Measurement of CC and CCQE Interactions at SciBooNE

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March 7th, 2011
NuInt11

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- SciBooNE experiments
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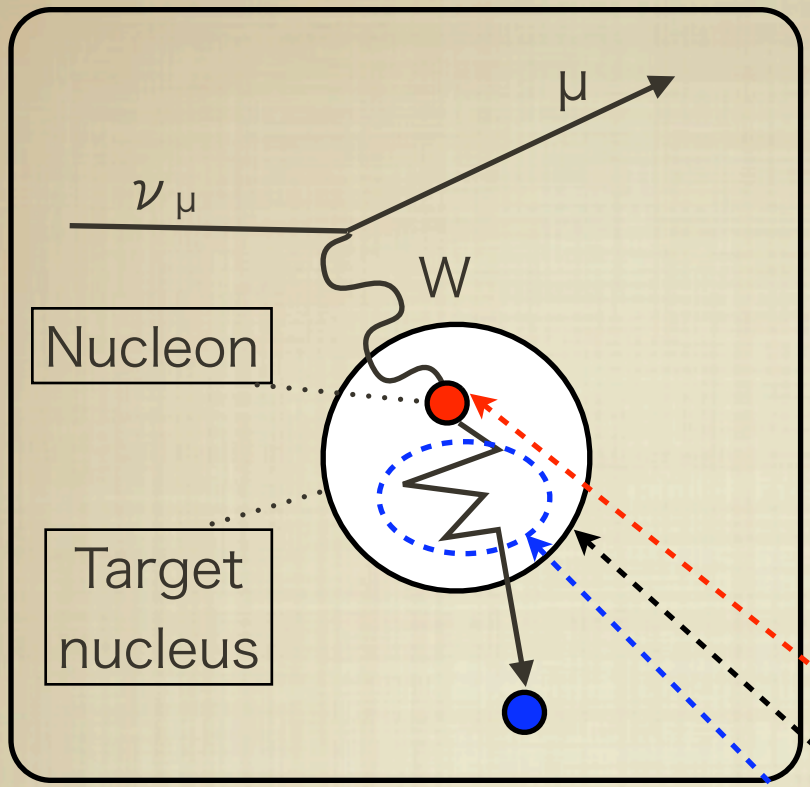
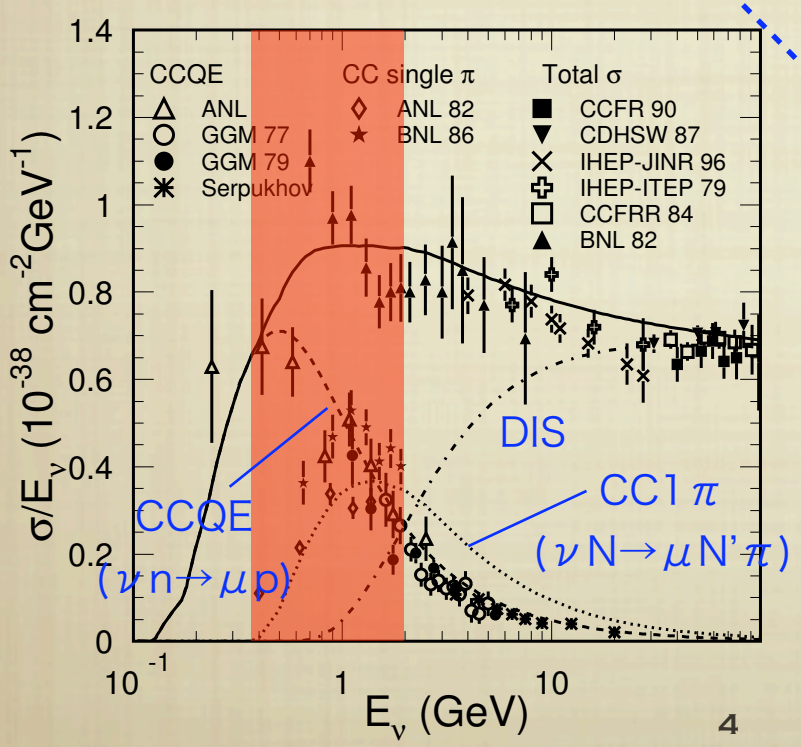
- CC-QE interaction measurements (updates from NuInt09)
- Summary

Introduction

Uncertainties of neutrino interactions



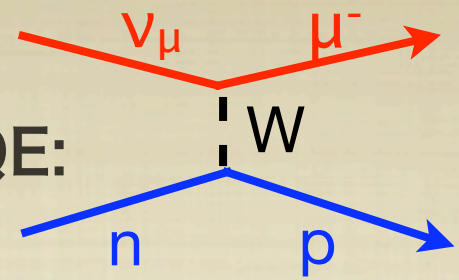


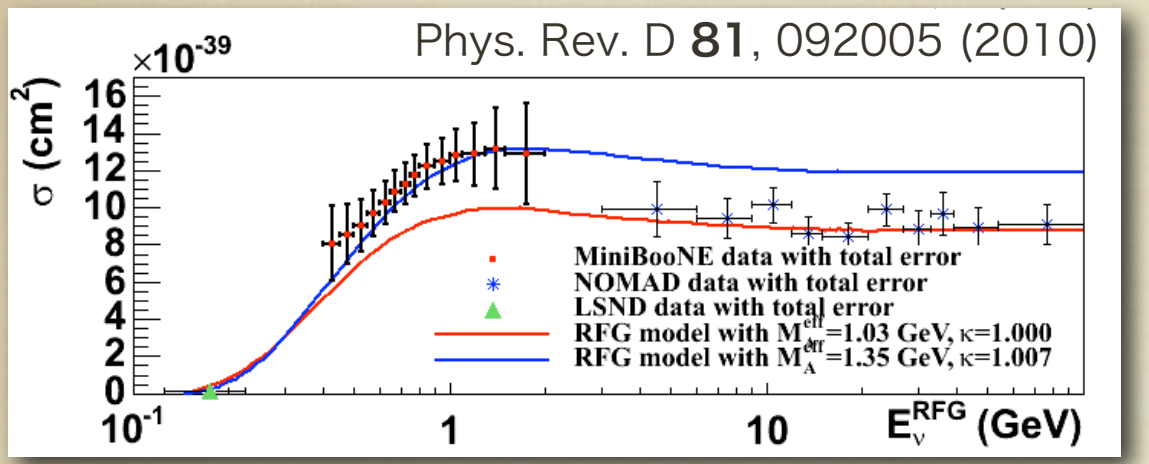
- Knowledge of neutrino interaction cross section in the 1 GeV region on nuclear target (eg. carbon) is essential for oscillation experiments: MiniBooNE / T2K
- Large uncertainties from
  - Neutrino-nucleon interaction model.
  - Nuclear model (Fermi momentum).
  - Intra-nuclear interaction, aka "FSI". (problem for exclusive measurements)
- Previous measurements are mostly from old bubble chamber (deuteron target)
  ➜ Not applicable for heavier nuclei

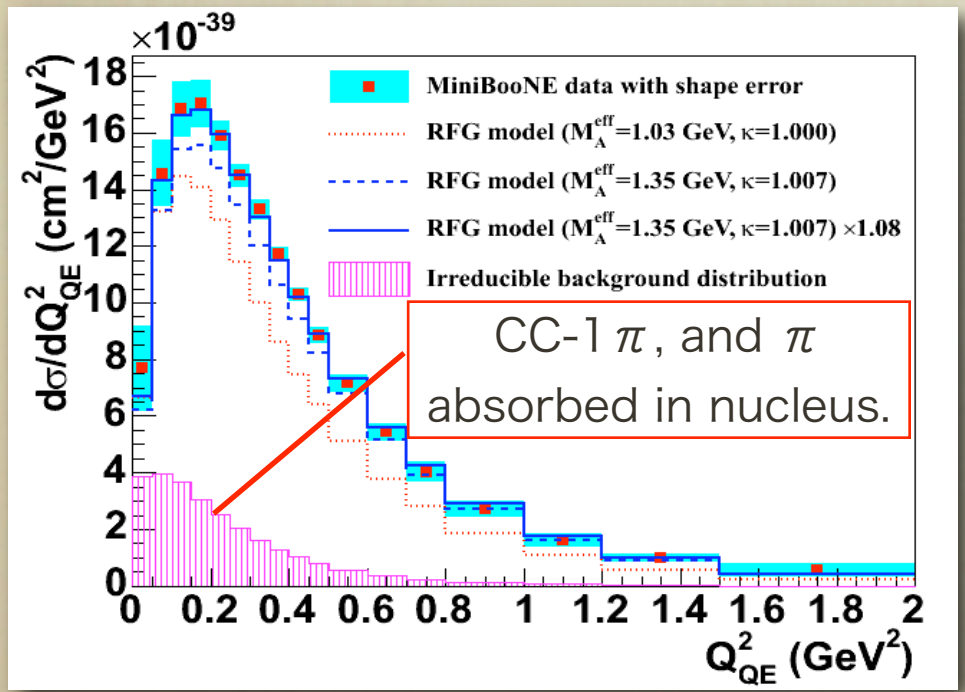
Both inclusive and exclusive cross section measurements are essential.

A hot topic

CC-QE:



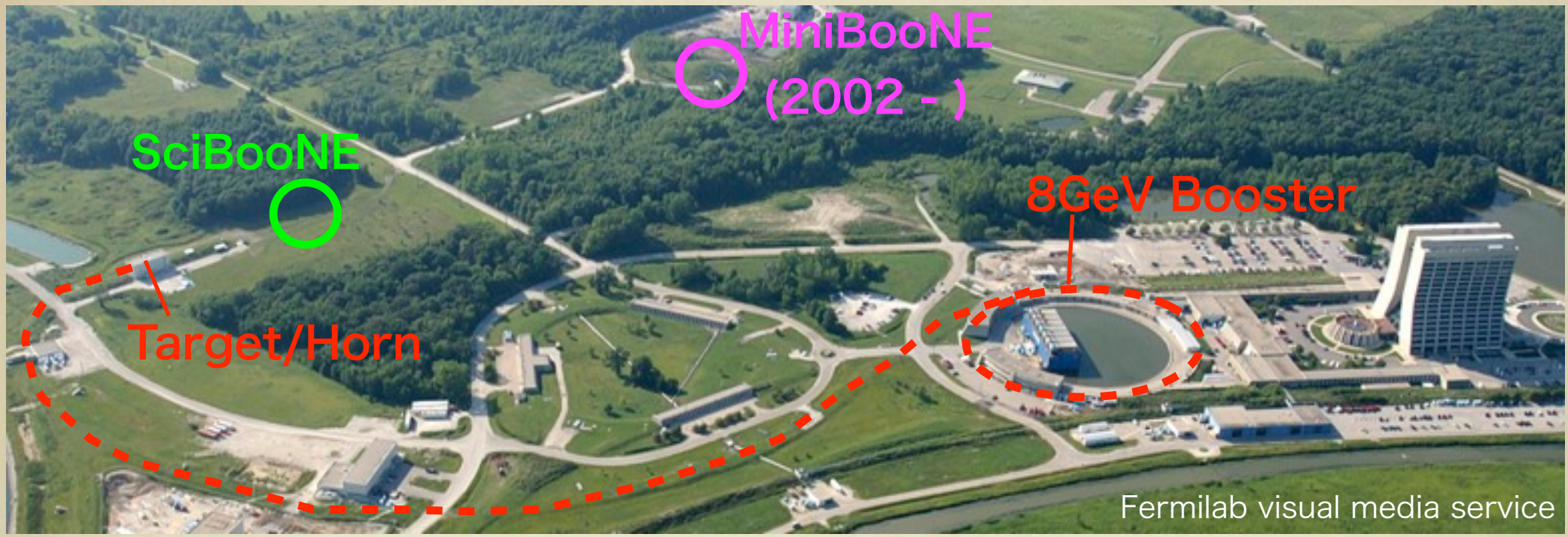


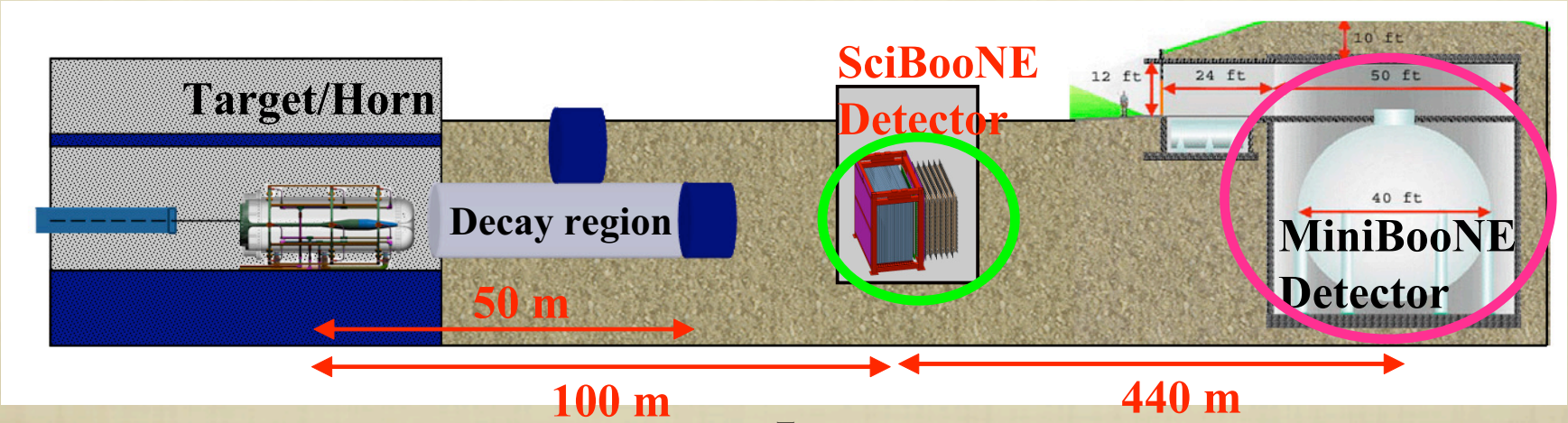


- Charged current (CC) quasi-elastic (QE) interaction cross section by MiniBooNE
- Enhancement of cross section in this region?
- Mismodeling of CC-1 π background? (~20%)
  - π absorbed in nucleus
- Need cross-check with **CC-inclusive sample**, preferably with **wide energy range**.

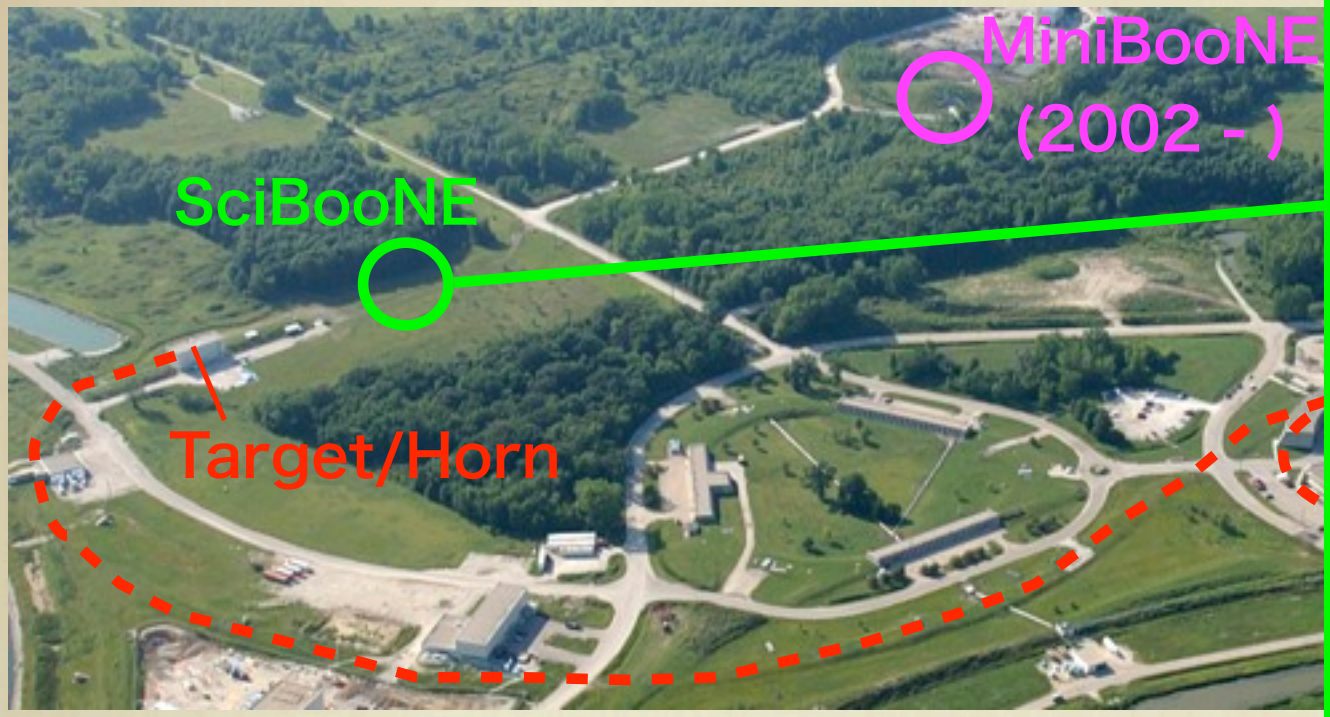
SciBooNE Experiment

Overview

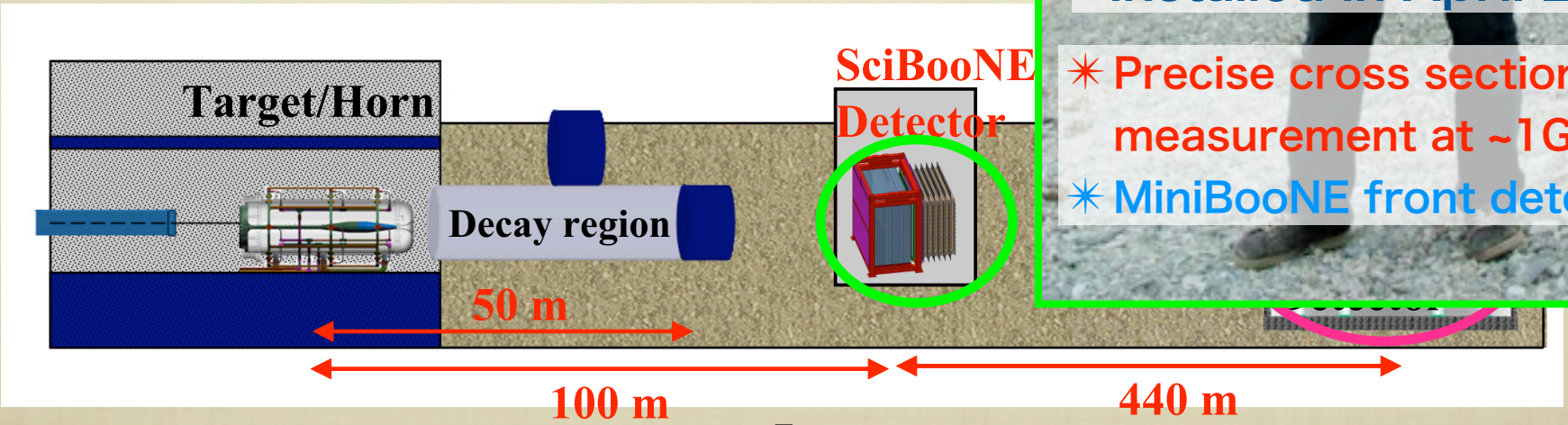

MiniBooNE
(2002 -)
SciBooNE
8GeV Booster
Target/Horn
Fermilab visual media service


Target/Horn
Decay region
SciBooNE
Detector
10 ft
12 ft
24 ft
50 ft
40 ft
MiniBooNE
Detector
50 m
100 m
440 m

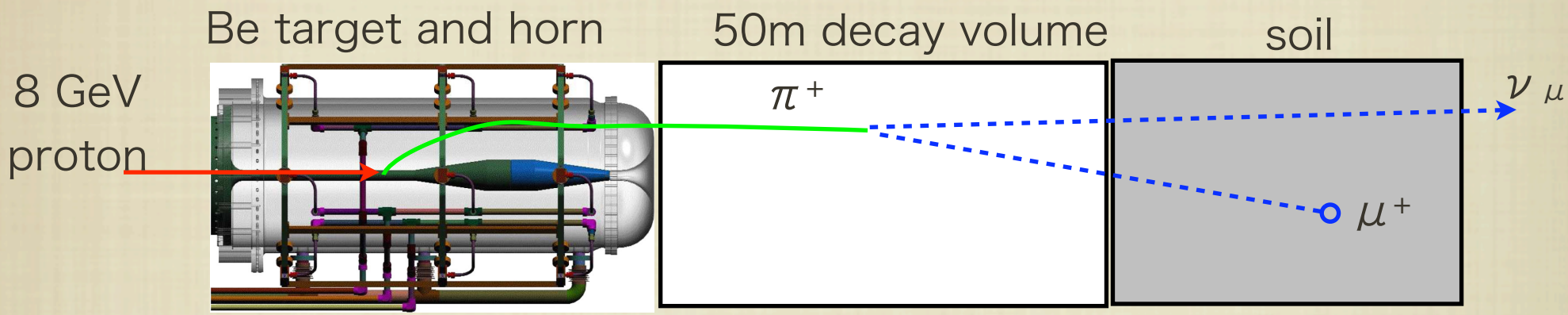
Overview


MiniBooNE
(2002 -)
SciBooNE
Target/Horn

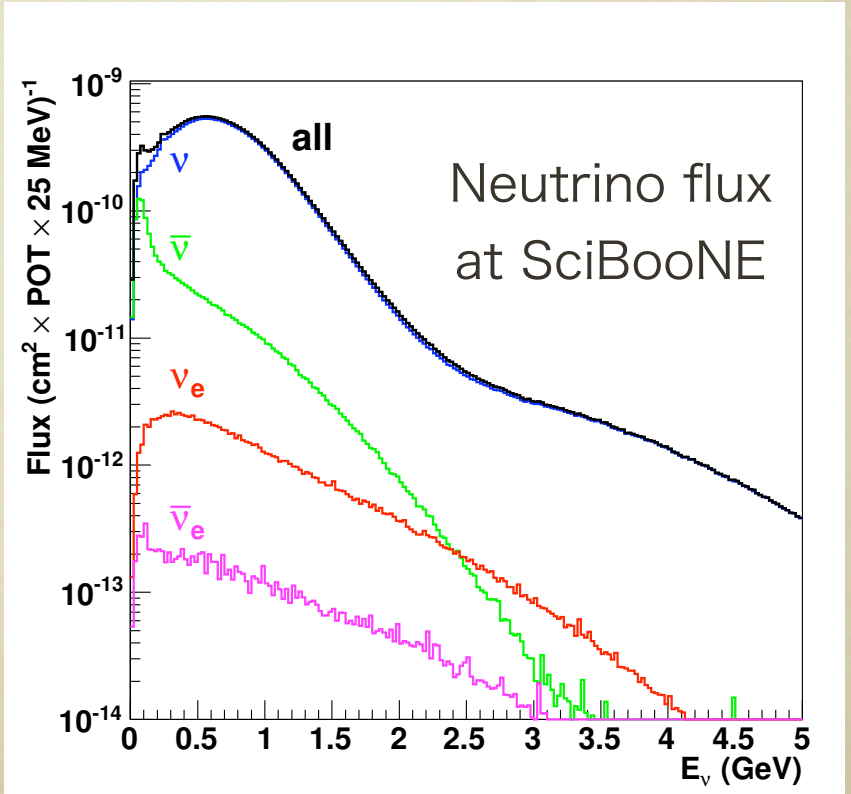
SciBooNE detector
installed in April 2007
✳ Precise cross section
measurement at ~1GeV
✳ MiniBooNE front detector


Target/Horn
Decay region
SciBooNE
Detector
50 m
100 m
440 m

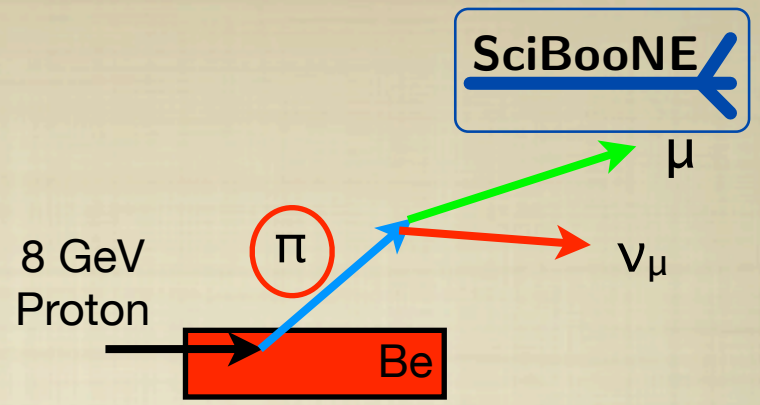
Fermilab Booster Neutrino Beam



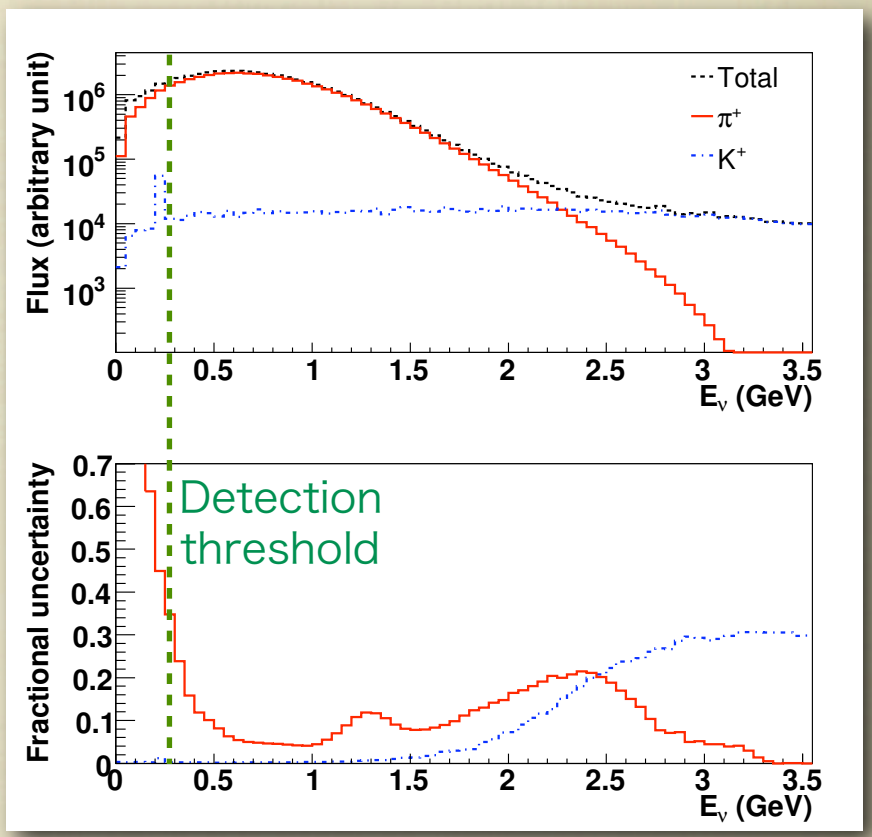
- Intense ν_μ beam with the mean energy of ~0.8 GeV
  - 93% pure ν_μ beam.
- Anti-ν_μ beam is also produced by inverting horn polarity.



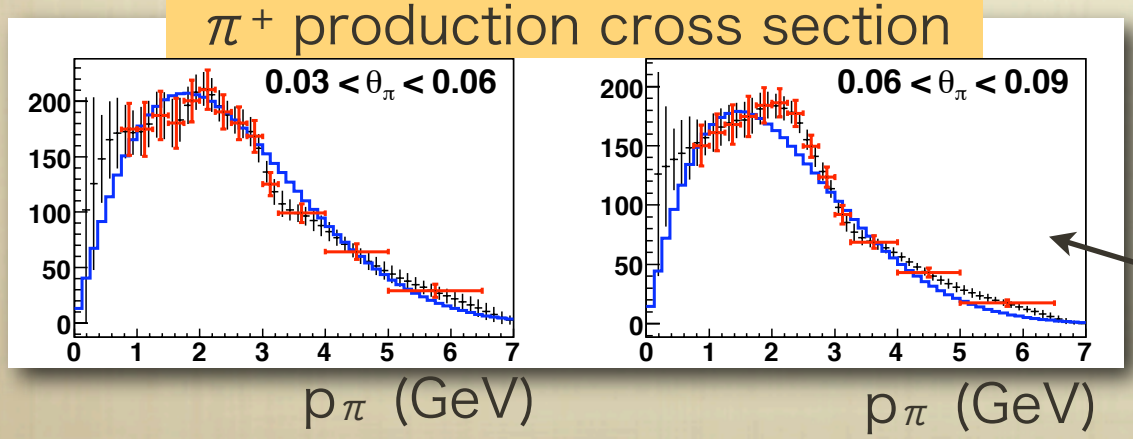
Neutrino flux uncertainties



- The dominant uncertainty: hadron production cross section from p-Be interaction.
- For π^+ production, use the measurement by HARP experiment (CERN PS214) to estimate the central value and the uncertainty.

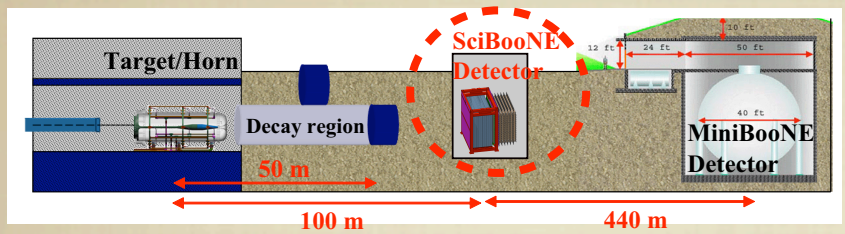


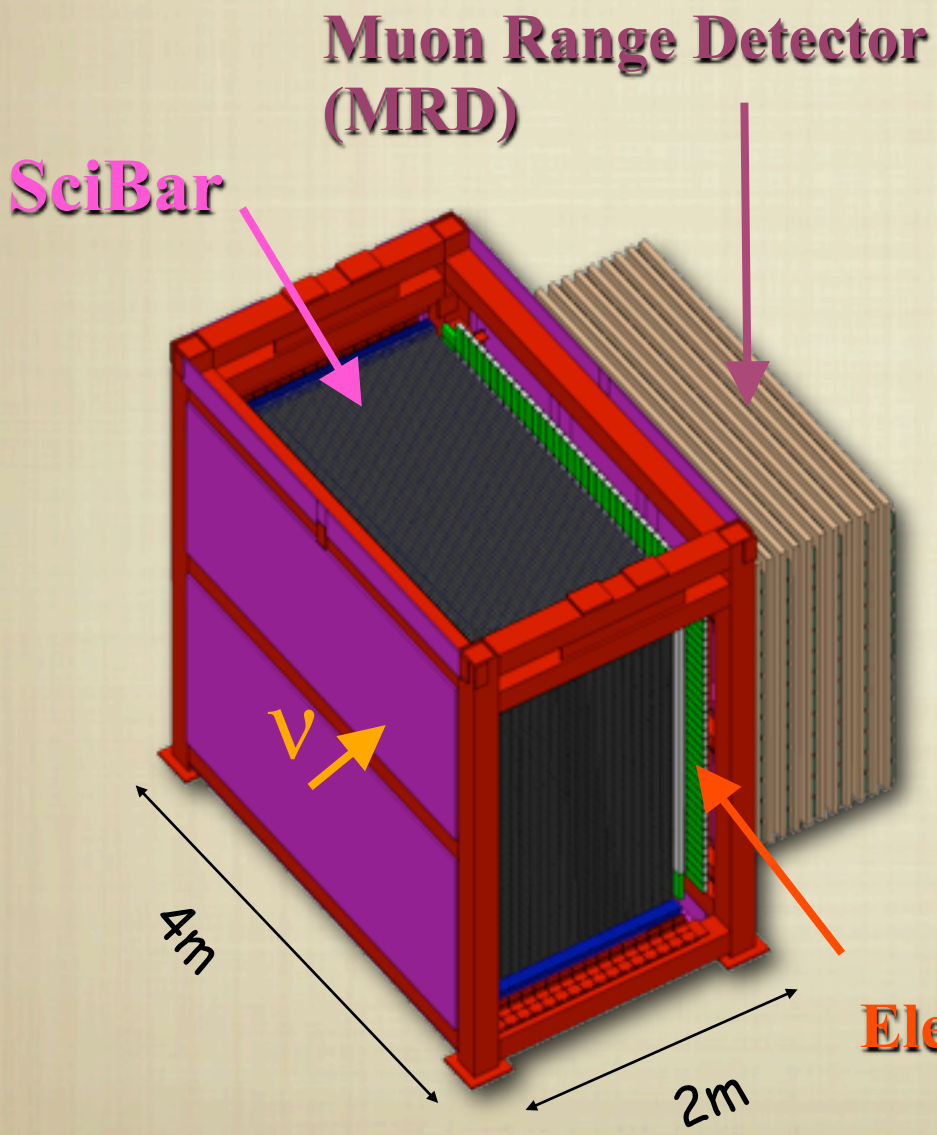
π^+ production cross section



-- Cross section used for MC production (Sanford-Wang)
-- HARP data
-- Profile of spline interpolations

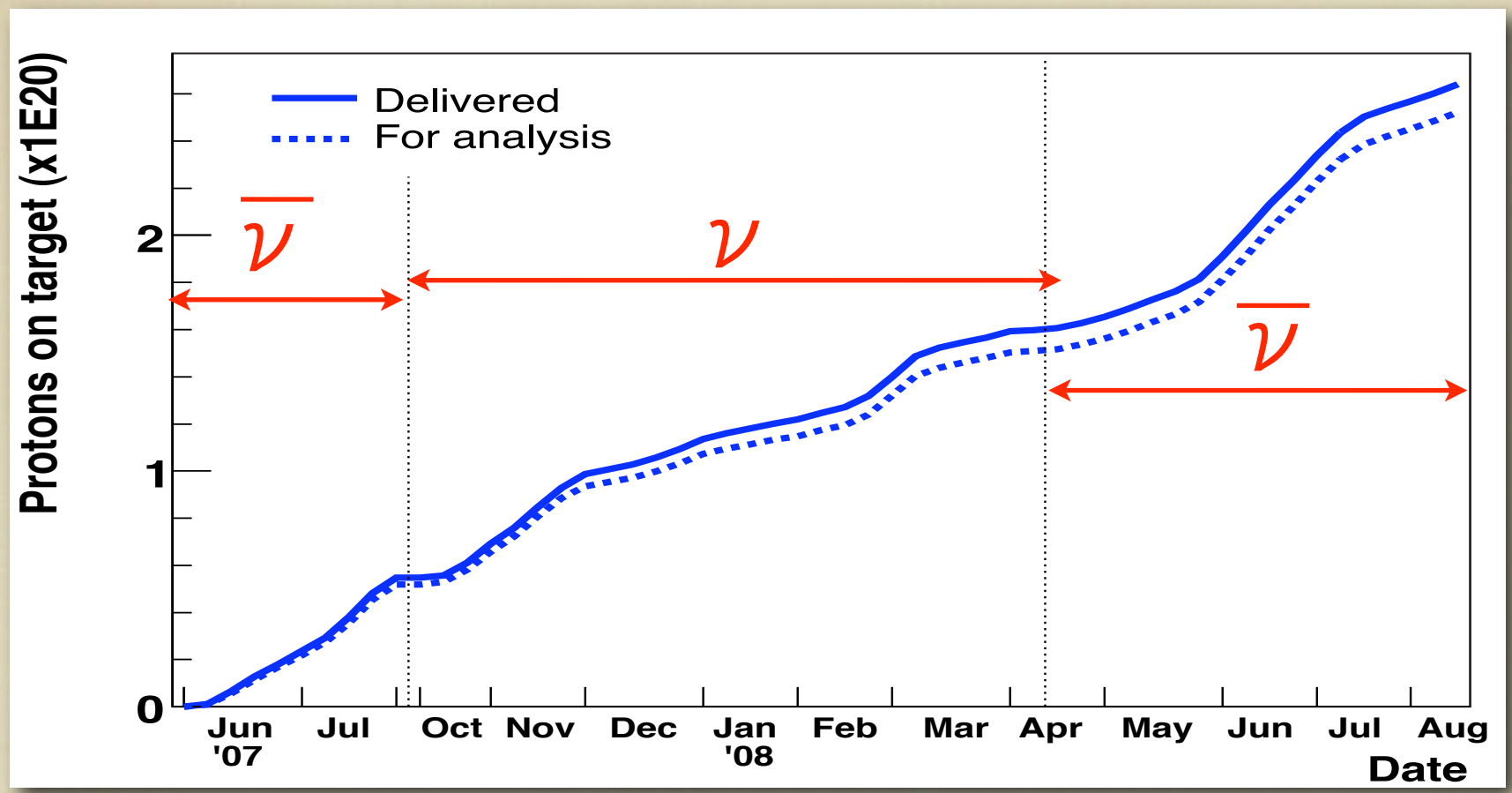
SciBooNE detector





- Located 100 m downstream of the target.
- SciBar:
  - Full active scintillator tracker (~14000 strips)
  - Neutrino target (~10 ton)
  - Main component： CH
- Muon Range Detector (MRD)
  - A sandwich type detector of steel + plastic scintillator.
  - Can stop muons up to ~1.2GeV
  - Reconstruct muon momentum from its path-length

Data set



- Data taking: Jun. 2007 - Aug. 2008
  - Neutrino mode: 0.99 x 10^{20} POT
  - Anti-neutrino mode: 1.53 x 10^{20} POT

Analysis of the full neutrino data set is presented today

CC-inclusive interaction measurement

Neutrino interaction simulation

SciBooNE

Two neutrino interaction simulators are used:

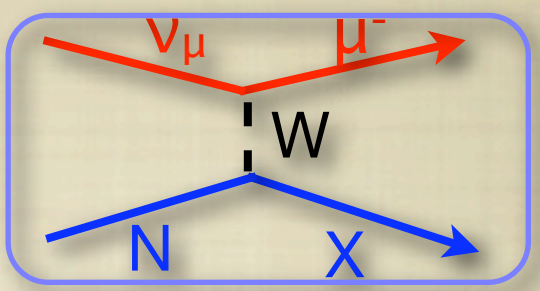
NEUT: SK, K2K, T2K, etc ➜CC-inclusive and CC-QE analyses
NUANCE: MiniBooNE, etc ➜CC-inclusive analysis

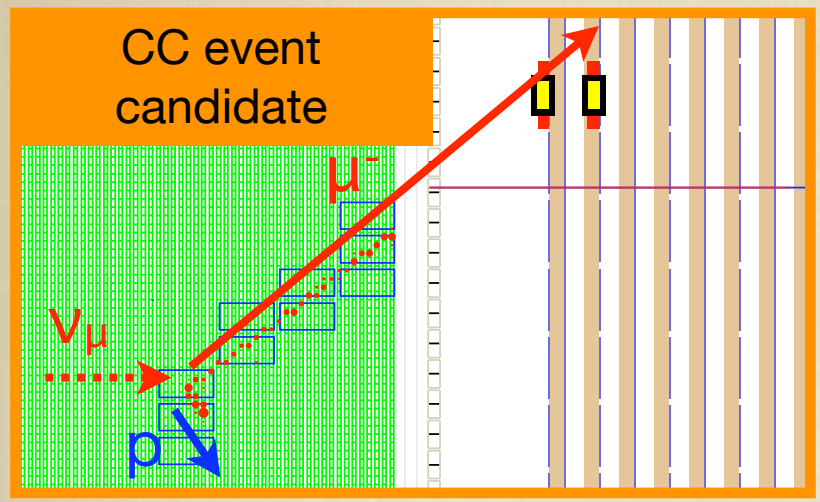
- Both use essentially same models
  - CCQE: Smith-Monitz Relativistic Fermi gas model
  - CC-1π: Rein-Shegal Model
- Parameter (eg. M_A) values are different
- FSI models are different

	NEUT	NUANCE
p_F	217 MeV	220 MeV
E_B	25 MeV	34 MeV
M_A^{QE}	1.21 GeV	1.23 GeV
κ	1.000	1.022
$M_A^{1\pi}$	1.21 GeV	1.10 GeV

κ: empirical parameter to enhance Pauli-blocking (1.0 is default)

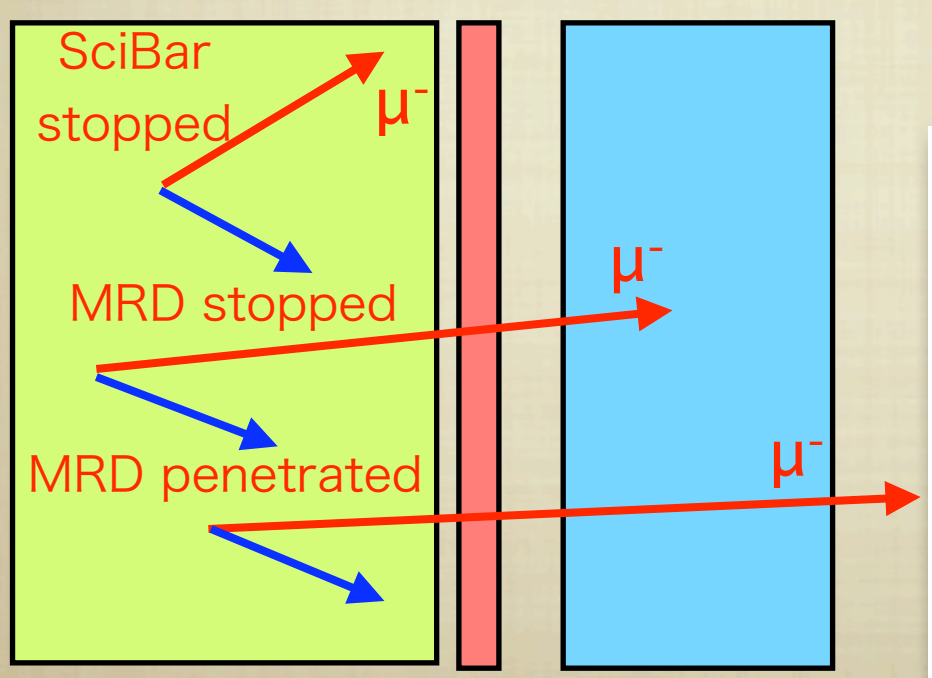
CC-inclusive selection

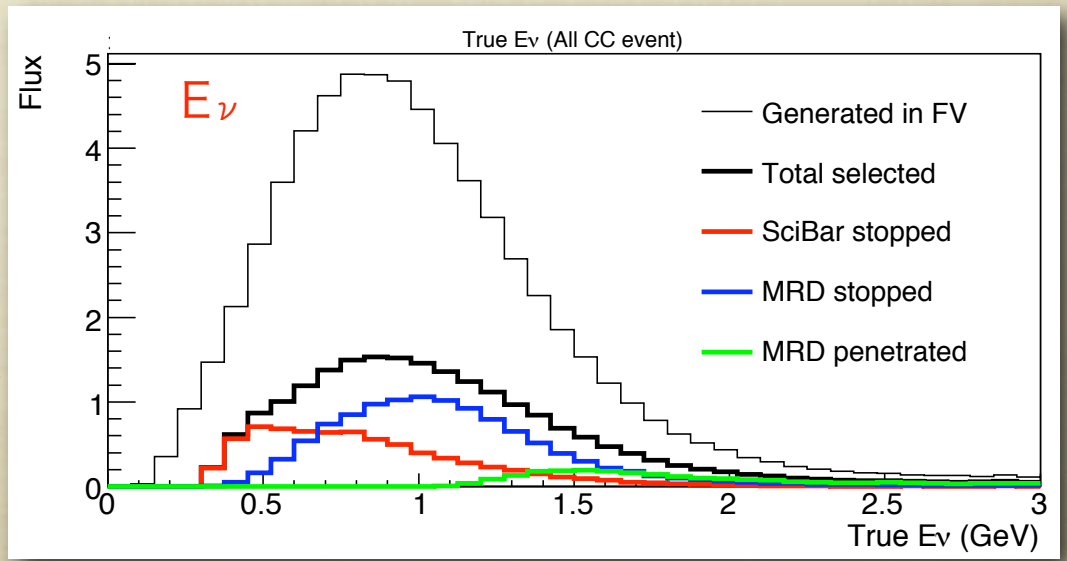




- Select MIP-like energetic tracks (P_μ>0.25GeV)
- Reject side-escaping muons.
- 3 samples:
  - SciBar-stopped (P_μ, θ_μ)
  - MRD-stopped (P_μ, θ_μ)
  - MRD-penetrated (θ_μ)

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

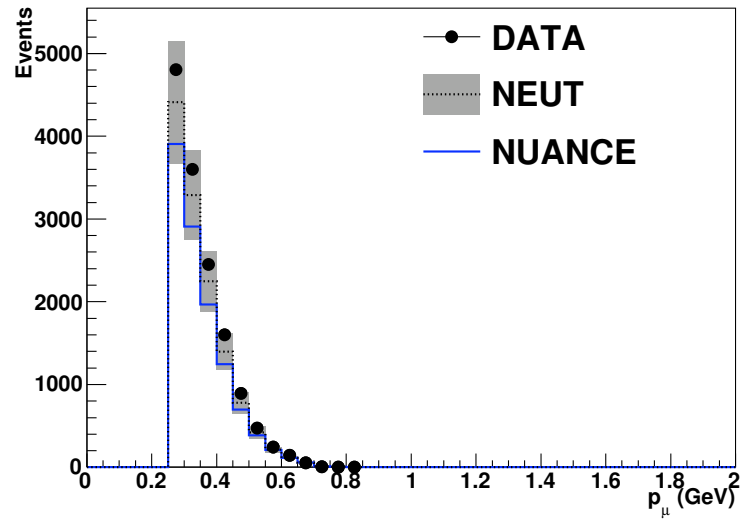


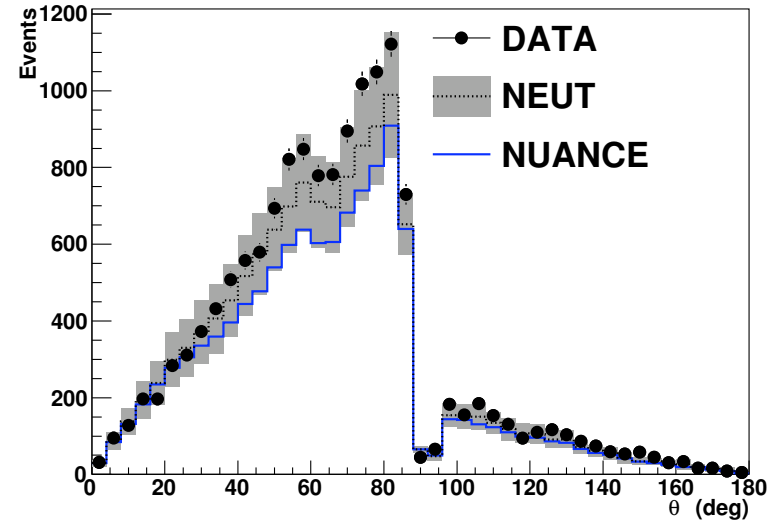


Muon distributions

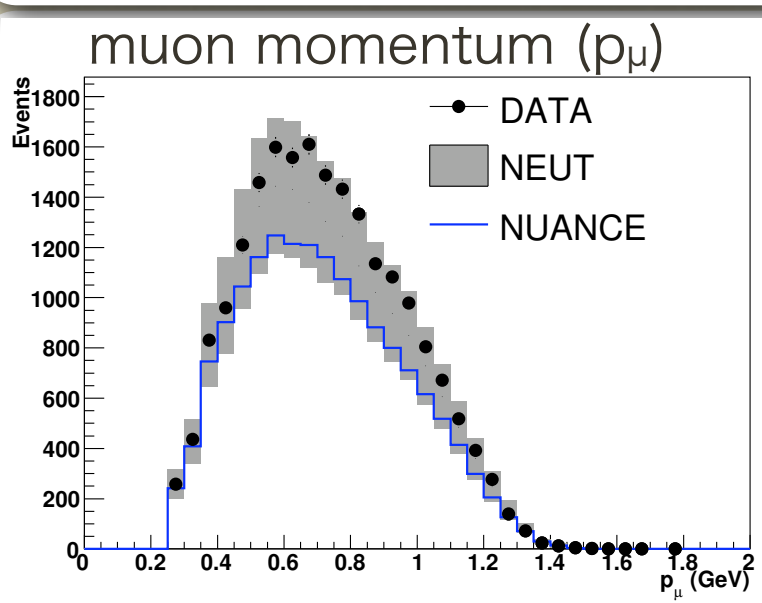
SciBooNE

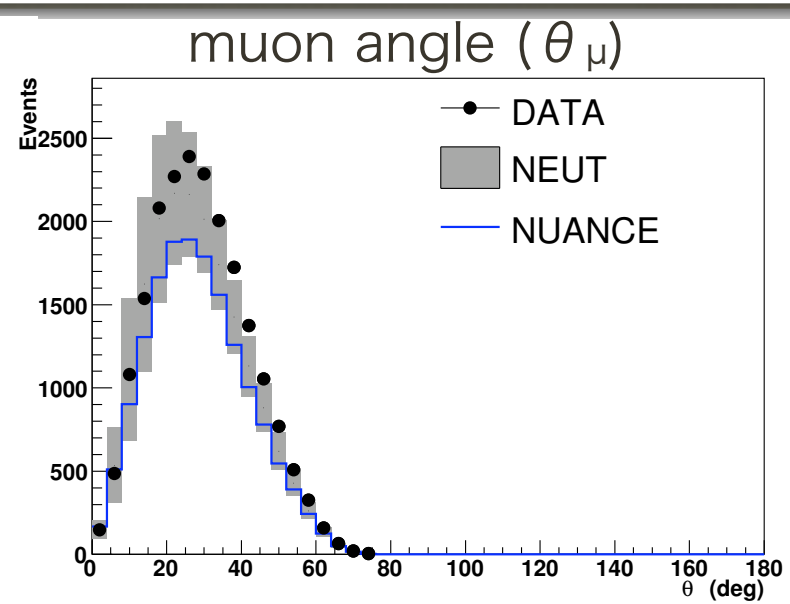
SciBar-stopped





MRD-stopped



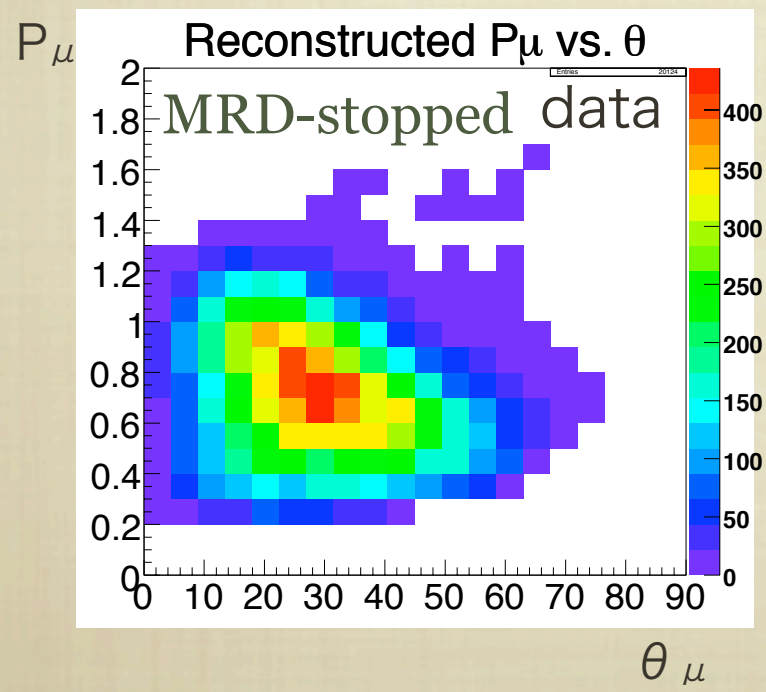


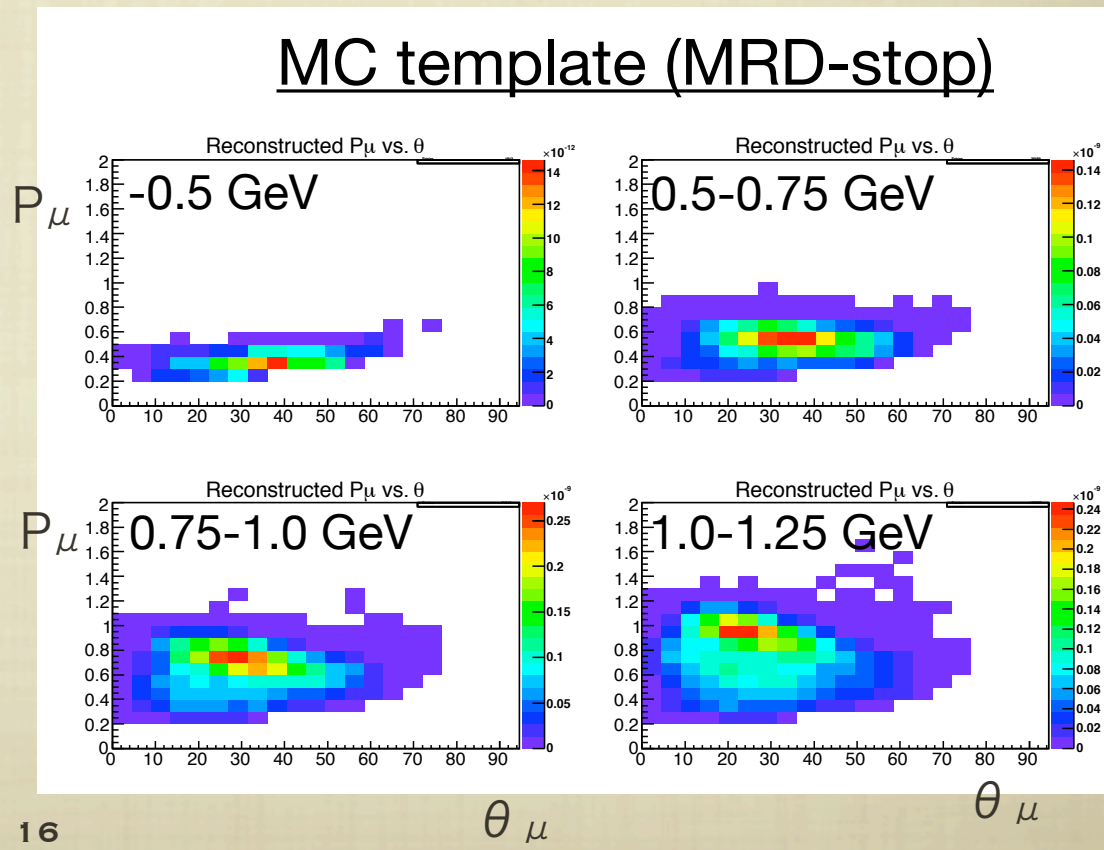
Plots are POT normalized

MC reproduce data within the systematic error

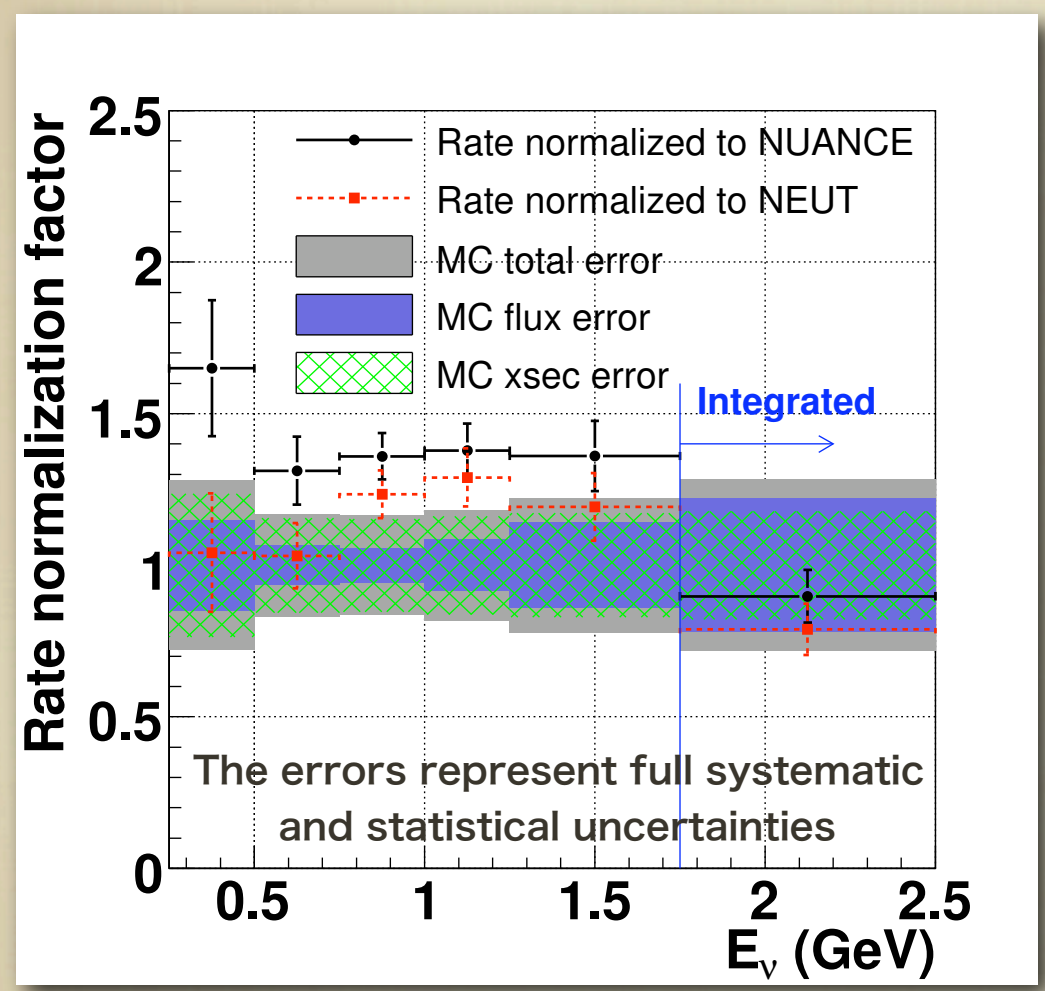
Spectrum fit

- Tune MC prediction by re-weighting as a function of true neutrino energy.
- Determine the rate normalization factor which best fits to p_μ vs. θ_μ 2D distributions.
  - SciBar-stop, MRD-stop and MRD-penetrated samples are used simultaneously.





CC interaction rate



- Extract CC interaction rate

$$\mathcal{R}_i = \frac{f_i \cdot \mathcal{N}_i^{pred} \cdot P_i}{\epsilon_i}$$

normalization factor

# of event prediction

Purity

Efficiency

- The product of (flux) x (cross-section)

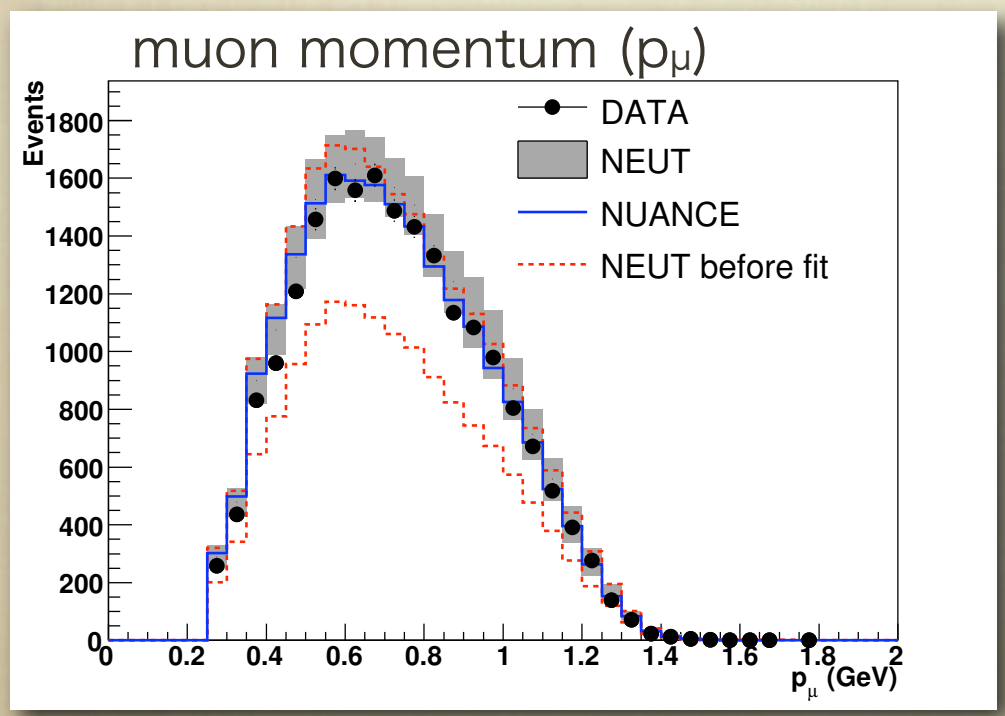
Input for SciBooNE-MiniBooNE joint ν_μ disappearance analysis

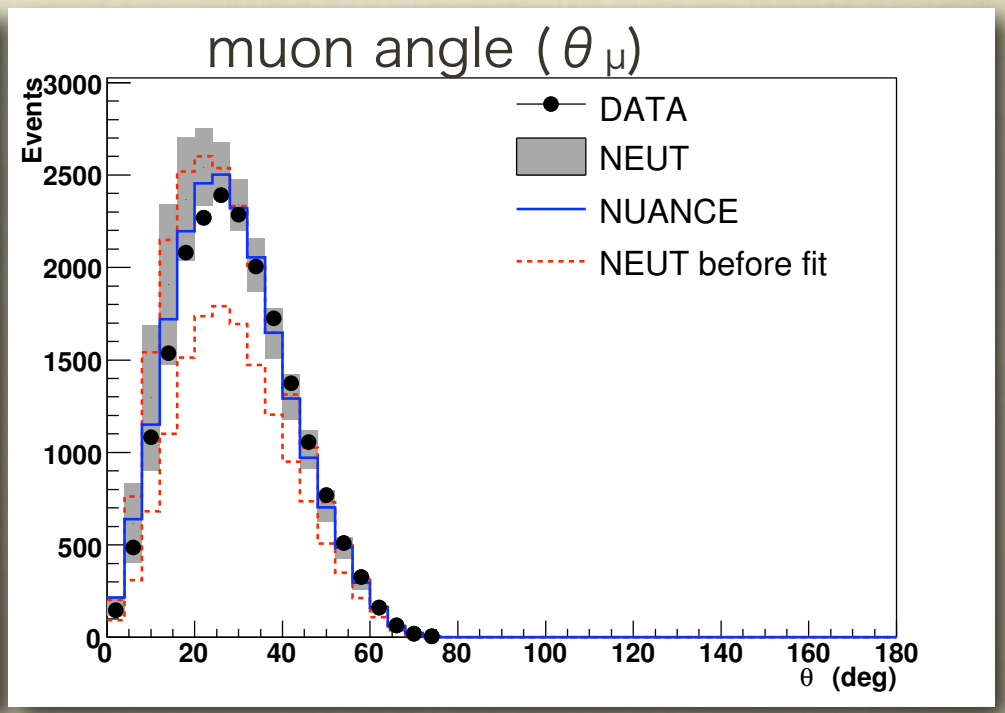
Parameter	f_0	f_1	f_2	f_3	f_4	f_5
E_ν range (GeV)	0.25 - 0.5	0.5 - 0.75	0.75 - 1.0	1.0 - 1.25	1.25 - 1.75	1.75+

Distributions after fit

- Apply obtained rate normalization factors.
- Confirmed that the distribution well reproduce the data, and the errors become much smaller.

MRD-stopped
POT normalized



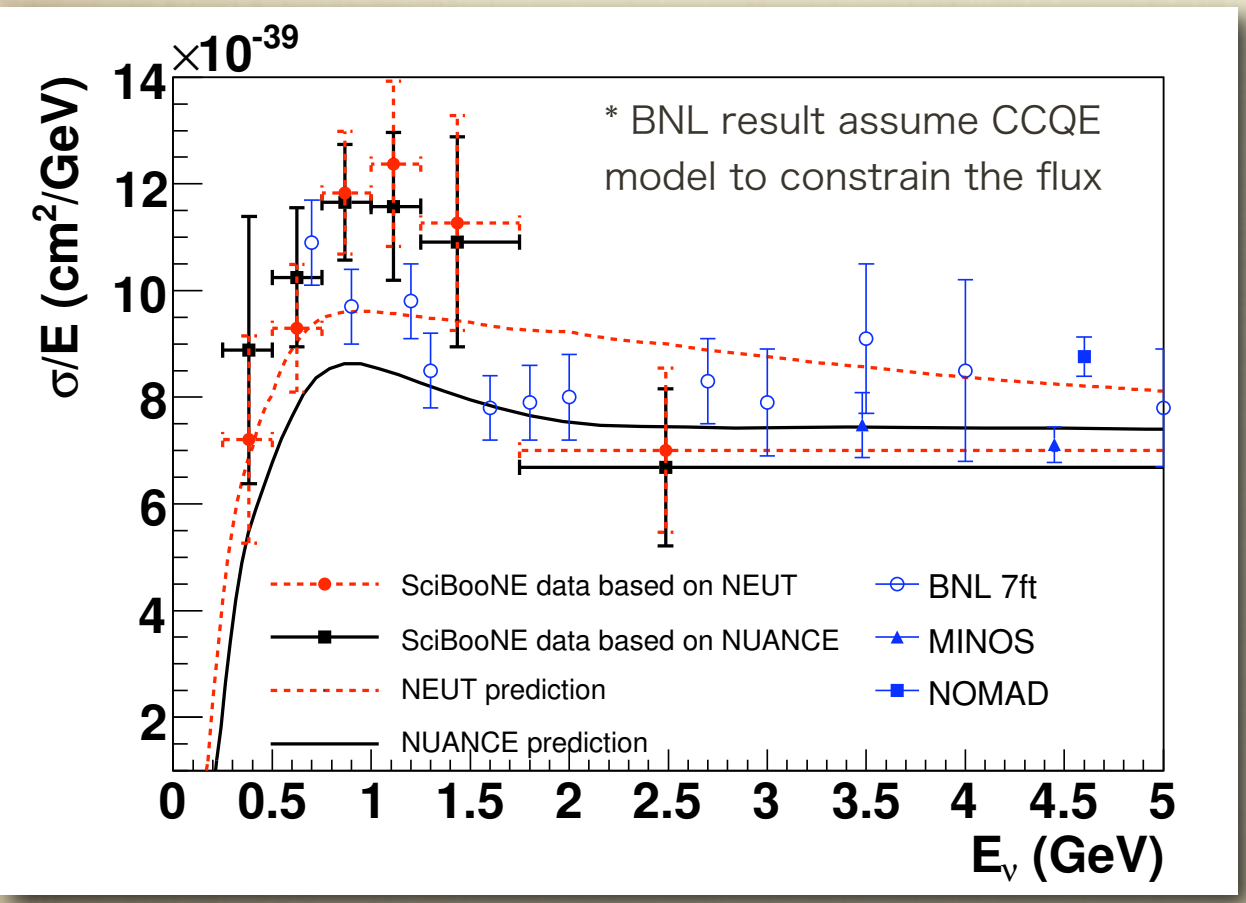


CC inclusive cross section

$$\sigma_i = f_i \cdot < \sigma_{CC}^{pred} >_i = \frac{f_i \cdot \mathcal{N}_i^{pred} \cdot P_i}{\epsilon_i \cdot T \cdot \Phi_i}$$

T: number of target nucleon

Φ: total flux

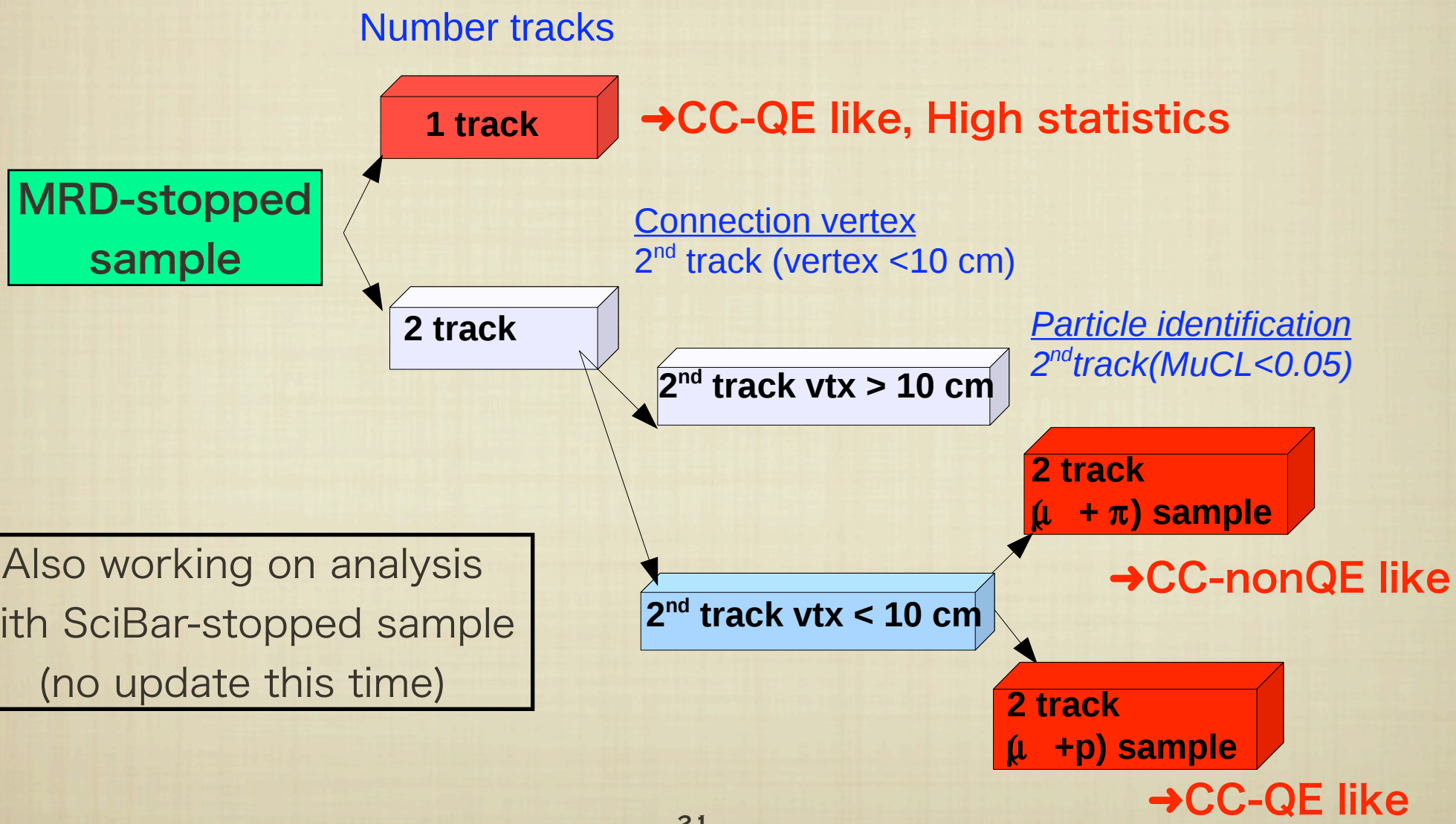


The result published in Phys. Rev. D **83**, 012005 (2001)

- First measurement of CC-inclusive cross section on carbon in the 1 GeV region
- NEUT and NUANCE based cross-section are consistent.
- Covers up to ~ 3 GeV.
- Consistent with MINOS, NOMAD and old BNL bubble chamber (deuterium) measurements

CC-QE interaction measurement

Samples for CC-QE analysis



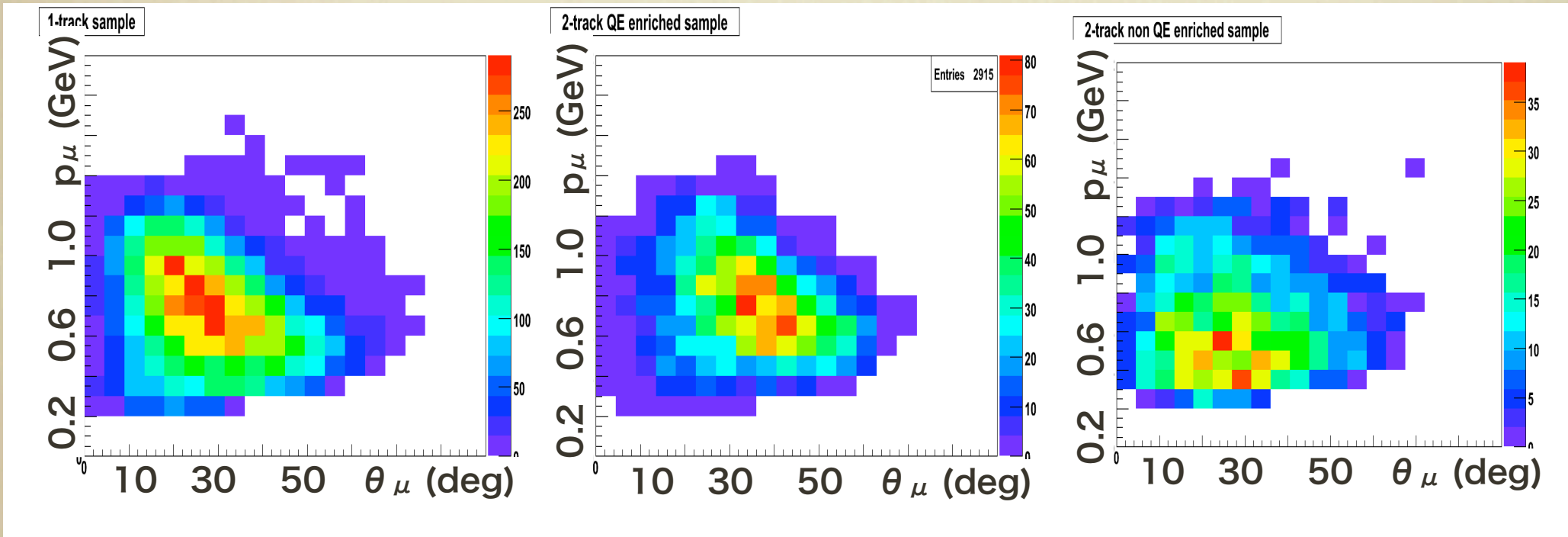
Also working on analysis with SciBar-stopped sample (no update this time)

Samples for CC-QE analysis (cont'd)

1-track sample

2-track QE-like samle

2-track non-QE-like samle



13585 events
66.2% CCQE

2915 events
68.5% CCQE

1628 events
32.3% CCQE

Extraction of number of CCQE events

- Fit three p_μ-θ_μ distributions simultaneously and obtain energy dependent normalization factors for CCQE events
- Updates from NuInt09:
  - Introduced 1trk-2trk migration factor "α" for CC-nonQE
    - Tune pion FSI in nucleus
  - Estimated the full systematic uncertainty

$$N_{ij}^{exp} = F_N \left[\sum_k^{n=10} a_k N_{ij}^{QE,k}, + a_{bck} N_{ij}^{nonQE} \right]$$

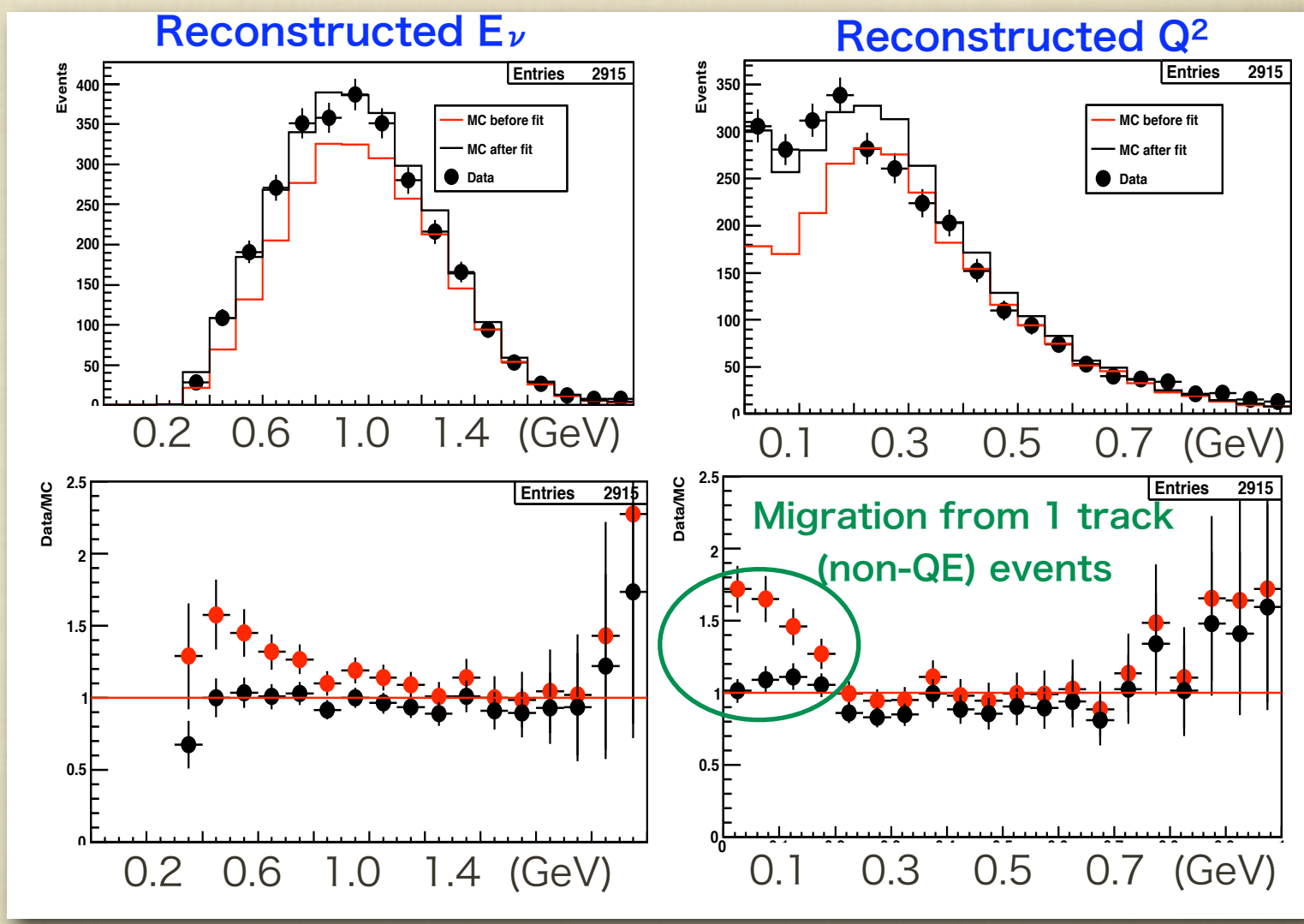
$$\begin{aligned} N_{ij,1-track}^{nonQE} &= (1. - \alpha) \times N_{ij,1-track}^{nonQE}, \\ N_{ij,2-track\ QE}^{nonQE} &= N_{ij,2-track\ QE}^{nonQE} + \alpha \times N_{ij,1-track}^{nonQE}. \end{aligned}$$

Fit results

2 tracks, CC-QE like sample

- Before fit
- After fit

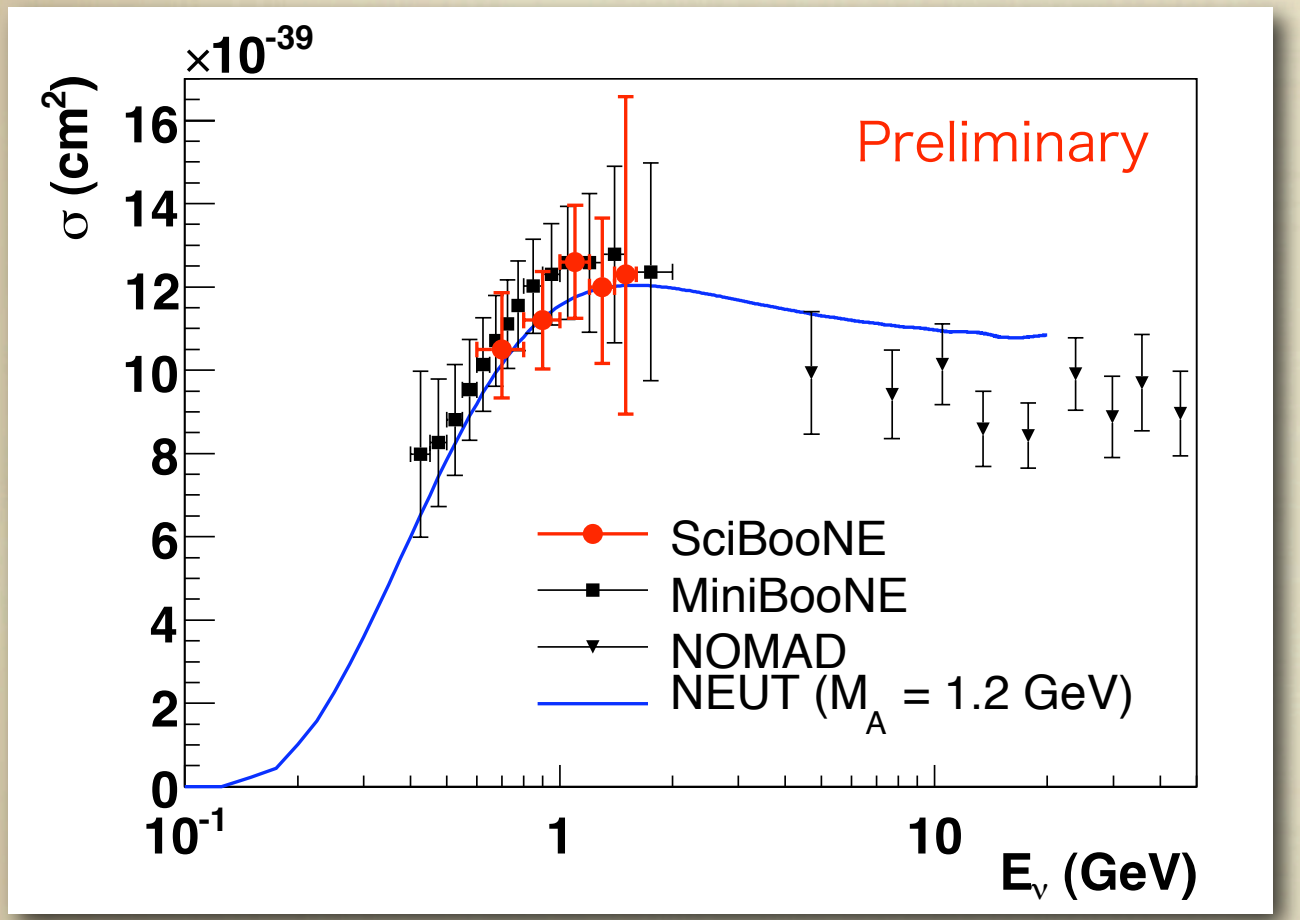
parameter	value
a(0.6-0.8)	1.01
a(0.8-1.0)	1.00
a(1.0-1.2)	1.09
a(1.2-1.4)	1.01
a(1.4-1.6)	1.04
a_{bck}	1.37
F_N	1.02
α	0.030



Good agreement after the fit

CCQE cross section

Cross section per proton

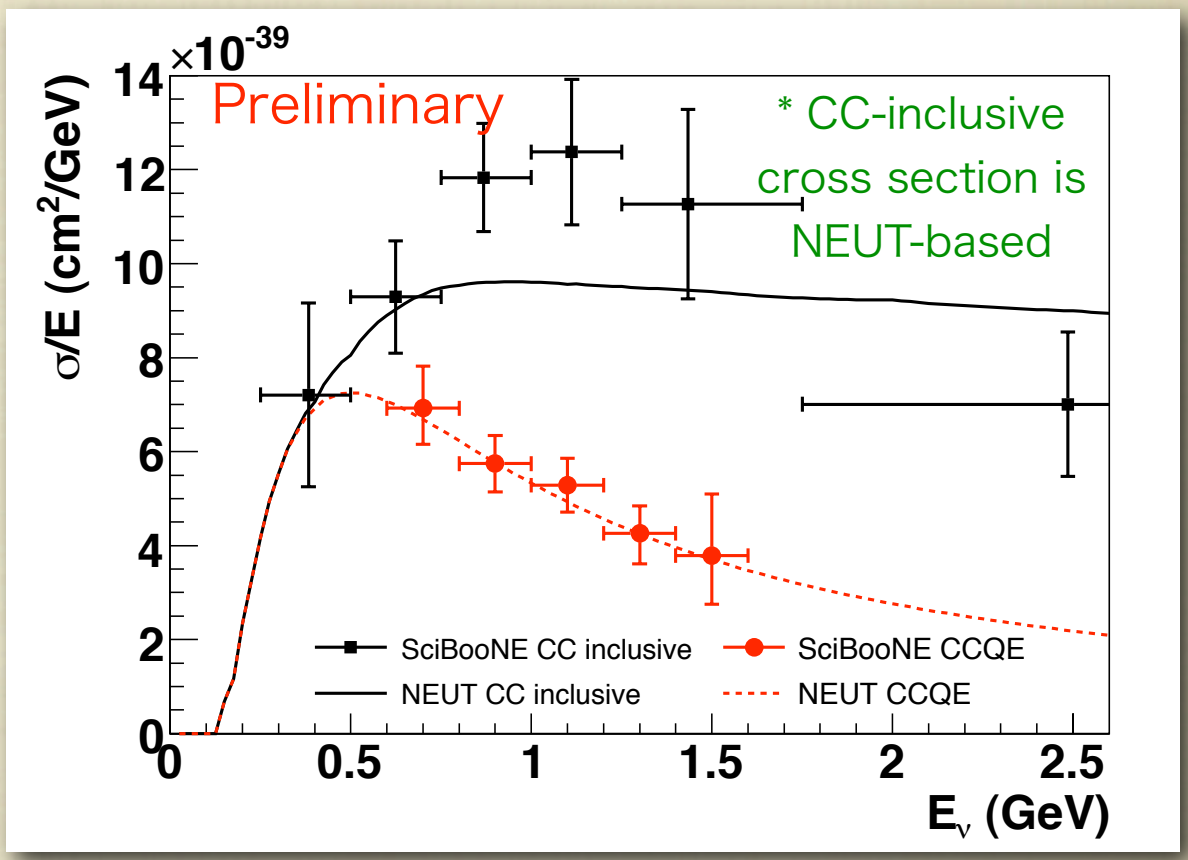


- Extracted cross section is consistent to the MiniBooNE result.
- Higher than the NOMAD result.
- Preparing for publication.
- Flux integrated $d\sigma/dQ^2$, informations of proton FSI will also be extracted.

CC-inclusive and QE cross sections

- CC-inclusive x-sec is larger, while CCQE is roughly consistent to NEUT.
  - Larger CC-1π x-sec?
  - Mismodeling of the FSI?
- Work to do:
  - CC-1π measurements
  - **Comparison with NUACNE etc. (different FSI model)**
  - **Comparison with MiniBooNE (different efficiency for p/π)**

Cross section per nucleon in CH



Will allow to tune the neutrino interaction model in the 1 GeV region including the FSI

Summary

- Results of CC-inclusive and CC-QE interaction measurements from SciBooNE are presented.
- CC-inclusive measurement
  - Extracted energy dependent CC-inclusive cross section for $0.25 < E_\nu < \sim 3$ GeV
  - Results published in Phys. Rev. D **83**, 012005 (2011)
- CC-QE measurements
  - Extracted CC-QE cross section using p/π track information for $0.6 < E_\nu < 1.4$ GeV
  - Working on publication
- These two results are complementary and will help tuning cross section models including the FSI effect.

Backup slides

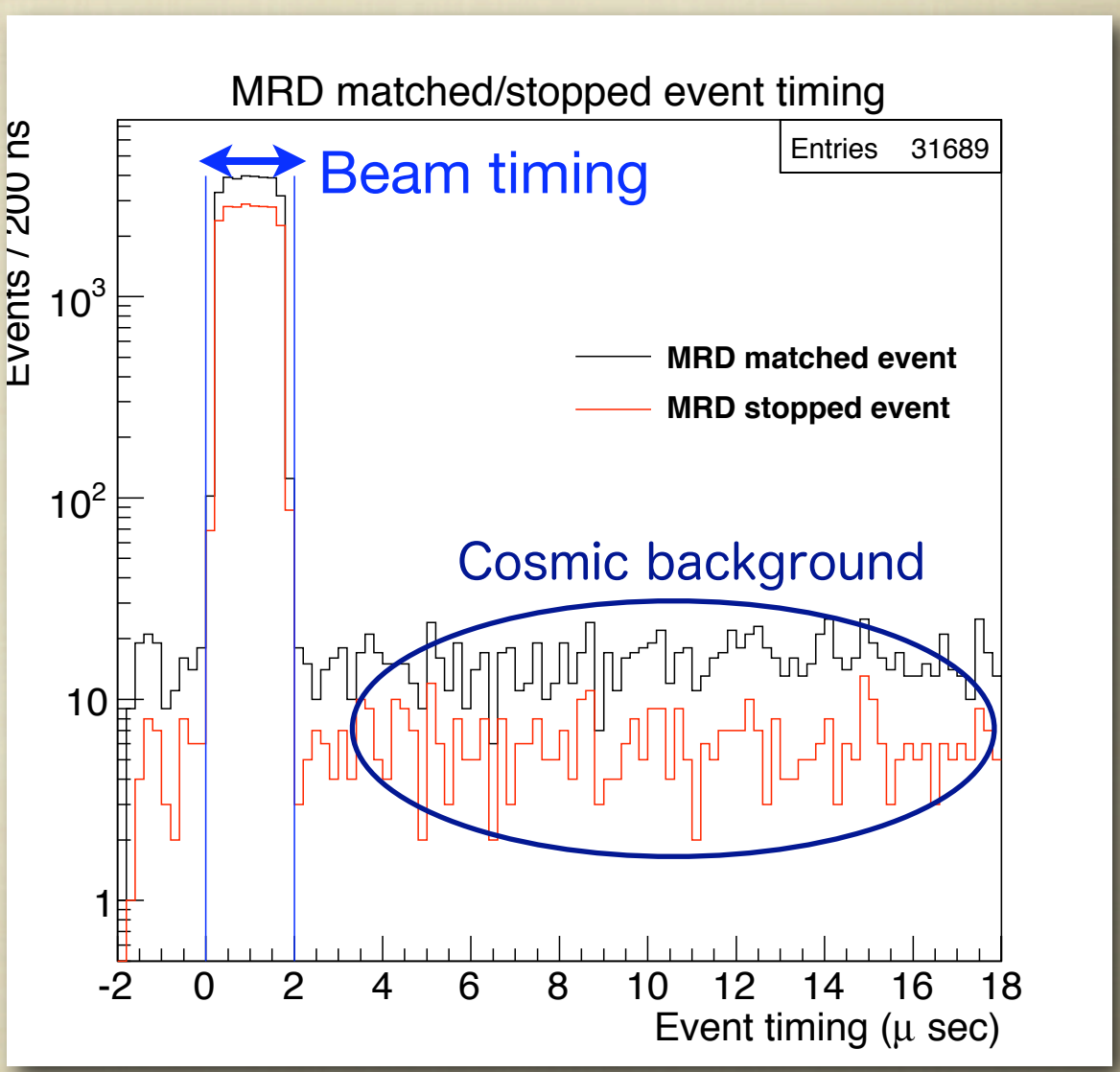
SciBooNE Collaboration

- 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

Neutrino event selection

- Booster provide pulsed beam with 1.6 μsec width.
- Require the event timing to be within the 2 μsec beam timing window.
  - Less than 0.5% cosmic ray contamination.

- ~14K SciBar-stopped events.
- ~20K MRD-stopped events.
- ~4K MRD-penetrated events.



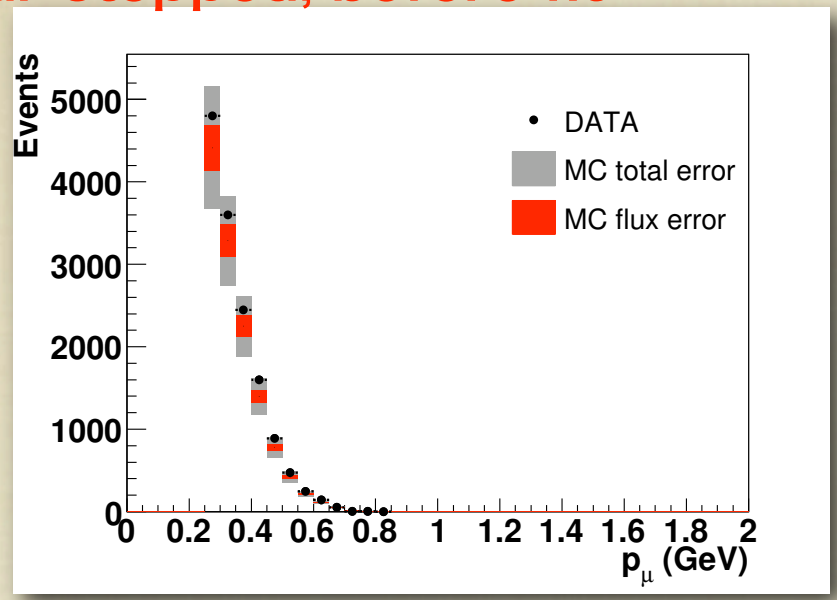
List of systematic uncertainties

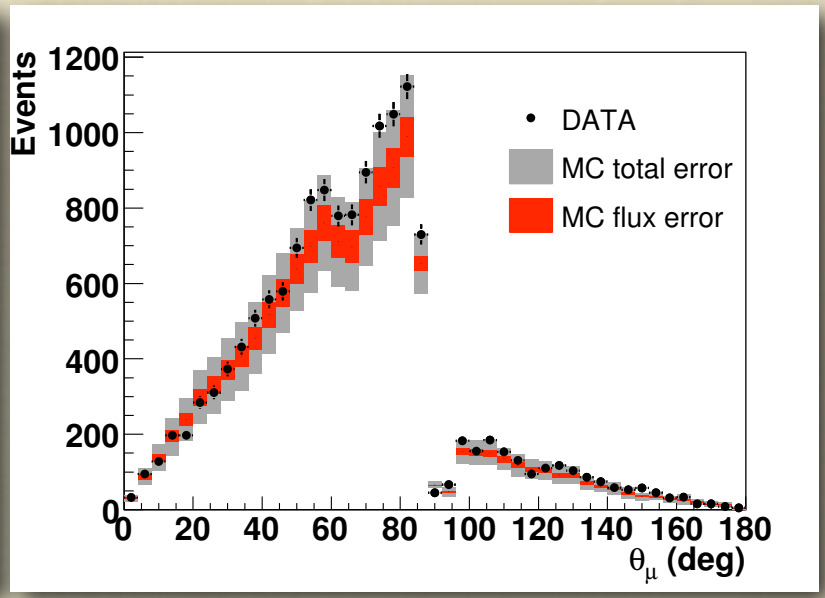
TABLE VIII. List of systematic uncertainties considered.

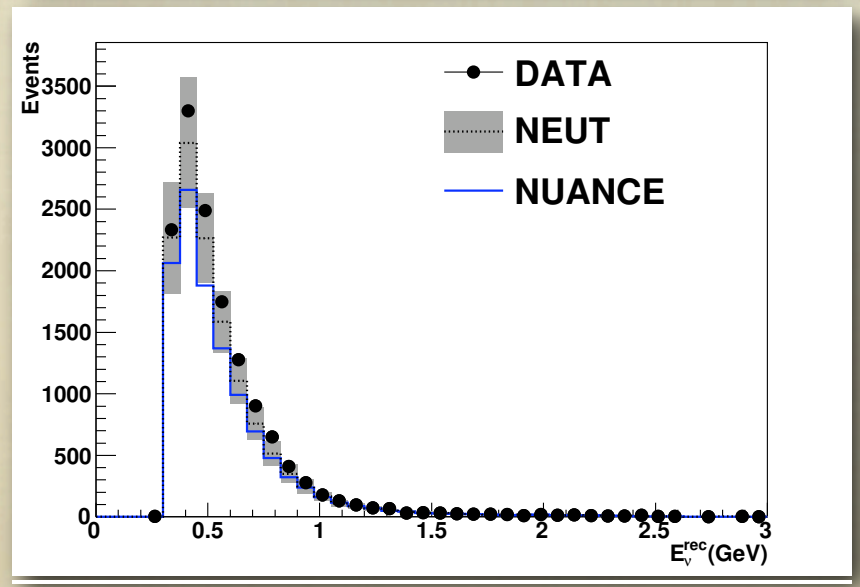
Category	Error Source	Variation	Description
(i) Flux	π^+/π^- production from p-Be interaction	Spline fit to HARP data [19]	Sec. II B
	K^+/K^0 production from p-Be interaction	Tables VIII and IX in Ref. [21]	Sec. II B
	Nucleon and pion interaction in Be/Al	Table XIII in Ref. [21]	Sec. II B
	Horn current	±1 kA	Sec. II B
	Horn skin effect	Horn skin depth, ±1.4 mm	Sec. II B
	Number of POT	±2%	Sec. II B
(ii) Neutrino interaction	Fermi surface momentum of carbon nucleus	±30 MeV	Sec. III B 1
	Binding energy of carbon nucleus	±9 MeV	Sec. III B 1
	CC-QE M_A	±0.22 GeV	Sec. III B 1
	CC-QE κ	±0.022	Sec. III B 1
	CC-1π M_A	±0.28 GeV	Sec. III B 2
	CC-1π Q^2 shape	Estimated from SciBooNE data	Sec. III B 2
	CC-coherent-π M_A	±0.28 GeV	Sec. III B 3
	CC-multi-π M_A	±0.52 GeV	Sec. III B 4
(iii) Intra-nuclear interaction	Δ re-interaction in nucleus	±100 %	Sec. III B 2
	Pion charge exchange in nucleus	±20 %	Sec. III B 5
	Pion absorption in nucleus	±35 %	Sec. III B 5
	Proton re-scattering in nucleus	±10 %	Sec. III B 5
	NC/CC ratio	±20 %	Sec. III B 5
(iv) Detector response	PMT 1 p.e. resolution	±0.20	Sec. II D
	Birk's constant	±0.0023 cm/MeV	Sec. II D
	PMT cross-talk	±0.004	Sec. II D
	Pion interaction cross section in the detector material	±10 %	Sec. II D
	dE/dx uncertainty	±3%(SciBar,MRD), ±10%(EC)	Sec. II D
	Density of SciBar	±1 %	Sec. II C
	Normalization of interaction rate at the EC/MRD	±20 %	Sec. III A
	Normalization of interaction rate at the surrounding materials	±20 %	Sec. III A

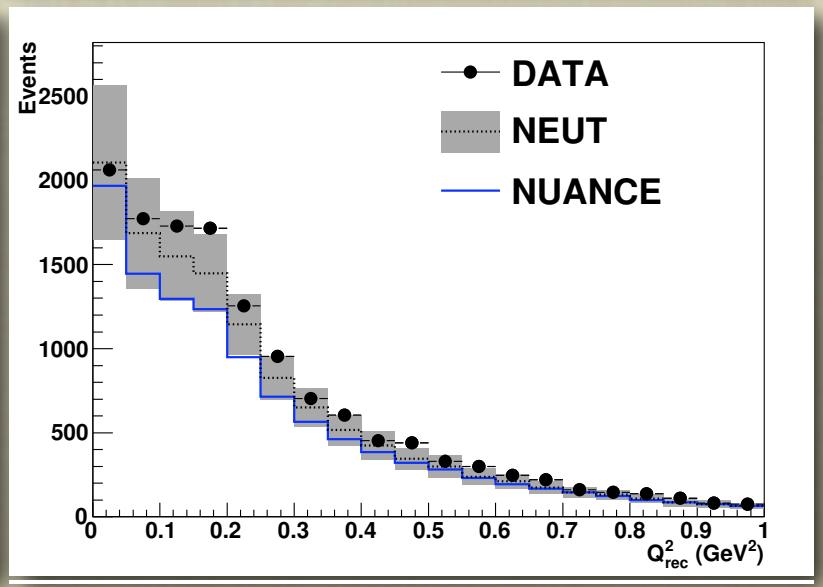
CC-inclusive analysis

SciBar-stopped, before fit



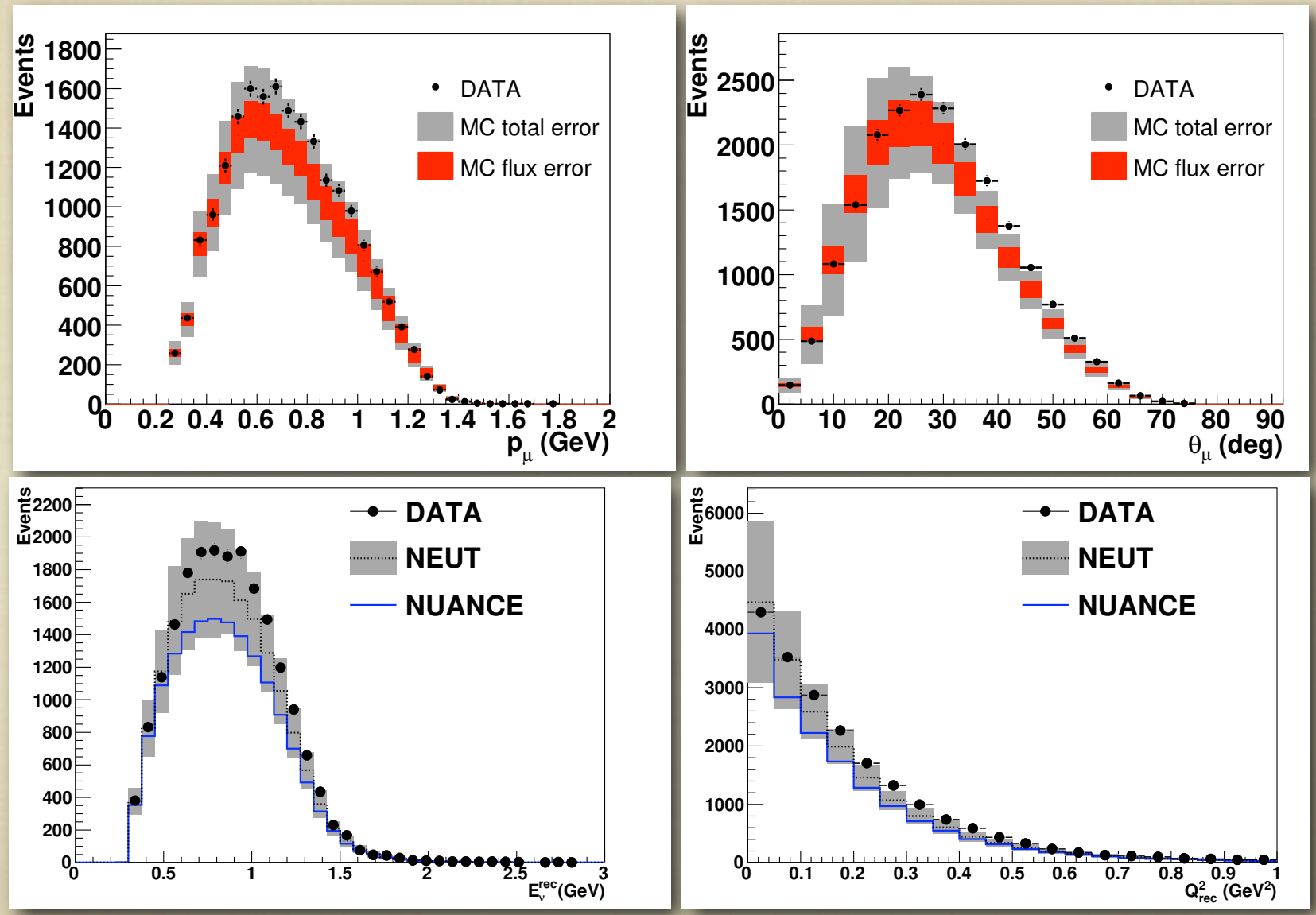






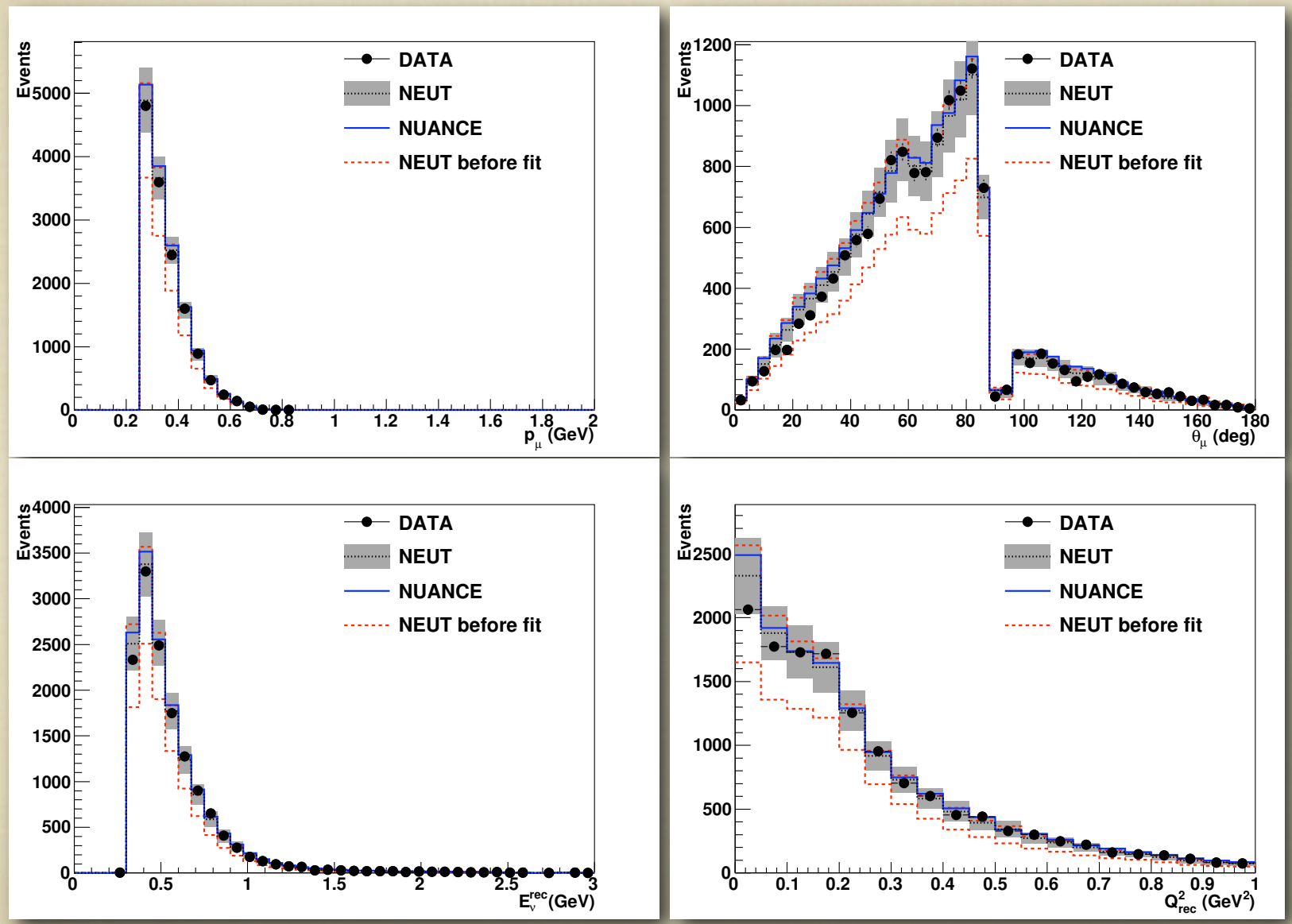
CC-inclusive analysis

MRD-stopped, before fit



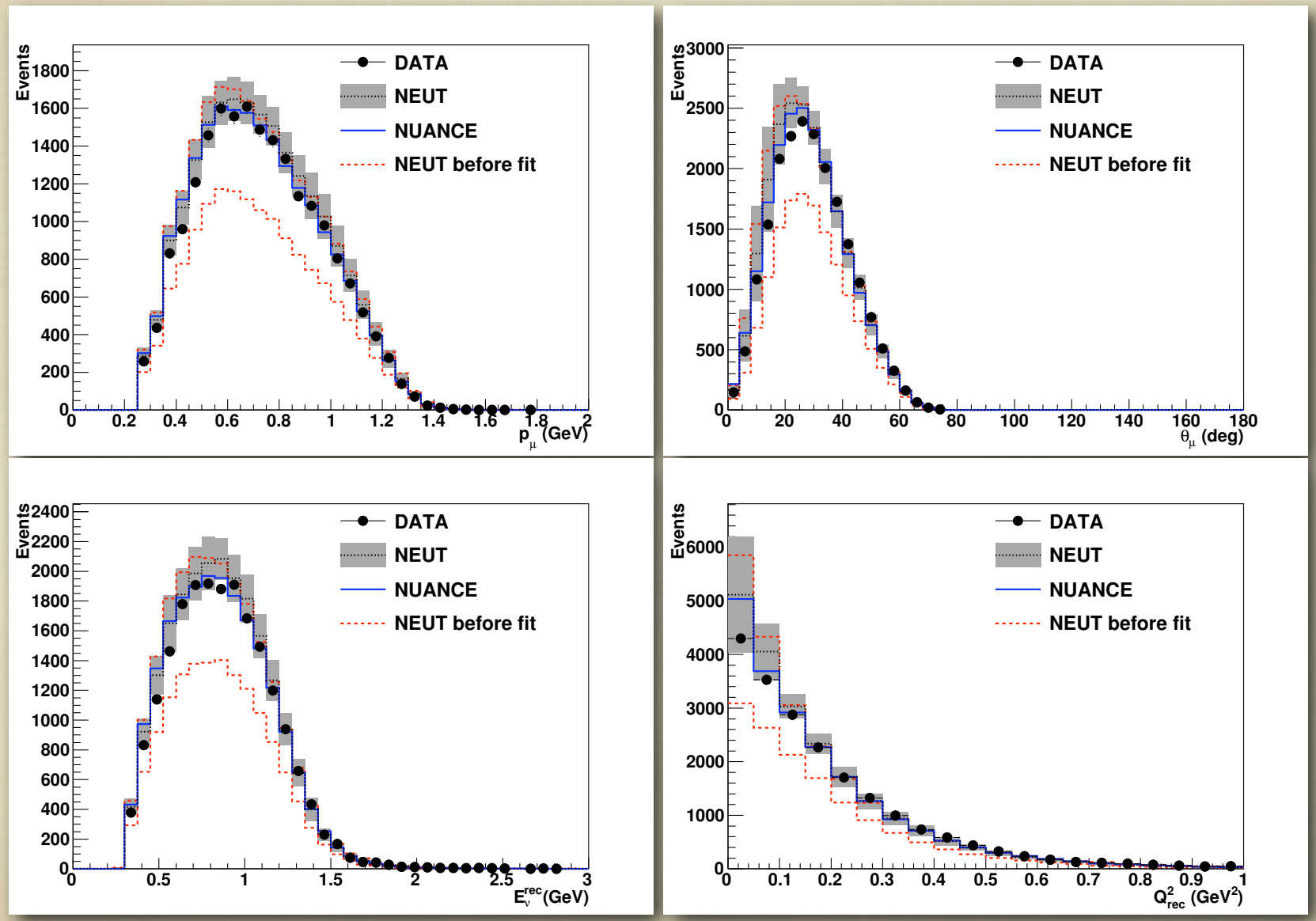
CC-inclusive analysis

SciBar-stopped, after fit



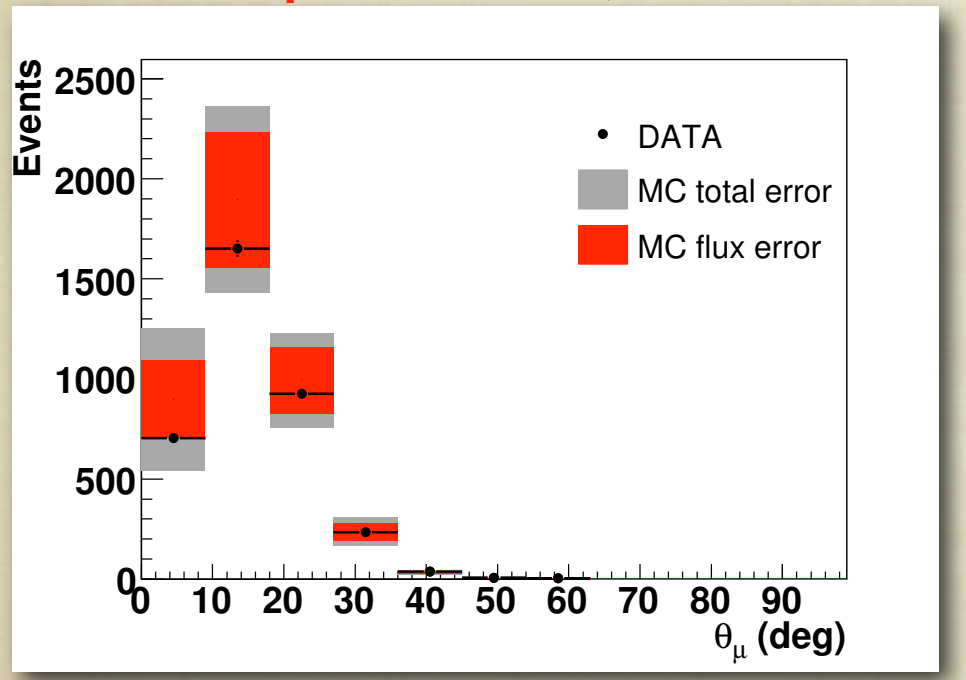
CC-inclusive analysis

MRD-stopped, after fit

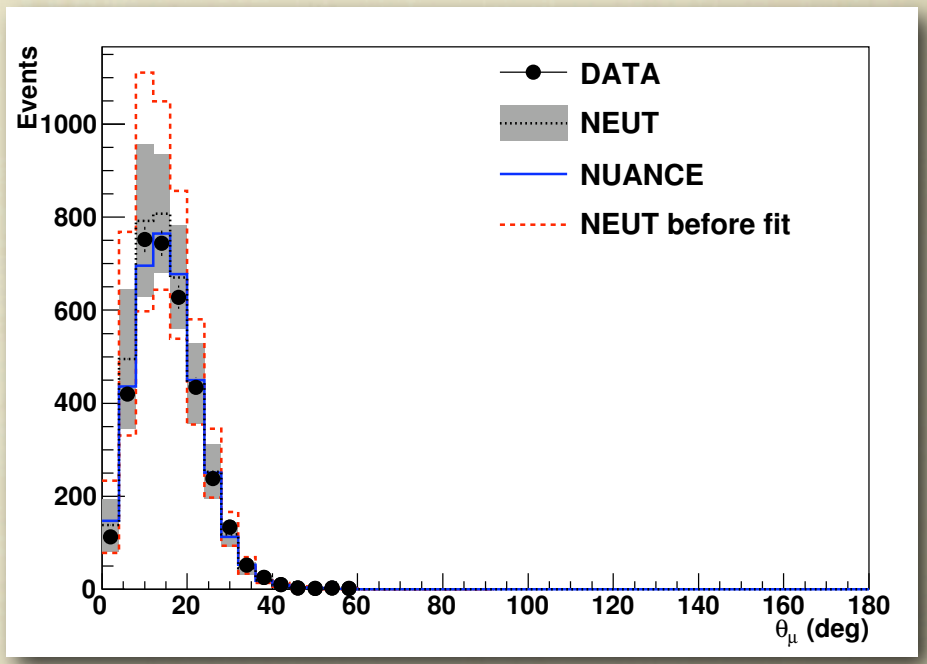


CC-inclusive analysis

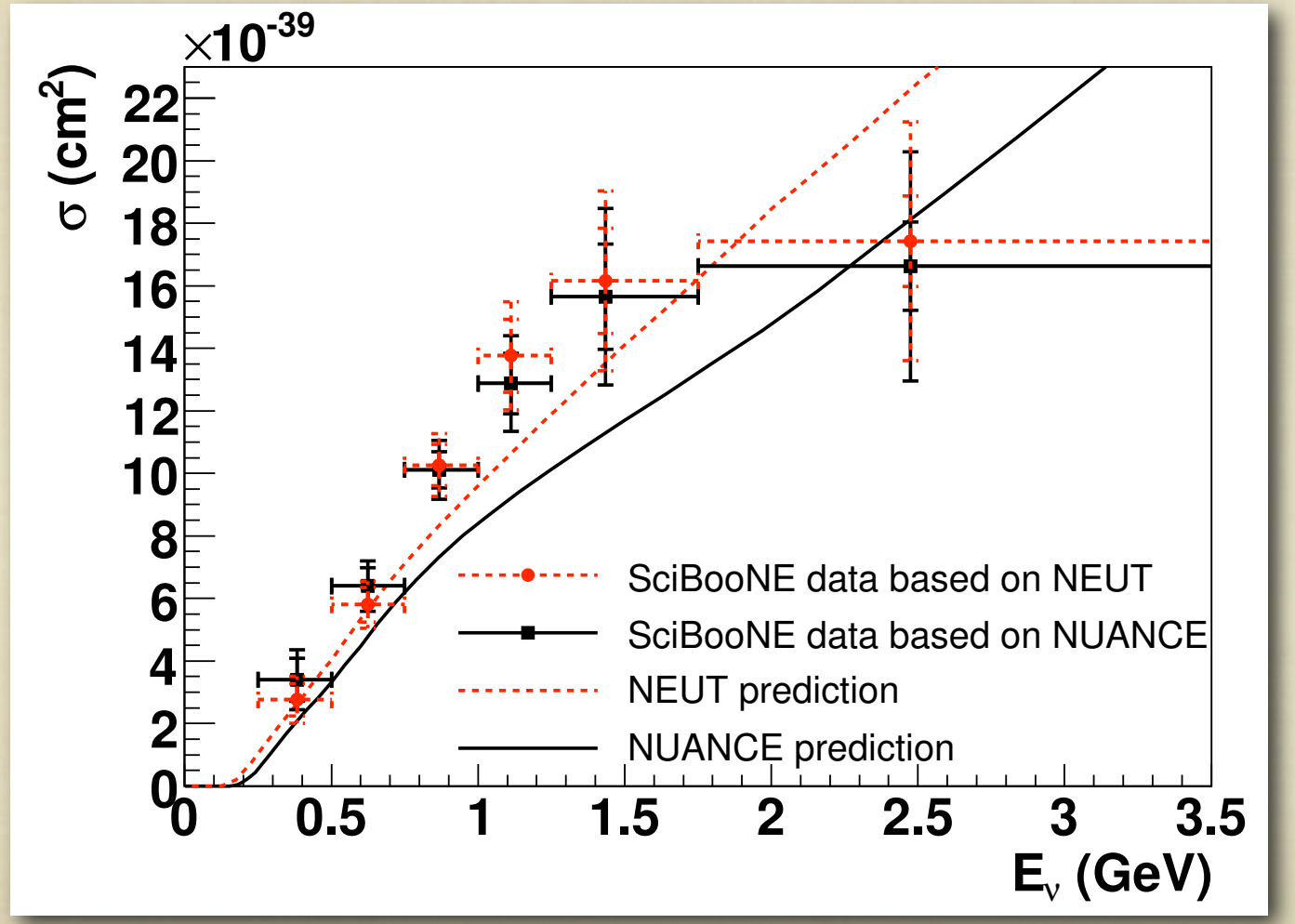
MRD-penetrated, before fit



MRD-penetrated, after fit

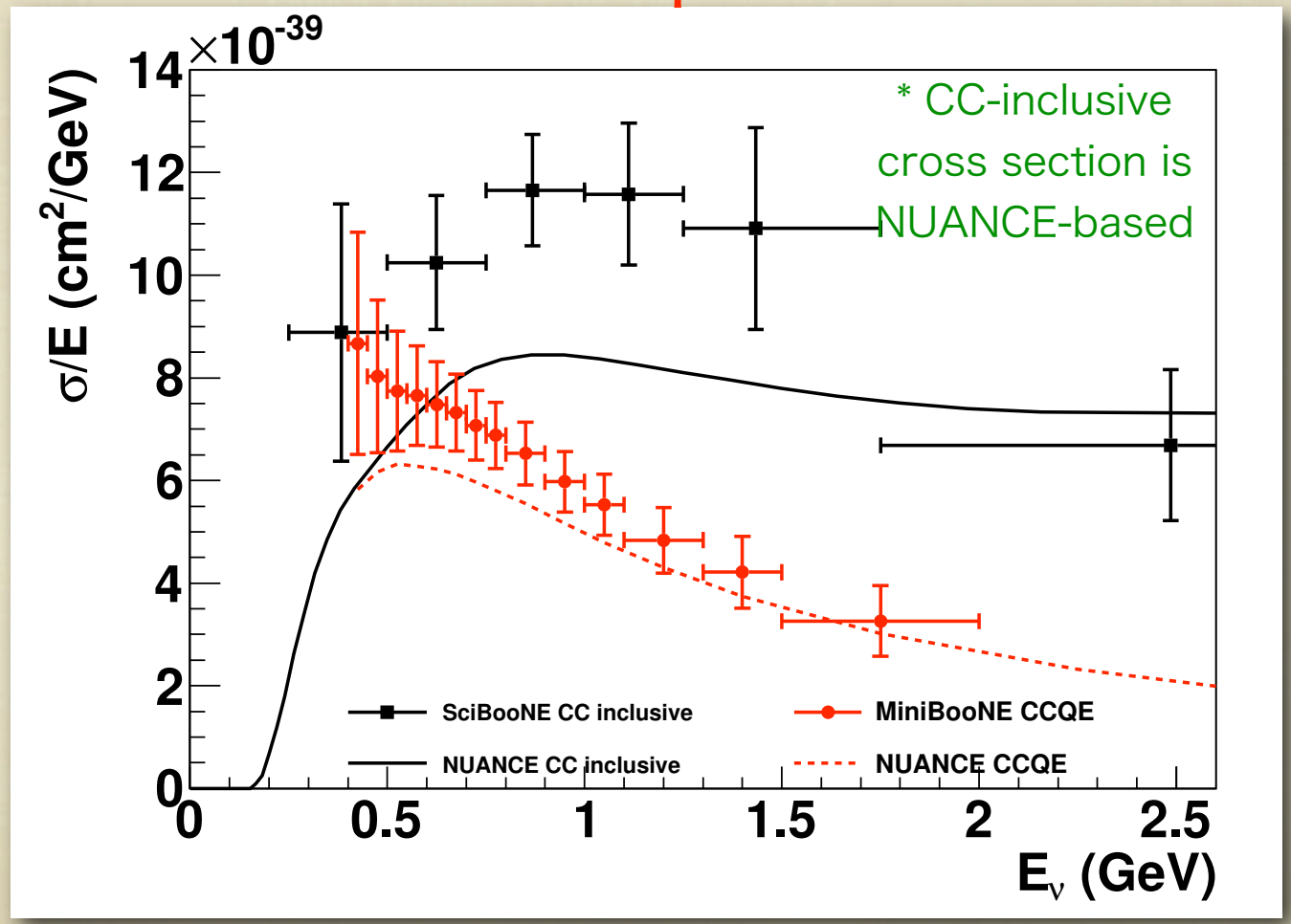


CC-inclusive cross section

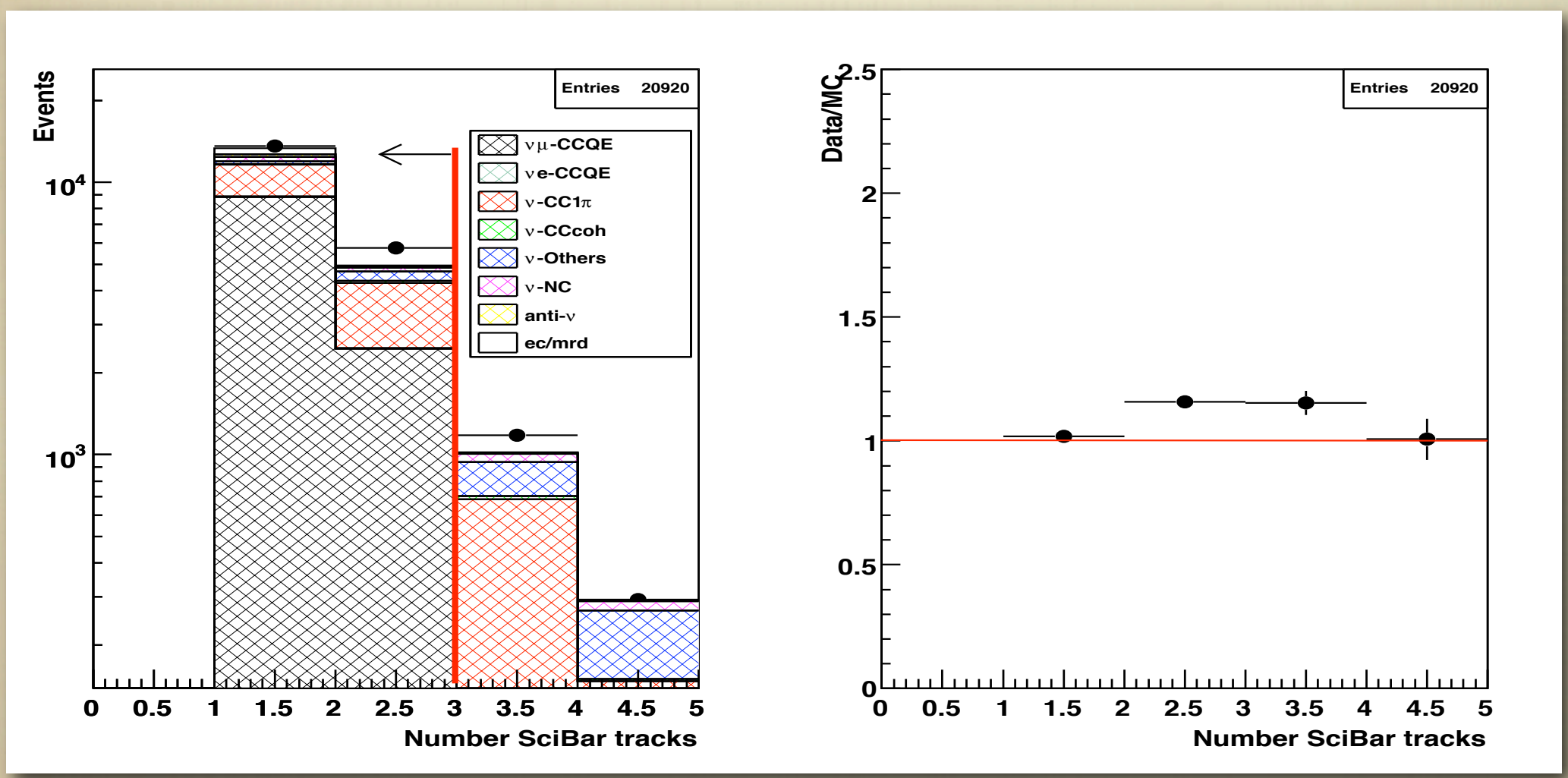


SciBooNE CC-inclusive and MiniBooNE CC-QE

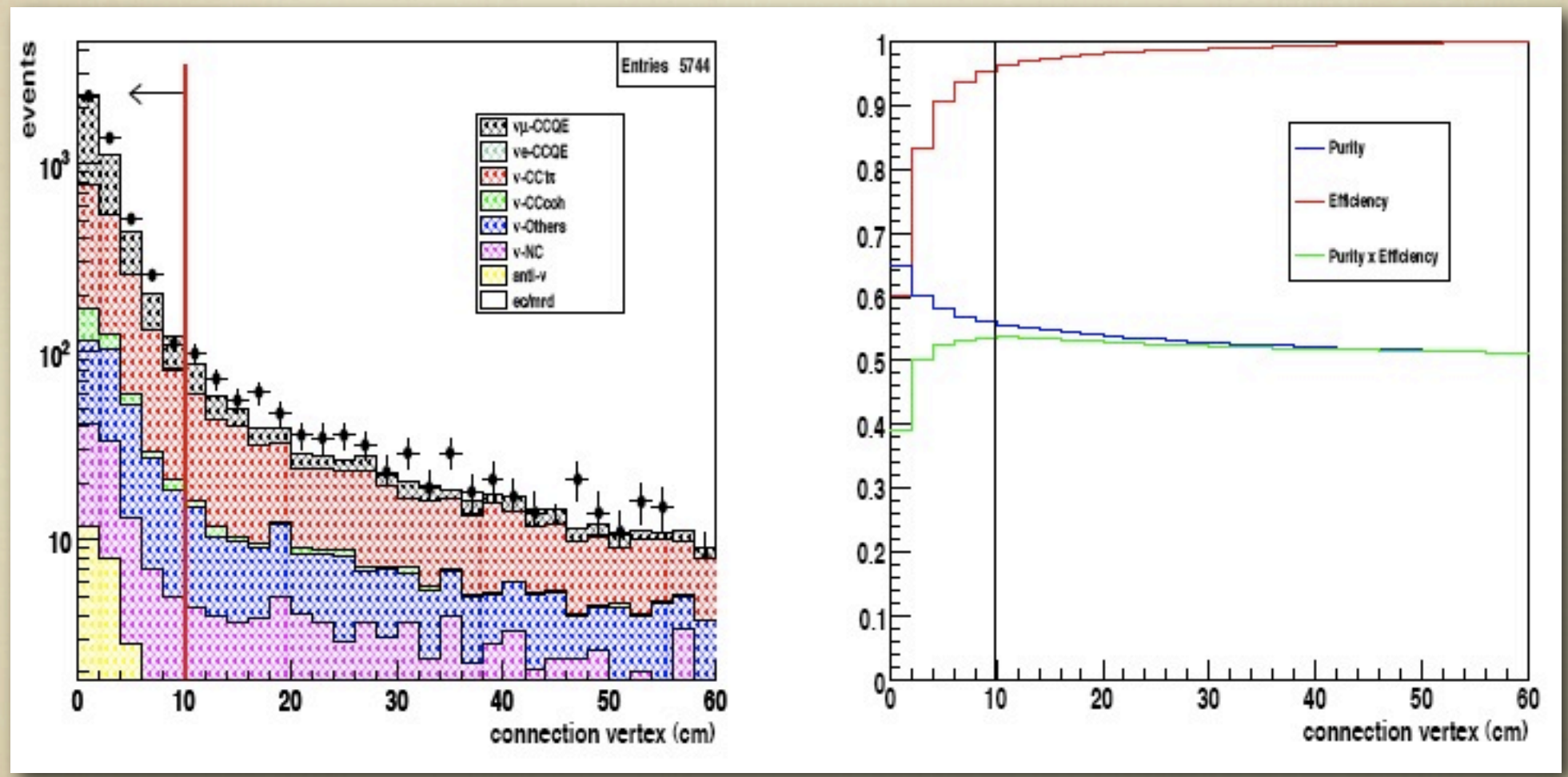
Cross section per nucleon in CH



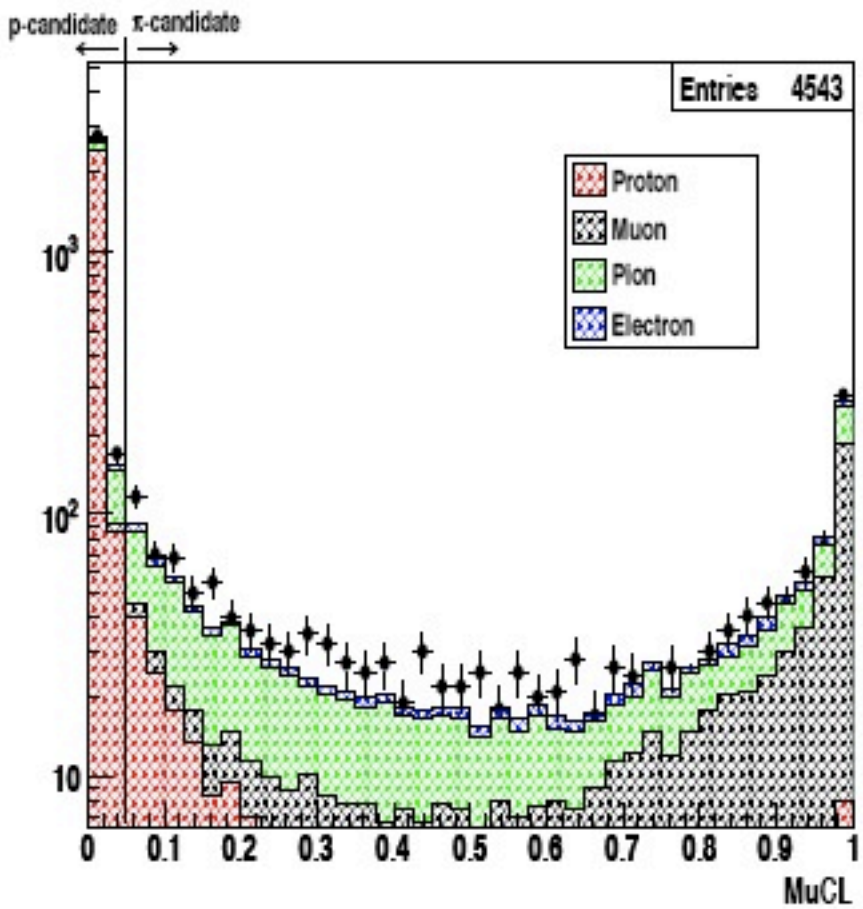
CCQE analysis: number of tracks

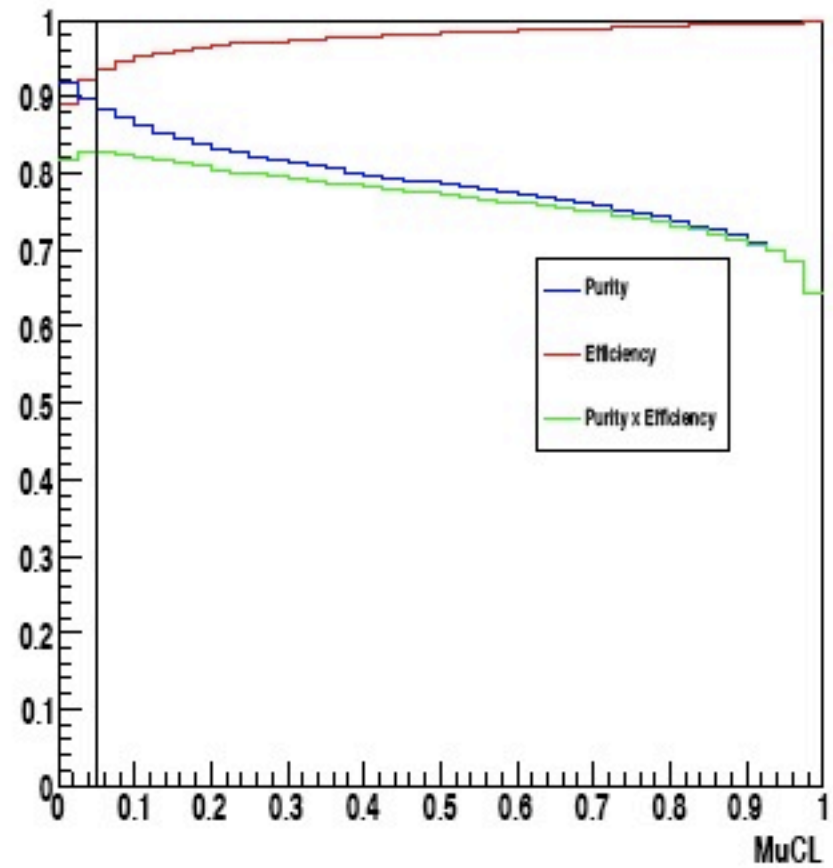


CC-QE analysis: vertex connetction

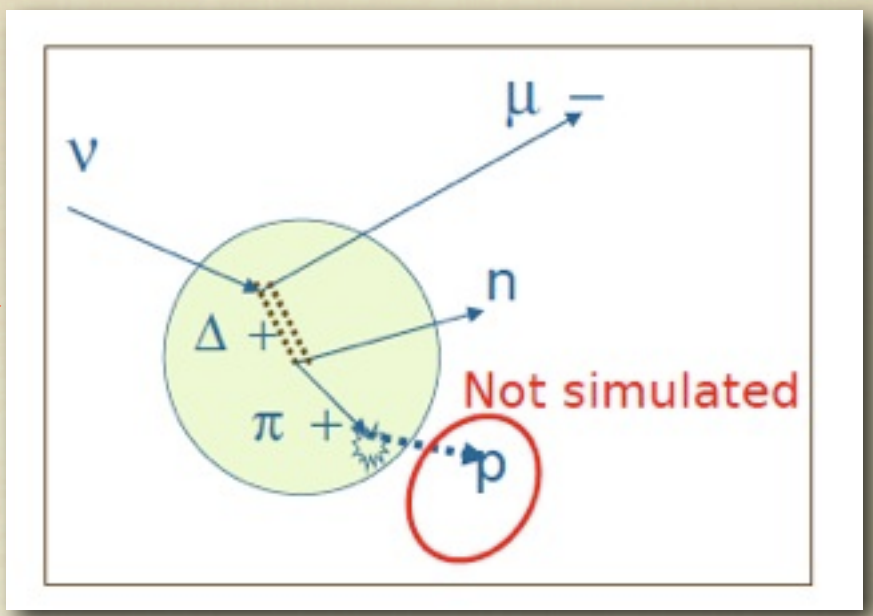


CC-QE analysis: particle identification





Motivation for migration factor α



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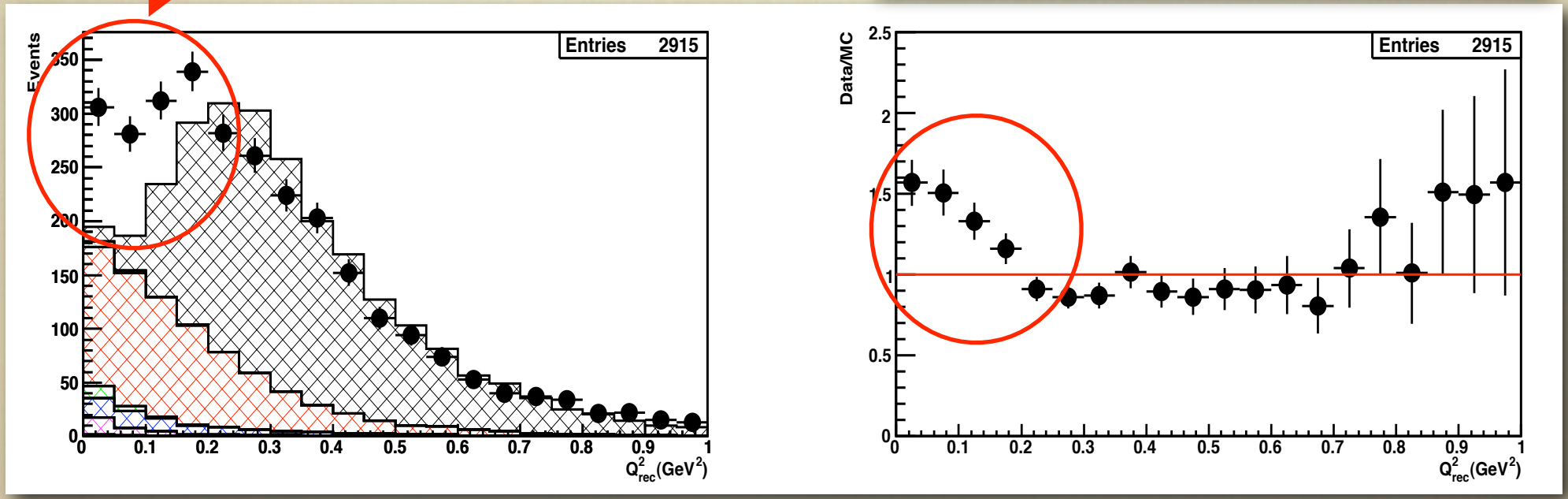
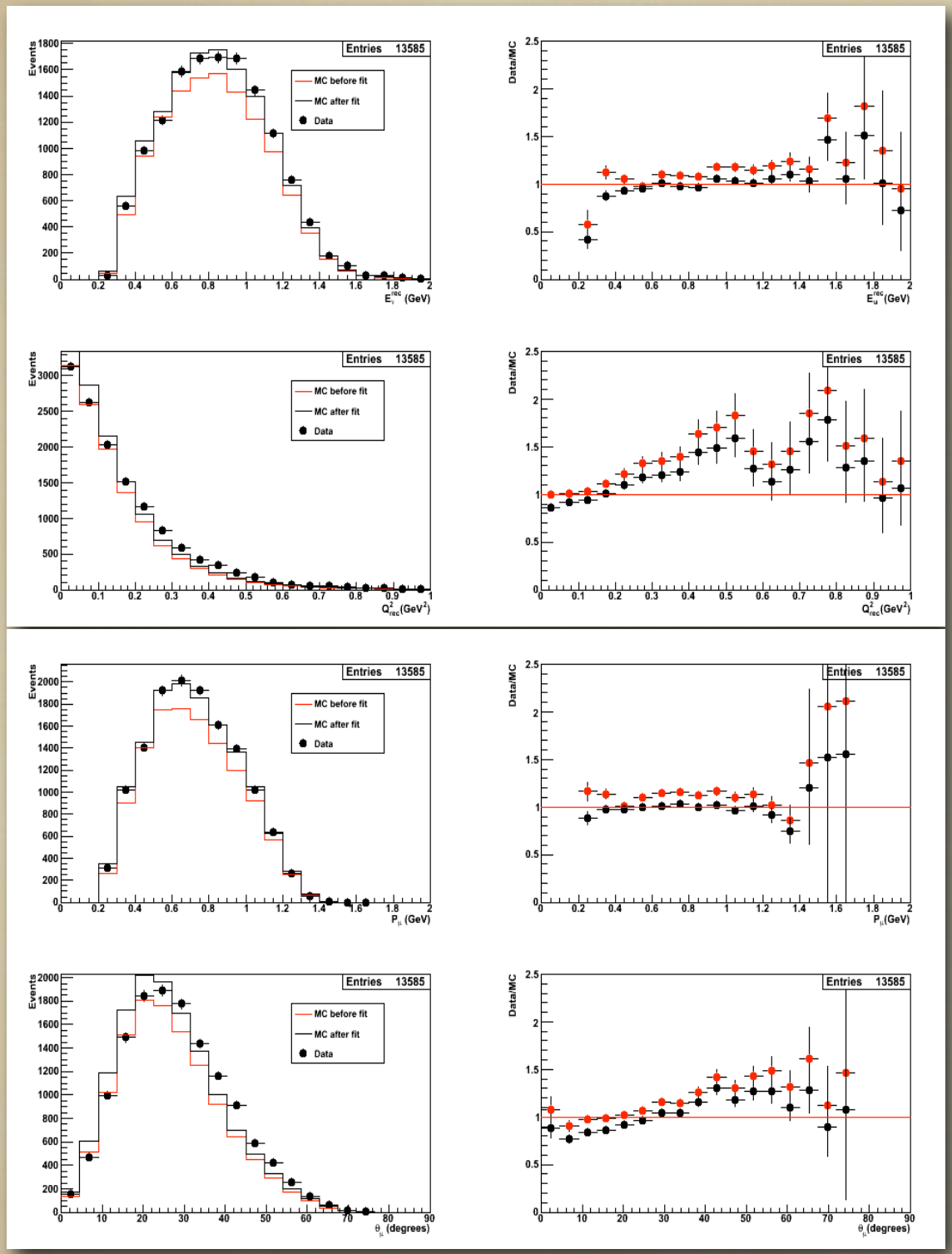
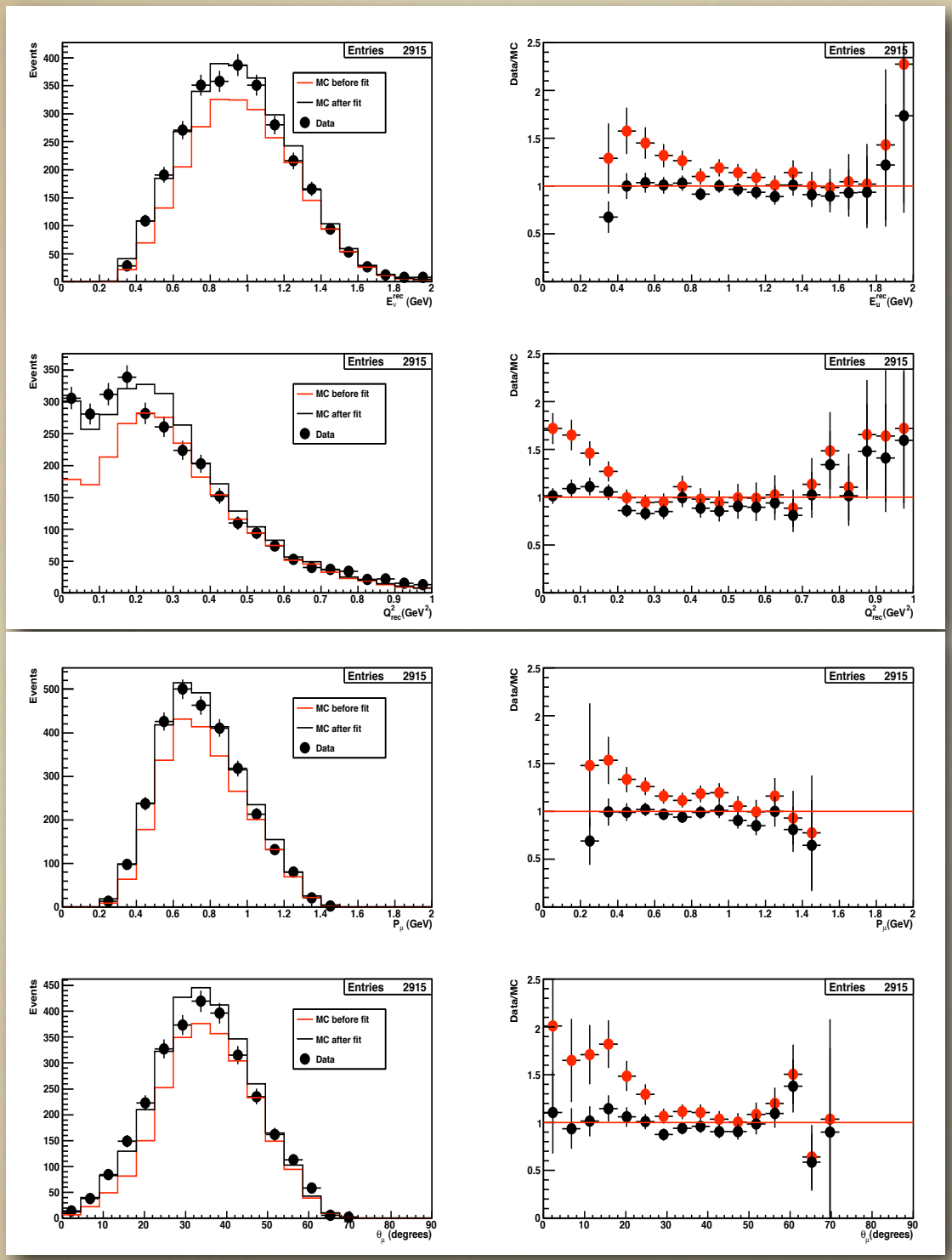
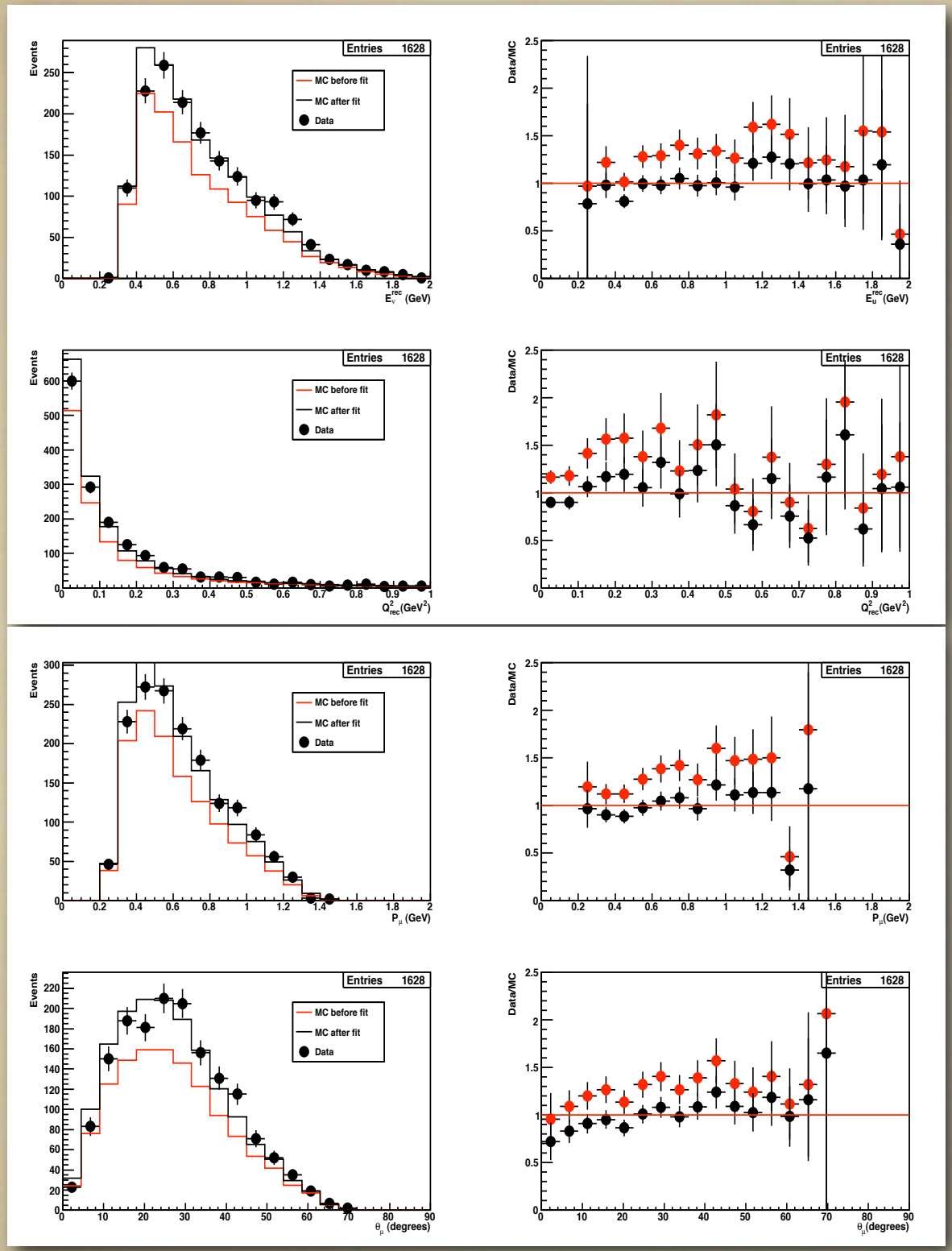




- CCQE analysis:
- 1-track sample



- CCQE analysis:
- 2-track, QE-like sample



- CCQE analysis:
- 2-track, nonQE-like sample

CCQE analysis: systematic errors

E_ν^{bin} (GeV)	MC statistics(%)	Flux(%)	Detector respesponse(%)	Interaction Model(%)	Nuclear Model(%)	Q^2 discrepancy(%)
0.3	43.3	66.67	113.9	203.22	39.16	400
0.5	10.9	36.36	21.8	37.97	28.07	100
0.7	1.3	10.42	2.9	2.33	3.41	2.71
0.9	0.8	9.62	2.5	2.18	2.64	0.38
1.1	0.9	8.62	3.6	1.81	1.77	0.34
1.3	1.3	12.73	5.1	2.03	1.93	2
1.5	2.5	21.05	15.6	2.6	2.17	14.04
1.7	12.1	42.42	98.4	6.7	12.55	21.21
1.9	5.0	28.57	35.8	5.76	4.17	6.43
a_{bck}	0.8	8.03	3.6	13.93	4.18	4.38
F_N	0.9	8.86	2.5	2.27	2.37	0.39
α	>0.0001	3.1	22.9	11.6	12.65	31.03

Table 10.7: Summary table with the relative errors for all the systematic variations. The relative error corresponds to the higher relative error between positive and negative variation. In black, the dominant sytematic error.

E_ν^{bin} (GeV)	absolute err. ($cm^2/nucleon$) ($\times 10^{-38}$)	relative err. (%)
0.3	0.2	66.7
	-0.19	63.3
0.5	0.04	36.4
	-0.03	27.3
0.7	0.05	10.4
	-0.04	8.3
0.9	0.05	9.6
	-0.04	7.7
1.1	0.05	8.6
	-0.05	8.6
1.3	0.06	10.9
	-0.07	12.7
1.5	0.12	21.1
	-0.11	19.3
1.7	0.14	42.4
	-0.11	33.3
1.9	0.4	28.6
	-0.3	21.4

E_ν^{bin} (GeV)	absolute err.	relative err. (%)
a_{bck}	0.11	8.0
	-0.11	8.0
F_N	0.09	8.9
	-0.08	7.9
α	0.0009	3.1
	-0.0008	2.8

Table 10.2: Flux systematic variations associated to the CCQE cross section (top table) and to other fit parameters (bottom table).

E_ν^{bin}(GeV)	Birk	PMT-res.	xtalk	Hit thres.	P_{scale}	subtotal
0.3	0.12	0.02	0.3	0.11	0.006	0.3
0.5	0.008	0.010	0.009	0.018	0.002	0.02
0.7	0.009	0.006	0.00013	10^{-6}	0.009	0.014
0.9	0.001	0.008	0.00005	0.002	0.010	0.013
1.1	0.012	0.012	0.008	0.001	0.011	0.02
1.3	0.016	0.004	0.02	0.001	0.011	0.03
1.5	0.05	0.02	0.07	0.003	0.011	0.09
1.7	0.1	0.07	0.3	0.02	0.007	0.3
1.9	0.19	0.12	0.4	0.2	0.03	0.5
a_{bck}	0.013	0.02	0.018	0.04	-0.00010	0.05
F_N	0.002	0.015	0.0001	0.005	0.020	0.03
α	0.005	0.003	0.0010	0.003	-0.000	0.006

Table 10.3: Detector response systematic errors. Dimensions for errors associated to cross sections are ($10^{-38} cm^2/nucleon$). The a_{bck},F_N and α are dimensionless.

E_ν^{bin}(GeV)	M_A^{QE}	$M_A^{CC\pi}$	$\sigma_\nu^{CC\pi}$	subtotal	relative err.(%)
0.3	-0.08	-0.09	0.4	0.5	171.4
	0.06	0.09	-0.4	-0.6	203.2
0.5	-0.0019	-0.011	0.02	0.03	29.1
	-0.0004	0.012	-0.018	-0.04	38
0.7	0.004	-0.005	-0.009	-0.005	1.7
	-0.005	0.006	0.011	0.008	2.3
0.9	0.003	-0.006	-0.008	-0.006	1.7
	-0.004	0.007	0.010	0.008	2.2
1.1	0.004	-0.005	-0.006	-0.005	1.4
	-0.005	0.006	0.008	0.007	1.8
1.3	0.007	-0.006	-0.005	-0.004	1.8
	-0.008	0.006	0.006	0.005	2.0
1.5	-0.0003	-0.011	-0.004	-0.003	2.
	0.0011	0.013	0.005	0.007	2.6
1.7	-0.008	-0.02	0.0019	-0.005	6.7
	0.004	0.016	0.003	0.002	5.03
1.9	0.05	-0.05	-0.010	-0.002	5.05
	-0.05	0.06	0.014	0.02	5.8
a_{bck}	-0.019	0.04	0.03	0.15	10.7
	0.02	-0.06	-0.04	0.19	13.9
F_N	0.006	-0.013	-0.015	0.018	1.8
	-0.007	0.015	0.019	0.023	2.27
α	0.0011	-0.0005	0.0011	0.002	8.06
	-0.0014	0.0006	-0.0011	0.003	11.6

Table 10.4: Systematic errors associated to neutrino interaction model parameters. The errors dimensions are $(10^{-38} cm^2/nucleon)$. The a_{bck}, F_N and α are dimensionless.

E_ν^{bin}(GeV)	π-absorp.	π-inel.	charge exch.	P_{Fermi}	p-scat	subtotal	rel. err(%)
0.3	-0.07	-0.04	-0.03	0.06	0.04	0.11	37.4
	0.08	0.02	0.03	-0.06	-0.05	0.12	39.2
0.5	-0.02	-0.005	-0.002	0.004	0.005	0.03	19.7
	0.03	0.003	0.0019	-0.004	-0.005	0.03	28.07
0.7	-0.014	-0.002	-0.0013	0.008	-0.0015	0.016	3.4
	0.014	0.002	0.0013	-0.008	0.0013	0.016	3.4
0.9	-0.012	-0.0019	-0.0006	0.006	-0.002	0.013	2.6
	0.012	0.0017	0.0006	-0.006	0.002	0.013	2.6
1.1	-0.008	-0.001	-0.0009	0.006	-0.002	0.010	1.8
	0.008	0.0007	0.0009	-0.006	0.0018	0.010	1.8
1.3	-0.009	-0.0019	-0.0004	0.005	-0.0016	0.010	1.9
	0.009	0.0019	0.0004	-0.004	0.0014	0.010	1.8
1.5	-0.002	0.0008	-0.0008	-0.008	-0.007	0.011	1.9
	0.0018	-0.0002	0.0010	0.010	0.007	0.012	2.2
1.7	0.00004	-0.009	0.004	0.03	-0.0004	0.04	9.6
	0.006	0.008	-0.004	-0.04	0.0005	0.04	12.6
1.9	-0.007	0.03	0.0005	-0.03	-0.03	0.06	3.8
	0.002	-0.03	-0.00013	0.04	0.03	0.06	4.2
a_{bck}	0.05	0.017	0.009	-0.02	-0.0018	0.06	4.2
	-0.05	-0.008	-0.008	0.02	0.004	0.06	4.03
F_N	-0.02	-0.004	-0.0012	0.012	-0.004	0.03	2.4
	0.02	0.003	0.0012	-0.011	0.004	0.03	2.3
α	-0.0019	-0.0003	-0.0001	-0.0005	0.002	0.003	12.4
	0.002	0.0004	0.0002	0.0005	-0.002	0.003	12.7

Table 10.5: Systematic errors associated to nuclear model effects. The errors dimensions are $(10^{-38} cm^2/nucleon)$. The a_{bck}, F_N and α are dimensionless.