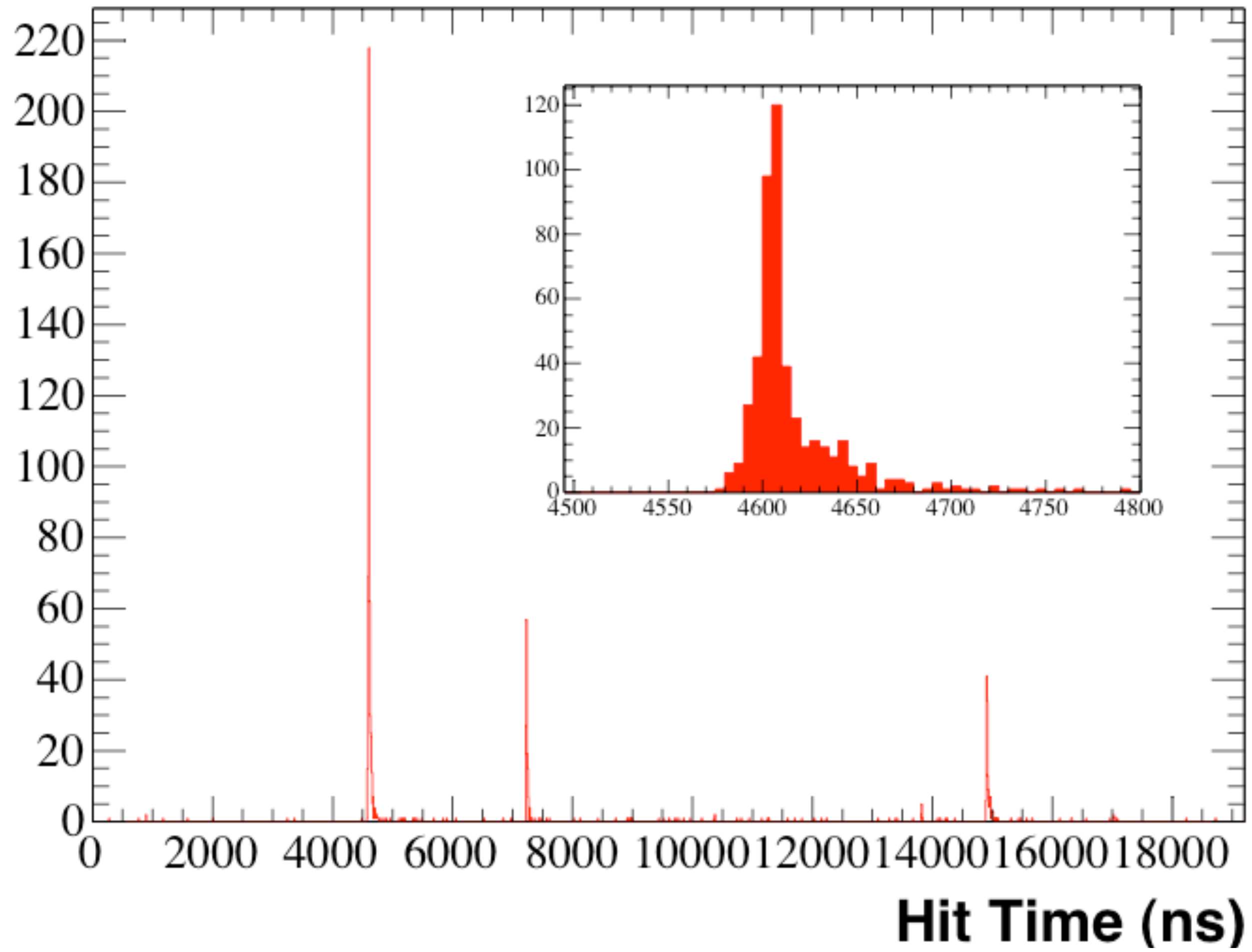


Lecture 3. $CC1\pi^+$

Lecture 3. CC1π^+

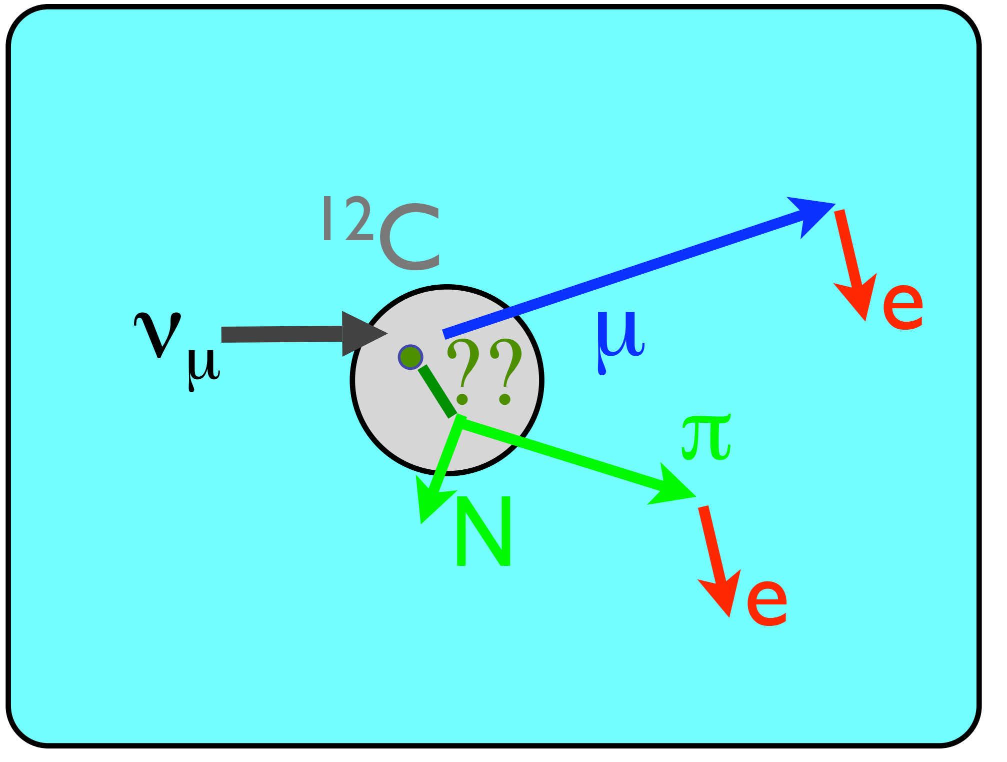
- Introduction - discussion of processes
- Event kinematics and topologies
- Experimental Searches
  - Event Selections
  - Efficiencies and Systematics
  - Extracted parameters
- Upcoming measurements

K2K (SciBar), MiniBooNE, SciBooNE

CC1π^+ Intro

- Charged current single pion production
- Anything producing a charged lepton and one pion

- Second largest cross section at 1 GeV
- Conflicting measurements of cross section
- Many models for production



CC1π^+ Intro

- Charged current single pion production
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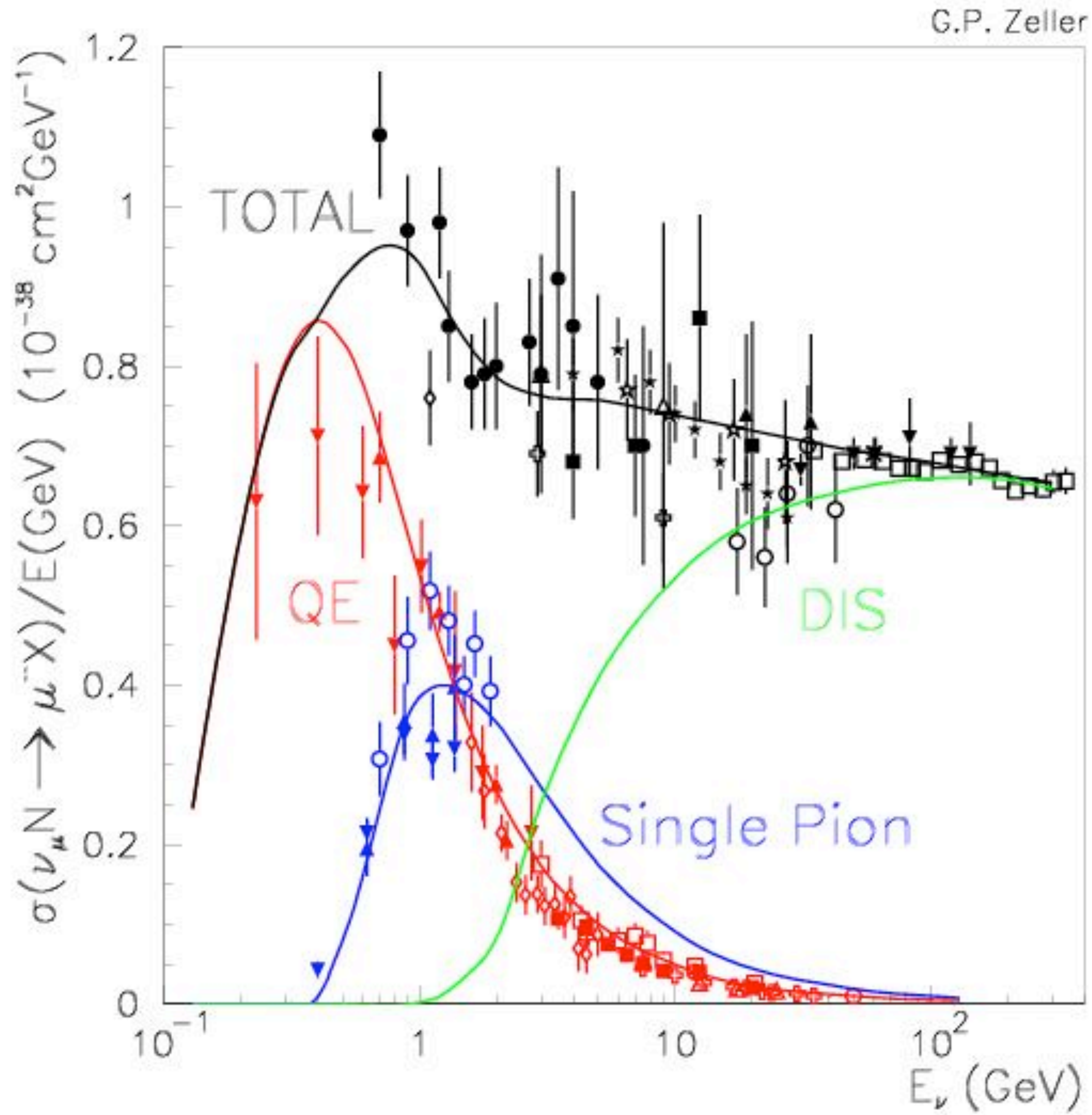
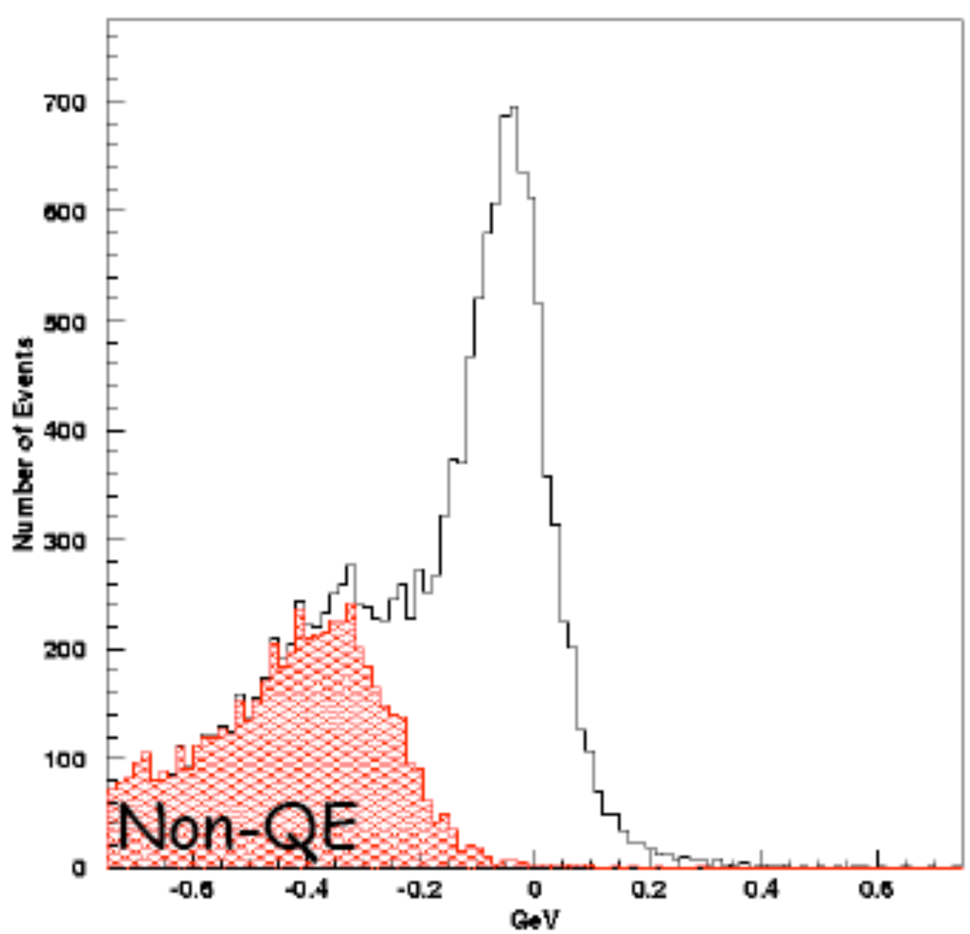


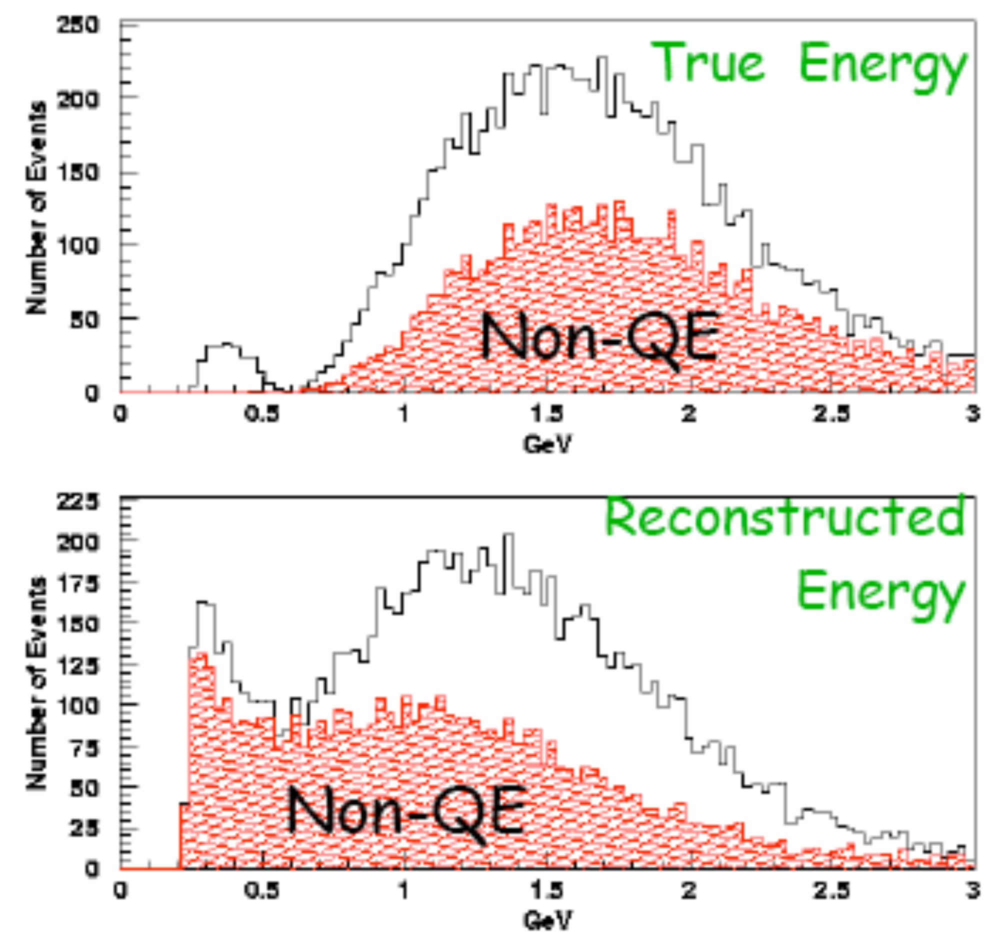
CC1π^+ and Oscillations

Non-QE interactions and E_ν Reconstruction

Example: K2K Flux MC



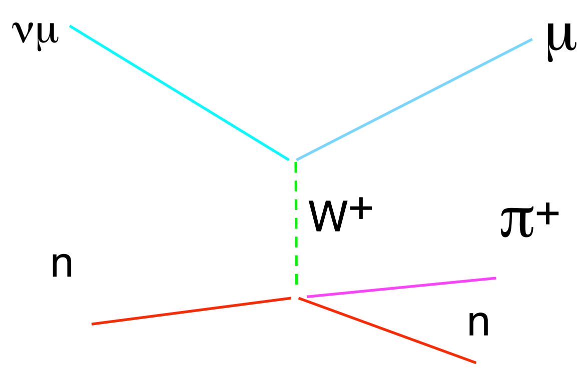
True - Reconstructed Energy

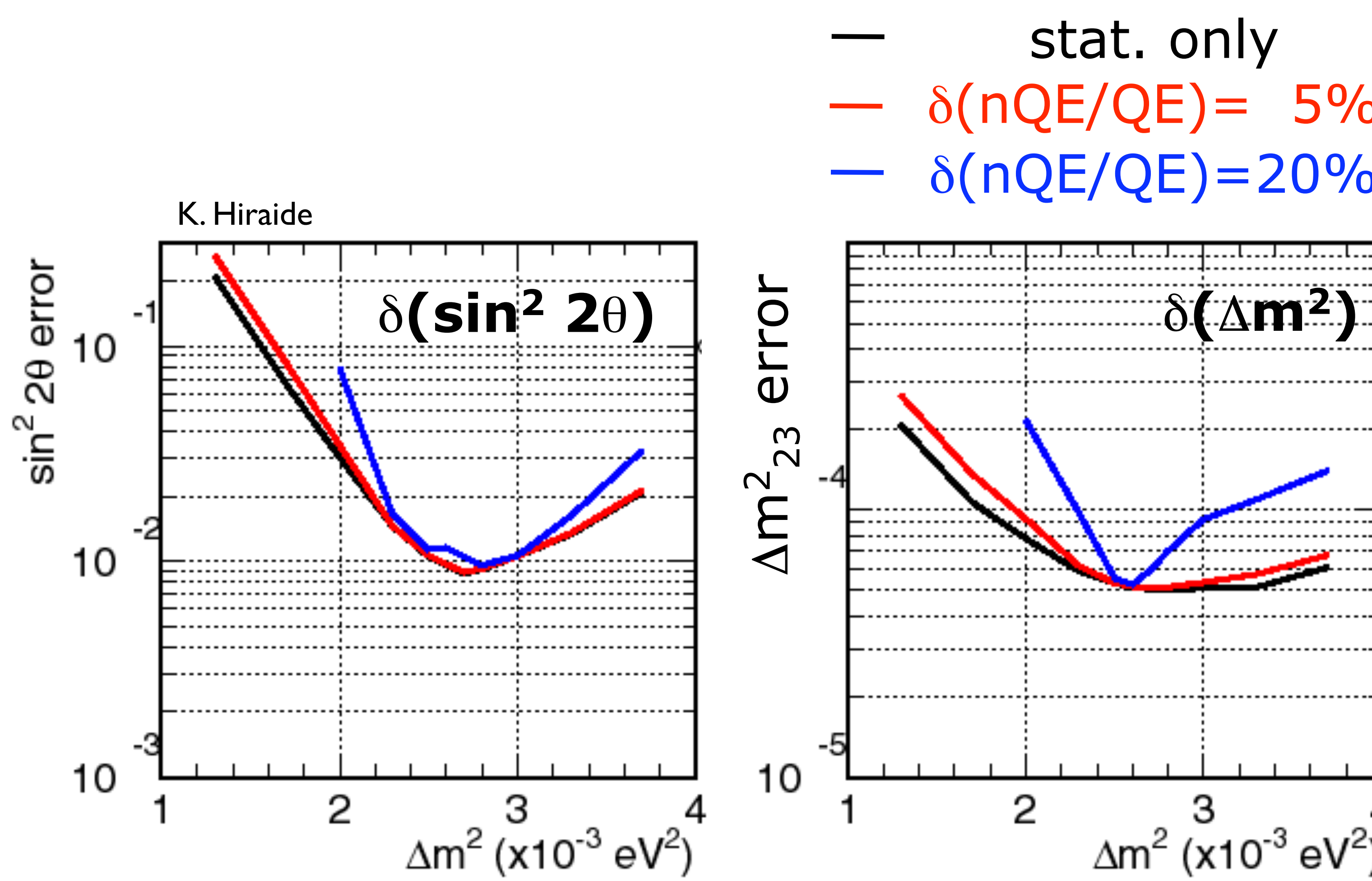


Non-QE reconstructs at low-energy in the oscillation dip!

C. Walter, NuInt07

CC1π^+ and Oscillations

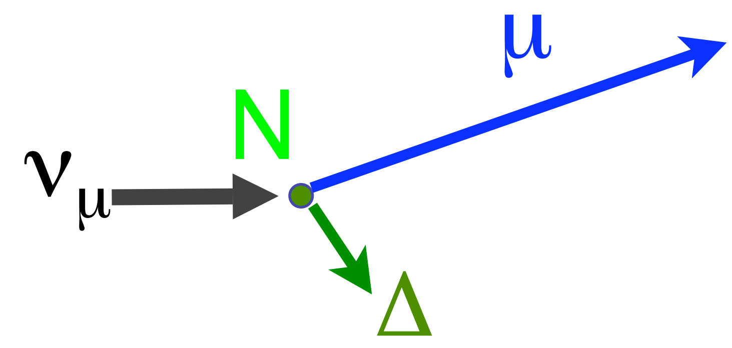




- CC1π^+ events can create *bias* in oscillation parameter extraction
- Must reduce uncertainty in $\sigma(CC1\pi^+)$ from 20% to 5% for T2K

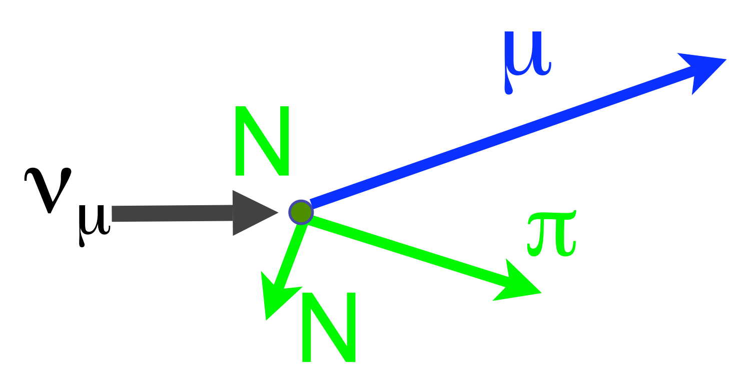
CC1π⁺ Reconstruction

- Two approaches to neutrino energy reconstruction



$$E_\nu^{QE} = \frac{1}{2}\frac{M_\Delta{}^2 - M_p{}^2 + 2M_pE_\mu - m_\mu{}^2}{M_p - E_\mu + \sqrt{(E_\mu^2 - m_\mu^2)}\cos\theta_\mu}$$

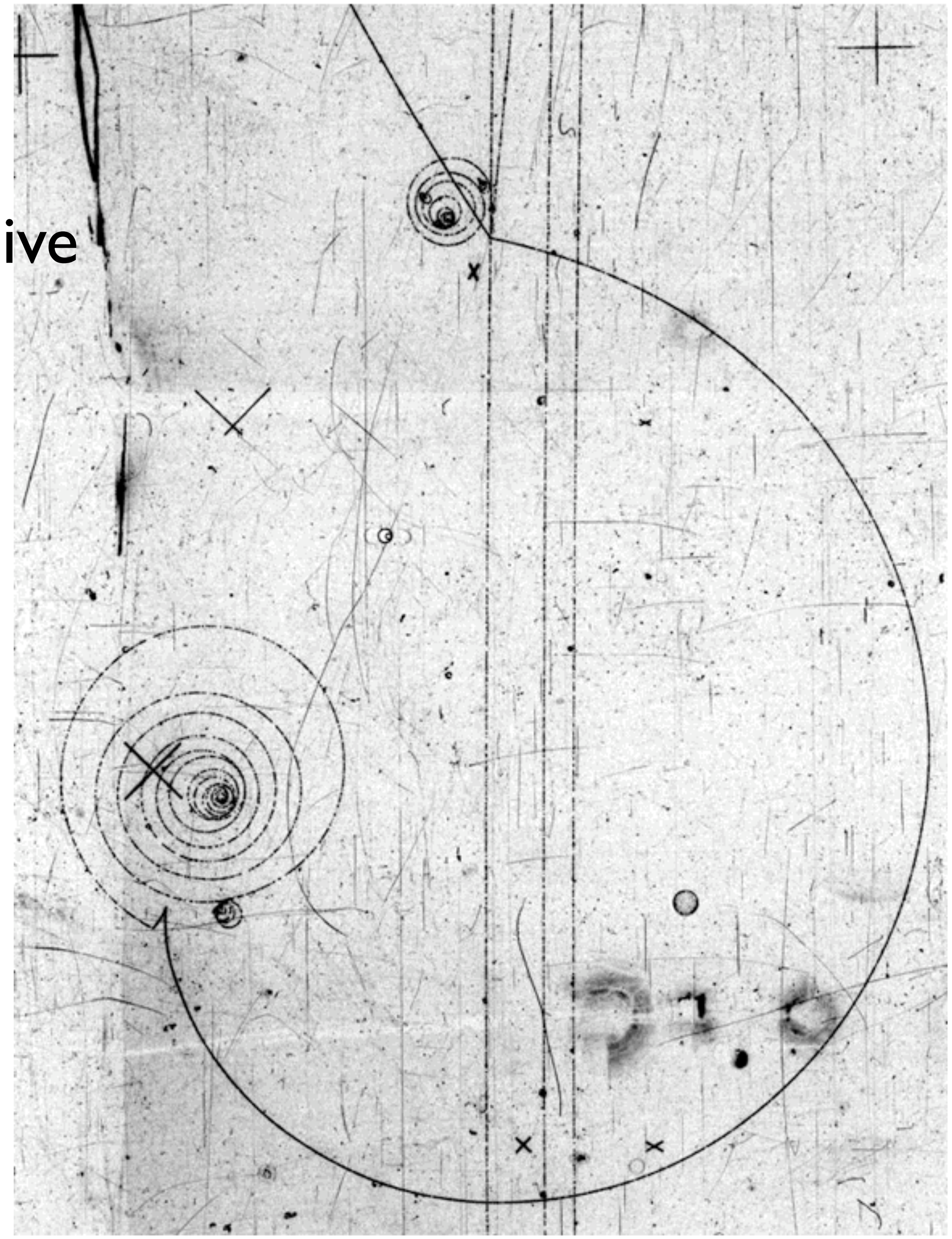
- Simple:
  - Assume QE kinematics with recoil Δ
- Better:
  - Use observed pion and muon tracks to reconstruct energy



$$E_\nu = \frac{m_\mu^2 + m_\pi^2 - 2m_N(E_\mu + E_\pi) + 2p_\mu \cdot p_\pi}{2\,(E_\mu + E_\pi - |\mathbf{p}|_\mu|\cos\theta_{\nu,\mu} - |\mathbf{p}_\pi|\cos\theta_{\nu,\pi} - m_N)}$$

CC1π^+ Agenda

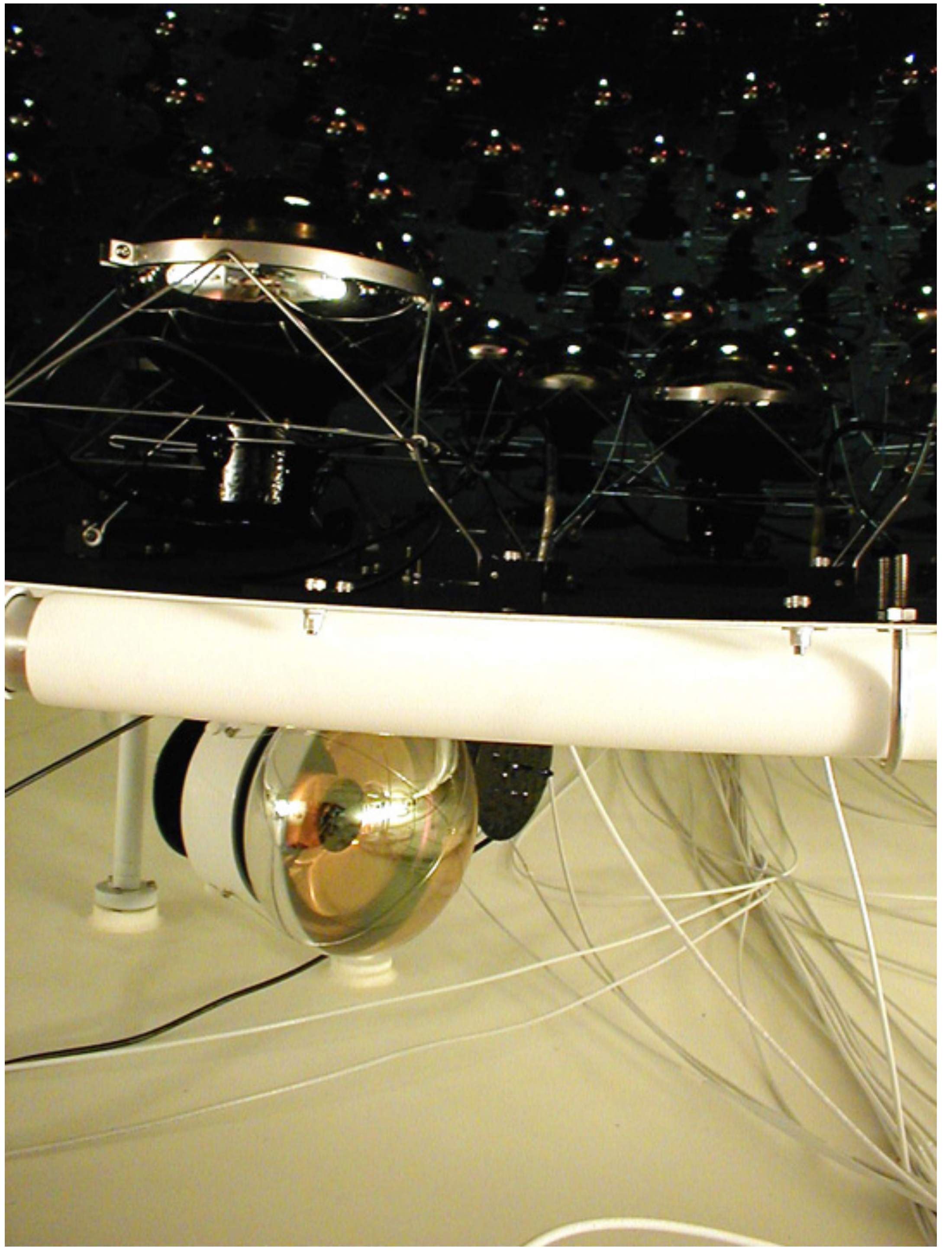
- MiniBooNE CC1π^+/CCQE inclusive
  - NUANCE
    - Rein-Sehgal Model
- K2K SciBar CC1π^+/CCQE ratio
  - NEUT
    - Rein-Sehgal
- SciBooNE & K2K SciBar CC1π^+ coherent search
  - Rein-Sehgal model
- Future Work



MiniBooNE CC1π^+ Ratio

MiniBooNE CC1π^+

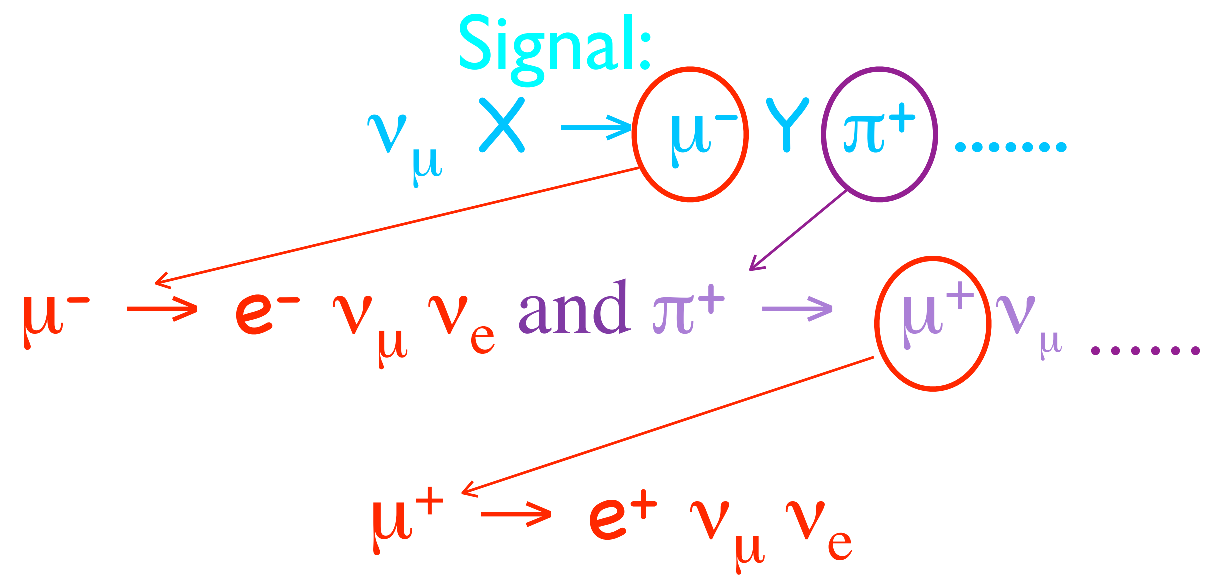
- CC1π^+/CCQE first shown in 2005
  - Since then, changed CCQE analysis and much of detector MC
- PRL draft now in circulation
  - Should be released soon

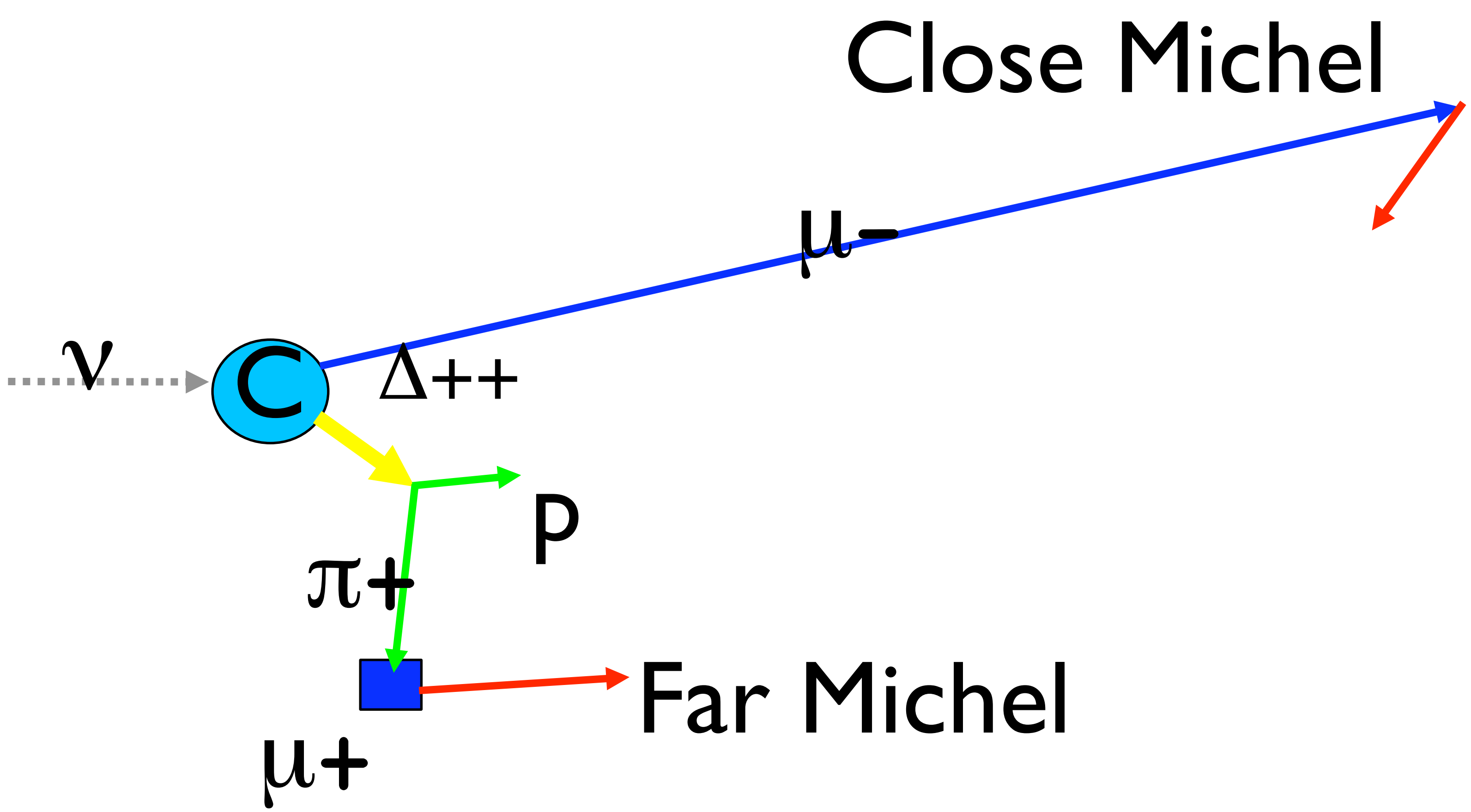


MiniBooNE CC1π^+

<u>First Level of Cuts:</u>

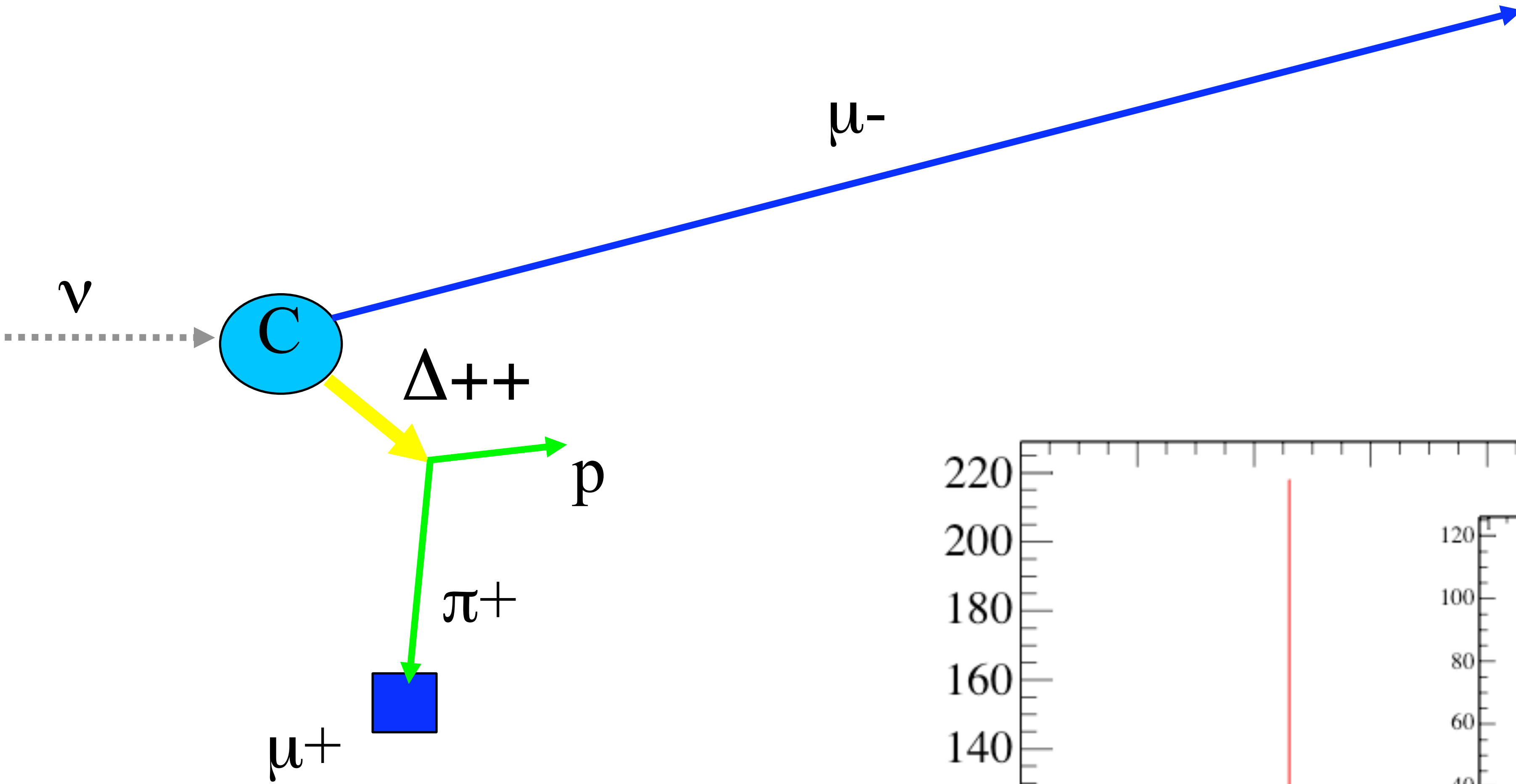
- Neutrino-Induced Event Selection Cuts
- exactly 3 sub-events
- 2nd 2 sub-events consistent with Michel e^- ($20 < N_{PMT} < 200$)

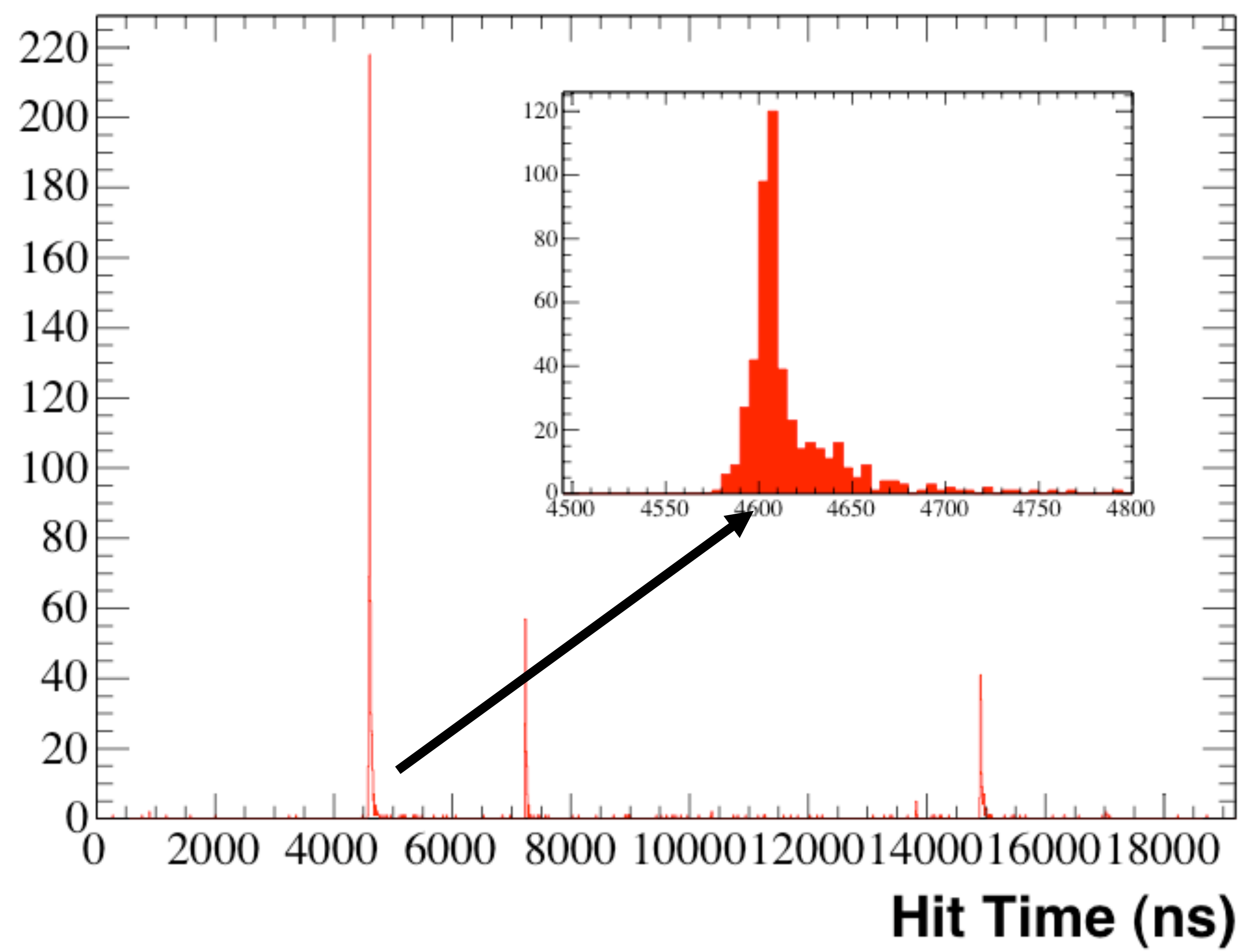




No
Final State ID
Cuts

84% purity
with 1st level
cuts,
bgnd from
Nπ and QE

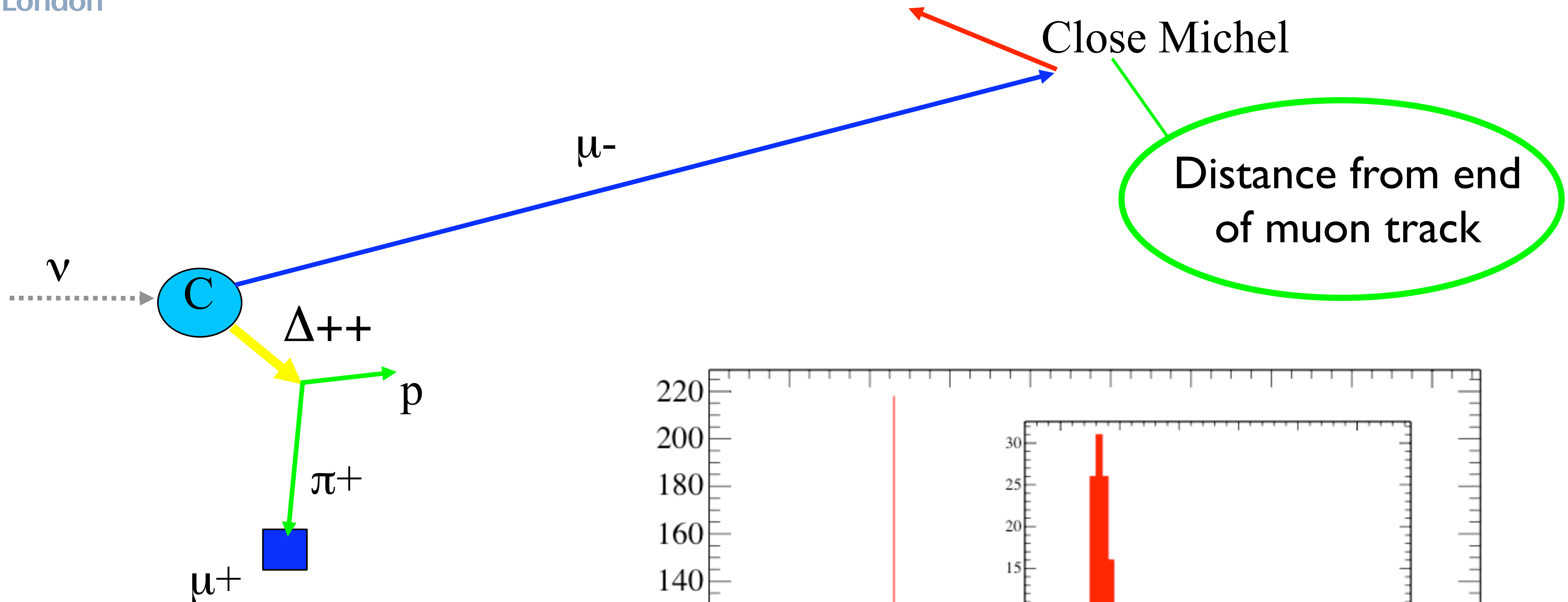


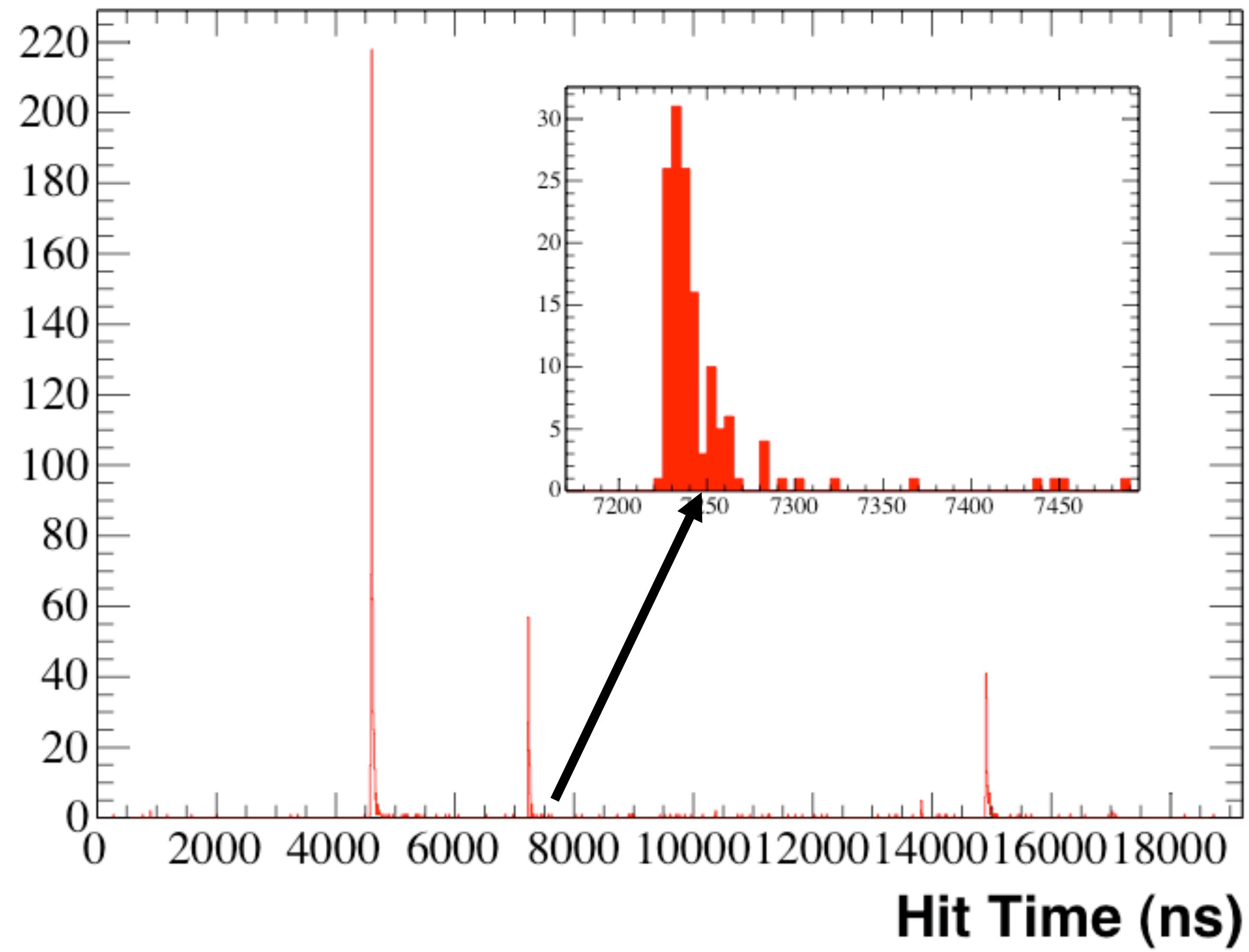


Neutrino subevent

Use these hits to reconstruct neutrino properties

Fit for muon Cherenkov ring

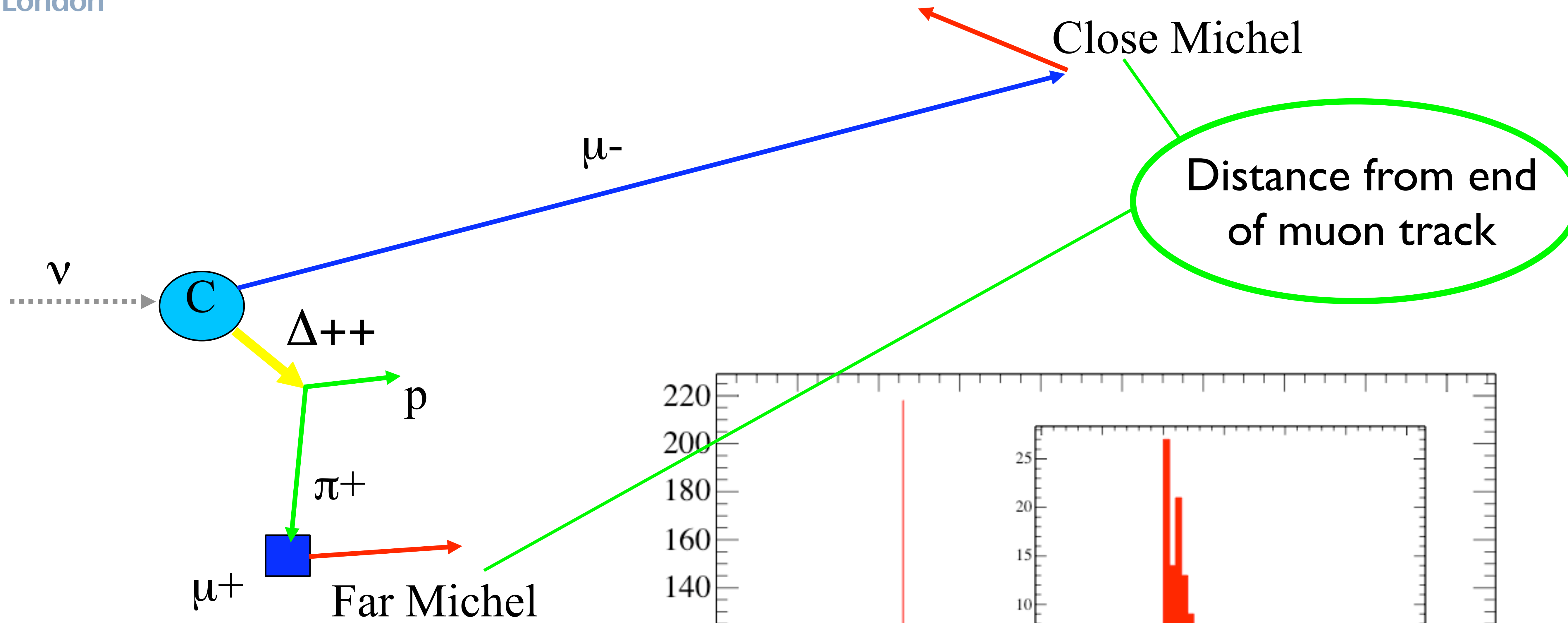


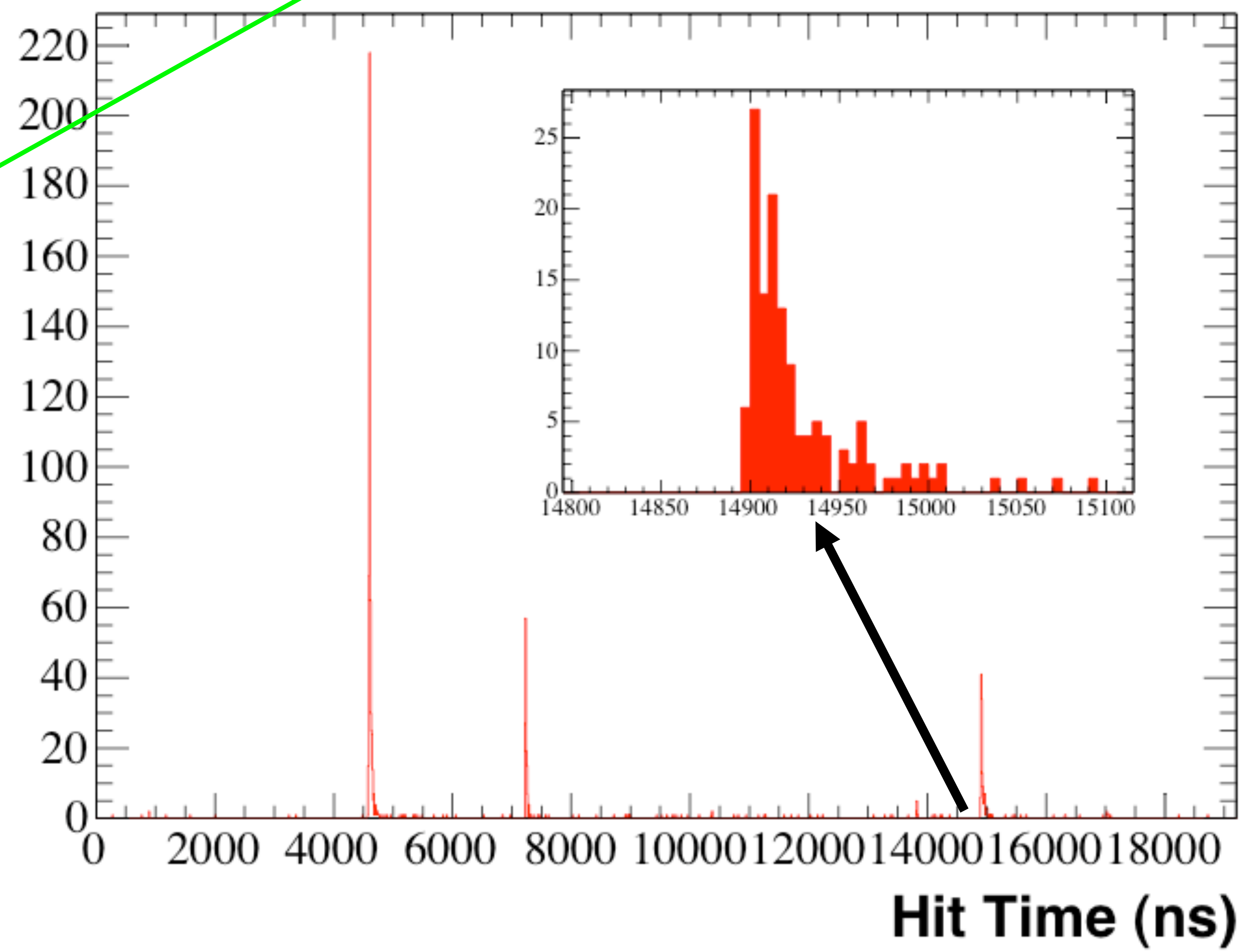


<u>1st Michel e± subevent</u>

Could be from μ- or π+(μ+) decay

In this case, I've drawn it as e-





2nd Michel e± subevent

Can use Michel subevents to help understand the neutrino subevent

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Event Selection Validation

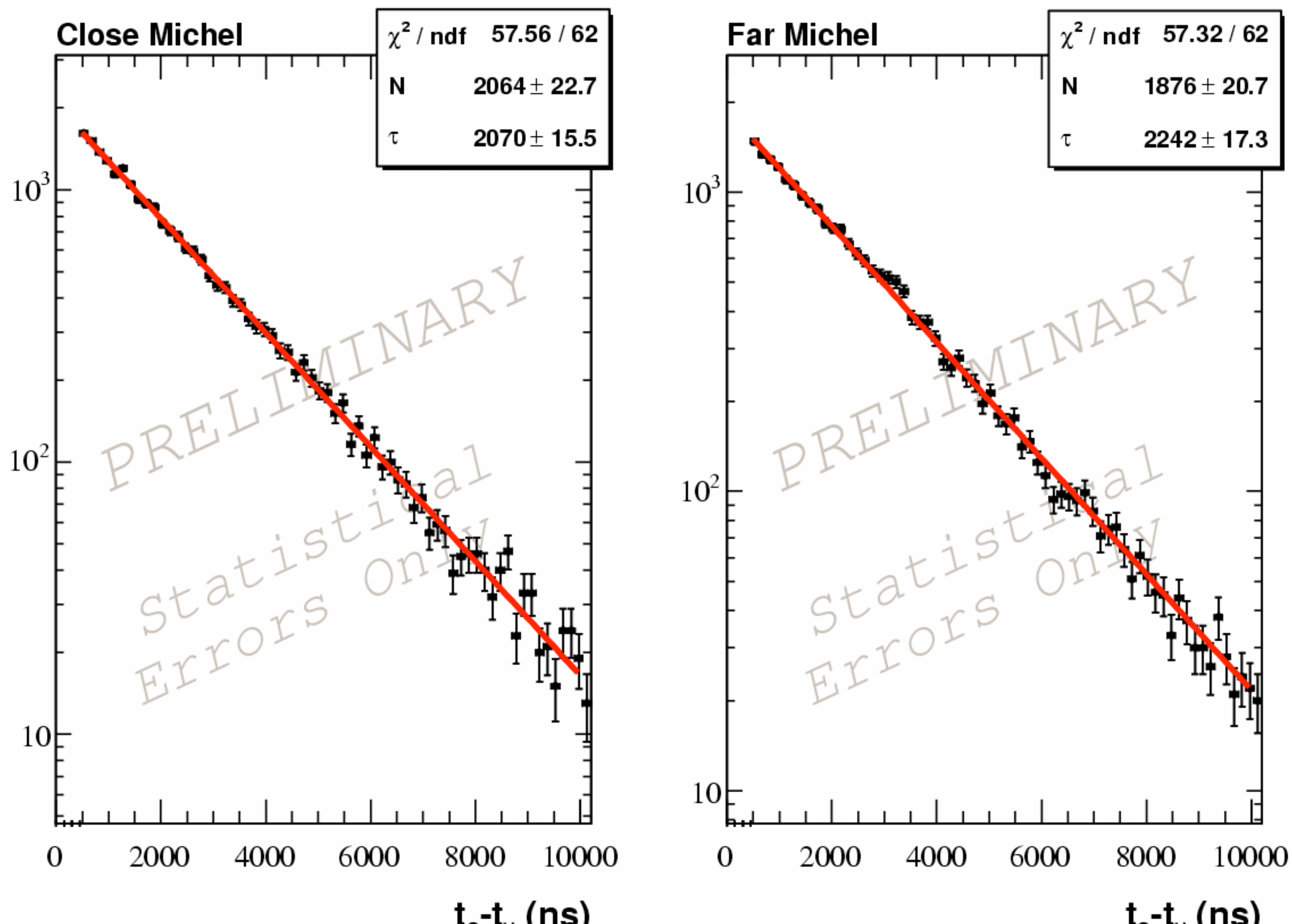
- validate CCPiP event selection with μ^+ and μ^- lifetime measurement
- separate Electrons from μ^+ and μ^- by distance to μ^- track

- close:
  μ^- capture (8%)

  expect
  $\tau = 2026 \pm 1.5$ ns
  measure
  $\tau = 2070 \pm 15.5$ ns

- far:
  μ^+: do not capture

  expect
  $\tau = 2197.03 \pm 0.04$ ns
  measure
  $\tau = 2242 \pm 17.3$ ns



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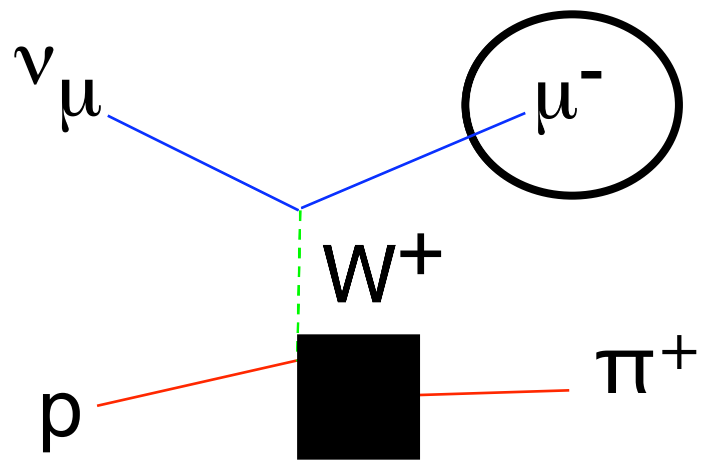
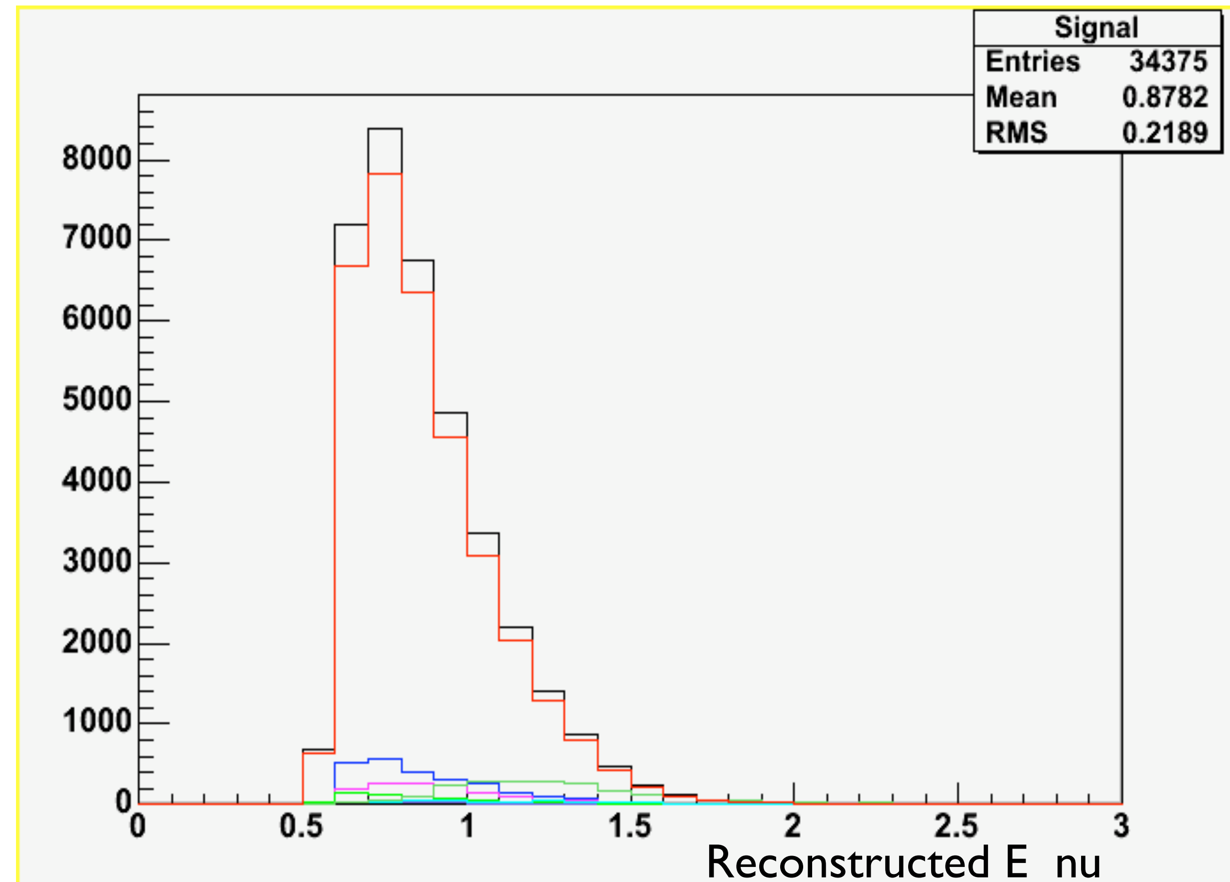
Event reconstruction



use measured μ visible energy
and angle to
reconstruct E_ν^{QE}

S. Linden



$$E_\nu^{QE} = \frac{1}{2}\frac{2m_p E_\mu + m_\Delta^2 - m_p^2 - m_\mu^2}{M_p - E_\mu + cos\theta_\mu\sqrt{E_\mu^2 - m_\mu^2}}$$

CCπ+ total	86.8%
CCπ+ resonant (red)	80.9%
CCπ+ coherent (dark blue)	5.9%
CCQE (dark green)	5.2%
Multi-pion (light purple)	3.8%
CCπ0 (light green)	1.5%
DIS (light blue)	1.0%
Other	1.6%

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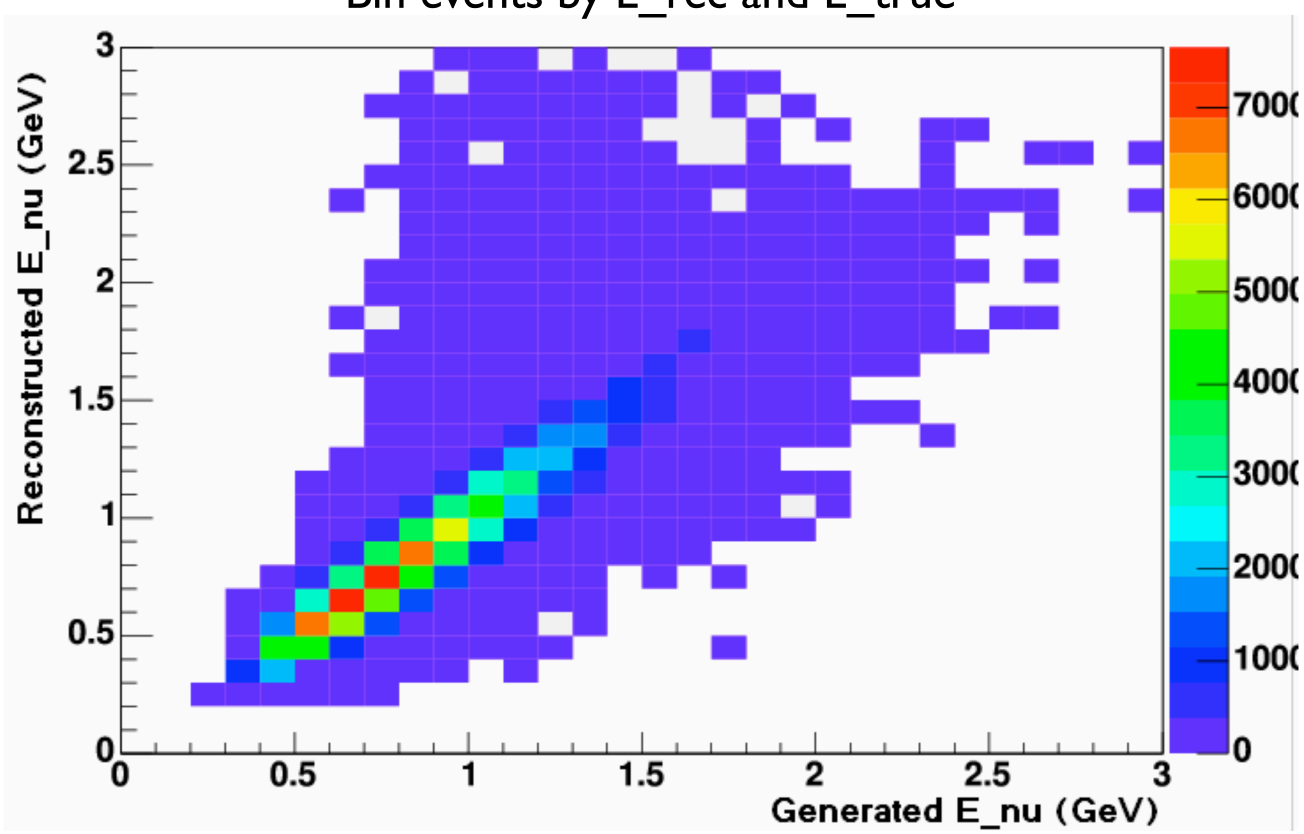
Energy Unsmearing

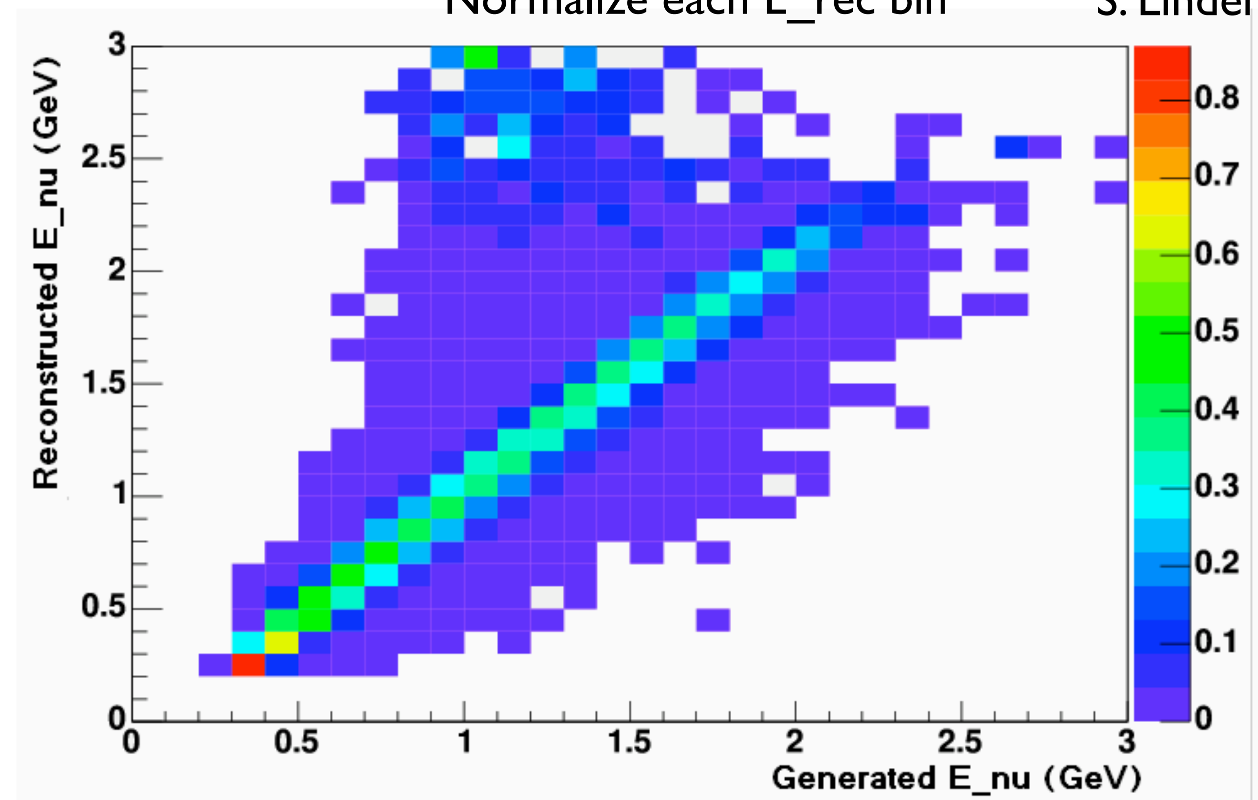
Bin events by E_rec and E_true



Migration Matrix (CCQE)

Normalize each E_rec bin

S. Linden



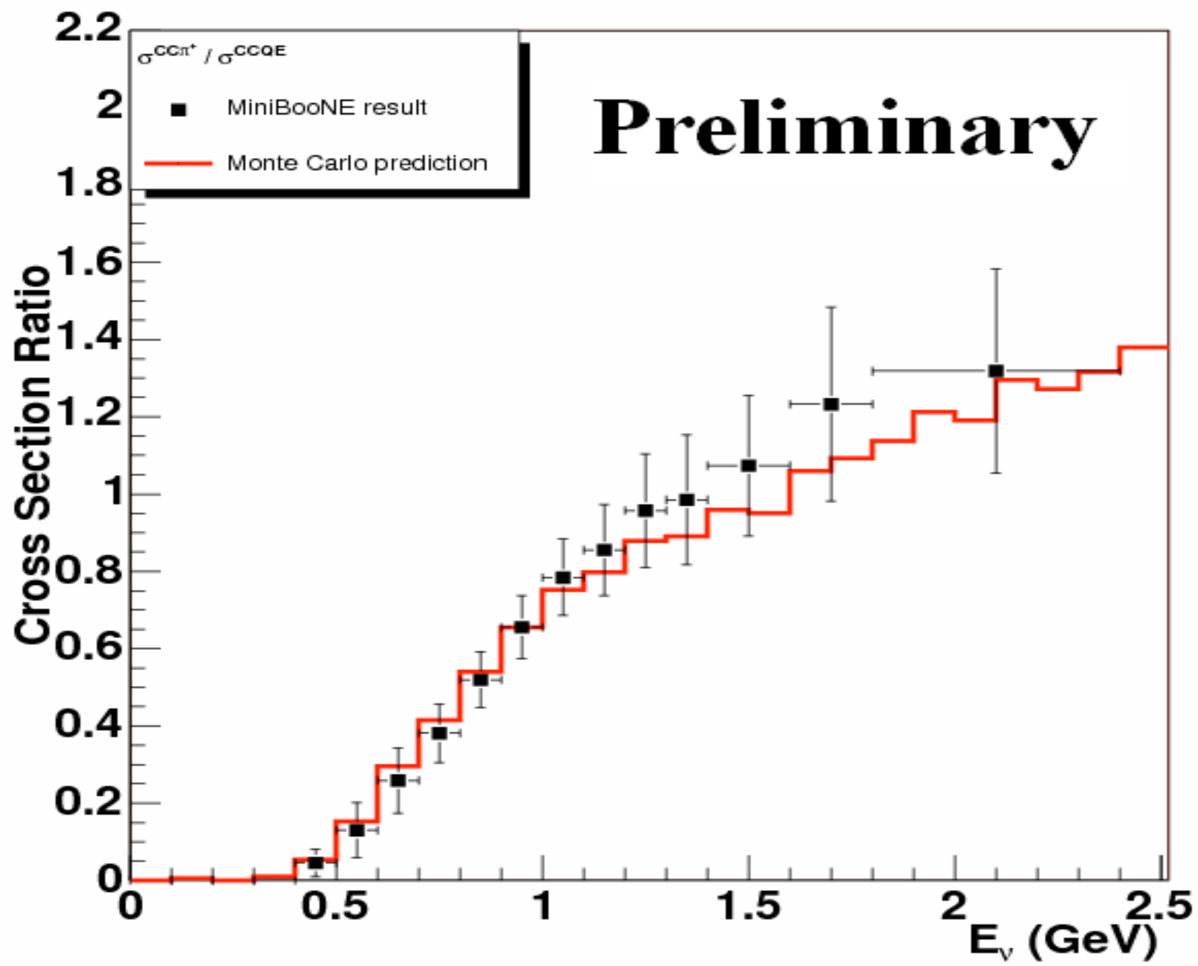
Unsmearing Matrix (CCQE)

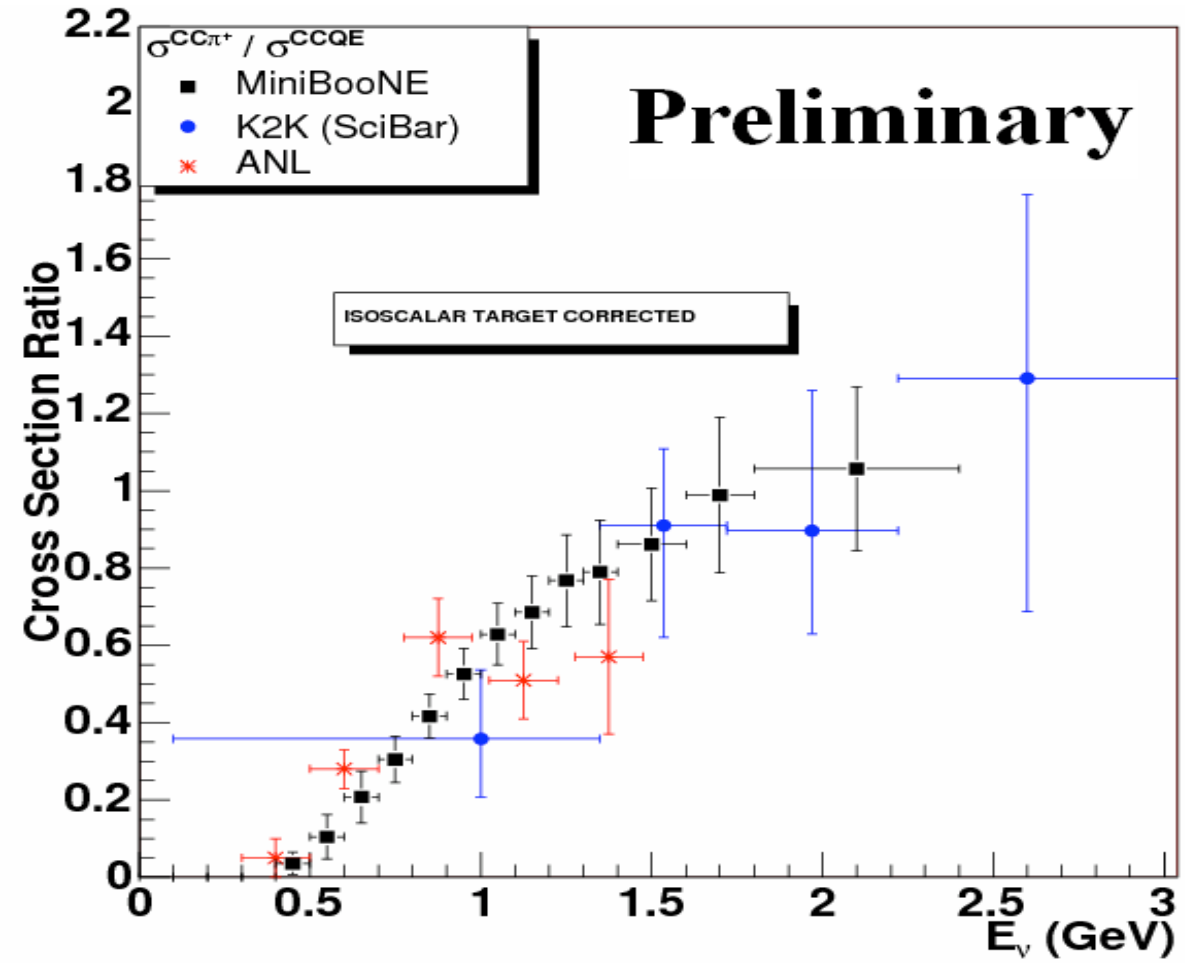
Avoids the problems of matrix inversion (which for this analysis was not viable).

Introduces bias from MC true energy distributions - net effect is increased systematic uncertainty.

Results

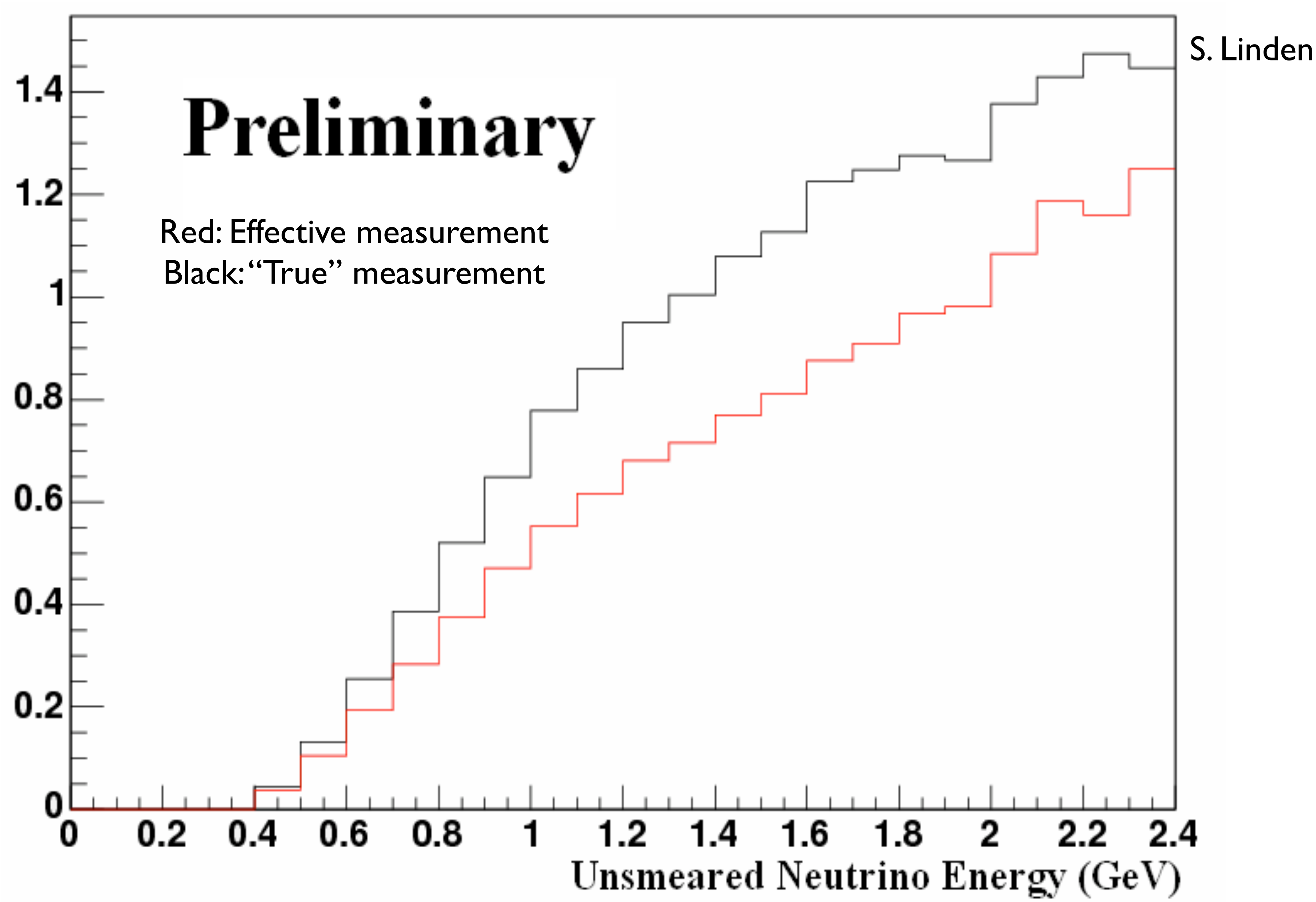
S. Linden





$$\frac{\sigma_{ccpip,i}}{\sigma_{ccqe,i}} = \frac{\epsilon_{ccpip,i}^{-1} * \sum_j U_{ij} * f_{ccpip,j} * N_{ccpip-cuts,j}}{\epsilon_{ccqe,i}^{-1} * \sum_j U_{ij} * f_{ccqe,j} * N_{ccqe-cuts,j}}$$

Effective Ratio Measurement

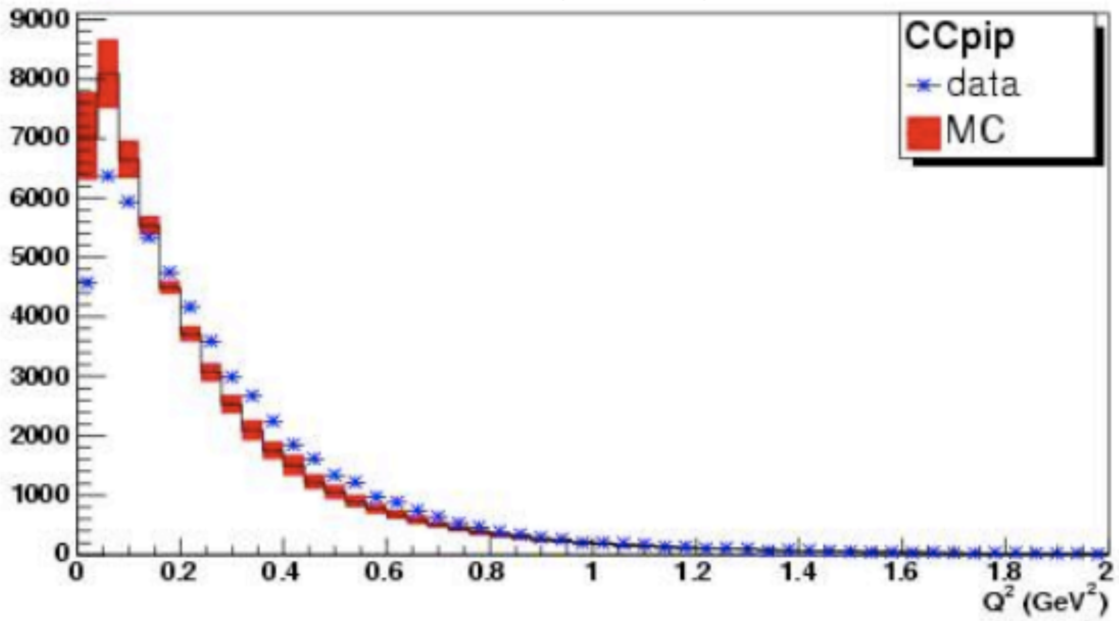


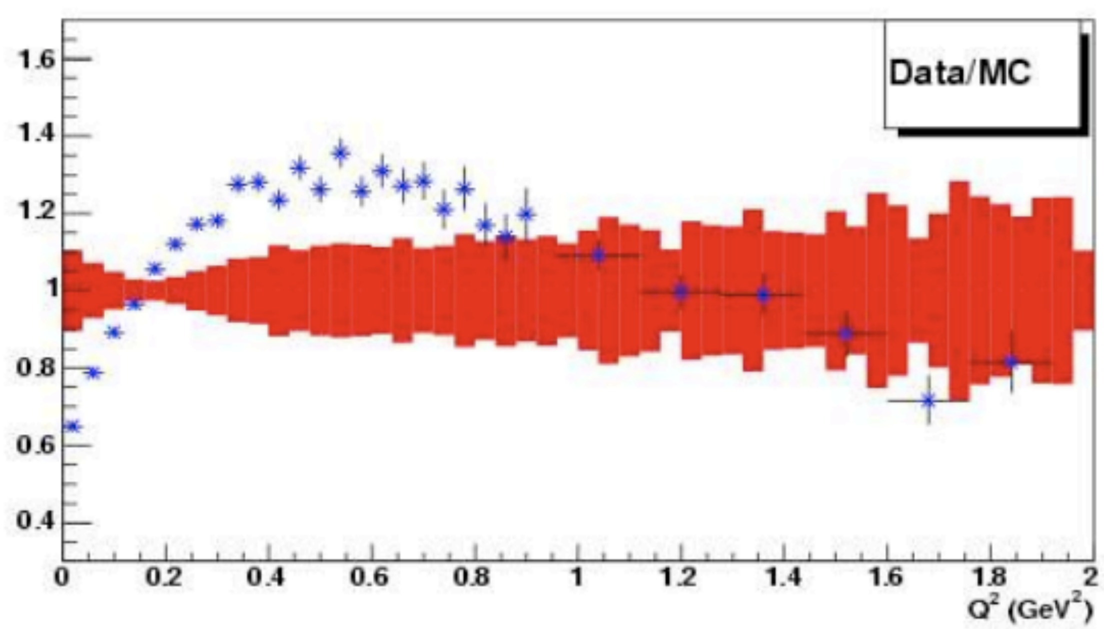
The effective ratio is smaller than the true ratio because there is a significant number of CCQE-like CCπ+ events due to pion absorption.

Model Comparisons

NuInt07

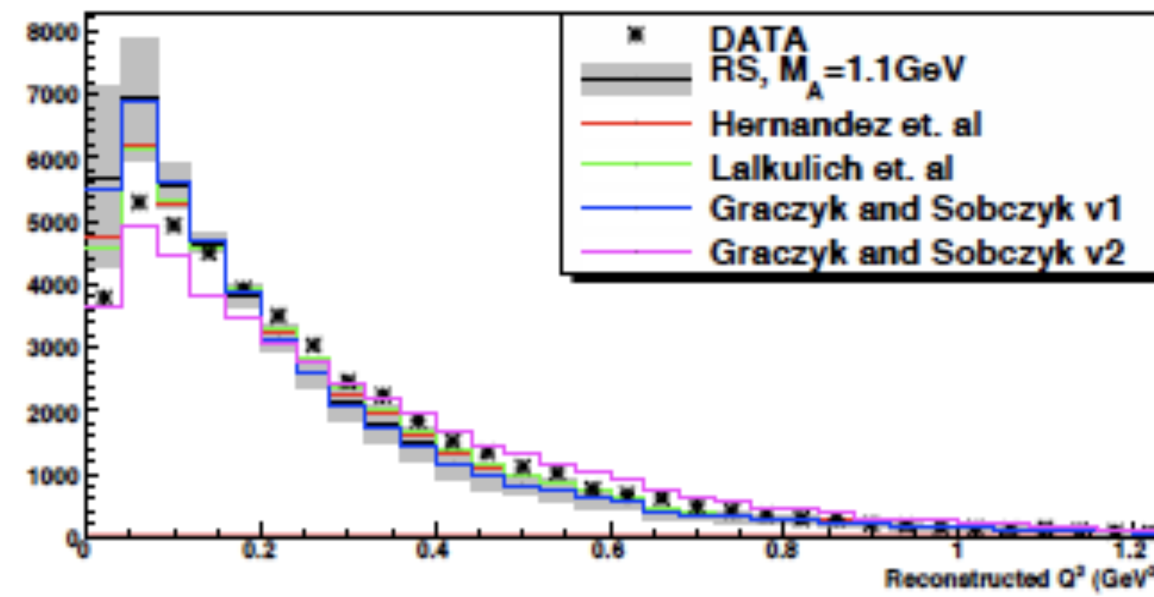
J. Nowak

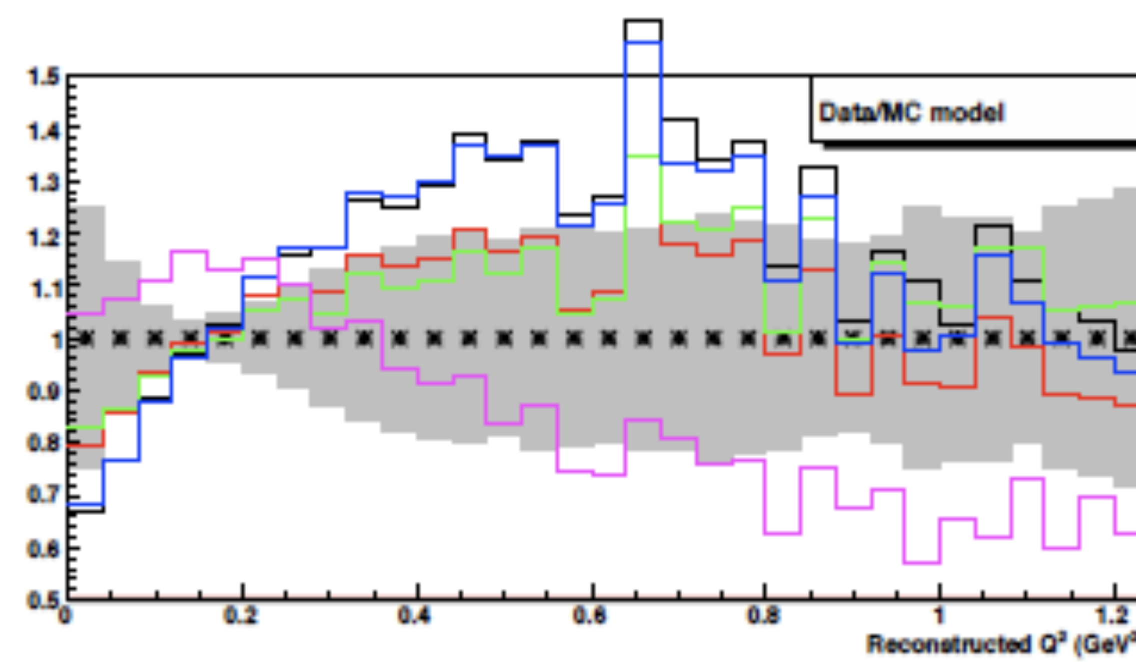




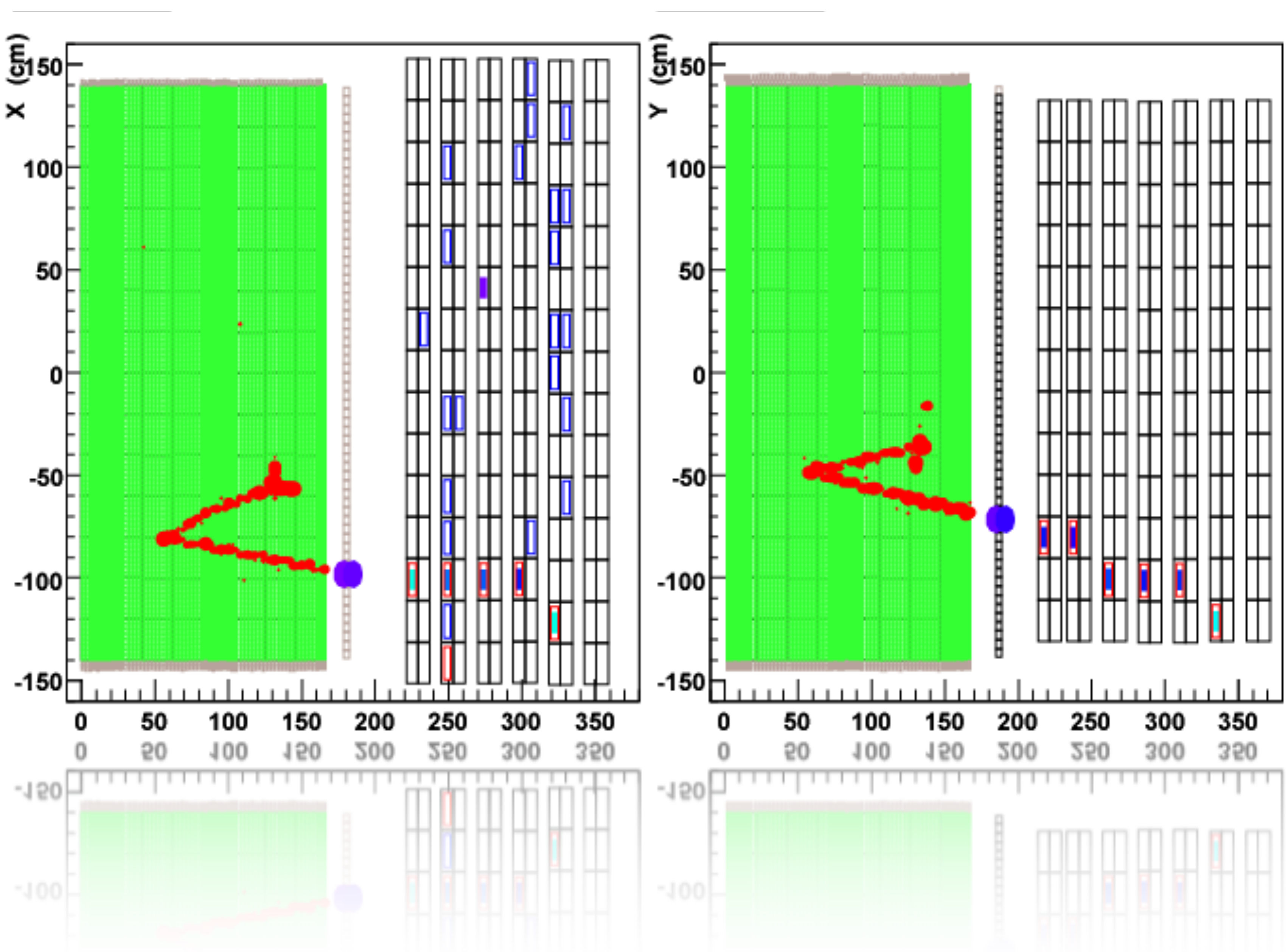
DNP08

J. Nowak





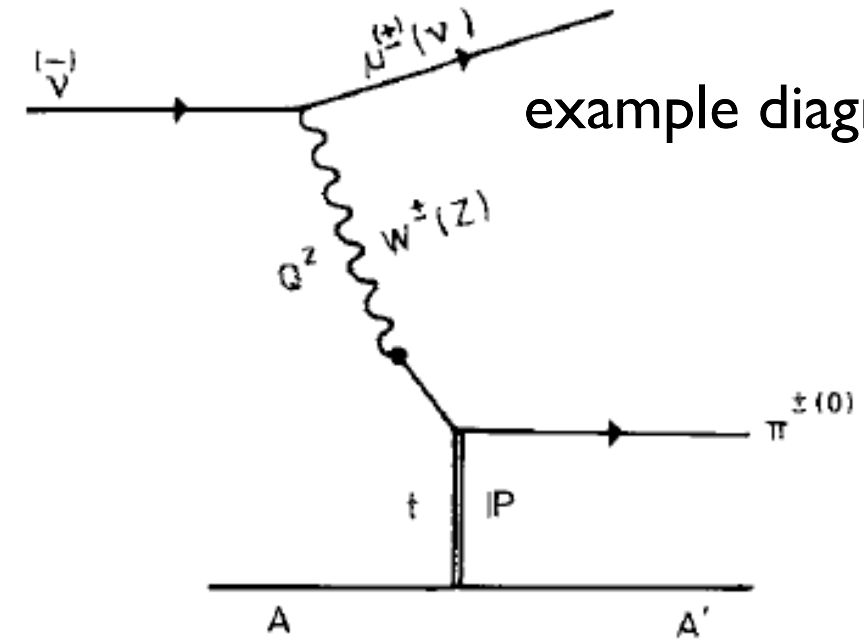
χ^2/ndf(Q2) = 19.5(Hernandez) , 14.9(Lalakulich), 55.1(G&S 1), 28.05(G&S 2)



Coherent pion searches

Coherent pion production

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

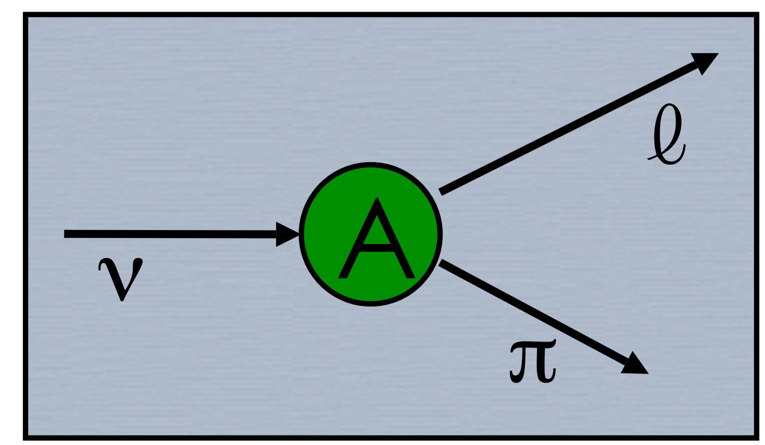


example diagram

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

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

- Interestingly theoretically because it requires large wavelength in massive propagator



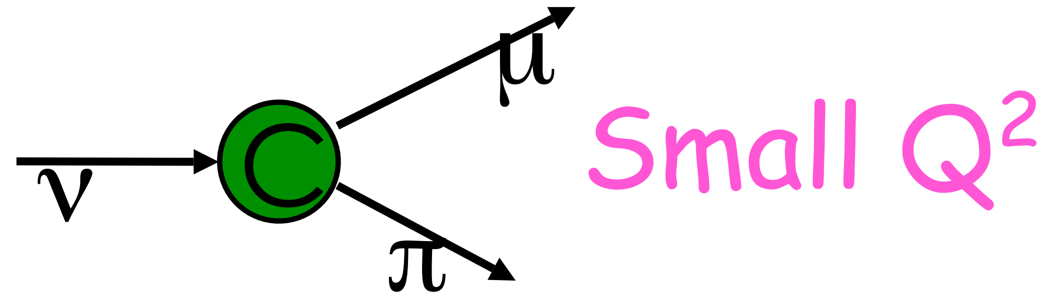
Several past measurements
- both NC and CC
- both neutrino and antineutrino
- >2 GeV (NC), >7 GeV (CC)   up to ~100 GeV

CC Coherent Pion Production

Signal

CC-coherent π production

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

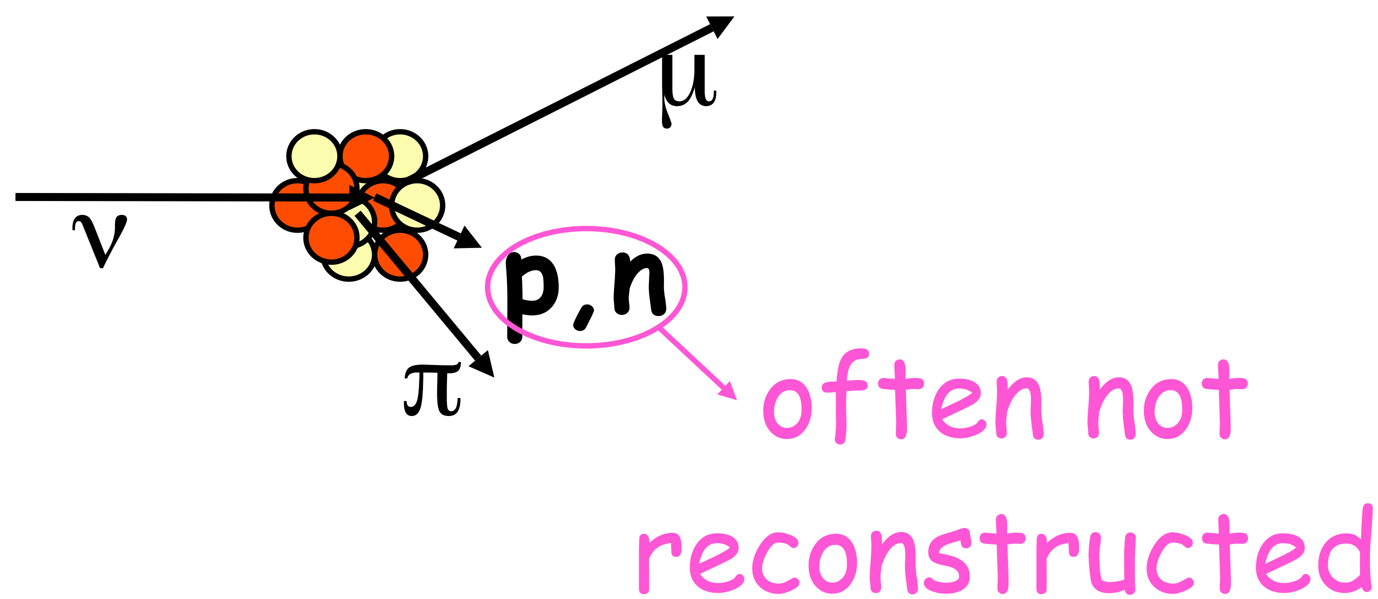


- 2 MIP-like tracks (a muon and a pion)
- ~1% of total ν interaction based on Rein-Sehgal model

Background

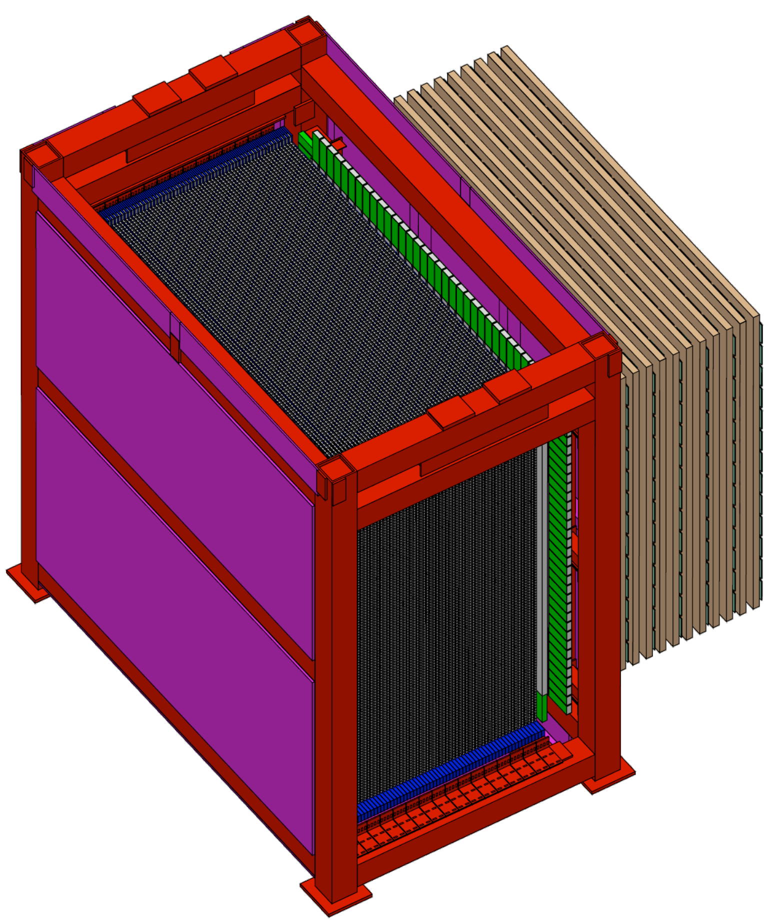
CC-resonant π production

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

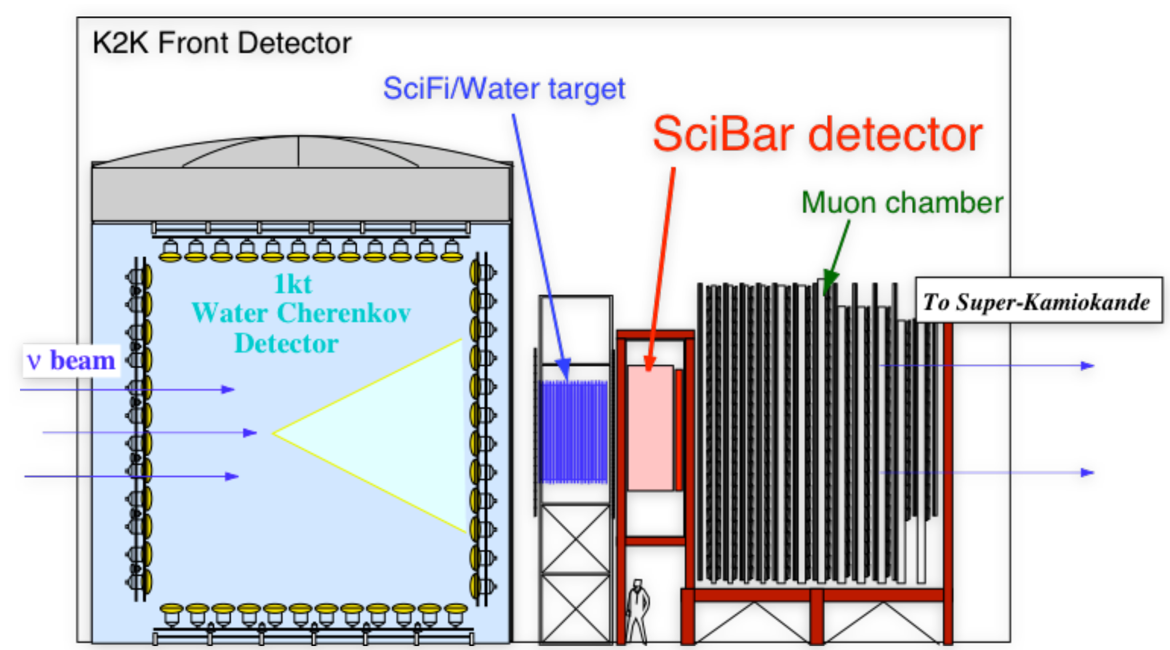


1 Detector in 2 Beams

- Unique opportunity today to show the same search in two different neutrino beams using the same detector

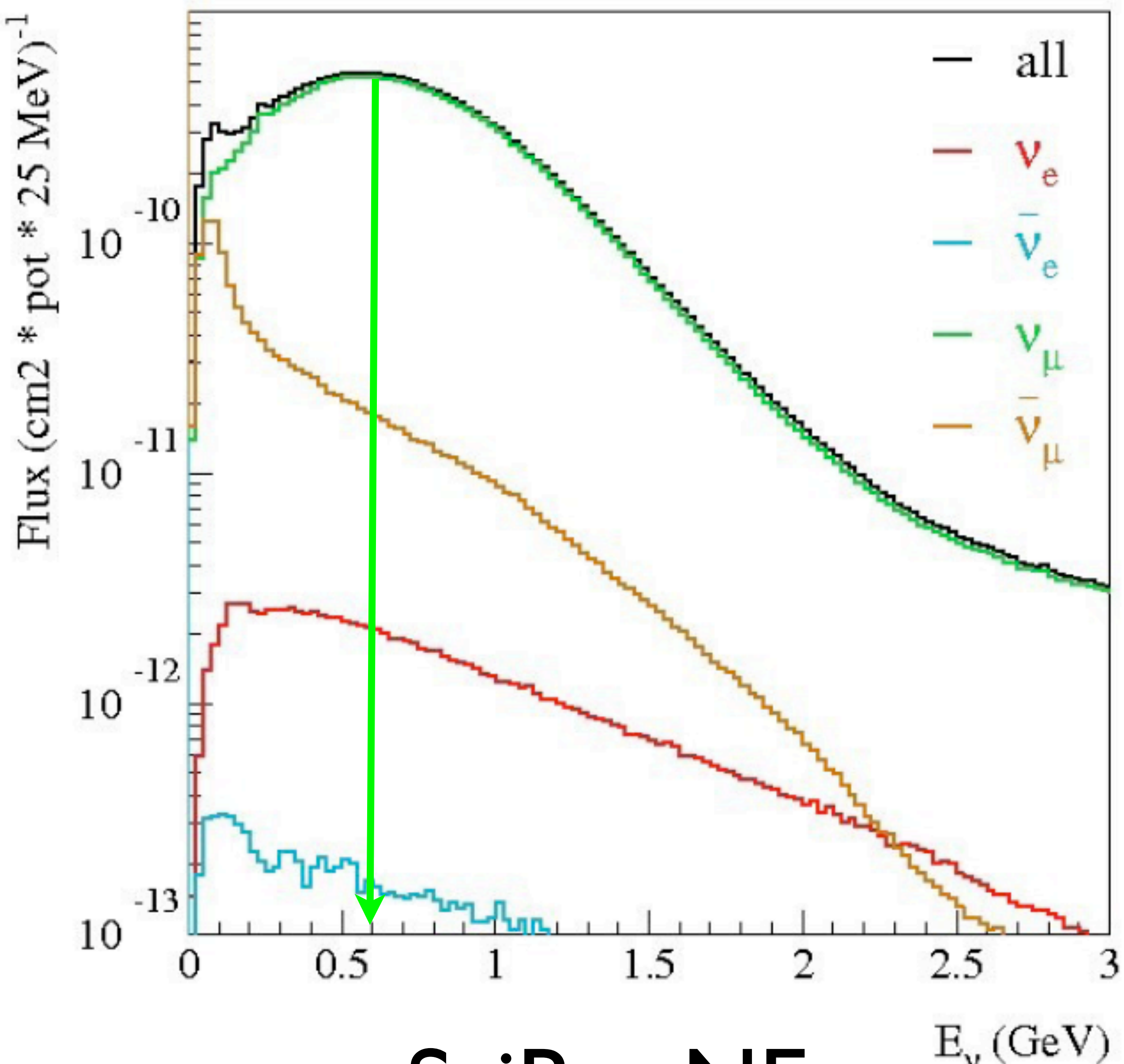


SciBooNE



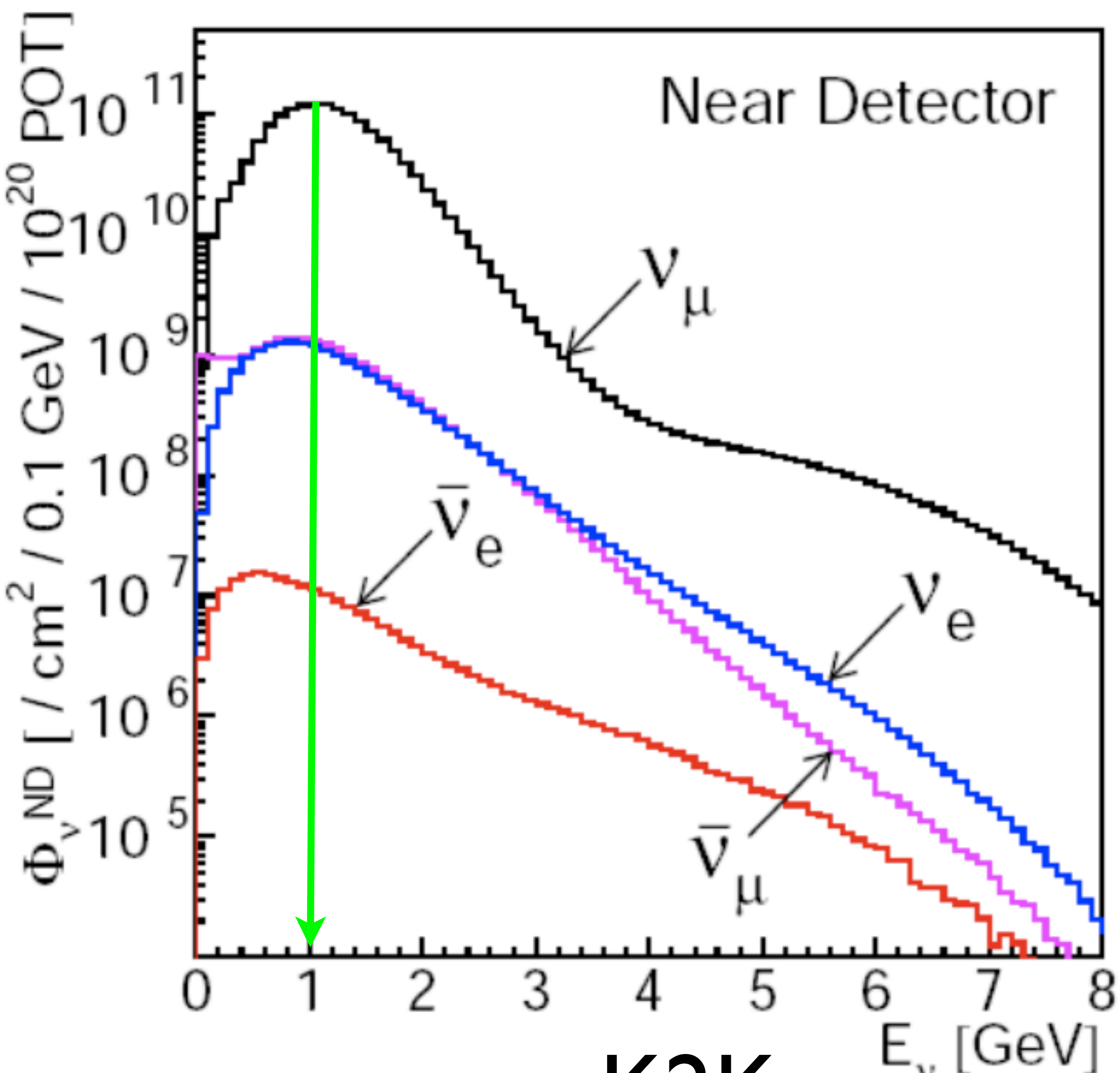
K2K

Neutrino Fluxes



SciBooNE

$<E_{\nu}>\sim 0.8$GeV

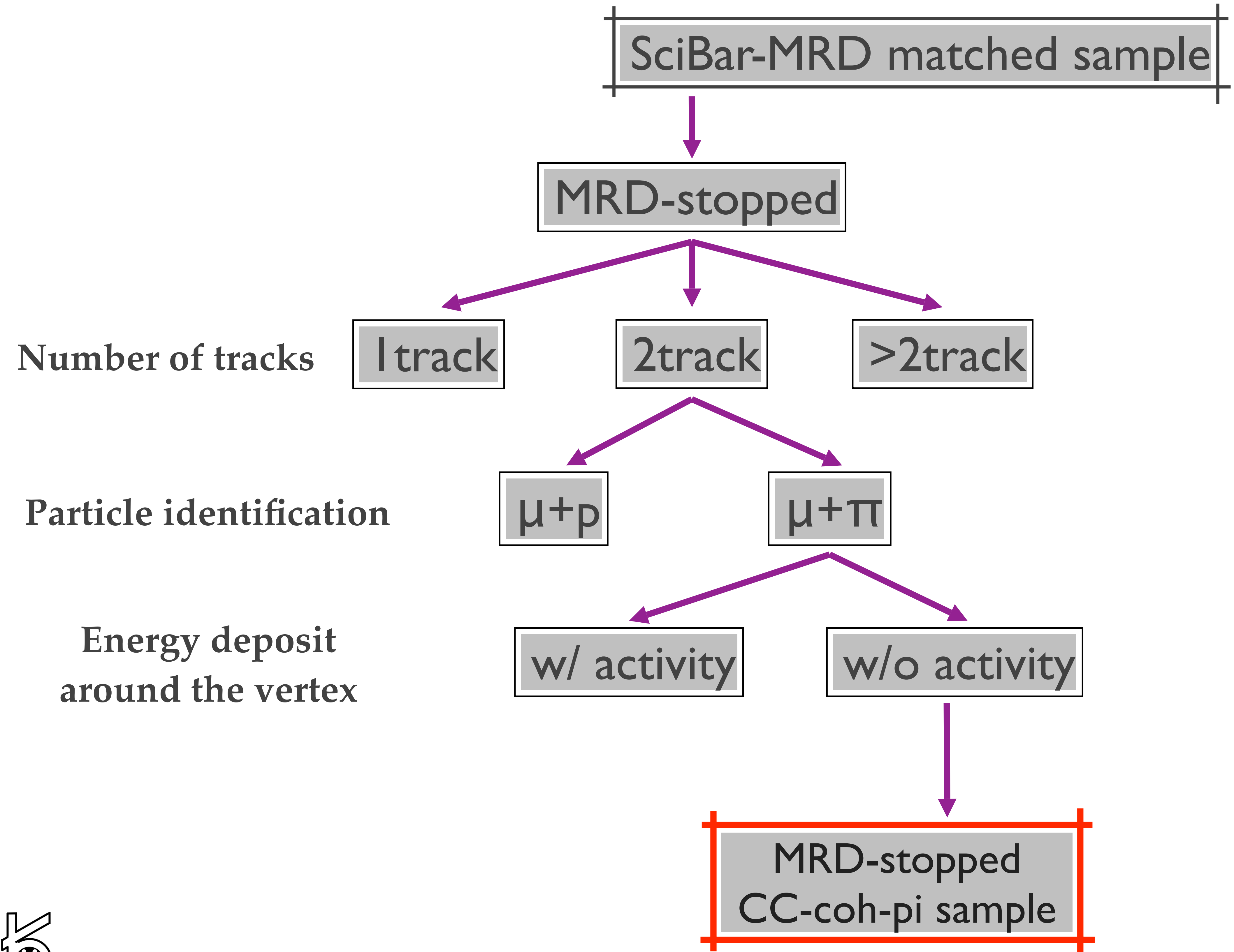


K2K

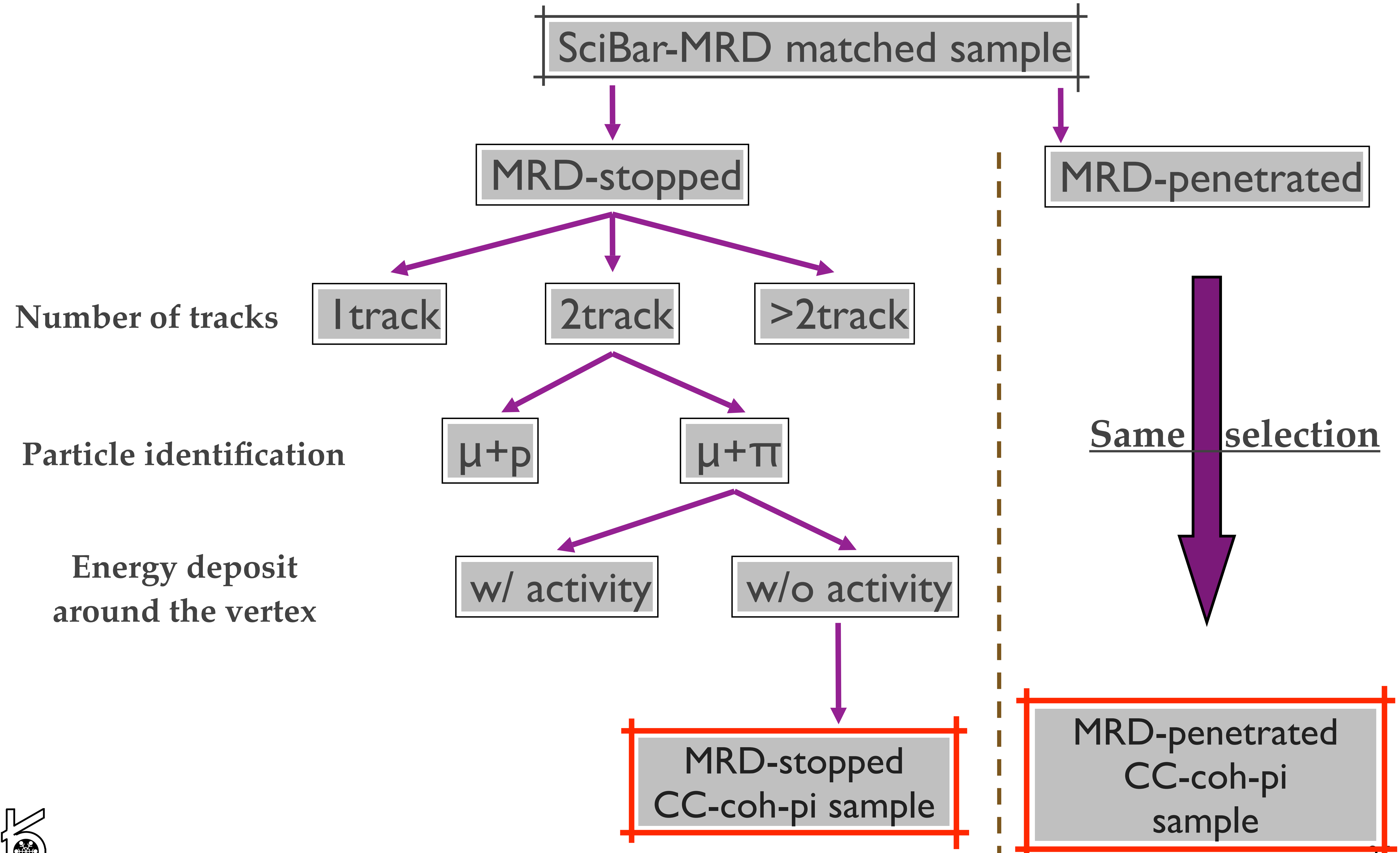
$<E_{\nu}>\sim 1.3$GeV

Similar fluxes per POT

CC event classification

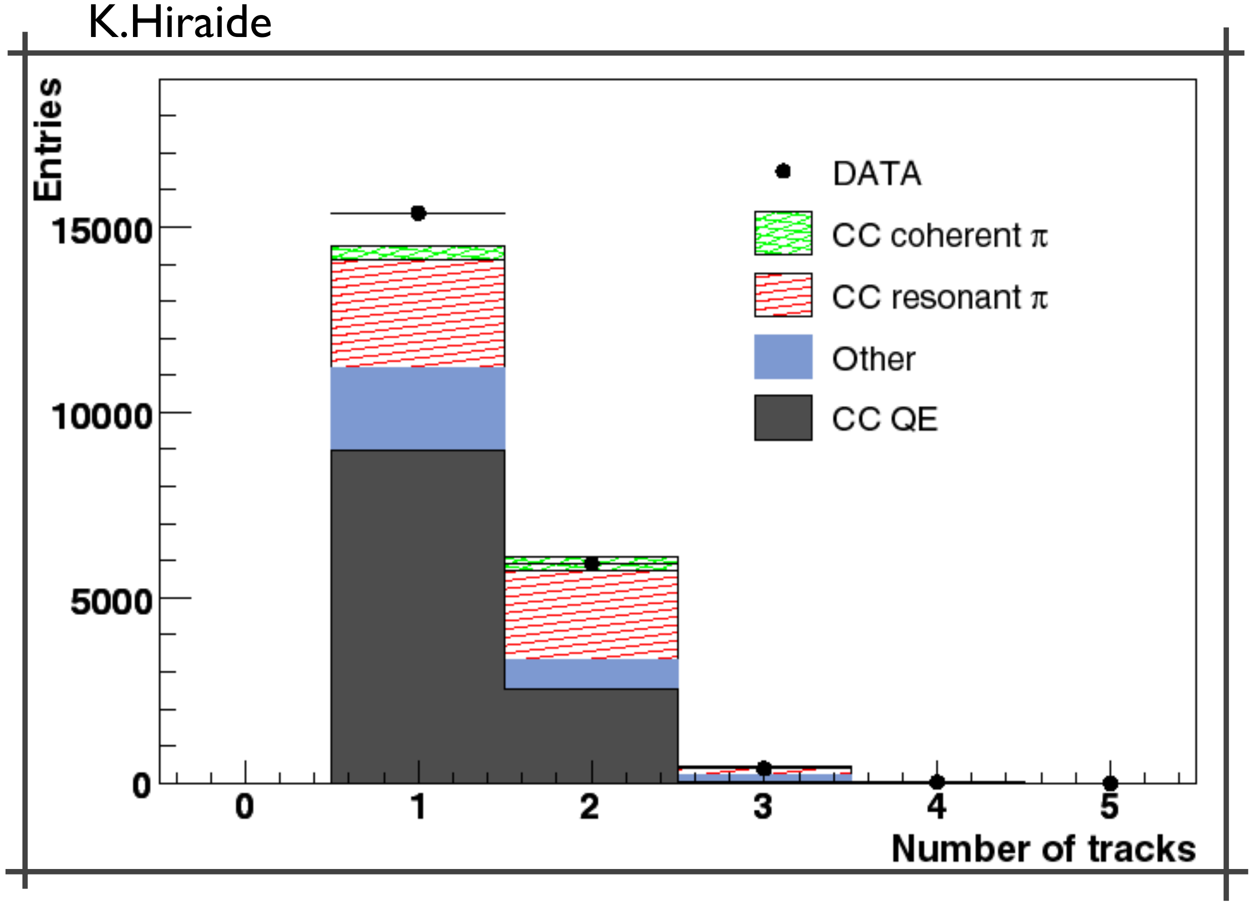


CC event classification

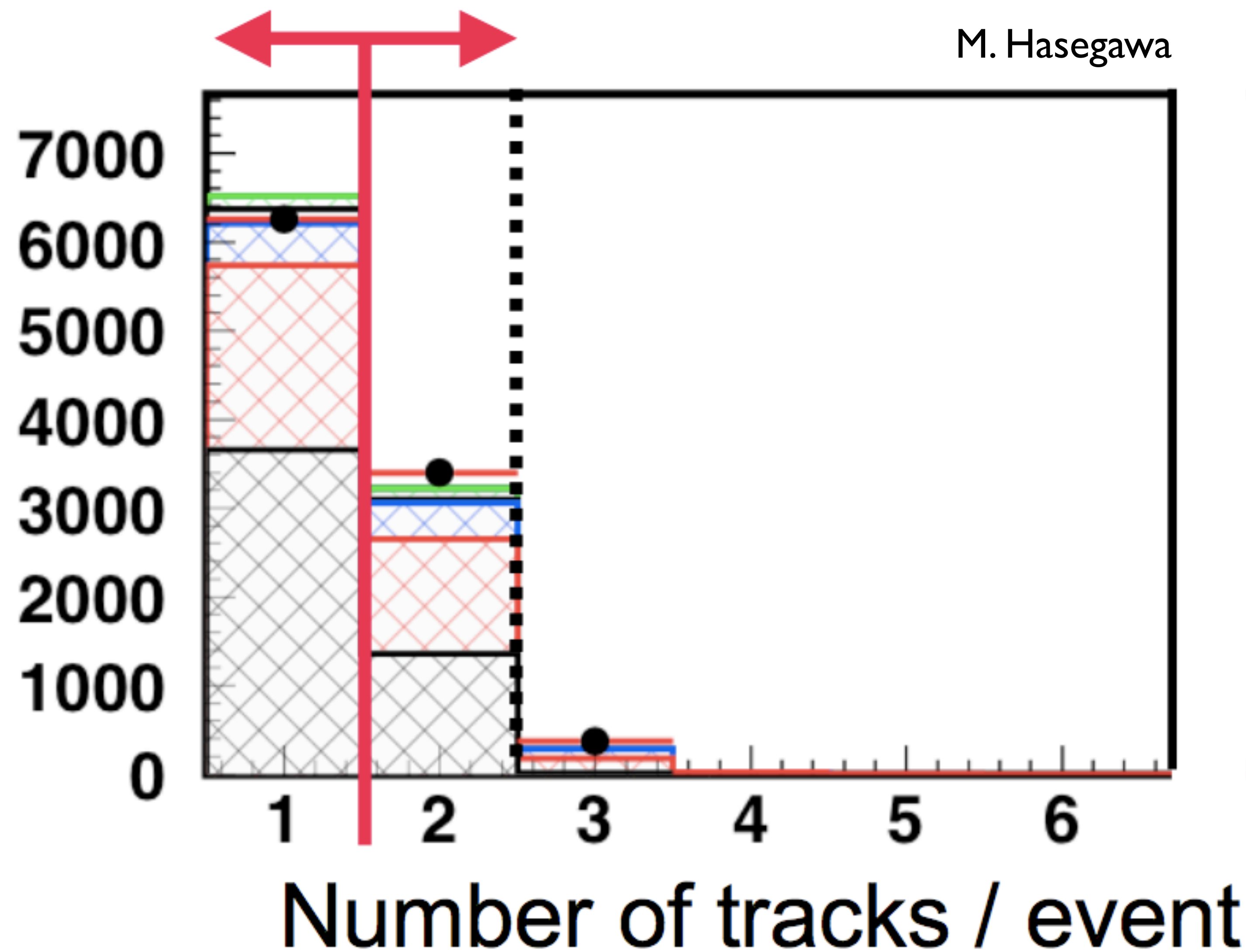


Number of Tracks

K.Hiraide



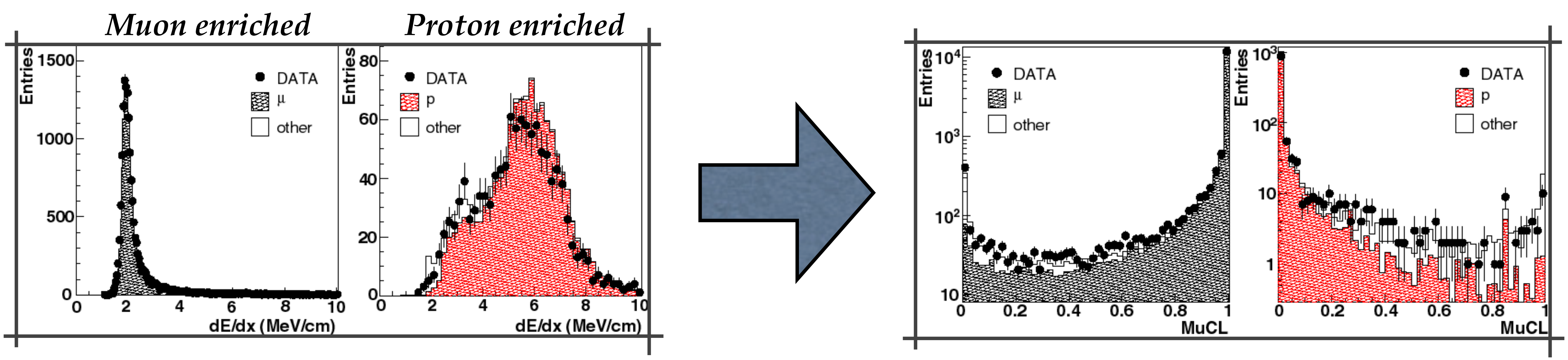
M. Hasegawa

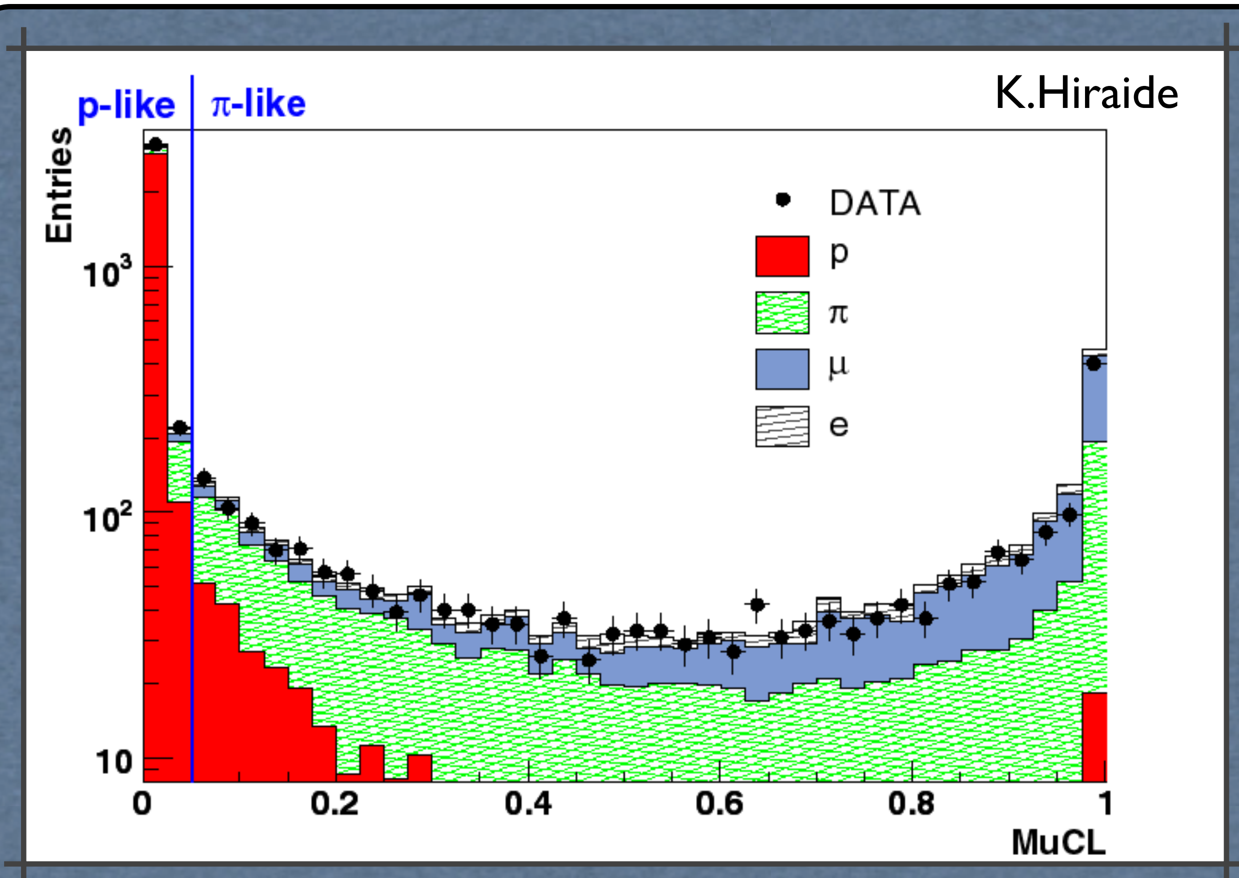


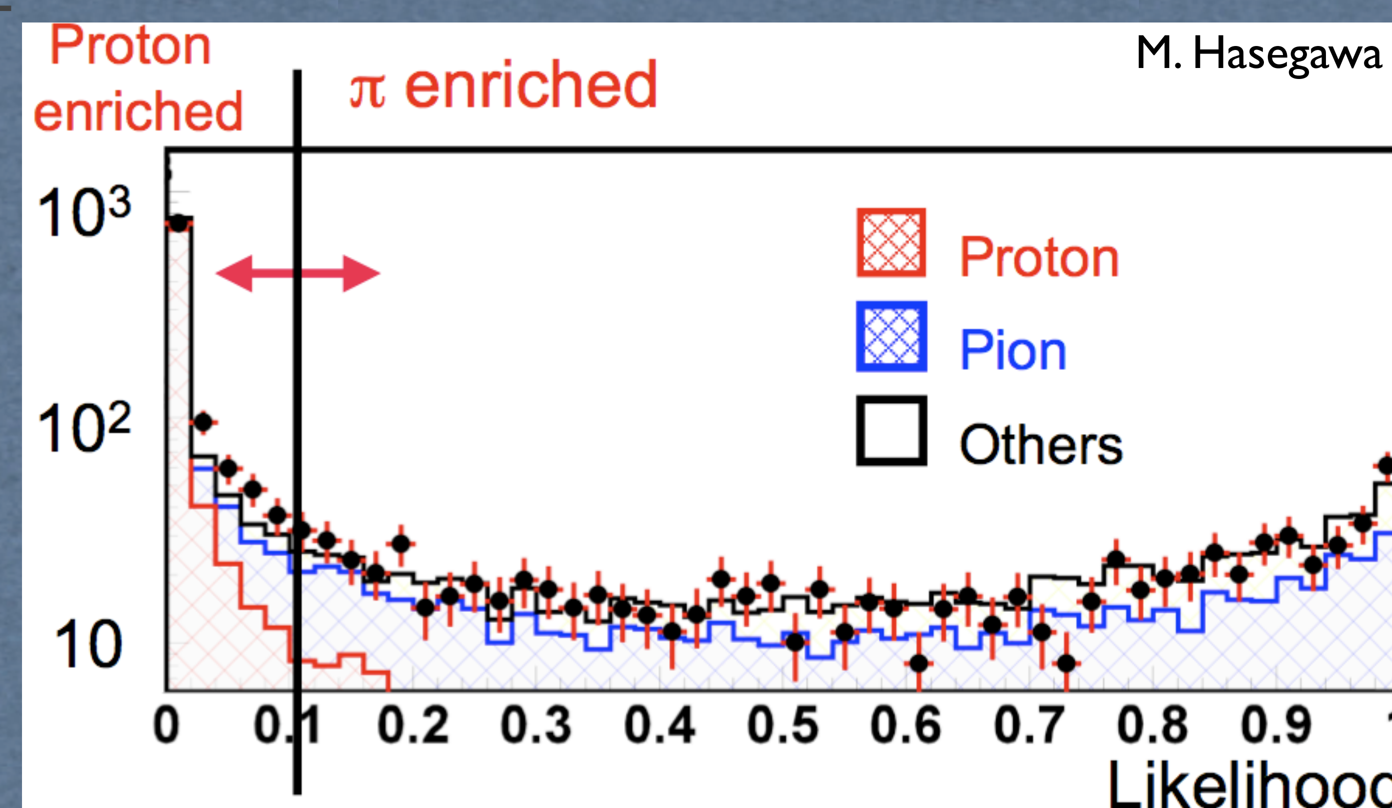
SciBooNE

K2K

Particle ID



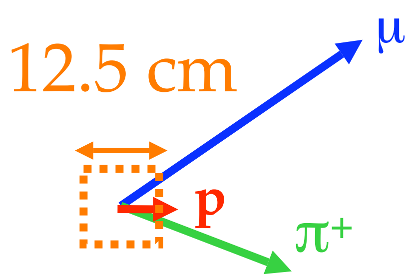




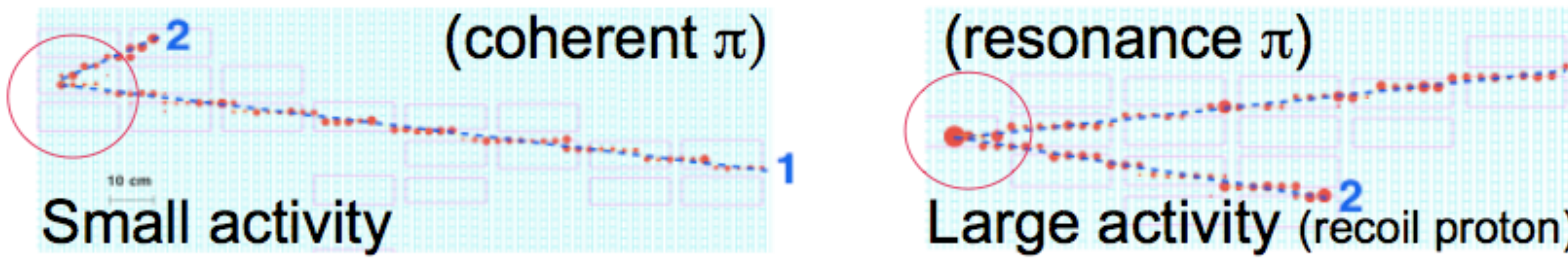
SciBooNE

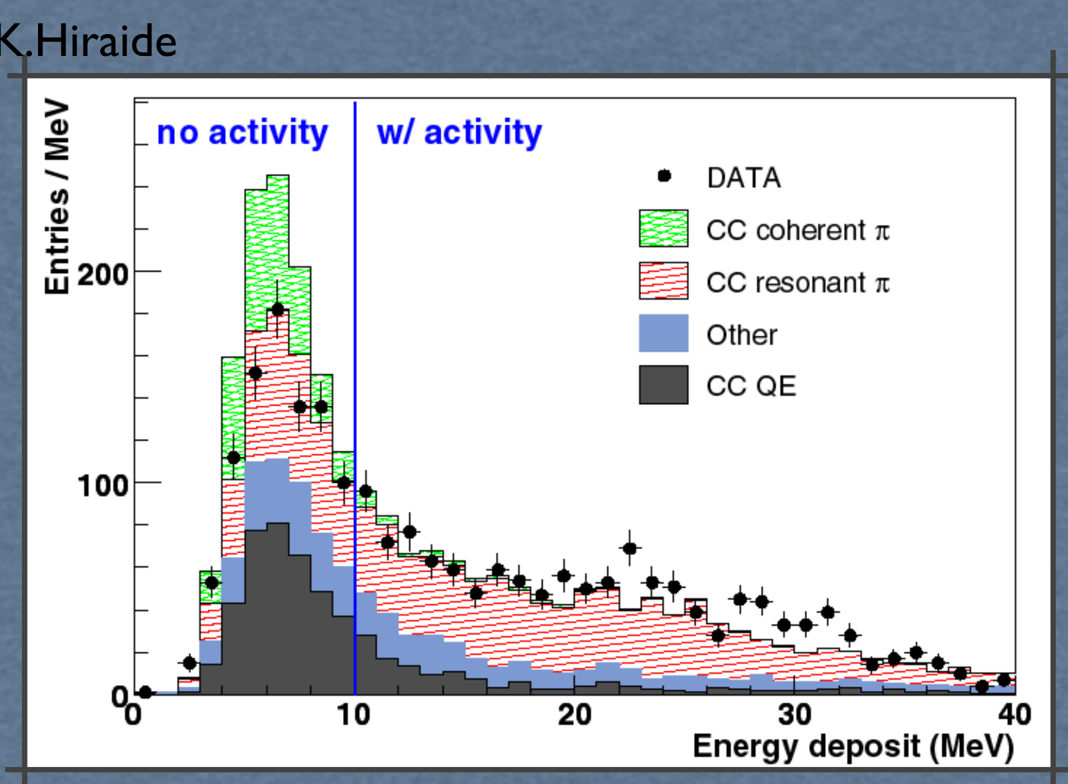
K2K

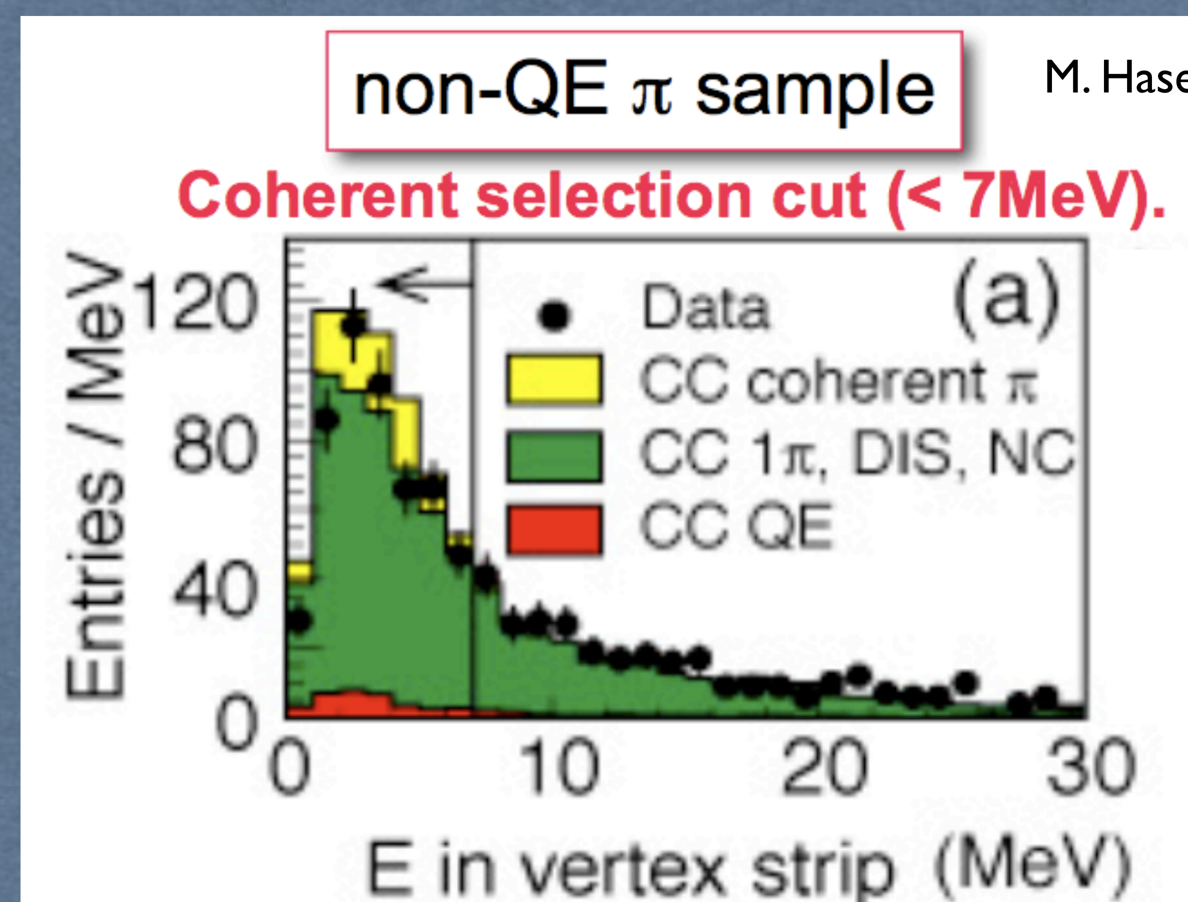
Untracked protons



- Vertex Activity : Energy deposit in vertex strip
  →Reject BG : un-reconstructed particles (proton) of resonance pi prod.







SciBooNE

K2K

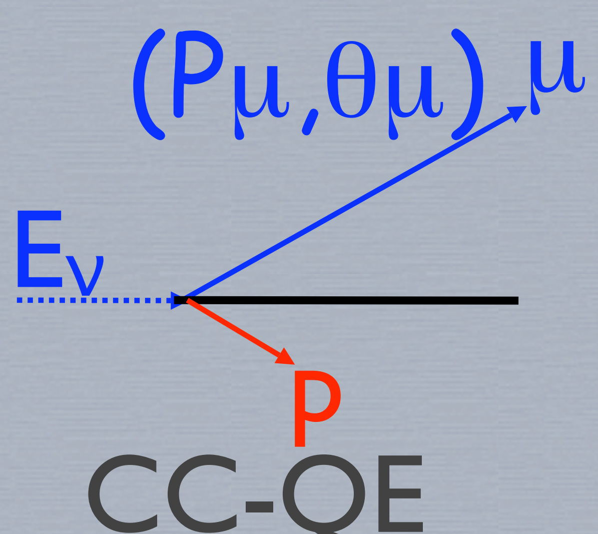
Tuning of MC

To constrain systematic uncertainties due to

- detector responses
- nuclear effects
- neutrino interaction models
- neutrino energy spectrum

Q^2 distributions of sub-samples are fitted to data

Q^2 reconstruction assuming CC-QE ($\nu+n \rightarrow \mu+p$) interaction



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

$$E_\nu^{rec} = \frac{1}{2}\frac{(m_p^2 - m_\mu^2) - (m_n - V)^2 + 2E_\mu(m_n - V)}{(m_n - V) - E_\mu + p_\mu \cos\theta_\mu}$$

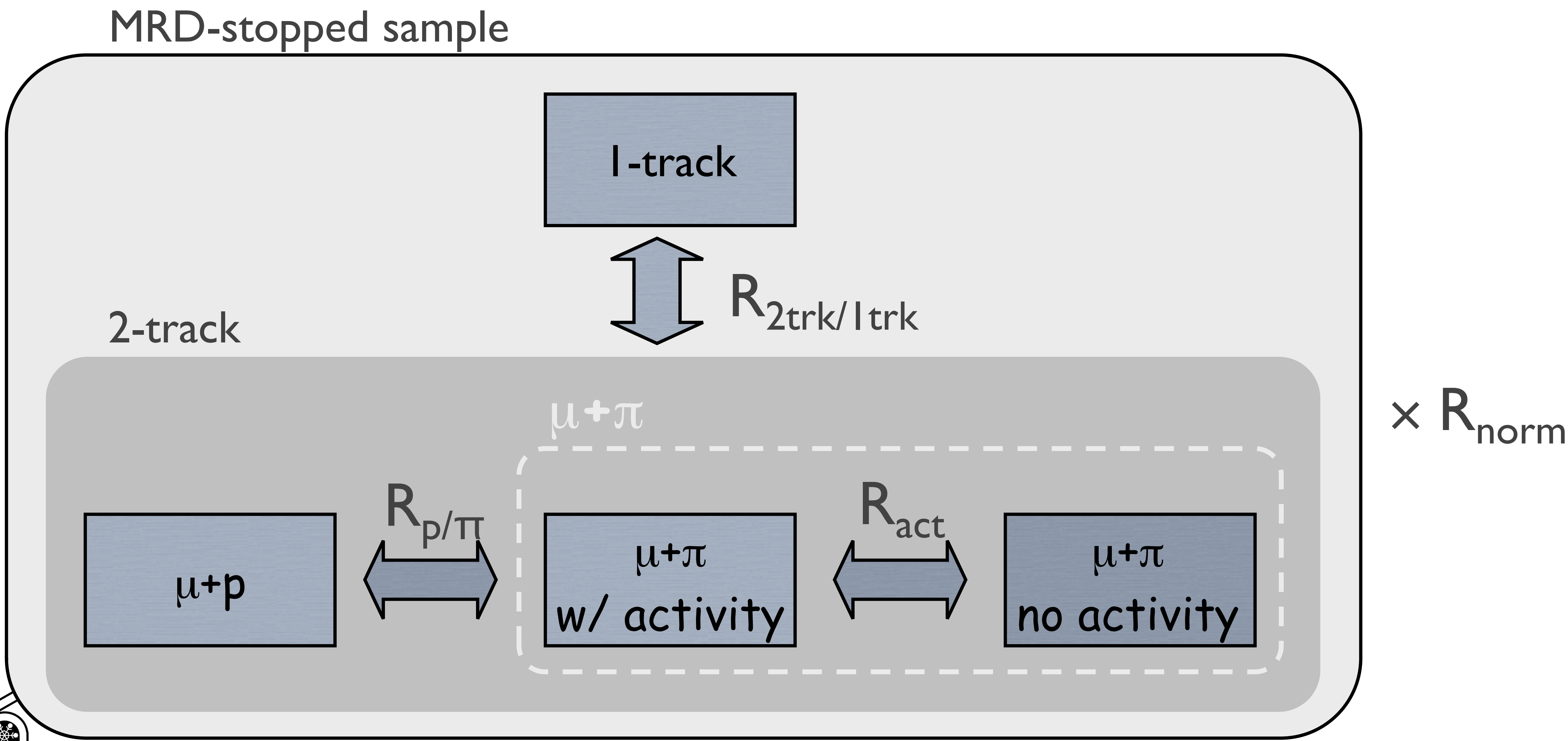
V: nuclear potential (27MeV)

Fitting parameters (1)

Normalization parameter: R_{norm}

Migration parameters : $R_{2trk/1trk}$, $R_{p/\pi}$, R_{act}

Muon momentum scale : P_{scale}



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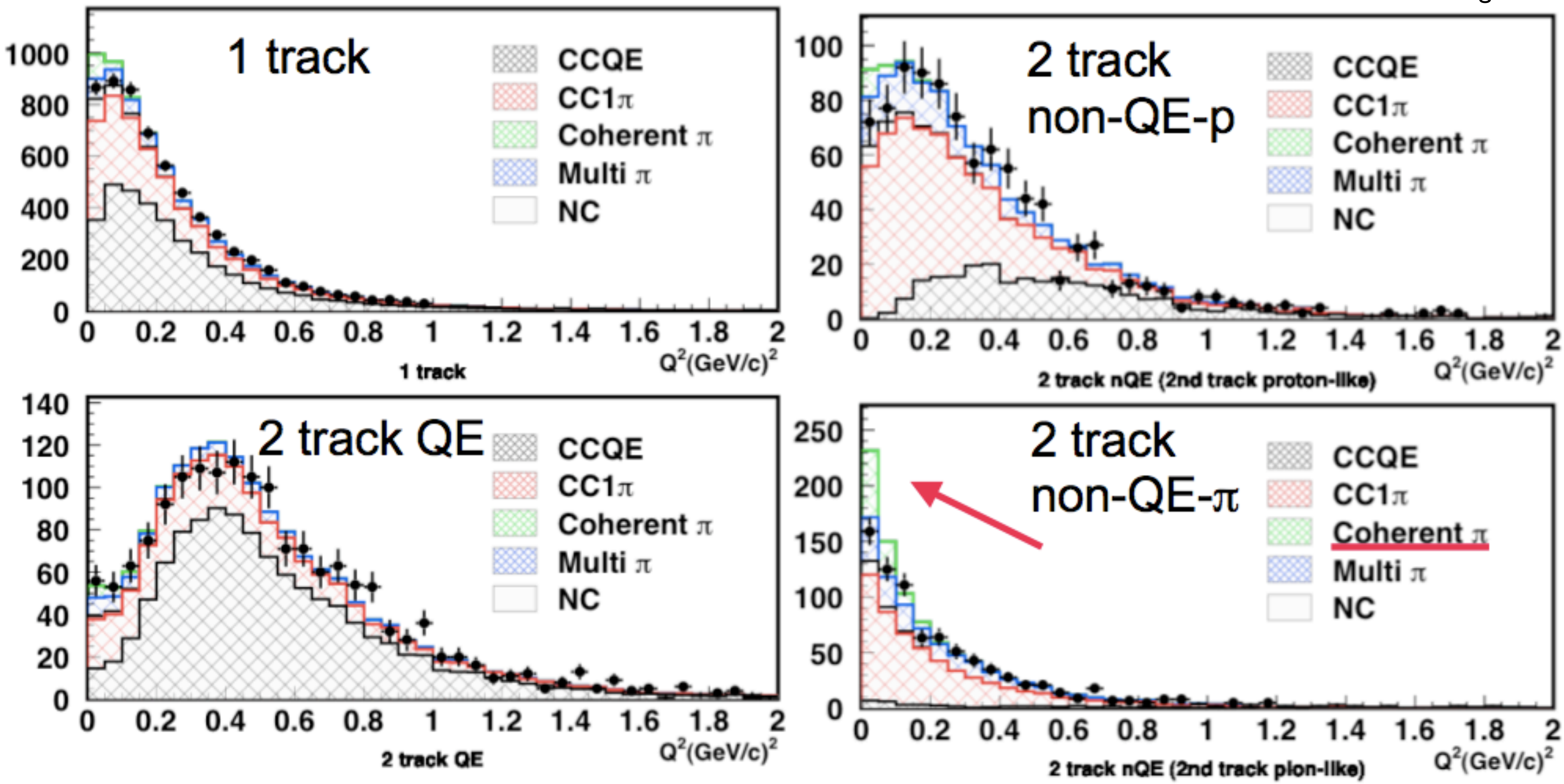
K2K After fit

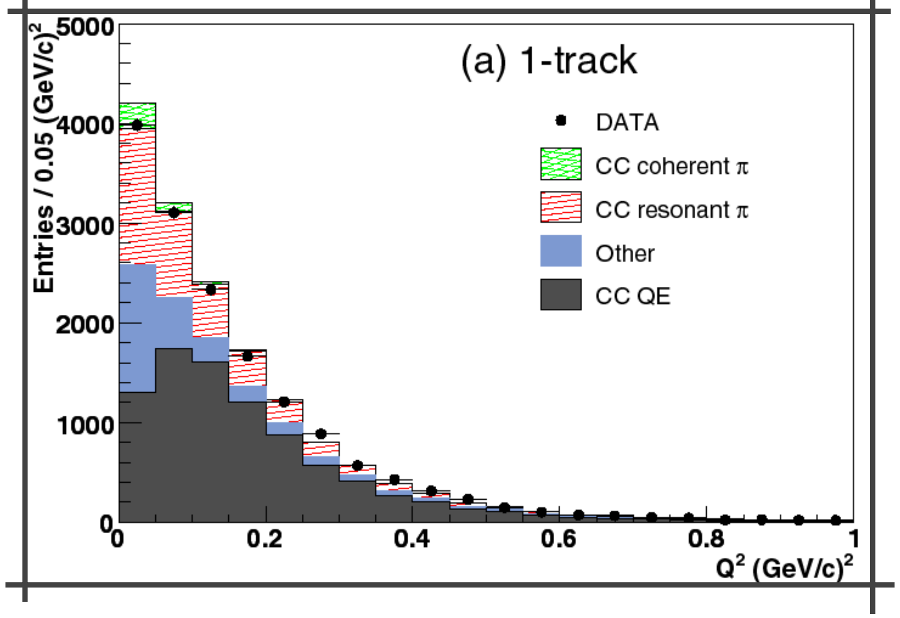
M. Hasegawa



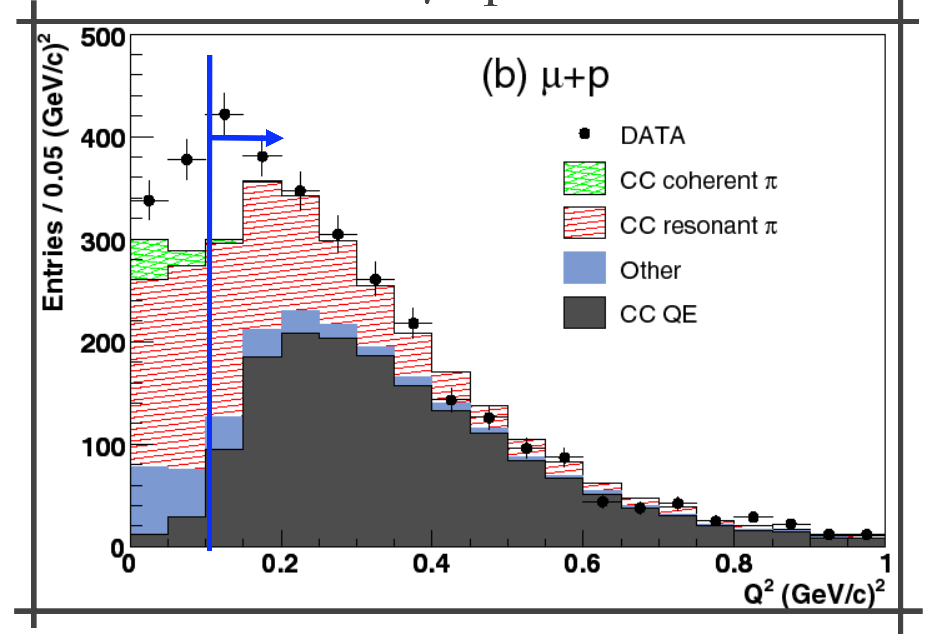
SciBooNE After Fit

K.Hiraide

1-track

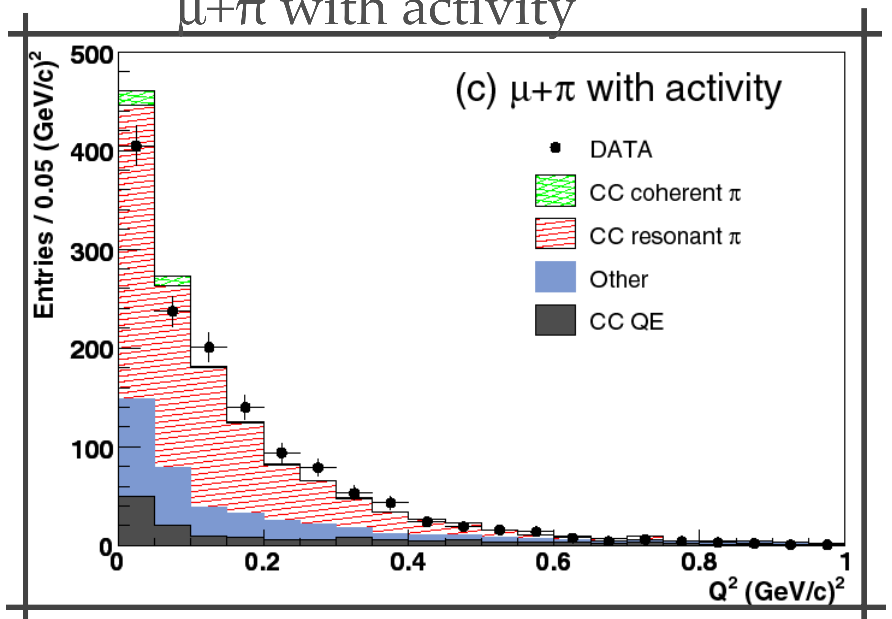


μ+p

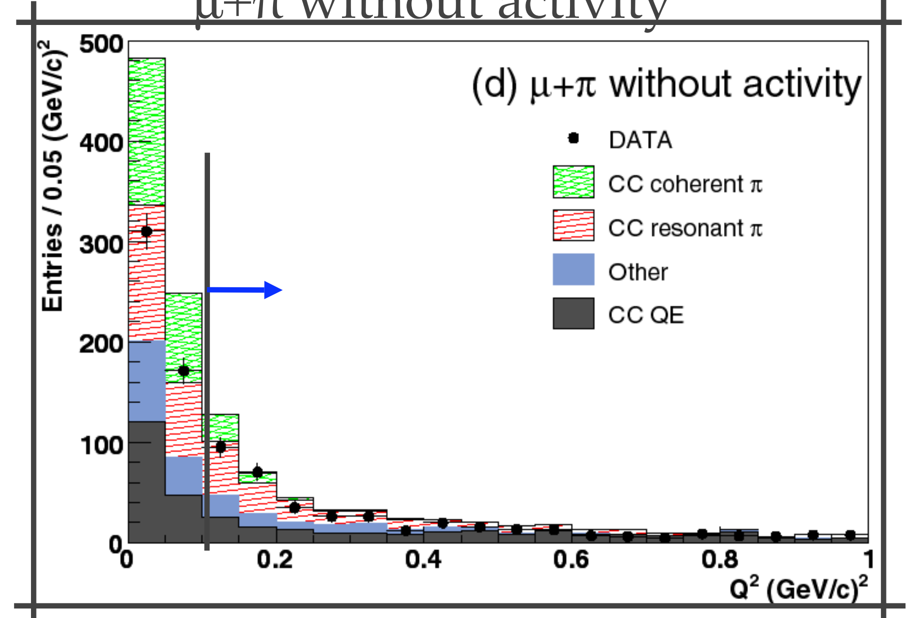


low Q^2 region in μ+p events is excluded from fitting

μ+π with activity



μ+π without activity



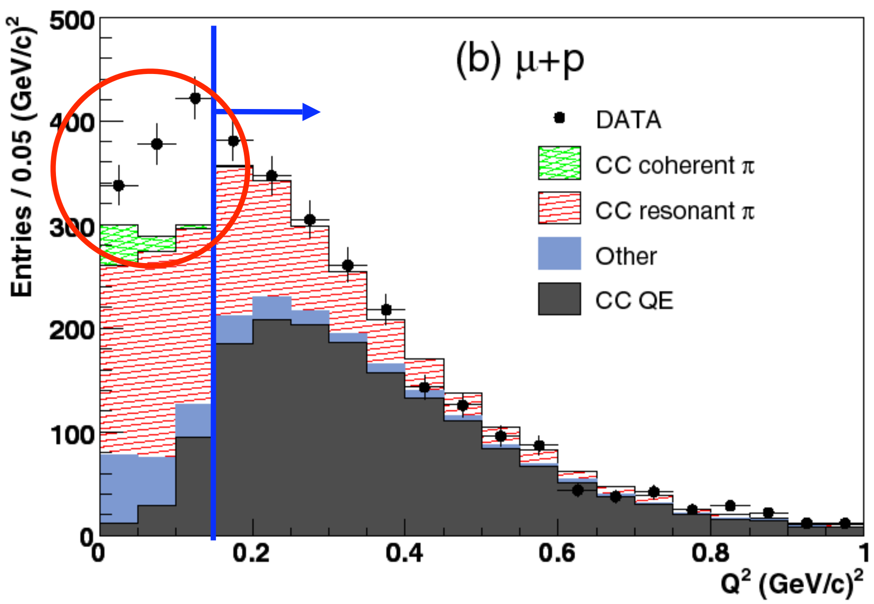
CC coherent π signal region is excluded from fitting

Before fit : $\chi^2/ndf = 473/75 = 6.31$

After fit : $\chi^2/ndf = 117/67 = 1.75$

Data excess in μ+p

K.Hiraide

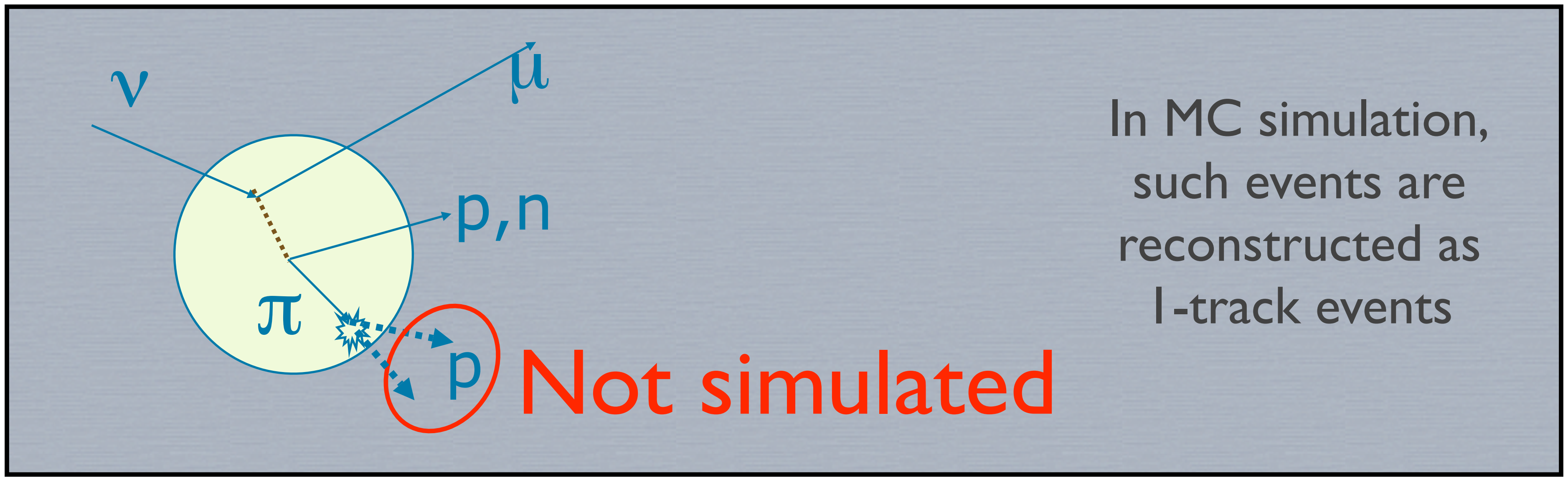


Features of excess events

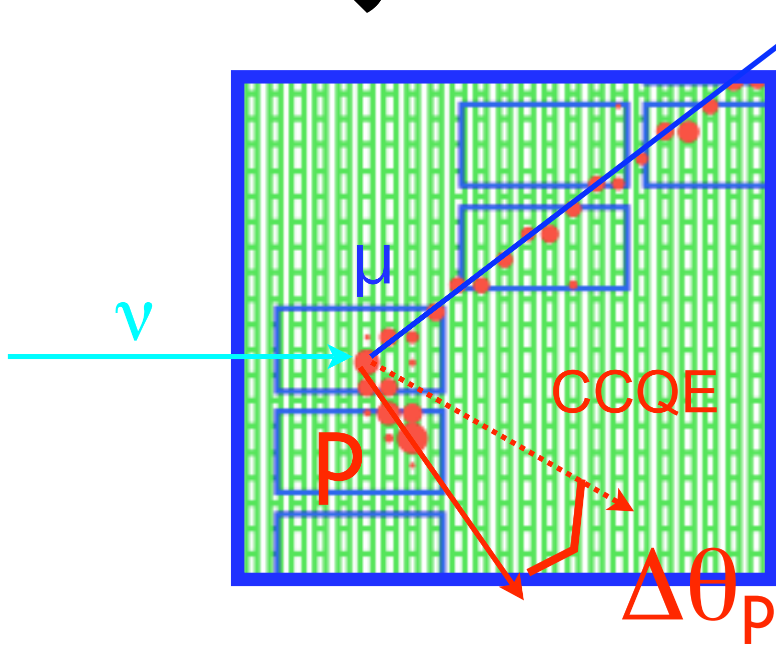
- proton candidate goes at large angle
- additional activity around the vertex

Possible candidate

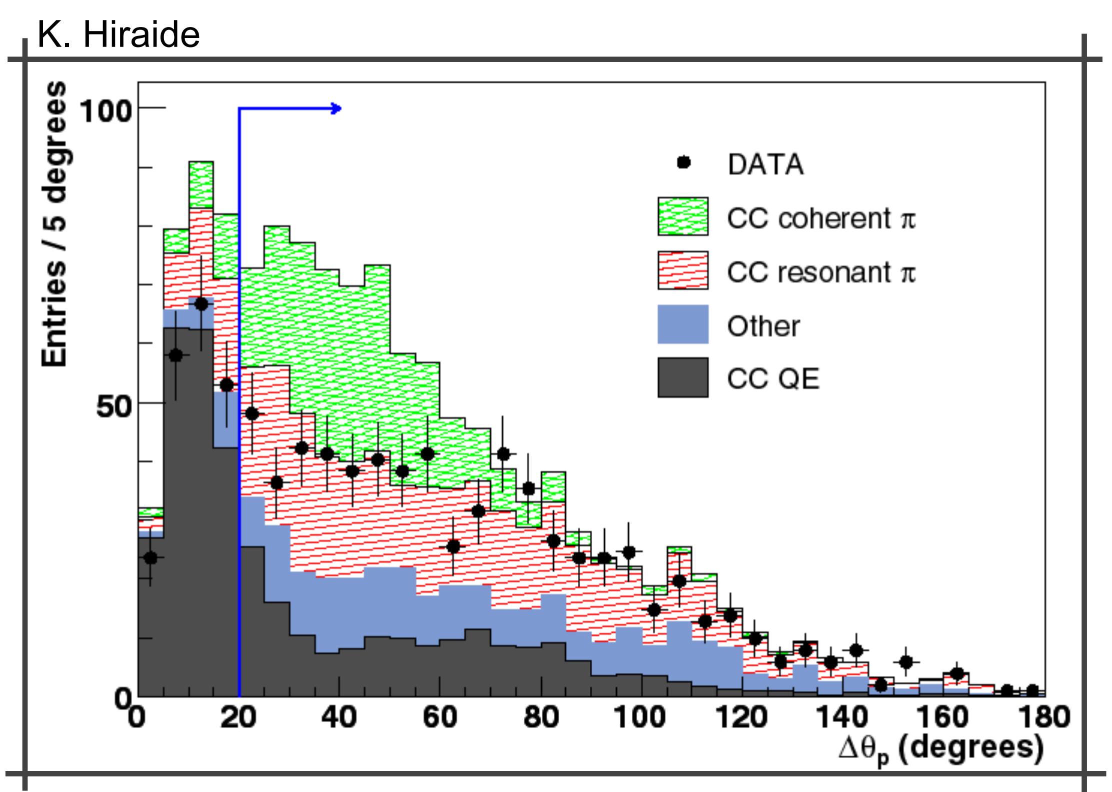
CC resonant pion events in which pion is absorbed in the nucleus



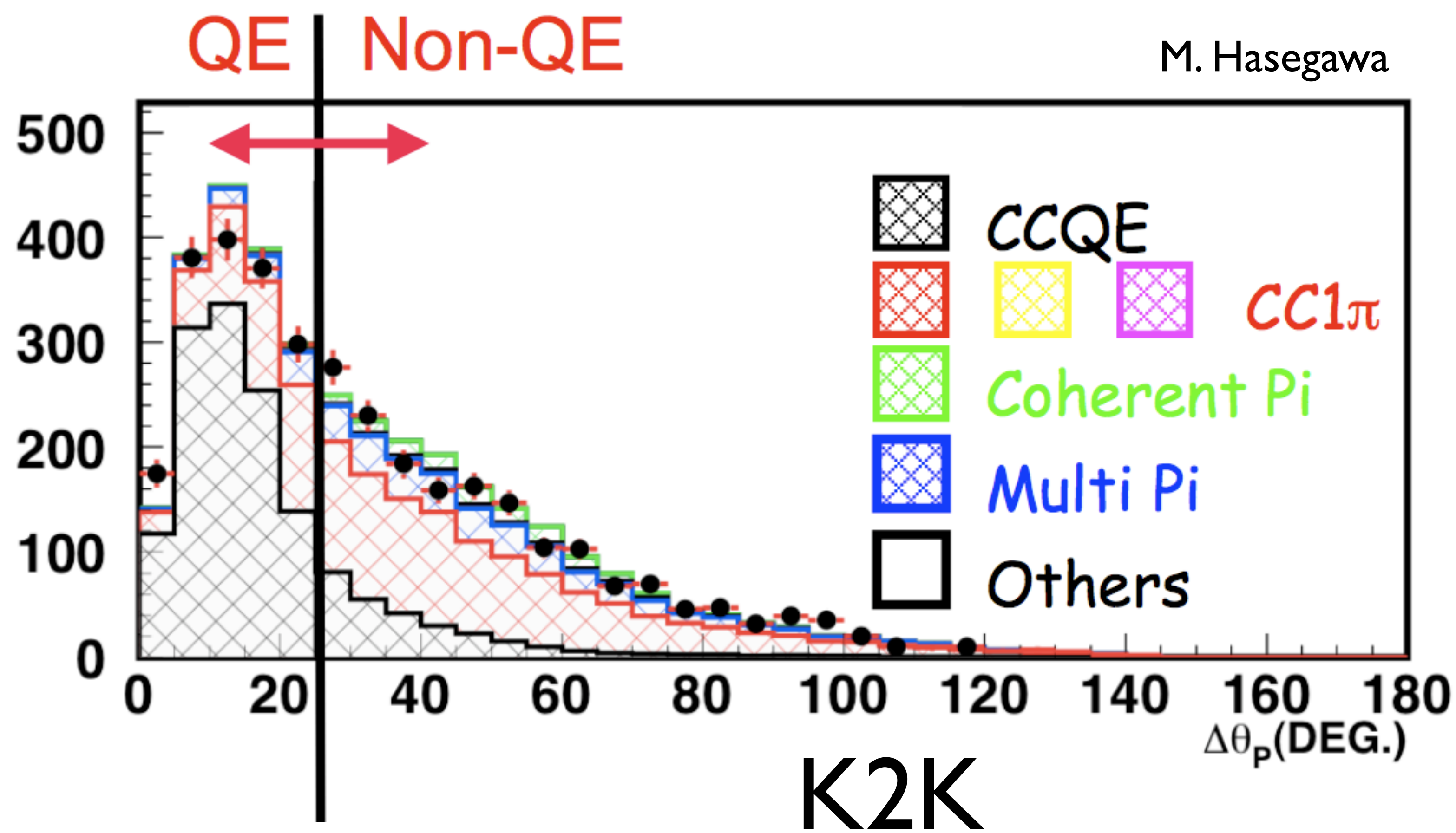
Rejecting QE events



$\Delta\theta_p$ is the angle between the second track and the predicted proton direction assuming CCQE reactions.



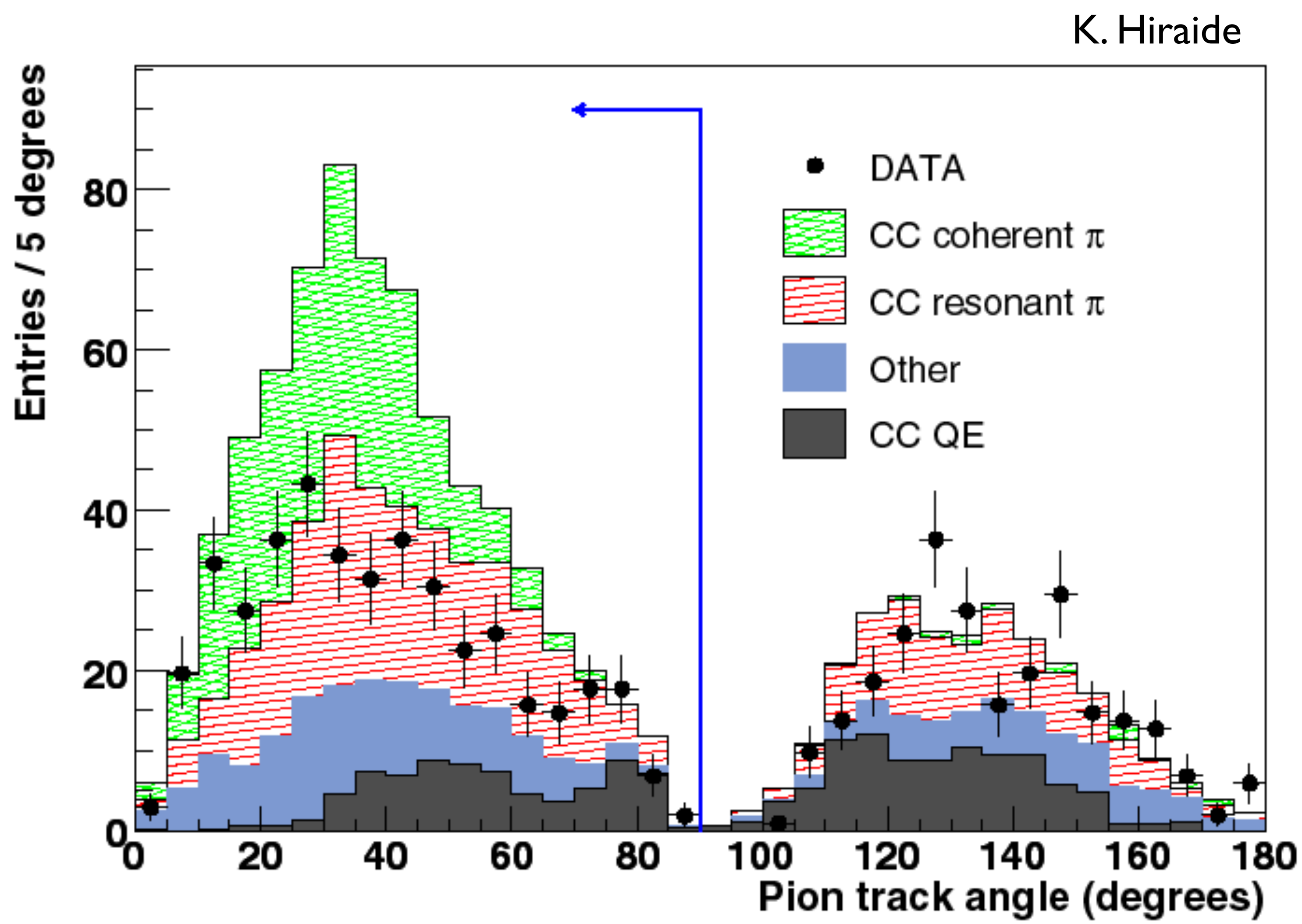
SciBooNE



K2K

SciBooNE

Resonant pion rejection



Events with a forward-going
Pion candidate are selected

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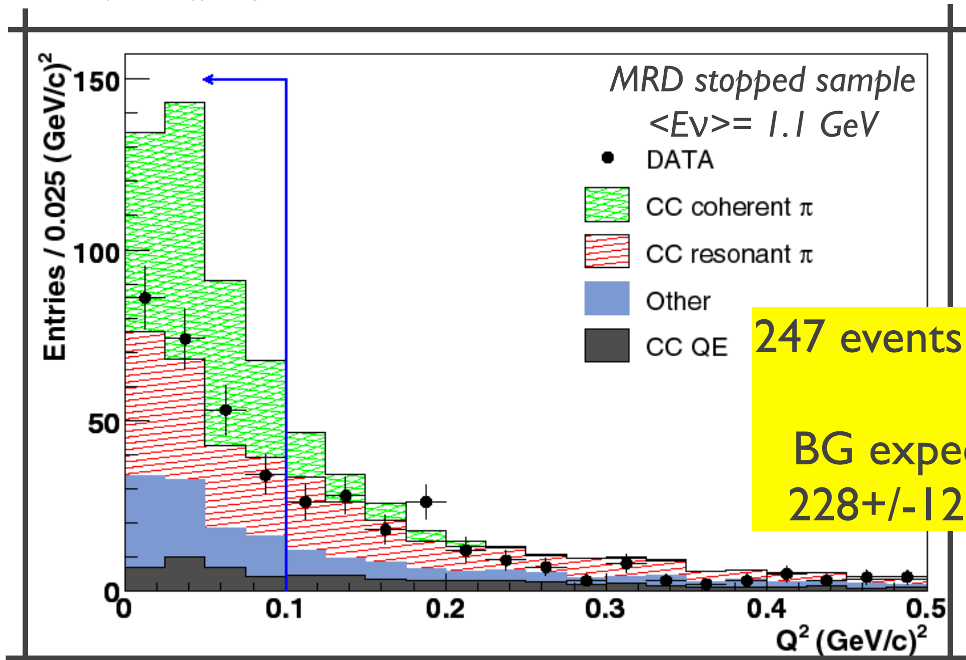
CC coherent pion sample

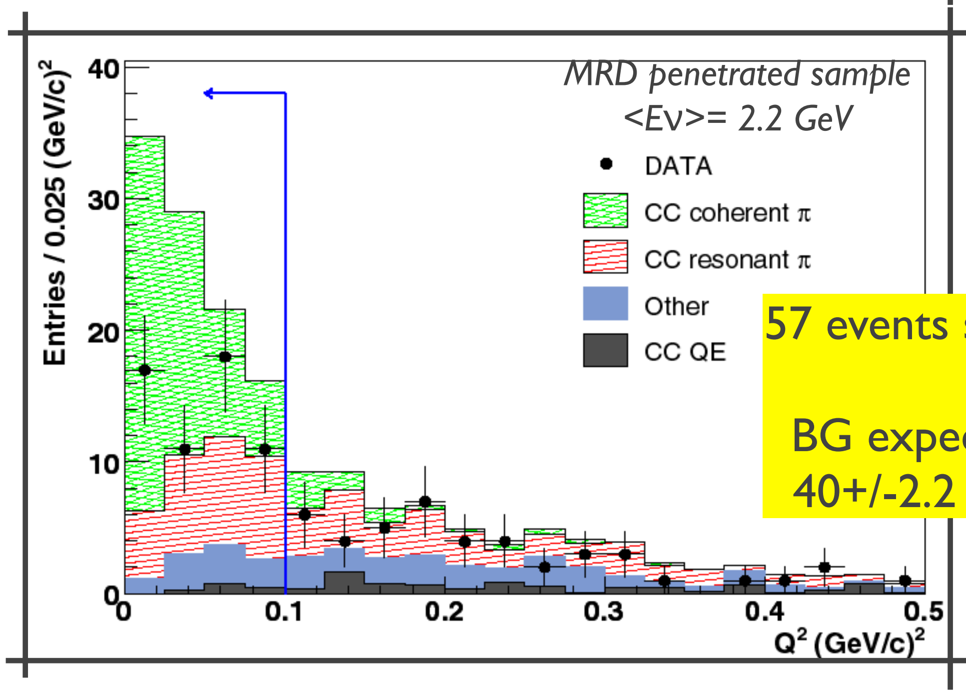
$Q^2 < 0.1\ (GeV/c)^2$

K. Hiraide



247 events selected

BG expectation 228+/-12 events

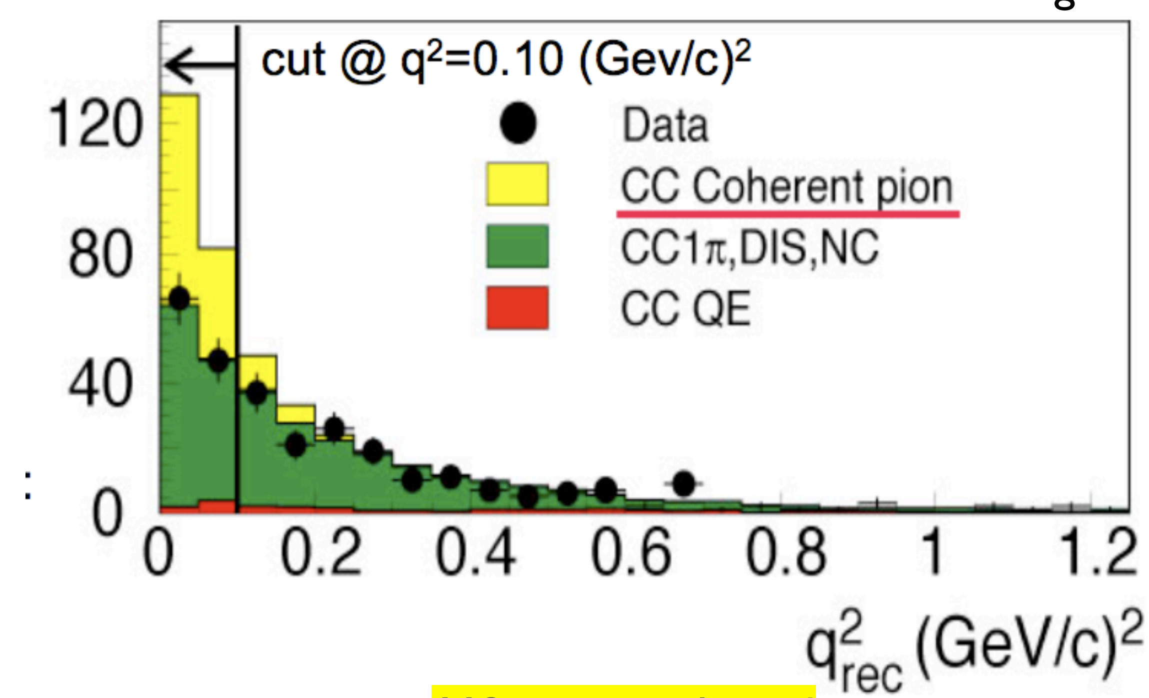


57 events selected

BG expectation 40+/-2.2 events

SciBooNE

M. Hasegawa



113 events selected

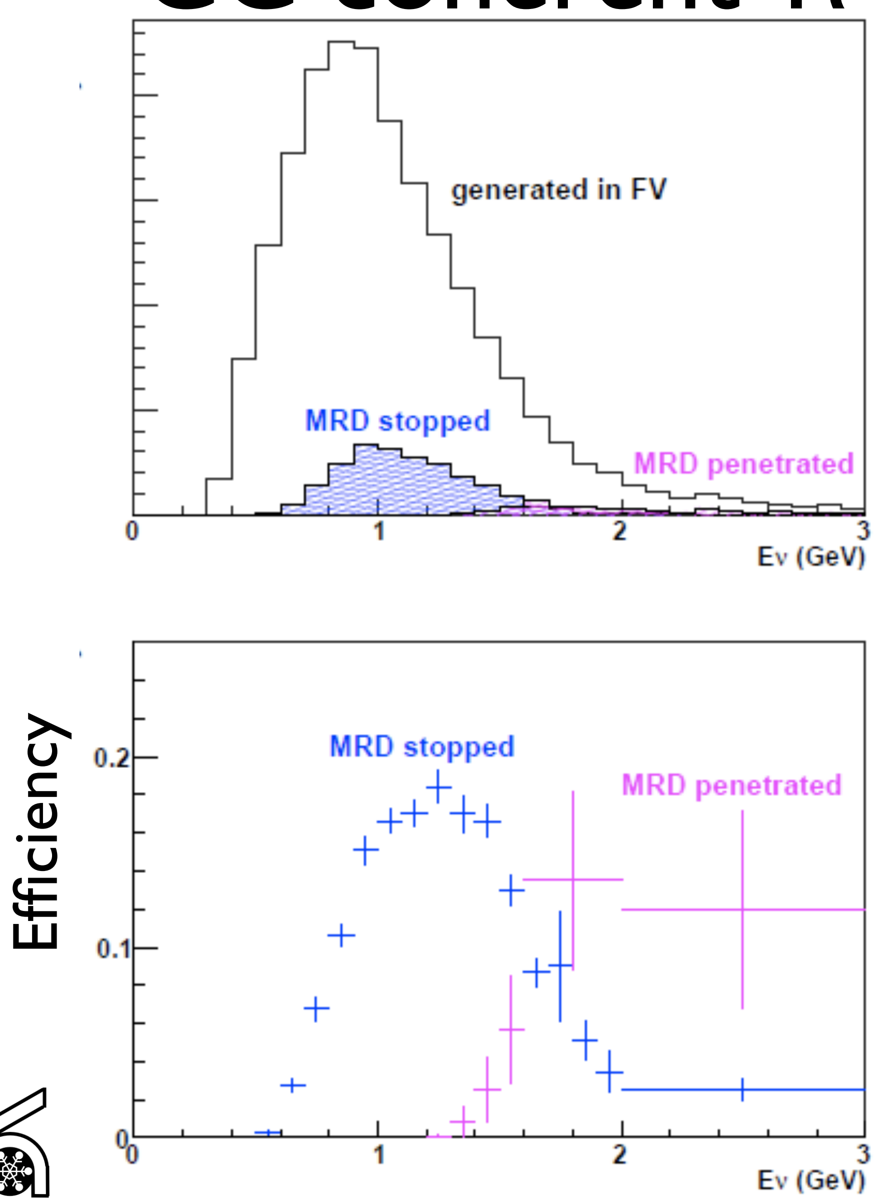
BG expectation 111.4+/-2.2 events

K2K

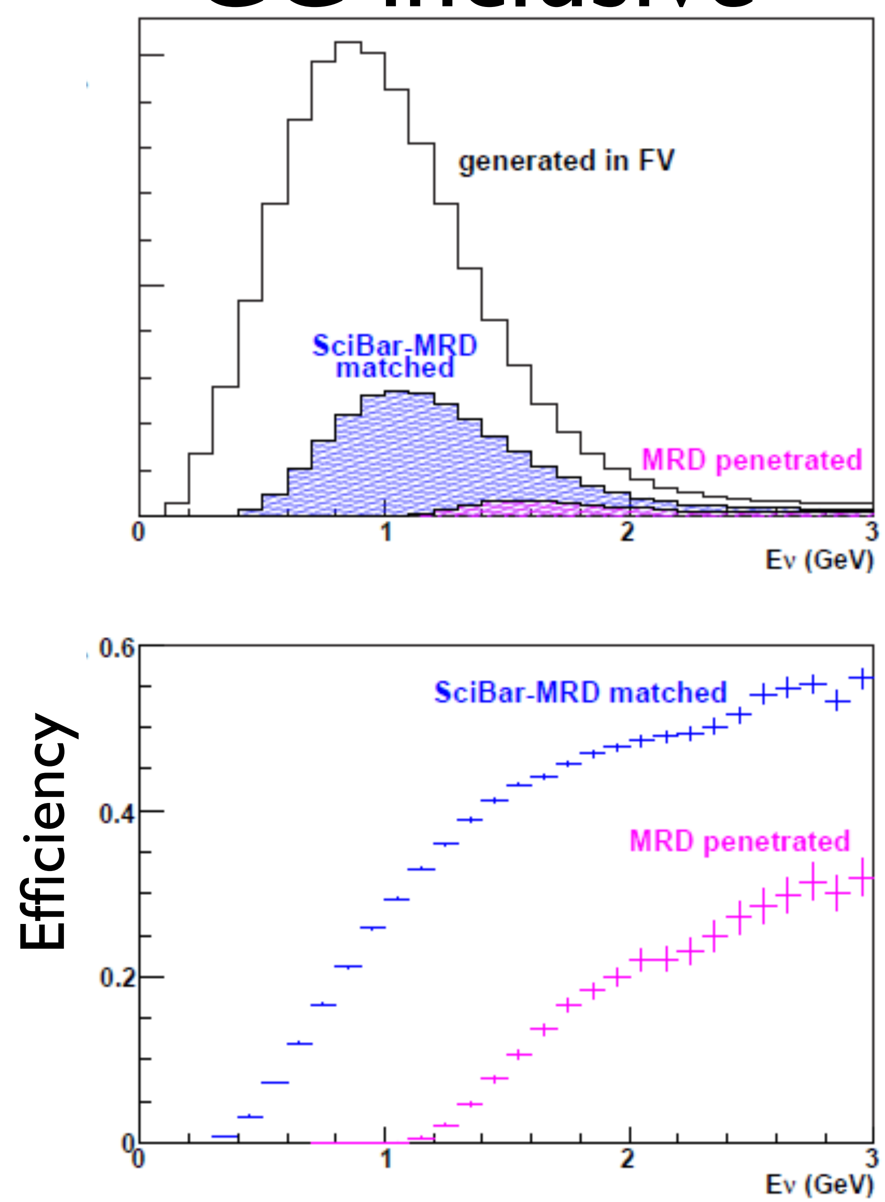
Cross section ratio

To reduce neutrino flux uncertainty, we measure
σ(CC coherent π)/σ(CC) cross section ratio

CC coherent π



CC inclusive



For denominator,
CC inclusive samples
are chosen so that
they cover similar
neutrino energy range
as coherent π samples.

Comparison

K2K (<Eν>=1.3 GeV)

$$\sigma(\text{CC coherent}\,\pi)/\sigma(\text{CC}) = (0.04 \pm 0.29(stat)^{+0.32}_{-0.35}(sys)) \times 10^{-2}$$

SciBooNE (<Eν>=1.1 GeV)

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

K2K result (90% CL U.L.=m+1.28*σ)

σ(CC coherent π)/σ(CC) < 0.60×10^{-2} for <Eν>=1.3 GeV

SciBooNE results (Bayesian 90% CL U.L.)

σ(CC coherent π)/σ(CC) < 0.67×10^{-2} for <Eν>=1.1 GeV

< 1.36×10^{-2} <Eν>=2.2 GeV

SciBooNE results are consistent with K2K result

Comparison

K2K (<Eν>=1.3 GeV)

$$\sigma(\text{CC coherent}\,\pi)/\sigma(\text{CC}) = (0.04 \pm 0.29(stat)^{+0.32}_{-0.35}(sys)) \times 10^{-2}$$

improved

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SciBooNE results are consistent with K2K result

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Comparison

K2K (<Eν>=1.3 GeV)

$$\sigma(\mathrm{CC\ coherent}\ \pi)/\sigma(\mathrm{CC}) = (0.04 \pm 0.29(stat)^{+0.32}_{-0.35}(sys)) \times 10^{-2}$$

improved

slightly improved

SciBooNE (<Eν>=1.1 GeV)

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

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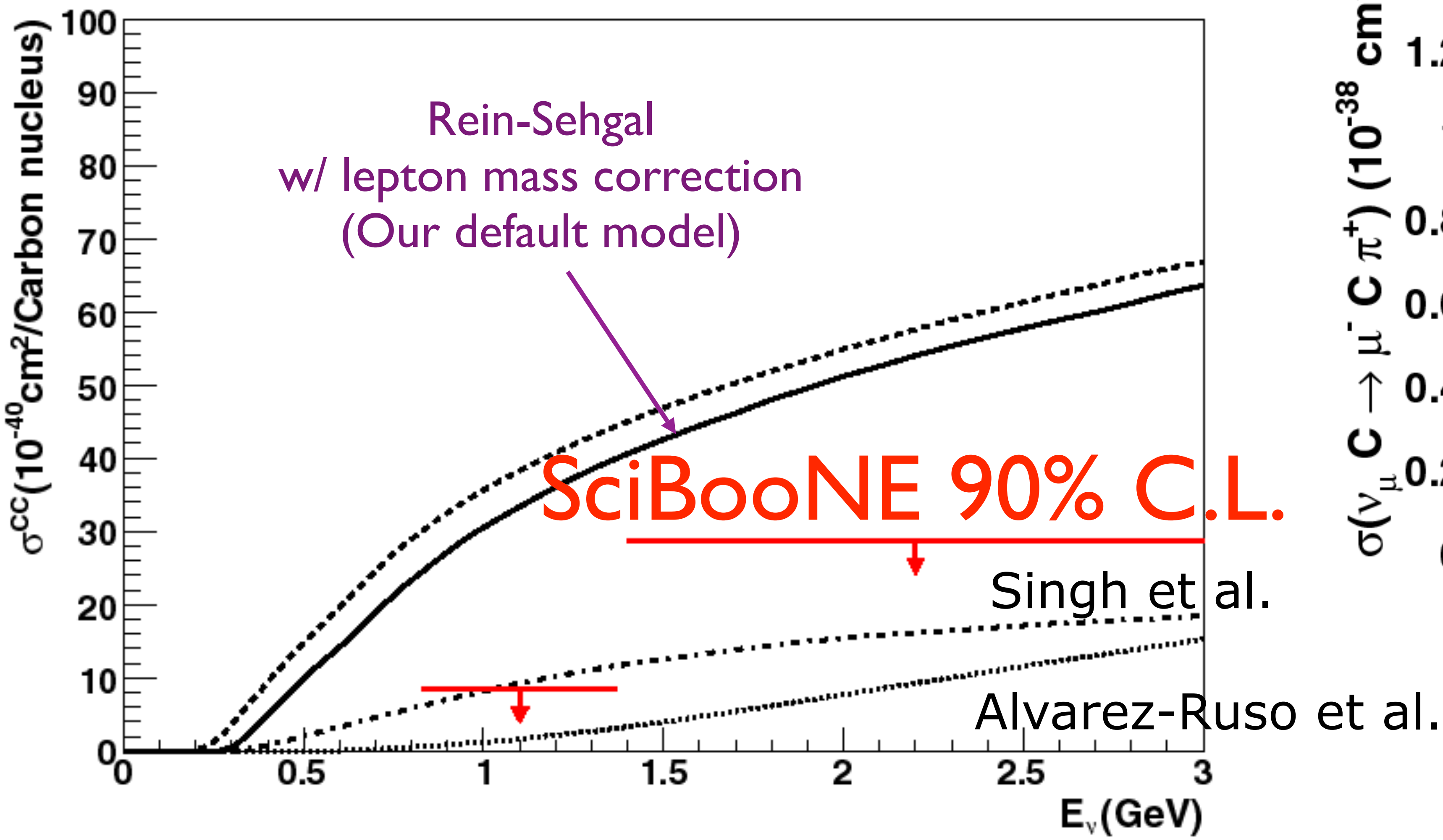
SciBooNE results are consistent with K2K result

SciBooNE Systematics

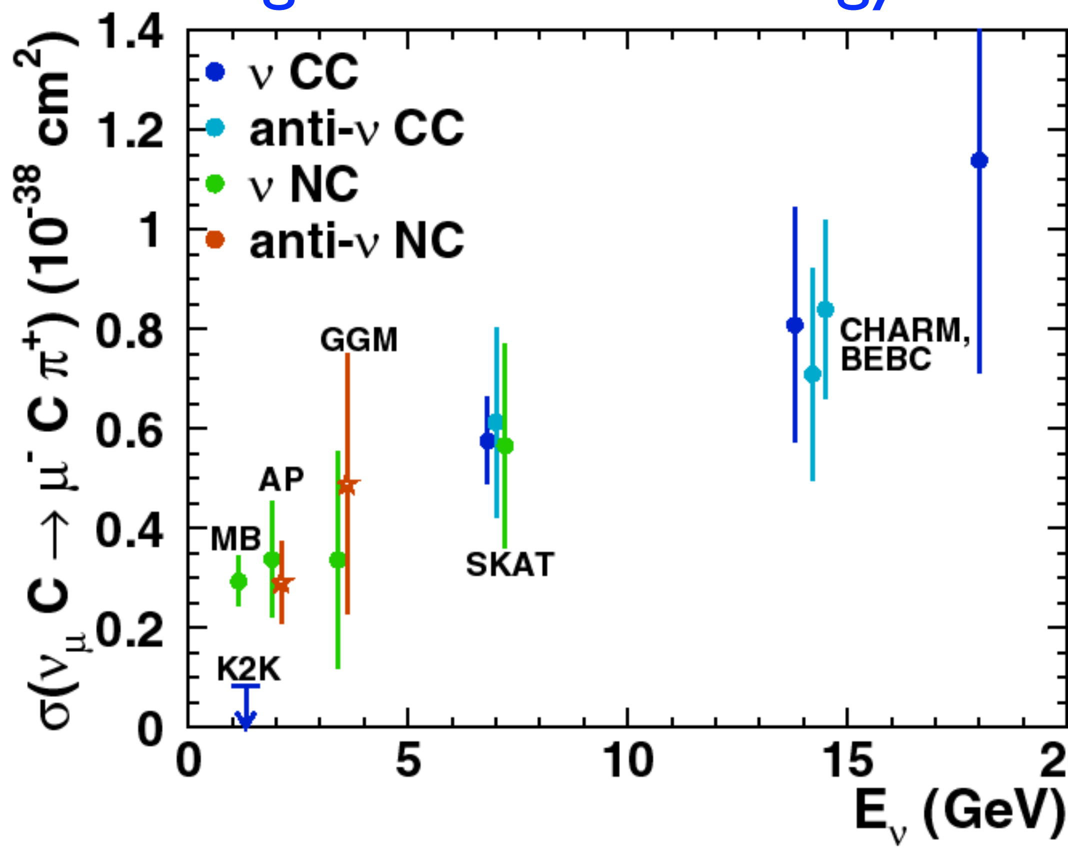
	MRD stopped Error ($\times 10^{-2}$)	MRD penetrated Error ($\times 10^{-2}$)
Detector response	+0.10 / -0.18	+0.18 / -0.18
Nuclear effect	+0.20 / -0.07	+0.19 / -0.09
Neutrino interaction model	+0.17 / -0.04	+0.08 / -0.04
Neutrino beam	+0.07 / -0.11	+0.27 / -0.13
Event selection	+0.07 / -0.14	+0.06 / -0.05
Total	+0.30 / -0.27	+0.39 / -0.25

Discussion

Comparison with theoretical models



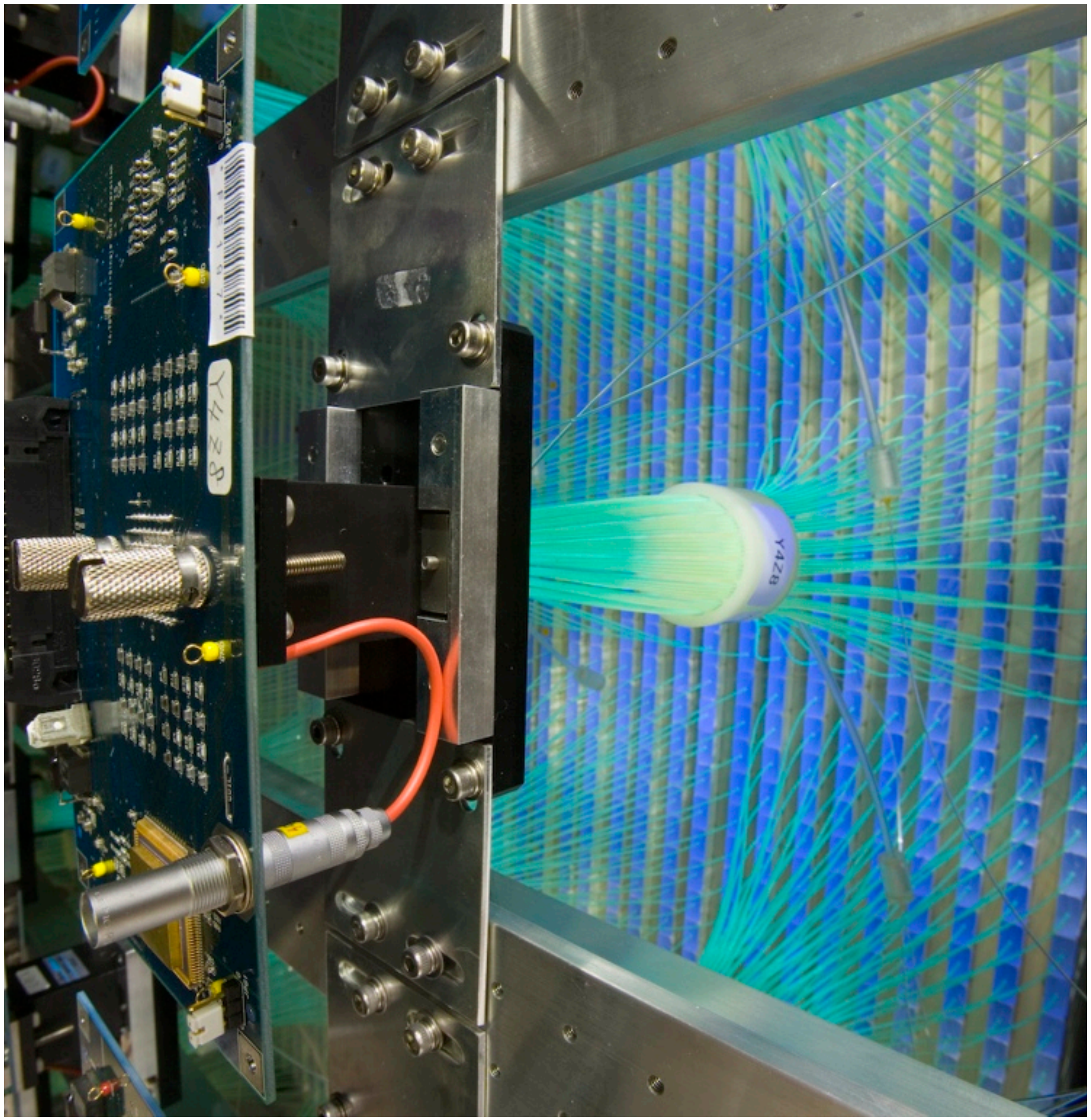
Other measurements at higher neutrino energy

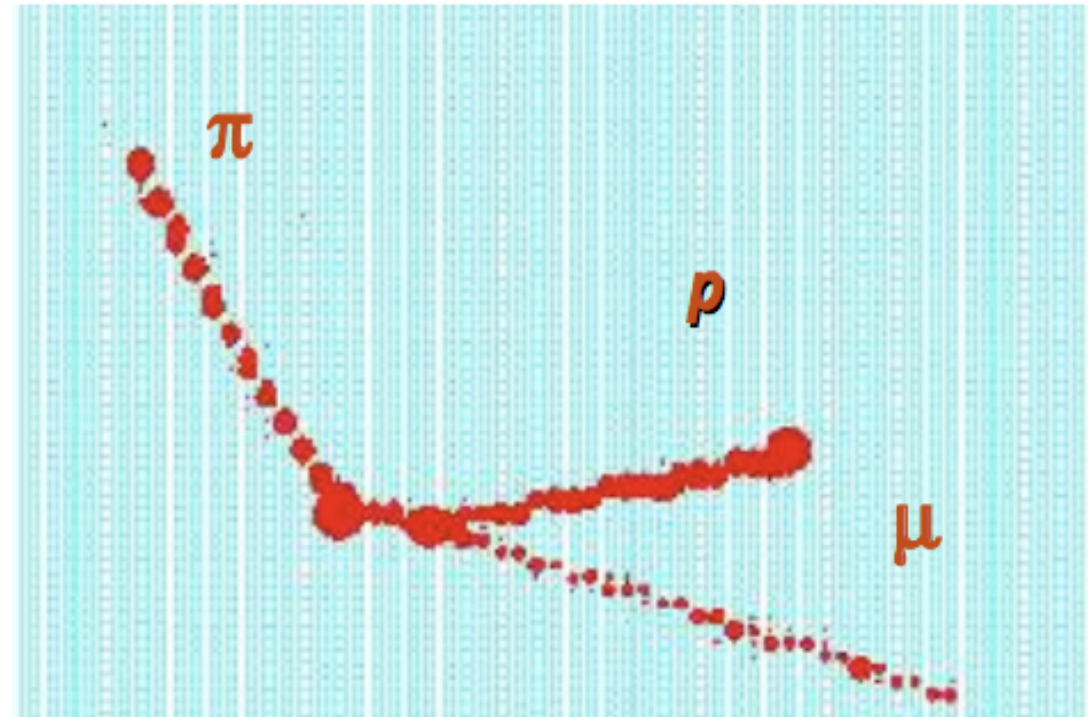


assuming
- $A^{2/3}$ dependence
- σ(CC coh)=2*σ(NC coh)

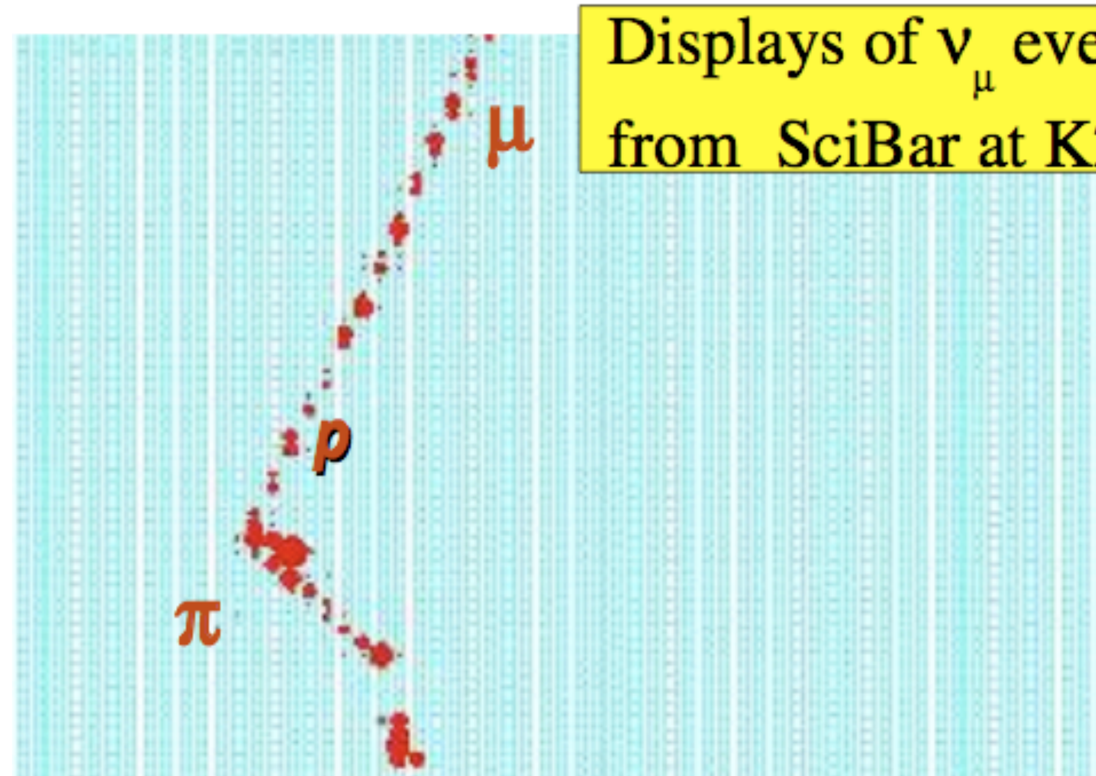
Measured upper limits on σ(CC coherent π)/σ(CC) ratios are converted to upper limits on absolute cross sections by using σ(CC) predicted by MC simulation

K2K SciBar CC1pi





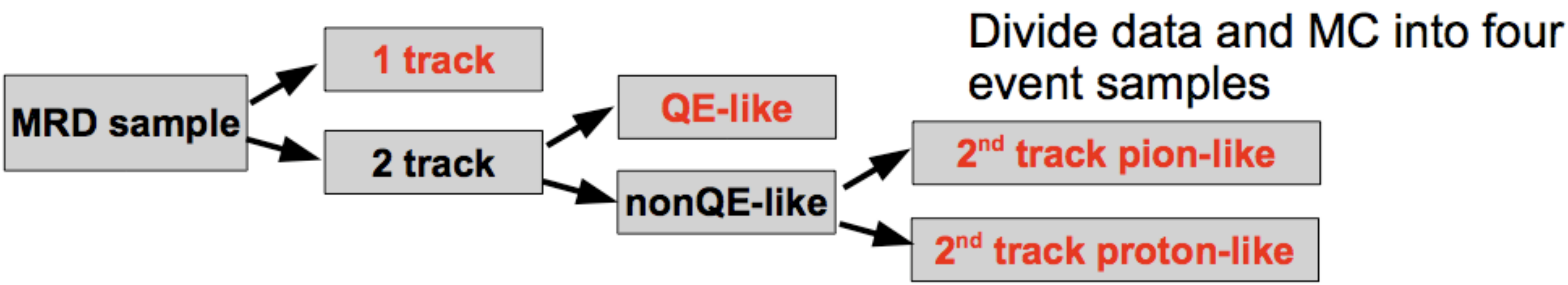
Displays of ν_μ events from SciBar at K2K



Method and Goals

L. Whitehead, NuInt07

Bin the data using muon kinematic variables and perform a maximum likelihood fit based on Poisson statistics



MC events further divided based on:

- **interaction type** – CCQE, CC1π^+, and background.
- **true neutrino energy**

Data and MC binned in **p_μ vs. θ_μ bins** (0.2 GeV/c, 10° bins)

Fit gives number of CCQE, CC1π^+, and bkgd. interactions in data relative to MC – can extract cross section ratio from this

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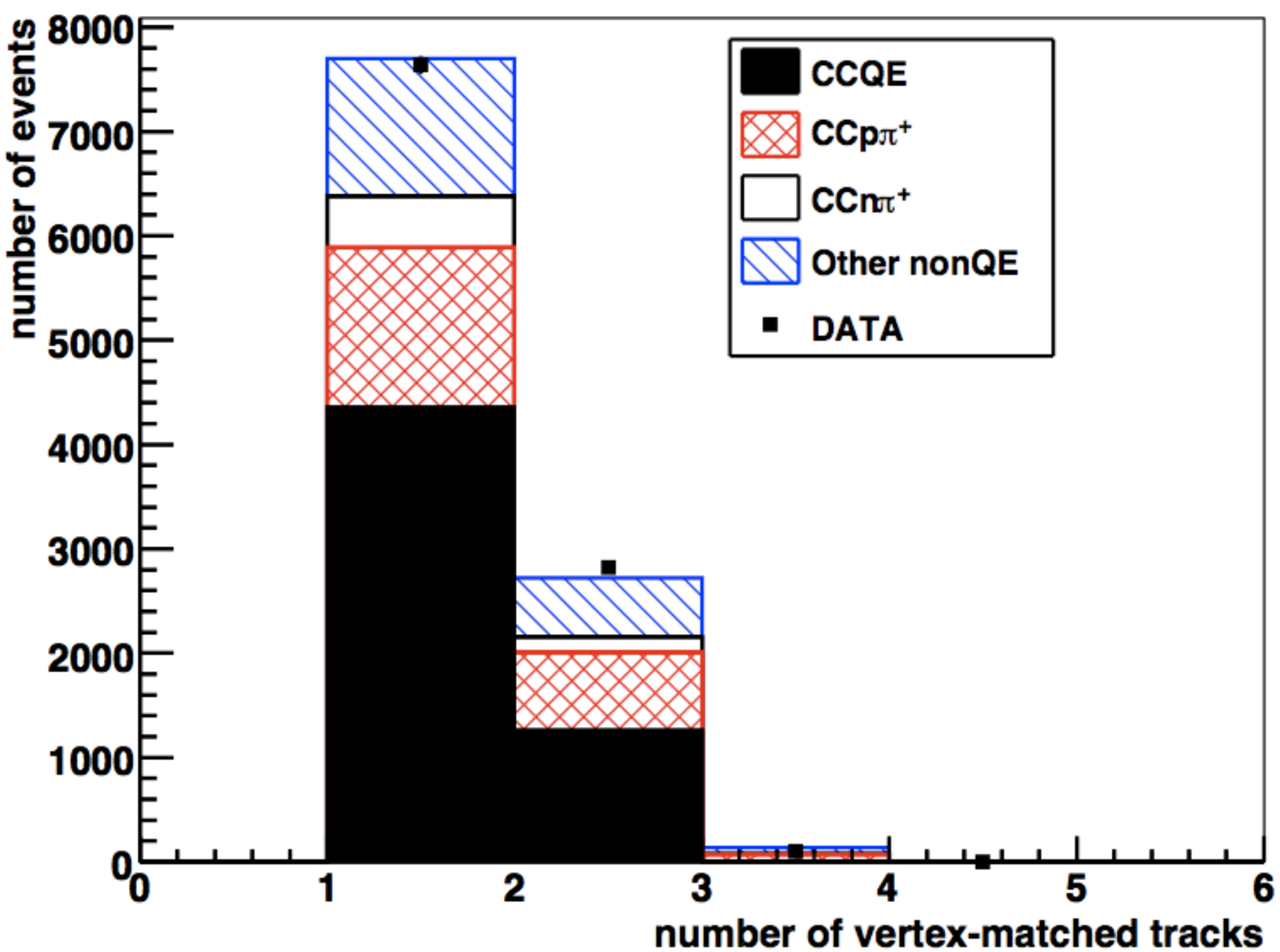
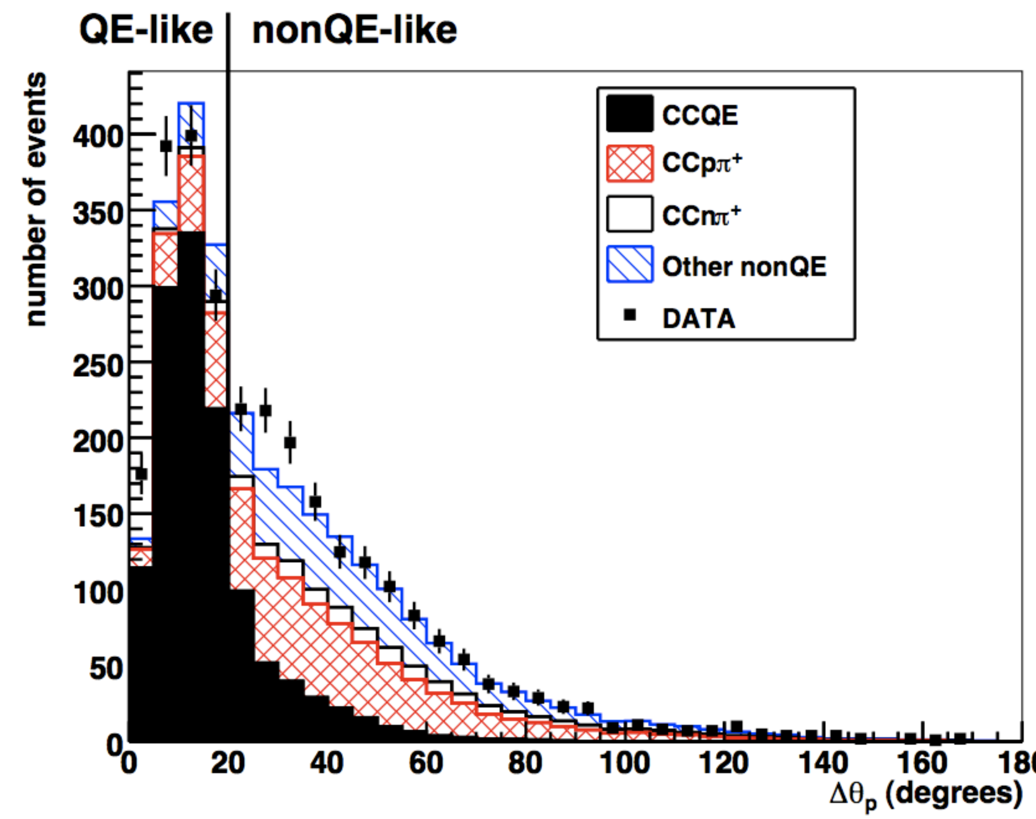
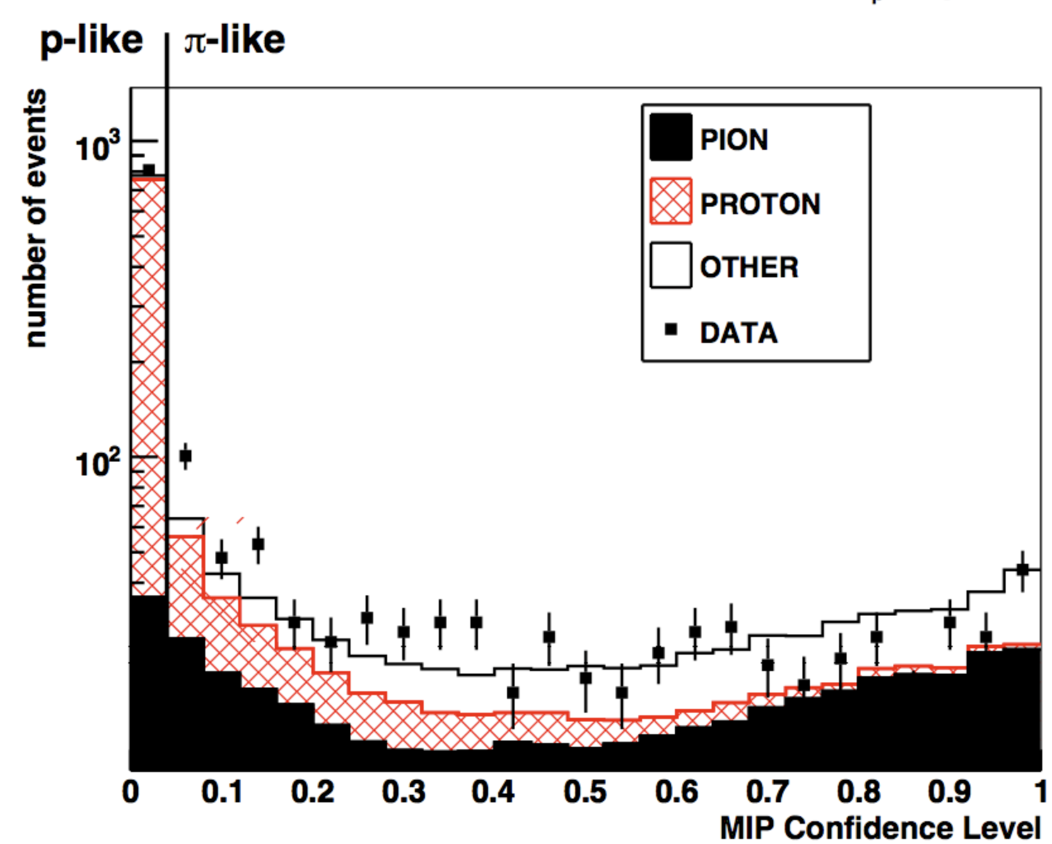
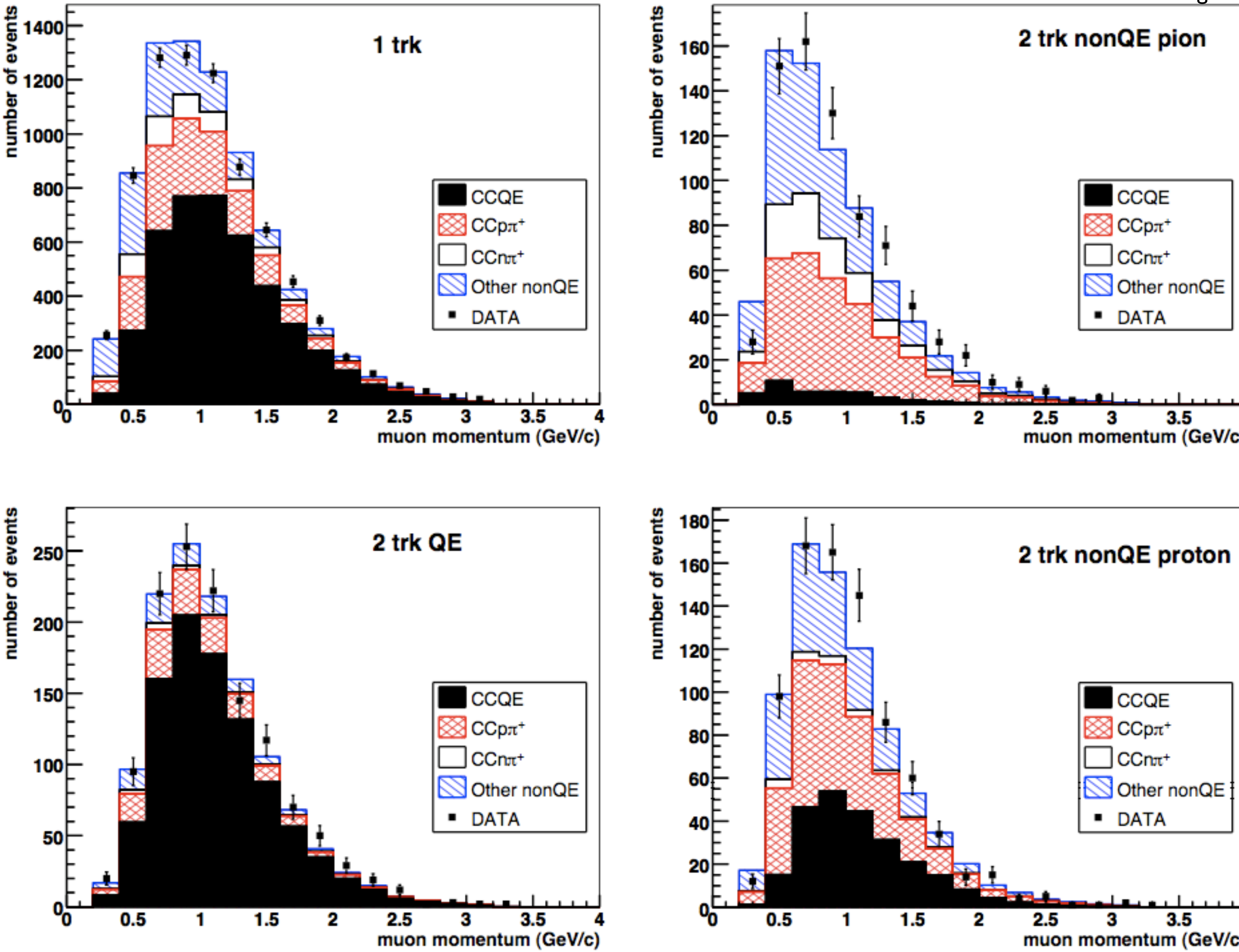
Event Selection

A. Rodriguez








1 trk
number of events
muon momentum (GeV/c)
CCQE
CCpπ+
CCnπ+
Other nonQE
DATA
2 trk nonQE pion
number of events
muon momentum (GeV/c)
CCQE
CCpπ+
CCnπ+
Other nonQE
DATA
2 trk QE
number of events
muon momentum (GeV/c)
CCQE
CCpπ+
CCnπ+
Other nonQE
DATA
2 trk nonQE proton
number of events
muon momentum (GeV/c)
CCQE
CCpπ+
CCnπ+
Other nonQE
DATA

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Fitting procedure

$$F = 2\sum_{i,j}\left[N_{i,j}^{exp} - N_{i,j}^{obs} + N_{i,j}^{obs}\ln\frac{N_{i,j}^{obs}}{N_{i,j}^{exp}}\right]$$

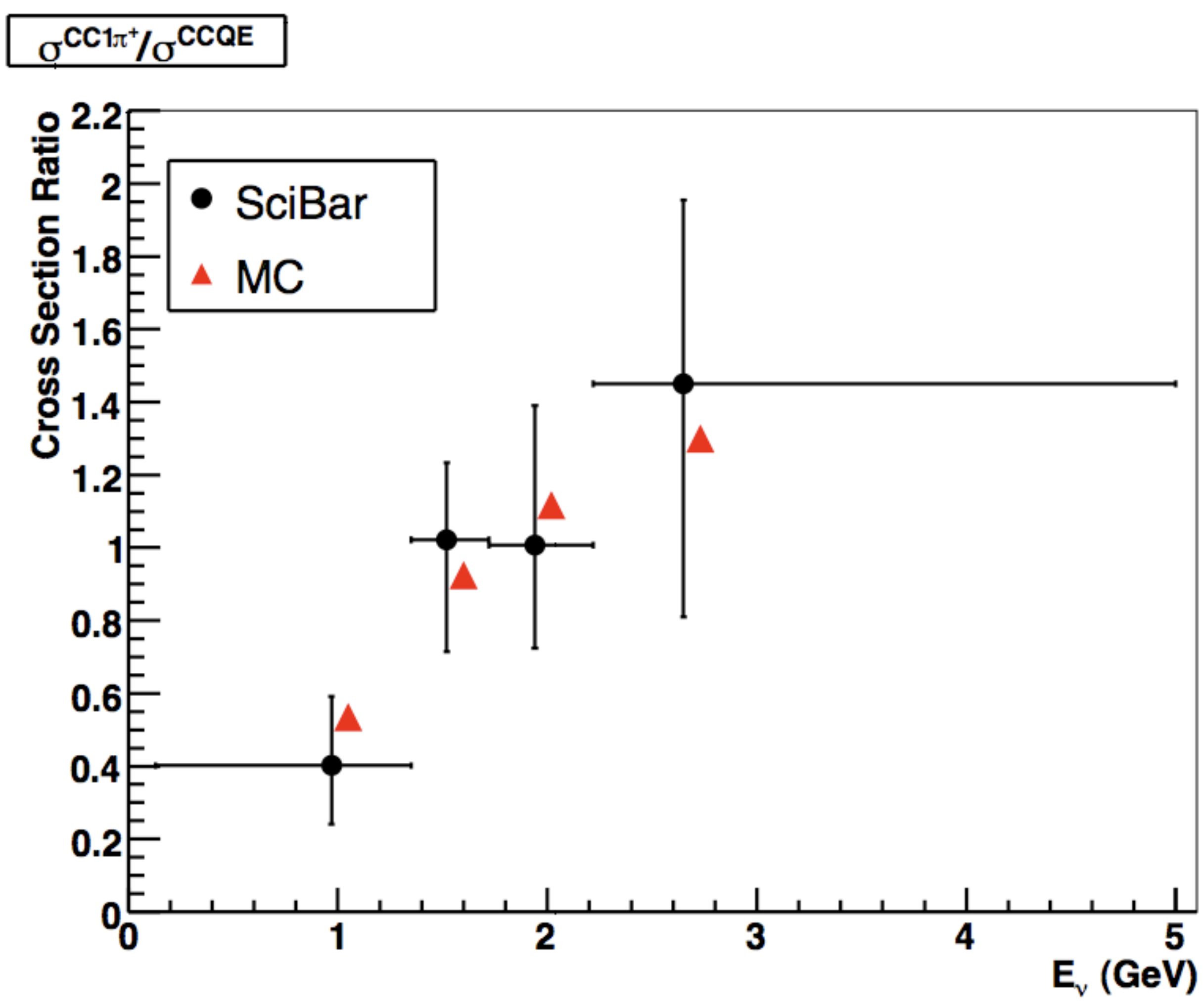
$i = p_\mu, \theta_\mu$ bins

j=data samples

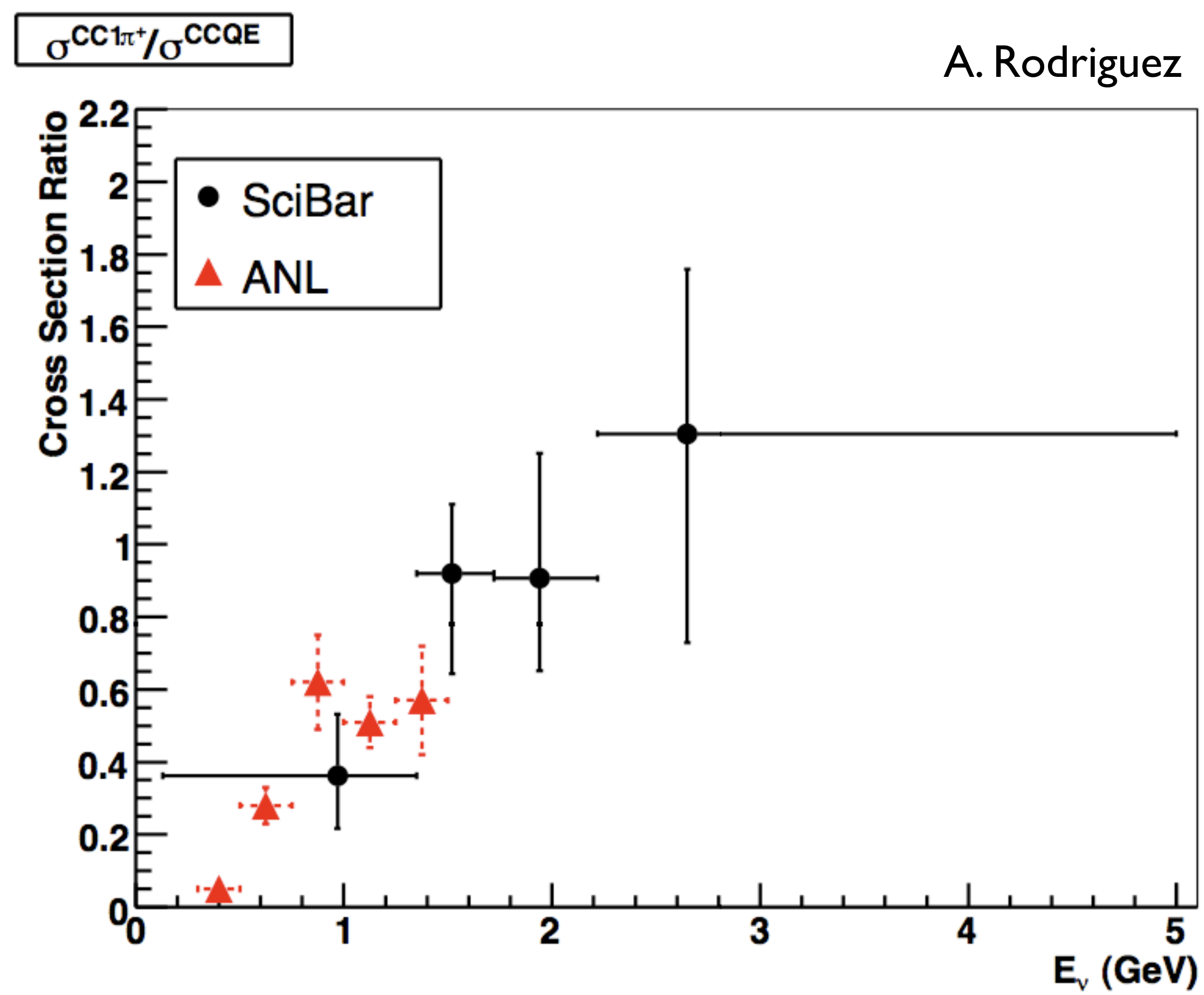
$$N_{i,j}^{exp} = \alpha[N_{i,j}^{CCQE} + \sum_k (R_k^{CC1\pi^+} N_{i,j,k}^{CC1\pi^+}) + R^{OtherNonQE} N_{i,j}^{OtherNonQE}],$$

α, $R^{CC1\pi^+}$, $R^{OtherNonQE}$, P^{sc} are free parameters in fit

Results



A. Rodriguez



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Systematics

Condition	ΔR_0	ΔR_1	ΔR_2	ΔR_3
Nuclear				
π absorption	+0.023 +0.068	+0.007 −0.052	+0.128 +0.101	+0.197 −0.010
π scattering	+0.032 +0.013	+0.069 −0.173	+0.154 +0.026	+0.013 −0.231
p rescattering	−0.071 +0.025	−0.119 −0.019	−0.065 +0.059	−0.141 −0.086
Fermi momentum	±0.004	±0.021	±0.008	±0.029
Other				
M_A^{QE}	−0.038 +0.017	−0.053 +0.048	−0.032 +0.021	−0.276 +0.271
Bodek & Yang	+0.007 −0.013	+0.006 −0.021	+0.020 −0.032	−0.053 −0.044
E_ν Spectrum	+0.083 −0.078	+0.060 −0.080	+0.188 −0.164	+0.040 −0.221
Crosstalk	+0.024 +0.087	+0.031 −0.079	+0.103 +0.075	+0.052 −0.216
PMT 1 p.e. Resolution	−0.005 −0.017	+0.011 −0.025	+0.025 −0.003	−0.018 −0.083
Birks' Constant	+0.010 +0.044	−0.024 +0.047	−0.005 +0.099	−0.054 −0.135
Hit Threshold	±0.014	±0.045	±0.012	±0.168
Angular Resolution	±0.013	±0.001	±0.022	±0.039
MC Statistics	±0.006	±0.015	±0.017	±0.037
Total	+0.153 −0.116	+0.130 −0.258	+0.319 −0.185	+0.386 −0.552

References

- MiniBooNE CC1π/CCQE
  - NuInt05 & NuInt07 proceedings
  - hep-ex/0602050
- SciBooNE CC coherent pi
  - Phys.Rev.D **78** 112004 (2008); arXiv:0811.0369[hep-ex]
- K2K CC coherent pi
  - Phys.Rev.Lett. **95** (2005) 252301; hep-ex/0506008
- K2K CC1pi/CCQE
  - Phys.Rev.D**78** (2008) 032003 arXiv:0805.0186v2[hep-ex]

Future Measurements

- MiniBooNE CC1π/ CCQE ratio
- MiniBooNE CC1π differential cross section
  - New fitter
- SciBooNE CC1π inclusive/exclusive cross section

M.Wilking