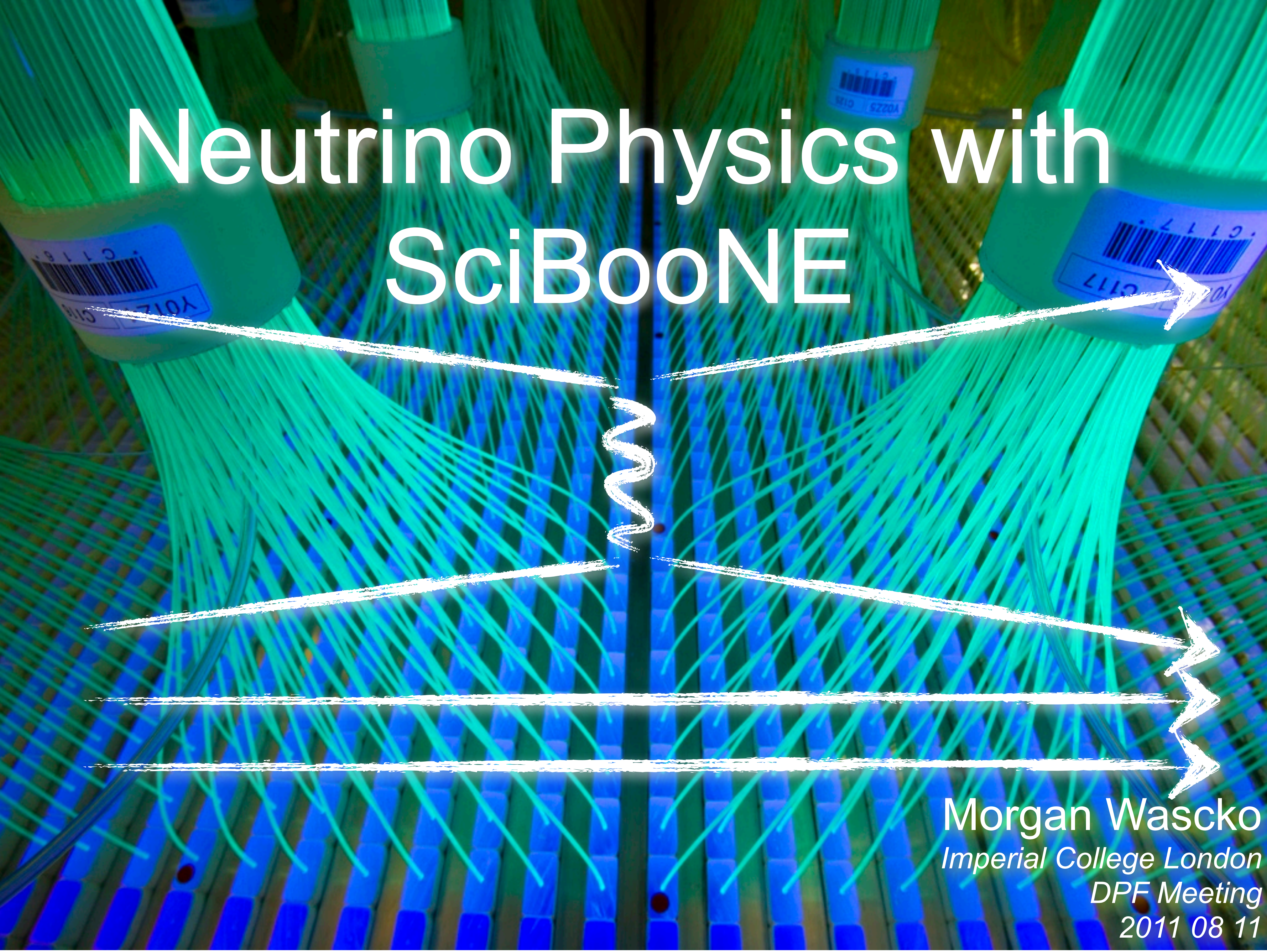


Neutrino Physics with SciBooNE

Morgan Wascko

Imperial College London

DPF Meeting

2011 08 11

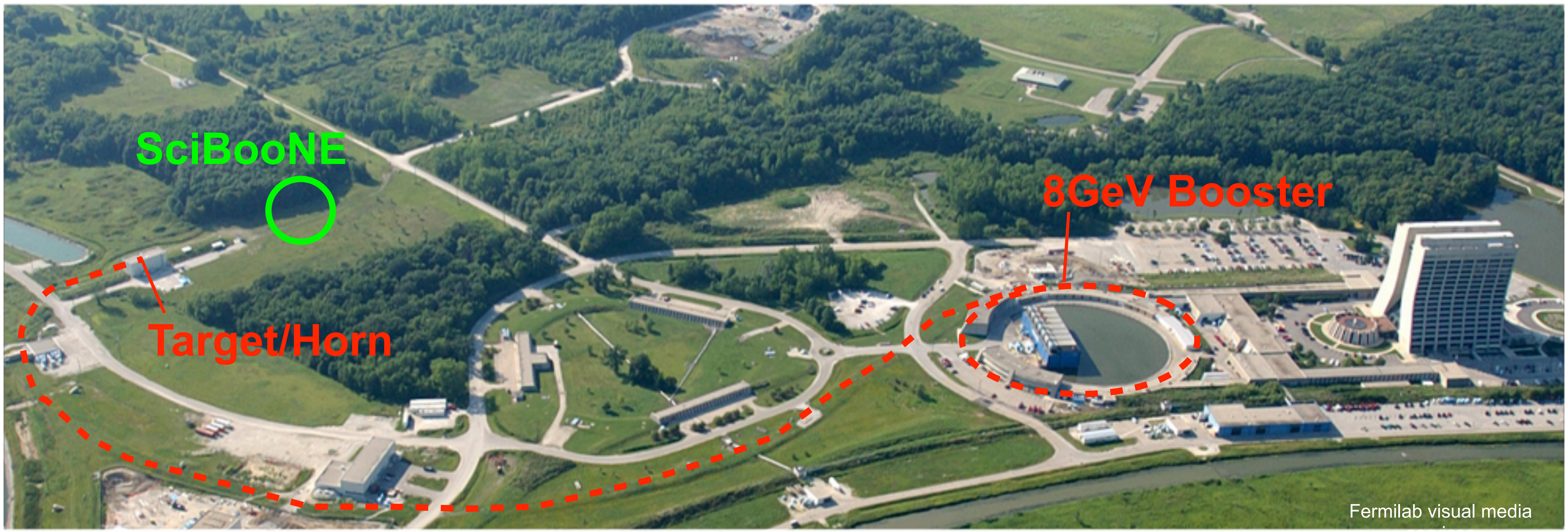
Outline

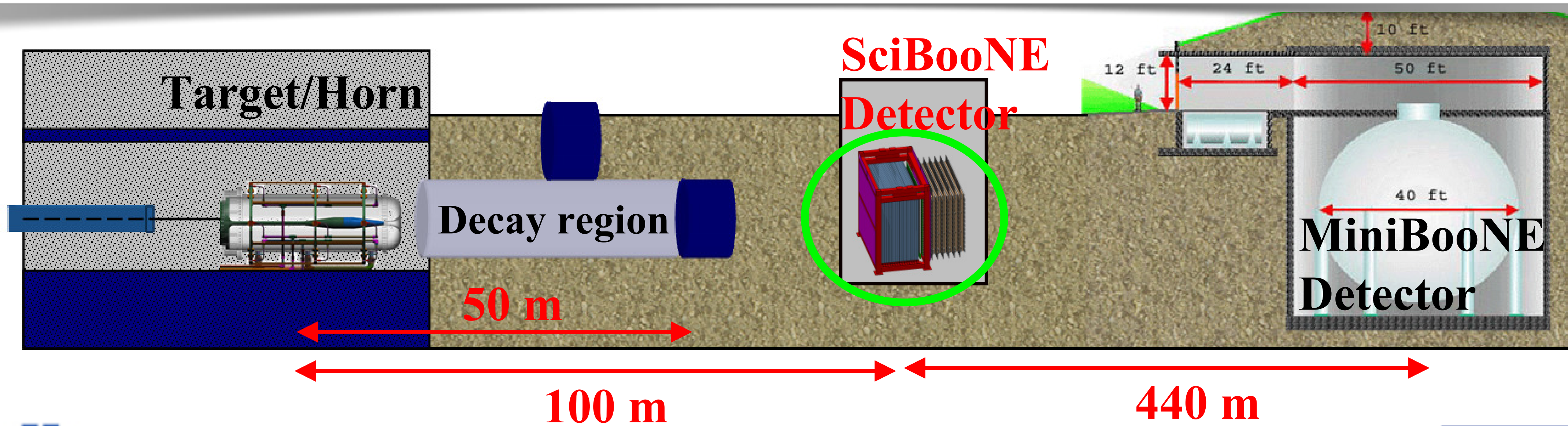
- Introduction
  - SciBooNE goals, description, performance
- Data analysis
  - Cross sections, CC & NC
  - Neutrino oscillation searches
- Conclusions
  - Future outlook for cross section measurements

Introduction

SciBooNE Groundbreaking 2006

SciBooNE Overview



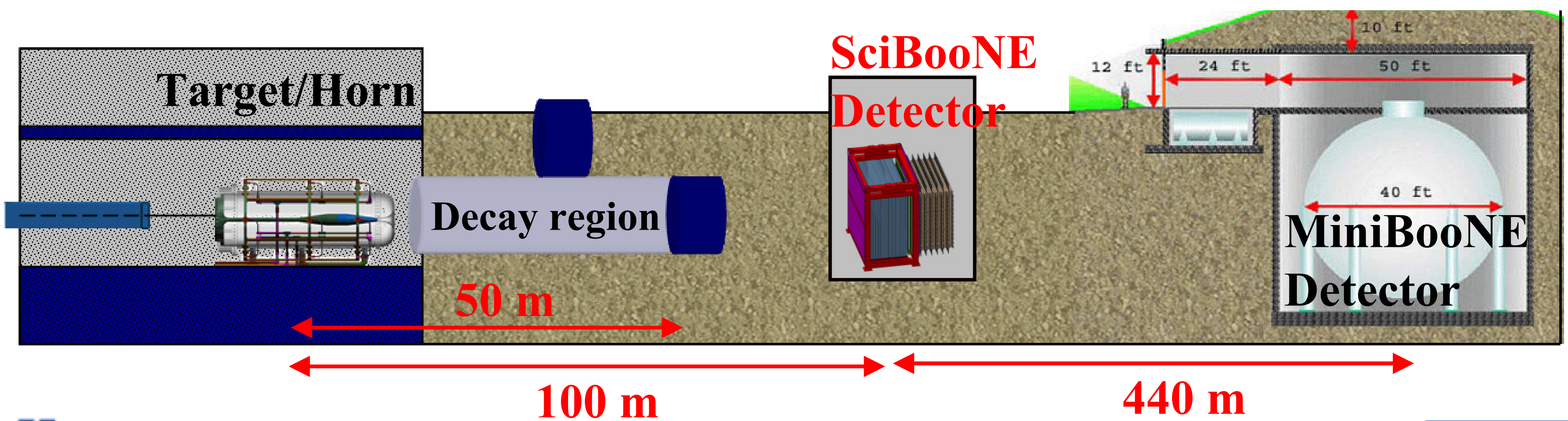


SciBooNE Overview

arXiv:hep-ex/0601022v1

- Precise measurements of ν and $\bar{\nu}$ σs near 1 GeV
  - Essential for future neutrino oscillation experiments
  - MiniBooNE data have already revealed the need for a new paradigm in neutrino xsecs at 1 GeV.
- MiniBooNE/SciBooNE joint ν_μ disappearance
- ν_e & $\bar{\nu}_e$ constraint for MiniBooNE

See Rex Tayloe's talk!



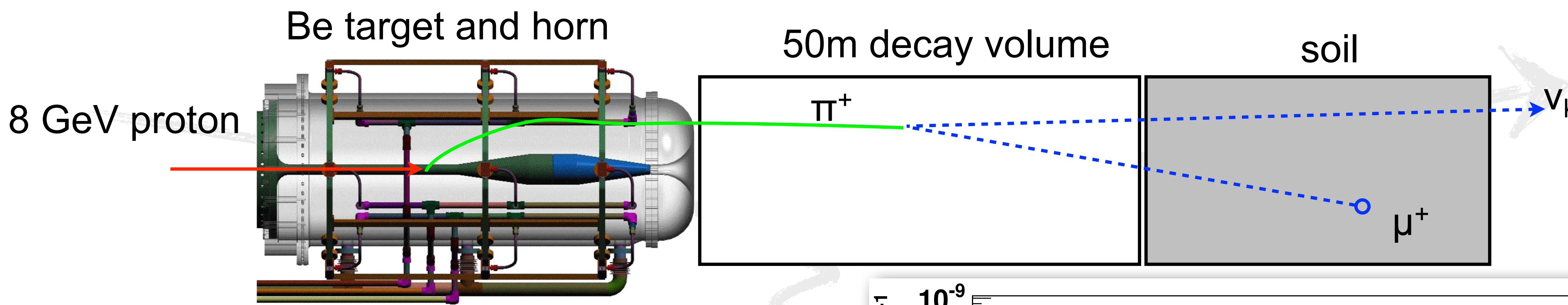
SciBooNE Collaboration

~65 physicists, 5 countries, 18 institutions

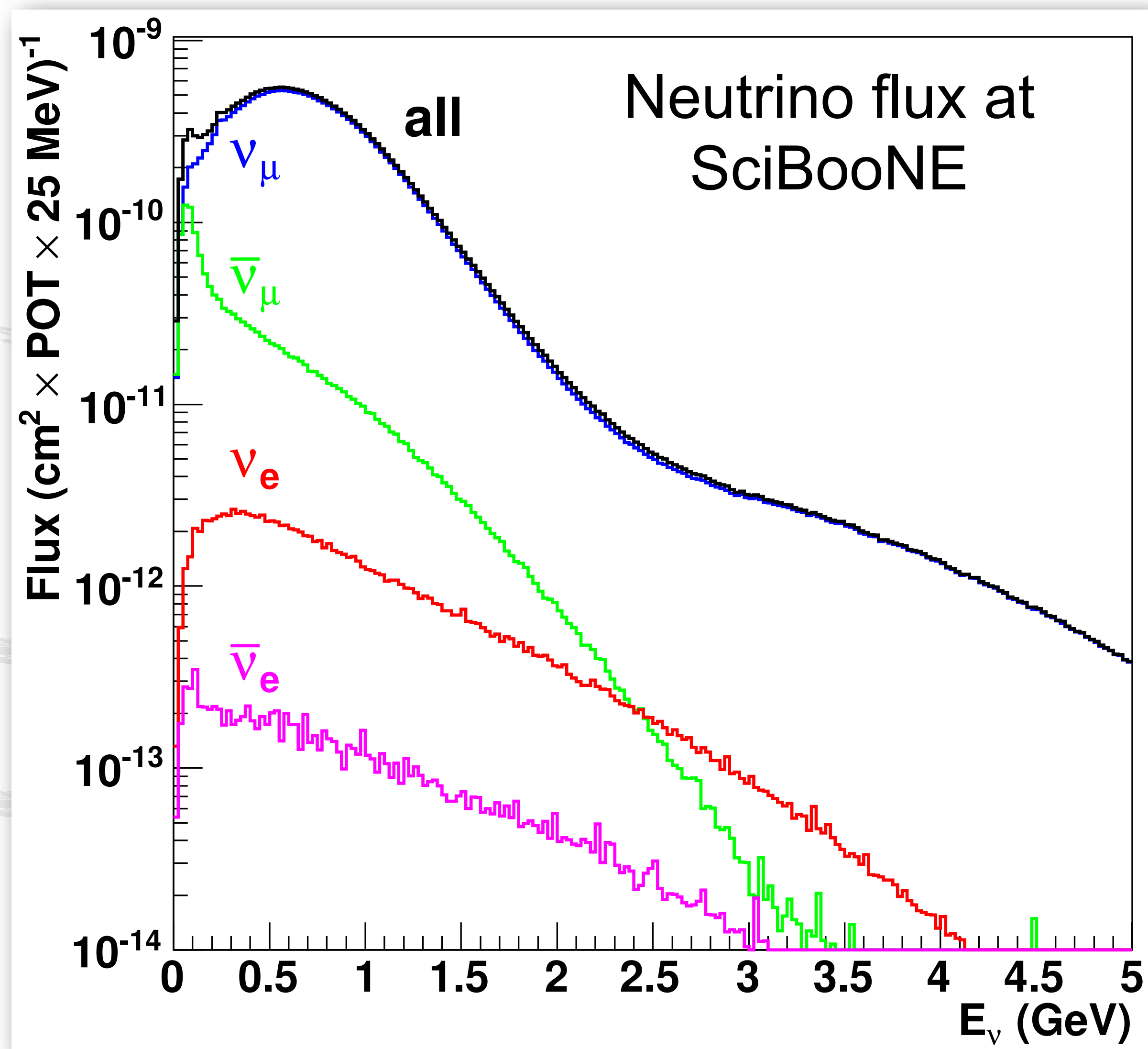
Universitat Autonoma de Barcelona
University of Colorado, Boulder
Columbia University
Fermi National Accelerator Laboratory
High Energy Accelerator Research Organization (KEK)
Imperial College London
Indiana University
Institute for Cosmic Ray Research (ICRR)
Kyoto University
Los Alamos National Laboratory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

***Spokespersons*:**
M.O. Wascko (Imperial), T. Nakaya (Kyoto)

Booster Neutrino Beam



- Intense ν_μ beam with mean energy ~0.8 GeV
  - 93% pure ν_μ beam.
- $\bar{\nu}_\mu$ beam is produced by inverting horn polarity.
- Uncertainties reduced with CERN HARP data



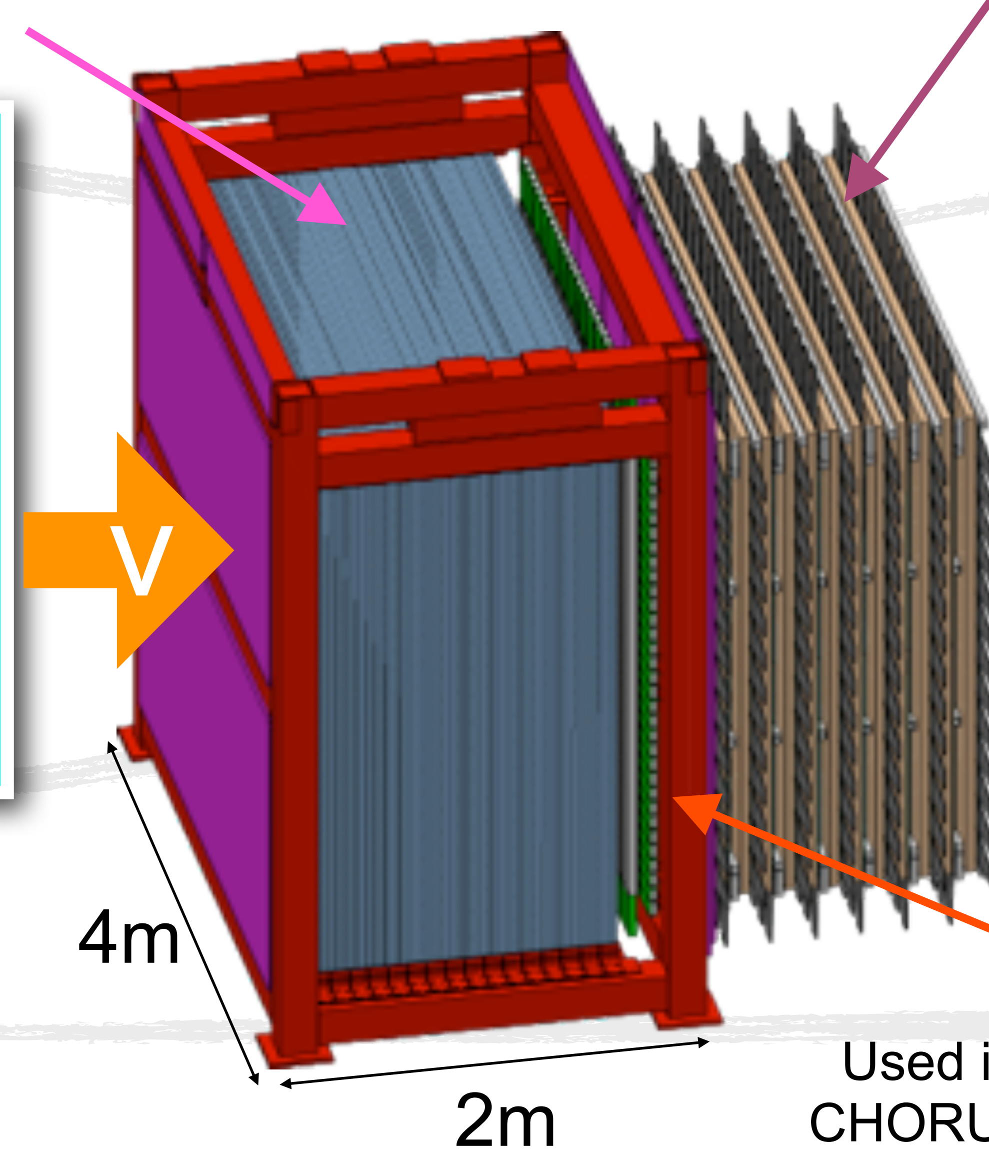
Phys.Rev.D**79** 072002 (2009)

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 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 experiments

Electron Catcher (EC)

Used in CHORUS, HARP and K2K

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

SciBooNE detector

DOE-wide Pollution Prevention Star (P2 Star) Award

n Range Detector

- scintilla
  detector
- 14,336
  bars (15
- Neutrin
- detect
  particles
- p/π se
  using dE

Used in K

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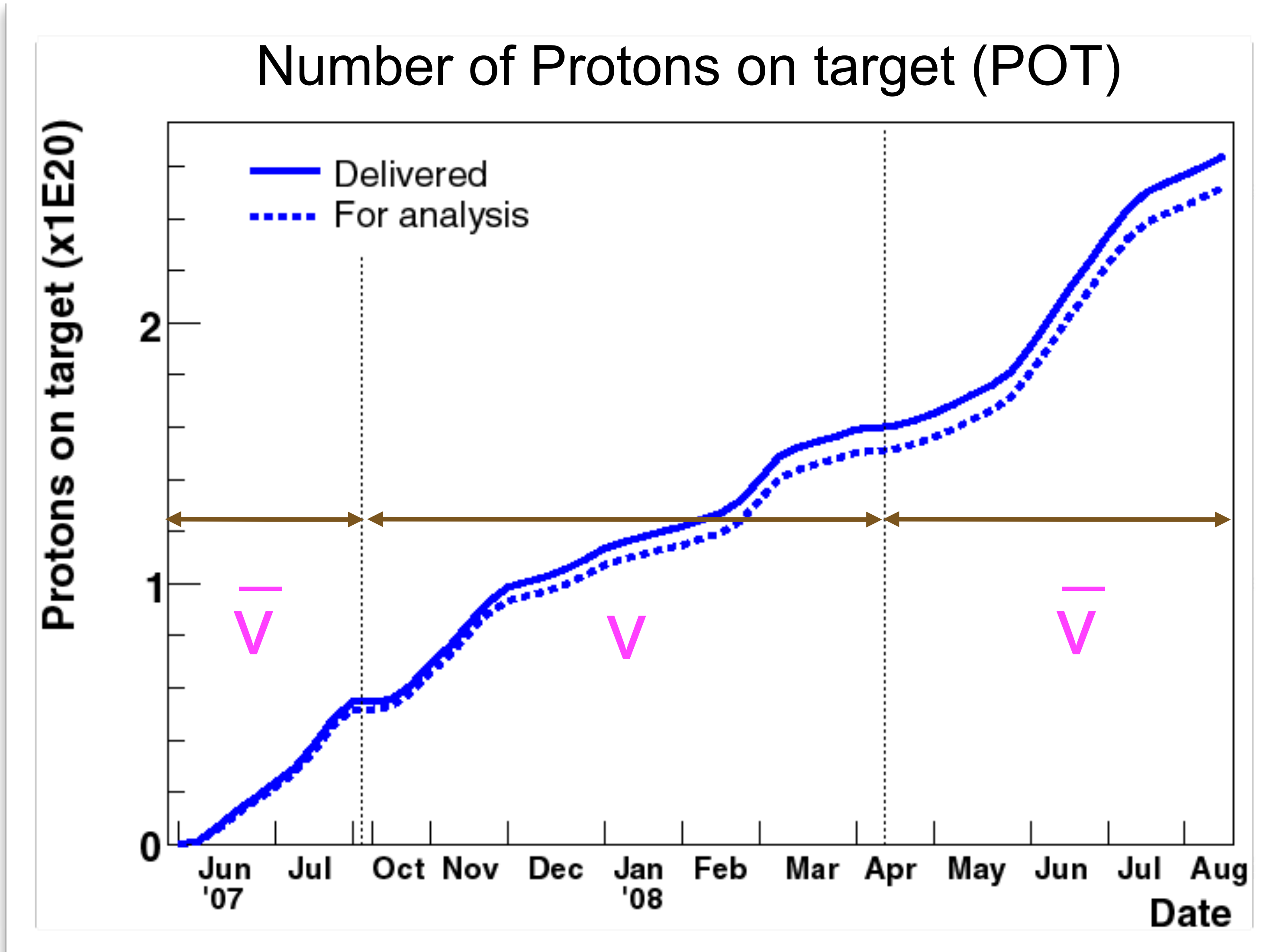
SciBooNE Data-Taking



- Jun. 2007 – Aug. 2008
- 95% data efficiency
- 2.52×10^{20} POT in total
  - neutrino : 0.99×10^{20} POT
  - antineutrino: 1.53×10^{20} POT

FERMILAB-TM-2421-DO
FERMILAB-TM-2401-DO,

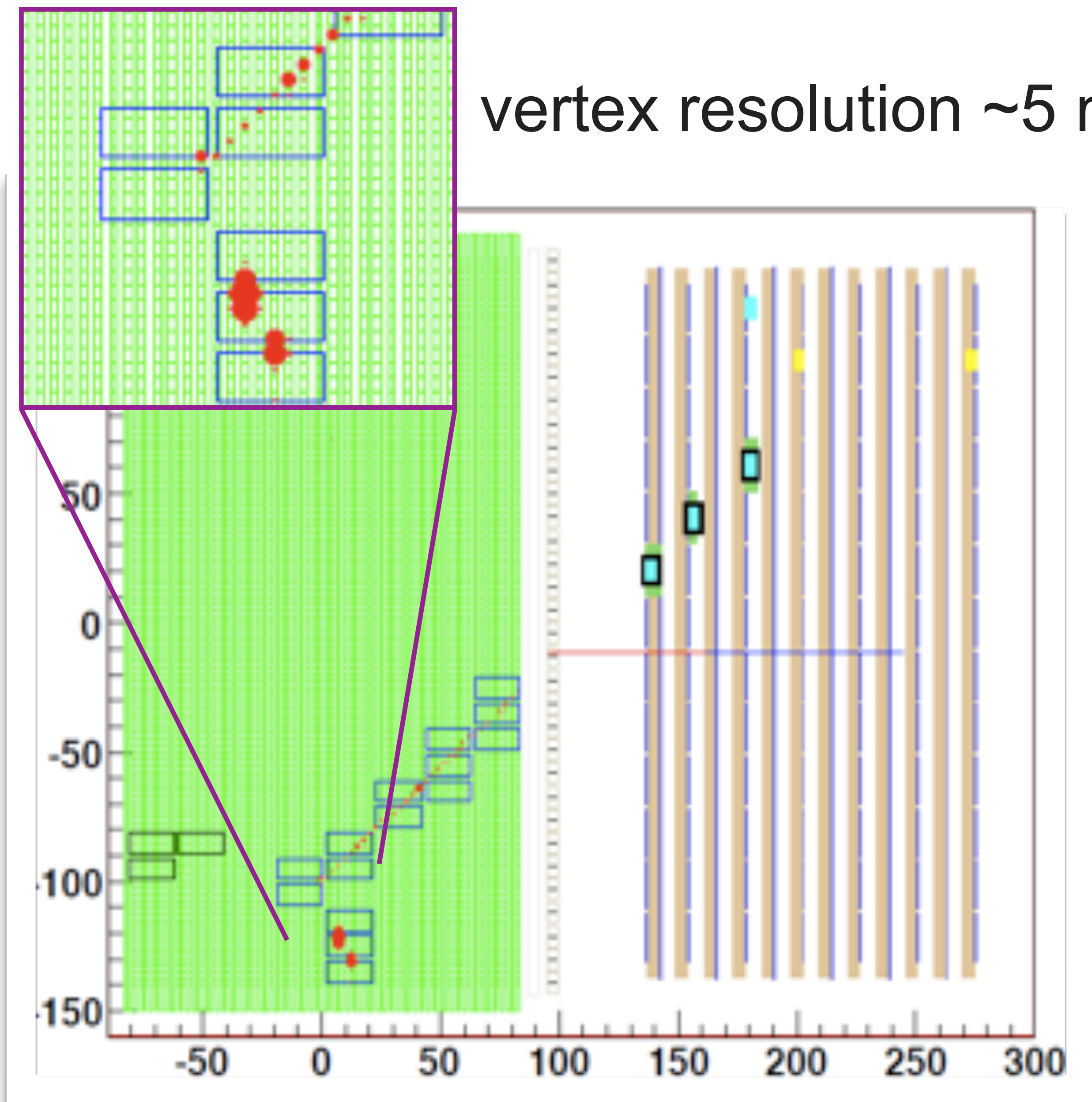
Analysis of neutrino and antineutrino data sets ongoing.

Neutrino event displays

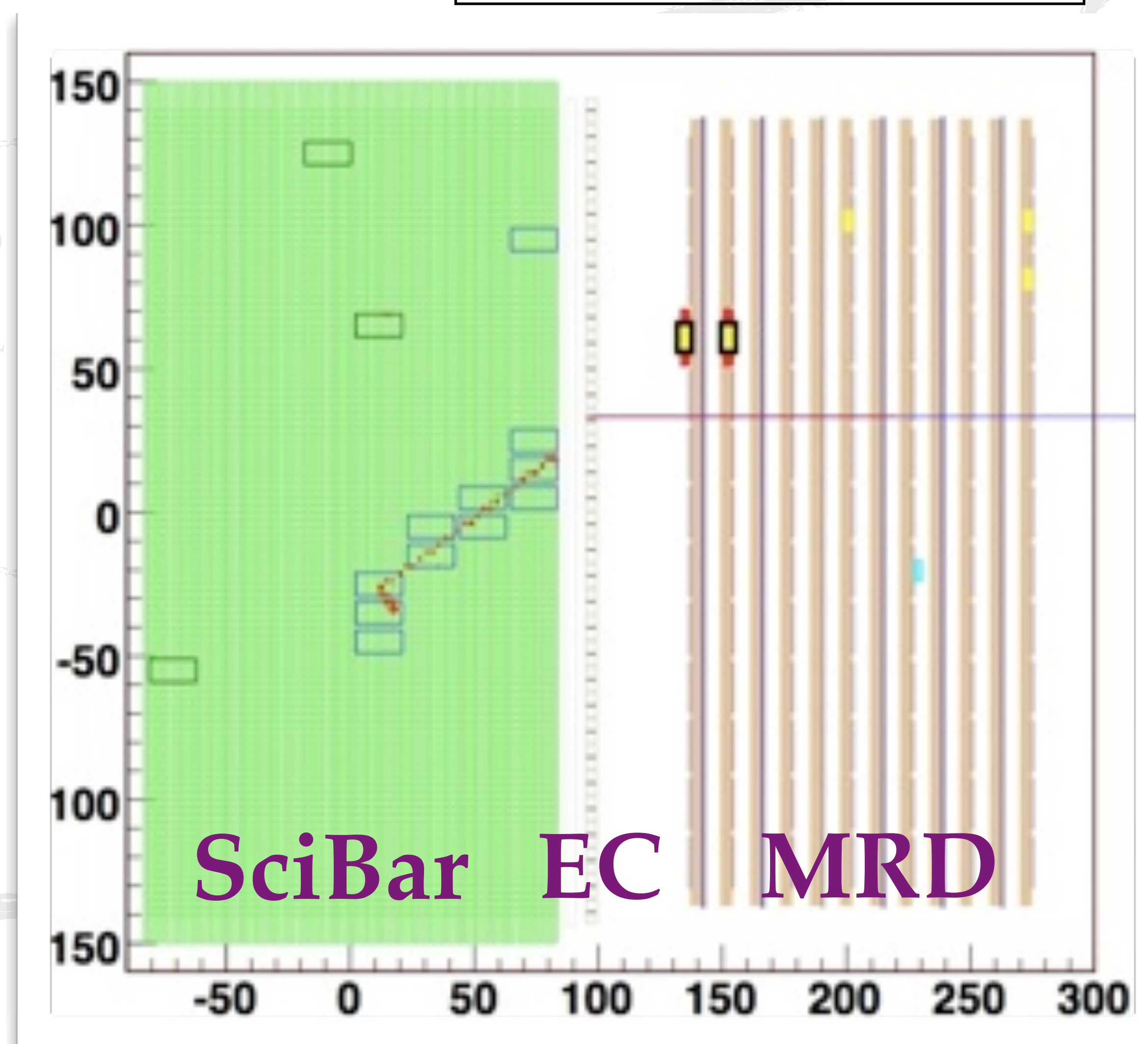
Real SciBooNE Data

vertex resolution ~5 mm

ADC hits (area ∝ charge)
TDC hits (32ch OR)

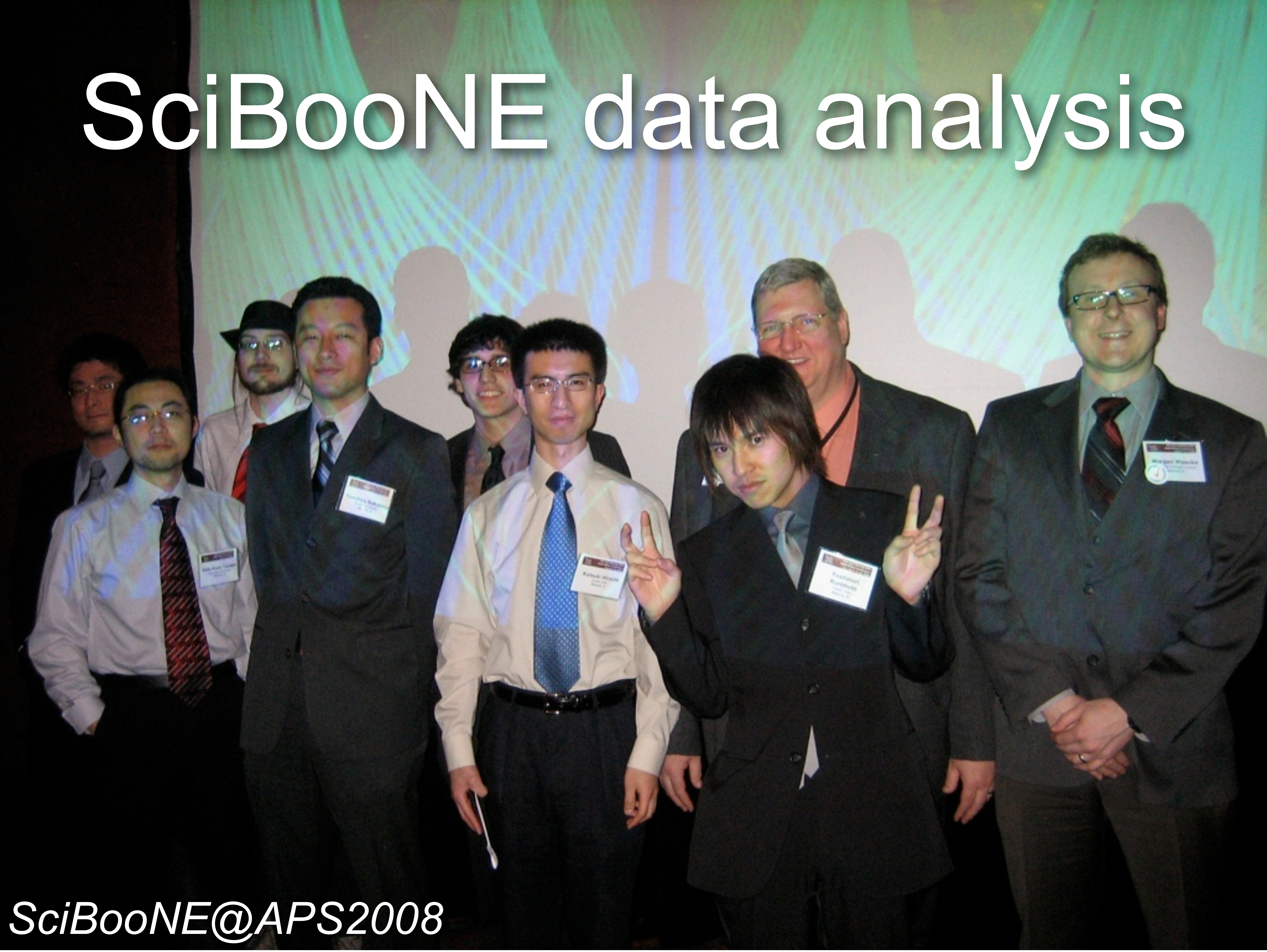


$\bar{\nu}_\mu$ CC-QE candidate
$(\bar{\nu}_\mu + p \rightarrow \mu + n)$



ν_μ CC-QE candidate
$(\nu_\mu + n \rightarrow \mu + p)$

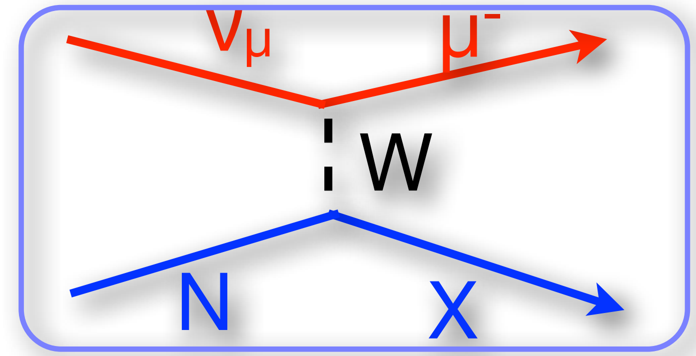
SciBooNE data analysis

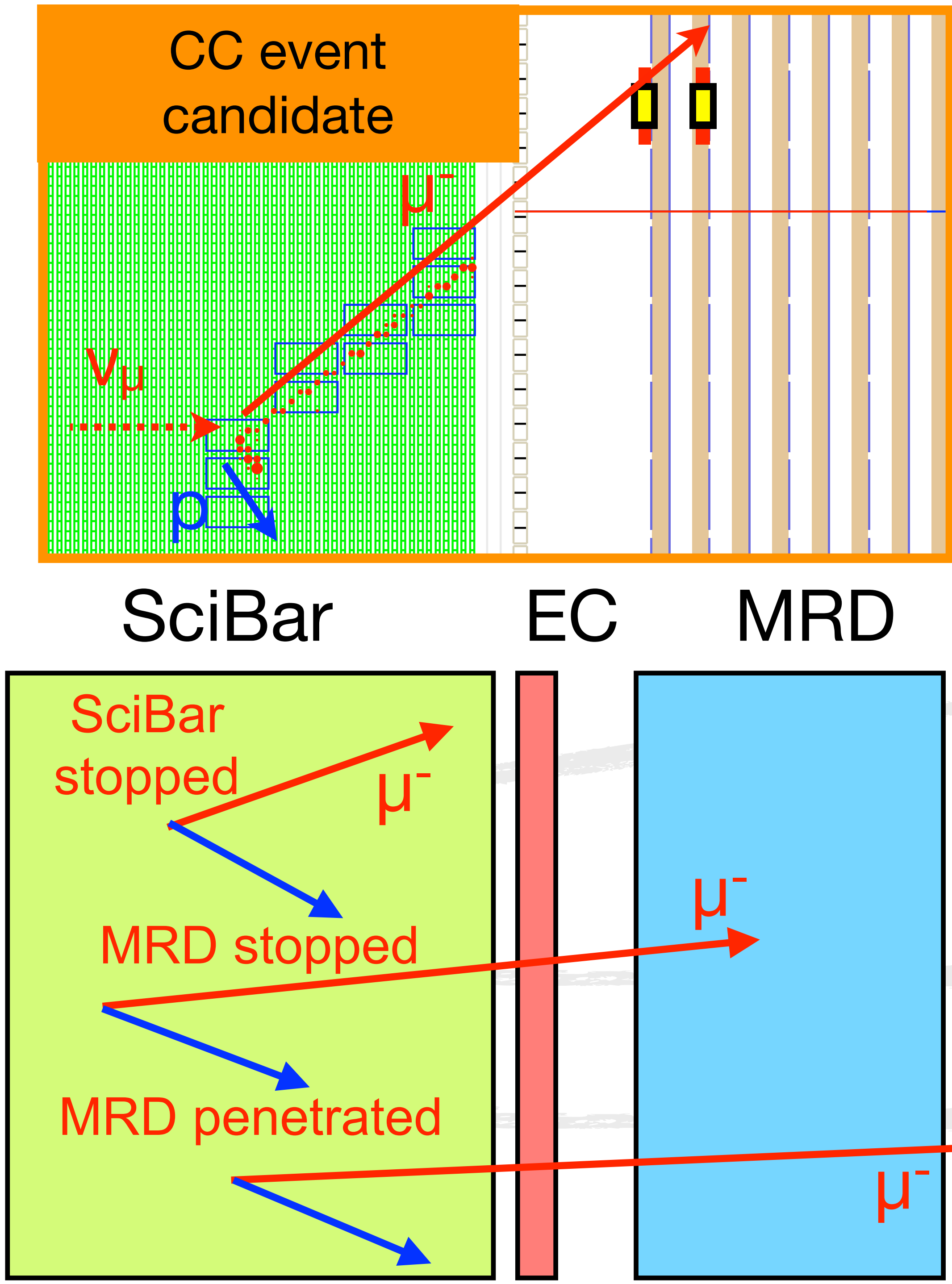


SciBooNE@APS2008

CC event selection

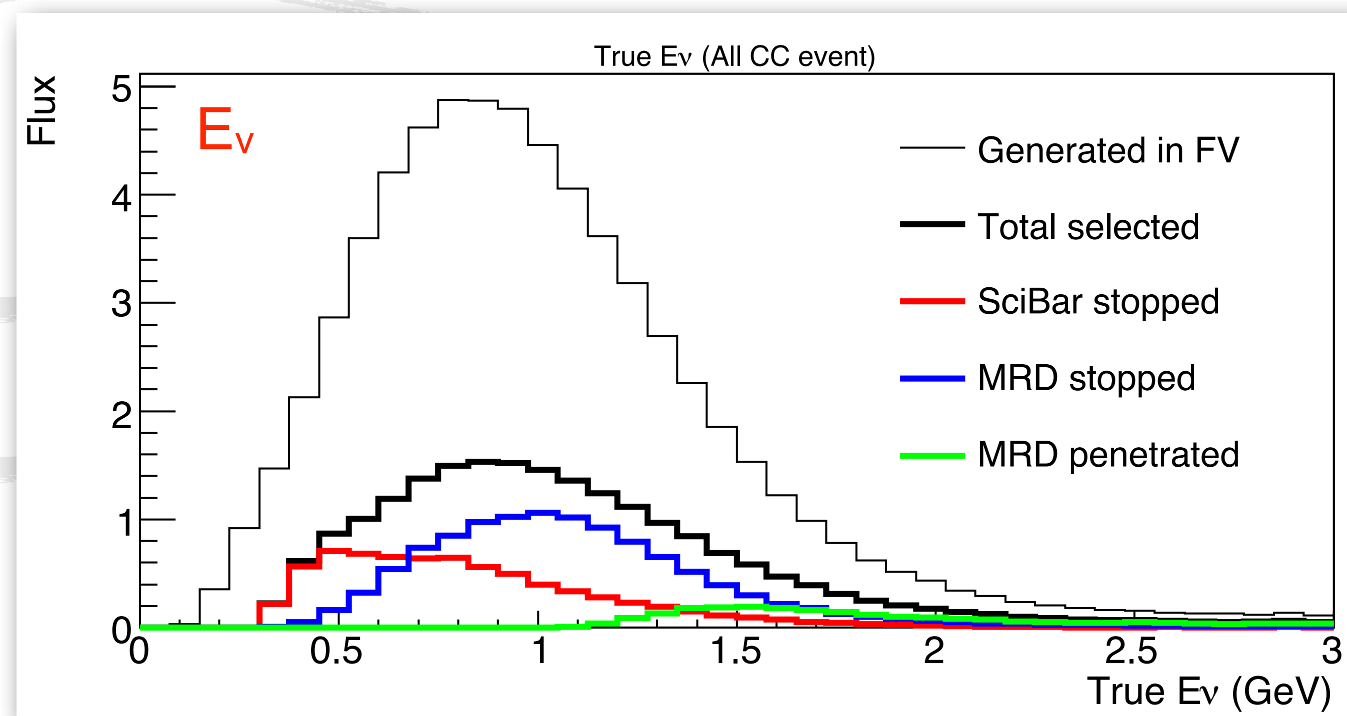
"charged current"





- 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



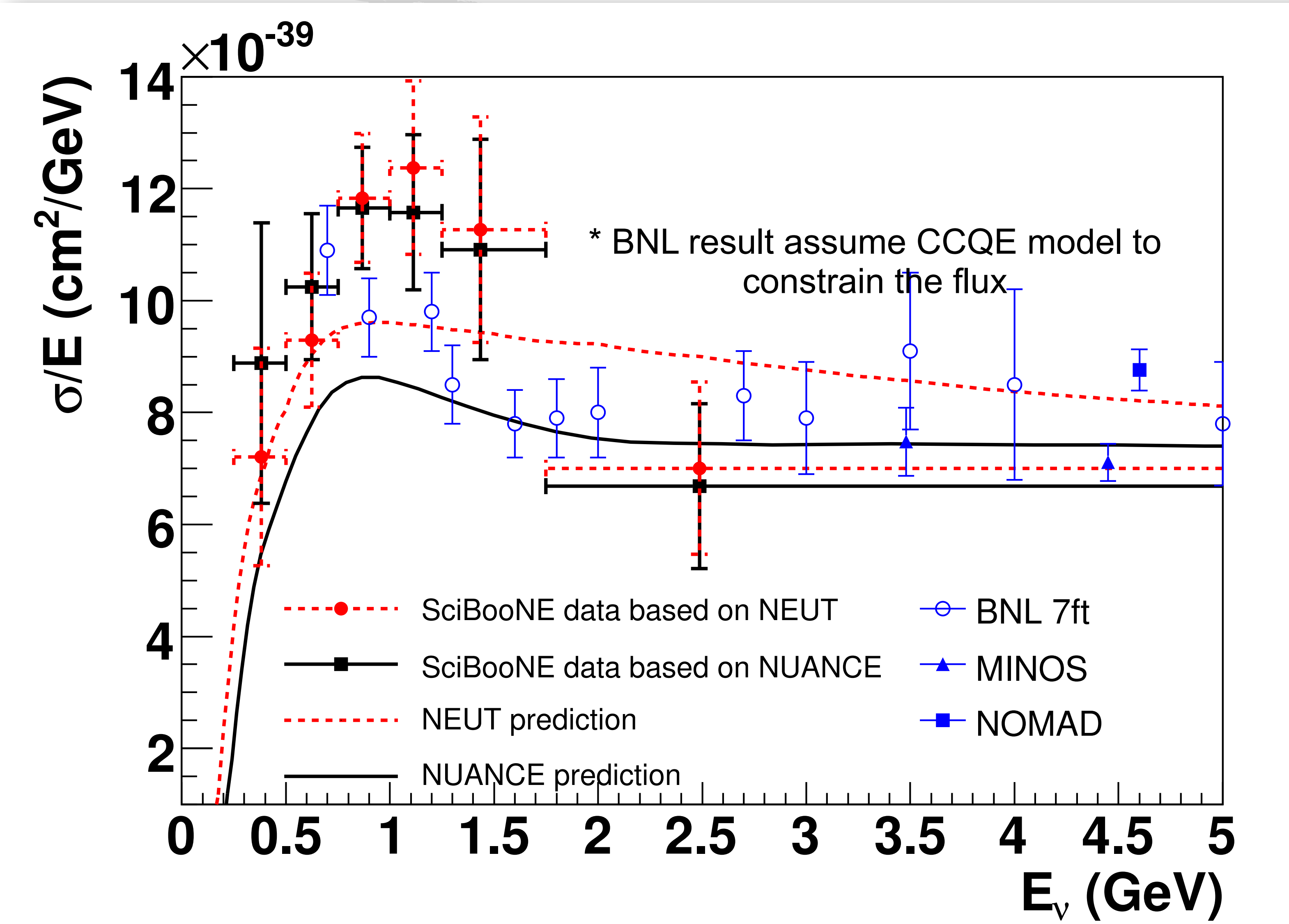
ν_μ CC inclusive xsec

Yasuhiro Nakajima

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

T: number of target nucleon
Φ: total flux

Model-independent signal definition.

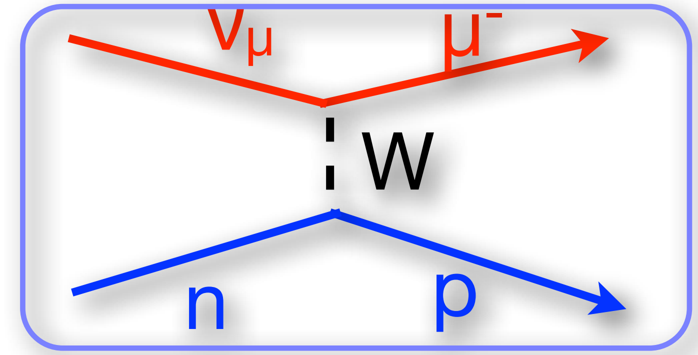


[Phys. Rev. D **83**, 012005 (2001)]

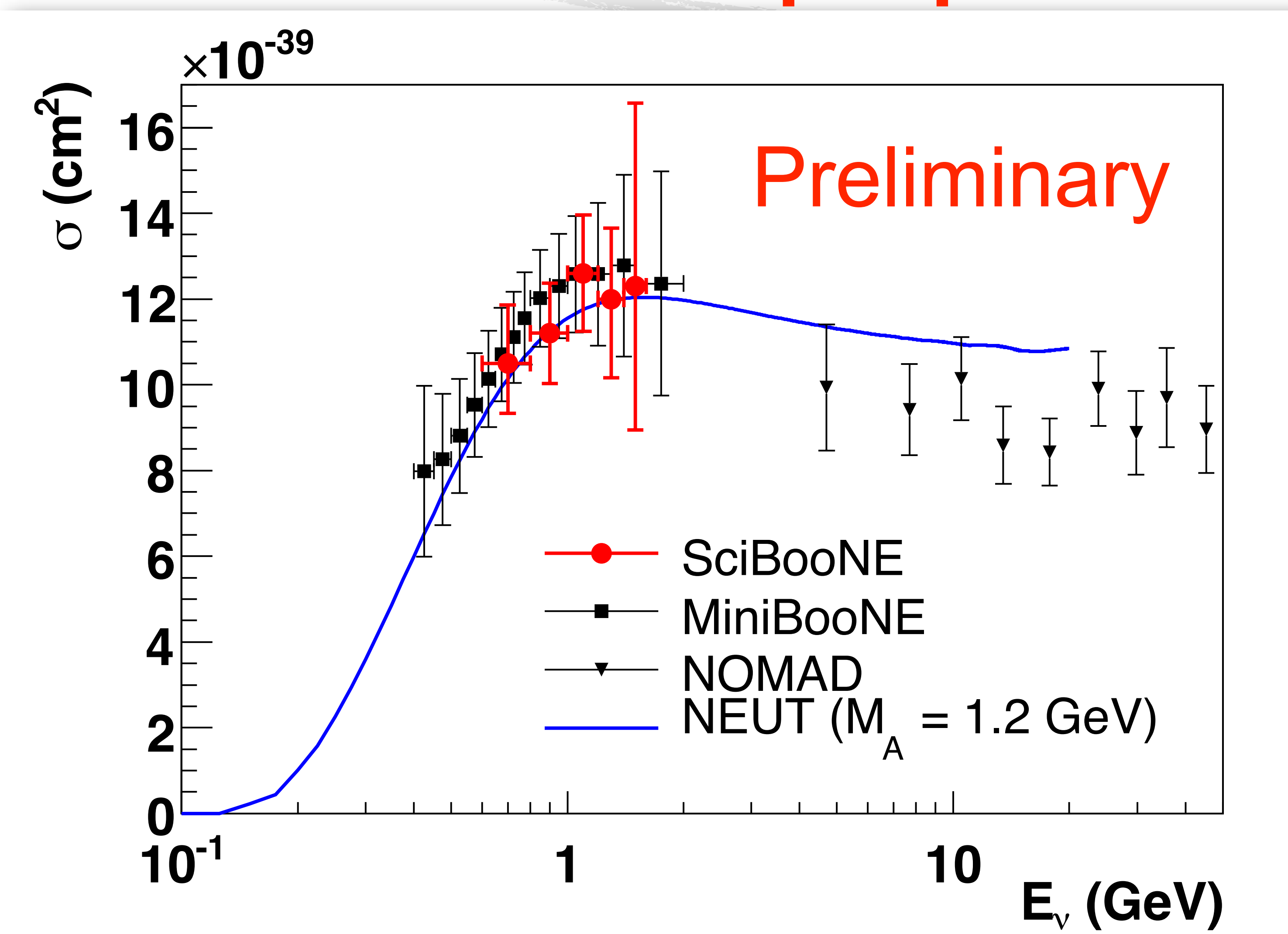
- First measurement of CC-inclusive xsec on C near 1 GeV
  - NEUT and NUANCE based measurements are consistent.
- Consistent with MINOS, NOMAD and old BNL (deuterium) measurements

ν_μ CCQE xsec

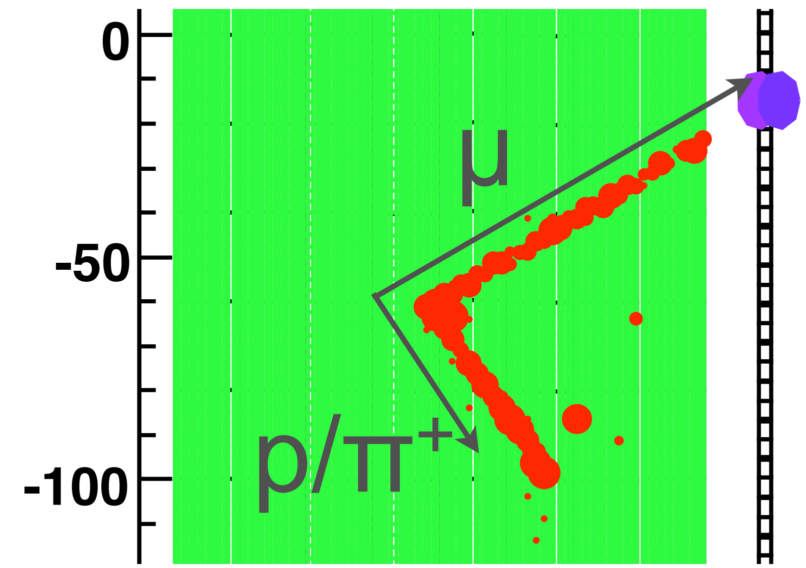
Jose Alcaraz, Joe Walding



Cross section per proton



Publication in preparation



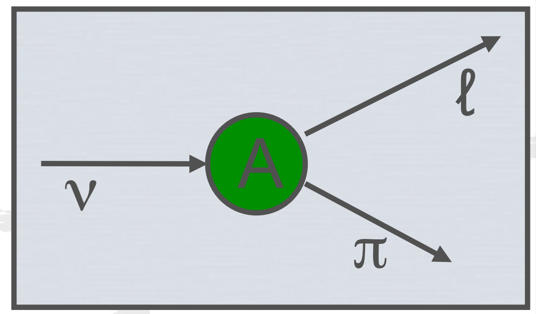
- Separate data into QE/ nonQE samples based on second track PIDs
  - Consistent with MiniBooNE result!

➡Impulse approximation?
➡Multinucleon scattering?

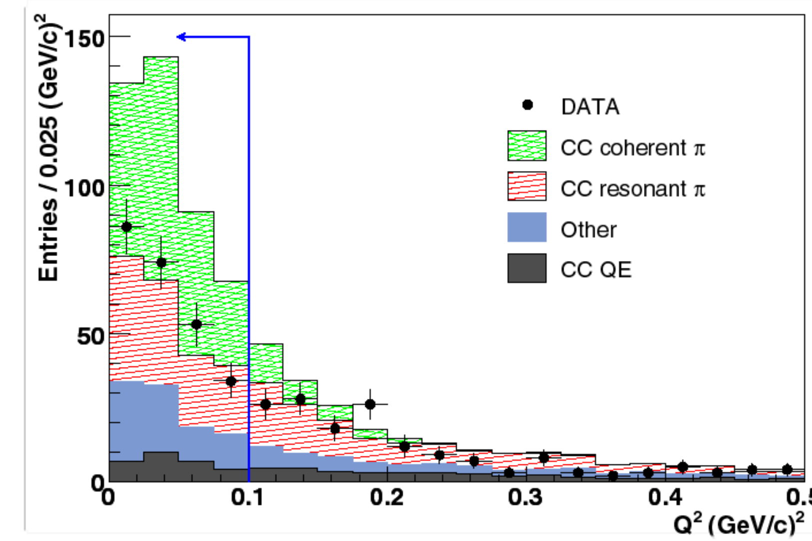
ν_μ CC coherent pions

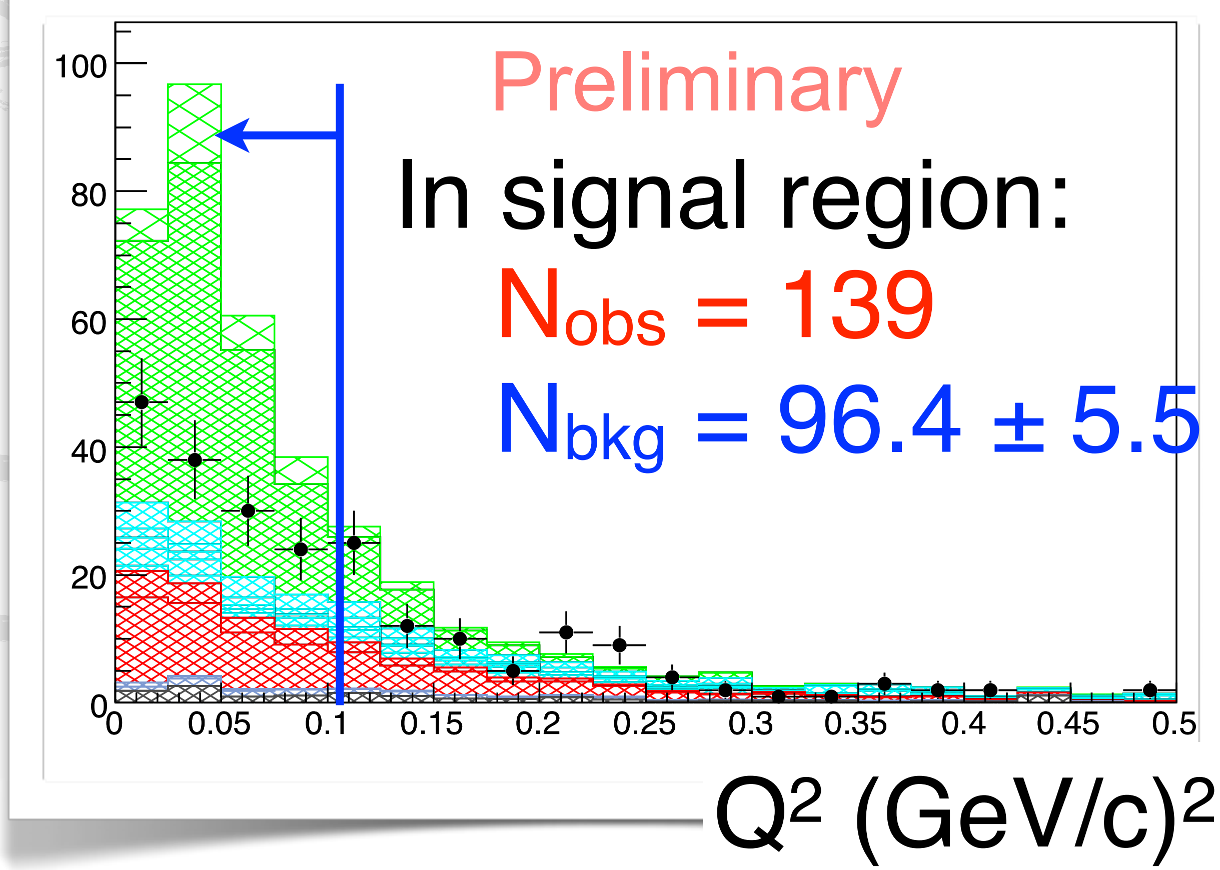
Katsuki Hiraide

- Neutrino interacts with entire nucleus
  - Observed at high energy
  - Not seen by K2K
- Select 2 MIP events
  - very forward pion, low Q^2
- Observed no signal in neutrino mode
- Small excess in antineutrino mode
  - Consistent with limit set in neutrino mode



[Phys.Rev.D78, 112004 (2008)](https://doi.org/10.1103/PhysRevD.78.112004)



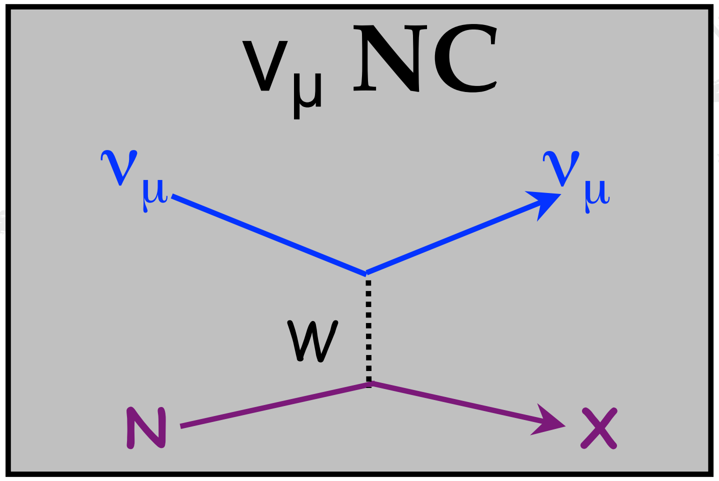


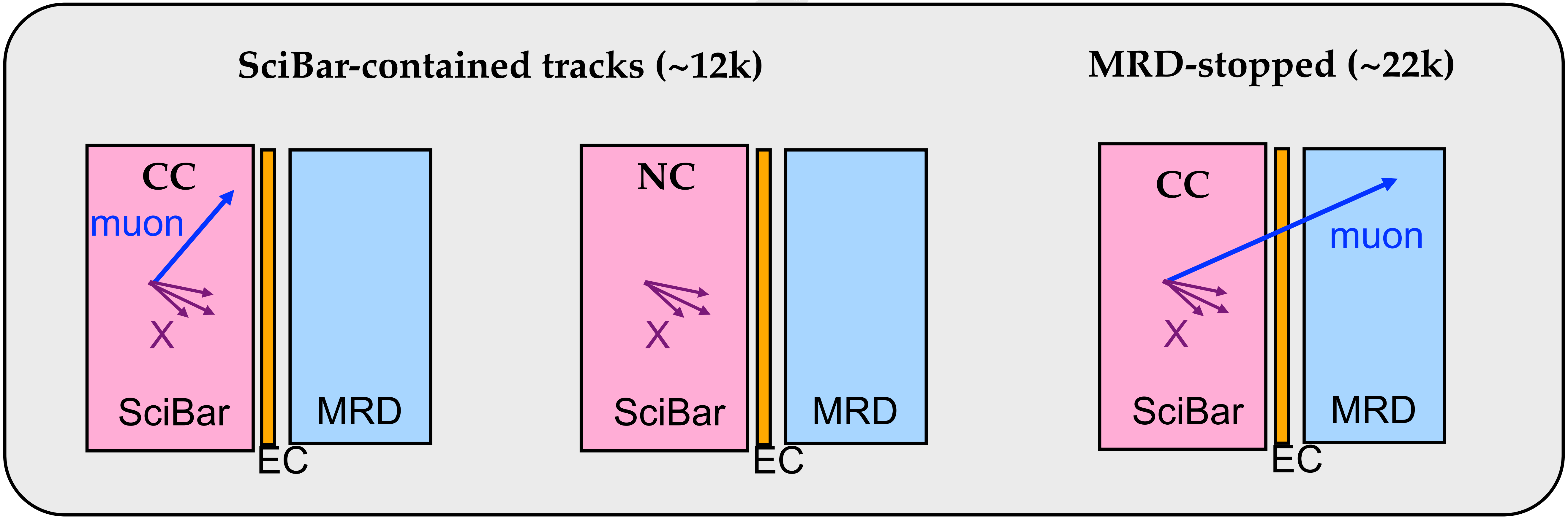
Hidekazu Tanaka

NC event selection

"neutral current"

- Require tracks contained in SciBar
  - Further cuts remove contained muons
- MRD-matched events used for normalisation





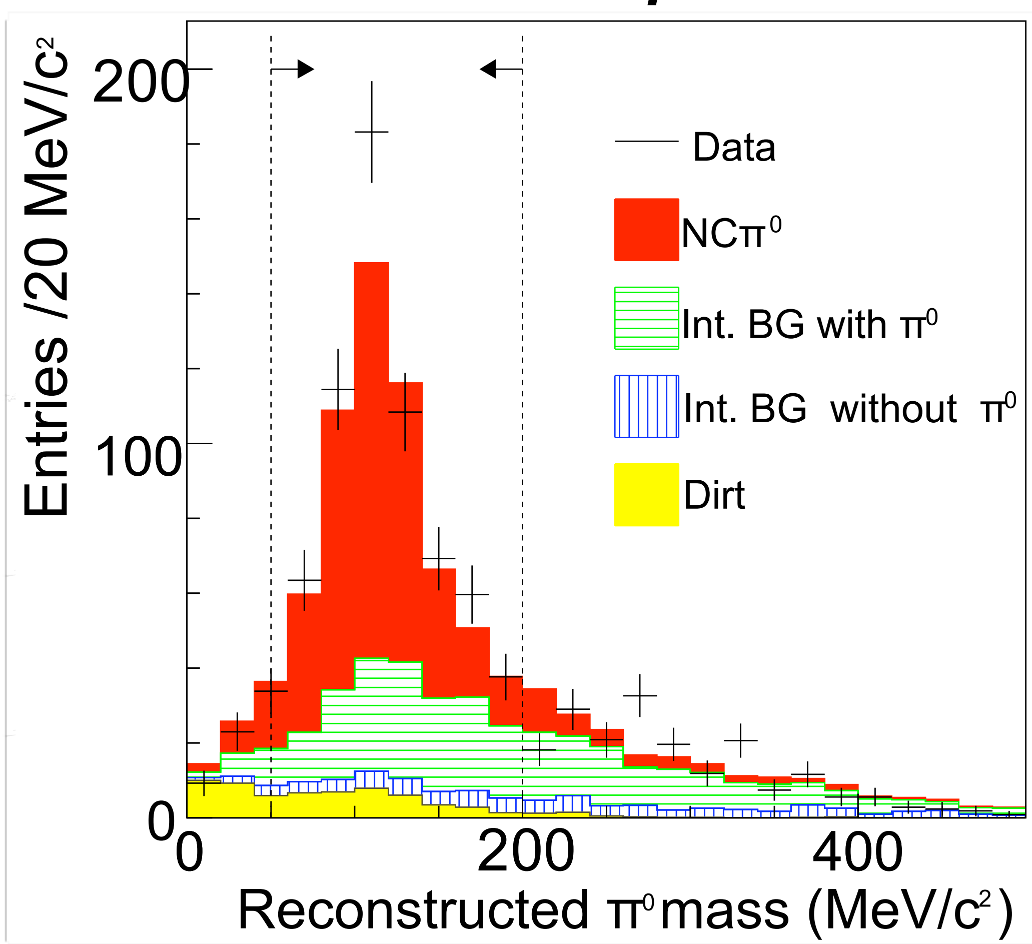
NC π^0 selection

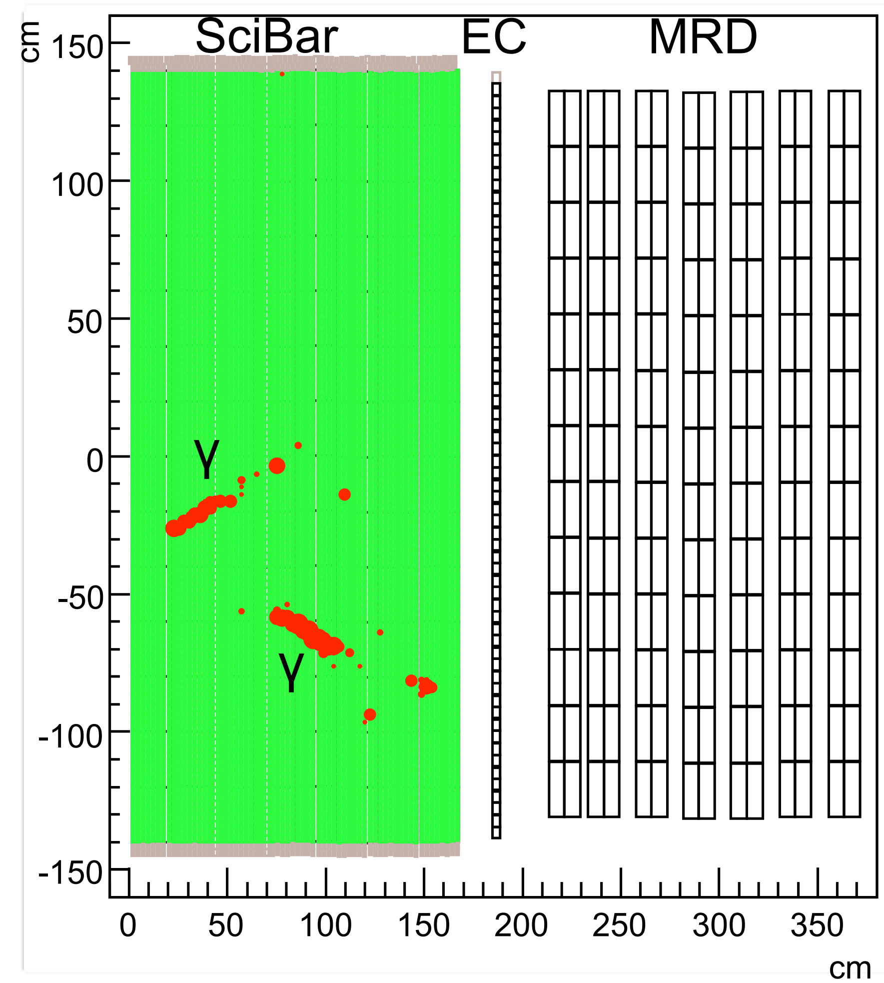
Yoshinori Kurimoto

Select 2 electromagnetic shower pairs and reconstruct invariant mass.

Model-independent signal definition.

Clean π^0 peak!





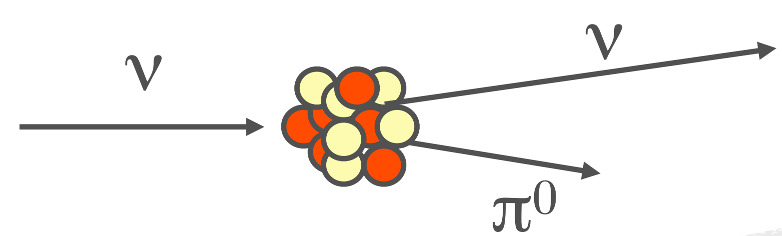
Extract ratio to CC-inclusive xsec, which can now be converted to absolute xsec.

Phys.Rev.D81, 033004 (2010)

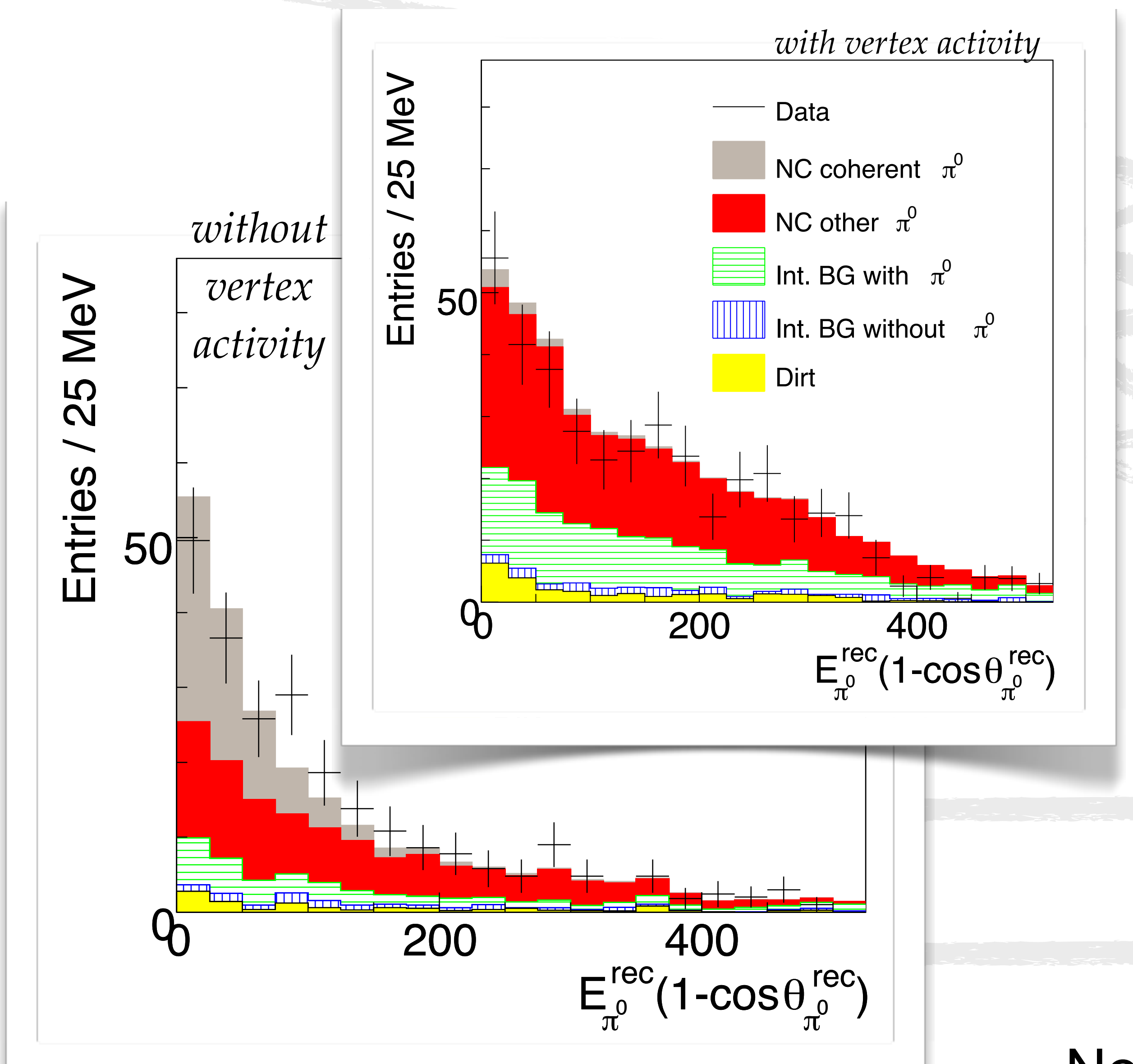
NC coherent π^0

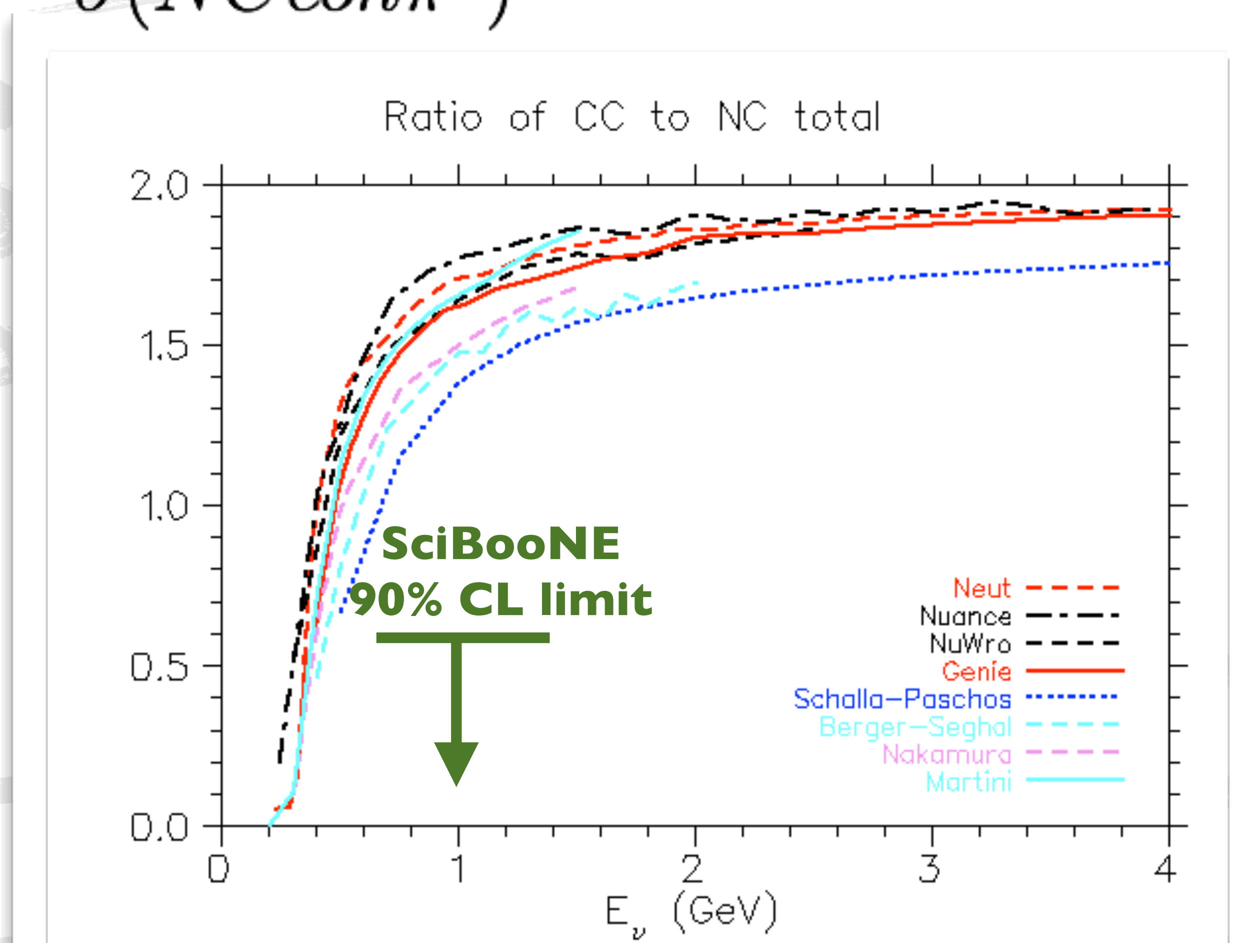
Phys.Rev.D81, 111102 (2011)

Use "vertex activity" to separate coherent and resonant NC π^0 events.



$$\frac{\sigma(CCcoh\pi^+)}{\sigma(NCcoh\pi^0)} = (0.14^{+0.30}_{-0.28}) \times 10^{-2}$$





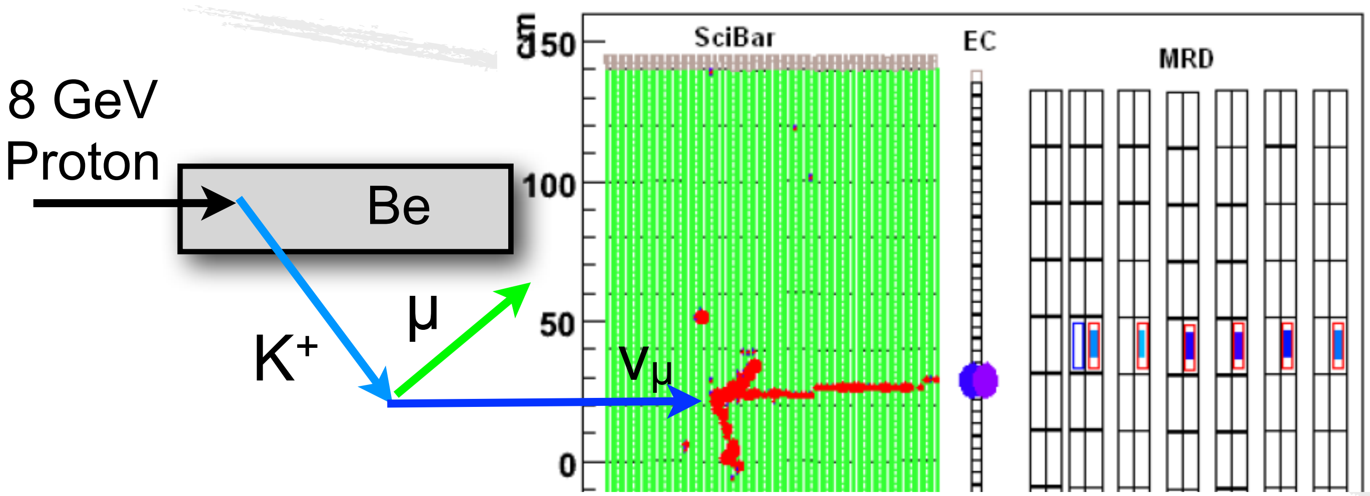
S. Boyd, et al., AIP Conf. Proc. 1189, 60 (2009)

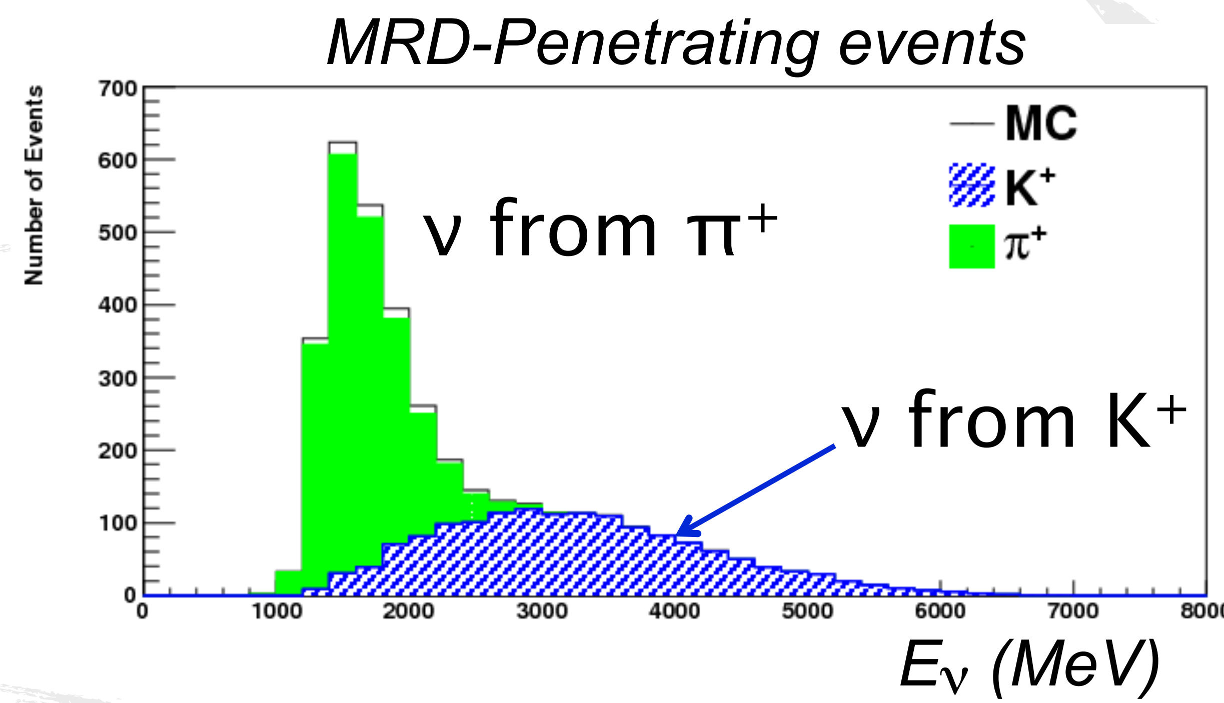
Yoshinori Kurimoto

No model predicts a ratio of CC/NC coherent pion production as low as our measurement.

Kaon production

Gary Cheng & Camillo Mariani   Phys.Rev.D84, 012009 (2011)

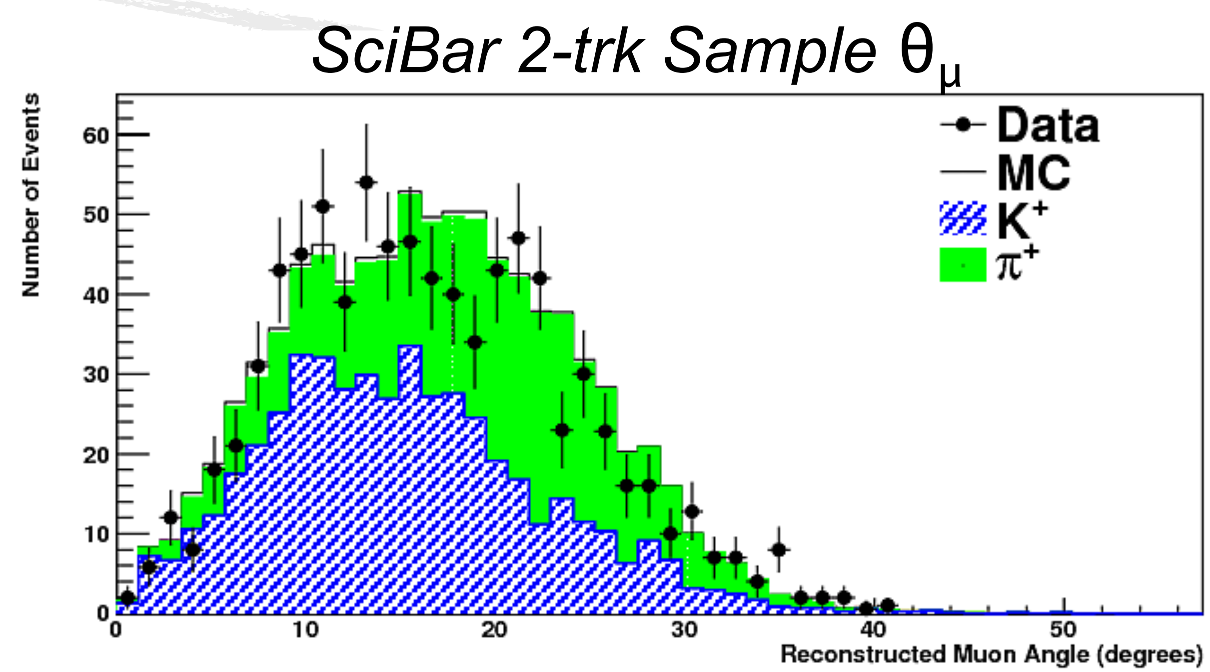




High energy neutrinos predominantly come from kaon decay.

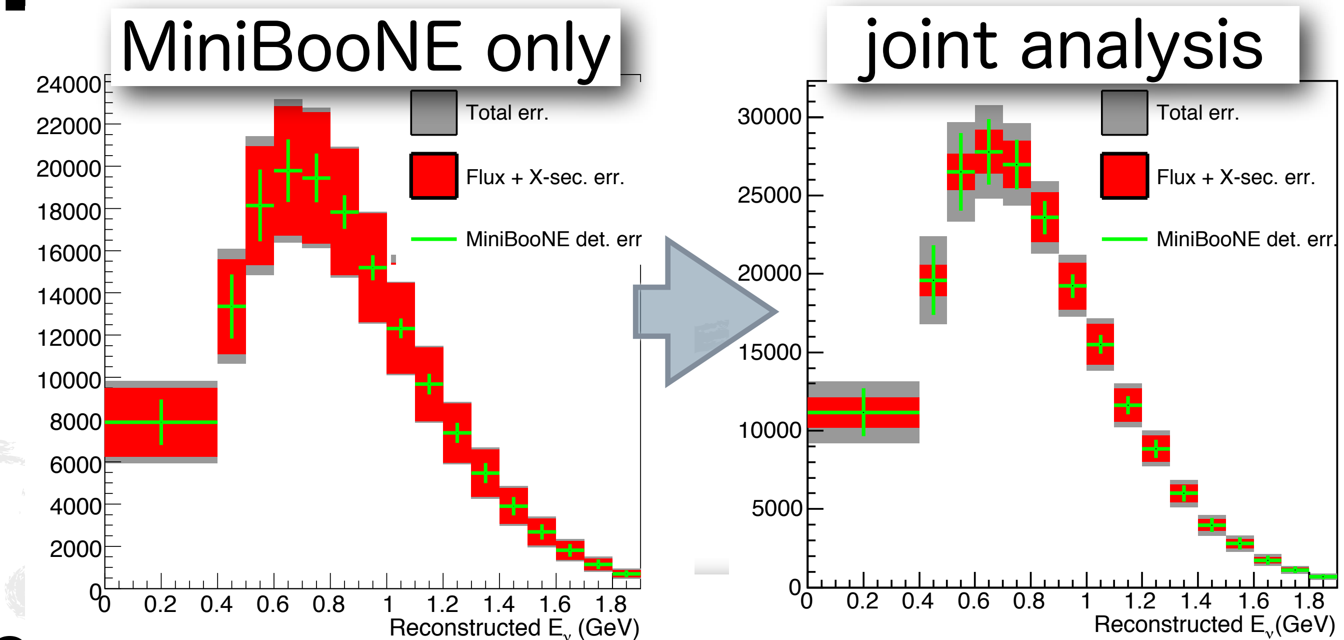
Selecting MRD-penetrating events gives sample of high energy neutrinos.

Fit for kaon fraction, and tune Feynman scaling production model. Reduces model dependence of MiniBooNE ν_e BG prediction.



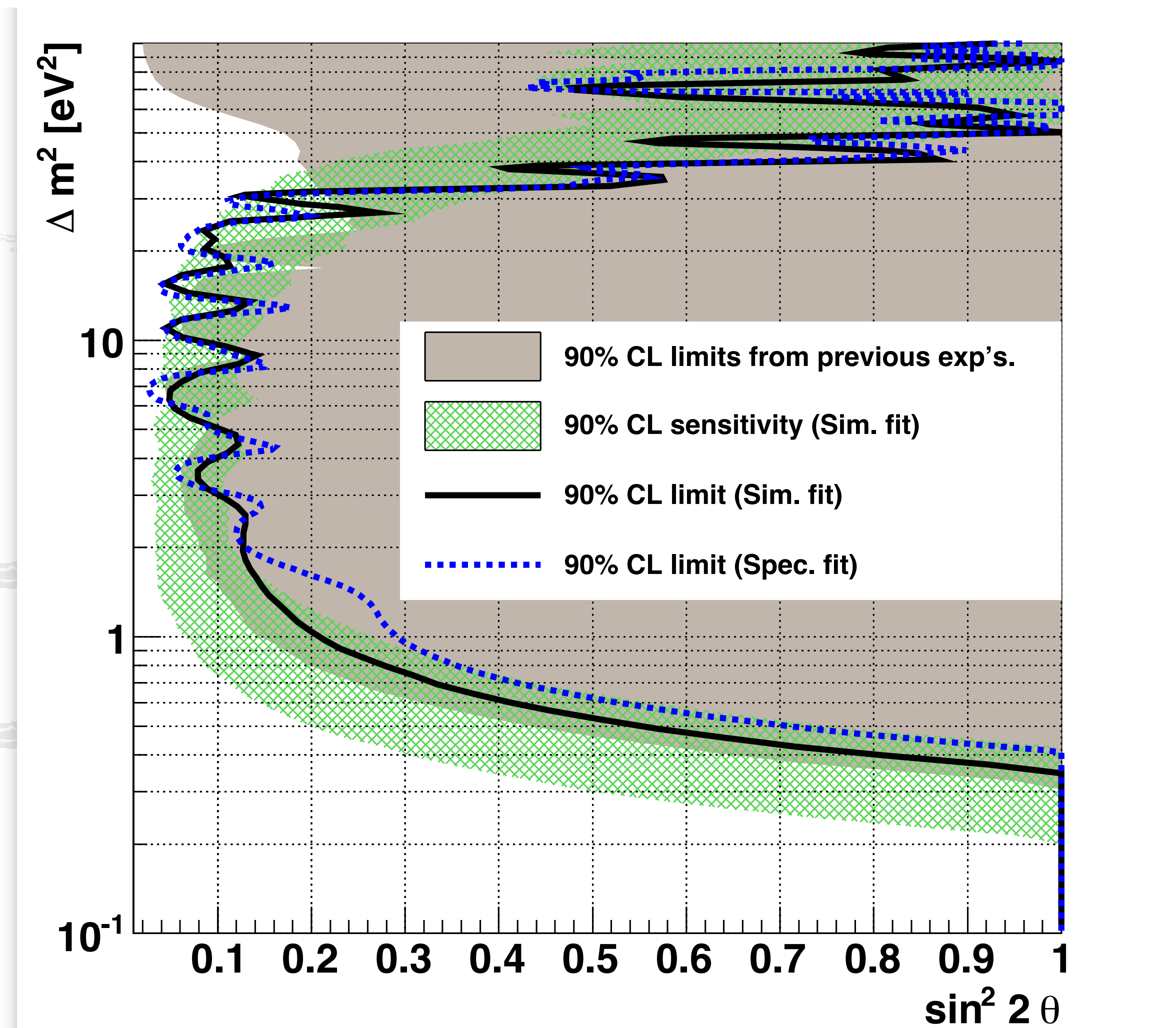
ν_μ disappearance

Kendall Mahn & Yasuhiro Nakajima



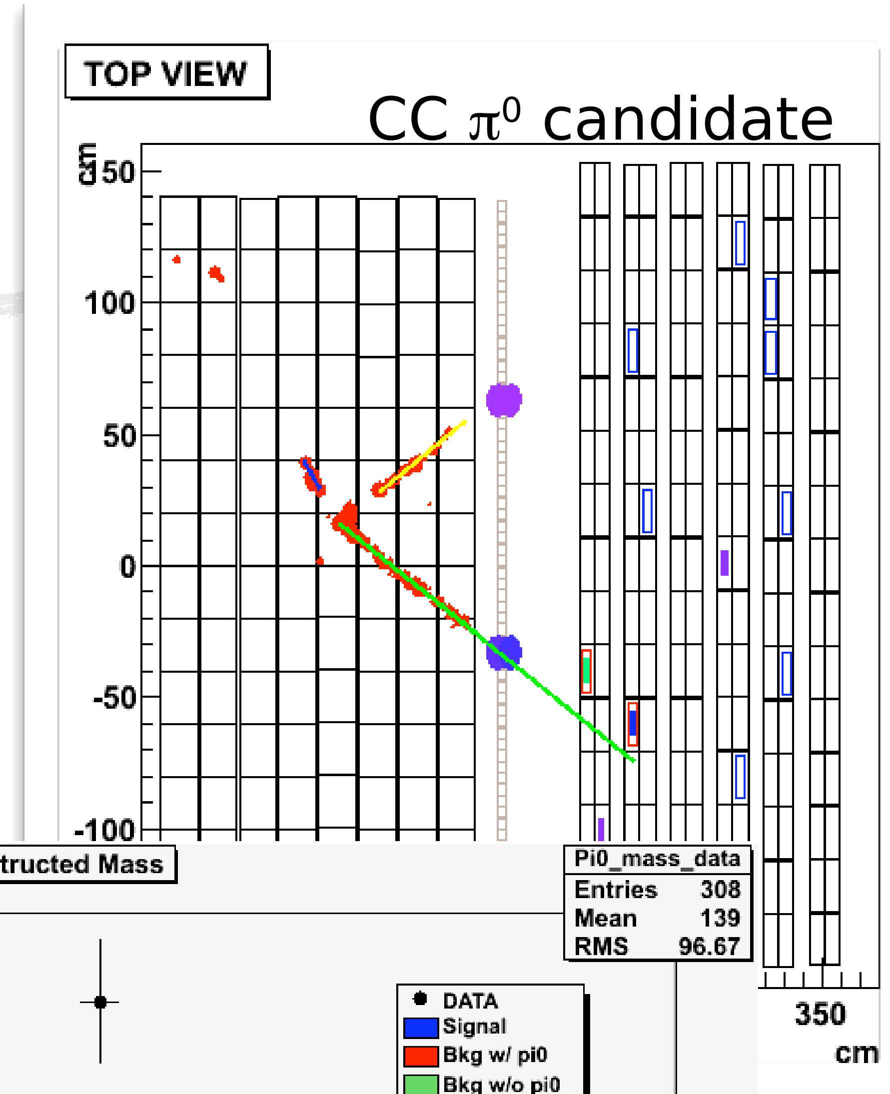
- SciBooNE acts as a near detector for MiniBooNE ν oscillation search
  - Same neutrino beam, same target nucleus (C)
  - Significant reduction in total systematic uncertainty
- Disappearance constrains sterile neutrino models.
- World's best limit in 5-30 eV^2 range

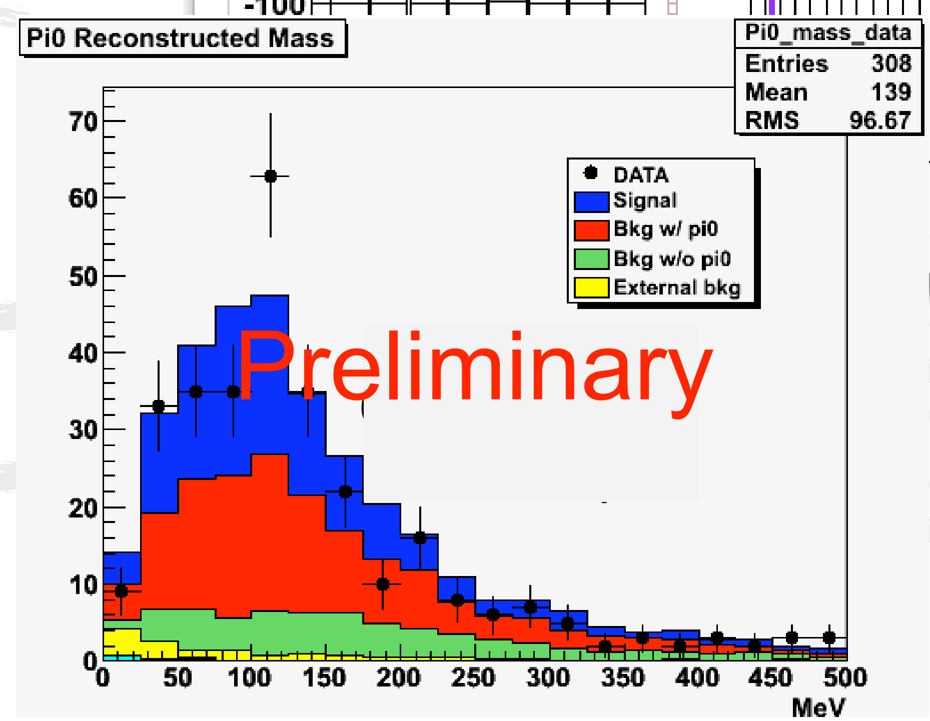
[arXiv:1106.5685[hep-ex]](arXiv:1106.5685)



Ongoing analyses

- CC π^0 Joan Catala
  - Select muon events with 2 EM showers
- NC elastic Hideyuki Takei, Ben Jones
  - select single proton-like tracks
  - Cross section gives access to Δs
- $\bar{\nu}_\mu$ disappearance Gary Cheng, Warren Huelsnitz
  - Need to understand wrong-sign backgrounds!



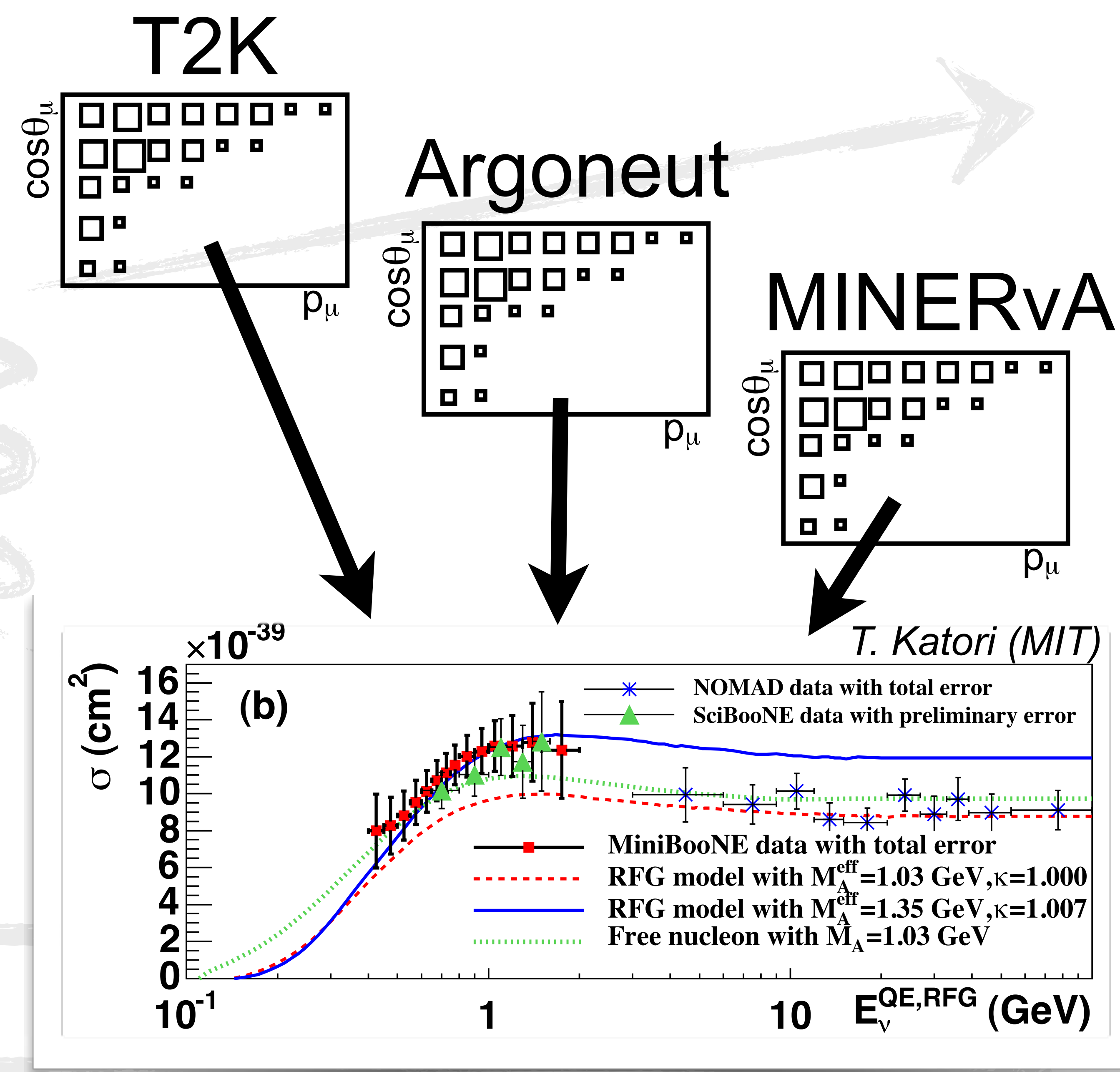


Conclusions

Growing Consensus

- We need broad coverage
  - ➡ Model independent measurements at many energies, nuclei
- Move away from process cross-sections
  - σ(QE), σ(res π), σ(coh π)
- Instead measure final state particle cross-sections
  - σ(CC), $\sigma(\mu)$, $\sigma(\mu+p)$, $\sigma(\mu+\pi)$

➡ *If θ_{13} is large, we need to understand these systematics in order to measure CP violation!*



Same goes for NC...

- SciBooNE has a unique, high quality data set in both neutrinos and antineutrinos
  - ➡ Improving MiniBooNE neutrino oscillation studies.
  - ➡ Contributing to growing understanding of neutrino-nucleus interactions at 1 GeV

6 analysis publications and counting


Y. Nakajima@MRD installation

There's more to learn!

SciBooNE, 2008

Thanks!

SciBooNE History

Groundbreaking ceremony (Sep. 2006)

Detector Assembly (Nov. 2006 -Mar.2007)

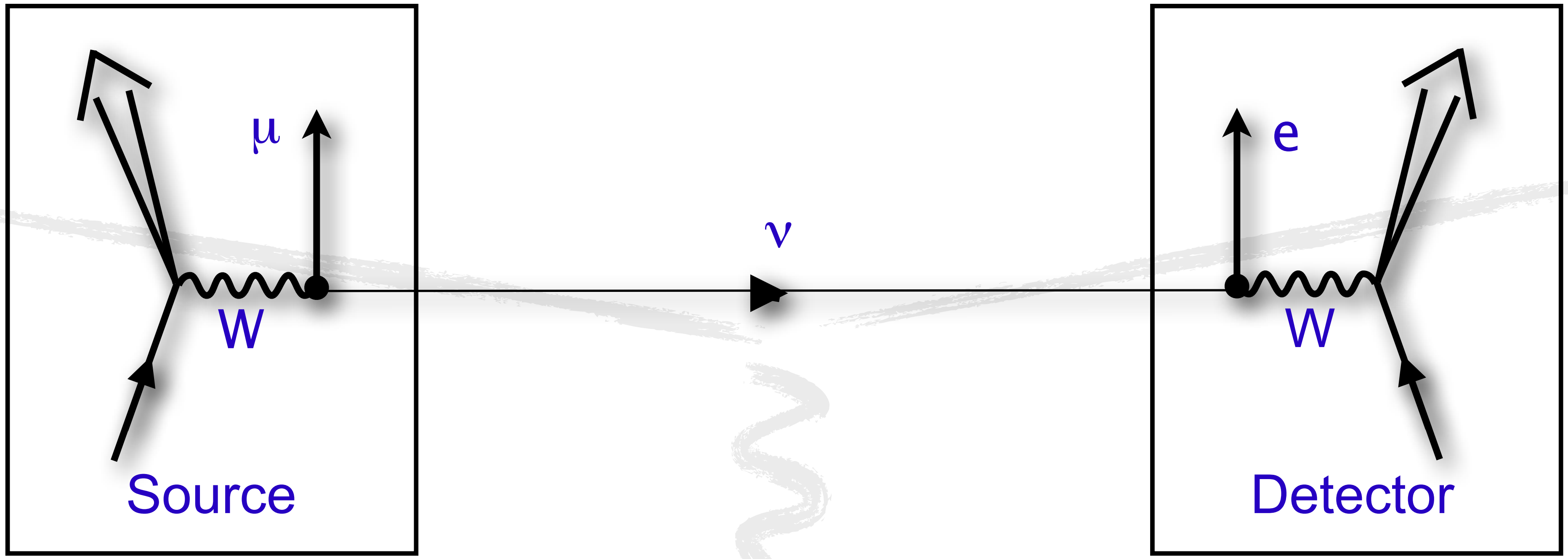
SciBooNE History

Students contributed significantly

Detector installation (Apr. 2007)

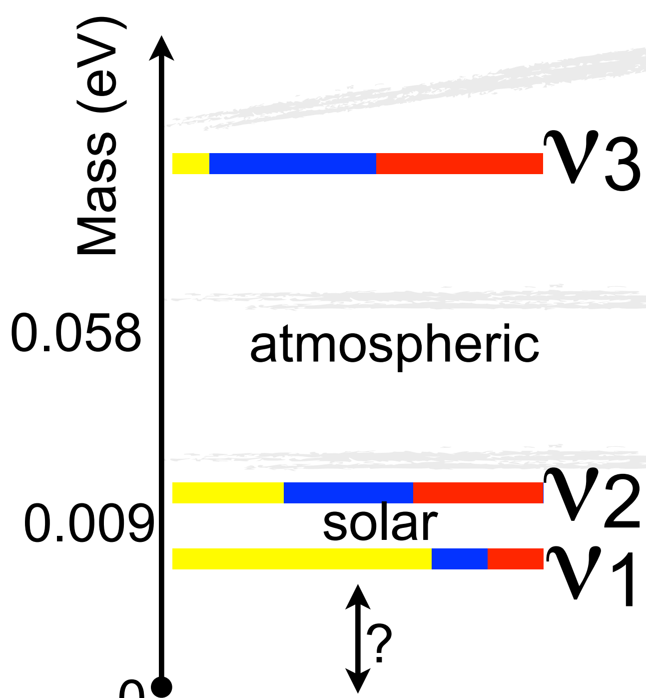
End-of-run party (Aug. 2008)

Neutrino oscillation



$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$

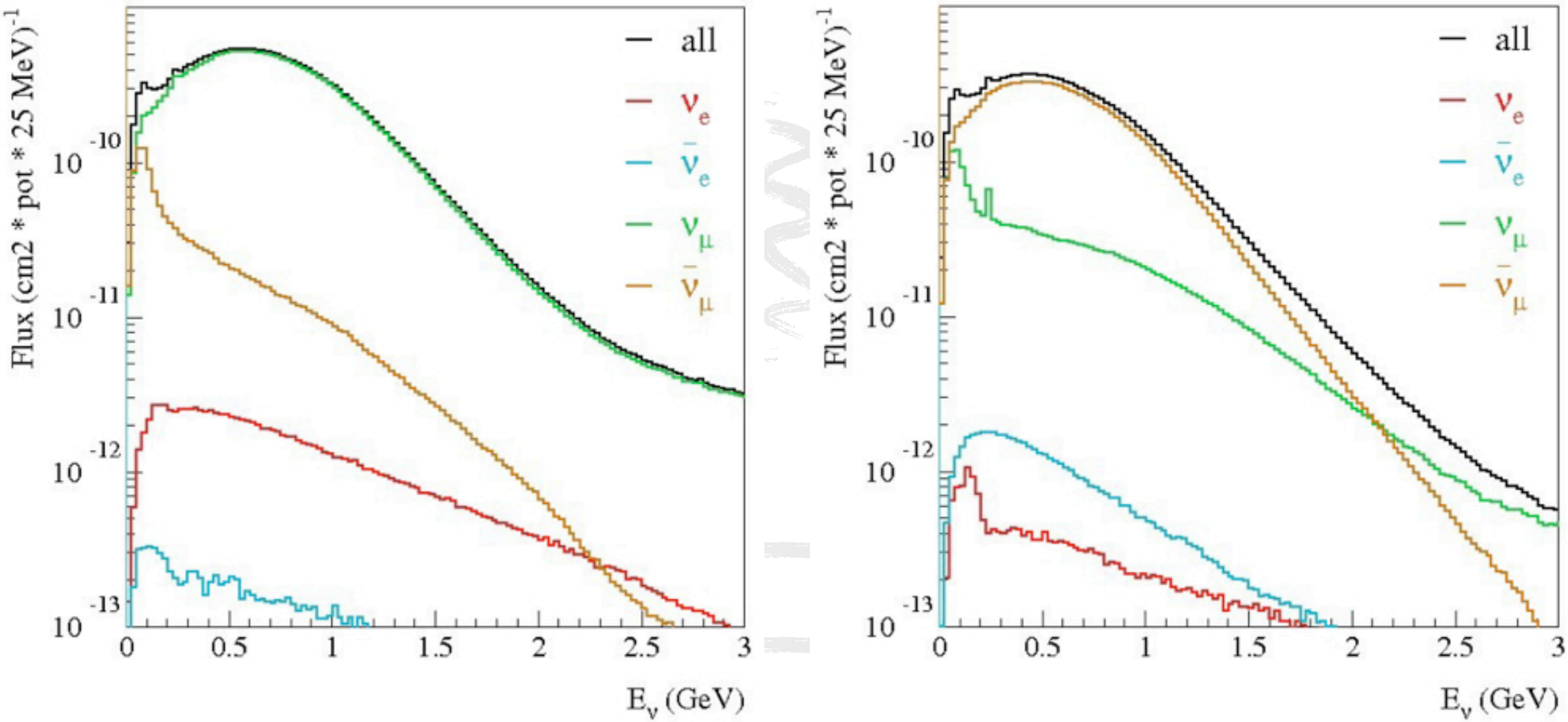
flavour — mass



$$\mathbf{U}=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}=\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

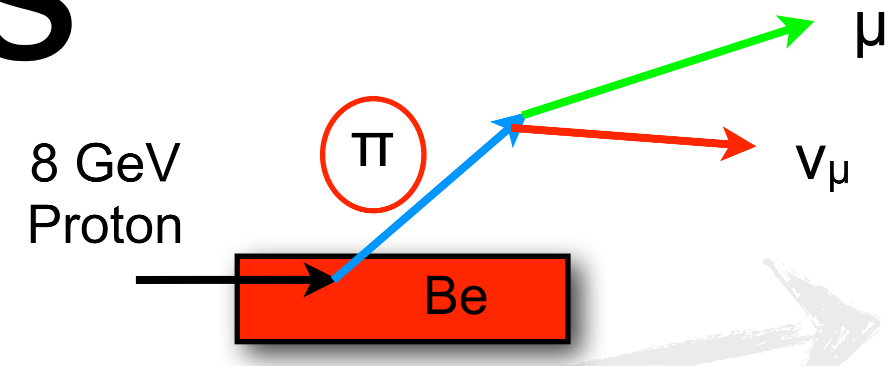
Pontecorvo, Maki, Nakagawa, Sakata

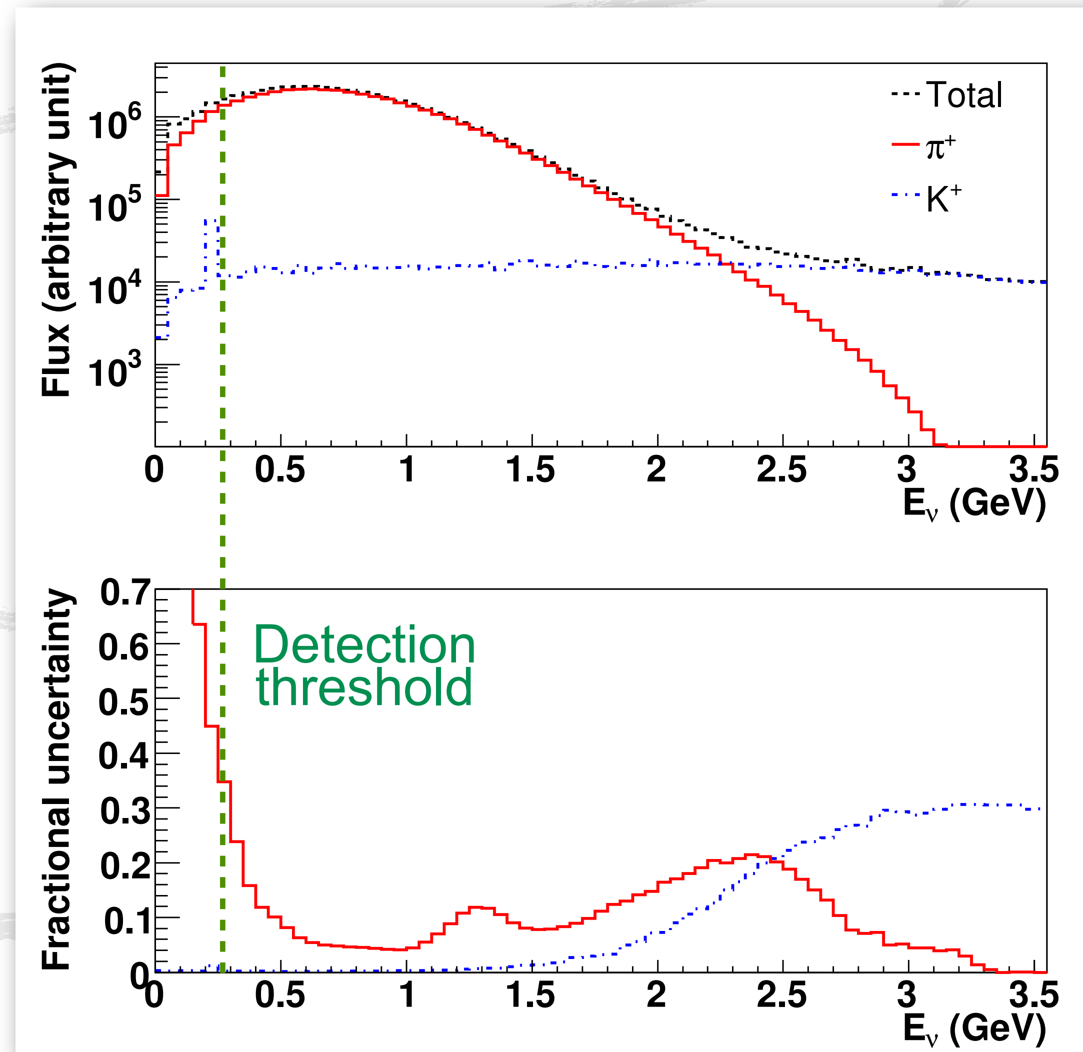
Flux Predictions

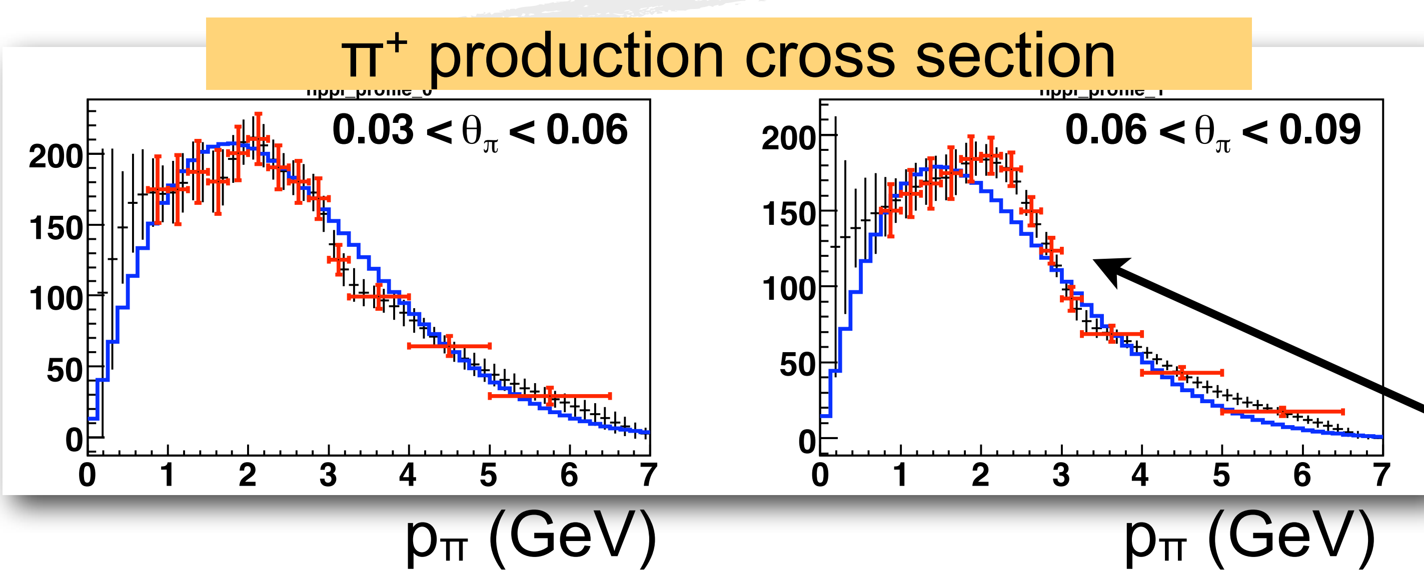


Flux uncertainties

- The dominant uncertainty: hadron production cross section from p-Be interaction.
- For $\pi^{\pm}$ production, use measurements from HARP (CERN PS214) to estimate the central values and uncertainties.





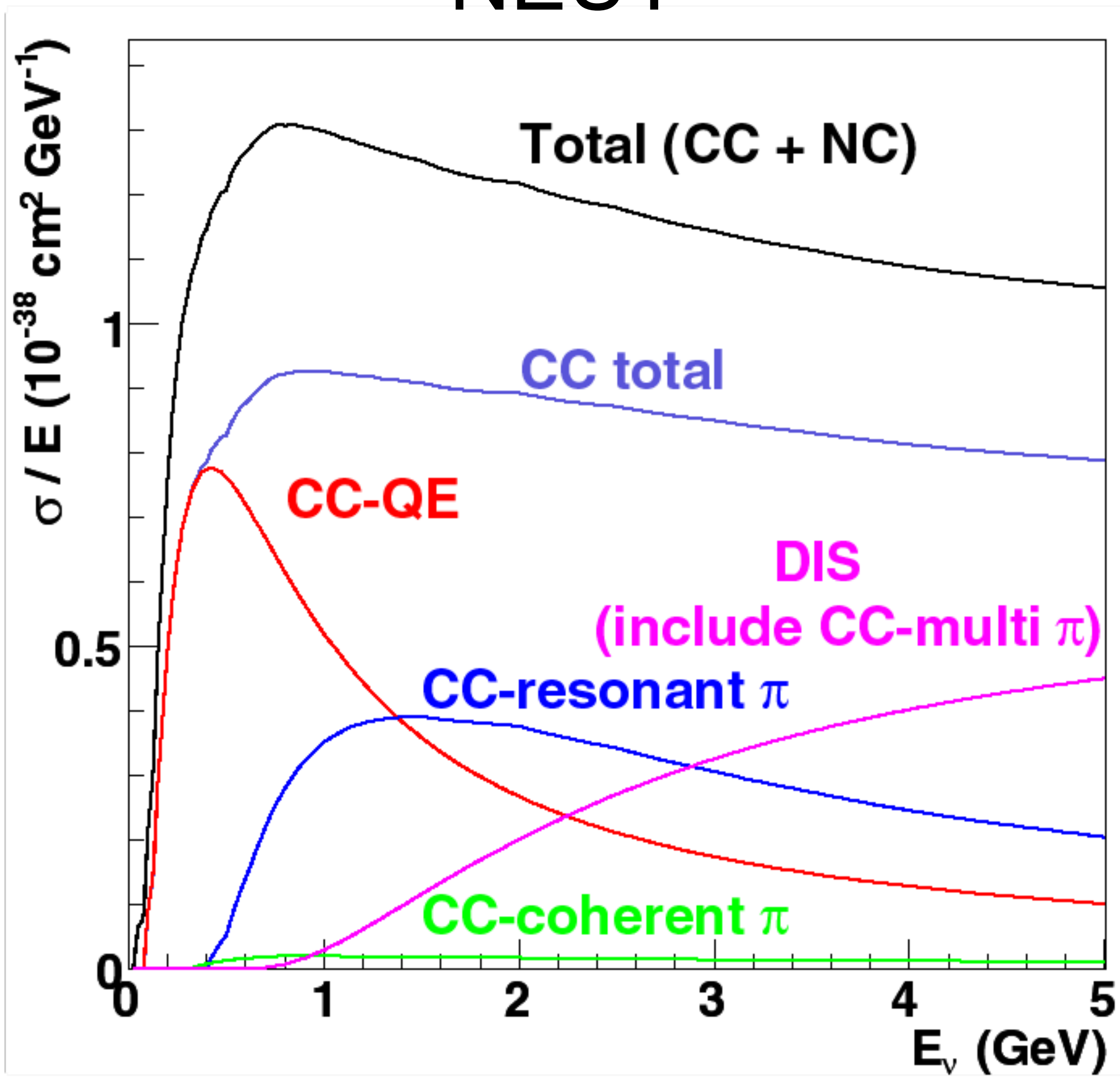


[*Eur.Phys.J.C52:29-53,2007*]

-- MC cross section (Sanford-Wang)
-- HARP data
-- Profile of spline interpolations

Neutrino Event Generator

NEUT



Nucl. Phys. B, Proc. Suppl. 112, 171 (2002)

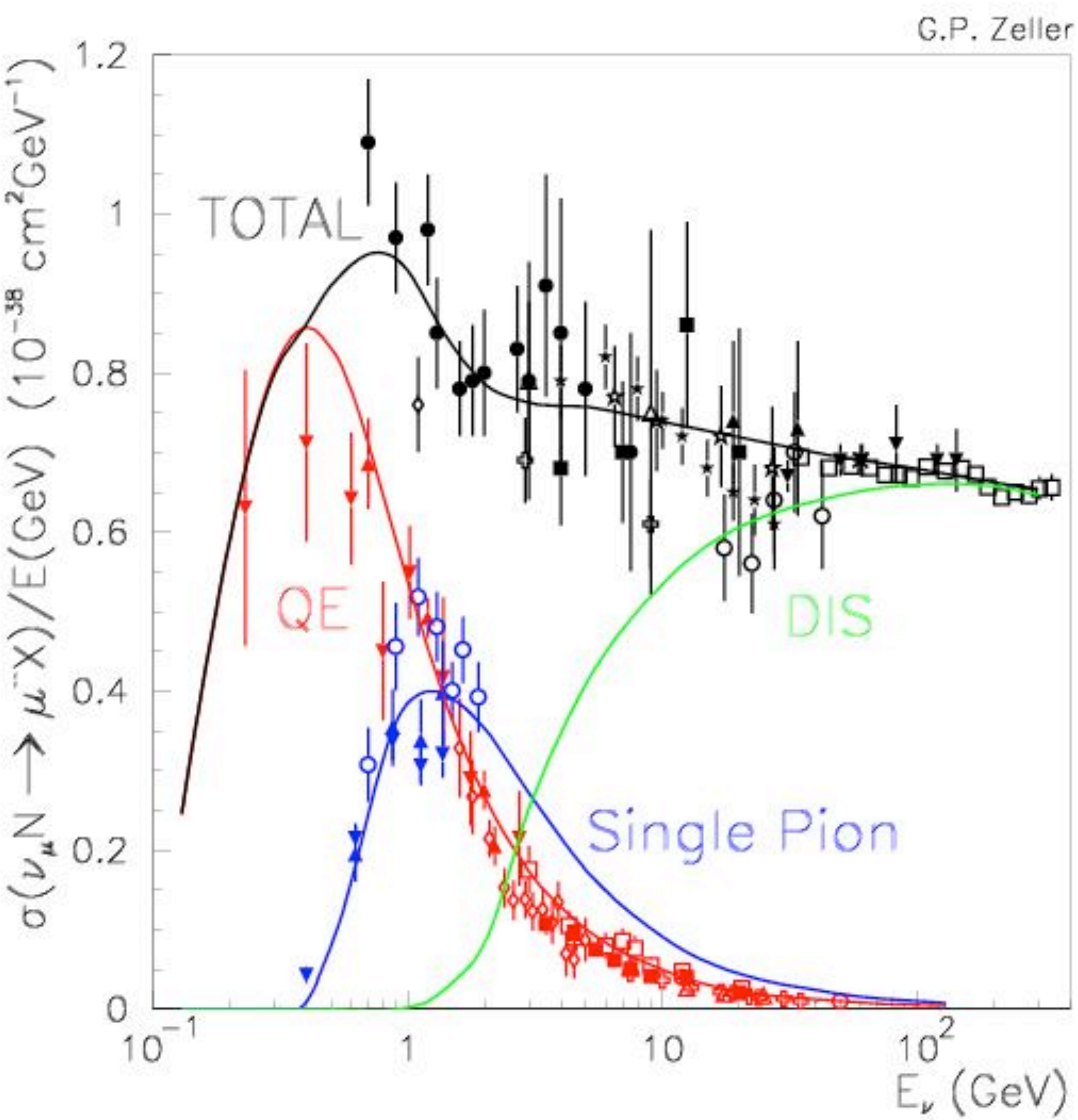
- QE
  - Llewellyn Smith, Smith-Moniz
  - M_A=1.2 (GeV/c)^2
  - P_F=217 MeV/c, E_B=27 MeV (for Carbon)
- Resonant π
  - Rein-Sehgal (2007)
  - M_A=1.2 (GeV/c)^2
- Coherent π
  - Rein-Sehgal (2006)
  - M_A=1.0 (GeV/c)^2

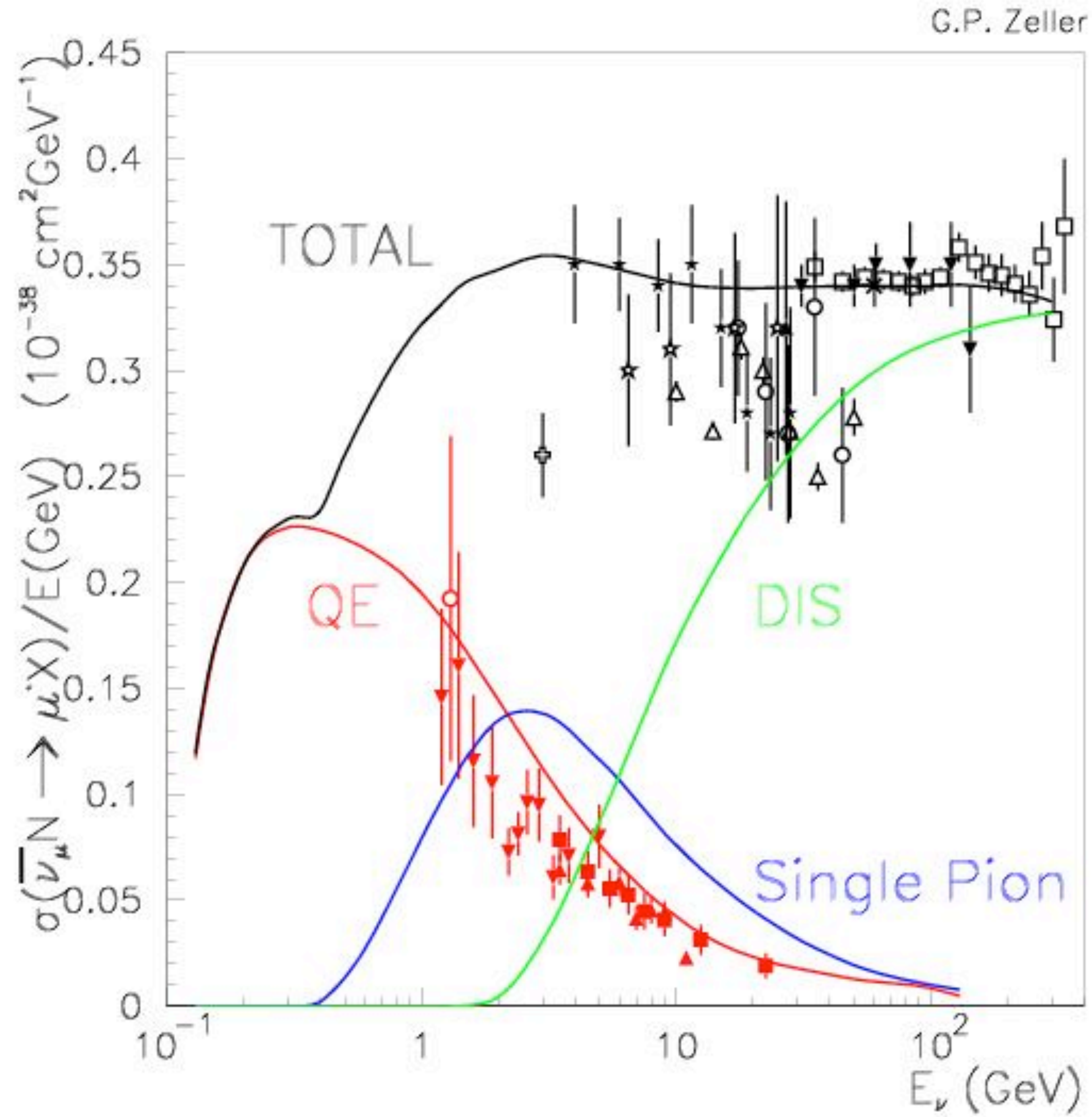
CC/NC-1π

- Deep Inelastic Scattering
  - GRV98 PDF
  - Bodek-Yang correction
- Intra-nucleus interactions

*Also use the **nuance** generator.*

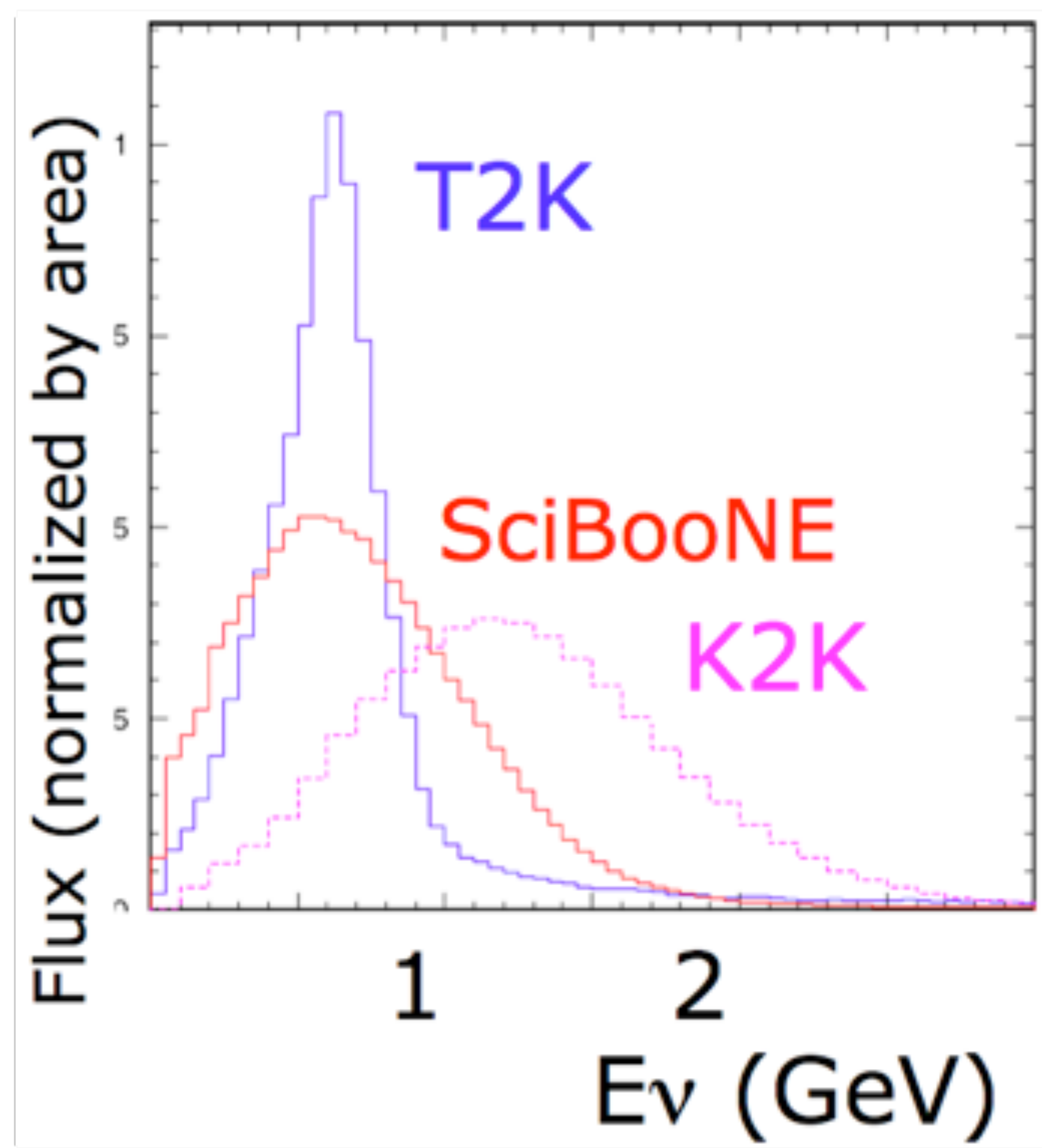
Past measurements





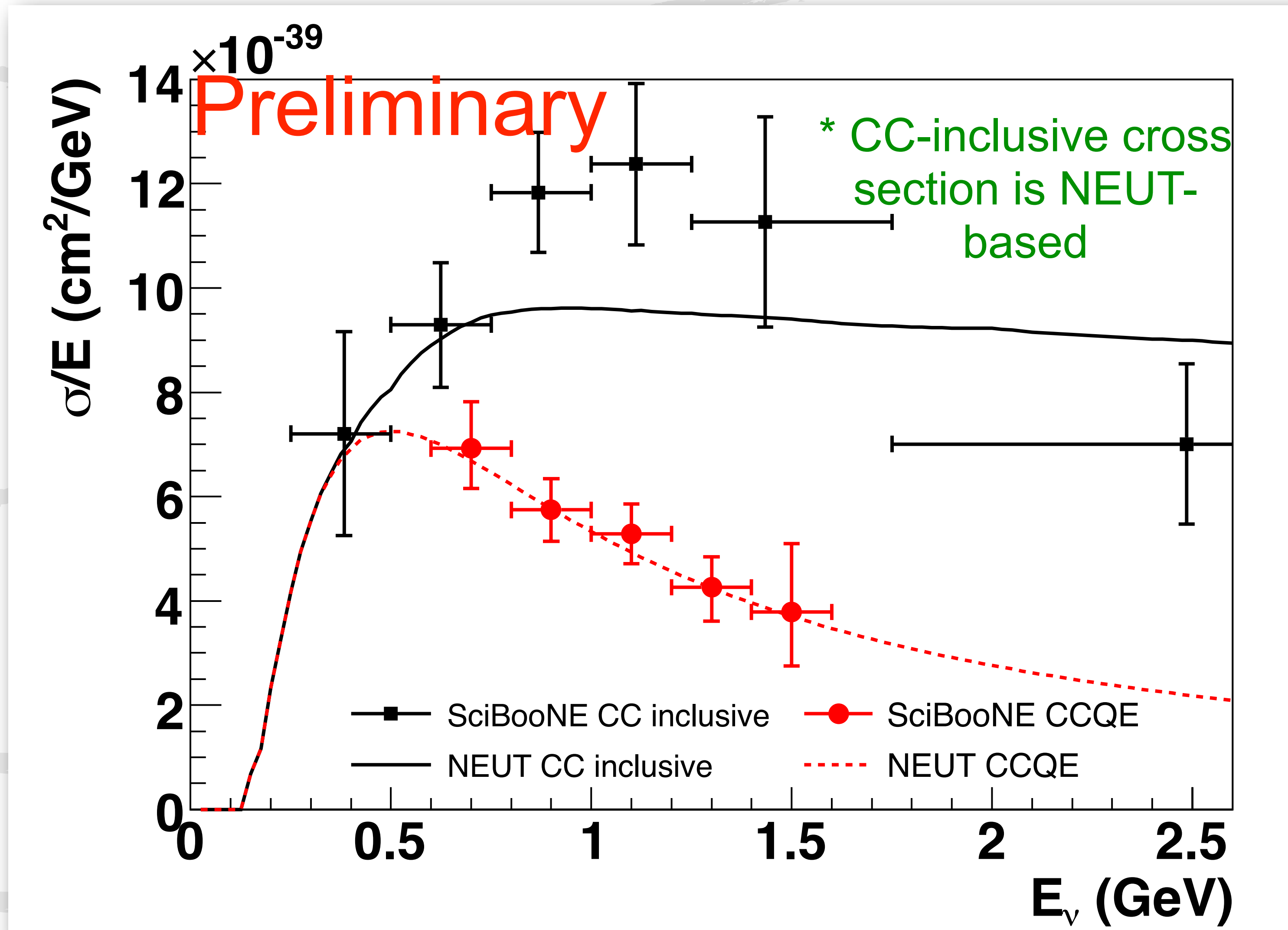
SciBooNE & T2K

- Very similar neutrino energy between SB and T2K off axis flux
- Measurements made at SB are directly applicable to T2K!



CC-inclusive and QE cross sections

Cross section per nucleon in CH

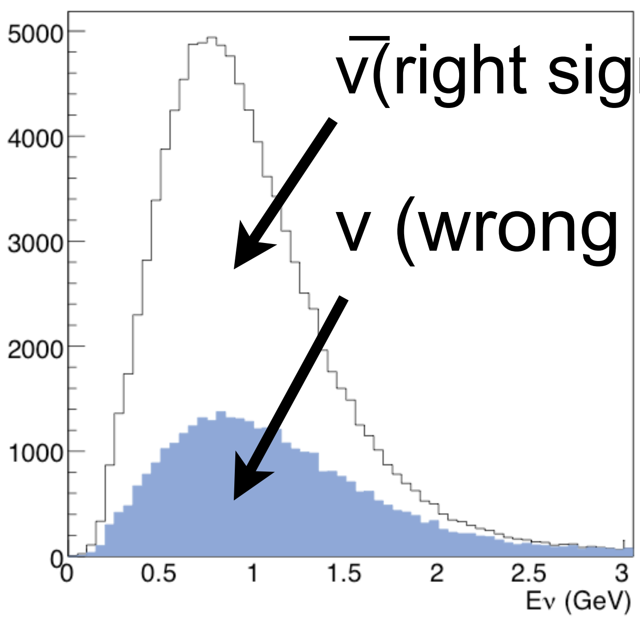


- CC-inclusive x-sec is larger, while CCQE is roughly consistent to NEUT.
  - Larger CC-1π x-sec?
  - Mismodeling of the FSI?
- Work to do:
  - CC-1π measurements
  - **Comparison with NUACNE etc. (different FSI model)**
  - **Comparison with MiniBooNE (different efficiency for p/π)**

Allows tuning of neutrino interaction model in the 1 GeV region including the FSI

Right Sign $\bar{\nu}$ CC-QE

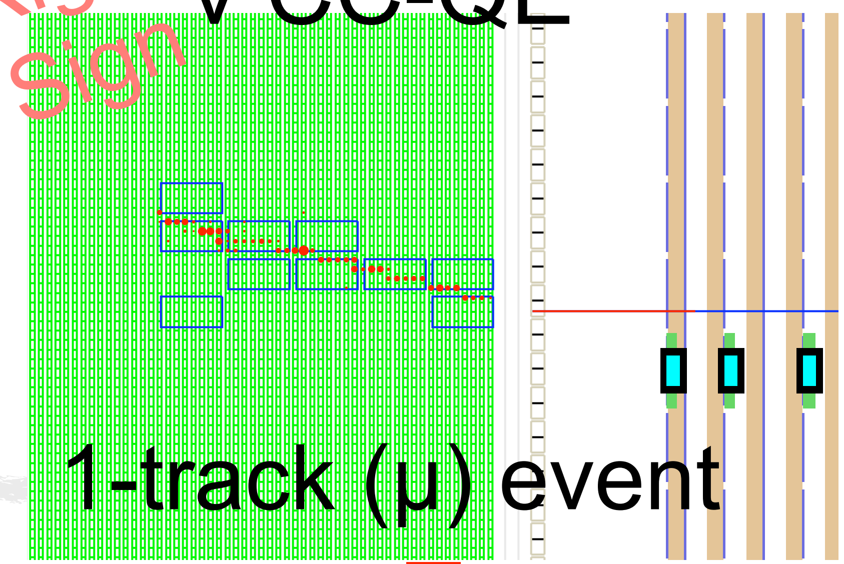
Wrong Sign ν CC-QE



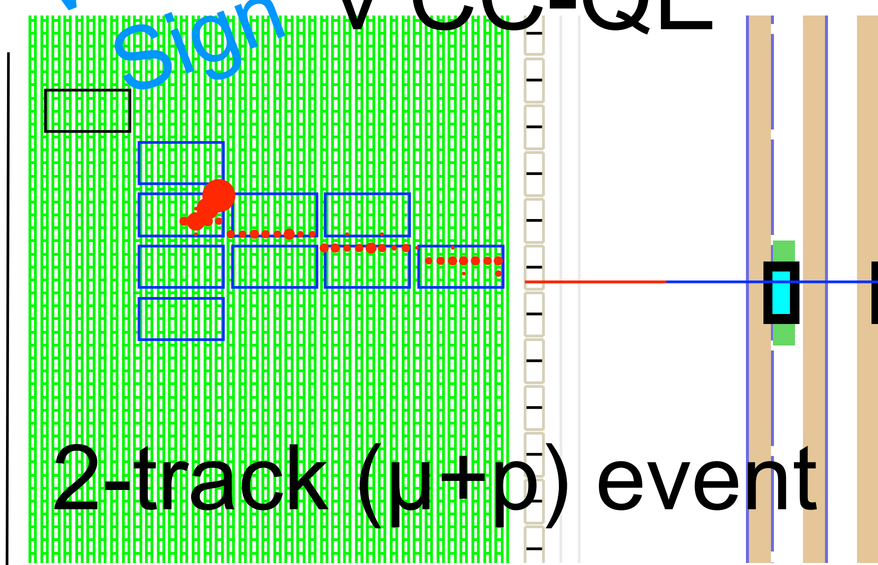
$\bar{\nu}$(right sign)

ν (wrong sign)

ν (wrong sign) ~30% background in MRD stopped sample



1-track (μ) event



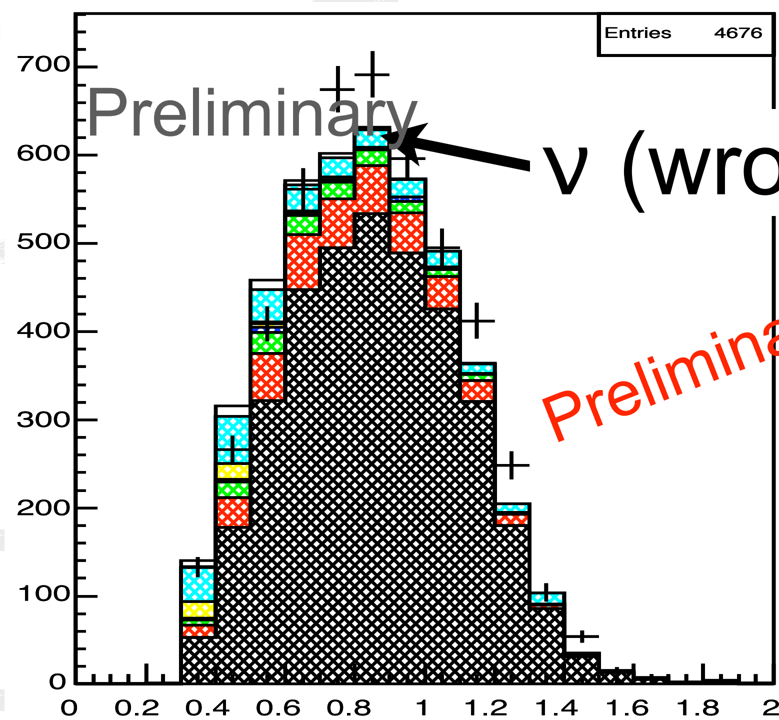
2-track (μ+p) event

~90% $\bar{\nu}$ purity

($\bar{\nu}$ CC-QE: 80%)

~90% ν purity

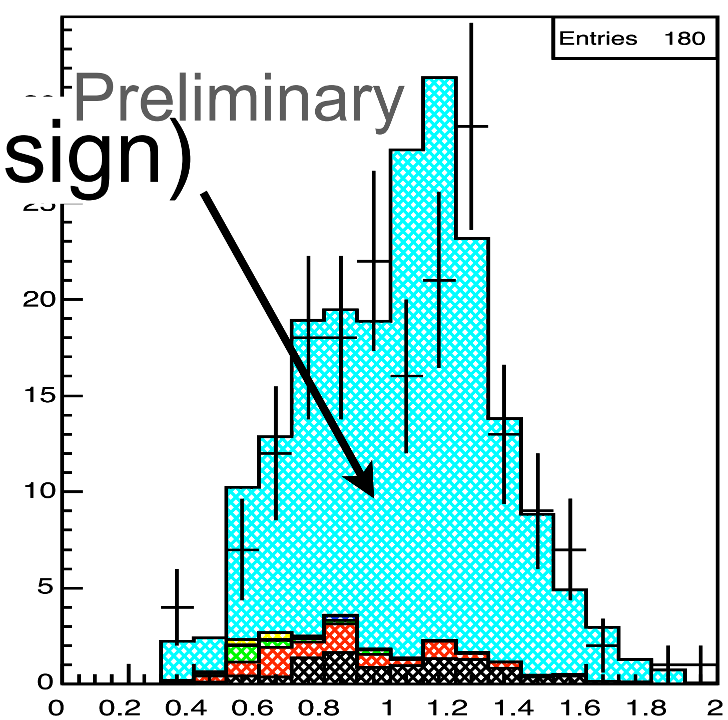
(ν CC-QE: 75%)



Eν (GeV)

1-track w/o activity sample

ν (wrong sign)



Eν (GeV)

2-track QE-like sample

Appearance v. Disappearance

Testing appearance signals with disappearance measurements

$\nu_\mu \rightarrow \nu_e$ appearance

$$P(\nu_\mu \rightarrow \nu_e) = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left[1.27\Delta m^2_{41}\frac{L}{E}\right]$$

ν_e disappearance

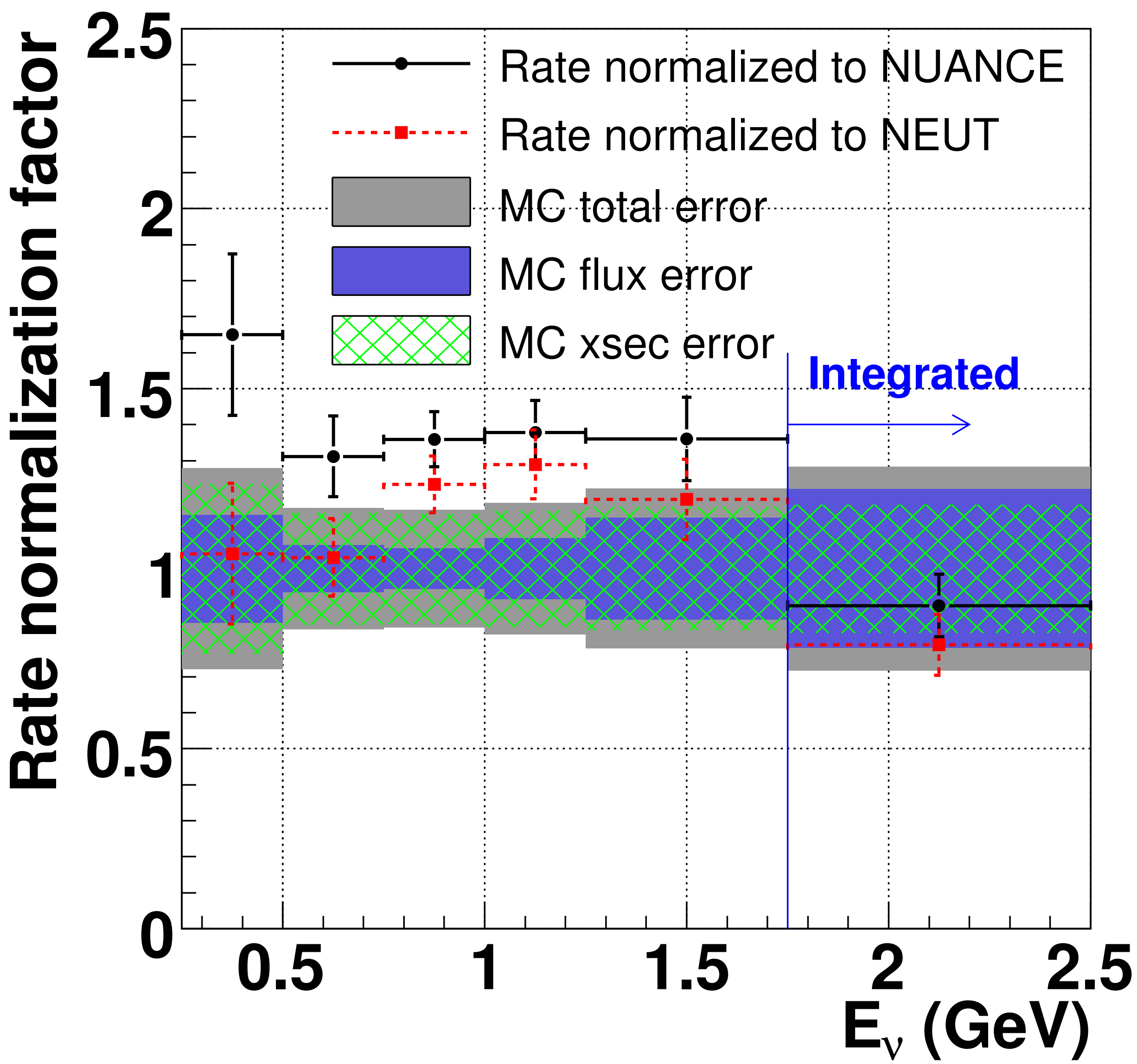
$$P(\nu_e \rightarrow \nu_x) = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2) \sin^2\left[1.27\Delta m^2_{41}\frac{L}{E}\right]$$

ν_μ disappearance

$$P(\nu_\mu \rightarrow \nu_x) = 1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2) \sin^2\left[1.27\Delta m^2_{41}\frac{L}{E}\right]$$

$\nu_\mu \rightarrow \nu_e$ appearance probability can be constrained by ν_e and ν_μ disappearance measurements.

CC interaction rate



- Extract CC interaction rate

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

normalisation factor (f_i); predicted # of events ($\mathcal{N}_i^{pred}$); Purity (P_i); Efficiency (ϵ_i)

- This is product of (flux) x (cross-section)

Direct input for this joint ν_μ disappearance analysis

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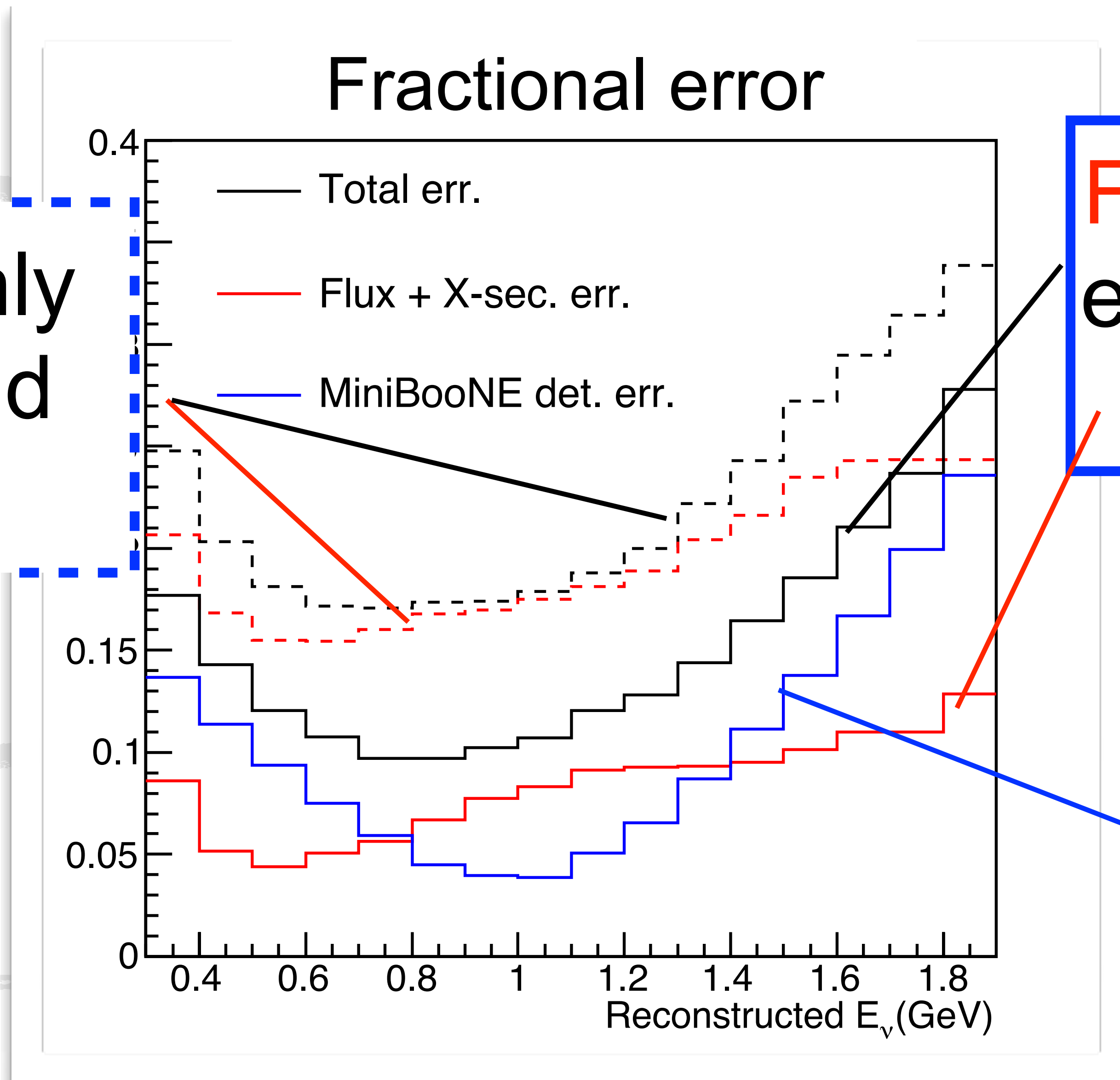
Parameter	f_0	f_1	f_2	f_3	f_4	f_5
E_ν range (GeV)	0.25 - 0.5	0.5 - 0.75	0.75 - 1.0	1.0 - 1.25	1.25 - 1.75	1.75+

MiniBooNE prediction

MiniBooNE-only Flux/X-sec and total error



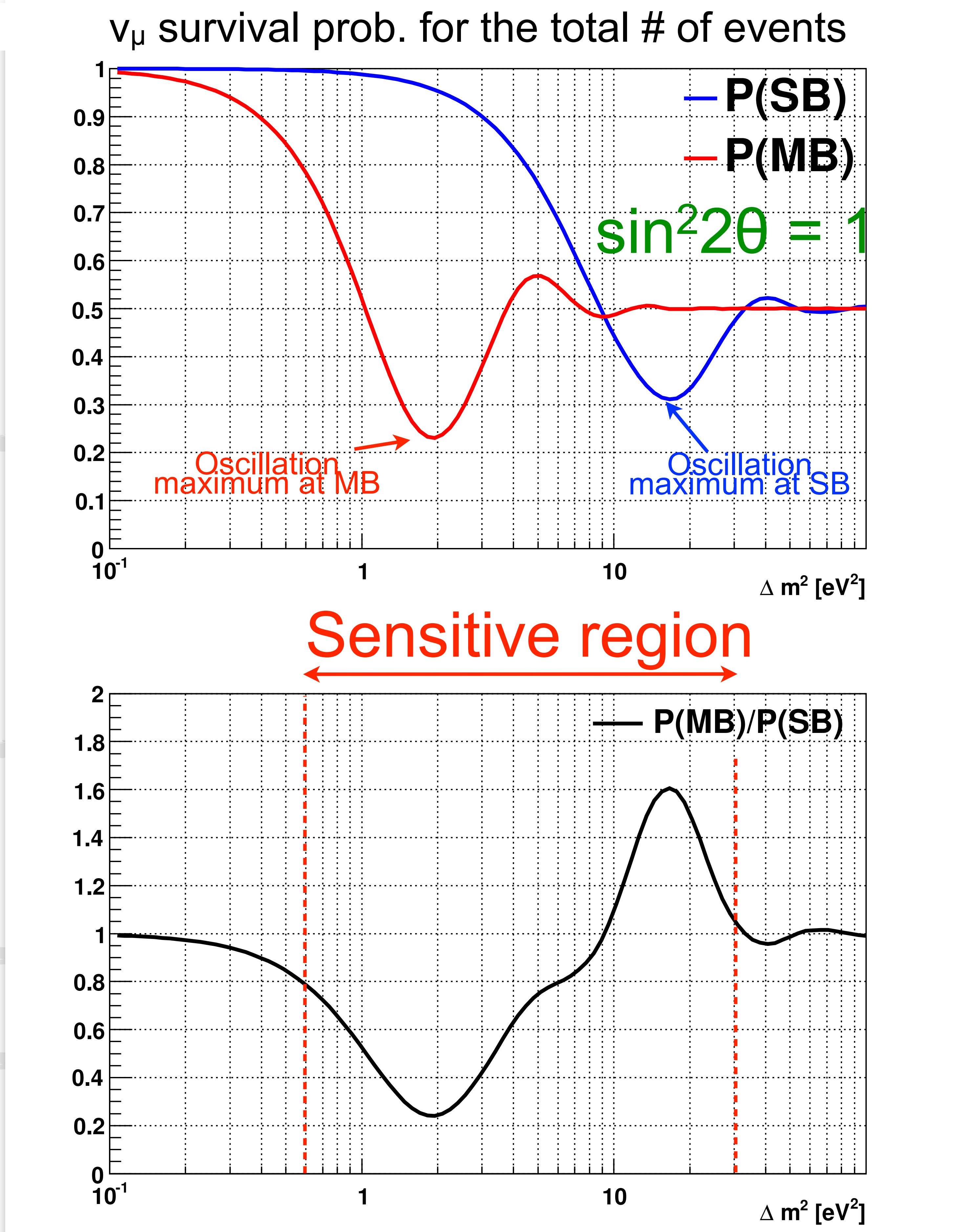
Flux/X-sec and total error constrained by SciBooNE data

MiniBooNE detector response error

Successfully reduced flux and cross section errors to the same level as the MiniBooNE detector response errors.

Oscillation probability

- Oscillation reaches maximum at the first oscillation peak,
- then washes out at high Δm^2 by integrating over neutrino energy.
- Since we compare the MB flux with SB, P(MB)/P(SB) is the expected signal.
- Sensitive to oscillations in $0.5 < \Delta m^2 < 30$ eV^2.



Spectrum fit result

Fit both MiniBooNE new and old data

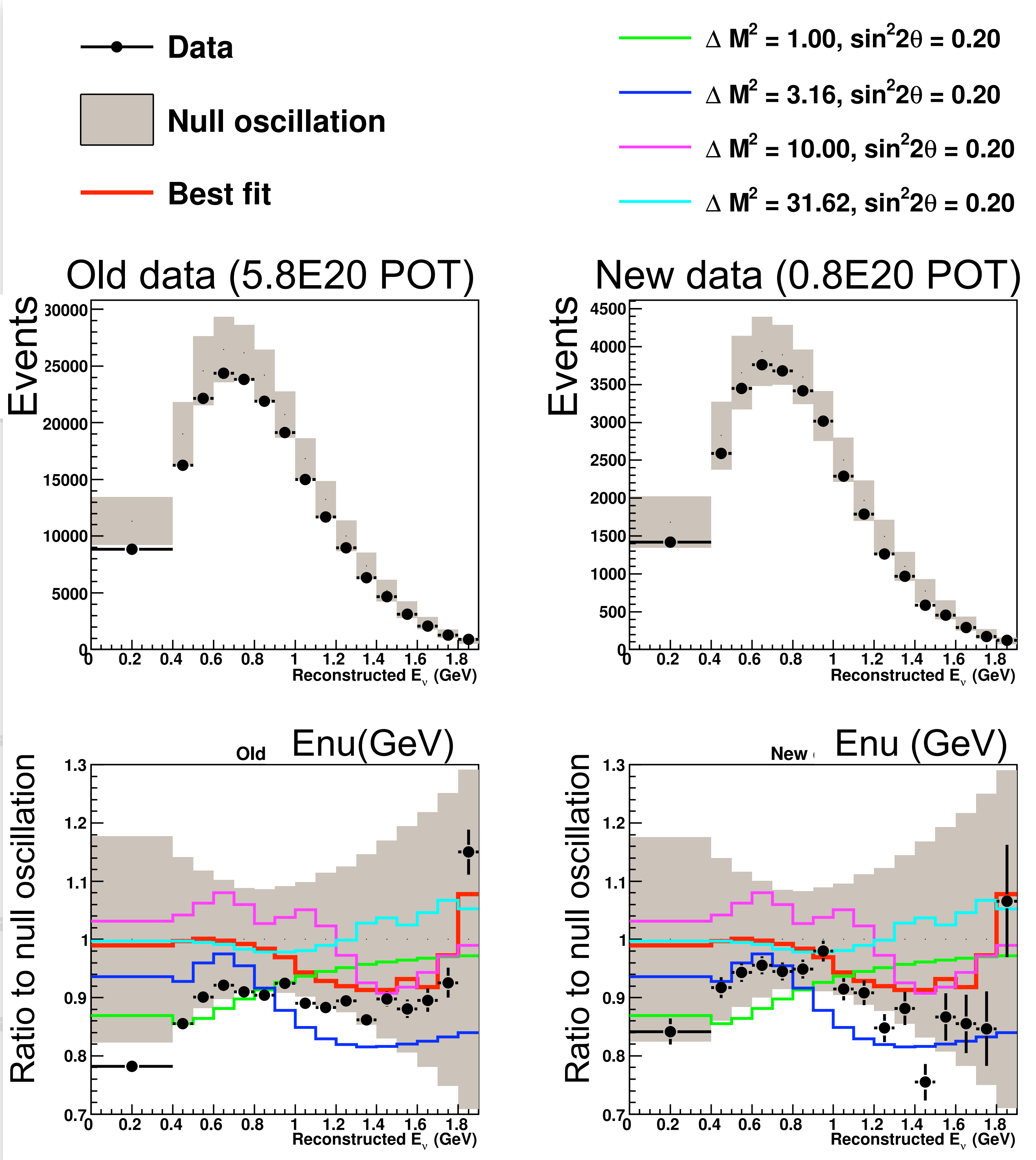
Best: Δm^2 = 41.7 eV^2, $\sin^2 2\theta$ = 0.51

χ^2(null) = 41.5/32(DOF)
χ^2(best) = 35.6/30(DOF)
$\Delta\chi^2 = \chi^2$(null) - χ^2(best) = 5.9

$\Delta\chi^2$ (90%CL, null) = 8.4
(estimated by simulation)

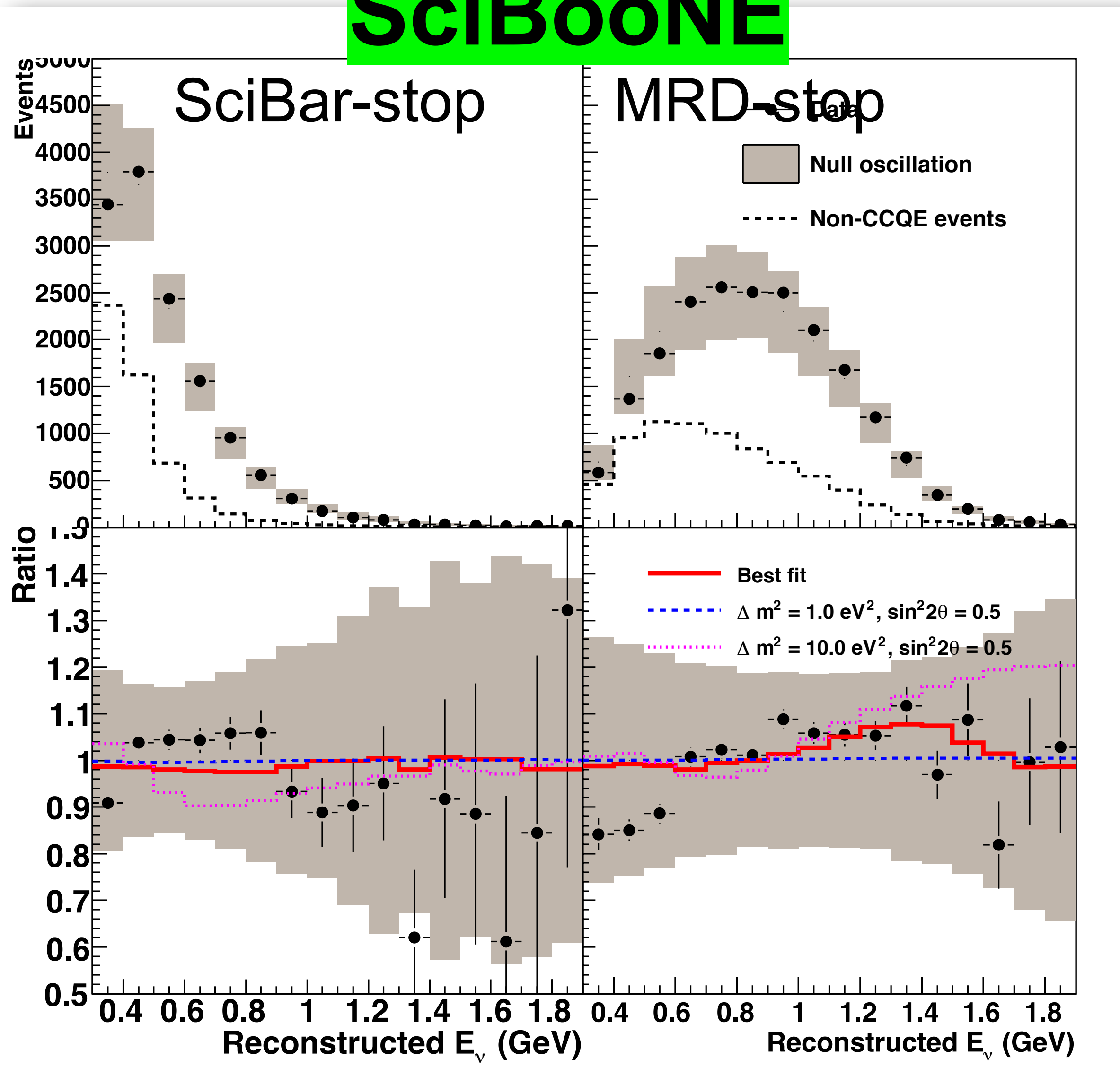
No significant oscillation signal observed.

Small data/MC discrepancy found, but doesn't match oscillation signature.

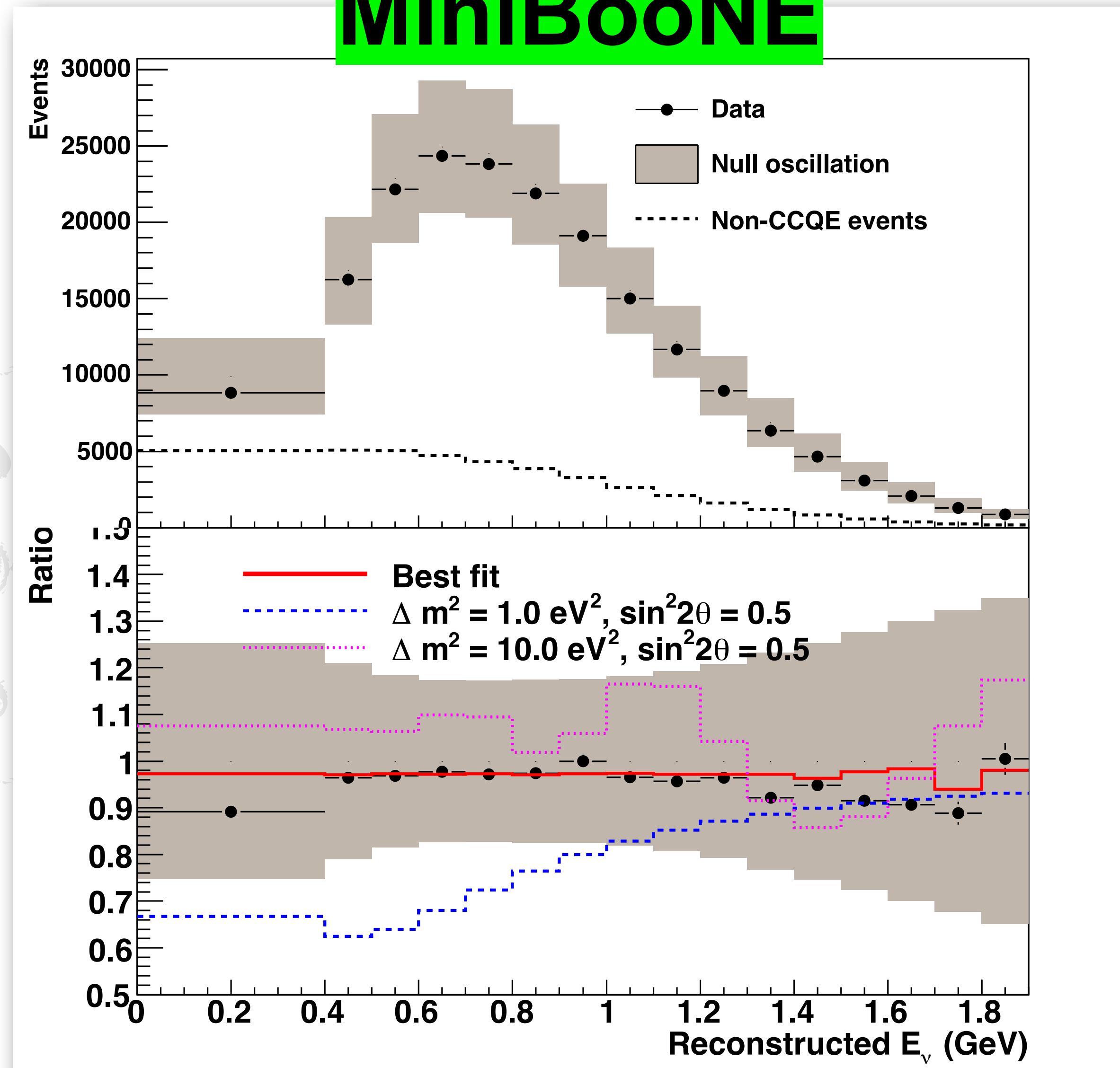


Simultaneous fit result

SciBooNE



MiniBooNE



Best: $\Delta m^2 = 43.7\ eV^2$, $\sin^2 2\theta = 0.60$

χ^2(null) = 45.1/48(DOF)

χ^2(best) = 39.5/46(DOF)

$\Delta\chi^2 = \chi^2$(null) - χ^2(best) = 5.6

$\Delta\chi^2$ (90%CL, null) = 9.3
(estimated by simulation)

No significant oscillation signal observed.