SciBooNE Results for NuInt09 Workshop

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Outline

- Introduction
- SciBooNE experiment
- Physics progress
  - New SciBooNE physics results
    - (all plots approved yesterday)
- Summary

What's SciBooNE?

- Neutrino experiment at Fermilab (E954)
- Precision measurement of ν and $\bar{\nu}$-nucleus cross section around 1GeV.
  - Important for accelerator based neutrino oscillation experiments.

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
- Kamioka Observatory
- Institute for Cosmic Ray Research (ICRR)
- Kyoto University
- Los Alamos National Laboratory
- Louisiana State University
- Massachusetts Institute of Technology
- Purdue University Calumet
- Universita degli Studi di Roma "La Sapienza"
- Saint Mary's University of Minnesota
- Tokyo Institute of Technology
- Unversidad de Valencia

5 countries 19 institutions

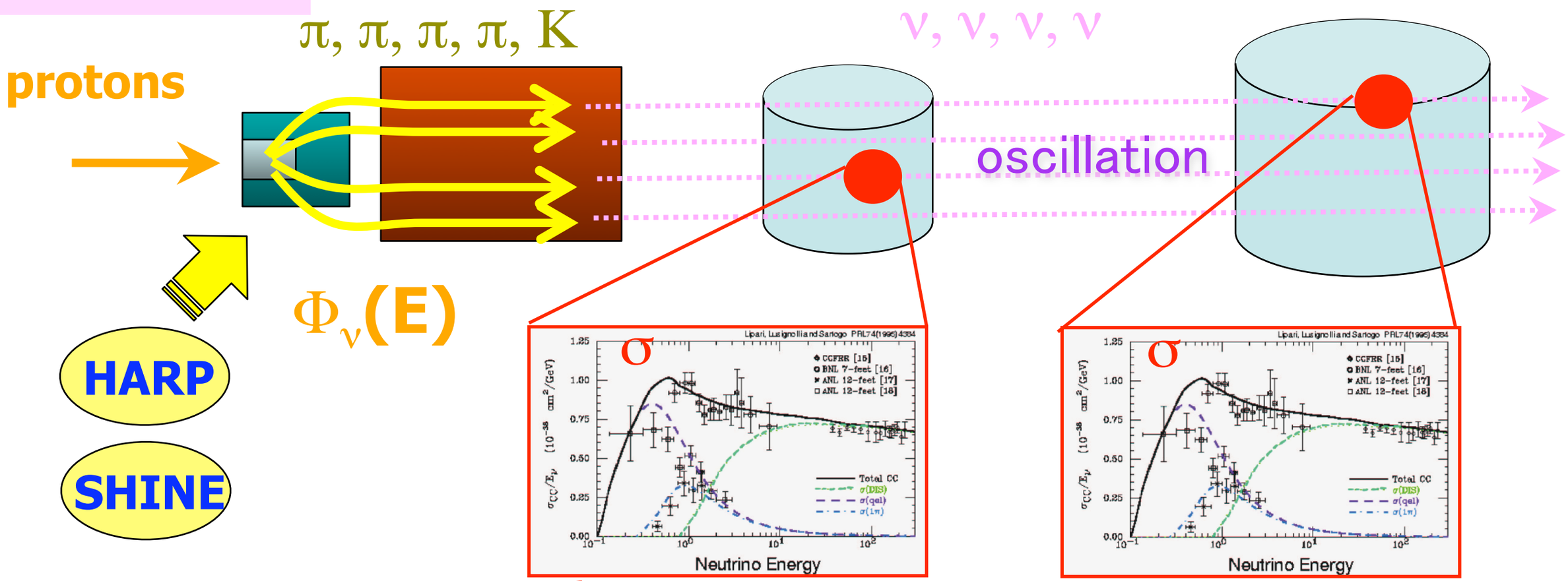
<u>Spokespeople</u>:
M.O. Wascko (Imperial), T. Nakaya (Kyoto)

Introduction

Introduction

Intense beam

Gigantic detector



HARP

SHINE

$\sigma_\nu(E)$

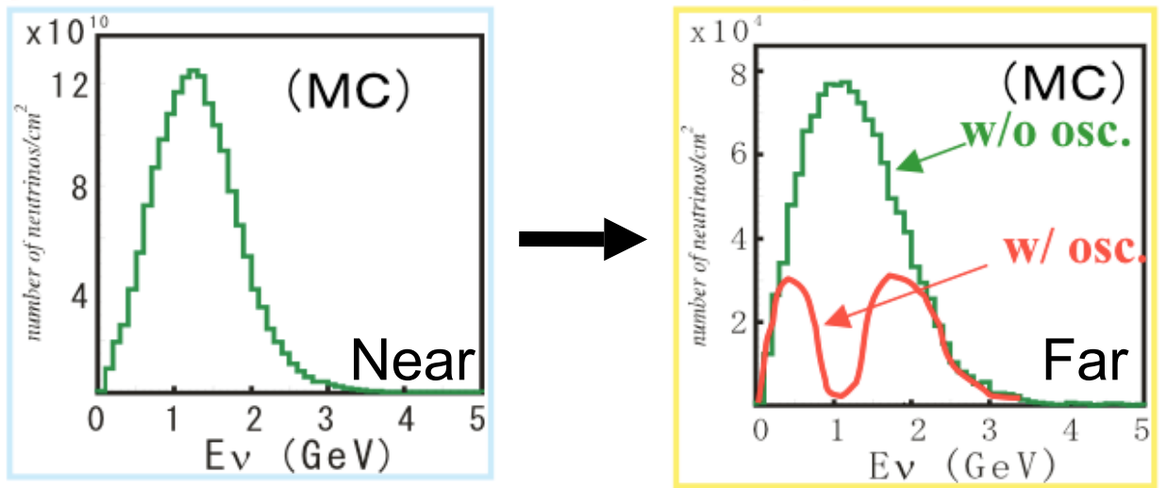
MiniBooNE

K2K

SciBooNE

MINERνA

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



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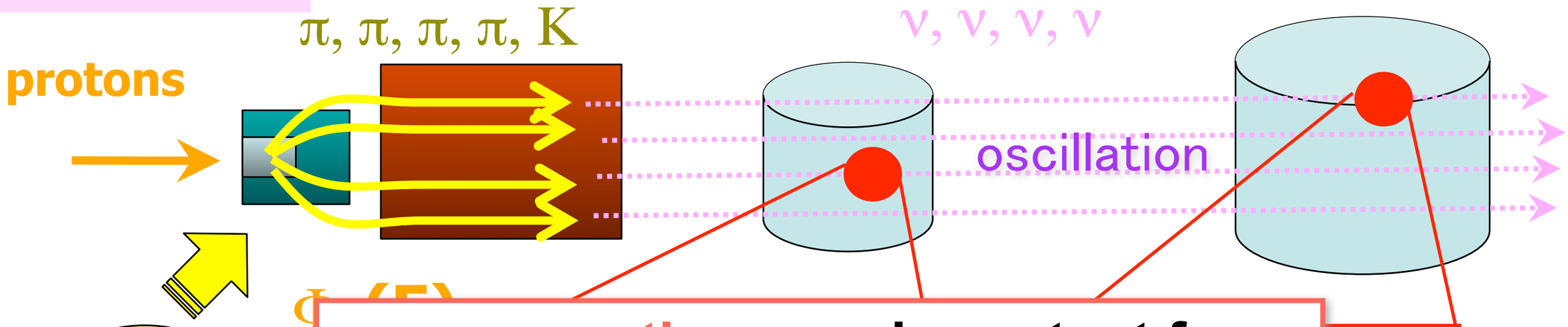
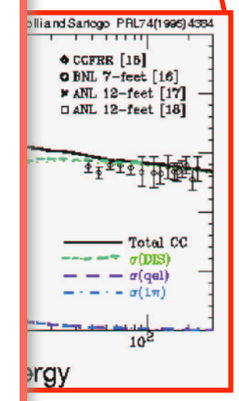


HARP

SHINE

ν cross sections are important for extracting oscillation parameters from ν_μ disappearance ν_e appearance measurements.



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

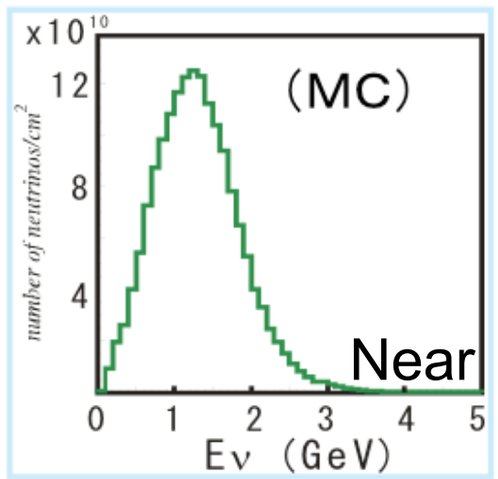
$\sigma_\nu(E)$

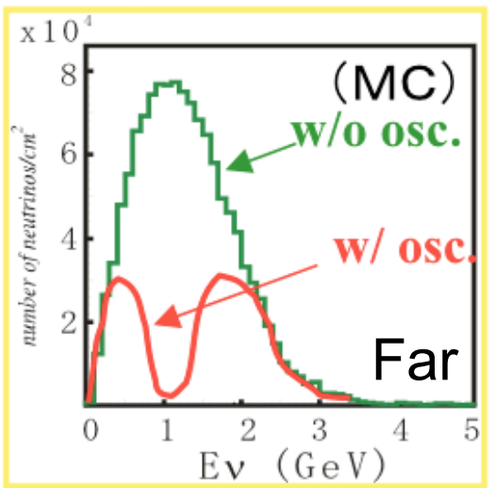
MiniBooNE

K2K

SciBooNE

MINERνA





Signal & background

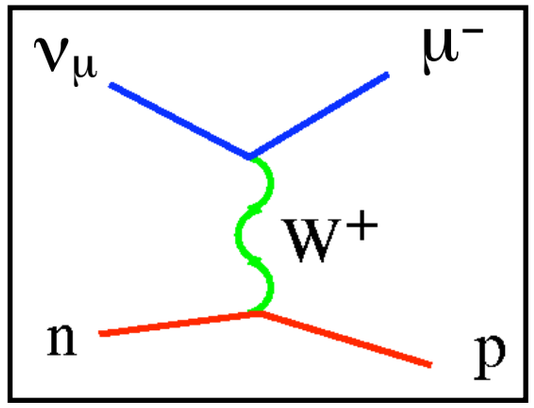
for oscillation measurement

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

Signal

CC-QE:
Charged Current
Quasi-Elastic

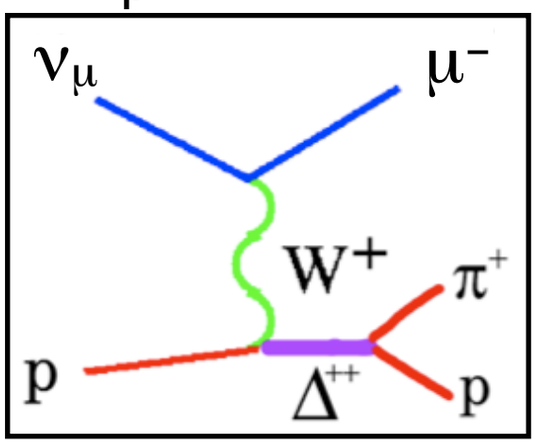
ν_μ CC-QE



Background

CC-1π:
Charged Current
Single-π^+ ($1\pi^+$) production

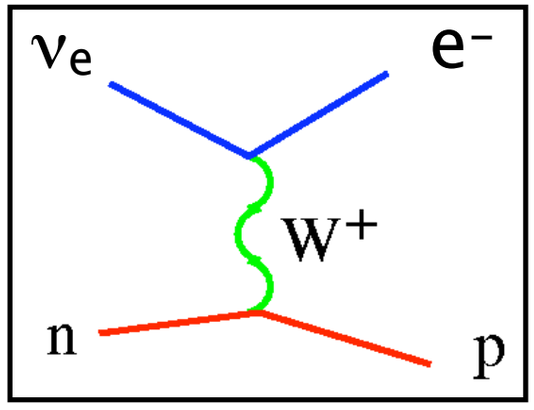
ν_μ CC-$1\pi^+$



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

Signal

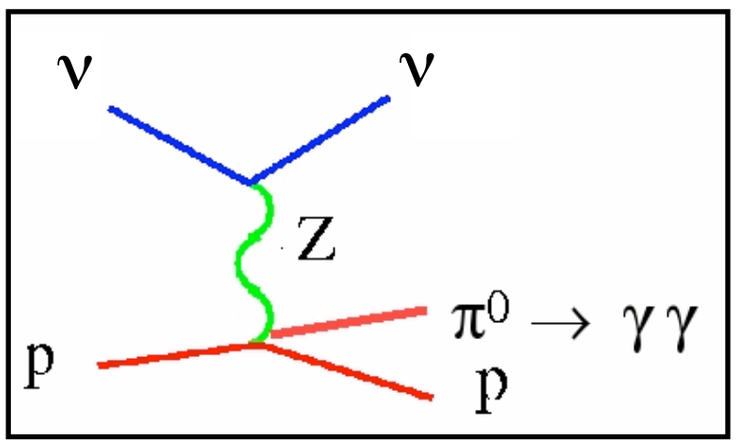
ν_e CC-QE



Background

NC-π0:
Neutral Current
Single-π^0 ($1\pi^0$) production

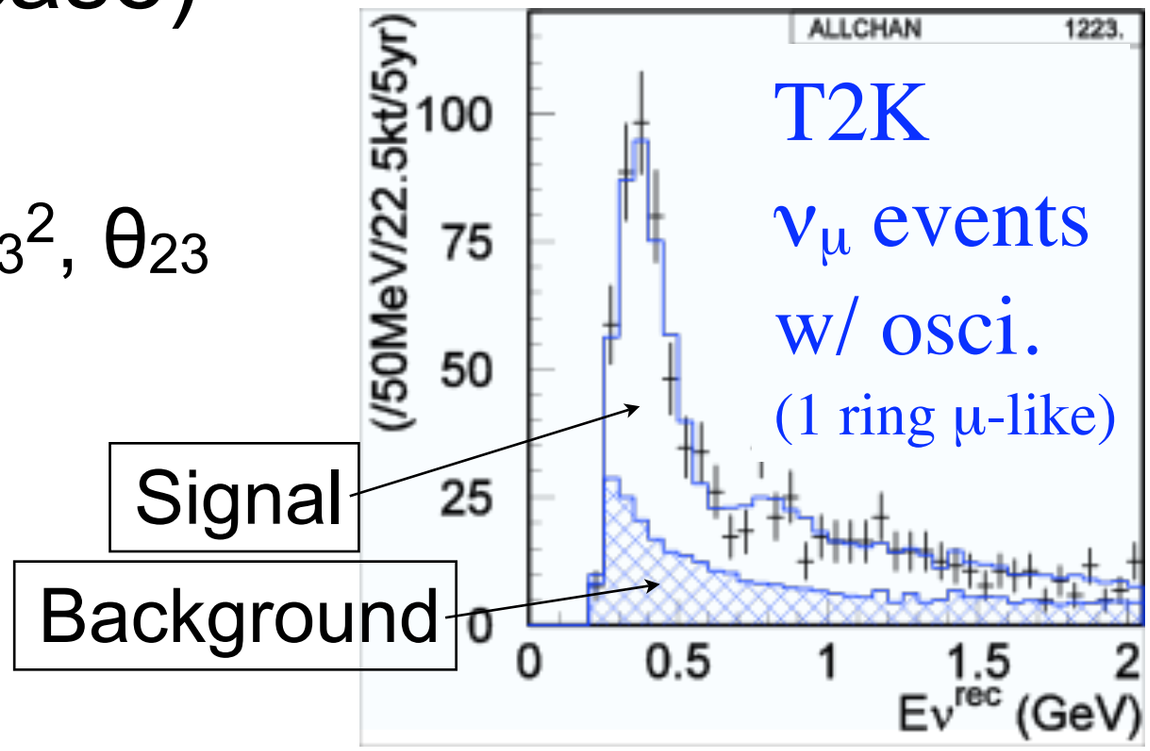
ν NC-$1\pi^0$



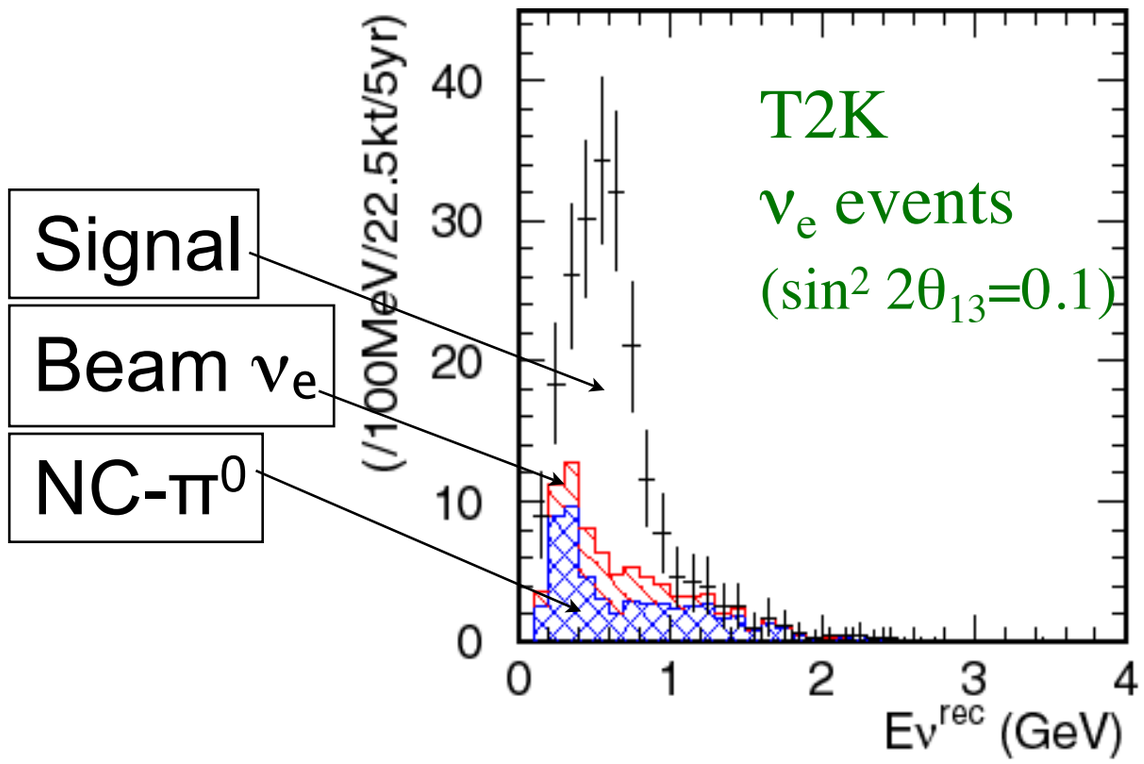
Need to understand background processes as well

Impact σ_ν on oscillation measurement (T2K case)

- ν_μ disappearance ($\nu_\mu \rightarrow \nu_X$)
  - Precision measurement of Δm_{23}^2, θ_{23}
  - Signal: ν_μ CC-QE
  - Background: mainly CC-1π^+



- ν_e appearance ($\nu_\mu \rightarrow \nu_e$)
  - Search for θ_{13}
  - Signal: ν_e CC-QE
  - Background:
    - Intrinsic beam ν_e
    - NC-π^0



- Search for CP violation:
  - $\bar{\nu}$ cross sections

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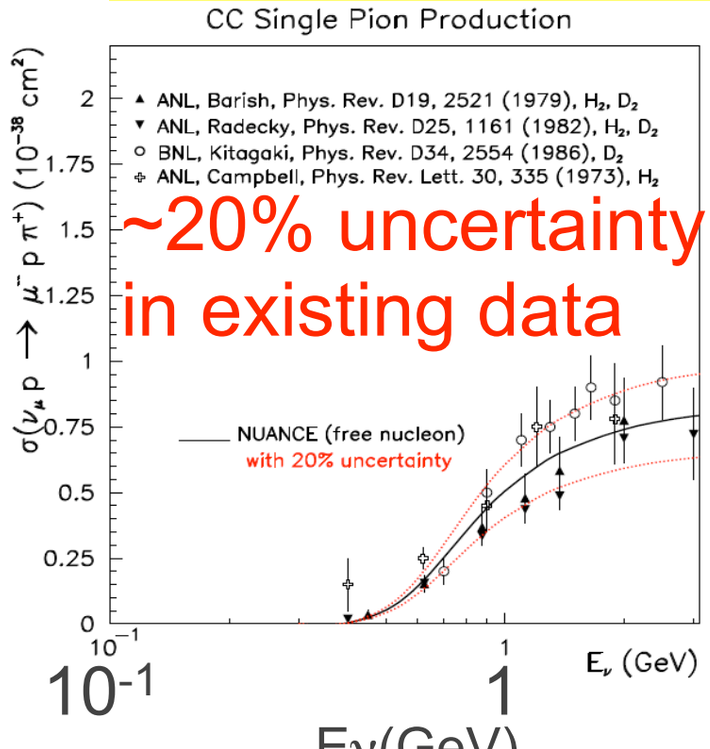
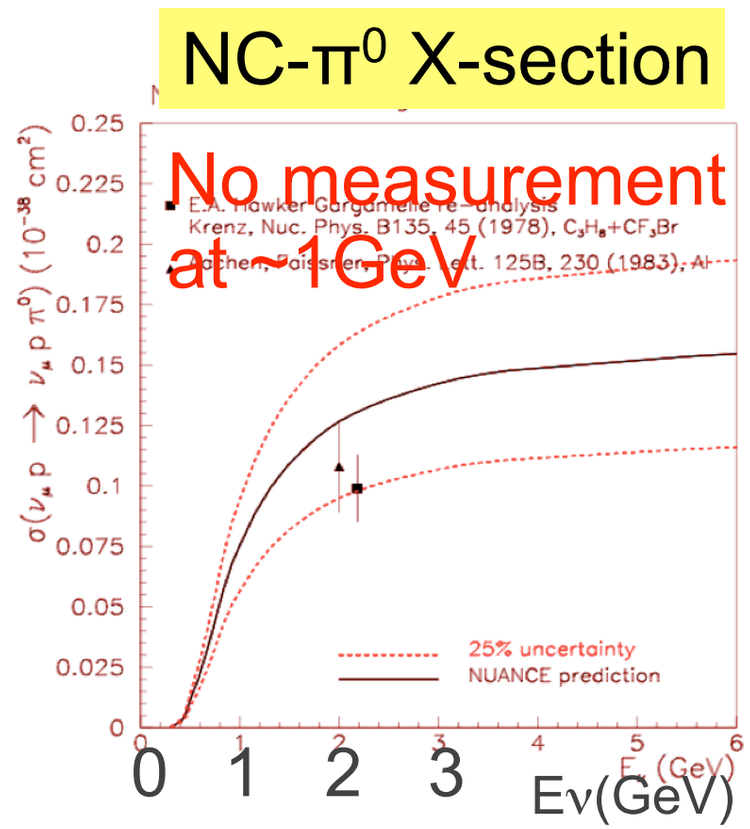
  - $\overline{\nu}$ cross sections

CC-1π^+ X-section



NC-π^0 X-section



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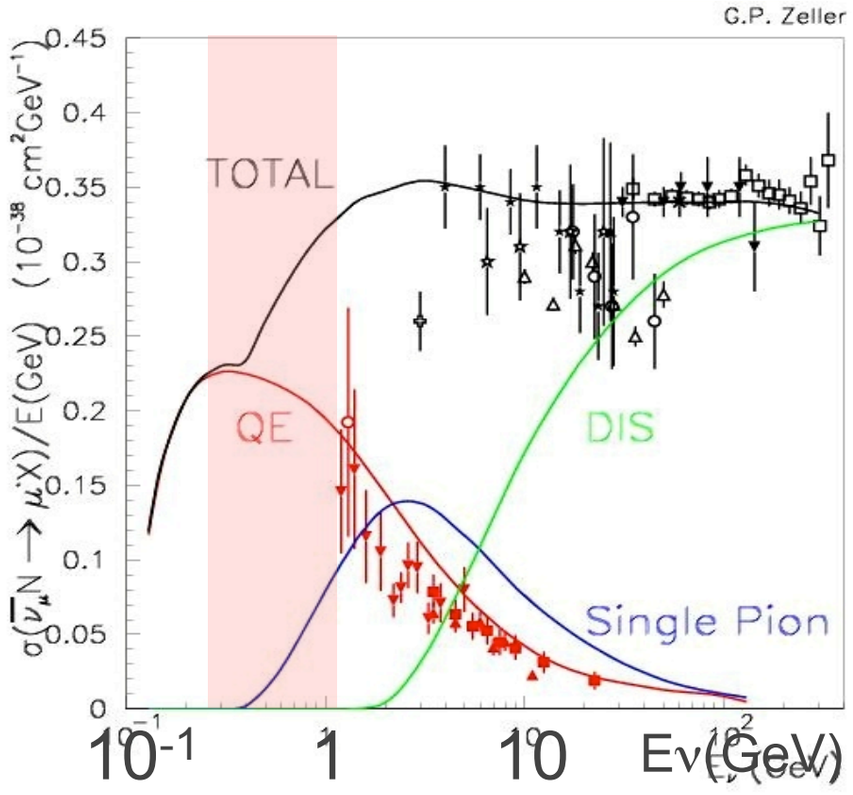
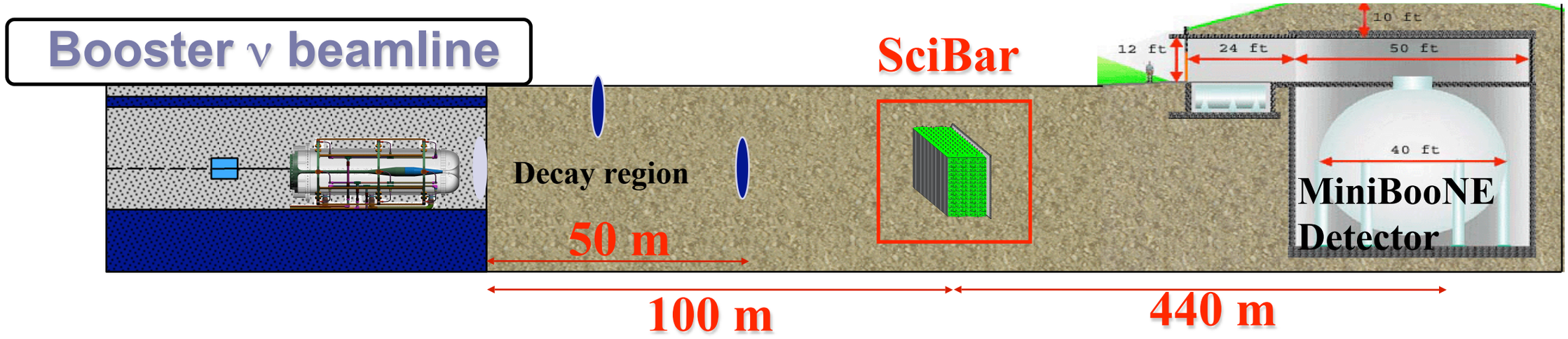
$\overline{\nu}$ CC X-section



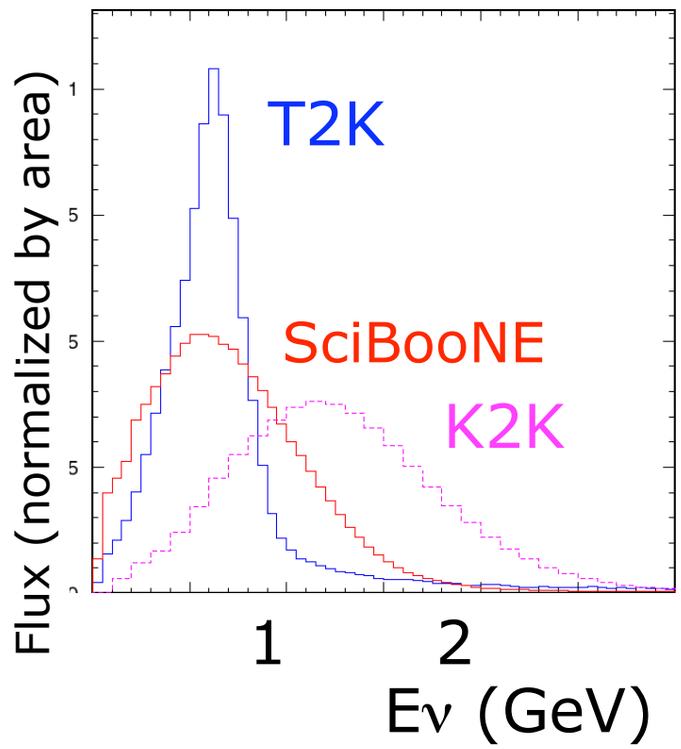
SciBooNE Experiment

SciBooNE Experiment

(K2K-SciBar detector at FNAL Booster Neutrino Beam line)

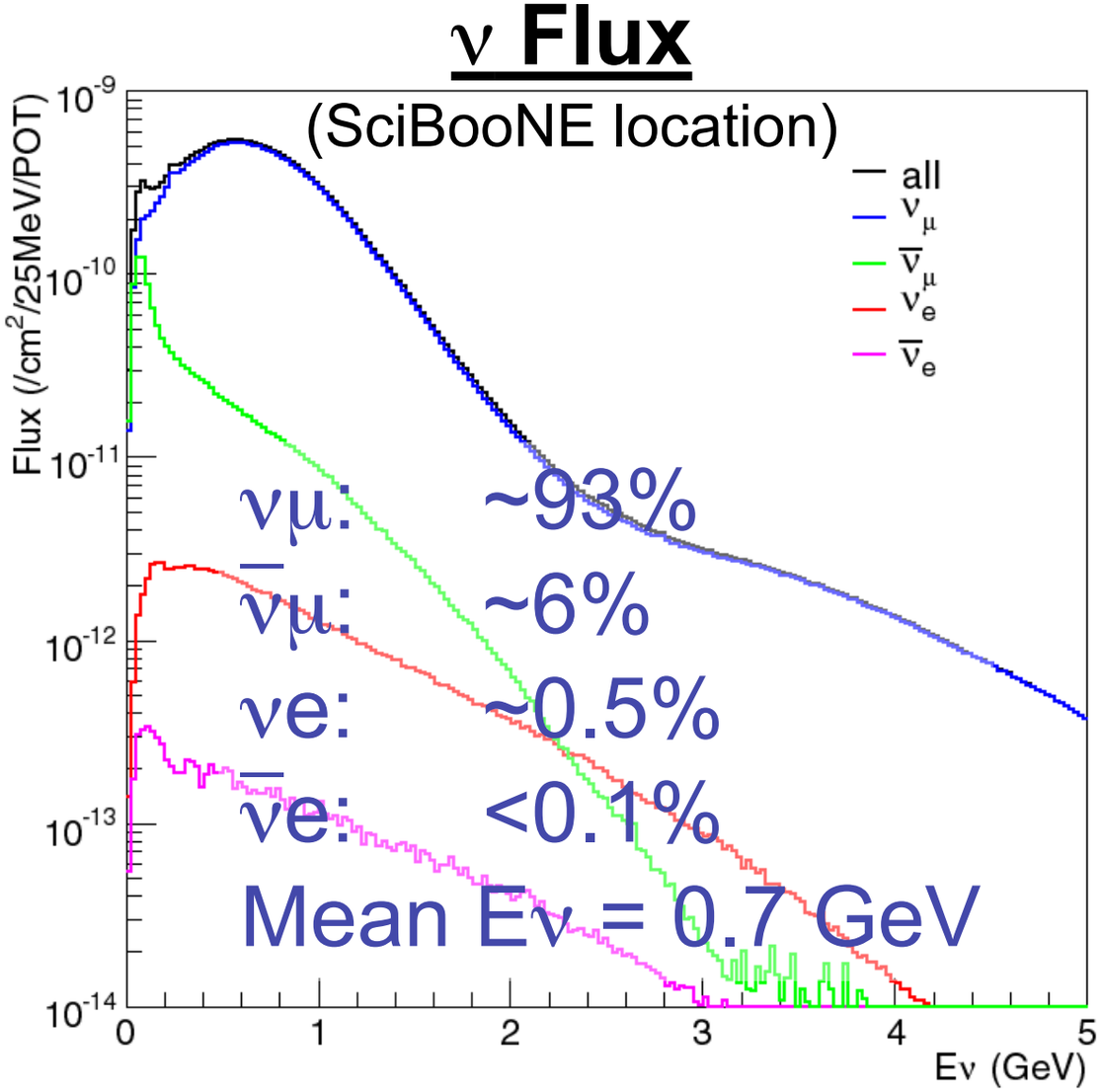


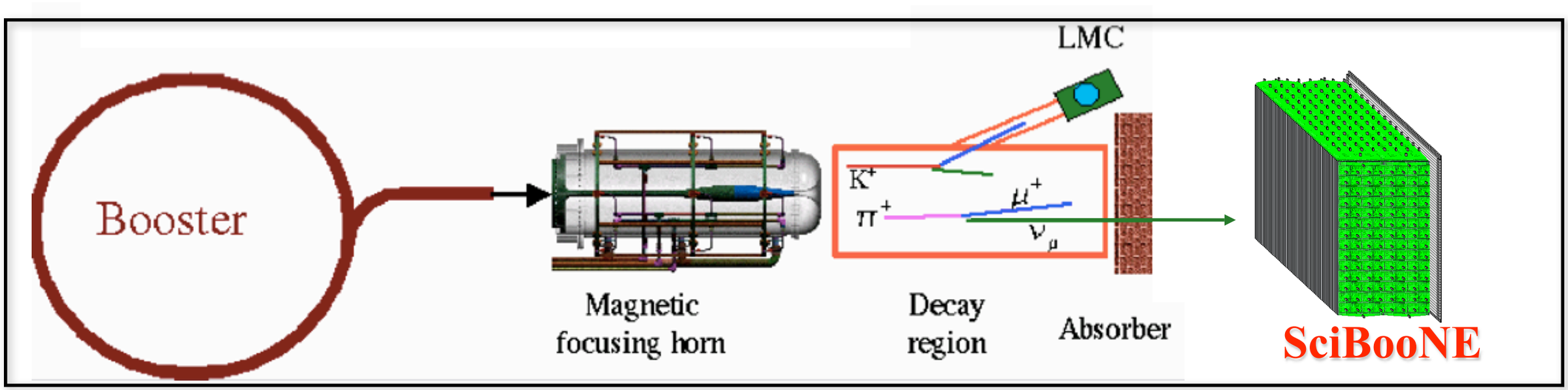
- Precision measurement of ν & ν-bar cross sections at ~1GeV ← Important for future oscillation experiments
- **SciBar:**
  - Originally K2K-near detector
  - Shipped to FNAL
- **BNB: Intense & low energy ν beam**
  - Eν good match to T2K
  - ν and $\bar{\nu}$ beam
- MiniBooNE near detector



Neutrino Beam

- 8 GeV protons from Booster
- Protons hit beryllium target (71 cm long, 1 cm diameter) within a magnetic focusing horn and produce mesons
- The mesons decay into neutrinos in 50m decay region
- Neutrinos are observed in SciBooNE (100m)
- **$\bar{\nu}$ beam by changing horn polarity**





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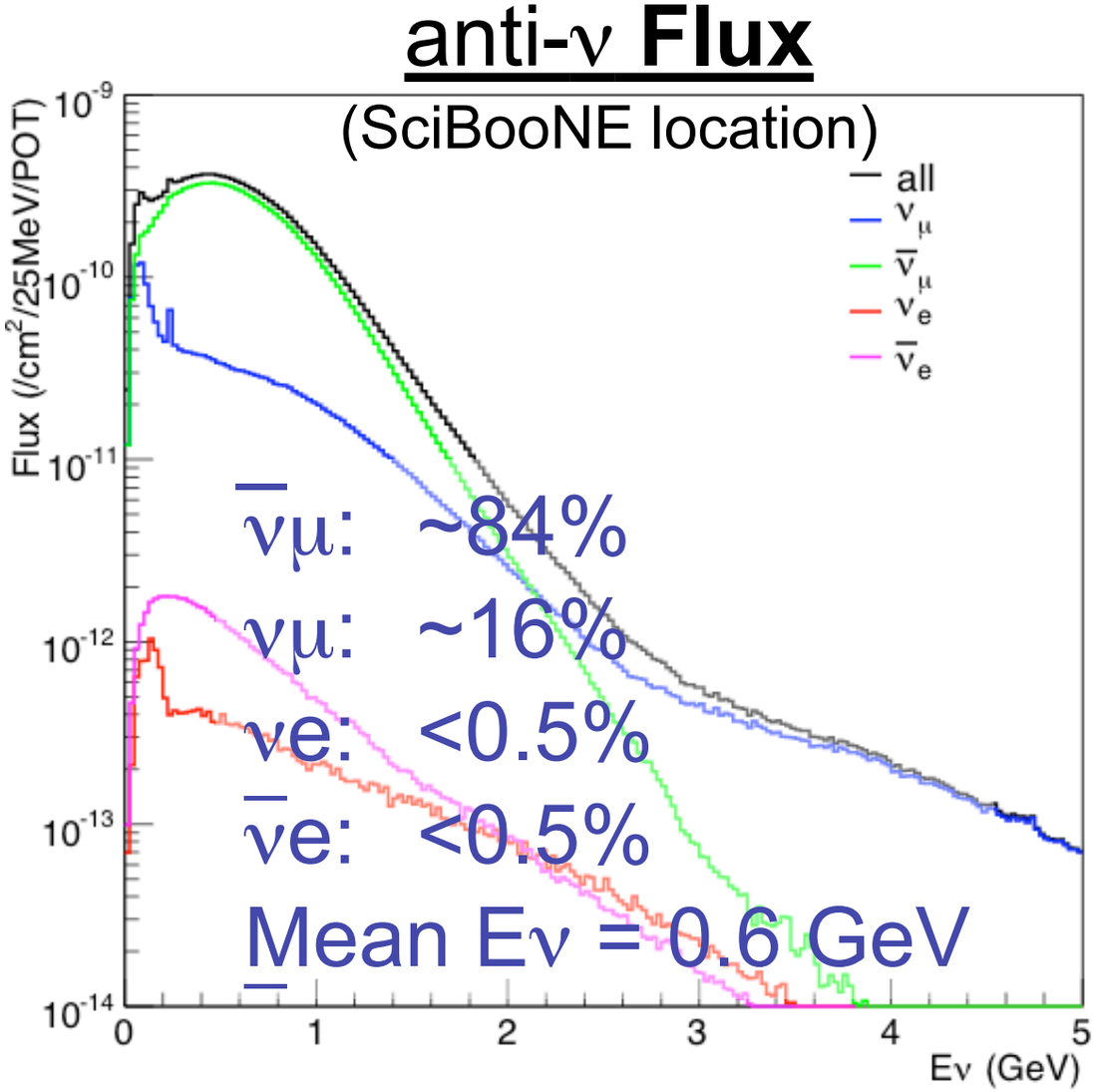
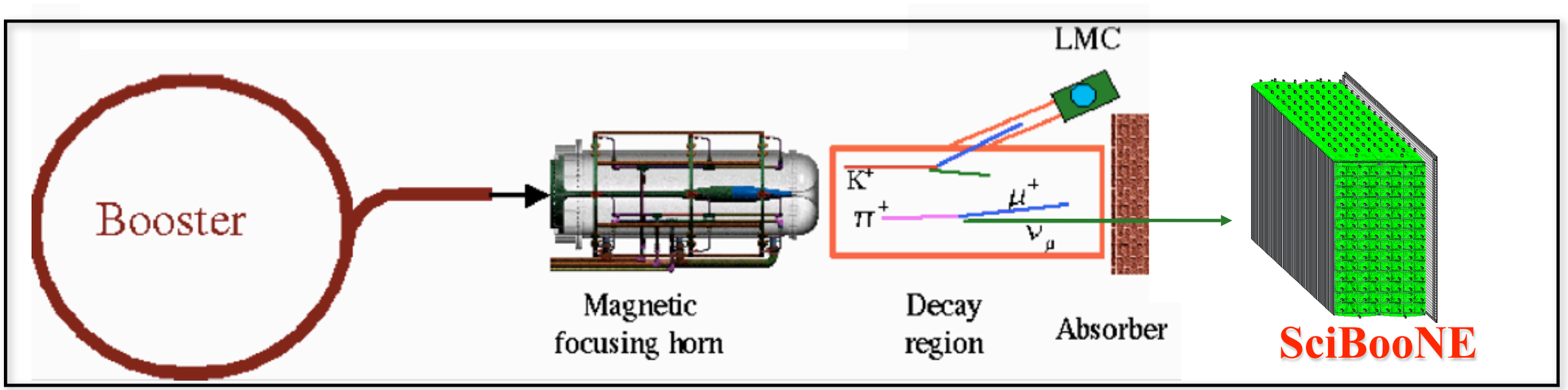
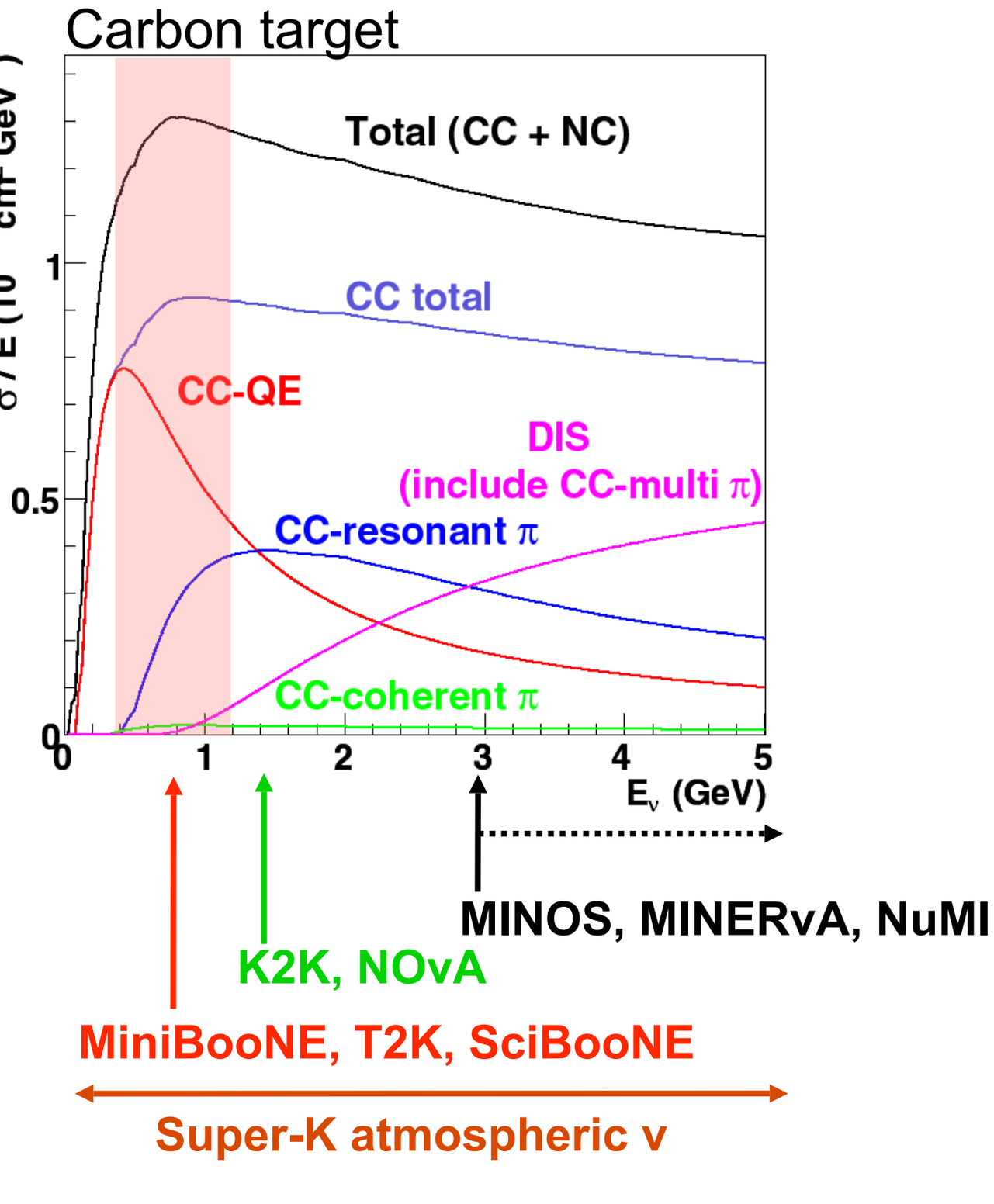




Neutrino cross section (NEUT prediction)



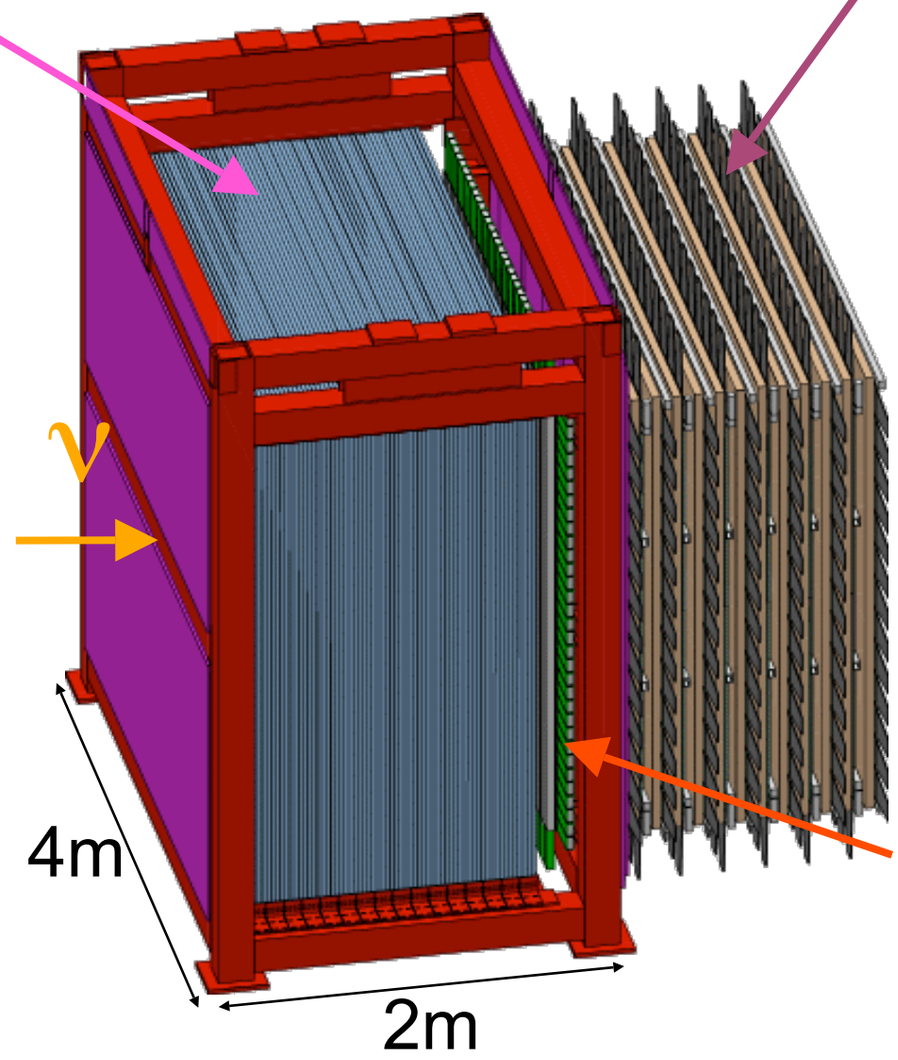
- QE
  - Llewellyn Smith, Smith-Moniz
  - M_A=1.2GeV/c^2
  - P_F=217MeV/c, E_B=27MeV (for Carbon)
- Resonant π
  - Rein-Sehgal (2007)
  - M_A=1.2 GeV/c^2
- Coherent π
  - Rein-Sehgal (2006)
  - M_A=1.0 GeV/c^2
- DIS
  - GRV98 PDF
  - Bodek-Yang correction
- Intra-nucleus interactions

SciBooNE detector

SciBar

- Scintillator tracking detector
- 14,336 scintillator bars (15 tons)
- Neutrino target (CH)
- 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)

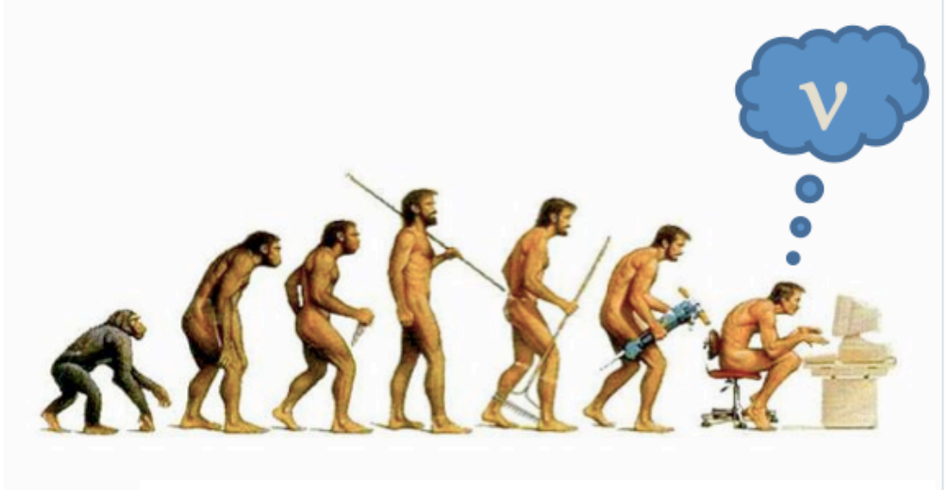
- spaghetti calorimeter
- 2 planes (11 X_0)
- identify π^0 and ν_e

Used in CHORUS, HARP and K2K

DOE-wide Pollution Prevention Star (P2 Star) Award

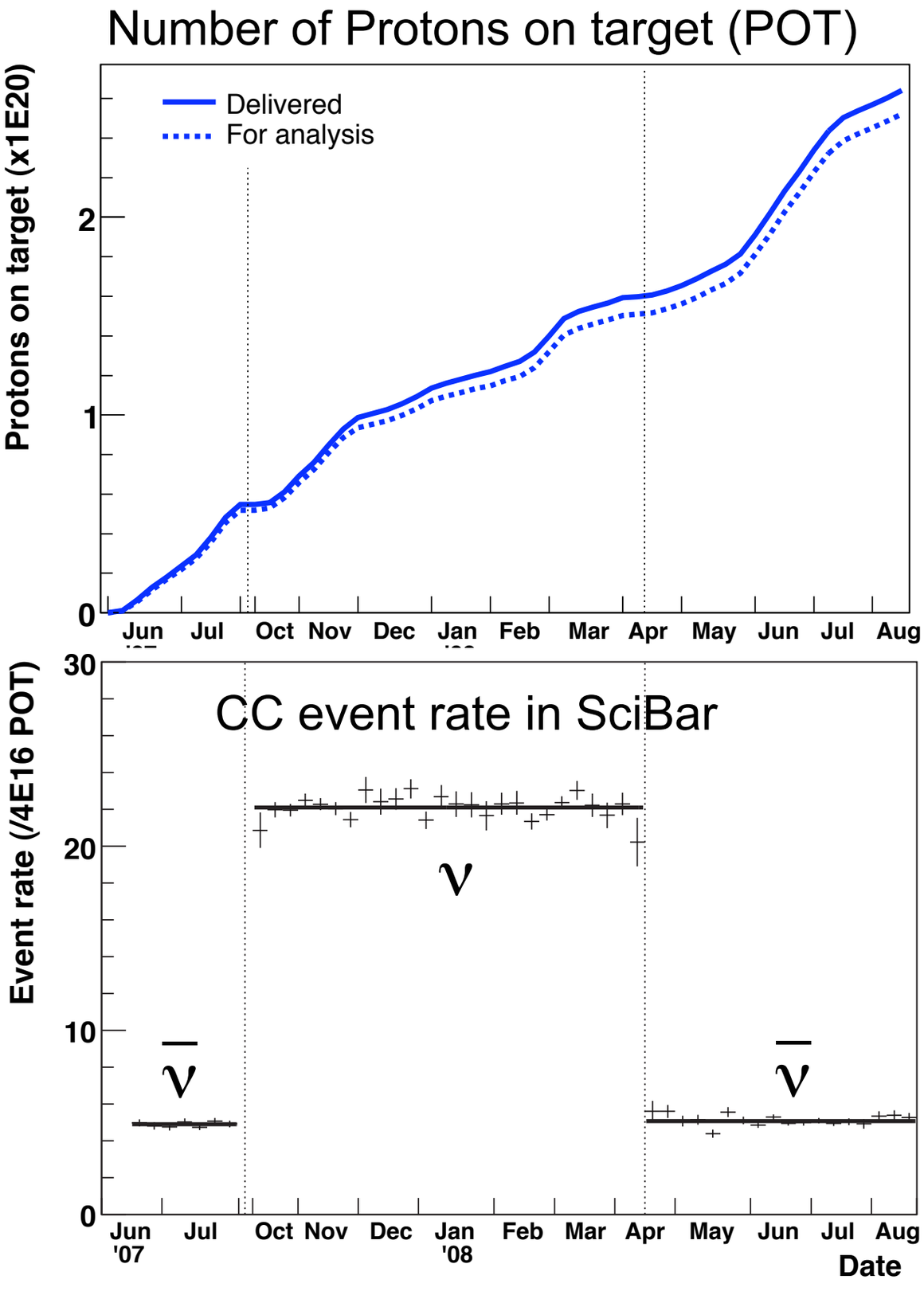
SciBooNE Timeline

- **2005, Summer - Collaboration formed**
- 2005, Dec - Proposal
- 2006, Jul - Detectors move to FNAL
- 2006, Sep - Groundbreaking
- 2006, Nov - EC Assembly
- 2007, Feb - SciBar Assembly
- 2007, Mar - MRD Assembly
- 2007, Mar - Cosmic Ray Data
- 2007, Apr - Detector Installation
- 2007, May - Commissioning
- 2007, Jun - Start data taking ($\bar{\nu}$ mode)
- 2007, Oct - Neutrino Data Run
- 2008, Apr - Antineutrino Data Run
- 2008, Aug - Complete data taking
- **2008, Nov - First physics results**
- **2009, May - Second results**



Three years
from
formation to
the first results!

Data set

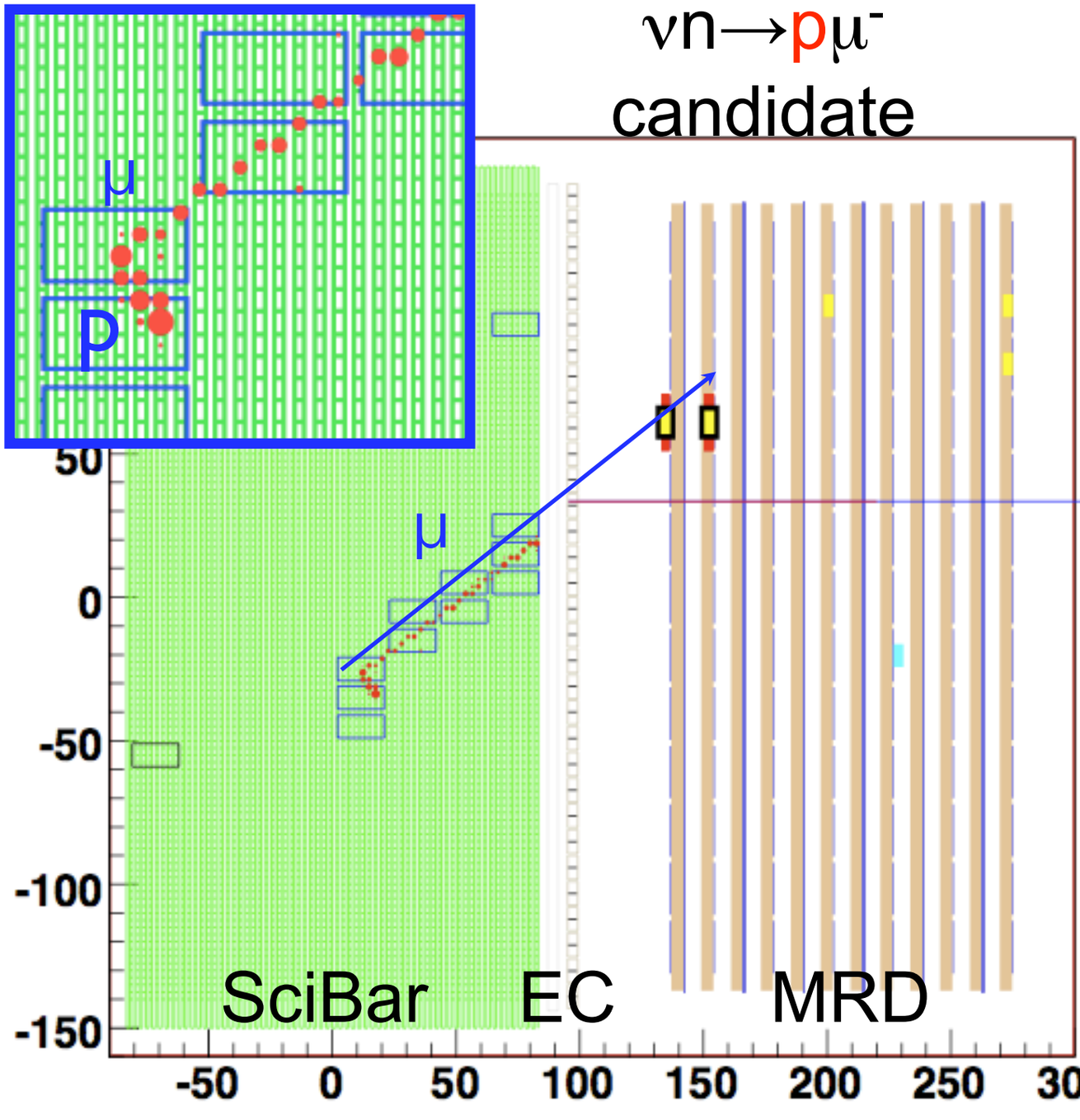


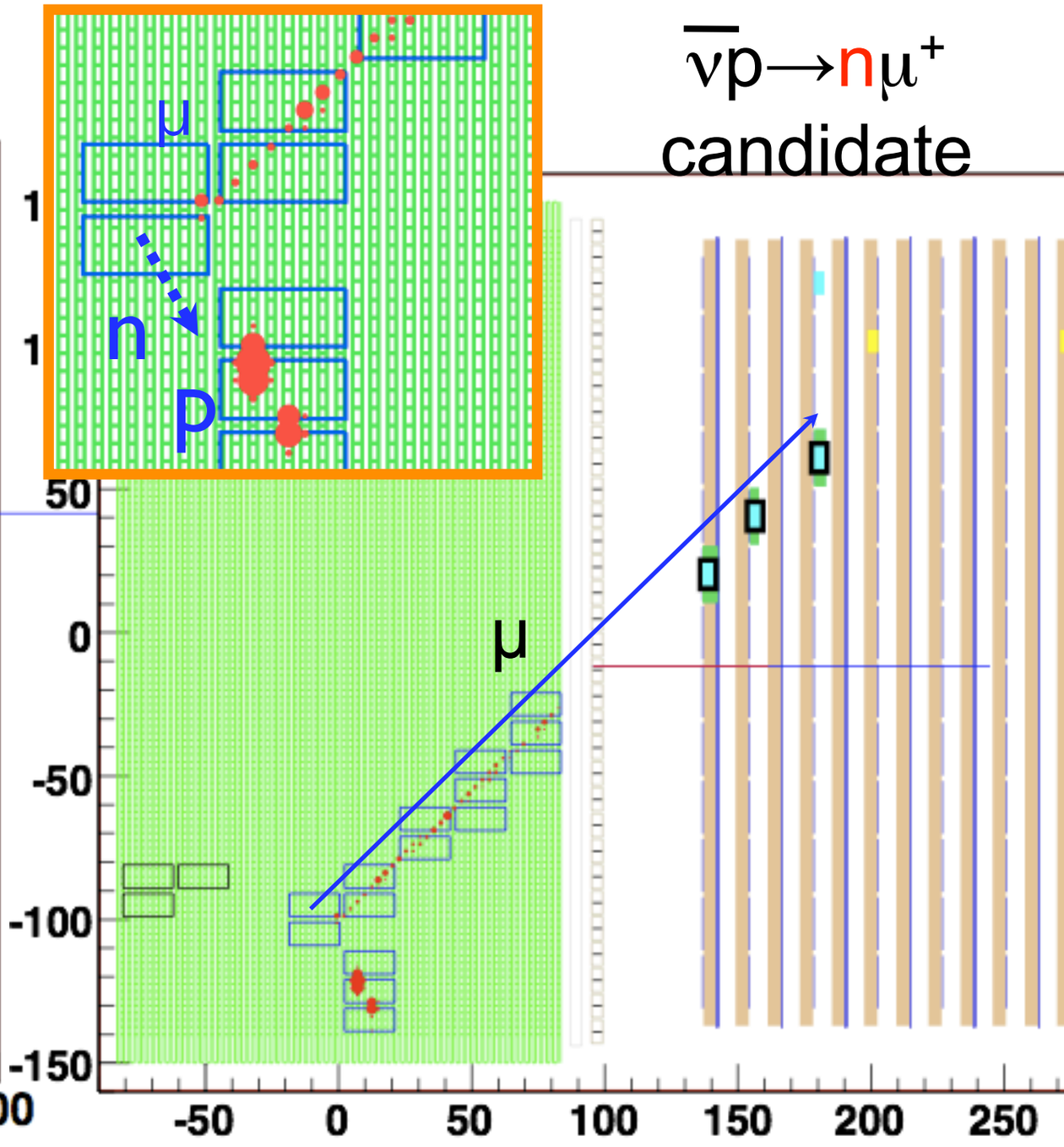
- Data taking period:
  - Jun. 2007 – Aug. 2008
- 95% efficiency

- 2.52×10^{20} POT in total
  - neutrino : 0.99×10^{20} POT
  - antineutrino: 1.53×10^{20} POT

Results with full neutrino and antineutrino data set will be presented in this talk.

ν and $\bar{\nu}$ CCQE event candidates





SciBar vertex resolution ≤ 5mm

: SciBar hit, area∝energy deposit

: SciBar TDC hit

SciBooNE

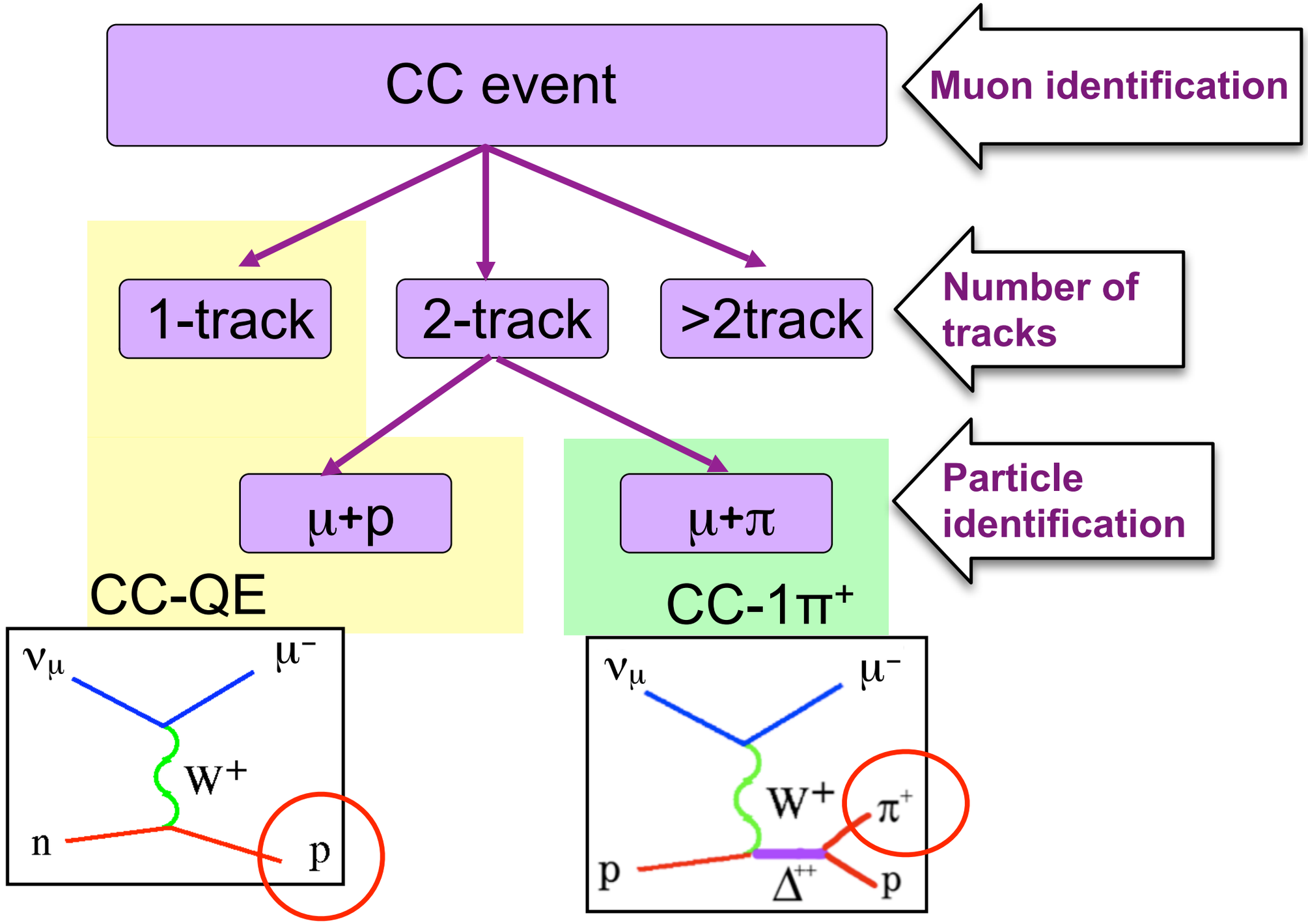
Physics Analyses

Physics Topics

Several analyses are in progress

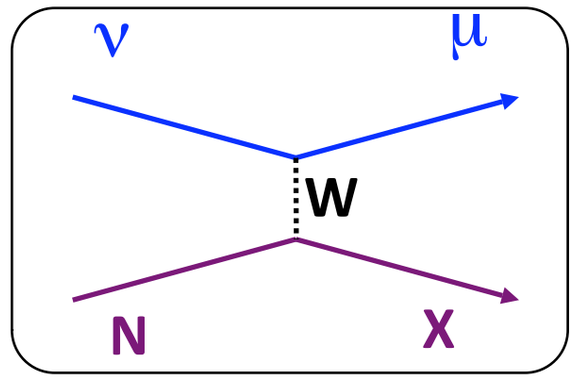
- ν Charged Current
  - CC-QE (Jose A. & Joe W.)
  - CC-1π^+ (Katsuki H.)
  - CC-π^0 (Joan C.)
- ν Neutral Current
  - NC-π^0 (Yoshinori K.)
  - NC-elastic (Hideyuki T. & Aaron H.)
- $\bar{\nu}$ CC analysis
  - $\bar{\nu}$ CC coherent π search (Hide T.)
- Short-baseline ν_μ disappearance search
  - Joint analysis MB+SB (Kendall M & Yasuhiro N.)
- ν_e flux measurement (Gary C.)

CC analysis overview



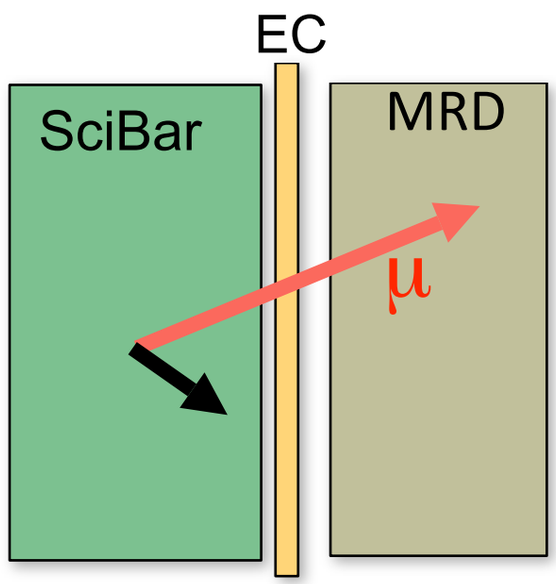
Charged Current event selection

- Muon is identified using MRD
- The track should start from SciBar fiducial volume
  - **SciBar-MRD matched track ≡ muon track**

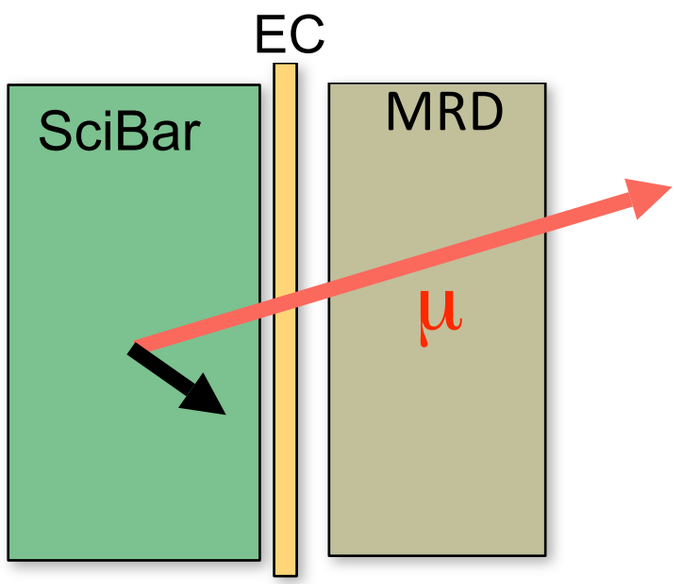


SciBar-MRD matched event (~30k events)

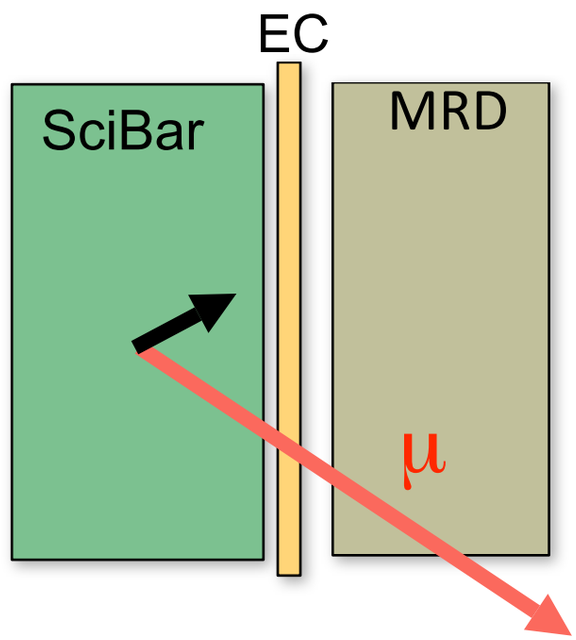
MRD-stopped (low-energy sample)



MRD-penetrated (high-energy sample)



MRD-side escaped

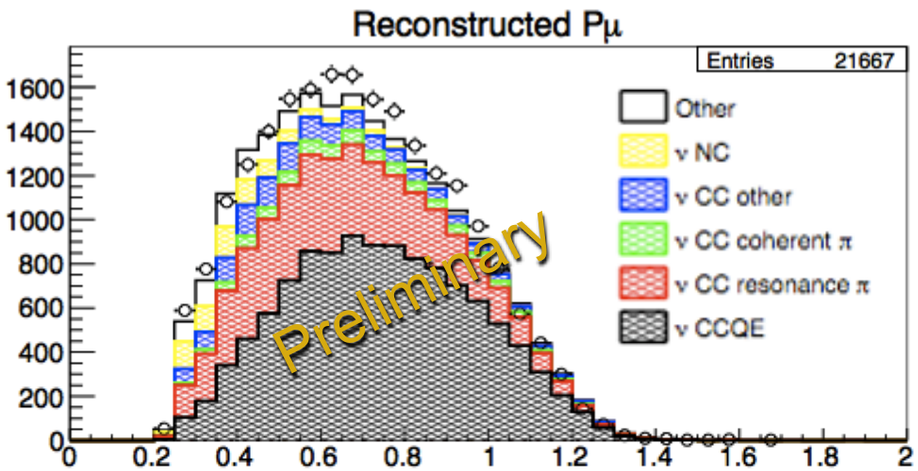


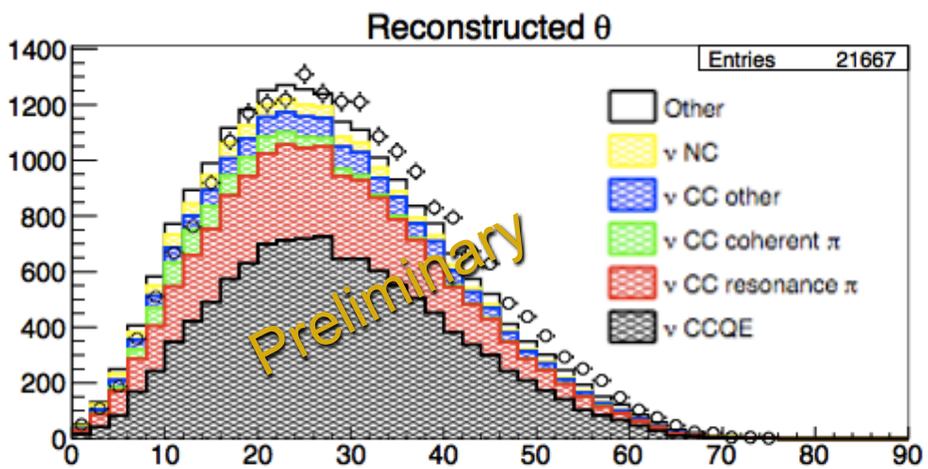
93% pure CC-inclusive (ν+N→μ+X) sample

CC event (inclusive)

~Muon stopped in MRD~

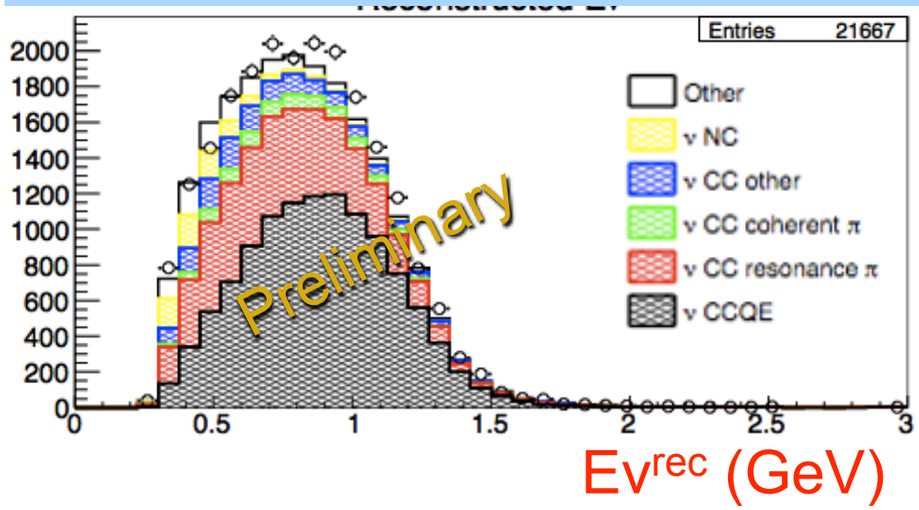
Muon kinematics





Resolution:
ΔP_μ ~50 MeV/c
$\Delta\theta_\mu$ ~0.9 deg.

Reconstructed Ev assuming CC-QE

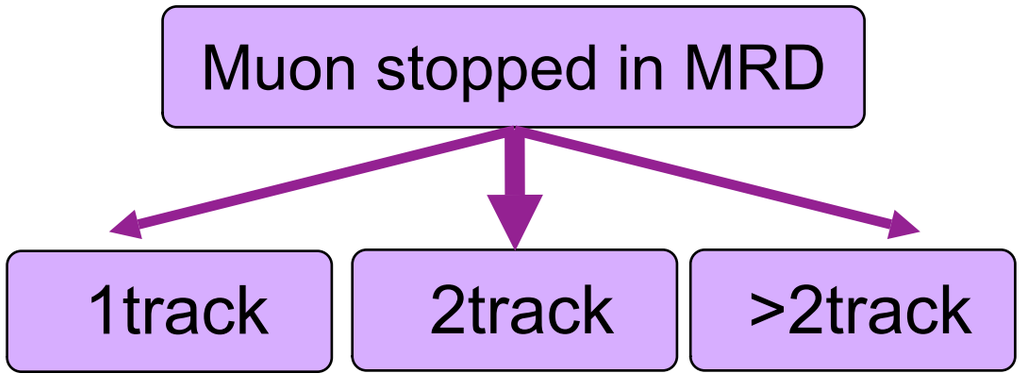


Assume CC-QE event, Ev can be reconstructed from only muon kinematics (Pμ, θμ)

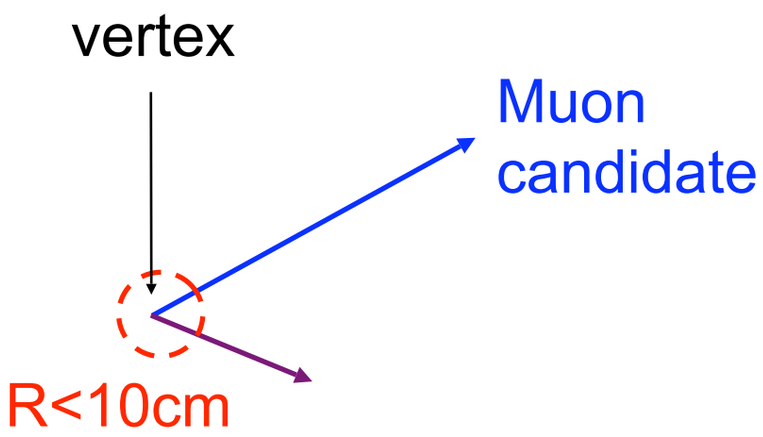
$$E_\nu^{rec} = \frac{1}{2}\frac{M_p^2 - m_\mu^2 - M_n^2 + 2E_\mu M_n}{M_n - E_\mu + p_\mu \cos\theta_\mu}$$

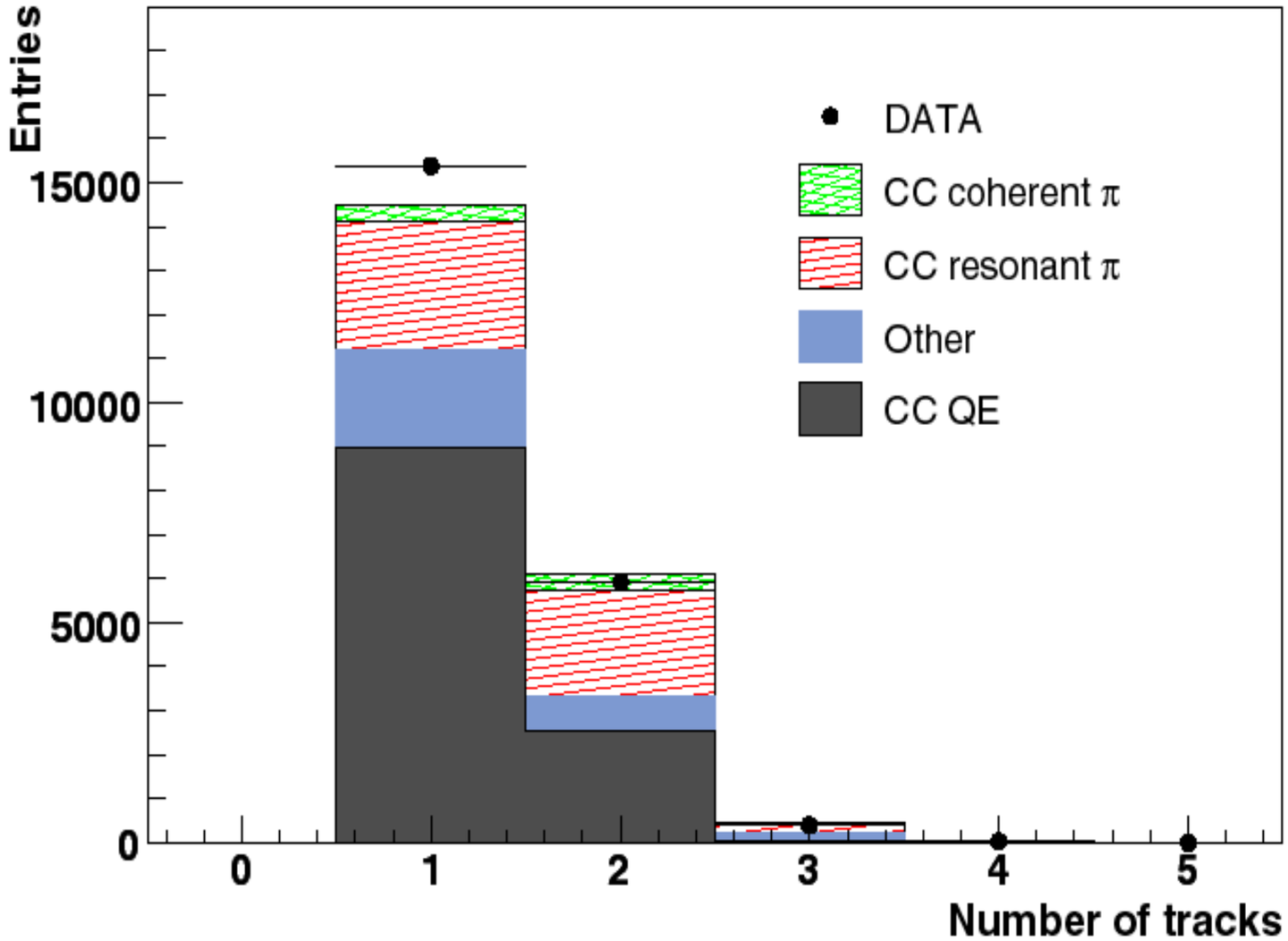
MC is normalized to SciBar-MRD matched sample.

Number of tracks



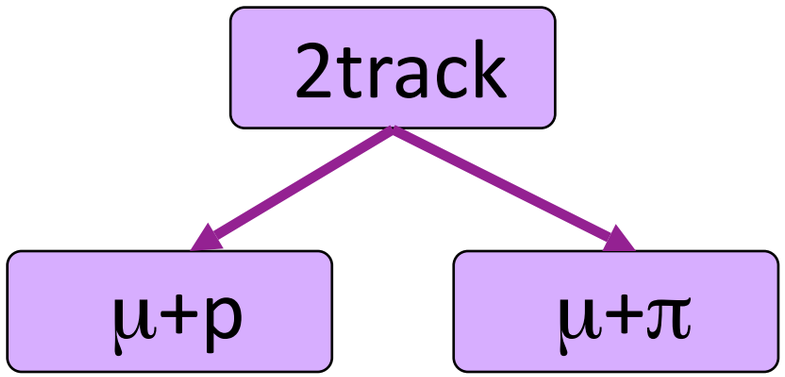
Search for tracks from the vertex (R<10cm)



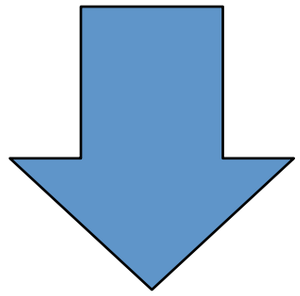


MC: SciBar-MRD match normalization

Particle identification



Particle ID using dE/dx in SciBar



"Muon confidence level" (MuCL)

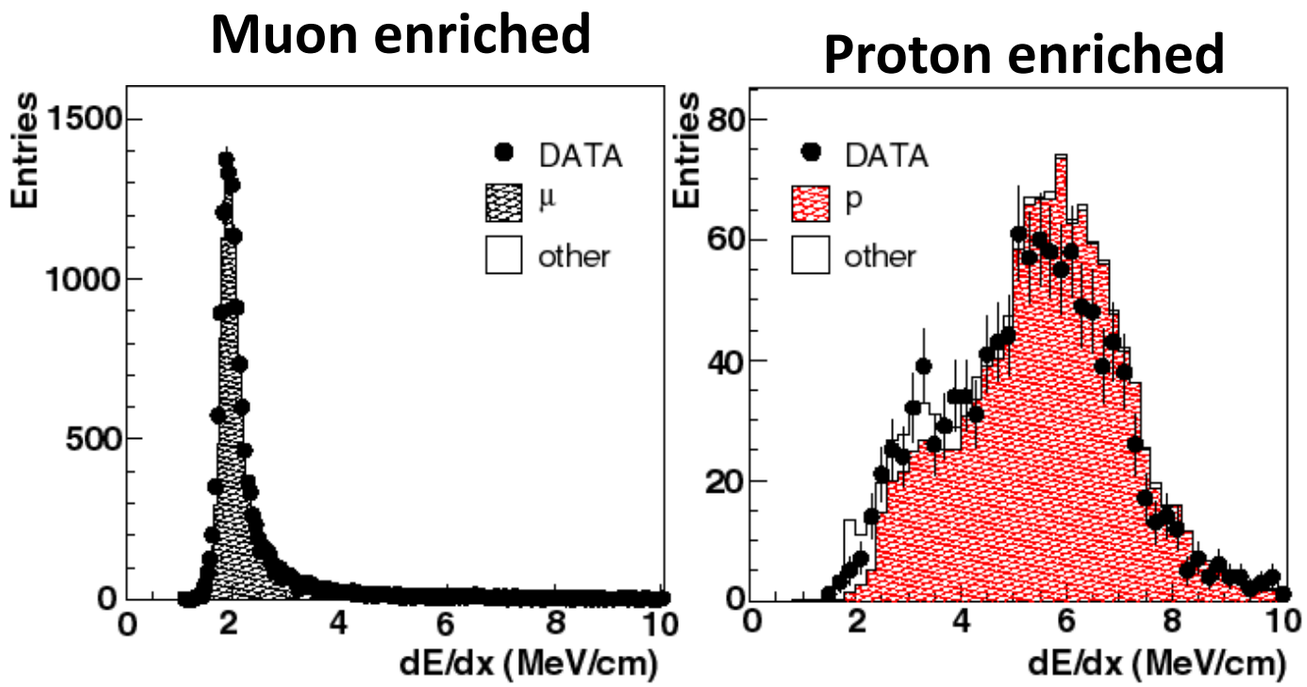
MuCL→1: MIP-like (μ, π)

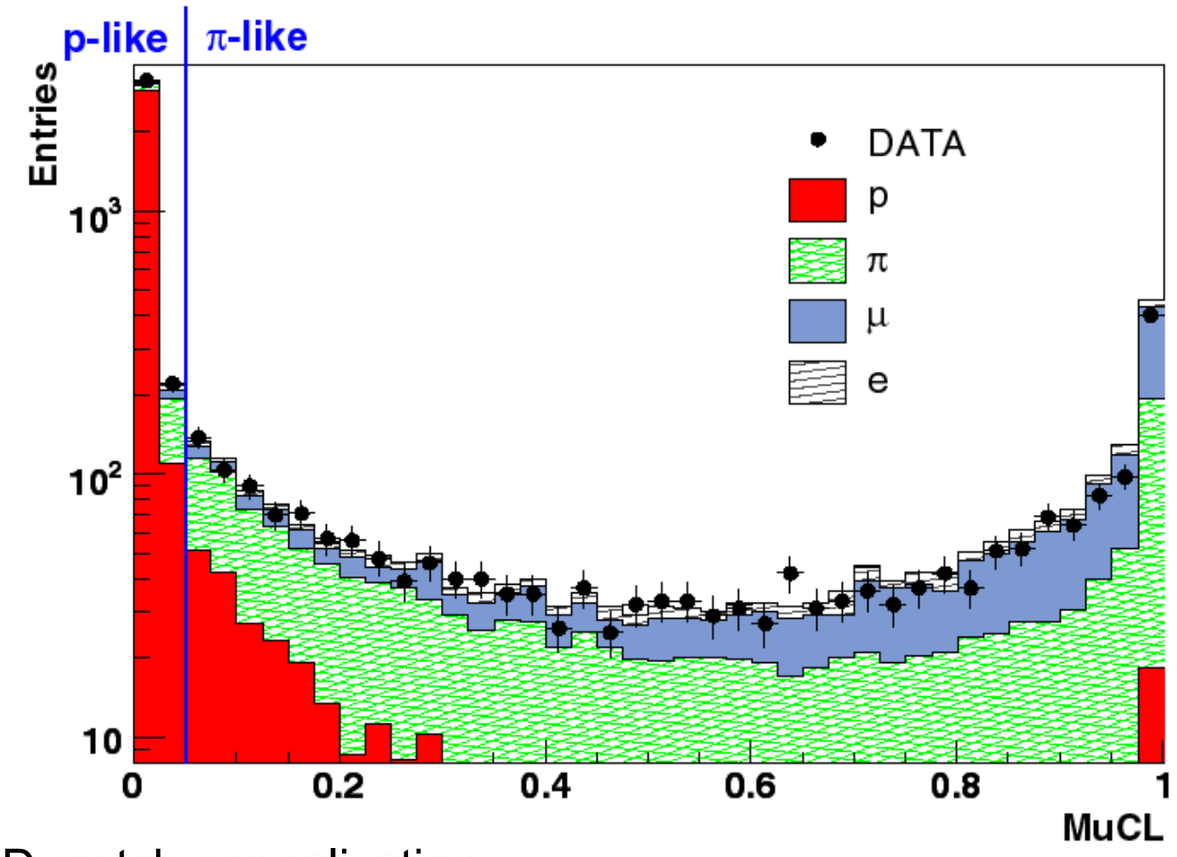
MuCL→0: proton-like

MuCL>0.05 for 2nd tracks:

~90% p rejection

84% π efficiency





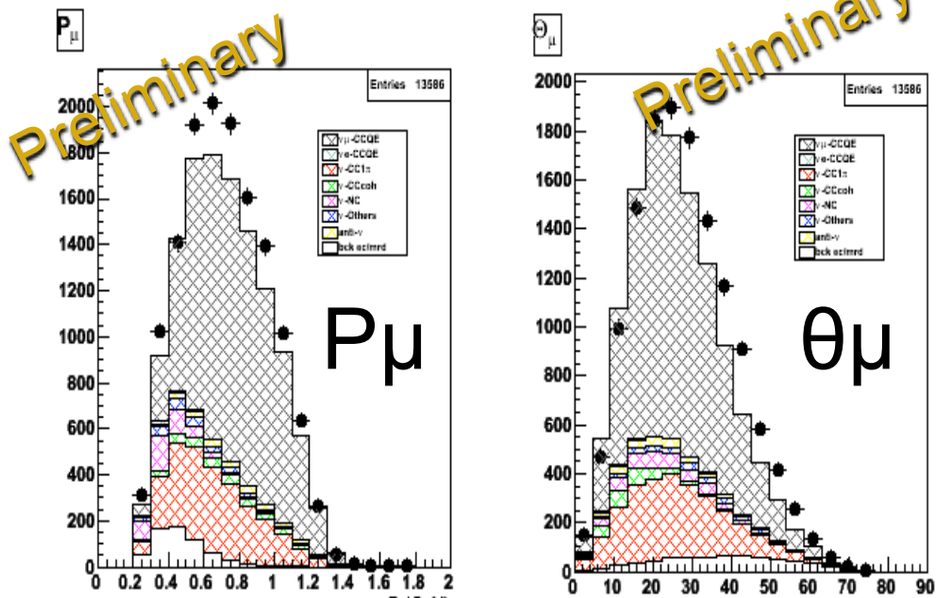
MC: SciBar-MRD match normalization

CC-QE

Charge Current Quasi Elastic

CC-QE samples

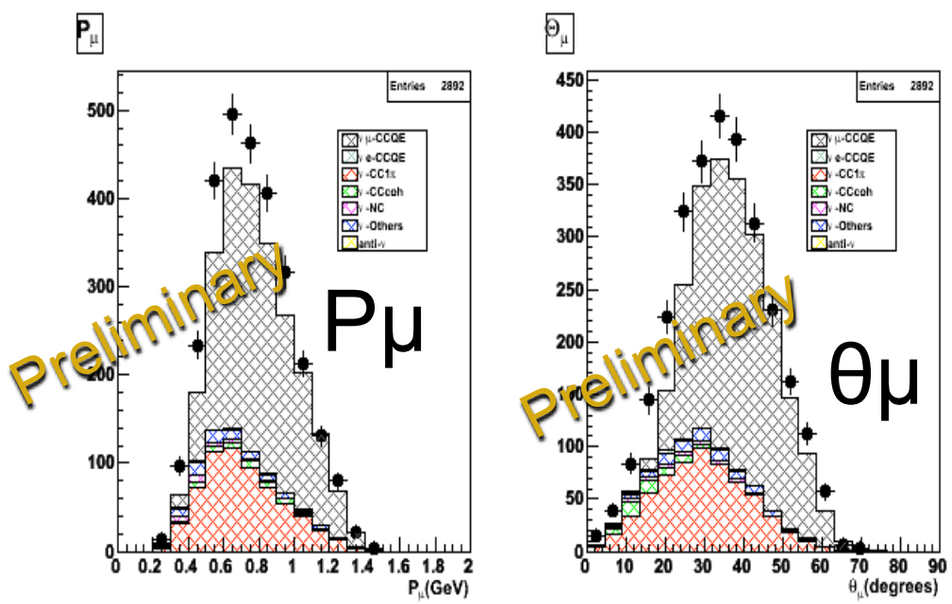
1-track sample



~13,500 event
65% CC-QE purity

CC-QE
CC-resonant π
CC-coherent π
NC
Bkg (EC/MRD)

2-track μ+p sample



~2,900 event
68% CC-QE purity

MC: Absolutely normalized (POT normalization)

Extracting CC-QE cross section

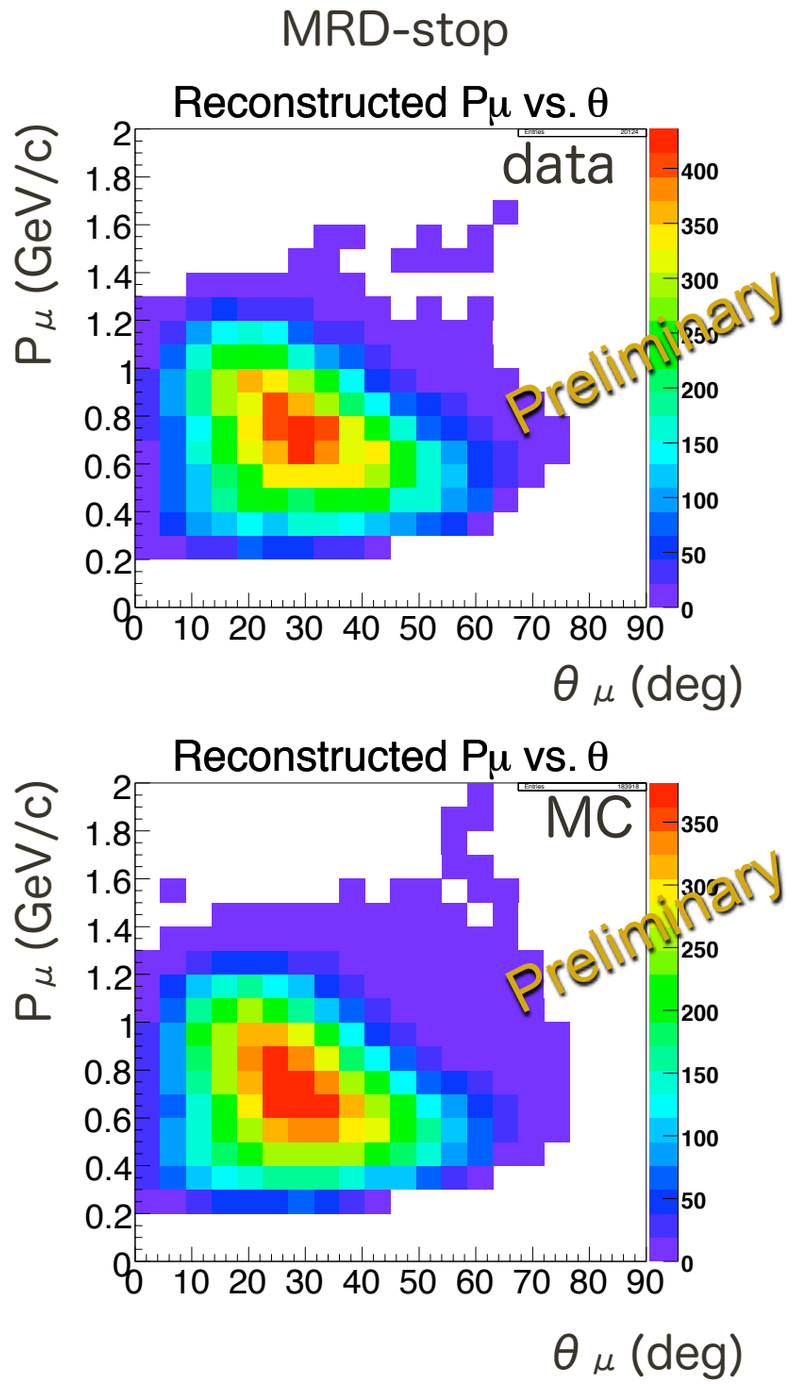
Fit the MC template to data,
minimizing the chi2 function with the binned Poisson log likelihood method.

$$\chi 2 = \; 2 * \sum_{i,j} \left[N_{ij}^{\exp} - N_{ij}^{obs} + N_{ij}^{obs} \times \left(\ln \frac{N_{ij}^{obs}}{N_{ij}^{\exp}} \right) \right]$$

Use 2 dimensional distributions in Pμ and θμ space:

Data: $N^{obs} = N^{obs}(P\mu, \theta\mu)$,
MC: $N^{exp} = N^{exp}(P\mu, \theta\mu)$.

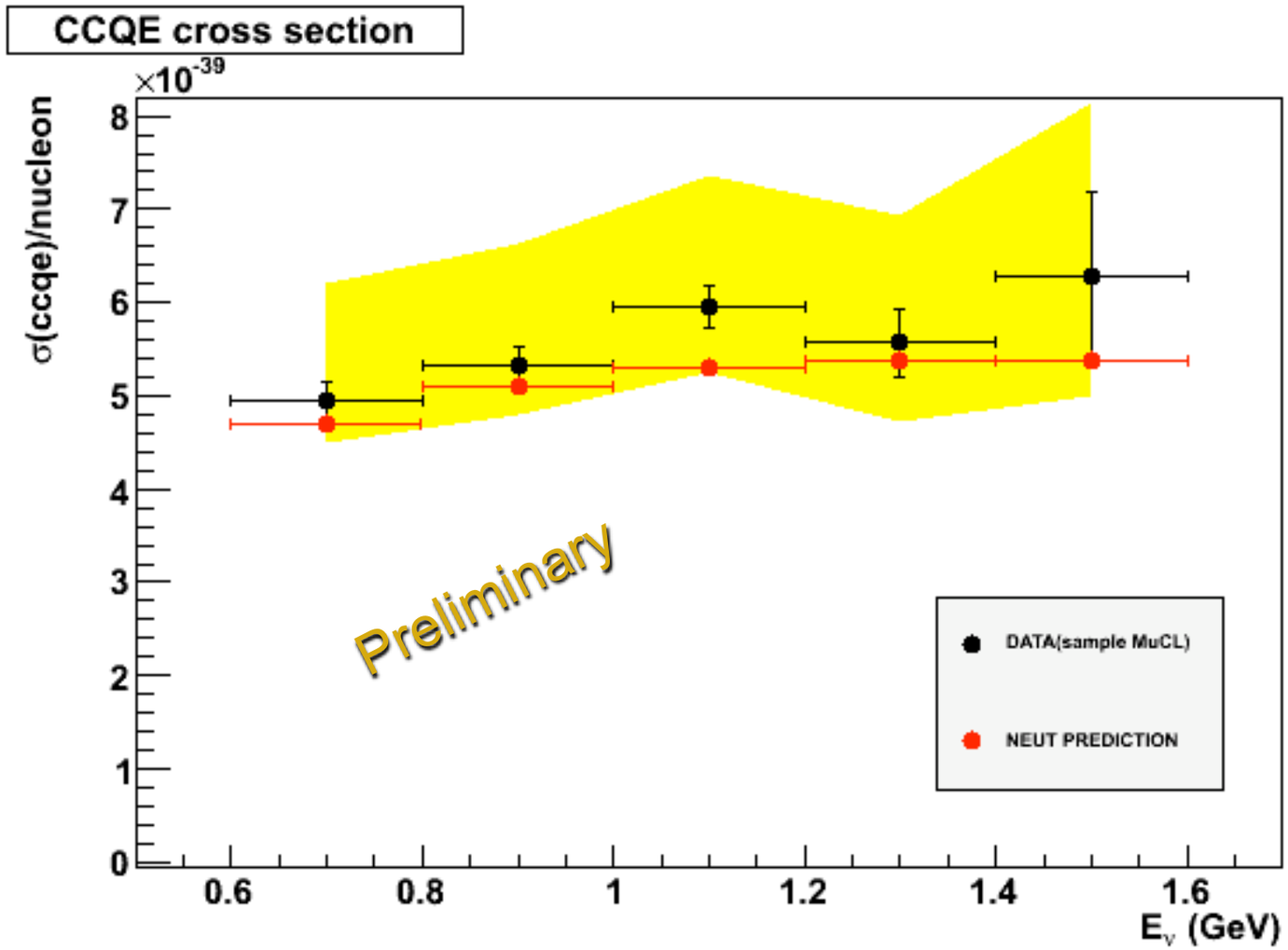
MC template (Pμ, θμ) distributions are in each true Eν bin.



Results

CC-QE differential cross section

J. Alcaraz



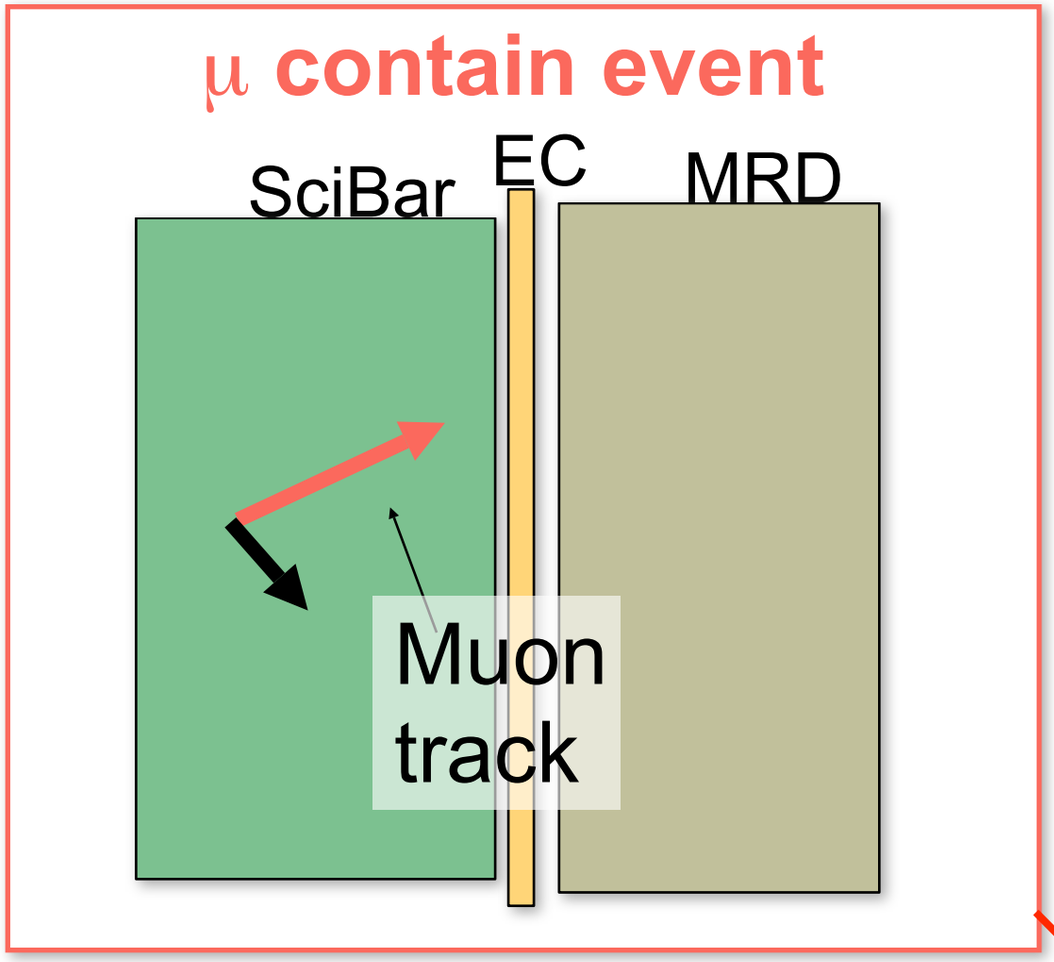
: Data (stat error only)

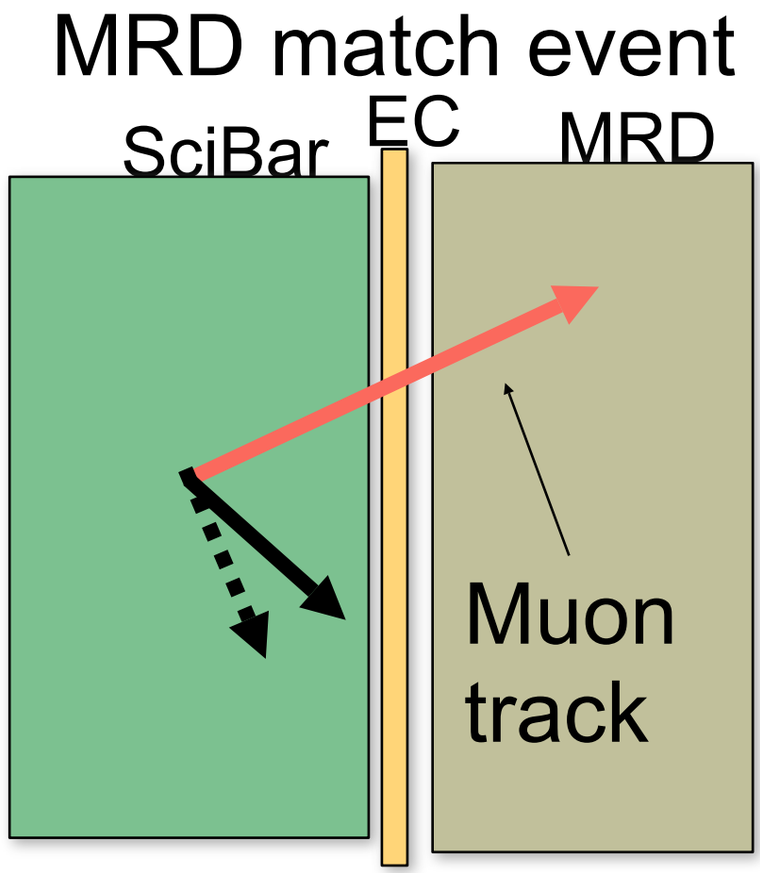
: MC prediction

: Syst. error of ν beam (conservative)

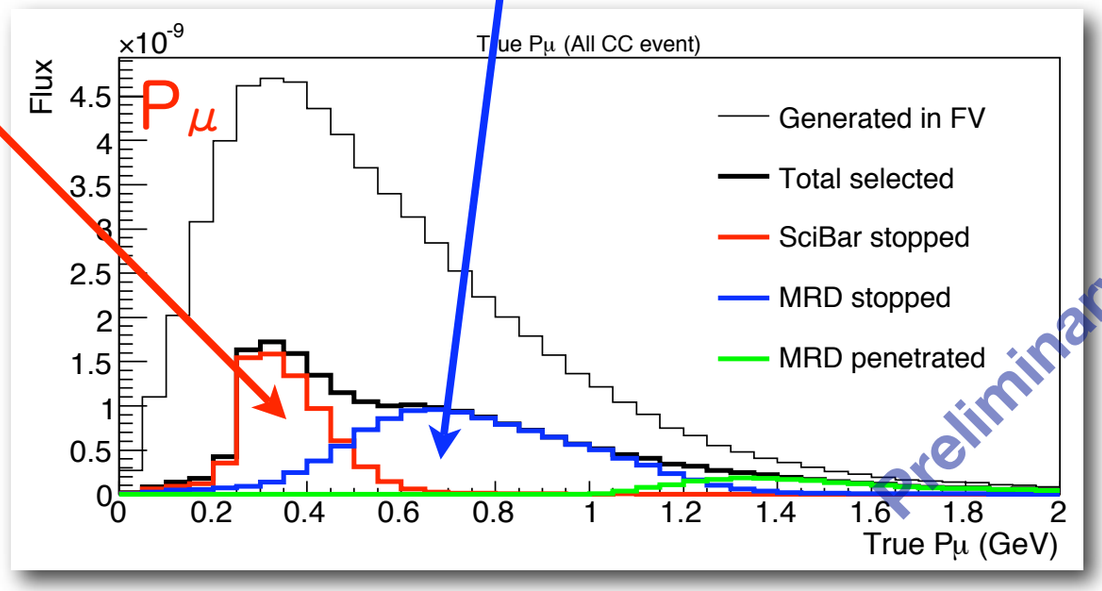
Systematic study on detector response, interaction models is in progress -- final results in this summer.

Low energy CC-QE





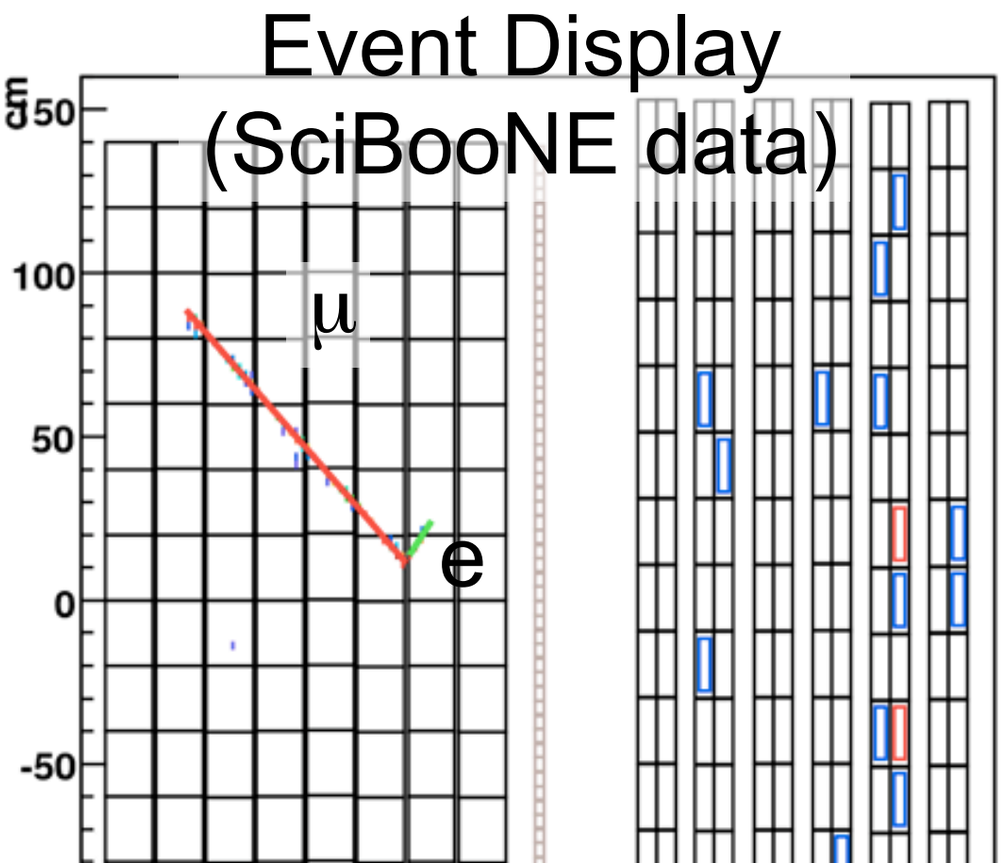
<u>Muon stopped inside SciBar.</u>
Low Pμ → Low energy events.

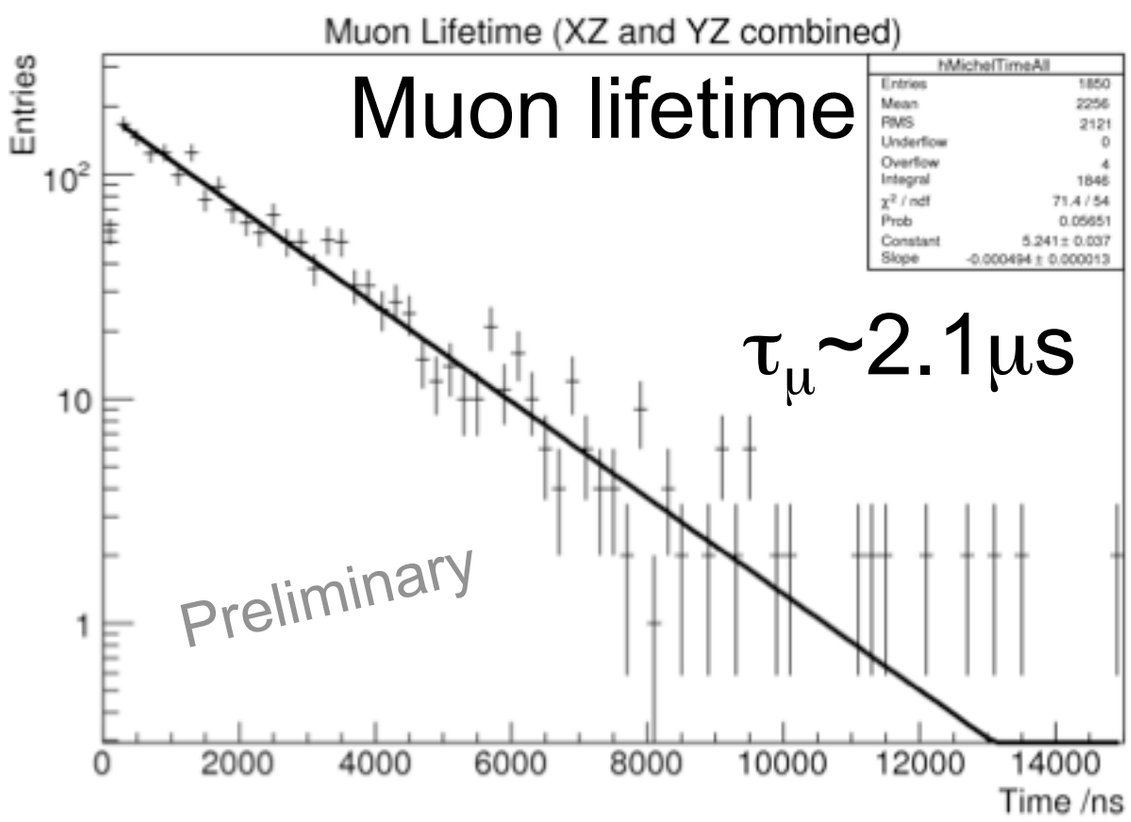


Muon ID for contain event:
muon decay tagging

- Muon decay: μ→e+ν's
- Tag Michel electron with SciBar-TDC info:
  - hit from muon and hit from Michel electron
- Clear signature of muon Michel decay

J. Walding

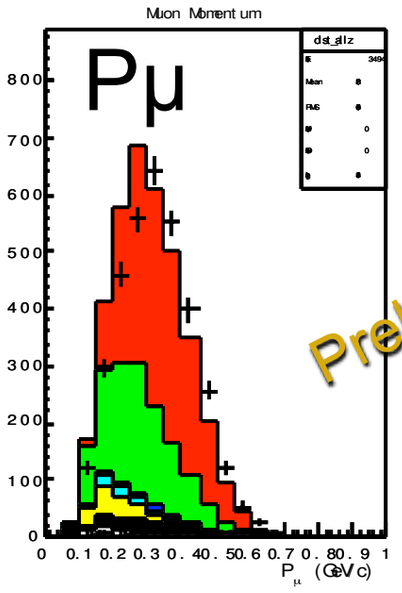


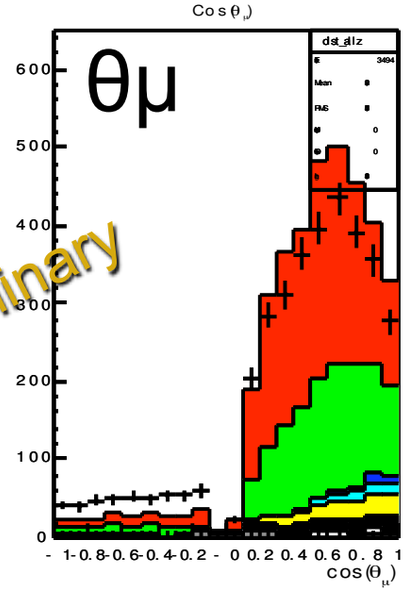


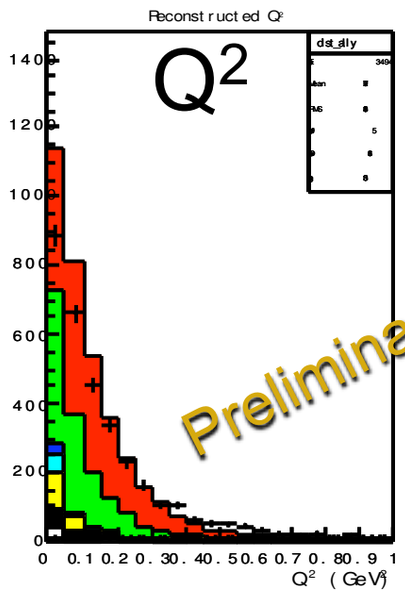
Low energy CC-QE sample

J. Walding

1-track







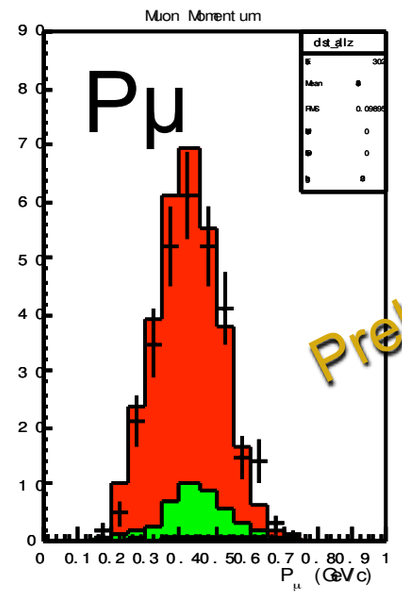
Preliminary

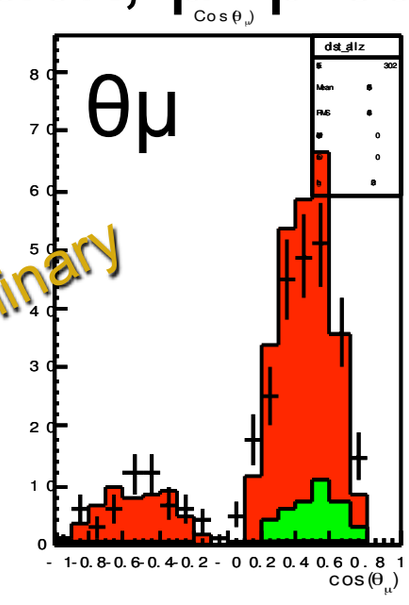
Preliminary

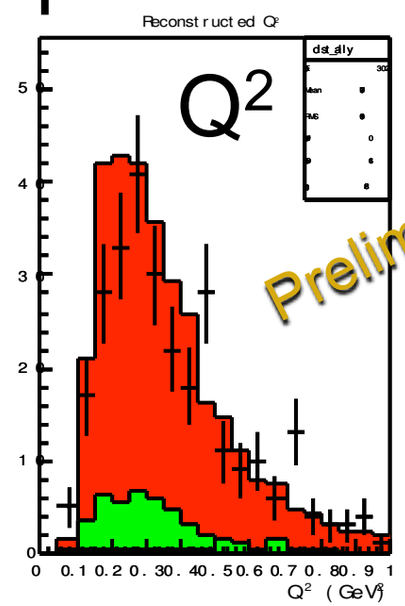
Data: ~3500 events
MC: 55% CC-QE purity

CC-QE
CC-resonant π
CC-coherent π
NC
MC: Absolutely normalized

2-track, μ+p sample







Preliminary

Preliminary

Data: ~300 events
MC: 86% CC-QE purity

Analysis is on-going.
Will be combined with MRD-match CC-QE sample for wide coverage of Ev.

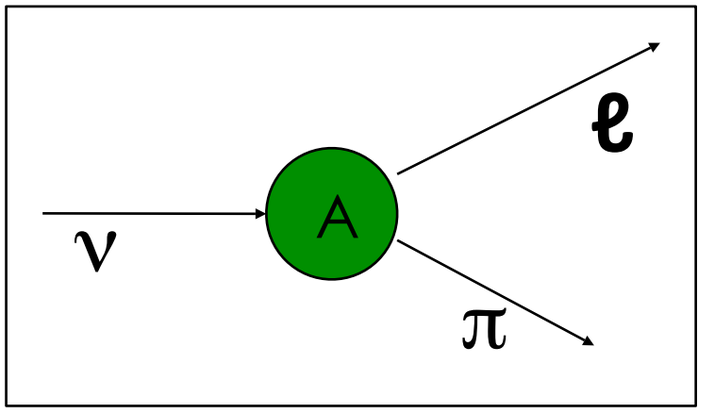
CC-1π+

CC coherent π production

Phys. Rev. D78:112004,2008
and further analysis

Coherent pion production

- Neutrino interacts with nucleons *coherently*, producing a pion
- No nuclear breakup occurs

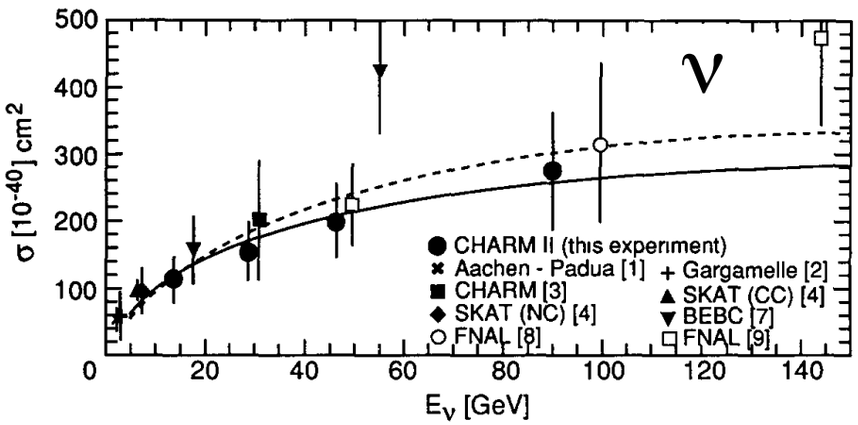


Charged Current (CC): $\nu_\mu + A \rightarrow \mu + A + \pi^+$

Neutral Current (NC): $\nu_\mu + A \rightarrow \nu_\mu + A + \pi^0$

Several measurements in past (‘80-’90):

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

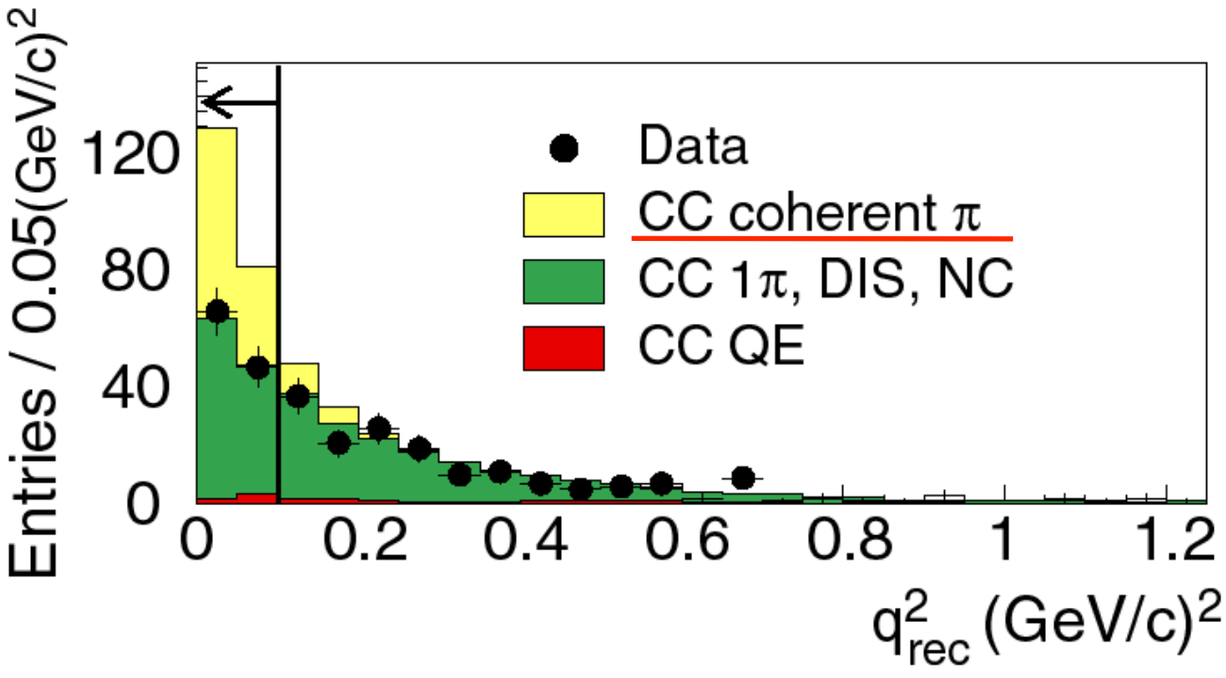


Plots from Phys.Lett. B313, 267-275 (1993)

Recent results at low energy (~1GeV)

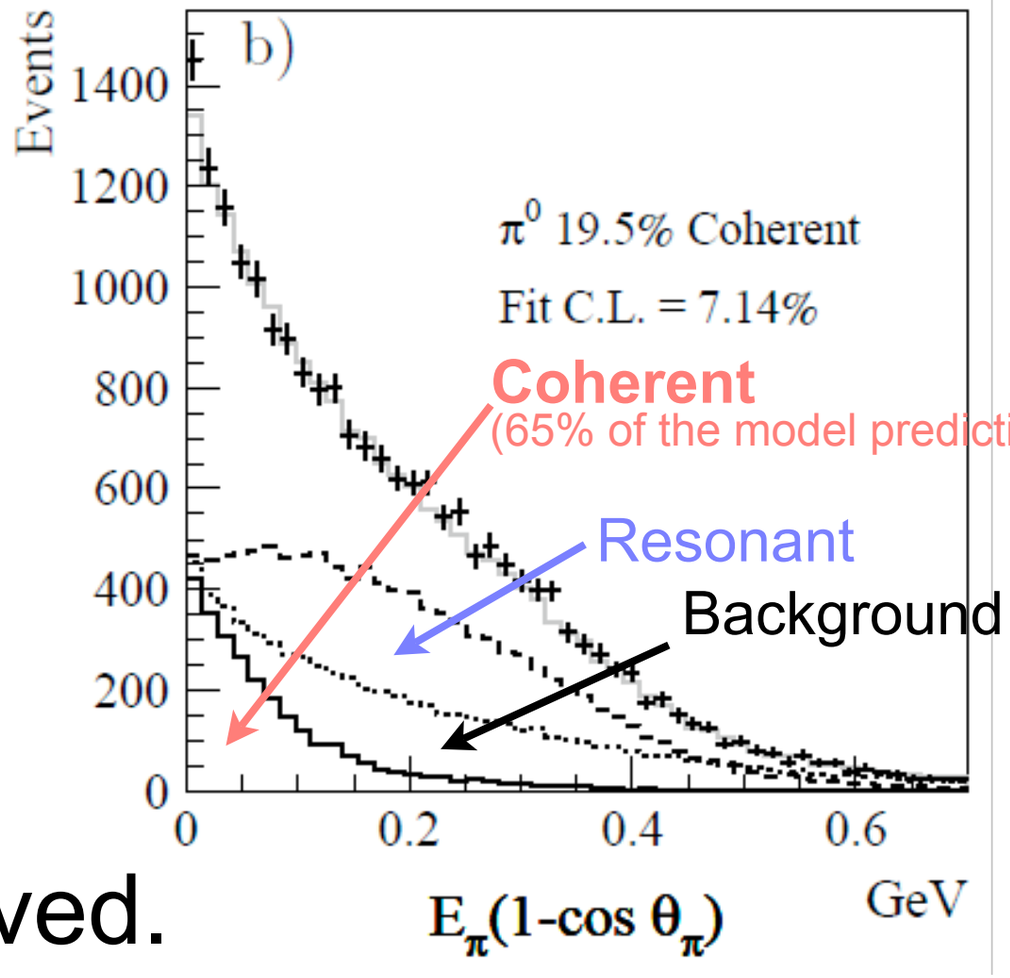
ν CC coherent π^+

K2K,
Phys.Rev.Lett. 95,252301 (2005)



ν NC coherent π^0

MiniBooNE,
Phys.Lett. B664,41 (2008)



- **CC**-coherent π^+ is NOT observed.
- **NC**-coherent π^0 is observed.

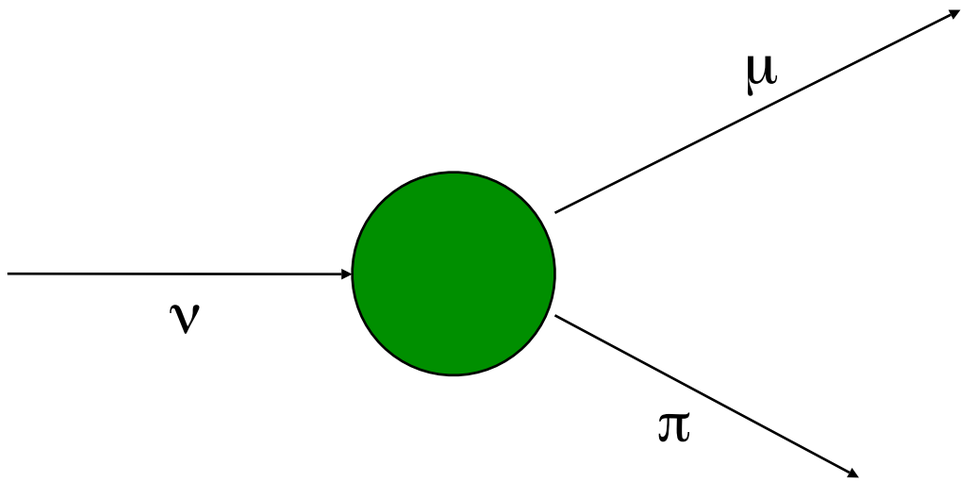
Consistent? ➜ New results from SciBooNE (CC)
(or need to be consistent?)

CC coherent π signature

Signal

CC-coherent π (ν+A→μ+A+π)

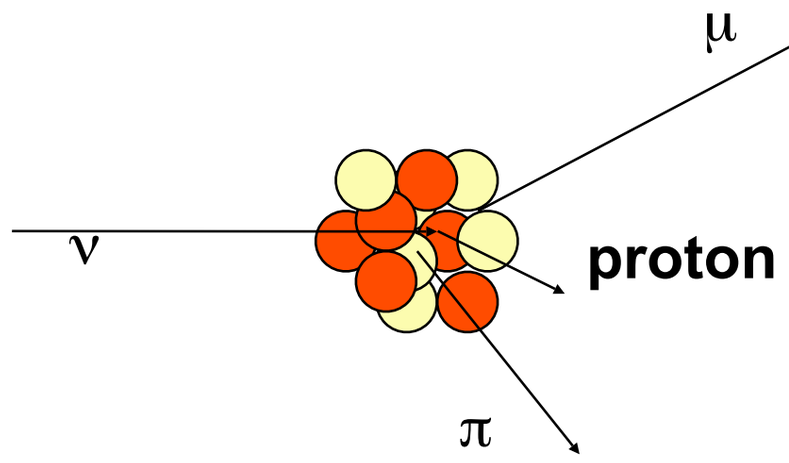
~1% of total ν interaction
(according to Rein-Sehgal model)



Background

CC-resonant π (ν+p→μ+p+π)

Predominant process in ~1GeV.
Mainly through Δ resonance.



Coherent π signature

- One muon and one pion in the final state
- No recoiled nucleon
  - No vertex activity
- Low momentum transfer (small Q^2)

Event selection

Define MC normalization

SciBar-MRD matched sample

Low energy sample

High energy sample

MRD-stopped

MRD-penetrated

Number of tracks

1track

2track

>2track

Particle identification

μ+p

μ+π

Energy deposit around the vertex

w/o activity

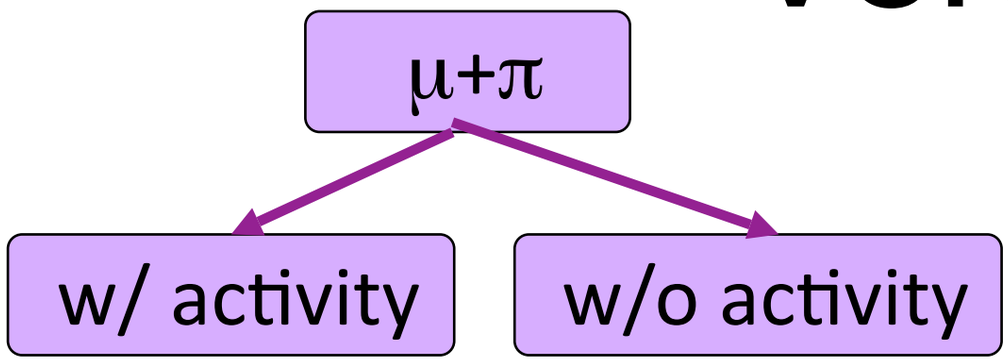
w/ activity

MRD-stopped CC-coherent π sample

Same selection

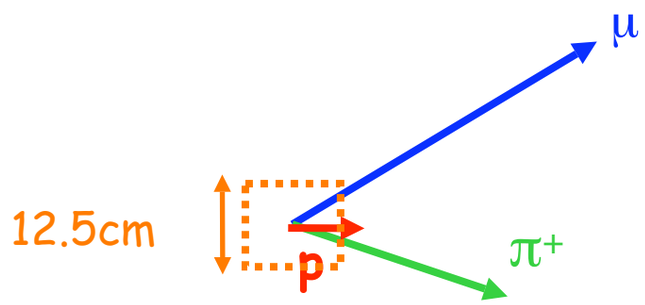
MRD-penetrated CC-coherent π sample

Vertex activity

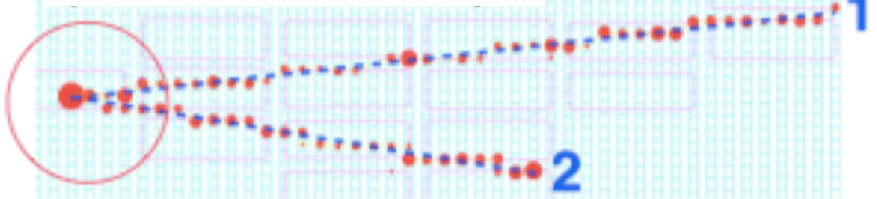


Resonant π have recoiled proton while coherent π do not.

Low energy proton make "vertex activity" (energy deposit).

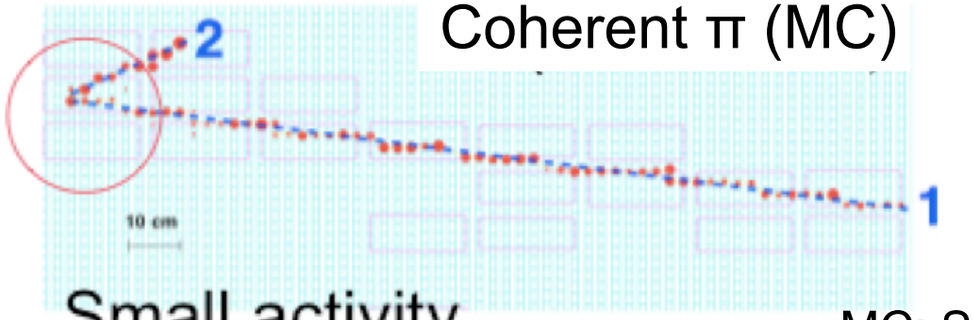


Resonant π (MC)



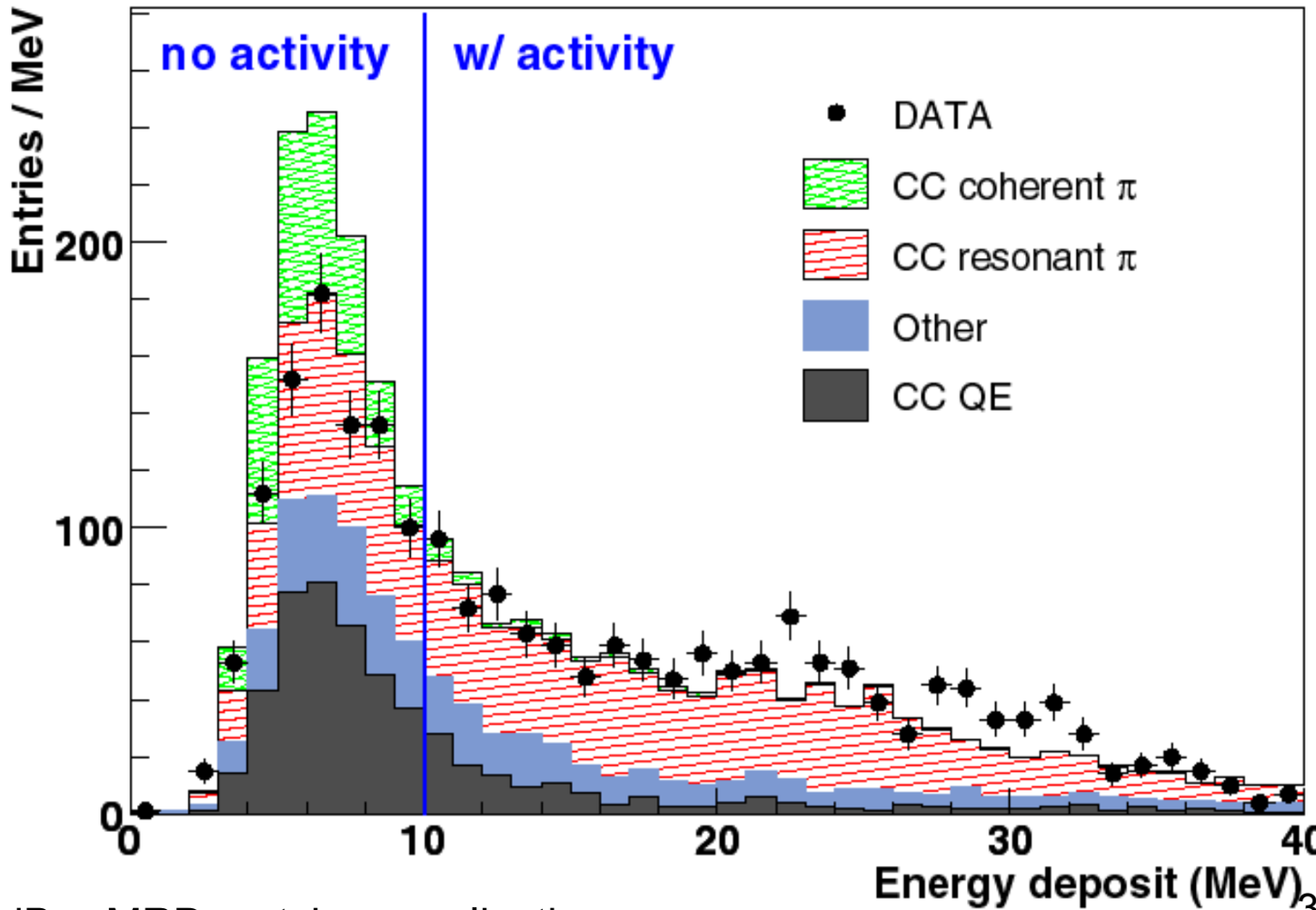
Large activity (recoil proton)

Coherent π (MC)



Small activity

K. Hiraide

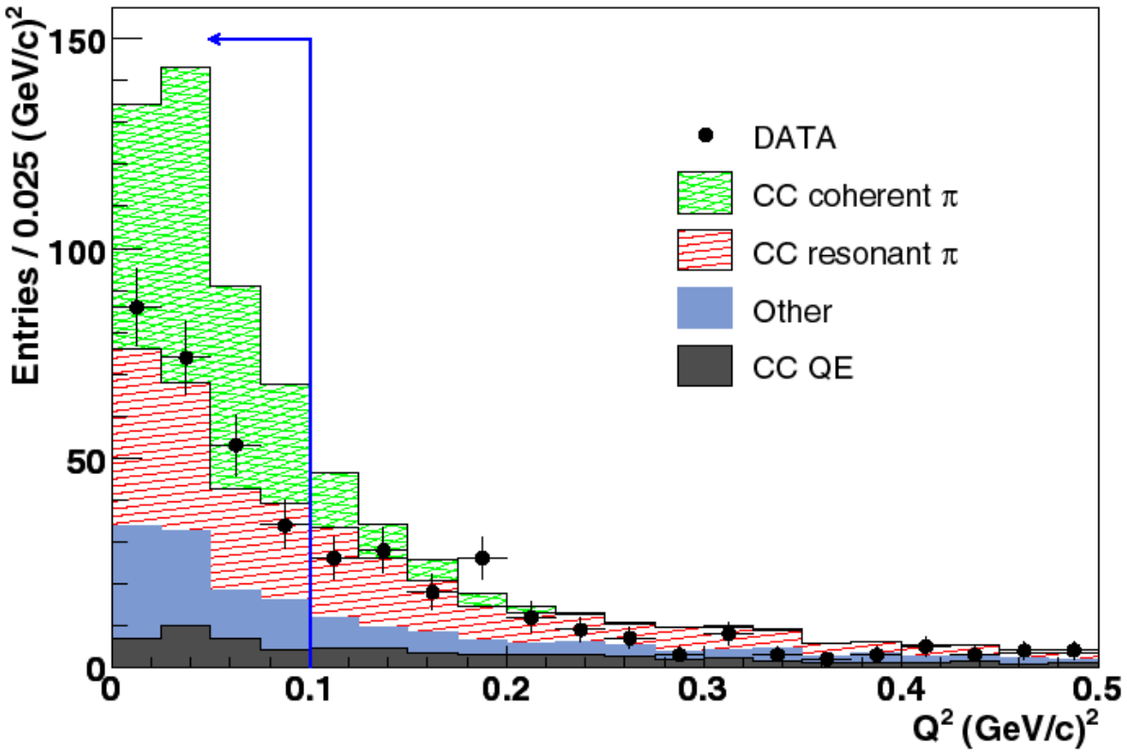


MC: SciBar-MRD match normalization

CC coherent pion enhanced sample

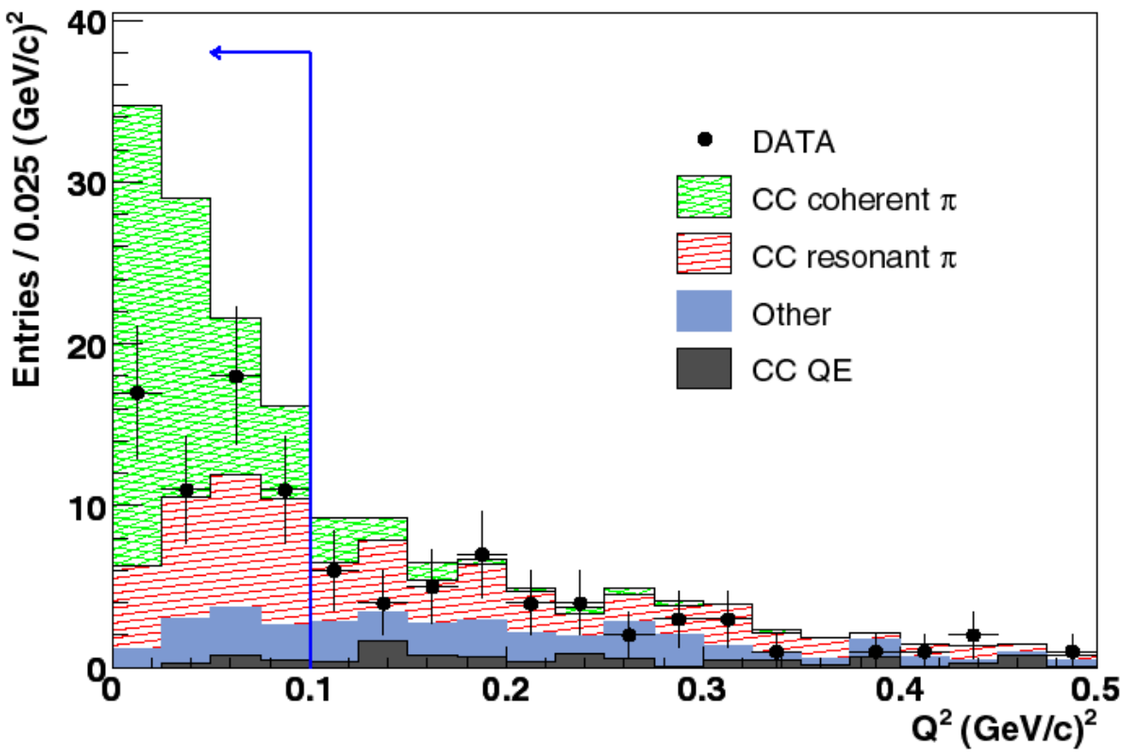
K. Hiraide

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



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

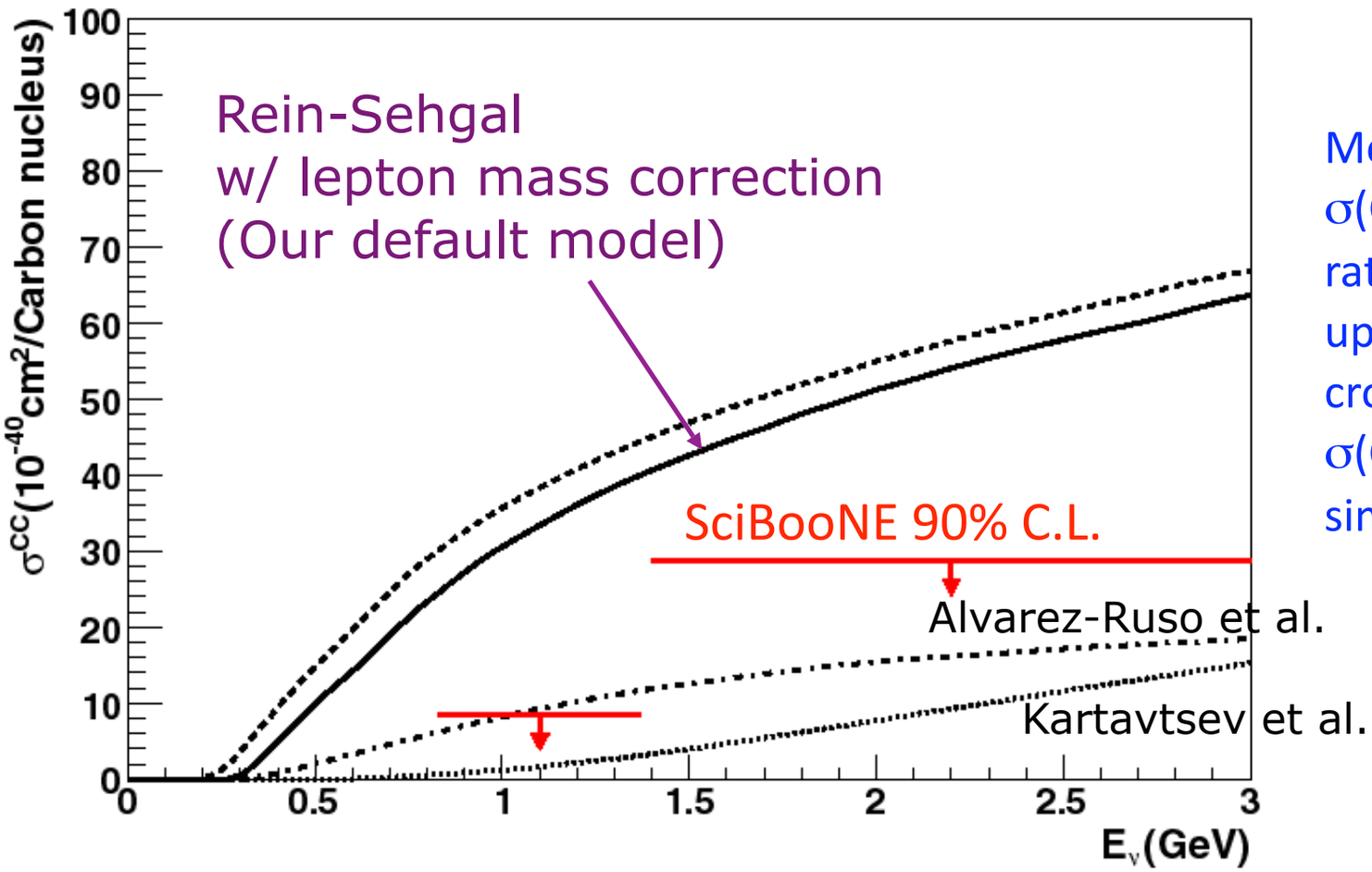
No evidence of CC coherent pion production was found

➜ set upper limit

MC: SciBar-MRD match normalization

Upper limit on cross section

K. Hiraide



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

New theoretical models:

[1] Phys.Rev.D79:013002,2009.
[2] arXiv:0812.2653 [hep-ph]
[3] arXiv:0901.2837 [nucl-th]
[4] arXiv:0901.2366 [nucl-th]
[5] ...

Recently proposed CC coherent π models predict production of CC coherent π events just below our upper limit.

Published CC coherent π search was based on muon kinematics.

➜

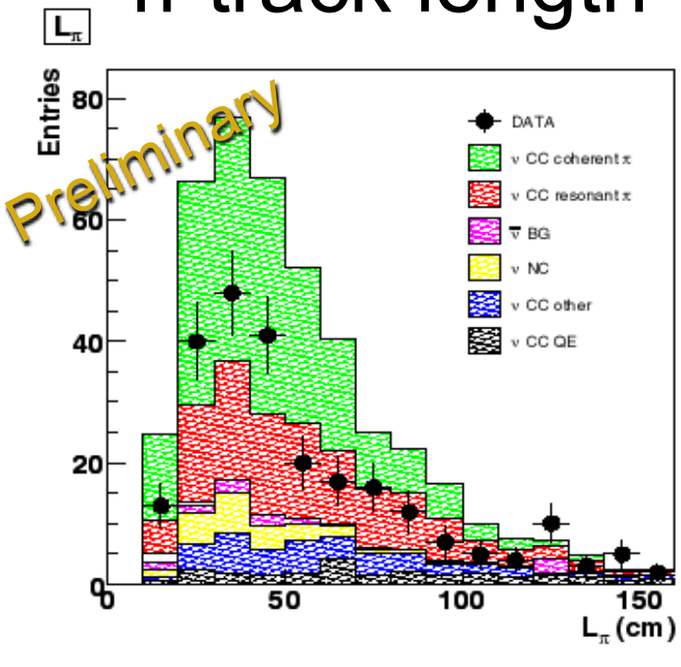
Search for CC coherent π with π kinematics.

π kinematics

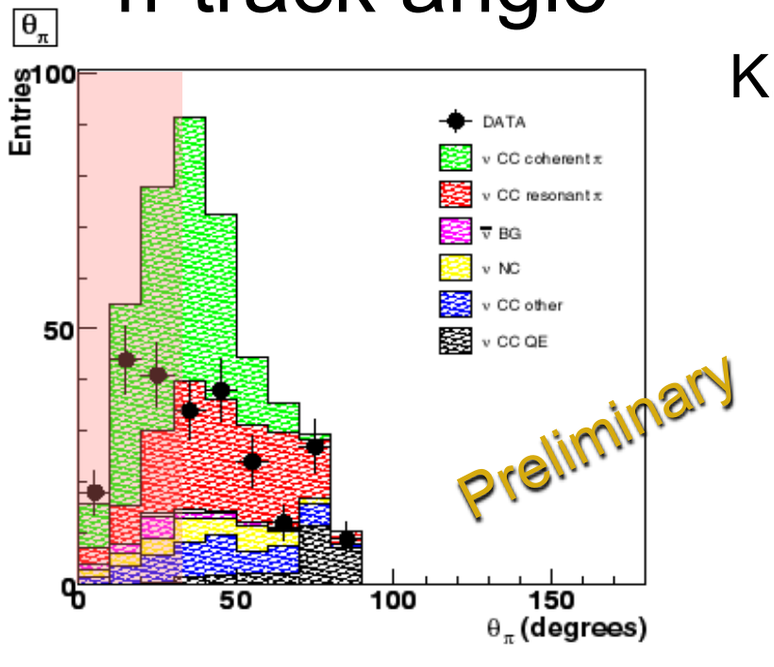
K. Hiraide

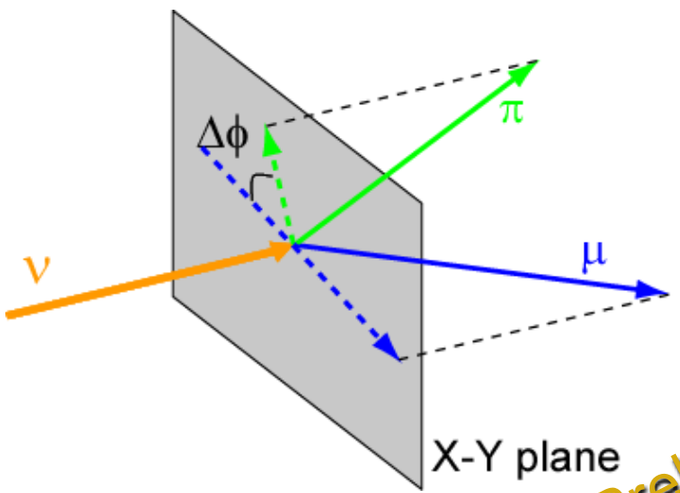
MC: SciBar-MRD
match normalization

π track length

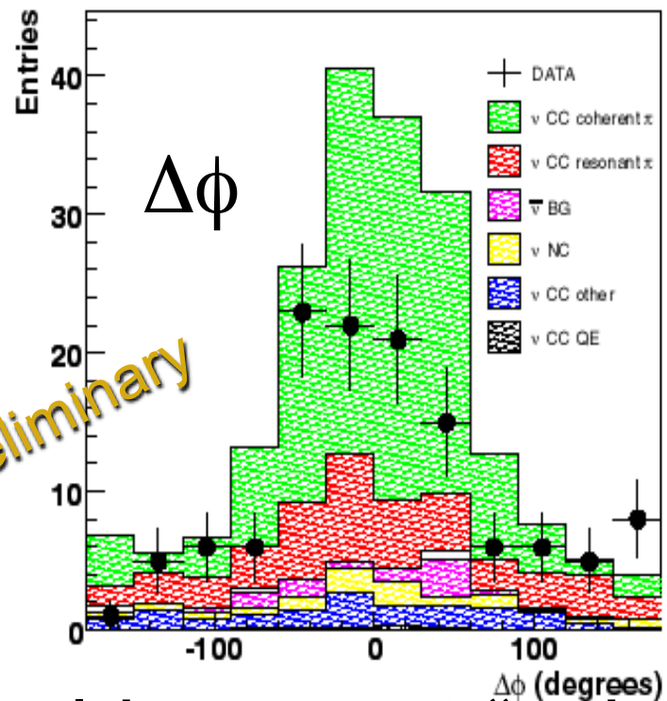


π track angle

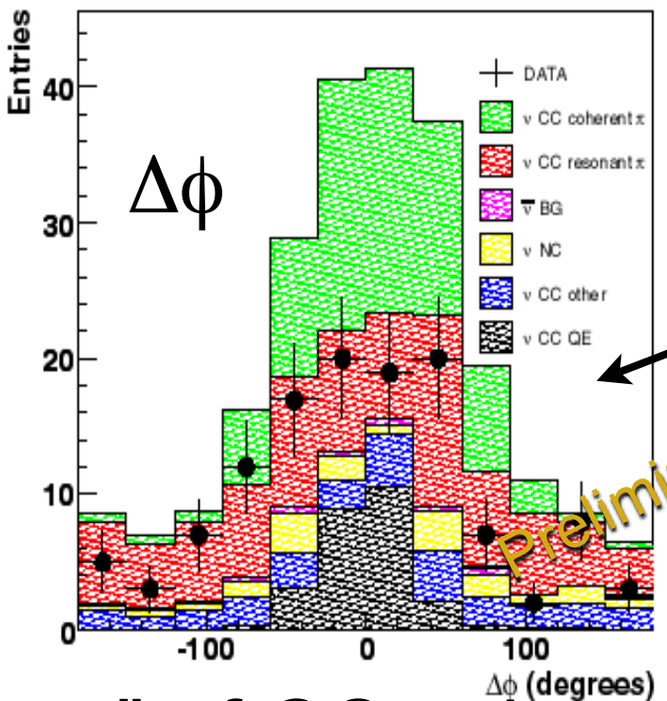




θπ < 35 deg



θπ > 35 deg



Background consistent

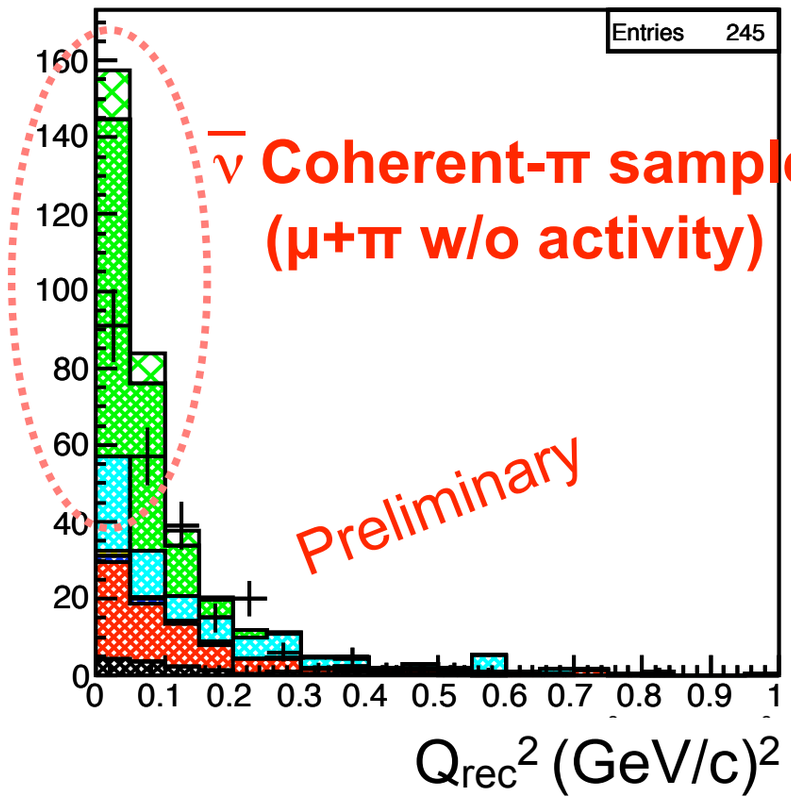
Data could suggest “existence” of CC coherent π events at small π angle (θπ) region.

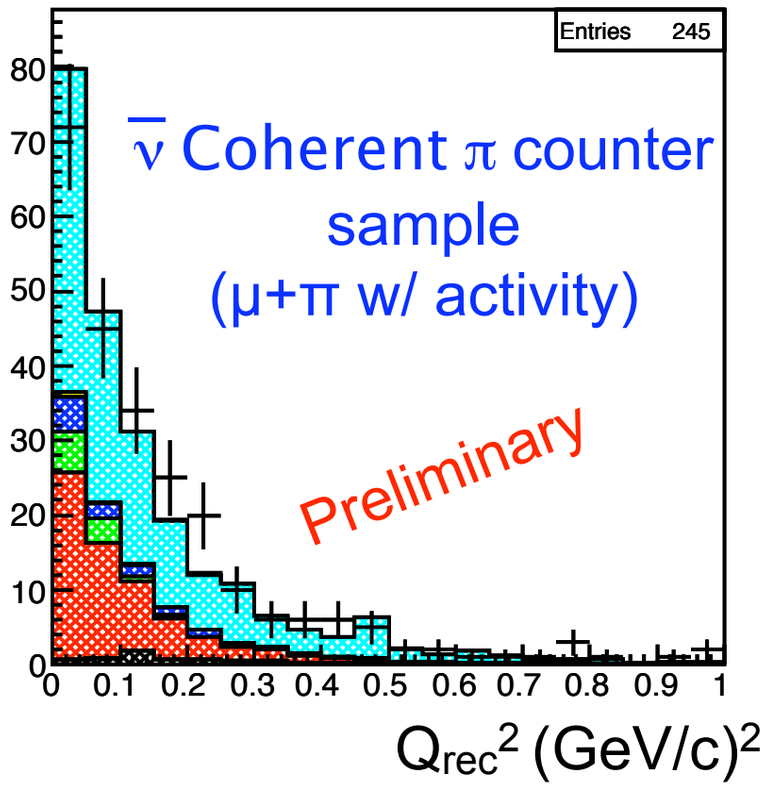
Search for $\bar{\nu}$ CC coherent π

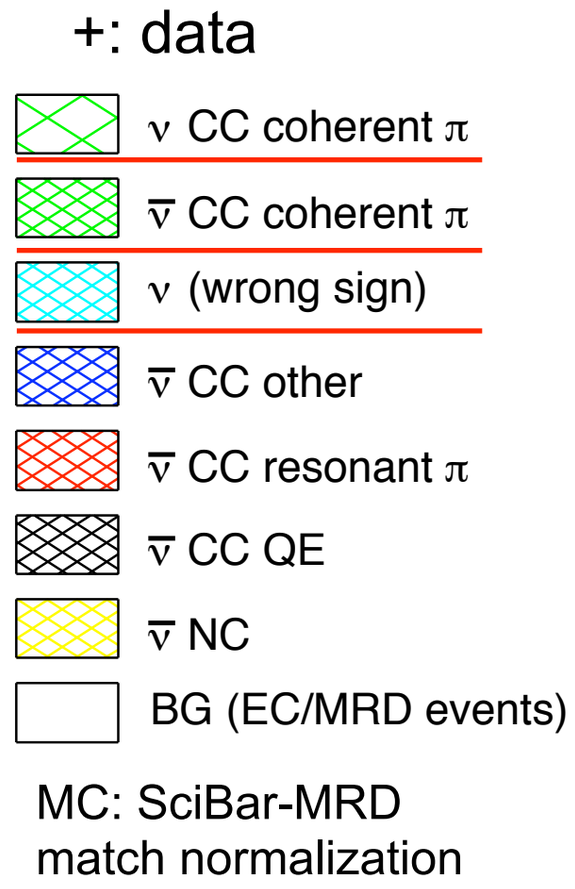
Used the same selection criteria as ν coherent π

(NOTE: no syst. error included, no MC tuning yet)

H. Tanaka







$\bar{\nu}$ coherent π sample also show <u>data deficit</u> at low Q^2 region.

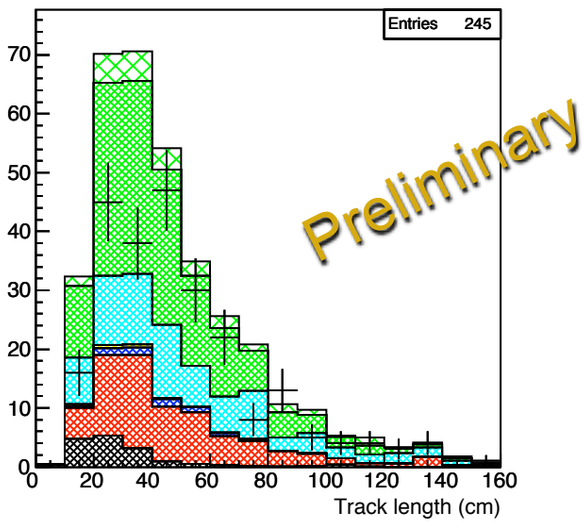
But data suggest non-zero CC coherent π component.

π kinematics

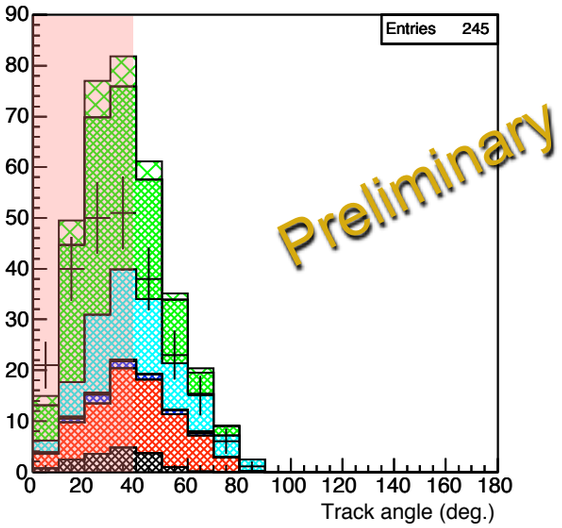
H. Tanaka

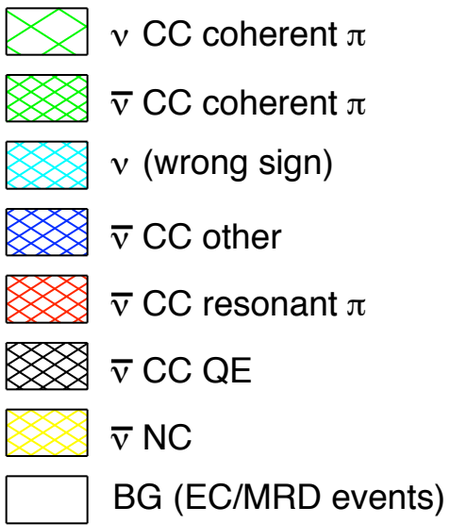
MC: SciBar-MRD
match normalization

π track length

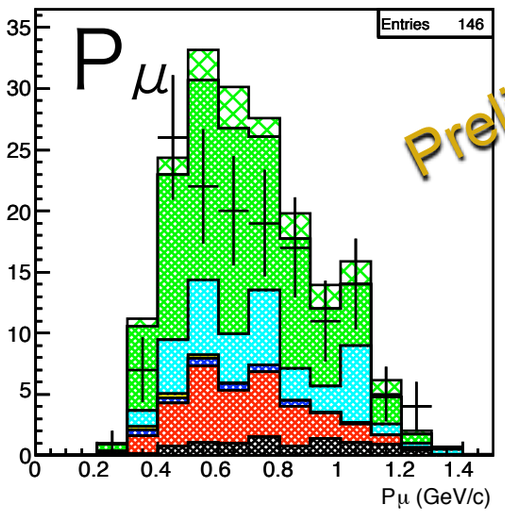


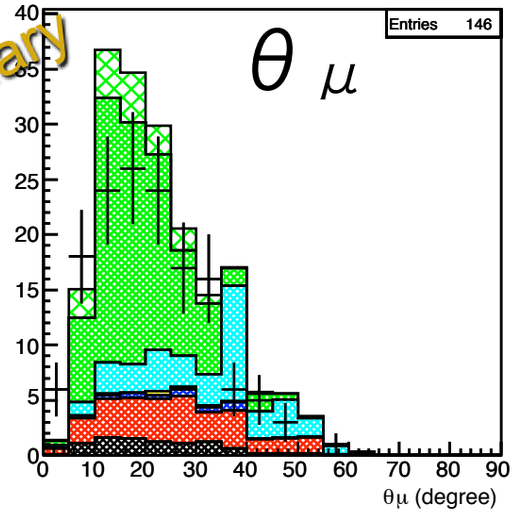
π track angle





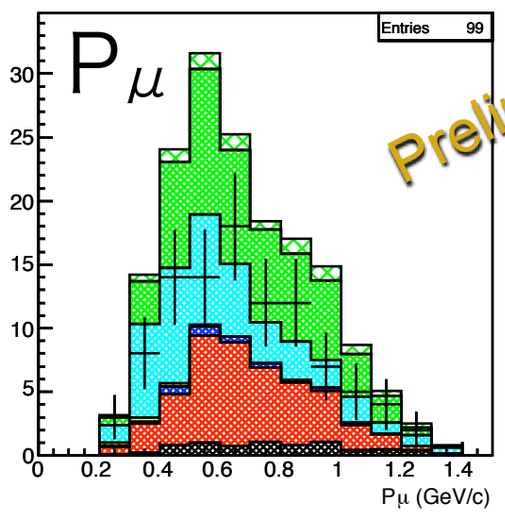
$\theta_\pi < 35$ deg

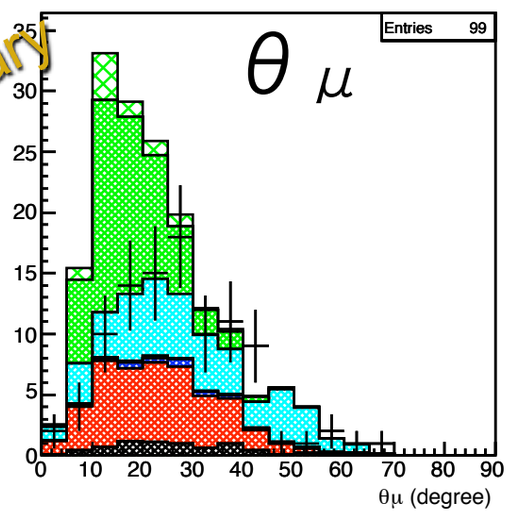




Preliminary

$\theta_\pi > 35$ deg





Preliminary

CC coherent π enhancement is similar to ν data.

Data suggest pion from CC coh π production tend to be more forward than model prediction.

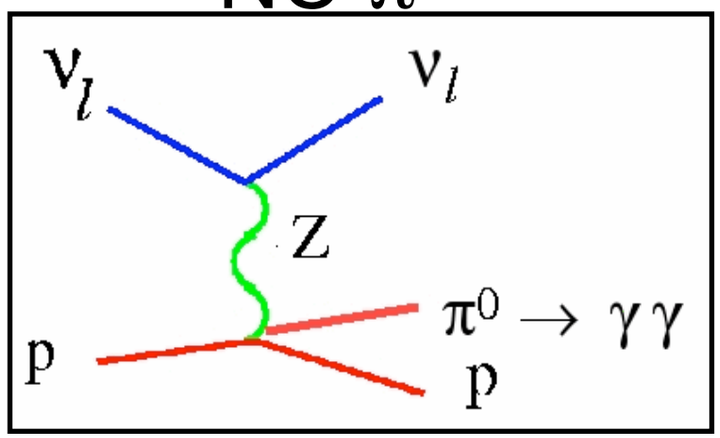
NC-π0

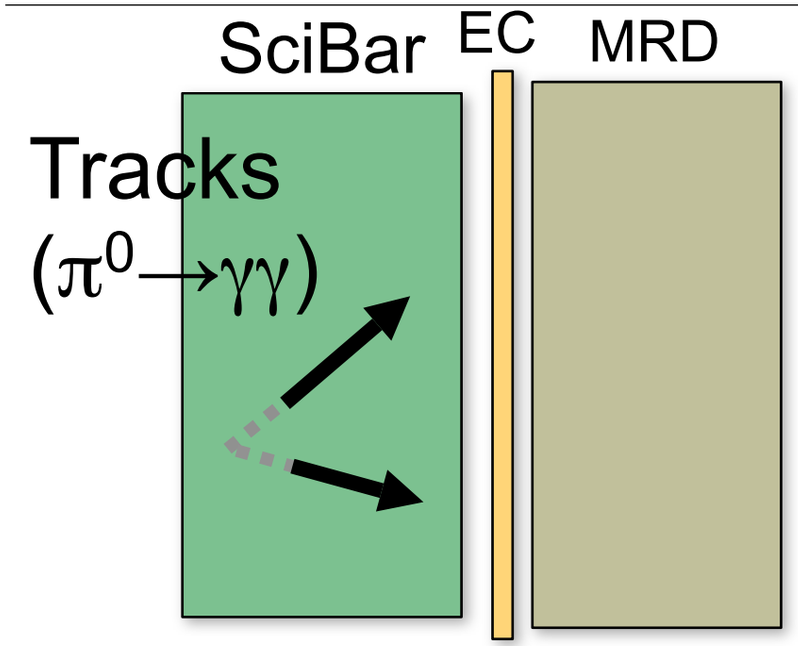
Neutral Current π0 production

NC-π0 in SciBooNE

Signal

NC-π^0

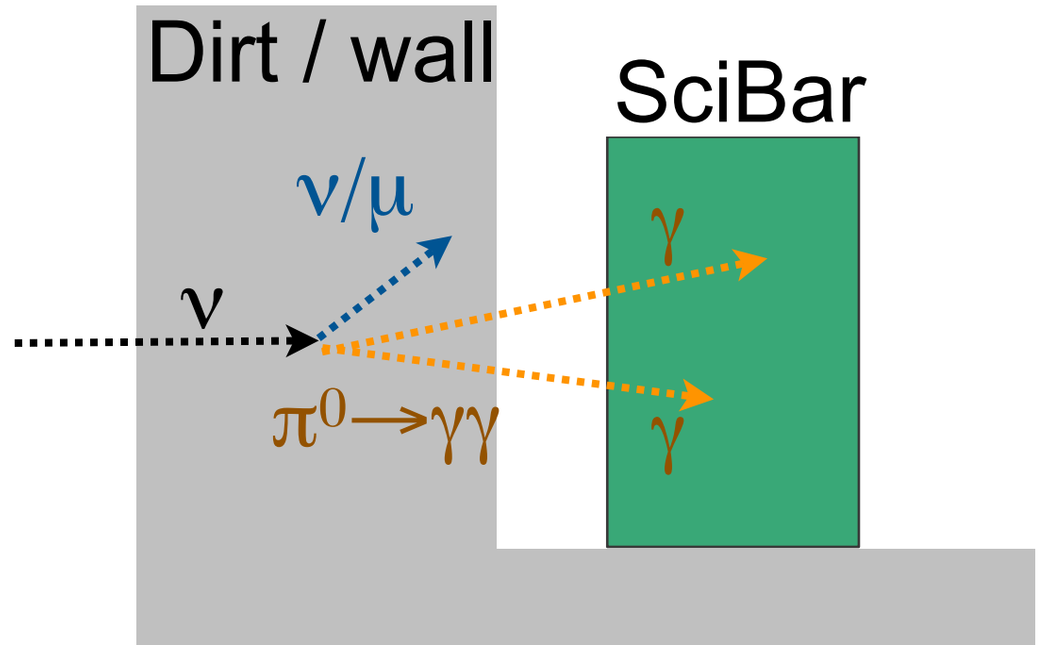




- No muon track
- Two isolated γ-like ($\gamma \rightarrow e^+e^-$) tracks
- All tracks full-contained in SciBar

Background

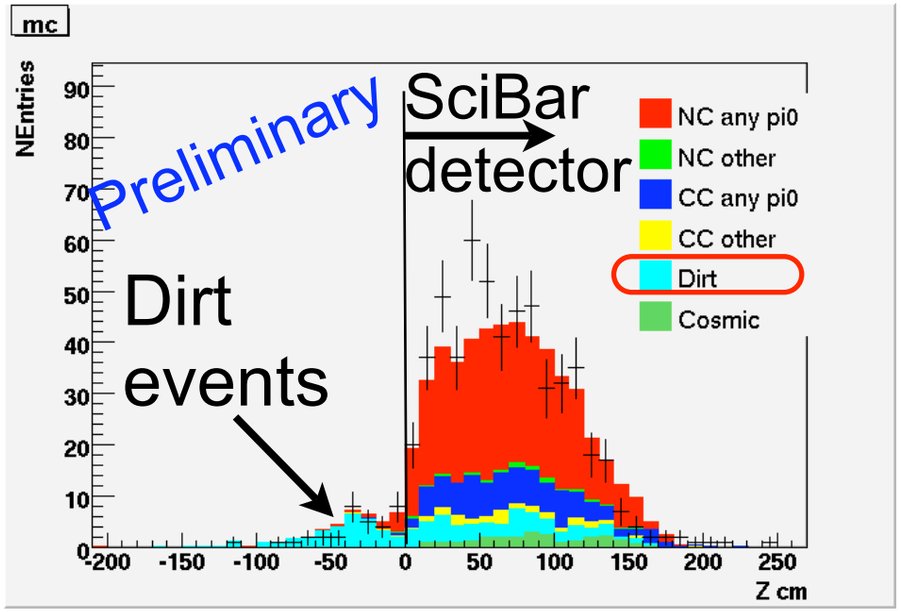
"Dirt event"
Neutrino interaction with material outside of SciBar detector (dirt), producing $\pi^0 \rightarrow \gamma\gamma$.



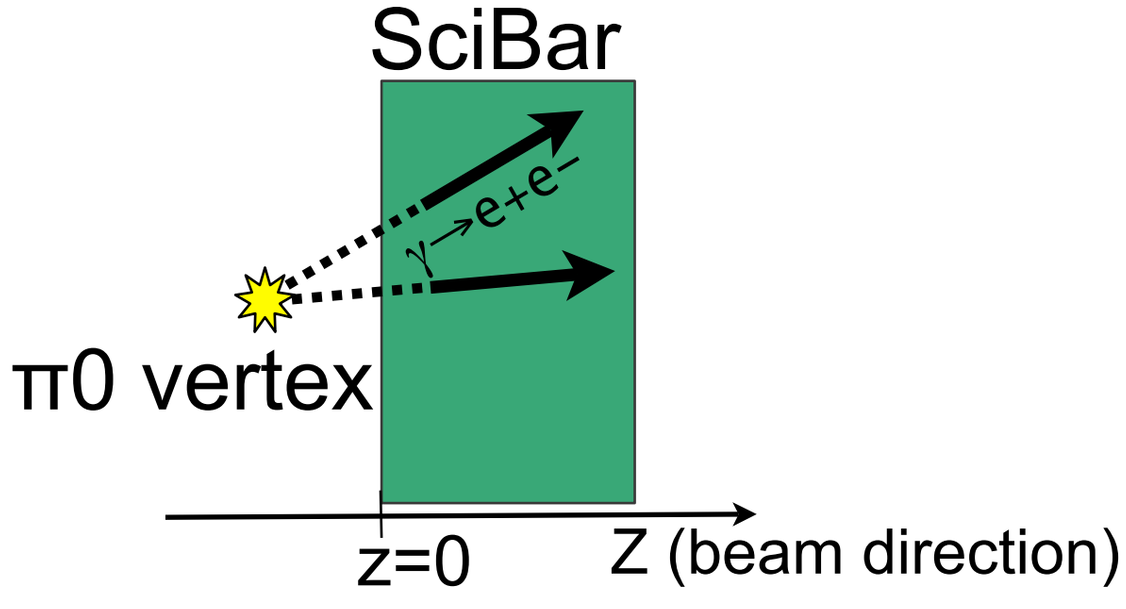
Reconstructing π0

Y. Kurimoto

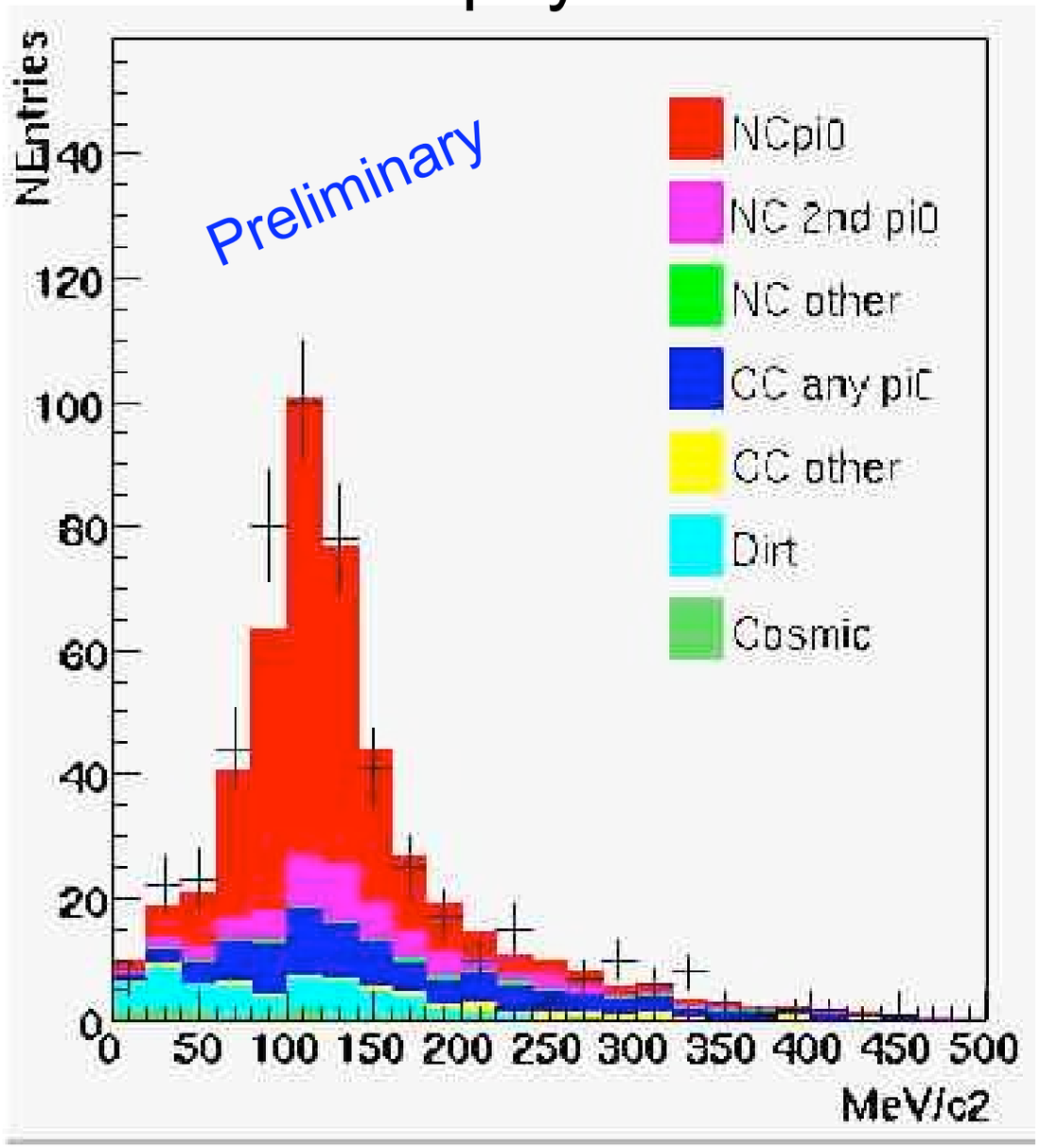
Reconstructed π0 vertex position



ex. Dirt event



Reconstructed invariant mass for 2γ system



Data: ~550 events
MC: ~60% NCπ0 purity

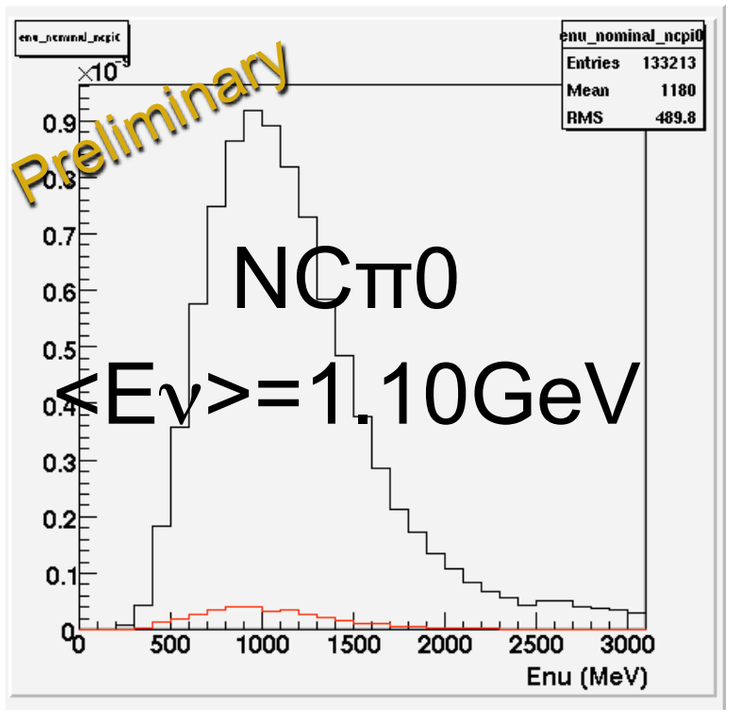
Results: cross section ratio

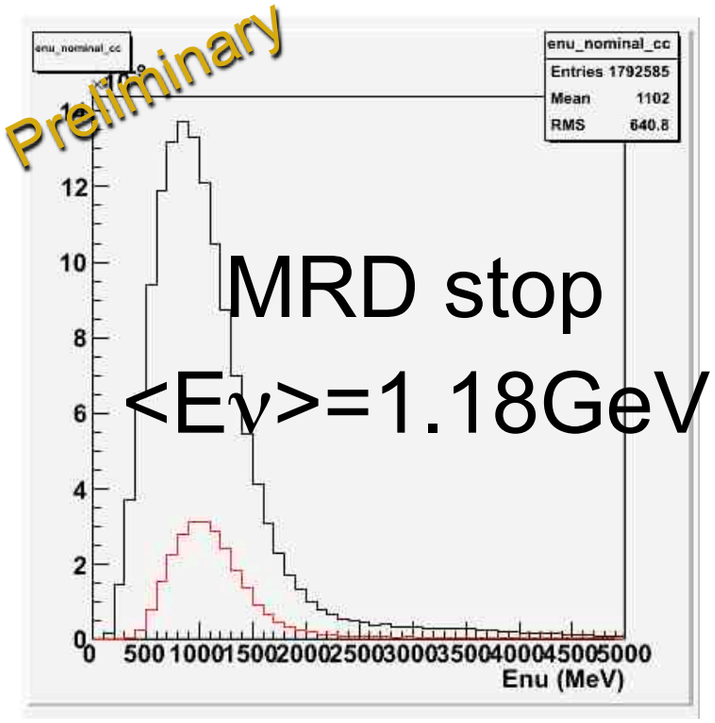
Cross section ratio: σ(NCπ0) / σ(CC)
(averaged over measured region)

Y. Kurimoto

$$\frac{\sigma(\text{NC-}\pi0)}{\sigma(\text{CC})} = 7.7 \pm 0.6(\text{stat}) \,^{+0.55}_{-0.55} (\text{syst}) \times 10^{-2}$$

cf. MC prediction: $\frac{\sigma(\text{NC-}\pi0)}{\sigma(\text{CC})} = 6.8 \times 10^{-2}$





Full systematic study is on-going.
Goal: Cross section as function of π0 momentum.

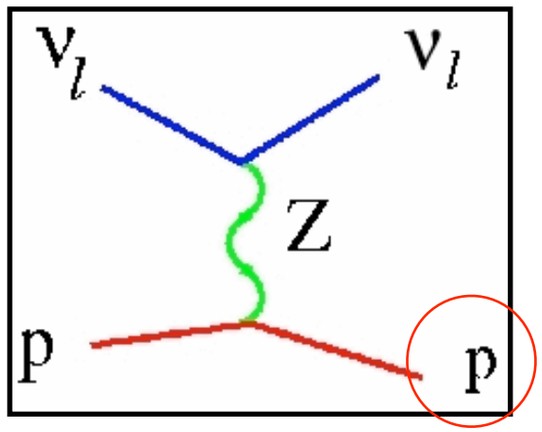
NC-elastic

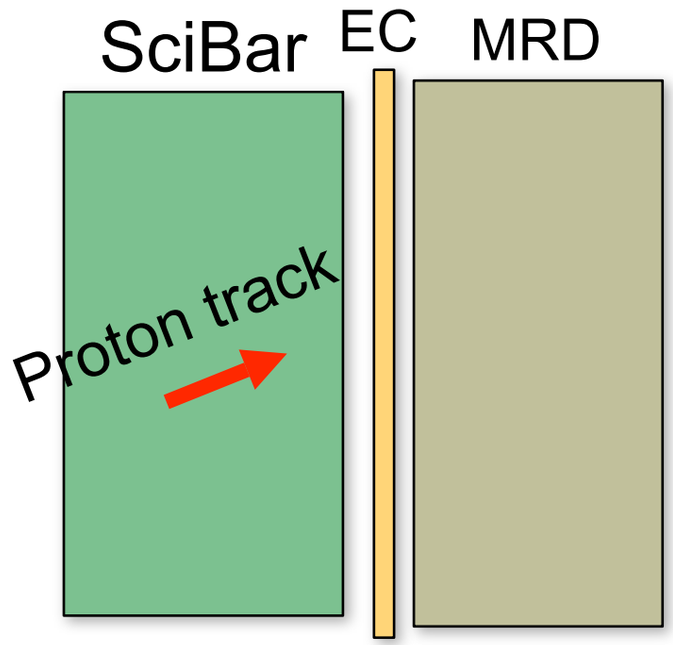
Neutral Current Elastic

NC-elastic in SciBooNE

Signal

NC-elastic

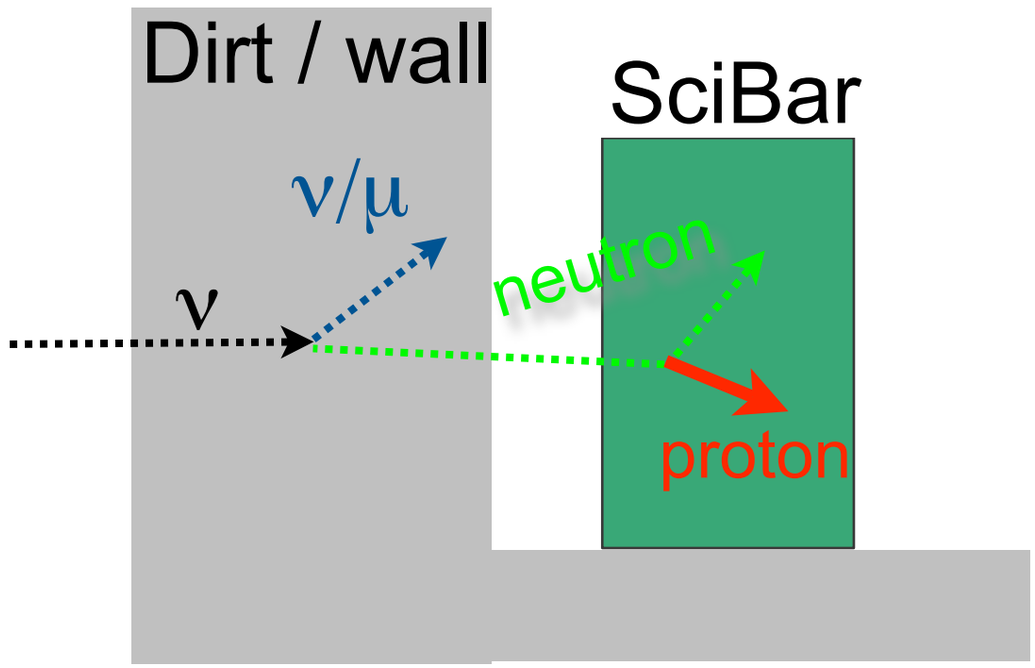




- No muon
- Only one proton track full-contained in SciBar

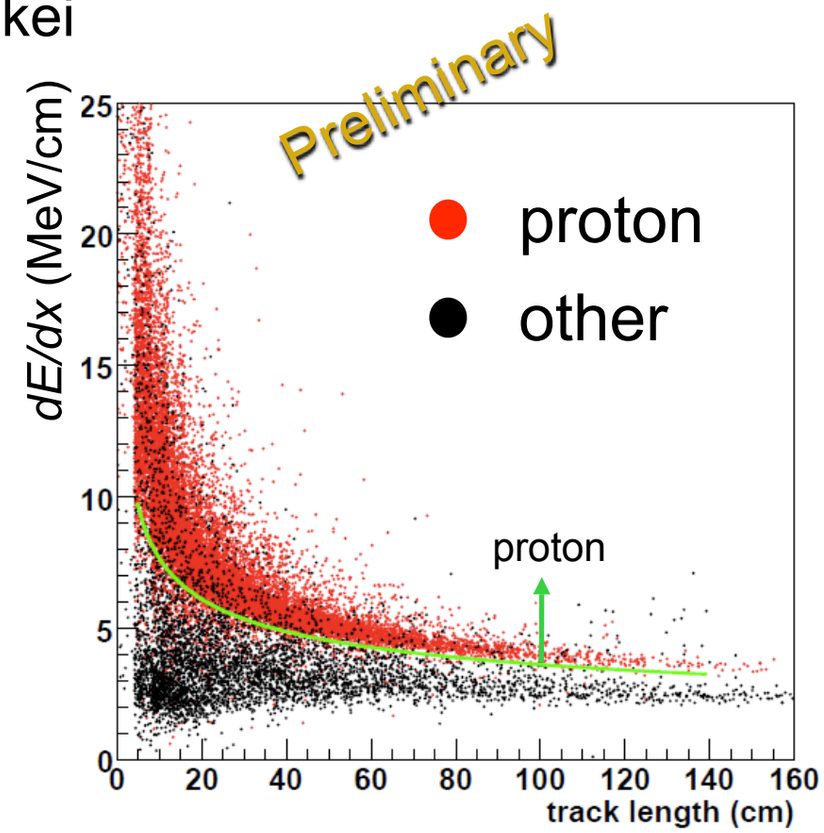
Background

"Dirt event"
Neutrino interaction with material outside of SciBar detector (dirt), producing neutron.

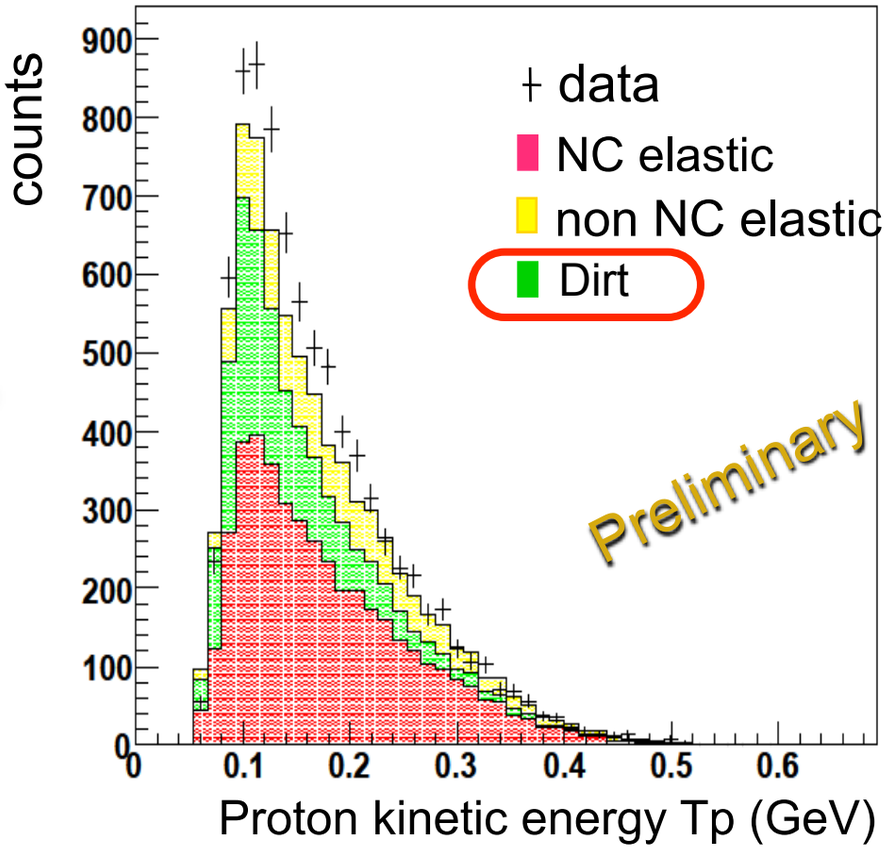


“Dirt event” contribution

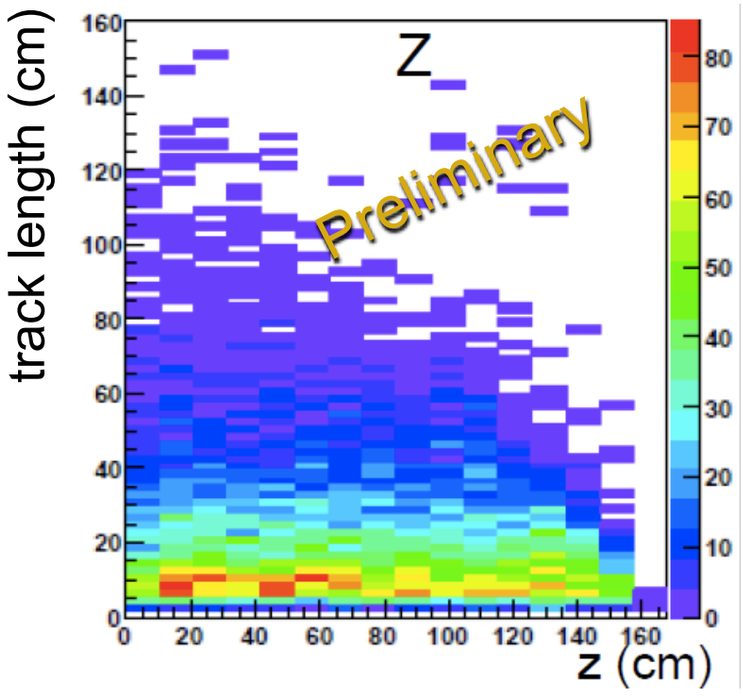
H. Takei



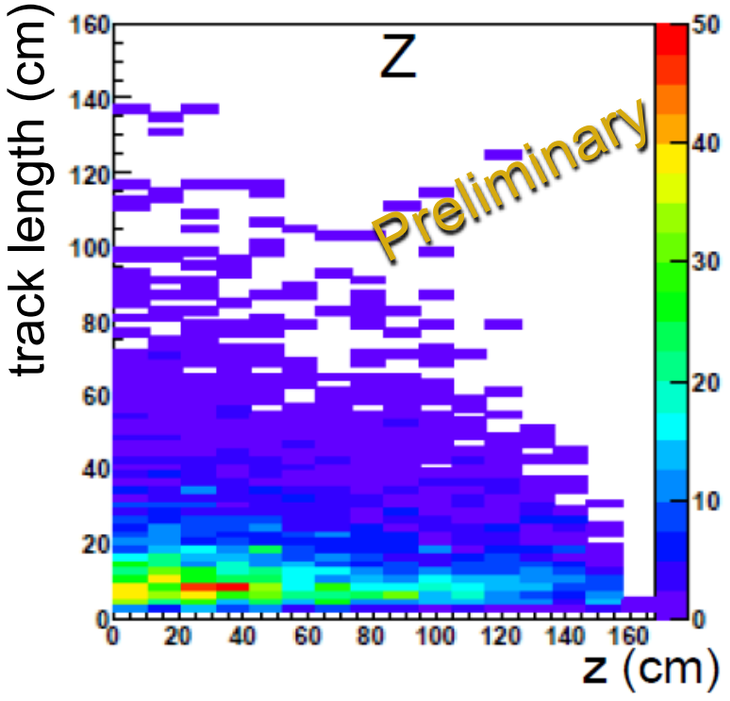
select proton-like events



Data



MC (Dirt)

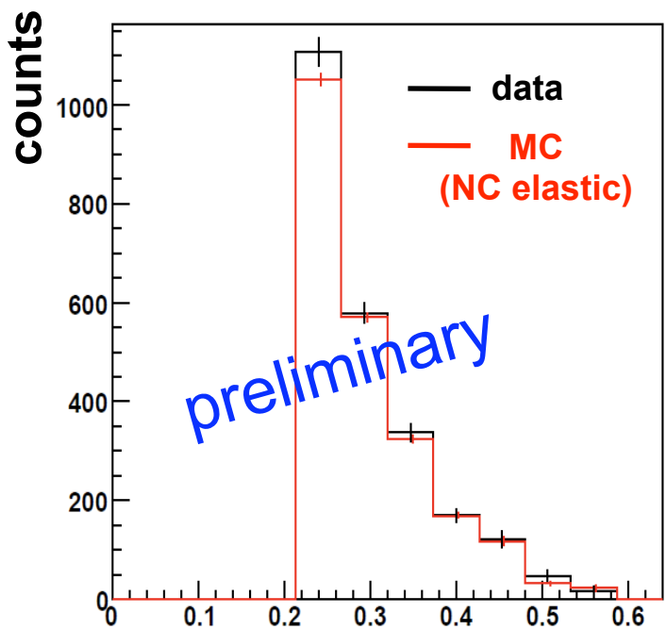


Dirt events tend to be:
- Low proton-kinetic energy
- Concentrate in upstream (near wall)

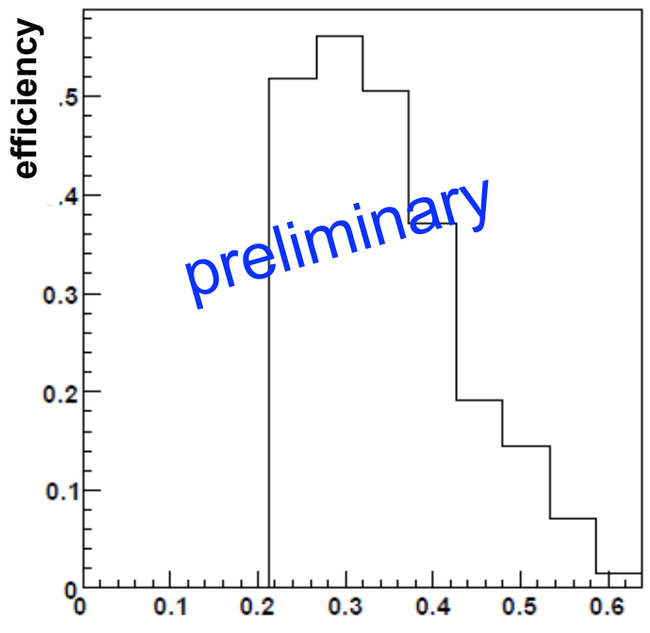
➜ Cut off low-*Tp* events && subtract “Dirt event”

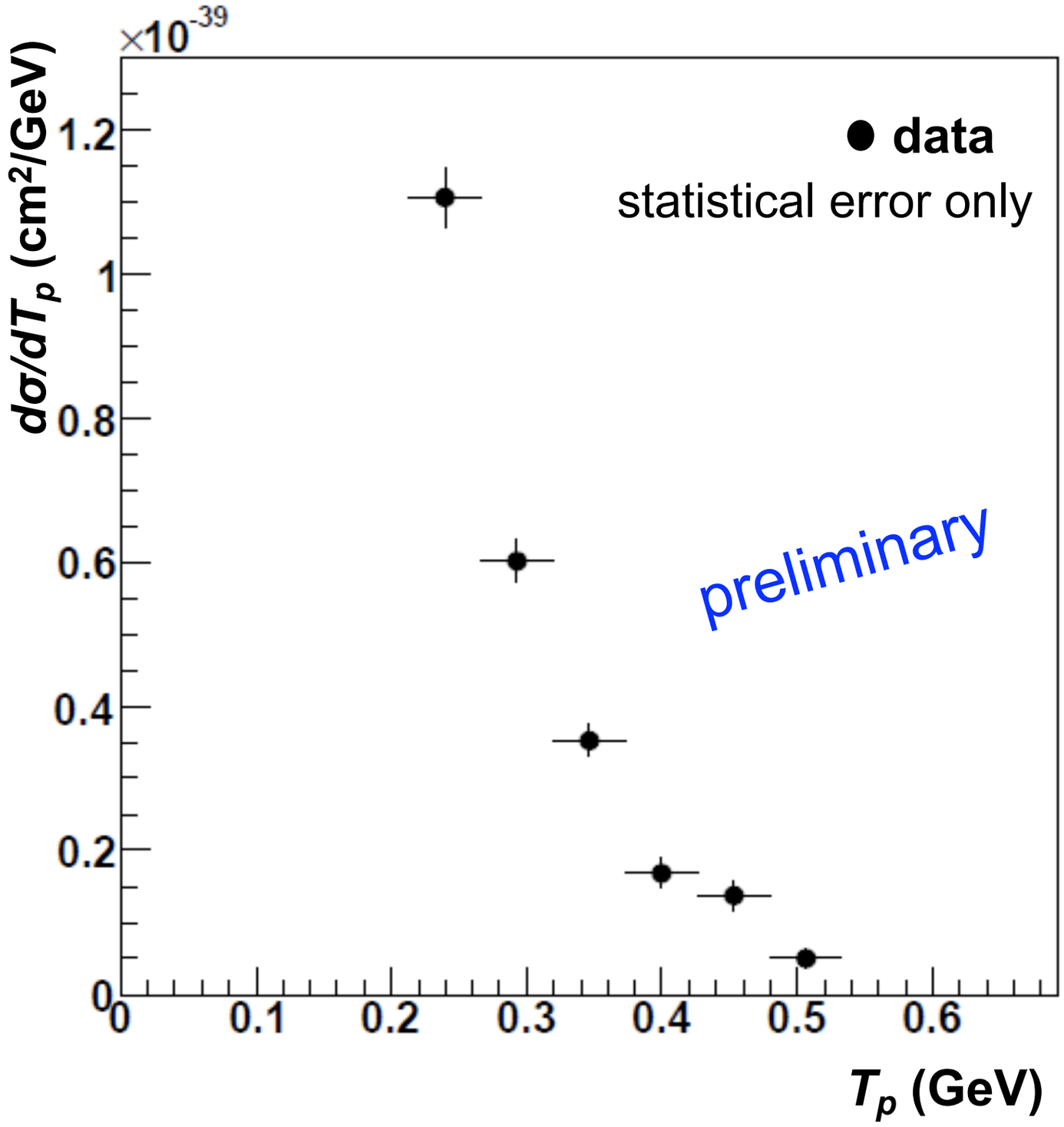
Differential cross section

H. Takei



T_p efficiency

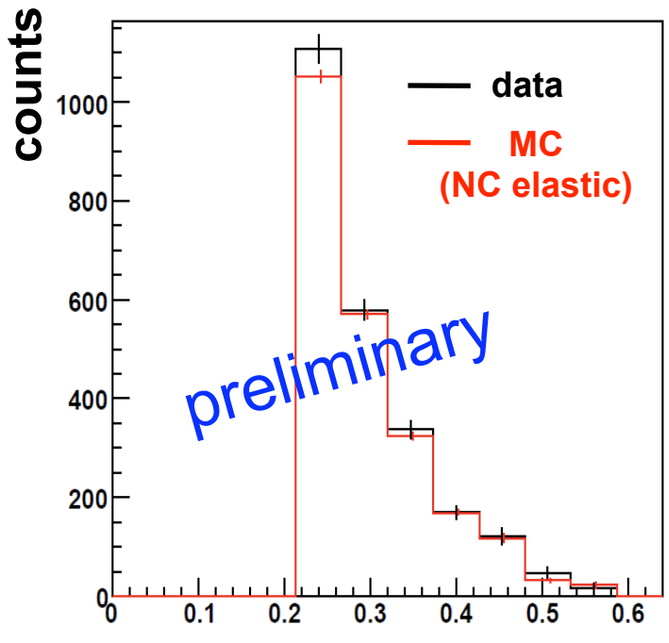




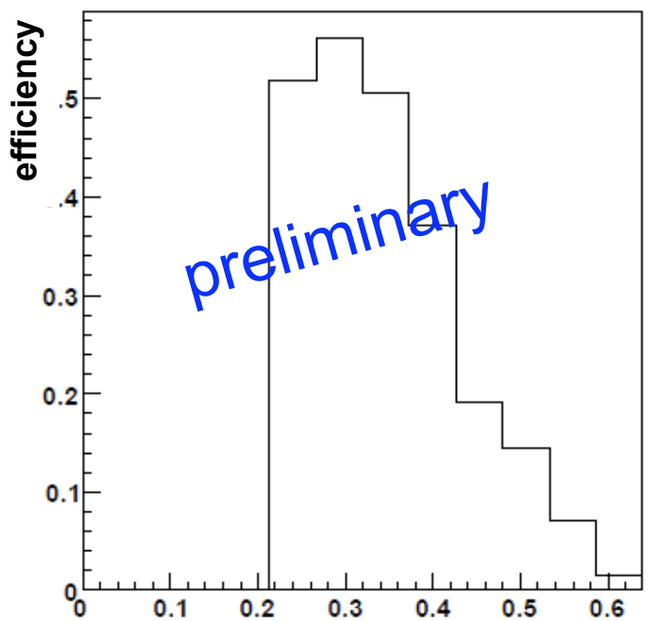
Systematic study is on-going.

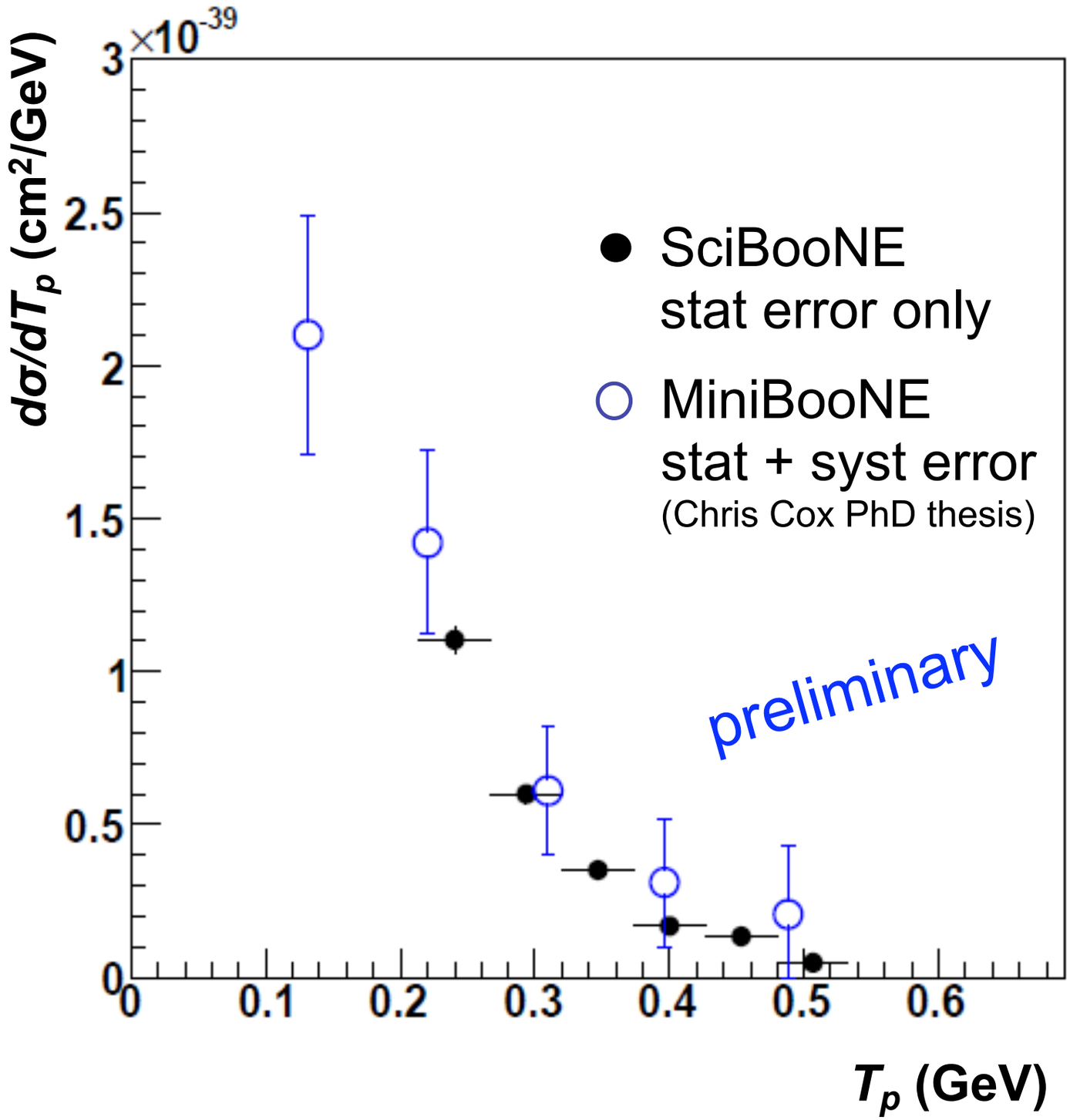
Differential cross section

H. Takei



T_p efficiency



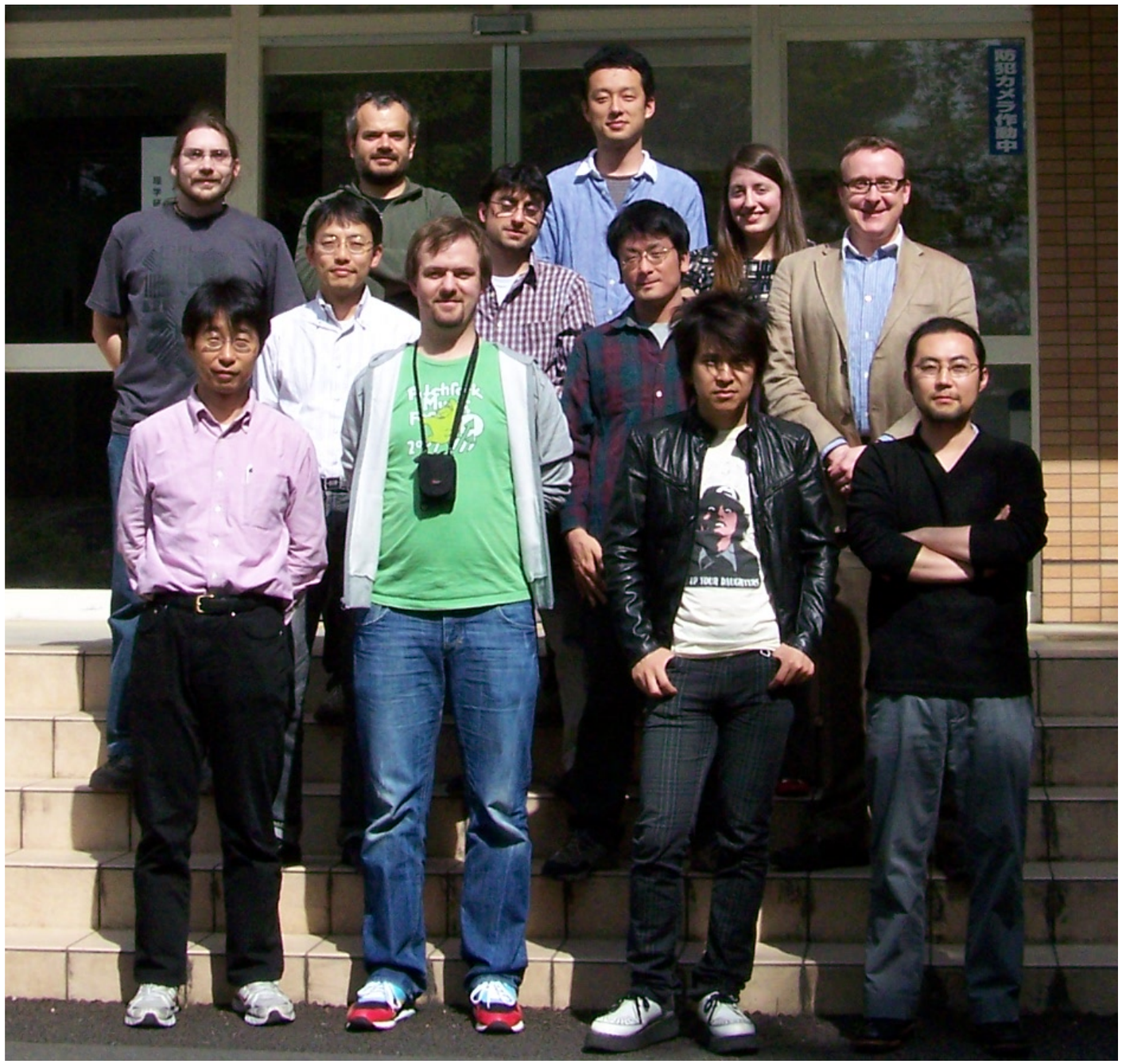


Systematic study is on-going.

Summary

- New SciBooNE results
  - –CC-QE:
    - Absolute cross section (Eν)
  - –CC coherent π in ν and $\overline{\nu}$ beam:
    - Non zero CC coherent π
    - Pion from CC coh. π production tend to be more forward than model prediction.
  - –NC-π0:
    - Cross section ratio to total CC events
  - –NC-elastic:
    - Absolute cross section (T_p)
- All these analyses will be finalized in this summer.

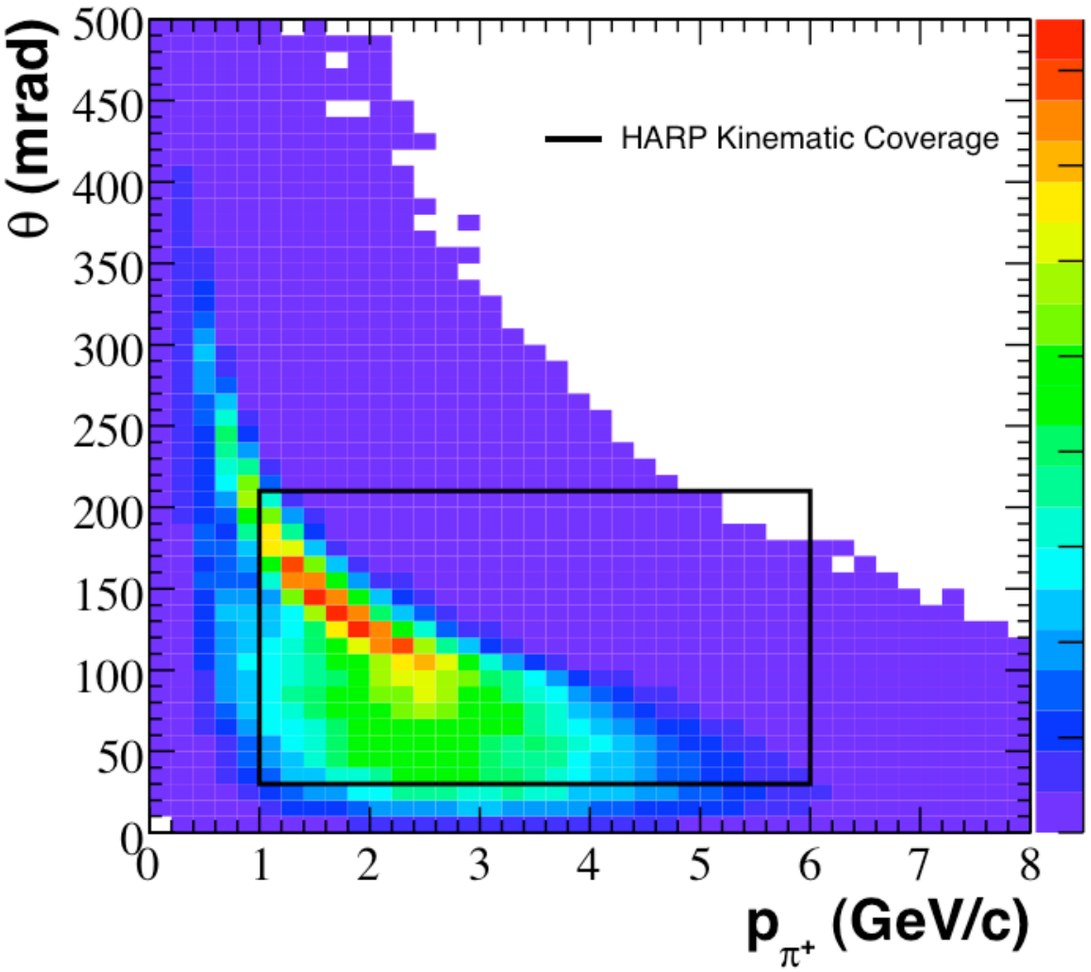
Thank you!

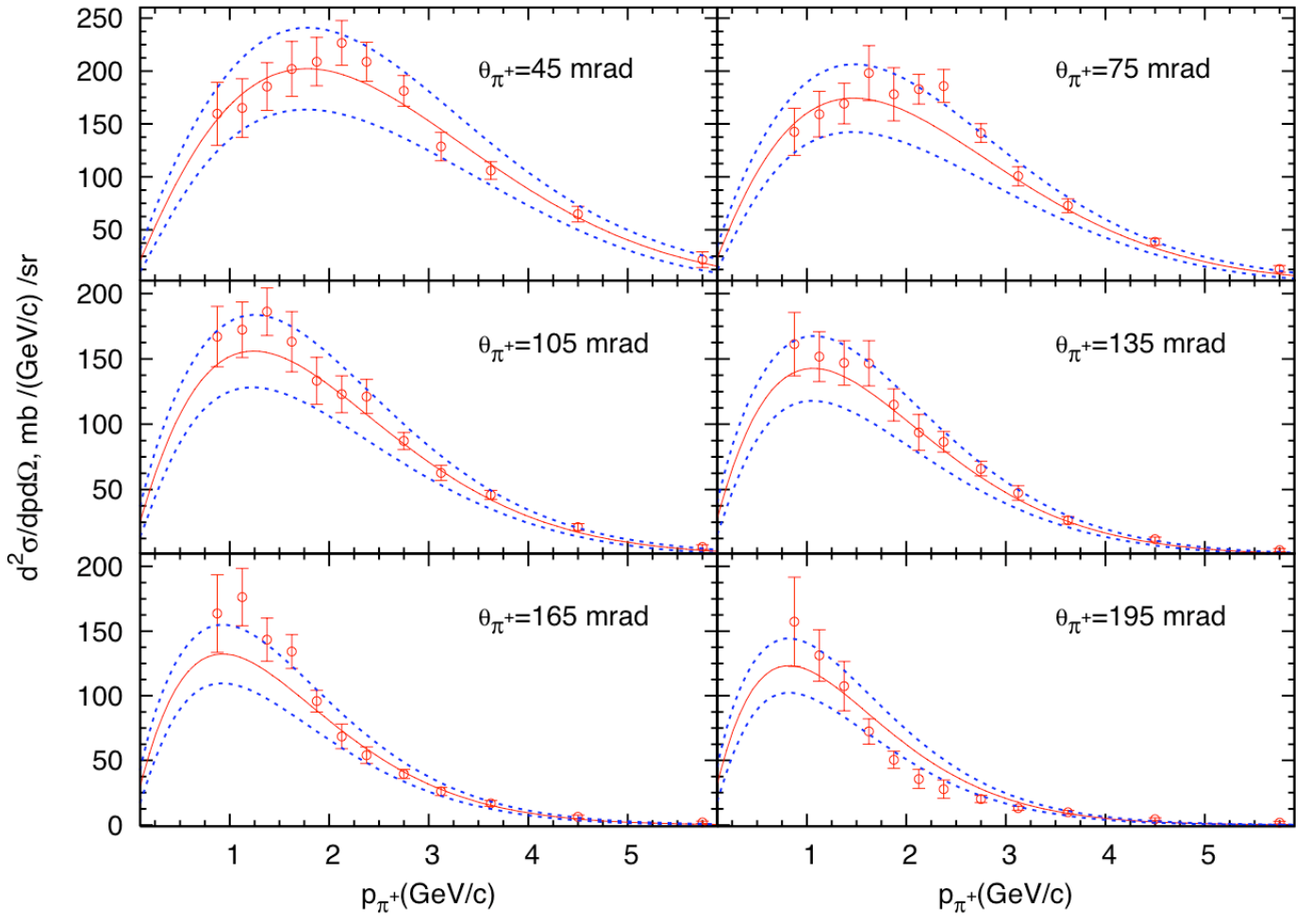


Collaboration Meeting at Kyoto
May, 2009

Backup

Hadron production



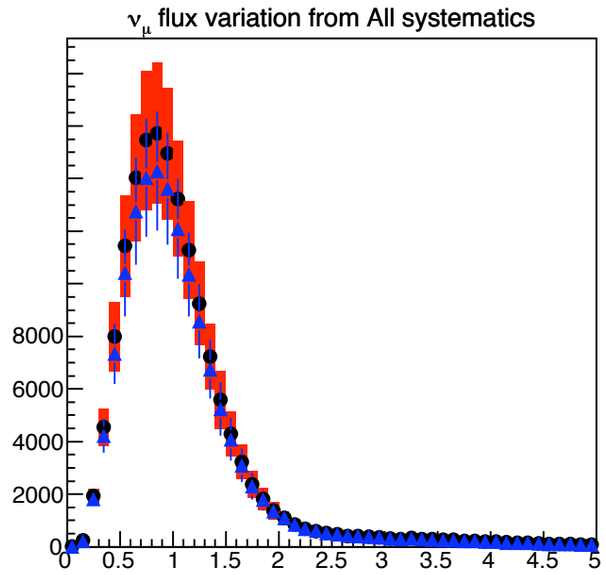


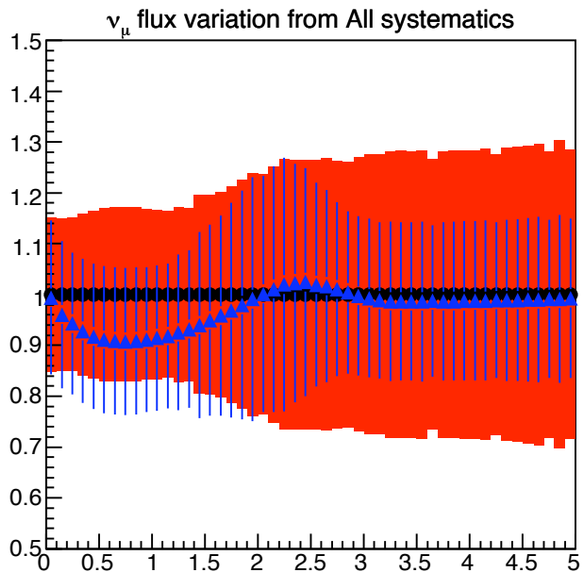
HARP -- 8.89 GeV/c p-Be (thin target)

Plots from arXiv:0806.1449

Systematic error on flux

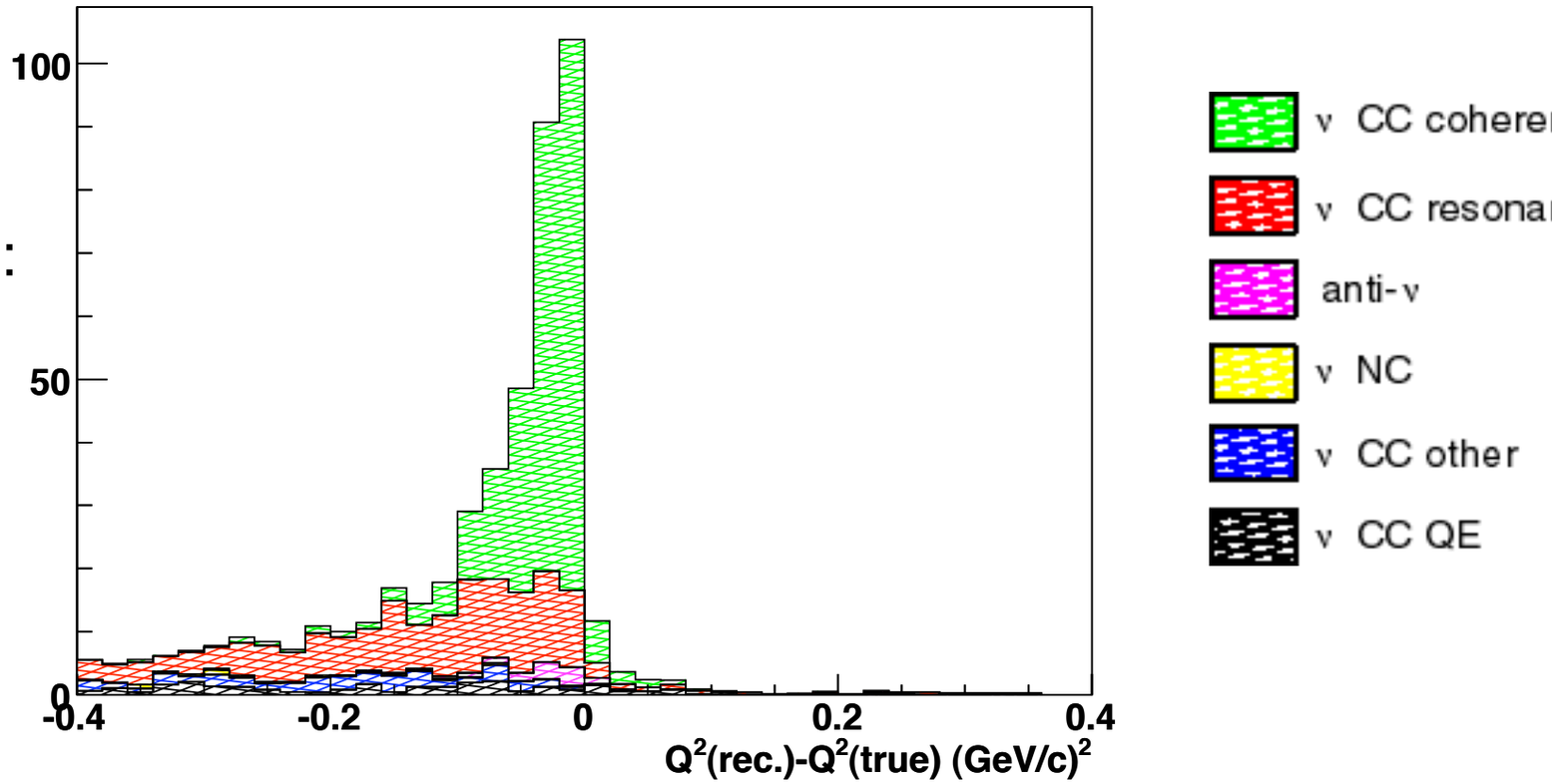
Pi+ production	14.1%
Pi- production	0.0%
K+ production	1.8%
K0 production	0.0%
Horn skin effect	3.2%
Horn current	0.7%
nucleon-Be	3.0%
Pion-Be	1.8%
Total	15.0%





Q^2 resolution (coherent π)

Q^2 resolution of CC-coherent π :
Mean: -0.024 $(GeV/c)^2$
Sigma: 0.016 $(GeV/c)^2$



Assume CC-QE

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

$$E^{rec}_{\nu} = \frac{1}{2}\frac{(M^2_p - m^2_\mu) - (M_n - V)^2 + 2E_\mu(M_n - V)}{(M_n - V) - E_\mu + p_\mu \cos\theta_\mu}$$