Study of neutrino interactions using the FNAL booster neutrino beam

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1. Introduction
2. FNAL Booster neutrino beam-line
   and two neutrino experiments
   MiniBooNE and SciBooNE.
3. Quasi-elastic scattering and elastic scattering
4. Single pion productions
5. Summary

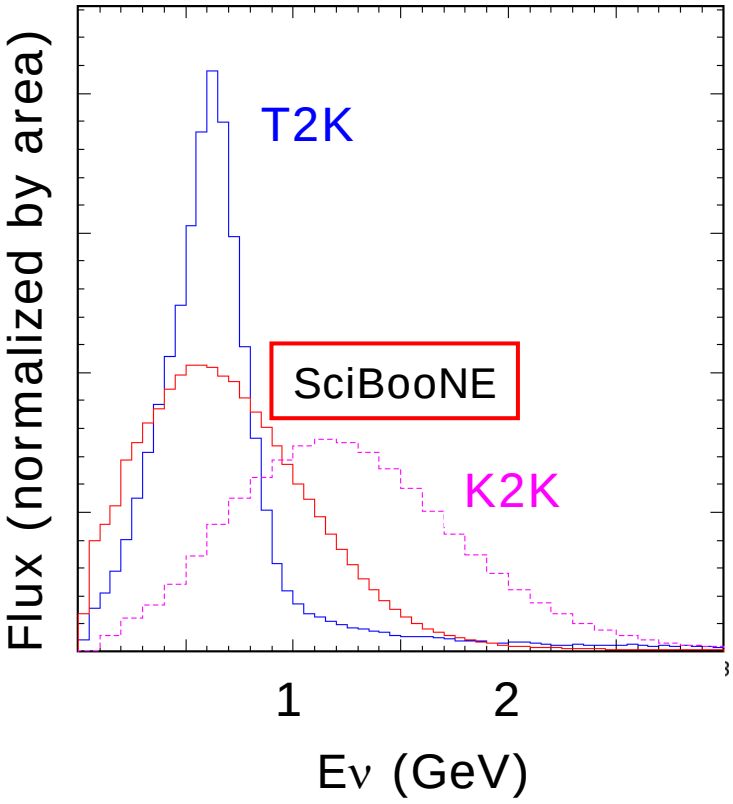
(Thank to the MiniBooNE collaboration
for providing the MiniBooNE figures and plots.)

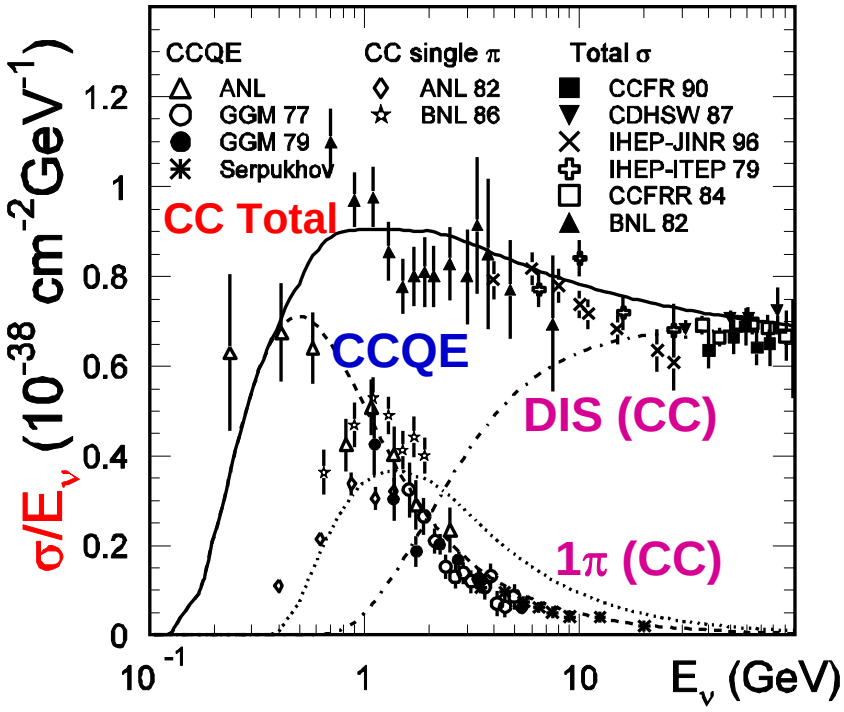
1. Introduction

Precise study of neutrino oscillation phenomena

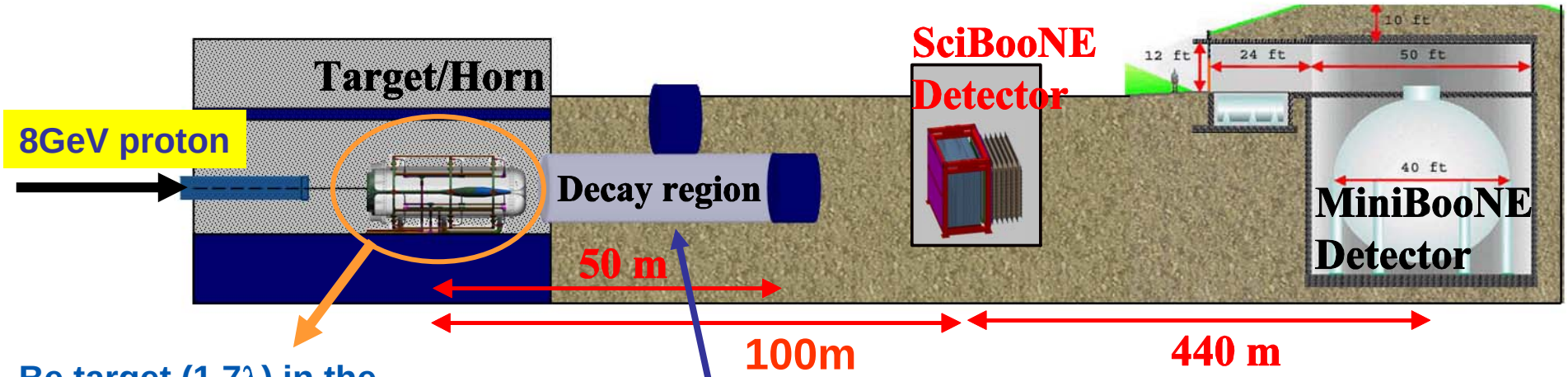
→ Precise understanding of neutrino interactions in the detectors.

However, low energy (≤ 1GeV) neutrino interactions have quite large uncertainties mainly due to lack of data.

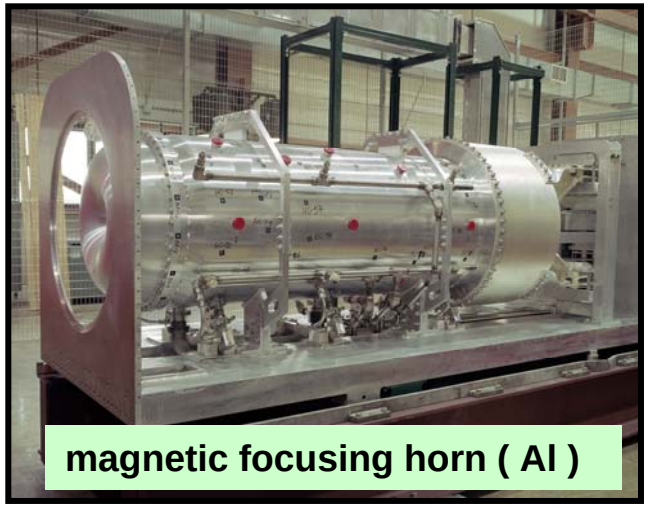




FNAL Booster neutrino beamline



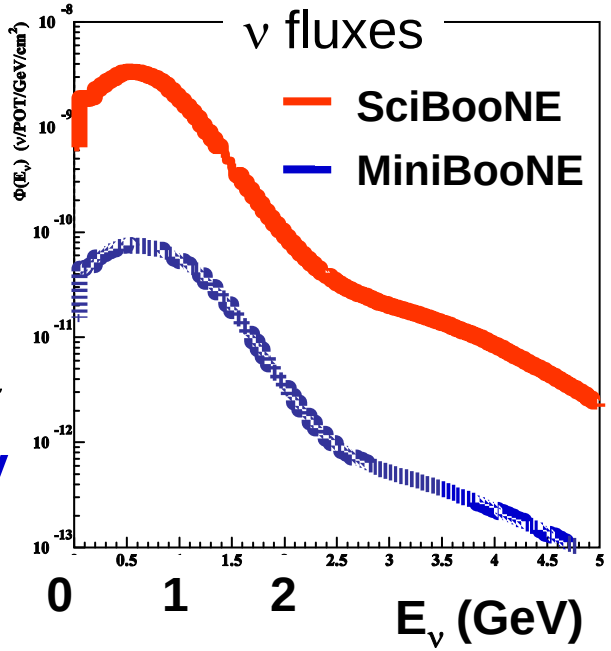
Be target (1.7λ) in the magnetic horn for meson focusing



π/K decays into ν in the decay region

ν_μ mode: >99% pure ν_μ

Mean neutrino energy ~0.7GeV

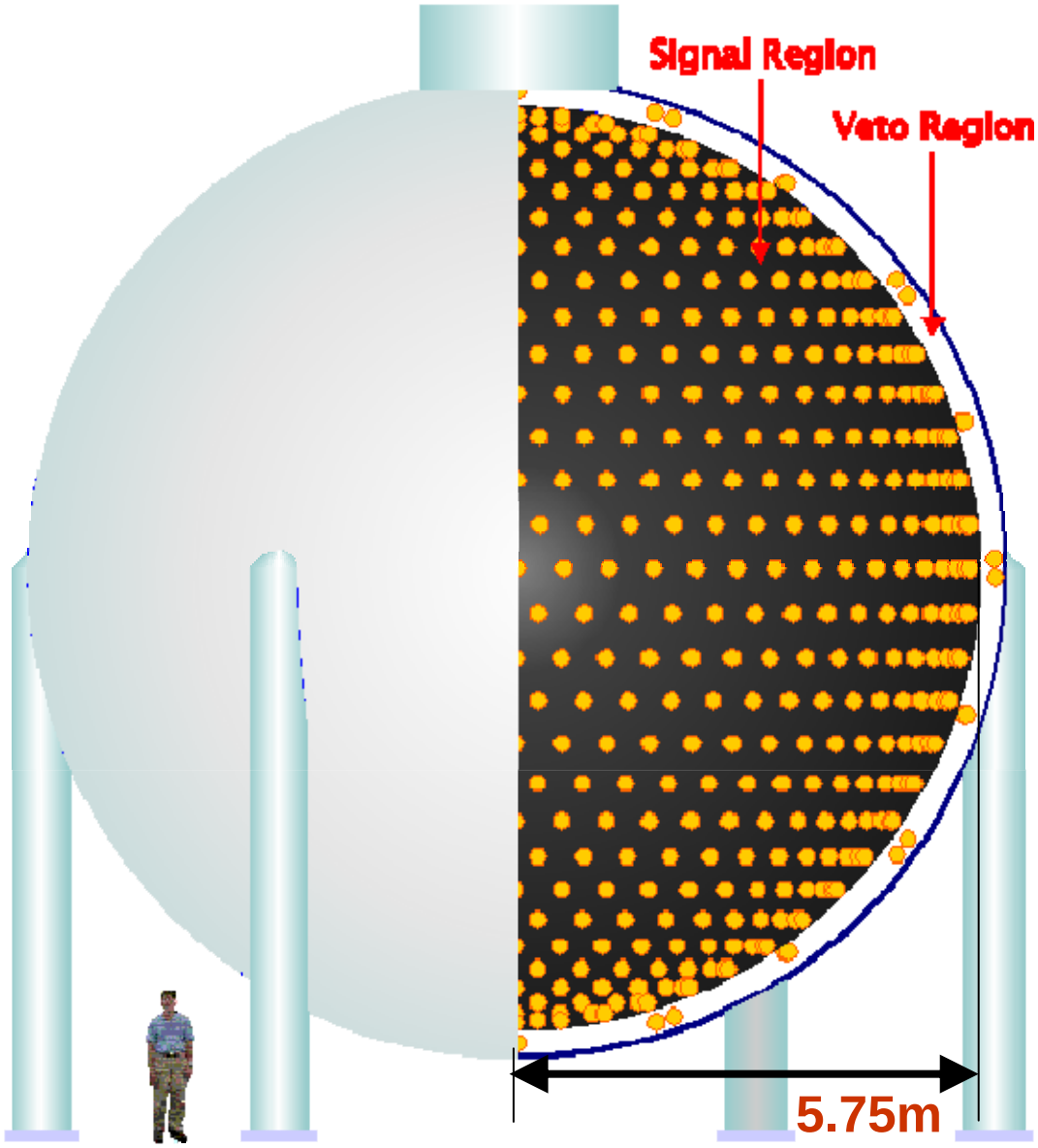


π^+ / K^+ or π^- / K^- are focused
(depending on the polarity of the horn current)

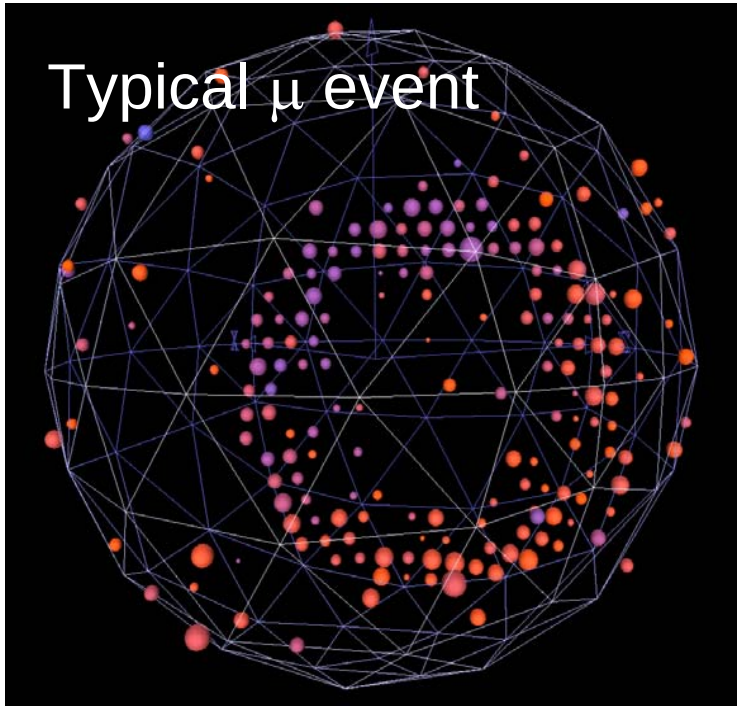
⟶ **ν or $\bar{\nu}$ beam can be produced**

MiniBooNE detector

Experiment started in August 2002.



- 800 ton CH_2 detector
- Signal region
  1280 8inch PMTs
- Veto region
  240 8inch PMTs
- Use Cherenkov light
  and scintillation light



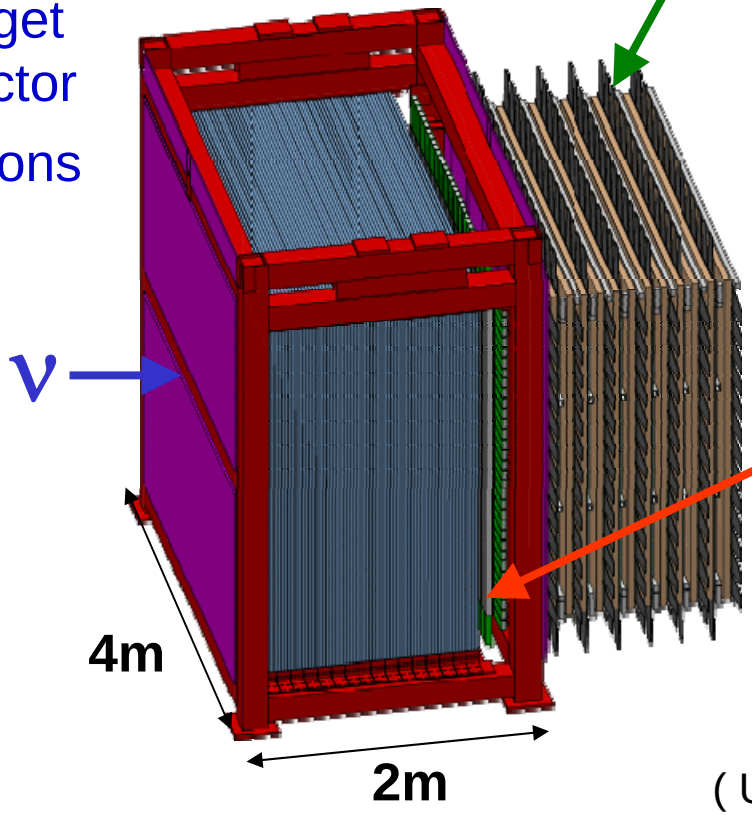
SciBooNE detectors

(Data taking: June 2007 to August 2008.)

SciBar (Used in K2K experiment)

- Full active tracking detector
  - 15 tons of scintillator (14336 bars)
    - also acts as the interaction target.
  - Cell size : **2.5 x 1.3** x 300cm^3
  - WLS fiber readout, 64ch MA-PMT

- ν Interaction target & tracking detector
- Identify interactions
- PID (p/π ID) using dE/dx



Muon Range Detector (MRD)

- 12 2”-thick steel layers + scintillator planes (alternate x & y)
- Measure μ momentum using range (up to ~ 1.2 GeV/c)

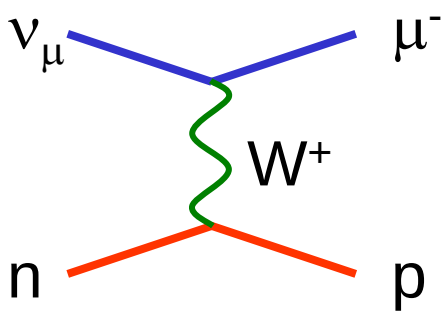
(Components are recycled from past experiment)

Electron Catcher (EC)

- Spaghetti calorimeter
- 2 planes (11 X_0)
  - 4 x 4 cm^2 cell x 128
- Identify π^0 and ν_e

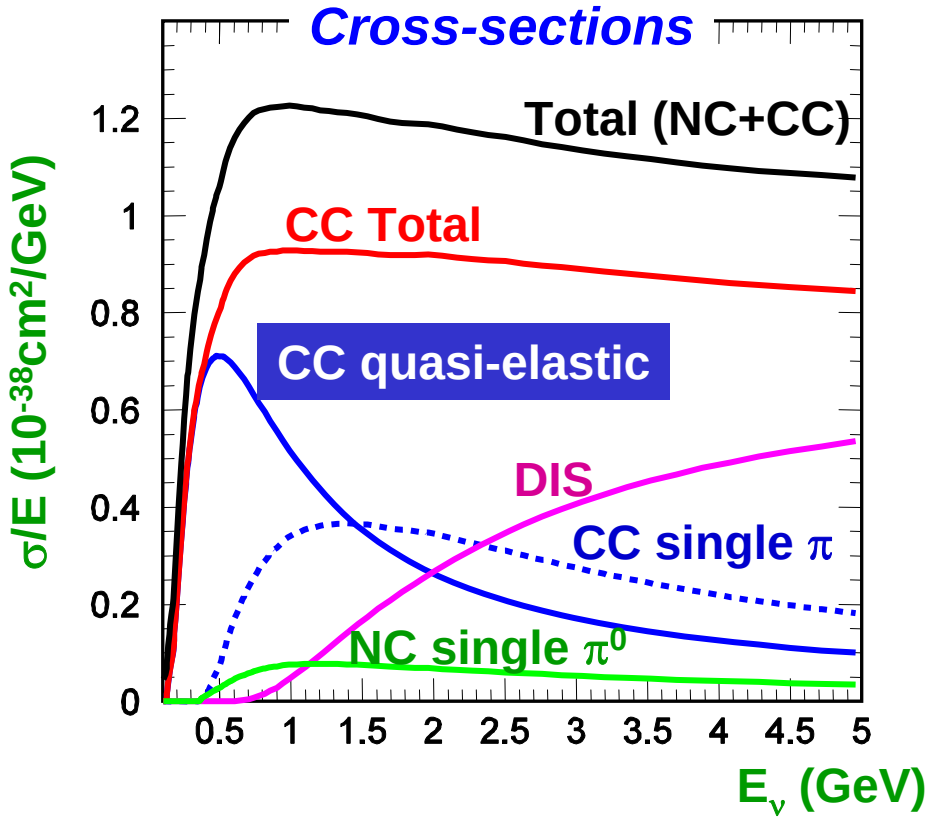
(Used in CHORUS, HARP and K2K)

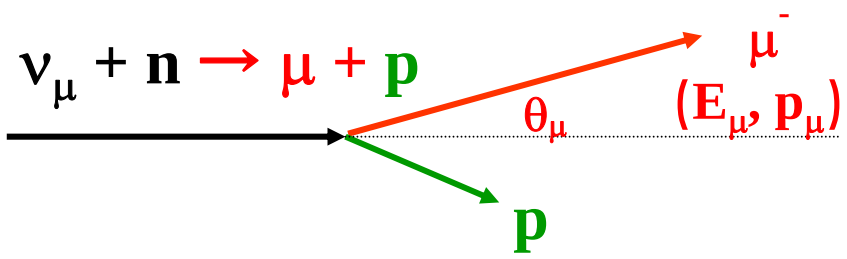
Charged current Quasi-elastic scattering



Dominant interaction in the low energy region.

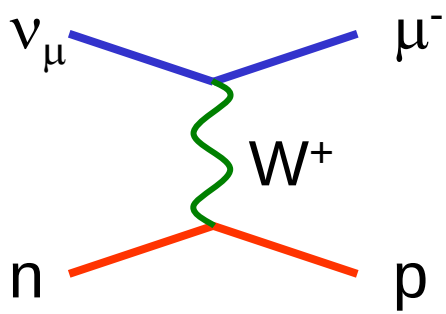
Useful interaction mode to reconstruct incident neutrino energy ~ used to measure the spectrum shape of the neutrino flux





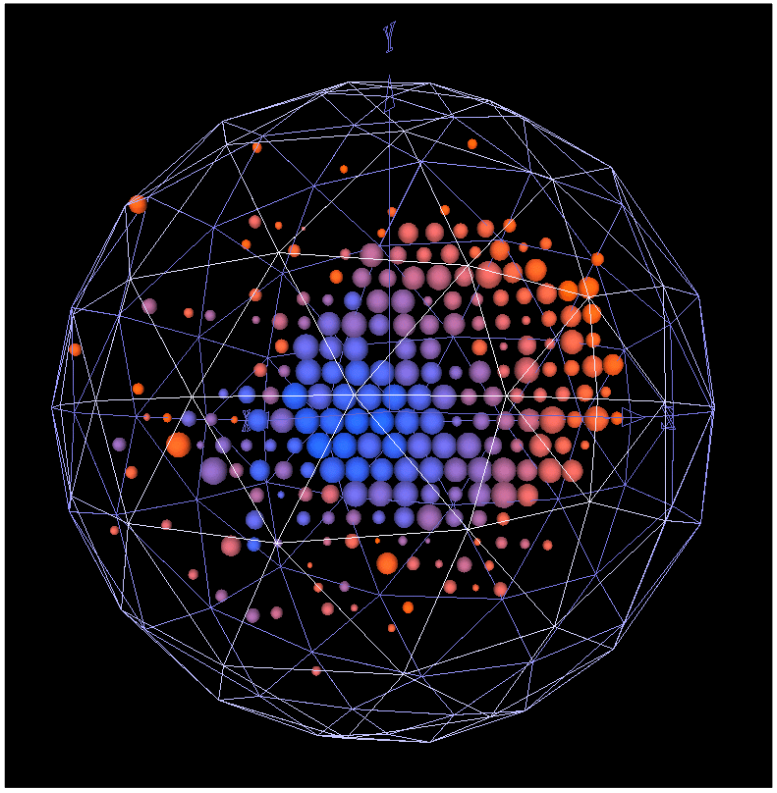
$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

Charged current Quasi-elastic scattering



MiniBooNE

Measure energy and direction of μ



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

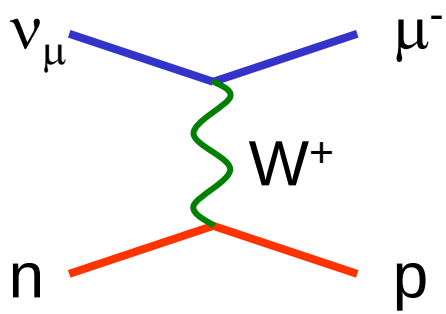
$\mu^- \rightarrow \nu_\mu + e^- + \nu_e$

Prompt μ^- with delayed e^- from the decay of μ^-.

(26.5% efficiency, 75.8% purity)

146,070 ν_μ QE candidate events observed in 5.58×10^{20}POT

Charged current Quasi-elastic scattering

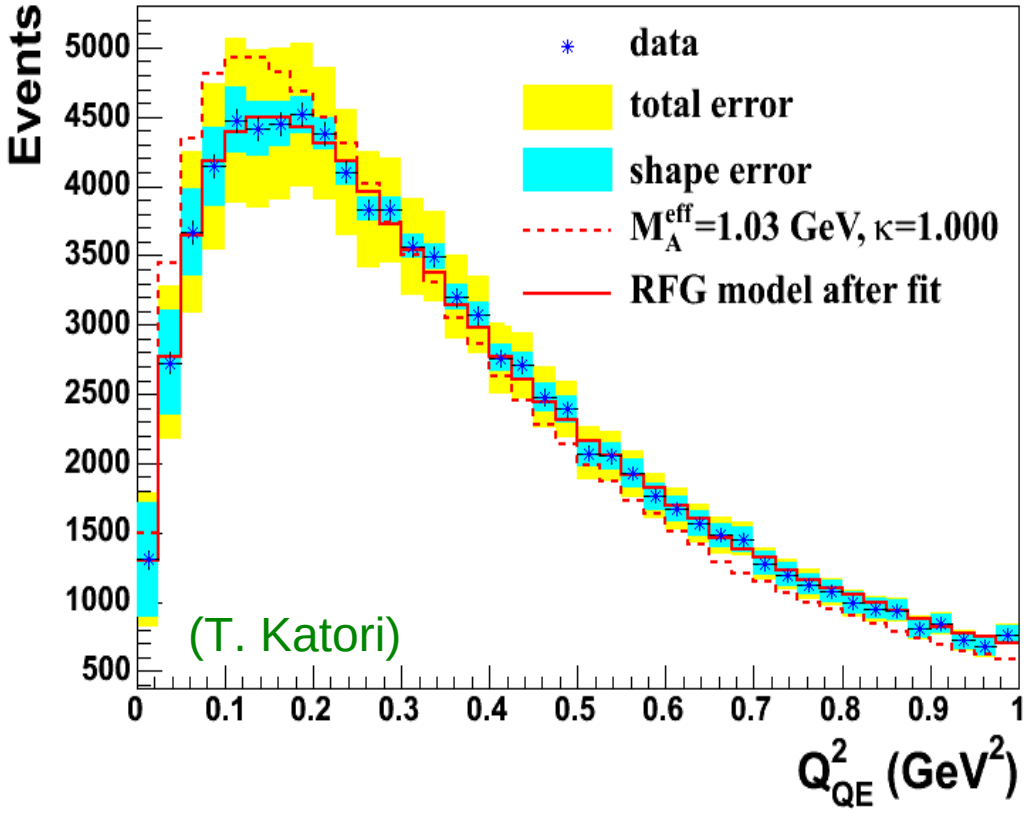


MiniBooNE

Axial vector form factor parameter M_A

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

Need to be determined from the neutrino scattering data.



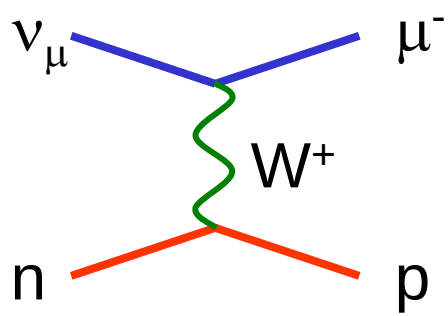
$M_A = 1.35 \pm 0.17$ GeV

- **World avg.**
  $M_A = 1.02 \pm 0.17$ GeV

- **K2K SciFi** (^{16}O, $Q^2>0.2$)
  Phys. Rev. **D74**, 052002 (2006)
  $M_A = 1.20 \pm 0.12$ GeV

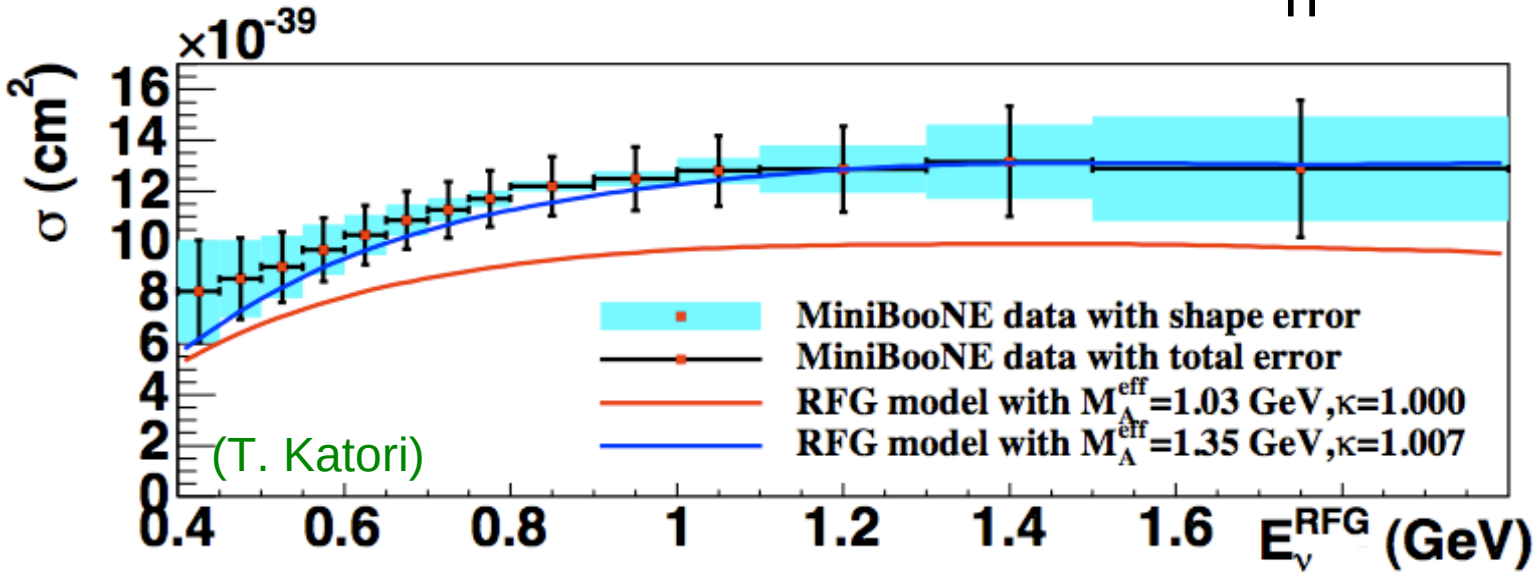
- **K2K SciBar** (^{12}C, $Q^2>0.2$)
  $M_A = 1.14 \pm 0.11$ GeV

Charged current Quasi-elastic scattering



MiniBooNE

Interaction cross-section measurement

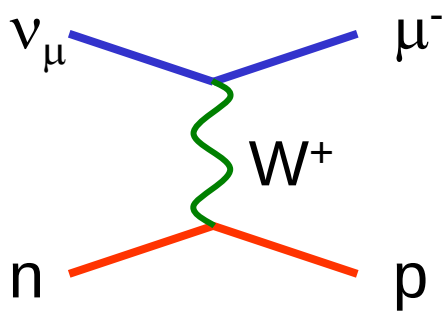


RFG model with **M_A=1.03 GeV (World Avg.)**

RFG model with **M_A=1.35 GeV**

- 35% higher than world average value (M_A=1.03 GeV)
- in better agreement with RFG w/ params coming from shape only fit (M_A=1.35 GeV)

Charged current Quasi-elastic scattering



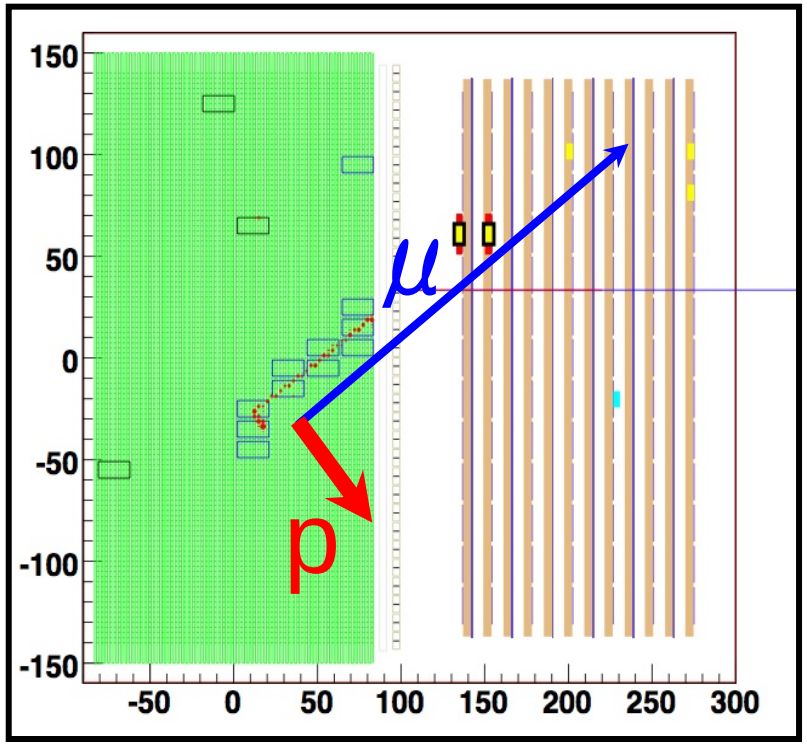
SciBooNE (Analysis is now on-going.)

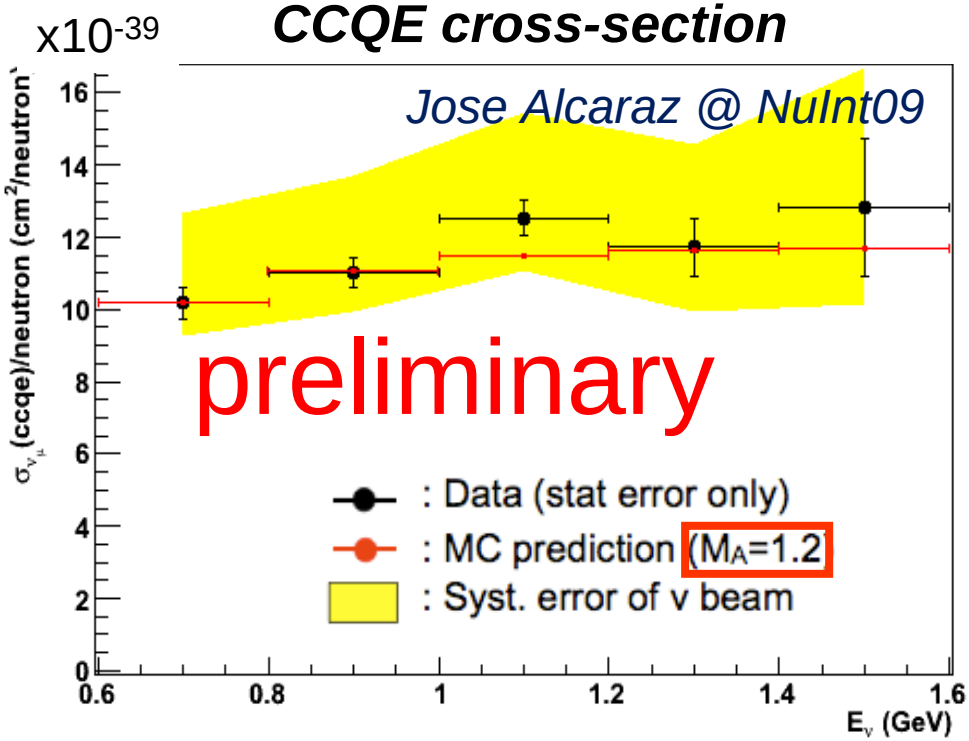
Measure momenta and directions of μ and p

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

(23% efficiency, 69% purity)

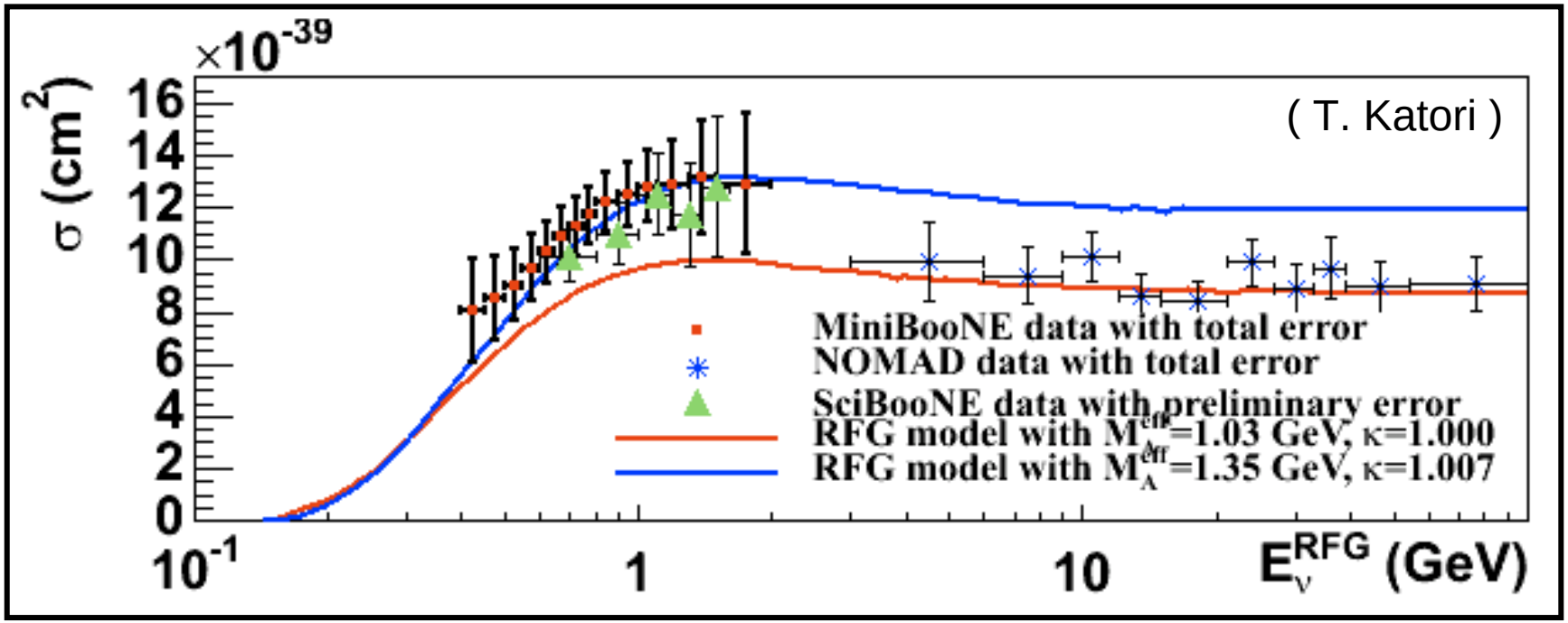
2,680 ν_μ 2-track QE event candidates





Charged current Quasi-elastic scattering

Current status of the cross-section measurements



Recently, NOMAD released their results as shown in this figure.

(V. Lyubushkin et al., arXiv:0812.4543 [hep-ex])

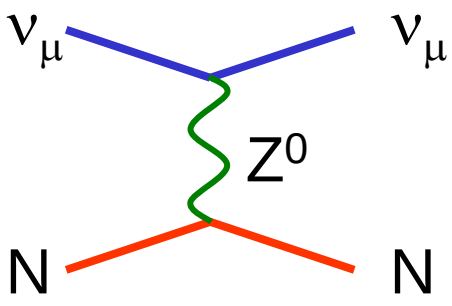
Their M_A value was consistent with the world average.

→ Still need further studies.

- a few GeV region : MINERνA, MINOS
- less than 1 GeV : T2K-near detectors ...

Neutral current elastic scattering

$\nu_\mu + N \rightarrow \nu_\mu + N$

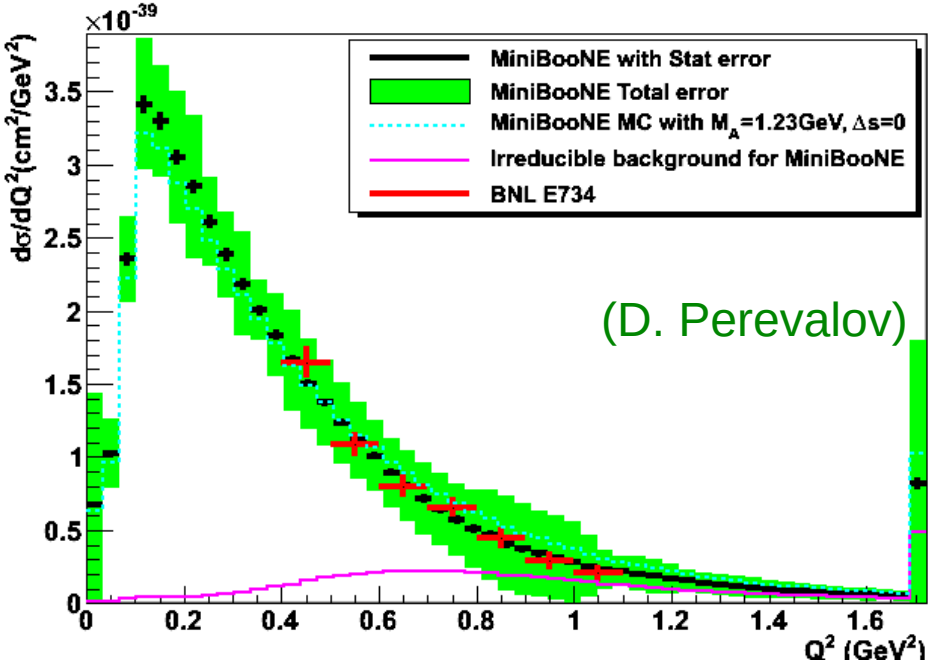


Use recoil proton to tag this kind of events.

MiniBooNE

of candidate events : 94,500
(purity 65%, efficiency 26%)

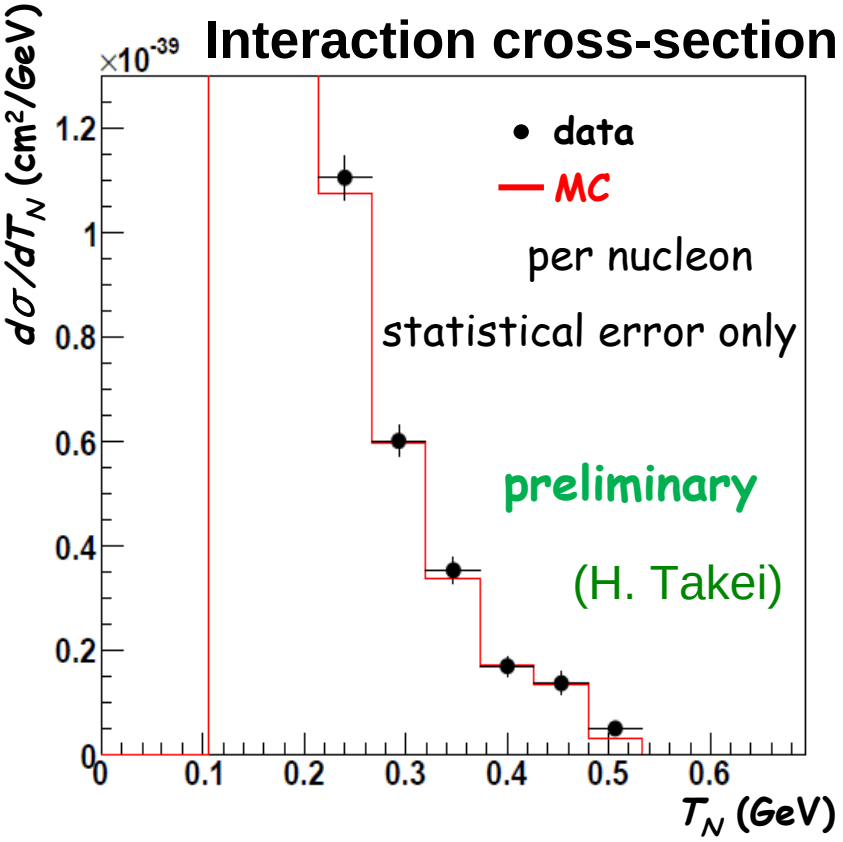
Differential cross-section($d\sigma/dq^2$)



SciBooNE

of candidate events : 8,441
(purity 57%)

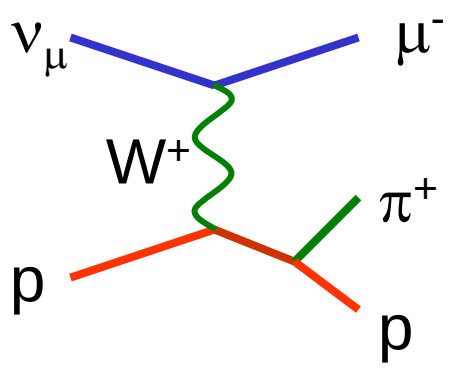
Interaction cross-section



Single pion production

Another dominant interactions in a few GeV range.

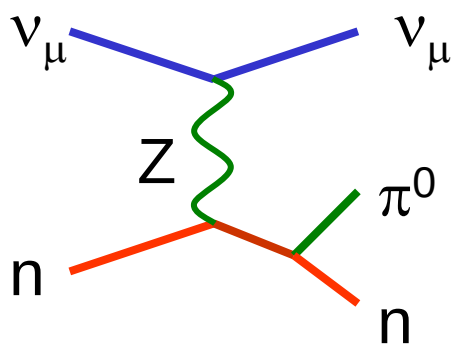
Charged current



Possible background in the energy determination using CC quasi-elastic scattering.

Similar event topologies are observed
if pion is absorbed in the target nucleus
or in the detector.
(When we use the Water / Oil Cherenkov detectors.)

Neutral current

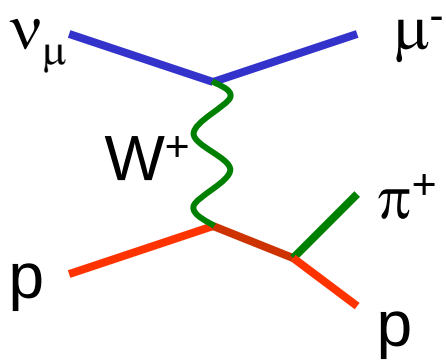


Possible background in the study of ν_e appearance. using ν_e CC quasi-elastic scattering.

Low momentum γ from the asymmetric decay of π^0
might be missed.

Two γs from high momentum π^0
might be identified as single γ
due to the small opening angle.

Charged current single π^+ production



MiniBooNE

Search for the events
with two decay electrons

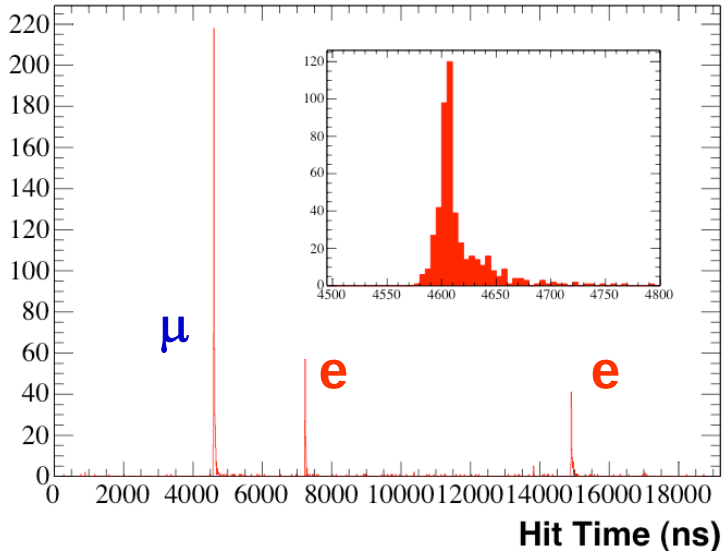
$\nu_\mu + N \rightarrow \mu^- + N' + \pi^+$

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

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

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

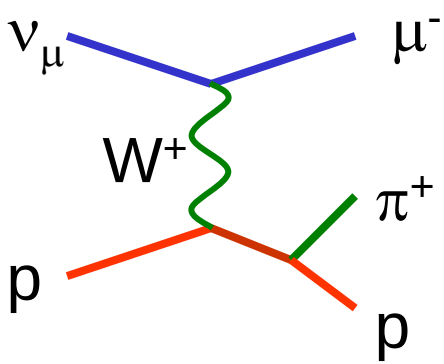
Hit timing distribution



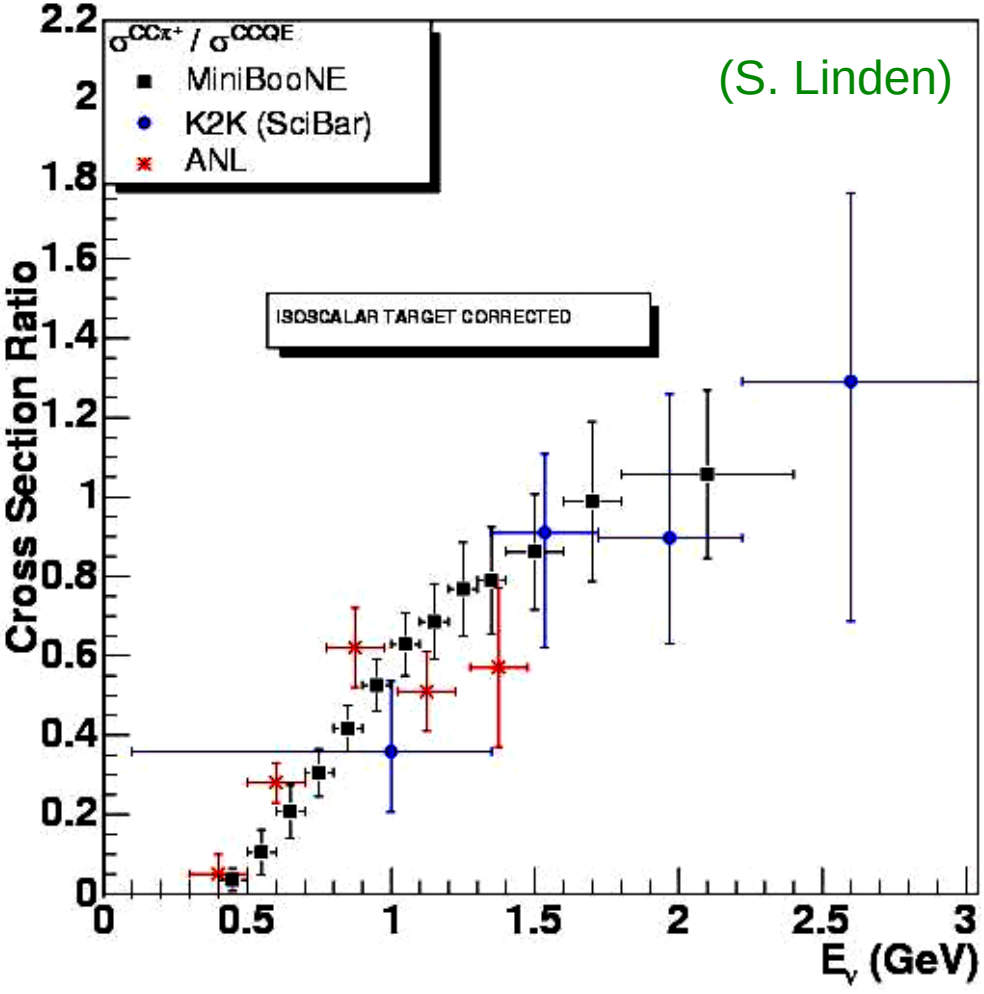
# of candidate events	46,172
Signal detection efficiency	26%
Estimated fraction of signal in the candidate events	~ 92%
CC resonant single π^+	86.0%
CC coherent single π^+	6.3%

Charged current single π^+ production

MiniBooNE



CC π^+/ CC QE cross-section ratio



(S. Linden)

Phys. Rev. Lett. 103, 081801 (2009)

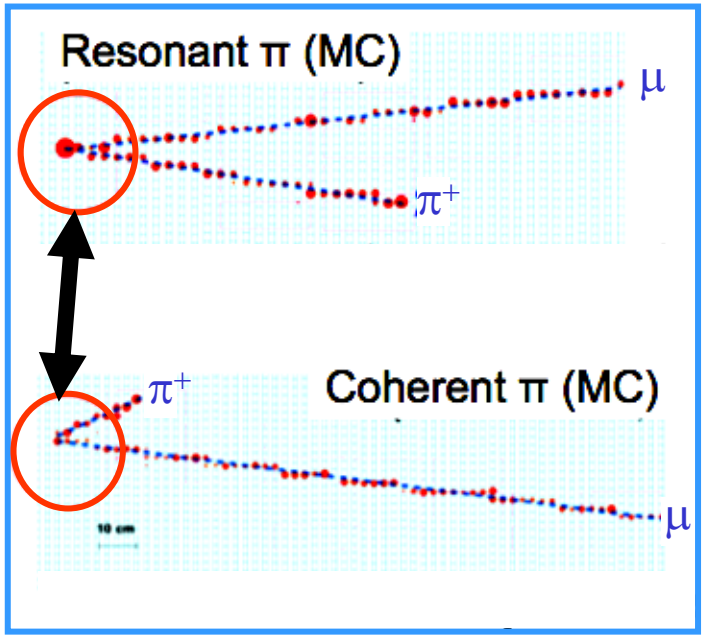
Charged current single π production

SciBooNE

Both μ and $\pi^{\pm}$ can be identified as tracks.

(Usually, proton track is too short to be identified.)

Actually, there are two types of single π productions.



- Resonant π production

  ν_μ + **N** -> μ^- + **N'** + $\pi^{\pm}$

  Large energy deposit at the vertex.

- Coherent π production

  ν_μ + ^{12}**C** -> μ^- + ^{12}**C** + π^+

  No significant vertex activity is expected.

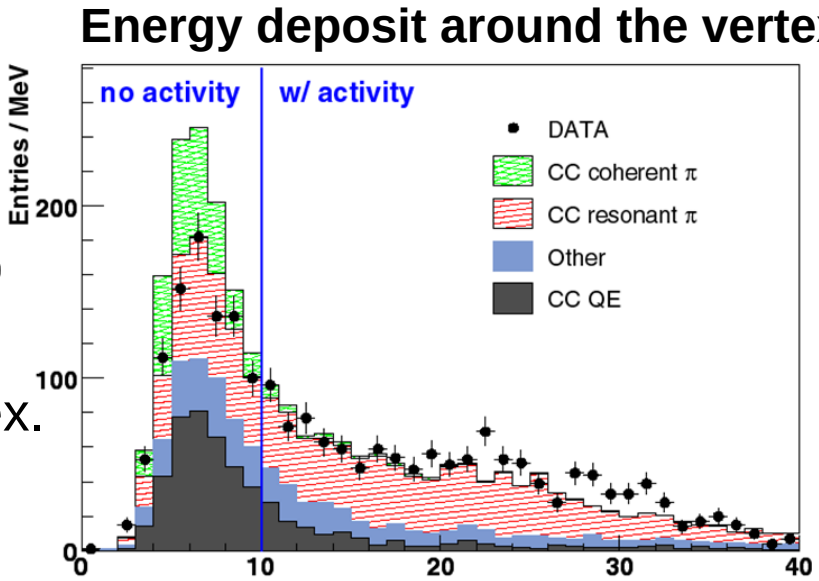
There should be no activity around the vertex
in case of the coherent π production.

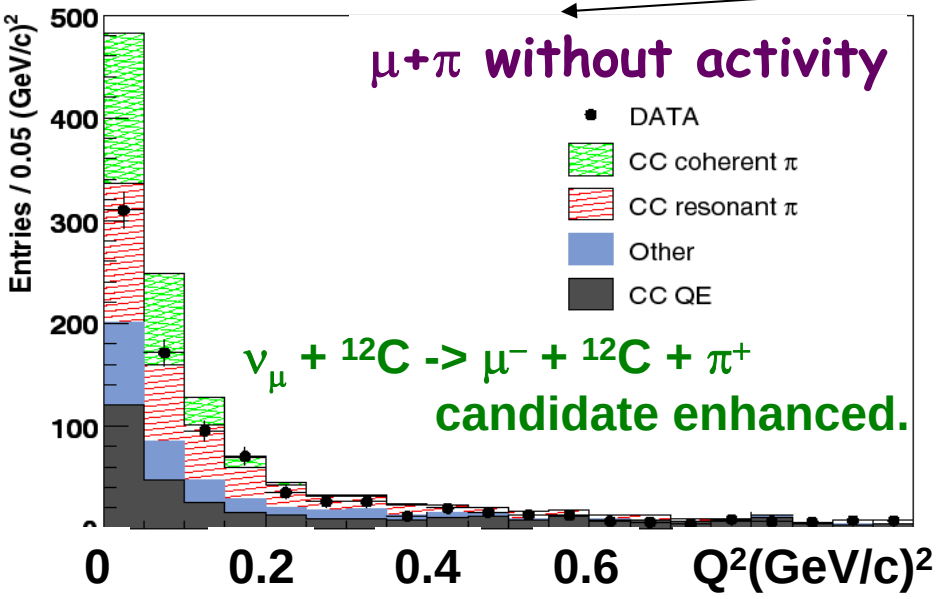
→ Possible to discriminate these two using the SciBar detector.

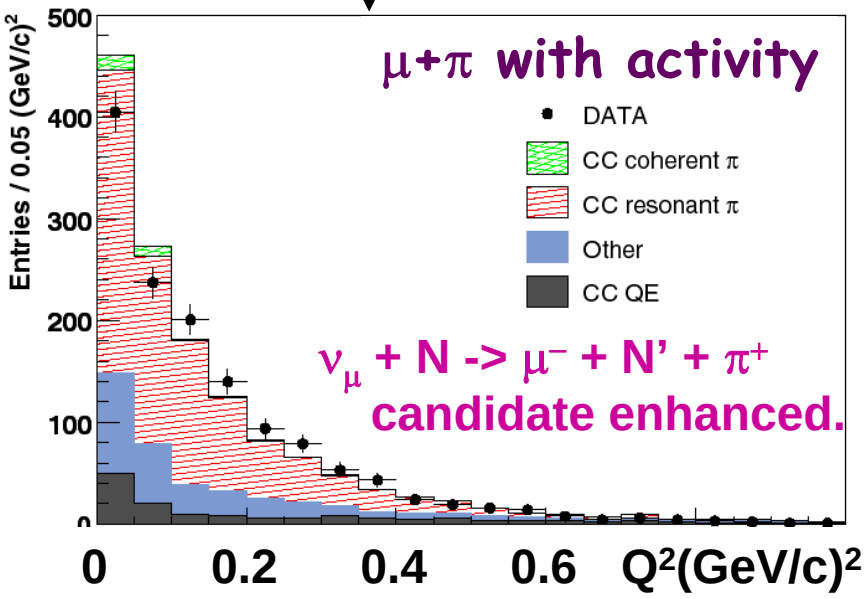
Charged current coherent π production

SciBooNE

- Select single π prod. candidates.
  2 tracks from μ + π
  (Both tracks are not proton like.)
- Split candidates into two categories by energy deposit around the vertex.







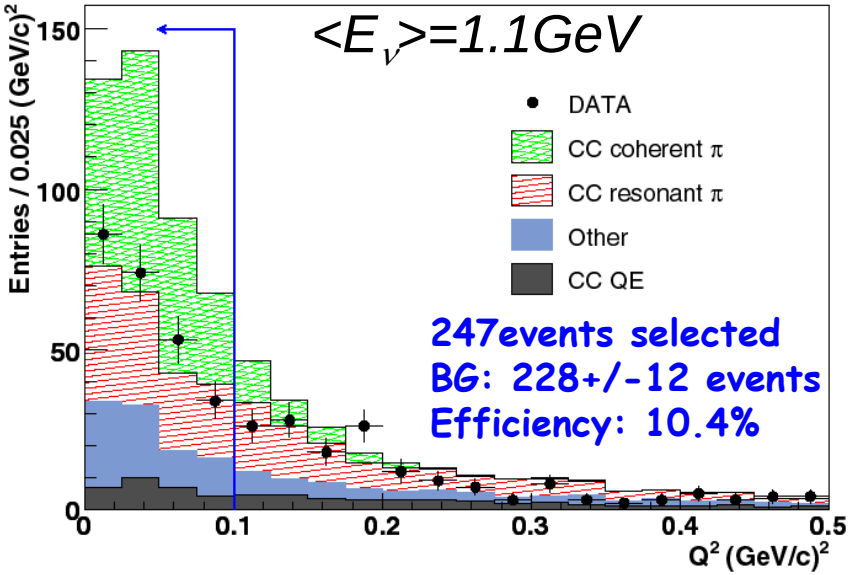
Charged current coherent π production

SciBooNE

Select small Q^2_{rec} events from the "small activity" samples to enhance the fraction of coherent p production.

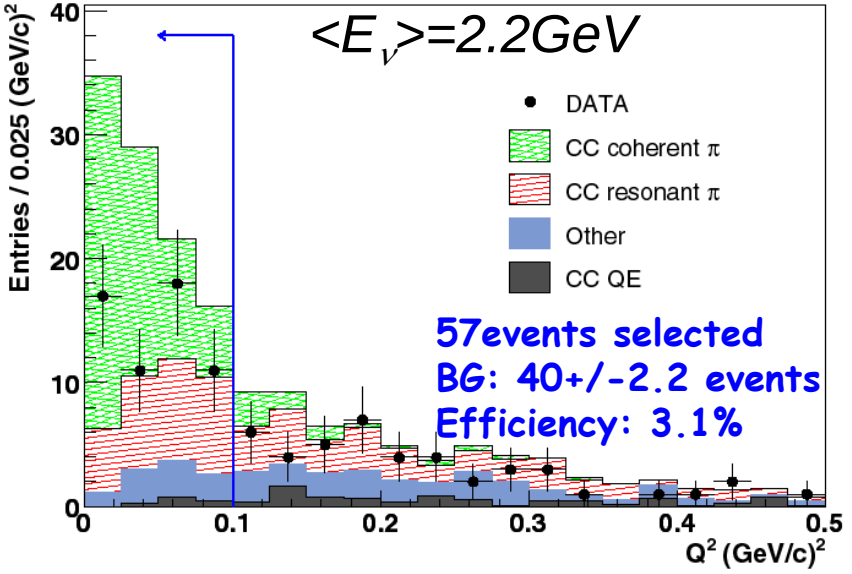
$Q^2_{rec} < 0.1$ (GeV/c)^2

MRD stopped sample



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

MRD penetrated sample



$$\sigma(\text{CC coherent } \pi) / \sigma(\text{CC})$$
$$= (0.68 \pm 0.32(stat)^{+0.39}_{-0.25}(sys)) \times 10^{-2}$$

Phys. Rev. D78 112004 (2008)

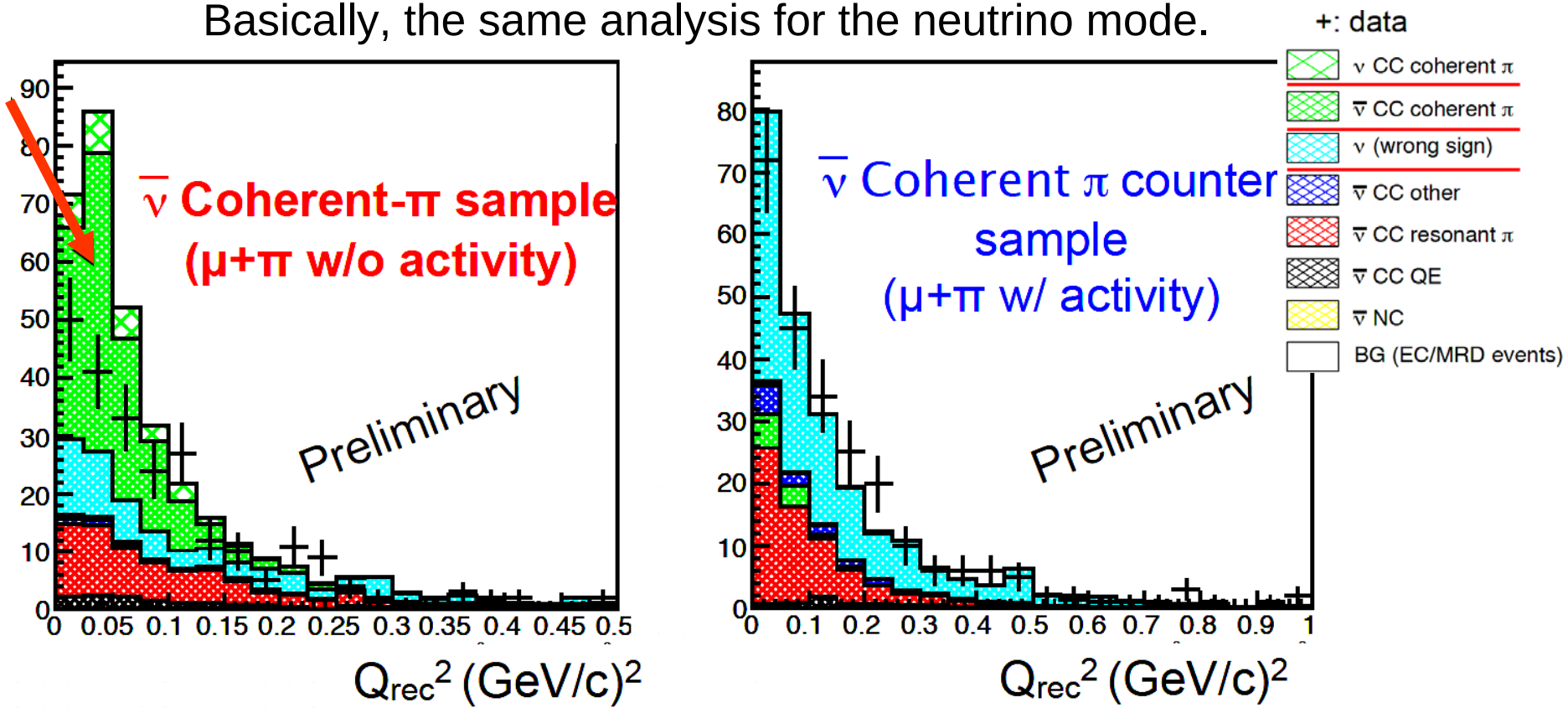
Charged current coherent π production

SciBooNE

Study of anti-neutrino charged current coherent π production

Cross-section is relatively large.

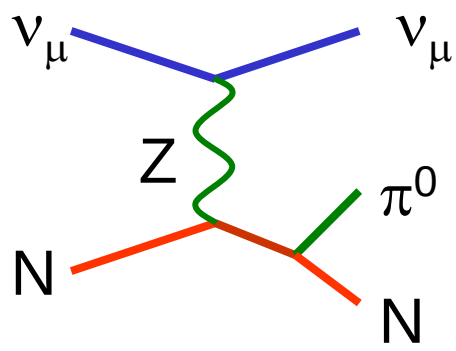
Basically, the same analysis for the neutrino mode.



Events in small Q^2_{rec} region : 139 events

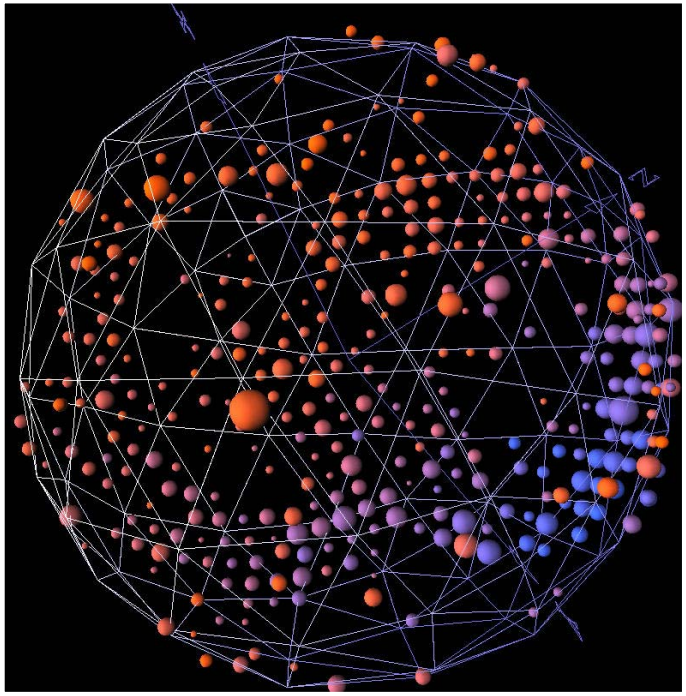
Expected non-coherent π events ~ 80

Neutral current single π^0 production



MiniBooNE

Measure energy and direction of two γs.



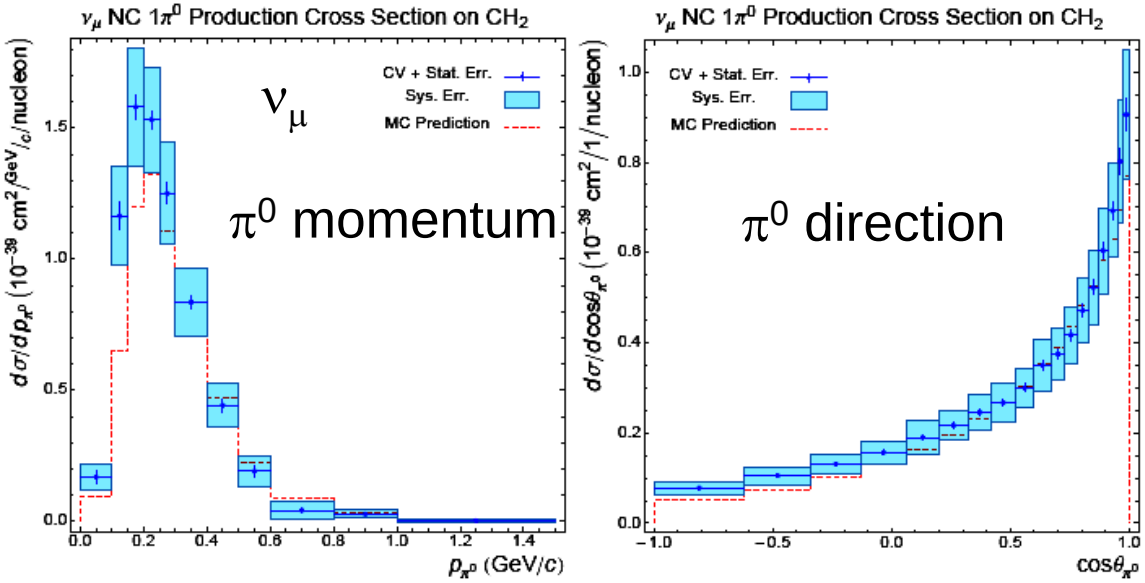
21,542 ν_μ NC π^0 events
(73% purity, 36% efficiency)

2,305 $\bar{\nu}_\mu$ NC π^0 events
(58% purity, 36% efficiency)

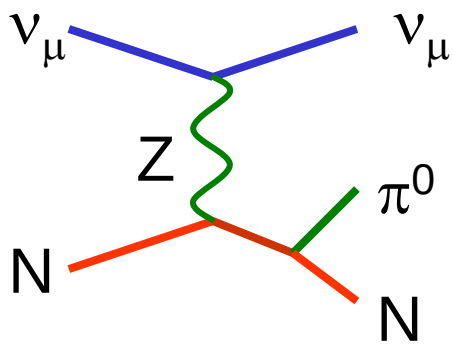
world's largest sample of NC π^0 events
(important constraint for ν_e)

Neutral current single π^0 production

MiniBooNE



(C. Anderson)



Obtained cross-sections

ν_μ induced π^0 production

4.54 ± 0.04 (stat.) ± 0.71 (sys)

$\times 10^{-40}$ cm^2

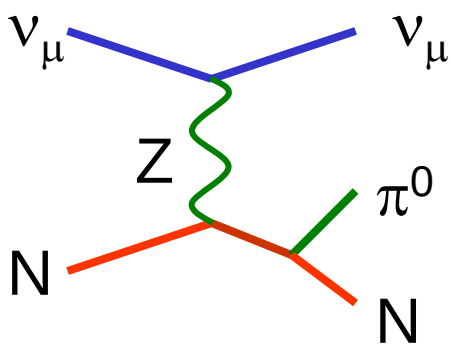
$\bar{\nu}_\mu$ induced π^0 production

1.43 ± 0.03 (stat.) ± 0.23 (sys)

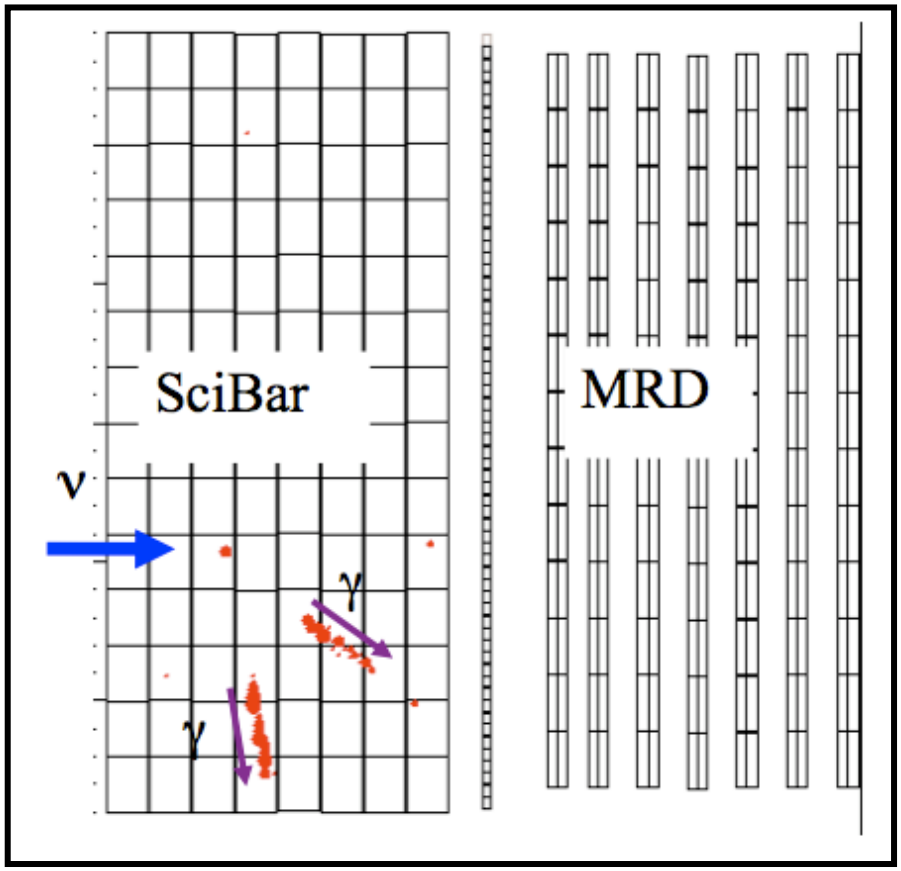
$\times 10^{-40}$ cm^2

Neutral current single π^0 production

SciBooNE



Measure energy and direction of two γs.



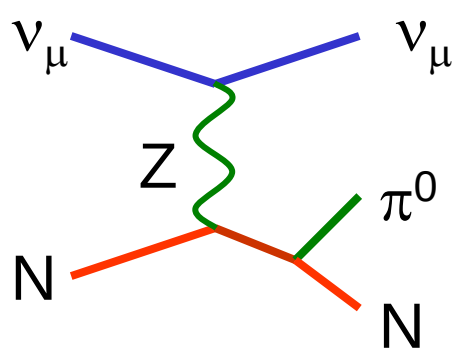
Search for the two isolated tracks

Require no decay electron observed.

Reject proton tracks using dE/dx.

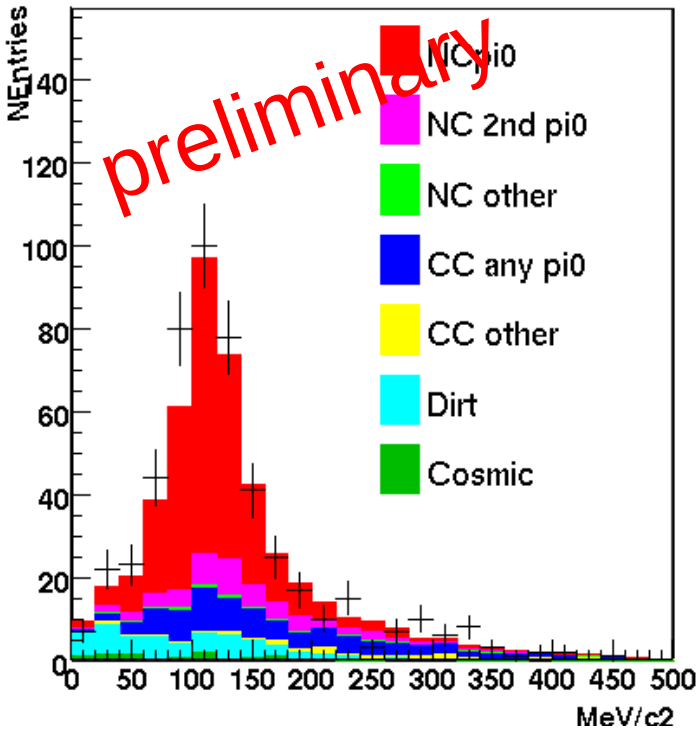
545 ν_μ NC π^0 candidates
(63% purity)

Neutral current single π^0 production

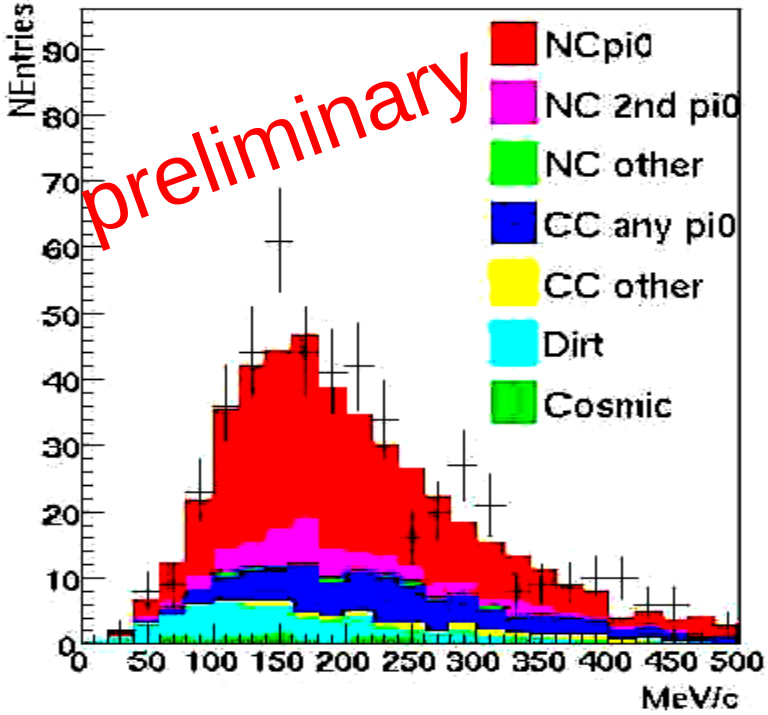


SciBooNE

Reconstructed mass of π^0



Reconstructed momentum of π^0



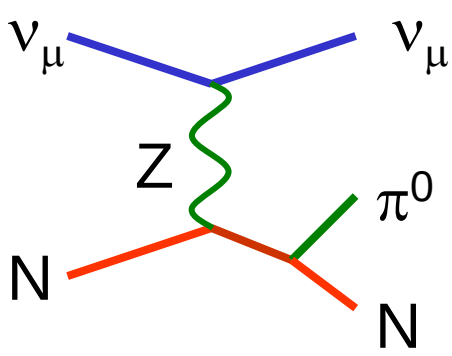
$$\frac{\sigma(\text{NC } \pi^0)}{\sigma(\text{CC inclusive})} = 7.7 \pm 0.6(\text{stat}) \pm 0.6(\text{prelim syst}) \times 10^{-2}$$

- agrees with NEUT prediction (6.8×10^{-2})

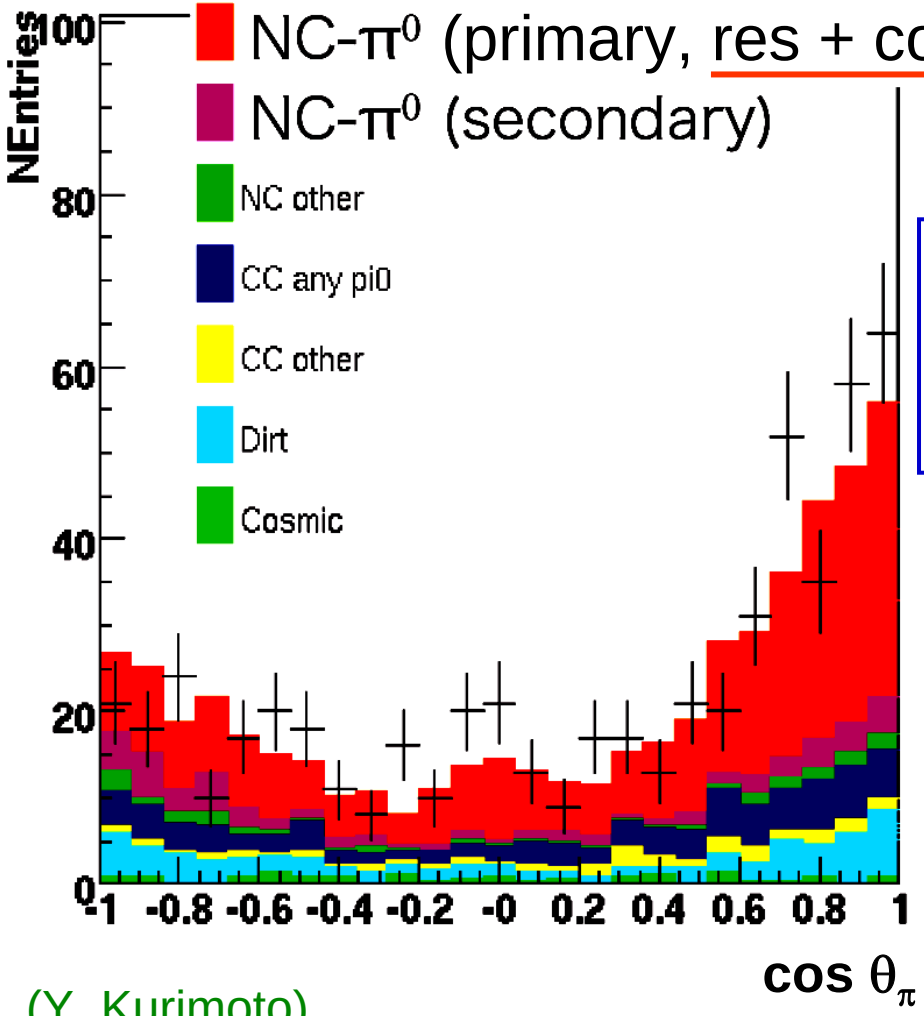
(Y. Kurimoto)

Neutral current single π^0 production

SciBooNE



Directional distribution of π^0



(Y. Kurimoto)

Together with the vertex activity, it will be possible to enhance NC coherent π^0 events.

$$\nu_\mu + {}^{12}C \rightarrow \nu_\mu + {}^{12}C + \pi^0$$

There will be no activity around the interaction vertex.

Summary I

Intense low energy neutrino beam is available
in the FNAL booster neutrino beam-line.

→ Various neutrino interactions have been studied
using the MiniBooNE and the SciBooNE detectors.

- Charged current quasi-elastic scattering

Interaction cross-section and $d\sigma/dq^2$ shows some difference
when we compare the results from the past experiments.

Also different from the result from NOMAD.

On the other hand, K2K, MiniBooNE, SciBooNE and MINOS
seems to be consistent (?).

Need further studies : same energy region (T2K Near detectors),
higher energy region (MINERνA)
Anti neutrino data (MiniBooNE, SciBooNE).

Summary II

- Neutral current elastic scattering

  MiniBooNE result seems to be consistent with BNL E734.

- Charged current and neutral current
  resonance single pion productions

  Fairly good agreement with the predictions
  (Rein & Sehgal's model)

  Some discrepancies especially in the momentum of π.

  Initial momentum of π?
  Nuclear effects?

  → Compare neutral and charged π.
  Study dependence of the interaction target nuclei etc..

- Charged current coherent π production

  Neutrino mode ~ SciBooNE result is consistent with the K2K
  but some indication of existence.

  Study of anti neutrino data seems to be interesting.