Measurements of Neutrino Charged Current Interactions at SciBooNE

Yasuhiro Nakajima (Kyoto University)

November 13th, 2008

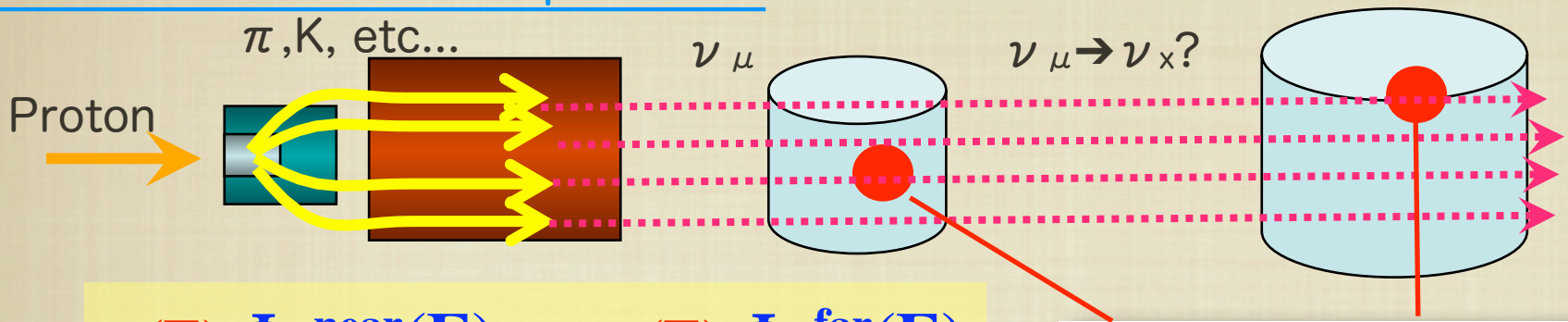
PANIC 2008, Eilat, Israel

Contents

- SciBooNE Experiment
- Neutrino Flux Measurement
- Search of Charged Current Coherent Pion Production
- Summary

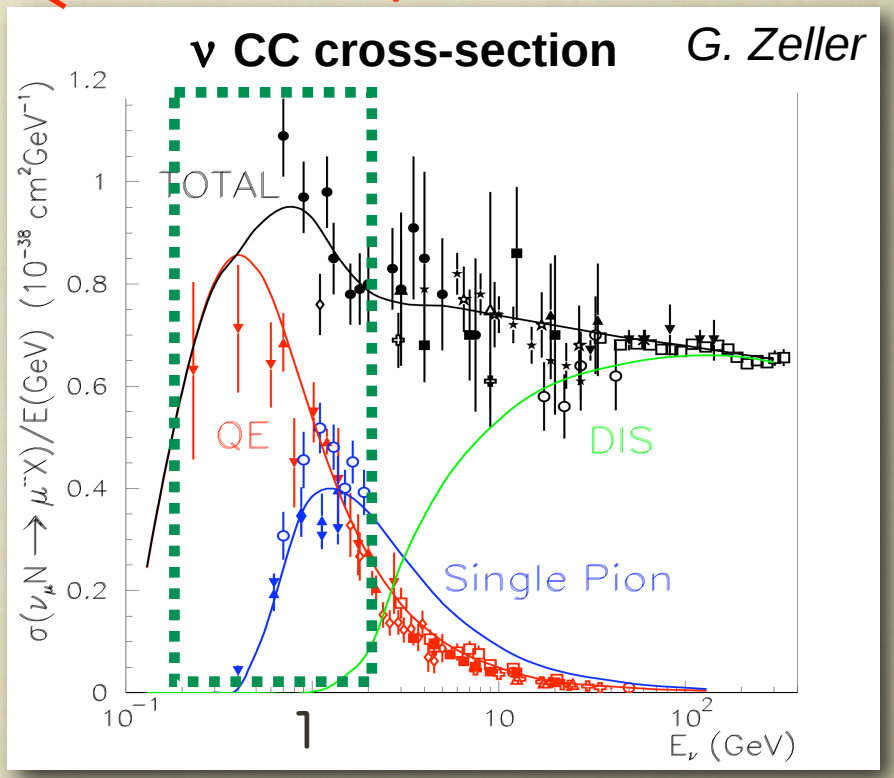
Introduction

Neutrino oscillation experiment



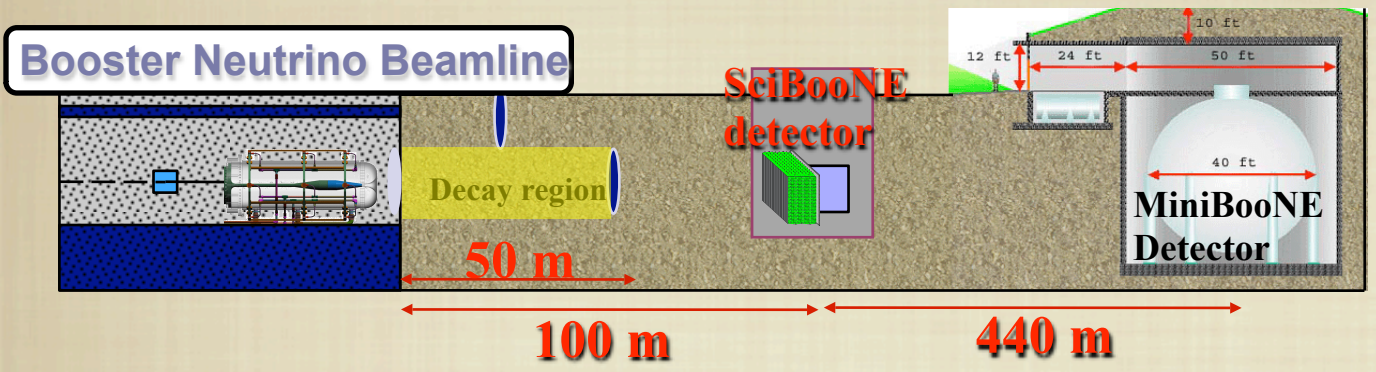
$$\sigma(E)\cdot\Phi_{\nu}^{near}(E) \Leftrightarrow \sigma(E)\cdot\Phi_{\nu}^{far}(E)$$

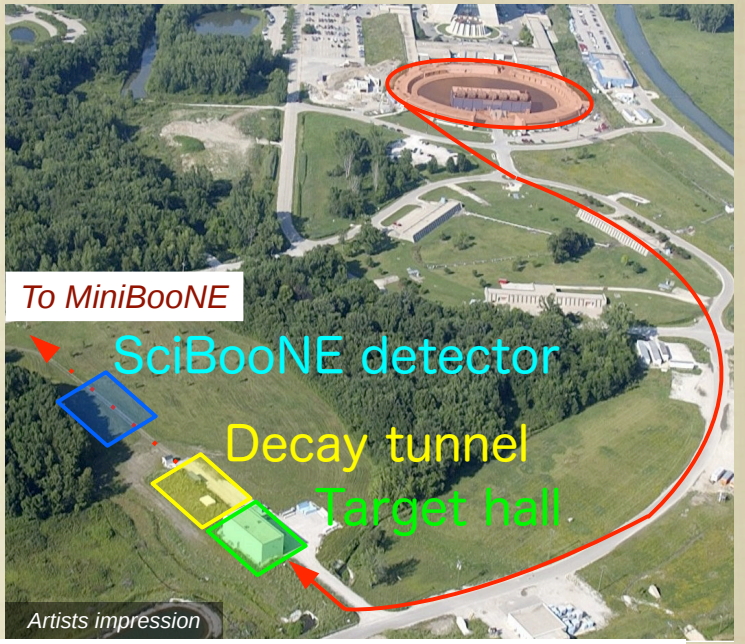
- Neutrino-nucleus cross-sections at 1 GeV region are not well known
  - Energy region for future neutrino experiments (T2K/ Noνa)
- MiniBooNE and K2K are revealing surprises.



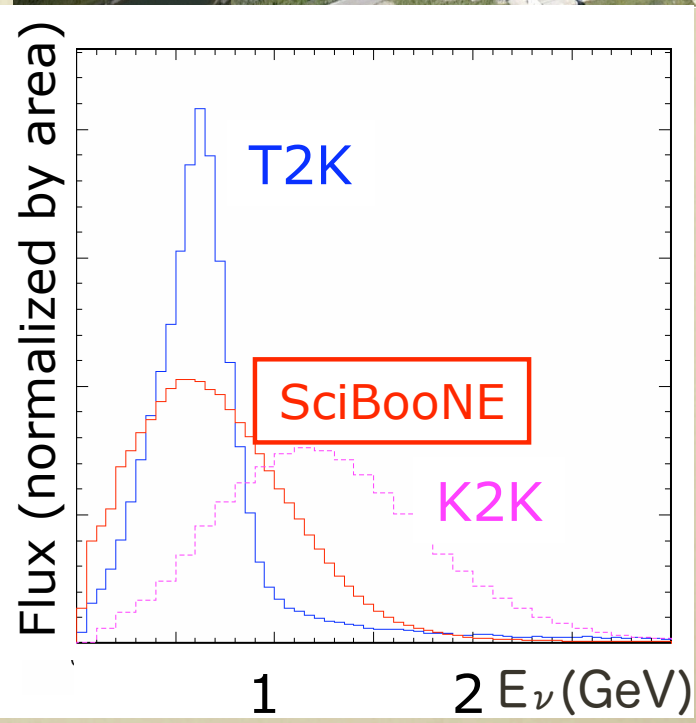
Need precise measurements in this energy region.

SciBooNE Experiment





- Fine-grained detector (SciBar) on the Fermilab Booster Neutrino Beamline.
- Cross section measurement for ~1 GeV neutrino and anti-neutrino
  - Essential for future neutrino oscillation measurements (T2K, etc)
- MiniBooNE near detector

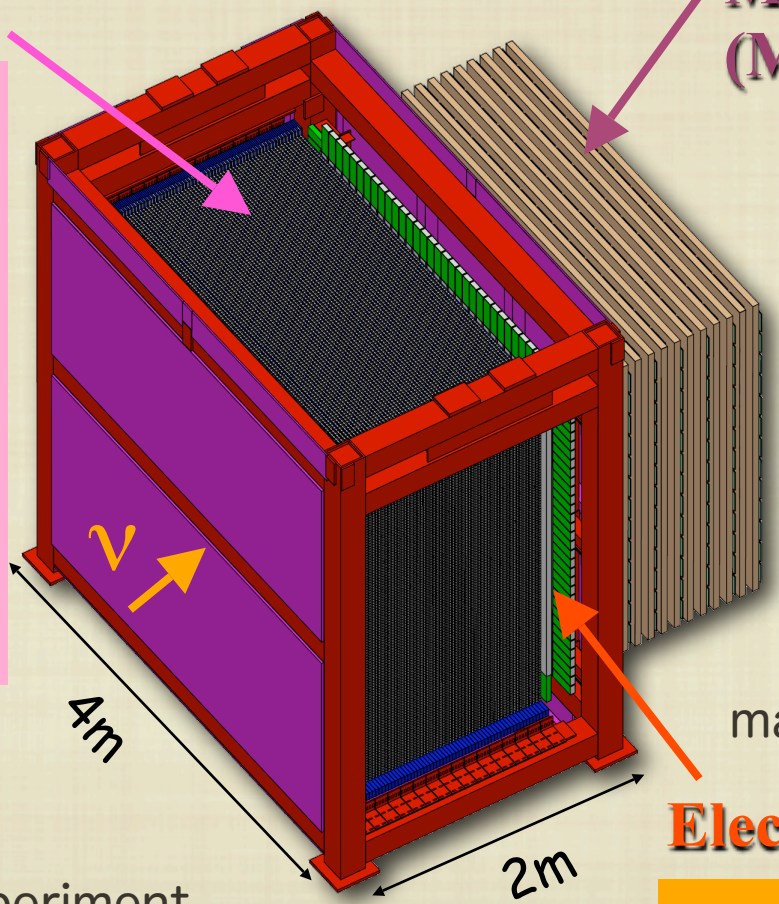


SciBooNE Detector

SciBar

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

Used for K2K experiment. Shipped to and re-assembled at FNAL



Muon Range Detector (MRD)

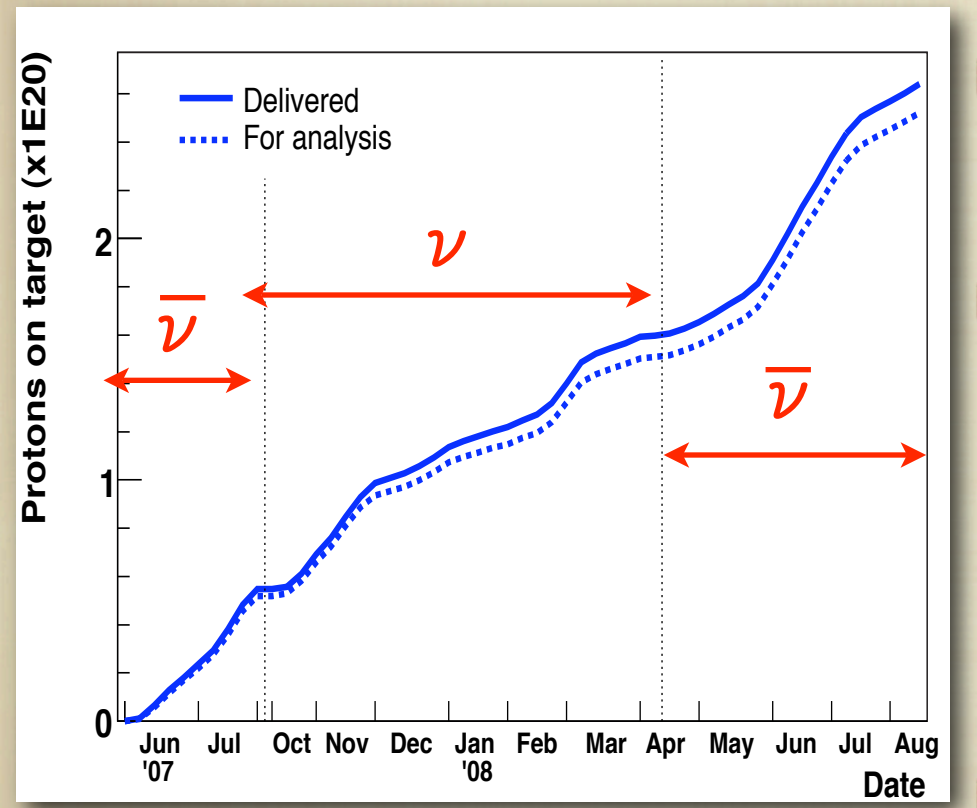
- 12 2"-thick steel + scintillator planes
- measure muon momentum with range up to 1.2 GeV/c

Newly built at FNAL with materials from past experiments

Electron Catcher (EC)

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

SciBooNE Data Taking



- Start beam data taking in June 2007
- Data taking completed on August 18th, 2008
- Total 2.52x10^{20} POT for analysis (95% of delivered)
  - Neutrino: 0.99x10^{20} POT
  - Anti-neutrino: 1.53x10^{20} POT
- Stable data taking

Results from full neutrino data set are presented today

SciBooNE Analysis

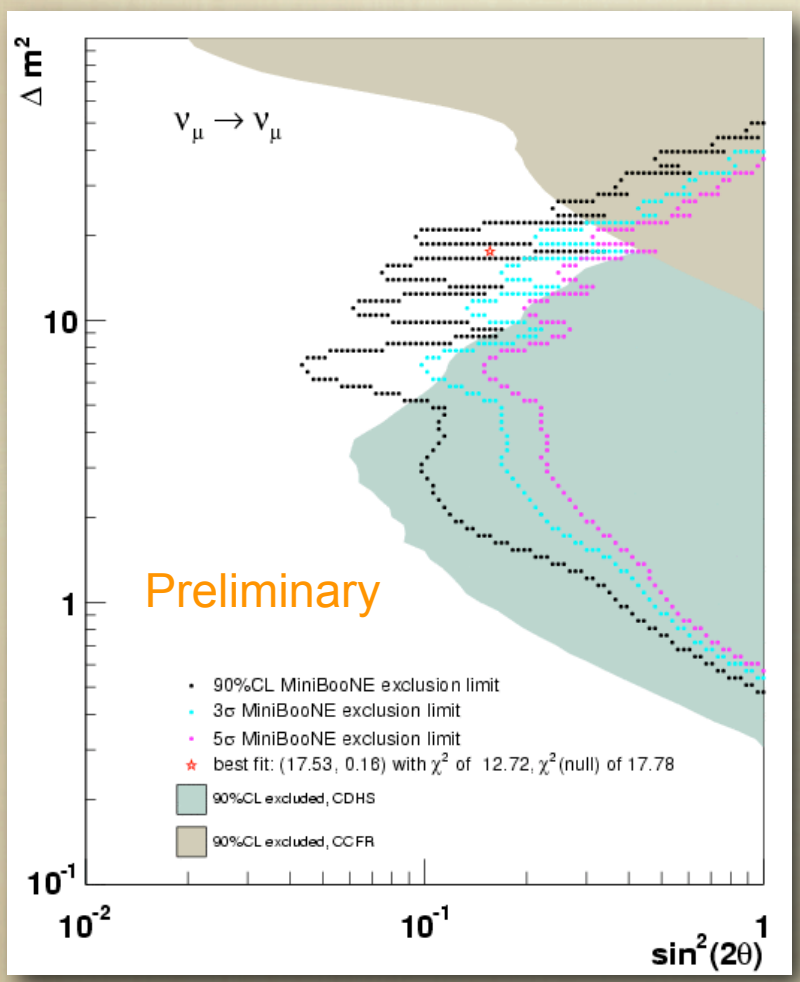
- Neutrino energy spectrum measurements
  - SciBooNE/MiniBoooNE joint ν_μ disappearance search
  - Beam ν_e flux measurement for MiniBooNE
- Cross section measurements
  - CC-1π^+ production
  - CC-QE scattering
  - CC-1π^0 production
  - NC-1π^0 production
  - NC elastic scattering
  - Anti-neutrino cross-sections

Covered by this talk

Presented by J. Catala at the poster session

ν_μ Spectrum Measurement

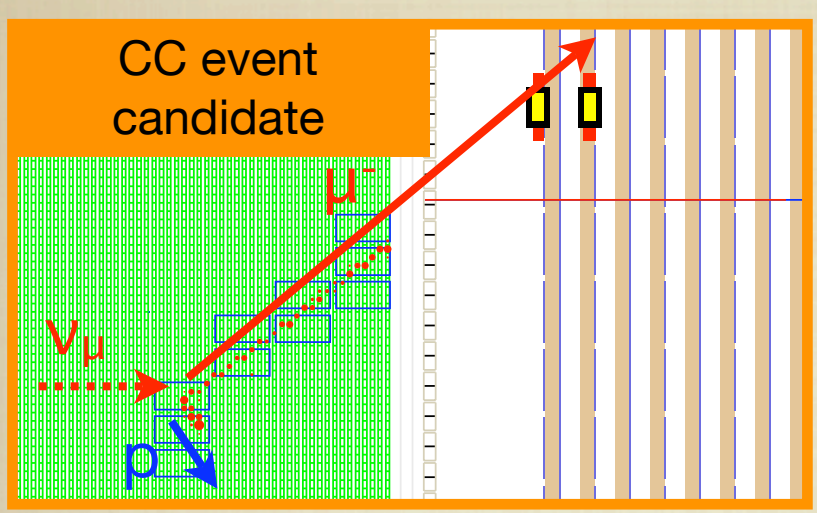
Result of MiniBooNE-only ν_μ disappearance search (**shape only** analysis)

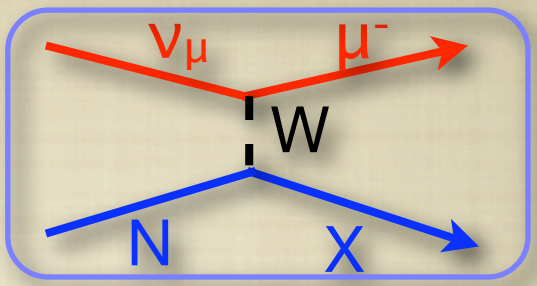


- MiniBooNE/SciBooNE joint ν_μ disappearance search
  - Share beamline
  - Share target material

  ⇒ Strong constraint for flux and cross-sections at MiniBooNE (Shape + Normalization)
- Feed-back to cross section measurements at SciBooNE

Event Selection

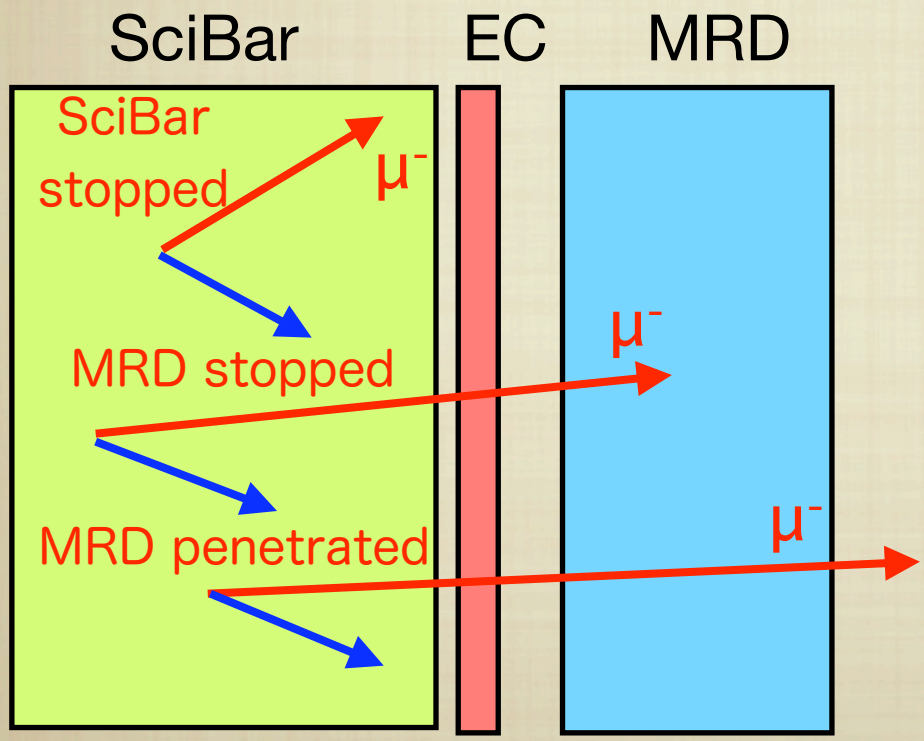


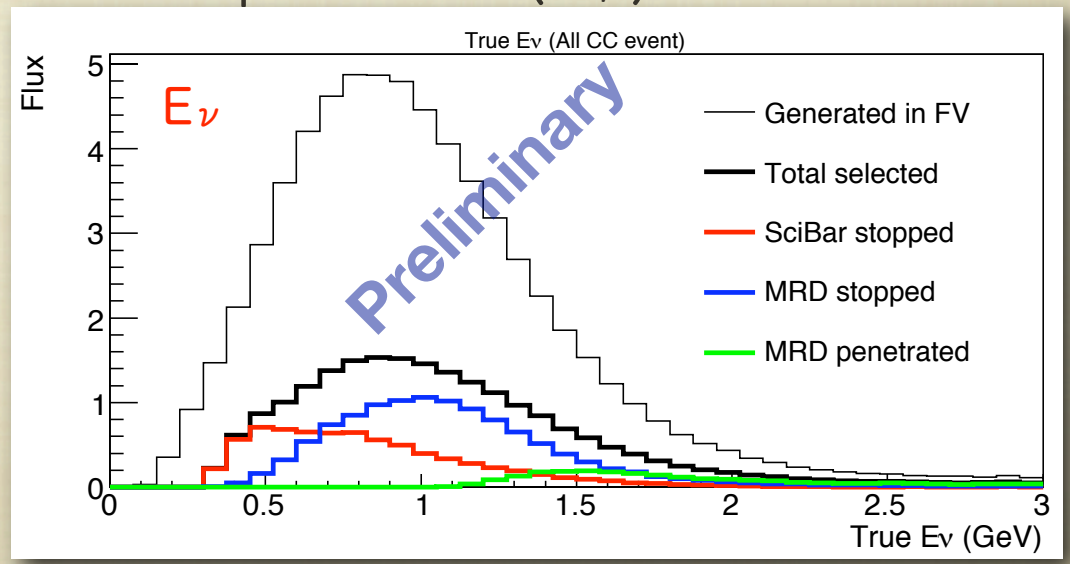


Use charged current inclusive sample

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

P_μ: Muon momentum reconstructed by its path-length
θ_μ: Muon angle w.r.t. beam axis





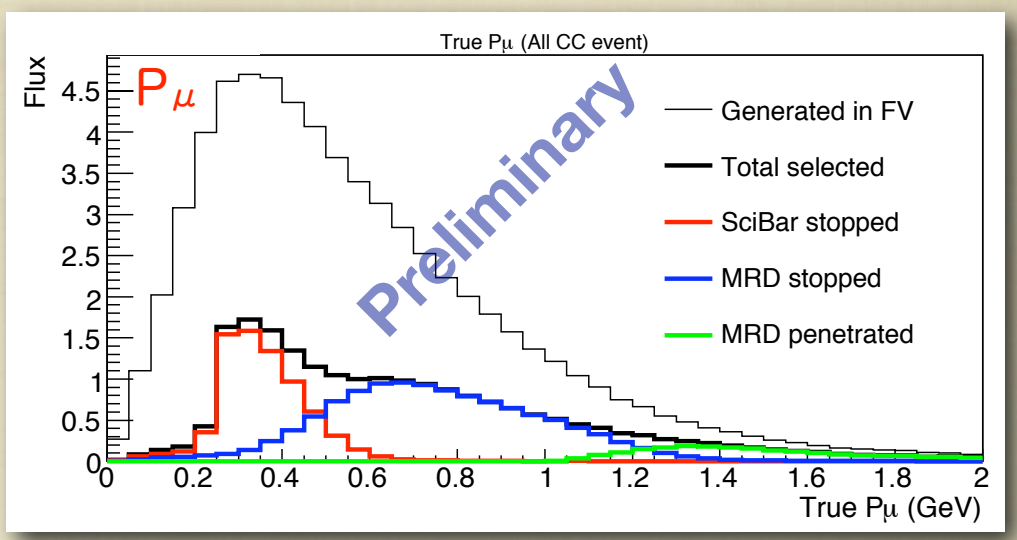
Extracting E_ν Spectrum

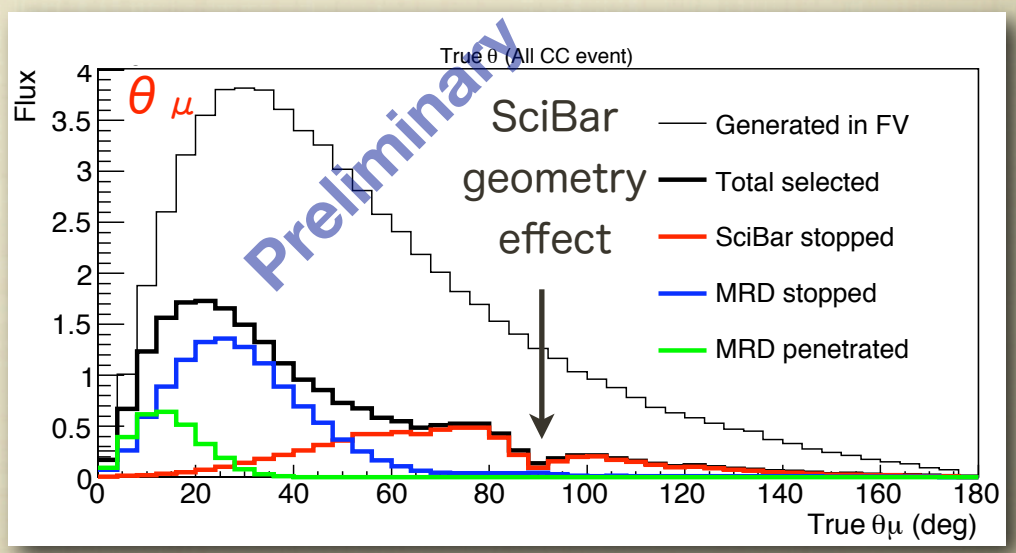
- Use muon kinematics to extract E_ν information

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

(Assuming CC-quasi-elastic scattering)

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

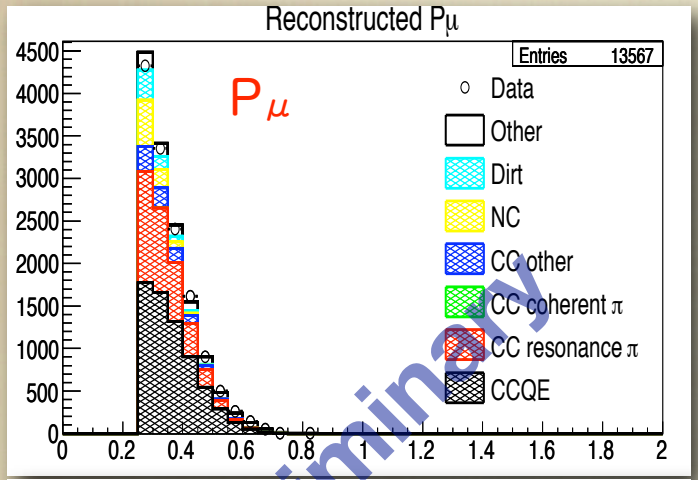


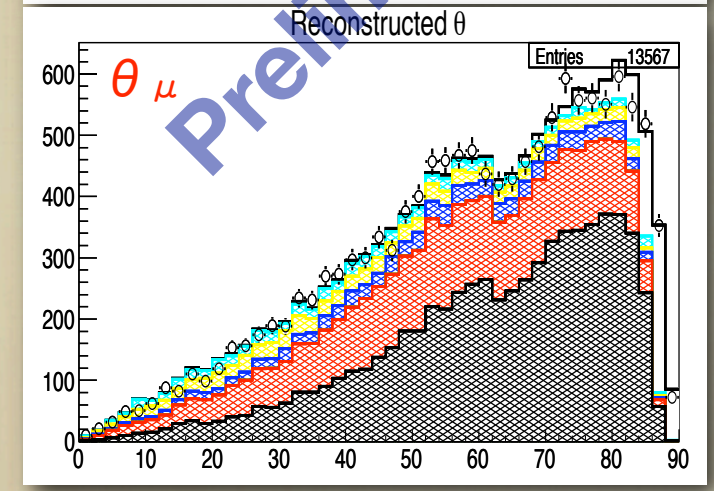


Muon Kinematics

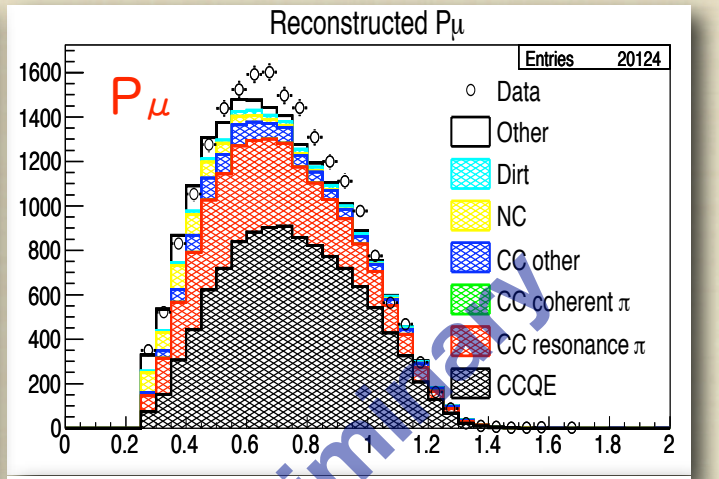
MC are relatively normalized to data by the number of SciBar-MRD matched event.

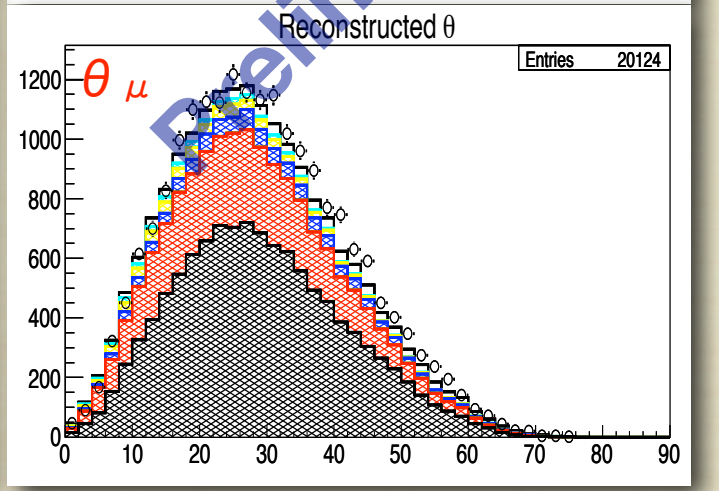
SciBar stopped (P_μ, θ_μ)



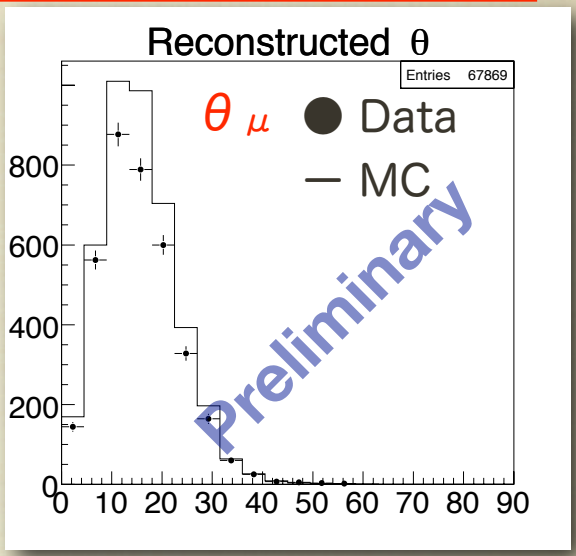


MRD stopped (P_μ, θ_μ)





MRD penetrated (θ_μ)

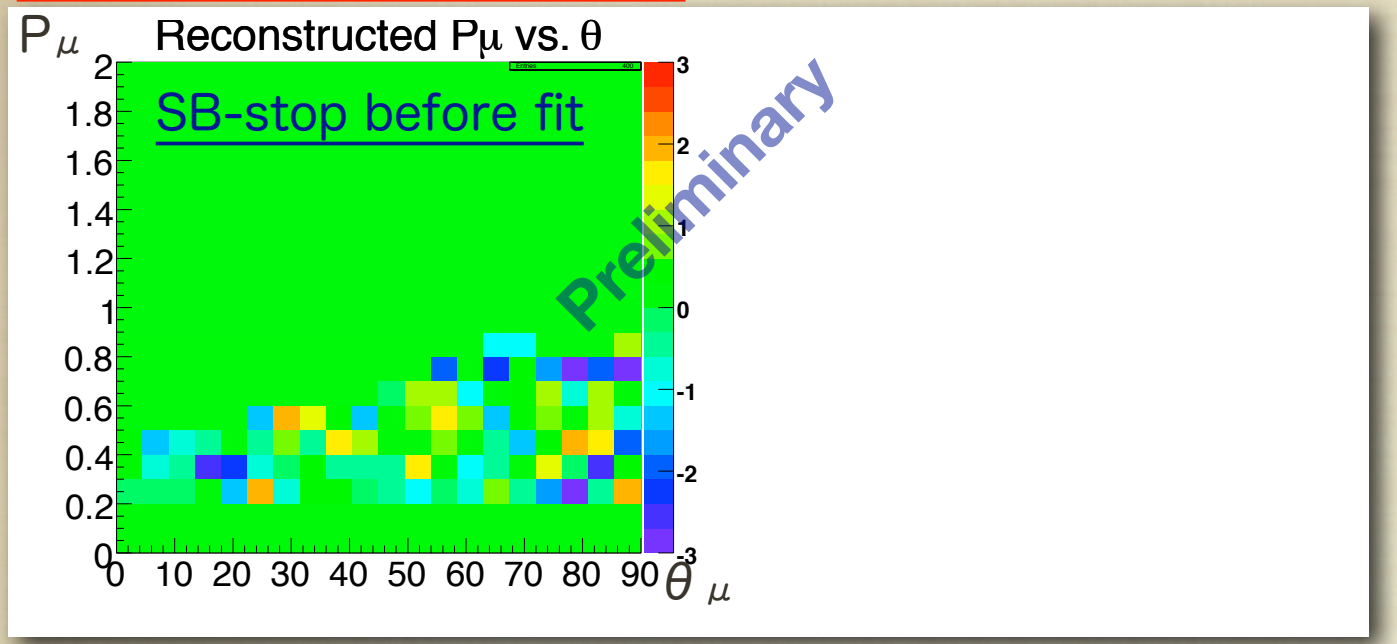


(Unable to reconstruct P_μ since muons are not stopped in the detectors)

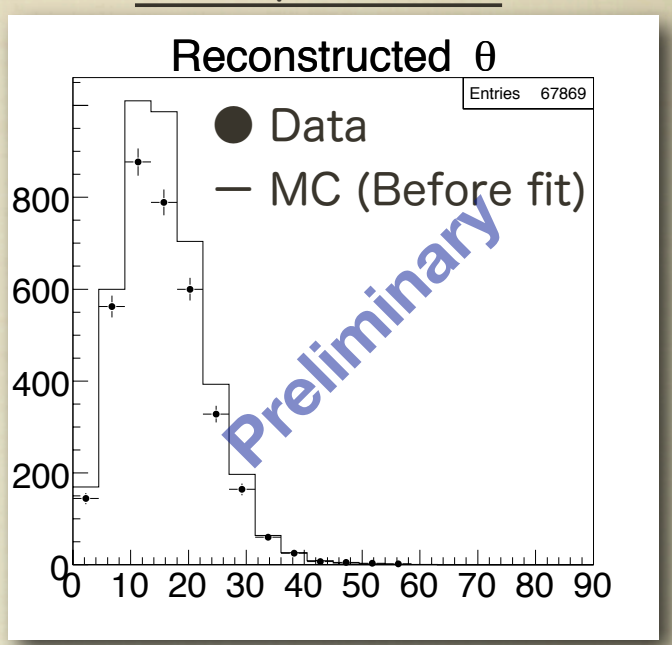
Predict neutrino energy spectrum at SciBooNE by fitting P_μ and θ_μ distribution from each sample

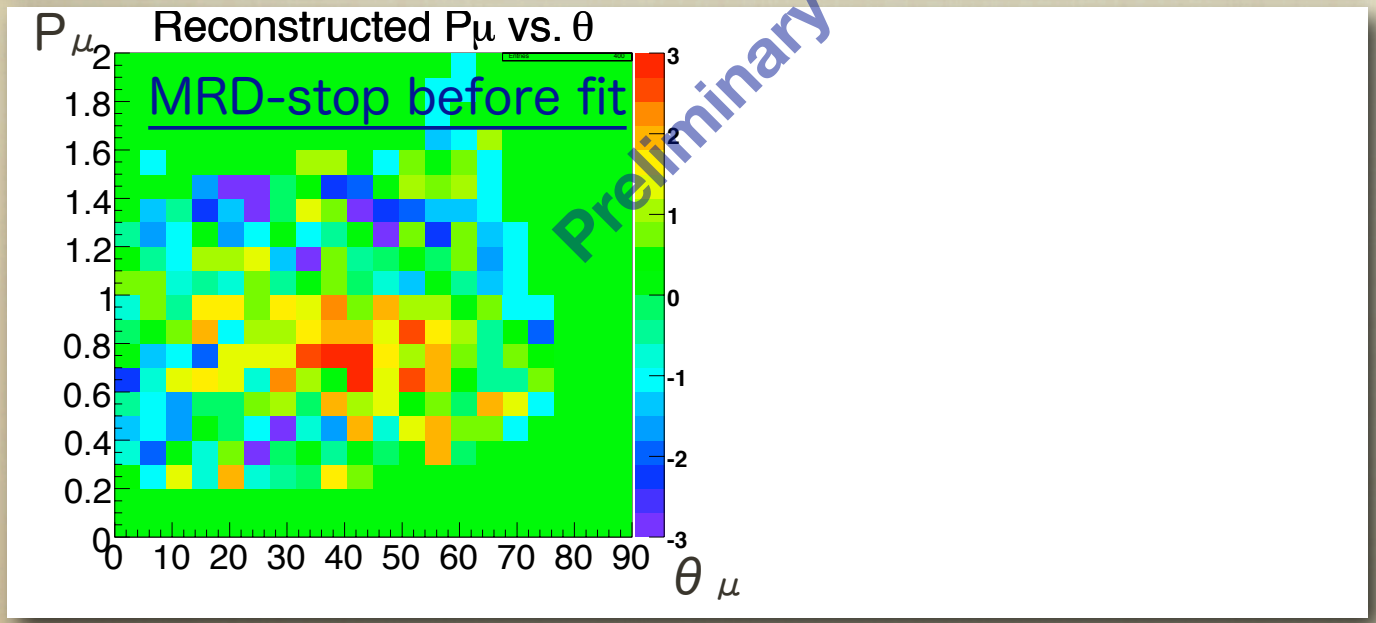
Spectrum Fit Result

(data-MC)/(stat. error)



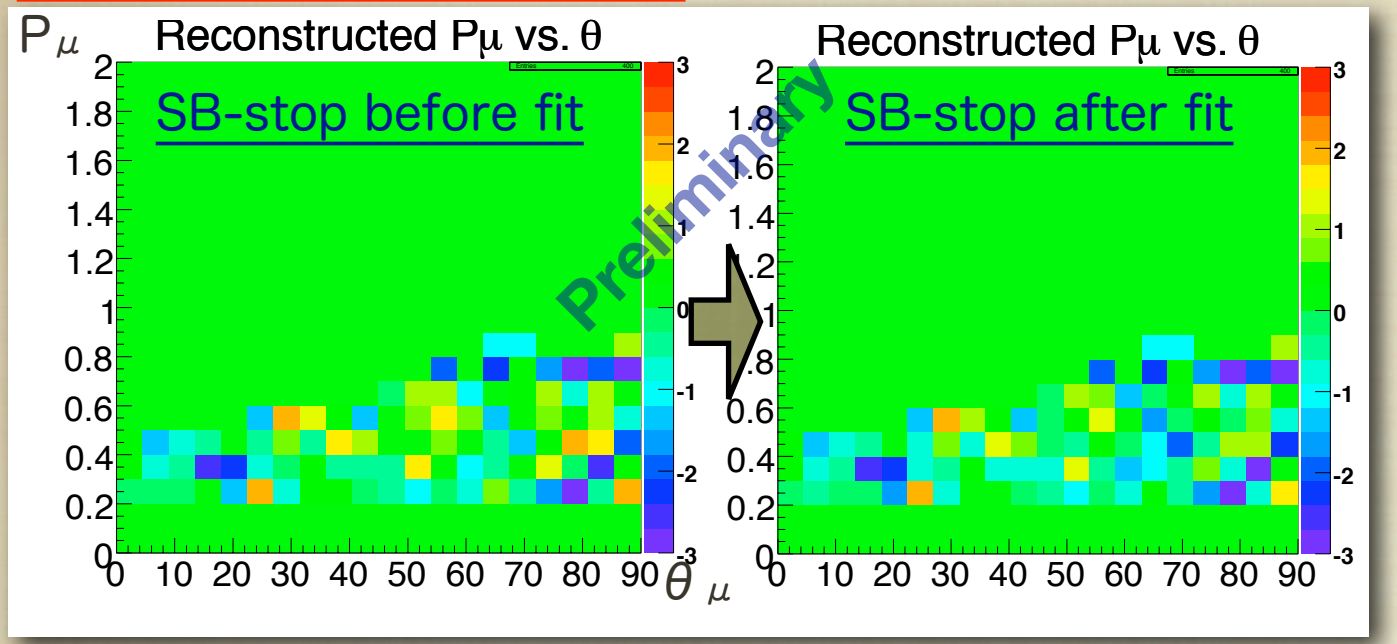
MRD-penetrate



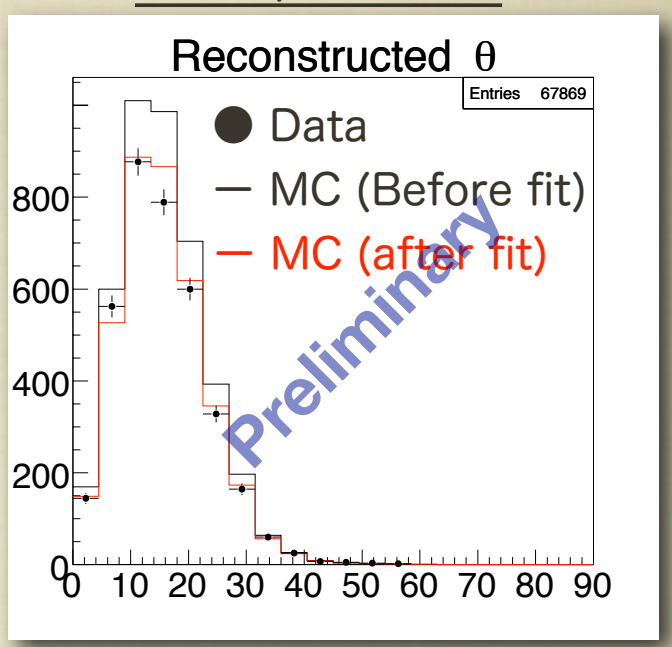


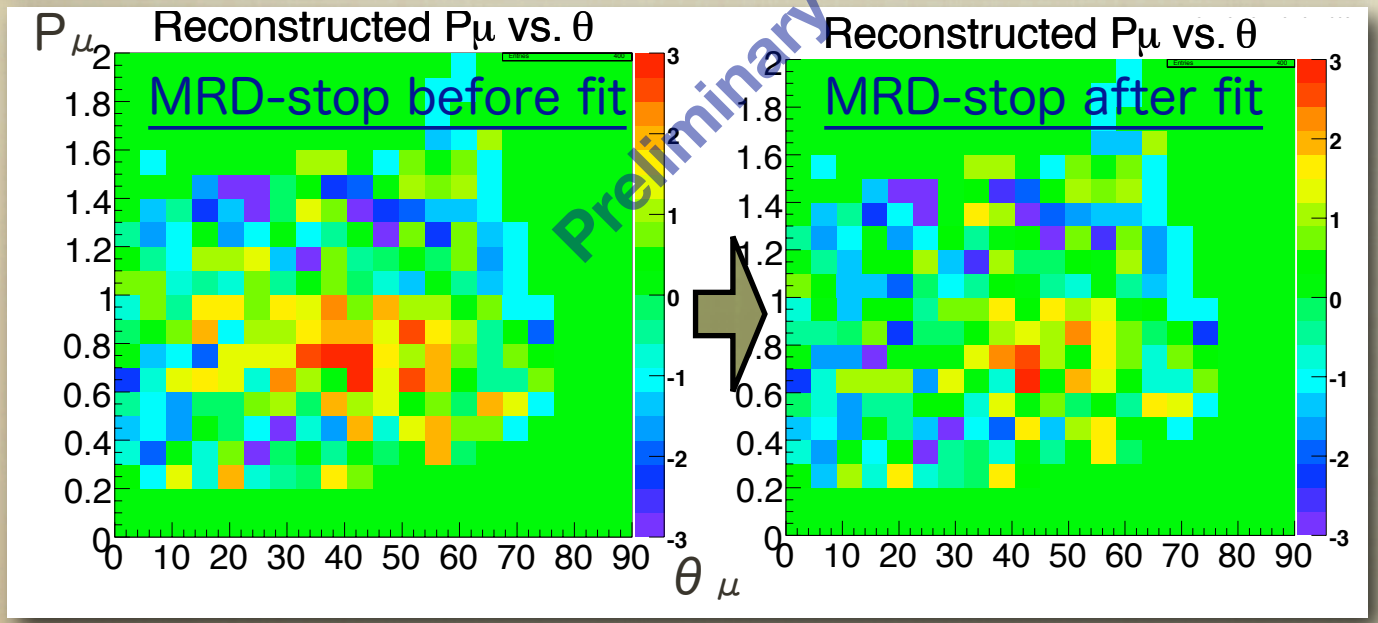
Spectrum Fit Result

(data-MC)/(stat. error)



MRD-penetrate





- Better data/MC agreement after fitting.

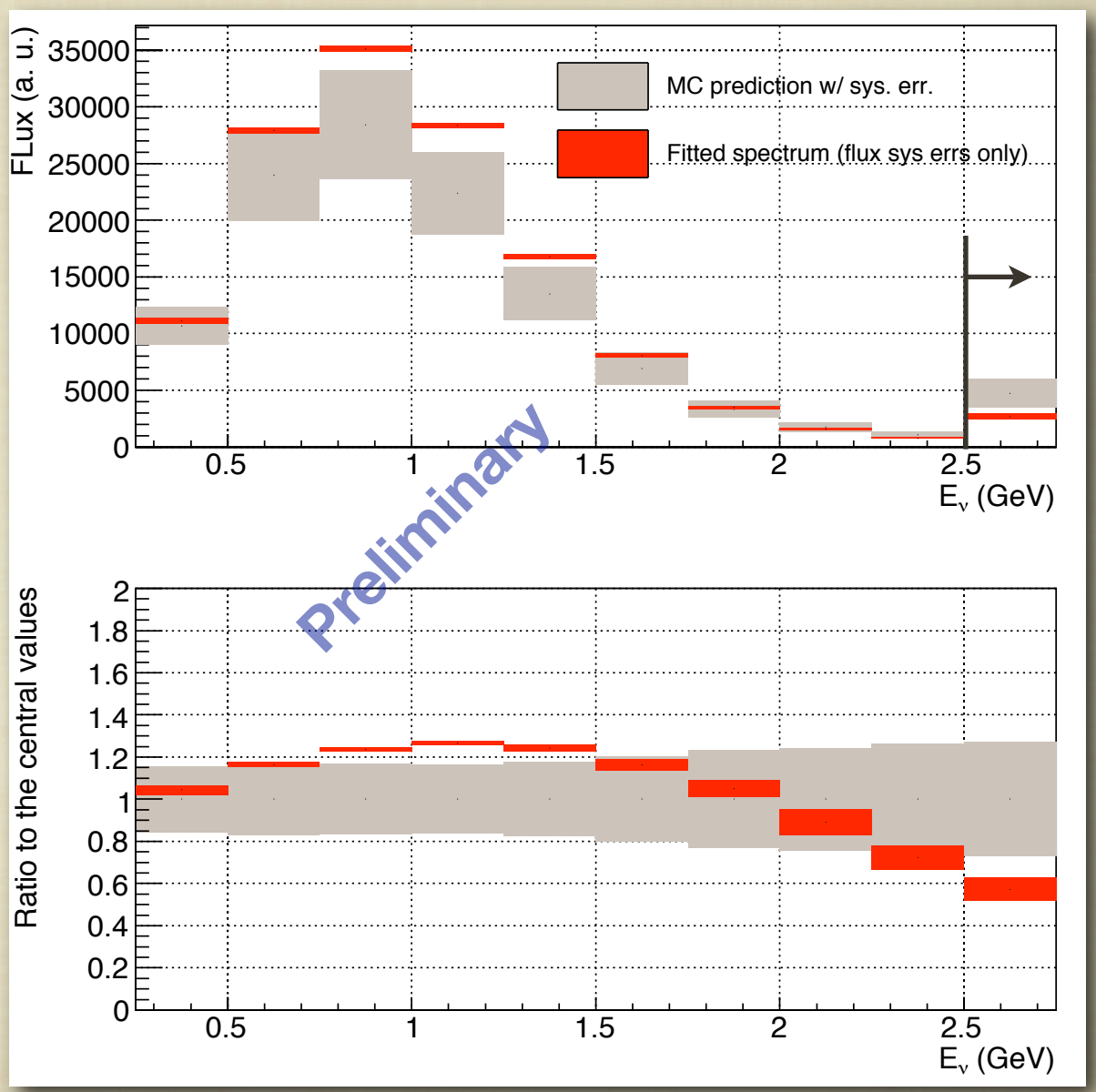
(Plots are relatively normalized)

χ^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

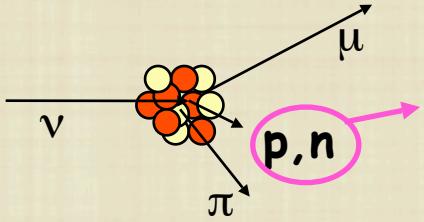
CC-1π^+ Measurement

Physics Motivation

- Dominant background process to ν_μ disappearance measurement
- Need precise measurement in the 1 GeV region

CC-resonant π production

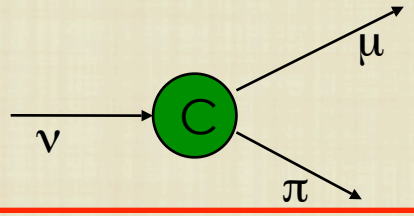
- $\nu + p \rightarrow \mu + p + \pi^+$
- $\nu + n \rightarrow \mu + n + \pi^+$



often not reconstructed

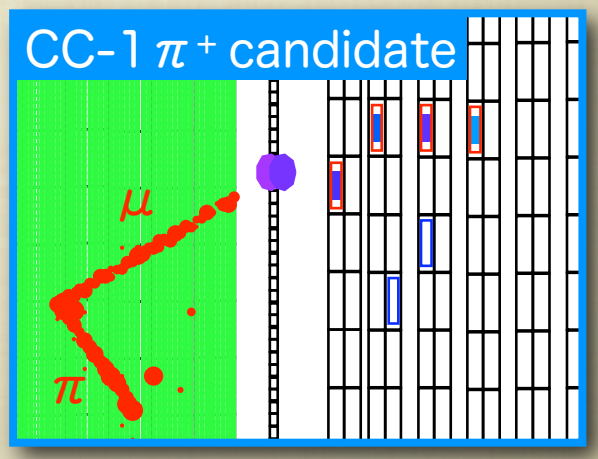
CC-coherent π production

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



Small Q^2

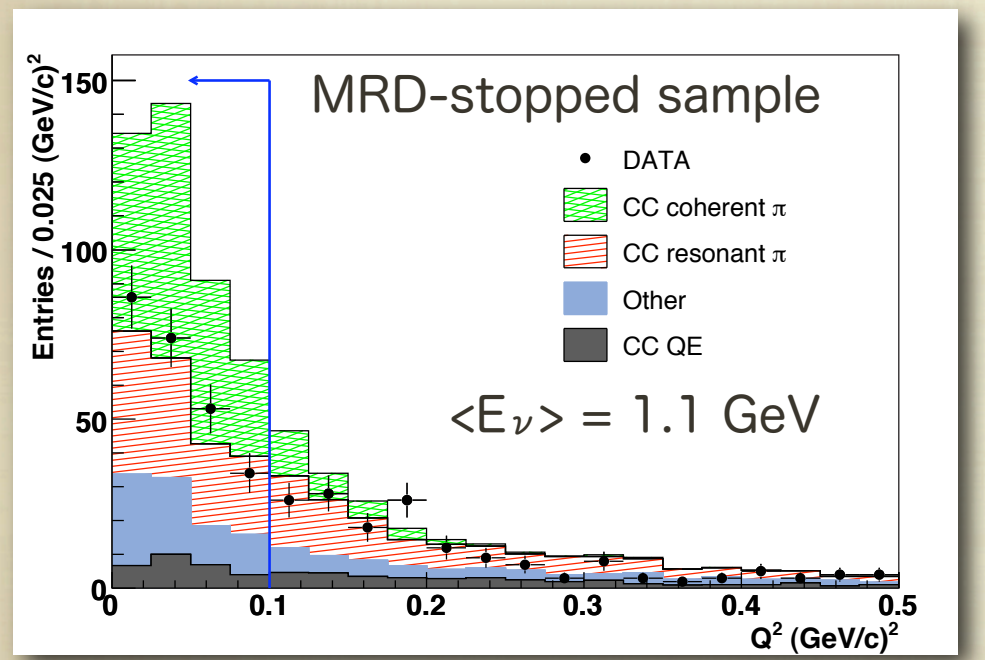
- ☑ Select MRD-stopped and -penetrated event
- ☑ Require 2-MIP like tracks
- ☑ Require small energy deposit around the vertex
- ☑ Require forward pions
- ☑ Require non-QE kinematics

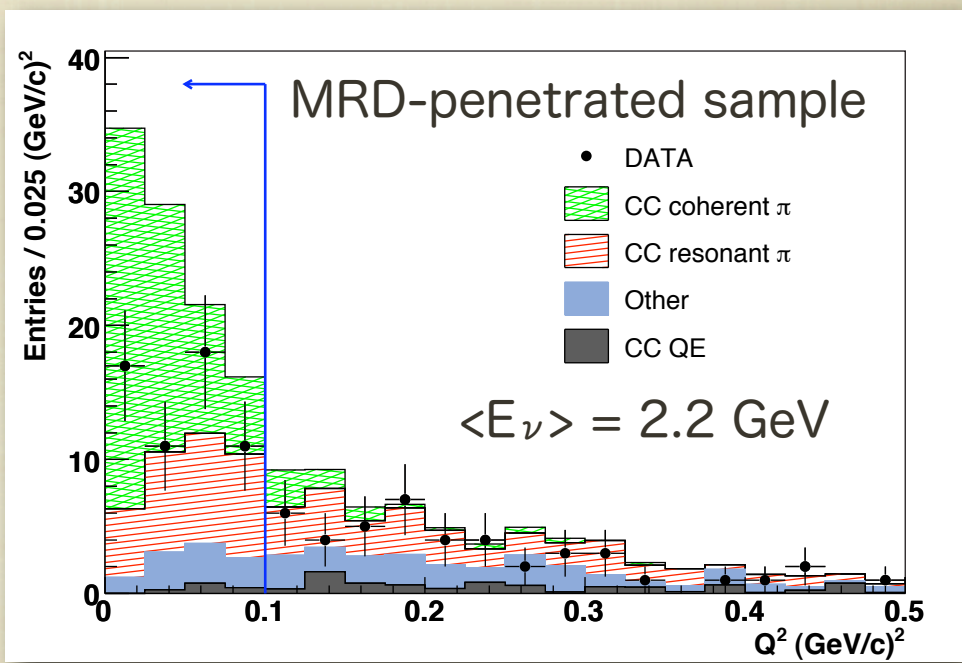


Search for CC Coherent π^+ Production

Coherent π prediction based on Rein and Sehgal model
Nucl. Phys. B 223, 29 (1983)

- No evidence for CC coherent production found.





$\sigma_{Coh}/\sigma_{CC} < 0.67 \times 10^{-2}$ (90% CL) at 1.1 GeV

$\sigma_{Coh}/\sigma_{CC} < 1.36 \times 10^{-2}$ (90% CL) at 2.2 GeV

Paper submitted to PRD.
Hiraide et. al, arXiv:0811.0369

Summary

- SciBooNE experiment:
  - Precise cross-section measurement at 1 GeV region
  - Neutrino flux measurement as a MiniBooNE near detector.
- Successfully completed data taking.
- ν_μ spectrum measurement:
  - Established the method for spectrum fitting
- Search for CC coherent π^+ production
  - No evidence for the signal found
  - First official SciBooNE result (submitted to PRD)
- Many results coming soon in the next year!

Thank you

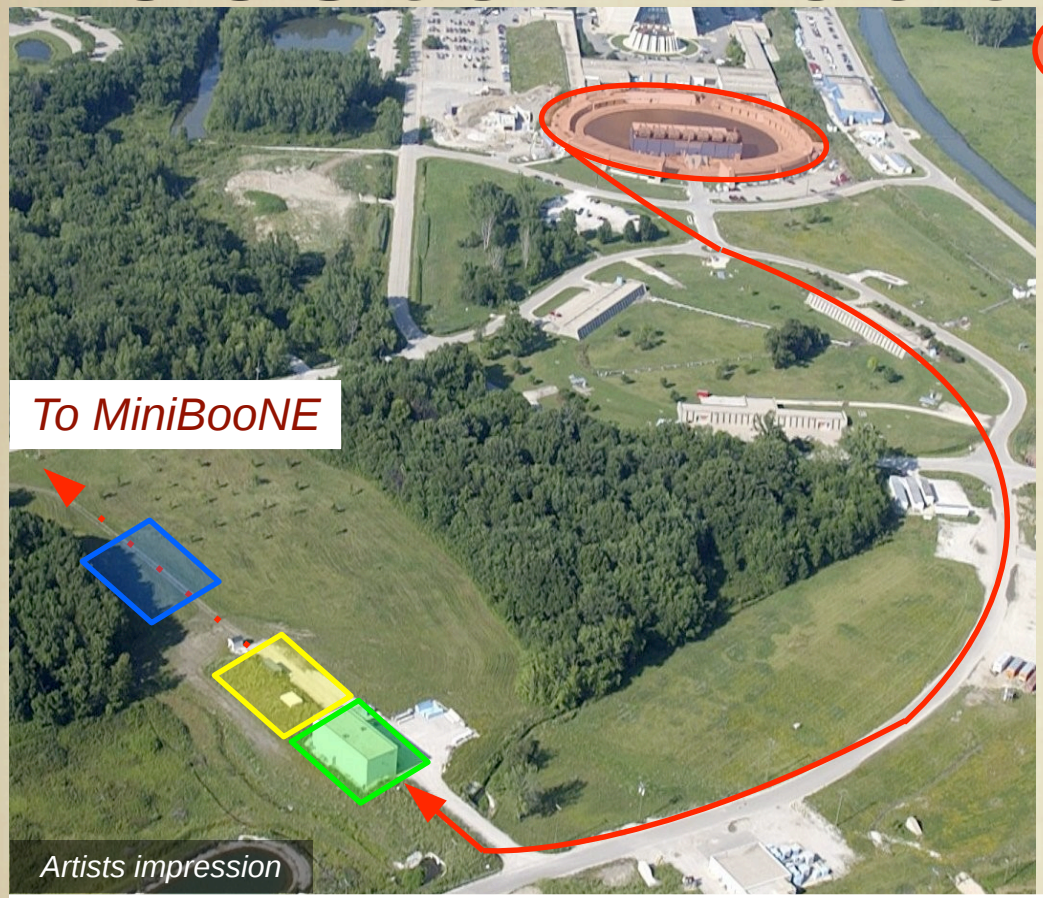
SciBooNE Collaboration

- Universitat Autonoma de Barcelona
- University of Cincinnati
- University of Colorado
- Columbia University
- Fermi National Accelerator Laboratory
- High Energy Accelerator Research Organization (KEK)
- Imperial College London*
- Indiana University
- Institute for Cosmic Ray Research
- Kyoto University*
- Los Alamos National Laboratory
- Louisiana State University
- Purdue University Calumet
- Università degli Studi di Roma and INFN-Roma
- Saint Mary's University of Minnesota
- Tokyo Institute of Technology
- Universidad de Valencia

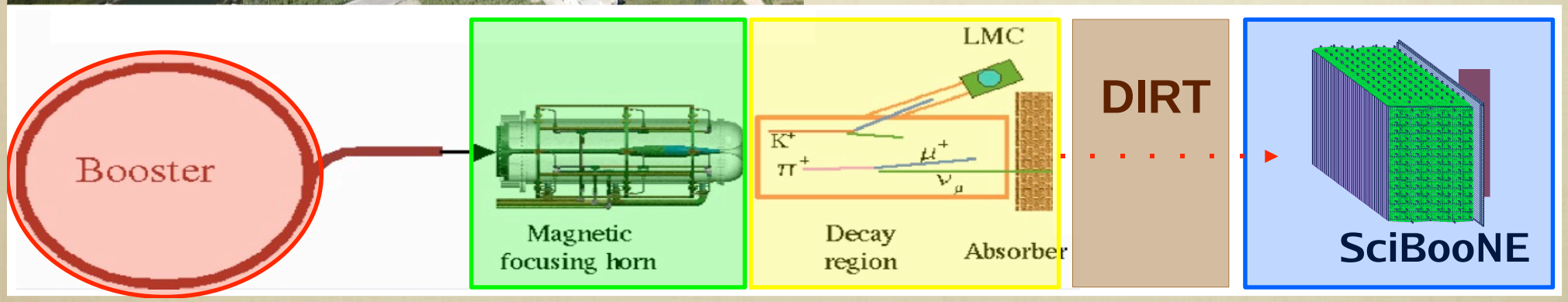
SciBooNE

Backup slides

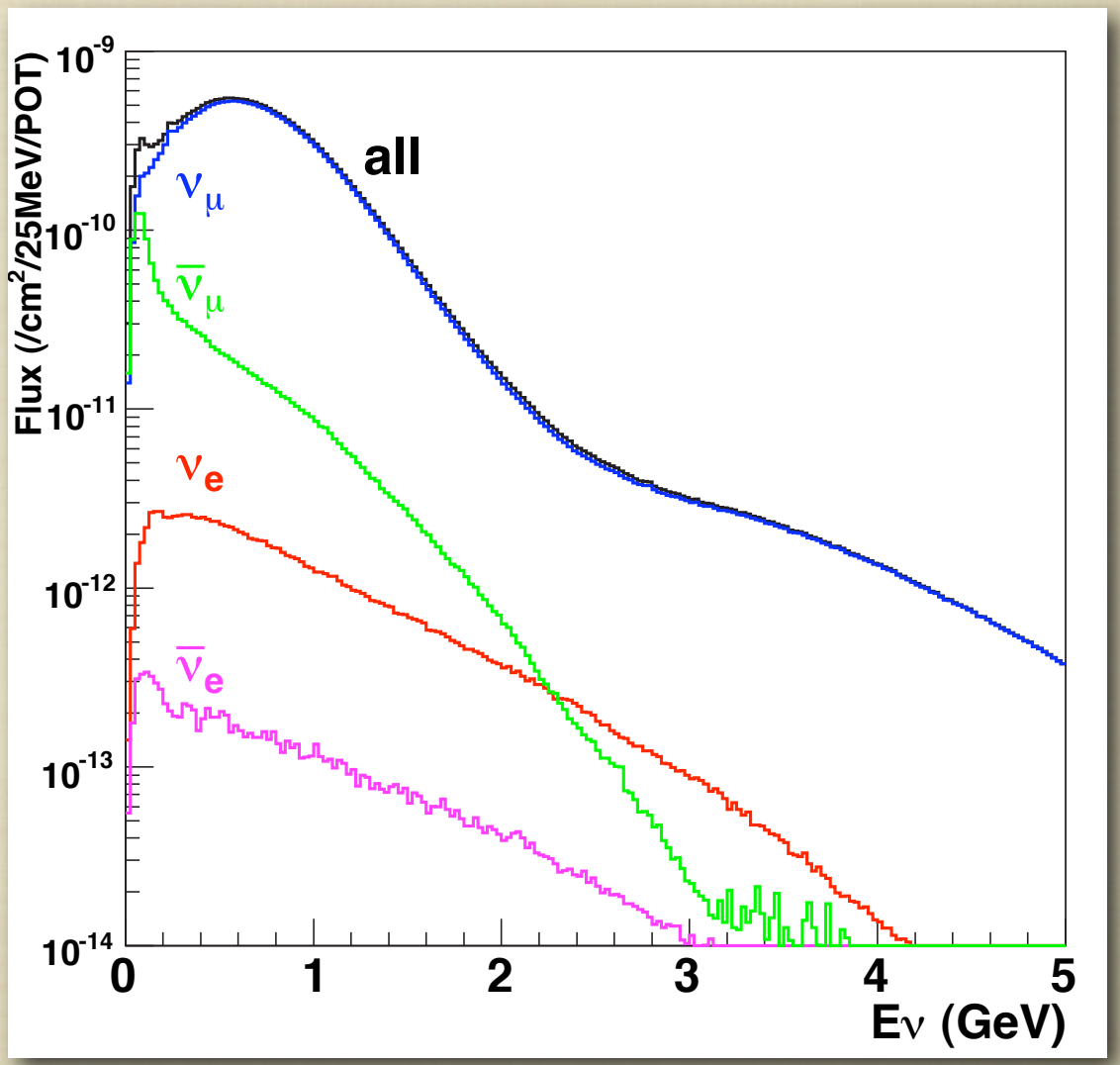
Booster Neutrino Beamline



- 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 minimises $\mu \rightarrow \nu_e$ decay
- SciBooNE located 50m from absorber



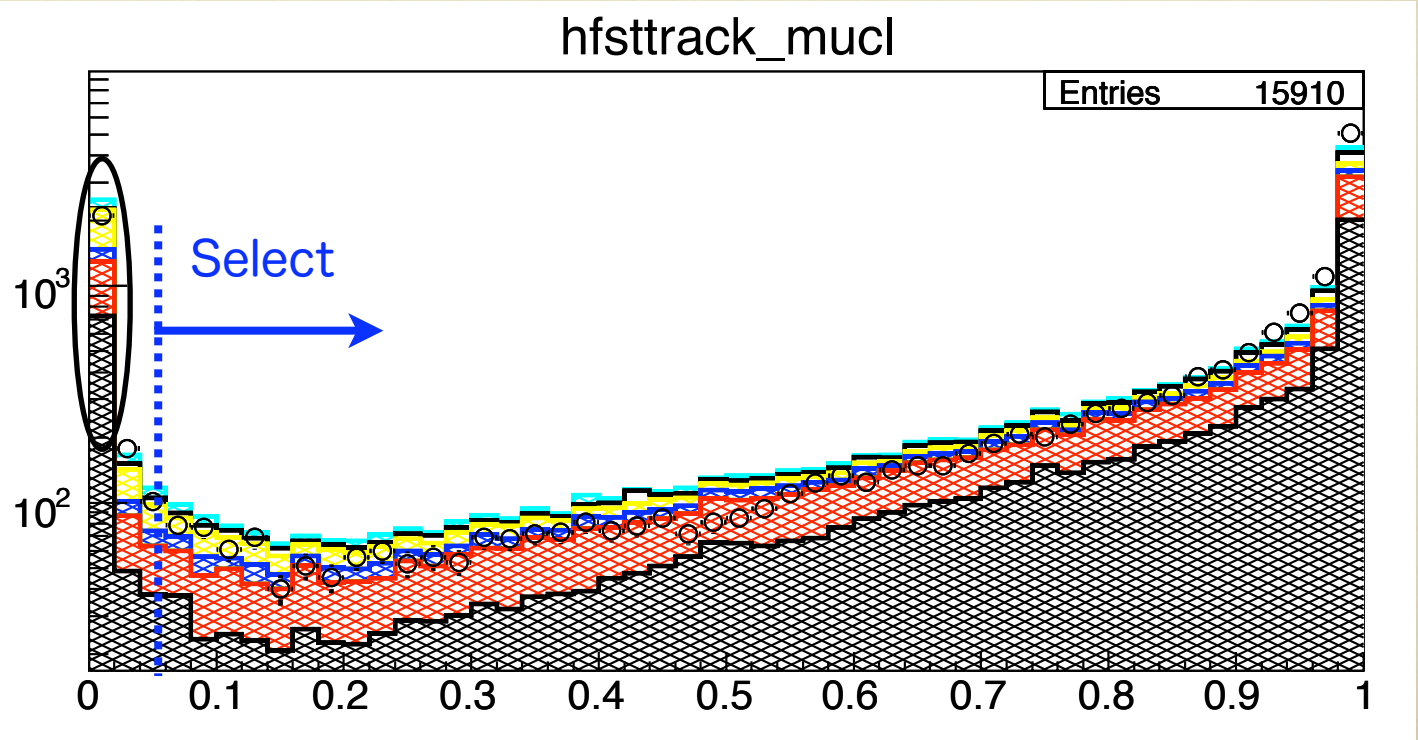
Neutrino Flux



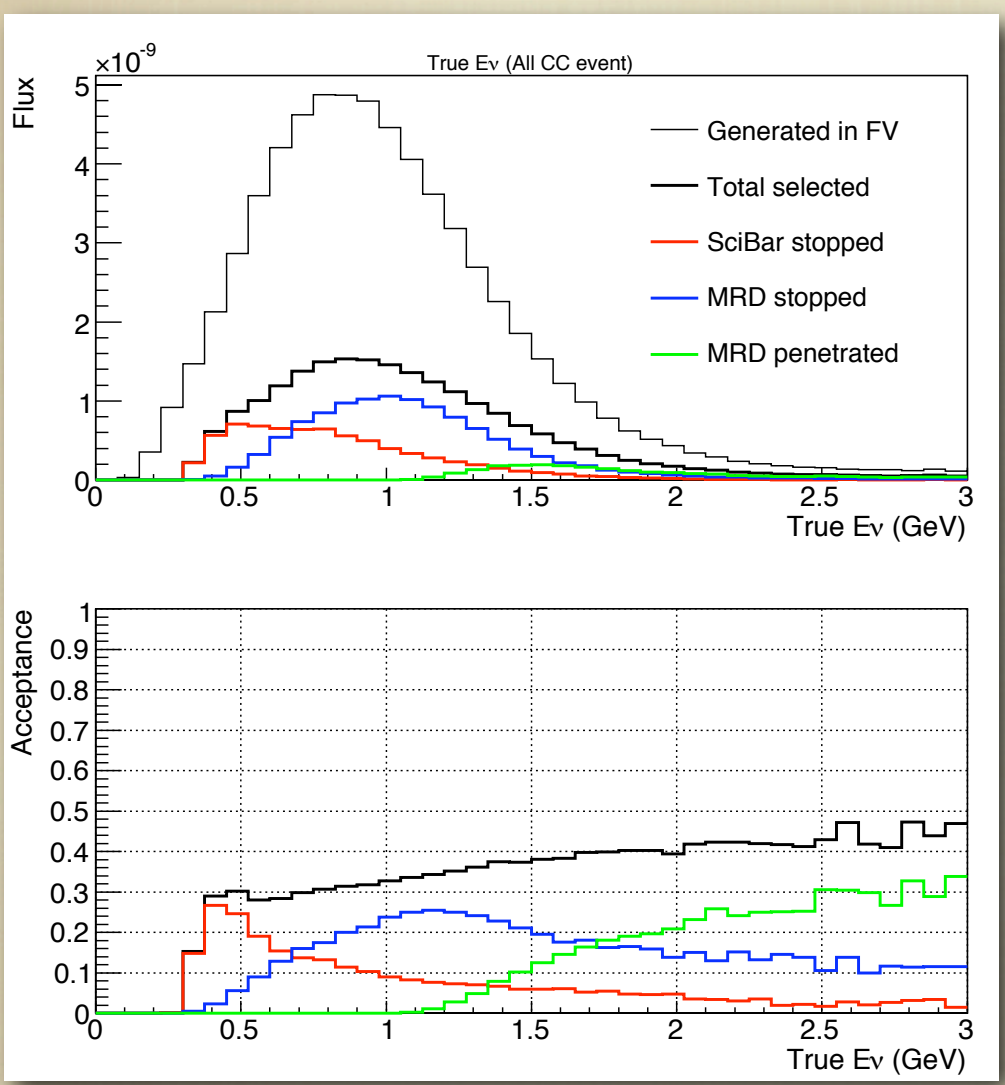
MuCL cut to remove non-muon tracks

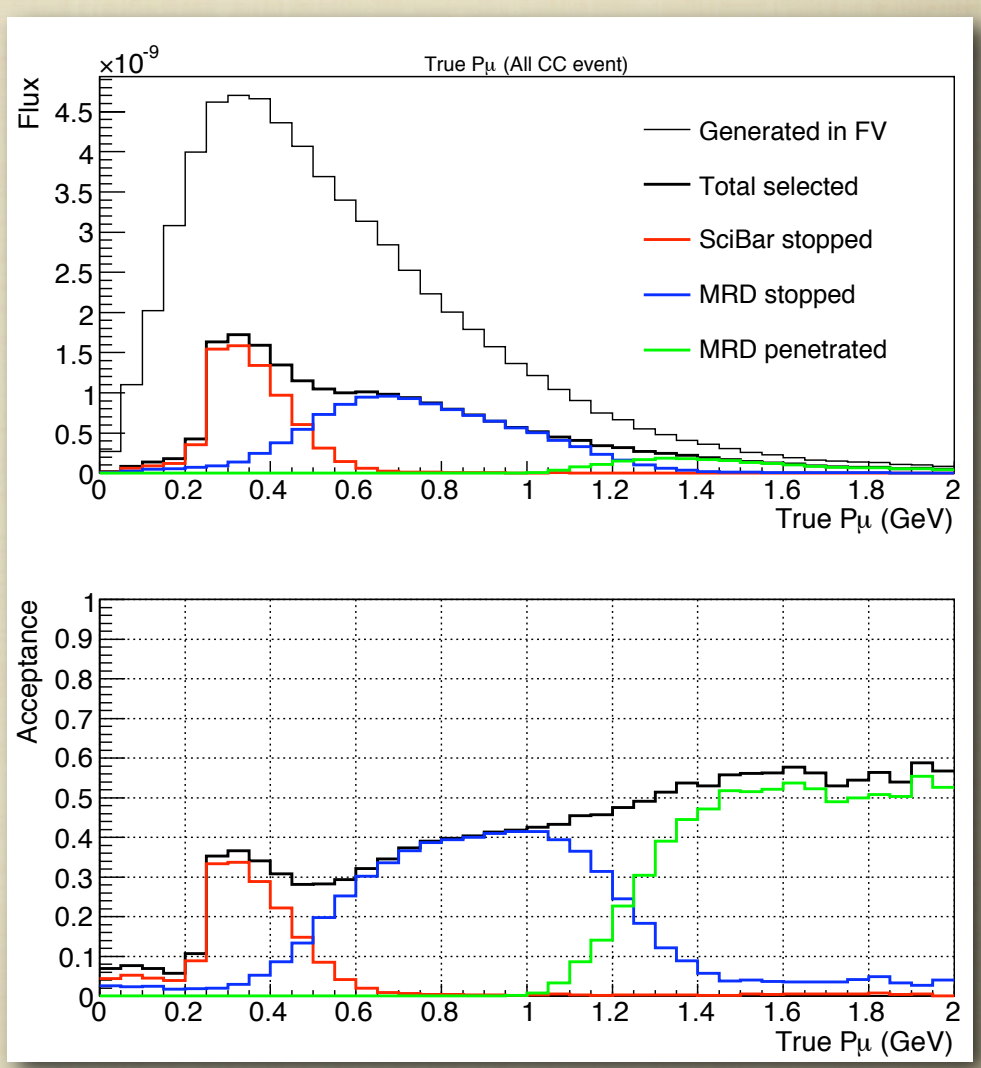
- Remove large portion of NC event
- Reject if proton etc are miss-reconstructed as muon.
  - Can be recovered by finding “real” muon

CCQE: Proton is the longest track and identified as muon



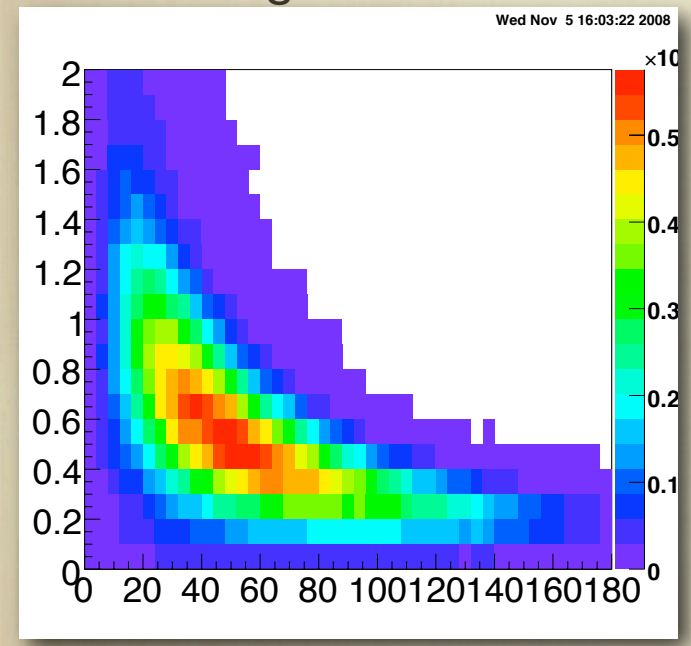
Acceptance


True Eν (All CC event)
×10^-9
Flux
Generated in FV
Total selected
SciBar stopped
MRD stopped
MRD penetrated
True Eν (GeV)
Acceptance
True Eν (GeV)

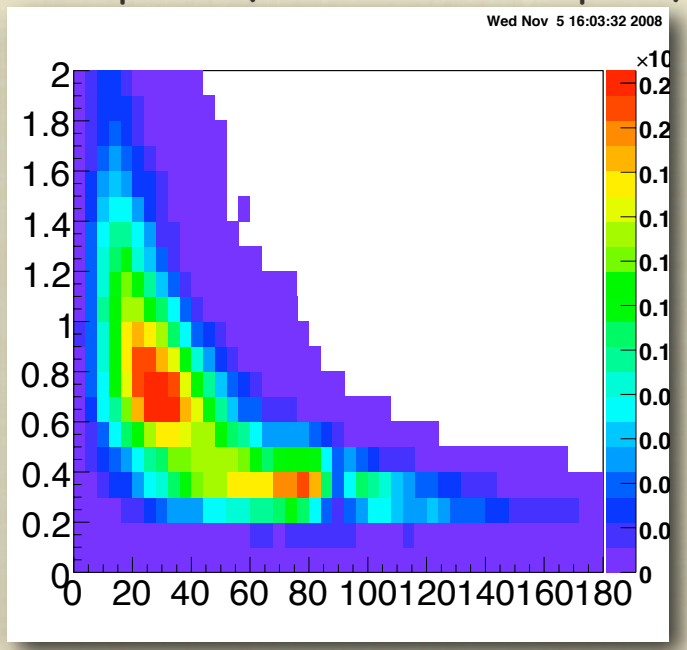

True Pμ (All CC event)
×10^-9
Flux
Generated in FV
Total selected
SciBar stopped
MRD stopped
MRD penetrated
True Pμ (GeV)
Acceptance
True Pμ (GeV)

Acceptance in P_μ vs. θ_μ

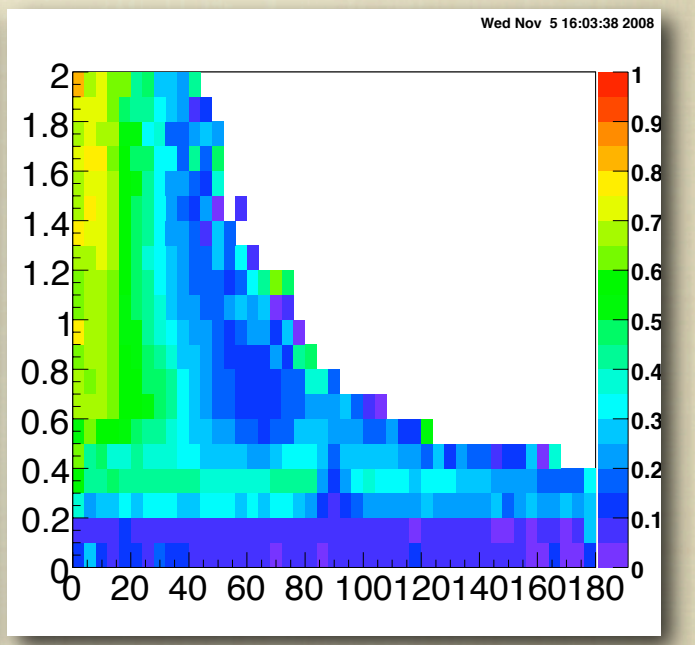
All generated



Accepted (sum of 3 samples)

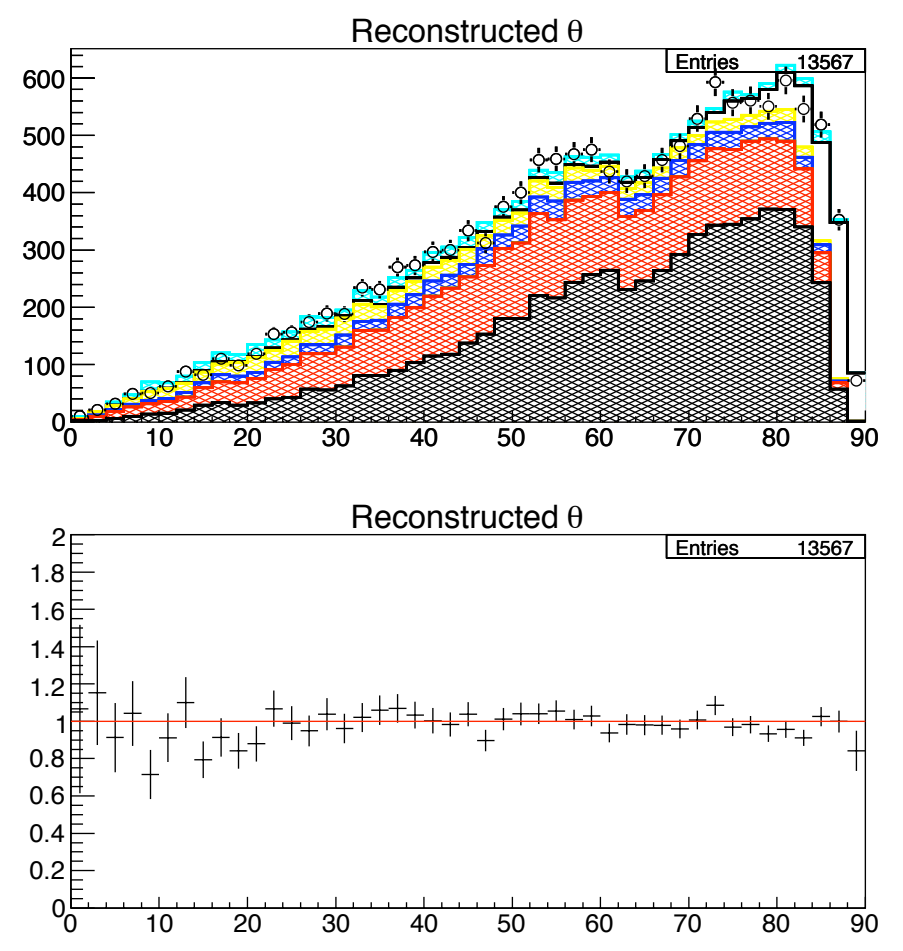


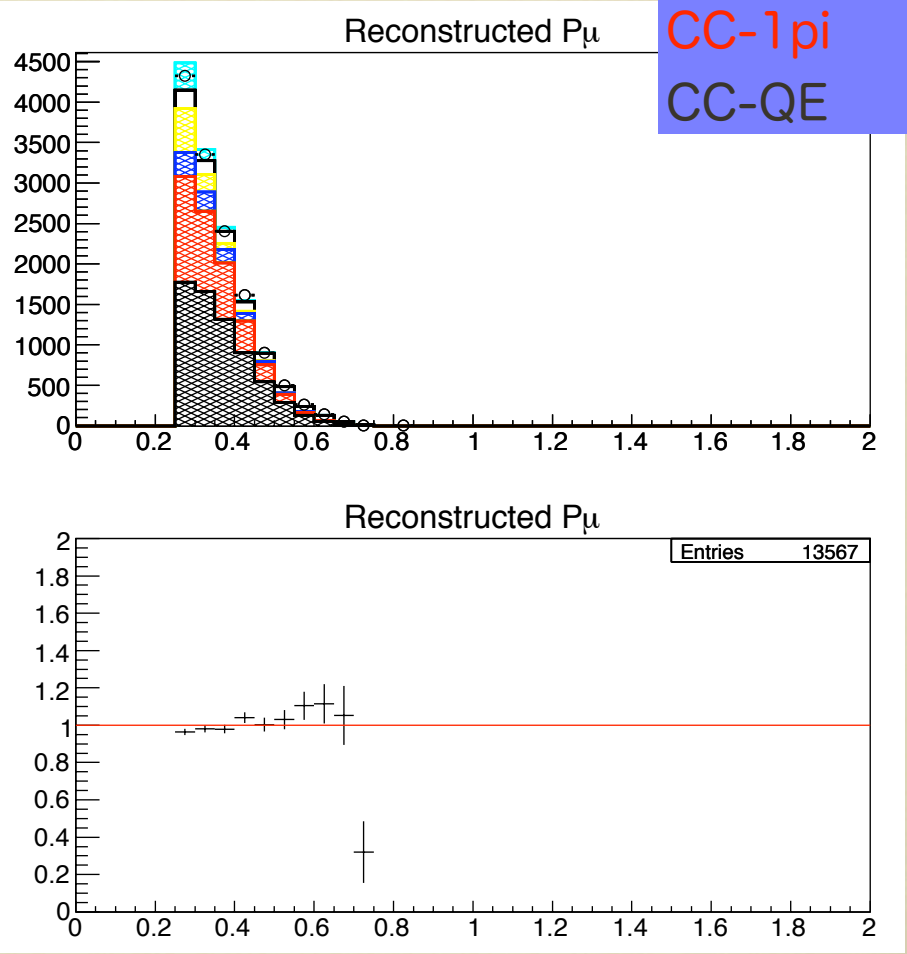
Efficiency
(generated/accepted)



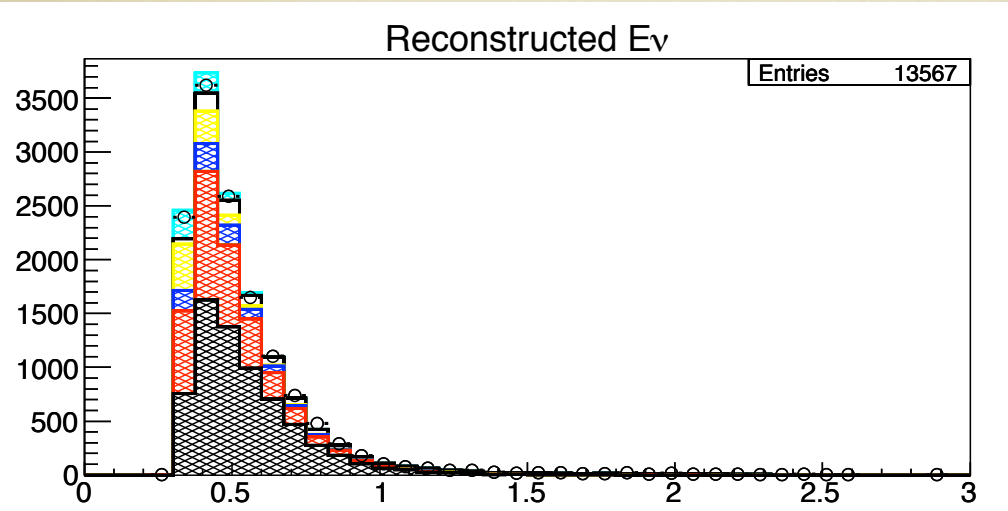
Muon angle, momentum

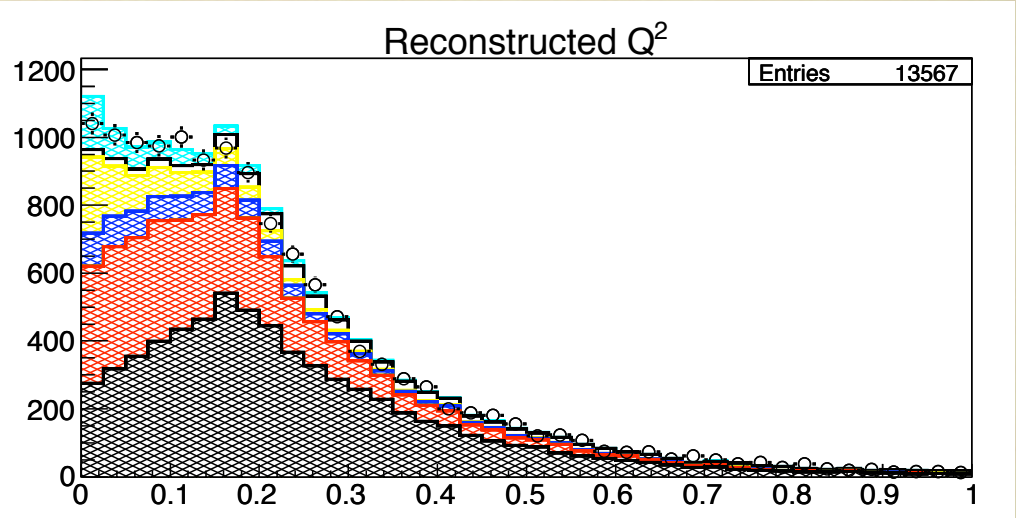
Dirt
NC
CC-multi-pi
CC-1pi
CC-QE

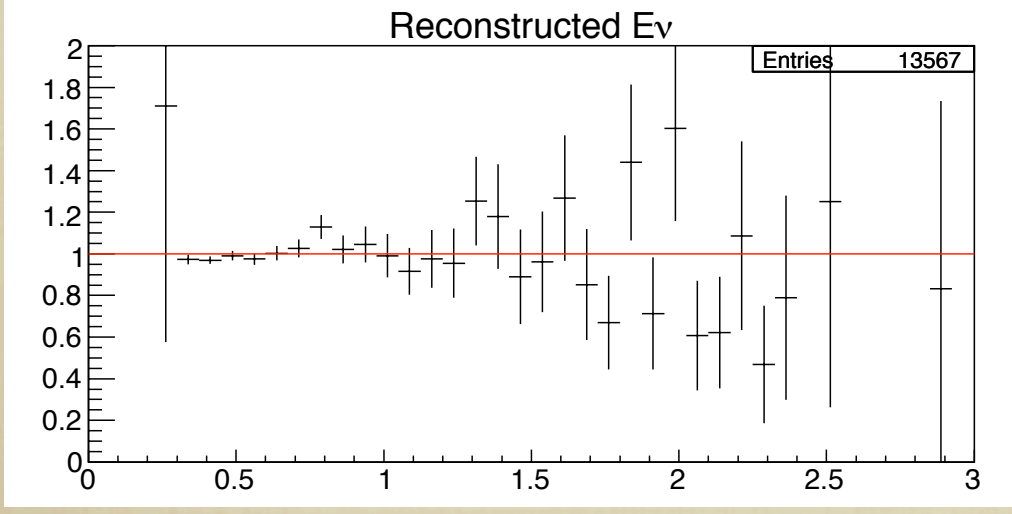


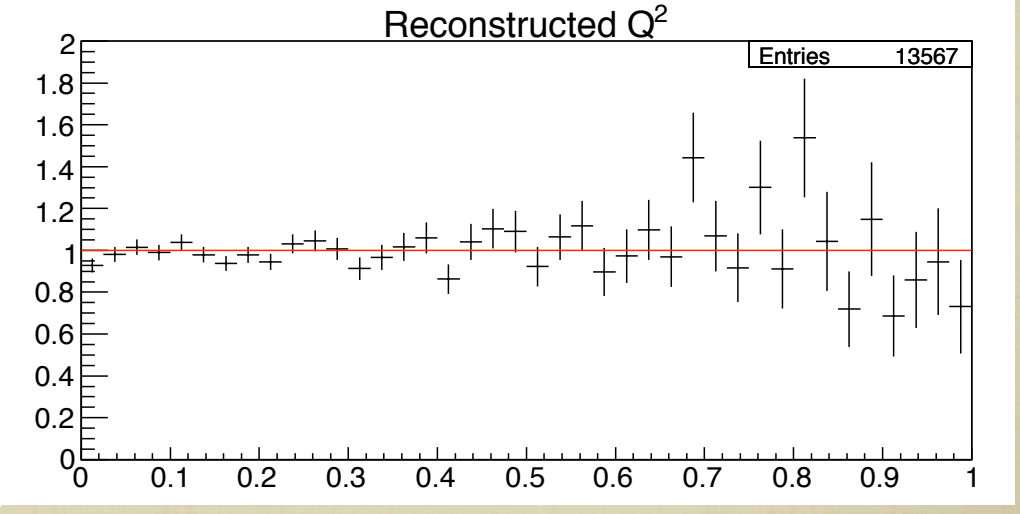


Enu, Q2

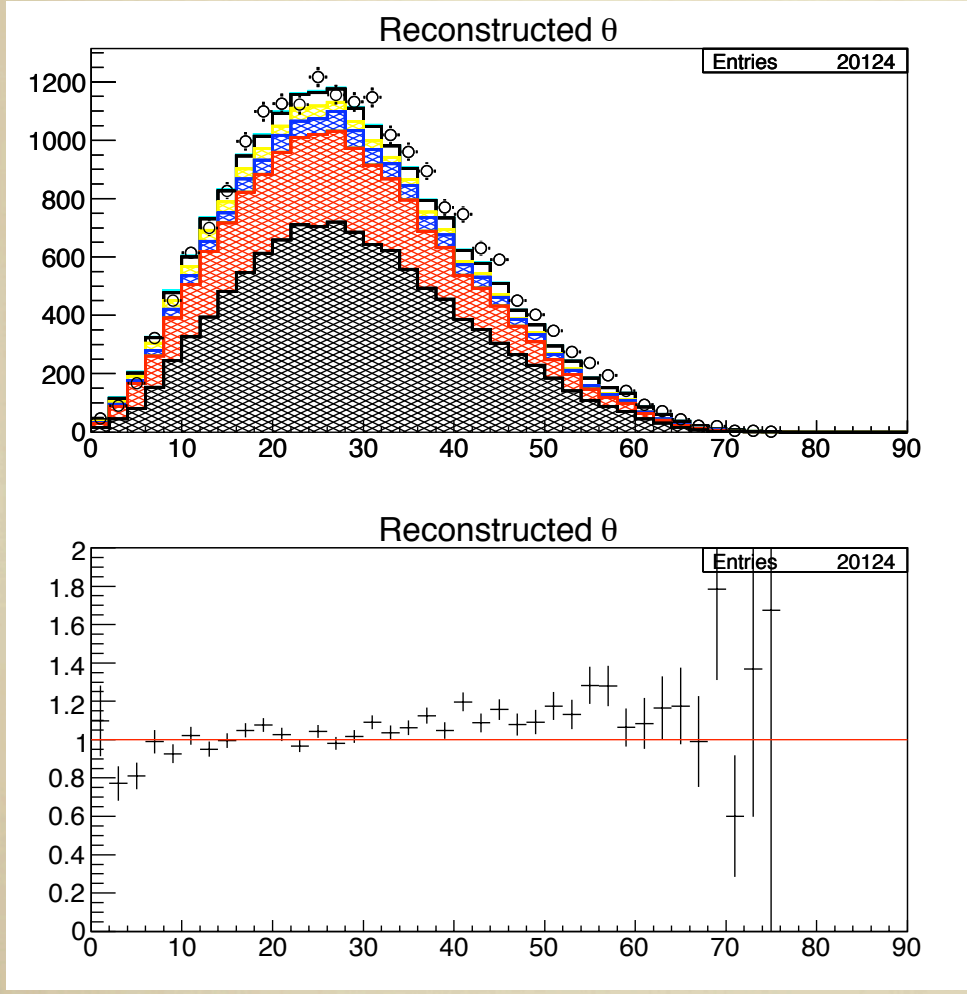

Reconstructed Eν
Entries 13567
3500
3000
2500
2000
1500
1000
500
0
0 0.5 1 1.5 2 2.5 3

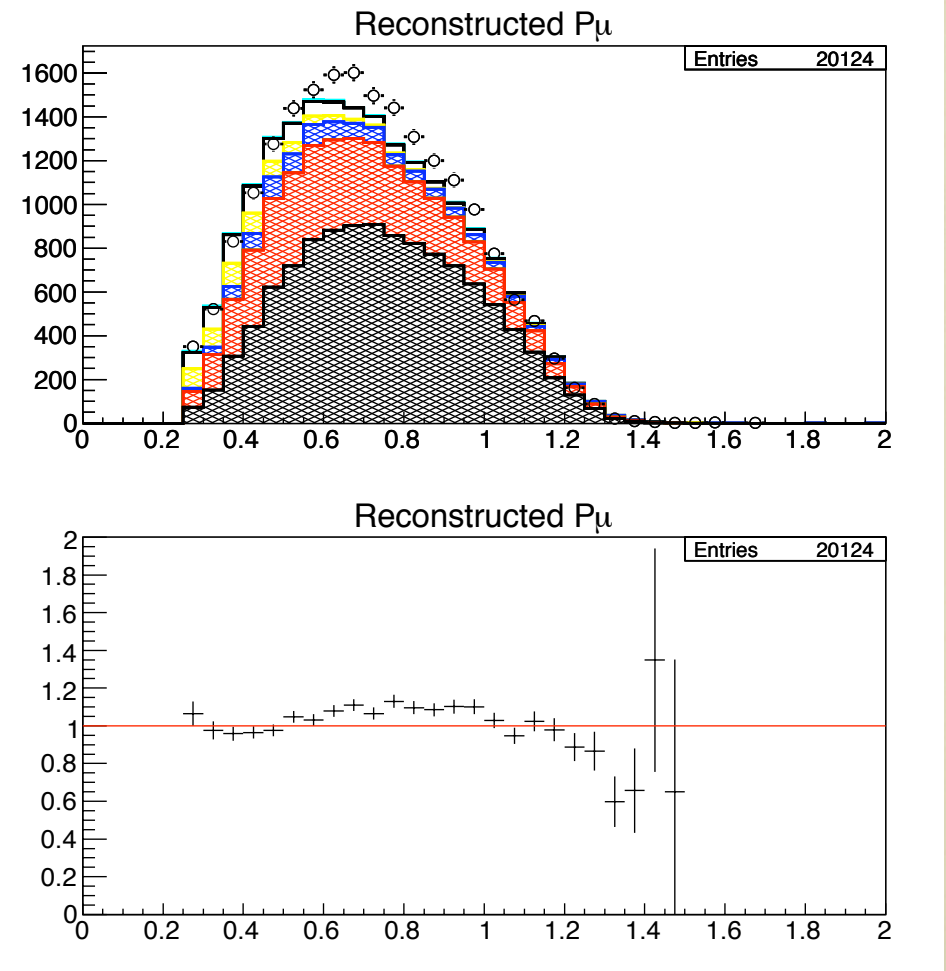

Reconstructed Q2
Entries 13567
1200
1000
800
600
400
200
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1


Reconstructed Eν
Entries 13567
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 0.5 1 1.5 2 2.5 3


Reconstructed Q2
Entries 13567
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

Muon angle, momentum



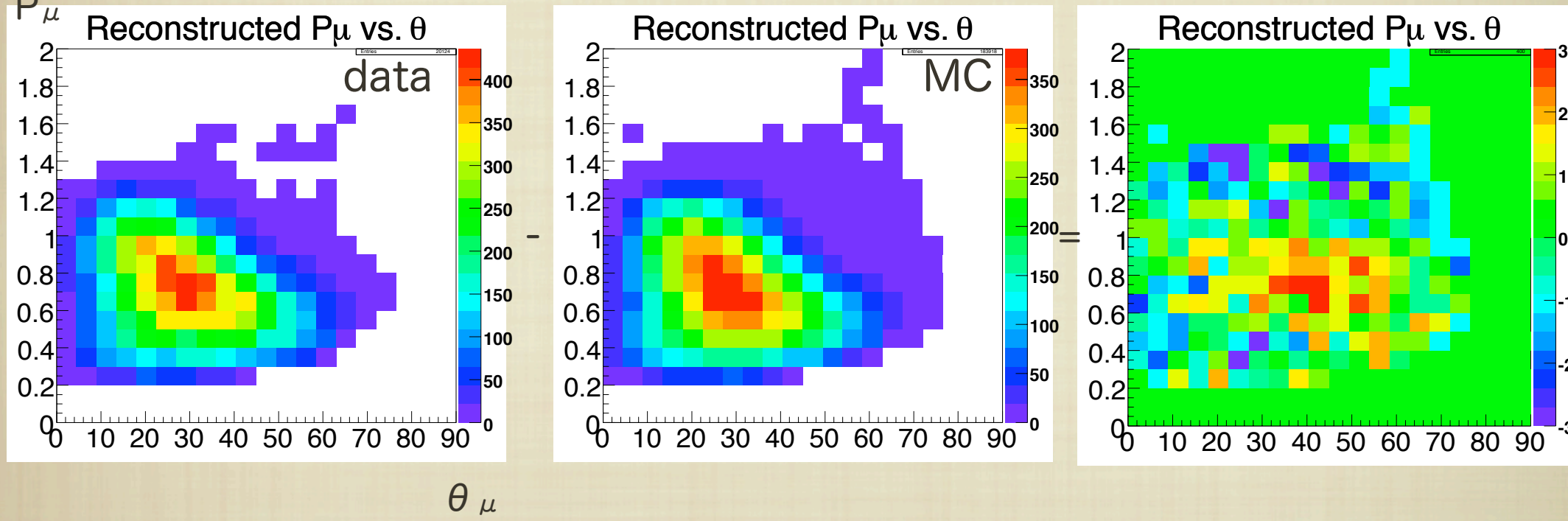


Distribution to fit

- Pmu vs. theta-mu
- All bins which has more than 1 MC entry are used for fit

MRD-stop

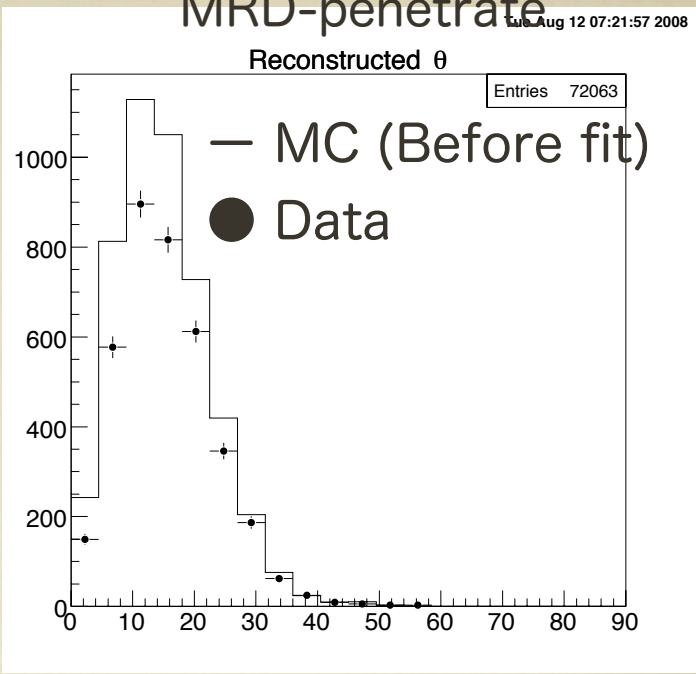
(data-MC)/(stat. error)



Distribution to fit

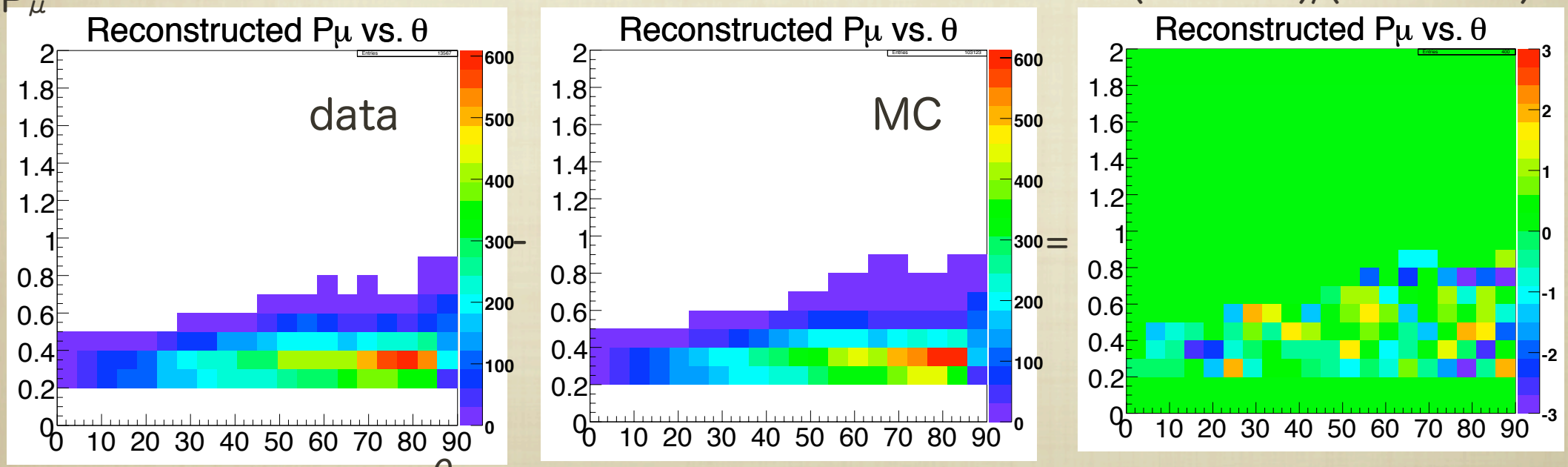
- Same distribution for SciBar stopped
- Just use muon angle for MRD-penetrate sample.

MRD-penetrate



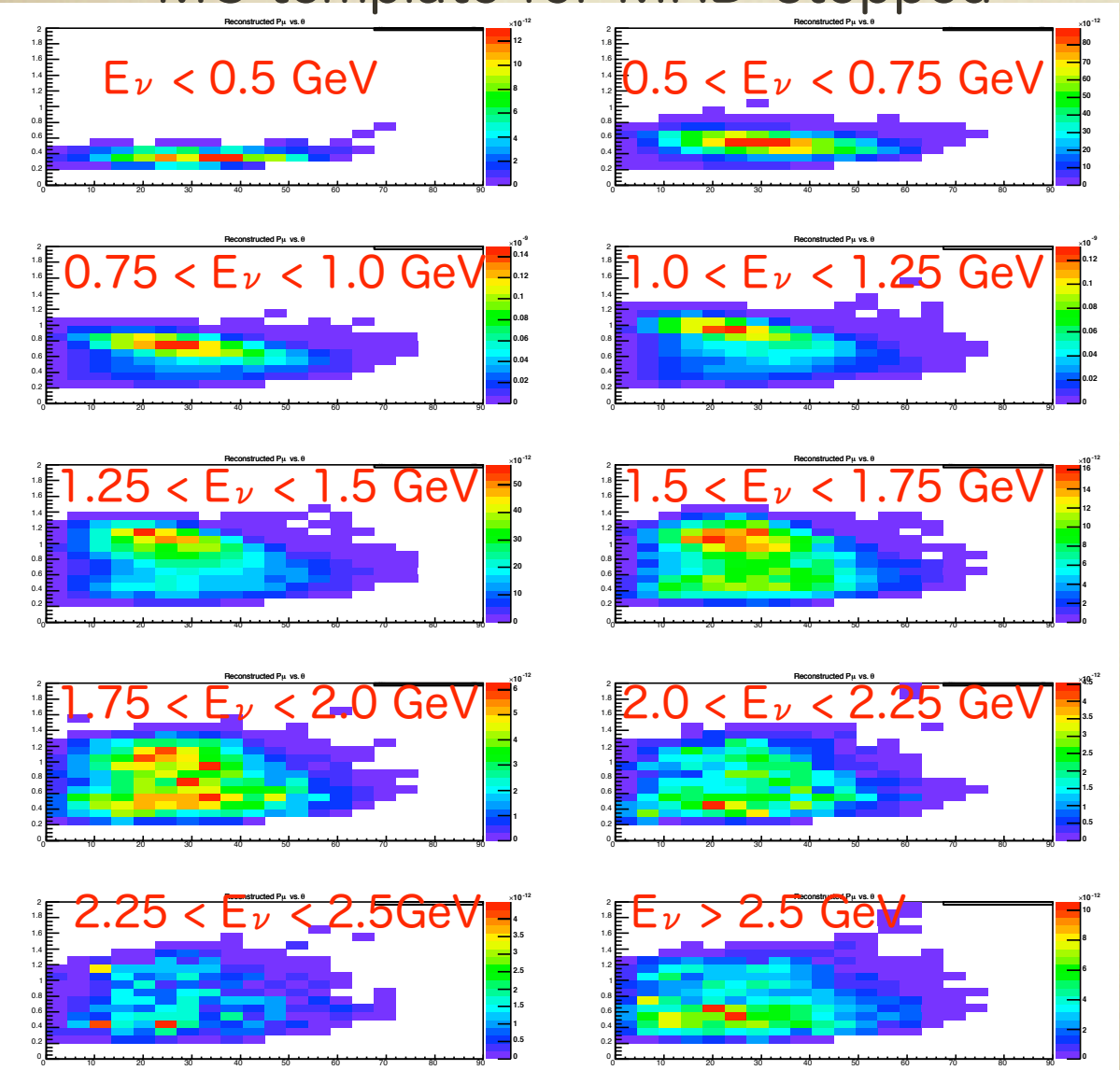
SciBar-stop

(data-MC)/(stat. error)



Fitting method

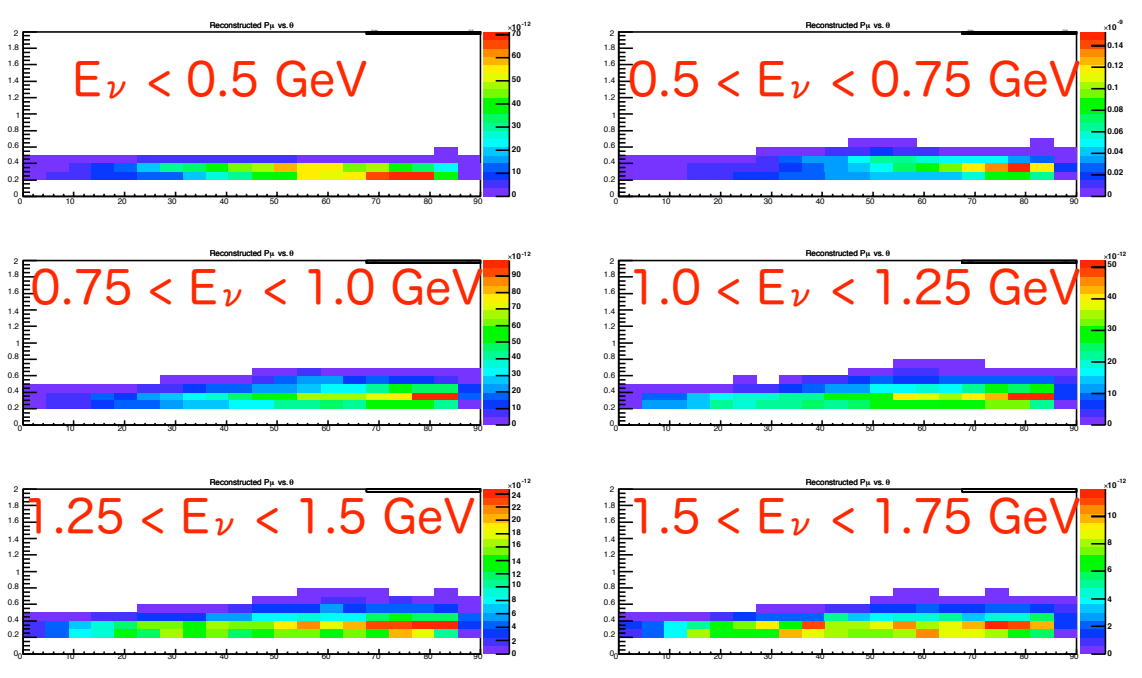
MC template for MRD-stopped



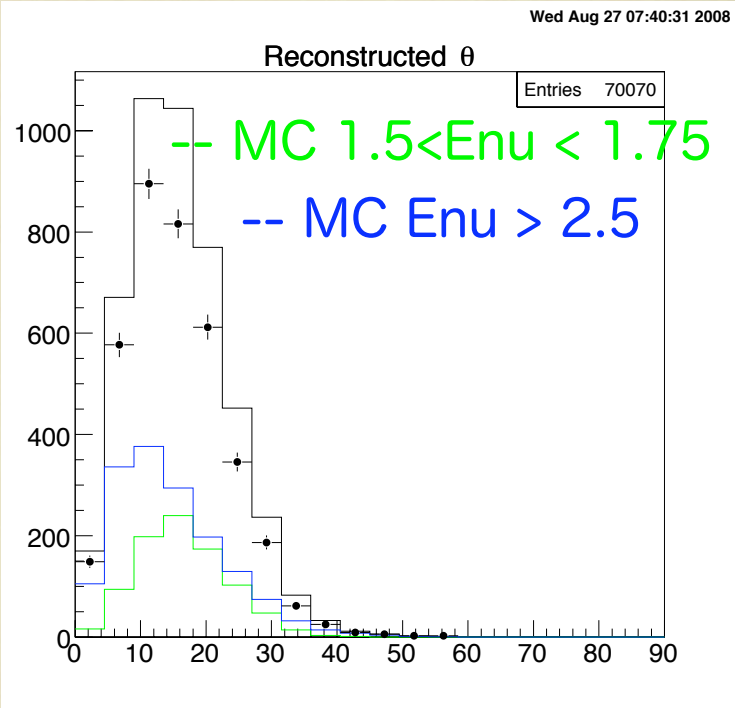
- Enu: 10bins
  - 0.25 - 2.5 GeV, 0.25 GeV step,
  - Final bin contain events >2.5GeV

Fitting method

MC template for SciBar-stopped



MRD penetrated

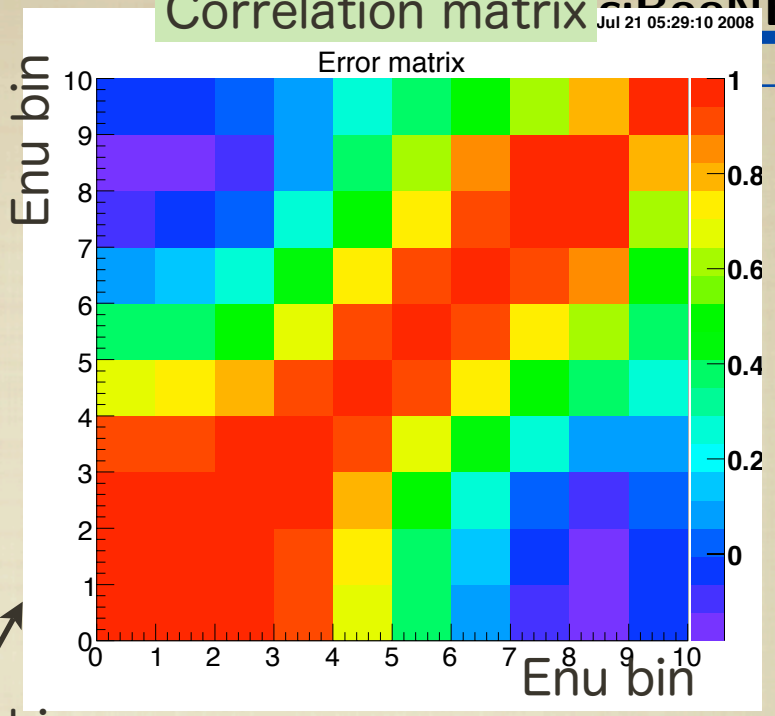


SciBar-stop and MRD-penetrate samples have less sensitivity to energy distribution.
Mostly normalization for low/high energy part.

χ^2 definition

- Parameters: (total 10)
  - Enu scale factor: 10 bins
    - $f_0, f_1, \ldots, f_9$

Correlation matrix



Error matrix for each Enu bins (from flux uncertainty only. No other systematics.)

Constrain correlation between each E_ν bins and their absolute value

$$\chi^2 = -2 \sum_{i}^{Nbin(P_\mu,\theta_\mu)} \ln\left[\frac{P(N_i^{data}; N_i^{MC})}{P(N_i^{data}; N_i^{data})}\right] + \sum_{i,j}^{NBin(E_\nu)} V_{ij}^{-1}(f_i - 1)\phi_i^{CV}(f_j - 1)\phi_j^{CV}$$

$$P(N,\mu) = \frac{\mu^N e^{-\mu}}{N!}$$

Poisson log likelihood

$$N(P_\mu,\theta_\mu) = \sum_{k}^{NBins(E_\nu)} f_k n_k(P_\mu,\theta_\mu)$$

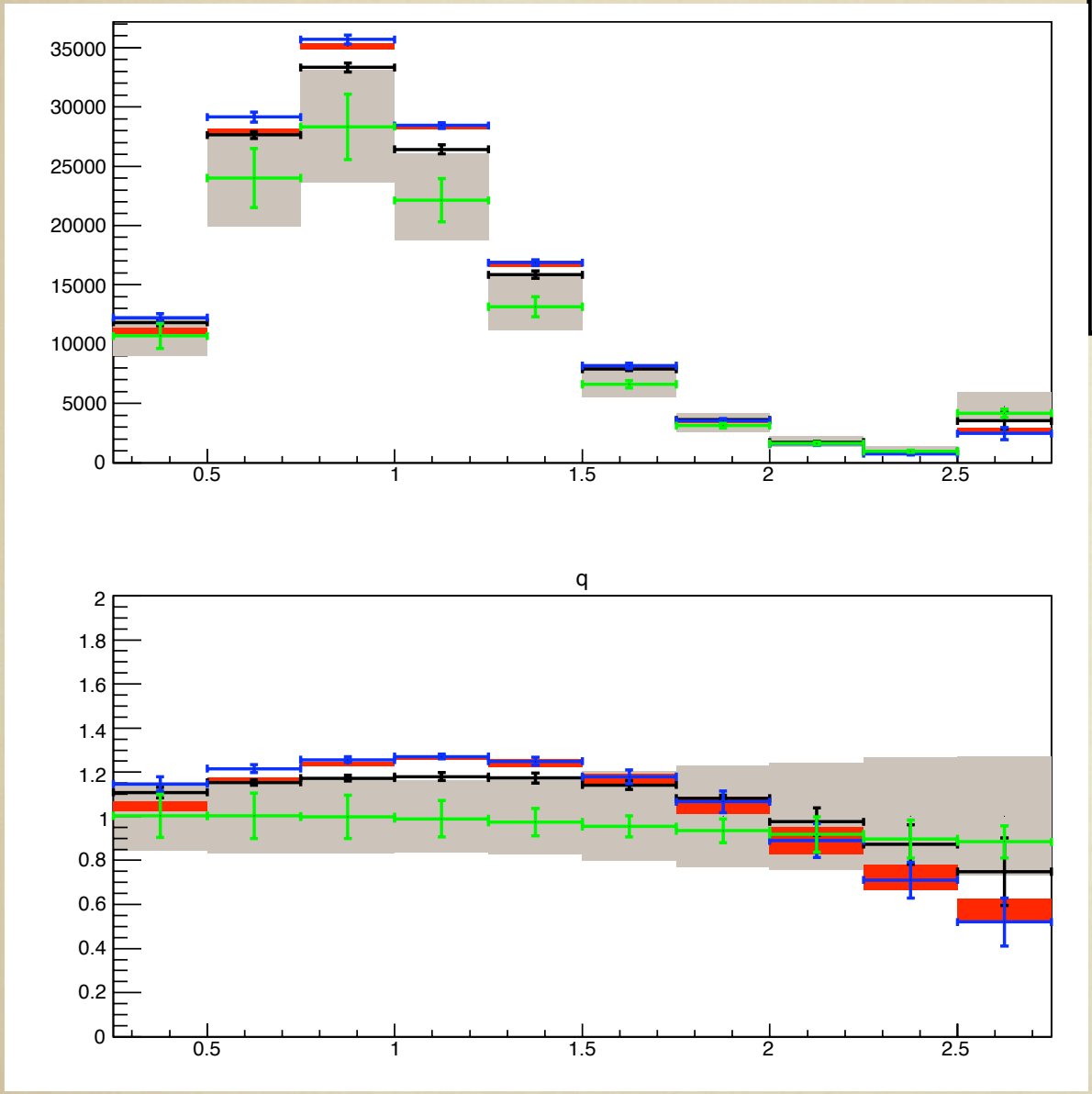
MC expectation for each P_μ-θ_μ bins

Contribution from k-th E_ν bins

MC expected flux (CV) for each E_ν bins

$$\phi_k = \sum_{P_\mu,\theta_\mu} n_k(P_\mu,\theta_\mu)$$

Fitted spectrum



-- MC prediction w/ sys. err.
-- Fit w/ SciBar stopped sample.
-- Fit w/ MRD stopped sample.
-- Fit w/ MRD penetrated sample.
-- Fit w/ all combined sample.

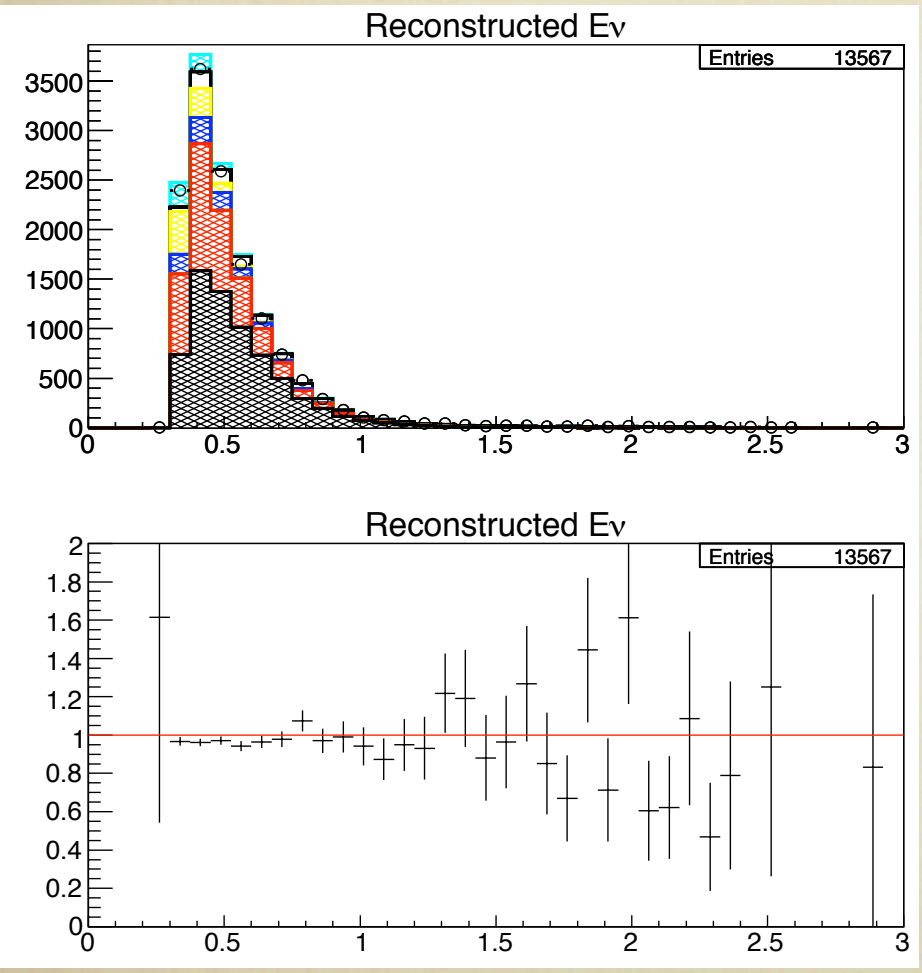
- SciBar / MRD stopped sample are (roughly) consistent

Plots/Numbers from CC Coherent π^+ Production Paper

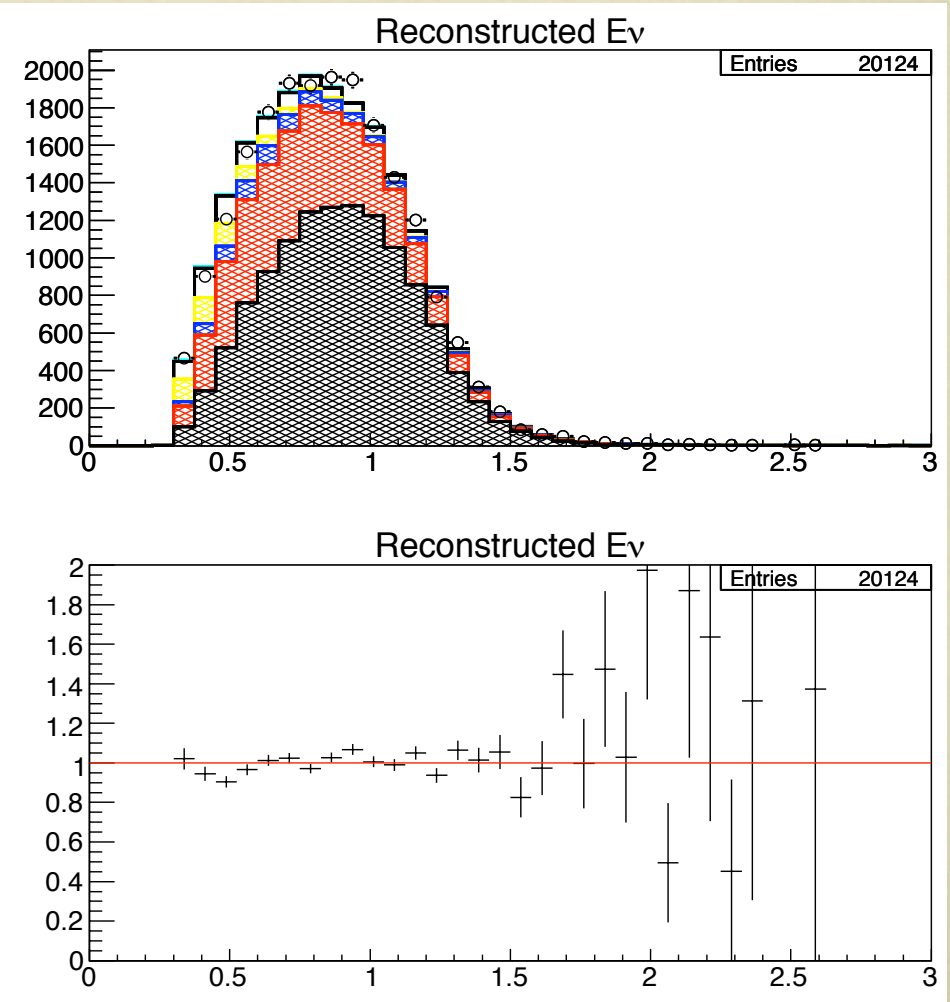
Reconstructed Enu after fitting

SciBooNE

SciBar stopped



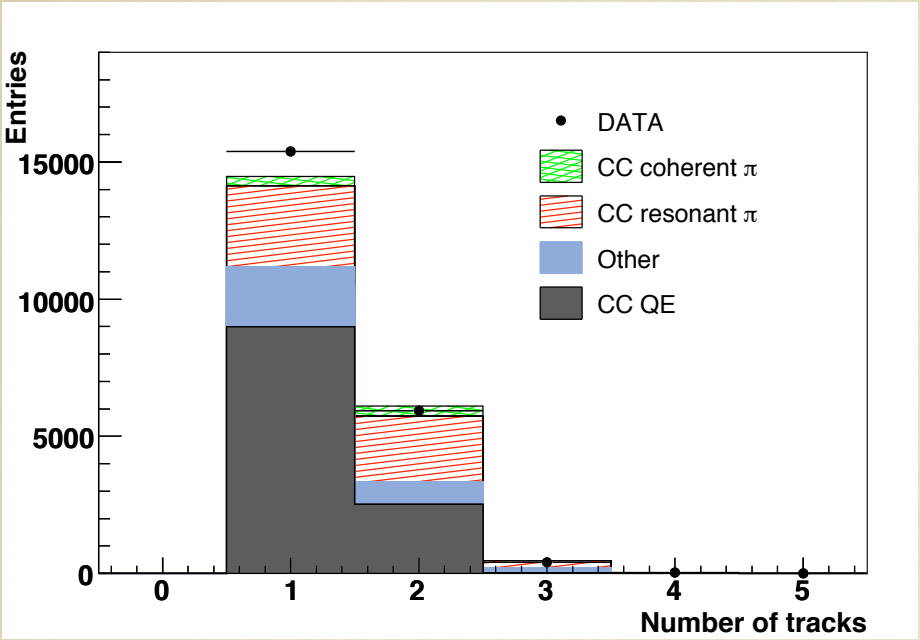
MRD stopped



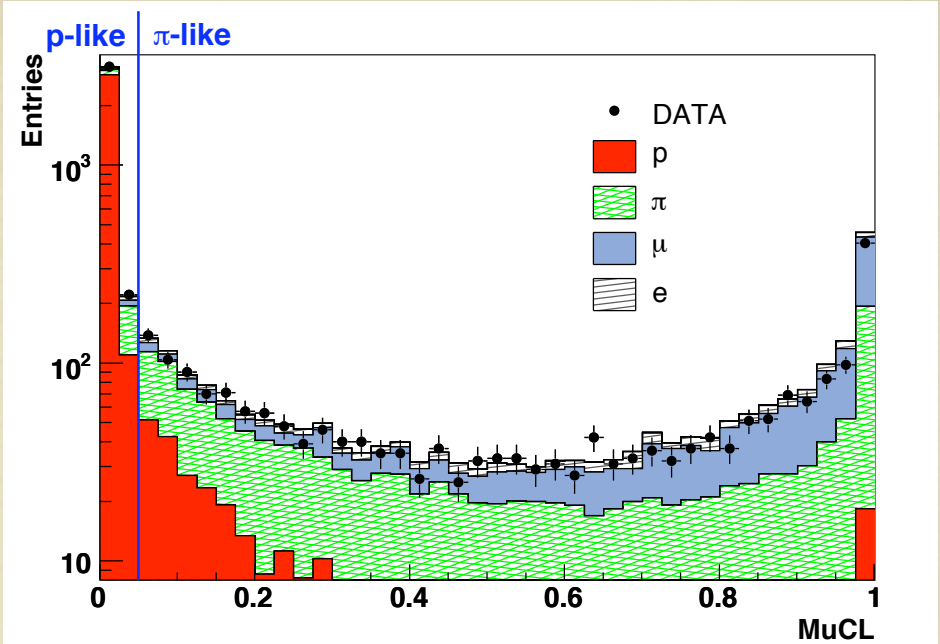
Good agreement!

SciBooNE

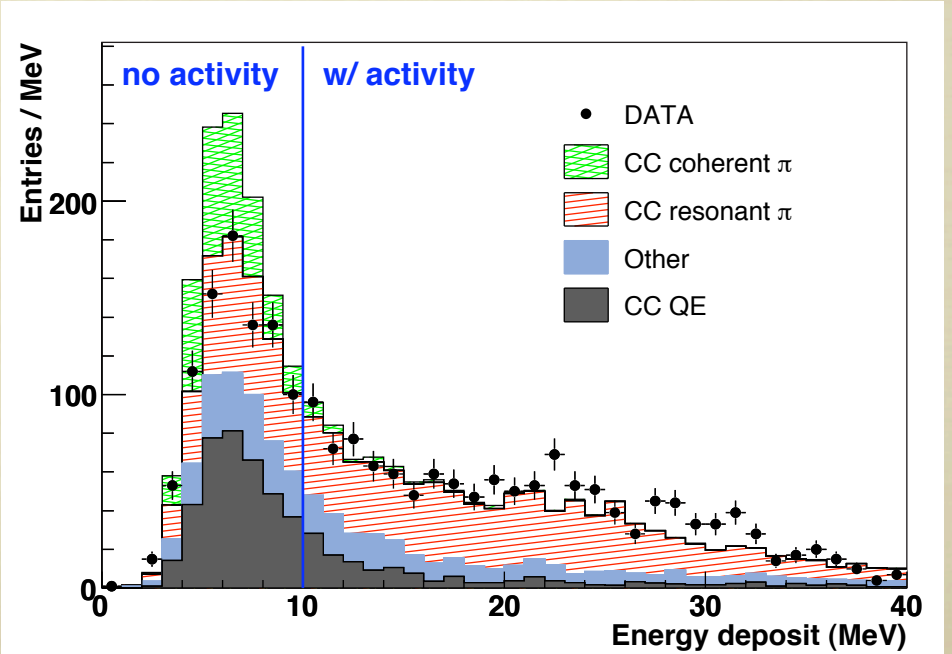
Number of tracks from the vertex (MRD stopped sample)



MuCL of 2nd track for 2 track sample

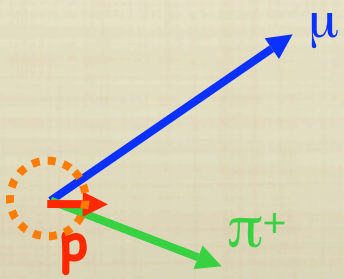


Vertex activity of $\mu+\pi$ sample

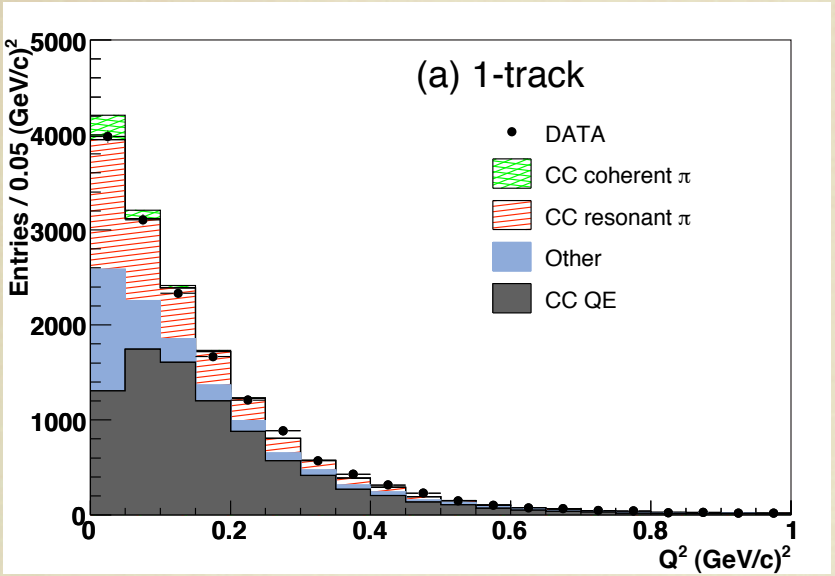


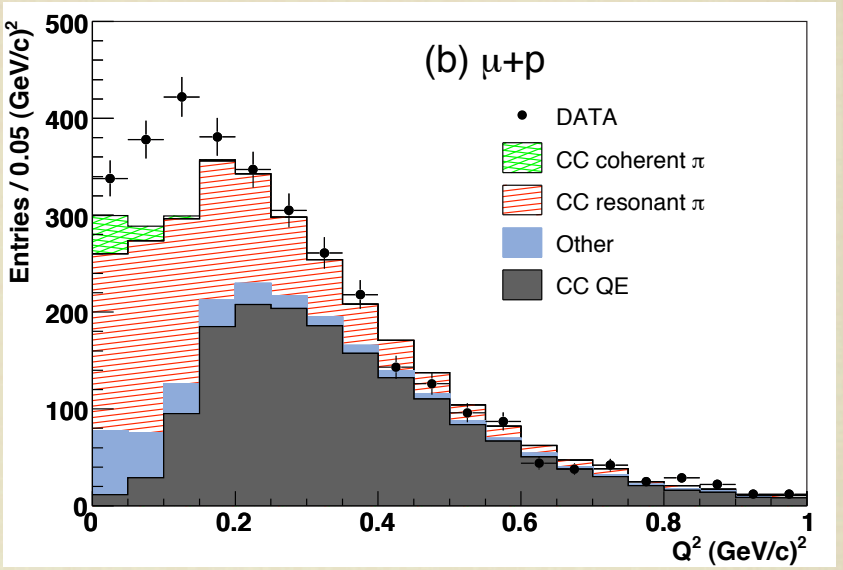
Vertex activity

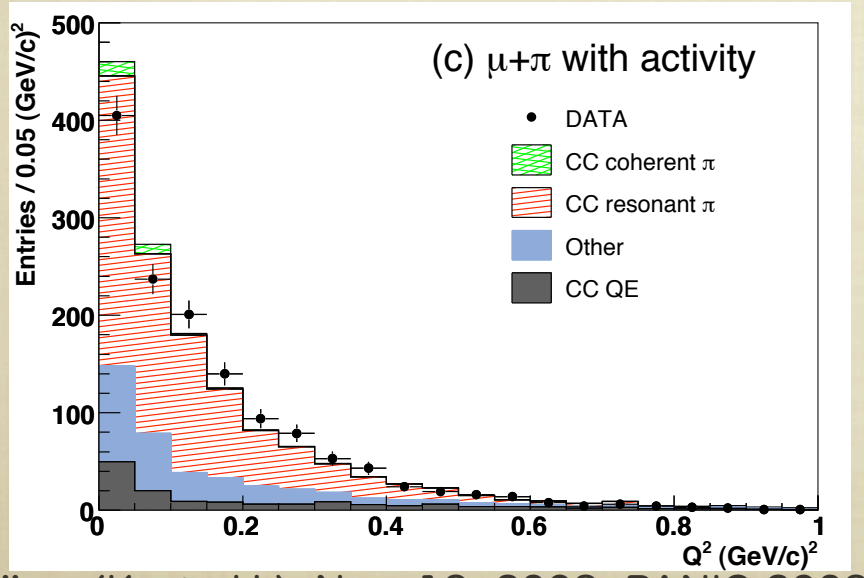
Low energy proton is identified as a large energy deposit around the vertex

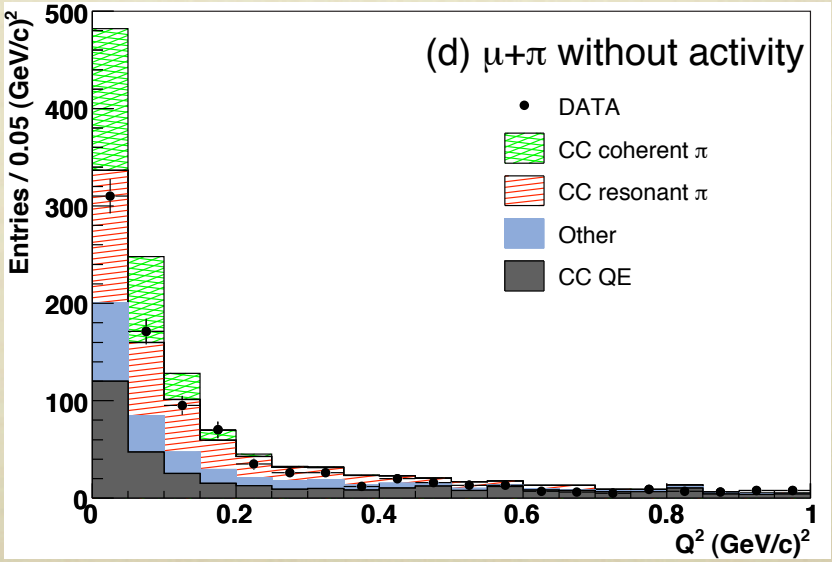


Q^2 distributions for fit



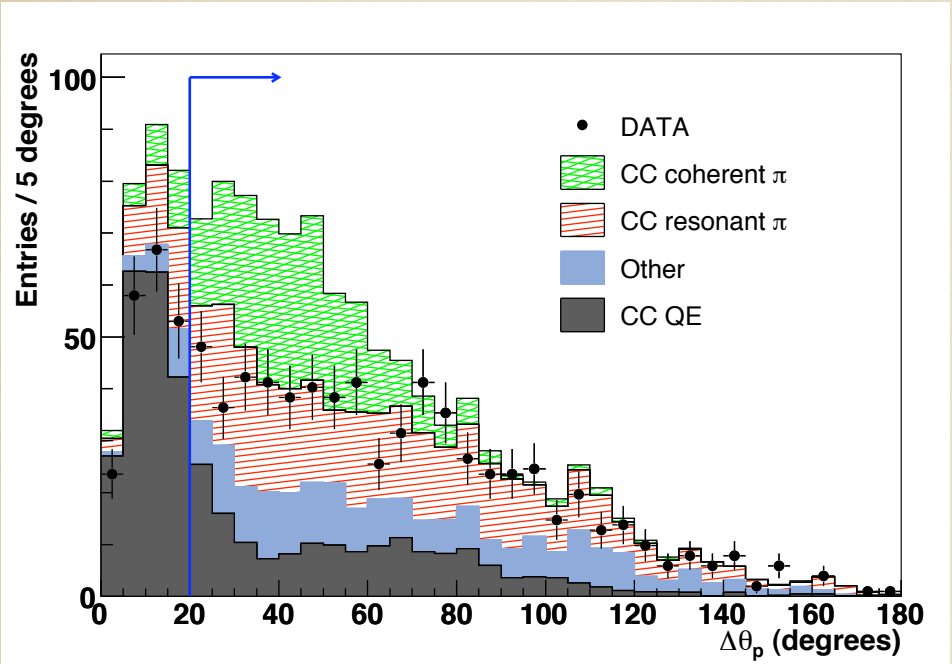




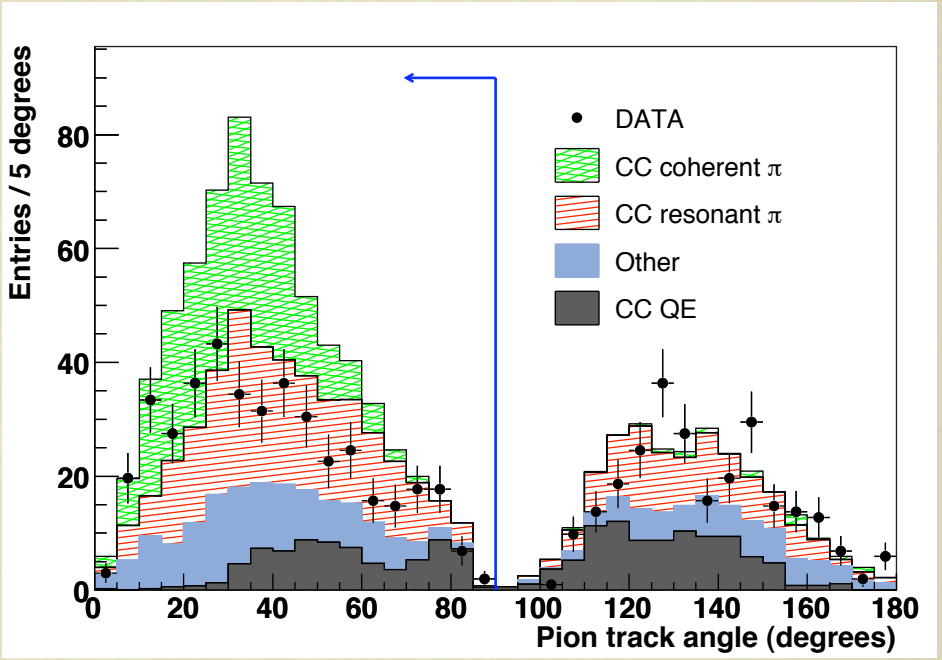


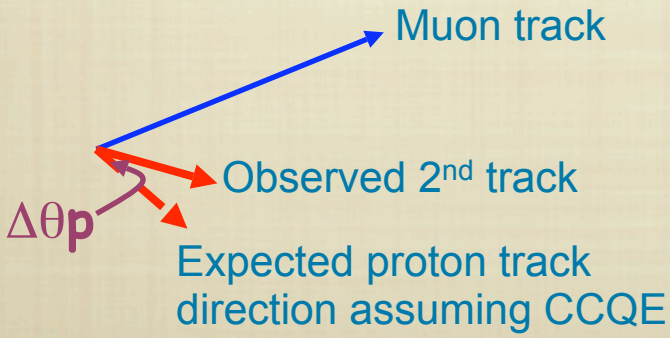
CC coherent π^+ selection

$\Delta\theta_p$



Pion angle





Event selection summary

TABLE III: Event selection summary for the MRD stopped charged current coherent pion sample.

Event selection	DATA	MC		Coherent π
		Signal	B.G.	Efficiency
Generated in SciBar fid.vol.		1,939	156,766	100%
SciBar-MRD matched	30,337	978	29,359	50.4%
MRD stopped	21,762	715	20,437	36.9%
2 track	5,939	358	6,073	18.5%
Particle ID ($\mu + \pi$)	2,255	292	2,336	15.1%
Vertex activity cut	887	264	961	13.6%
CC-QE rejection	682	241	709	12.4%
Pion track direction cut	425	233	451	12.0%
Reconstructed Q^2 cut	247	201	228	10.4%

TABLE IV: Event selection summary of MRD penetrated CC coherent pion sample.

Event selection	DATA	MC		Coherent π
		Signal	B.G.	Efficiency
Generated in SciBar fid.vol.		1,939	156,766	100%
SciBar-MRD matched	30,337	978	29,359	50.4%
MRD penetrated	3,712	177	4,375	9.1%
2 track	1,029	92	1,304	4.7%
Particle ID ($\mu + \pi$)	418	78	474	4.0%
Vertex activity cut	167	71	186	3.6%
CC-QE rejection	134	67	135	3.5%
Pion track direction cut	107	66	109	3.4%
Reconstructed Q^2 cut	57	60	40	3.1%

Systematic errors

TABLE V: Summary of the systematic errors in the charged current coherent pion cross section ratio.

Source	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