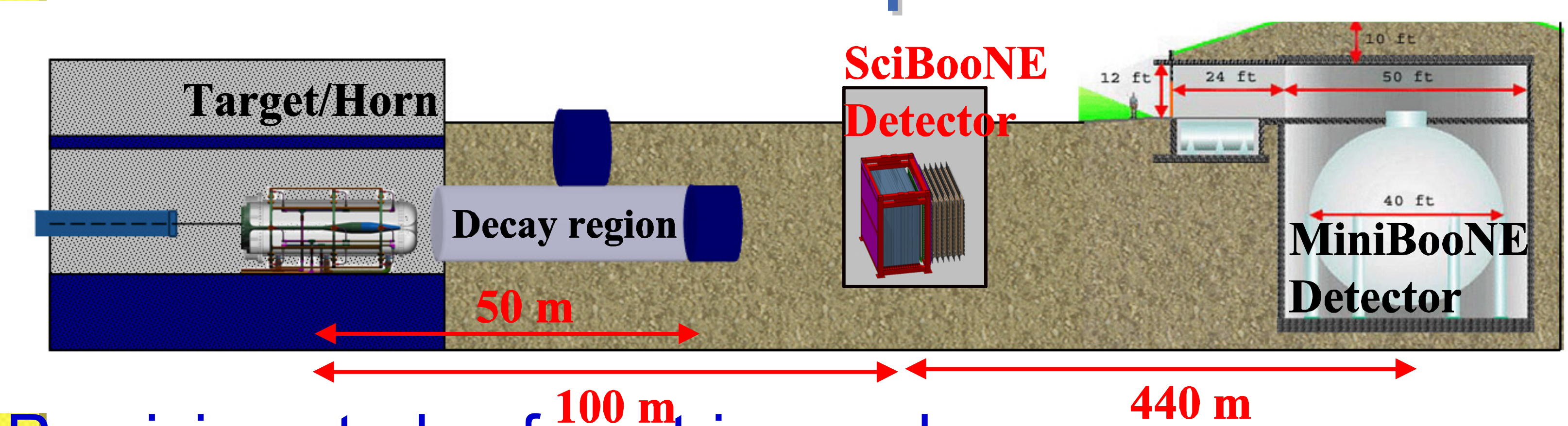
Aug. 20th, 2009
@14th Lomonosov Conference ,
Moscow State University

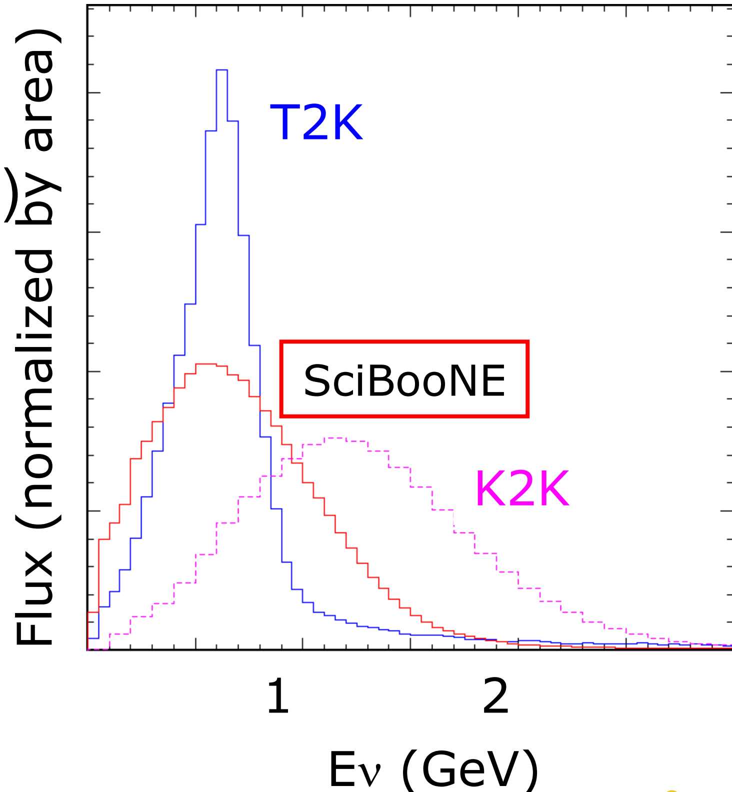
New Results from the FNAL SciBooNE neutrino experiment (FNAL E954)

T. Nakaya (Kyoto University, JAPAN)
for the SciBooNE collaboration

The SciBooNE Experiment



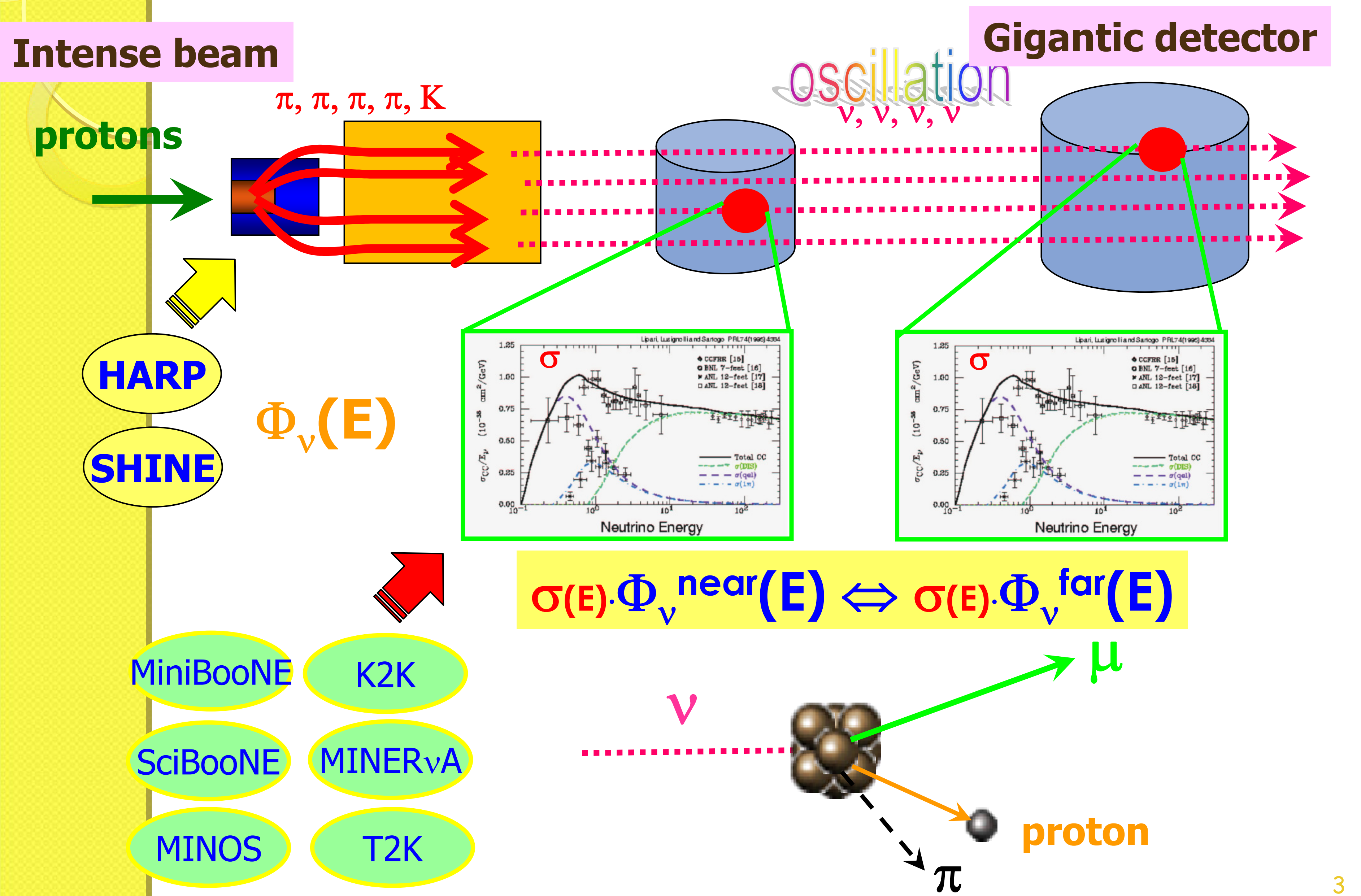
- Precision study of neutrino and anti-neutrino cross sections around 1GeV.
  - Interesting (but poorly understanding) Physics itself
  - Important for neutrino oscillation experiments
  - Important for future CP study in neutrinos
- MiniBooNE near detector.



K2K-SciBar + FNAL-BNB

- Well developed Detector
- Most intense low energy neutrino

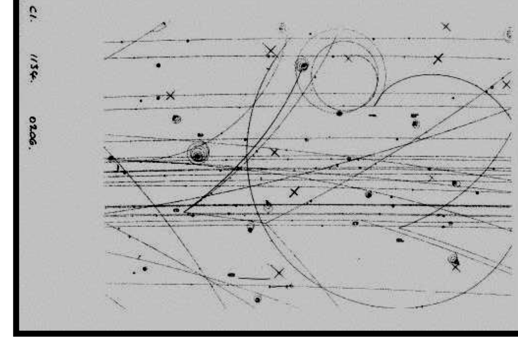
1. Introduction



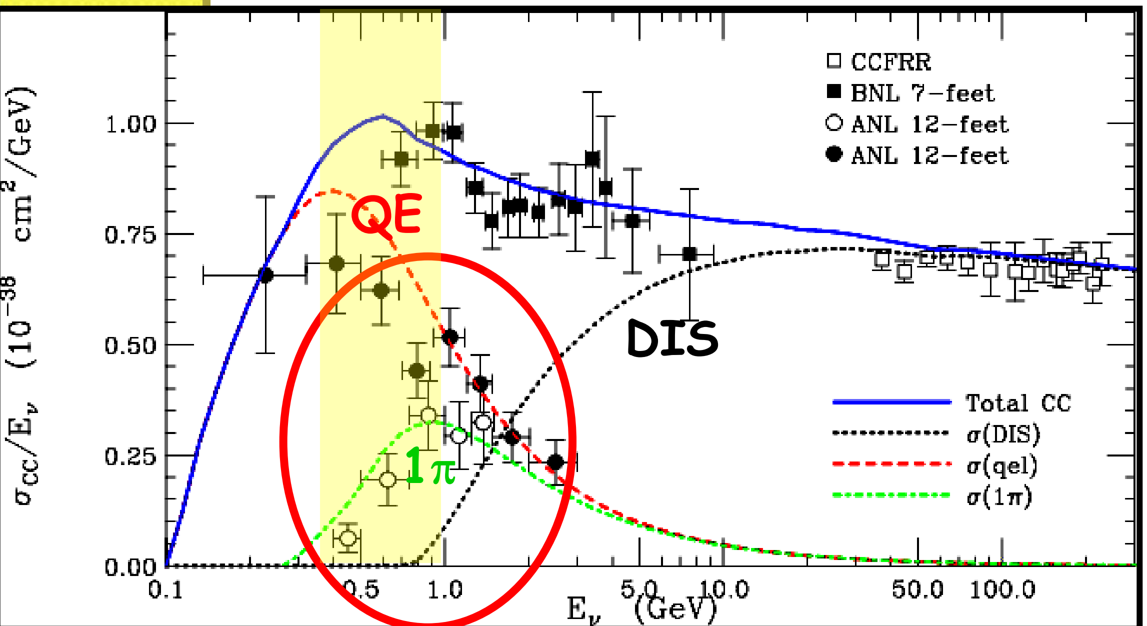
Physics Interests

- Elastic and Quasi-Elastic (QE) Scatterings
  - Simple and Important Channels to be understood.
    - Charged Current (CC) QE: ν_μ+n□μ+p
    - Neutral Current (NC) Elastic: ν_μ+(n,p)□ν_μ +(n,p)
  - Initial and final state nucleons are coupled with the nuclear state (“Nuclear Effect”).
- π production in neutrino interactions
  - Several production mechanisms
    - Resonance π Production (Δ, etc..)
    - Coherent π production (CC and NC)
    - DIS and multi-pion productions
  - Final state π meson is affected by nuclear medium in the nucleus (“Nuclear Effect”).
- Understanding of nuclear effects is also an important subject beneficial to experiments.
- (maybe more)

Unexplored Areas of Neutrino Physics



σ_ν **in this E range of interest:**



MINOS, Minerva @NuMI

K2K, NOvA

MiniBooNE, T2K, SciBooNE

Super-K atmospheric ν

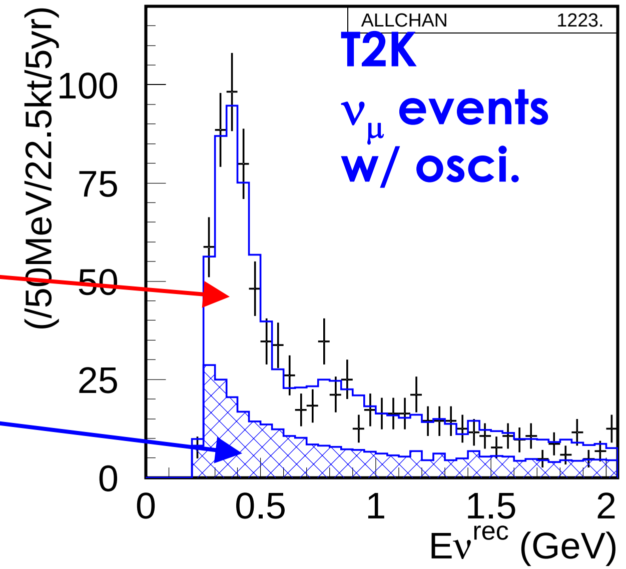
- **Data from old experiments** (1970~1980)
  - Low statistics
  - Systematic Uncertainties
- **Nuclear effects** (π/p/n absorption/scattering, shadowing, low Q^2 region)
  - Not well-modeled
- **New data** from K2K & MiniBooNE revealing surprises
- **More data at 1GeV with fine grained resolution will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

Anti-ν cross sections are in a poor situation.

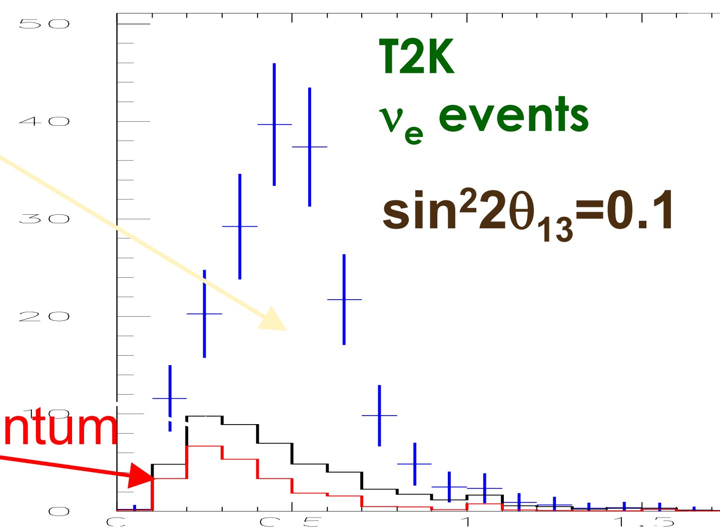
Impact of Neutrino Cross sections on oscillation measurements (T2K case)

SciBooNE

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



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



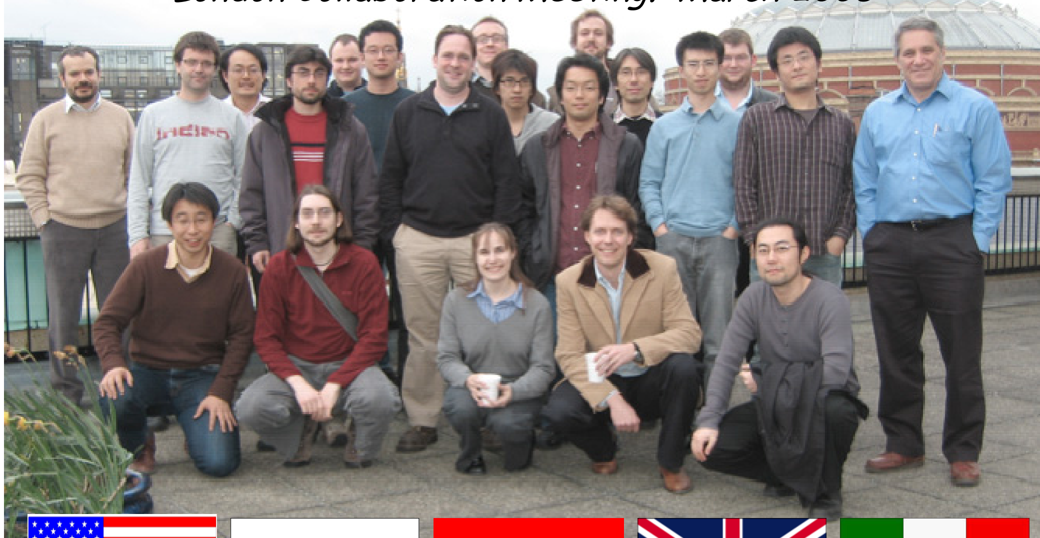
Anti-ν for CP violation study

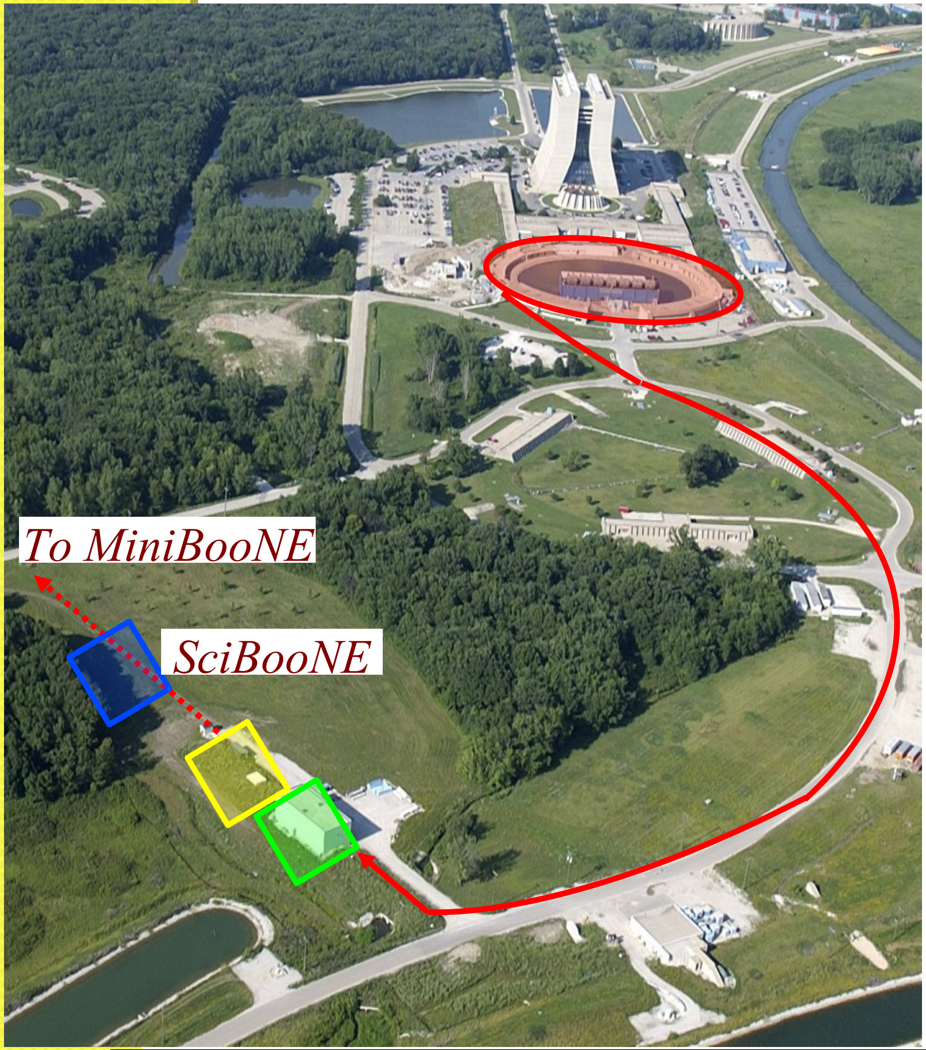
The SciBooNE experiment (FNAL E954)

SciBooNE collaboration

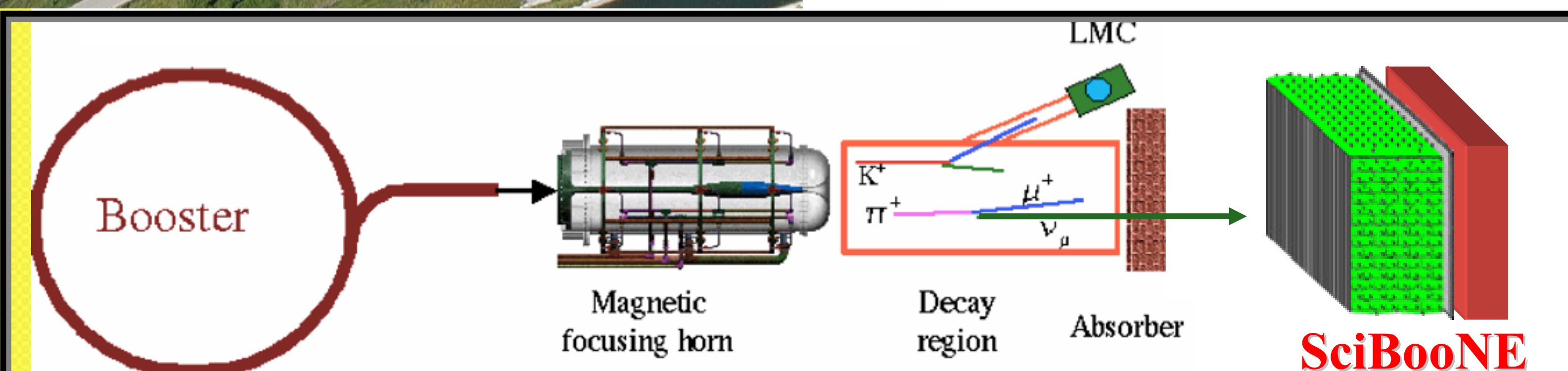
- Universitat Autonoma de Barcelona
- University of Cincinnati
- University of Colorado, Boulder
- Columbia University
- Fermi National Accelerator Laboratory
- High Energy Accelerator Research Organization (KEK)
- Imperial College London
- Indiana University
- Kyoto University
- Kamioka Observatory,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

A selection of SciBooNE collaborators at the London Collaboration Meeting. March 2008



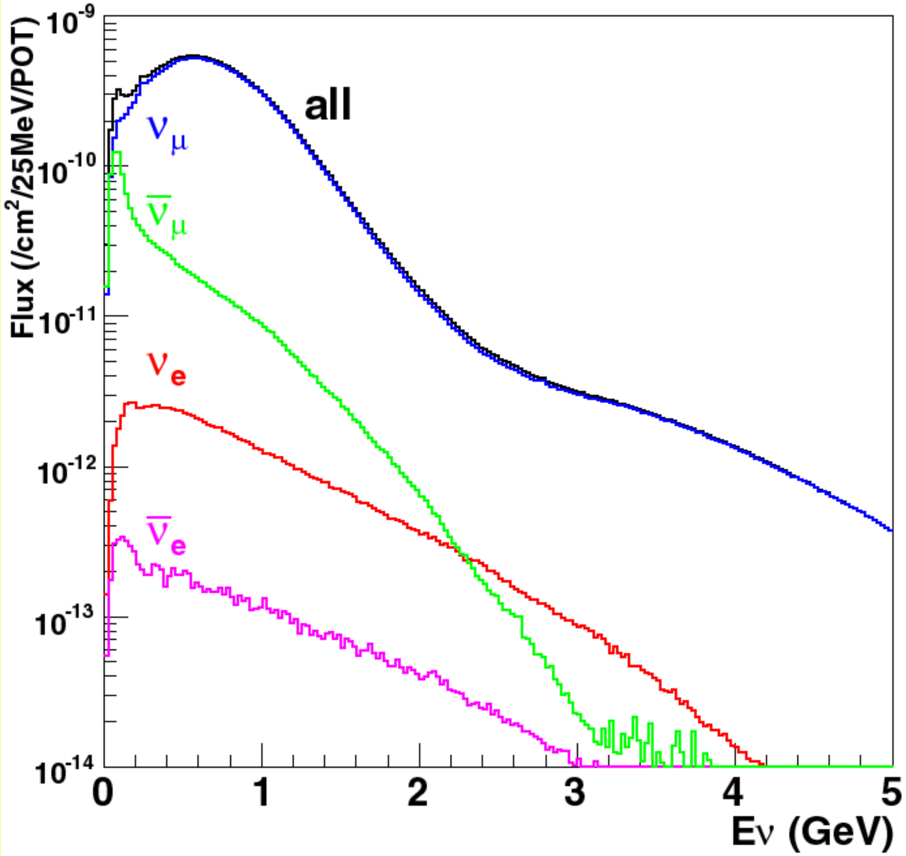


- Booster Proton accelerator
  - 8 GeV protons sent to target
- Target Hall
  - Beryllium target: 71cm long 1cm diameter
  - Resultant mesons focused with magnetic horn
  - Reversible horn polarity
- 50m decay volume
  - Mesons decay to μ & ν_μ
  - Short decay pipe minimizes $\mu \rightarrow \nu_e$ decay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



Booster Neutrino Beam (BNB)

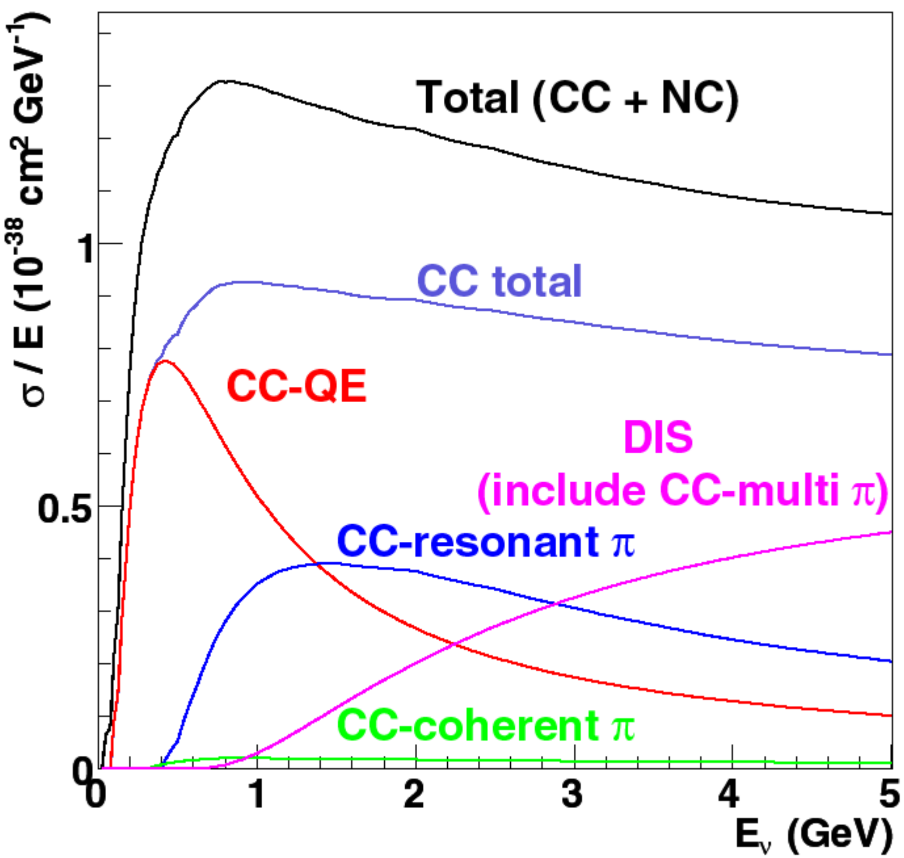
Expected neutrino flux at SciBooNE
(neutrino mode)



- 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)

*NUANCE for MiniBooNE joint analysis



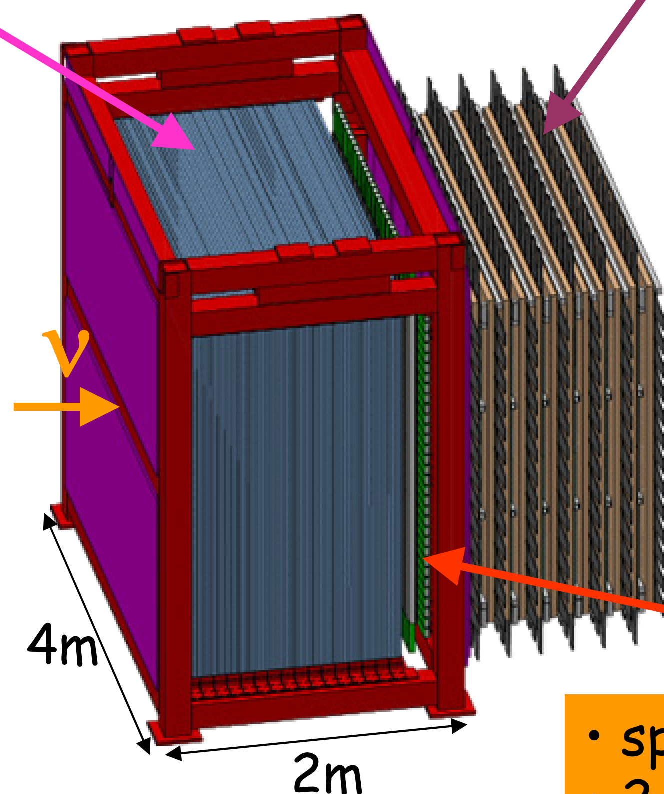
- QE
  - Llewellyn Smith, Smith-Moniz
  - M_A=1.2GeV/c^2
  - P_F=217MeV/c, E_B=27MeV (for Carbon)
- Resonant π
  - Rein-Sehgal (2007)
  - M_A=1.2 GeV/c^2
- Coherent π
  - Rein-Sehgal (2006)
  - M_A=1.0 GeV/c^2
- DIS
  - GRV98 PDF
  - Bodek-Yang correction
- Intra-nucleus interactions

SciBooNE detector

SciBar

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

Used in K2K experiment



Muon Range Detector (MRD)

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

Parts recycled from Past experiment

Electron Catcher (EC)

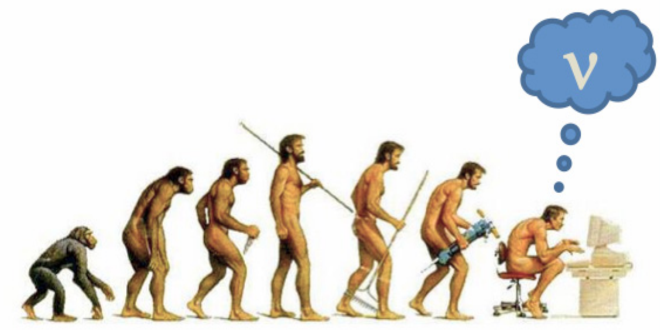
- spaghetti calorimeter
- 2 planes (11 X_0)
- identify π^0 and ν_e

Used in CHORUS, HARP and K2K

DOE-wide Pollution Prevention Star (P2 Star) Award

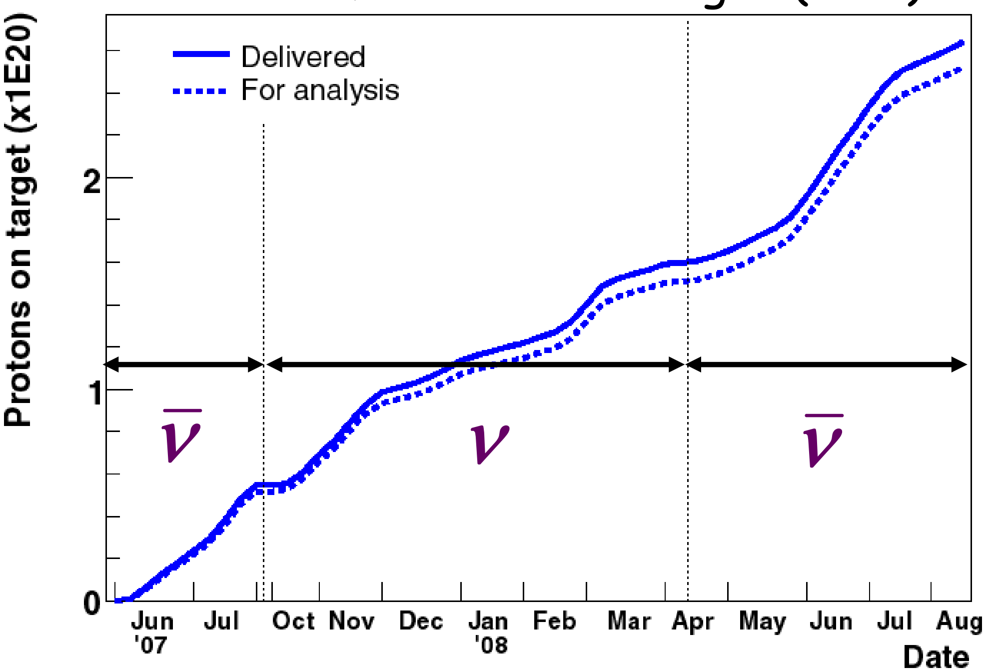
SciBooNE Timeline

- 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

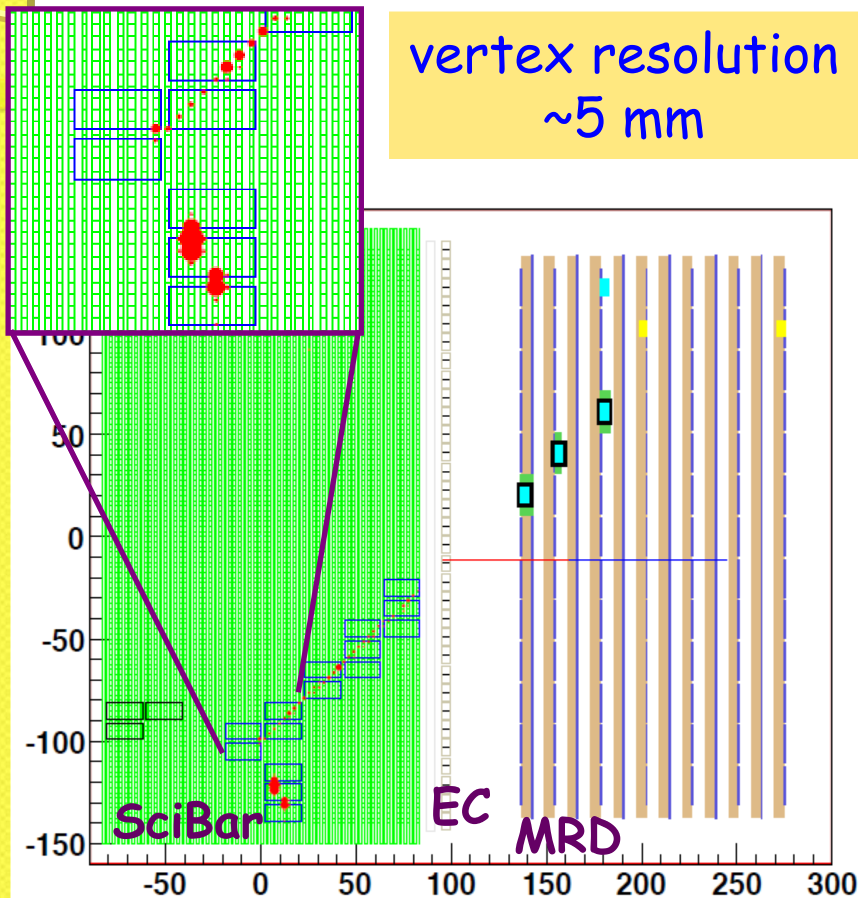
Results from full neutrino data set are presented

Neutrino event displays

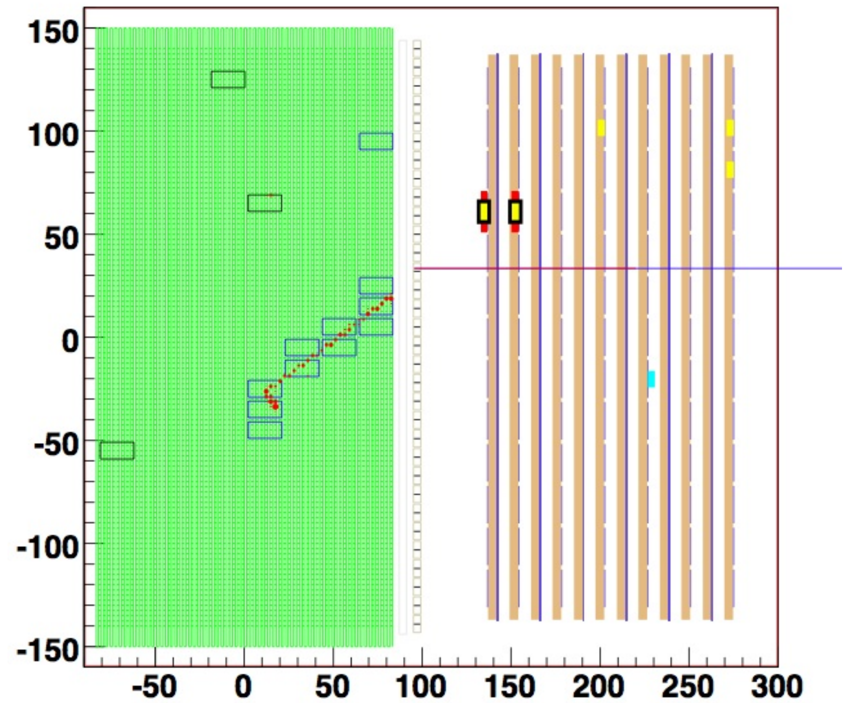
Real SciBooNE Data

vertex resolution
~5 mm

- ADC hits (area→charge)
- TDC hits (32ch “OR”)



anti-ν_μ CC-QE candidate
($\overline{\nu_\mu}$ + p → μ + n)



ν_μ CC-QE candidate
(ν_μ + n → μ + p)

SciBooNE Physics Results

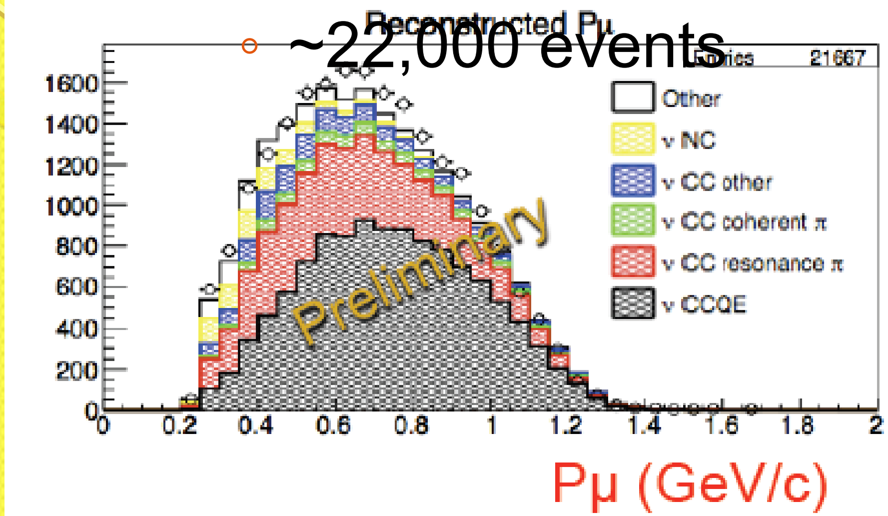
Both ν beam and anti-ν data

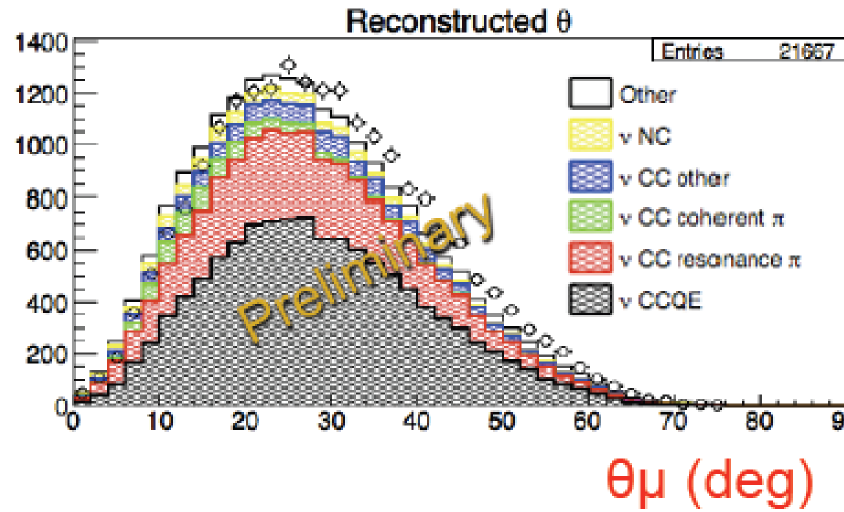
[ν results comes first, and anti-ν results will follow]

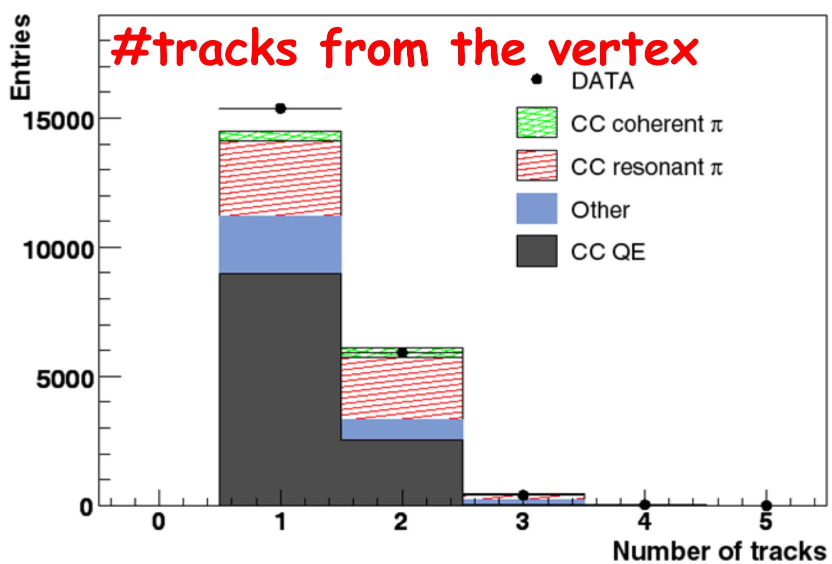
- Elastic and Quasi-Elastic (QE) Scatterings
  - CC-QE: ν_μ+n□μ+p
  - NC-Elastic: ν_μ+(n,p)□ ν_μ+(n,p)
- π production
  - CC-coherent π production
  - NC π^0 production
  - CC π^0 production
- Short Baseline ν oscillation between SciBooNE and MiniBooNE

SciBooNE ν data

- CC inclusive sample (muons stopped in MRD)
  - ~22,000 events





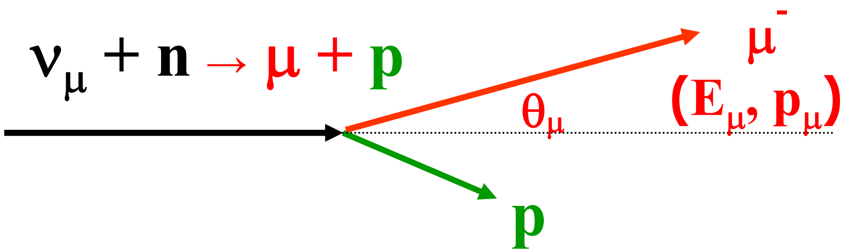


MC predictions

- CC-QE
- CC-res. π
- CC-coh. π
- Others

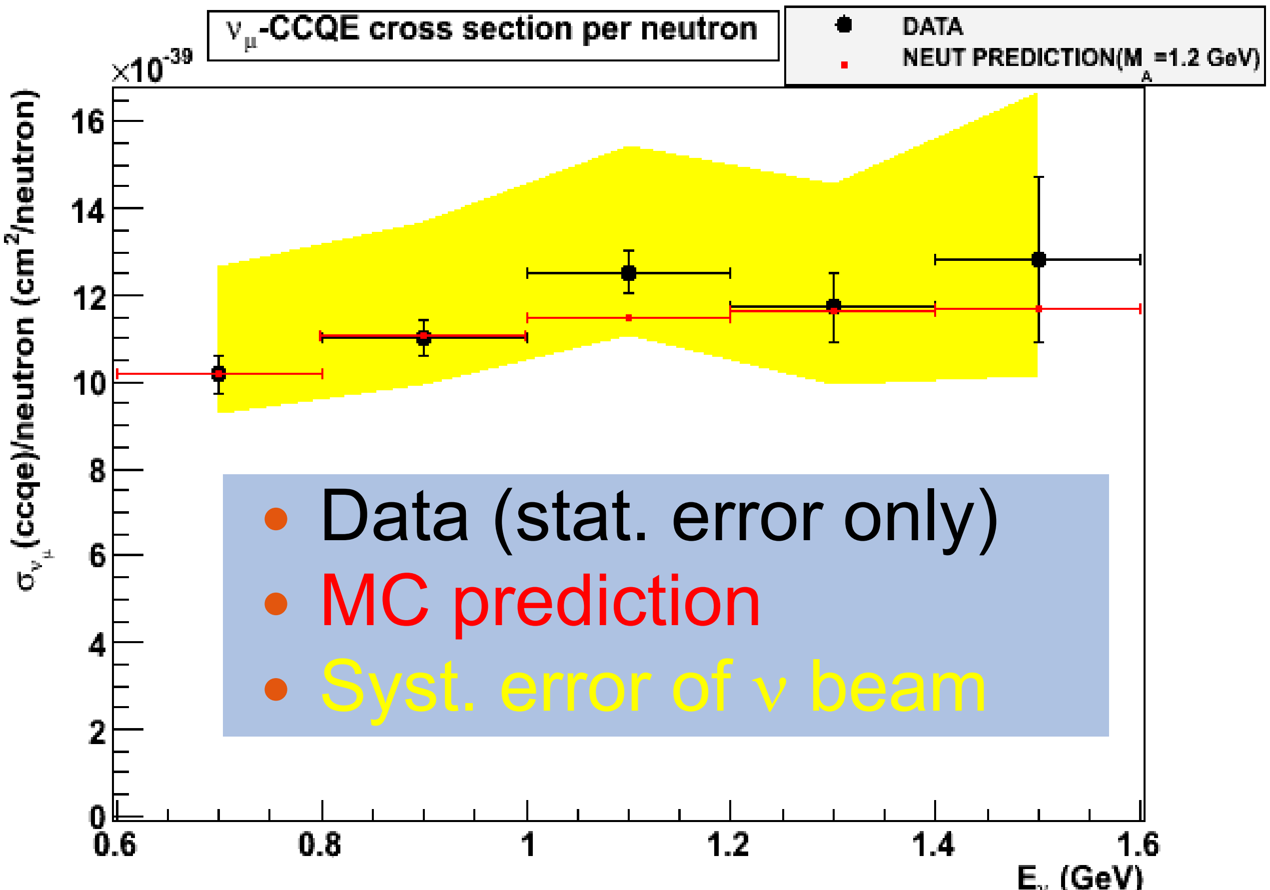
CC-QE

SciBooNE



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

Cross Section



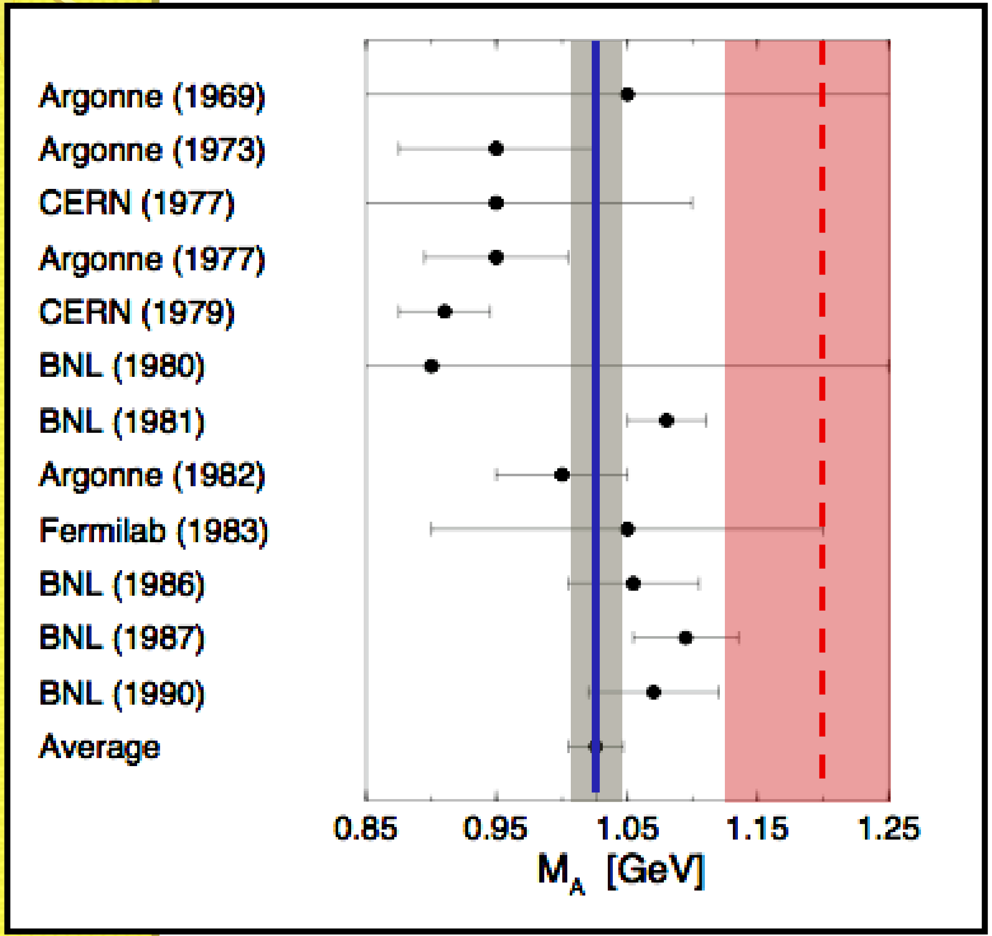
- Data (stat. error only)
- MC prediction
- Syst. error of ν beam

Jose Alcaraz @ NuInt09

CC-QE kinematics

- Form Factor & axial mass (M

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



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

- **K2K SciFi** (^{16}O, Q^2>0.2)
  Phys. Rev. **D74**, 052002 (2006)
  M_A=1.20 ± 0.12 GeV
- **K2K SciBar** (^{12}C, Q^2>0.2)
  M_A=1.14 ± 0.11 GeV
- **MiniBooNE** (^{12}C)
  NuInt09
  M_A=1.35 ± 0.17 GeV

Systematic Difference?
Effective M_A in nucleus?

- **NOMAD** (Q^2 distribution)
  NuFact09
  M_A=1.07 ± 0.06 ± 0.07 GeV

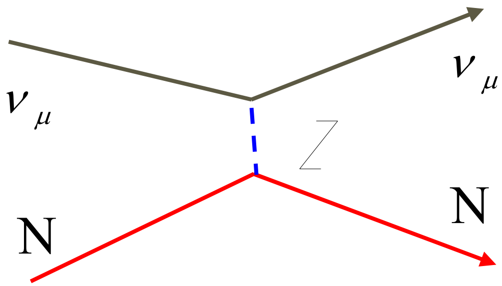
Wait for SciBooNE results

NC-Elastic

H. Takei@ NuInt09

SciBooNE

ŕJIN →ŕJIN



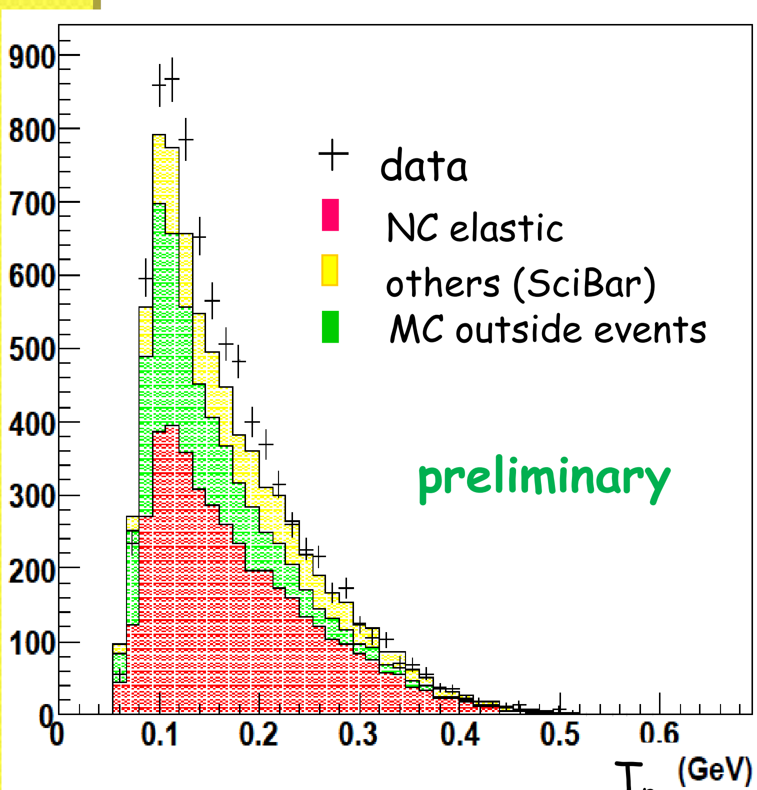
$$\frac{d\sigma}{dQ^2} = \frac{M_N^2 G_F^2}{8\pi E_\nu^2}\left[A(Q^2) \pm B(Q^2)\frac{s-u}{M_N^2} + C(Q^2)\frac{(s-u)^2}{M_N^4}\right]$$

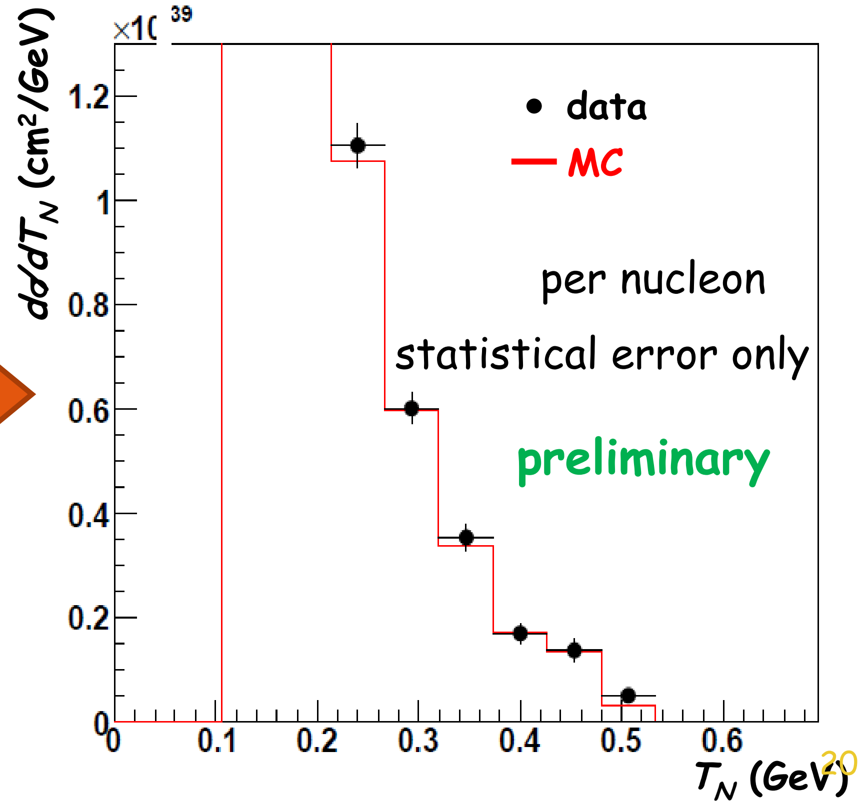
$$C(Q^2) = \frac{1}{4}\left[G_A^2 + F_1^2 + F_2^2\frac{Q^2}{4M_N^2}\right]$$

$$G_1 = \left[-\frac{G_A(Q^2)}{2}\tau_z + \frac{G_1^s(Q^2)}{2}\right]$$

$$s-u = 4M_N E_\nu - Q^2$$

Proton track events





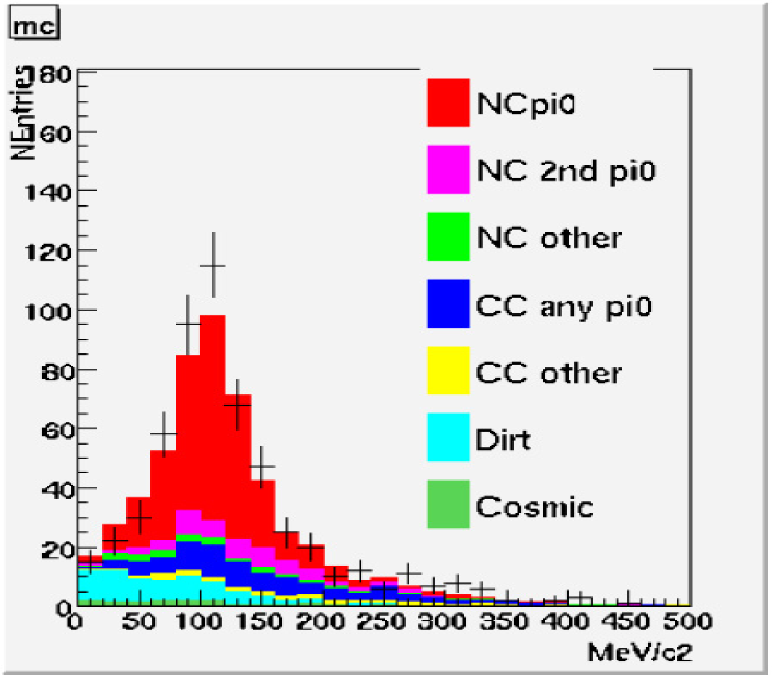
NC π^0

Y. Kurimoto@ NuInt09

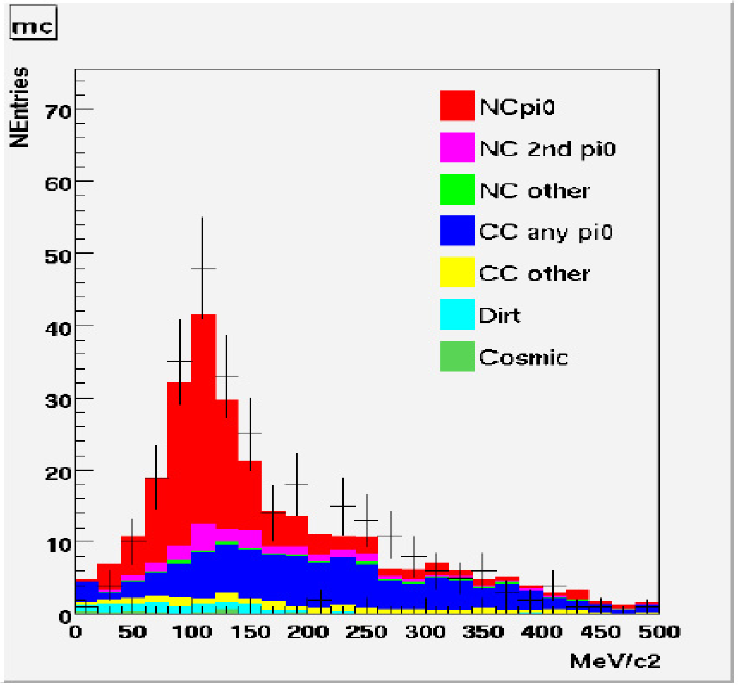
SciBooNE

- 2 γ events w/o muons

Contain sample



Non contain sample



$$\frac{\sigma_{NC\pi^0}}{\sigma_{CC-all}}$$

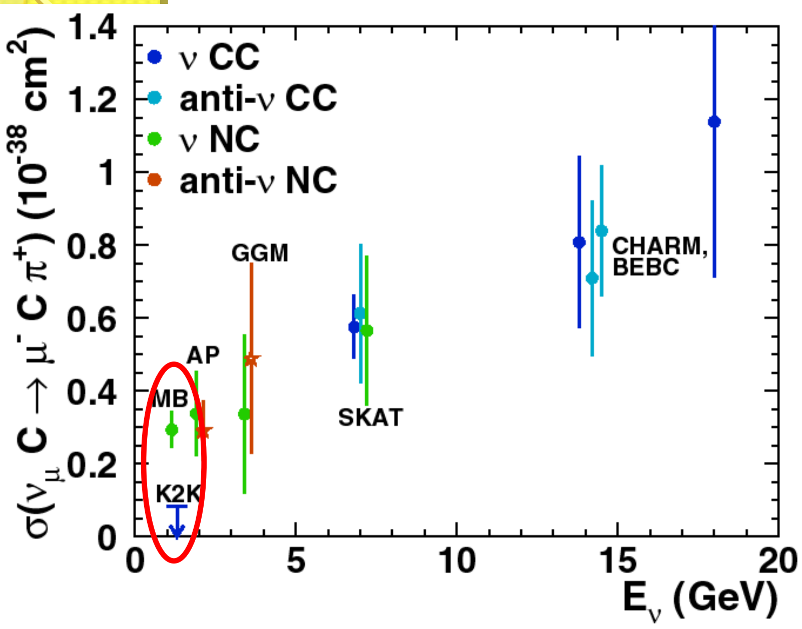
$$= 0.075 \pm 0.00574(stat.)^{+0.00756}_{-0.00901}(sys.)$$

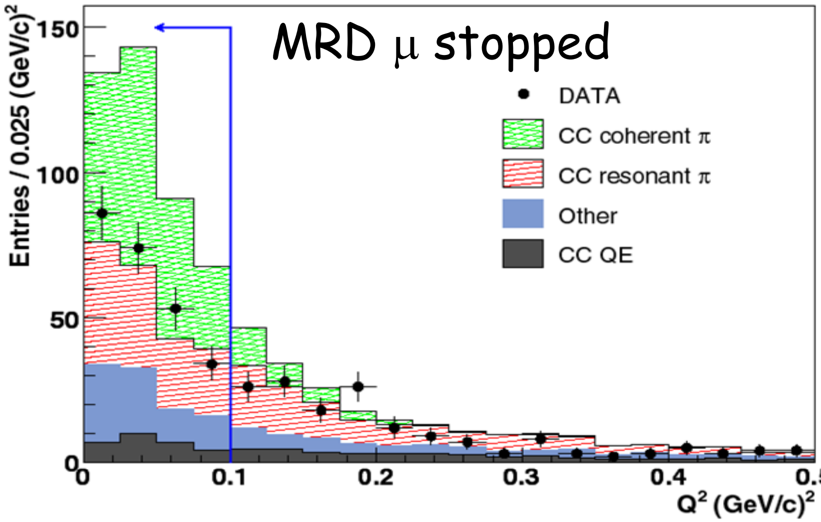
$$= 0.073 \pm 0.00924(stat.)^{+0.00626}_{-0.00838}(sys.)$$

CC-coherent π

K. Hiraide@ NuInt09

- μ+π events (look for Q^2 distribution)





247events selected

BG: 228+/-12 events
Efficiency: 10.4%

<u>**90% CL upper limit (Bayesian)**</u>

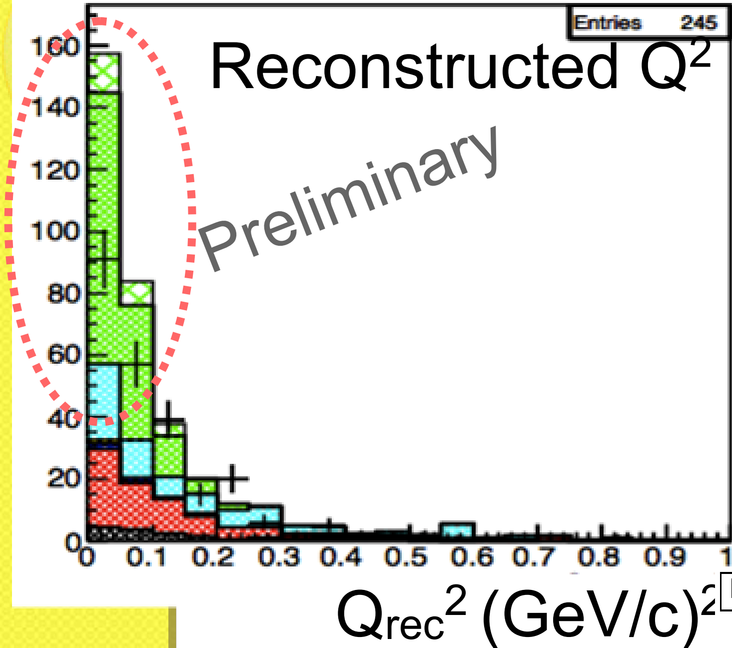
σ(CC coherent π)/σ(CC) < 0.67×10^{-2} for <Eν>=1.1 GeV
< 1.36×10^{-2} <Eν>=2.2 GeV

Most stringent limit
(~1/3 of Rein&Sehgal model)

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

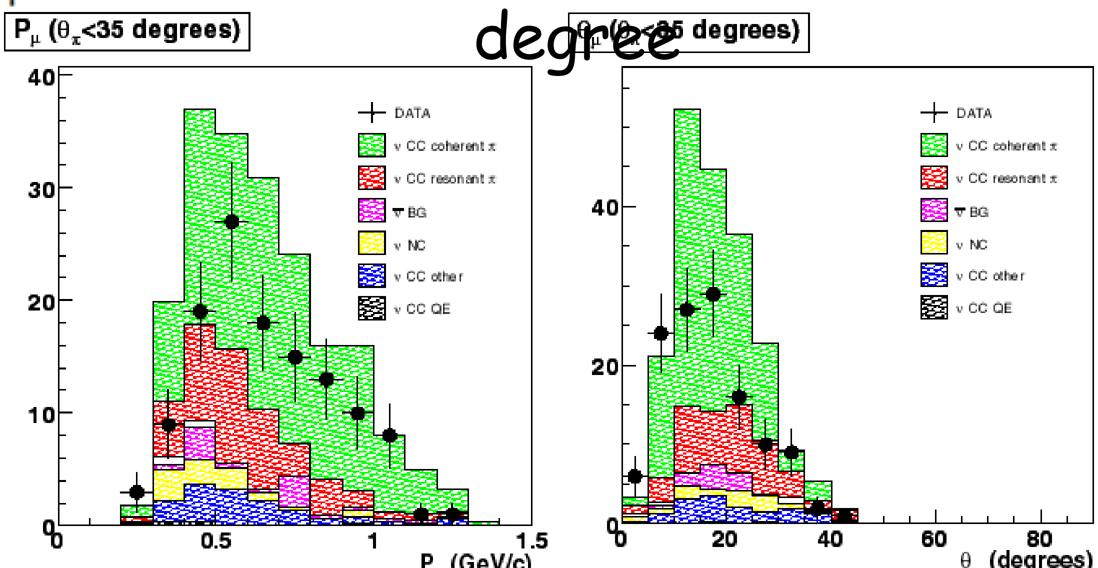
Anti-neutrino CC coherent π

- μ+π events in ***anti-ν*** data set



Excess observed in anti-ν data over no coherent π prediction: ~4σ (stat. error only)

Similar excess is found for ***neutrino*** events with θ_π < 35 degree



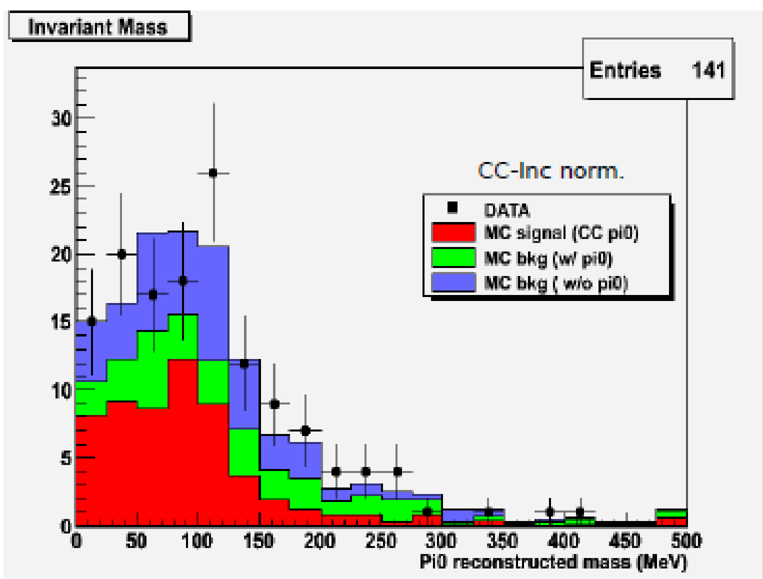
H. Tanaka@ NuInt09

CC π^0

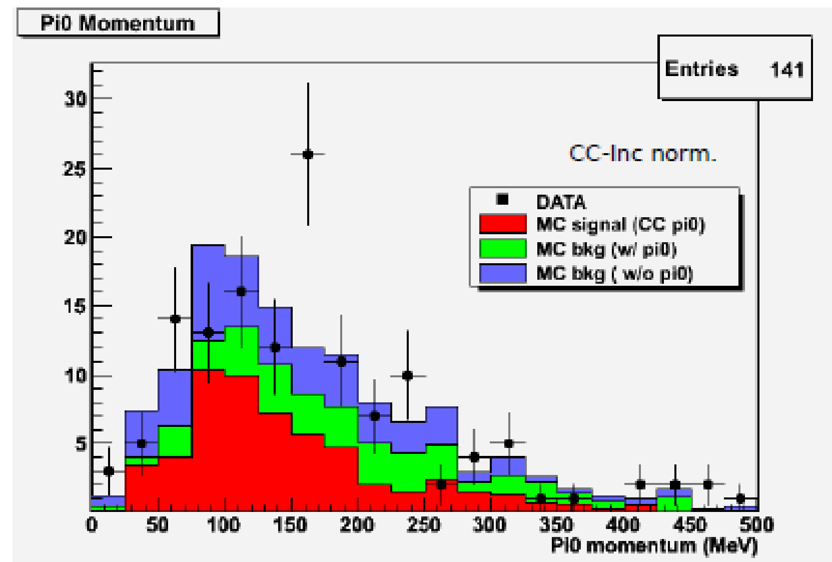
J. Catala @ NuFact09

SciBooNE

- $\mu+2\gamma$ events: Complicated events



$M_{\gamma\gamma}$ (MeV)



$p_{\pi 0}$ (MeV)

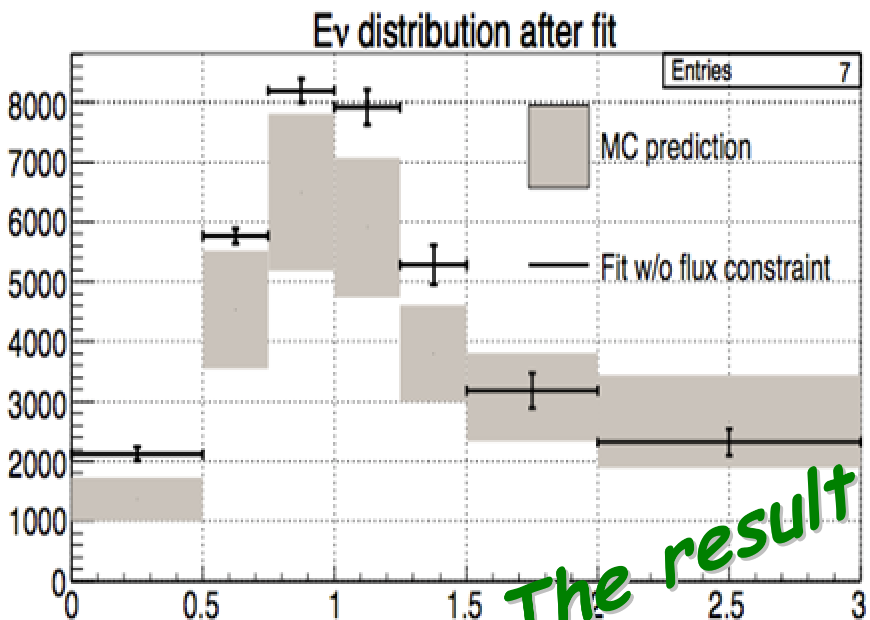
- Analysis will be improved and update soon.

ν_μ disappearance between SciBooNE and MiniBooNE

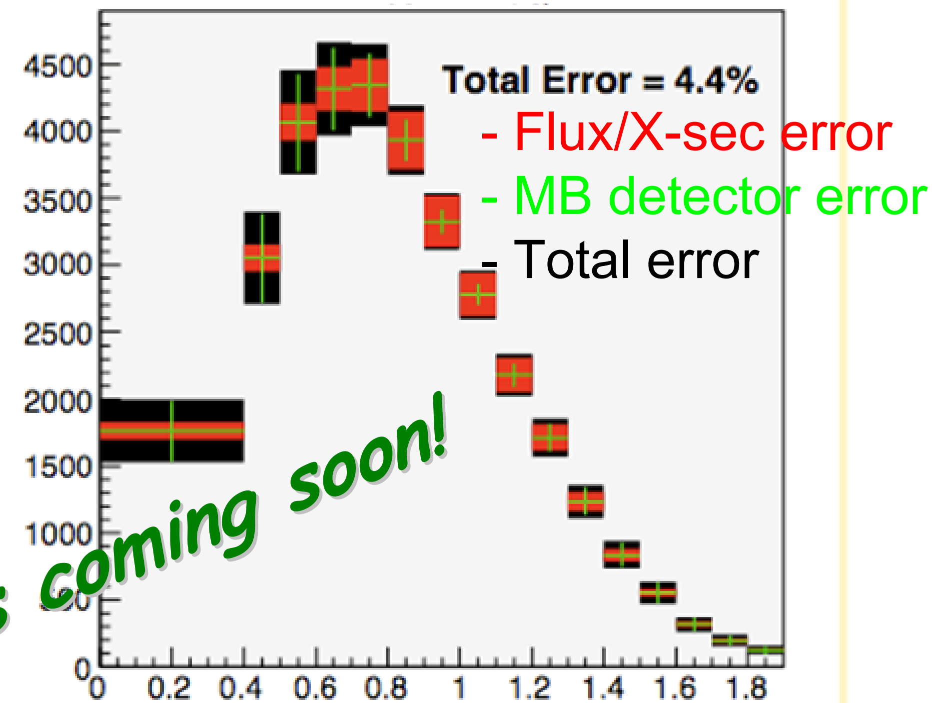
SciBooNE

- Exotic model of neutrino oscillation

Beam flux ⊗ cross sections constrained by SciBooNE w/ NUANCE



MiniBooNE MC sample



The result is coming soon!

Rec. E_ν of MiniBooNE with the NUANCE MC prediction by using the SciBooNE measurements

Y. Nakajima@ Fermilab New Perspectives Conference 2009

More results

- Electron neutrinos
- More studies on anti-neutrino data

:

:

- Interesting results w/ more ideas

Summary and Outlook

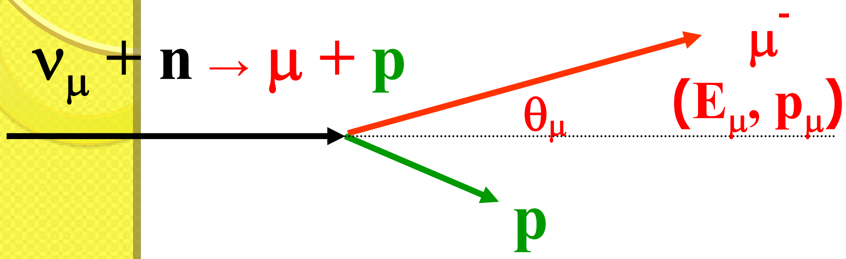
- SciBooNE successfully collected neutrino and anti neutrino data from June 2007 to Aug. 2008.
  - neutrinos : 0.99×10^{20} POT
  - antineutrinos: 1.53×10^{20} POT
- Analysis are underway and many interesting results are coming soon!
- The SciBooNE measurements will be essential for future neutrino oscillation experiments, especially T2K.

BACKUP

2.1 QE (Quasi-Elastic) scattering

CC quasi elastic (QE)

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



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

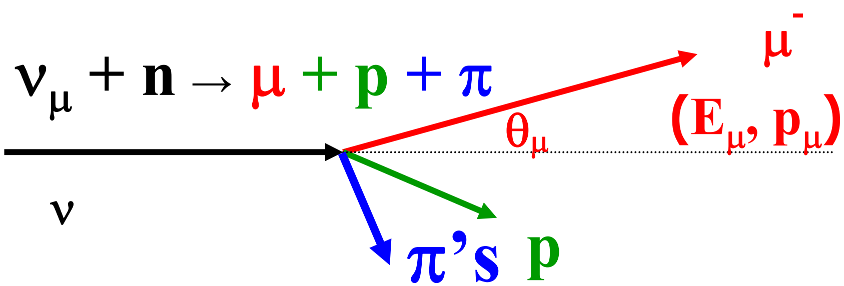
Rate(Eν,Near) → <u>φ(Eν,Near)</u>

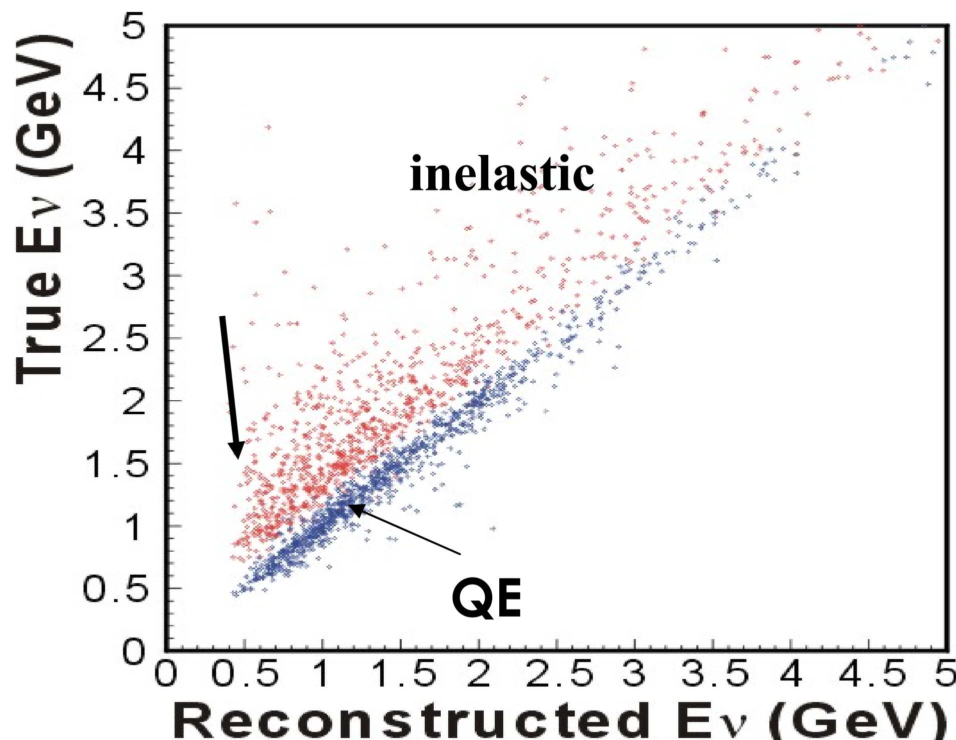
↑

σ(QE), σ(nonQE)

CC inelastic

$\nu_\mu + n \rightarrow \mu + p + \pi$





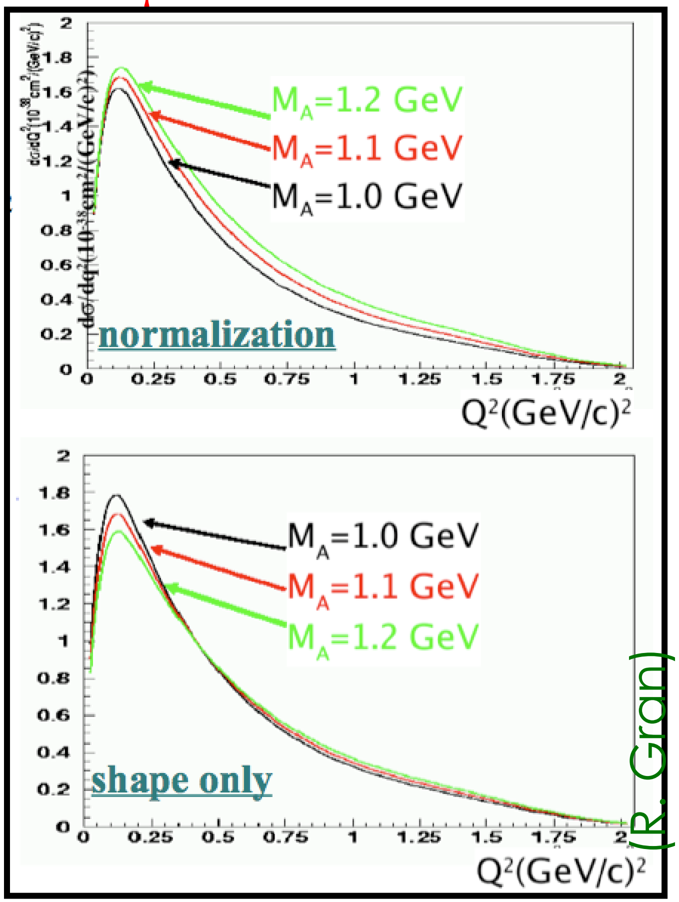
QE Scattering

- 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

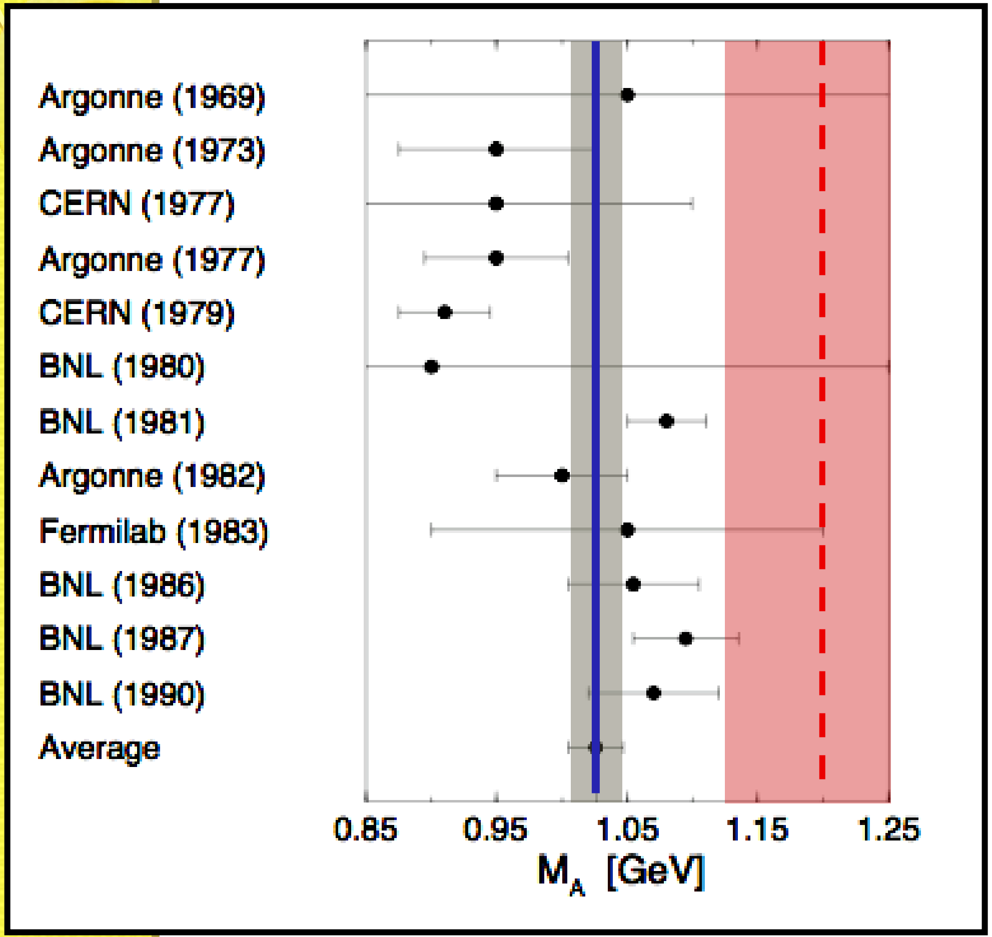
$$F_A(Q^2) = \frac{g_A}{\left(1 + Q^2 / M_A^2\right)^2}$$

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

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



Recent measurements of M_A



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J. Phys. **G28**, R1 (2002)

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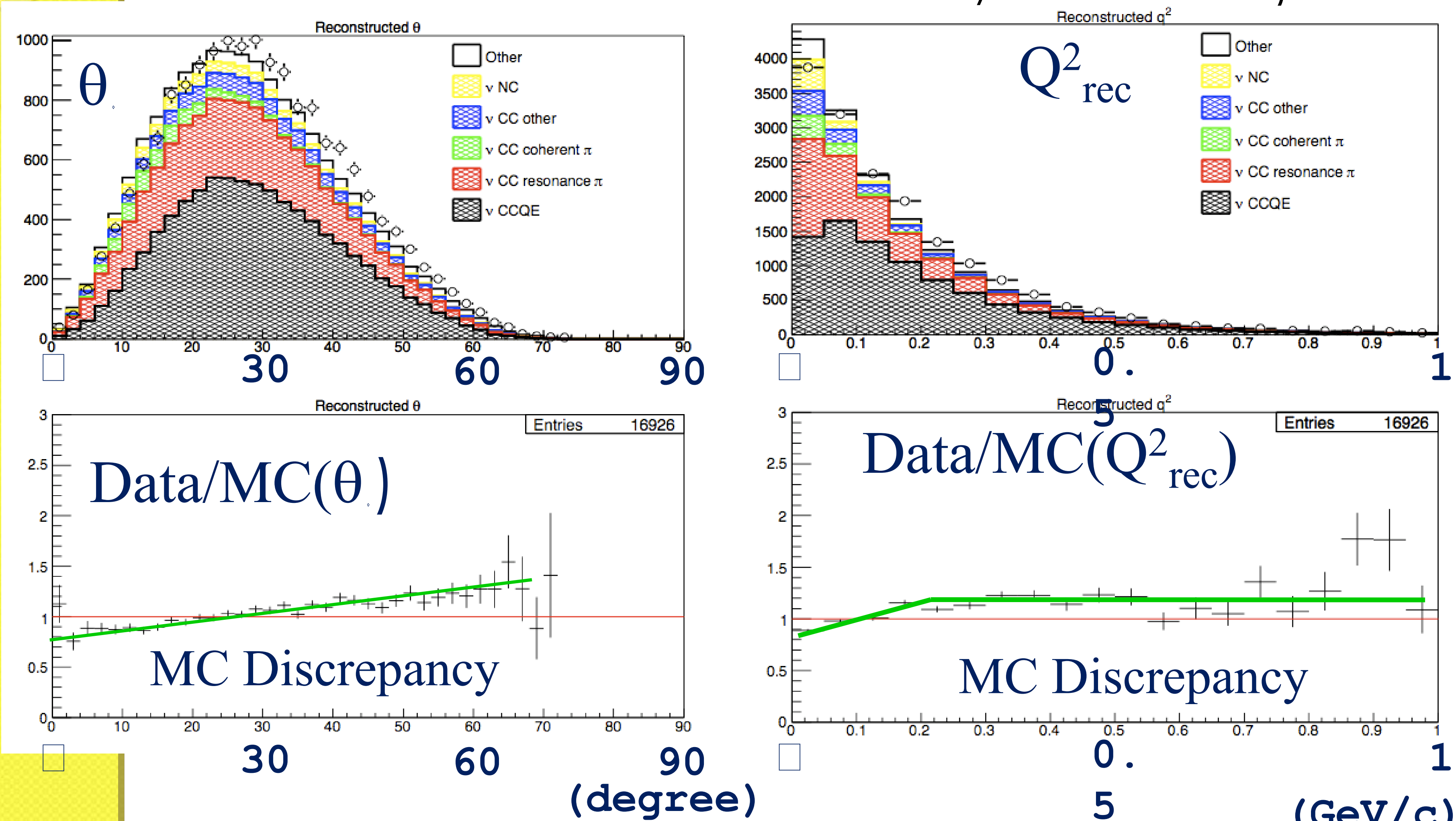
  $M_A = 1.14 \pm 0.11$ GeV
- **MiniBooNE** (^{12}C, $Q^2>0.25$)
  Phys. Rev. Lett. **100**, 032301 (2008)
  $M_A = 1.25 \pm 0.12$ GeV

Systematic Difference?
Effective M_A in nucleus?

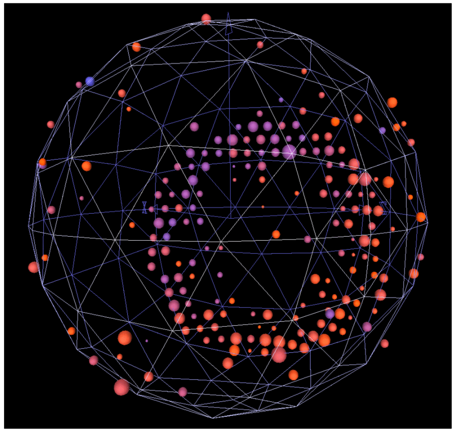
and Q^2 in SciBooNE

MRD Stopped sample(normalized by muon events)

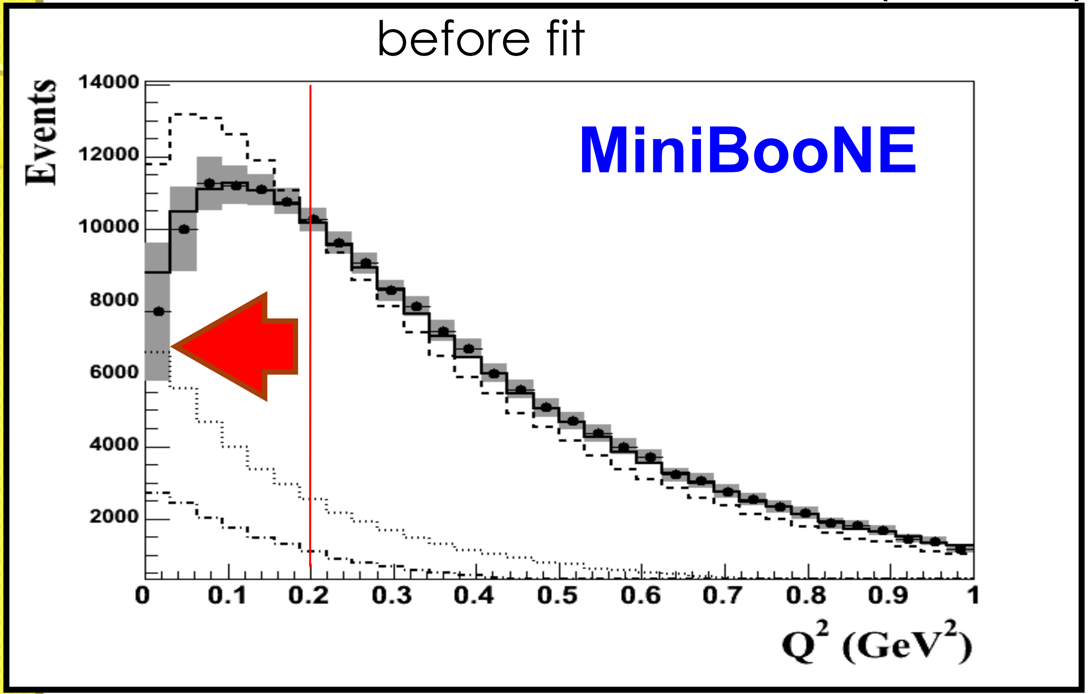


M_A effect or other sources ?

Low Q^2 region in QE



(T. Katori)



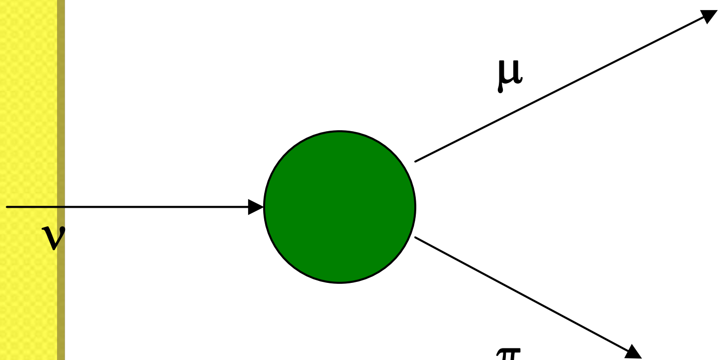
- fit to Q^2 distribution, $Q^2>0$, carbon
  - $M_A = 1.23 \pm 0.20$ GeV → fixes high Q^2
  - $\kappa = 1.019 \pm 0.011$ (Pauli blocking par) → fixes low Q^2

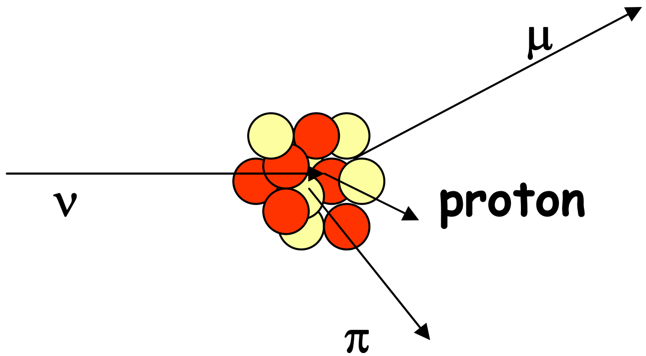
(PRL **100**, 032301 (2008))

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

CC-1π (ν+p→μ+p+π)
Mainly through Δ resonance.

CC-coherent π (ν+A→μ+A+π)

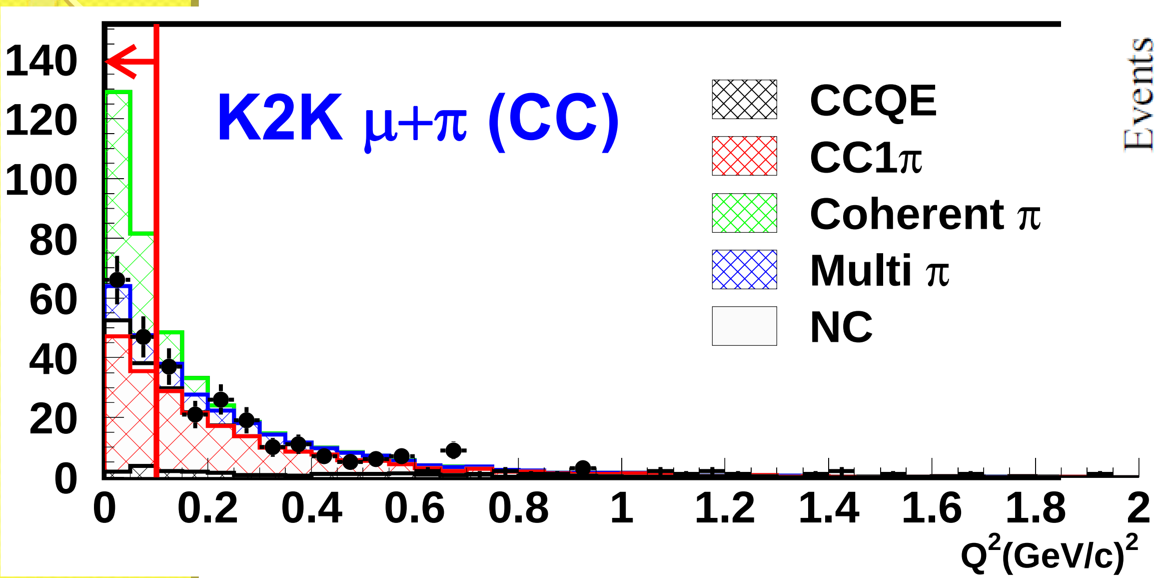


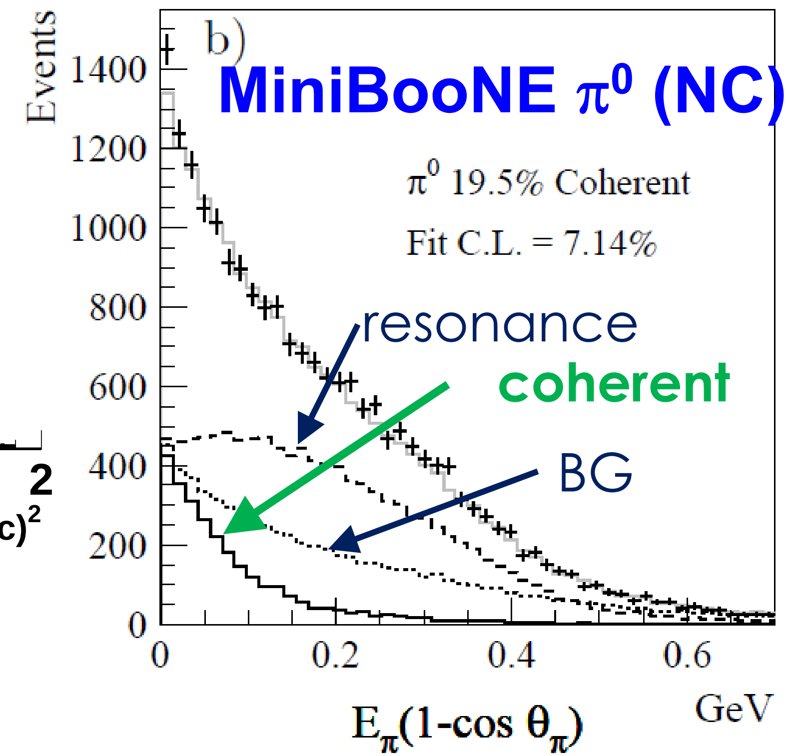


Coherent π signature

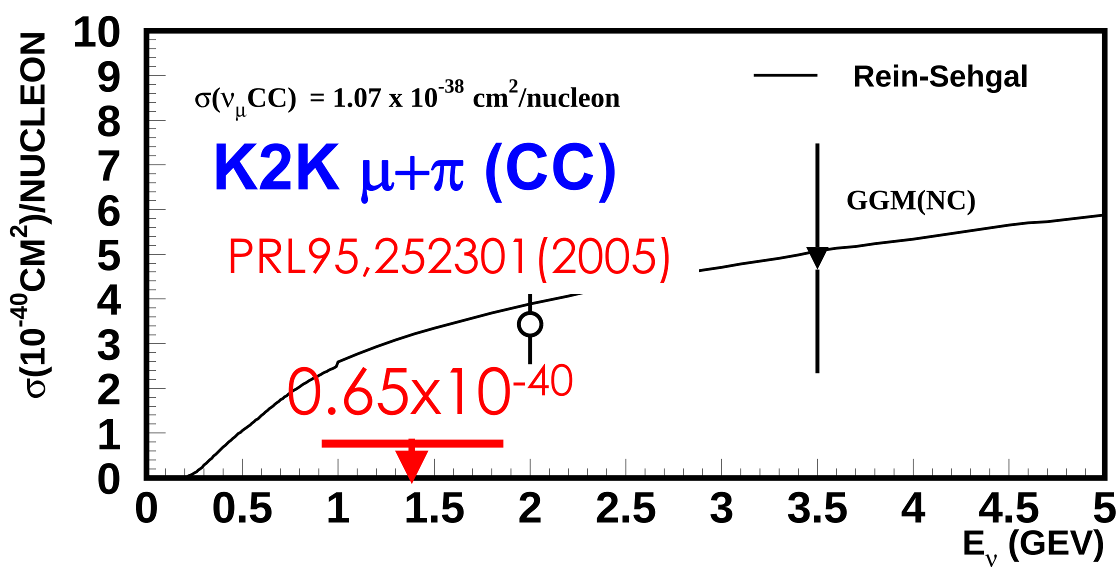
- One muon and one pion in the final state
- Low momentum transfer
- No vertex activity due to no proton

Coherent π production in CC and NC reaction





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



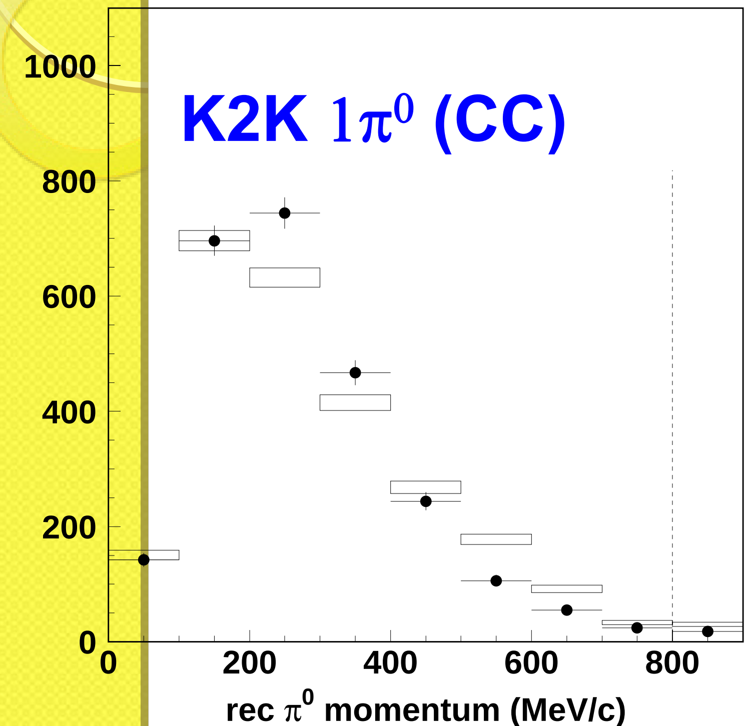
MiniBooNE π^0 (NC)

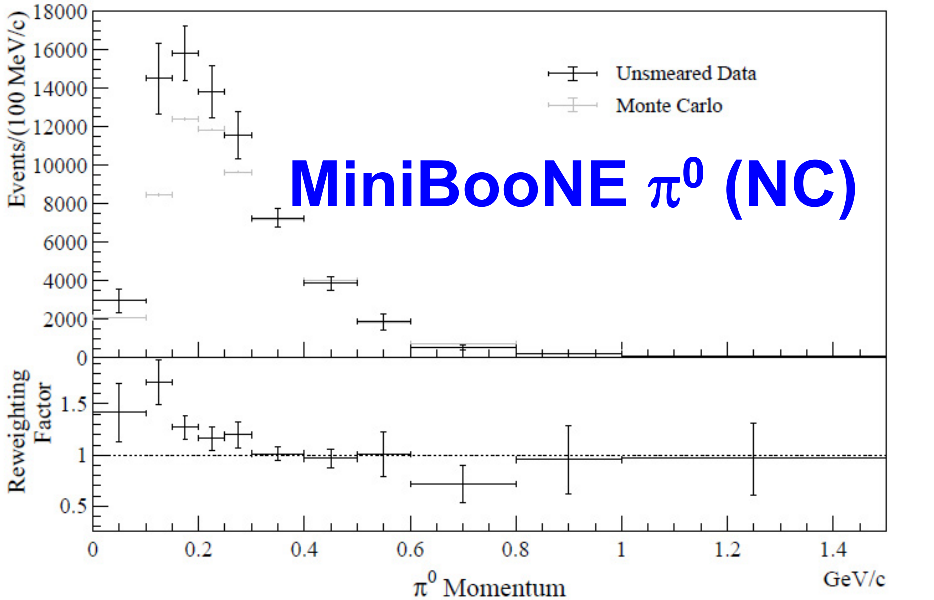
First observation of NC coherent pion production at Eν<2GeV

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)

First Result in

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

K. Hiraide,[10] J. L. Alcaraz-Aunion,[1] S. J. Brice,[4] L. Bugel,[13] J. Catala-Perez,[18] G. Cheng,[3] J. M. Conrad,[13] Z. Djurcic,[3] U. Dore,[15] D. A. Finley,[4] A. J. Franke,[3] C. Giganti*,[15] J. J. Gomez-Cadenas,[18] P. Guzowski,[6] A. Hanson,[7] Y. Hayato,[8] G. Jover-Manas,[1] G. Karagiorgi,[13] T. Katori,[7] Y. K. Kobayashi,[17] T. Kobilarcik,[4] H. Kubo,[10] Y. Kurimoto,[10] W. C. Louis,[11] P. F. Loverre,[15] L. Ludovici,[15] K. B. M. Mahn,[3] C. Mariani†,[15] S. Masuike,[17] K. Matsuoka,[10] W. Metcalf,[12] G. Mills,[11] G. Mitsuka,[9] Y. Miyachi,[17] S. Mizugashira,[17] C. D. Moore,[4] Y. Nakajima,[10] T. Nakaya,[10] R. Napora,[14] P. Nienaber,[16] V. Nguyen,[13] D. Orme,[10] M. Otani,[10] A. D. Russell,[4] F. Sanchez,[1] M. H. Shaevitz,[3] T.-A. Shibata,[17] M. Sorel,[18] R. J. Stefanski,[4] H. Takei,[17] H.-K. Tanaka,[3] M. Tanaka,[5] R. Tayloe,[7] I. J. Taylor,[6] R. J. Tesarek,[4] Y. Uchida,[6] R. Van de Water,[11] J. J. Walding,[6] M. O. Wascko,[6] H. White,[4] M. J. Wilking,[2] M. Yokoyama,[10] G. P. Zeller,[11] and E. D. Zimmerman[2]

(The SciBooNE Collaboration)

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[2] *Department of Physics, University of Colorado, Boulder, Colorado 80309, USA*
[3] *Department of Physics, Columbia University, New York, NY 10027, USA*

The SciBooNE Collaboration has performed a search for charged current coherent pion production from muon neutrinos scattering on carbon, $\nu_\mu {}^{12}C \rightarrow \mu^- {}^{12}C \pi^+$, 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)

New σ_ν Calculations (2006-2008)

SciBooNE

Compiled by Sam Zeller (LANL)

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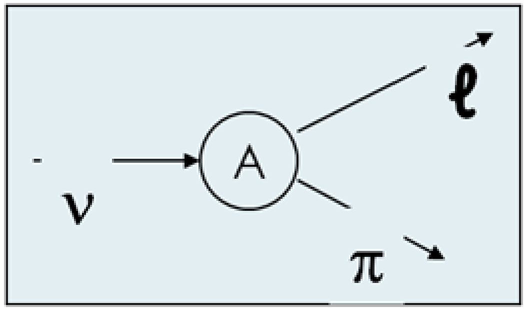
4.1 Search for Charged Current Coherent Pion Production

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

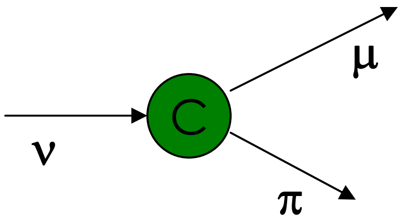
Several measurements (before K2K and MiniBooNE)
- both NC and CC
- both neutrino and antineutrino
- >2 GeV (NC), >7 GeV (CC) up to ~100 GeV

CC coherent pion production in SciBooNE

Signal

CC-coherent π production

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



Small Q^2

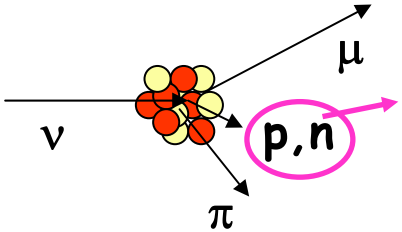
→ 2 MIP-like tracks (a muon and a pion)

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

Background

CC-resonant π production

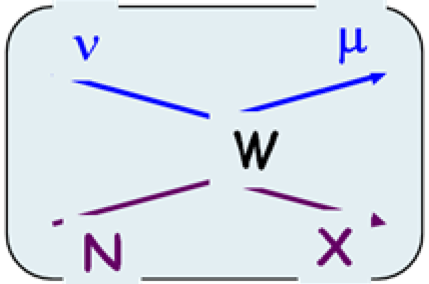
- $\nu + p \rightarrow \mu + p + \pi^+$
- $\nu + n \rightarrow \mu + n + \pi^+$



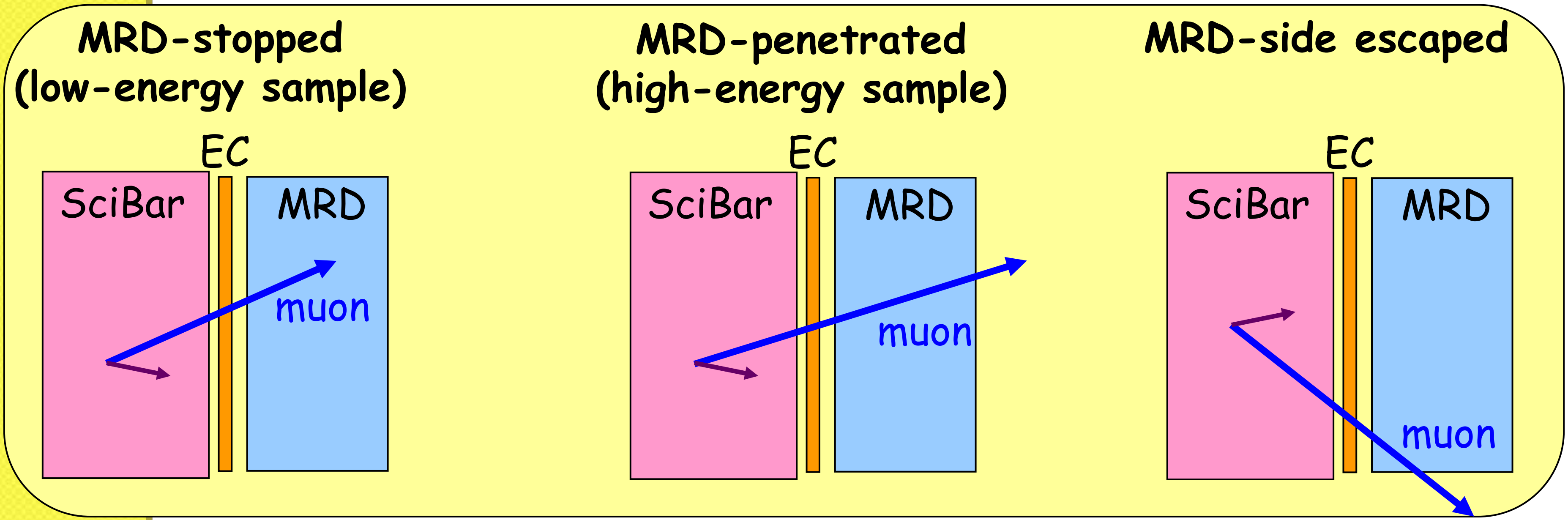
often not reconstructed

Charged Current (CC) event selection

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

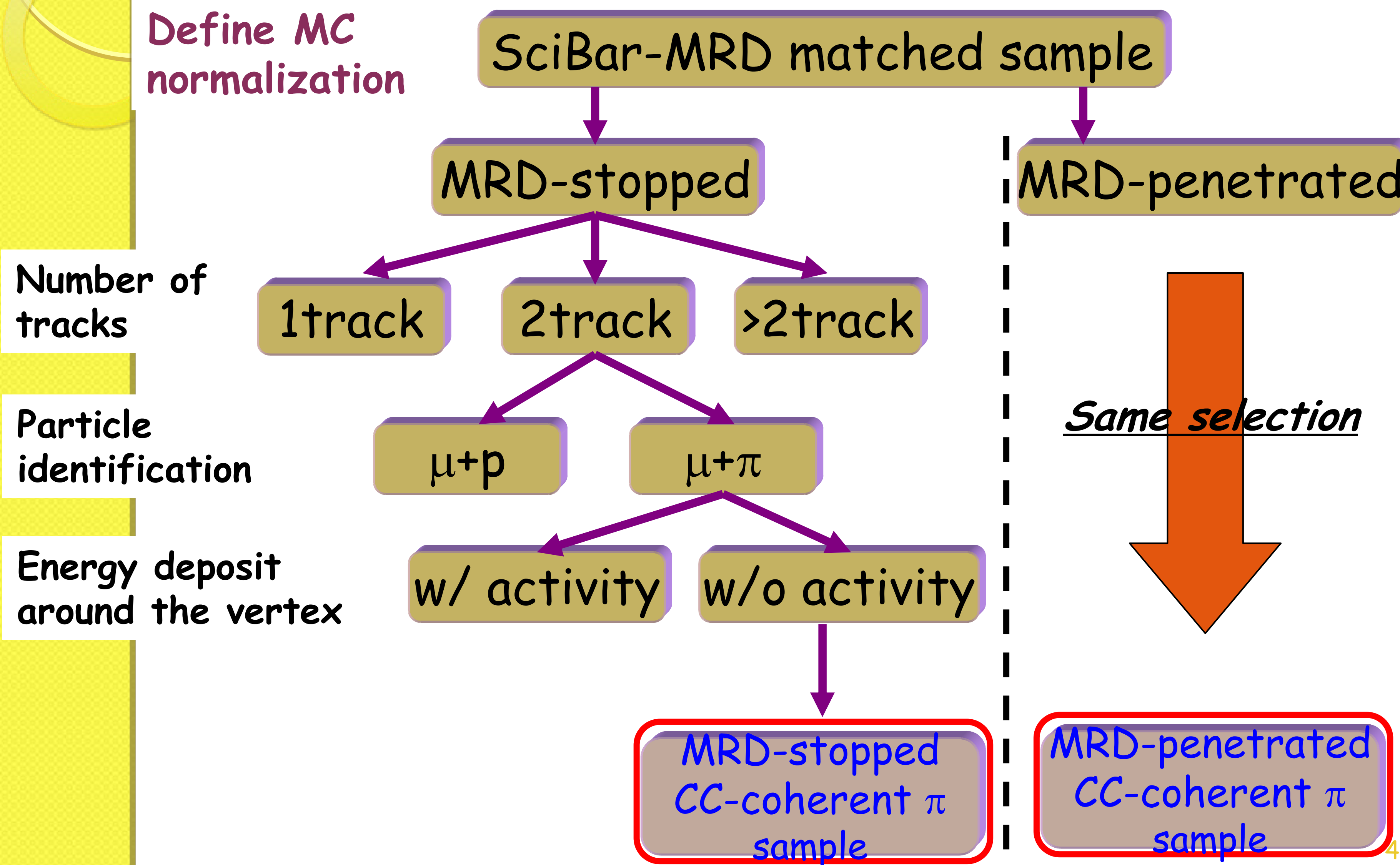


SciBar-MRD matched event (~30k events)

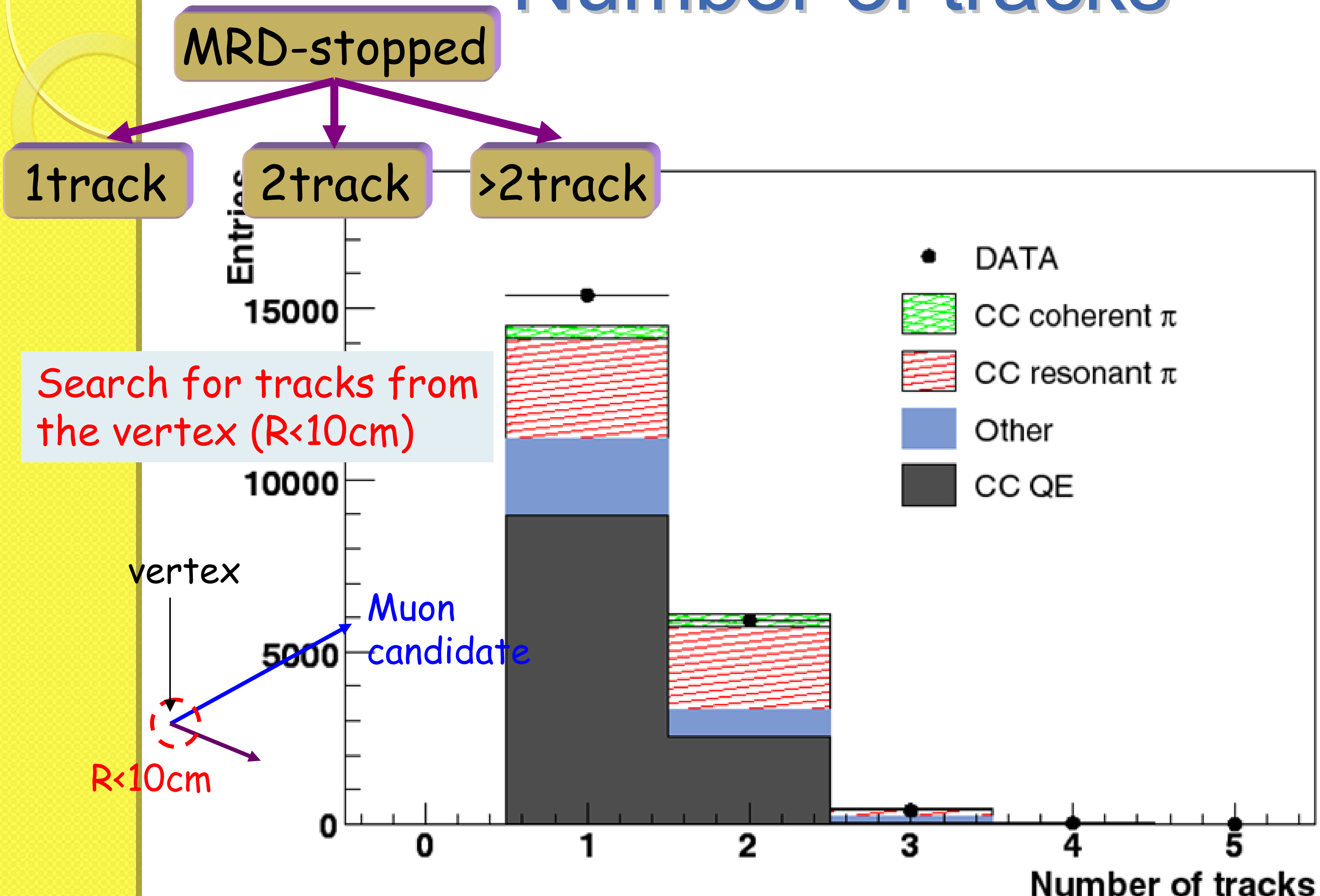


93% pure CC-inclusive ($\nu + N \rightarrow \mu + X$) sample

CC event classification



Number of tracks



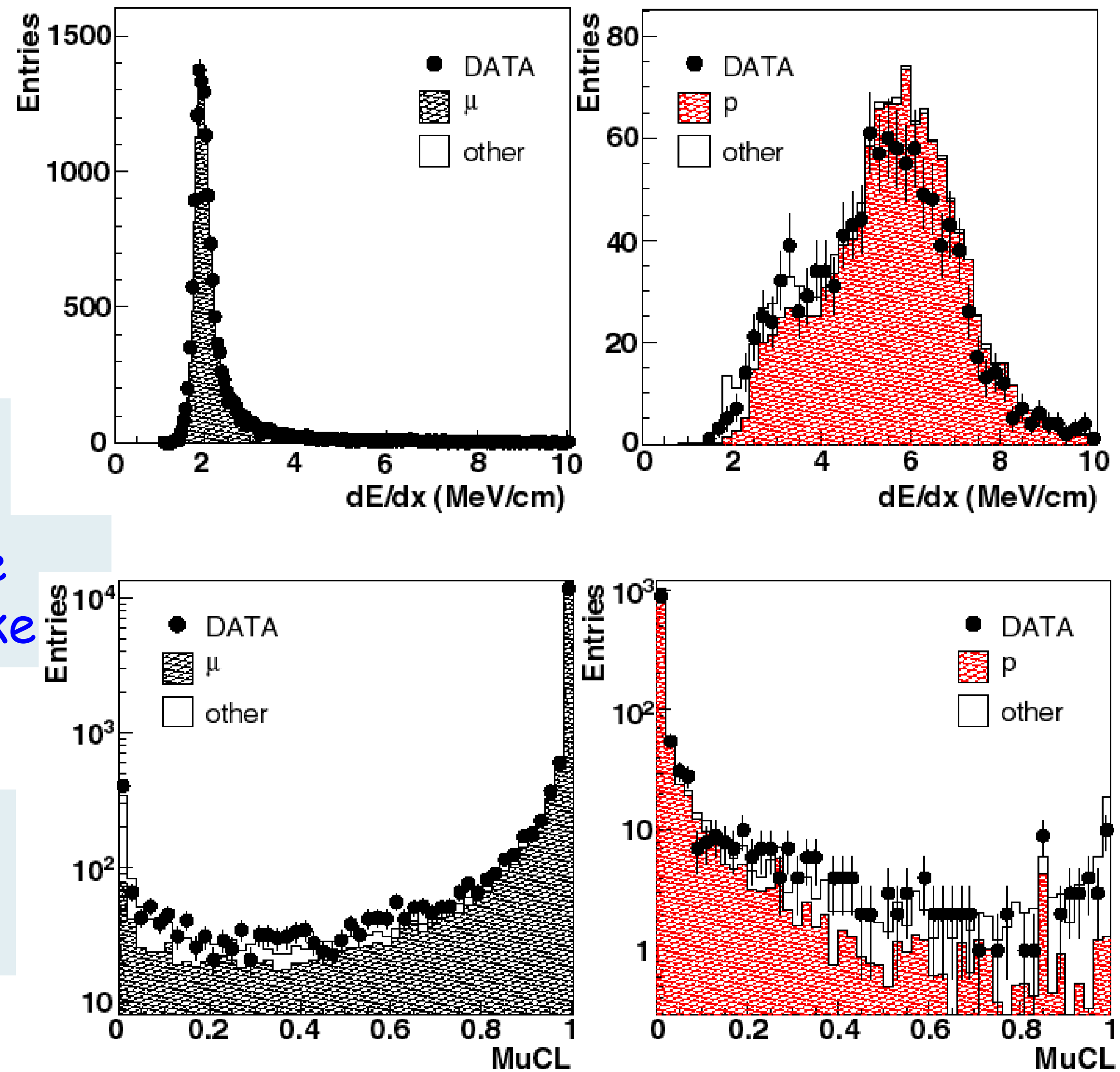
Search for tracks from the vertex (R<10cm)

Particle identification

Using dE/dx in SciBar

Muon enriched

Proton enriched



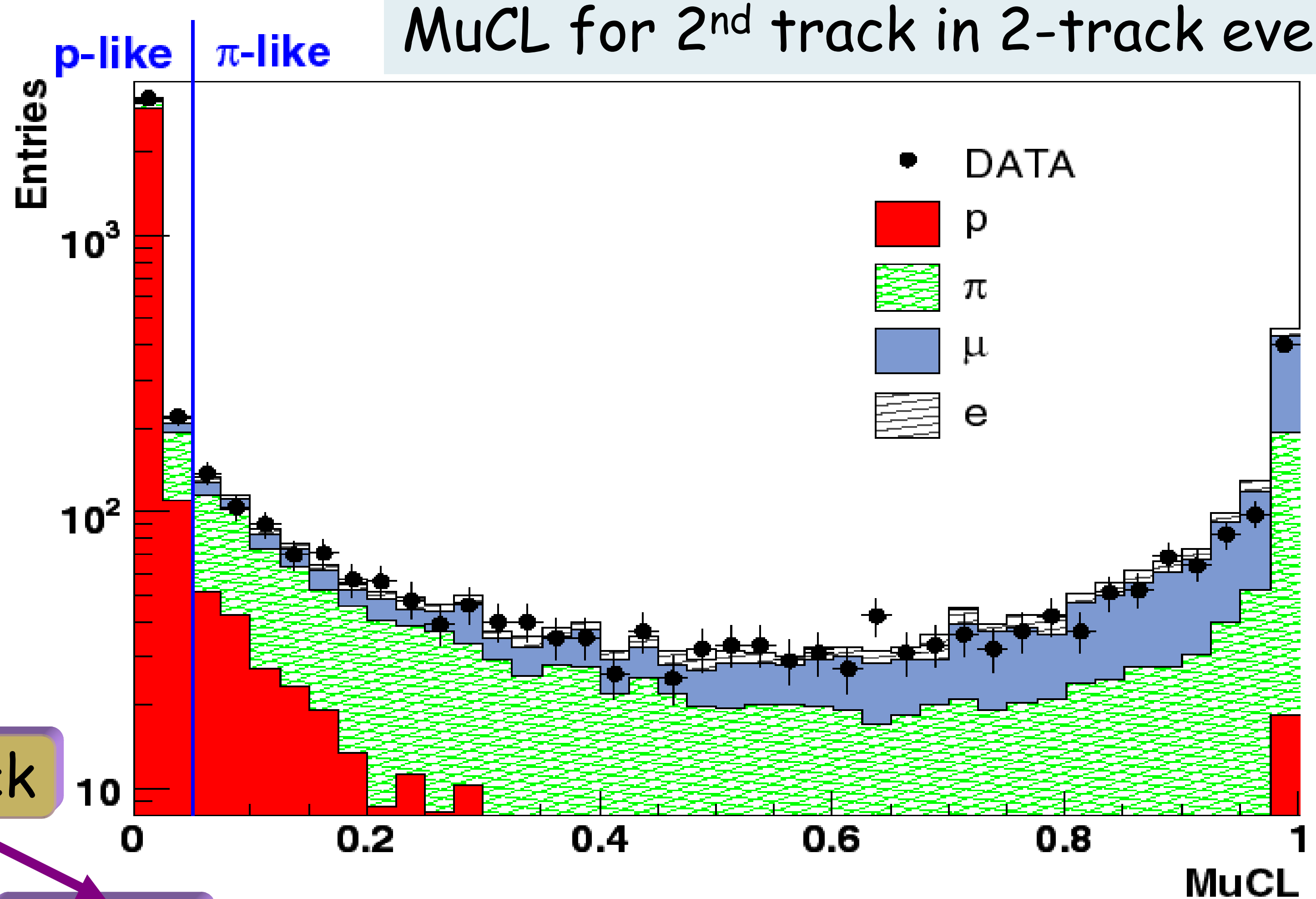
Muon confidence level (MuCL)

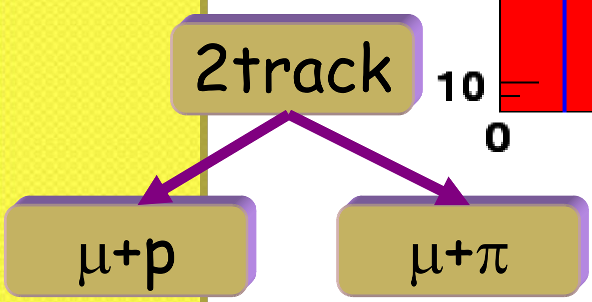
- MuCL >0.05 → muon-like
- <0.05 → proton-like

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

Particle identification (cont'd)

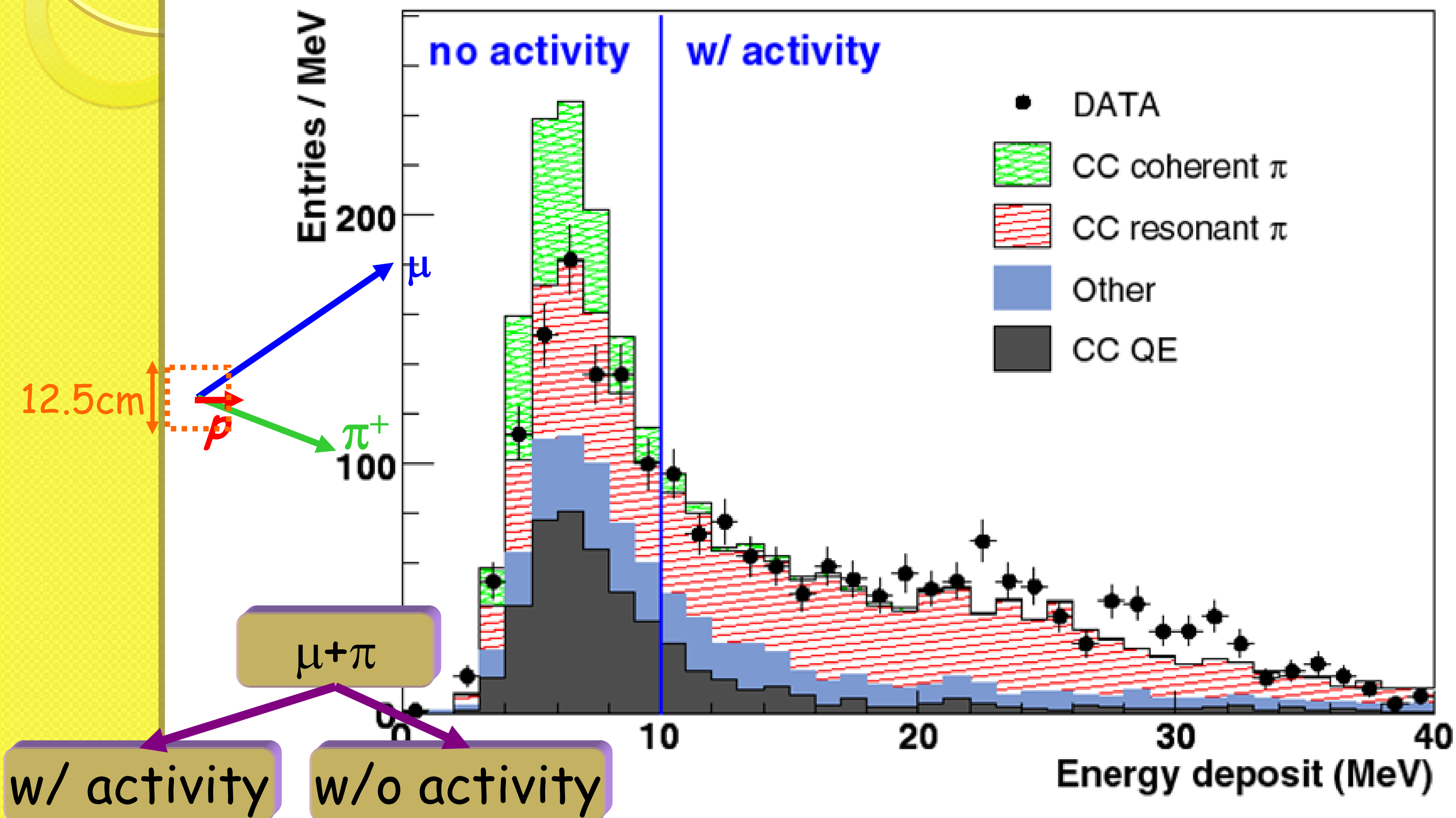
MuCL for 2nd track in 2-track event



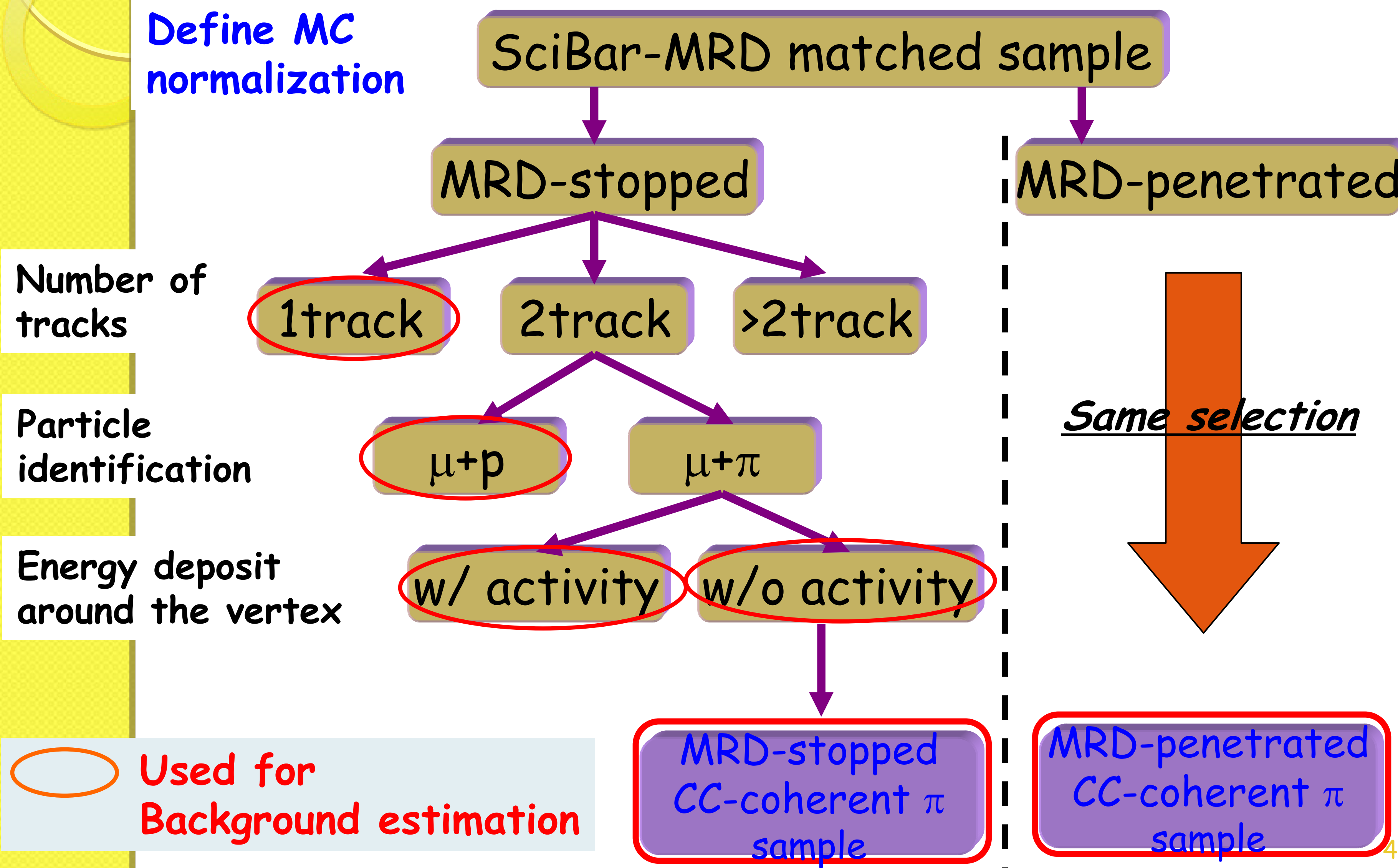


Vertex activity

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



CC event classification



Tuning of MC simulation

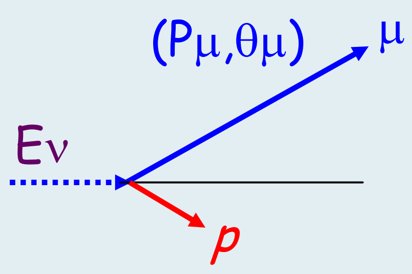
To constrain systematic uncertainties due to

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

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

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

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



CC-QE

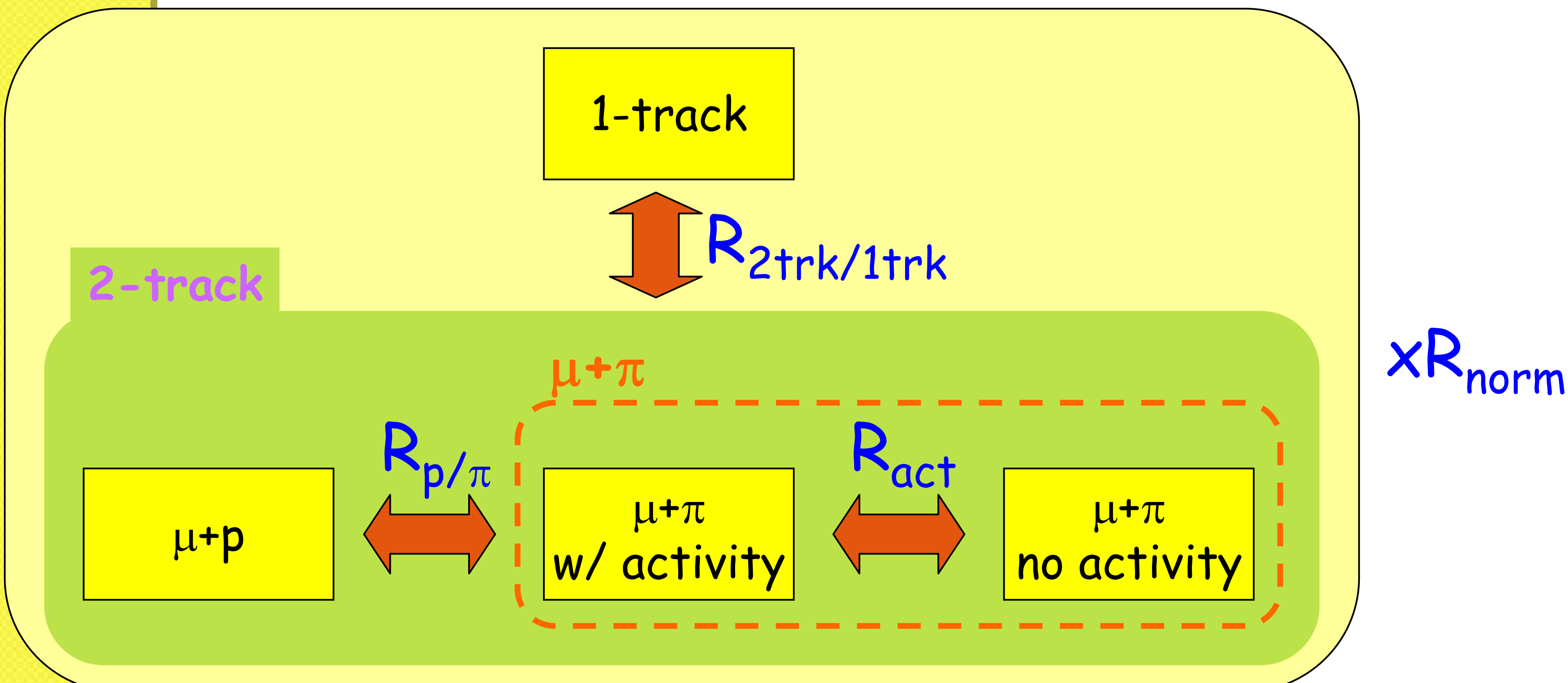
$$E_\nu^{rec} = \frac{1}{2}\frac{(m_p^2 - m_\mu^2) - (m_n - V)^2 + 2E_\mu(m_n - V)}{(m_n - V) - E_\mu + p_\mu \cos\theta_\mu}$$

V: nuclear potential (27MeV)

Fitting parameters (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

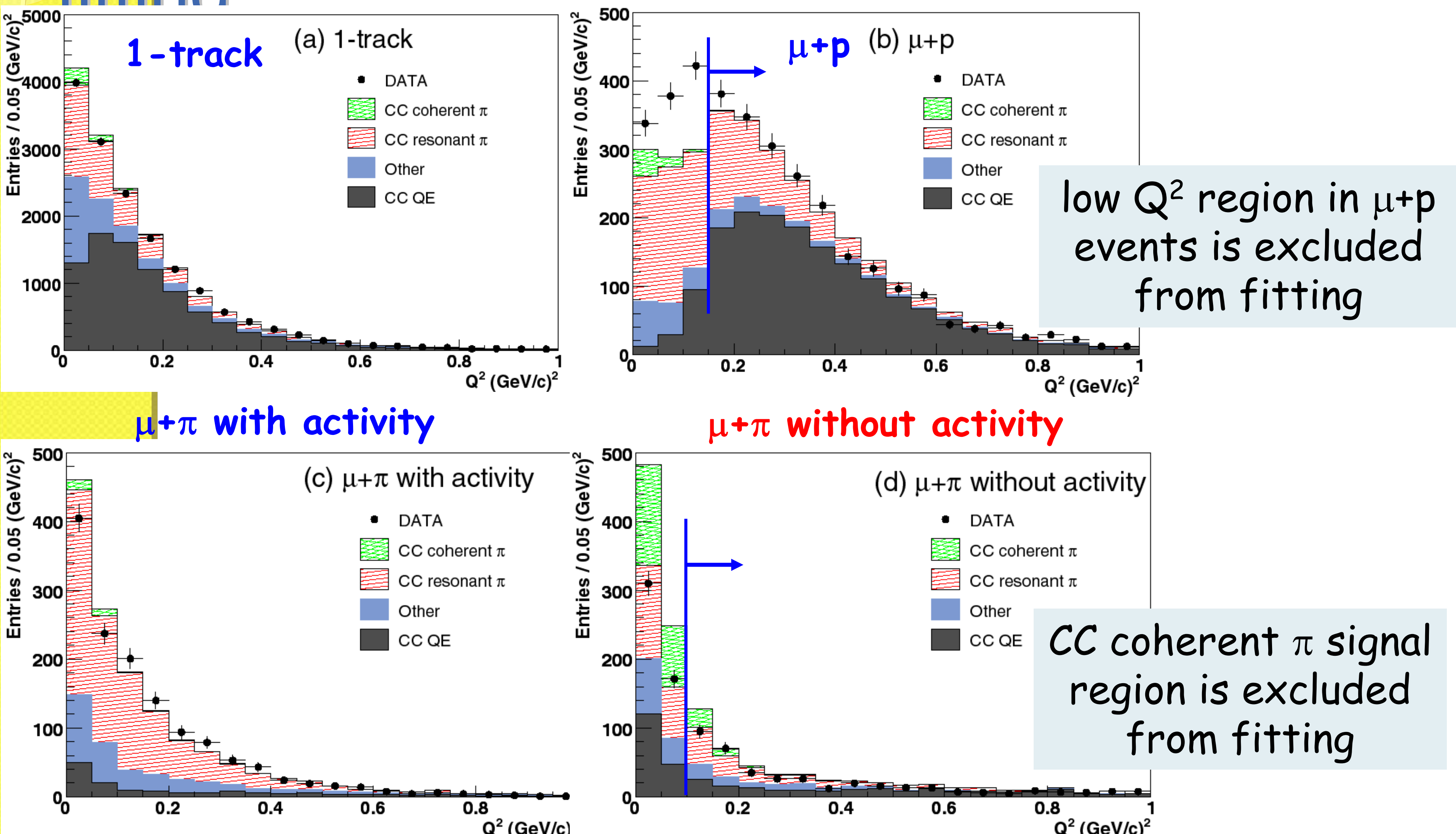
$$E_{lo} = \kappa(\sqrt{p_F^2 + m_p^2} - \omega + E_B)$$

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

Fitting result

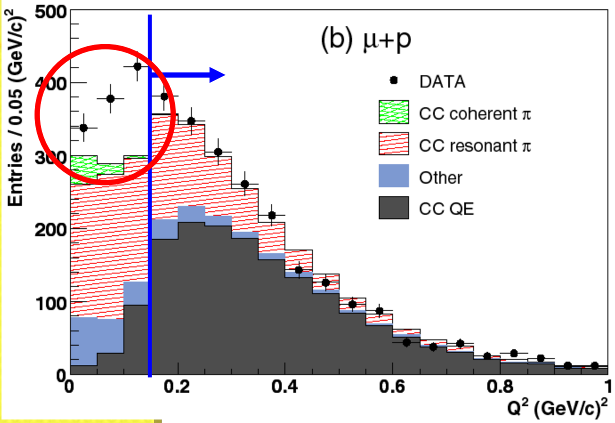
Parameter	Value	Error
R_{norm}	1.103	0.029
$R_{2trk/1trk}$	0.865	0.035
$R_{p/\pi}$	0.899	0.038
R_{act}	0.983	0.055
R_{pscale}	1.033	0.002
R_{res}	1.211	0.133
R_{other}	1.270	0.148
kappa	1.019	0.004

Reconstructed Q^2 distributions after fitting



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

Data excess in μ+p sample

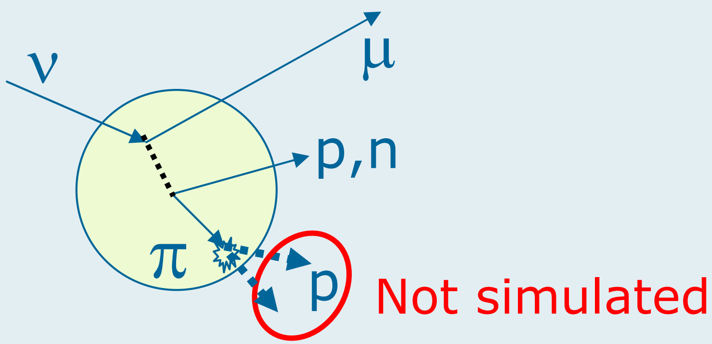


Features of excess events

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

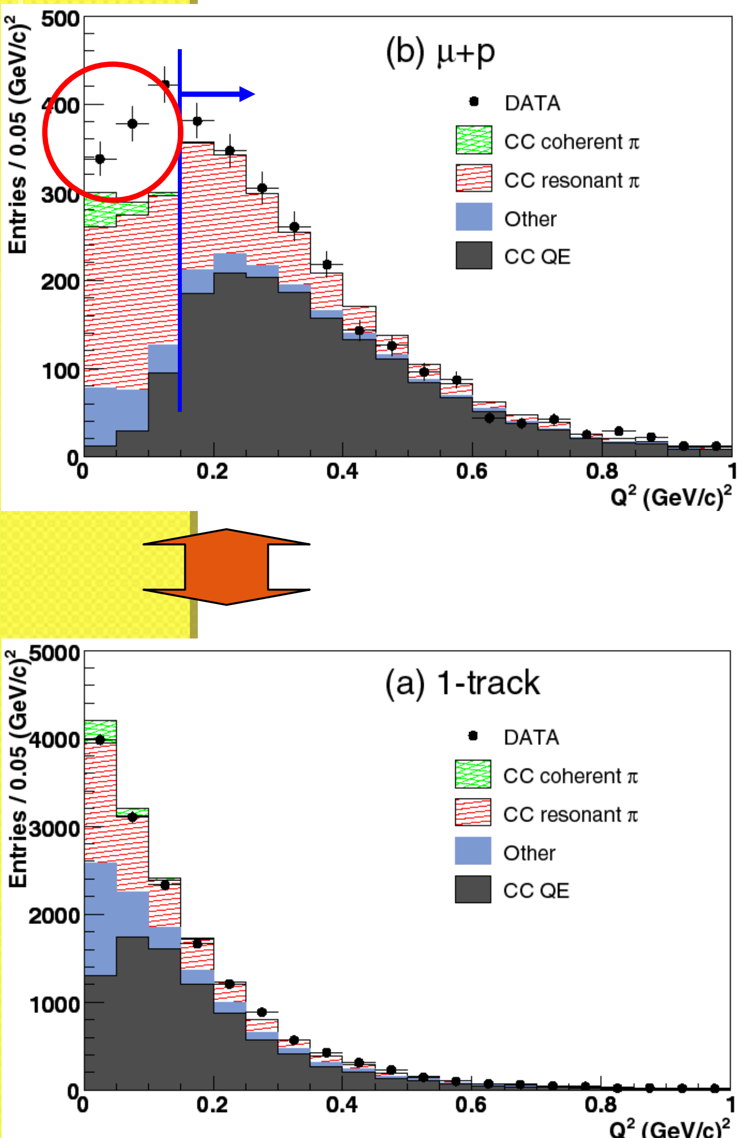
Possible candidate

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)



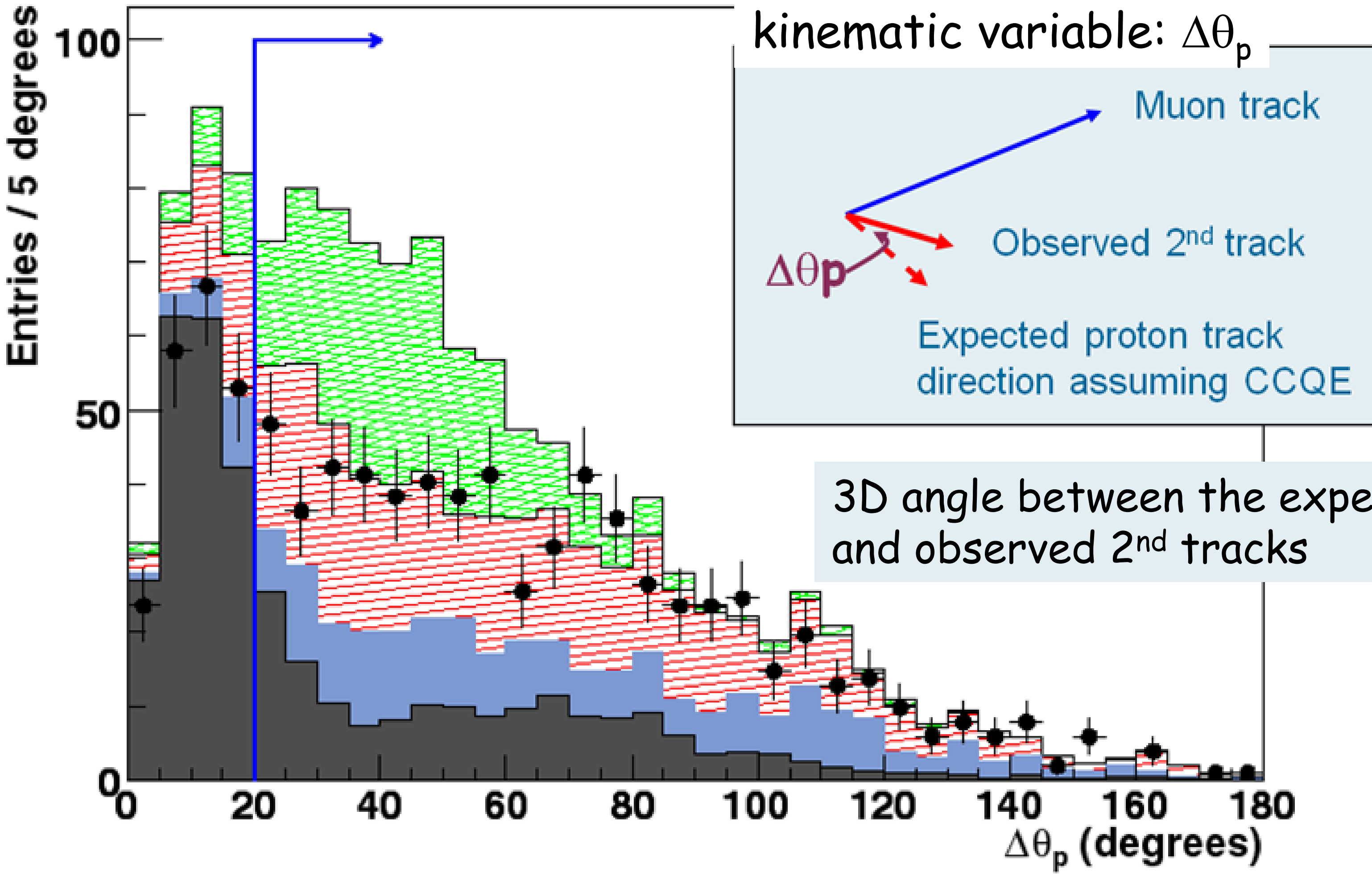
Therefore, we expect migration between the μ+p sample and 1-track sample.

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

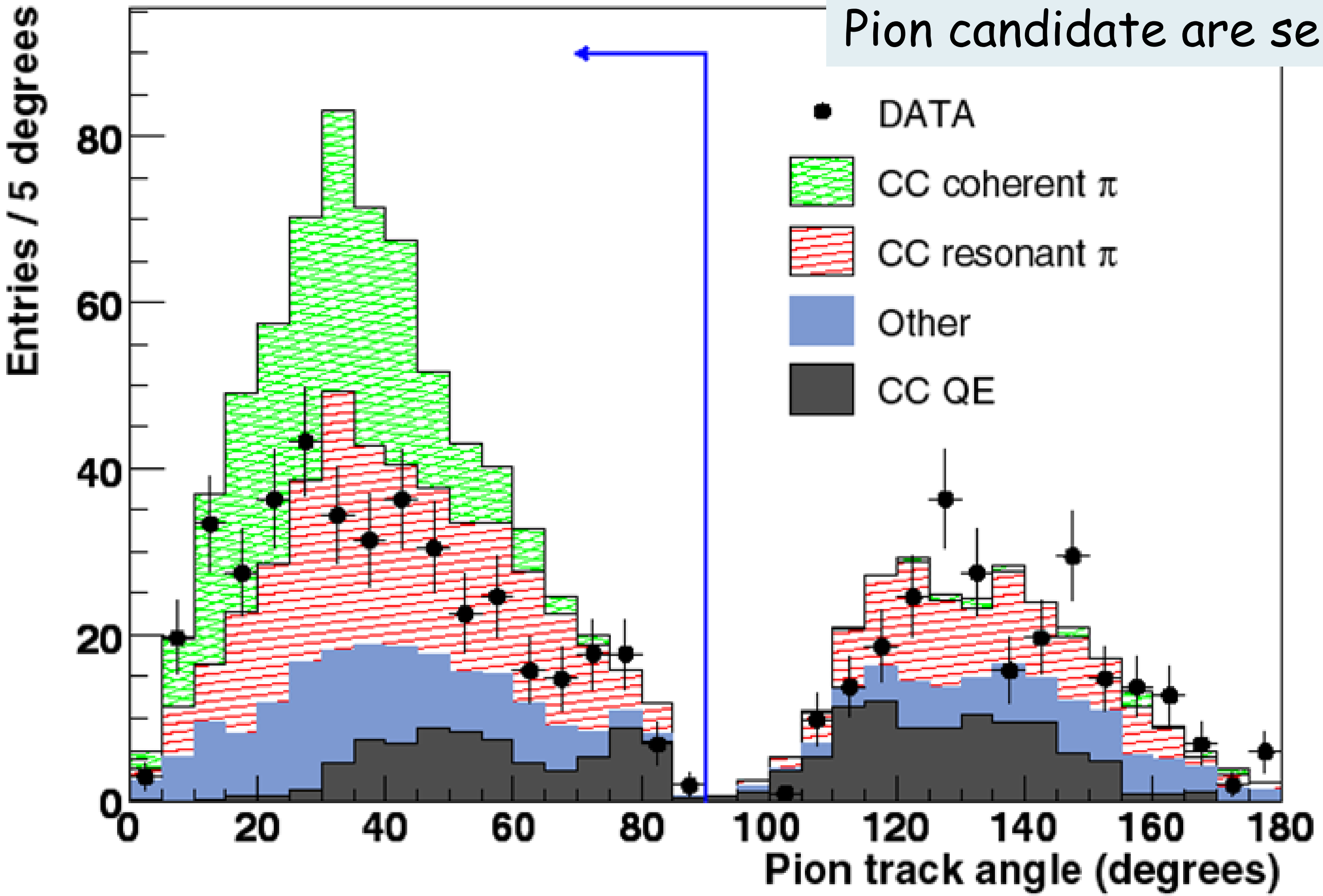


3D angle between the expected and observed 2nd tracks

Extracting CC coherent pion events

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

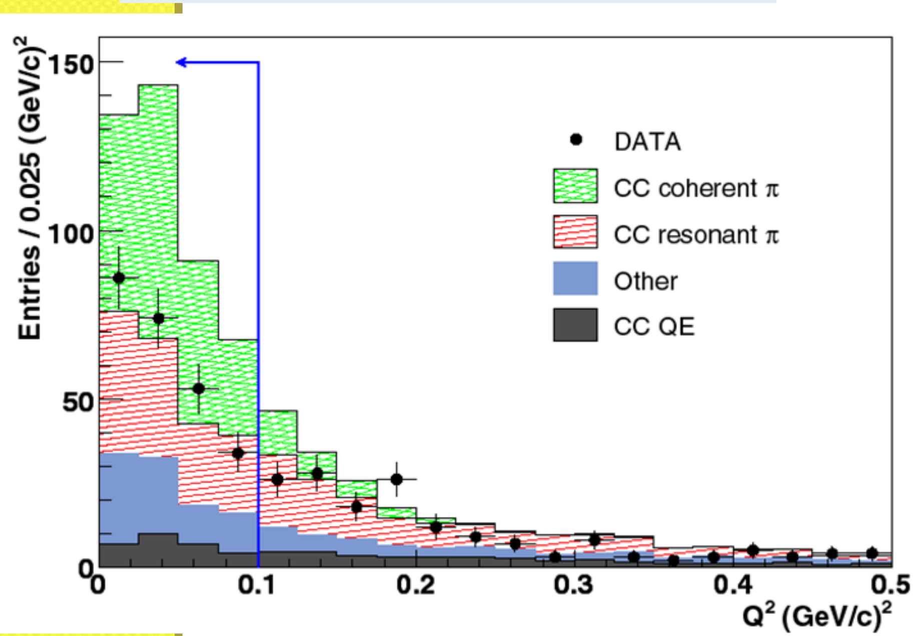
Events with a forward-going Pion candidate are selected

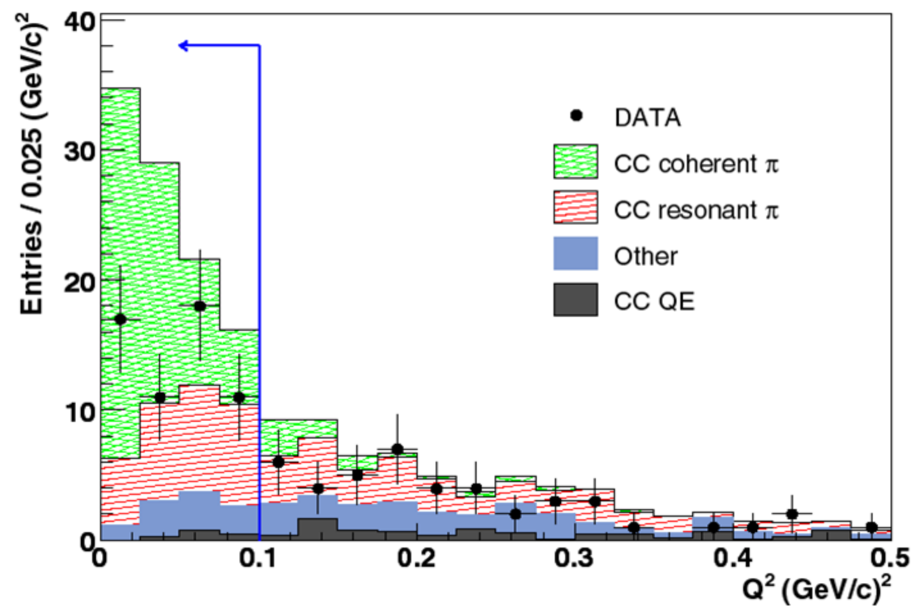


CC coherent pion sample ($Q^2<0.1$ (GeV/c)^2)

MRD stopped sample
<Eν>= 1.1 GeV

MRD penetrated sample
<Eν>= 2.2 GeV





247events selected

BG expectation
228+/-12 events

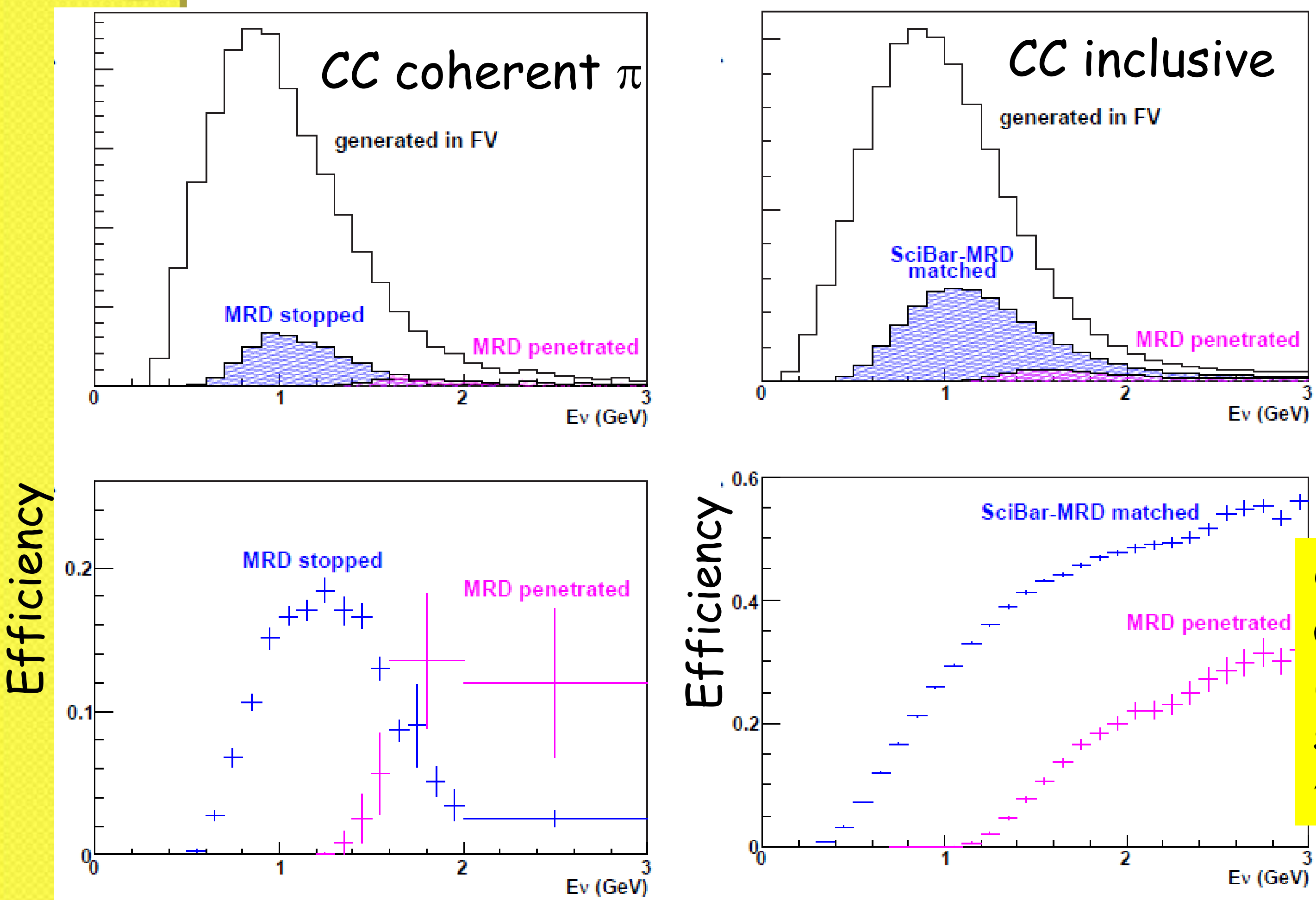
57events selected

BG expectation
40+/-2.2 events

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

SciBooNE

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

SciBooNE

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)

$\sigma(\text{CC coherent } \pi)/\sigma(\text{CC}) < 0.67\times10^{-2}$ for <Eν>=1.1 GeV

$< 1.36\times10^{-2}$ <Eν>=2.2 GeV

arXiv:0811.0369, Submitted to PRD

Result (cont'd)

K2K ($\langle E_\nu \rangle$=1.3 GeV)

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

SciBooNE ($\langle E_\nu \rangle$=1.1 GeV)

improved

slightly improved

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

K2K result (90% CL U.L.=m+1.28*σ)

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

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

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

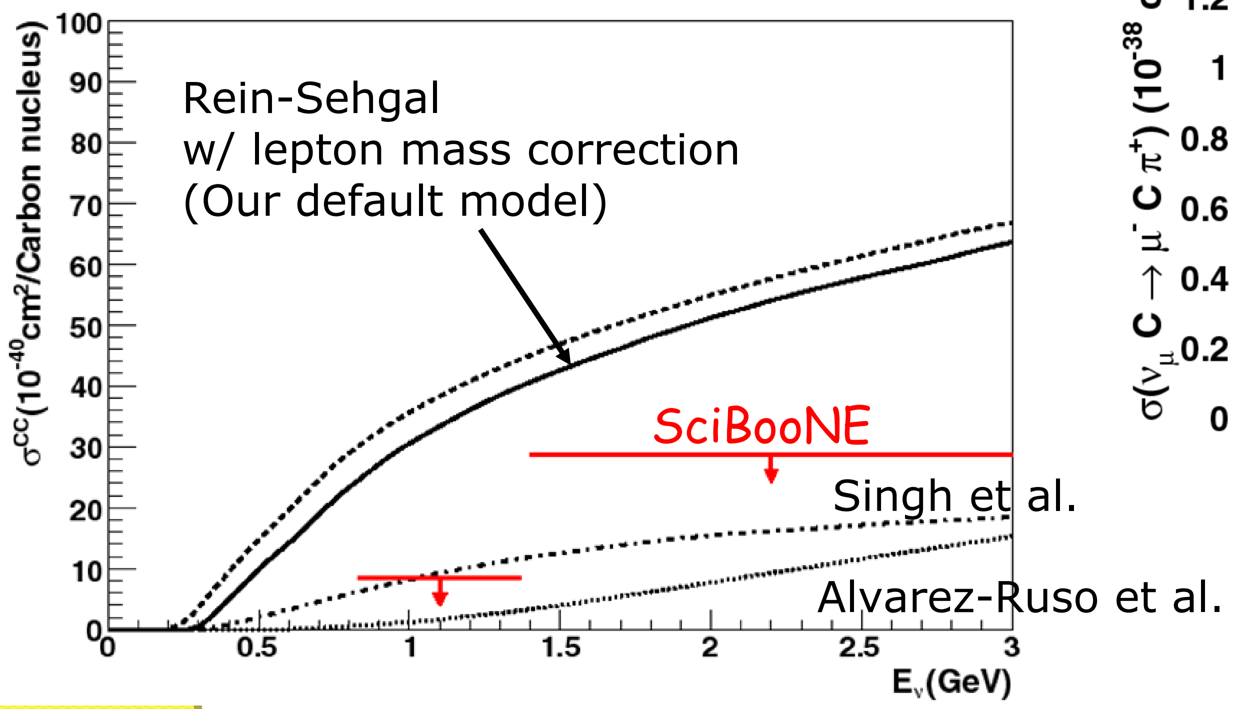
SciBooNE

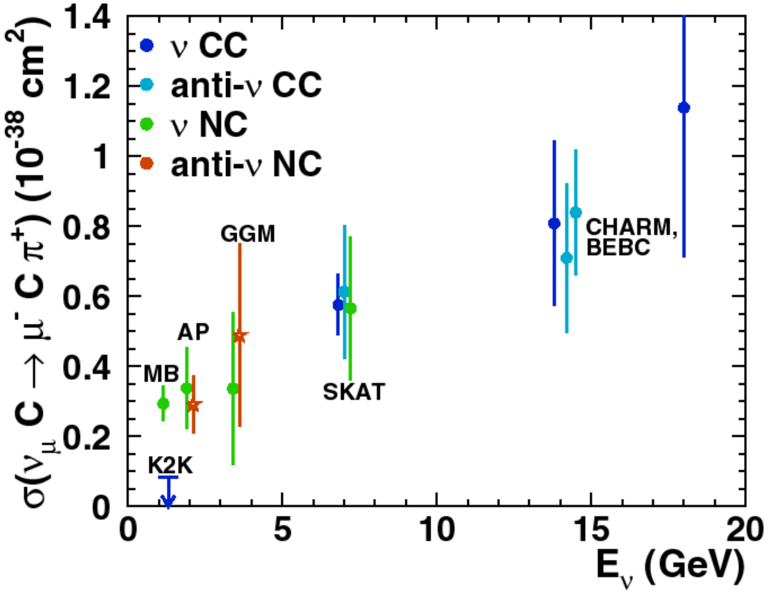
Systematic errors

	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

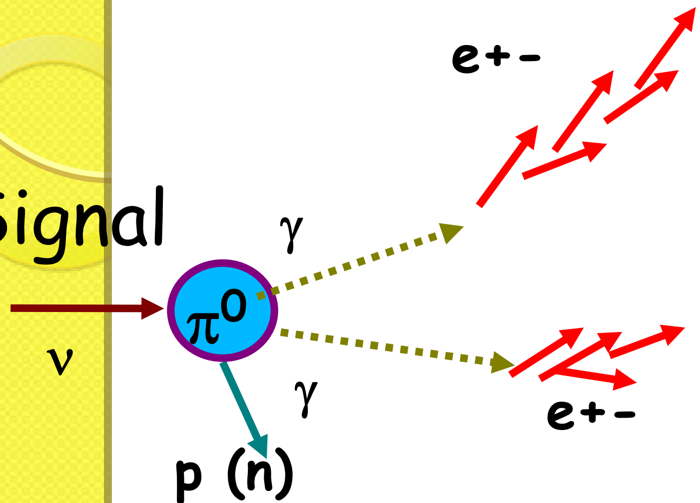




4.2 Neutral Current π^0 reconstruction in SciBooNE.

NCπ^0 signal and background

Signal

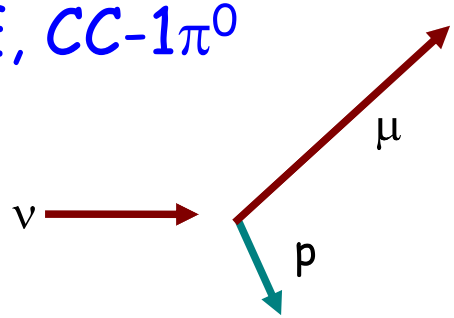


2γ from π^0

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

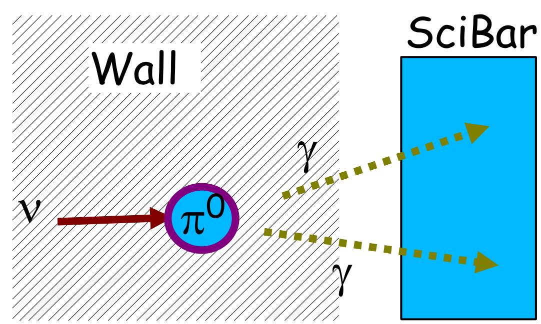
Internal B.G. : ν int. in SciBar

CCQE, CC-1π^0



External B.G : from outside

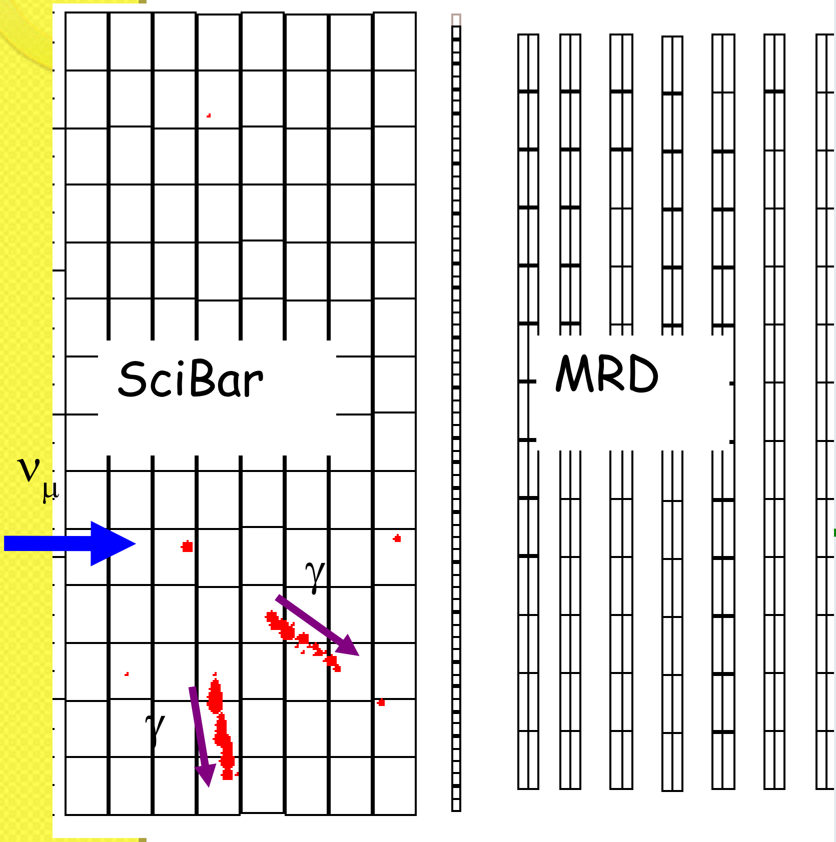
Dirt (wall), cosmic



Event Selection

SciBooNE

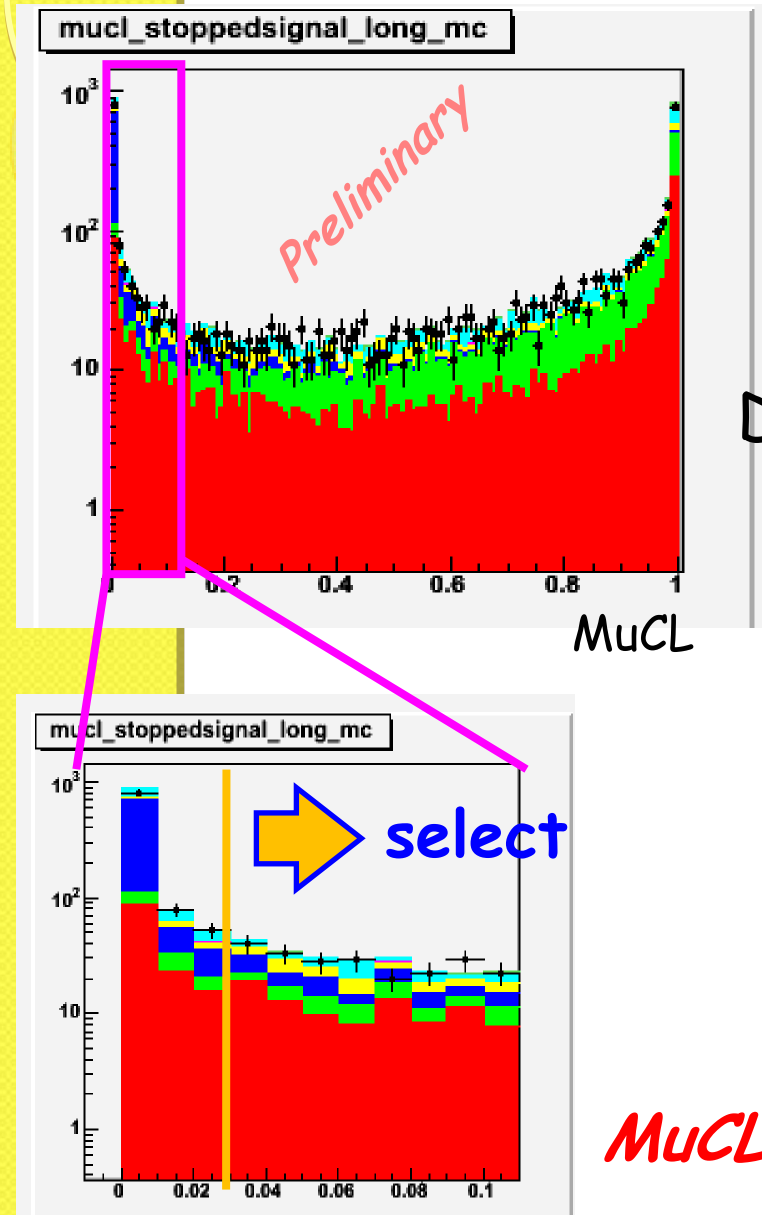
NCπ^0 Candidate



1. Pre-selection
    1. Two tracks or more(2γ)
    2. No 1st layer hits (against dirt BG)
2. Track information
    1. Stopped in SciBar (against μ BG)
    2. No proton track identified by dE/dX
    3. No decay-e
3. Event Topology
    1. Two tracks are separated.

Proton rejection by dE/dx

SciBooNE



2contained track sample w/o separation cut

Dot : data

Cosmic

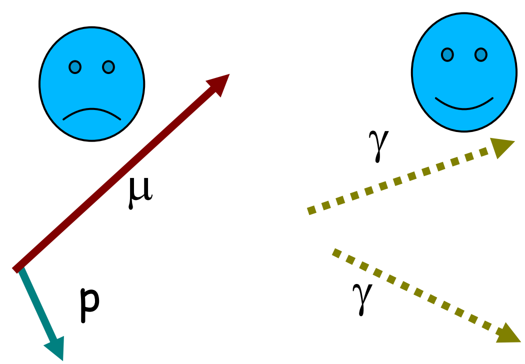
Dirt

Charge π

p

μ

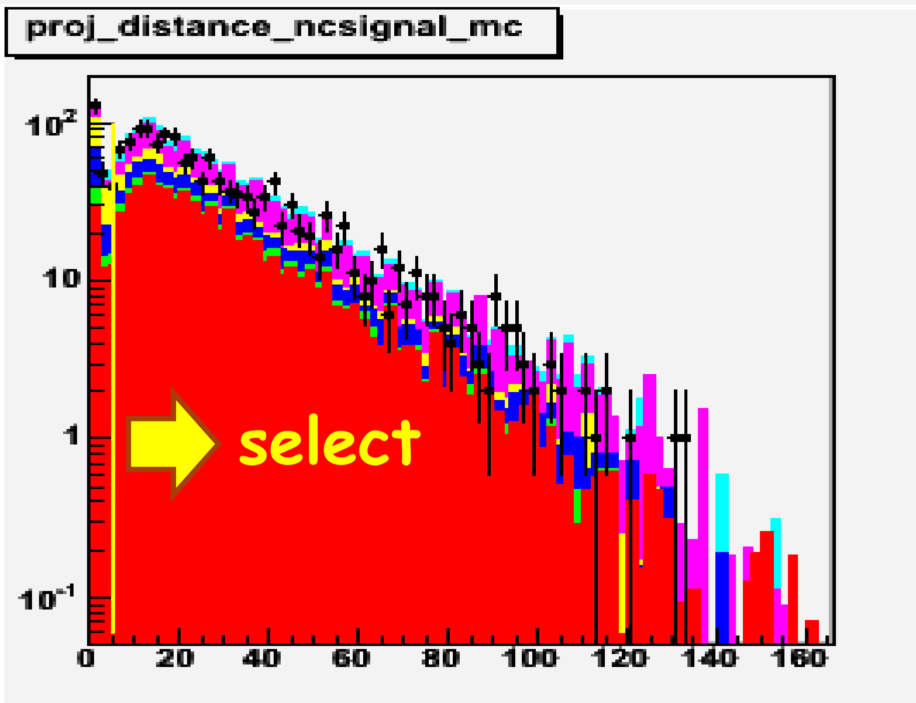
EMShower



MuCL > 0.03

Two track separation

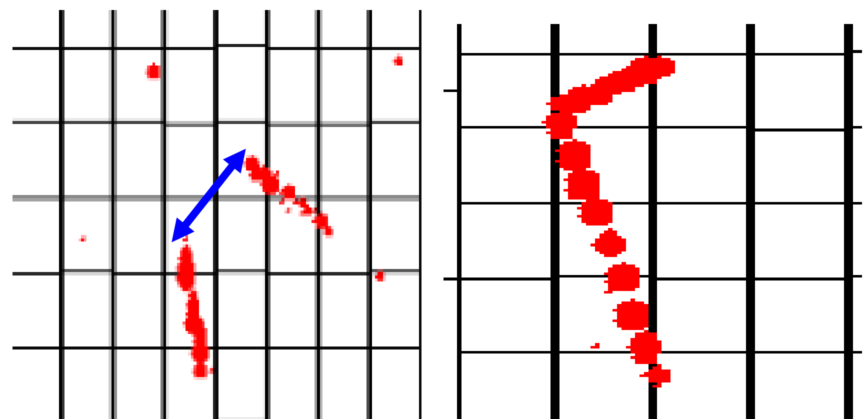
Minimum 2D-distance
between track edges



cm

Reject CC events

Distance > 6cm

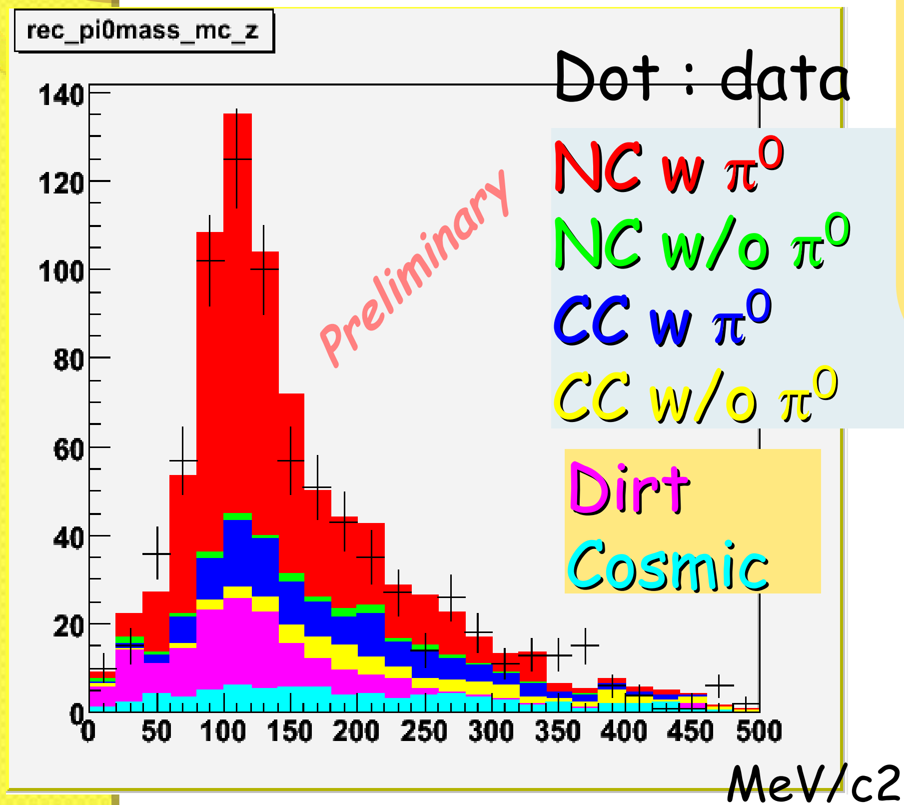


Reject 31 % of CC events

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 !

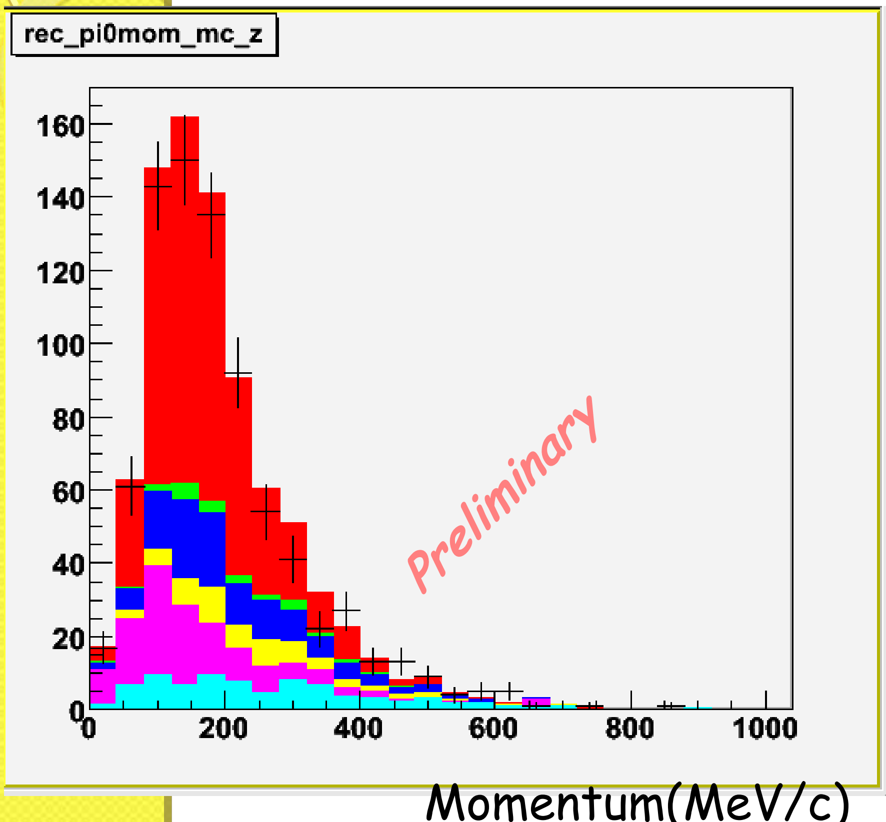
~850 events selected

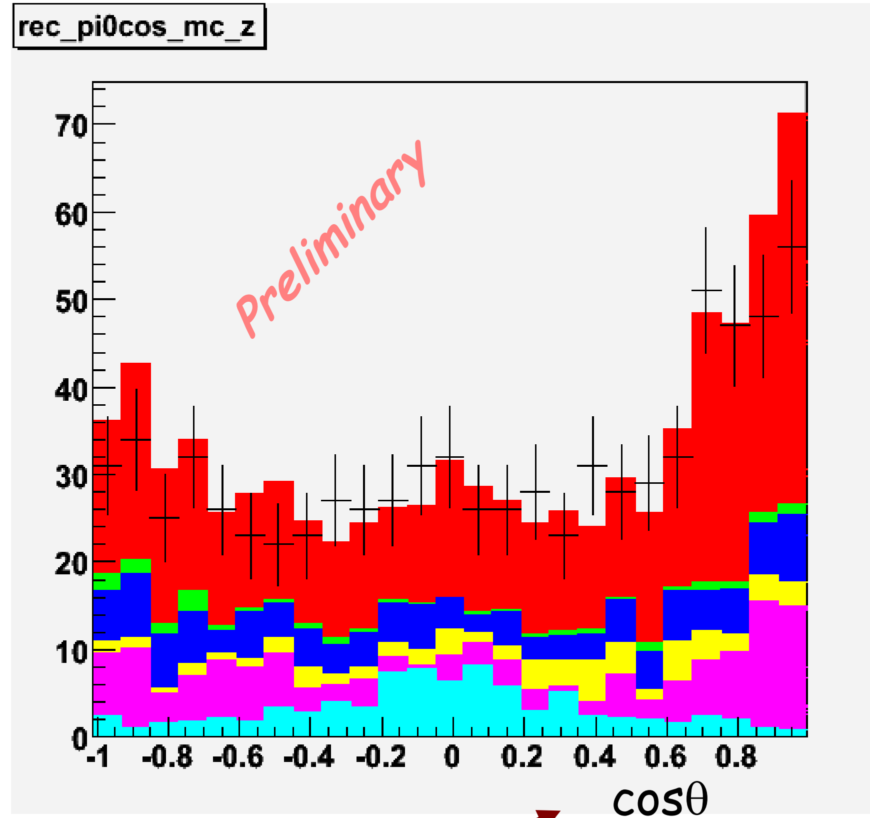
~460 π^0 events (NC)

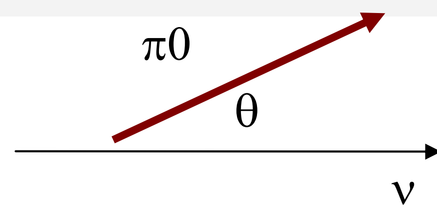
SciBar can reconstruct π^0 !!!

Next Step: Cross Section Measurement

π^0 Kinematics



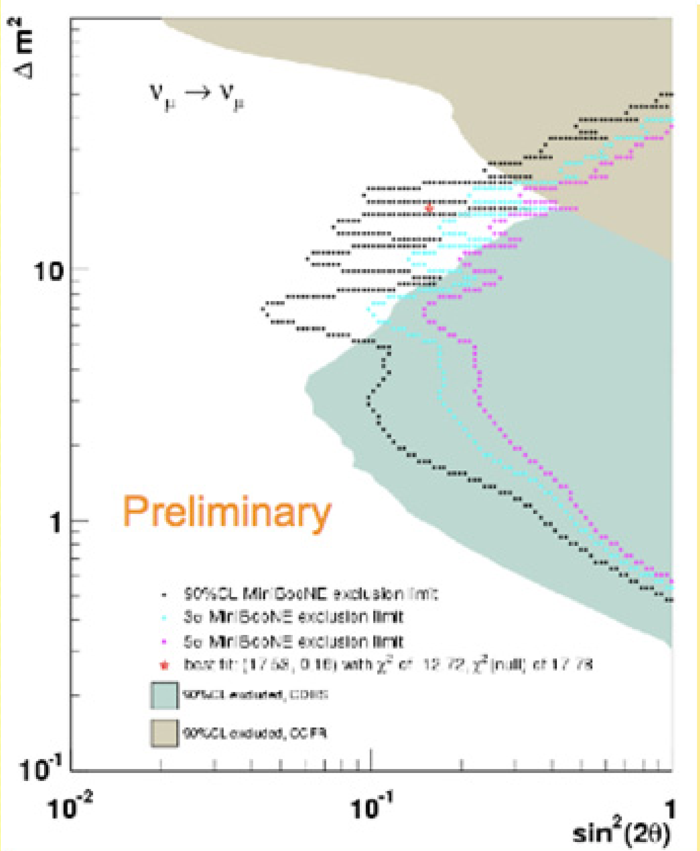




4.3 Beam Flux Measurements

Spectrum Measurement

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

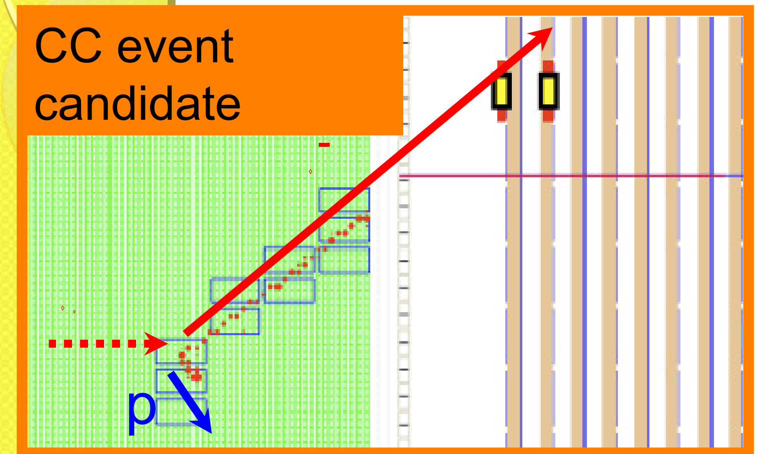


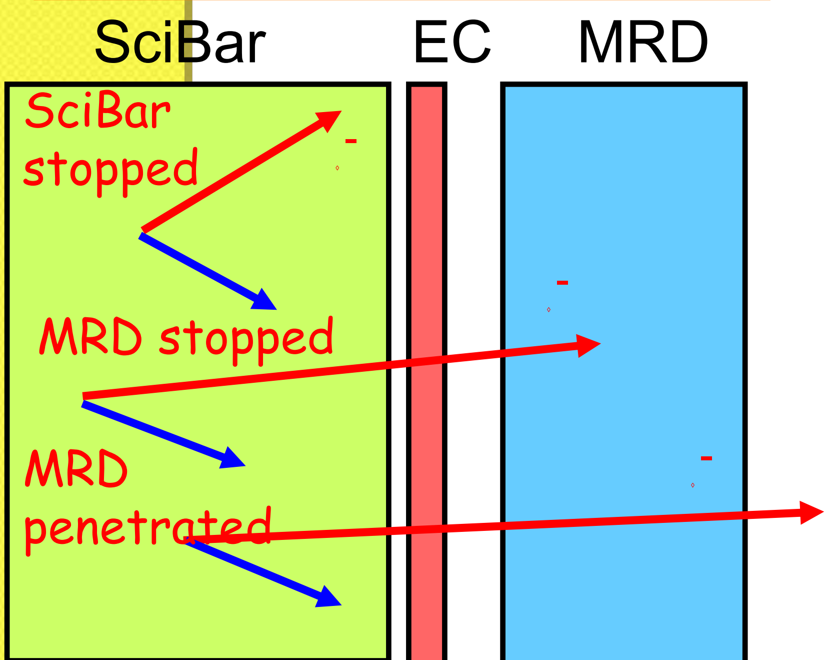
- MiniBooNE/SciBooNE joint disappearance search
  - Share beamline
  - Share target material

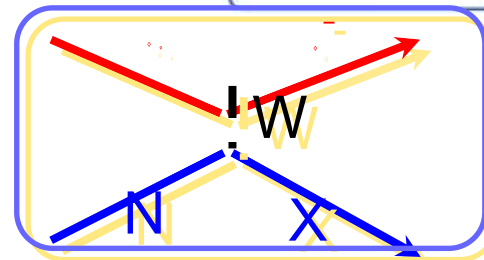
⇒ Strong constraint for flux and cross-sections at MiniBooNE (Shape + Normalization)

- Feed-back to cross section measurements at SciBooNE

Event Selection

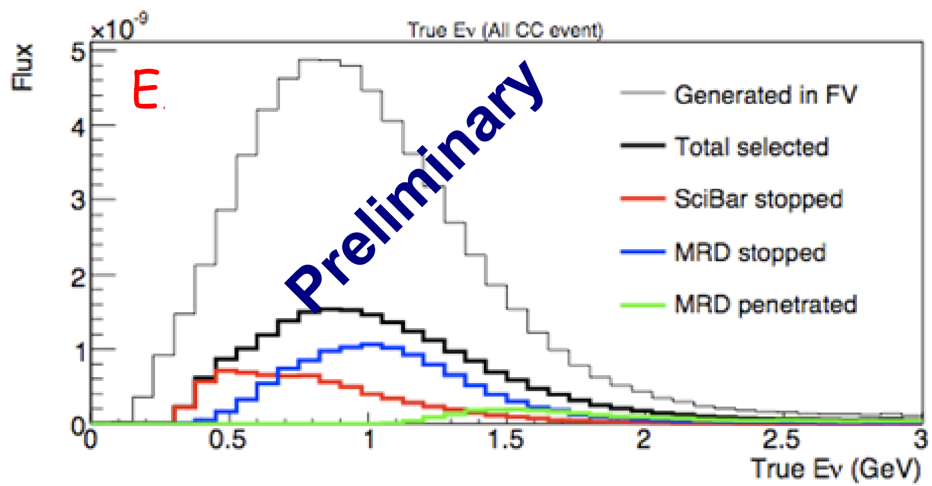






Use charged current inclusive sample

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

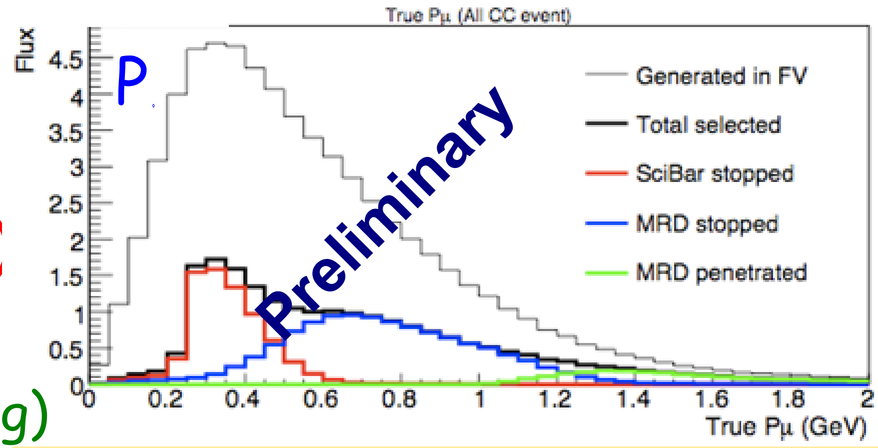


Extracting E_ν Spectrum

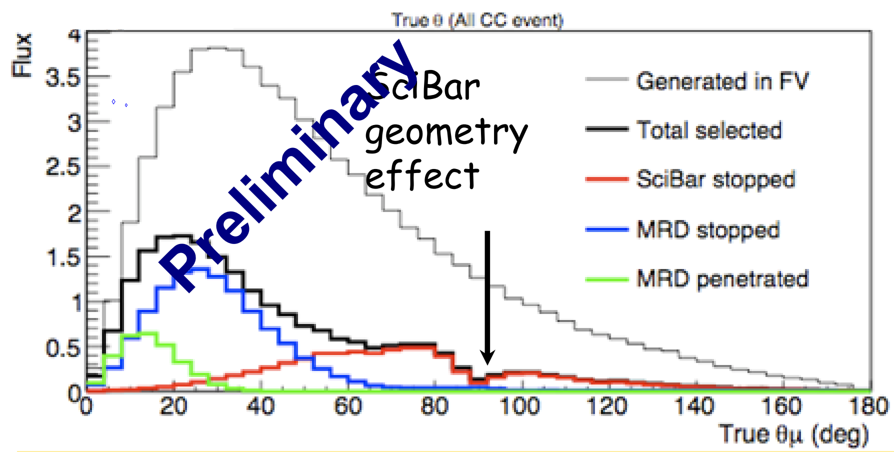
- Use muon kinematics to extract E_ν information

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

(Assuming CC-quasi-elastic scattering)



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

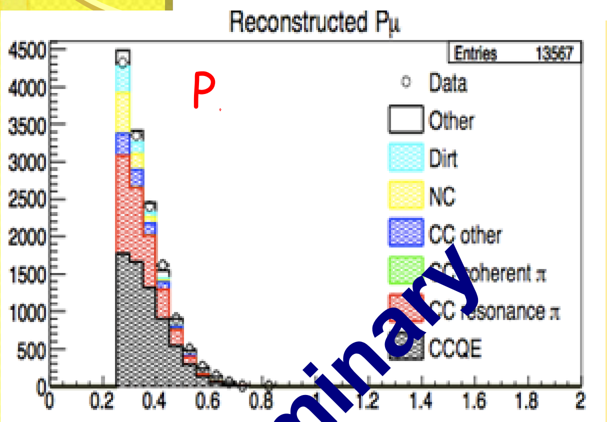


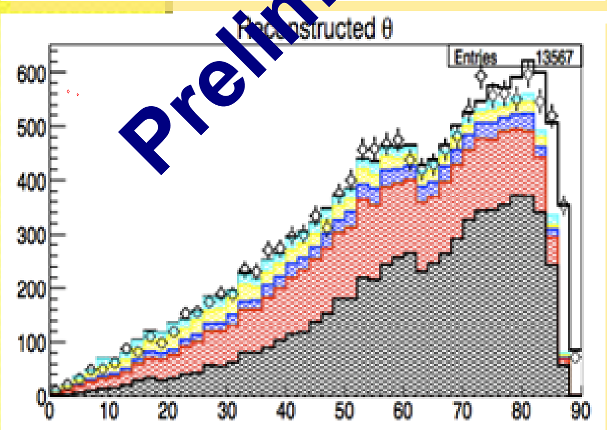
Muon Kinematics

SciBooNE

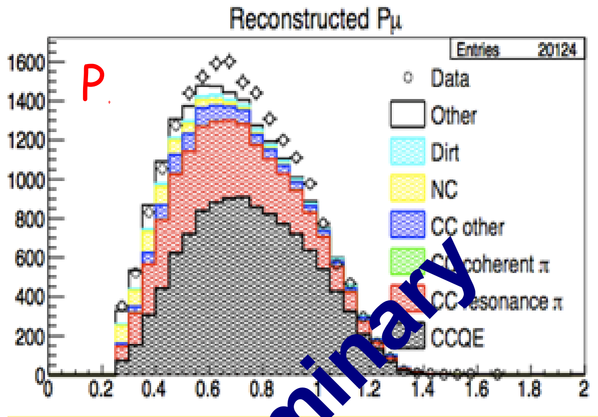
MC are relatively normalized to data by the number of SciBar-MRD matched event.

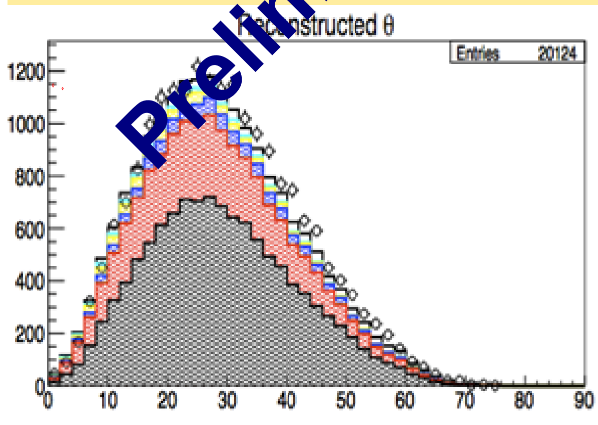
SciBar stopped (P ,)



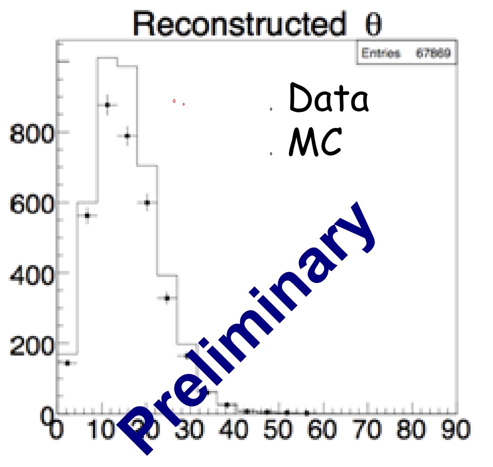


MRD stopped (P ,)





MRD penetrated ( )



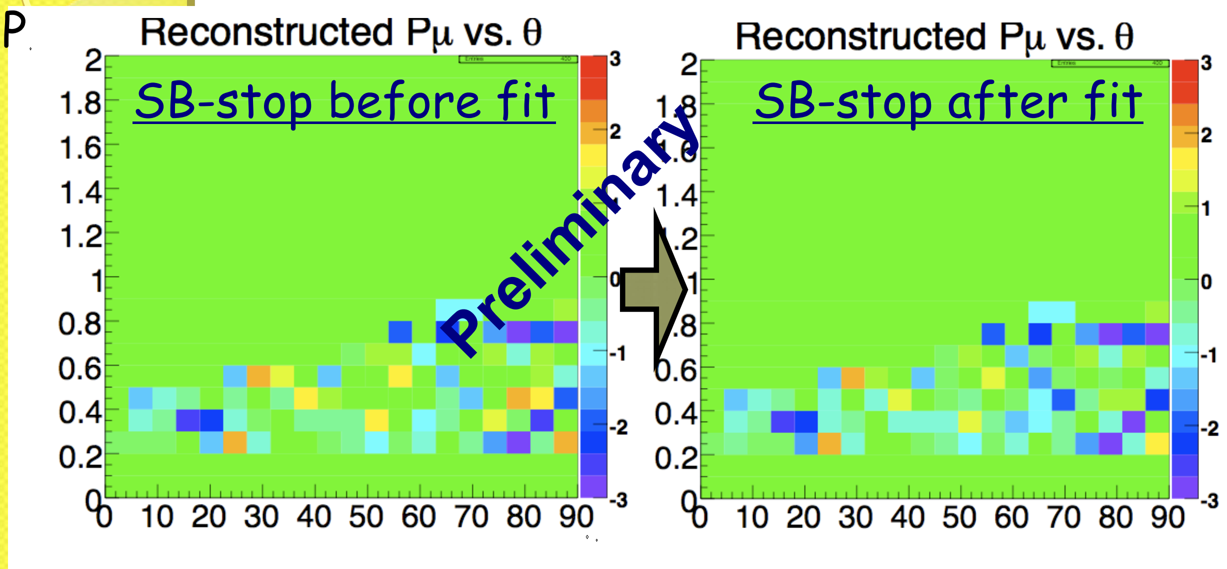
(Unable to reconstruct P since muons are not stopped in the detectors)

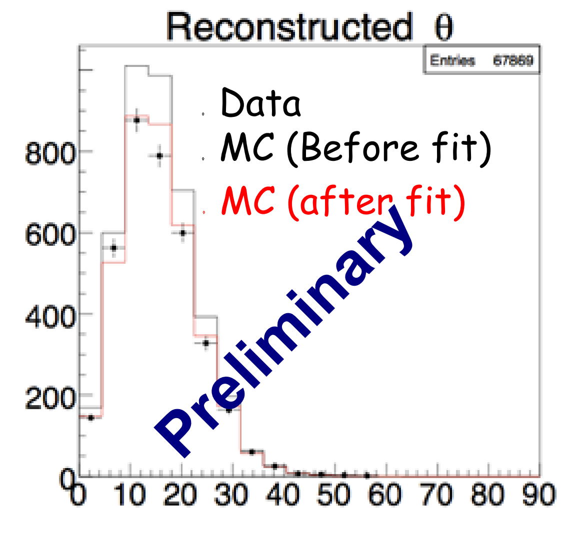
Predict neutrino energy spectrum at SciBooNE by fitting P and distribution from each sample

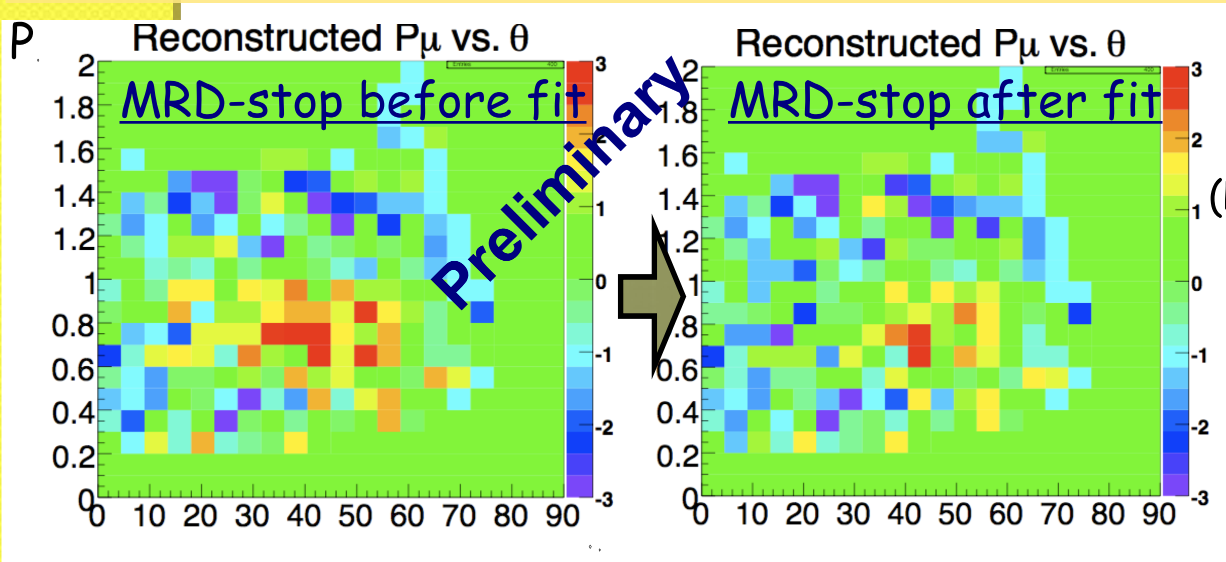
Spectrum Fit Result

(data-MC)/(stat. error)

MRD-penetrate







- Better data/MC agreement after fitting.

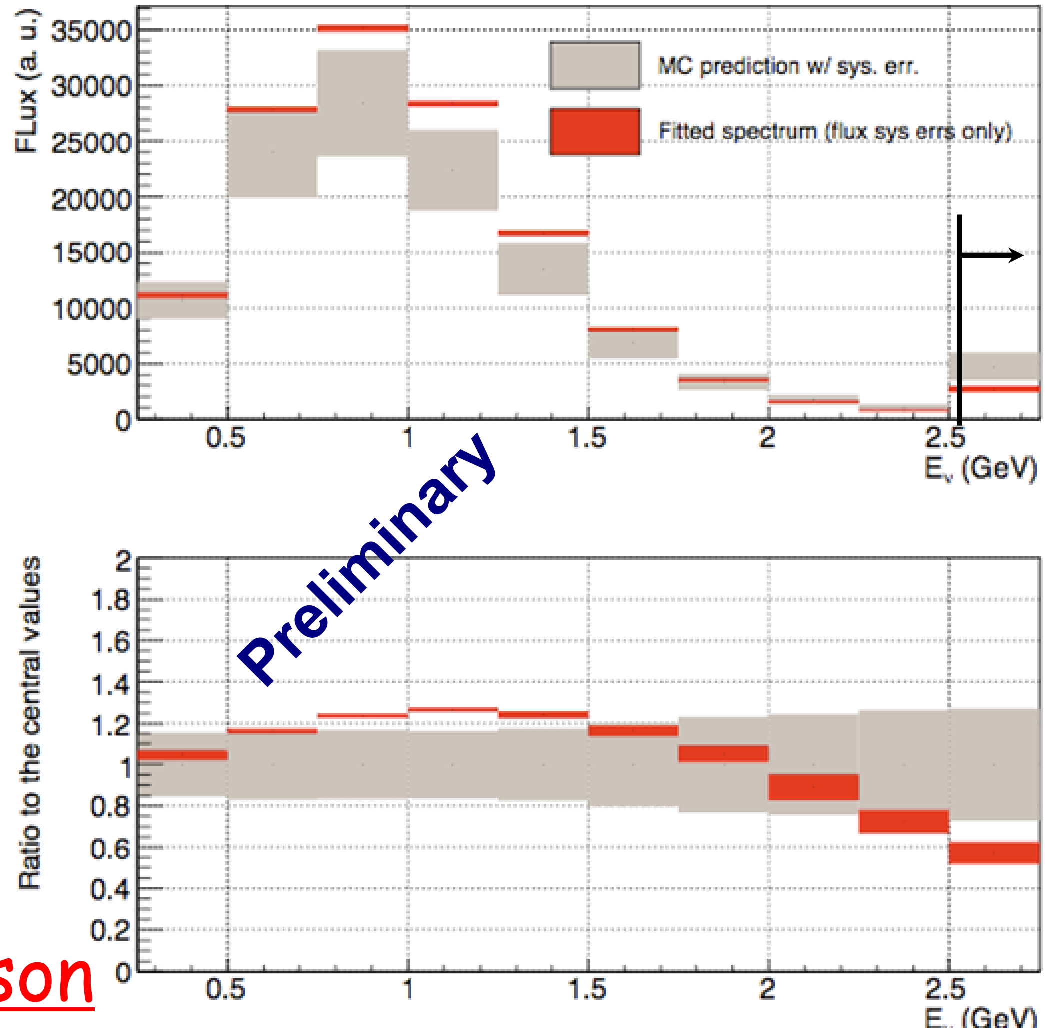
(Plots are relatively normalized)

^{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.



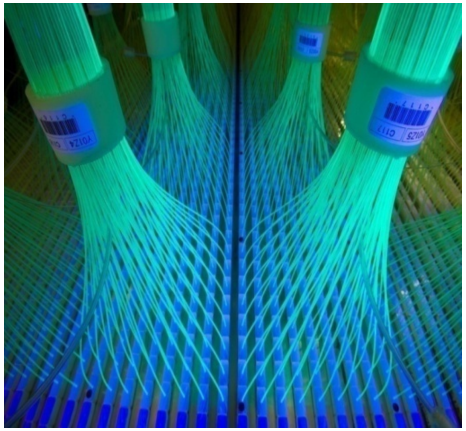
→ Flux comparison with MiniBooNE

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.

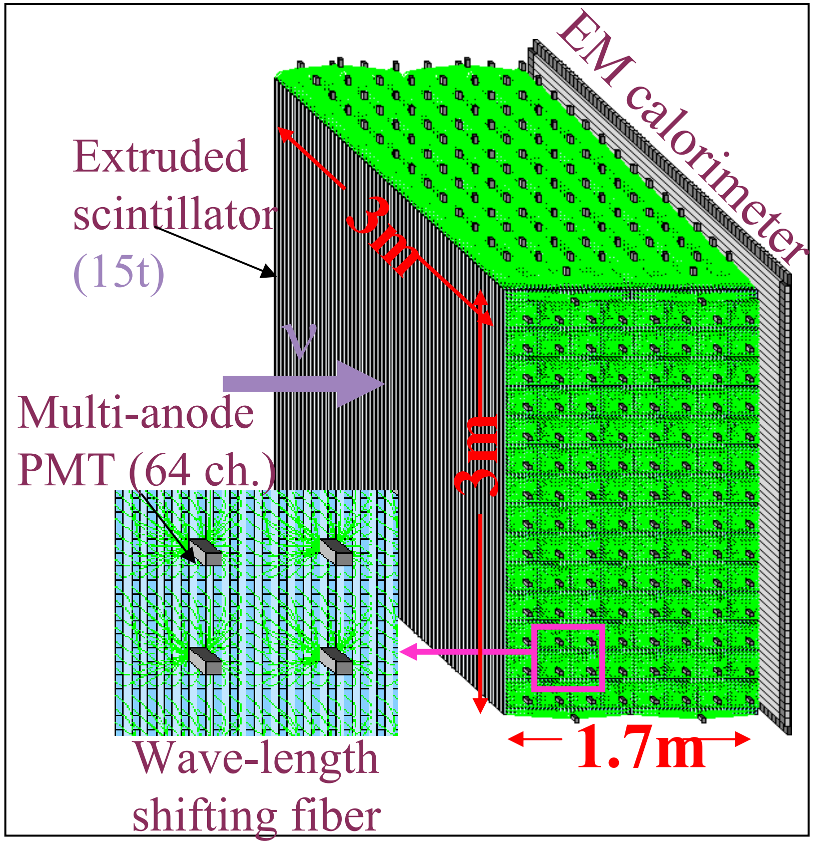
BACKUP

SciBar detector

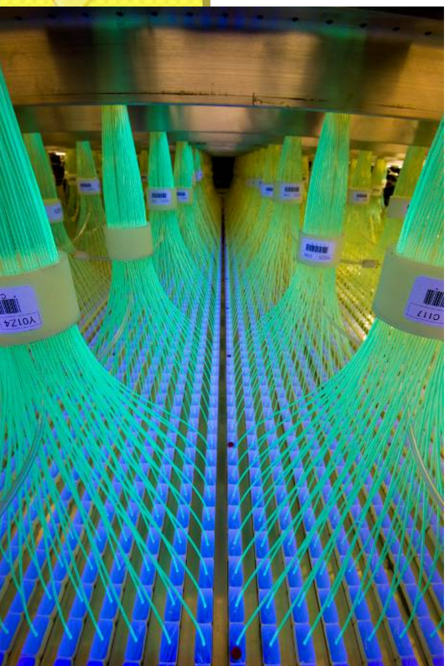


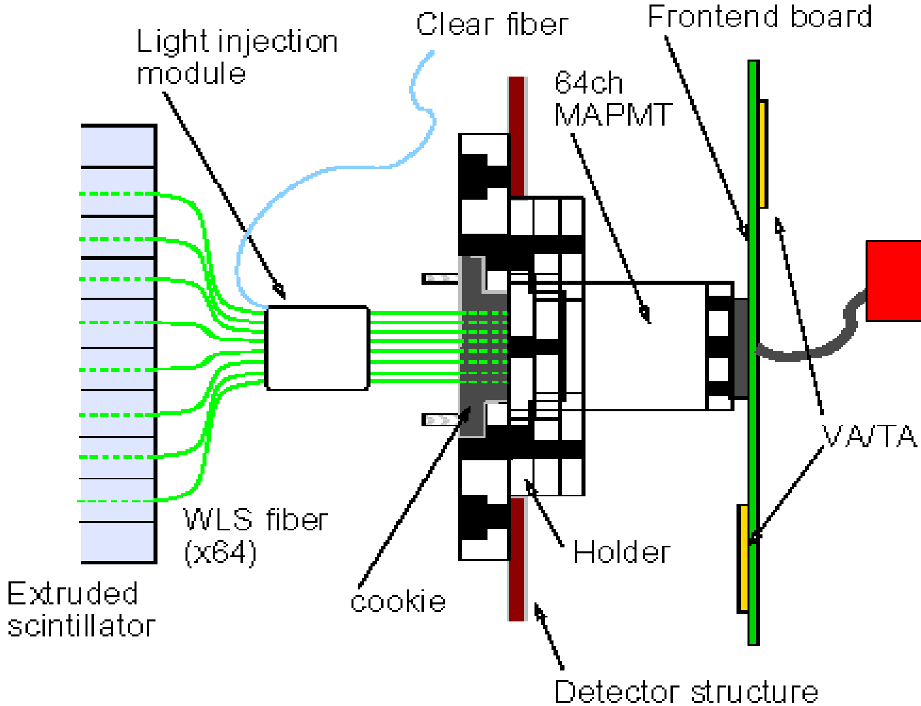
- Extruded scintillators with WLS fiber readout
- Scintillators are the neutrino target
- 3m x 3m x 1.7m (Total: 15 tons)
- 14,336 channels
- Detect short tracks (>8cm)
- Distinguish a proton from a pion by dE/dx

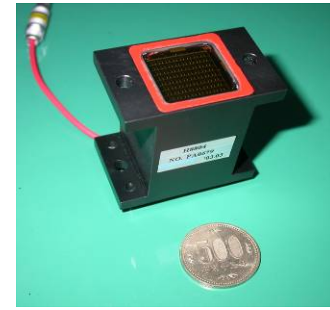
➔Clear identification of ν interaction process



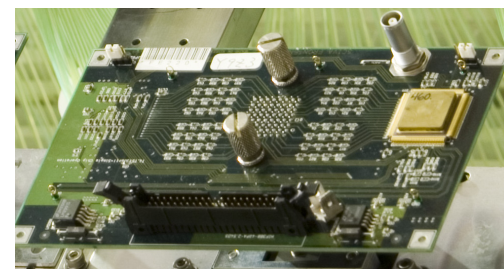
SciBar readout







64 charge info.
2 timing info.



<u>Extruded Scintillator (1.3.2.5.300cm^3)</u>
- **made by FNAL (same as MINOS)**

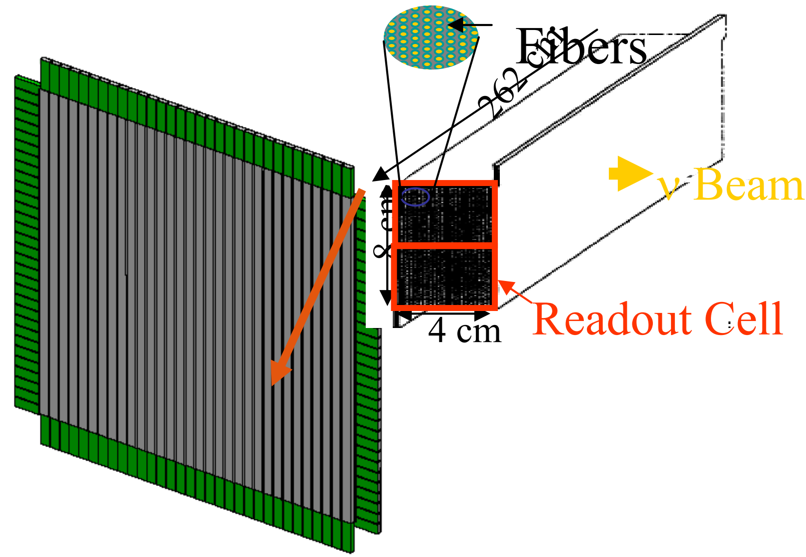
<u>Wave length shifting fiber (1.5mm.)</u>
- **Long attenuation length (~350cm)**
  → Light Yield : ~20p.e./1.3cm/MIP

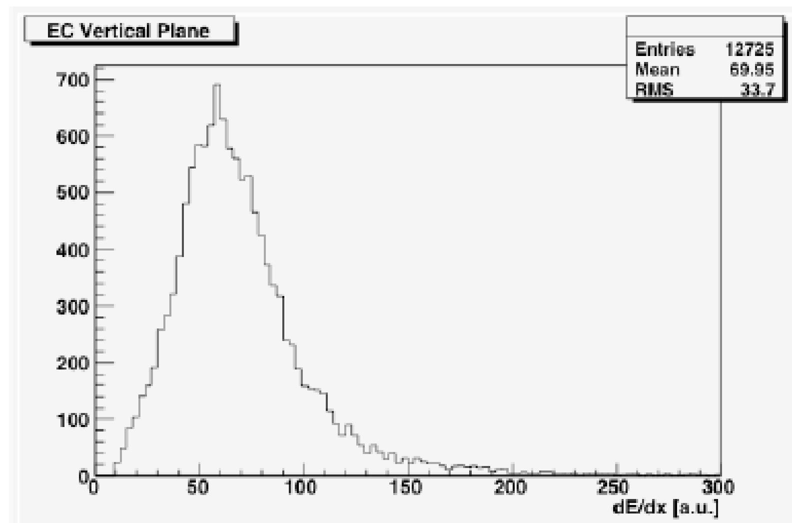
<u>64-channel Multi-Anode PMT</u>
- **2x2mm^2 pixel (3% cross talk@1.5mm.)**
- **Gain Uniformity (20% RMS)**
- **Good linearity (~200p.e. @6.10^5)**

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 **$14\%/\sqrt{E}$ (GeV)**
- Linearity: **better than 10%**

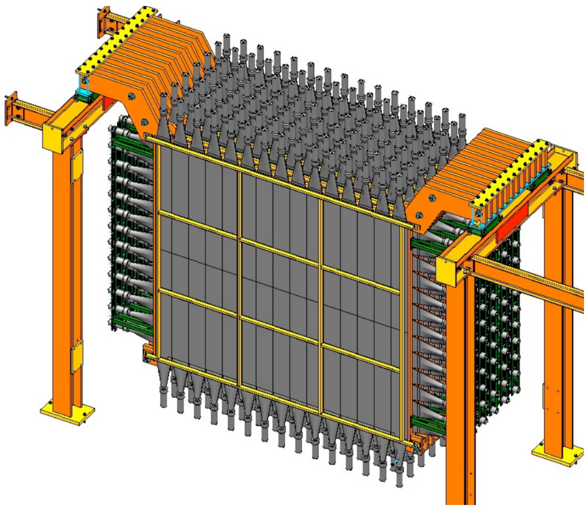




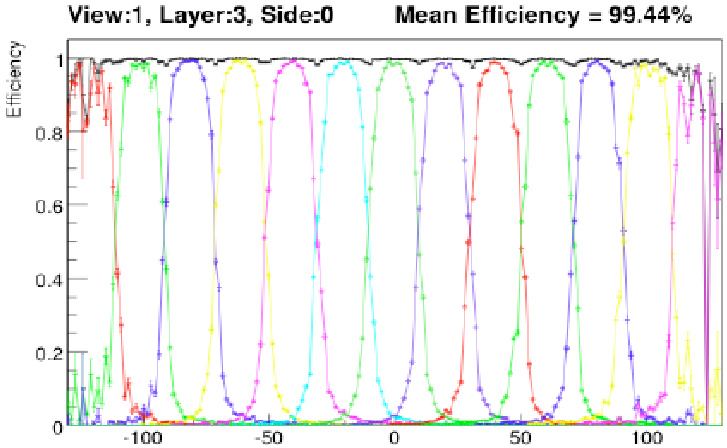
dE/dx distribution of vertical plane for cosmic ray muons

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

Detector installation (Apr. 2007)

Detector Hall

SciBar/EC

End-of-run party
(Aug. 2008)