Single π production in MiniBooNE and K2K

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1. Introduction
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3. Study of charged current coherent π^+ production at K2K
4. Study of charged current single π^+ production at MiniBooNE

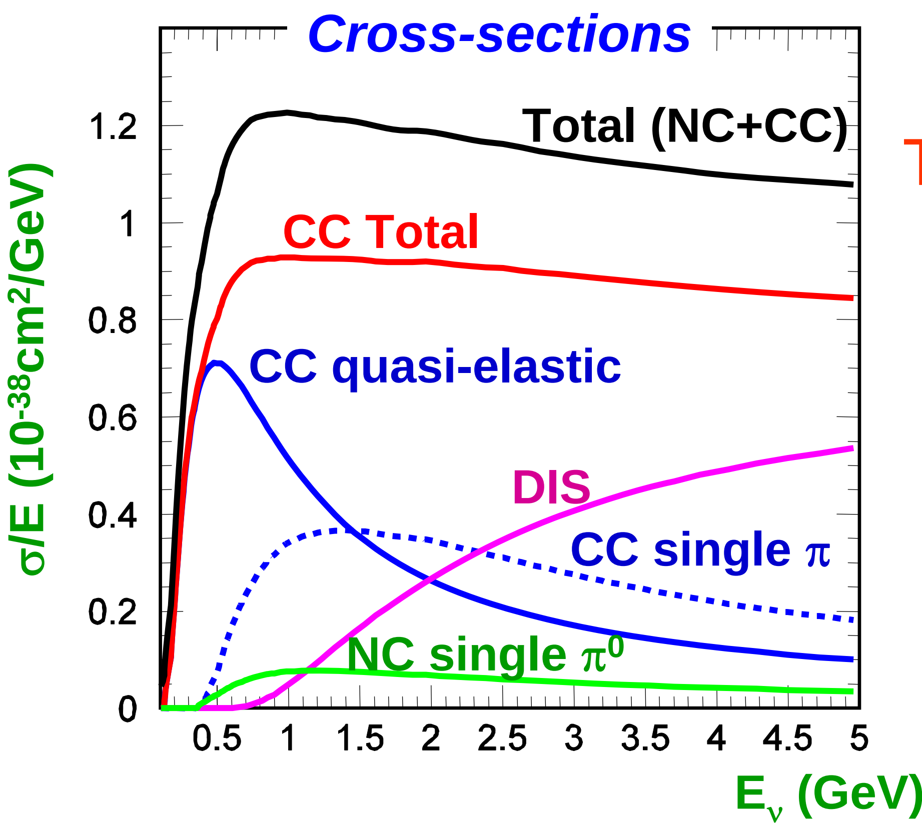
(Thanks to the MiniBooNE collaboration
especially, M. Wascko and S. Zeller for providing the MiniBooNE plots.)

Introduction

Neutrino interactions around 1GeV region

Charged current quasi-elastic scattering (CCQE)	$\nu_\mu + n \rightarrow \mu^- + p$
Neutral current elastic scattering	$\nu_\mu + N \rightarrow \nu + N$
Single π,η,K resonance productions	$\nu_\mu + N \rightarrow l + N' + \pi\ (\eta,K)$
Coherent pion productions	$\nu_\mu + X \rightarrow l + X' + \pi$
Deep inelastic scattering	$\nu_\mu + N \rightarrow l + N' + m\pi\ (\eta,K)$

(l : lepton, N,N' : nucleon, m : integer)



To study neutrino interactions, it is also important to take into account nuclear effects.

Mesons (especially π) and protons interactions in target nucleus.

(Oxygen, Carbon ..)

Importance of neutrino interaction studies

- To search for the ν_e appearance in the ν oscillation experiments, π^0 productions will be one of the major backgrounds.

  Asymmetric π^0 decay event looks like ν_e appearance signal.

  (Energetic γ looks like e from ν_e charged current interaction.)

- Charged Current Quasi-Elastic scattering ($\nu_\mu + n \rightarrow \mu^- + p$) is very useful to measure the neutrino energy spectrum.

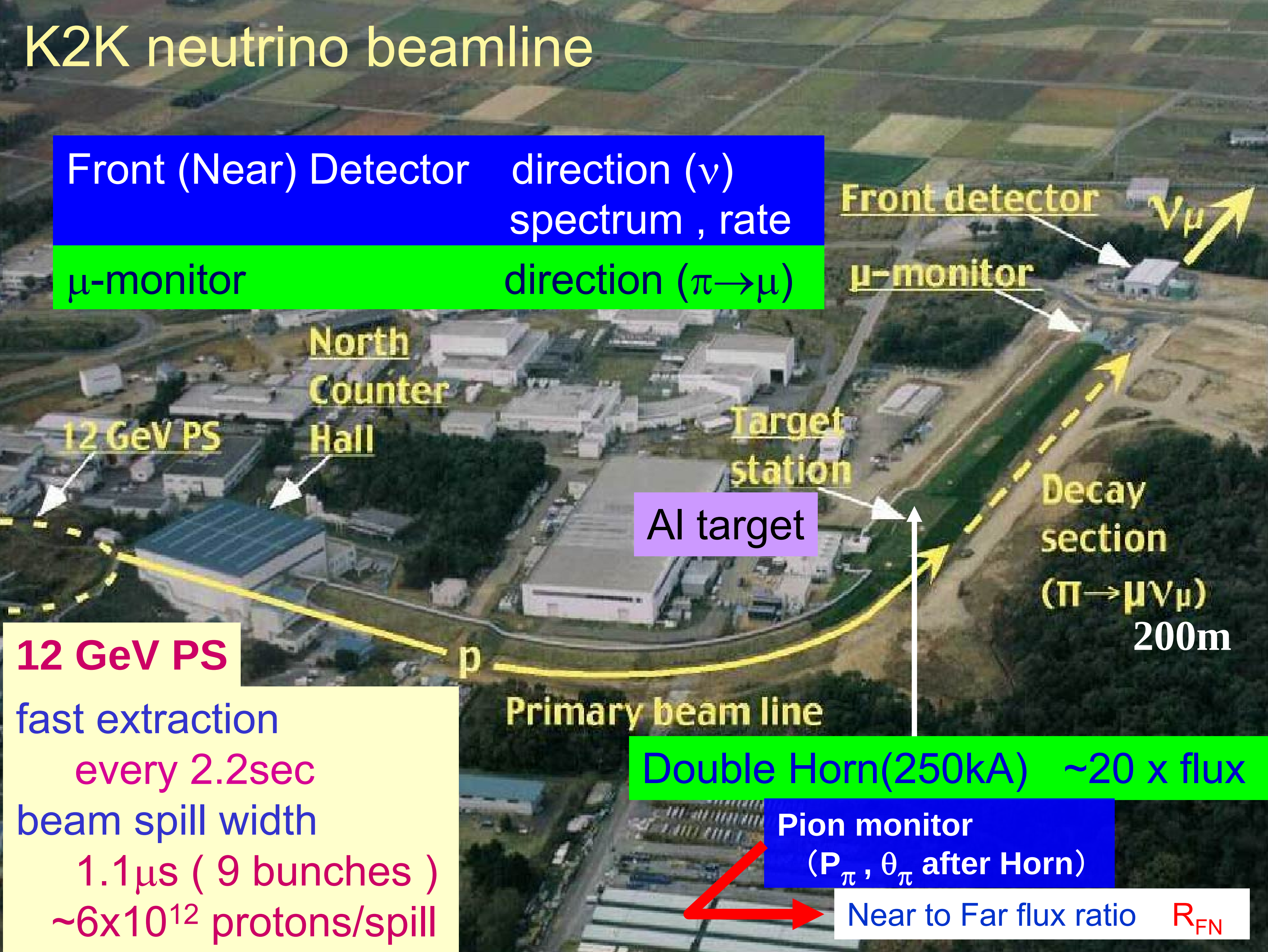
  However, π interacts in nucleus.

  Because of this, some of the single π production events looks like CC quasi-elastic events.

It is important to understand the neutrino induced π productions and π interactions in nucleus.

Study of neutral current single π^0 production at K2K (with water Cherenkov detector)

K2K neutrino beamline



Front (Near) Detector	direction (ν) spectrum , rate
μ-monitor	direction ($\pi \to \mu$)

Al target

12 GeV PS

fast extraction
every 2.2sec
beam spill width
1.1μs (9 bunches)
~6×10^{12} protons/spill

Double Horn(250kA) ~20 x flux

Pion monitor
(P_π , θ_π after Horn)

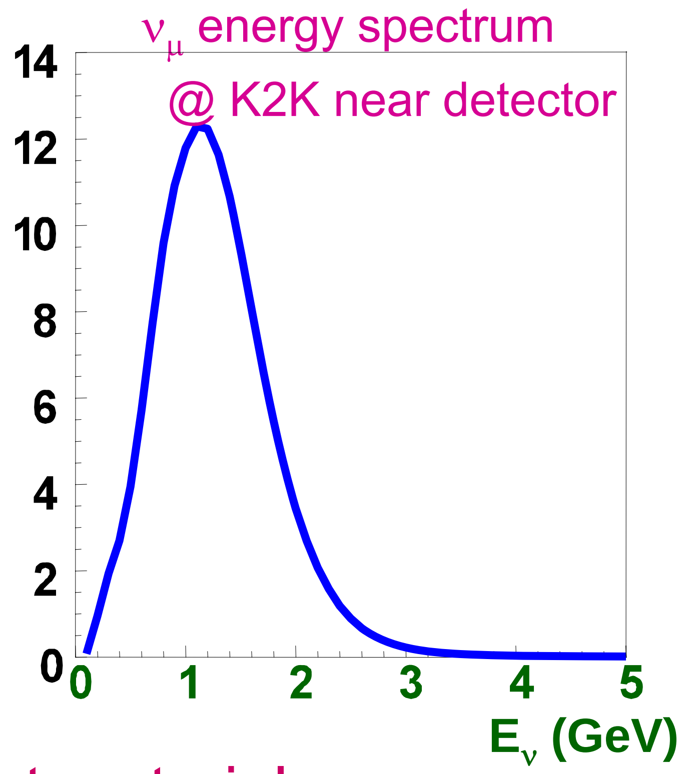
Near to Far flux ratio R_{FN}

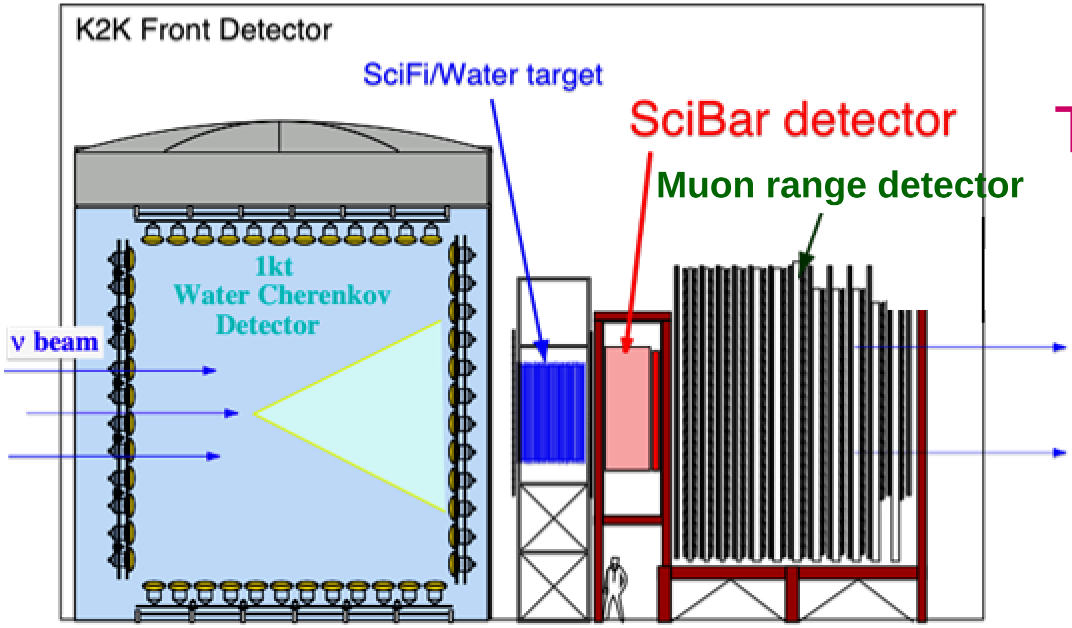
The K2K near detectors

E_ν ~ 1GeV

Almost pure ν_μ beam (~98%)

It is possible to investigate various neutrino interactions with the K2K near detectors.





Target material

Water (H_2O)

1kt water Cherenkov detector

SciFi detector

Scintilator (CH)

SciBar detector

Iron

MRD

NC π^0 measurements in 1kt detector

Neutral current single π^0 production

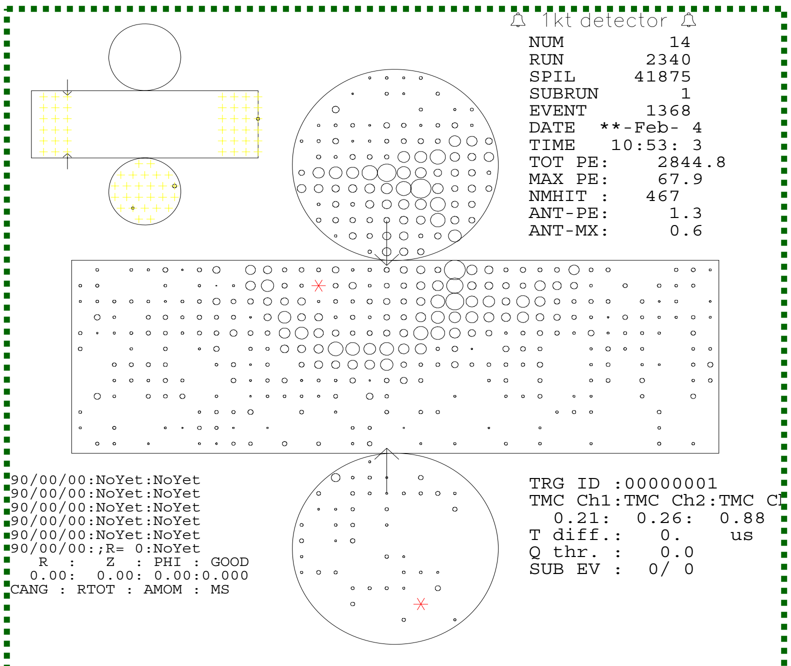
$$\nu + N \rightarrow \nu + N + \pi^0$$

Observable in 1kt : π^0

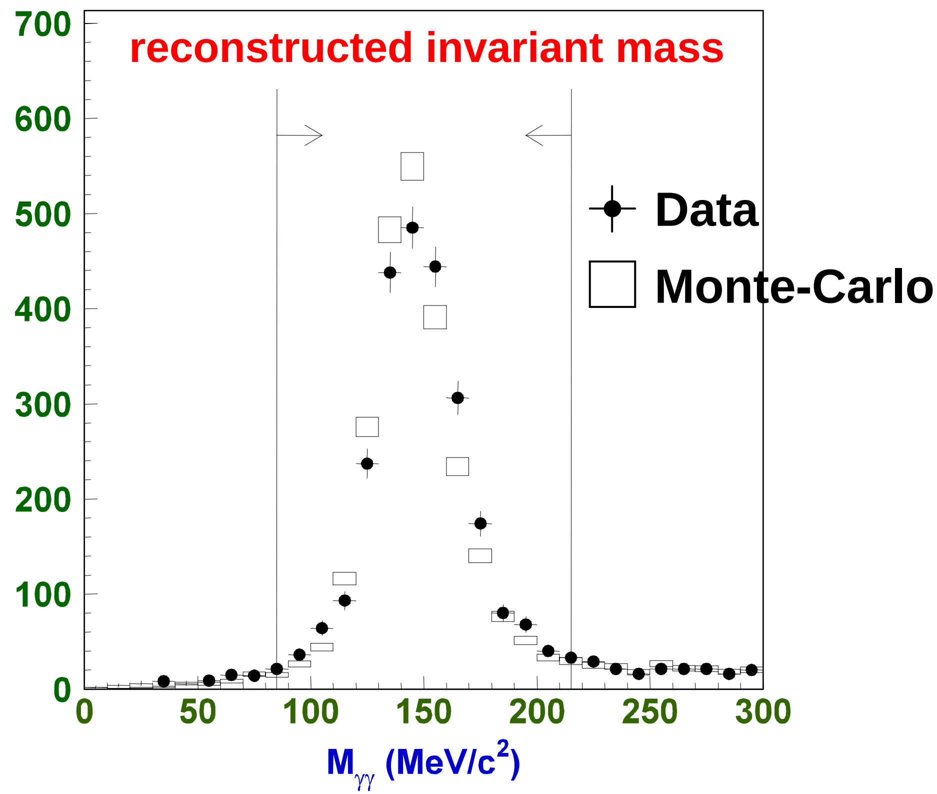
(Cherenkov threshold of proton > 1GeV/c)

2 γs from π^0 are identified as 2 electron like rings

$\rightarrow$ reconstruct invariant mass



Typical π^0 candidate



NC π^0 measurements in 1kt detector

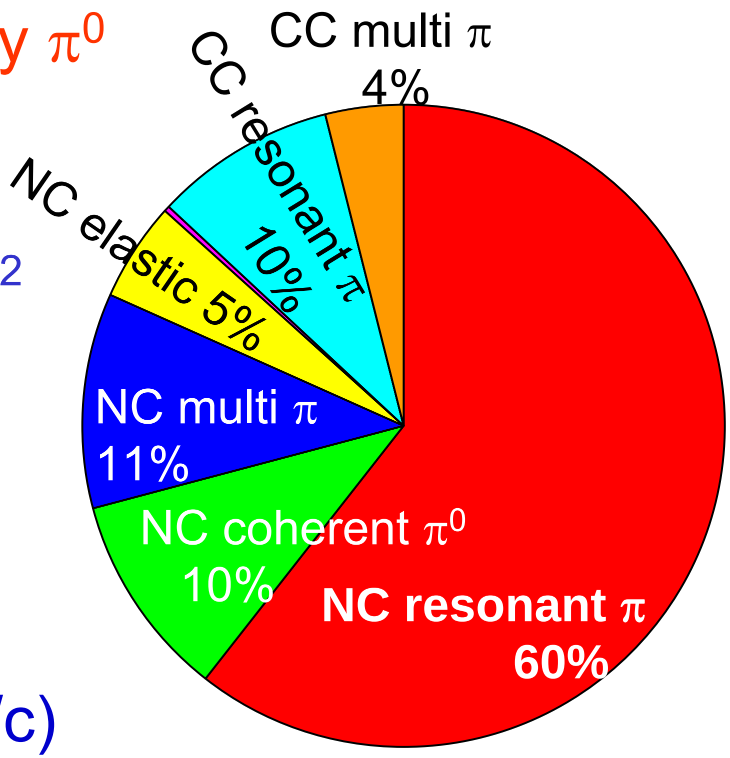
1kt water Cherenkov detector

high efficiency in finding low energy π^0

π^0 sample selection criteria

- 2 e-like rings
- reconstructed mass 85~215MeV/c^2

→ detection efficiency of π^0 ~49%
86% from NC interactions



Contamination from charged current

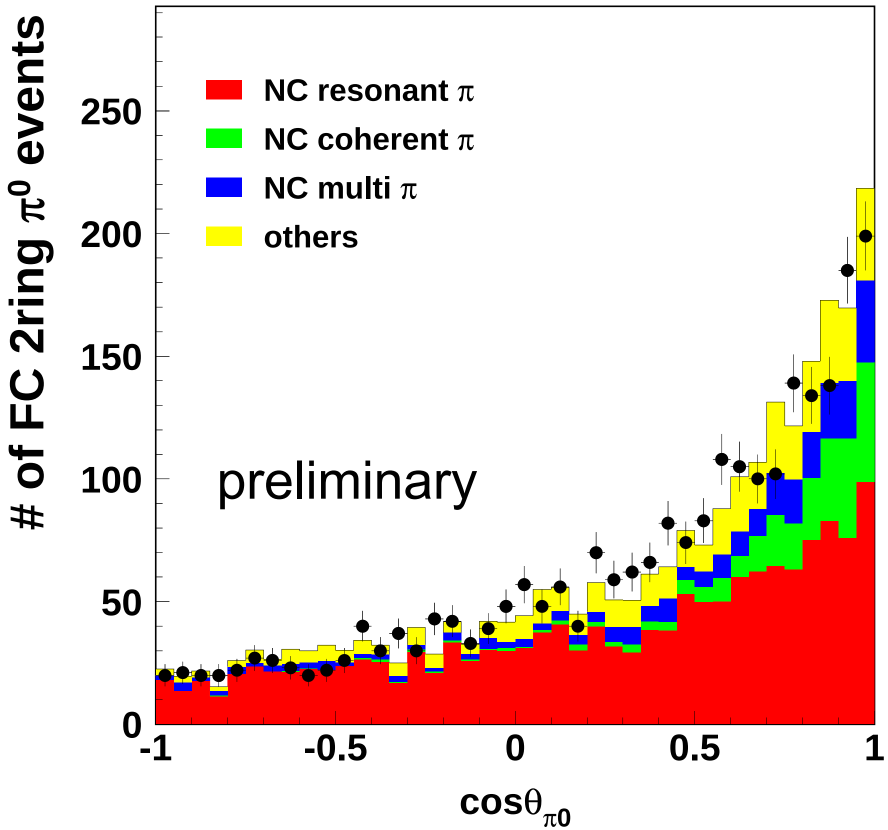
→ low momentum μ (Pμ < 200MeV/c) can not be identified.

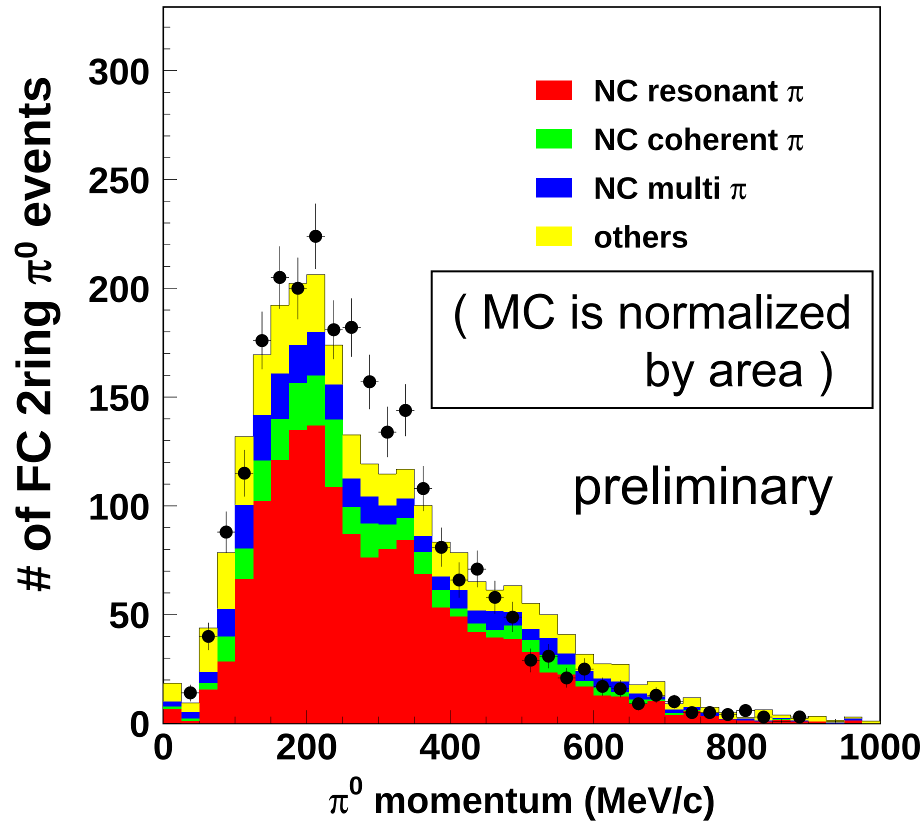
Pions generated in Oxygen interacts with nucleons.

(Inelastic scatterings, charge exchange and absorption in Oxygen are considered in Monte-Carlo simulation program)

NC π^0 measurements in 1kt detector

momentum and direction of π^0





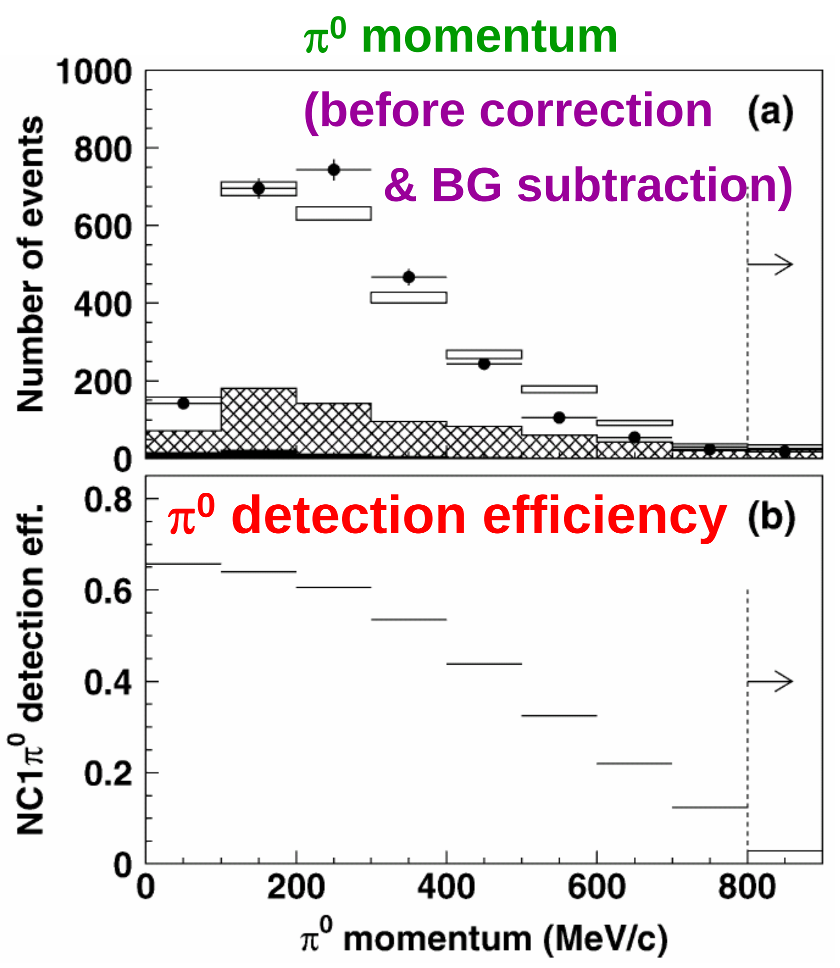
There still remains interactions other than the neutral current π^0 production

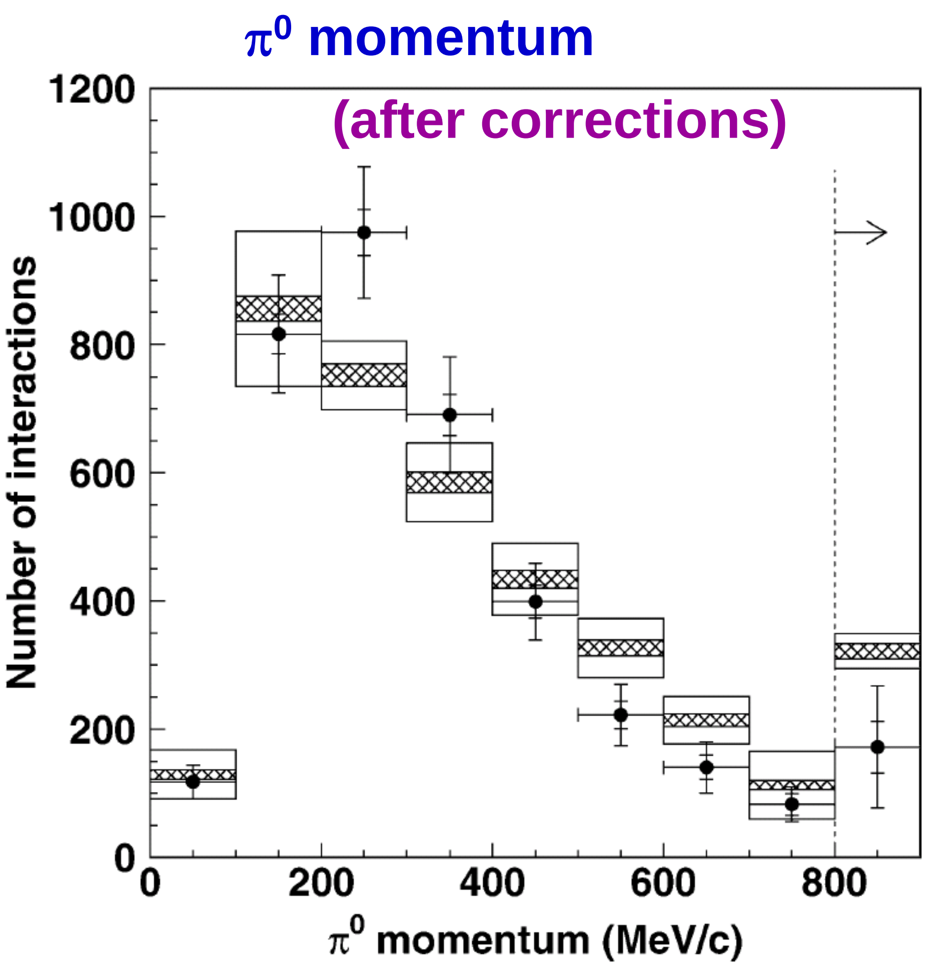
Estimate the efficiency and the purity by using Monte-Carlo simulation.

NC π^0 measurements in 1kt detector

Background subtraction (shaded area in Fig. a)

Efficiency correction (Use detection efficiency curve)





S. Nakayama et al. PLB619(2005) 255-

NC π^0 measurements in 1kt detector

K2K Data set : 3.2x10^{19} POT

Cross-section of NC π^0 production

Use single ring μ-like events as a reference.

π^0

25t fiducial (r<2m, -2m<z<0m)
2 ring FC events, both e-like
$M_{\gamma\gamma}$ = 85 – 215 MeV/c^2

(3.61±0.07±0.36)x10^3 events

Major sources of the systematic error
- DIS model dependence (5.6%)
- NC/CC σ uncertainty (3.2%)
- Ring counting (5.4%)
- Particle ID(4.2%)

μ

25t fiducial (r<2m, -2m<z<0m)
Fully contained μ-like events
and Partially contained events

(5.65±0.03±0.26)x10^4 events

Major source of the systematic error
- vertex reconstruction (4%)

π^0/μ ratio @ <Eν>~1.3GeV

0.064±0.001(stat.)±0.007(sys.)

(Prediction from our Monte-Carlo simulation : 0.065)

S. Nakayama et al. PLB619(2005) 255-

***)Flux averaged charged current total cross-section (used in Monte-Carlo simulation program)**

1.1 x 10^{-38}cm^2

Study of charged current coherent π production at K2K (with SciBar detector)

The SciBar detector

Installed in the summer 2003

- Full Active tracking detector

  Extruded scintillator

  with WLS fiber readout

  Cell size : **2.5 x 1.3** x 300cm^3

  Light yield :**7~20p.e.** /MIP/cm

  (2 MeV)

  → { reconstruct vertex
  identify the interaction

- High efficiency

  even for the short tracks

- Can detect

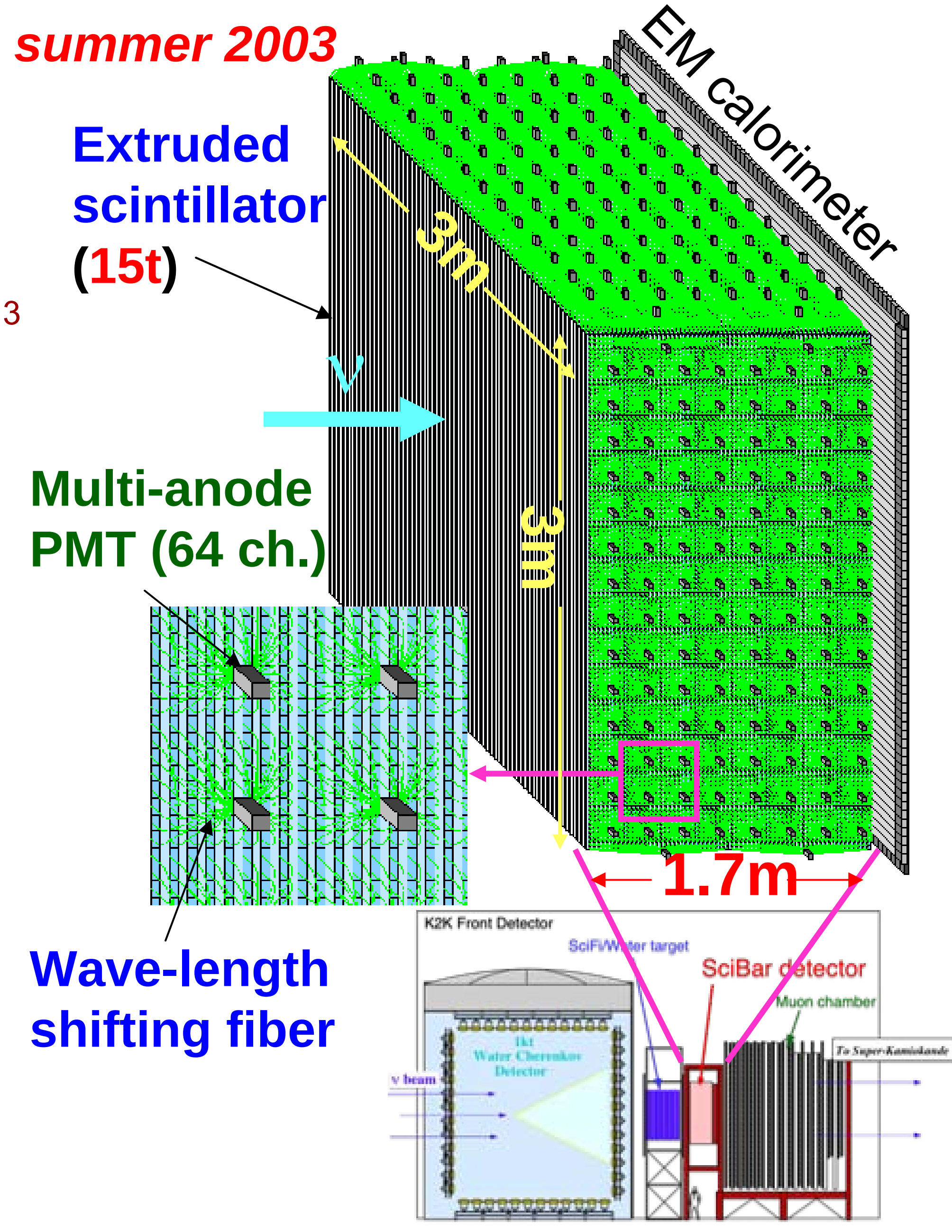
  low momentum protons

  down to ~350 MeV/c.

- PID (p/π)

  & momentum measurement

  by dE/dx.

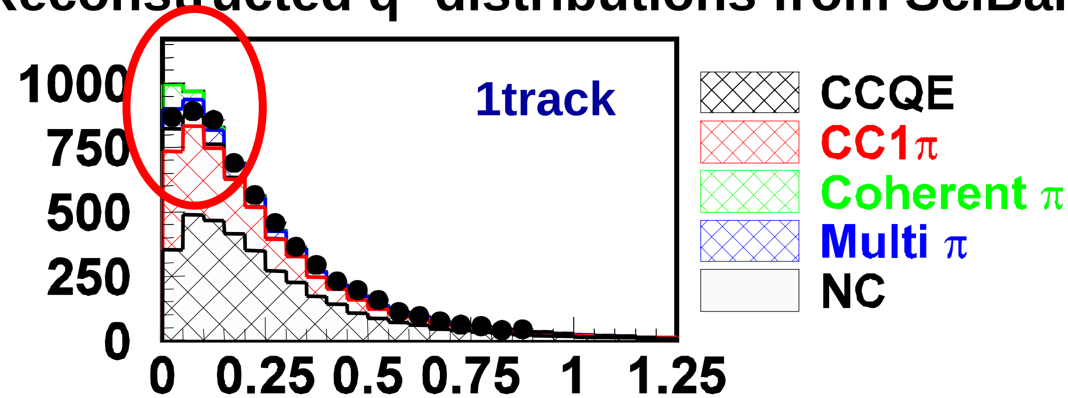


Some distributions from K2K

In K2K, number of forward going particles
was smaller than expected.

If we assume quasi-elastic scattering and reconstruct q^2,
deficits were observed in the small q^2 region.

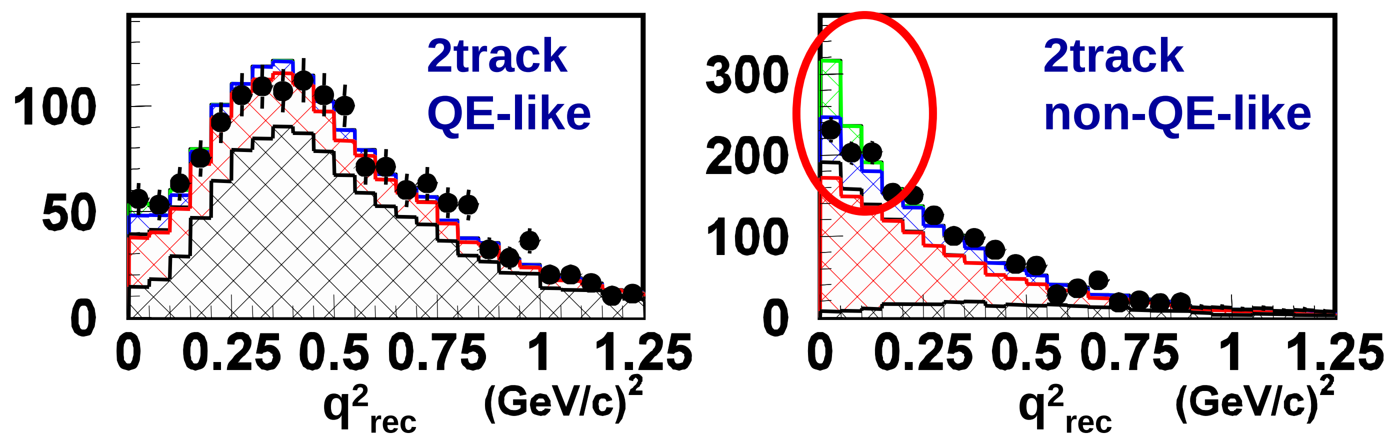
Reconstructed q^2 distributions from SciBar



q^2_{rec}: from p_μ/θ_μ, assuming CCQE kinematics

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

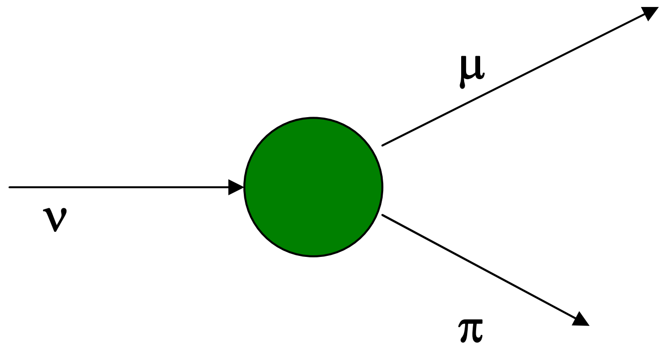
$$E_\nu^{rec} = \frac{m_n E_\mu - m_\mu^2/2}{m_n - E_\mu + p_\mu \cos\theta_\mu}$$



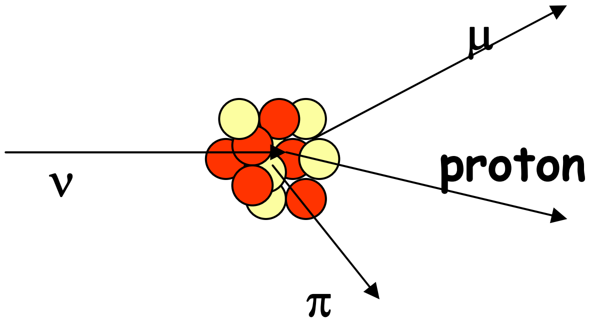
Disagreement of single π production or coherent π production?

Charged current coherent π production

Coherent π production



Resonance single π production



In the **coherent π production**,
the neutrino scatters off the nucleus with small energy transfer and **there is no nucleon in the final state**.

The model used in the Monte-Carlo simulation (Rein & Sehgal's model) has been checked in the higher energy region.

In the resonance π production,
proton or neutron exists in the final state.

Signature of charged current coherent π production

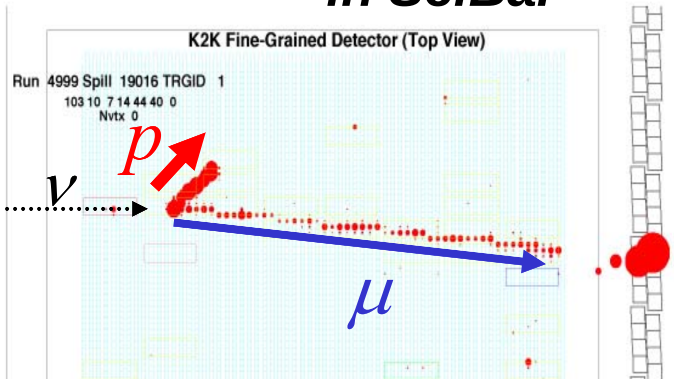
- a μ^- and a π^+ in the final state.
- No activity in the area of the vertex.

Charged current coherent π analysis with the SciBar detector

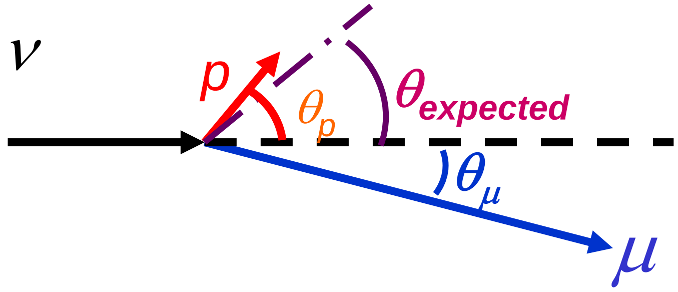
The SciBar detector is possible to find μ, π, p tracks.

How to identify type of interaction (2 track events)

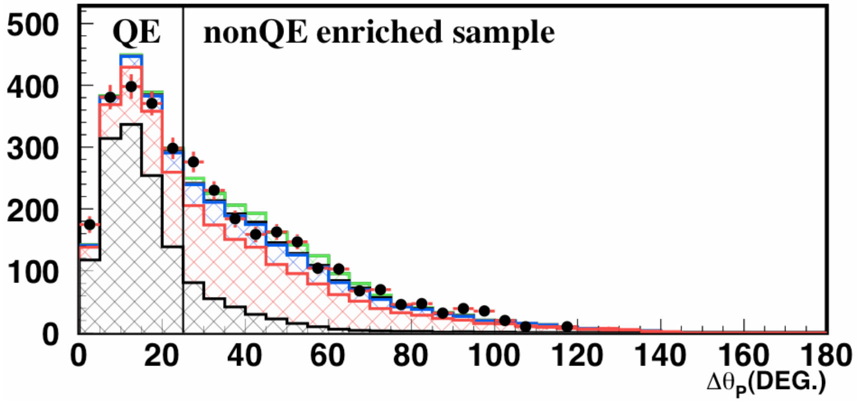
CCQE candidate in SciBar



- For CC quasi-elastic (CCQE) events, expected direction of proton can be derived from p_μ and θ_μ. (Direction of ν is well defined.)



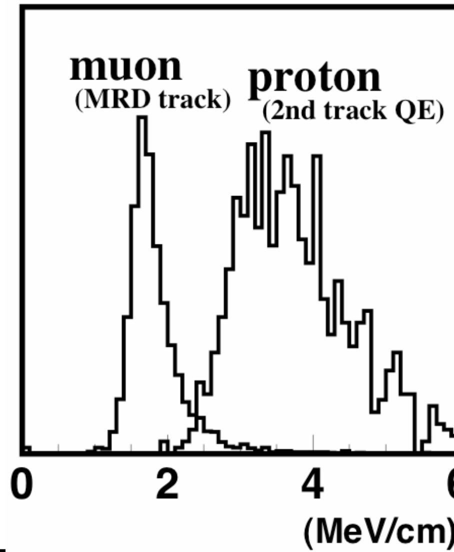
- To identify CCQE events, compare the observed direction of p with expectation.
  - a) CCQE-like : $|\theta_p - \theta_{expected}| < 25^o$
  - b) CC non-QE like : $|\theta_p - \theta_{expected}| > 25^o$

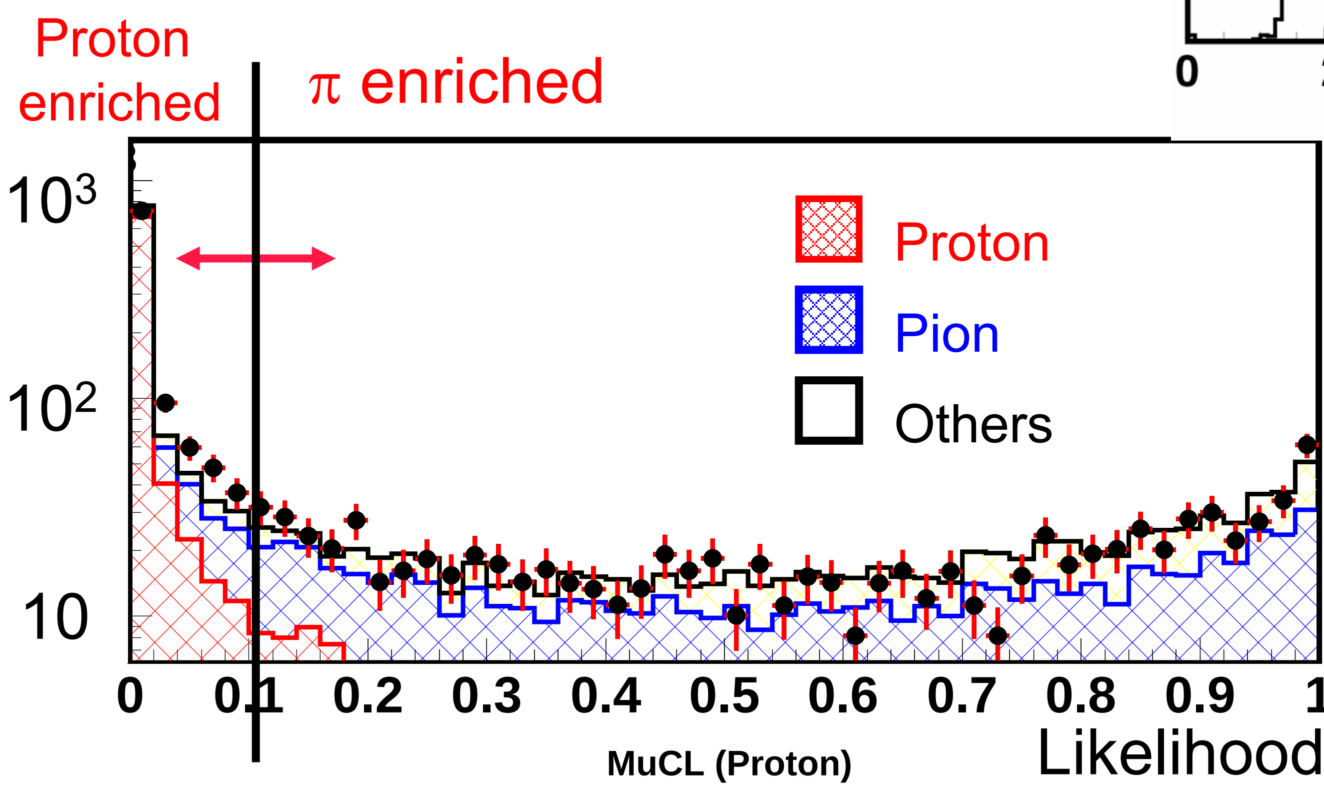


Charged current coherent π analysis with the SciBar detector

Use dE/dx to identify particle type (proton or pion/muon).

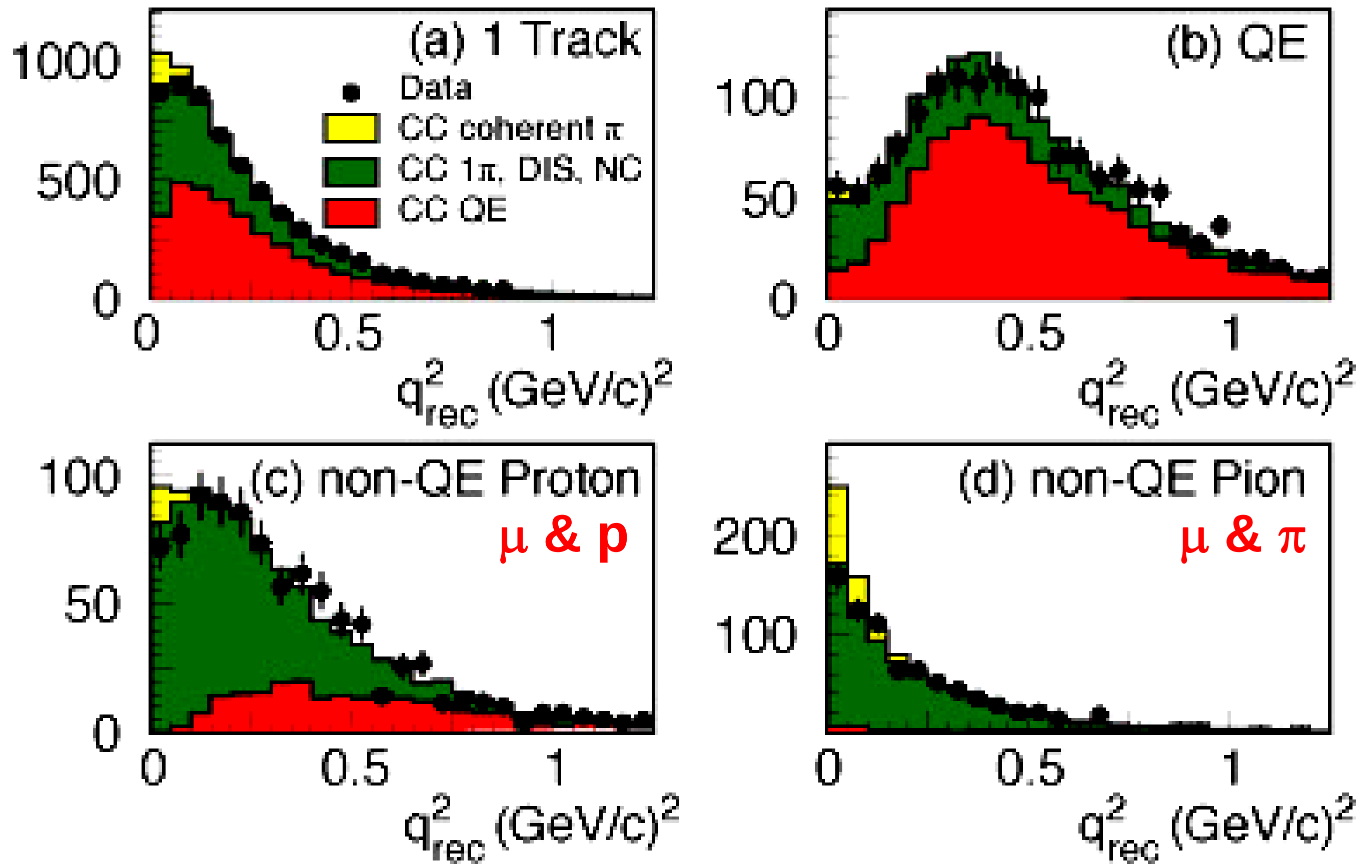
85% efficiency, 80% purity for protons (estimated by Monte-Carlo simulation).





Charged current coherent π analysis with the SciBar detector

Reconstructed q^2 distributions (SciBar)

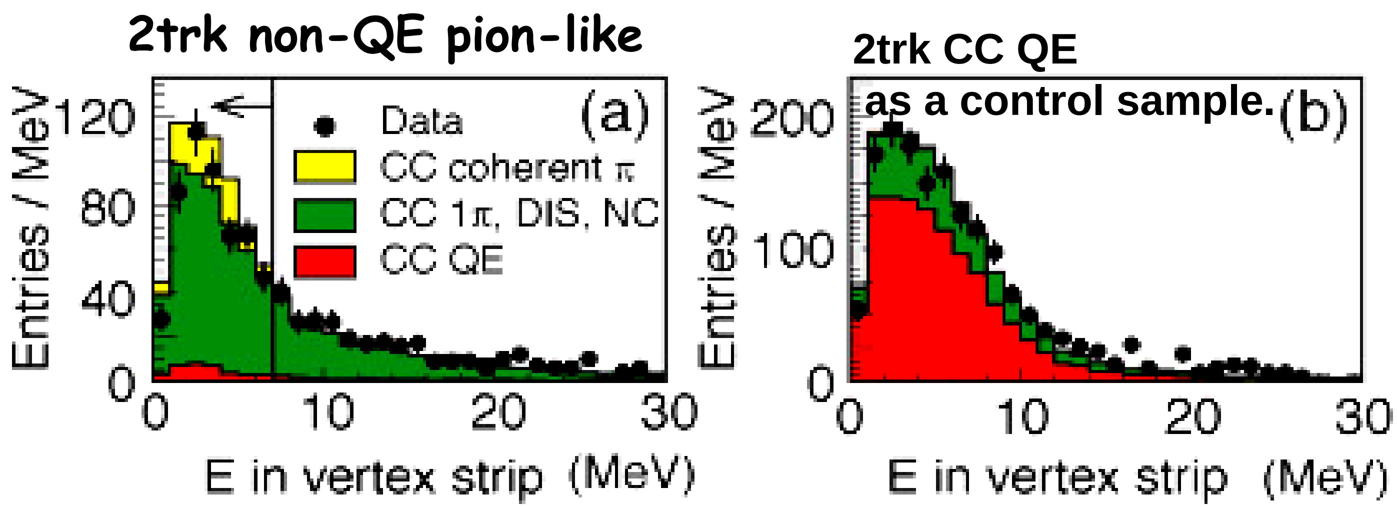


?? Indication of the much smaller cross-section of coherent π ??

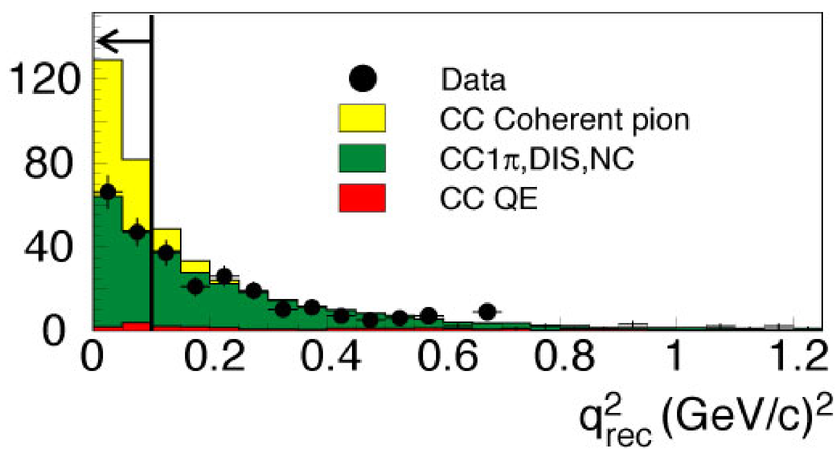
Charged current coherent π analysis

- **Vertex activity rejection**

Cut by the energy deposit around the vertex.



- **Reconstructed q^2 cut**



Select events with

$q^2_{rec} < 0.10$ (Gev/c)^2

# of events	113
Efficiency	21.1%
Purity	47.1%

Charged current coherent π analysis

In order to reduce the systematic uncertainties,
take ratio to the charged current total cross-section.

$$\frac{\sigma(CC-Coh\ \pi)}{\sigma(\nu_\mu CC)} = (\mathbf{0.04} \pm \mathbf{0.29}(\mathit{stat.})^{+0.32}_{-0.35}(\mathit{syst.})) \times \mathbf{10^{-2}}$$

And the upper limit of this cross-section ratio is obtained to be

$$\frac{\sigma(CC-Coh\ \pi)}{\sigma(\nu_\mu CC)} < \mathbf{0.60 \times 10^{-2}} \text{ @ 90\% CL}$$

M. Hasegawa et al.,
Phys.Rev.Lett.95:252301,2005

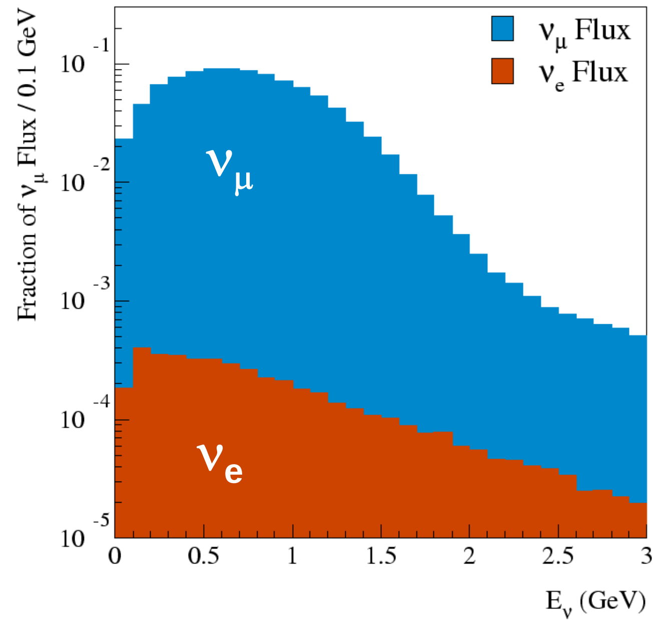
~30% of Rein-Sehgal's model expectation

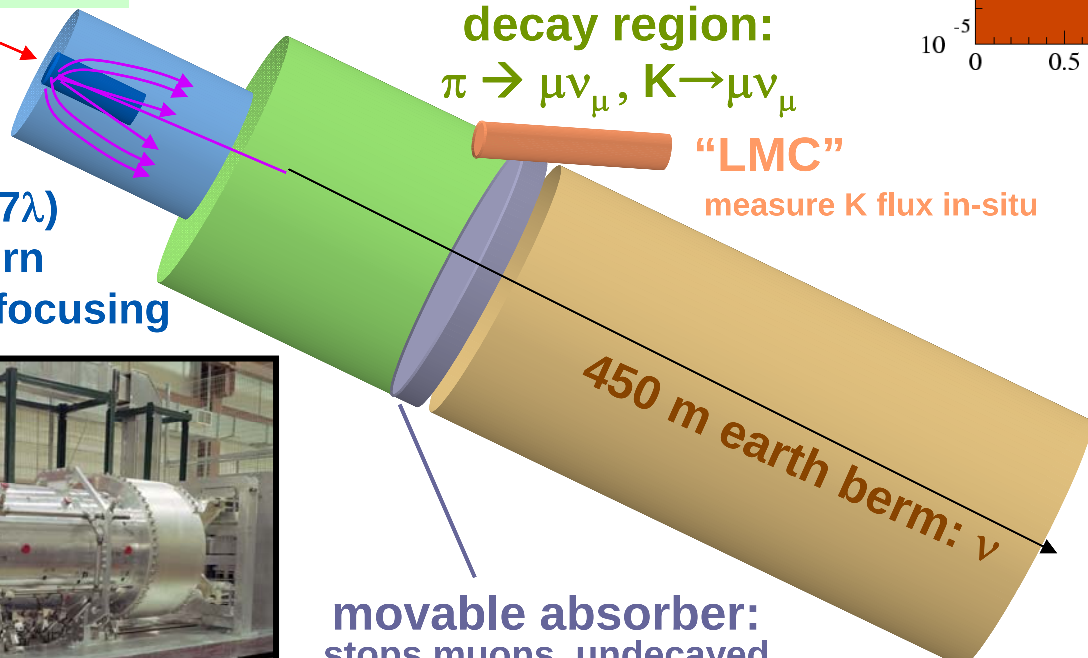
Major sources of systematic error
Uncertainty of
differential cross-section of resonant π production
and π interactions in carbon (from resonant π production)

Study of charged current single π^+ production at MiniBooNE

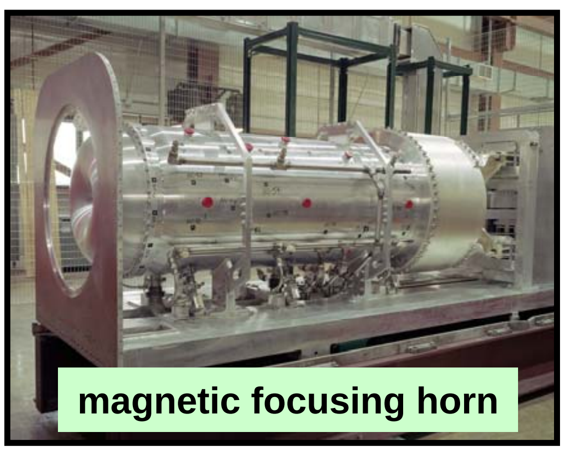
MiniBooNE beamline

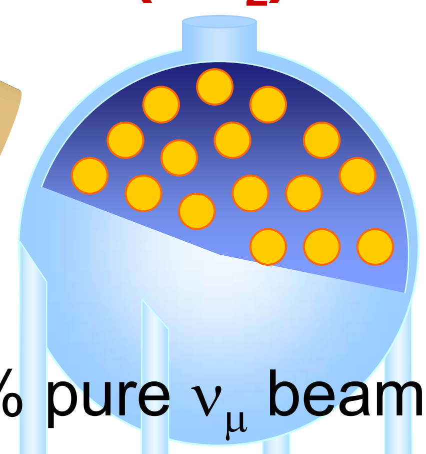
Almost pure ν_μ beam
(>99%)
Mean neutrino energy
~0.7GeV



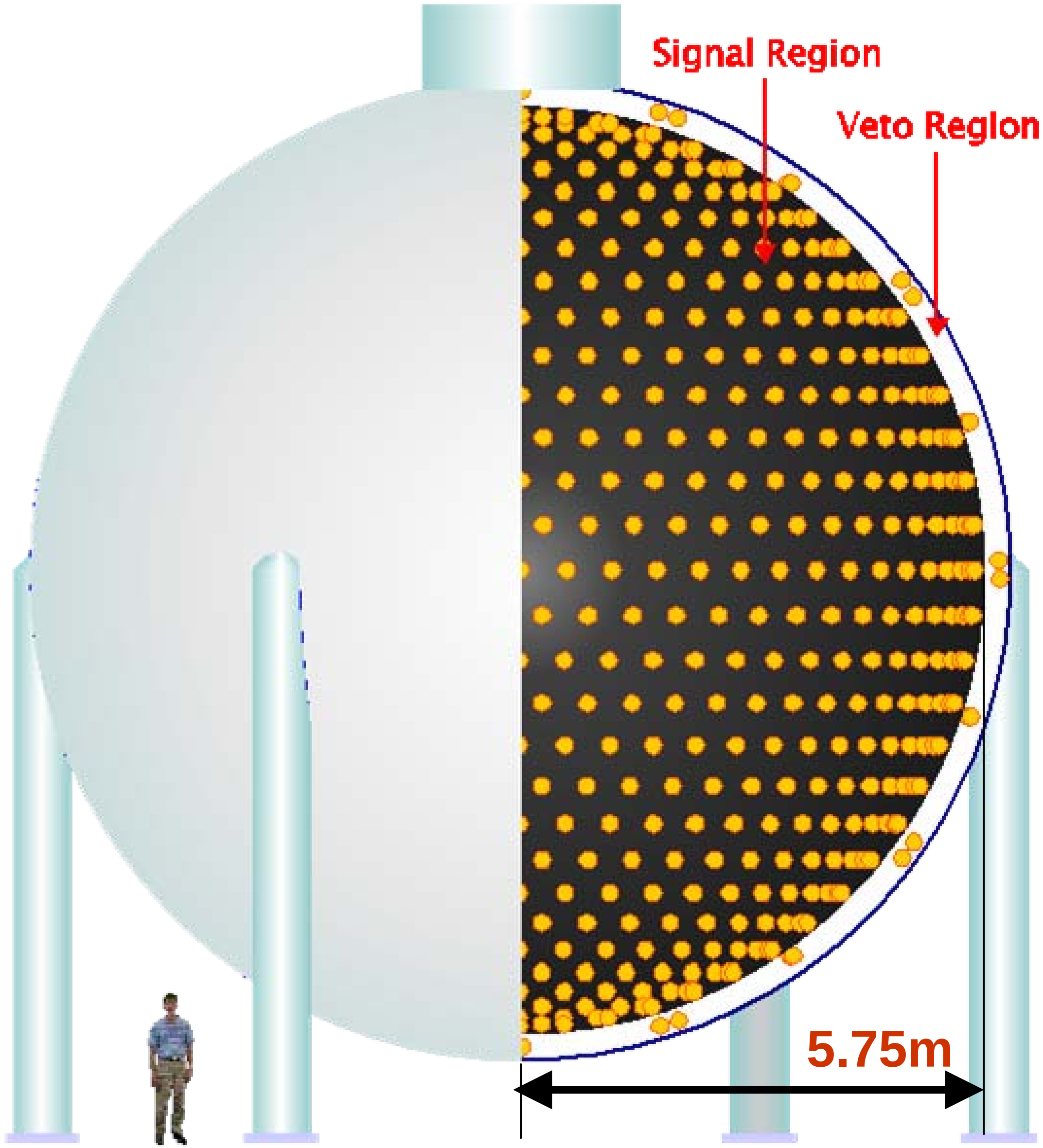


MiniBooNE detector (CH_2)



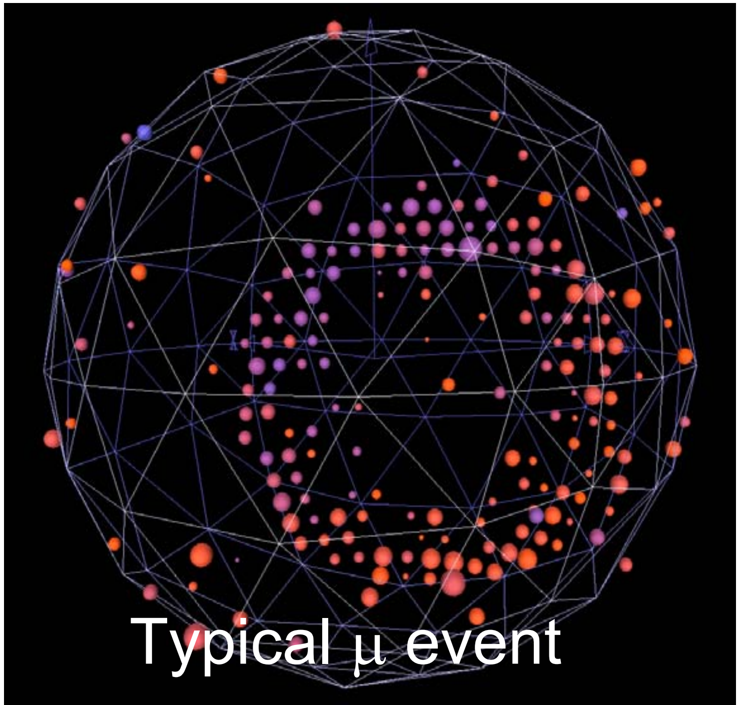


MiniBooNE detector



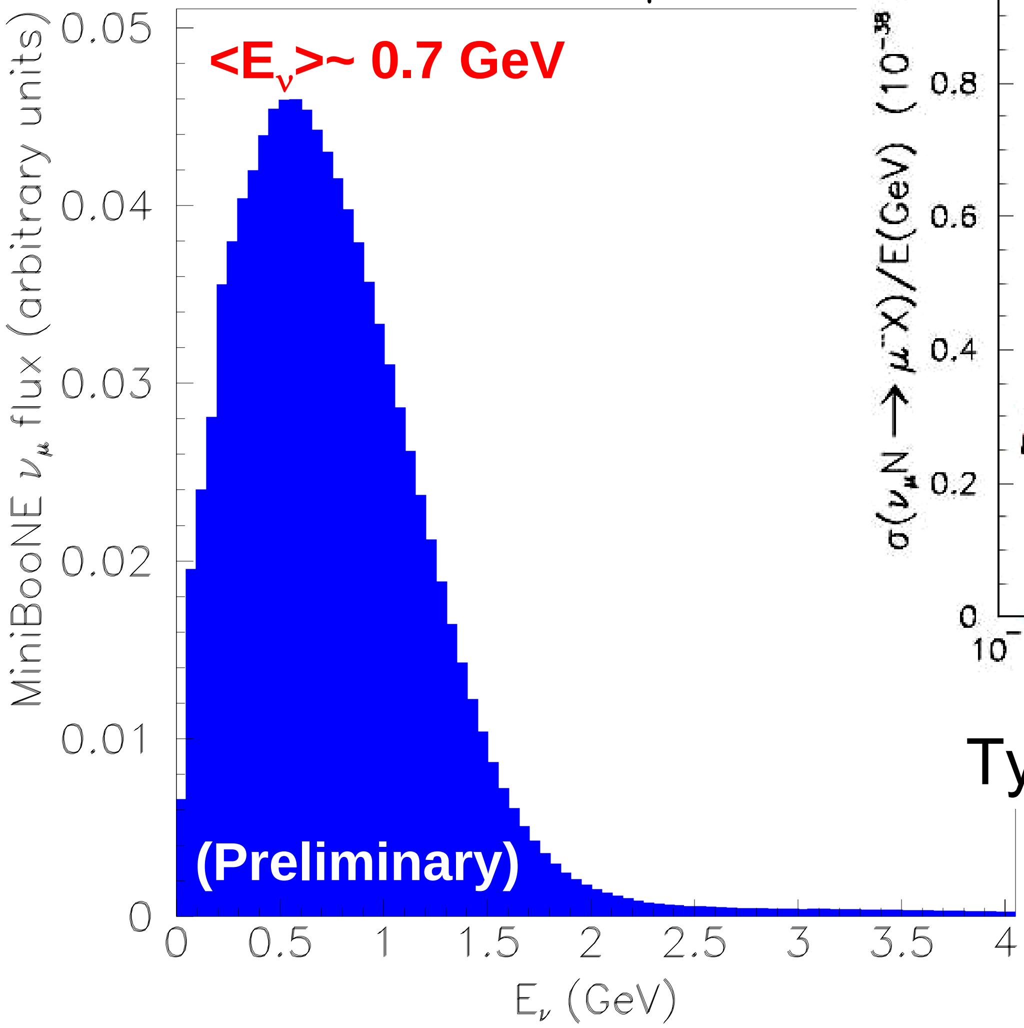
800 ton CH_2 detector
Signal region
1280 8inch PMTs
Veto region
240 8inch PMTs

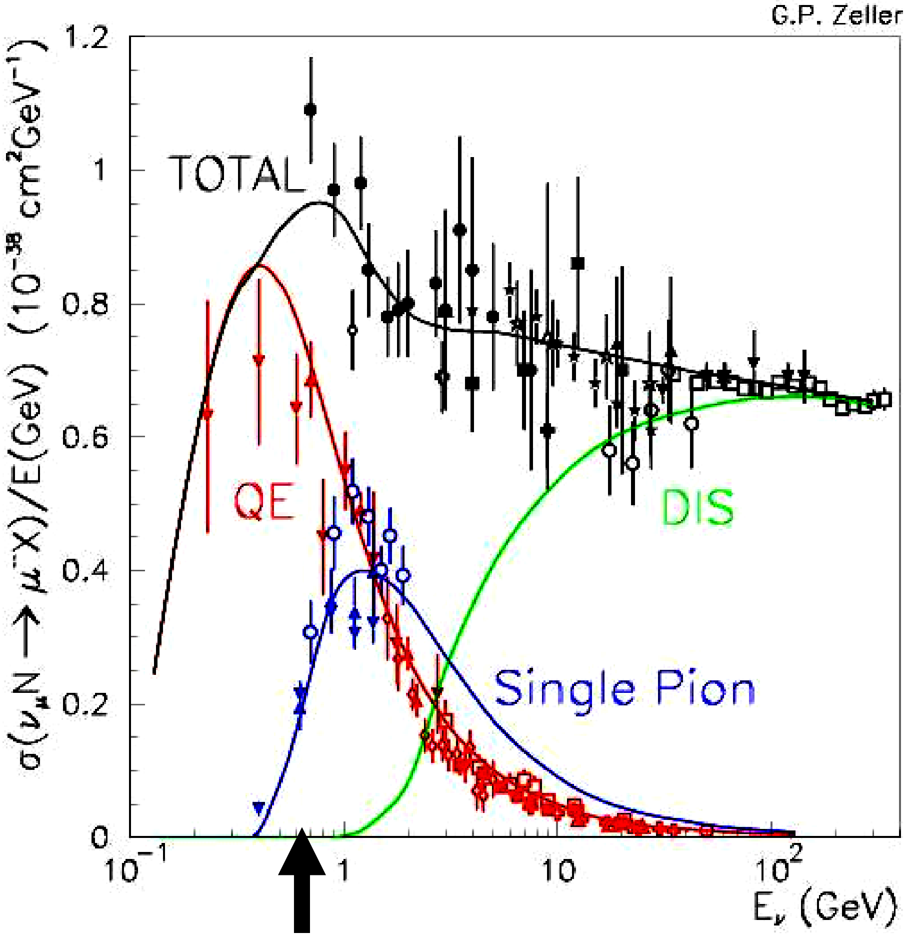
Use Cherenkov light
and scintillation light



Neutrino interactions at MiniBooNE

Monte-Carlo predicted ν_μ flux





Typical energy@MiniBooNE

Dominant interactions

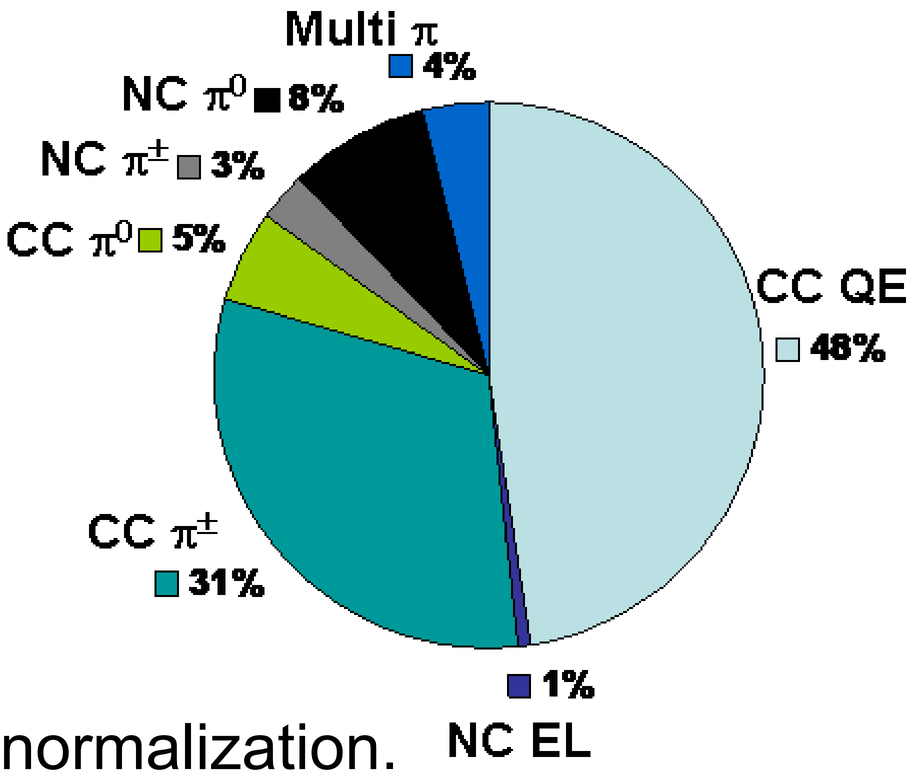
CCQE & CC 1π

Neutrino interactions at MiniBooNE

Dominant interactions

Charged current
quasi-elastic scattering

Charged & neutral current
single π production



To study single π production,
CCQE events are used for the normalization.
(In order to reduce systematic uncertainties.)

This Analysis:
3.2×10^{20} protons on target
60k CCQE events (after selection cuts)
40k CC1π^+ events (after selection cuts)

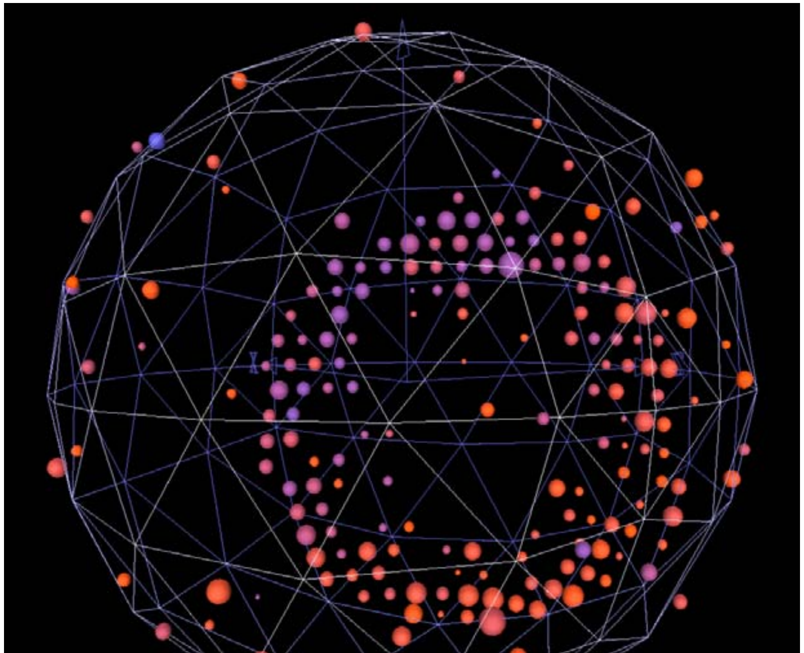
Charged current Quasi-Elastic scattering (MiniBooNE)

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

$\quad \hookrightarrow e^-\, \nu_\mu\, \bar{\nu}_e$

Observed particles

- μ^-
- decay electron



Typical μ event

- Neutrino-Induced Event Selection Cuts (Mainly timing and VETO cuts)
- CC Selection Cut (Search for the delayed signal from decay electron)
- < 3 sub-events (No invisible πs in an event)

- event topology
- Fraction of on- vs. off- ring light
- PMT hit timing
- Fraction of prompt vs. late light
- μ-like energy loss
- given E, is track length consistent with μ?
- 10 variable "Fisher discriminant"

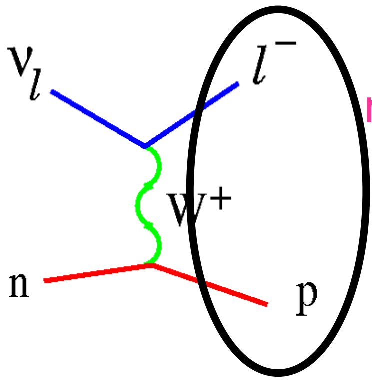
Result: 86% CCQE purity

most of background from $CC1\pi^+$

(due to π absorption in nucleus)

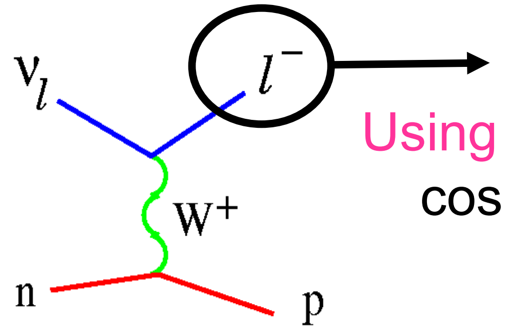
Charged current Quasi-Elastic scattering (MiniBooNE)

measured visible energy

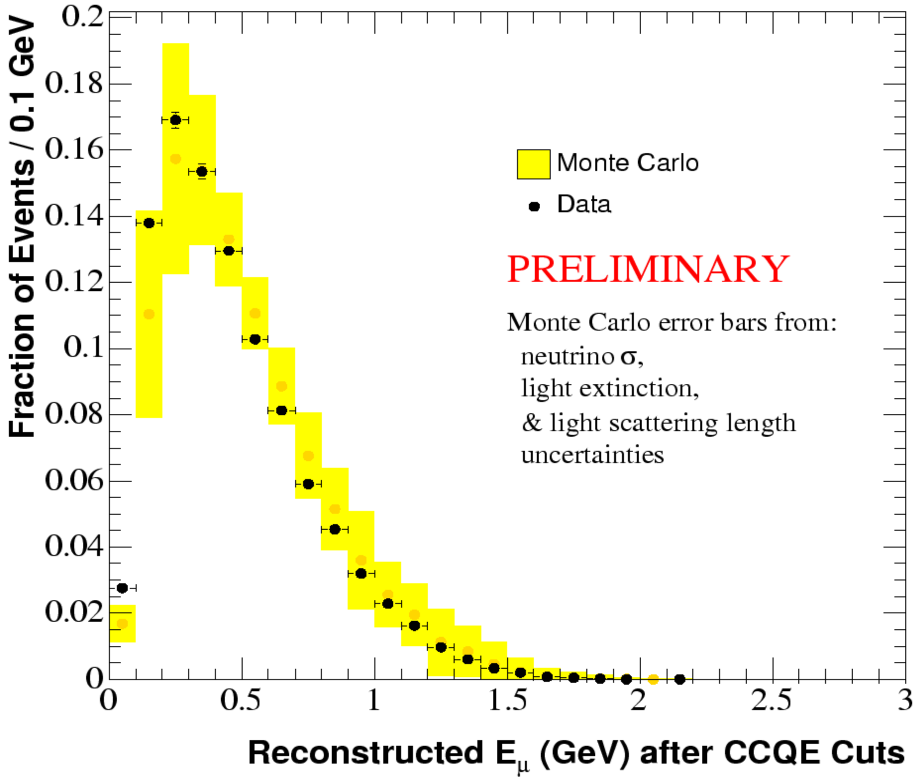


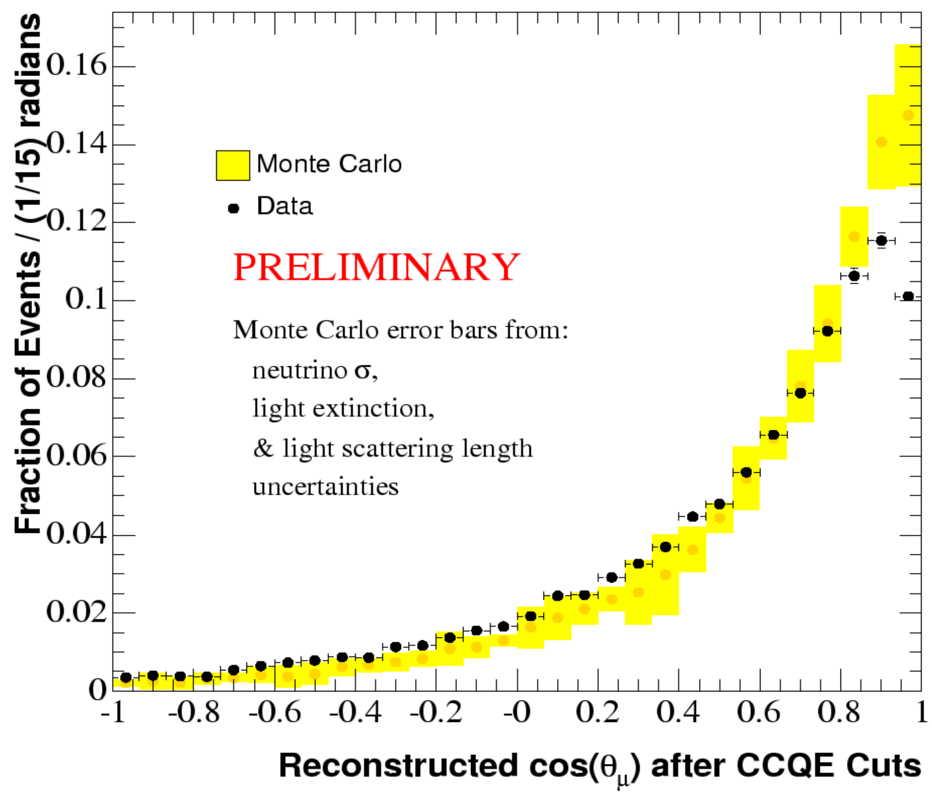
mostly Cherenkov from μ^-
+ a little scintillation light from proton

reconstructed direction of μ



Using Cherenkov light.
$\cos(\theta) = 1 \sim$ low Q^2



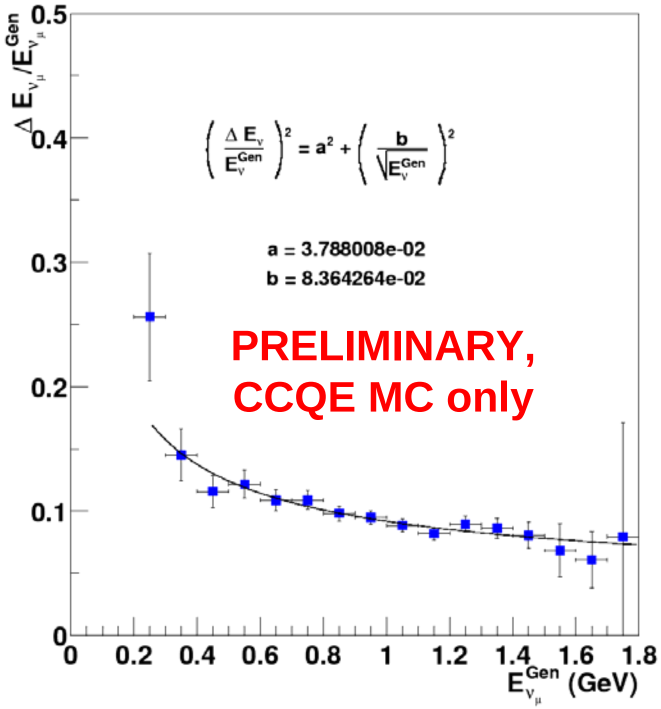


Charged current Quasi-Elastic scattering (MiniBooNE)

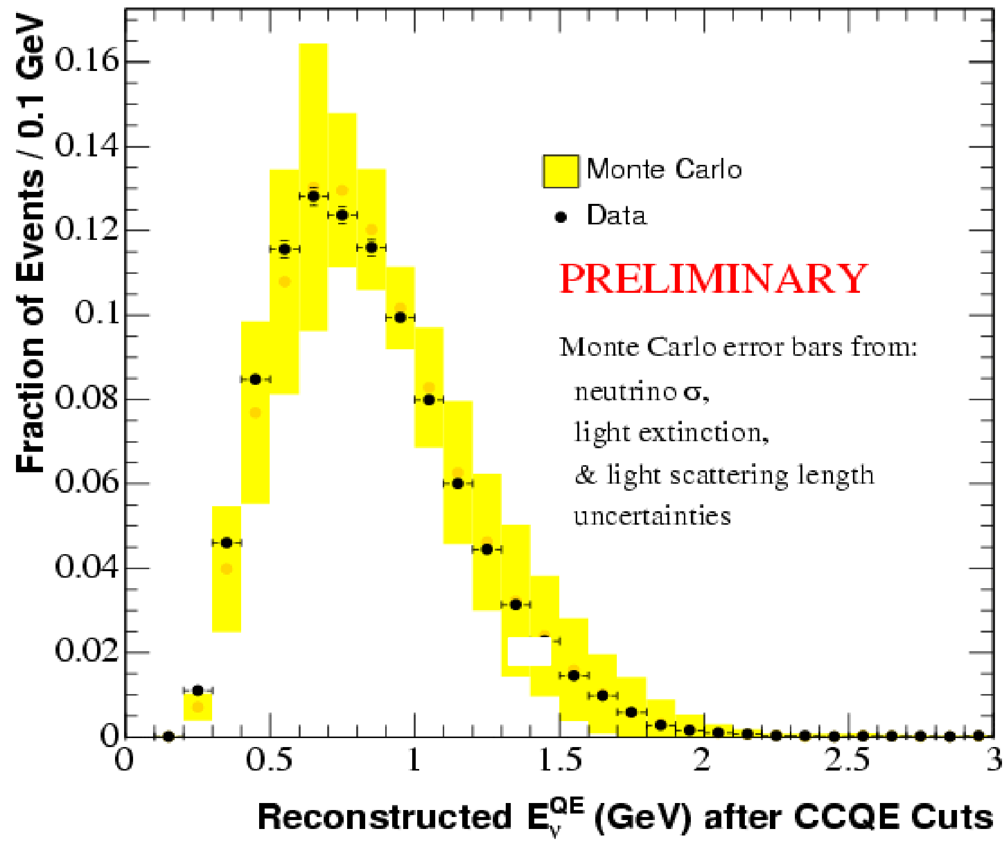
Using the obtained reconstructed energy and the direction of μ, energy of neutrino is calculated as follows:

$$E_{\nu}^{QE} = \frac{1}{2} \frac{2M_p E_\mu - m_\mu^2}{M_p - E_\mu + \sqrt{(E_\mu^2 - m_\mu^2)}\cos\theta_\mu}$$

<u>Neutrino energy resolution</u>



Energy distribution used for the cross section measurement



Charged current single π^+ production (MiniBooNE)

$\nu_\mu\, p \rightarrow \mu^-\, p\, \pi^+$

$\pi^+ \rightarrow \mu^+\, \nu_\mu$

$\mu^+ \rightarrow e^+\, \bar{\nu}_\mu\, \nu_e$

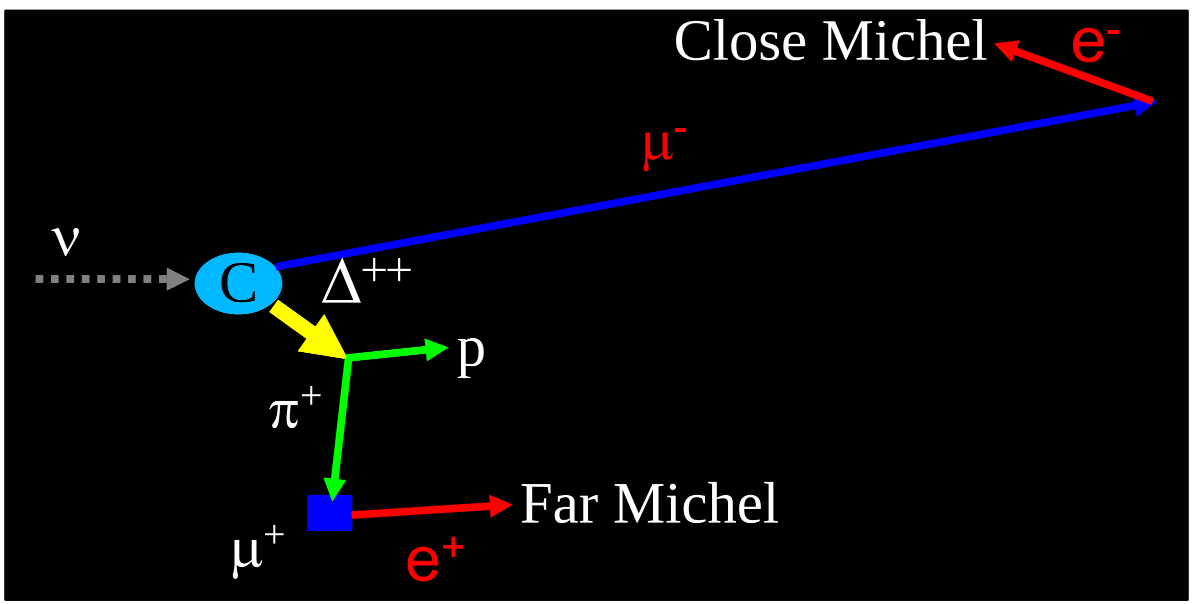
$\mu^- \rightarrow e^-\, \nu_\mu\, \bar{\nu}_e$

Observed particles

- μ^-
- 2 decay electrons (from μ^- and π^+)

Event selection criteria

- Neutrino-Induced Event Selection Cuts
- CC Selection Cut (require decay electron)
- exactly 3 sub-events
- 2nd 2 sub-events consistent with Michel e^- ($20 < N_{PMT} < 200$)



Purity : 84%

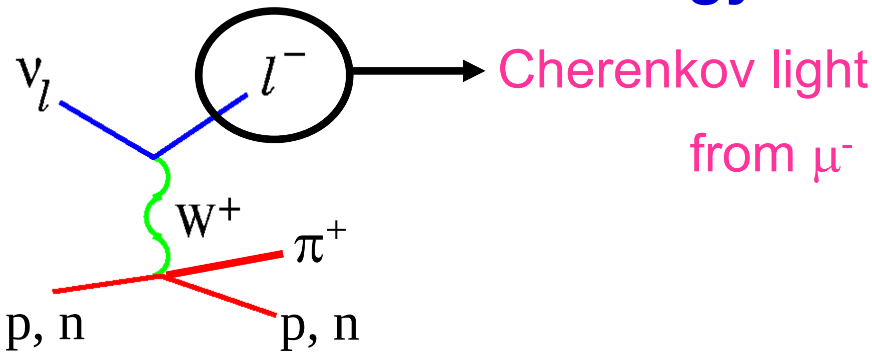
Main Backgrounds

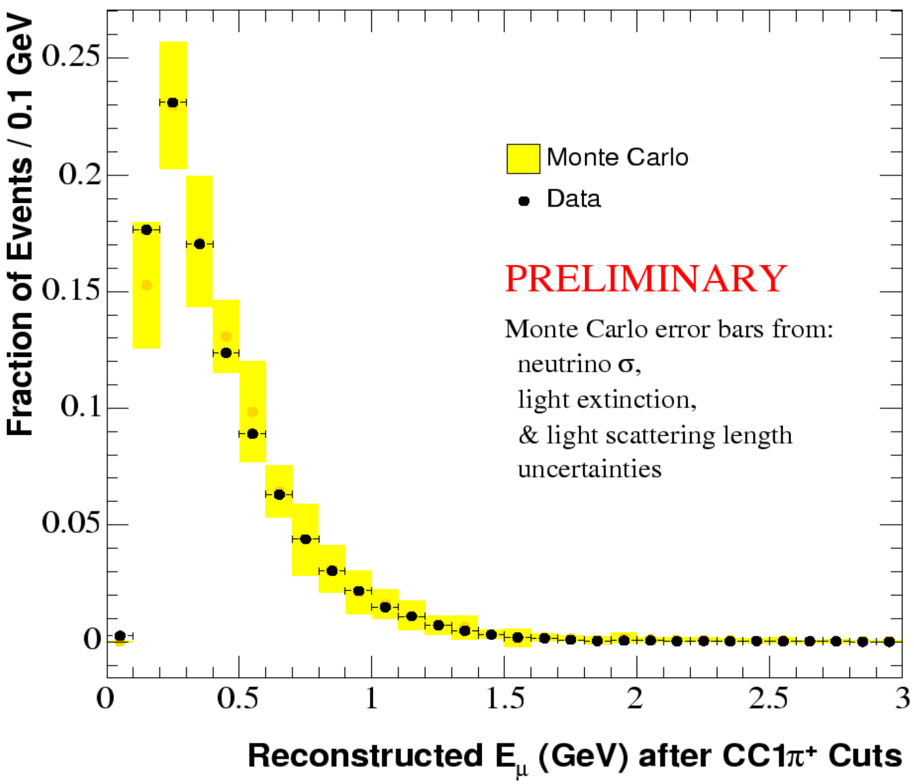
multi π production and QE

Inclusive final states

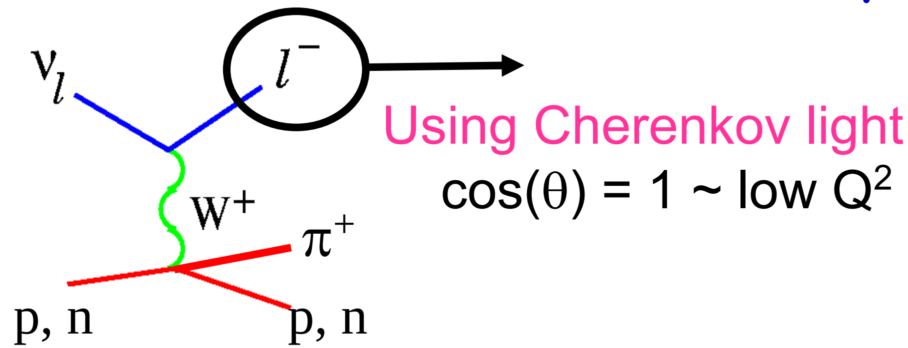
Charged current single π^+ production (MiniBooNE)

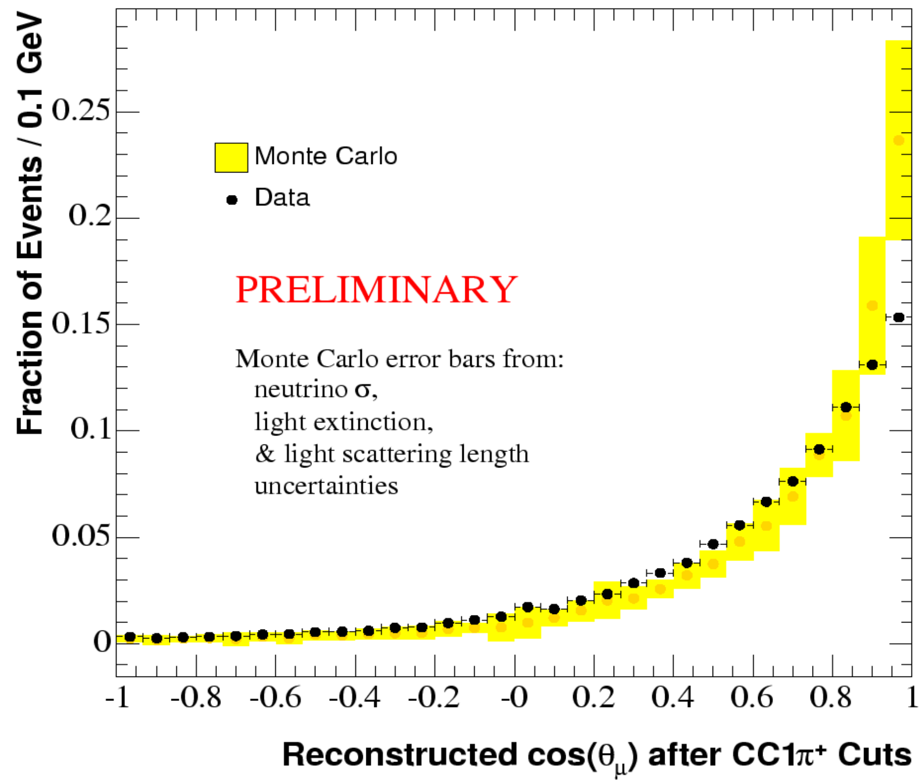
measured visible energy





reconstructed direction of μ





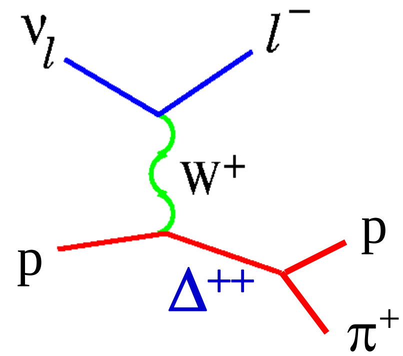
Charged current single π^+ production (MiniBooNE)

Neutrino Energy Reconstruction

Assume 2 body kinematics (as in CCQE)

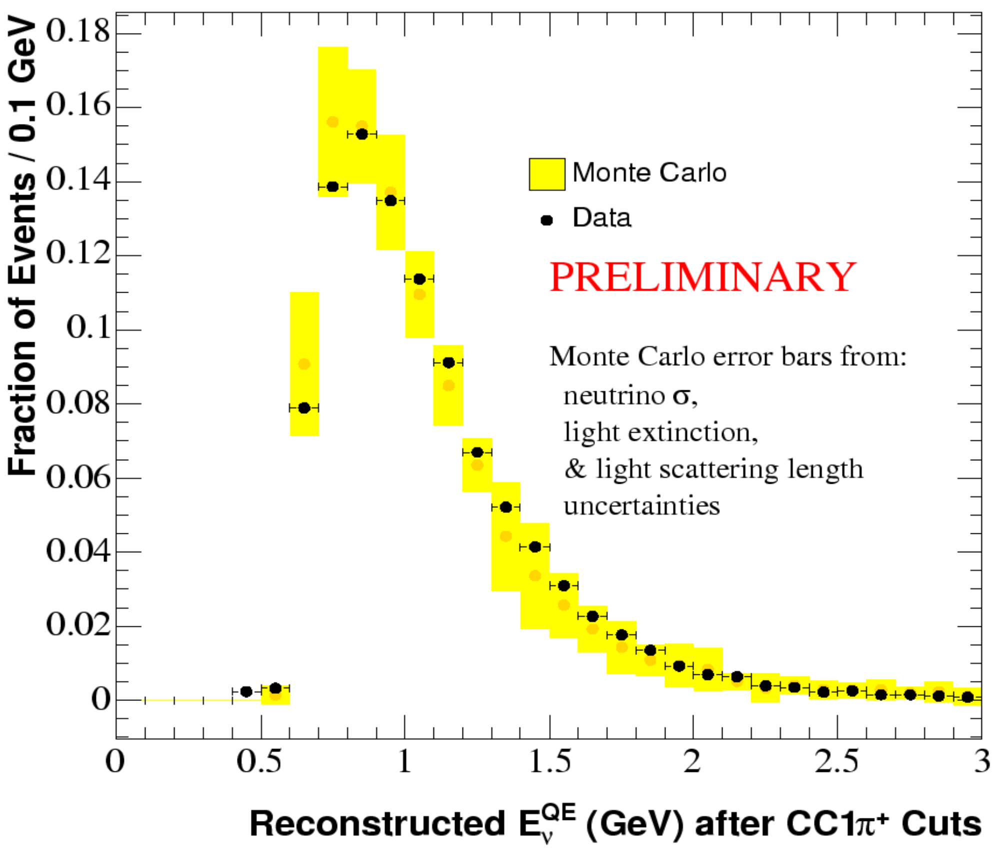
Assume $\Delta(1232)$ in final state

(instead of a proton in CCQE)



$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\mu - m_\mu^2 + \left(m_\Delta^2 - m_P^2\right)}{M_p - E_\mu + \sqrt{\left(E_\mu^2 - m_\mu^2\right)}\cos\theta_\mu}$$

Energy resolution ~20%

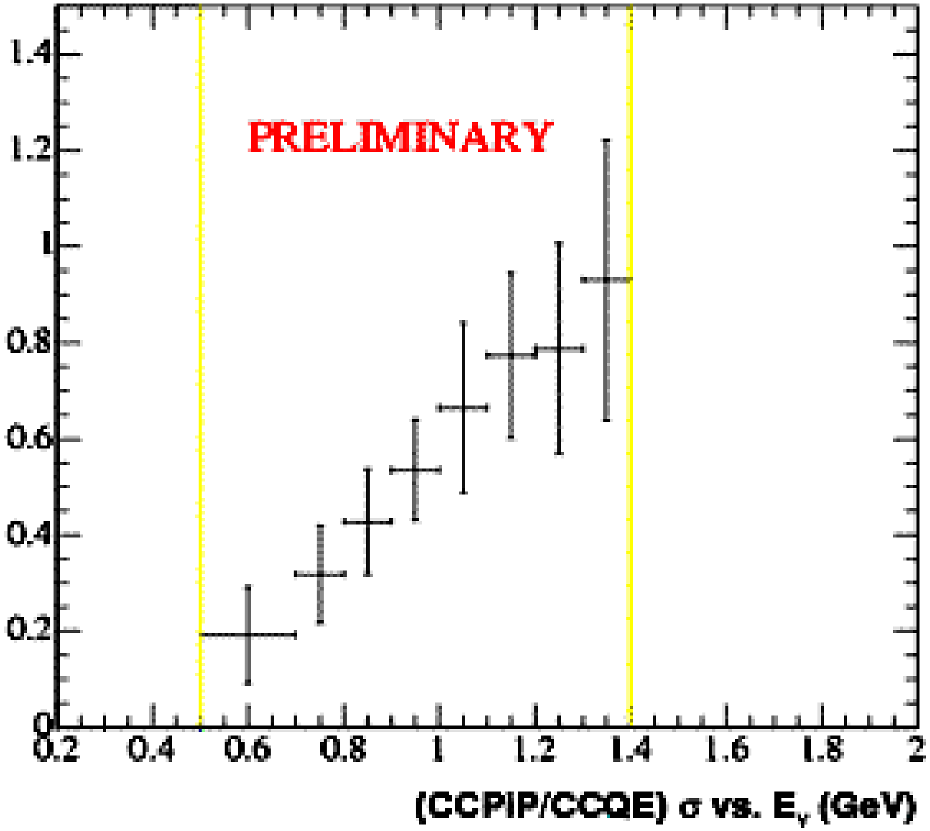


CC single π^+ / CC Quasi Elastic cross-section ratio

(MiniBooNE)

efficiency corrected σ (CC π^+)/ σ(CC QE)

measured on CH_2



(J. Monroe, M. Wascko)

(efficiency corrections from MC)

<u>current systematic errors</u>

- light propagation in oil: ~20%
- ν cross sections: ~15%
- energy scale: ~10%
- statistics: ~5%

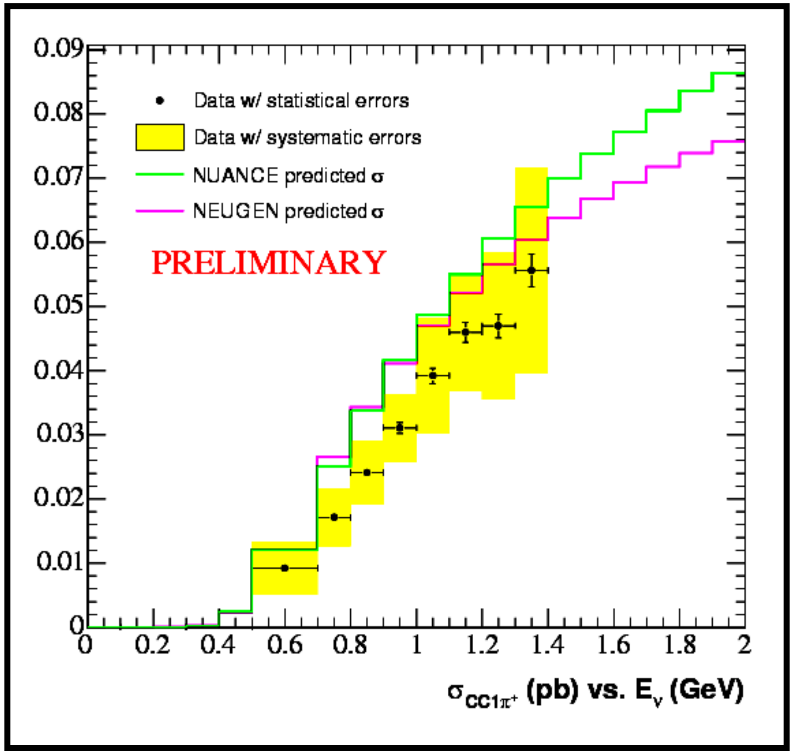
first measurement of this cross section ratio on a nuclear target at low energy!

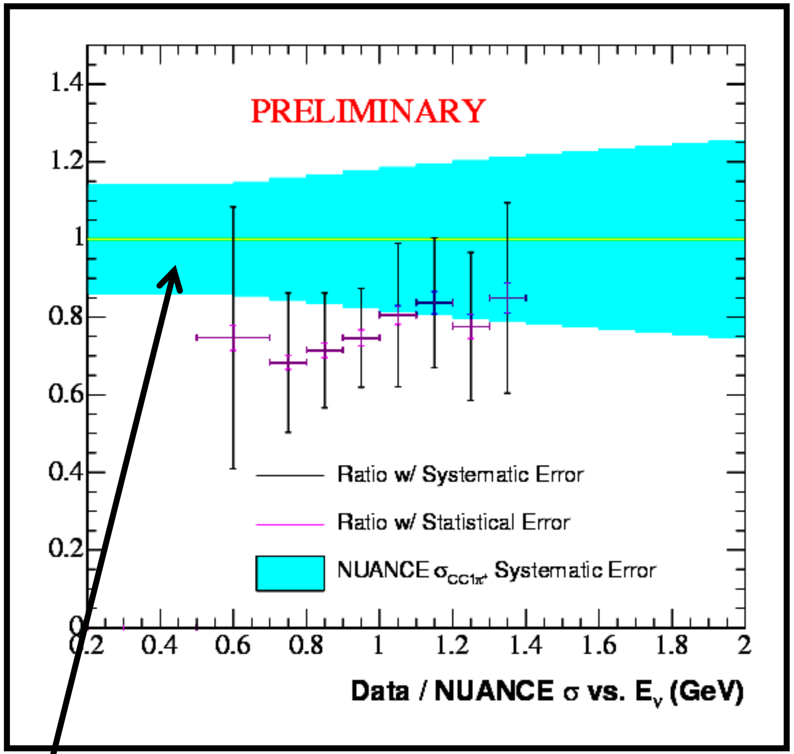
(Sam Zeller @ NO-VE workshop 2006)

CC single π^+ production effective cross-section

(MiniBooNE)

- multiplying measured CC π^+/QE ratio by QE σ prediction
  (σ_{QE} with M_A=1.03 GeV, BBA non-dipole vector form factors)
- ~25% lower than prediction, but within errors





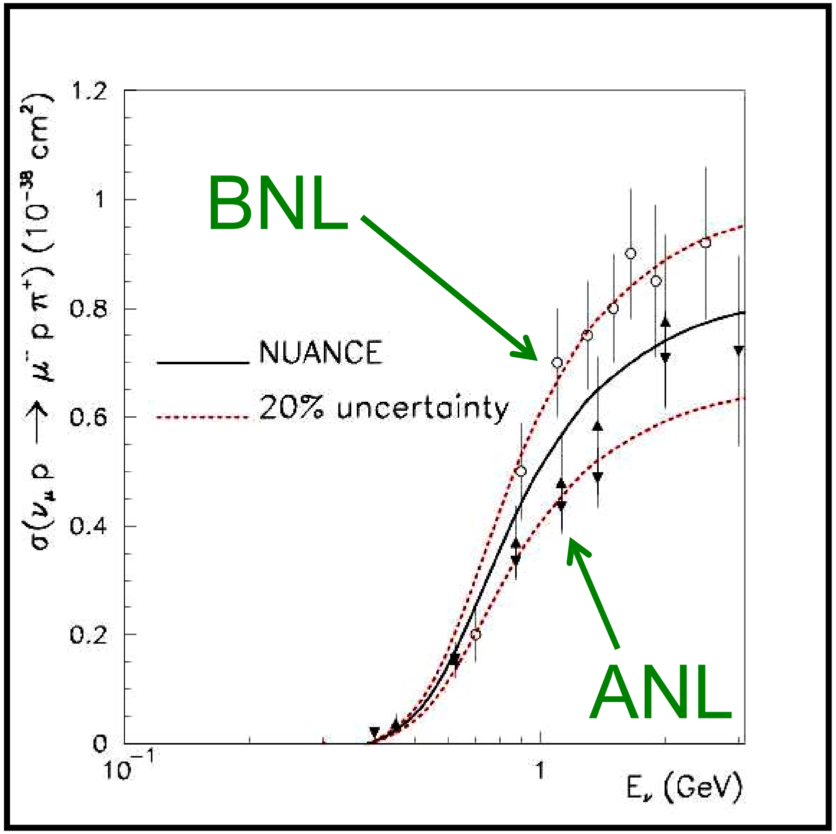
(J. Monroe, M. Wascko)

- MC error band from external ν data constraints

(Sam Zeller @ NO-VE workshop 2006)

Plausible Interpretation

- since MiniBooNE 1st meas on nuclear target at these E's
- at 1st glance, one might think this is pointing to a potential problem with nuclear corrs
- but free nucleon σ's disagree!
- MC prediction splits difference



- MiniBooNE results more consistent with ANL than BNL
  - new data helping to decide between 2 disparate σ meas
  - once final, type of info that can feed back into open source MC

(Sam Zeller @ NO-VE workshop 2006)

Summary

K2K neutral current π^0 production cross-section measurement

π^0/μ ratio @ <Eν>~1.3GeV

0.064±0.001(stat.)±0.007(sys.)

(Prediction from our Monte-Carlo simulation : 0.065)

S. Nakayama et al. PLB619(2005) 255-

K2K Charged current coherent π^+ production search

$$\frac{\sigma(CC - Coh\ \pi)}{\sigma(\nu_\mu CC)} < \mathbf{0.60 \times 10^{-2}} \text{ @ 90\% CL}$$

~30% of Rein-Sehgal's model expectation

MiniBooNE charged current single π^+ production cross-section measurement

Eν from 0.5 to 1.4 GeV

~25% smaller than the Monte-Carlo expectation.

But still within error.

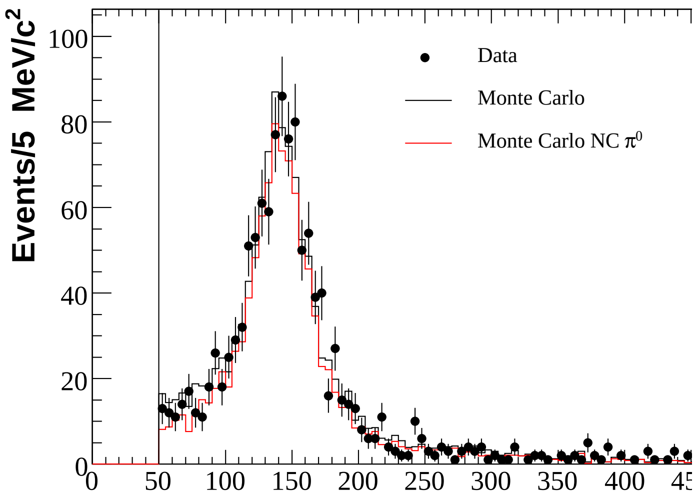
One of the old experiments gives similar result(?)

(Near) Future prospects

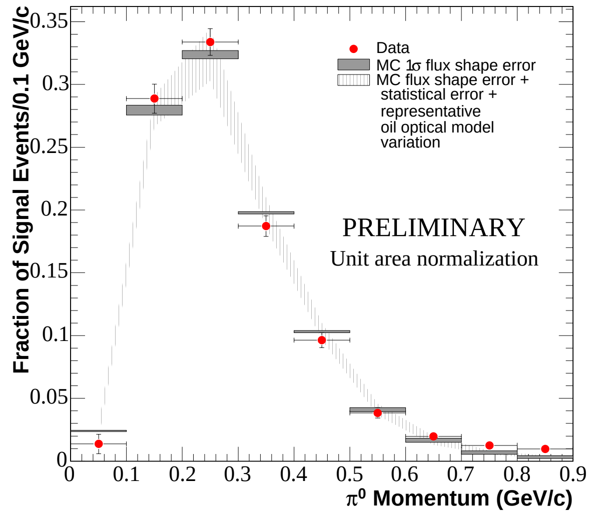
- New NC π^0 results from MiniBooNE

  Some results with improved π^0 ID were presented recently.

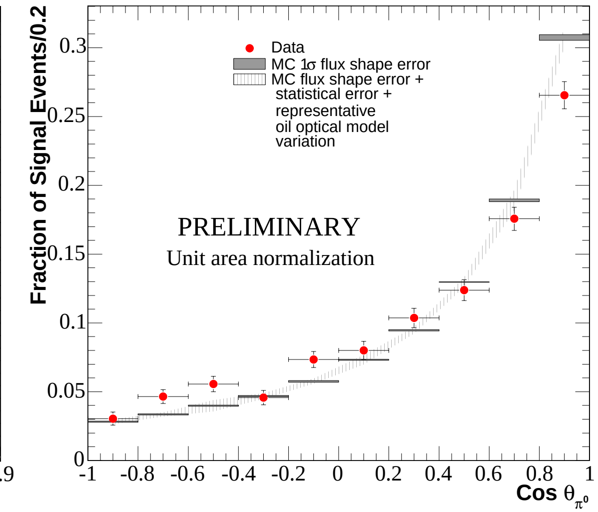
  (cross-section was not presented..)



Mass(MeV/c^2)



momentum



Direction

- SciBooNE (SciBar detector in the BooNE beamline) is expected to start soon.

  Study interactions with both ν and anti-ν beams.

fin.