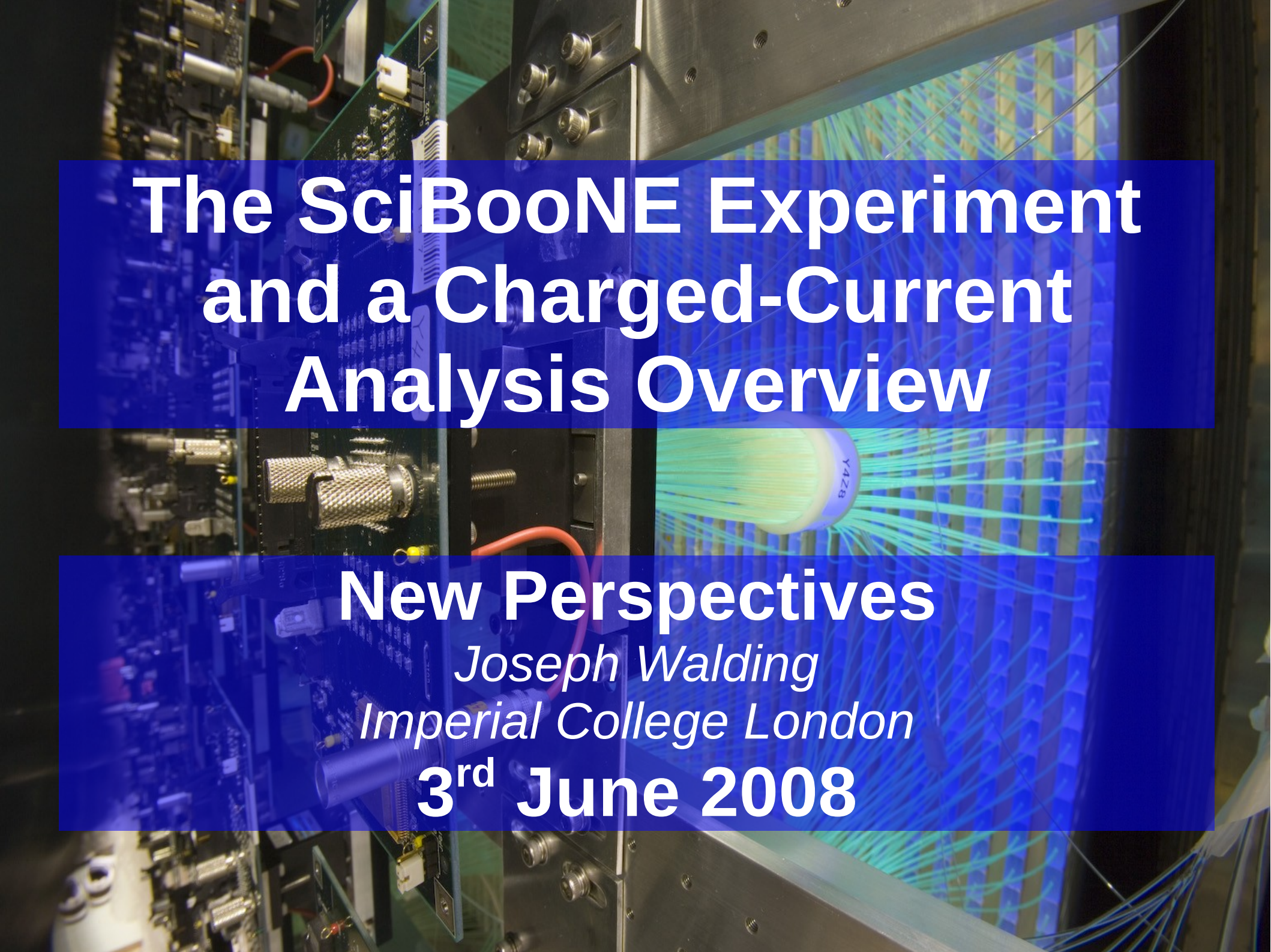


The SciBooNE Experiment and a Charged-Current Analysis Overview

New Perspectives

Joseph Walding
Imperial College London

3rd June 2008

Outline

- Why measure neutrino cross-sections?
- Why measure low energy neutrino cross-sections?

- **SciBooNE**
  - Experimental Overview
  - Detector Overview
  - Construction & Data Run
- **Status of charged-current analyses**
  - CC-inclusive, CCQE, $CC\pi^+$, $CC\pi^0$
- **Summary**

Neutrino x-sections

- Neutrino cross-section measurements vital to neutrino oscillation measurements
  - $\mathbf{N_\nu(E) = \varepsilon \times \Phi_\nu(E) \times \sigma_\nu(E)}$
    - $N_\nu(E)$ = Number of events observed
    - ε = Detector efficiency (experiment specific)
    - $\Phi_\nu(E)$ = Neutrino flux (experiment specific)
    - $\sigma_\nu(E)$ = Neutrino cross-section (universal)
- With the next generation of experiments about to start measuring neutrino cross-sections is crucial

- Atmospheric and long baseline oscillation experiments use low energy (~GeV) neutrinos

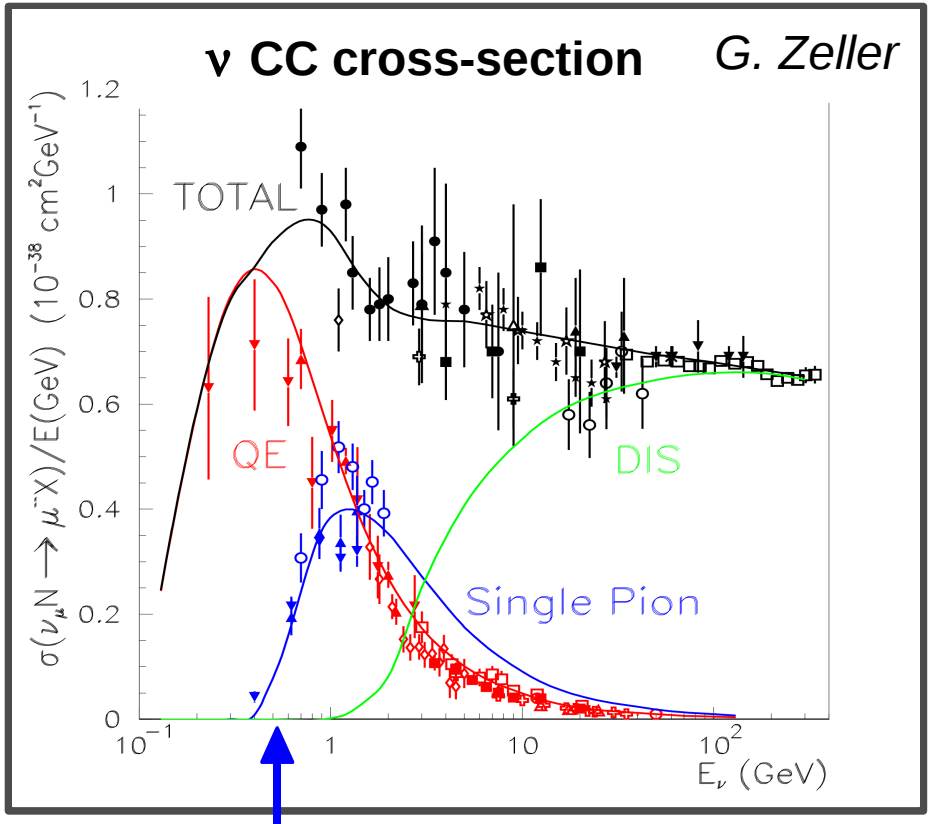
$$P_{\alpha \to \beta} \propto \sin^2\left(1.267 \frac{\Delta m^2 L}{E}\right)$$

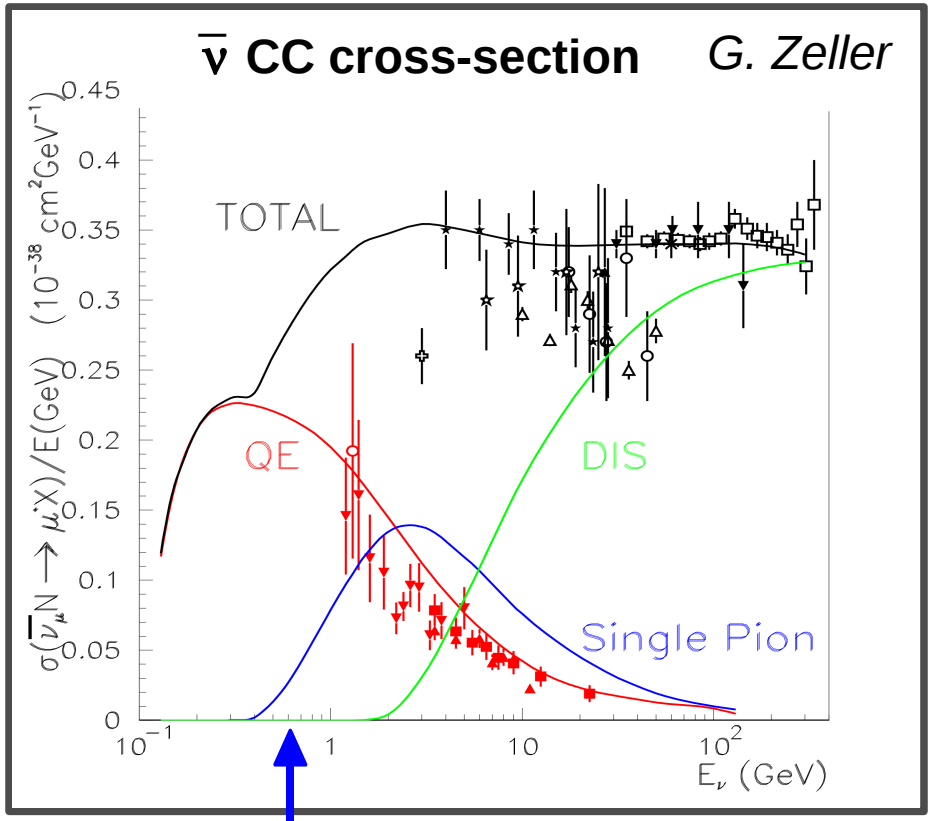
  - Where L(km), E(GeV), Δm^2(eV)
- If $L \sim 10^2$ km & $\Delta m^2 \sim 10^{-3} eV^2$
- Maximise oscillation probability:
  - Require O(1) GeV energy neutrino
- Therefore GeV cross-section measurements vital for neutrino programme

Low E x-sections

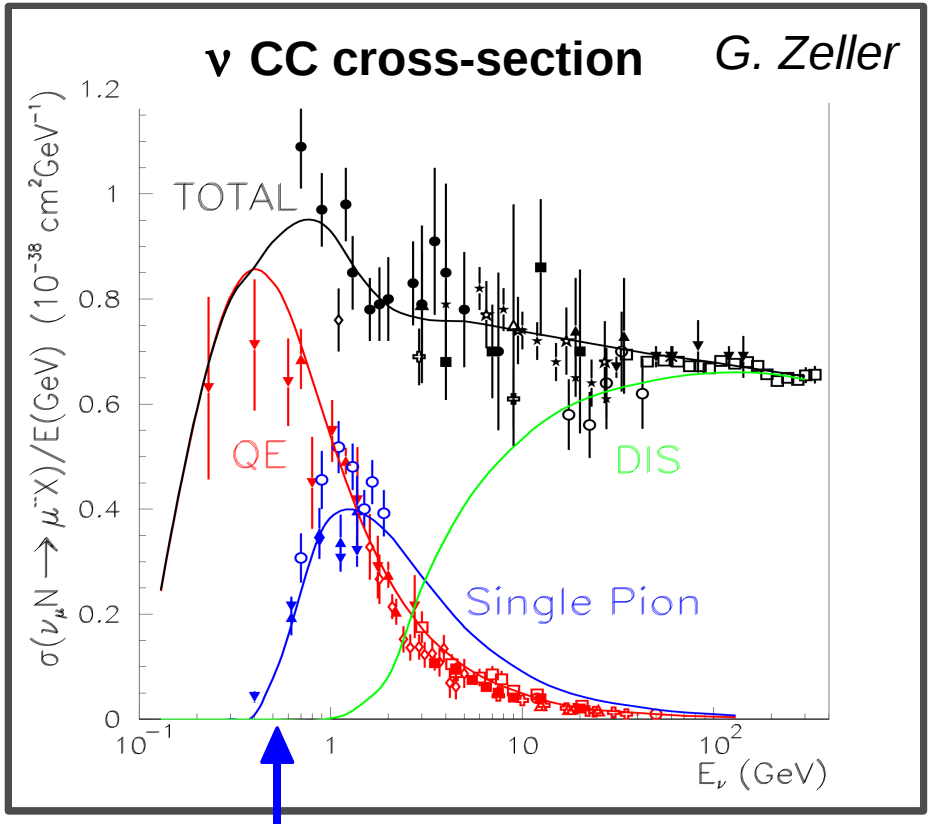
Good understanding of high E cross-sections (DIS)
Low E is different regime:

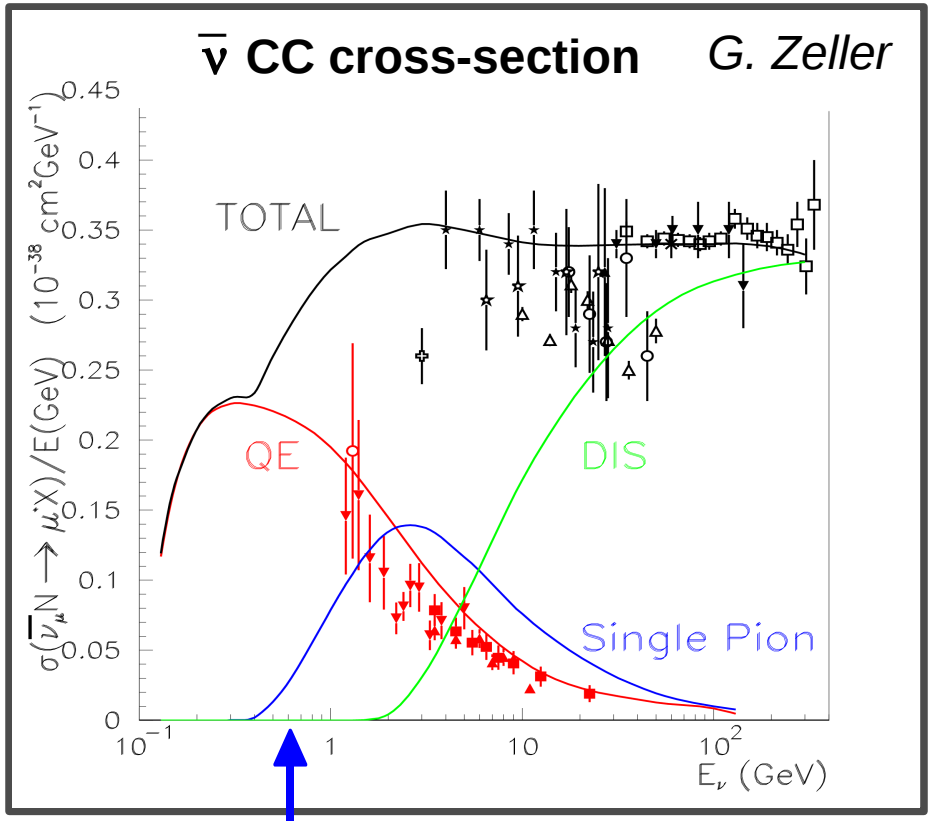
- Quasi-elastic (QE) and single pion (1π) events dominate
- No single dominant interaction mode
- In T2K signal and backgrounds are hard to distinguish





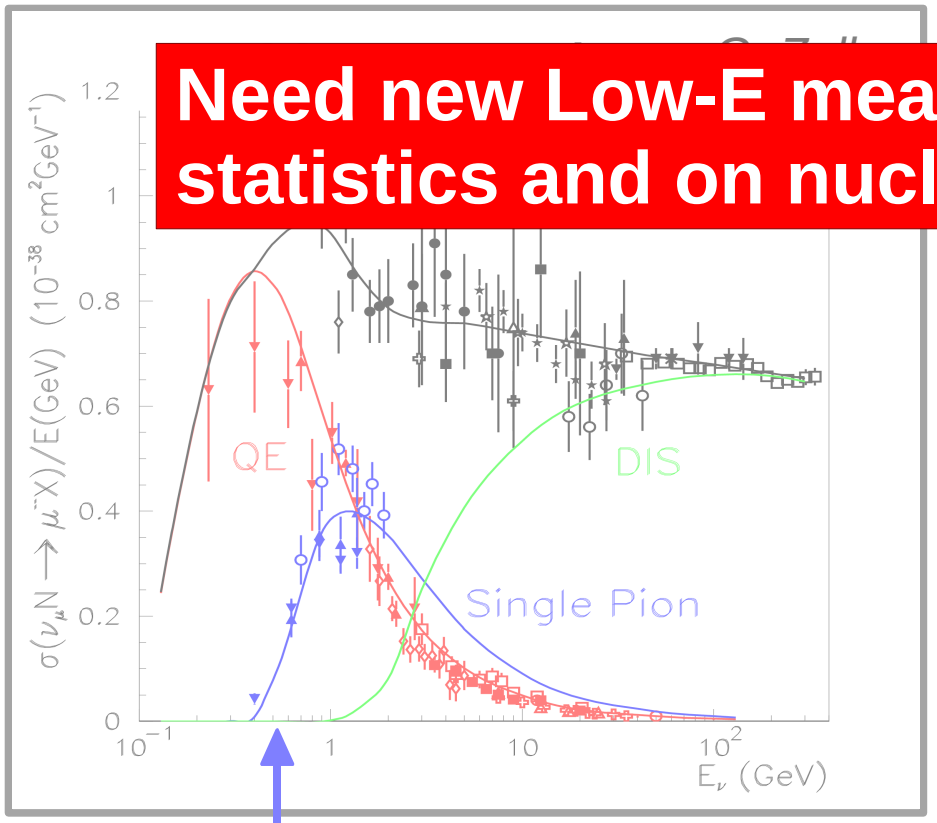
- Previous measurements from 70s-80s
  - Mostly H_2 & D_2 targets
  - Sample size of order hundreds
- No measurements of sub-GeV $\bar{\nu}$ cross-sections
  - Important for ~~CP~~ studies

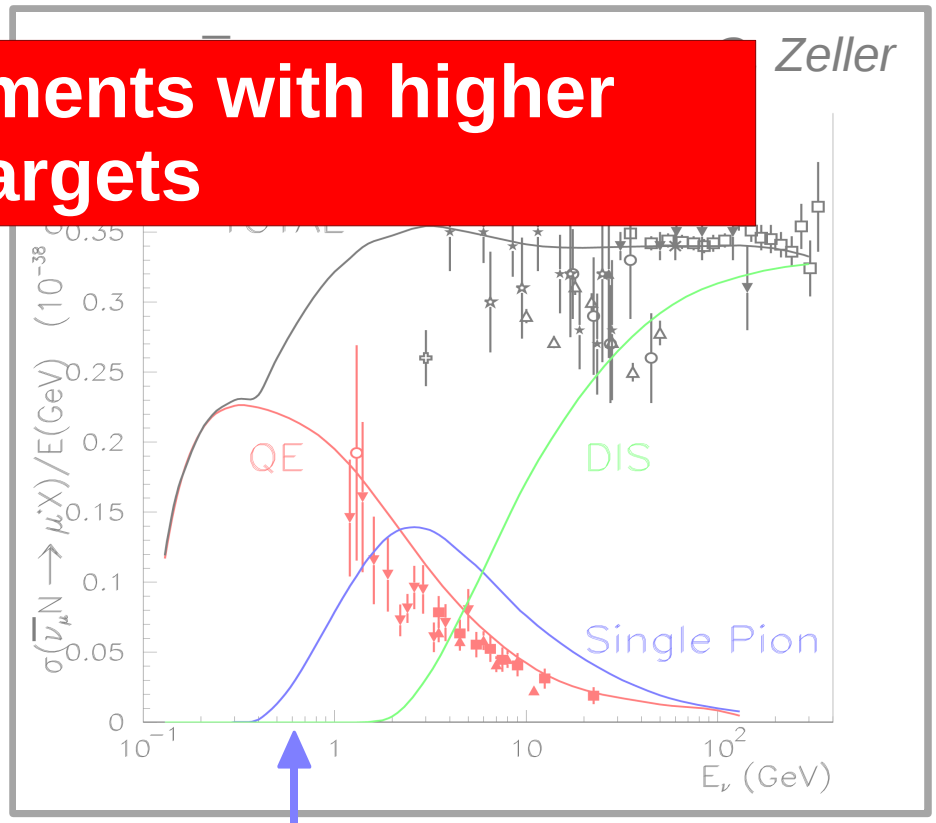




- Previous measurements from 70s-80s
  - Mostly H_2 & D_2 targets
  - Sample size of order hundreds
- No measurements of sub-GeV $\bar{\nu}$ cross-sections
  - Important for ~~CP~~ studies

Need new Low-E measurements with higher statistics and on nuclear targets



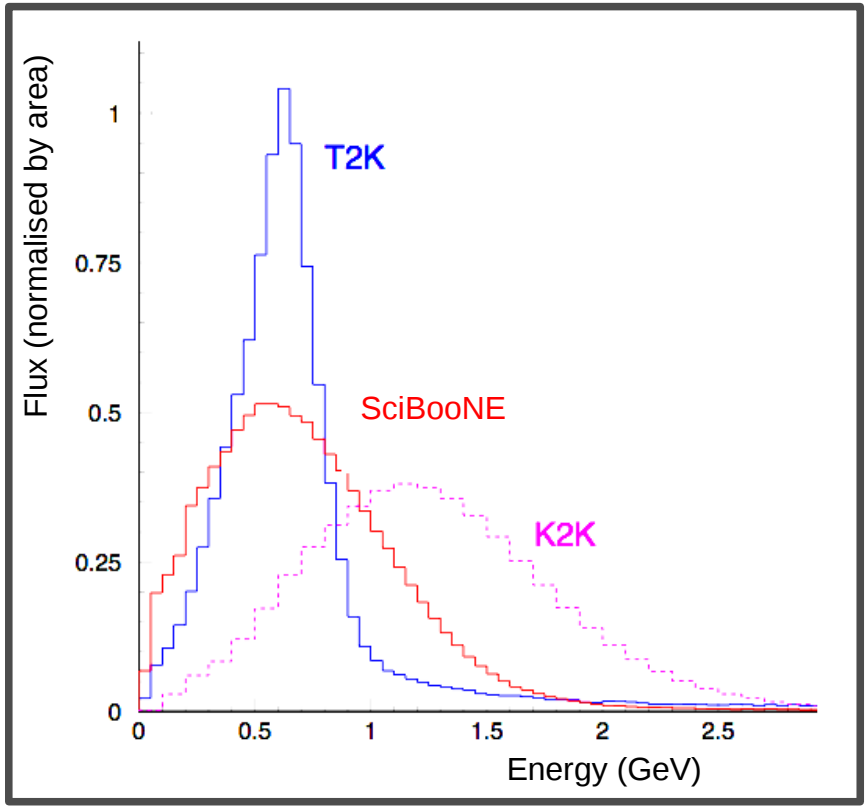


SciBooNE Experiment

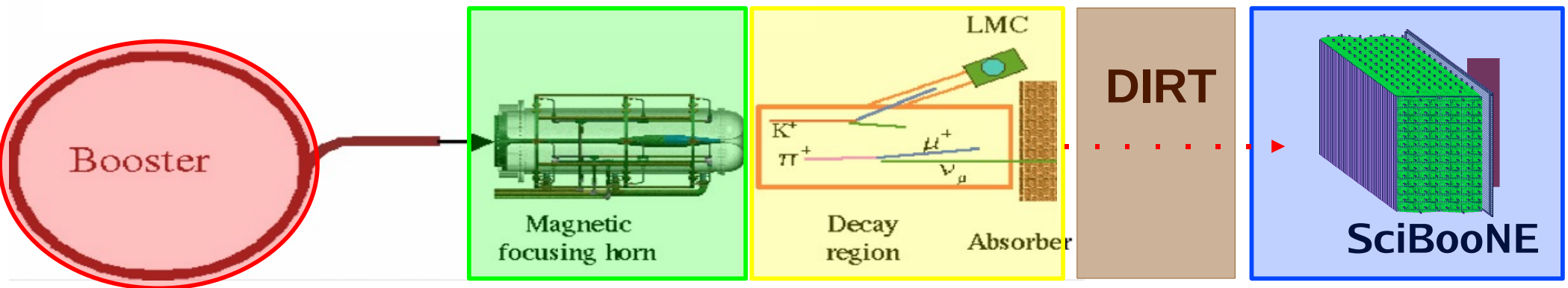
- Universitat Autonoma de Barcelona
- University of Cincinnati
- University of Colorado, Boulder
- Columbia University
- Fermi National Accelerator Laboratory
- High Energy Accelerator Research
- Organization (KEK)
- Imperial College London
- Indiana University
- Institute for Cosmic Ray Research (ICRR)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

A selection of SciBooNE collaborators at the last collaboration meeting. March 2008

- SciBooNE: A 'ν' experiment at Fermilab
- Aim to measure sub-GeV ν_μ & $\bar{\nu}_\mu$ cross-sections
  - Tracking detector
  - Higher statistics (>20,000 charged-current-inclusive ν-mode events)
  - Nuclear target
- T2K beam flux peak energy same as Booster neutrino beam (right)
  - Measurement very useful for T2K
  - Independent data set
- SciBooNE also a MiniBooNE near detector
  - ν_e appearance/backgrounds
  - ν_μ disappearance/normalisation

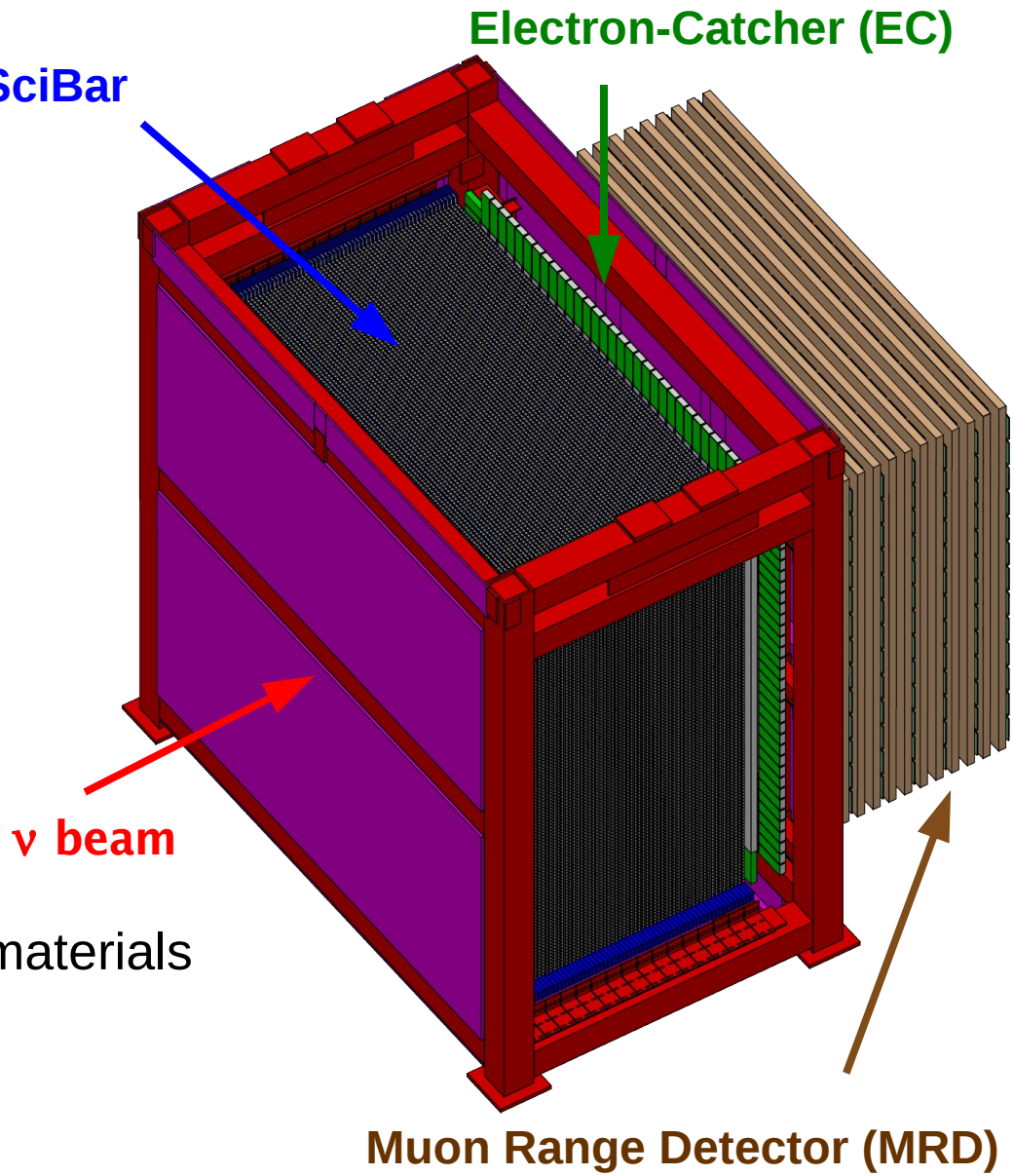


- Booster Proton accelerator
  - 8 GeV protons sent to target
- Target Hall
  - Beryllium target: 71cm long 1cm diameter
  - Resultant mesons focused with magnetic horn
  - Reversible horn polarity
- 50m decay volume
  - Mesons decay to μ & ν_μ
  - Short decay pipe minimises $\mu \rightarrow \nu_e$ decay
- SciBooNE located 50m from absorber

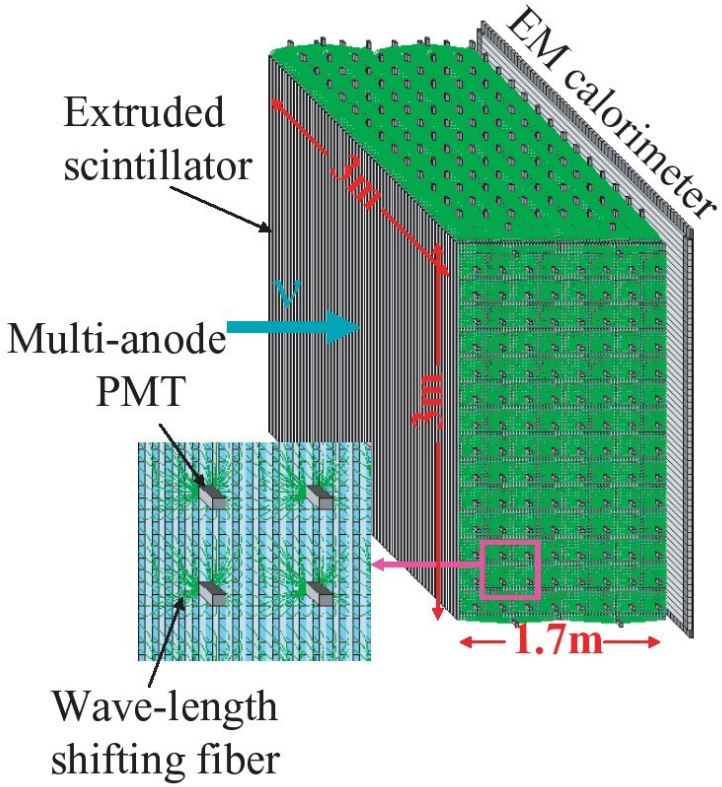


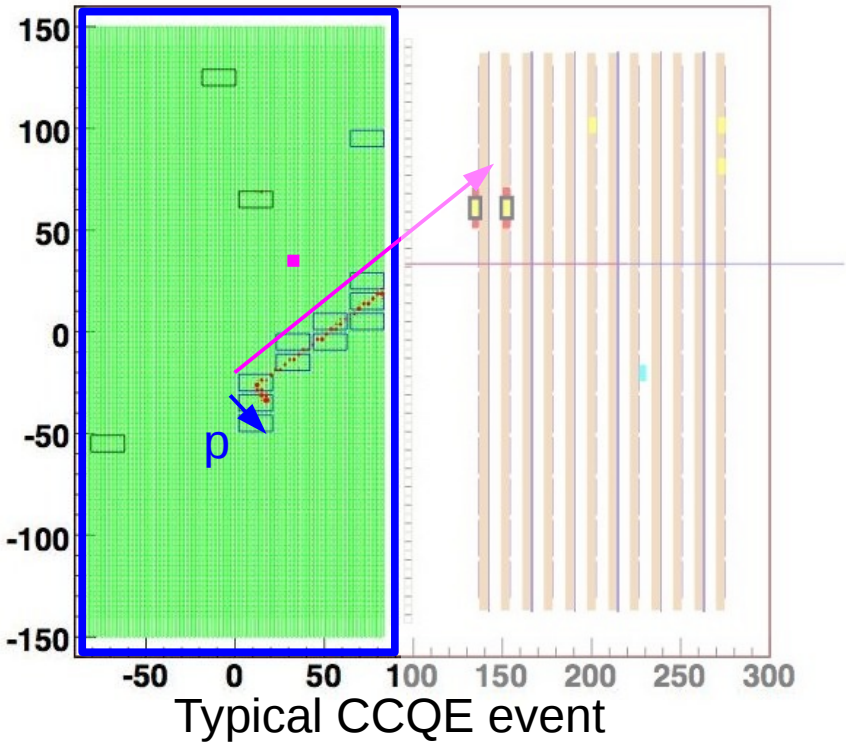
SciBooNE Detector

- SciBooNE consists of 3 sub-detectors
- **SciBar**
  - Used in K2K
  - Shipped from Japan to Fermilab
- **Electron-Catcher (EC)**
  - Used in CHORUS & K2K
  - Shipped from Japan to Fermilab
- **Muon Range Detector (MRD)**
  - 'New' detector built from recycled materials



- Extruded scintillators
  - Wavelength-shifting (WLS) fibre readout
- Fully active detector
  - Scintillator is the neutrino target
- Total mass: 15 tons
  - Fiducial volume: ~10 tons
- Identify short tracks (>8cm)
- Distinguish a proton from a pion by dE/dx

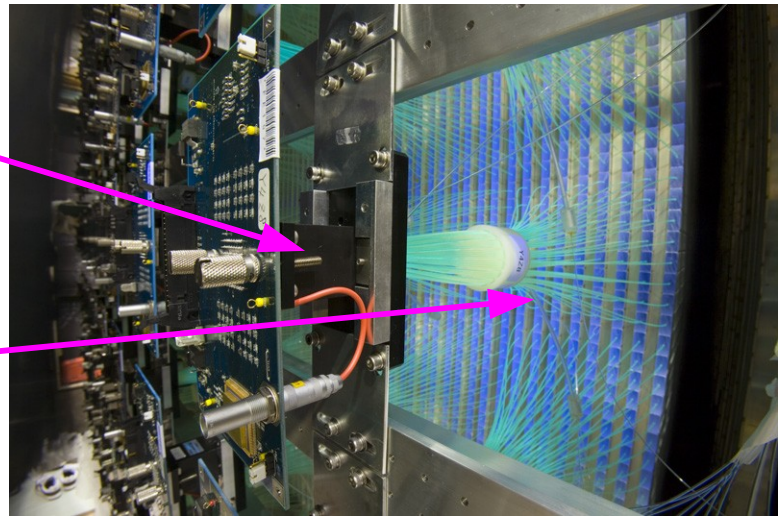




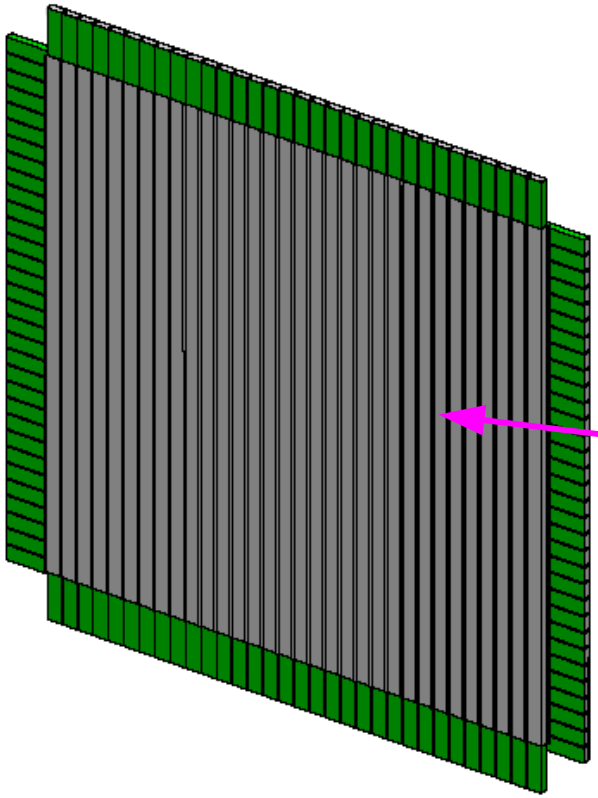
Typical CCQE event

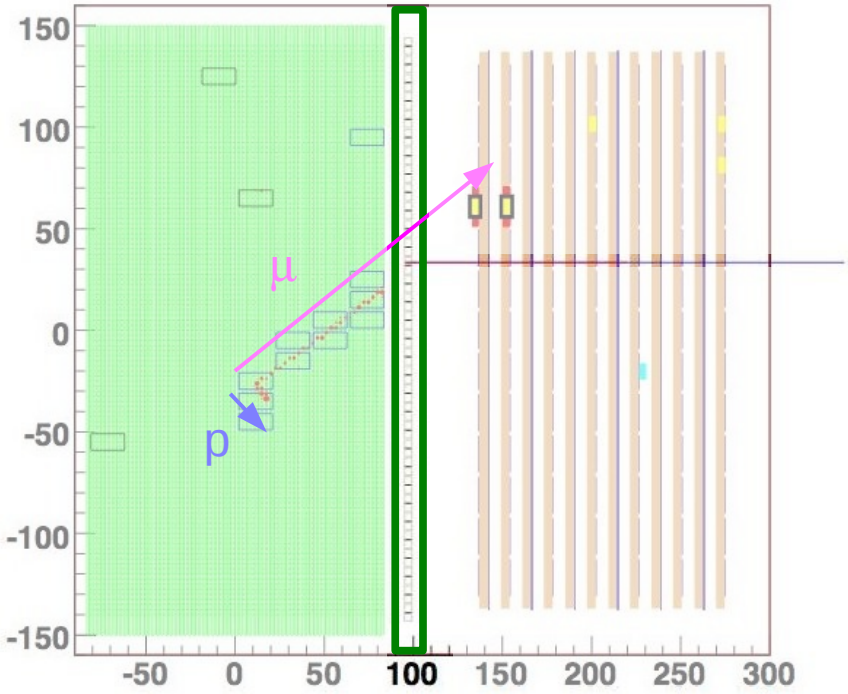
64 channel multi-anode PMT

WLS fibres

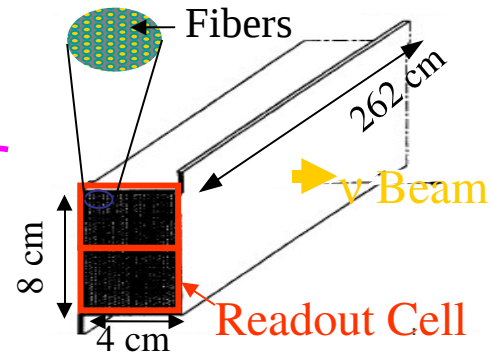


- Gamma and electron identification (ν_e & π^0)
- "Spaghetti" calorimeter
- 2 planes (X & Y) ≡ $11X_0$

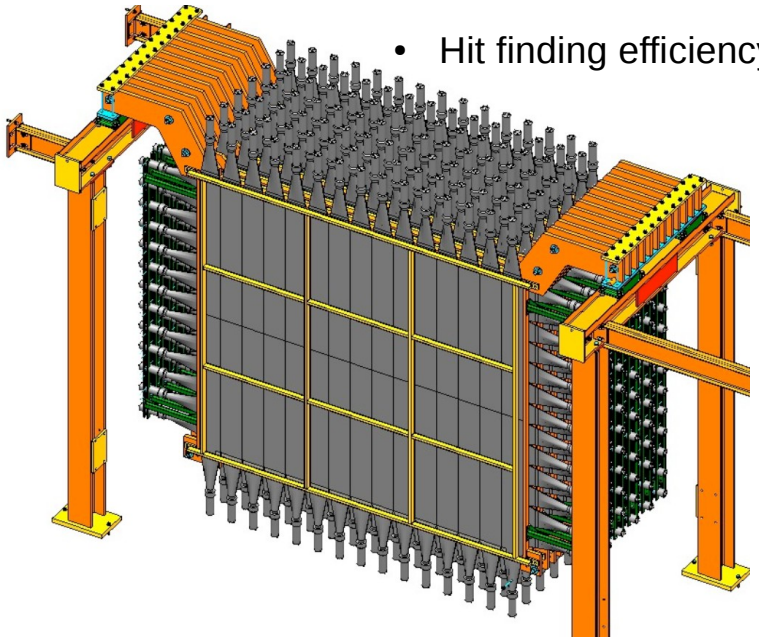




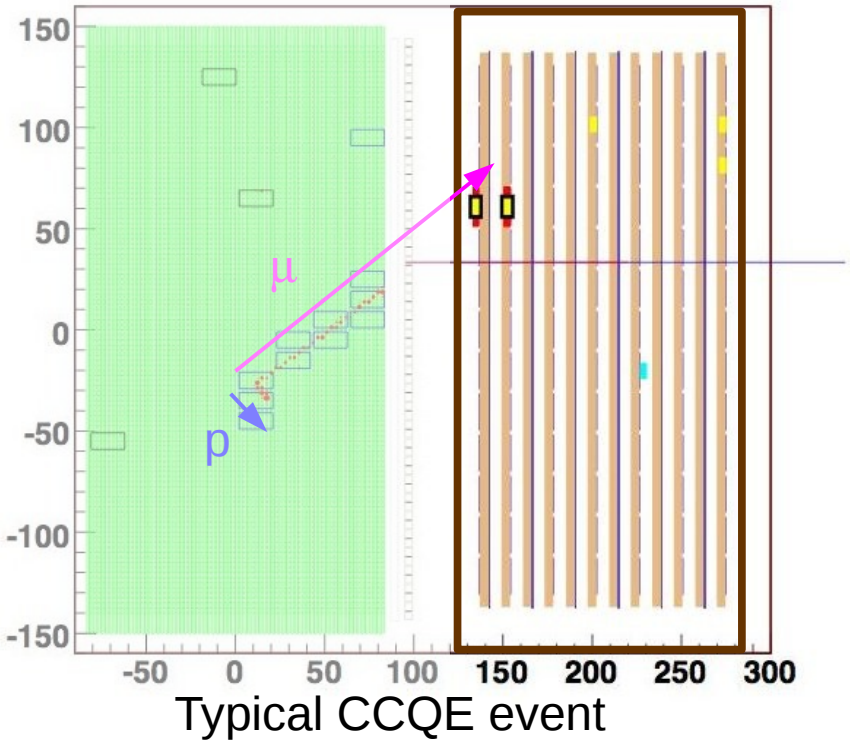
Typical CCQE event



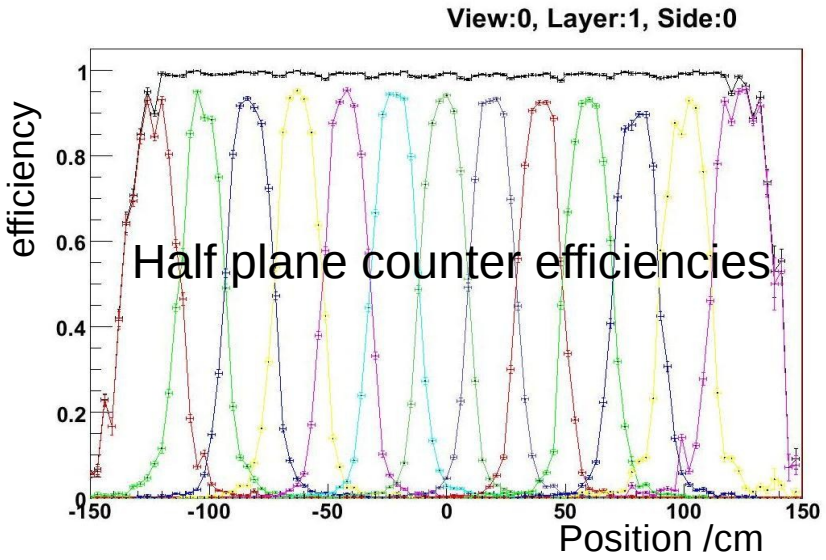
- The MRD reuses Fermilab materials
- Second-hand: Iron, scintillator, PMTs, electronics, signal cables and high voltage cables
- Ranging used to reconstruct muon energy
  - 13 alternating X & Y planes
  - 60cm iron total depth
  - MRD stops muons with momentum <1.2GeV/c
- Total ~ 55 tons
  - Large sample of CC events on iron



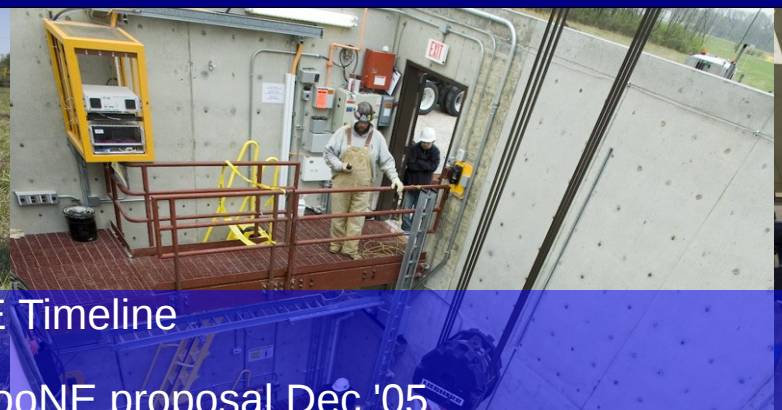
- Hit finding efficiency ~99% (see below right)

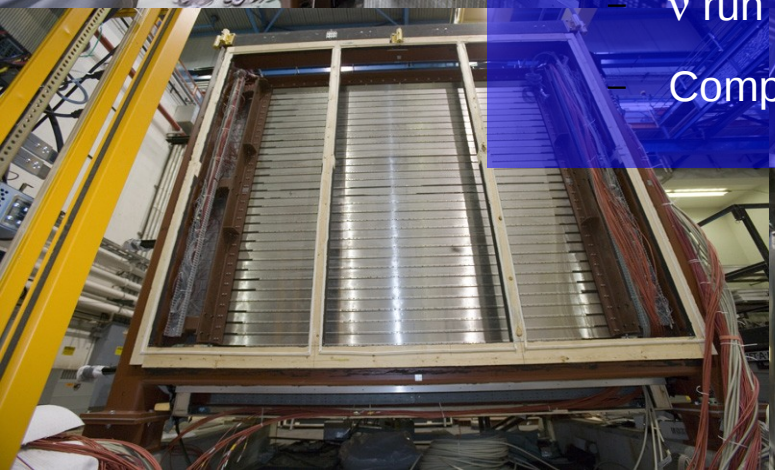


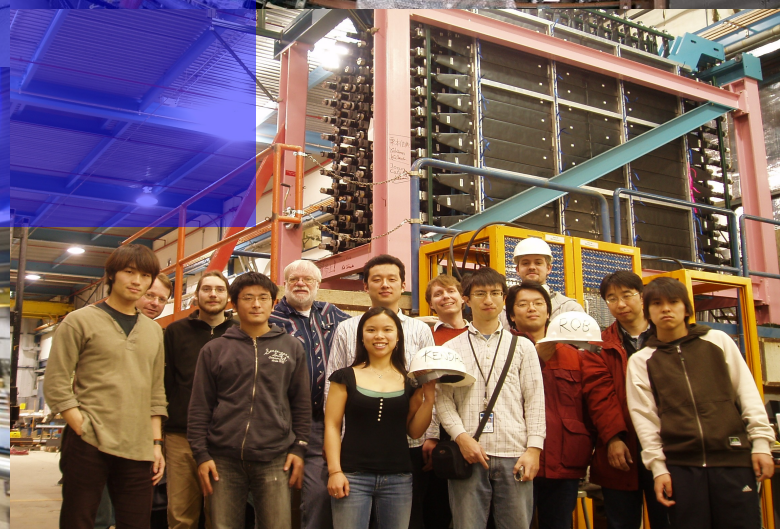
Typical CCQE event



Construction



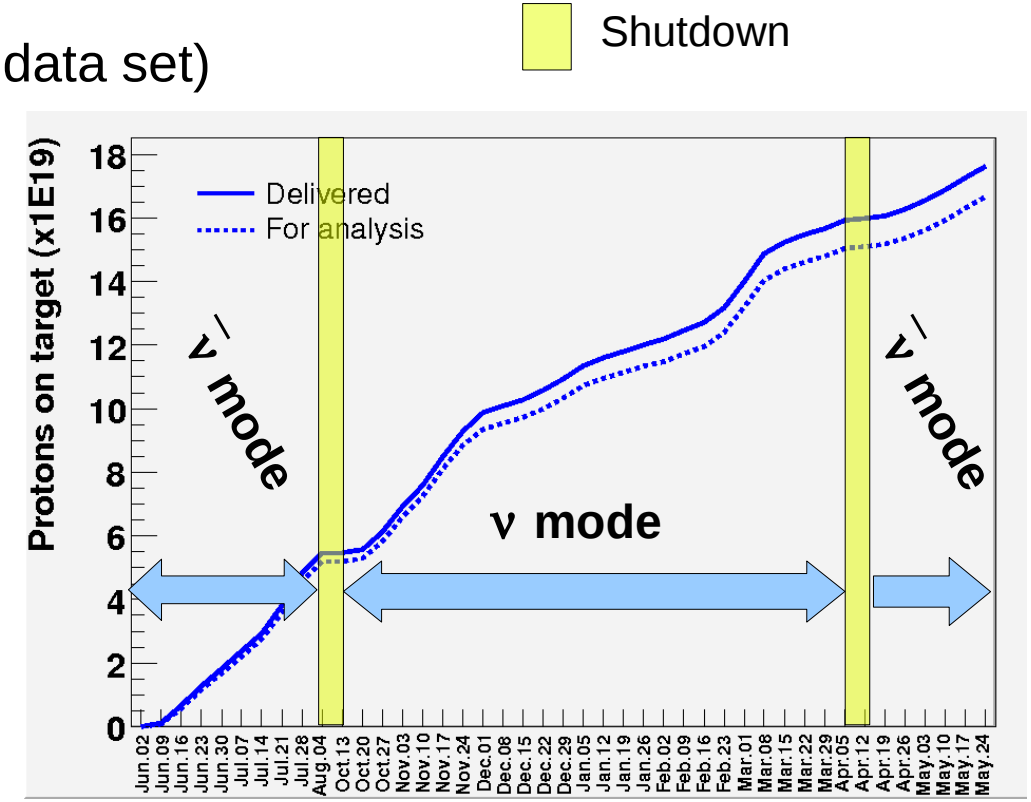




- SciBooNE Timeline
  - SciBooNE proposal Dec '05
  - MRD counter construction began June '06
  - SciBar & EC arrived at Fermilab July '06
  - Detector Assemblies completed March '07
  - Detectors moved to experiment hall April '07
  - anti-ν run began June '07
  - ν run began October '07
  - Completion of run by ~August '08

Data Run

- Full projected data set: 2×10^{20} Protons on Target (POT)
  - 1×10^{20} POT ν mode
  - 1×10^{20} POT $\bar{\nu}$ mode
  - ~1 year of running
- Present data set
  - ν mode: 0.99×10^{20} POT (complete data set)
  - $\bar{\nu}$ mode: 0.67×10^{20} POT
- Detector Live Fraction: 94.6%



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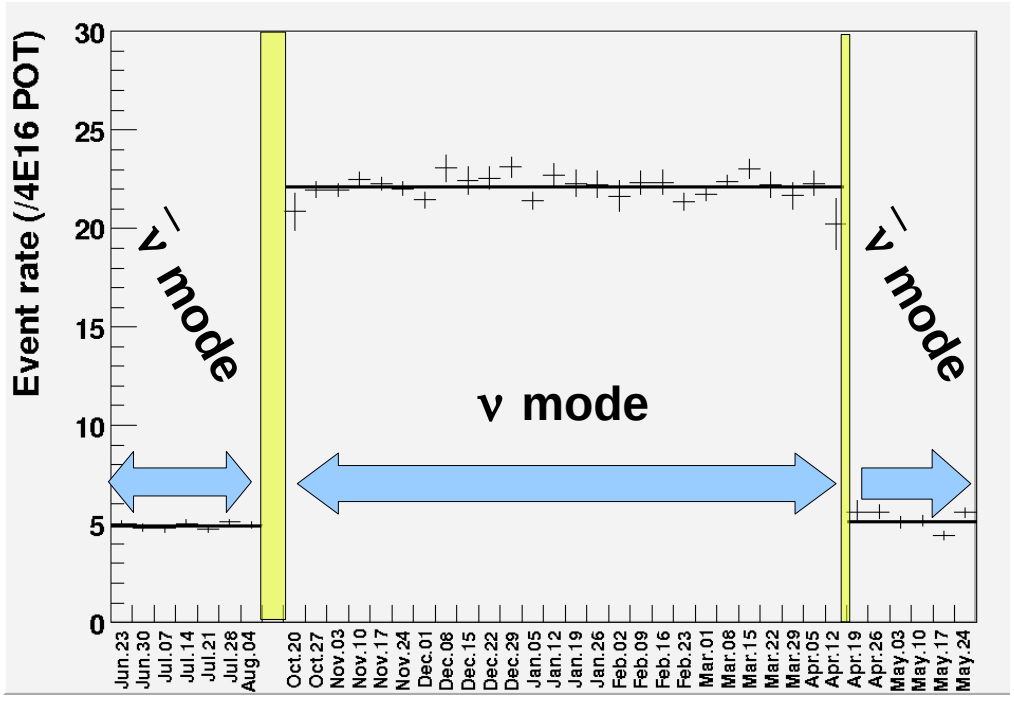
- Event rate/POT very stable
- $\bar{\nu}$ event rate stable



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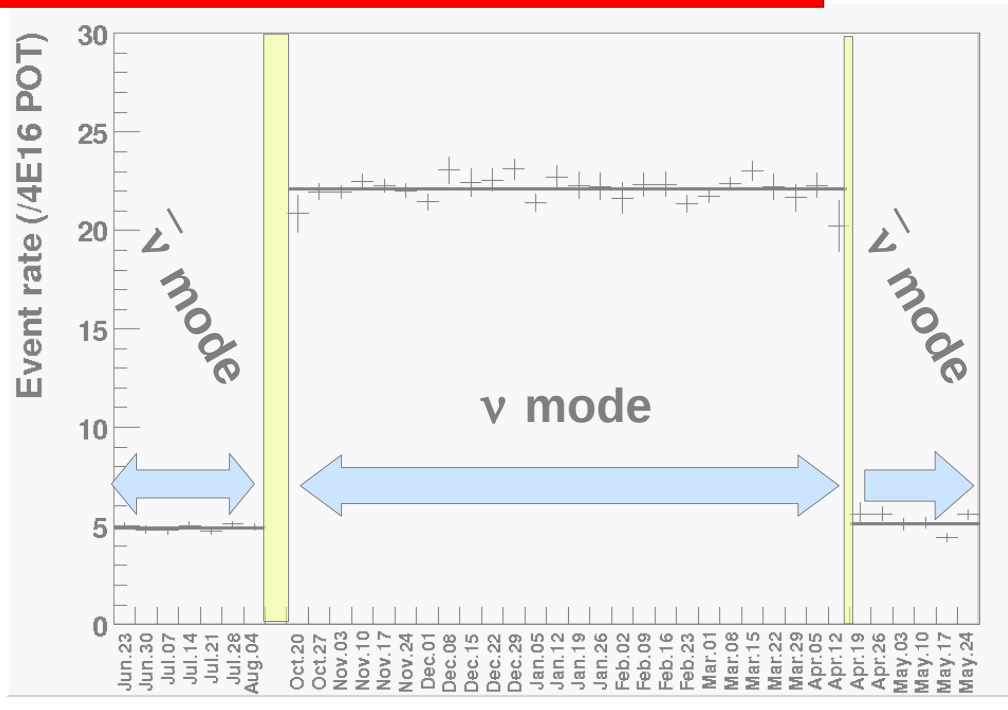
Data taking still ongoing!
Projected end of run for 18th August 2008!

- Event rate/POT very stable
- $\bar{\nu}$ event rate stable



SciBooNE Charged-Current (CC) Analyses

Charged-Current Outline

- 4 Charged-Current Analysis topics
  - **CC-inclusive:** *Y. Nakajima*
  - **CCQE:** *J. Walding, J Alcaraz*
  - **CC1π:** *K. Hiraide*
  - **CCπ^0 :** *J. Catala*
- 2 Neutral-Current Analyses ongoing (See Y. Kurimoto-san's talk)
- Joint MiniBooNE/SciBooNE disappearance measurement *(K. Mahn)*

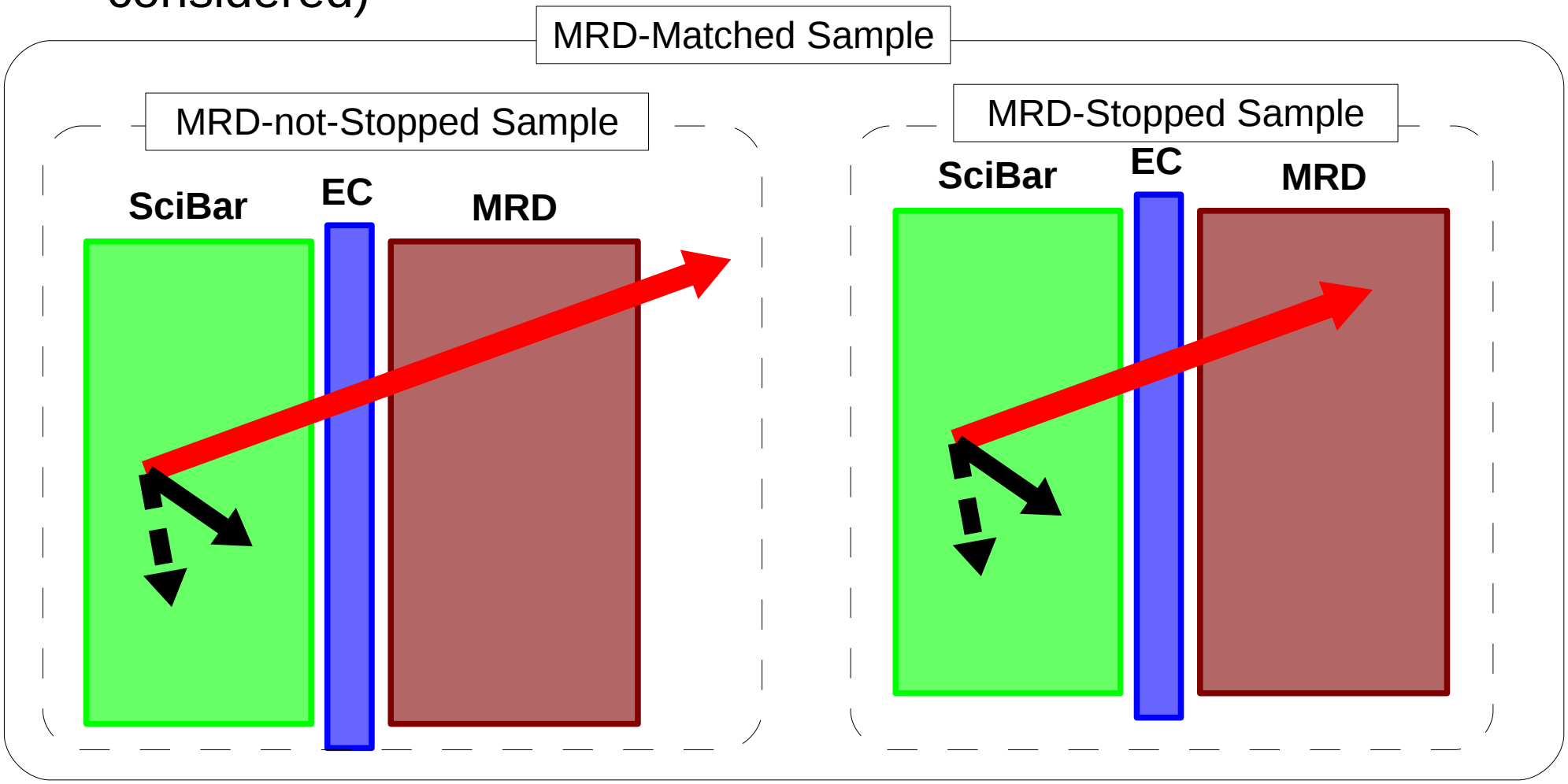
Charged-Current Outline

- 4 Charged Current Analysis topics
  - **CC-inclusive**
  - **CCQE**
  - **CC1π**
  - **CCπ^0**

→ Important for ν_μ disappearance

- CC-inclusive includes all CC channels and makes up complete oscillation dataset
- Neutrino energy scale can be calculated using CCQE events (μ kinematics)
- CC-1π and CC-π^0 are backgrounds to oscillation studies

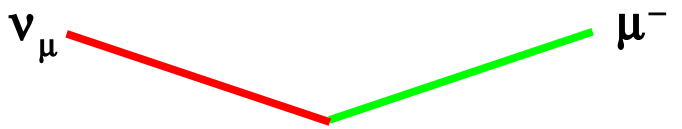
- **Note: MC normalised to data using MRD-matched (not stopped) sample**
- Data & MC: Only statistical errors shown (no systematics yet considered)

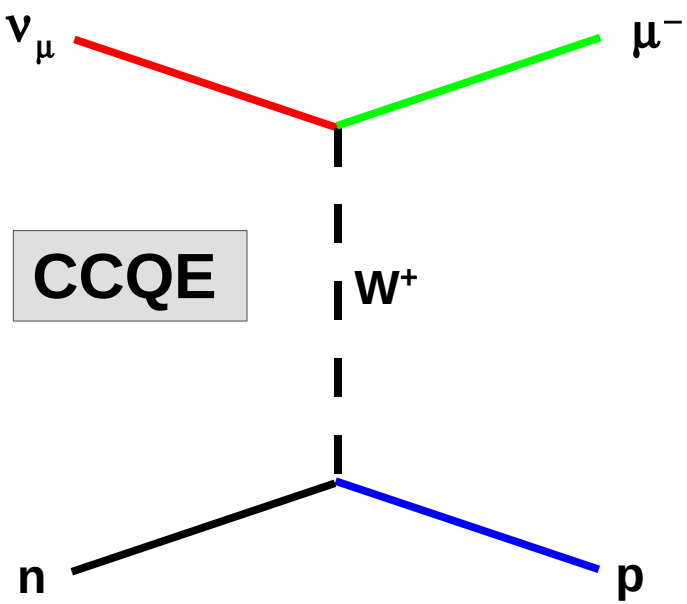


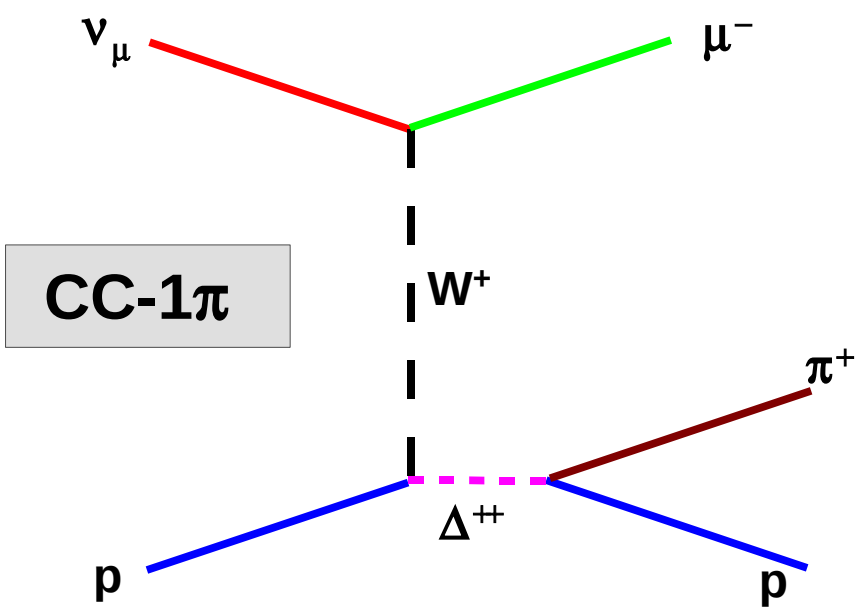
Charged-Current Inclusive

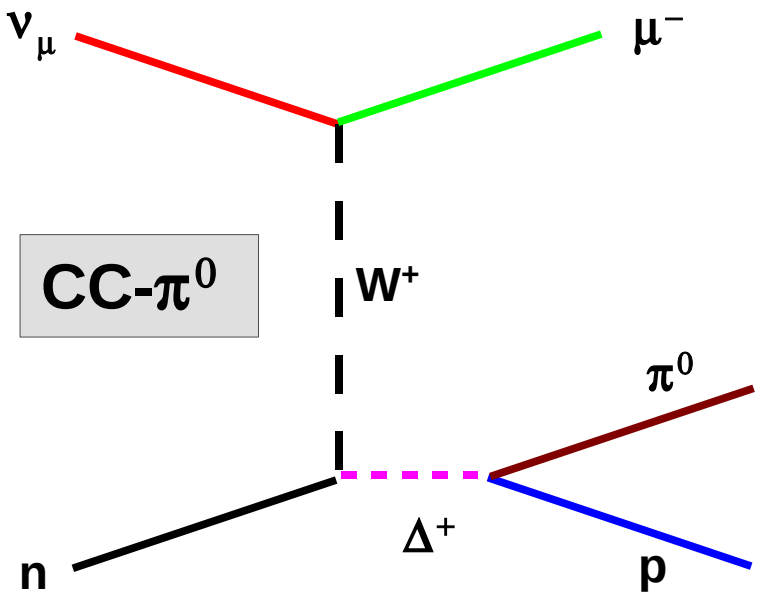
Charged-Current Inclusive

- Observed muon is tag of charged-current event

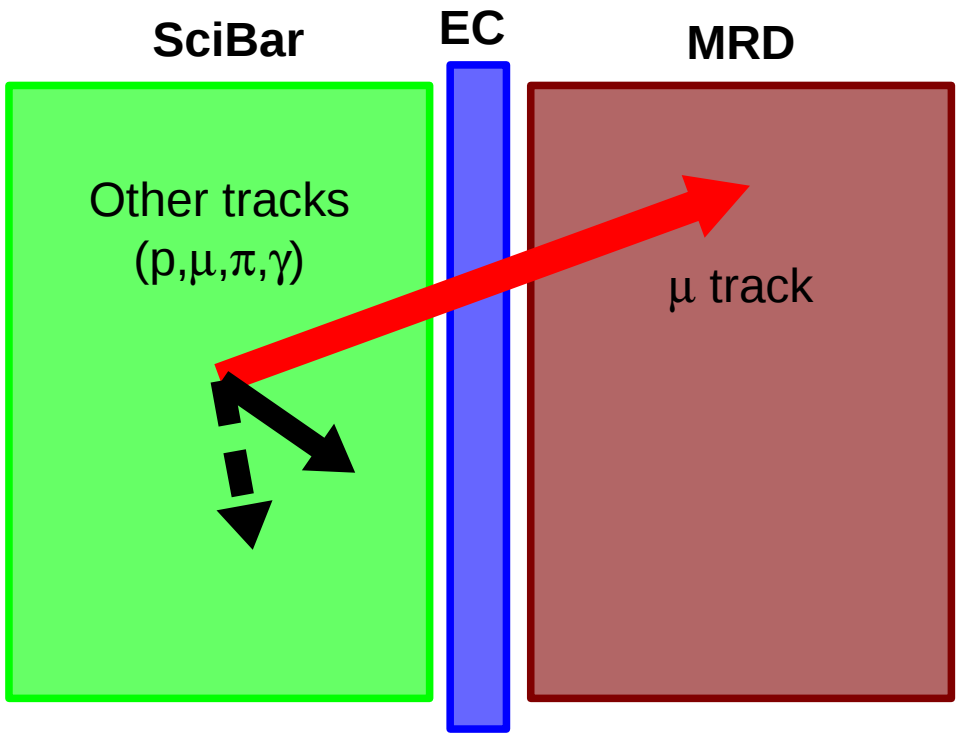




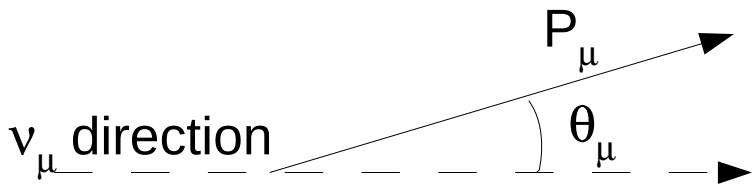


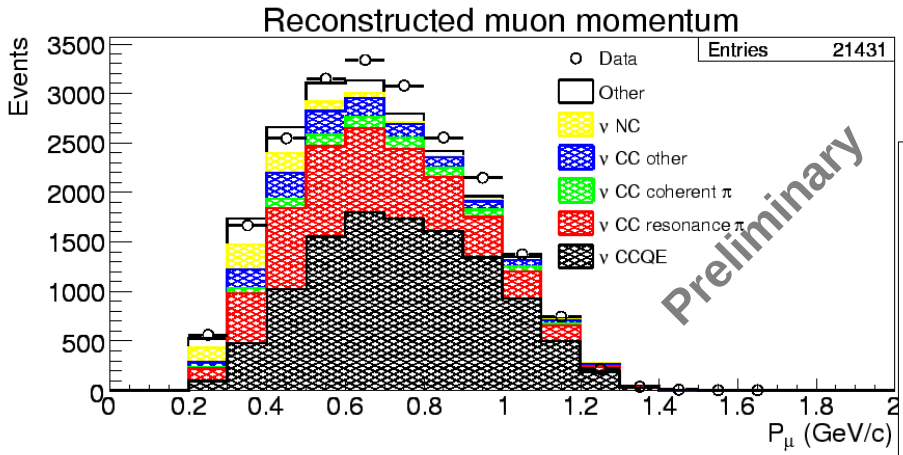


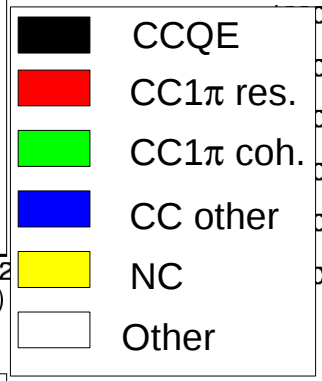
- Identify a muon using the Scibar-MRD matched tracks
  - CC purity = 96%
  - Cosmic ray background < 0.5%
- Data set contains only MRD-stopped tracks

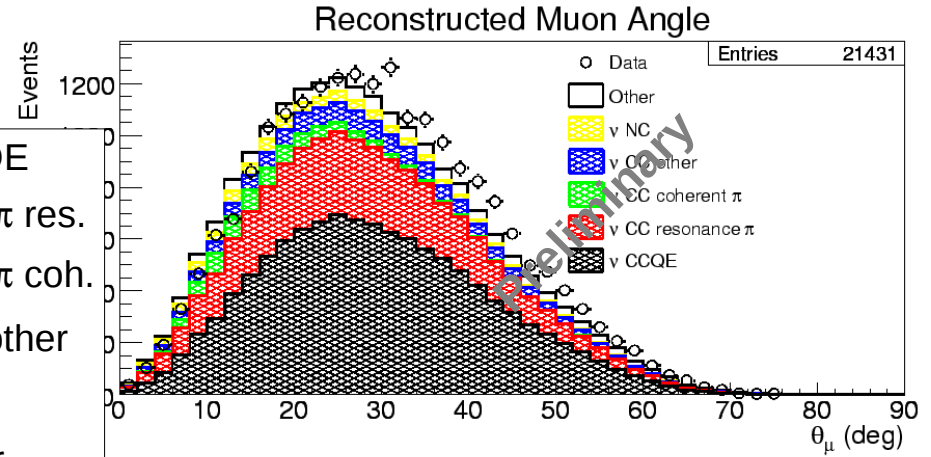


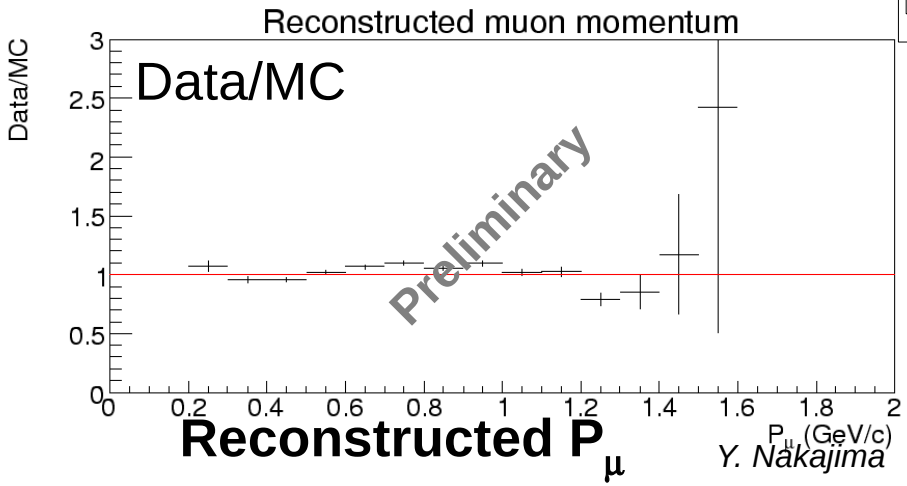
- Generally good Data/MC agreement
  - P_μ: Good shape agreement between data/MC
  - Larger θ_μ in data. Under investigation



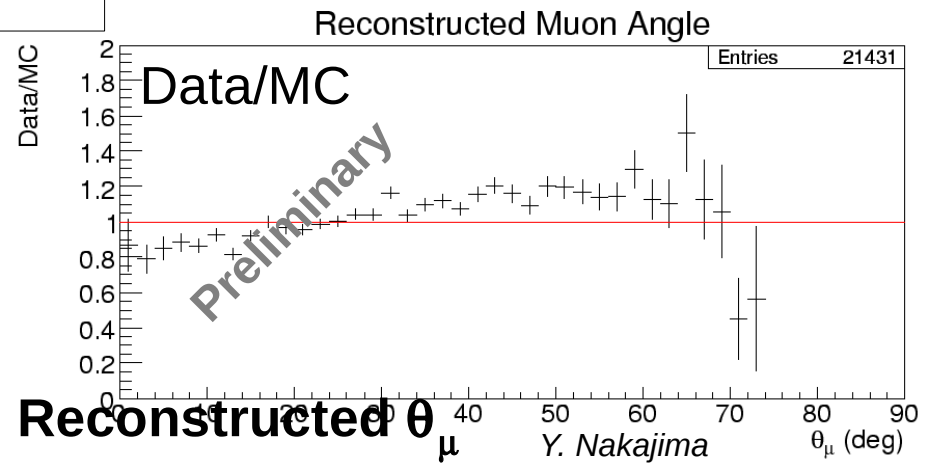








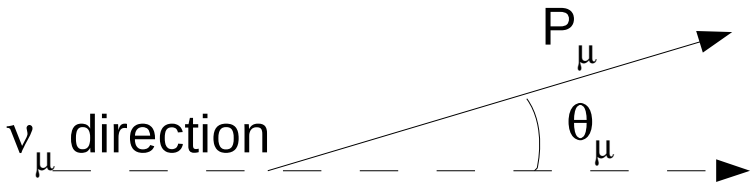
Reconstructed P_μ *Y. Nakajima*



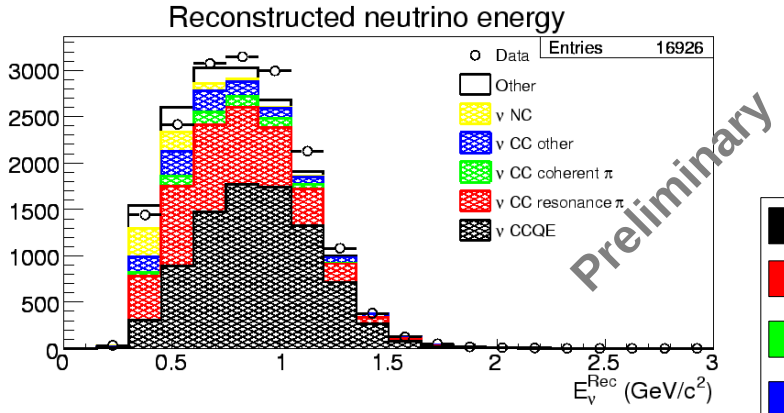
Reconstructed θ_μ *Y. Nakajima*

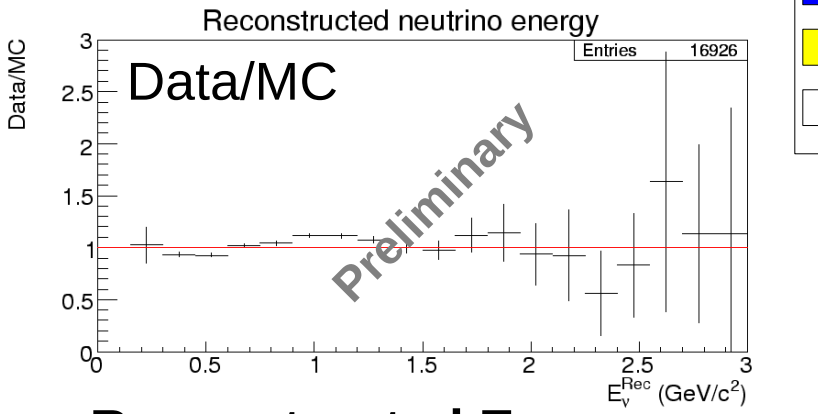
Assuming CCQE:

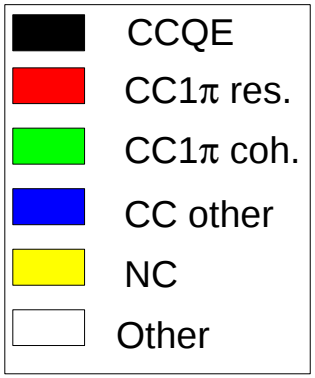
$$E_\nu^{rec} = \frac{m_n E_\mu - m_n^2/2}{m_n - E_\mu + P_\mu \cos\theta_\mu}$$

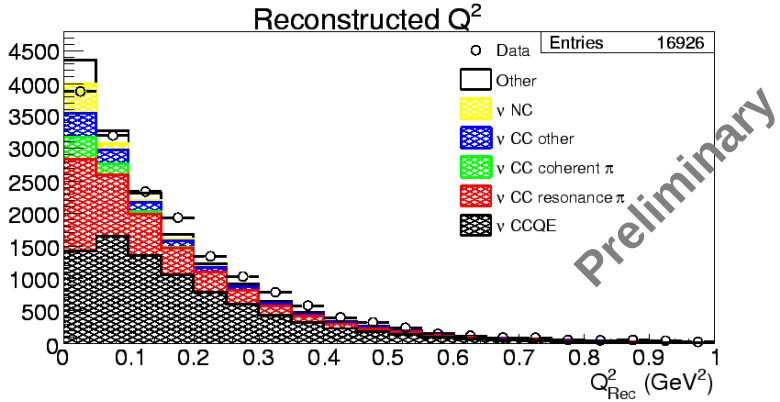


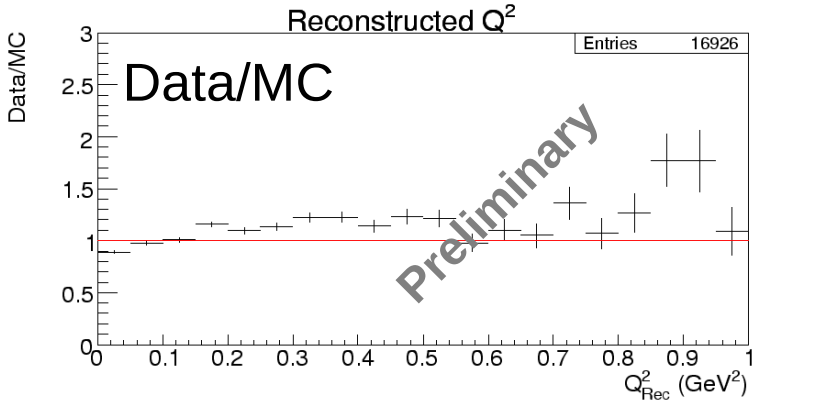
- Muon angle very important for reconstruction of E_ν
- Larger $\theta_\mu \rightarrow$ Larger E_ν









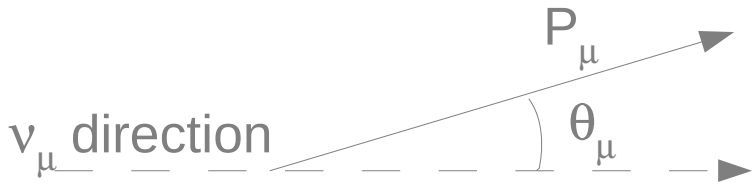


Reconstructed E_ν *Y. Nakajima*

Reconstructed Q^2 *Y. Nakajima*

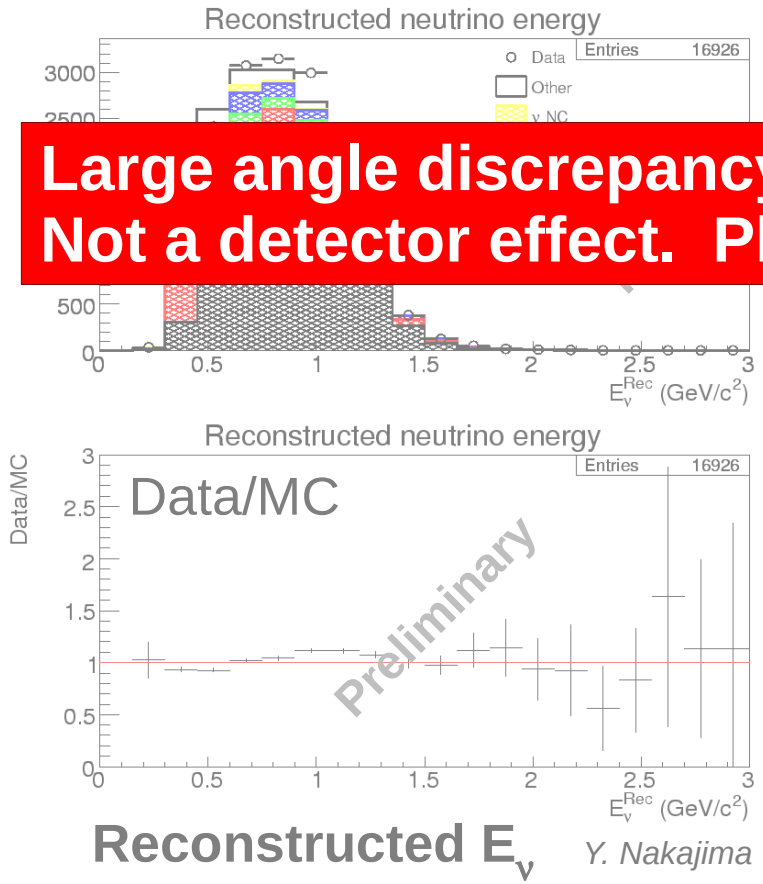
Assuming CCQE:

$$E_\nu^{rec} = \frac{m_n E_\mu - m_n^2/2}{m_n - E_\mu + P_\mu \cos\theta_\mu}$$

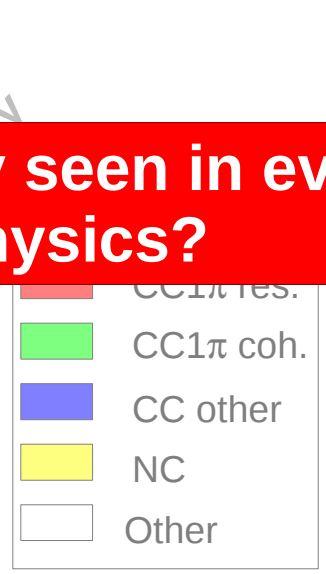


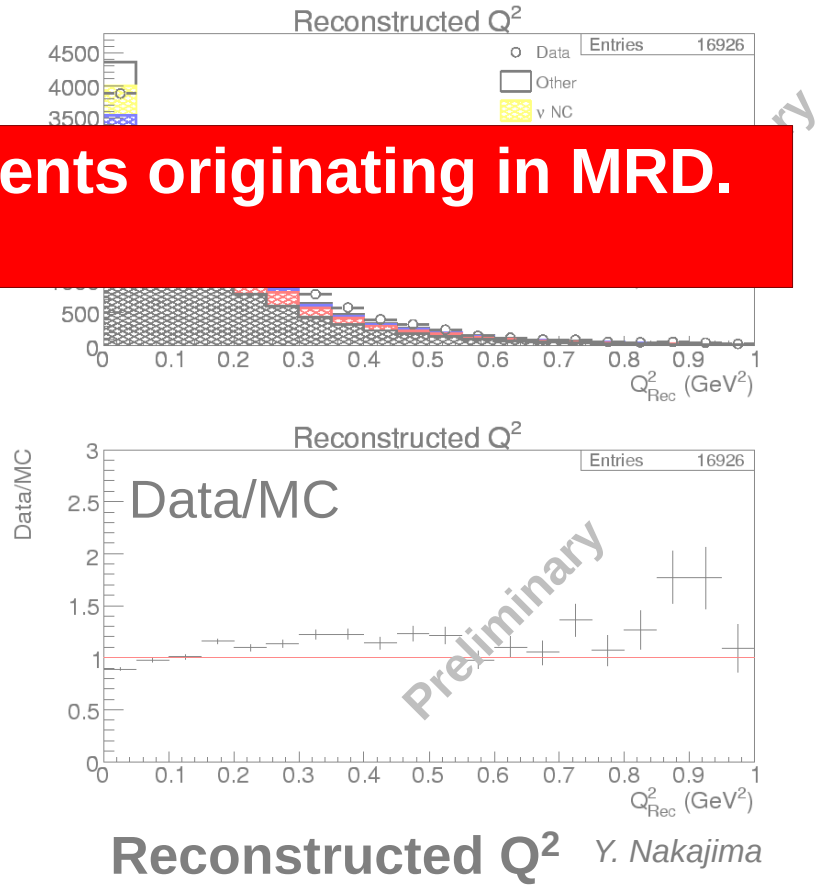
- Muon angle very important for reconstruction of E_ν
- Larger $\theta_\mu \rightarrow$ Larger E_ν

Large angle discrepancy seen in events originating in MRD. Not a detector effect. Physics?



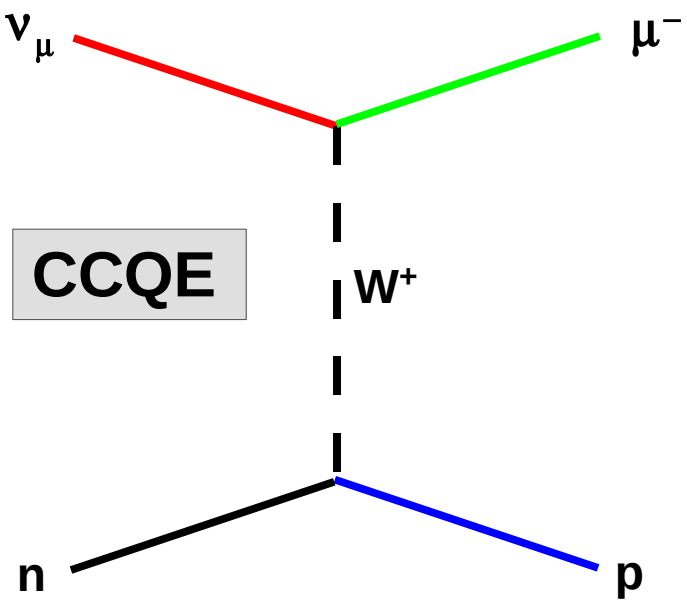
Reconstructed E_ν *Y. Nakajima*

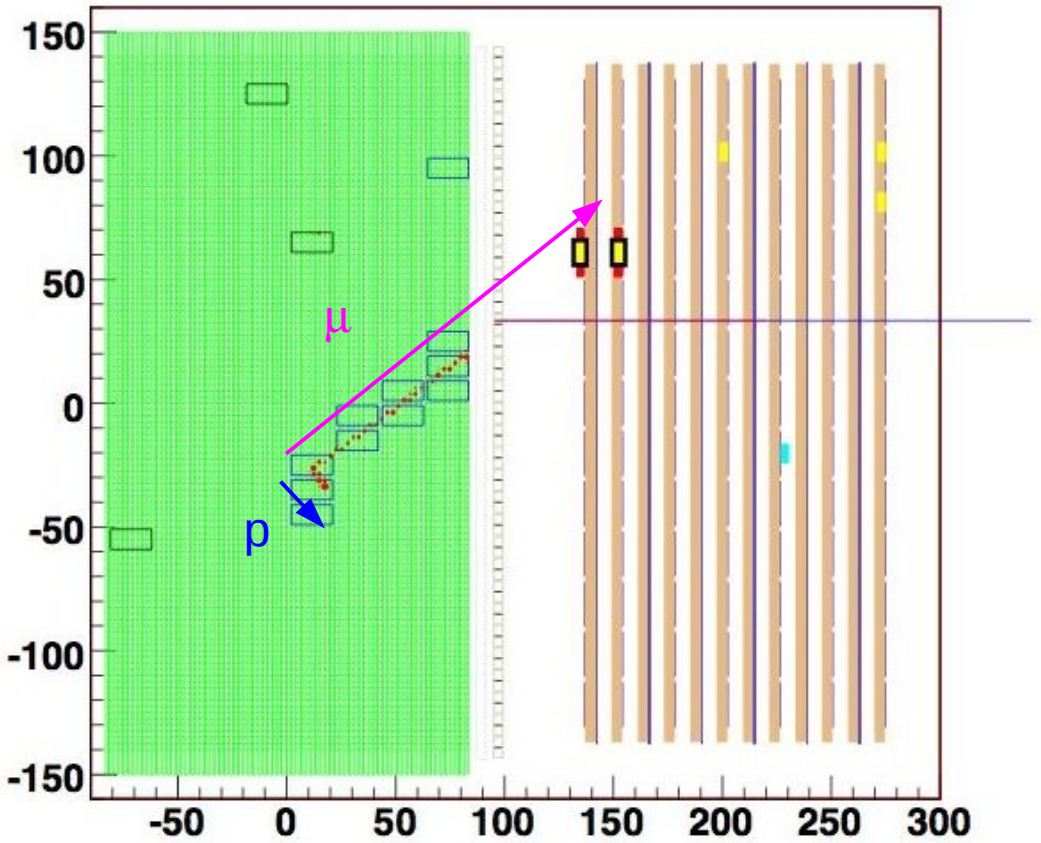




Reconstructed Q^2 *Y. Nakajima*

Charged-Current Quasi-Elastic



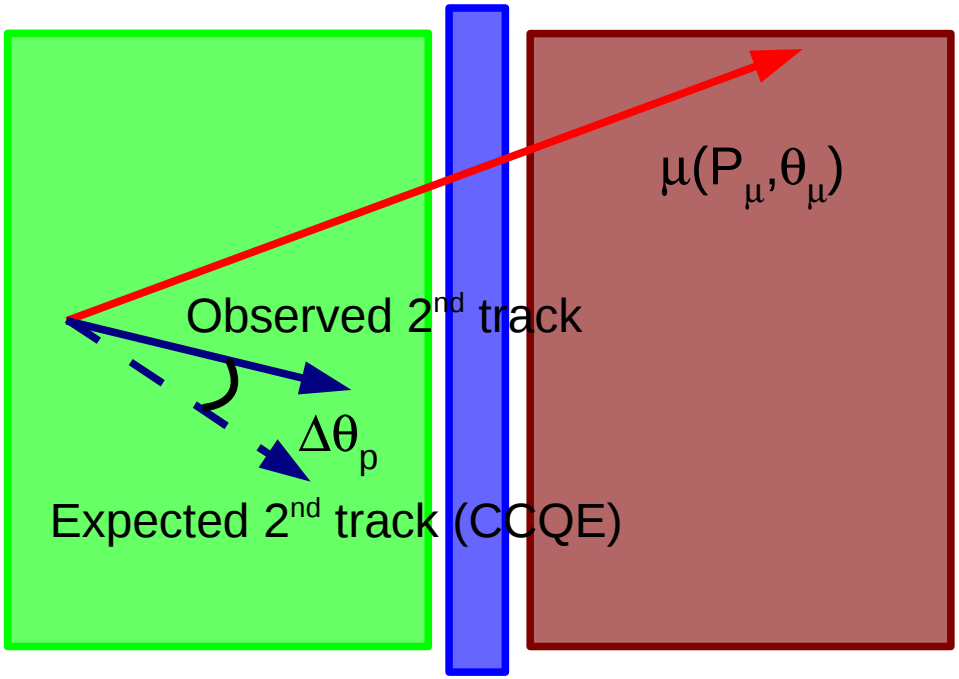


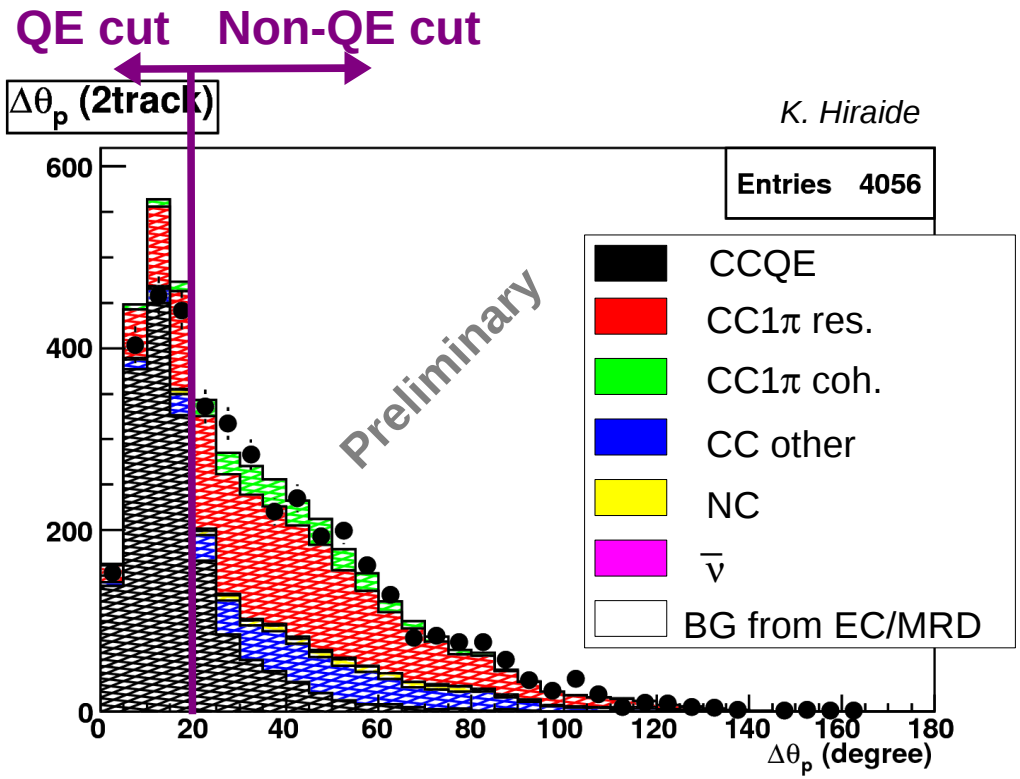
Typical CCQE event

- Signal mode for oscillation measurements
- 2 independent CCQE analyses on SciBooNE
  - MRD-matched muon (J. Alcaraz)
  - SciBar-contained muon (J. Walding)

MRD-Matched Sample

- 2 track sample with one tagged as μ (MRD-matched)
- CCQE sample isolated using $\Delta\theta_p$ cut on 2nd track
  - $\Delta\theta_p$: Angular separation between 2nd track and expected track direction assuming CCQE interaction
  - $\Delta\theta_p$ cut: 20° (QE sample purity: 81%)
  - Small angle data/MC disagreement





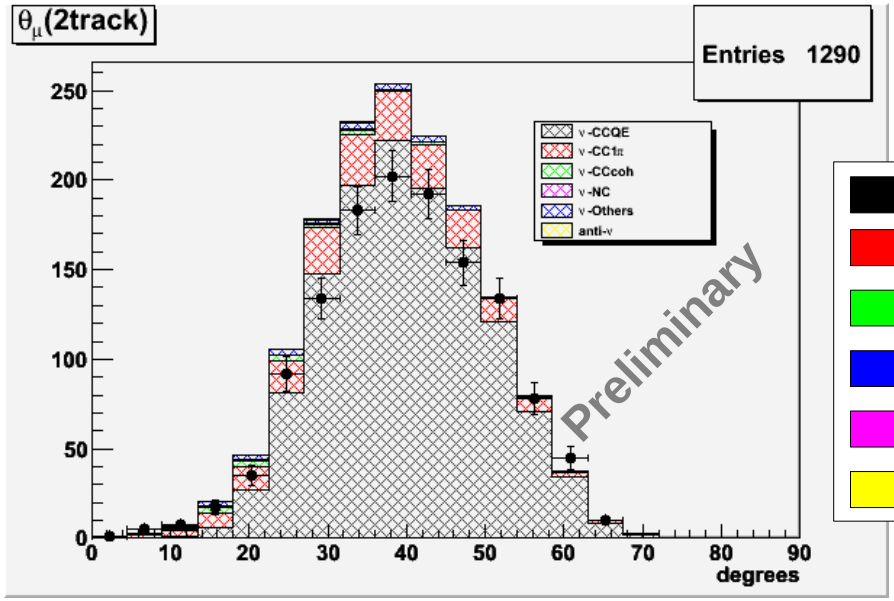
2 Track CCQE: θ_μ

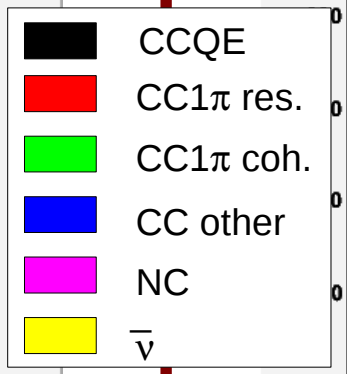
- Larger θ_μ in data not seen (cf. CC inclusive sample)

2 Track CCQE: P_μ

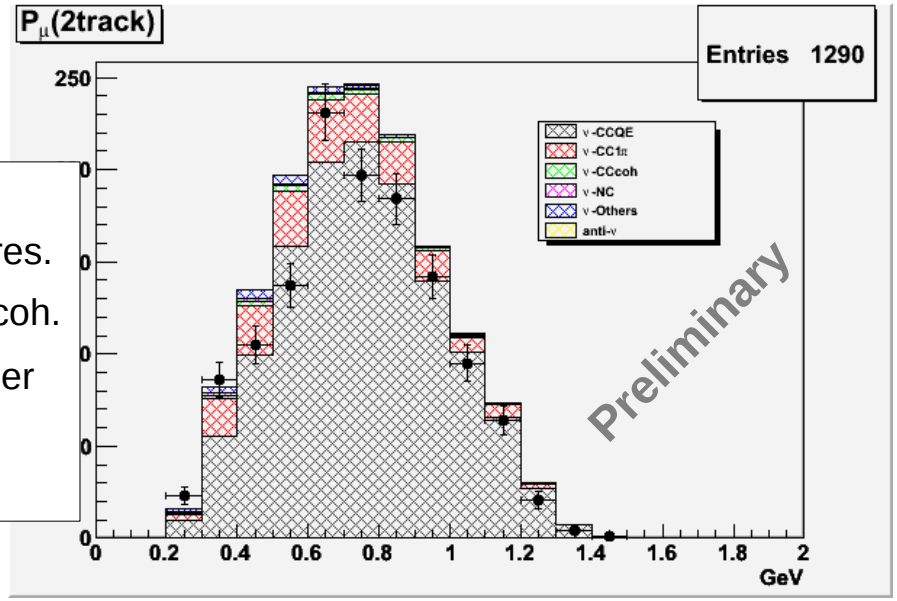
- Very high CCQE purity (81%)
- Data deficit in P_μ
- Reasonable data/MC shape agreement

J. Alcaraz





J. Alcaraz

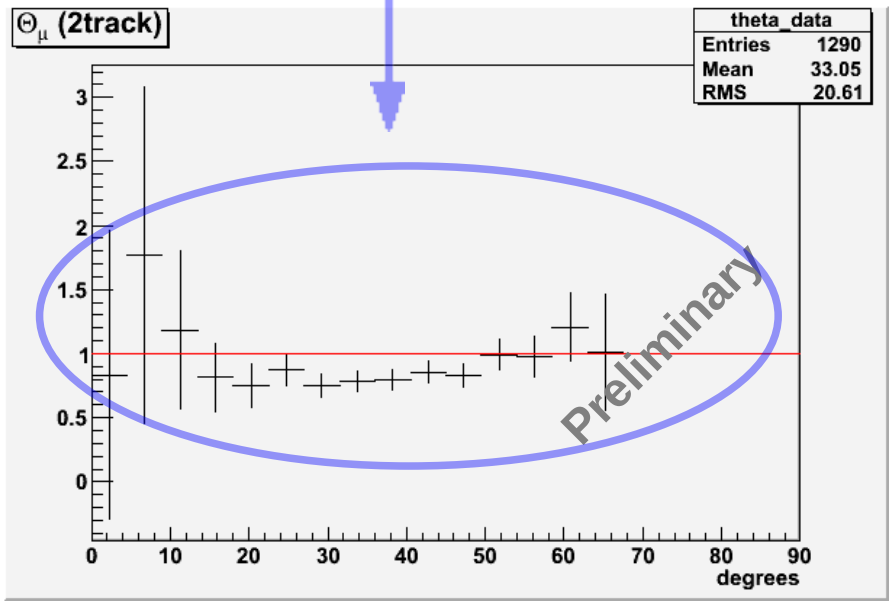


Muon Distributions

2 Track CCQE: θ_μ

- Larger θ_μ in data not seen (cf. CC inclusive sample)

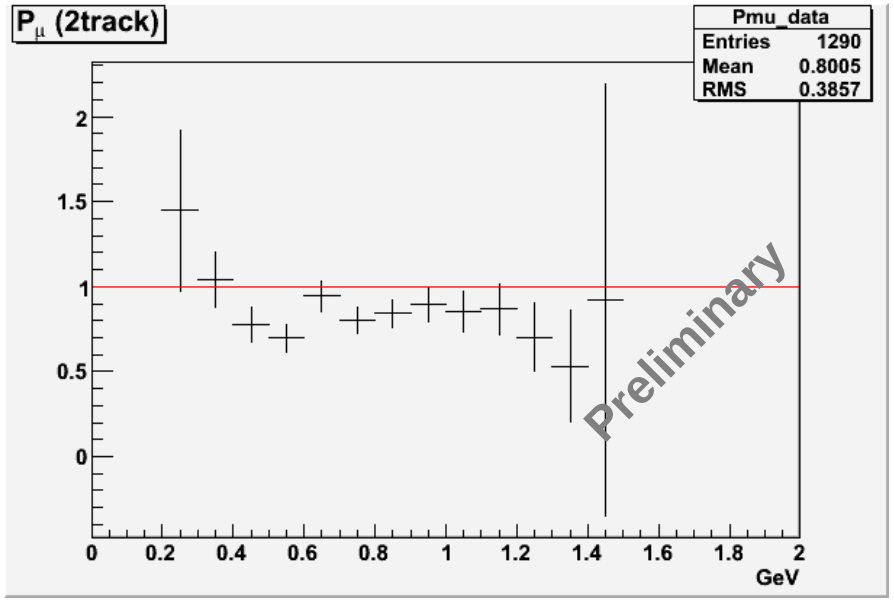
J. Alcaraz



2 Track CCQE: P_μ

- Very high CCQE purity (81%)
- Data deficit in P_μ
- Reasonable data/MC shape agreement

J. Alcaraz



2 Track CCQE: θ_μ

- Larger θ_μ in data not seen (cf. CC inclusive sample)

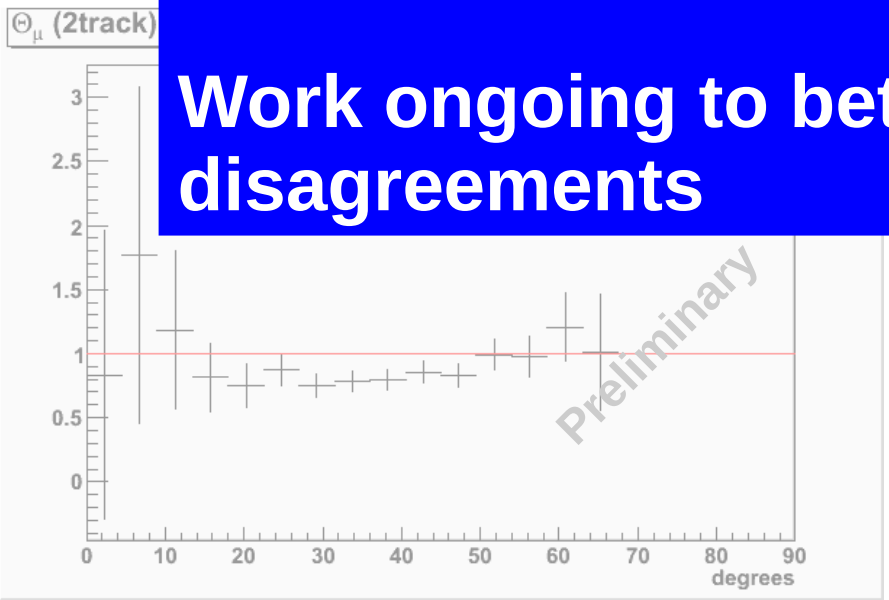
2 Track CCQE: P_μ

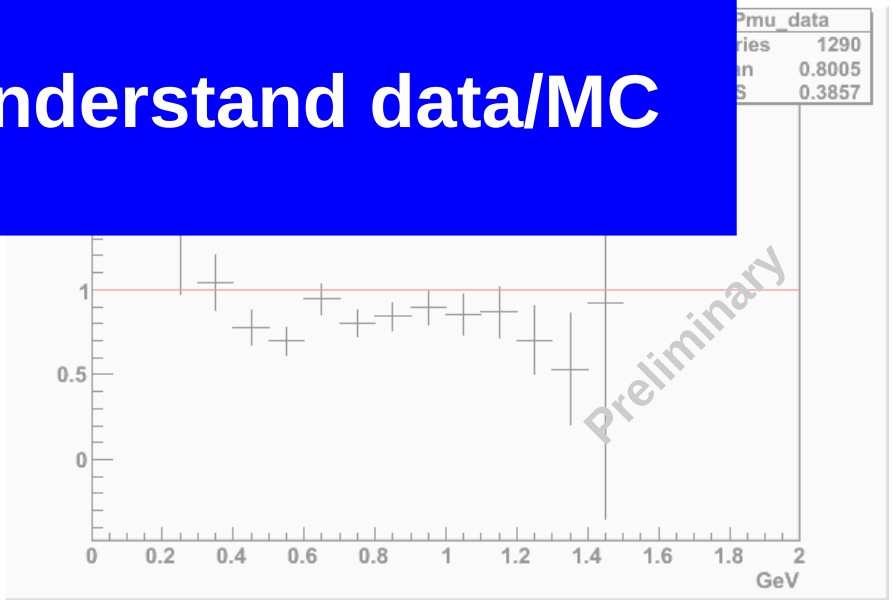
- Very high CCQE purity (81%)
- Data deficit in P_μ
- Reasonable data/MC shape agreement

Angular discrepancy not seen in CCQE sample → A non-QE effect?

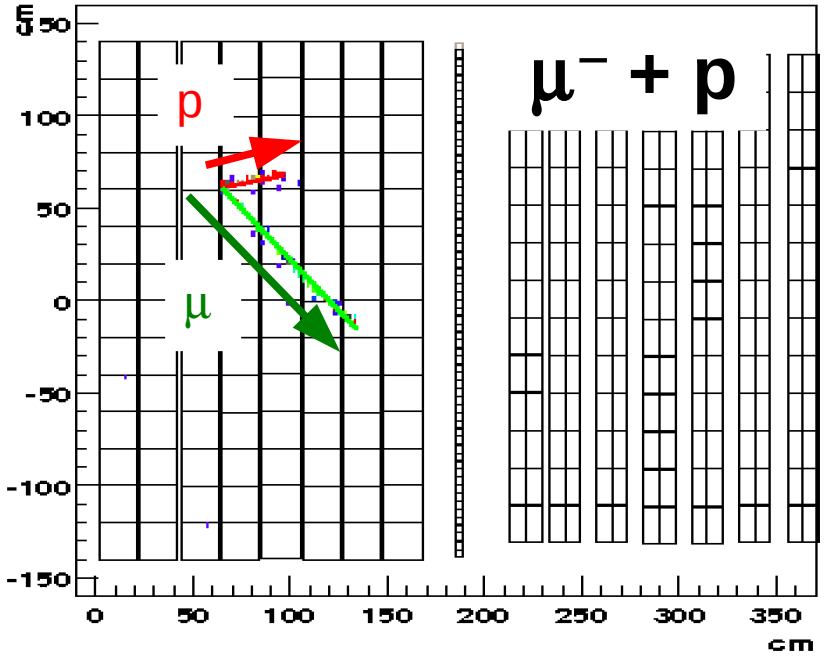
Work ongoing to better understand data/MC disagreements

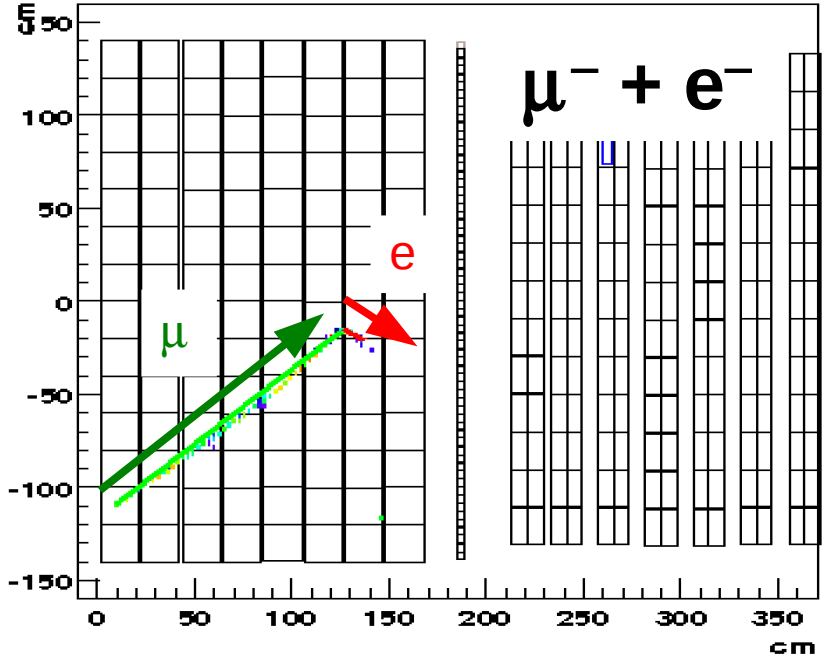
J. Alcaraz





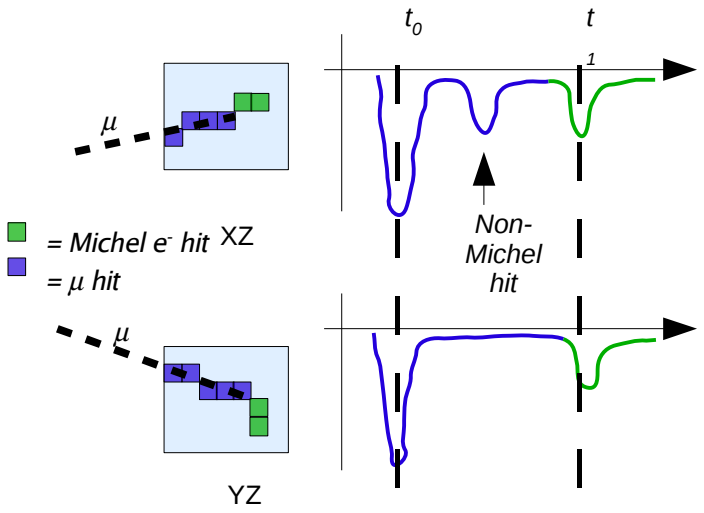
- SciBar contained sample: Higher Q^2 events from same spectrum
- Independent data set from MRD-stopped sample
- Require tracks to be contained within SciBar fiducial volume
  - $|x| = |y| < 1.3$m; 2^{nd} plane < z < 63^{rd} plane
- Track vertex separation < 10 cm
- 2-track data set has 2 types: μ^-+p & μ^-+e$^-$



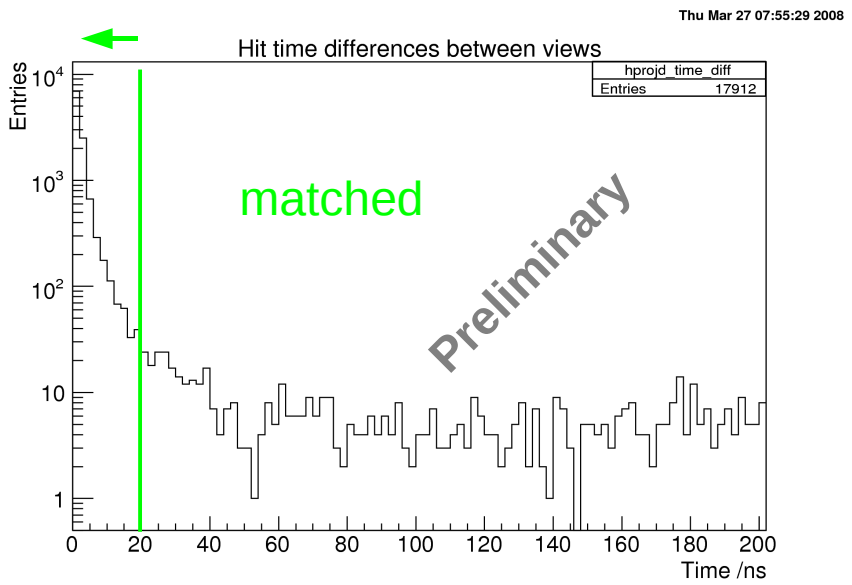


SciBar-Only CCQE Cuts

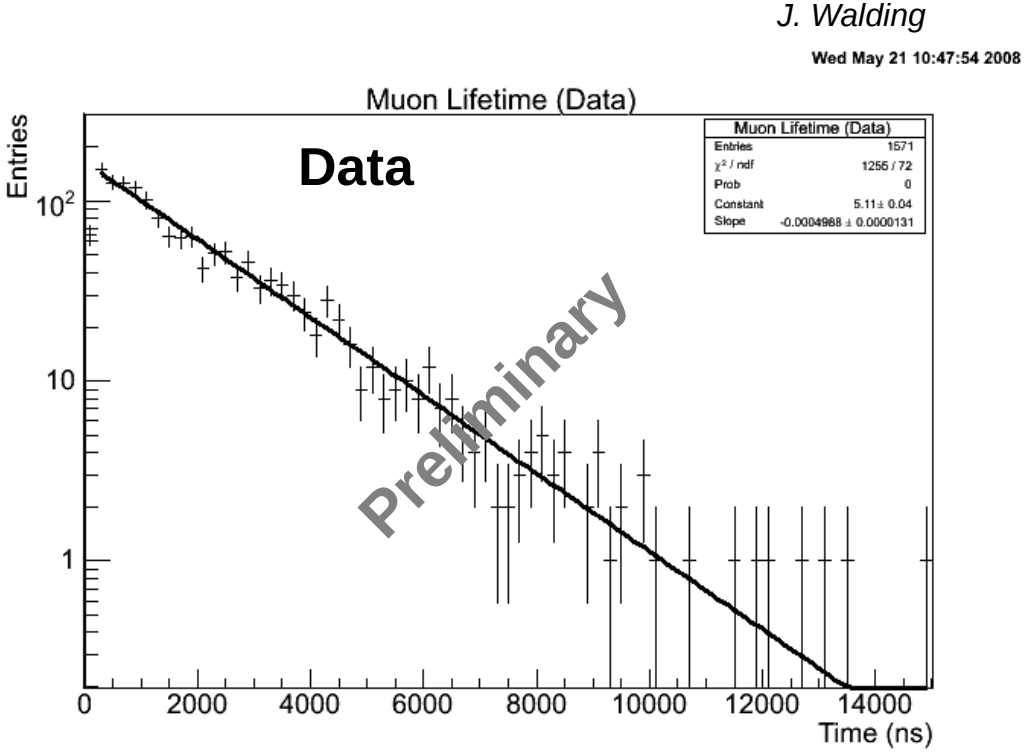
- SciBar stopped muons are tagged using decay electrons
- No track reconstruction of decay e^- needed
- Identify decay e^- using multi-hit TDC timing information
- Match hits between views
  - coincidence between top and side views to remove background hits
  - Matched if: $\Delta T_{diff} < 20ns$



J. Walding



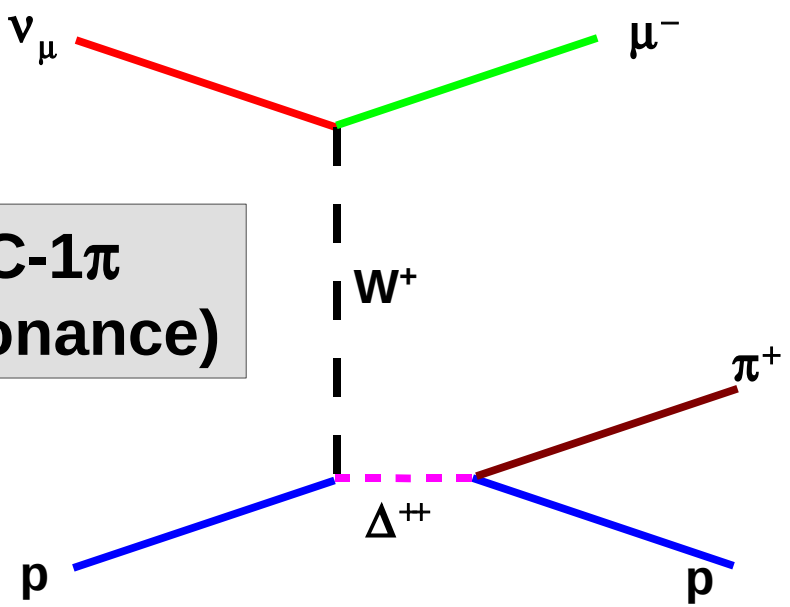
- Muon lifetime: $2.003 \pm 0.047(\text{stat}) \times 10^{-6}$s
  - cf. $2.0263 \pm 0.0015 \times 10^{-6}$s*
  - Agreement with world average (muon capture)
- TDC deadtime: <100ns
  - Exponential fit from 200ns bin
  - Deadtime modelled in MC
- No QE cut applied at present
  - No $\Delta\theta_p$ cut (independent)
- QE cut using event kinematics in development

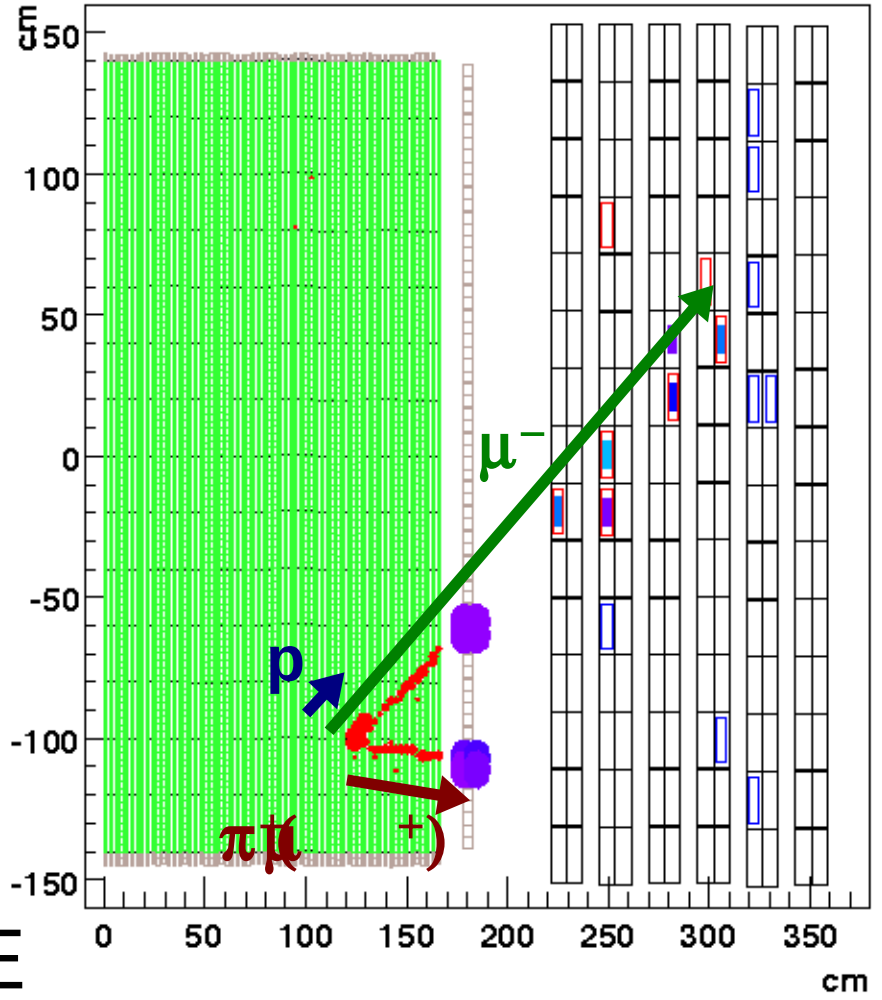


*Suzuki et al. Phys. Rev C. 35 (1987) 2212-2224

Charged-Current 1π

CC-1π (resonance)

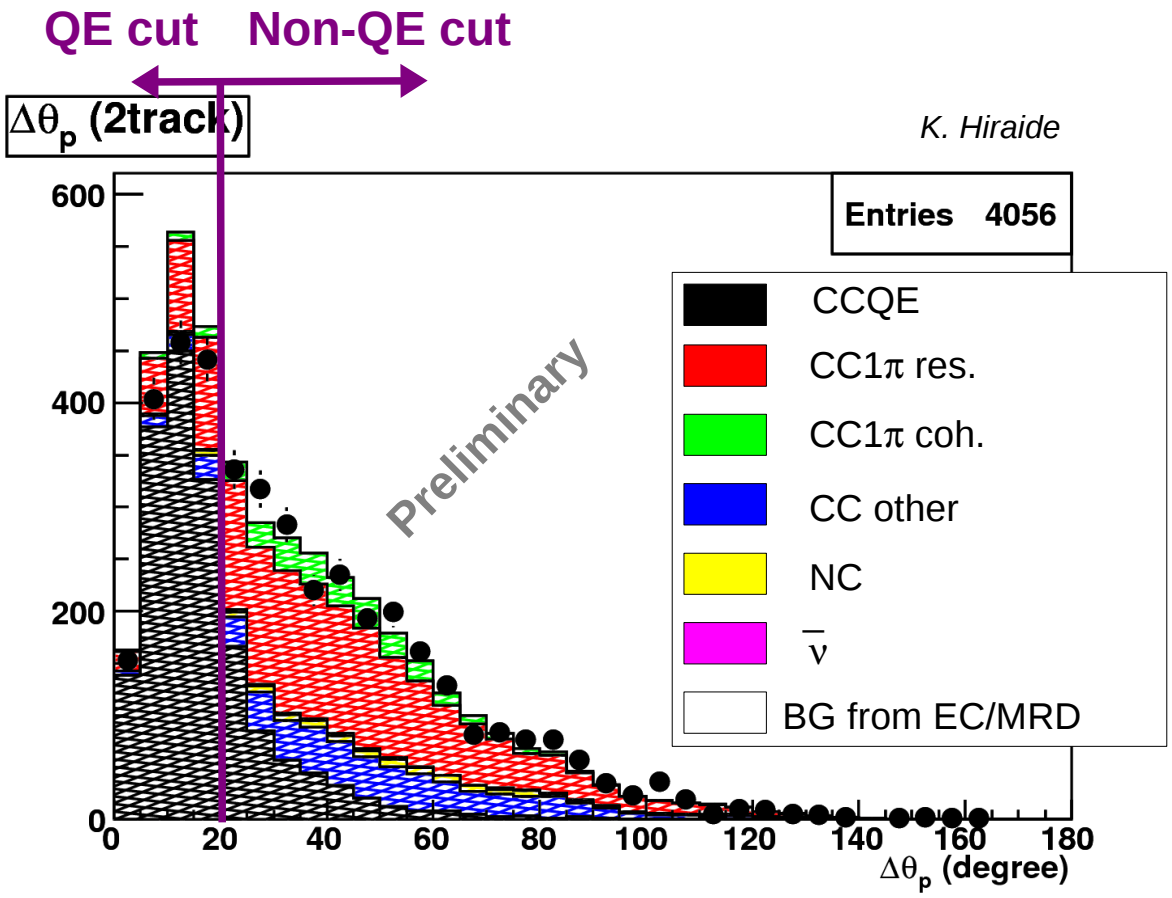




- Largest background to CCQE
- Hard to see in Cherenkov detectors
- Signal: resonant and coherent interactions

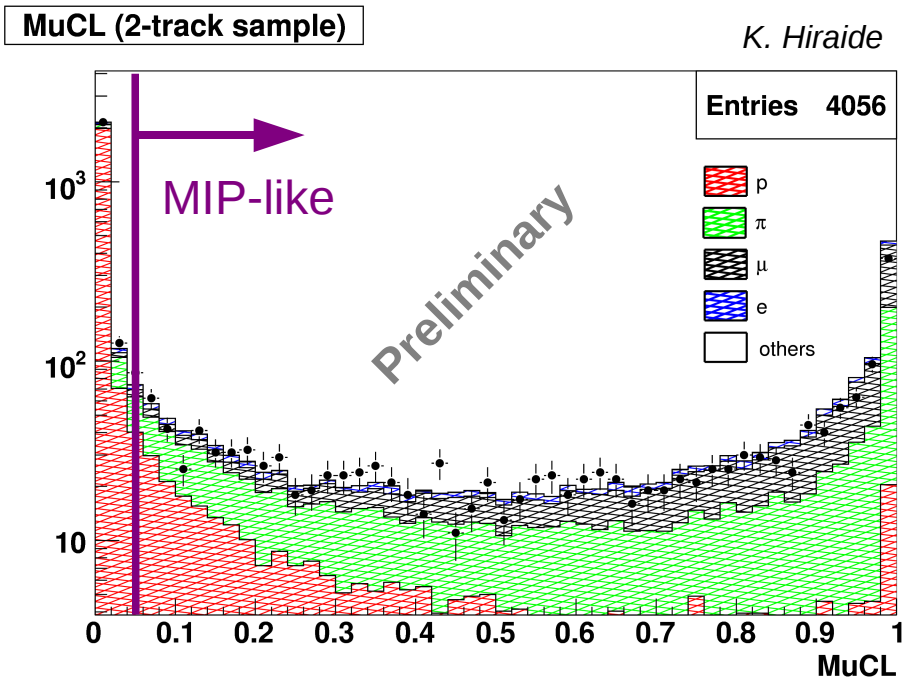
CC-1π^+ Cuts

- PID cuts applied to 2nd track to identify π
  - $\Delta\theta_p$ cut: $\Delta\theta_p > 20^o$

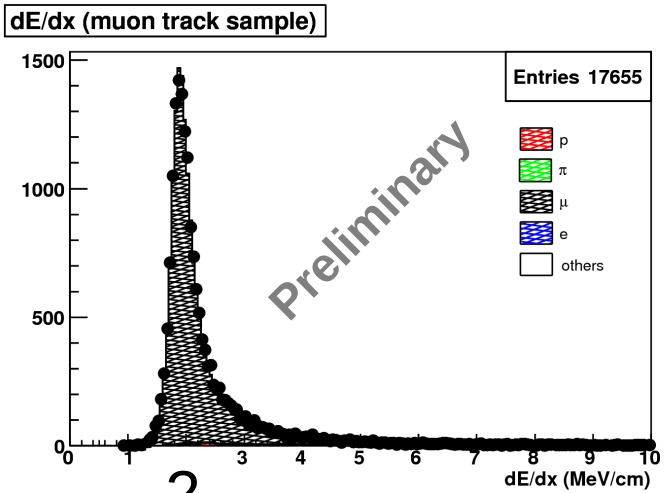


CC-1π^+ Cuts

- PID cuts applied to 2nd track to identify π
  - $\Delta\theta_p$ cut: $\Delta\theta_p > 20^o$
  - MuCL cut: MuCL>0.05
- MuCL: Muon Confidence Level. Use dE/dx information to distinguish protons from minimum ionising particles (MIPs)



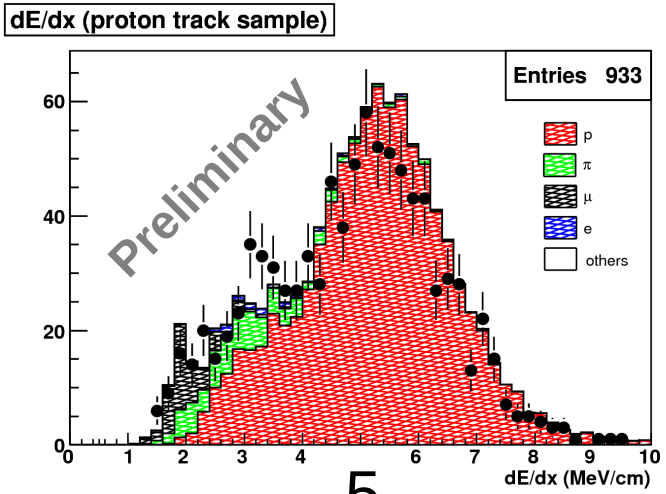
dE/dx: Muons



2

K. Hiraide

dE/dx: Protons



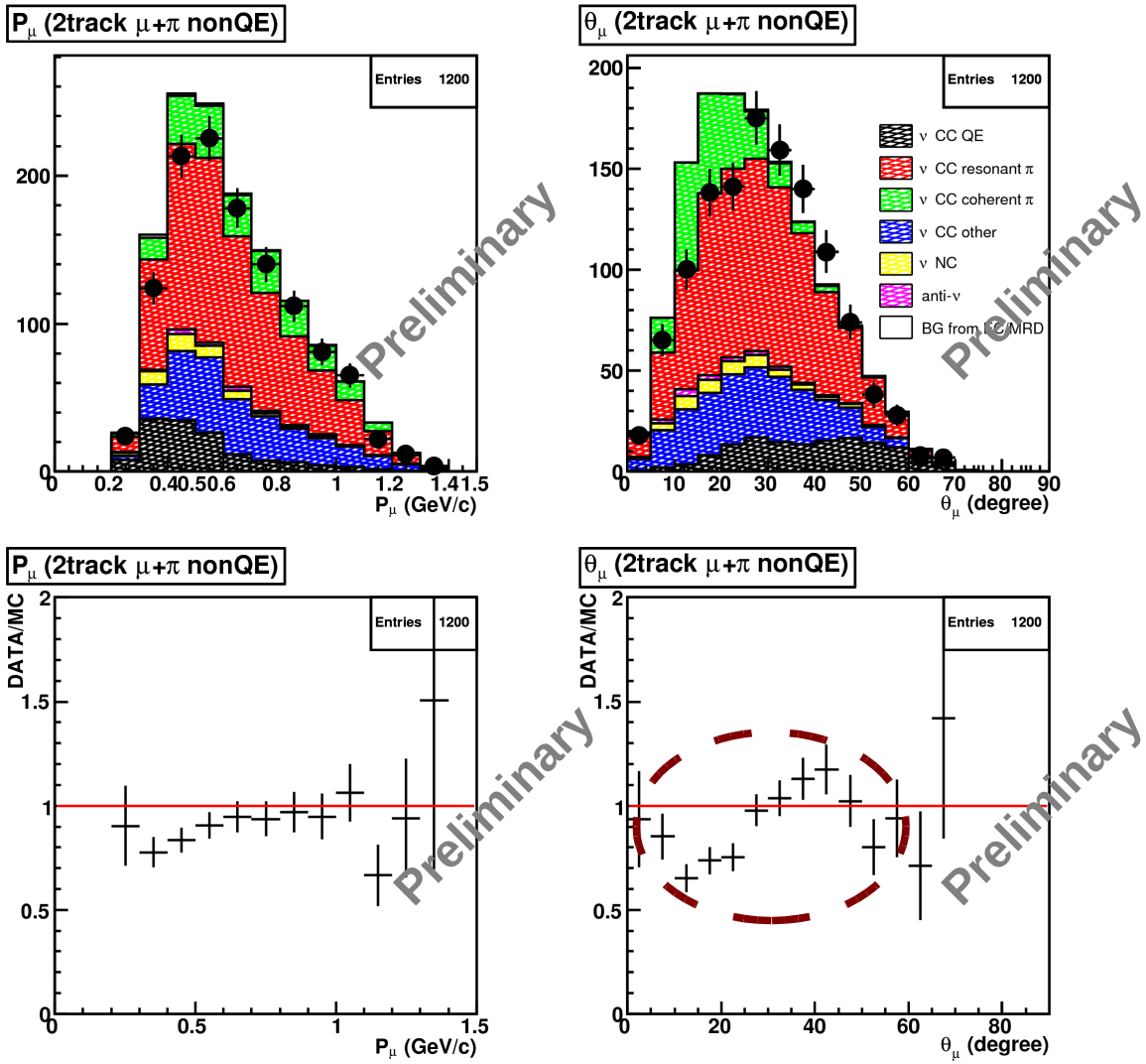
5

K. Hiraide

- θ_μ discrepancy seen
- CC1π^+ resonance purity: 66%

CCQE
CC1π res.
CC1π coh.
CC other
NC
$\overline{\nu}$
BG from EC/MRD

K. Hiraide



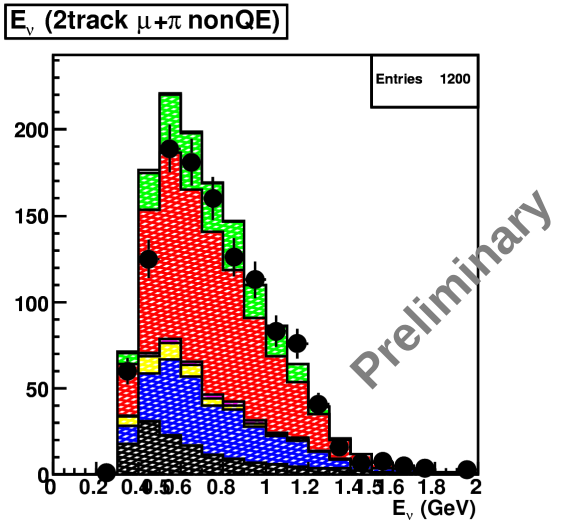
- E reconstructed assuming CCQE

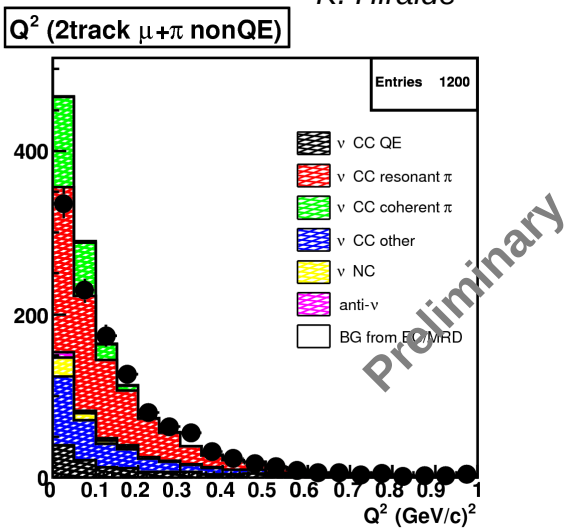
$$E_{\nu}^{rec} = \frac{m_n E_{\mu} - m_n^2/2}{m_n - E_{\mu} + P_{\mu}\cos\theta_{\mu}}$$

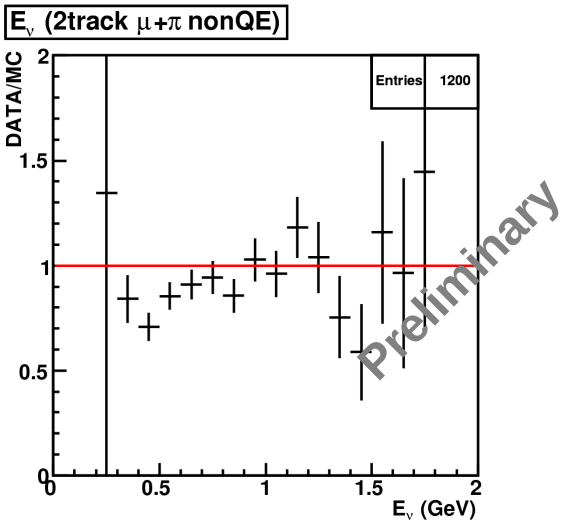
- θ_{μ} discrepancy $\rightarrow E_{\upsilon}$ discrepancy
- Low Q^2 discrepancy

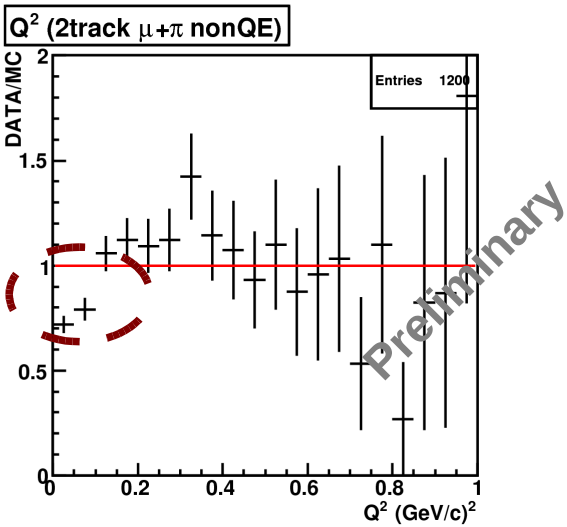
CCQE
CC1π res.
CC1π coh.
CC other
NC
$\overline{\nu}$
BG from EC/MRD

K. Hiraide

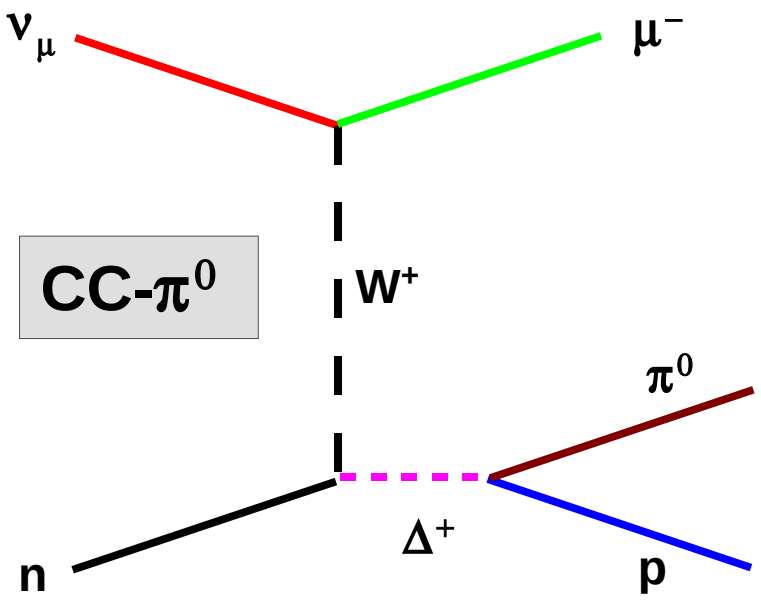


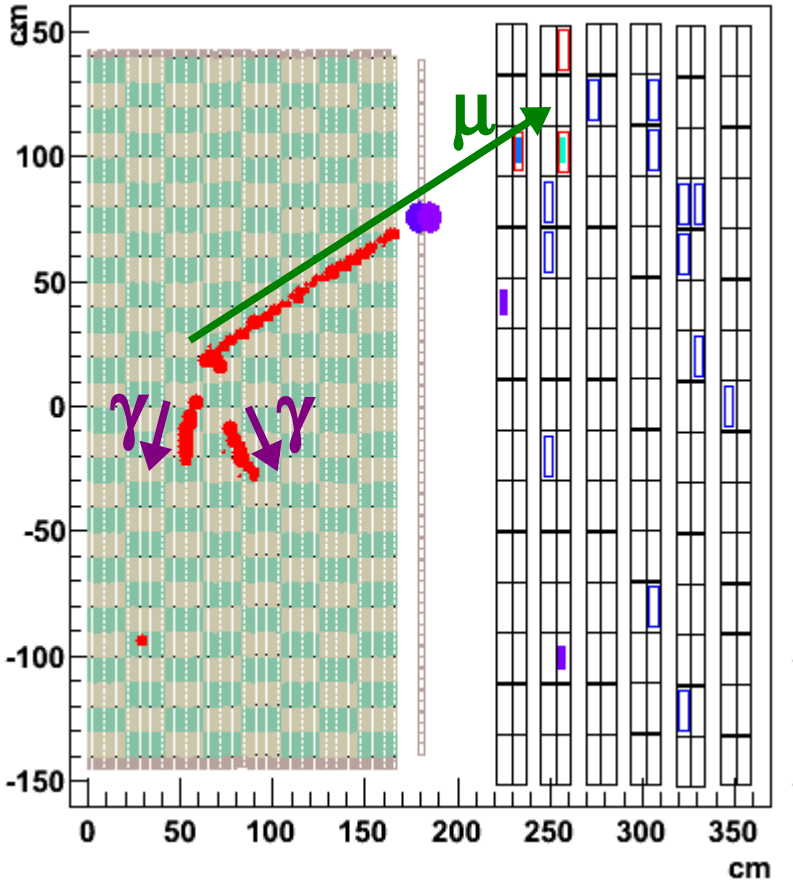






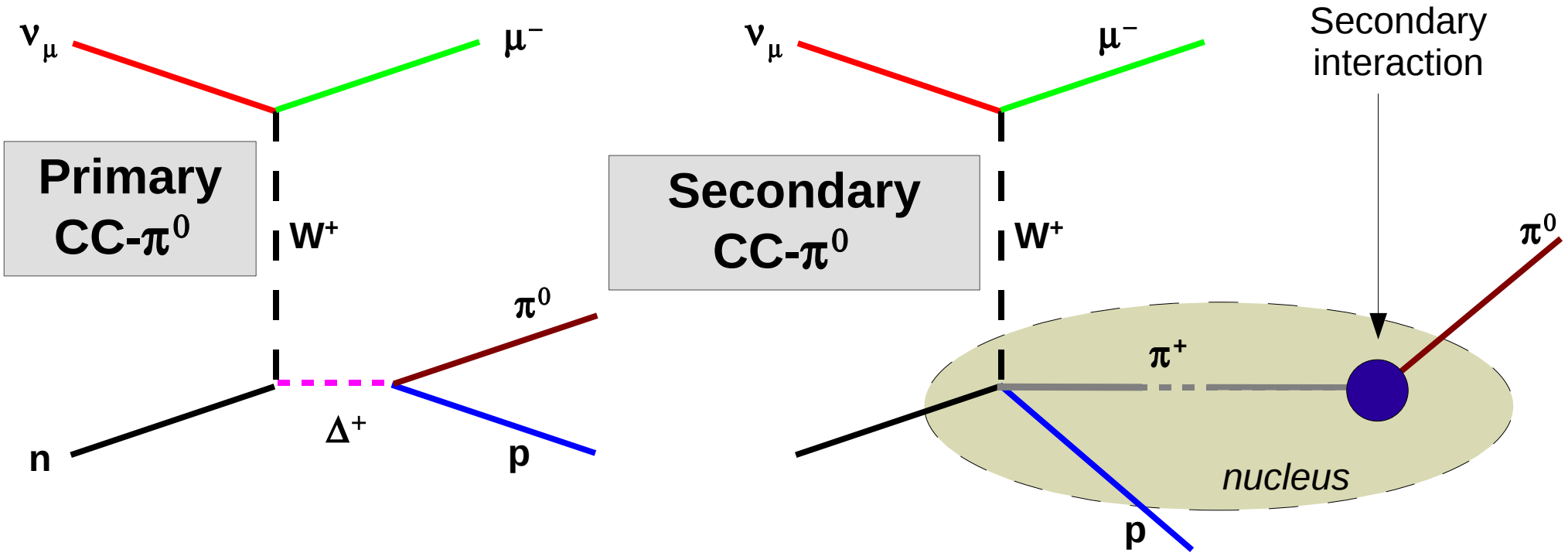
Charged-Current π^0





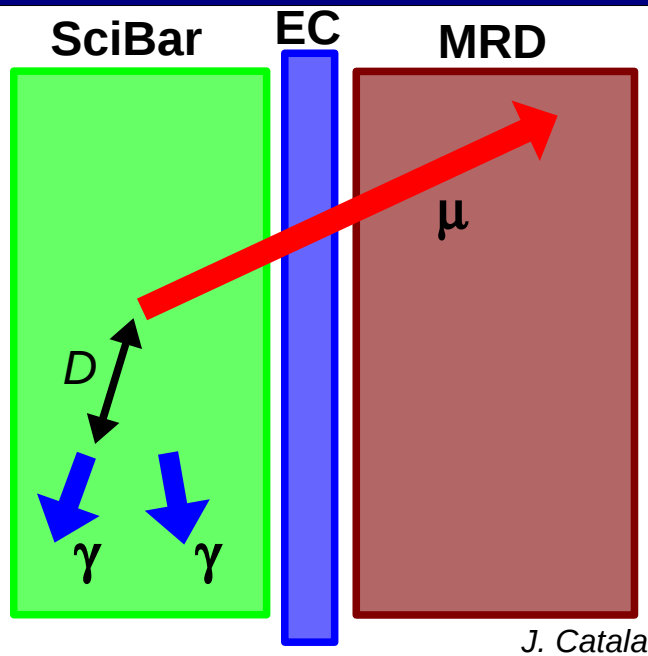
- Another background for oscillation measurements
- Signal: Primary and secondary interactions producing a π^0

- Final state interactions add to data sample
  - e.g. CCπ^+ undergoes charge exchange in nucleus results in primary CCπ^0-like event.
  - An irreducible background
  - Treated as signal

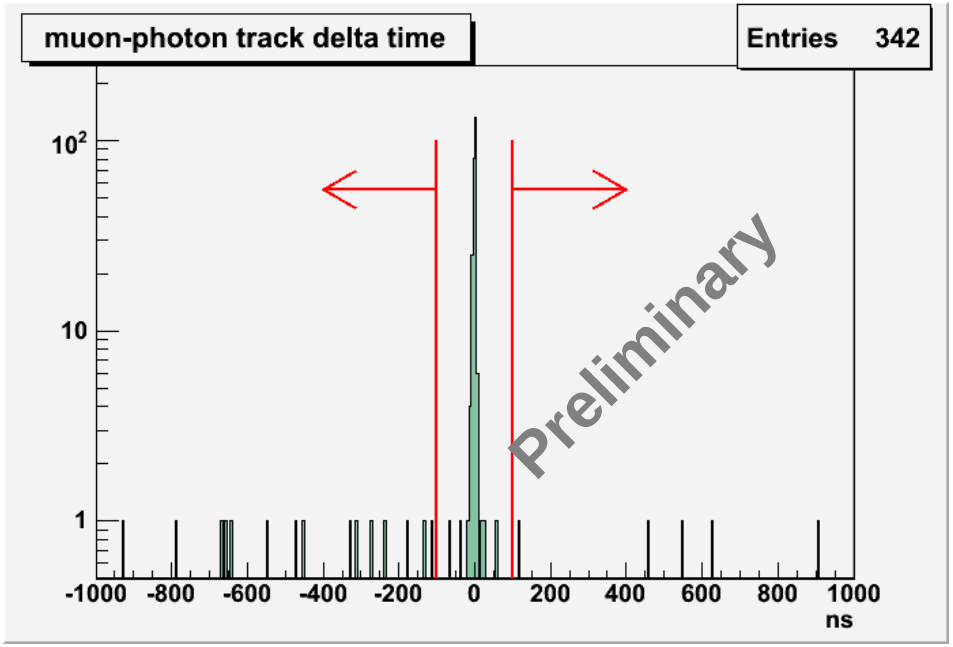


CC-π^0 Cuts

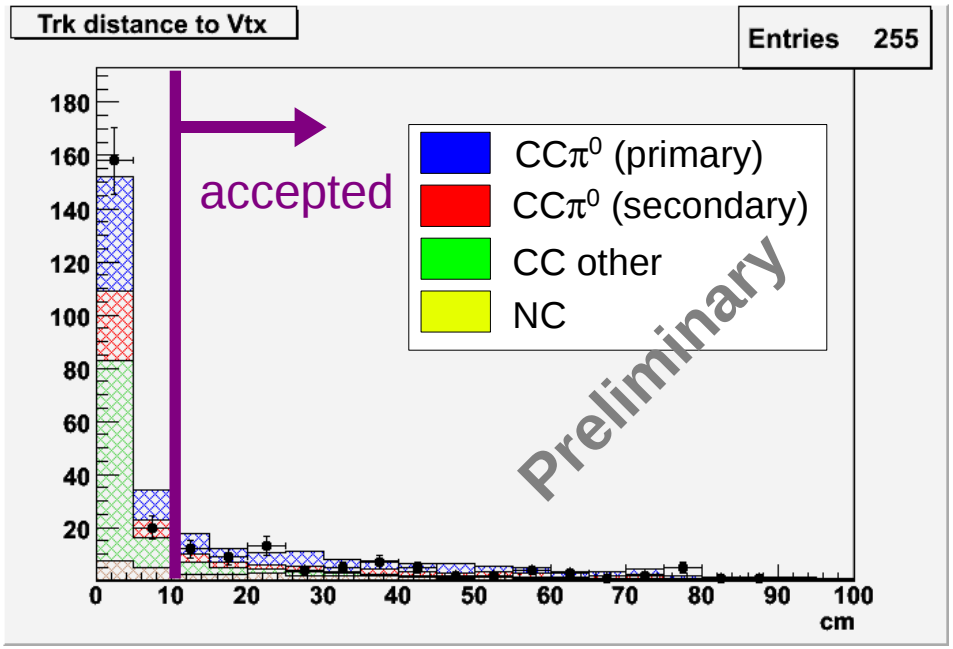
- 3-track data set
  - μ track + 2γ's
- μ–γ timing separation < |100ns|
- D = μ–γ vertex separation > 10cm



J. Catala

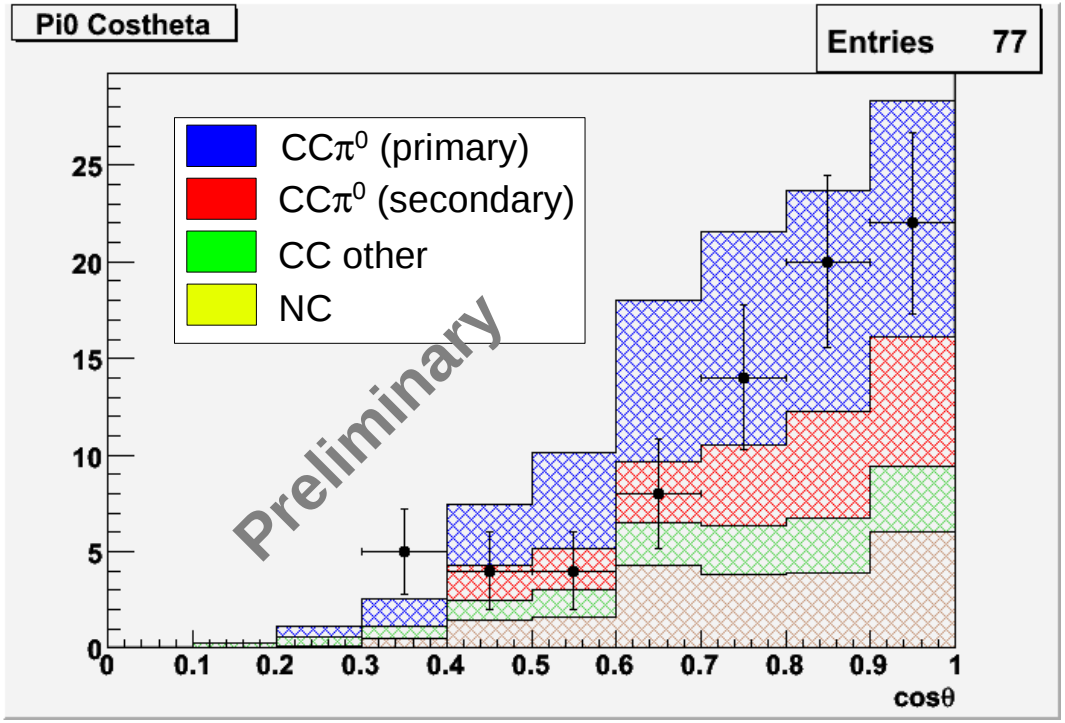


J. Catala



- Can use 2 γ's to reconstruct the pion direction
- Data/MC comparisons on shape only:
  - Only 77 events
  - Good shape agreement
- Improvements to reconstruction being made
- Next Steps
  - Include EC γ information
  - π^0 mass reconstruction
  - Increase data set
    - Look at single reconstructed γ events

J. Catala



Summary

Summary

- **Low Energy neutrino x-section measurements vital for future long baseline oscillation measurements**
  - QE: Signal (ν_μ disappearance)
  - CC$\pi^{+,0}$: Background (ν_μ disappearance)
- **SciBooNE will improve on previous measurements**
  - ν mode: Higher statistics, nuclear targets
  - $\bar{\nu}$ mode: Presently no sub-GeV measurements
- **5 charged-current analyses ongoing**
- **Data run: 100% ν mode; 70% $\bar{\nu}$ mode**
  - Completion date: 18th August 2008

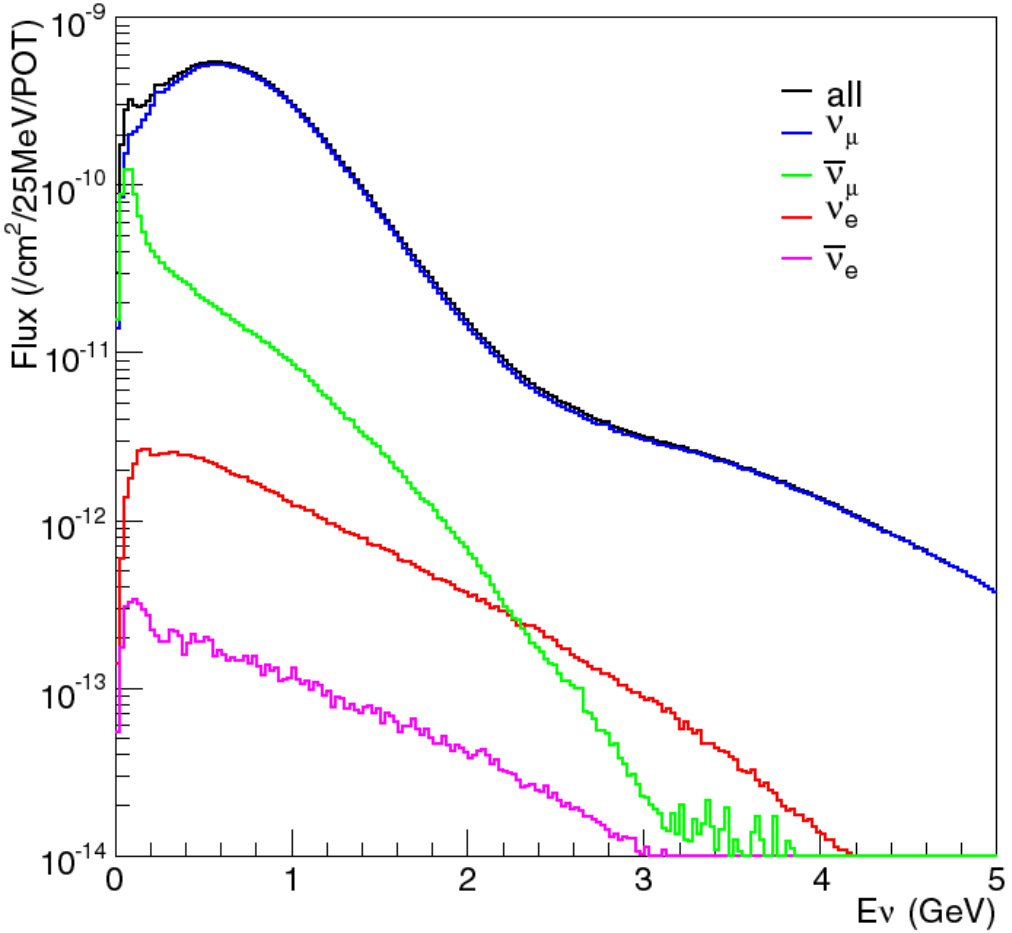
Summary

- **…nergy neutrino x-section measurements vital for … baseline oscillation measurements**
  - …appearance)
  - CC$\pi^{+,0}$: … appearance)
- **SciBooNE will i… …vious measurements**
  - ν mode: Higher statistic…
  - $\bar{\nu}$ mode: Presently no sub-GeV …
- **5 charged-current analyses ongo…**
- **Data run: 100% ν mode; 70% $\bar{\nu}$ mode**
  - Completion date: 18th August 2008

1st result expected this summer!

Backup Slides

Neutrino flux spectrum



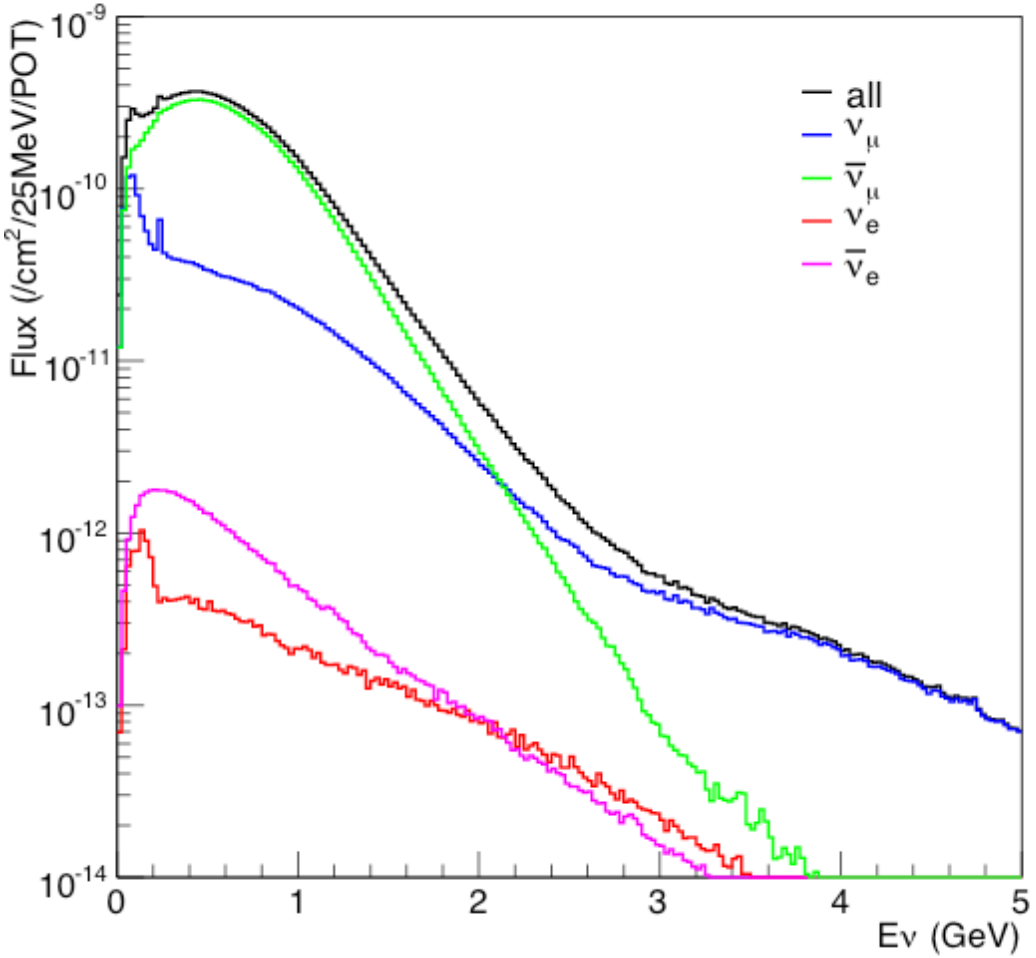
- version: Apr. ’07
- Neutrino mode (+174kA)
- 100m from Be target
- Average in R<2m

Mean Eν = 0.72 GeV

Peak Eν = 0.57 GeV

νμ:	92.9%
νμ-bar:	6.5%
νe:	0.6%
νe-bar:	0.05%

Anti-neutrino Flux



Mean Eν = 0.6 GeV

Peak Eν = 0.45 GeV

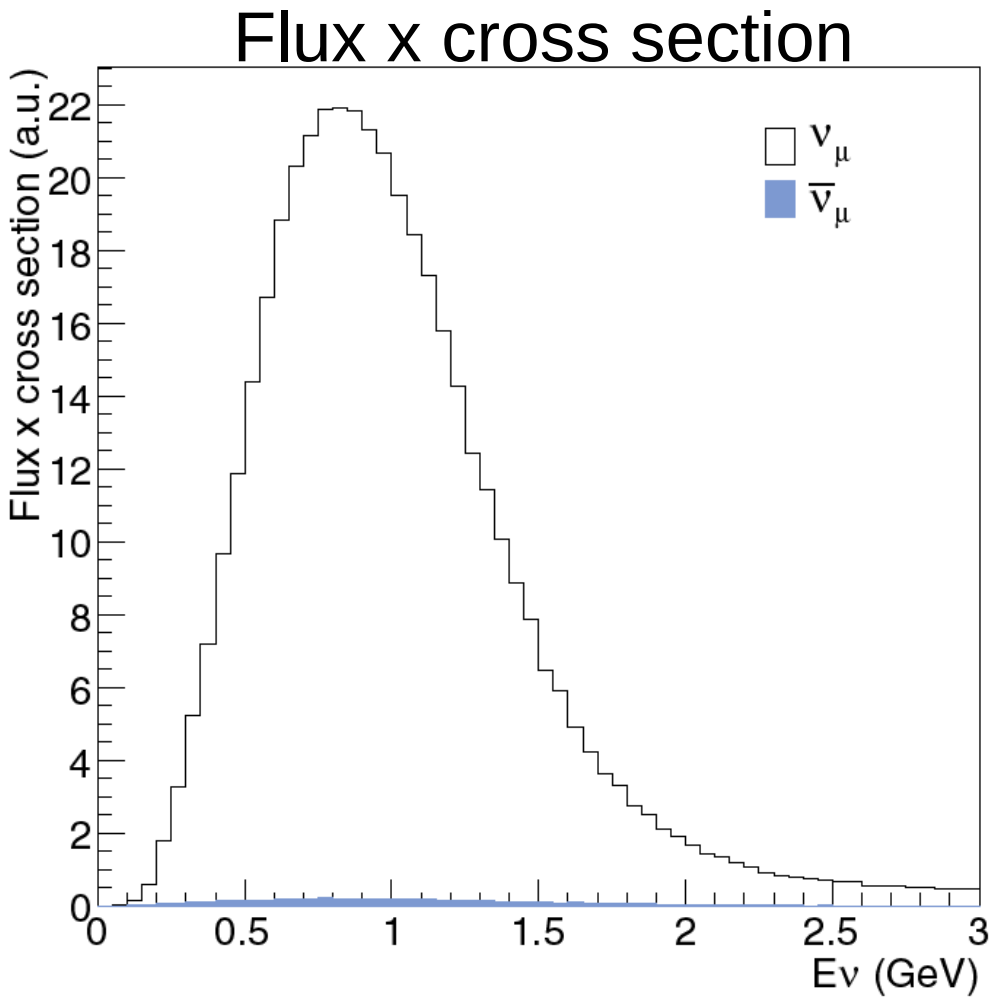
$\bar{\nu}\mu$: 83.5%

$\nu\mu$: 15.9%

νe: 0.2%

$\bar{\nu} e$: 0.4%

Neutrino energy distribution



- NEUT
- Target: CH
- generated in FV

Expected # of interactions in SciBar [/10tons/1E20POT]

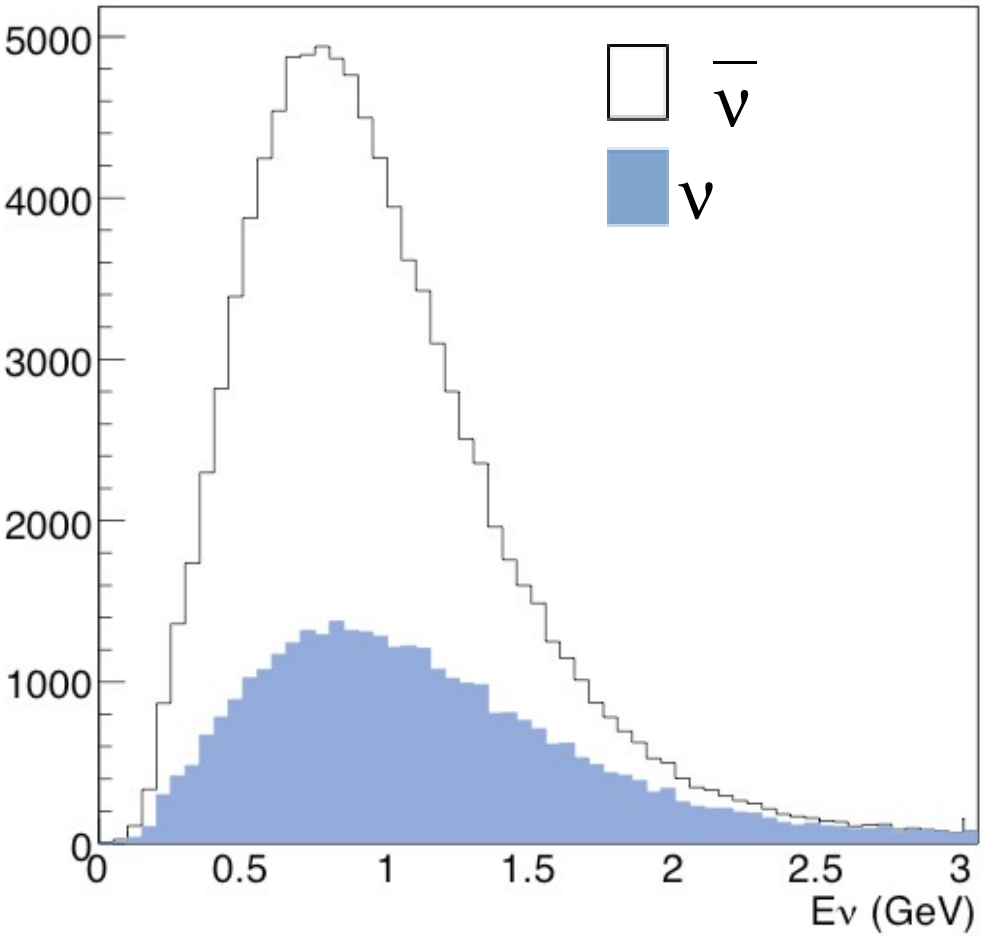
νμ:	102,000	(98.1%)
νμ-bar:	1,200	(1.2%)
νe:	730	(0.7%)
νe-bar:	30	(0.03%)

Mean Eν = 1.1 GeV

Peak Eν = 0.8 GeV

$\overline{\nu}$ flux spectrum

Flux x cross section



Anti-νμ : 62.8%
νμ : 36.2%
Anti-νe : 0.4%
νe : 0.6%

NEUT simulator

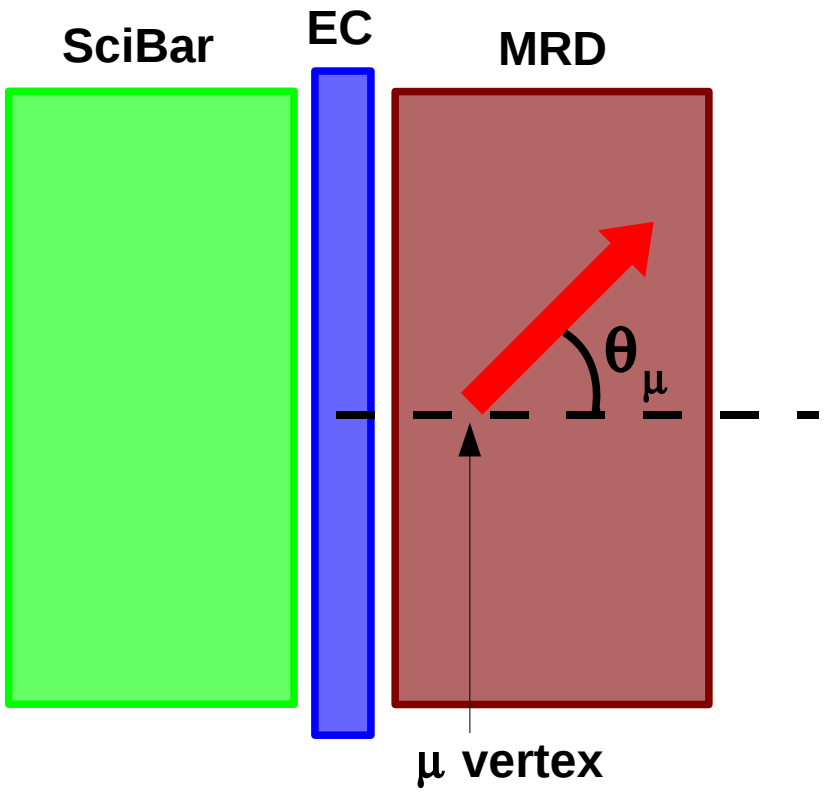
- MA = 1.1 GeV (QE, 1π)
- Coherent pi production
  Rein & Sehgal w/ lepton mass correction
- DIS
  GRV94 PDF
  w/ Bodek & Yang correction
- Nuclear effect

Average energy :
1.0GeV (anti-νμ + νμ)
0.9GeV (anti-νμ only)

Average energy :
1.0GeV (anti-νμ + νμ)
0.9GeV (anti-νμ only)

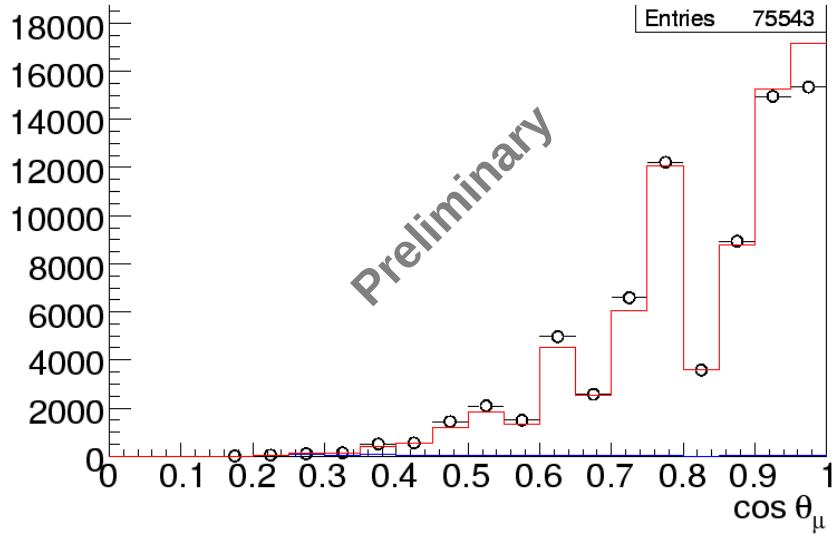
Independent Angle Check

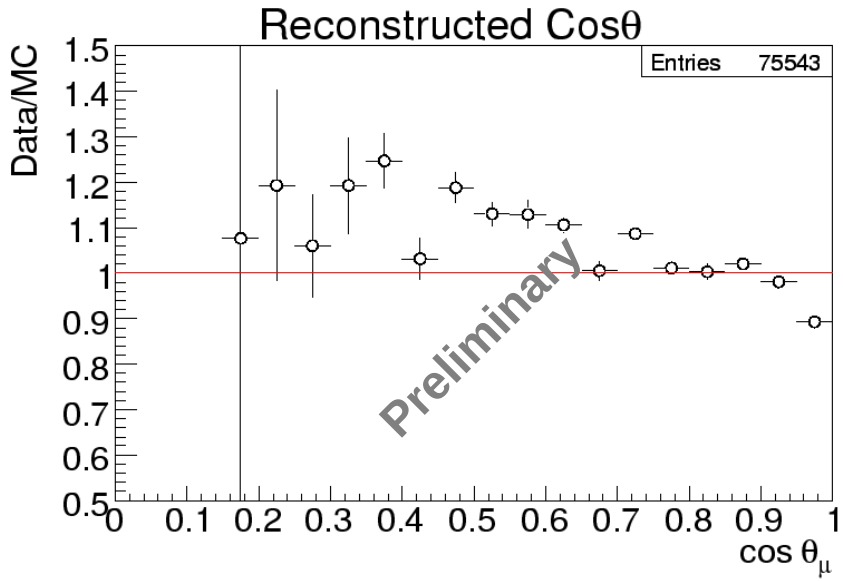
- Look at MRD originated events
  - SciBar not used
  - Opposite structure due to MRD geometry
- Same Data/MC disagreement seen
  - Discrepancy not a detector effect



Reconstructed cosθ$_\mu$ for MRD vertex events

Y. Nakajima

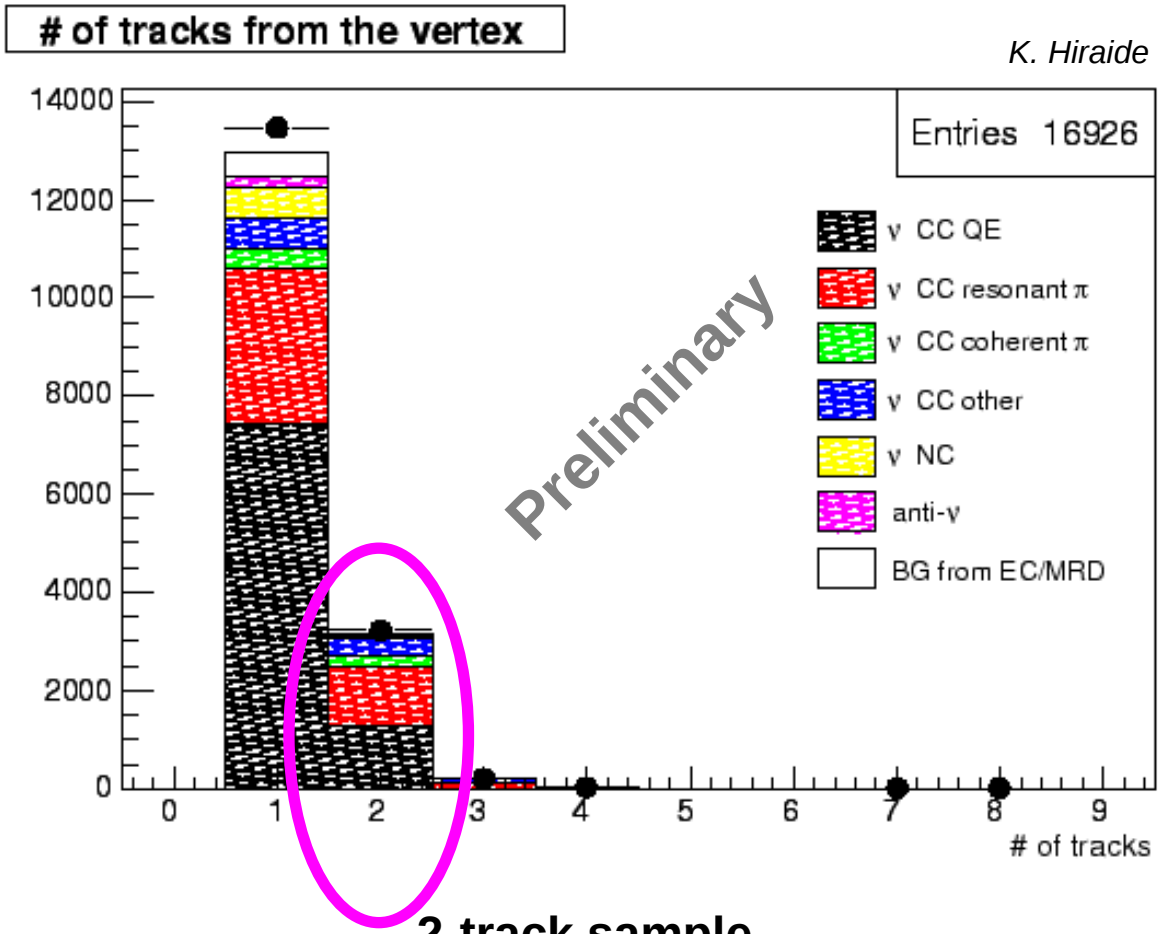




MRD-Matched Sample

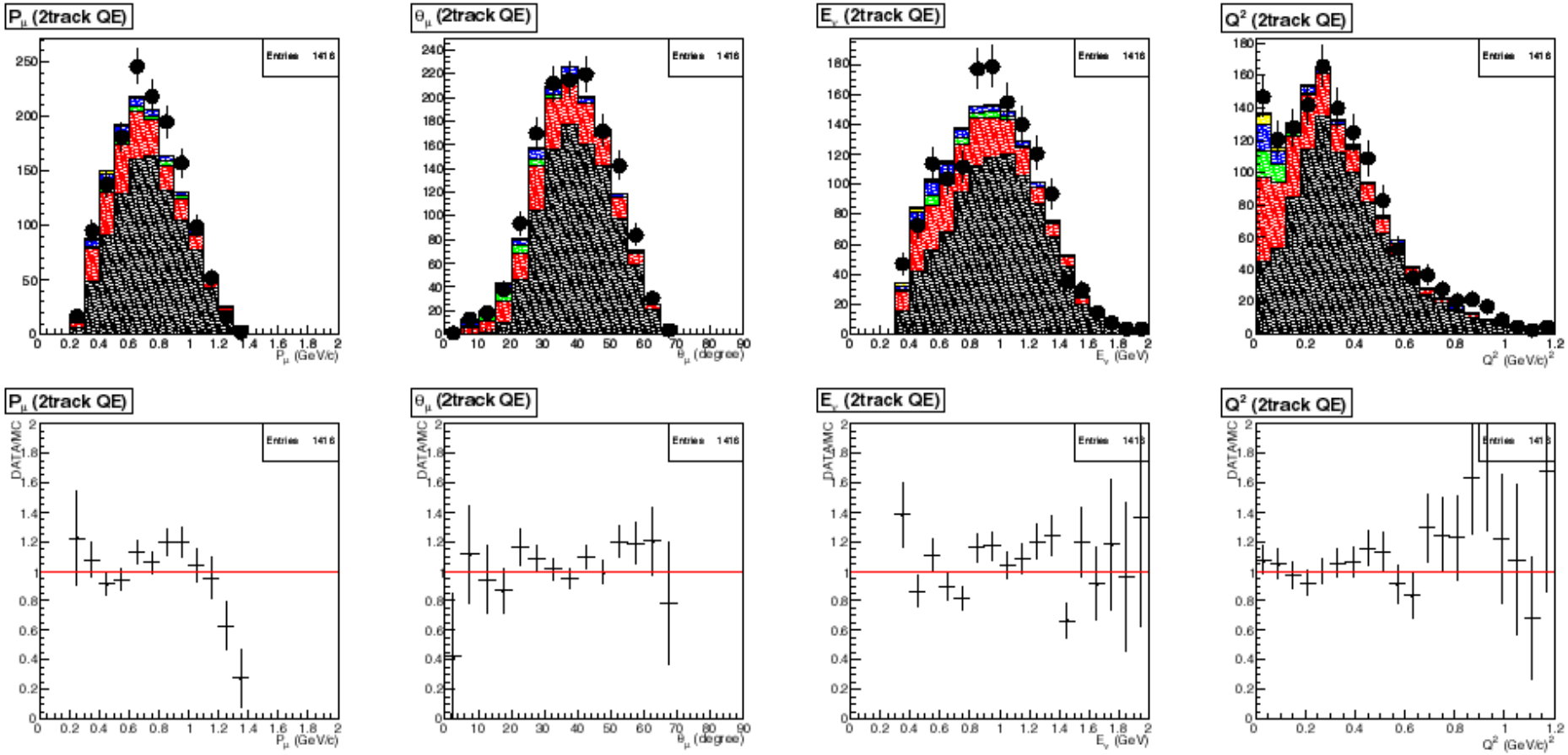
- 2 track sample with one tagged as μ (MRD-matched)

Below: MRD stopped events (MC normalised to MRD-matched events)

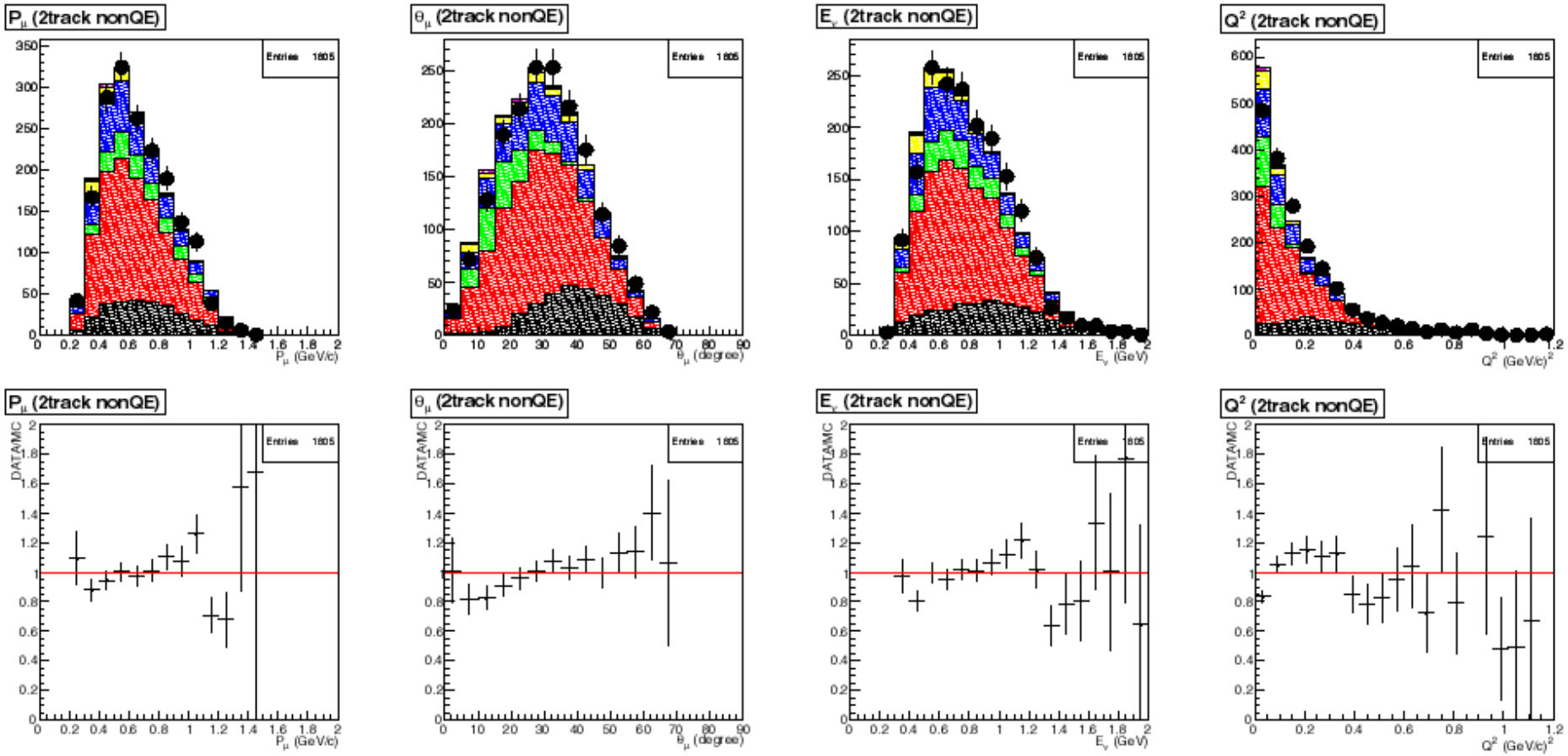


2-track sample

QE sample

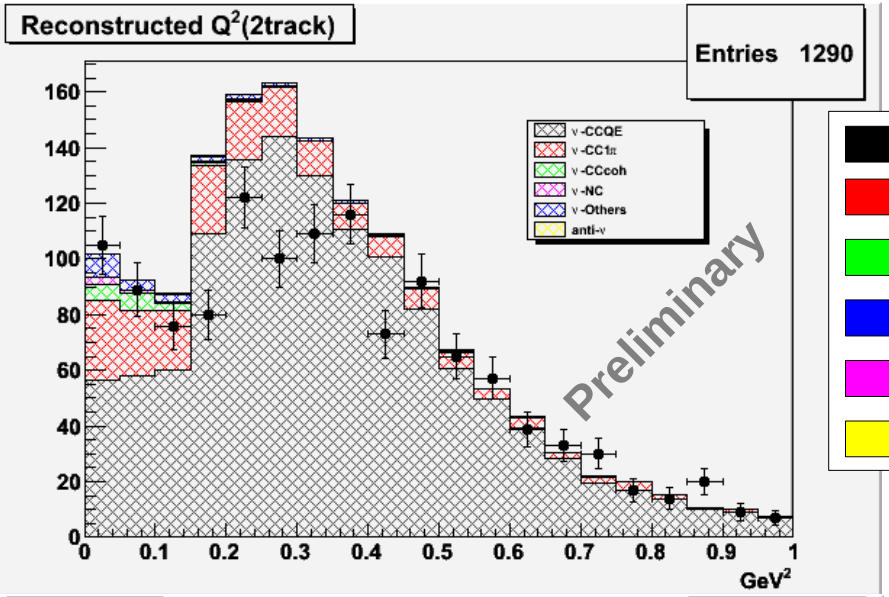

P_μ (2track QE)
θ_μ (2track QE)
E_ν (2track QE)
Q^2 (2track QE)
Entries 1416
P_μ (GeV/c)
θ_μ (degree)
E_ν (GeV)
Q^2 (GeV/c)^2
DATA/MC

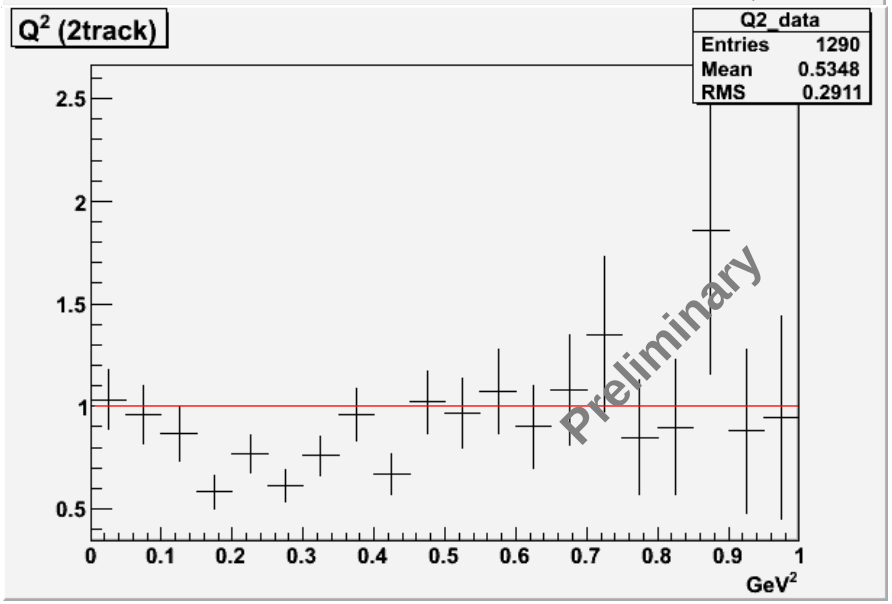
Non-QE sample

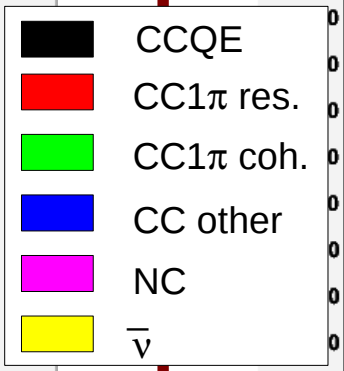


2 Track CCQE: Q^2

J. Alcaraz

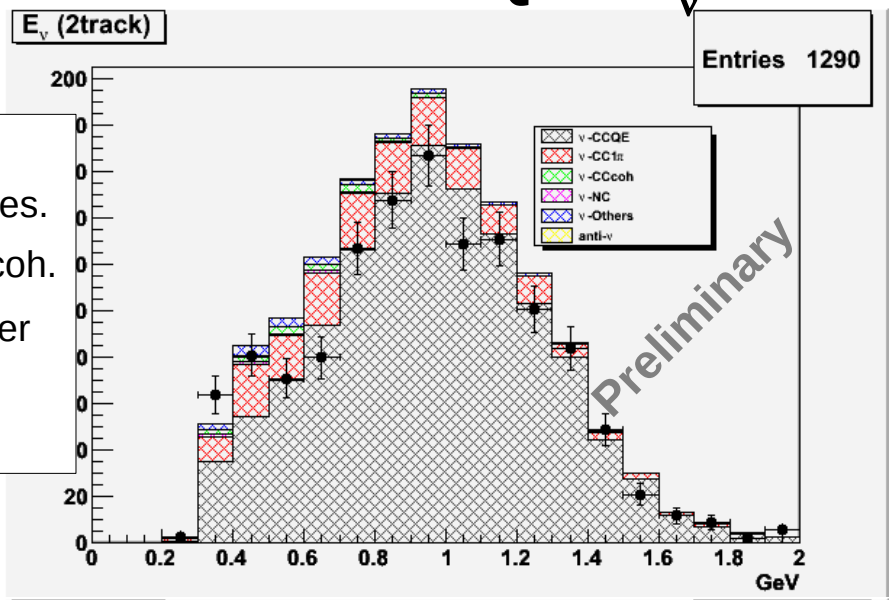


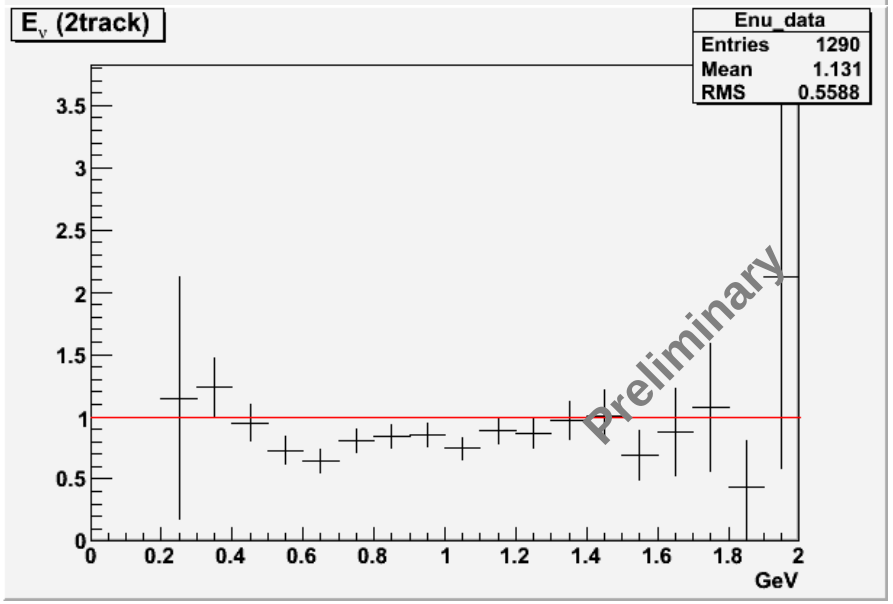




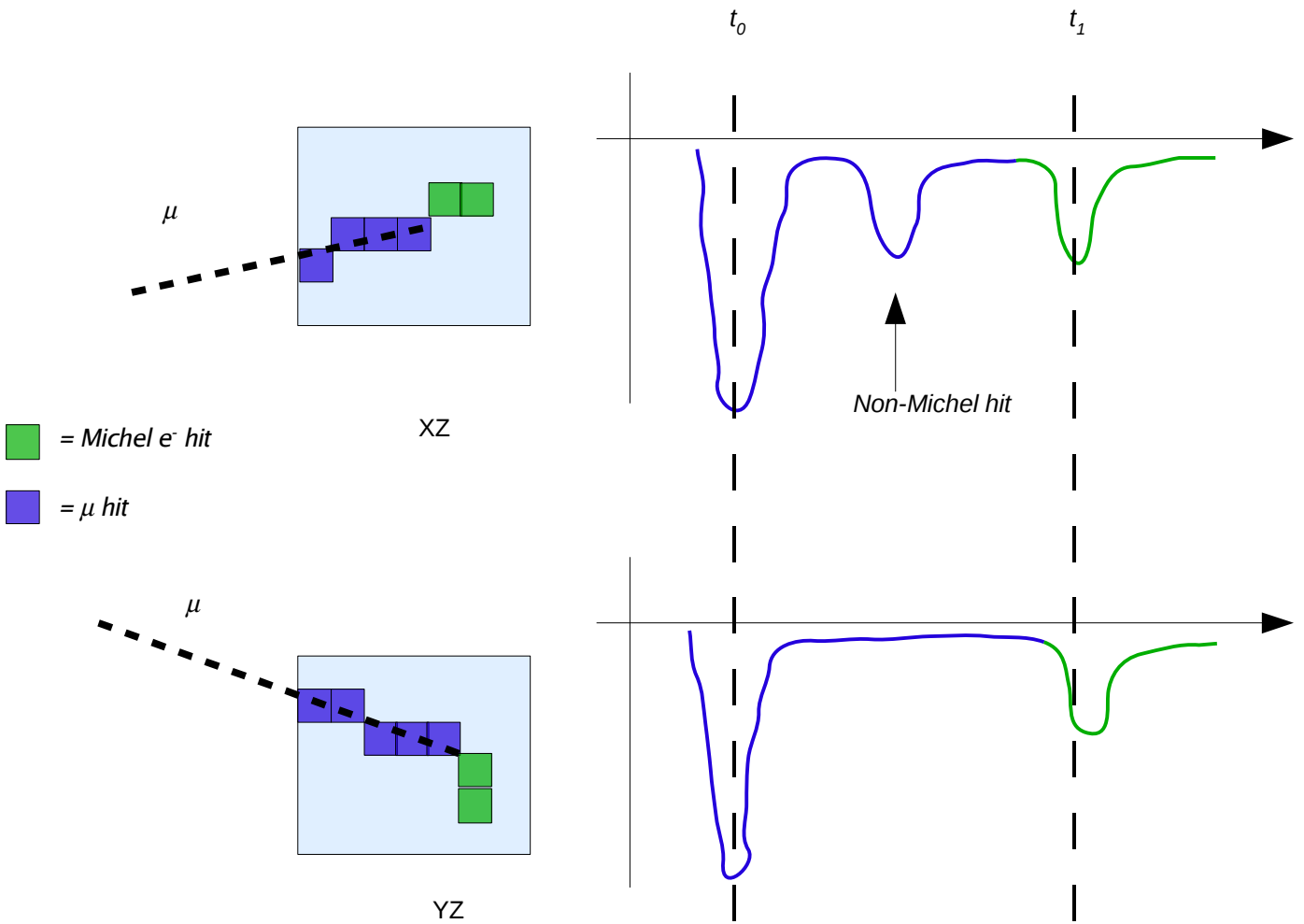
2 Track CCQE: E_ν

J. Alcaraz





SciBar contained CCQE TDC hit matching



Muon confidence level (MuCL)

dE/dx measurements in each plane
→ confidence levels (x1,x2,…,xn)

Combined probability assuming measurements are independent

$$P = x_1 \cdot x_2 \cdots x_n$$

Muon C.L. is the probability that the combined CL by muon is below the measured value P

$$MuCL = 1 - \int_P^1 \int_{\frac{P}{x_1}}^1 \cdots \int_{\frac{P}{x_1 x_2 \cdots x_{n-1}}}^1 dx'_1 dx'_2 \cdots dx'_n$$

$$= P\left(\sum_{i=0}^{n} \frac{(-\ln P)^i}{i!} \right)$$

MuCL ~1 → MIP-like
MuCL ~0 → non MIP-like

Sort & truncate confidence levels

plane-based confidence levels are sorted by ascending

$x1 < x2 < \ldots\ldots < \ldots\ldots < \ldots\ldots < xn$

C.L. : Small
dE/dx : Large

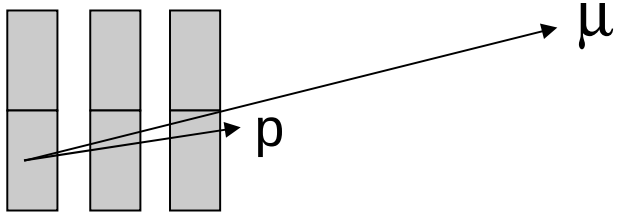
Large
Small

50%

10%

Removed to avoid effect
of track overlapping

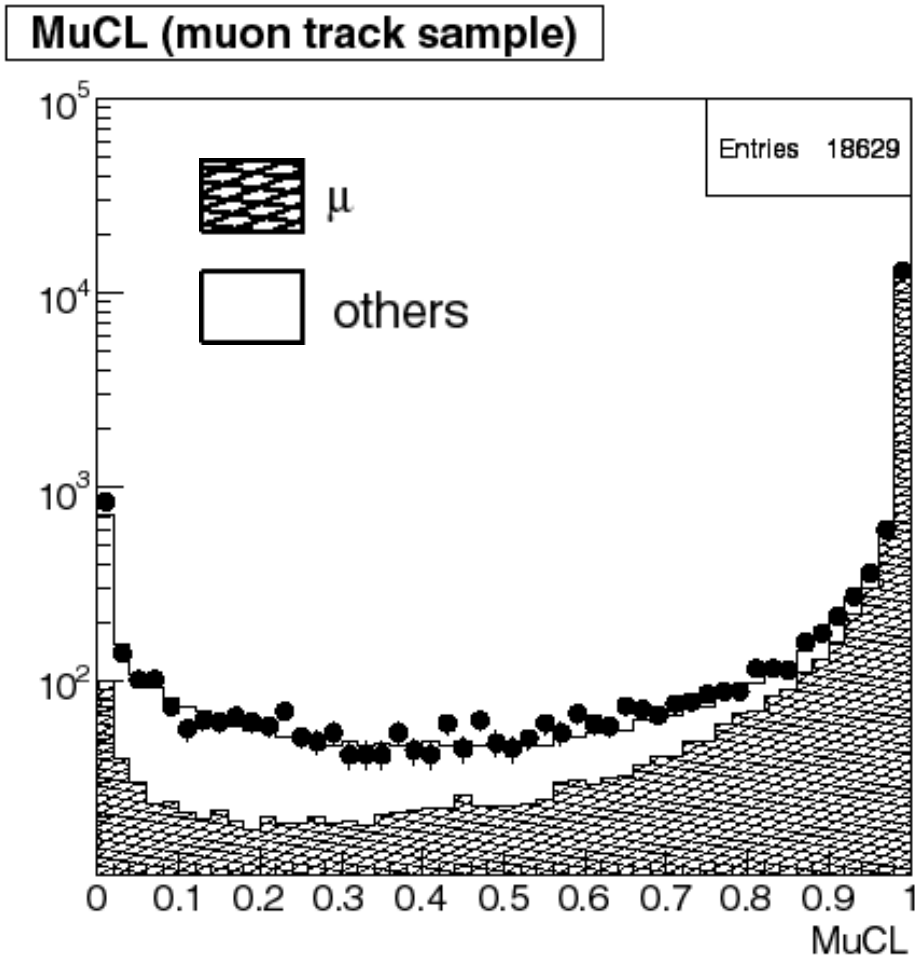
Removed to avoid effect of
inefficiency / cross-talk



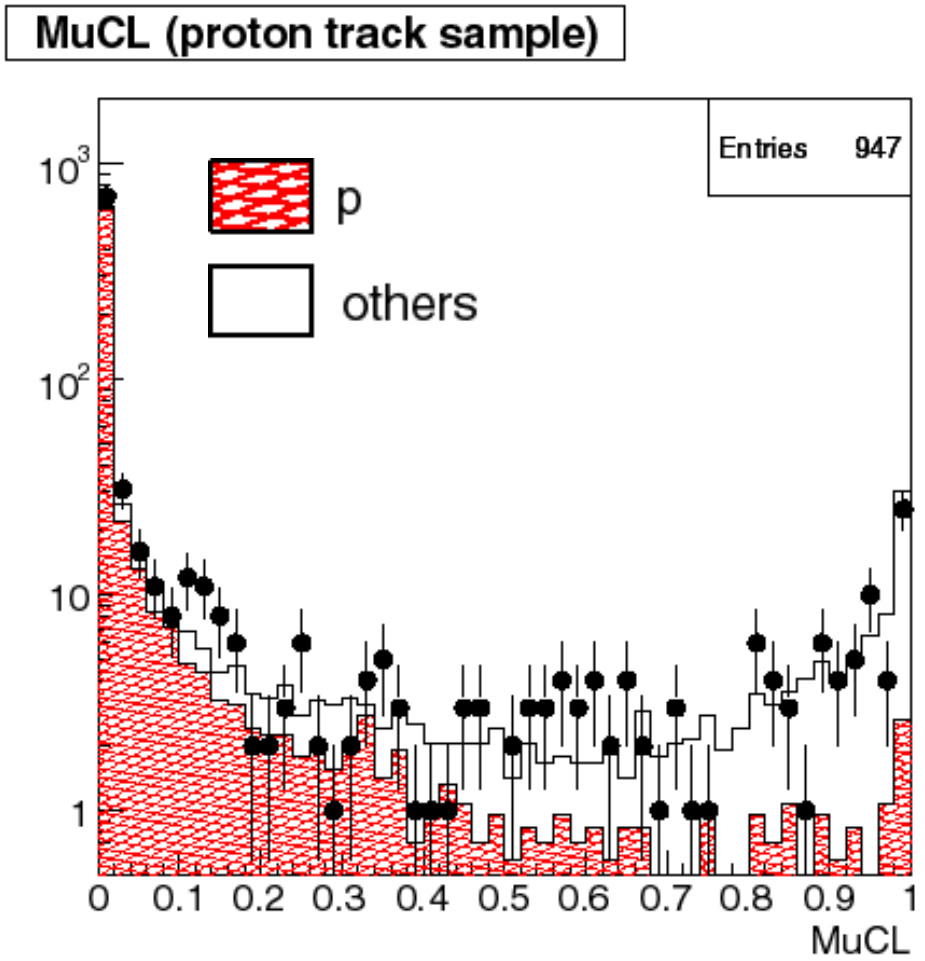
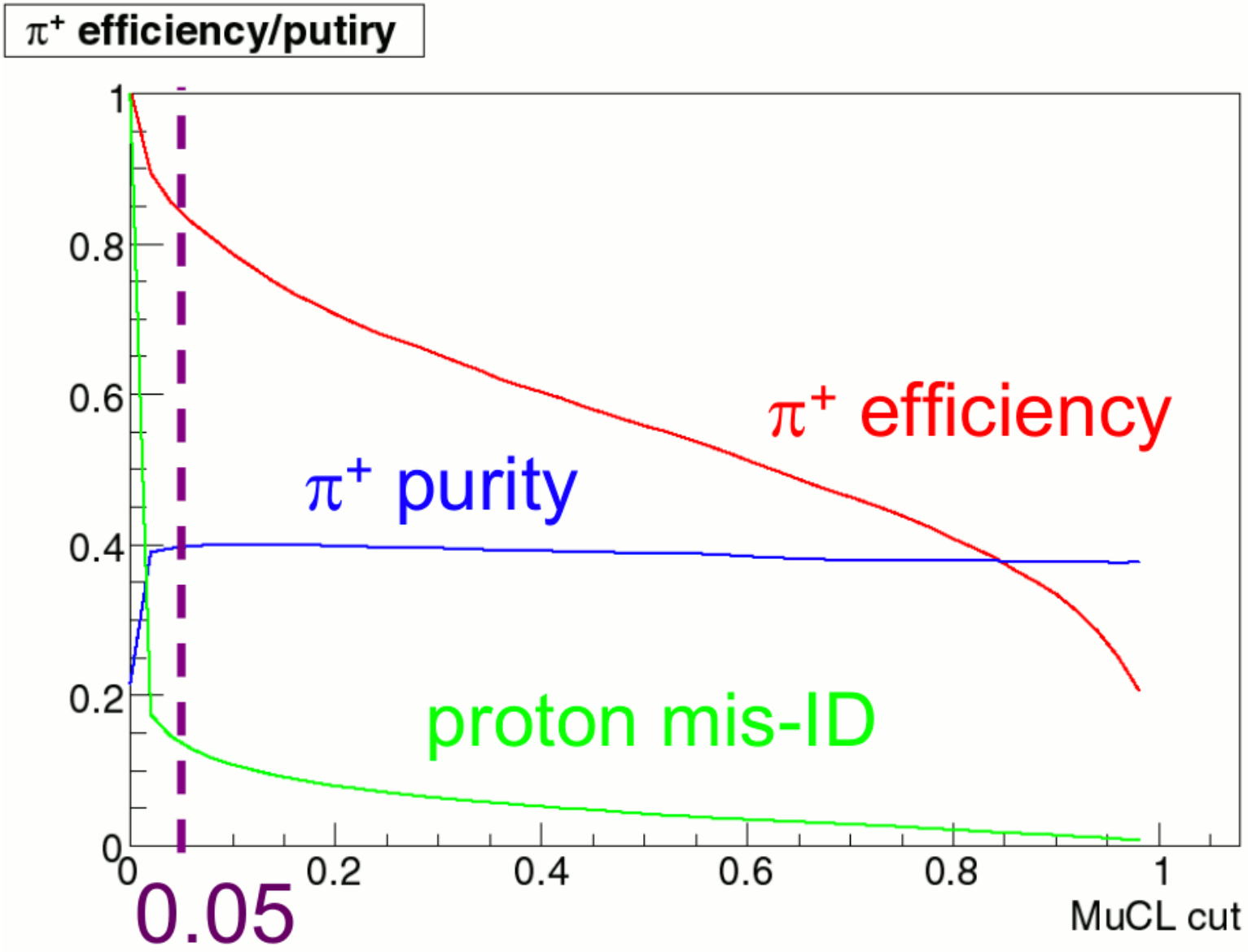
K. Hiraide

MuCL distributions

MRD matched, 1 track



MRD stopped, 2 track, Δθp<25degree



MuCL efficiency & purity