

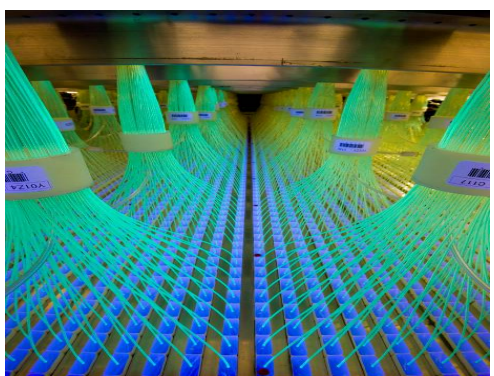
Spokespeople:
M.O. Wascko (Imperial), T. Nakaya (Kyoto)

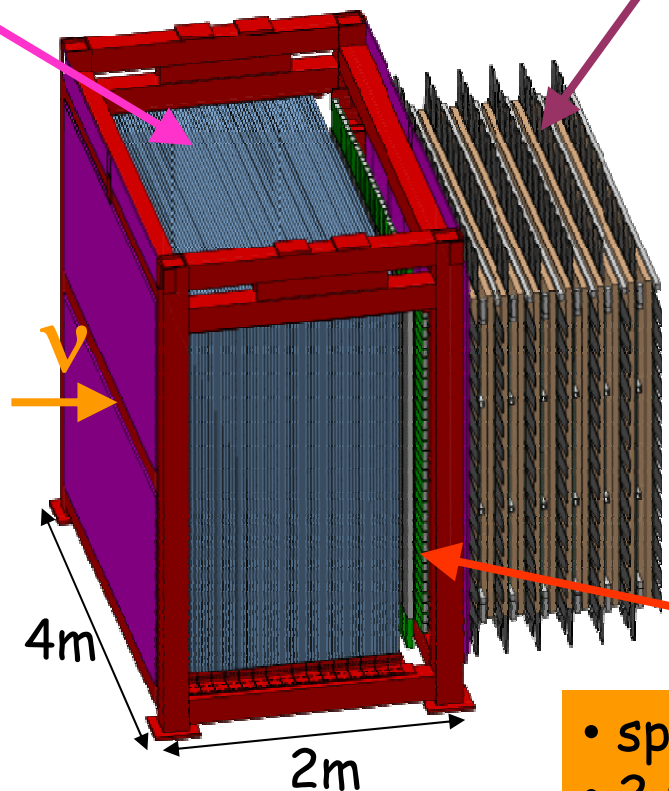
SciBooNE detector

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

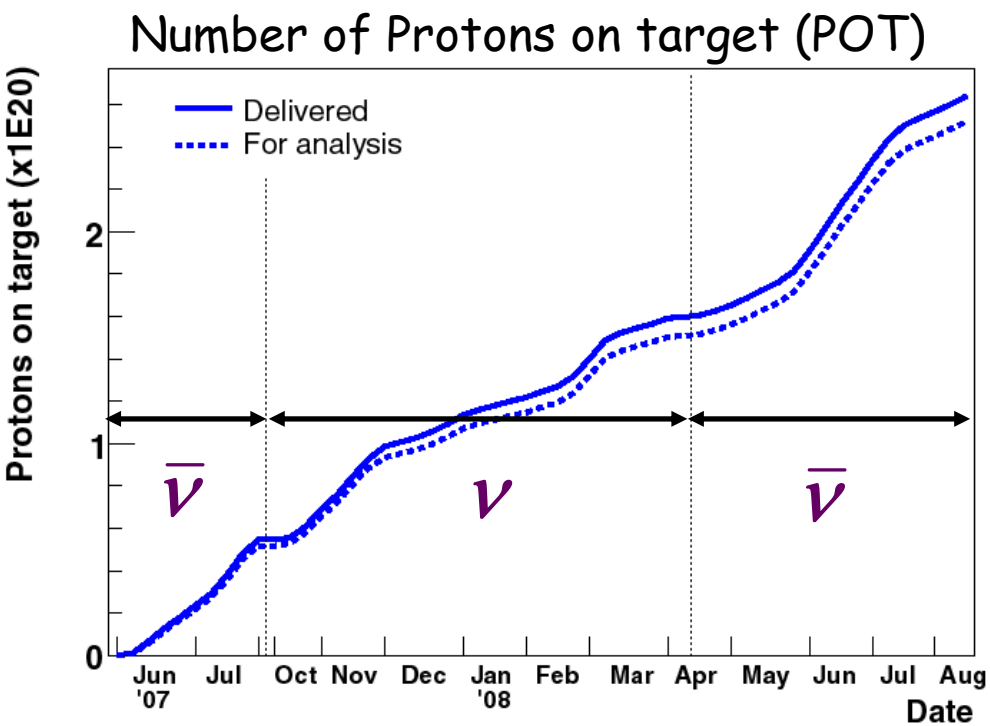
Parts recycled from Past experiment at FNAL

Electron Catcher (EC)

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

Used in CHORUS, HARP and K2K

SciBooNE data-taking

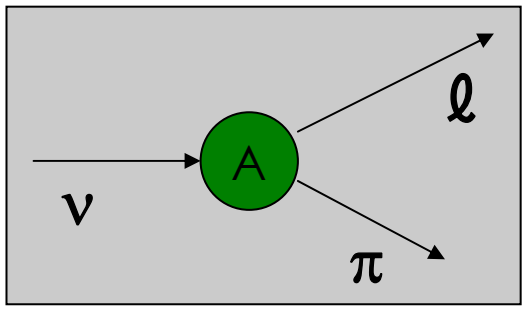


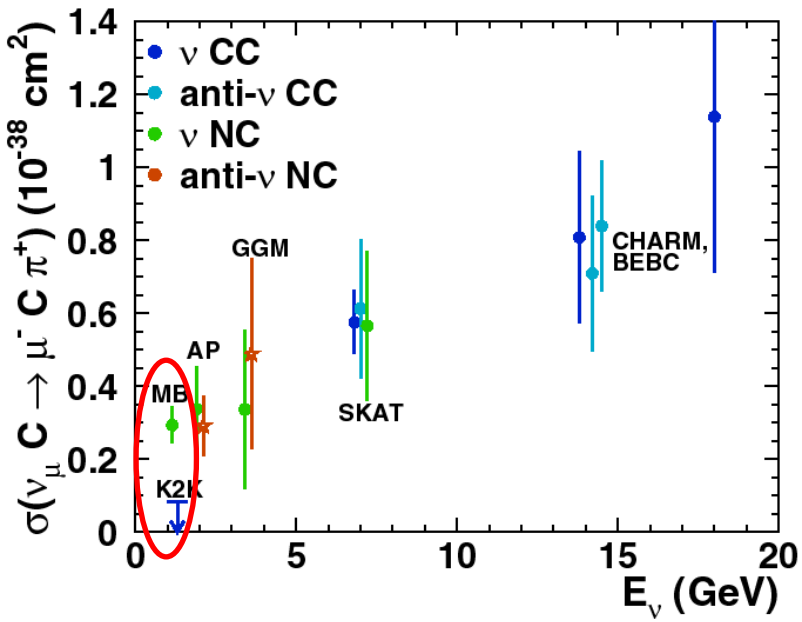
- Jun. 2007 – Aug. 2008
- 95% data efficiency
- 2.52×10^{20} POT in total
  - neutrino : 0.99×10^{20} POT
  - antineutrino: 1.53×10^{20} POT

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): $\nu_\mu + A \rightarrow \nu_\mu + A + \pi^0$





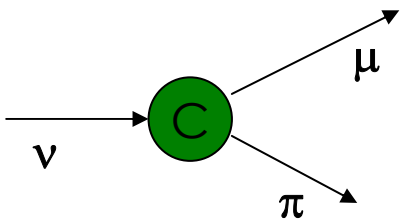
- No evidence of CC coherent π at 1.3GeV (by K2K Collaboration)
- hard to explain results from K2K and MiniBooNE at the same time
- Order-of-magnitude difference between theoretical predictions at $E\nu \sim 1$GeV

CC coherent pion production in SciBooNE

Signal

CC-coherent π production

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



Small Q^2

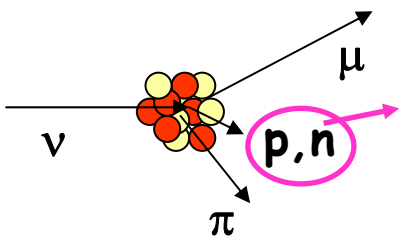
→ 2 MIP-like tracks (a muon and a pion)

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

Background

CC-resonant π production

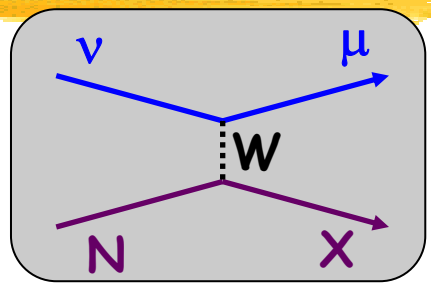
- $\nu + p \rightarrow \mu + p + \pi^+$
- $\nu + n \rightarrow \mu + n + \pi^+$



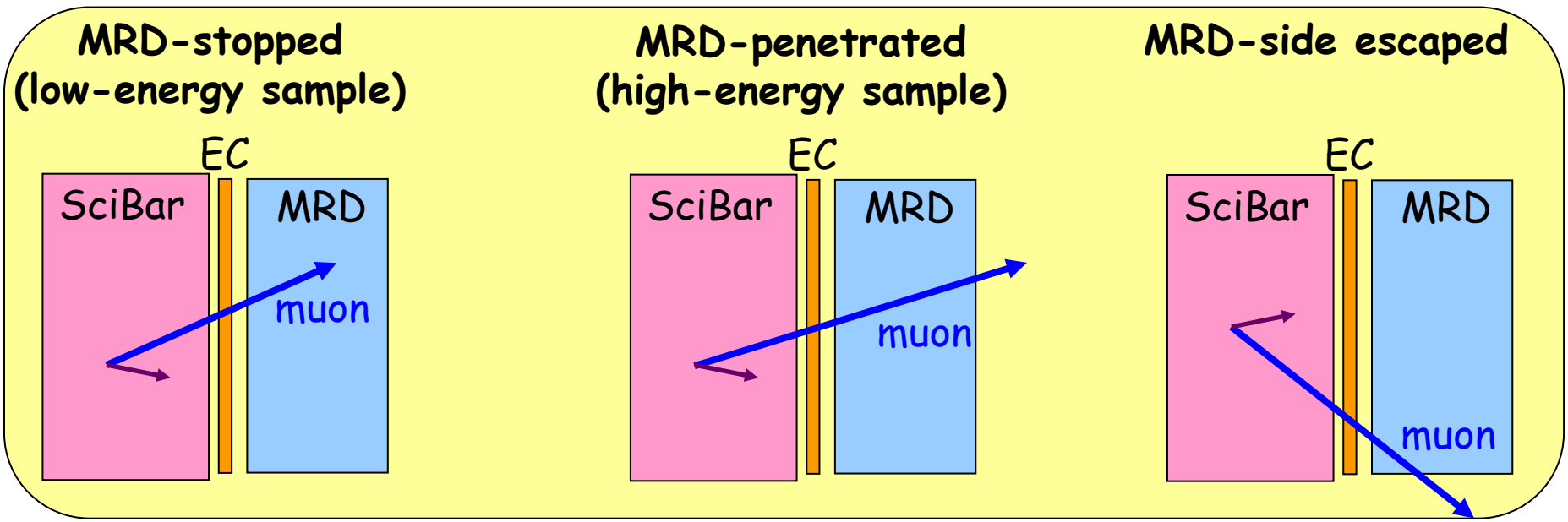
often not reconstructed

Charged Current (CC) event selection

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

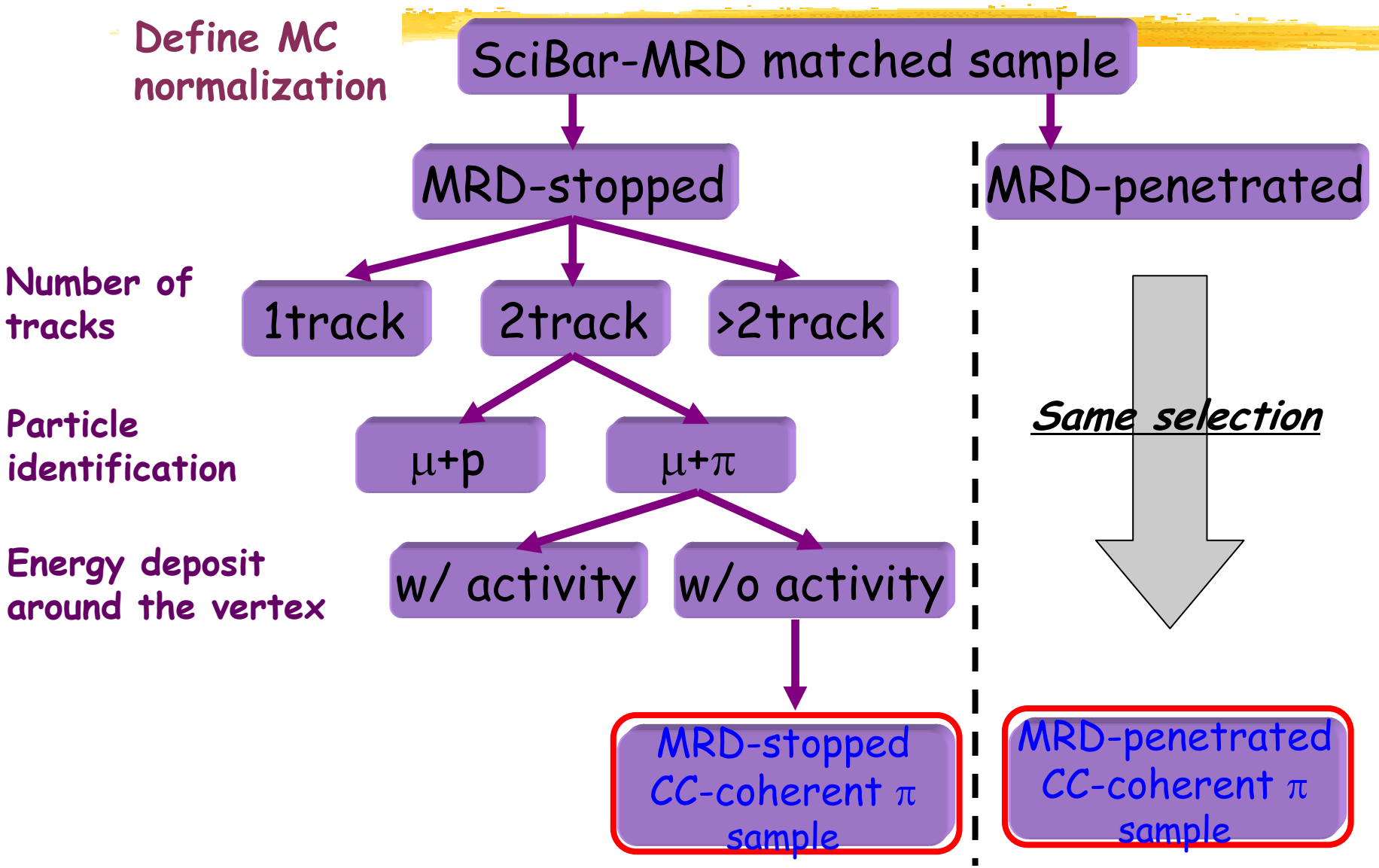


SciBar-MRD matched event (~30k events)



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

CC event classification



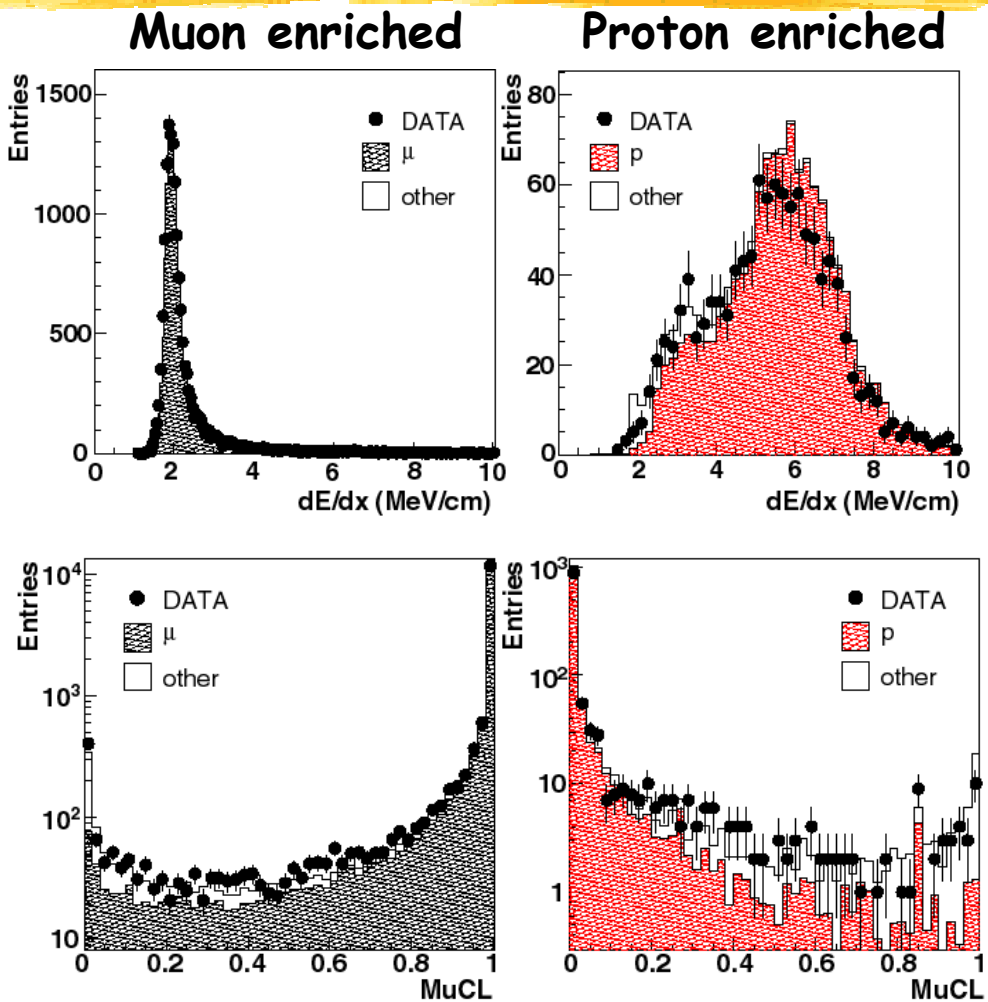
Particle identification

Particle ID using dE/dx in SciBar

Muon confidence level (MuCL)

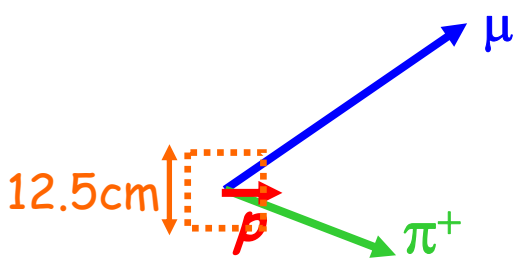
MuCL >0.05 → muon-like
<0.05 → proton-like

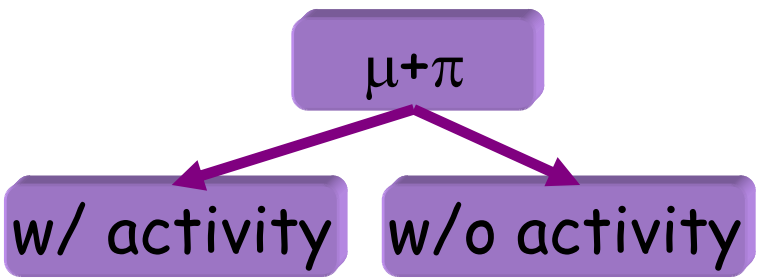
Mis-ID probability
Muon: 1.1%
Proton: 12%

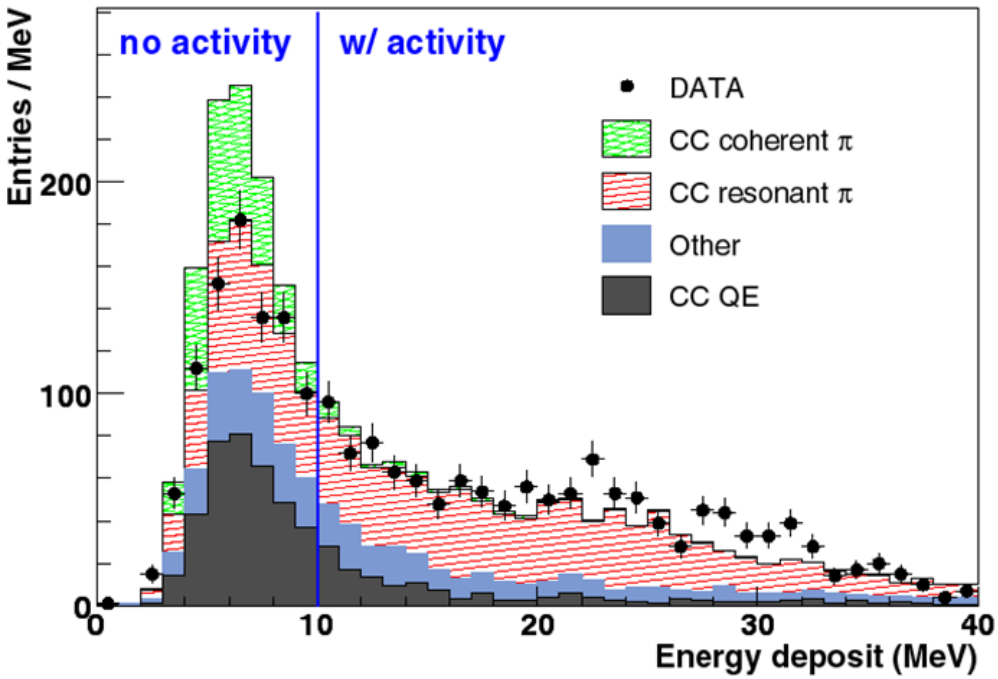


Vertex activity

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



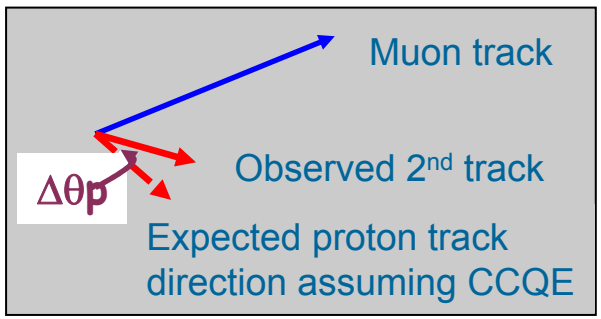


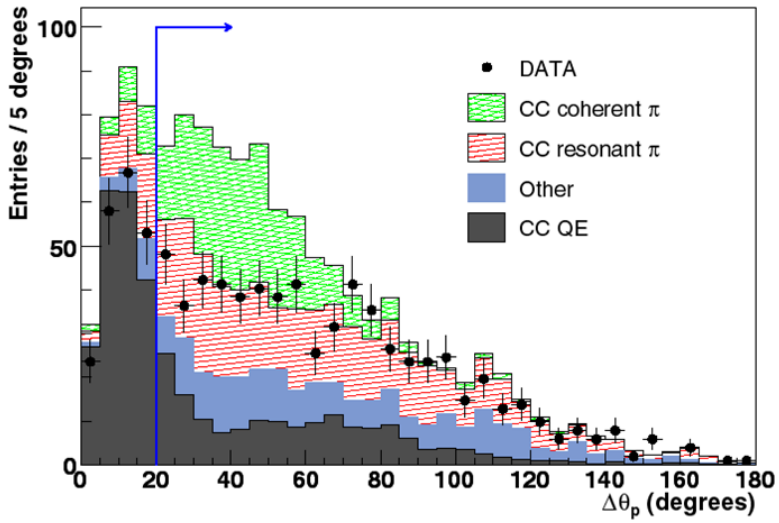


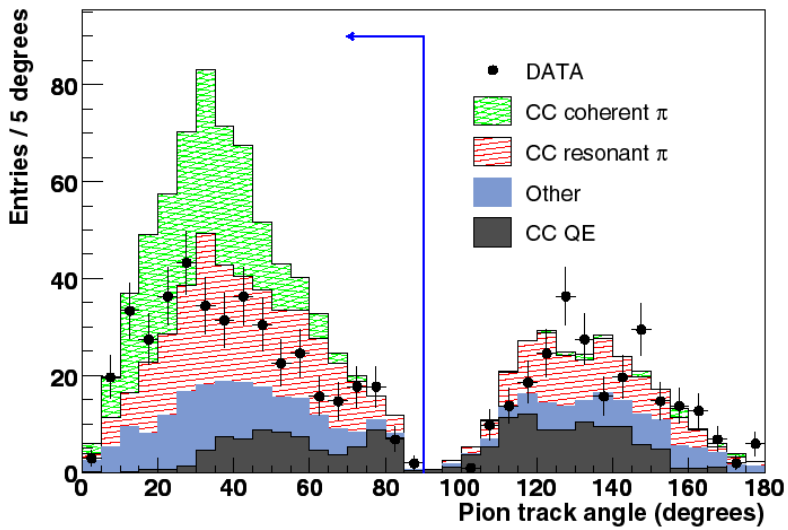
Extracting CC coherent pion events

1) CC-QE rejection

$\Delta\theta p$: 3D angle between the expected and the observed 2nd tracks







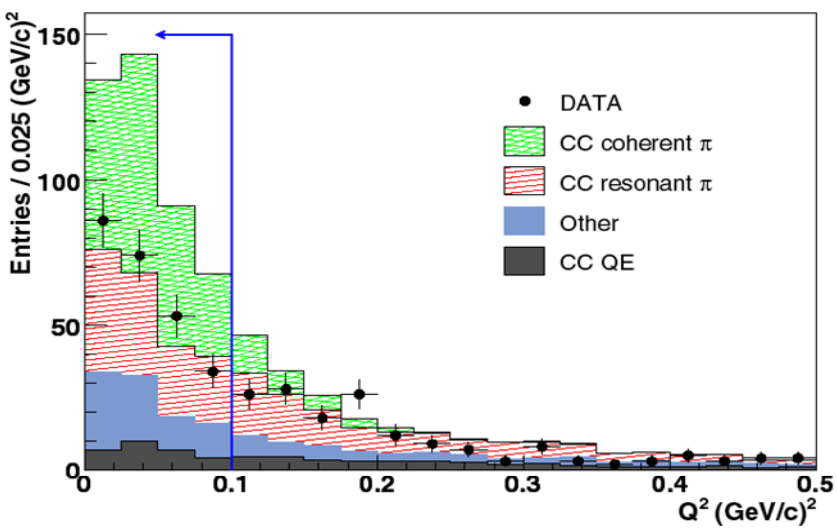
2) CC-resonant pion rejection

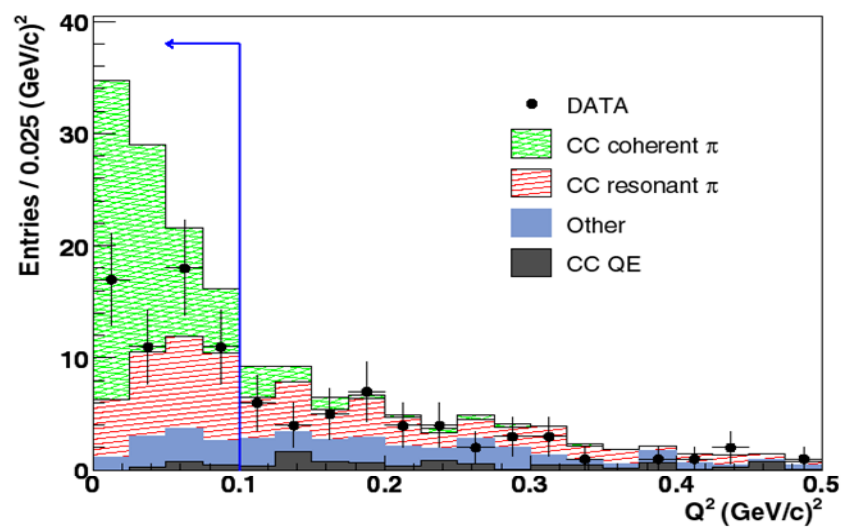
Events with a forward-going Pion candidate are selected

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

Results

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

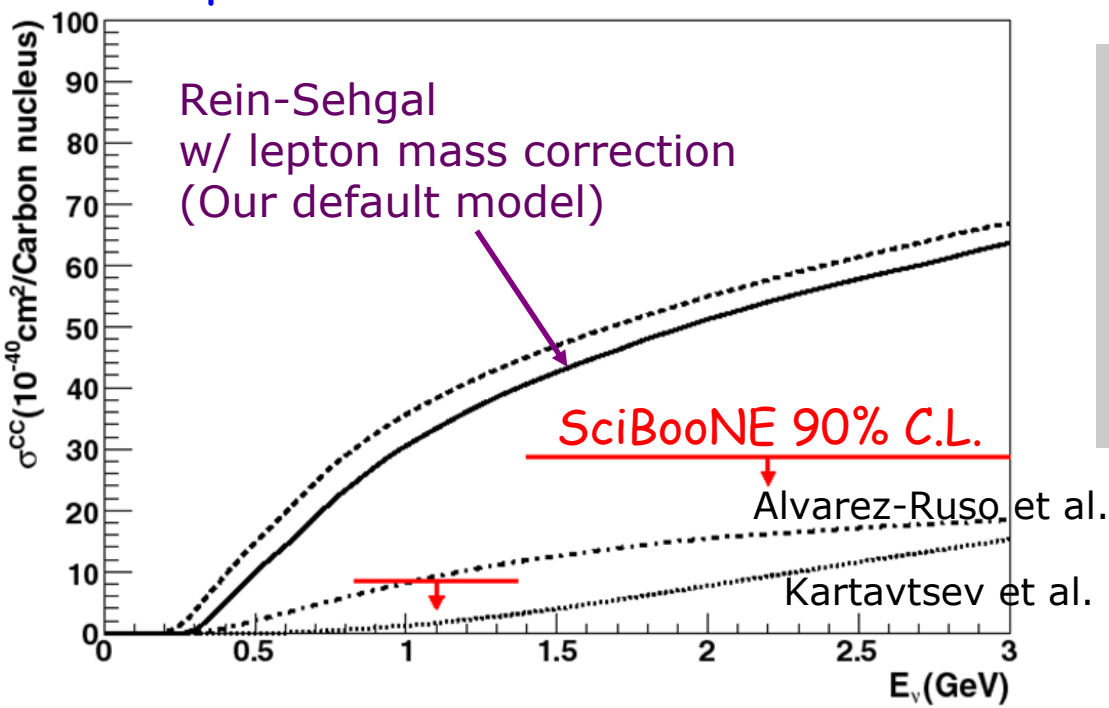
90% CL upper limit (Bayesian)

σ(CC coherent π)/σ(CC) < 0.67×10^{-2} for <Eν>=1.1 GeV
< 1.36×10^{-2} <Eν>=2.2 GeV

K. Hiraide et al, PRD78,112004 (2008)

Results (cont'd)

Comparison with theoretical models



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

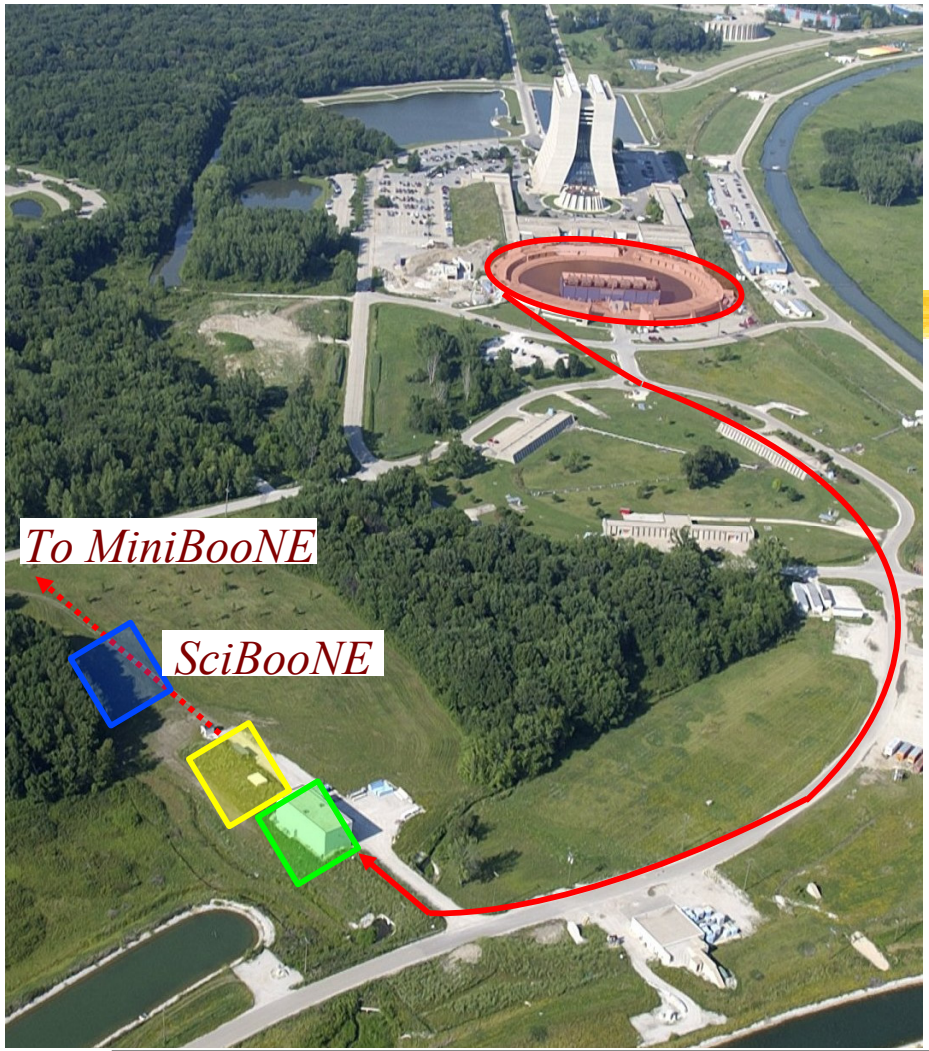
We reveal that the Rein-Sehgal model breaks down in the few-GeV region

Summary

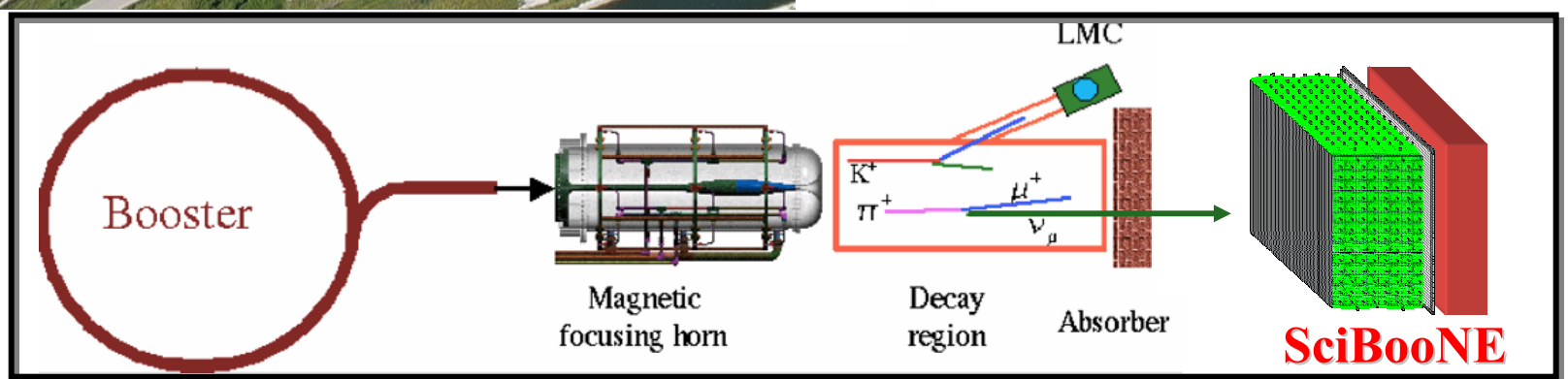
- 1st SciBooNE result
  - "Search for CC coherent pion production" published in Phys. Rev. D
  - σ(CC-coherent π)/σ(CC)<0.67x10^{-2} @ 1.1 GeV
  - σ(CC-coherent π)/σ(CC)<1.36x10^{-2} @ 2.2 GeV

- Many analyses are on-going
  - Cross section measurements
    - CC-QE, CC-π^+, CC-π^0, NC-π^0, NC-elastic, antineutrino
  - neutrino spectrum measurements
  - Expect many results at NuInt09

Backup slides

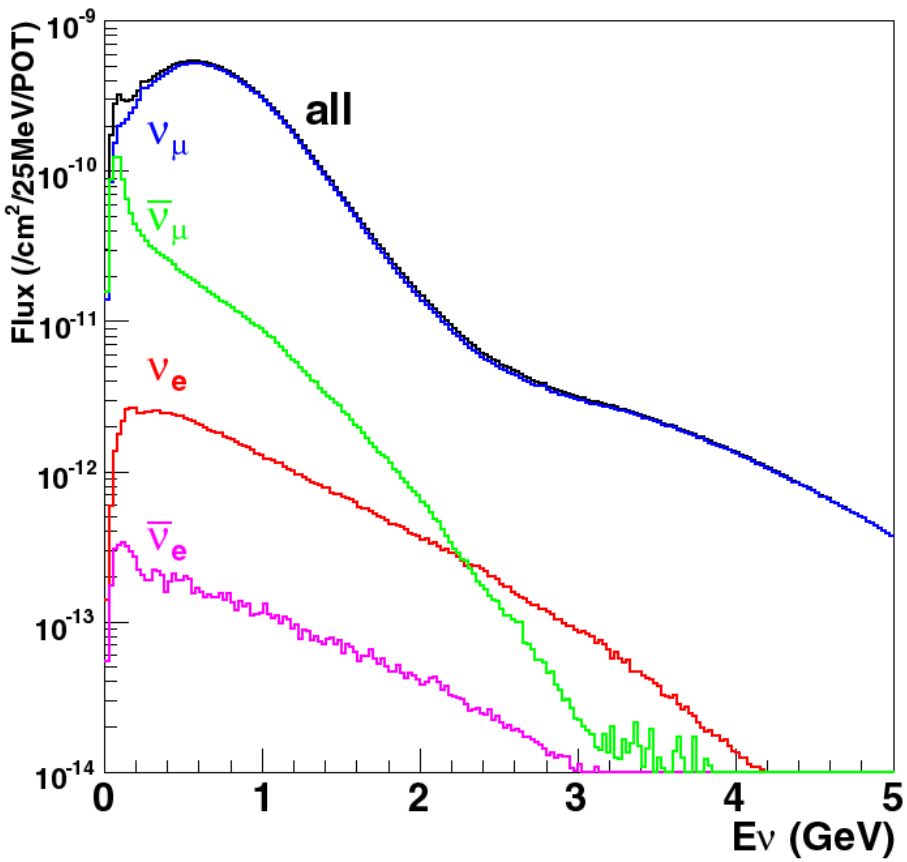


- Booster Proton accelerator
  - 8 GeV protons sent to target
- Target Hall
  - Beryllium target: 71cm long 1cm diameter
  - Resultant mesons focused with magnetic horn
  - Reversible horn polarity
- 50m decay volume
  - Mesons decay to μ & ν_μ
  - Short decay pipe minimizes $\mu \rightarrow \nu_e$ decay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



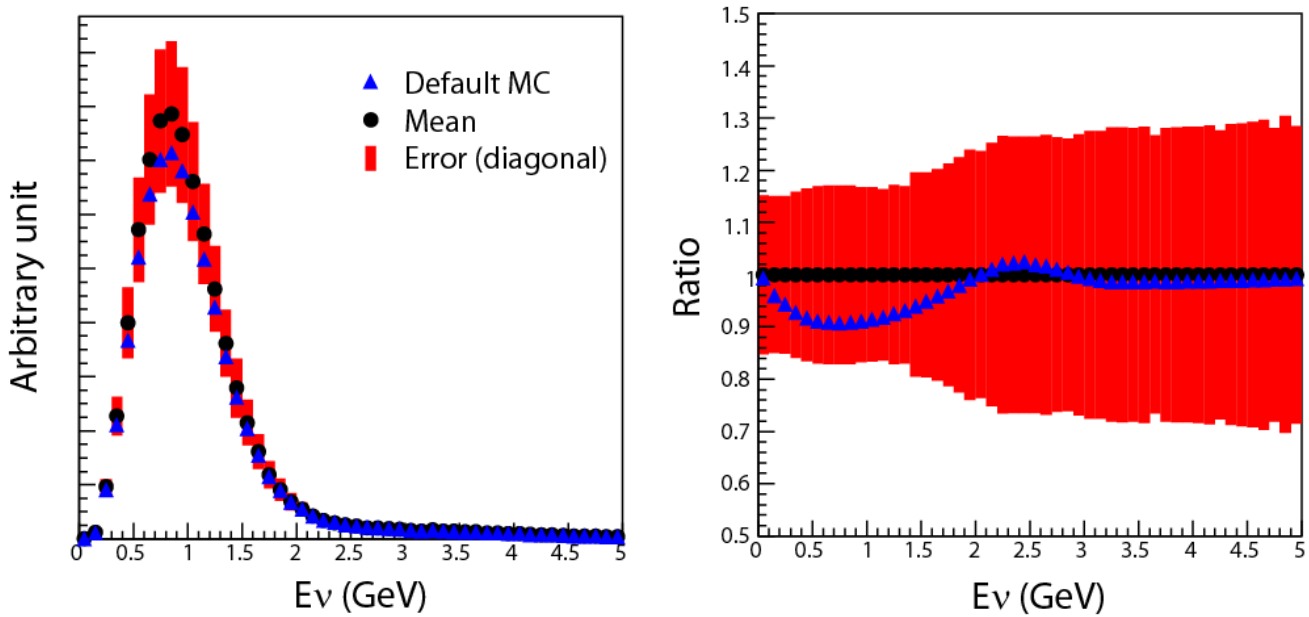
Booster Neutrino Beam (BNB)

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

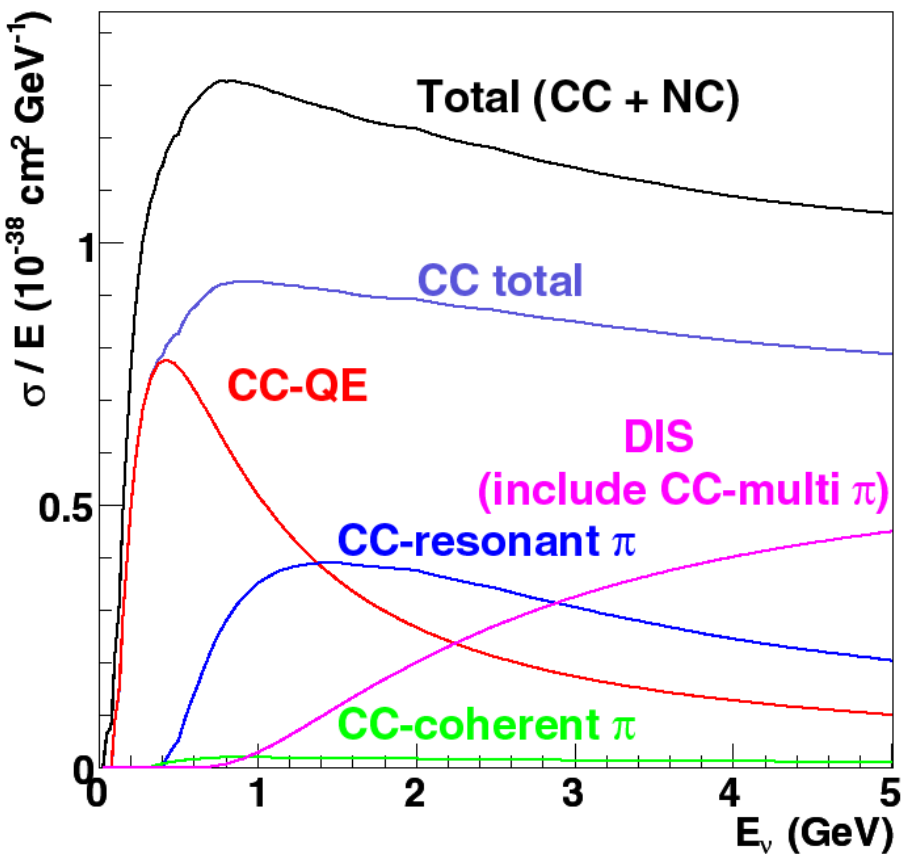
Neutrino flux uncertainties



- ~15% uncertainty in the overall normalization
- Mainly due to uncertainty in the pion production cross section

Measure cross section ratio (normalized to total CC)
Not absolute cross section

Neutrino event generator (NEUT)



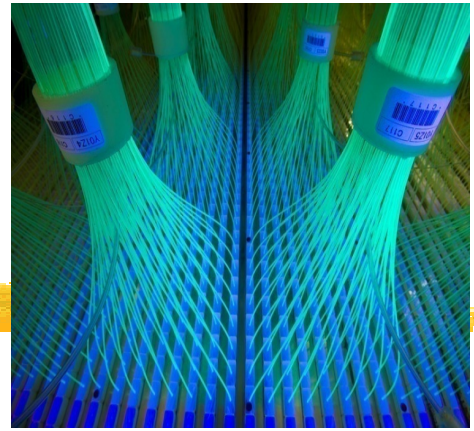
- QE
  - Llewellyn Smith, Smith-Moniz
  - M_A=1.2GeV/c^2
  - P_F=217MeV/c, E_B=27MeV (for Carbon)
- Resonant π
  - Rein-Sehgal (2007)
  - M_A=1.2 GeV/c^2
- Coherent π
  - Rein-Sehgal (2006)
  - M_A=1.0 GeV/c^2

  CC/NC -1π
- Deep Inelastic Scattering
  - GRV98 PDF
  - Bodek-Yang correction
- Intra-nucleus interactions

Neutrino events in SciBooNE

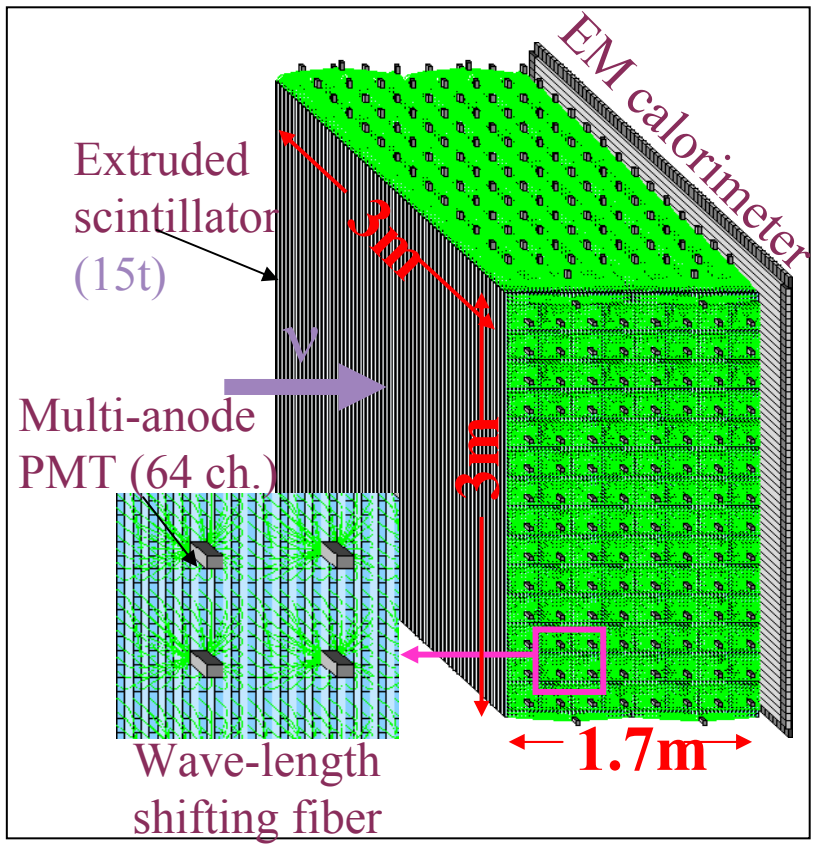
Mode	Number of ν_μ interactions (/10tons/10^{20}POT)
CC QE	50,800
CC resonant π	26,200
CC coherent π	1,700
CC DIS	6,300
NC elastic	21,400
NC resonant π	10,400
NC coherent π	1,000
NC DIS	2,000

SciBar detector

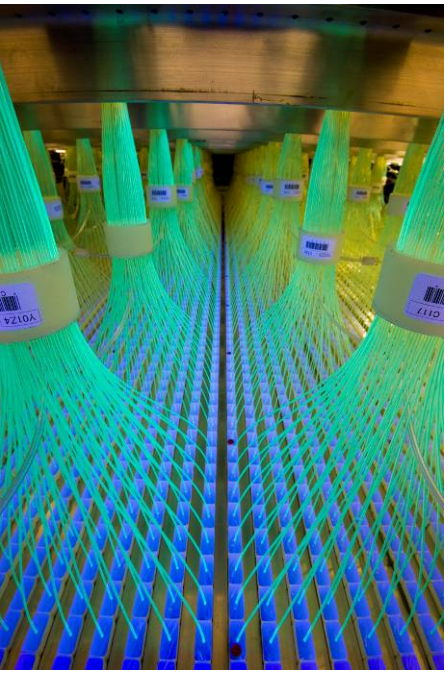


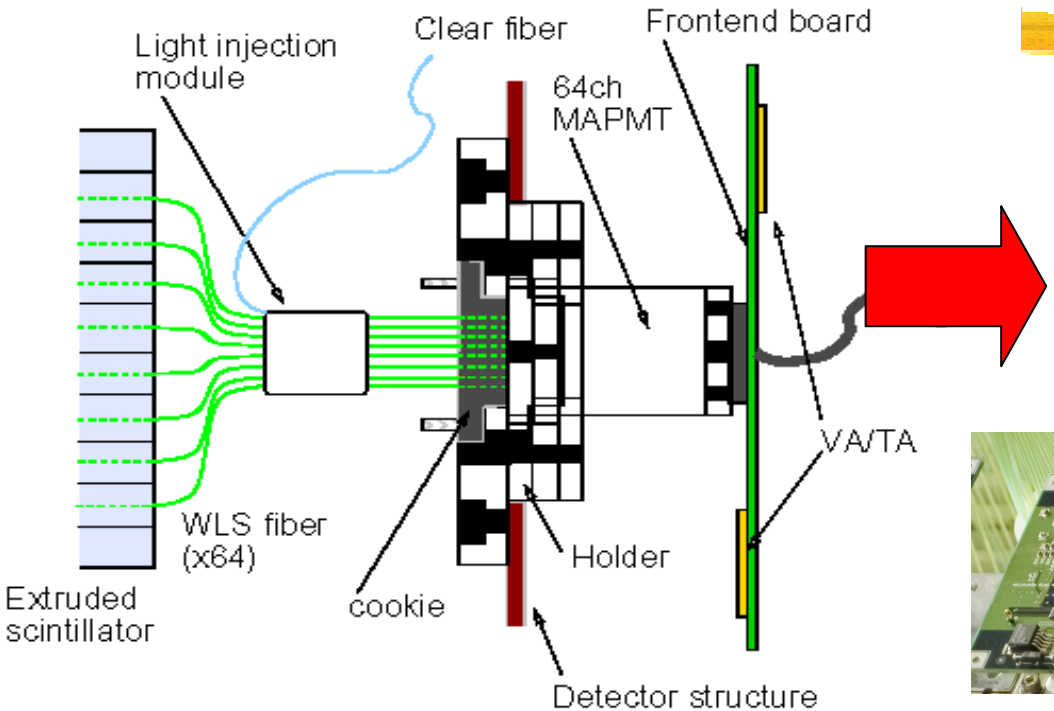
- Extruded scintillators with WLS fiber readout
- Scintillators are the neutrino target
- 3m x 3m x 1.7m (Total: 15 tons)
- 14,336 channels
- Detect short tracks (>8cm)
- Distinguish a proton from a pion by dE/dx

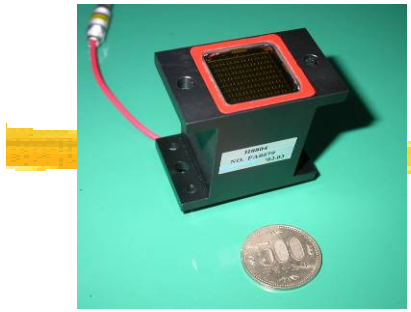
➔Clear identification of ν interaction process



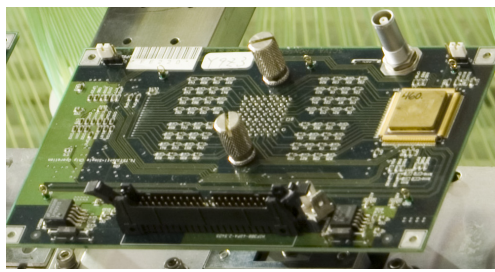
SciBar readout







64 charge info.
2 timing info.



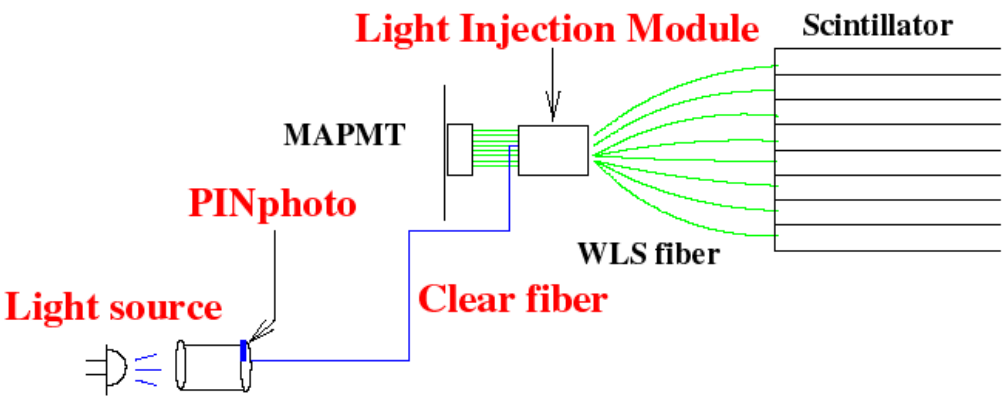
Extruded Scintillator (1.3×2.5×300cm³)
- made by FNAL (same as MINOS)

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

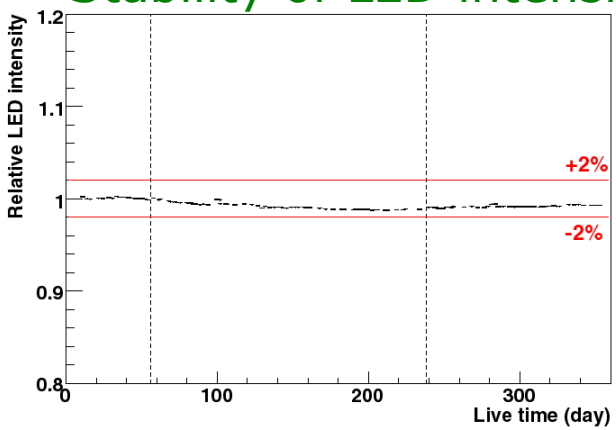
64-channel Multi-Anode PMT
- 2x2mm² pixel (3% cross talk@1.5mmΦ)
- Gain Uniformity (20% RMS)
- Good linearity (~200p.e. @6×10⁵)

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

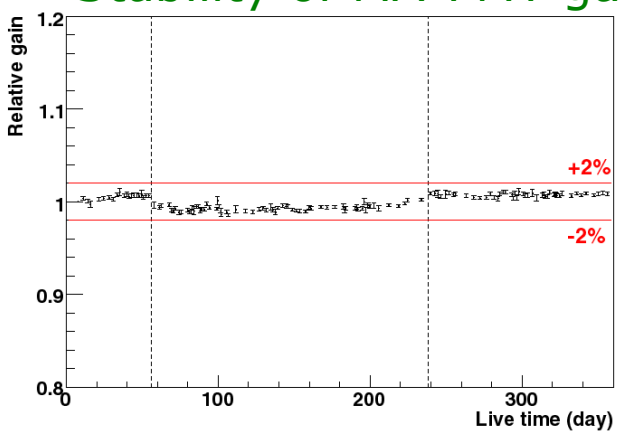
Gain monitoring system



Stability of LED intensity



Stability of MA-PMT gain



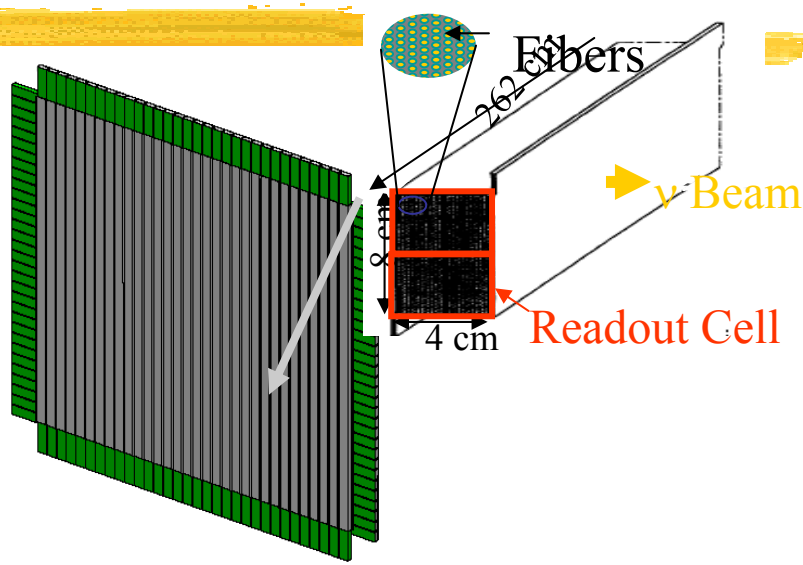
- MA-PMT gains are monitored every ~8 hours using custom-made monitoring system
- LED intensity is monitored with a precision of 0.1%
- MA-PMT gains were stable within 2%

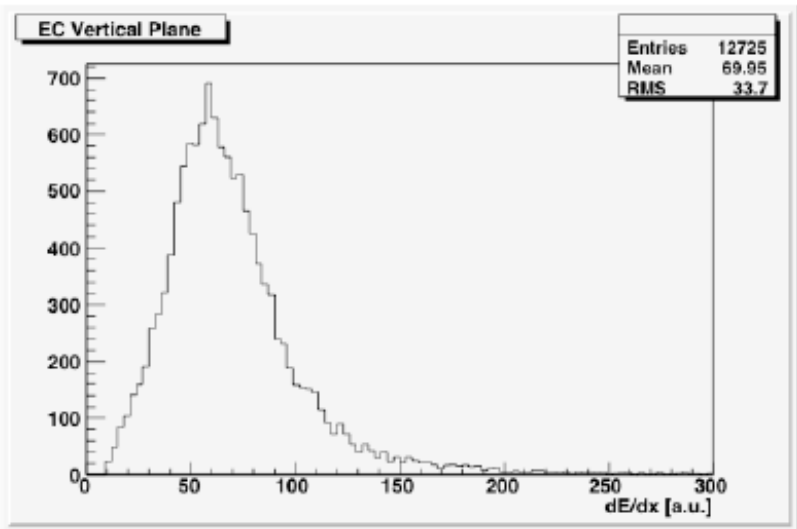
➔ Correct for the gain drift

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%

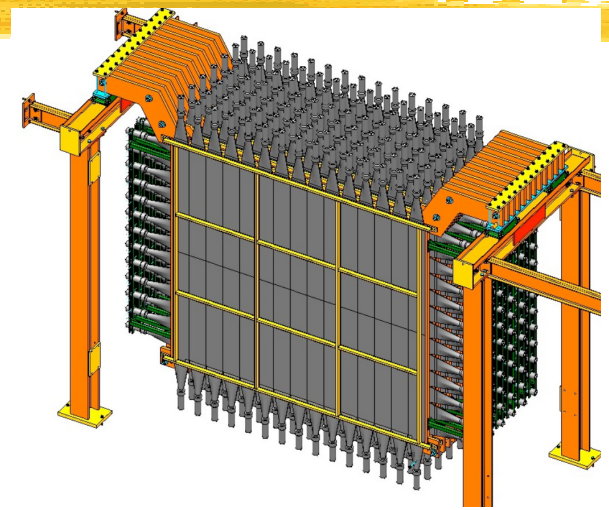




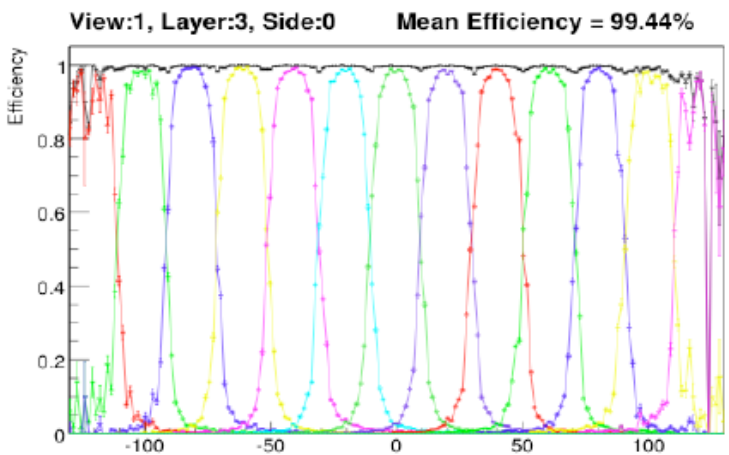
dE/dx distribution of vertical plane for cosmic ray muons

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

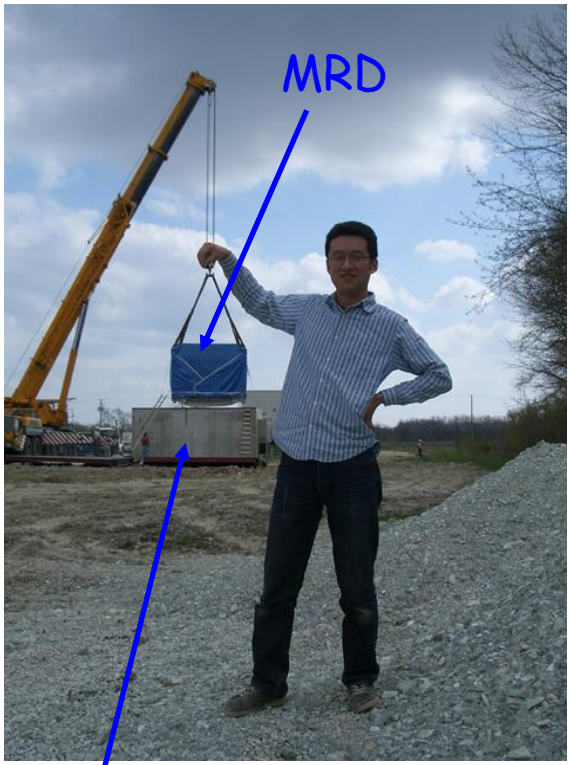
SciBooNE Timeline

Groundbreaking ceremony (Sep. 2006)

Detector Assembly (Nov. 2006 -Mar.2007)

SciBooNE Timeline

Detector installation (Apr. 2007)

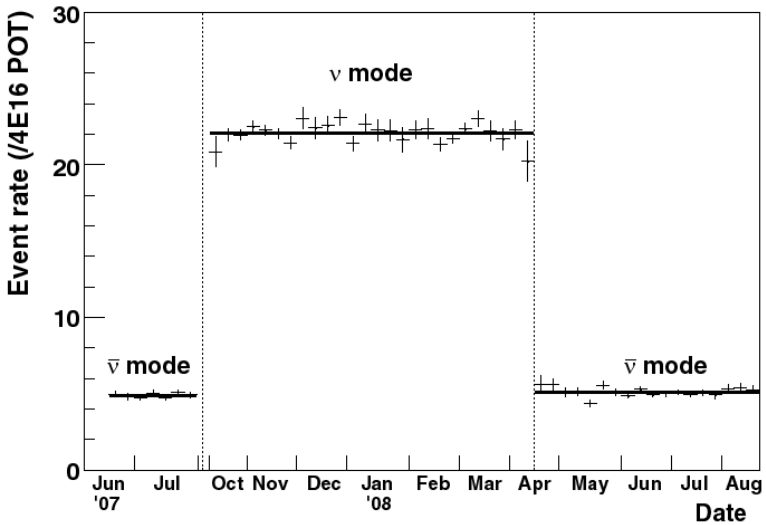


SciBar/EC

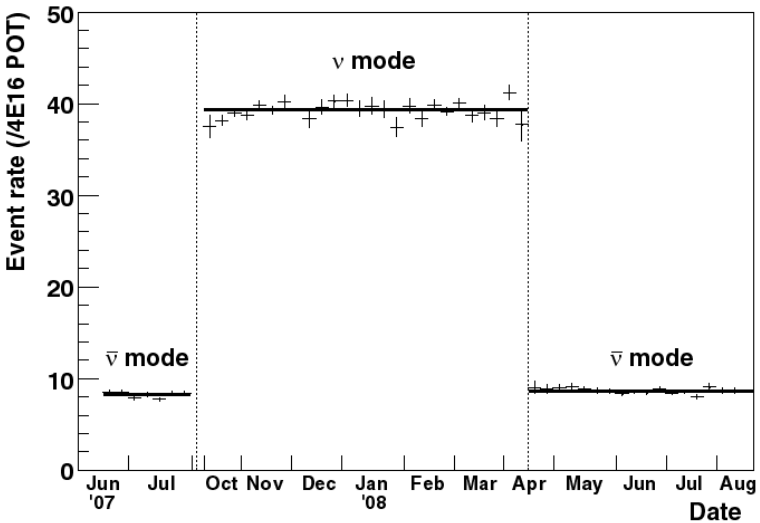
End-of-run party
(Aug. 2008)

Neutrino event rate stability

Neutrino events occured in SciBar



Neutrino events occured in MRD

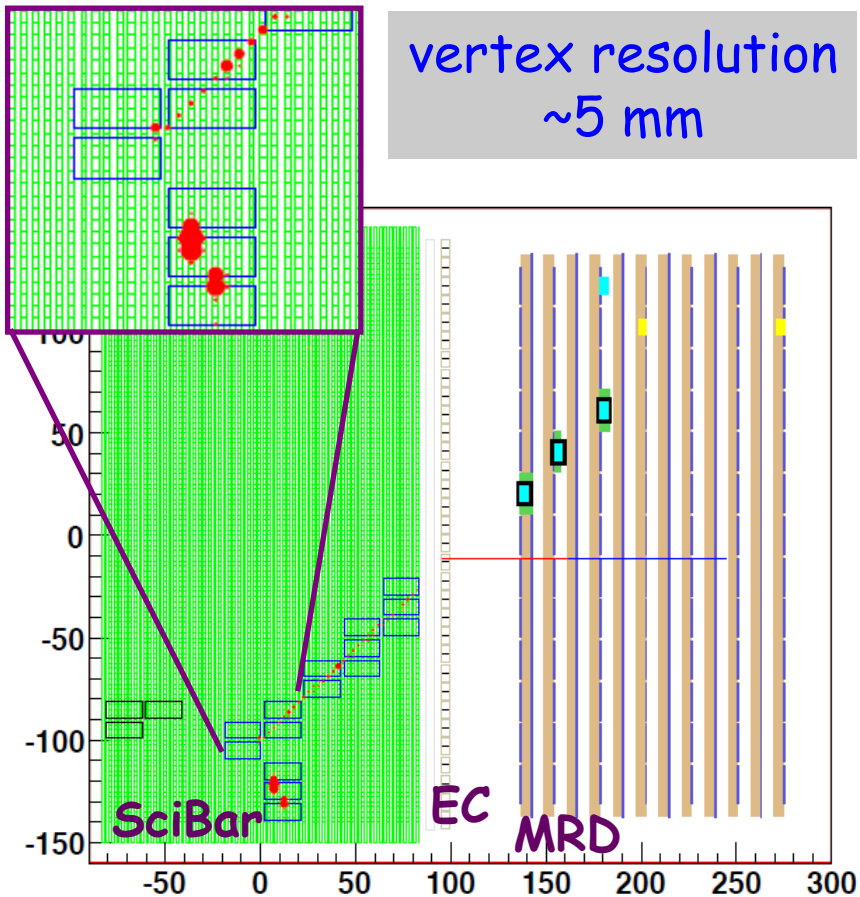


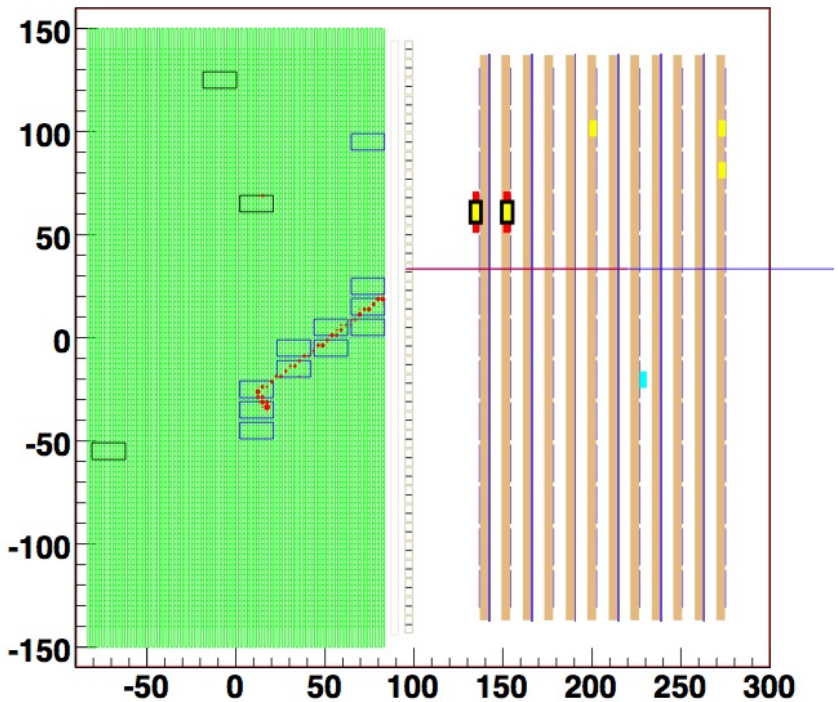
Neutrino event displays

Real SciBooNE Data

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

vertex resolution
~5 mm

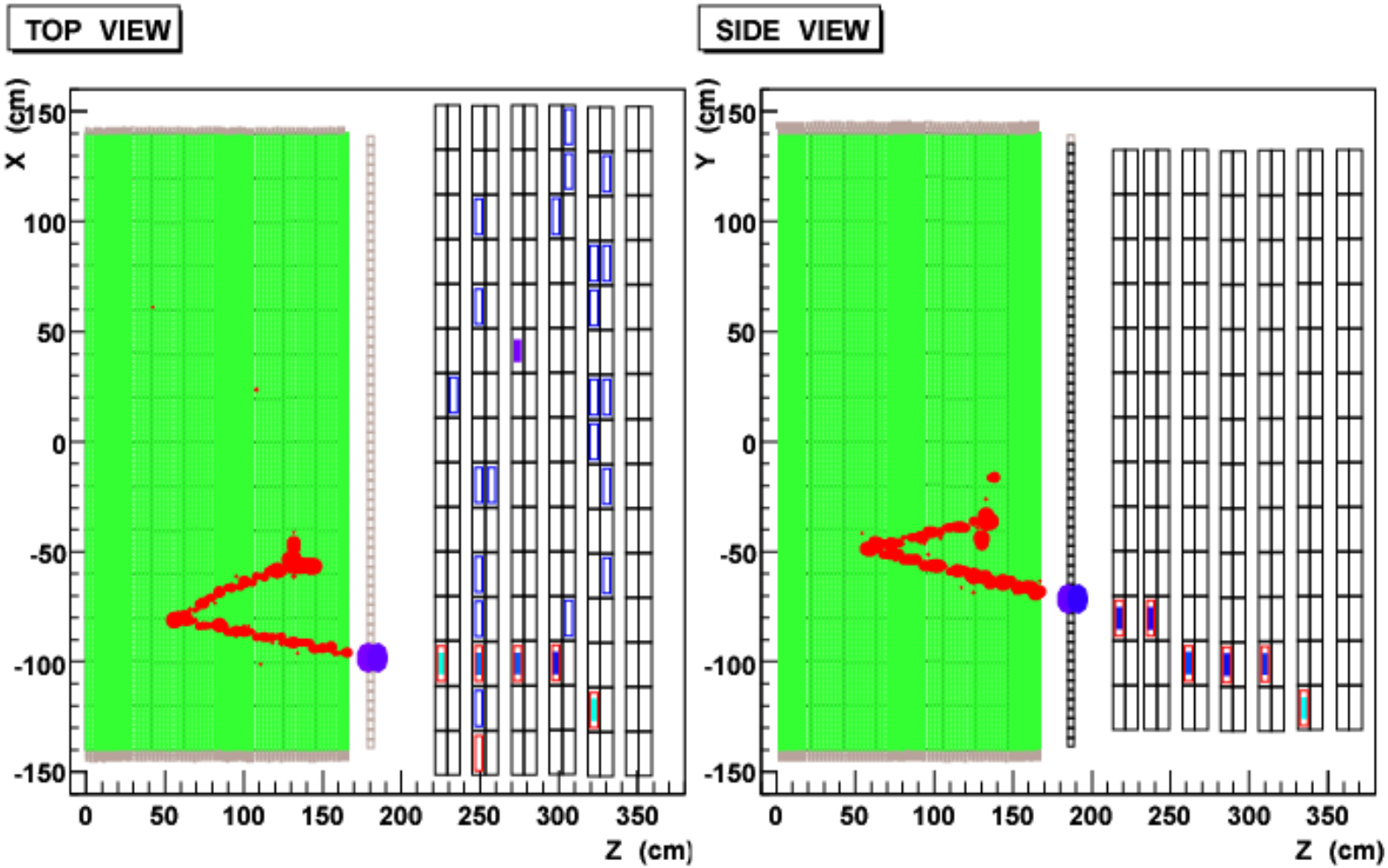




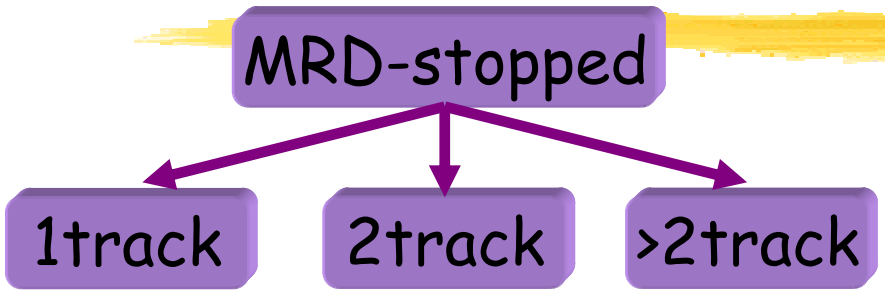
anti-ν_μ CC-QE candidate
($\bar{\nu}_\mu + p \rightarrow \mu + n$)

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

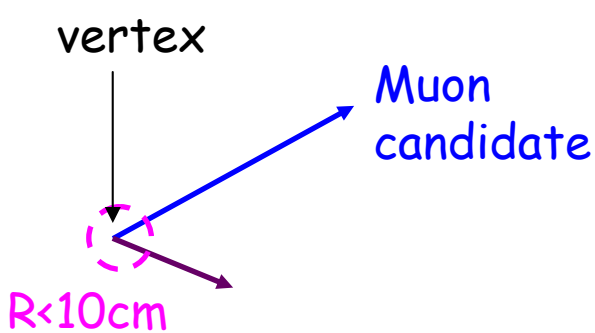
CC-1π^+ candidate

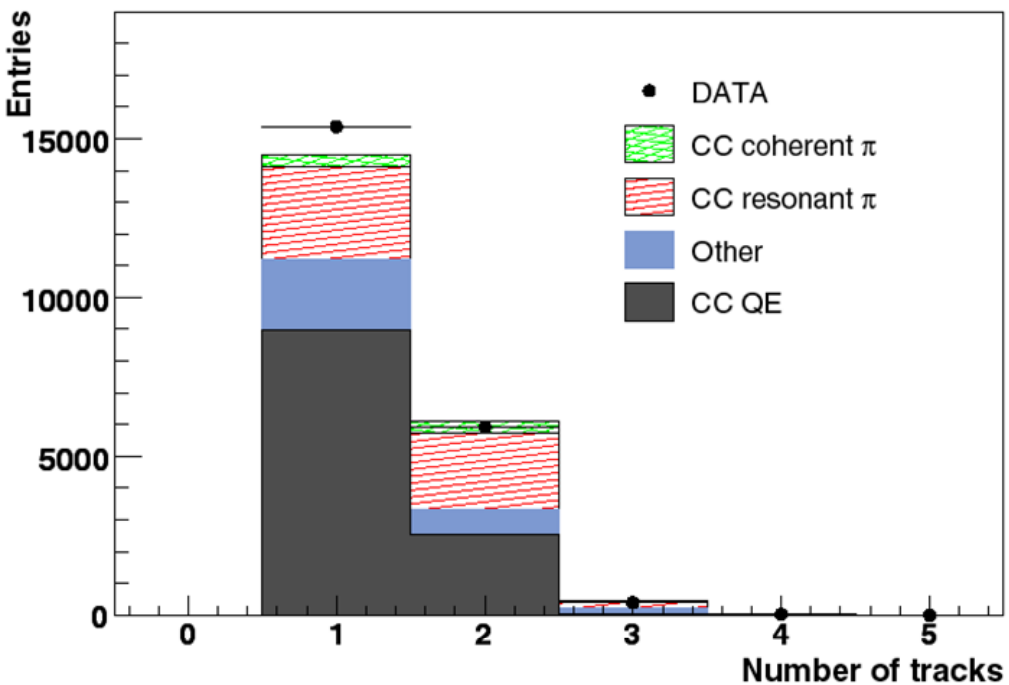


Number of tracks

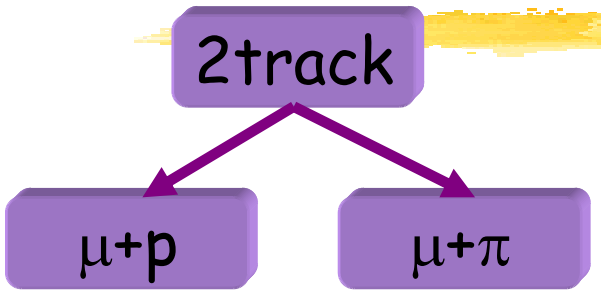


Search for tracks from the vertex (R<10cm)

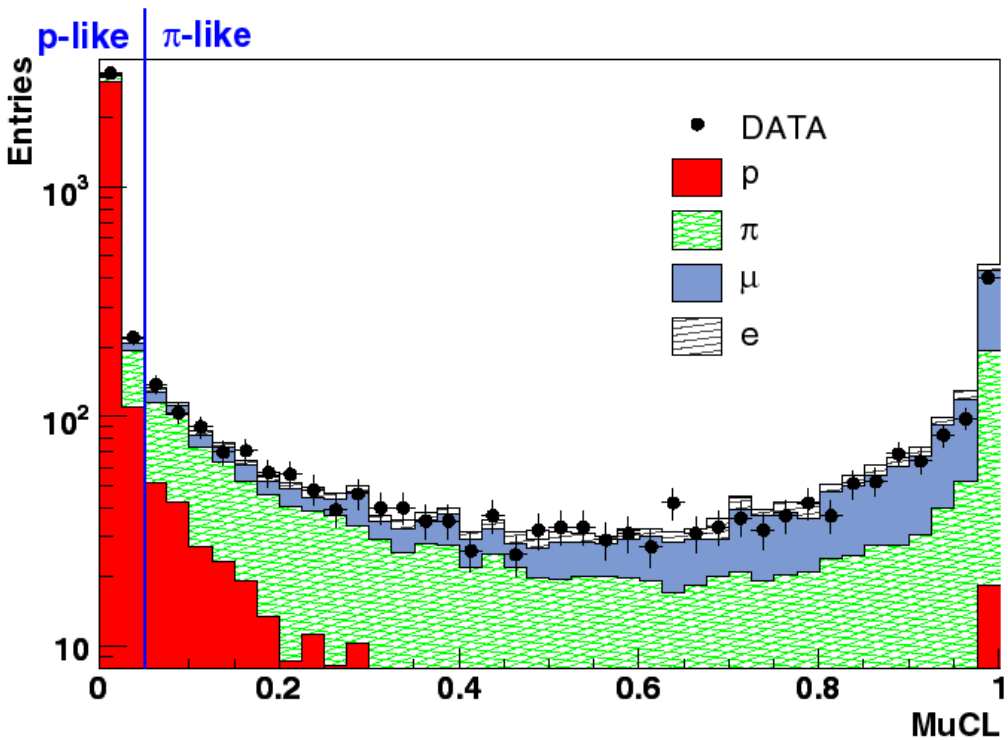




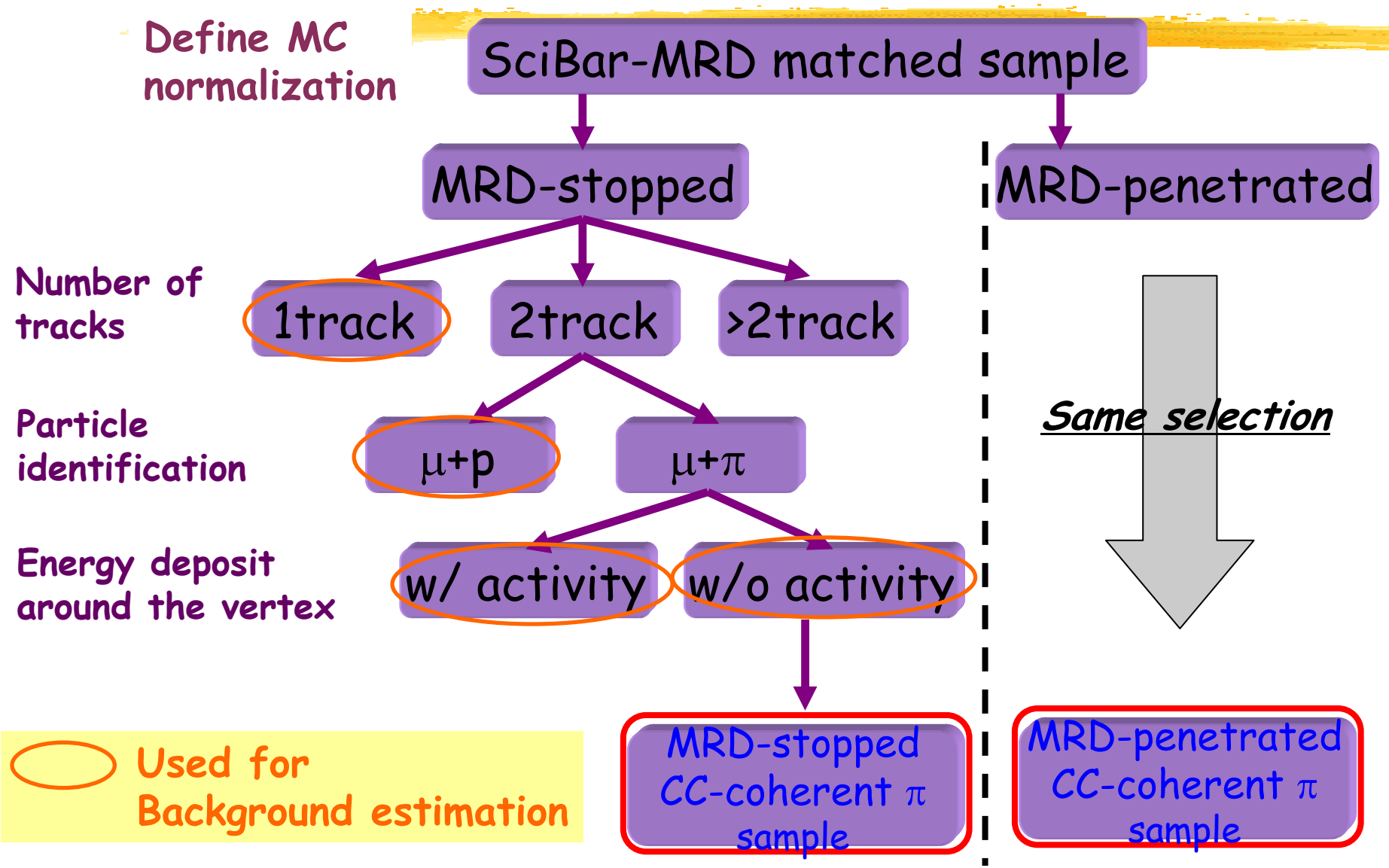
Particle identification (cont'd)



MuCL for 2nd track in 2-track event



CC event classification



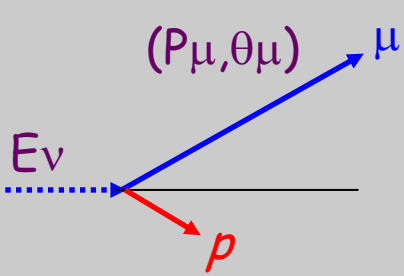
Tuning of MC simulation

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 reconstruction assuming CC-QE (ν+n→μ+p) interaction



CC-QE

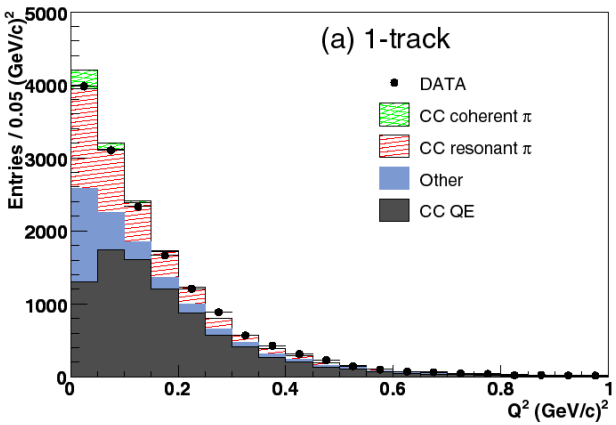
$$Q^2_{rec} = 2E_\nu^{rec}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

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

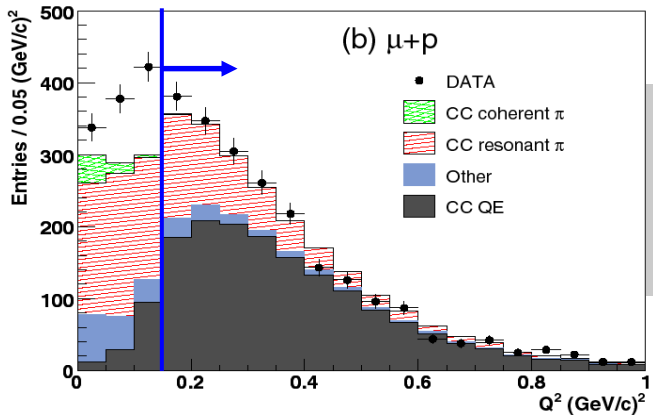
V: nuclear potential (27MeV)

Reconstructed Q^2 distributions after fitting

1-track

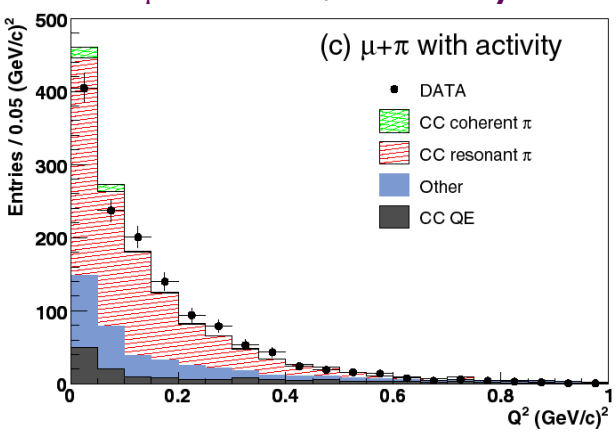


μ+p

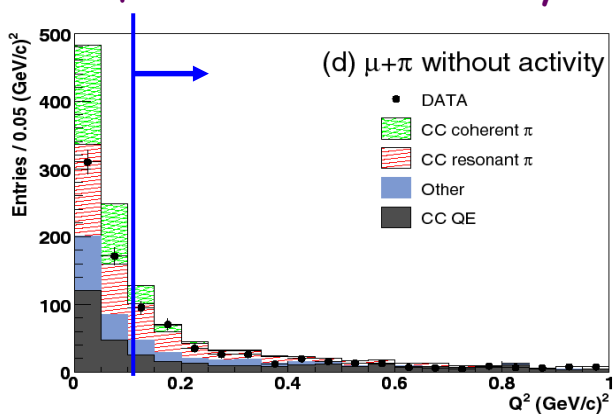


low Q^2 region in μ+p events is excluded from fitting

μ+π with activity



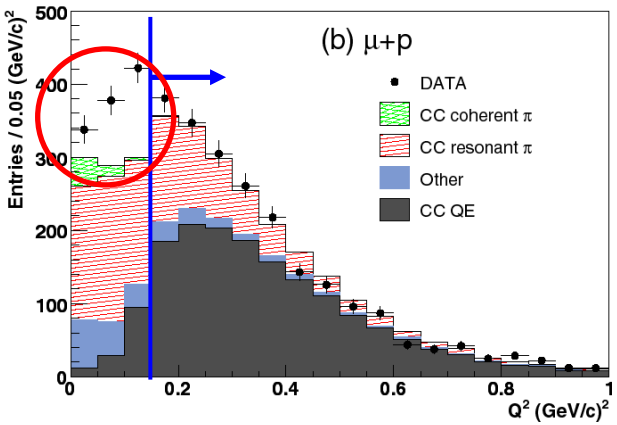
μ+π without activity



CC coherent π signal region is excluded from fitting

Before fit : χ^2/ndf = 473/75 = 6.31
After fit : χ^2/ndf = 117/67 = 1.75

Data excess in μ+p sample

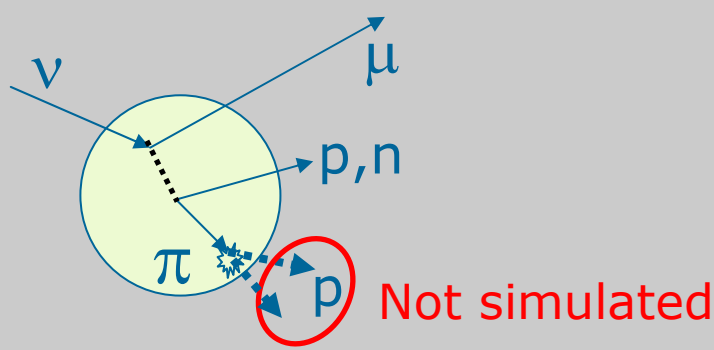


Features of excess events

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

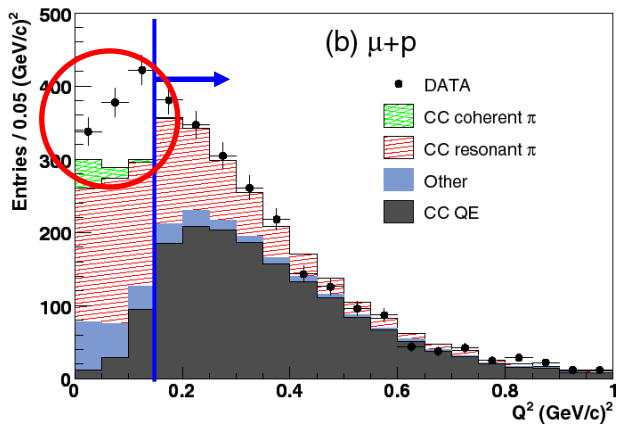
Possible candidate

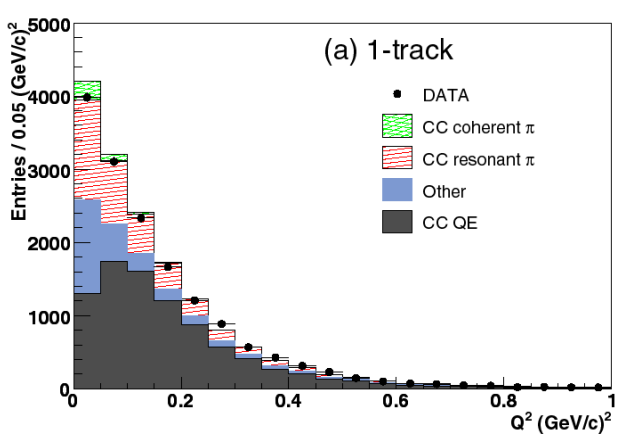
CC resonant pion events in which pion is absorbed in the nucleus



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

Data excess in μ+p sample (cont'd)



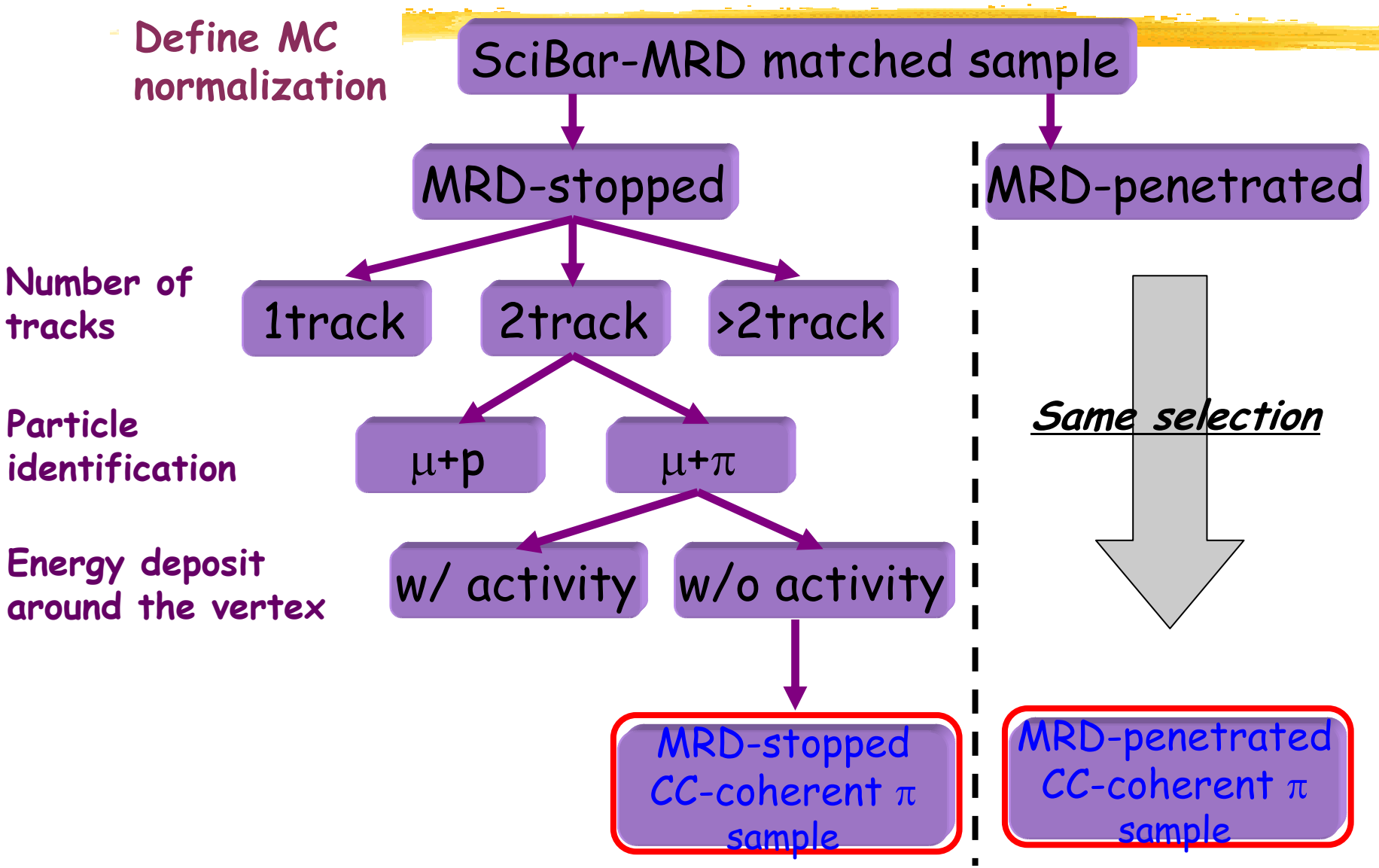


Therefore,
we expect migration between the μ+p sample and 1-track sample

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

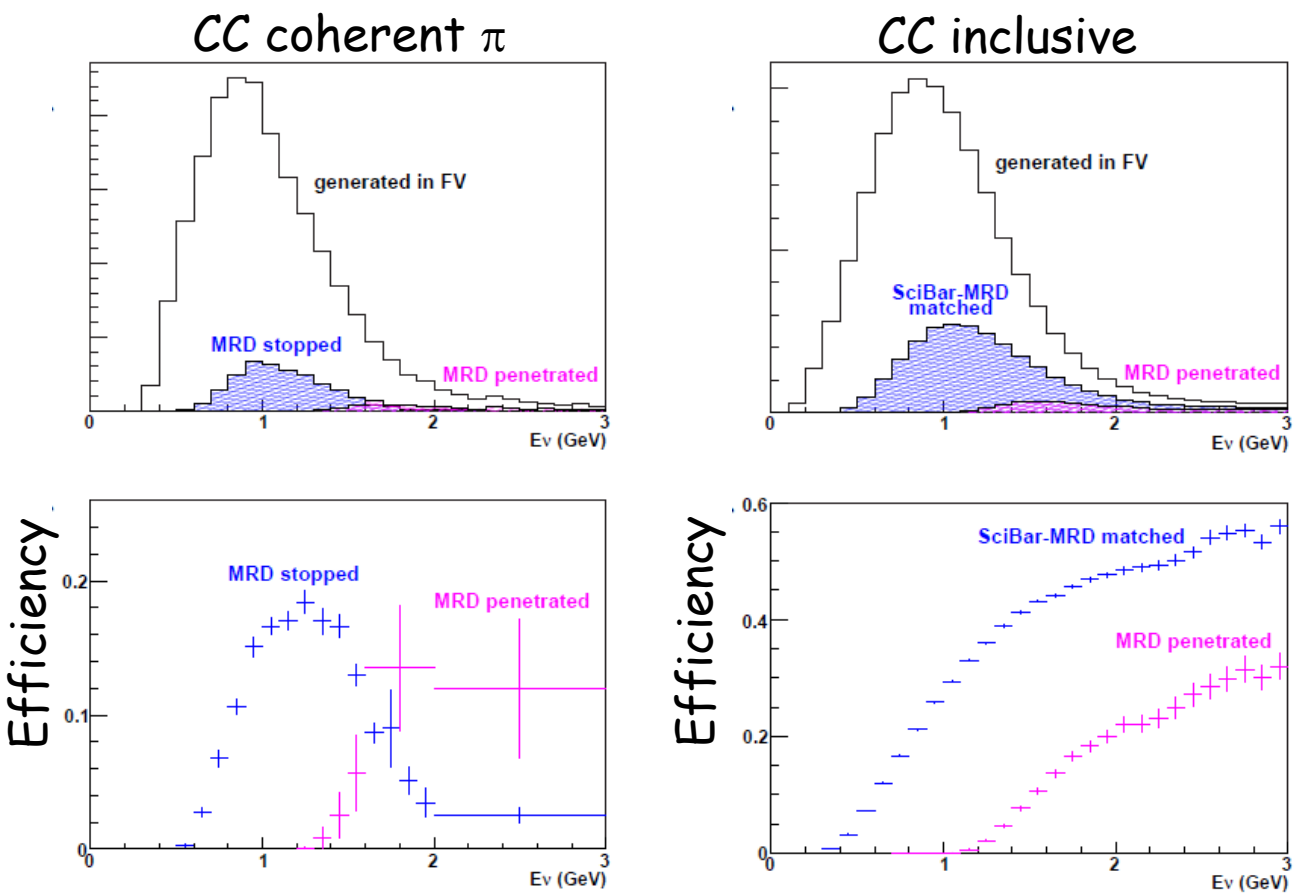
This doesn't affect CC coherent pion measurement

CC event classification



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

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



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

Systematic errors

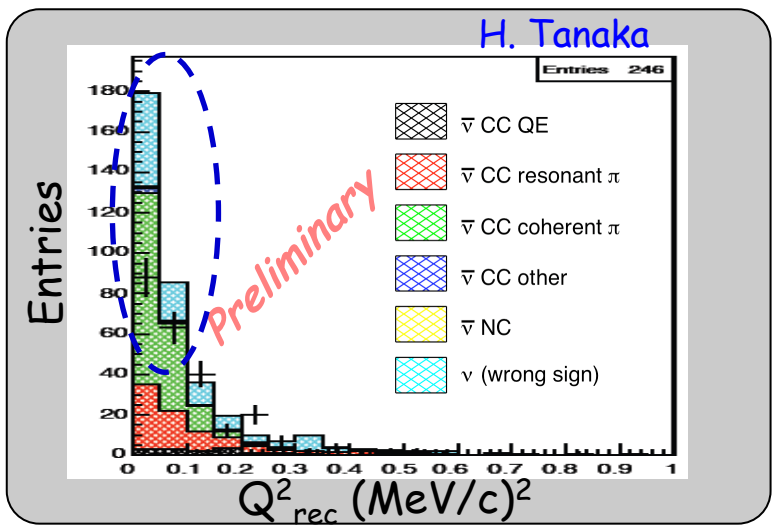
	MRD stopped Error ($x10^{-2}$)	MRD penetrated Error ($x10^{-2}$)
Detector response	+0.10 / -0.18	+0.18 / -0.18
Nuclear effect	+0.20 / -0.07	+0.19 / -0.09
Neutrino interaction model	+0.17 / -0.04	+0.08 / -0.04
Neutrino beam	+0.07 / -0.11	+0.27 / -0.13
Event selection	+0.07 / -0.14	+0.06 / -0.05
Total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

Future prospects of coherent pion analysis

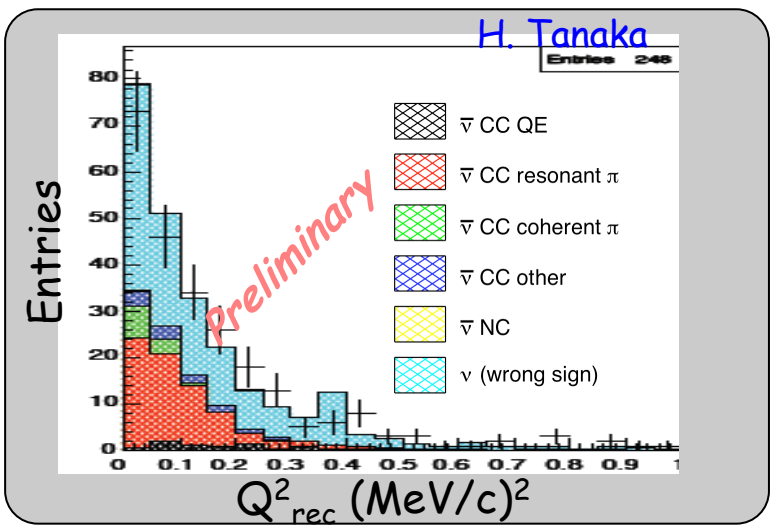
Antineutrino CC coherent pion production

Most models predict similar absolute cross sections for neutrino and antineutrino coherent pion production

Coherent pion enriched sample
($\mu+\pi$ w/o vertex activity)



Counter event sample
($\mu+\pi$ w/ vertex activity)



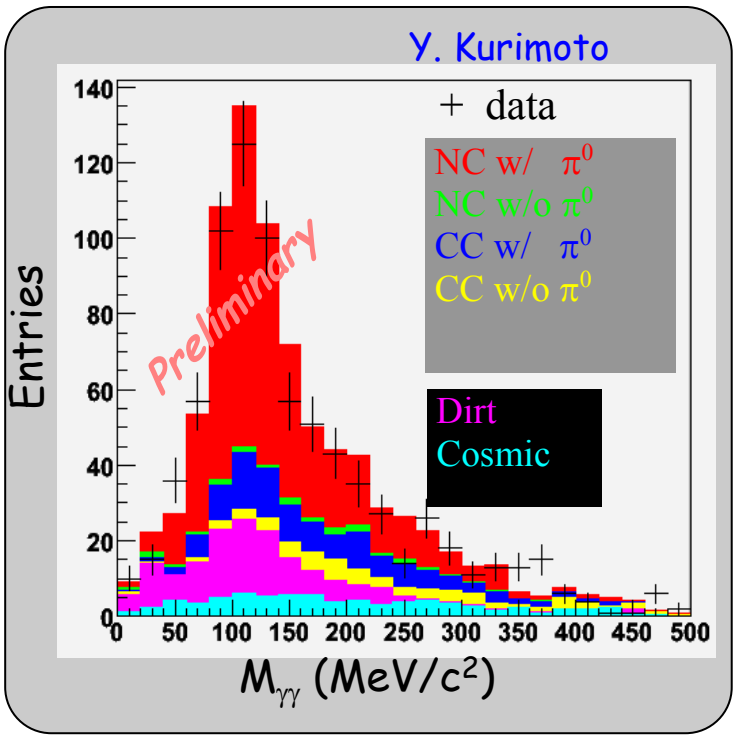
- Large DATA deficit in antineutrino coherent pion sample
- Analysis is on-going

Future prospects of coherent pion analysis

Neutrino NC coherent pion production

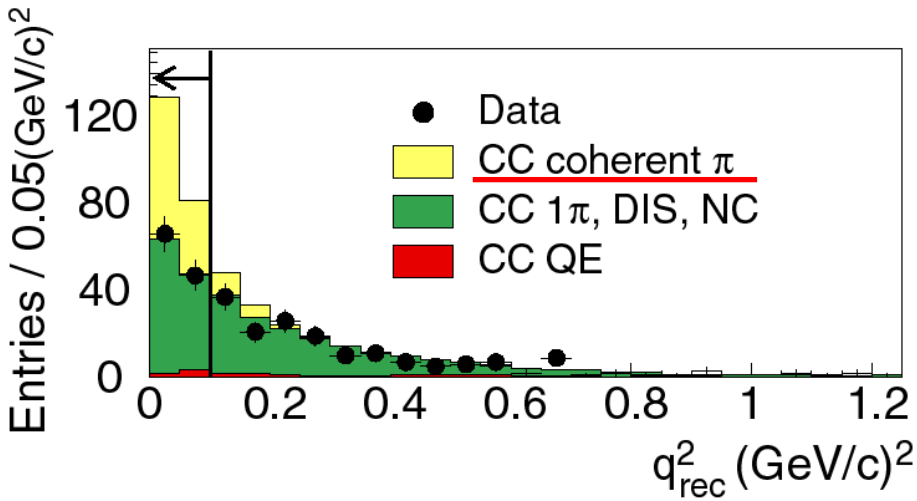
NC coherent pion measurement in SciBooNE may verify MiniBooNE's result

NC π^0 analysis is in process



Surprises

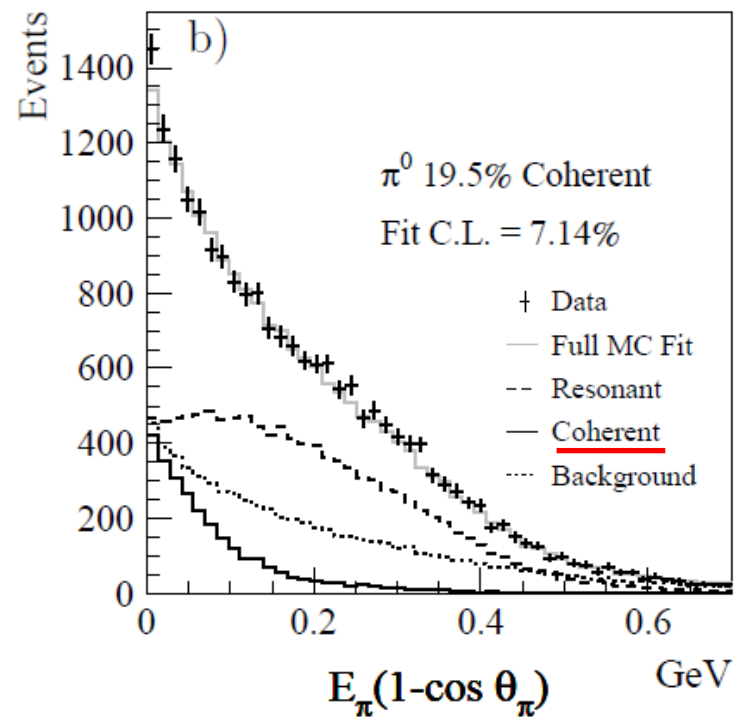
CC coherent π^+
K2K,
Phys.Rev.Lett. 95,252301 (2005)



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,
Phys.Lett. B664,41 (2008)

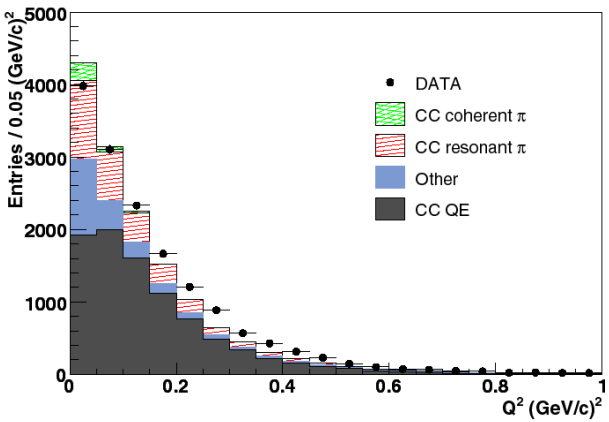


First observation of NC coherent pion production at $E\nu$<2GeV

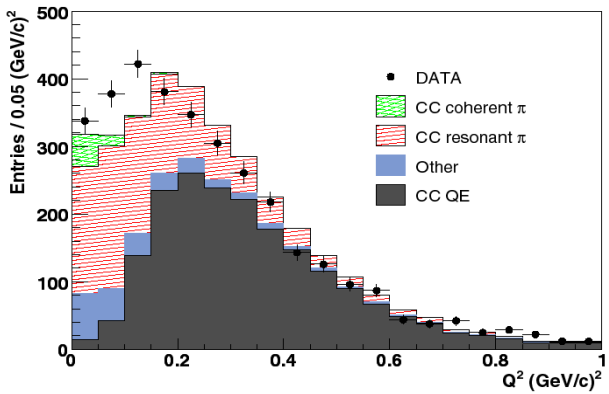
65% of the model prediction

Q^2 distributions before tuning MC

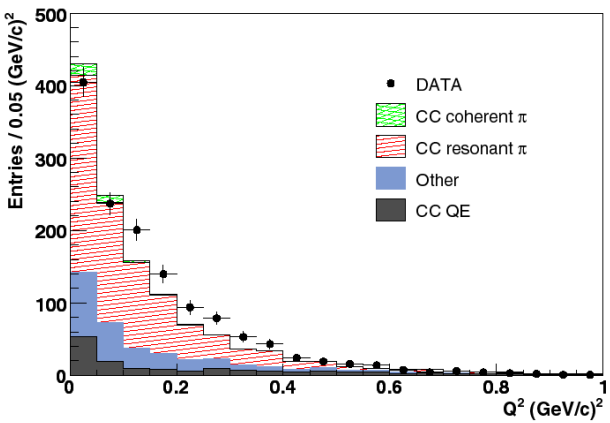
1-track



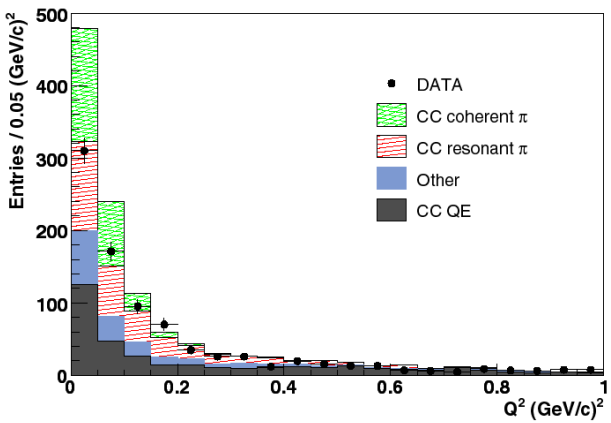
μ+p



μ+π with activity



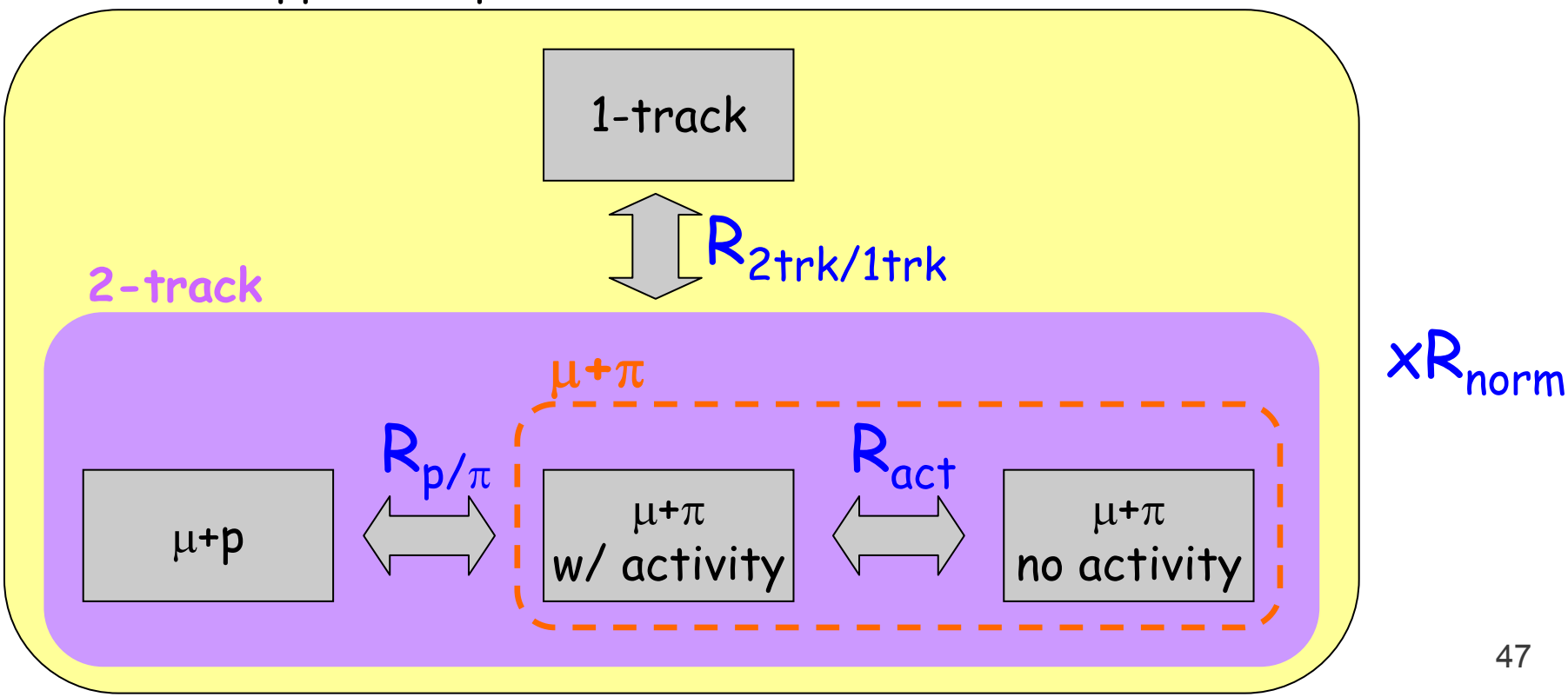
μ+π without activity



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-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

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

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

χ^2 definition

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

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

Binned likelihood

i: Q^2 bins

j: sub-samples

Constraint on fitting parameters

V: covariance matrix

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

Discussions

K2K (<Eν>=1.3 GeV)

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

improved

slightly improved

SciBooNE (<Eν>=1.1 GeV)

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

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

SciBooNE results are consistent with K2K result

Discussions (cont'd)

Our result creates active controversies on the model of coherent pion production in the community

Berger and Sehgal [arXiv:0812.2653]

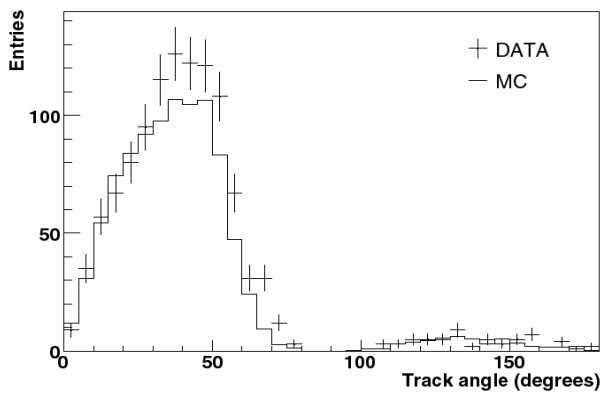
They pointed out that the original Rein-Sehgal model overestimates pion-Carbon cross sections in the Resonance region. ($0.2<P\pi$ (GeV/c)<0.4)

Their new predictions
σ(CC coherent π)/σ(CC) = 0.58×10^{-2} at 1.1 GeV
σ(CC coherent π)/σ(CC) = 0.68×10^{-2} at 2.2 GeV
Consistent with our results
However, cannot explain MiniBooNE result

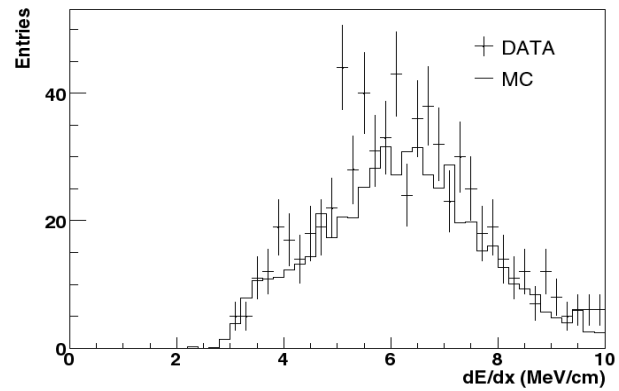
Further investigation can be performed in SciBooNE using a plenty of kinematic information ($P\mu$, $\theta\mu$, $L\pi$, $\theta\pi$ etc)
➔ Future prospect

Data excess in μ+p sample

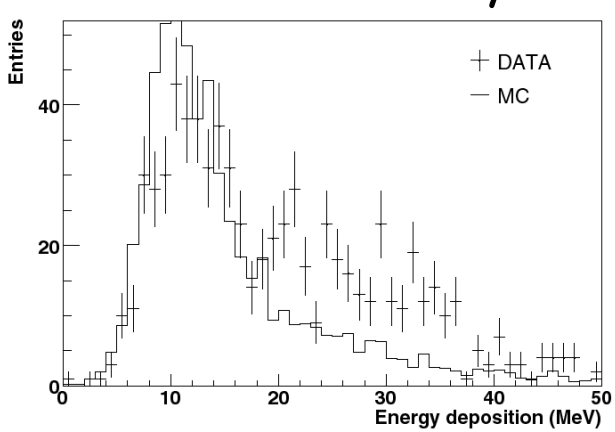
track angle of 2nd track

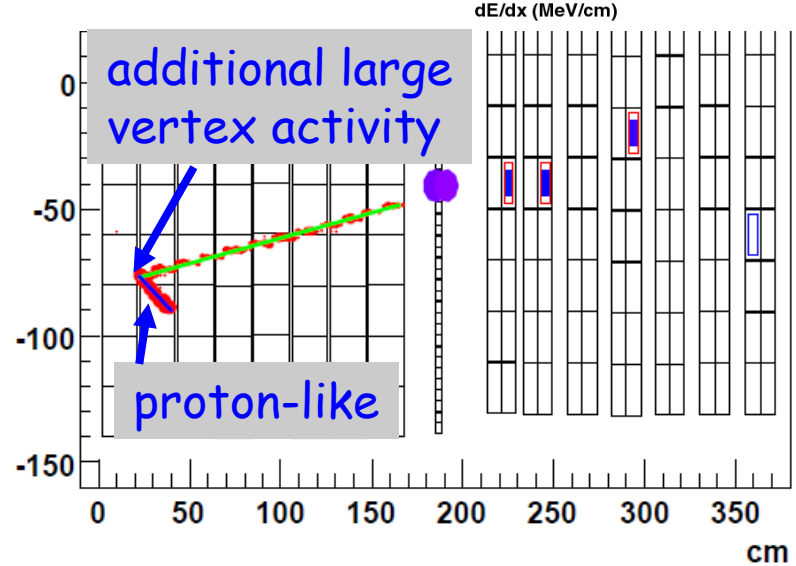


dE/dx of 2nd track



vertex activity





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:

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

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

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

$$\frac{\Delta(R_{2trk/1trk})\Delta(R_{p/\pi})|_+ + \Delta(R_{2trk/1trk})\Delta(R_{p/\pi})|_-}{2} = -21\times 10^{-4}$$

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

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

Fitting parameters

8 fitting parameters

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

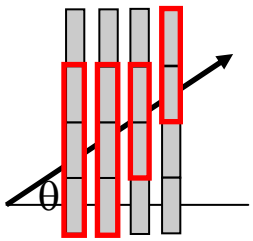
R_{norm} : MRD stopped sample normalization
$R_{2trk/1trk}$: Migration between 2track / 1track samples
$R_{p/\pi}$: Migration between μ+p / $\mu+\pi$ samples
R_{act} : Migration between low/high vertex activity samples
R_{pscale} : Muon momentum scale
R_{res} : CC-resonant pion cross section scale factor
R_{other} : Other nonQE cross section scale factor
κ : Pauli-suppression parameter for CCQE

Fitting result

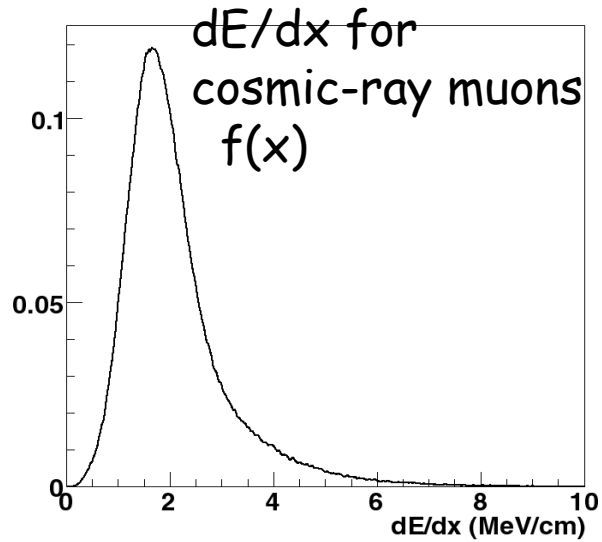
Parameter	Value	Error
R_{norm}	1.103	0.029
$R_{2trk/1trk}$	0.865	0.035
$R_{p/\pi}$	0.899	0.038
R_{act}	0.983	0.055
R_{pscale}	1.033	0.002
R_{res}	1.211	0.133
R_{other}	1.270	0.148
kappa	1.019	0.004

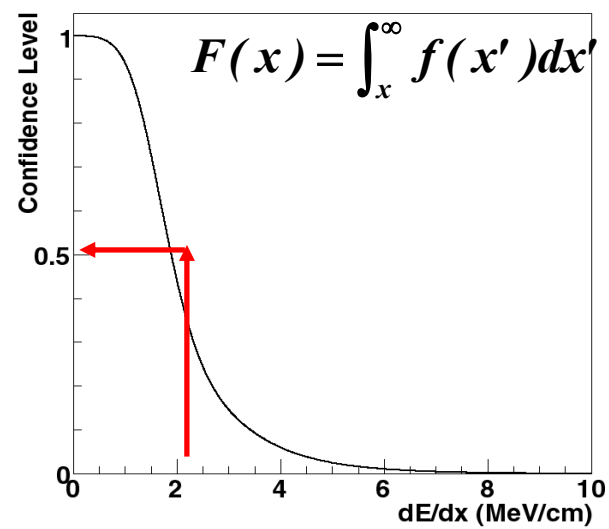
MuCL calculation

plane-by-plane dE/dx measurement



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



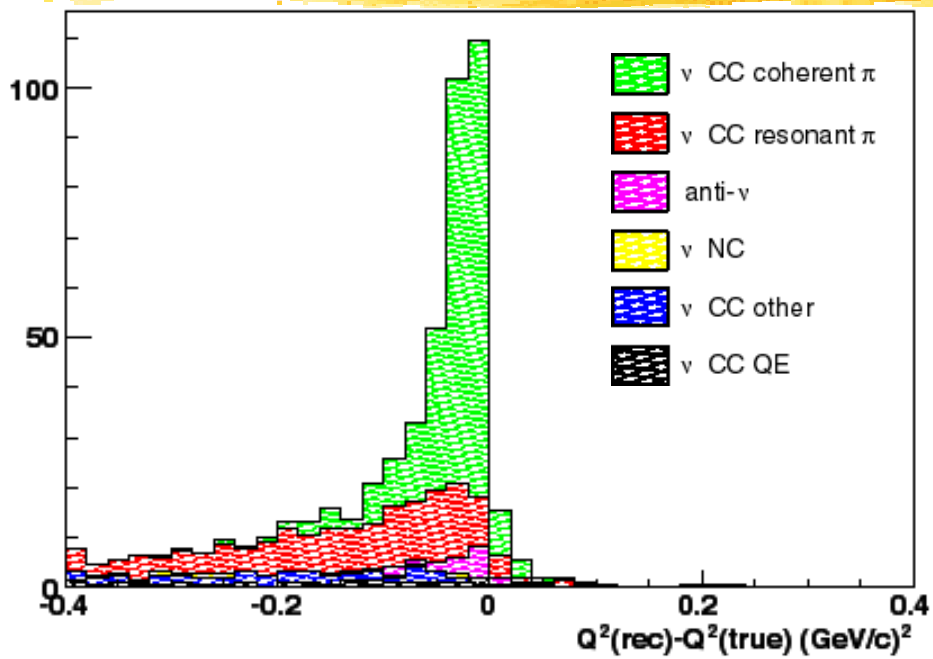


confidence level at each plane is calculated from the plot

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 $(GeV/c)^2$

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%

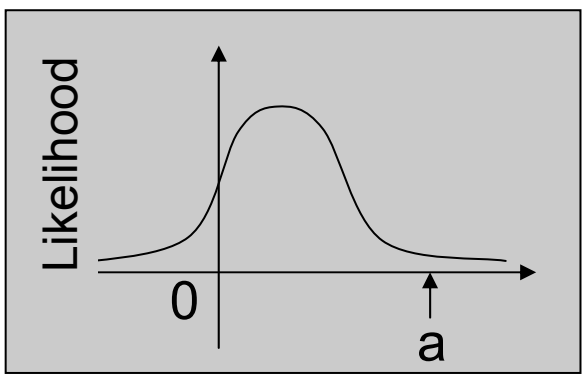
90% CL upper limit

Simple calculation

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

(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 $\langle E\nu\rangle$=1.1 GeV

< 1.36×10^{-2} $\langle E\nu\rangle$=2.2 GeV

K2K result (90% CL U.L.=m+1.28*σ)

σ(CC coherent π)/σ(CC) < 0.60×10^{-2} for $\langle E\nu\rangle$=1.3 GeV

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

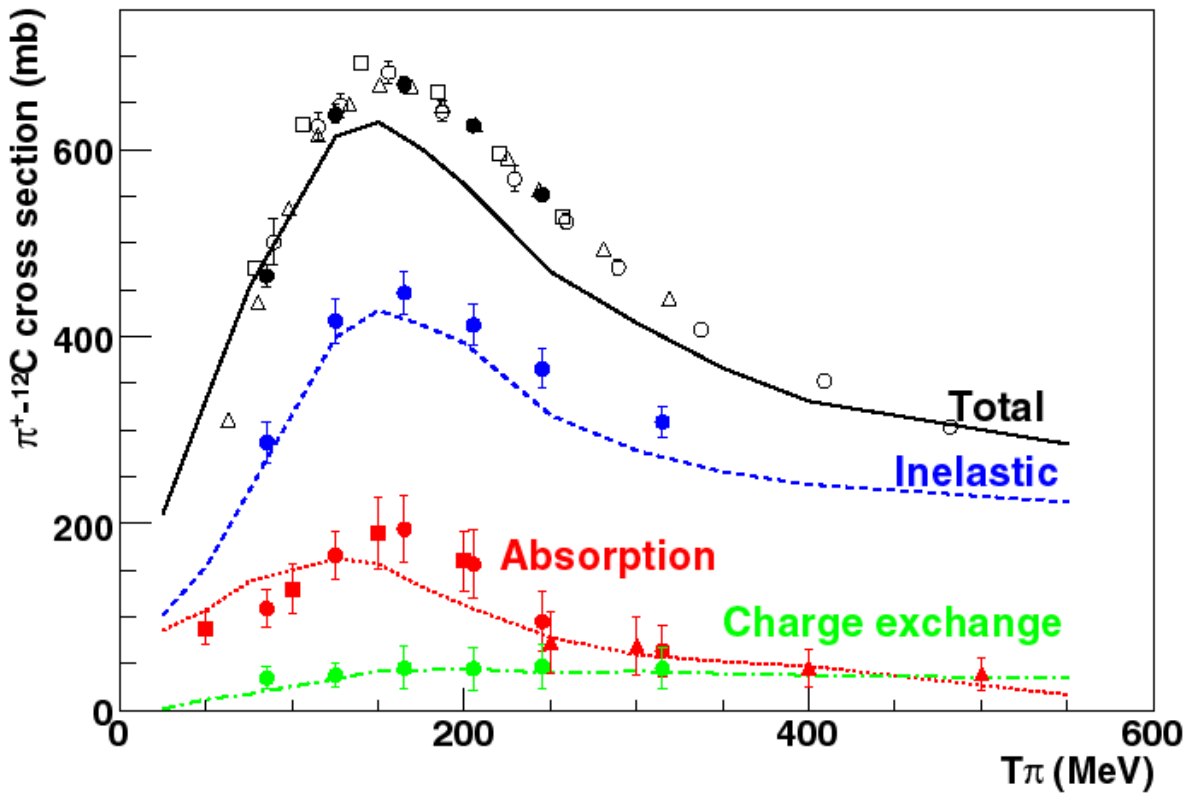
σ(CC coherent π)/σ(CC) < 0.60×10^{-2} for $\langle E\nu\rangle$=1.1 GeV

< 1.33×10^{-2} $\langle E\nu\rangle$=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

Pion interaction simulation in Geant4



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

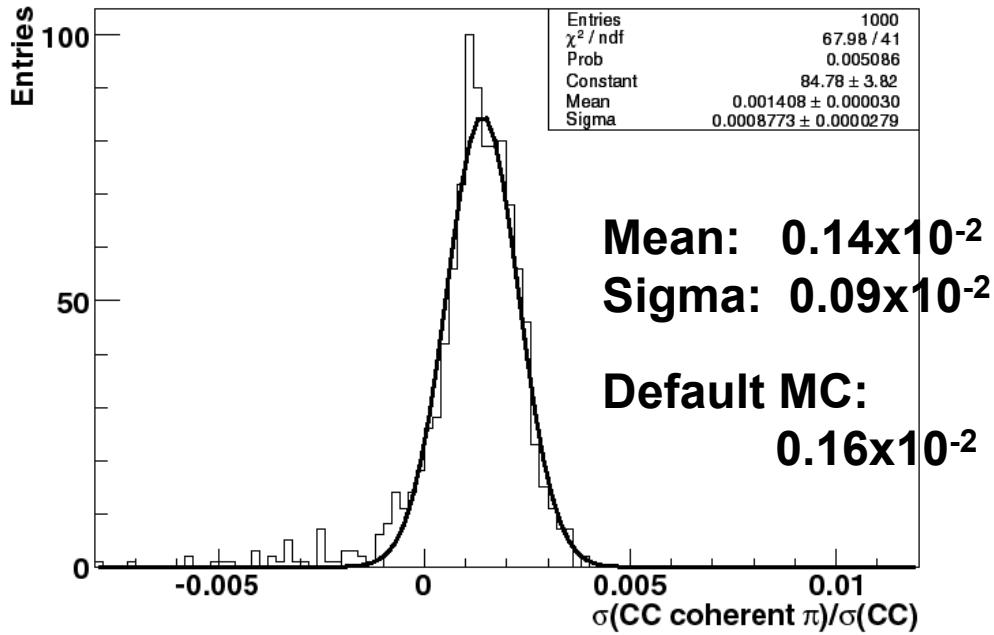
Systematic errors (neutrino interaction model)

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 ($E\nu$ 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

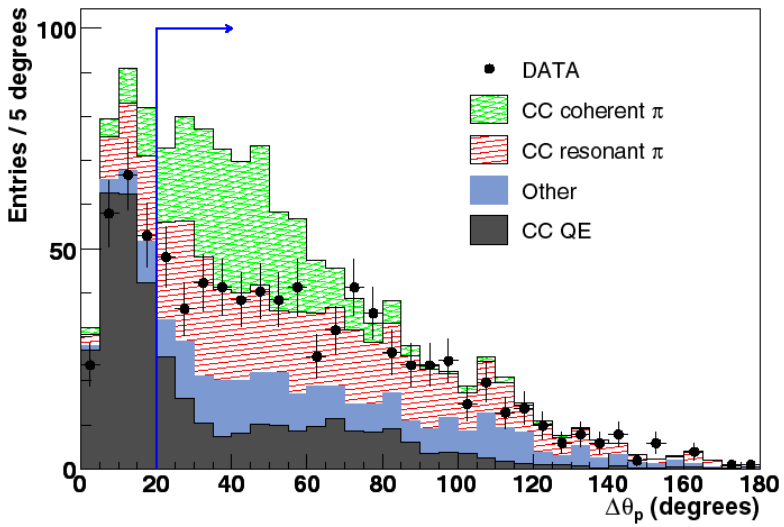
Variation of the cross section ratio using 1,000 multisim parameter sets



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

Systematic errors (Event selection)

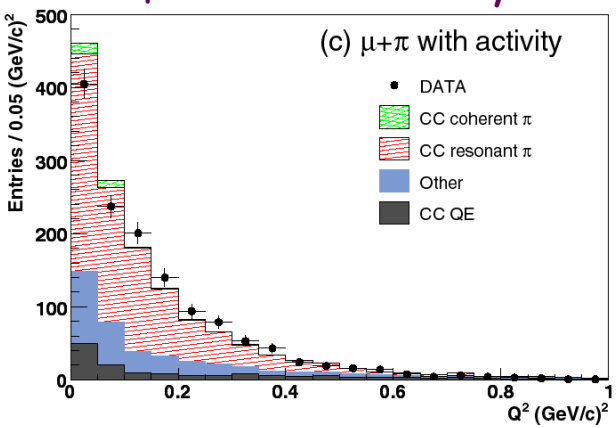
$\Delta\theta p$ for the $\mu+\pi$ events



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

Low Q^2 suppression in CC resonant π

$\mu+\pi$ with activity

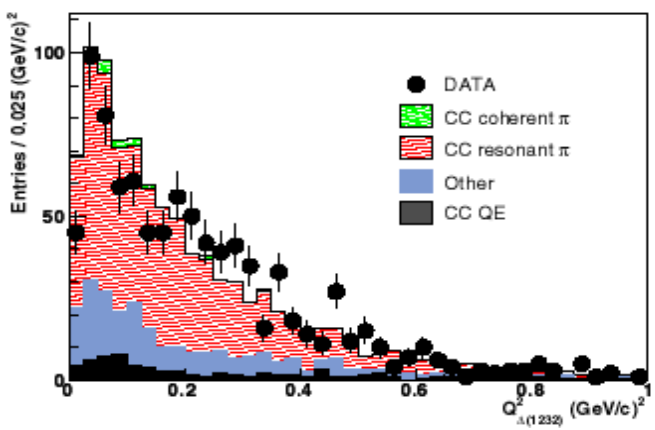


low Q^2 data deficit is observed in CC resonant pion enriched sample

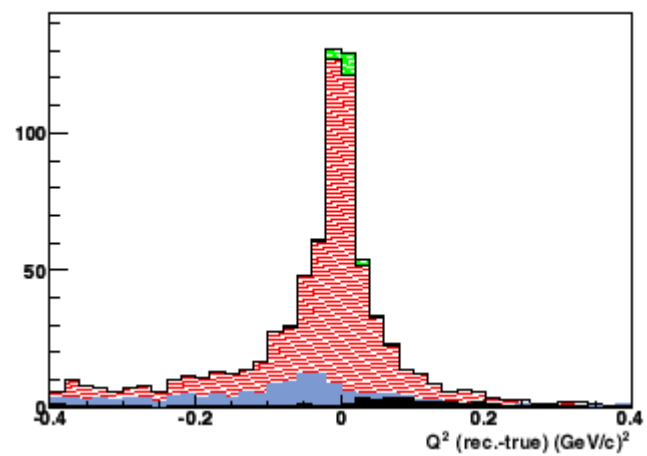
The Q^2 shape uncertainty affects background estimation for CC coherent pion sample

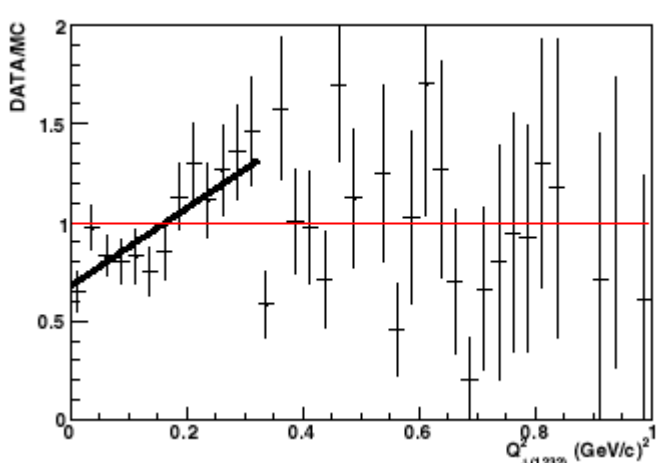
Low Q^2 suppression in CC resonant π

Rec. Q^2 assuming Δ-resonance



Q^2 resolution (rec-true)



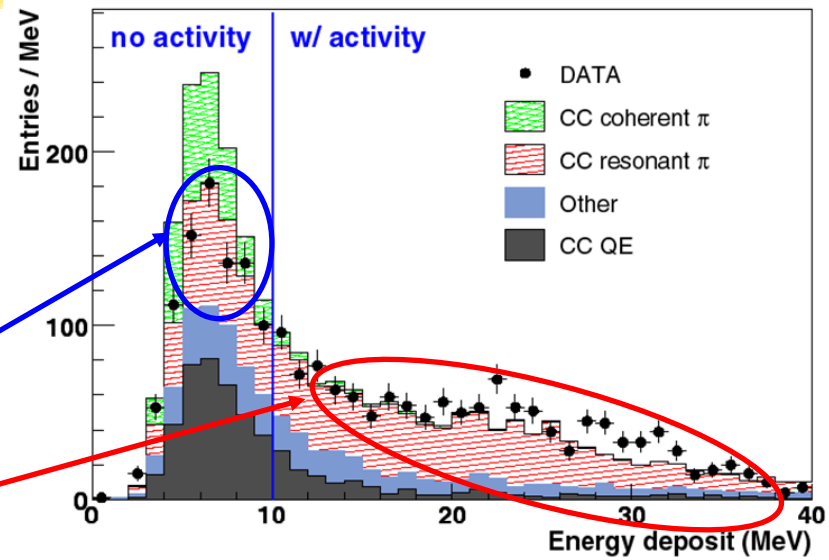


Apply this weighting function to CC coherent π sample in order to estimate systematic error

Uncertainty in CC resonant $\mu n\pi/\mu p\pi$ ratio

The uncertainty in the CC resonant $\mu n\pi/\mu p\pi$ ratio causes migration between low/high activity samples

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

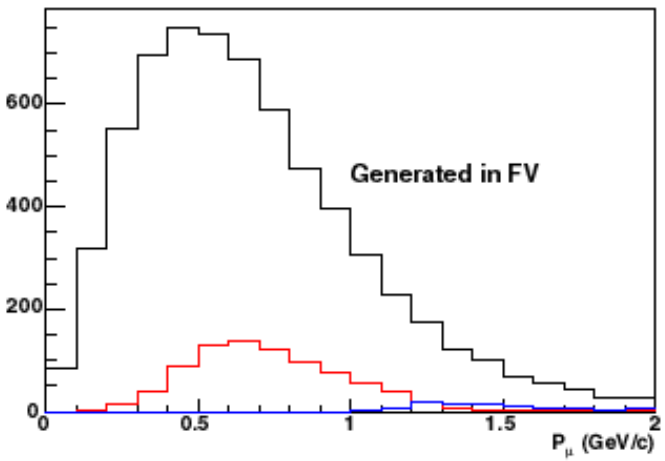


The uncertainty in the CC resonant $\mu n\pi/\mu p\pi$ ratio is ~7%, estimated using SciBooNE sub-samples

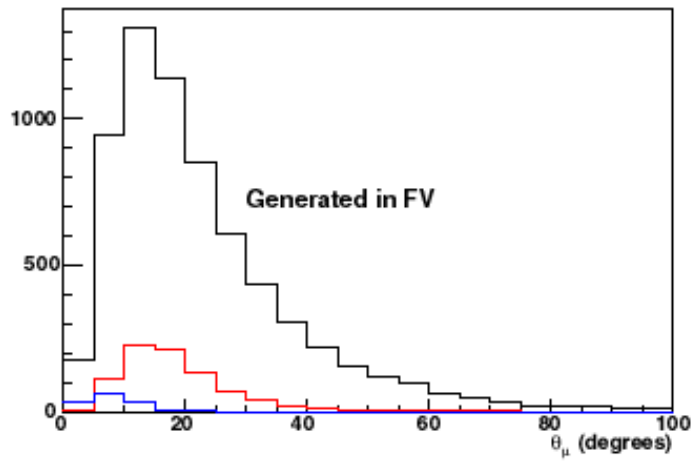
➔ $\delta(\sigma(coh)/\sigma(CC)) = +/-0.04\times10^{-2}$ considered as systematic error

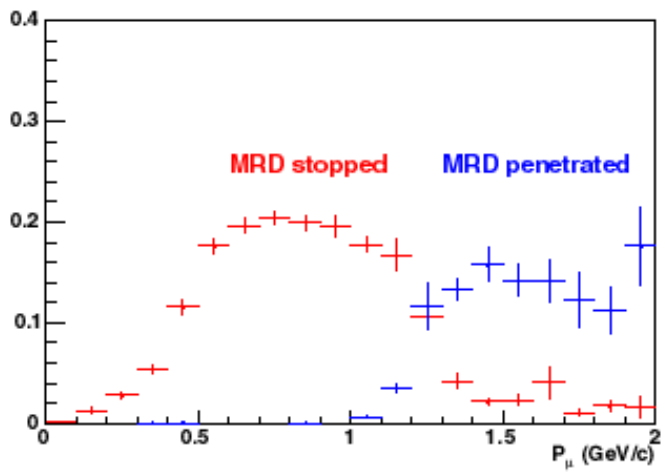
CC-coherent π Selection efficiencies vs. Pμ, θμ

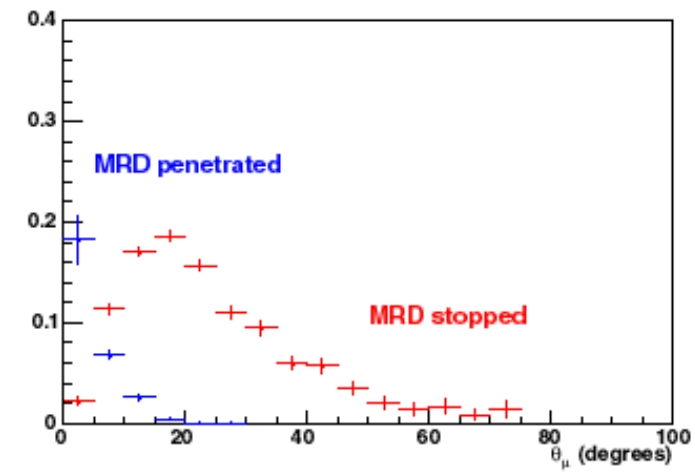
Pμ



θμ



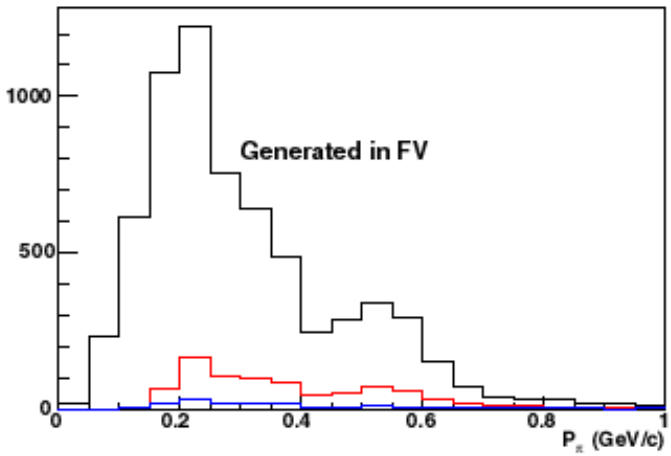


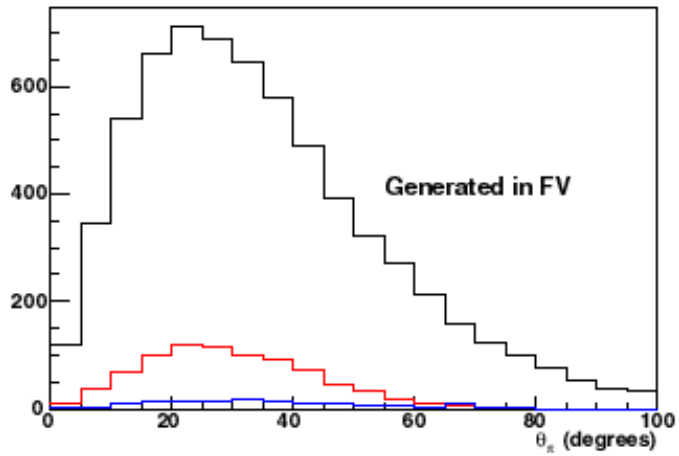


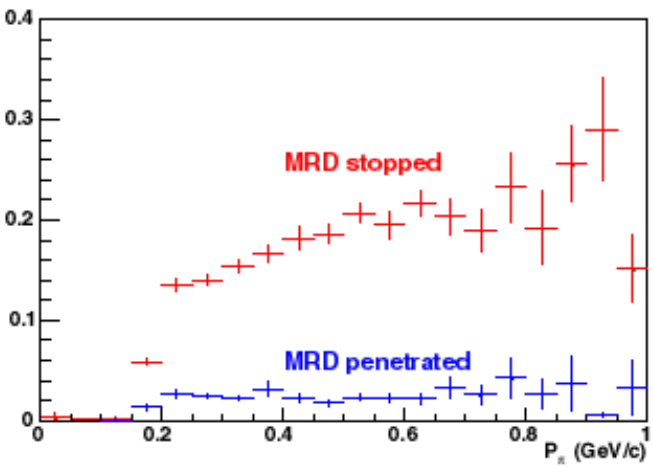
CC-coherent π Selection efficiencies vs. Pπ, θπ

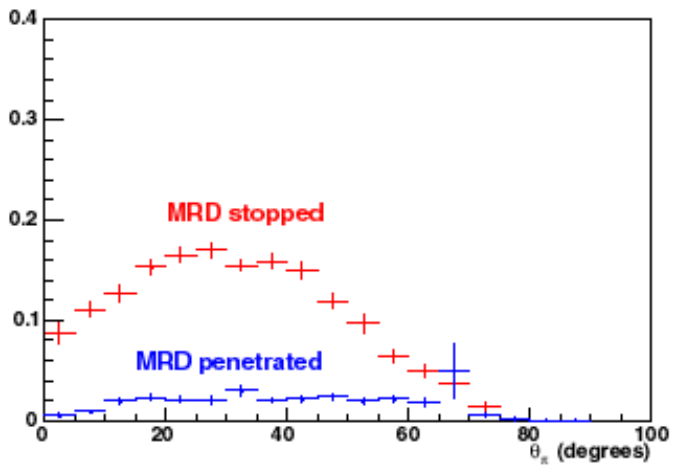
Pπ

θπ



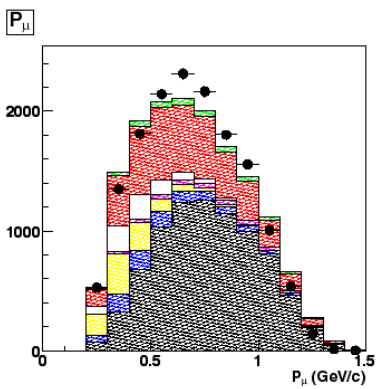


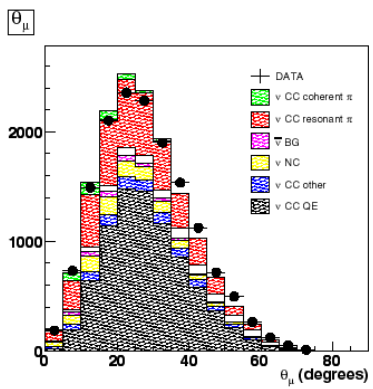




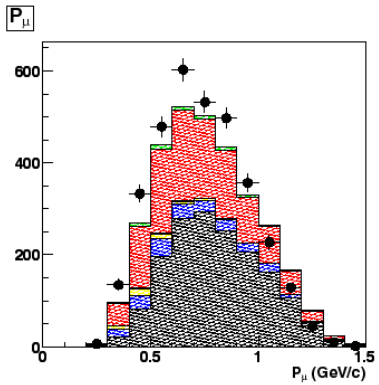
Kinematical distributions after MC tuning

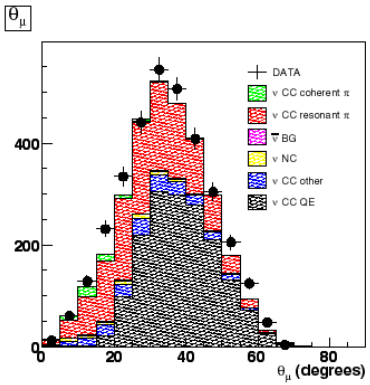
1 track

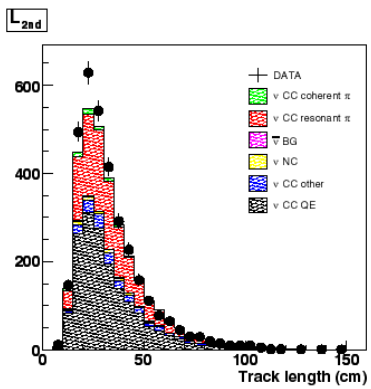


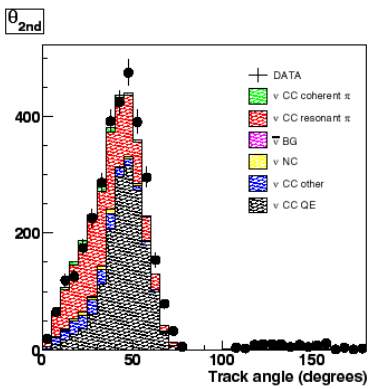


μ+p



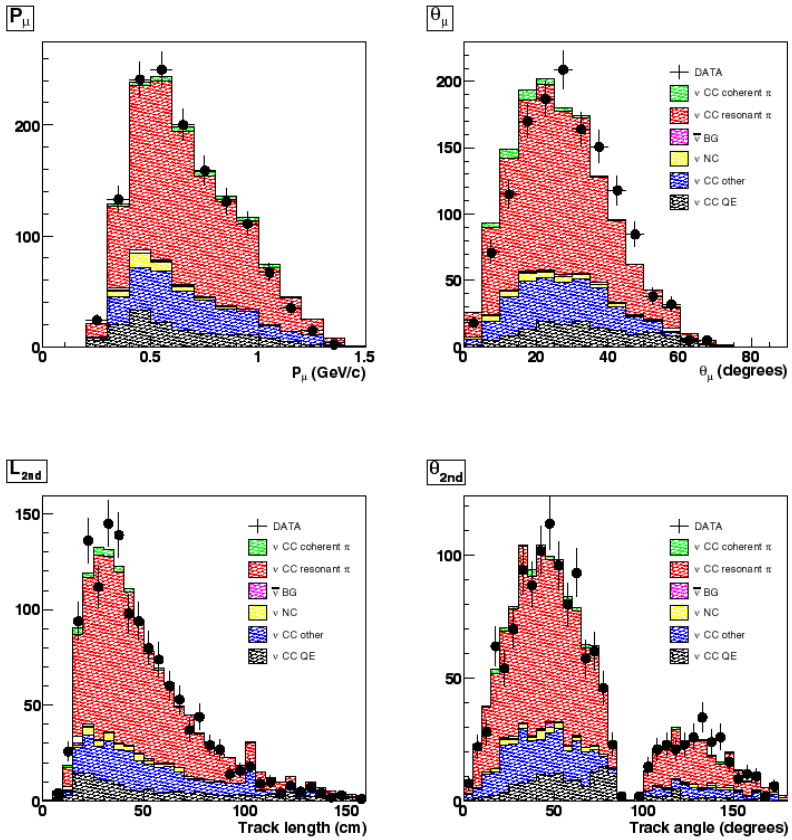




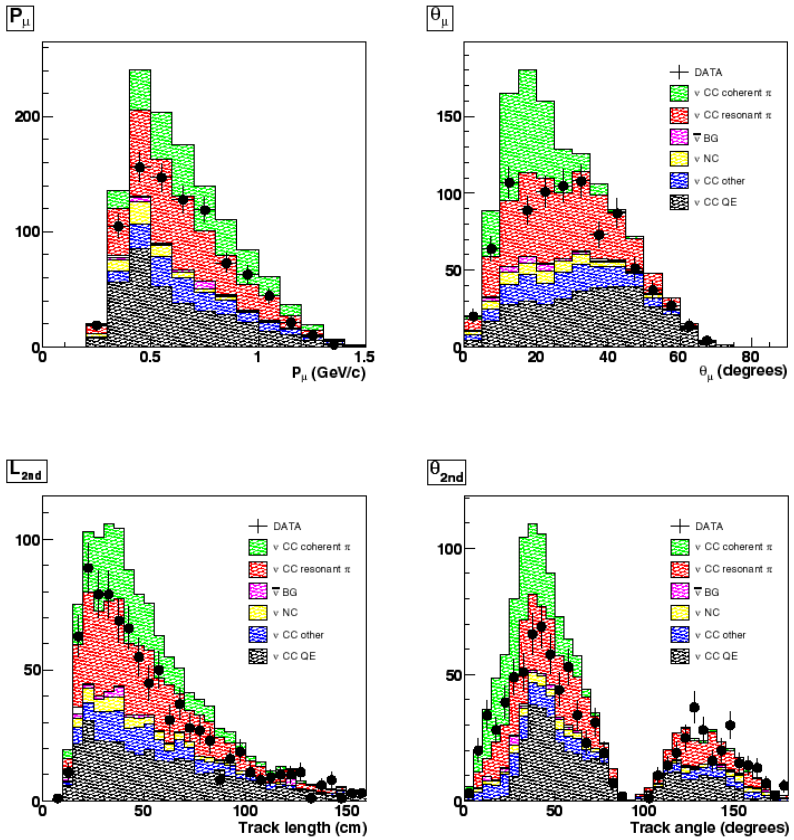


Kinematical distributions after MC tuning

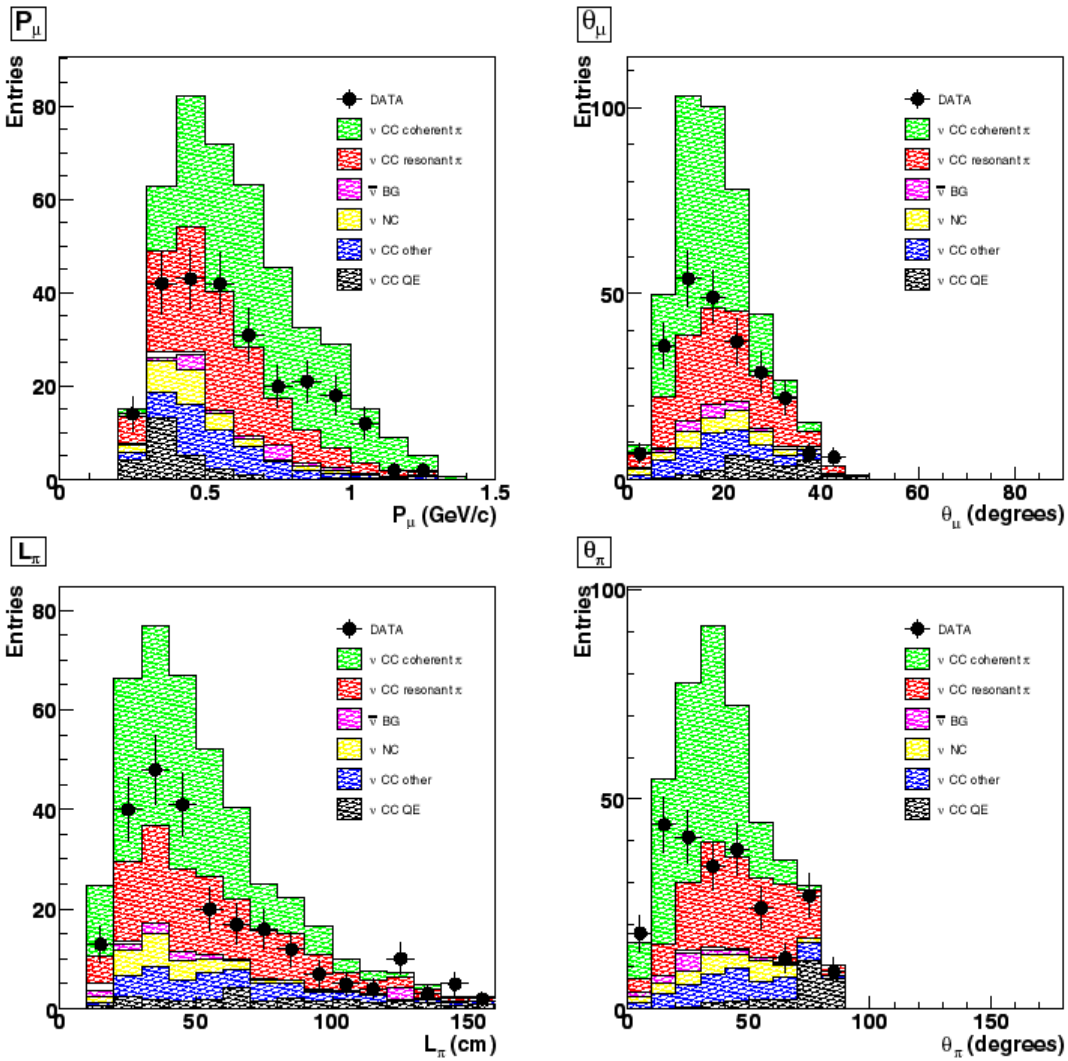
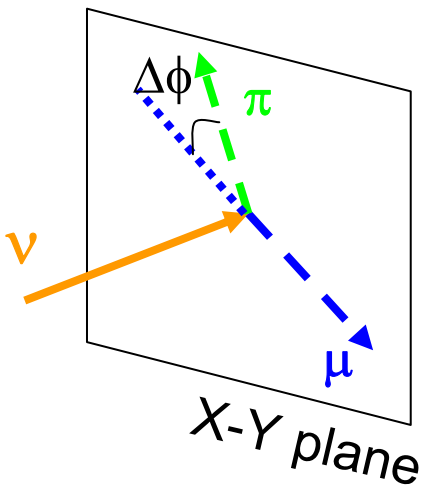
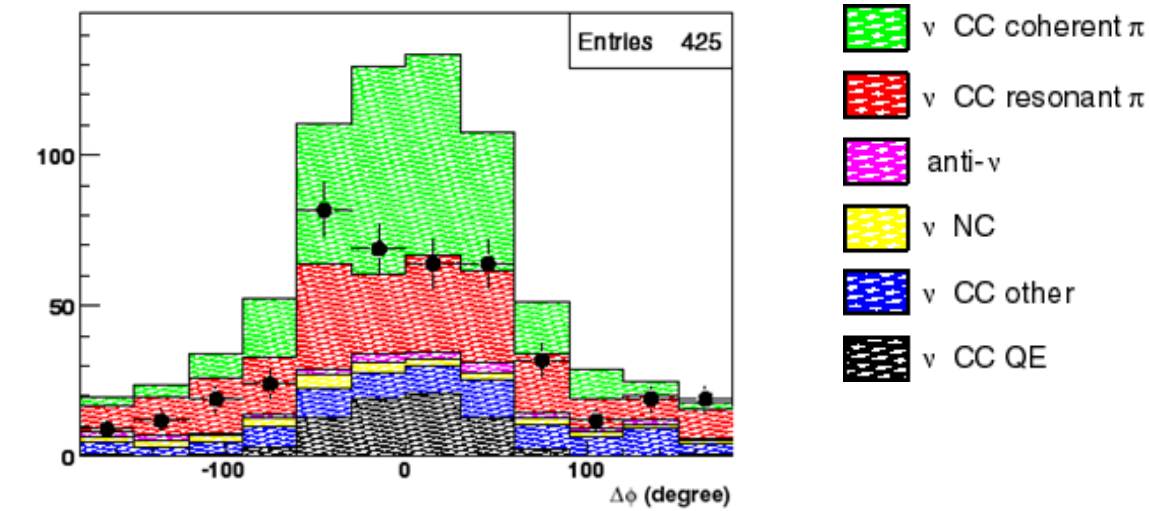
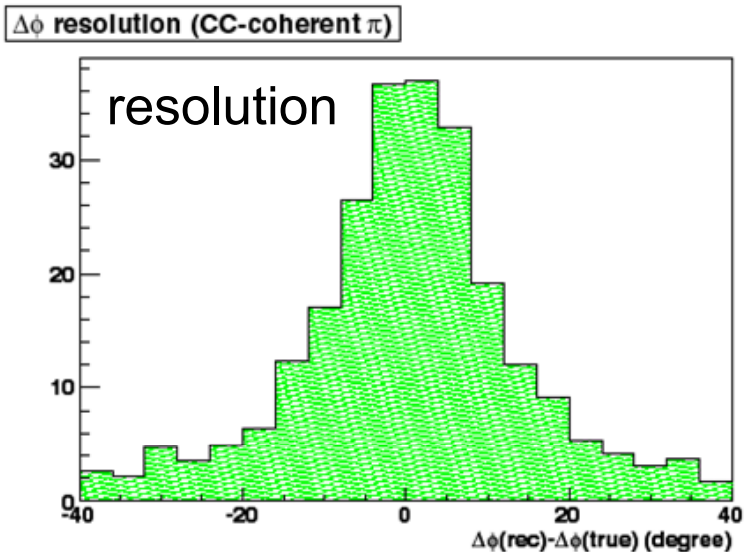
μ+π w/ vertex activity



μ+π w/o vertex activity



Kinematical distributions of MRD stopped coherent π sample



Kinematics variable