ν_μ CCQE σ Measurement for SciBooNE

NuInt '09

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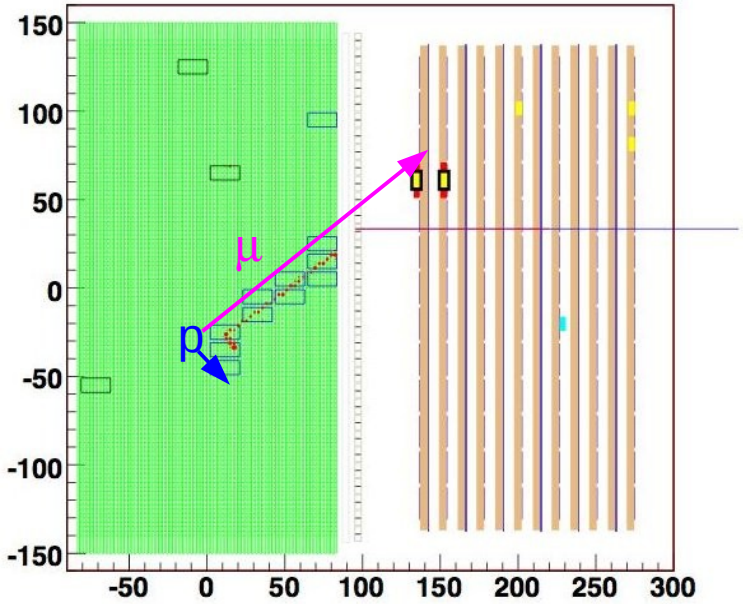
19th May 2009

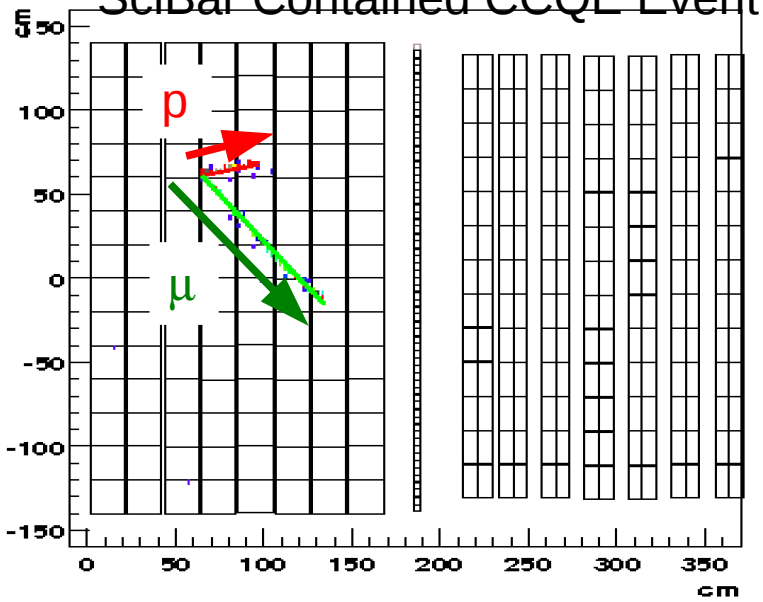
Outline

- **SciBooNE**
  - Experimental Overview
  - Detector Overview
- **CCQE Analyses**
  - SciBar Contained CCQE
    - Event Selection
  - MRD Matched CCQE
    - Event Selection
    - Cross-Section Extraction
- **Summary**

MRD Matched CCQE Event



SciBar Contained CCQE Event



SciBooNE Experiment

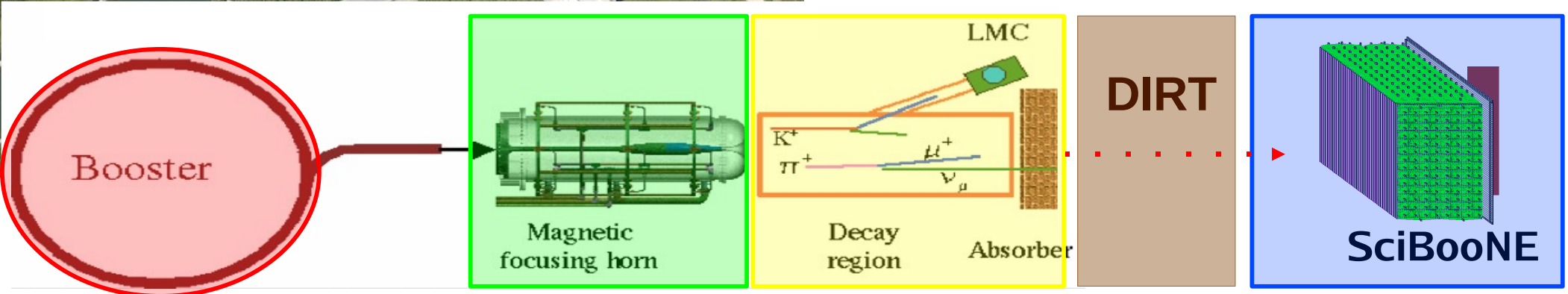
SciBooNE Collaboration

- 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
- Kamioka Observatory
- Los Alamos National Laboratory
- Louisiana State University
- MIT
- Purdue University Calumet
- Universita degli Studi di Roma "La Sapienza" & INFN
- Saint Mary's University of Minnesota
- Tokyo Institute of Technology
- Unversitat de Valencia

A selection of SciBooNE collaborators at the London Collaboration Meeting. March 2008

The Booster Neutrino Beam

- 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



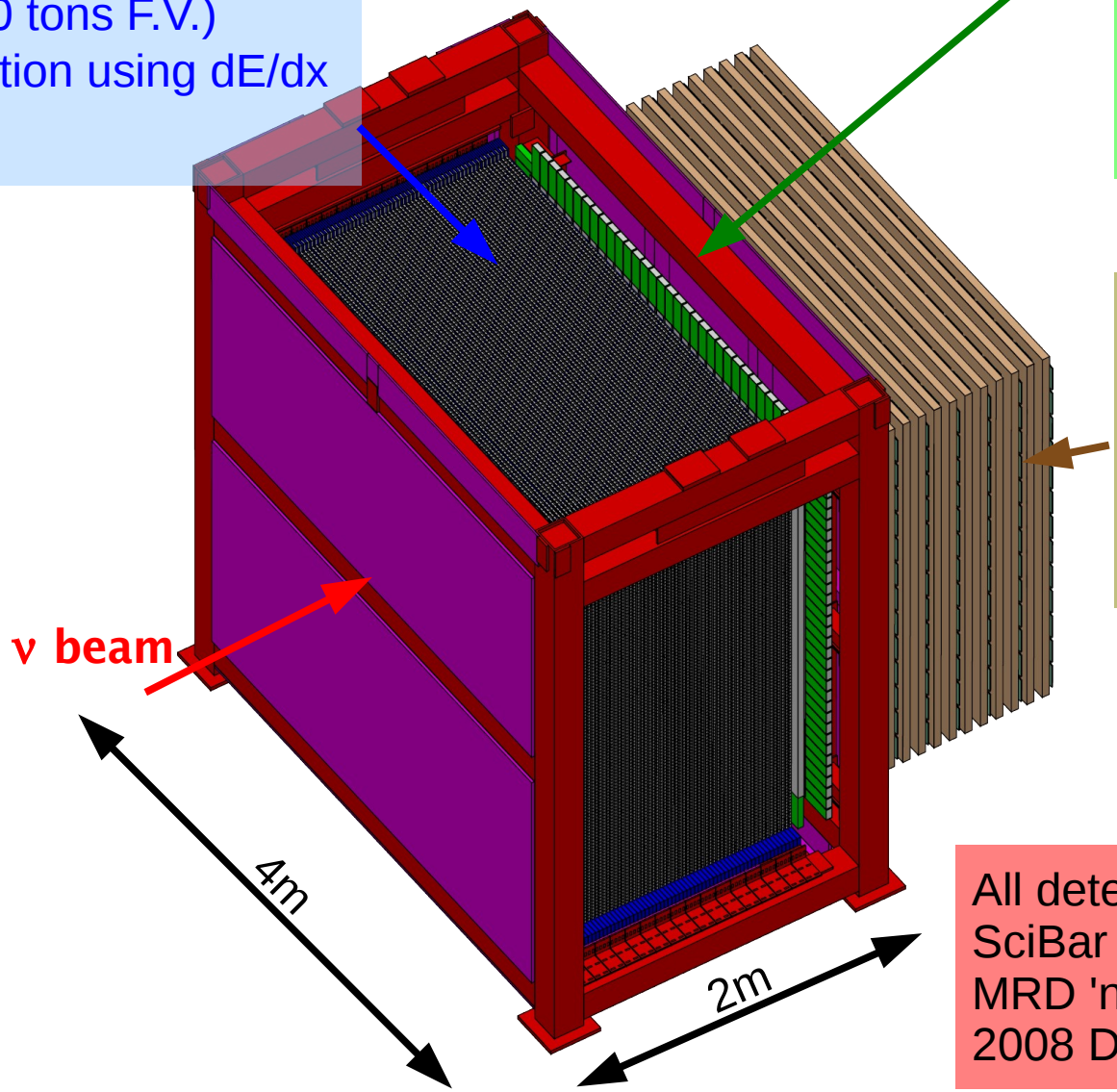
SciBooNE Detector

SciBar

14,336 Scintillator bars
15 tons (10 tons F.V.)
p/π separation using dE/dx

Electron-Catcher (EC)

'Spaghetti' Calorimeter
2 planes (x&y)
$11X_0$
identify π^0 & ν_e



Muon Range Detector (MRD)

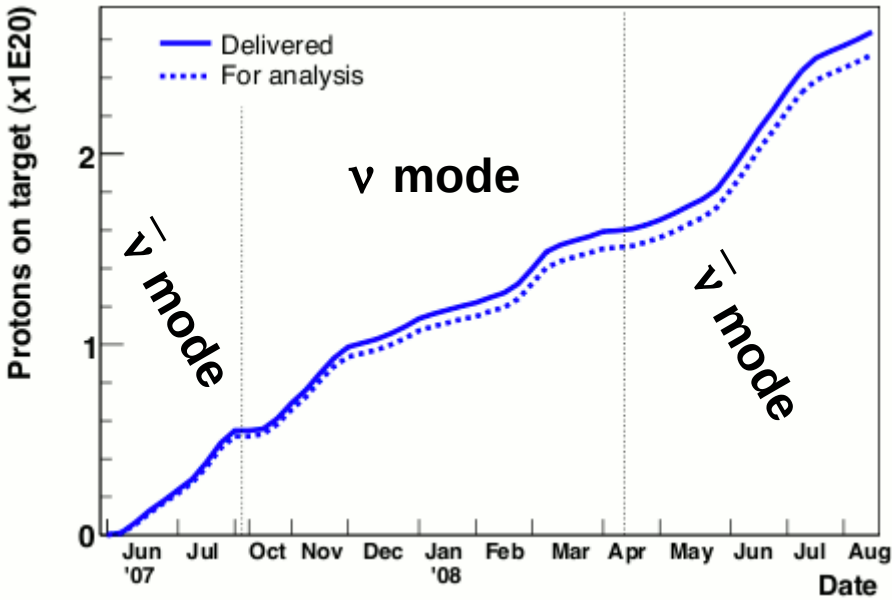
12 2" iron planes
362 scintillator panels
stop μ's with p < 1.2 GeV/c

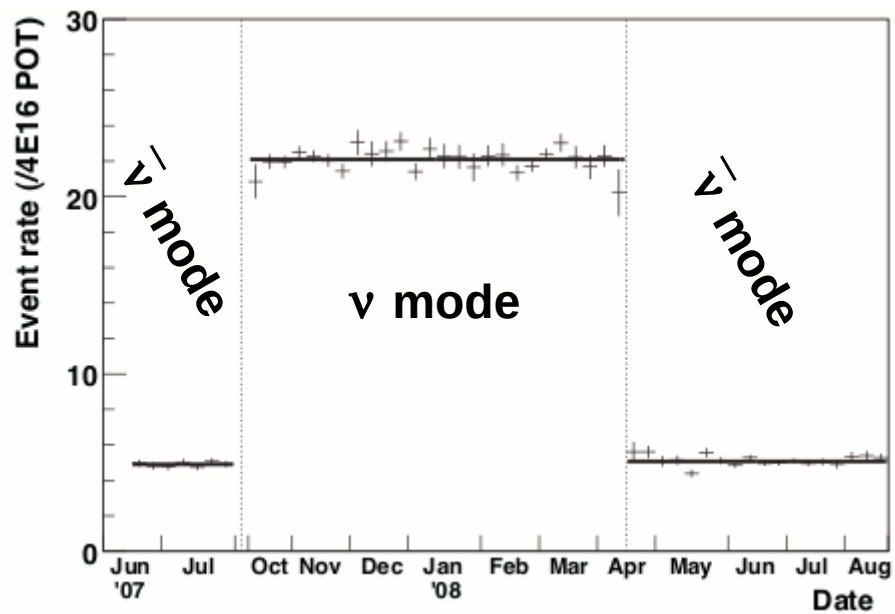
All detectors have X&Y views
SciBar & EC used at K2K
MRD 'new' detector built at FNAL
2008 DOE P2* Environmental Award

SciBooNE Operations

- **Nuclear target**
  - Tracking detector
  - 0.99×10^{20} POT ν_μ mode taken
  - 1.53×10^{20} POT $\bar{\nu}_\mu$ mode taken
  - 25% more data ($\bar{\nu}_\mu$) than requested!
- **Data Run completed August 2008**
- **Very stable event rate**
- **95% POT efficiency**

Note: All Data/MC plots are POT normalised

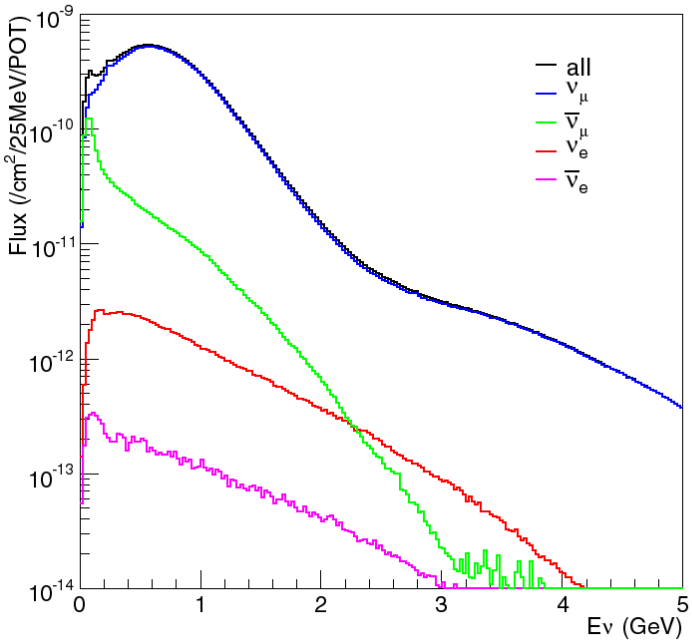




SciBooNE MC

- Neutrino Flux MC
  - π^+ production: Extrapolated from HARP data (same as MiniBooNE) with Sanford-Wang errors
- NEUT MC
  - CCQE interaction: Llewellyn-Smith Model
    - M_A = 1.2 GeV
  - CC1π : Rein-Sehgal Model
    - CC coherent interactions suppressed by 0.33 in MC
      - Consistent with SciBooNE
      - *Phys Rev D **78** 112004 (2008)*
  - Nuclear Model: Smith-Moniz Relativistic Fermi Gas Model
  - FSI: Formation Zone Parametrisation

Neutrino Flux Prediction



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

CCQE Analyses:
SciBar Contained Events

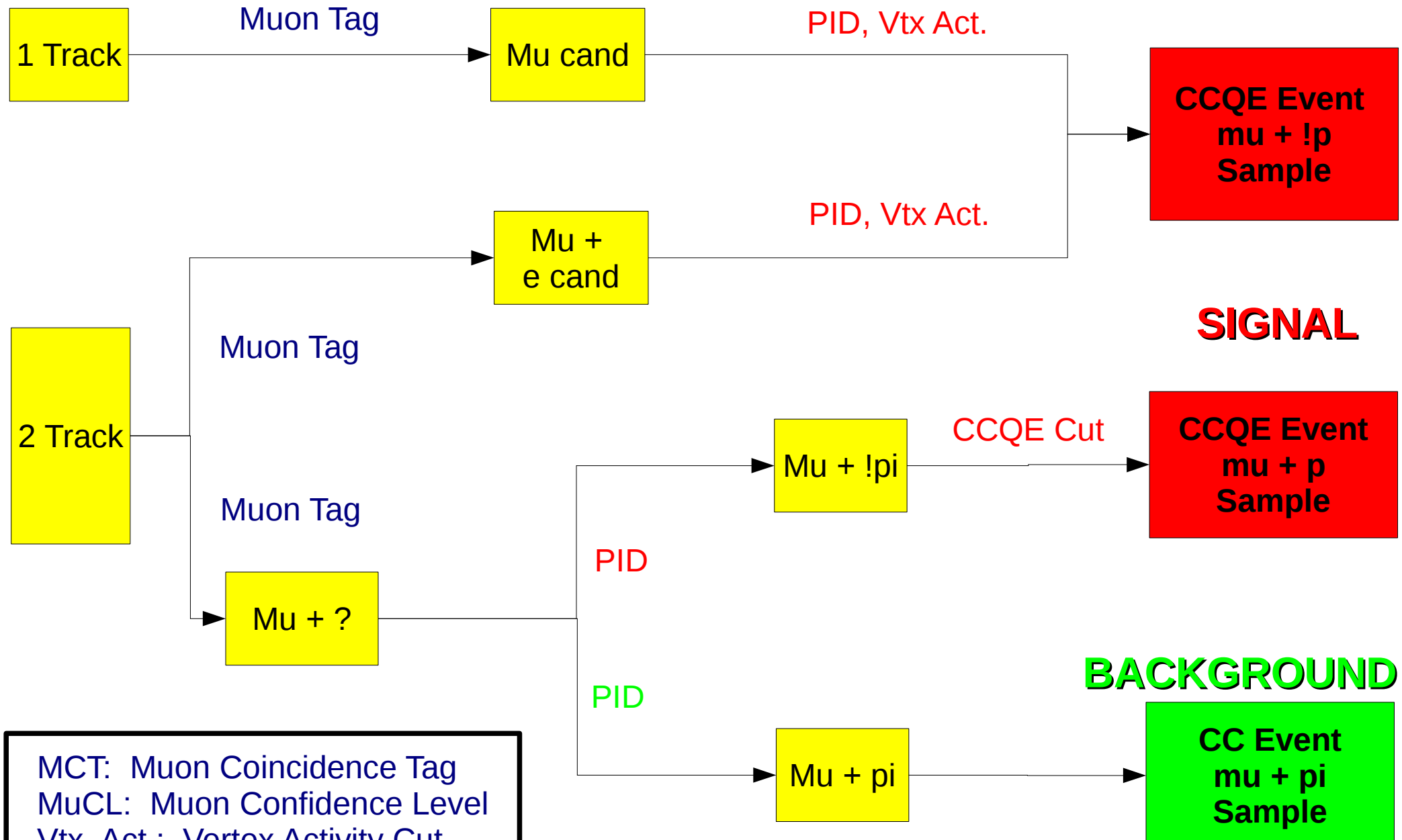
SciBar Contained CCQE

- Samples:
  - Signal
    - 1 track: μ
    - 2 track: $\mu + e^-$, $\mu + p$
  - Background
    - 2 track: $\mu + \pi$
  - No 3 track samples are considered

- Pre-Cuts:
  - Fiducial Volume
    - 260x260x155cm^3
    - 10 tons
  - Zero MRD tracks
  - μ track in beam window
    - $0 \leq t_\mu \leq 2\mu s$
  - Cosmic Filter: 1st SciBar layer veto (any hits)

Identifying muons with decay e^- (Michel) instead of MRD penetration

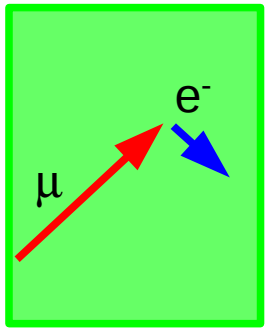
SciBar Contained Samples

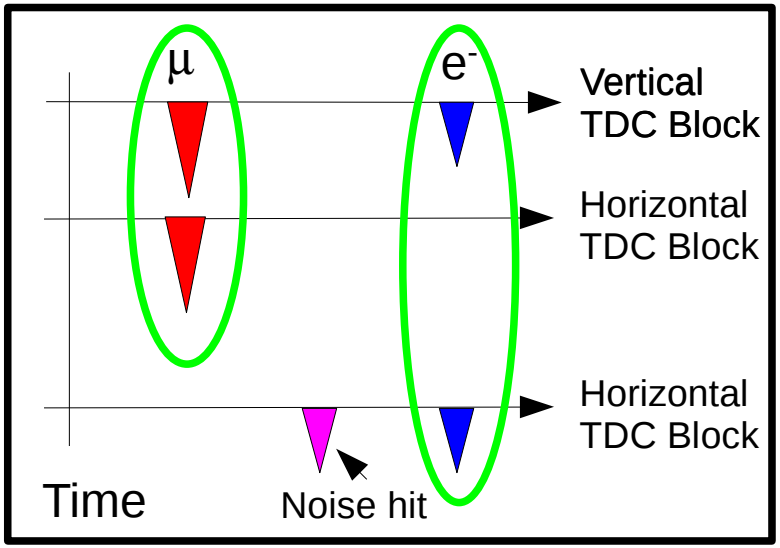


MCT: Muon Coincidence Tag
MuCL: Muon Confidence Level
Vtx. Act.: Vertex Activity Cut

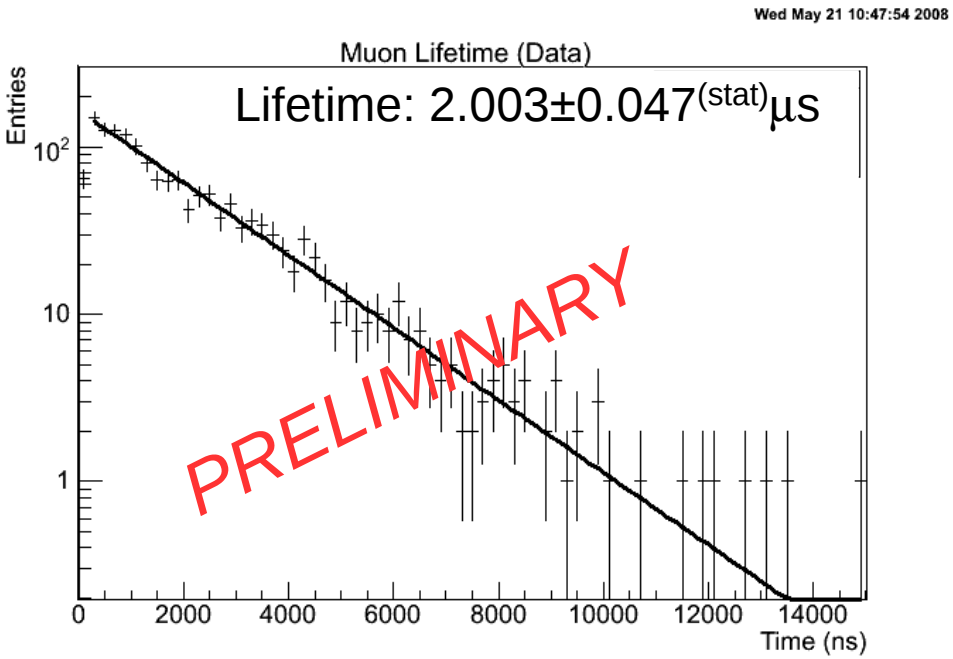
Muon Tagging

- MCT
  - SciBar has multi-hit TDC information
  - 32 channels per TDC (a TDC block)
  - Look for 2 single coincidences (<20ns) between top and side views
  - Apply a 1MeV cut to exclude noise hit matching
  - Muon lifetime from data:
    - $2.003 \pm 0.047^{(stat)} \mu s$
    - c.f. $2.0263 \pm 0.0015 \times 10^{-6} s$*





2 Single Coin.



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

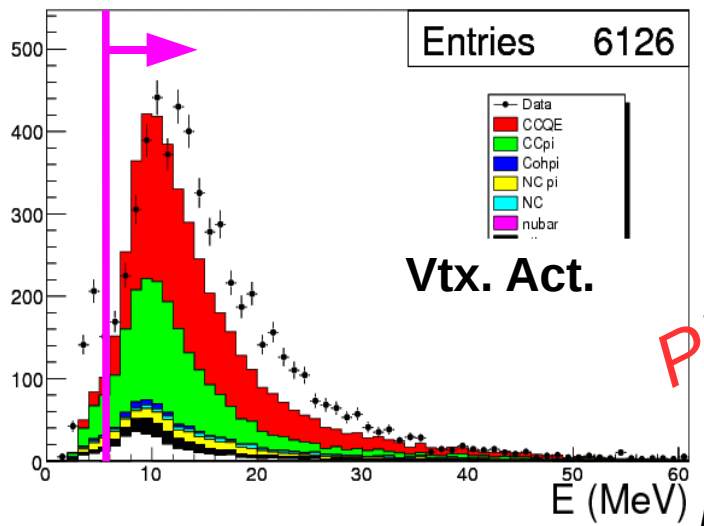
Cuts: MuCL & Vtx. Act.

1 Track Cuts (μ)

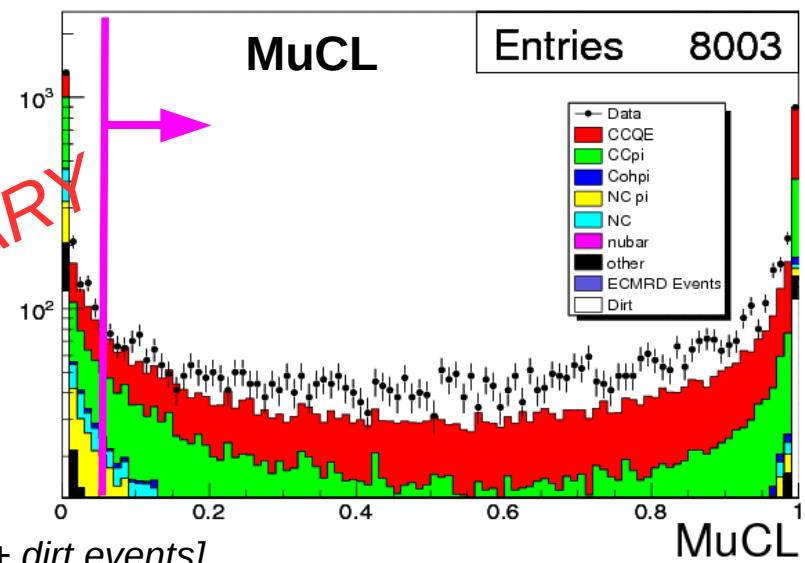
- MuCL: Improves μ purity
  - Use dE/dx to distinguish μ from p
- MuCL>0.05, μ-like
- Vertex Activity
  - Untracked proton leaves large E deposit near vertex
  - Vtx. Act. > 6MeV

2 Track Cuts (μ+p)

- MuCL:
  - μ-track - MuCL> 0.90
  - p-track - MuCL<0.05
- CCQE Cut
  - $\Delta\theta_p$ & 'ε' cut, see next slide



PRELIMINARY

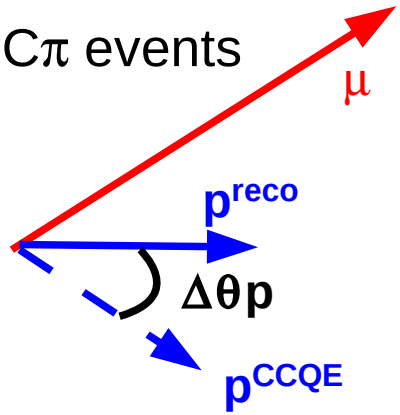


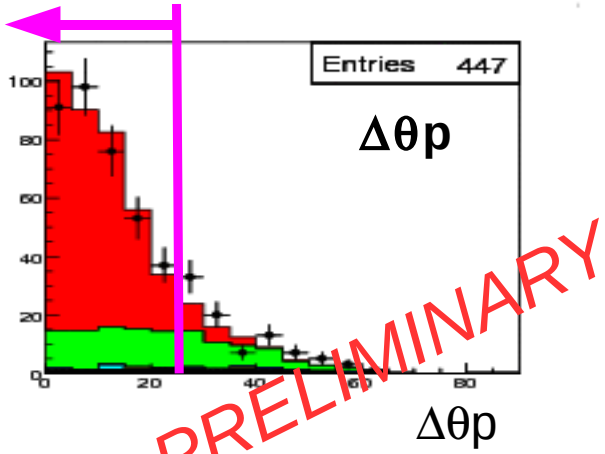
[Includes cosmics + dirt events]

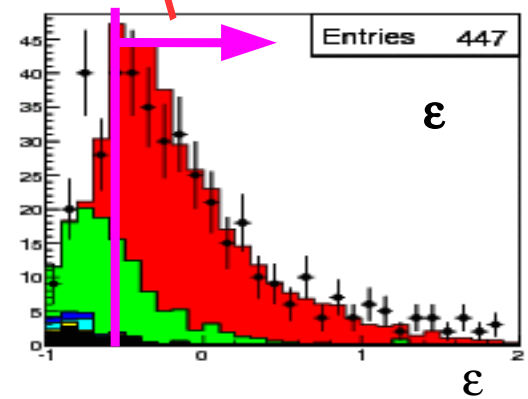
Cuts: CCQE Cut

- Apply 2 cuts to maximise CCQE purity for μ+p sample
  - $\Delta\theta_p < 25$
  - 'ε cut' > -0.6
- $\Delta\theta_p = \Delta\theta_p^{CCQE} - \Delta\theta_p^{reco}$
- $\varepsilon = (E_\nu^{reco} - E_\mu - T_p) / T_p$
- T_p and E_μ reconstructed from E deposited in SciBar
- CCπ events mis-reconstruct E_ν^{reco} too low
  - Separation of CCQE from CCπ events

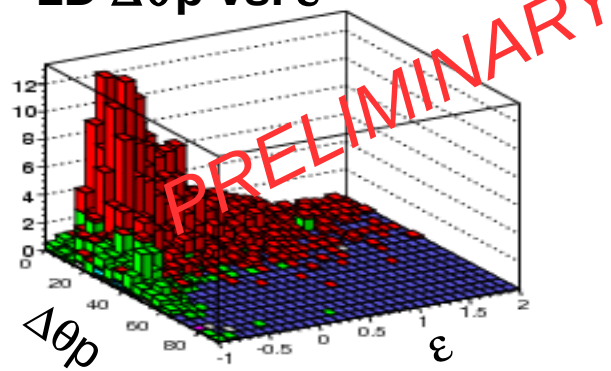
$$E_\nu^{reco} = \frac{m_n E_\mu - m_n^2/2}{m_n - E_\mu + P_\mu \cos\theta_\mu}$$



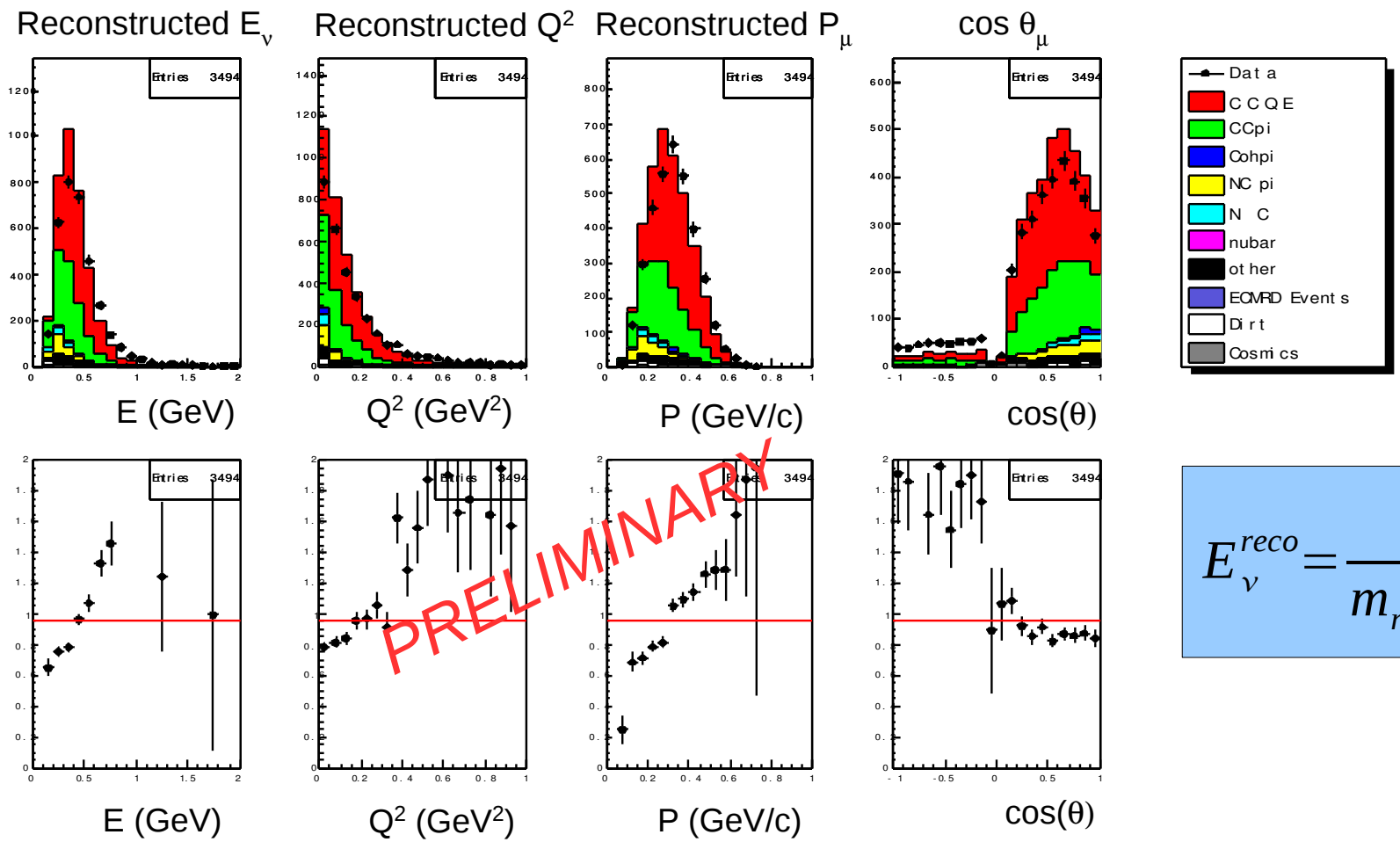




2D Δθp vs. ε

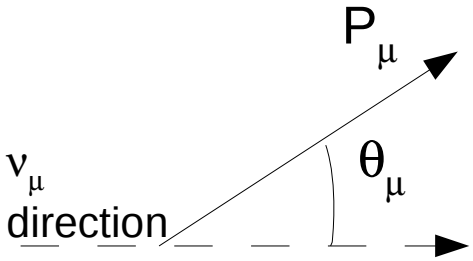


Signal: 1 Track μ

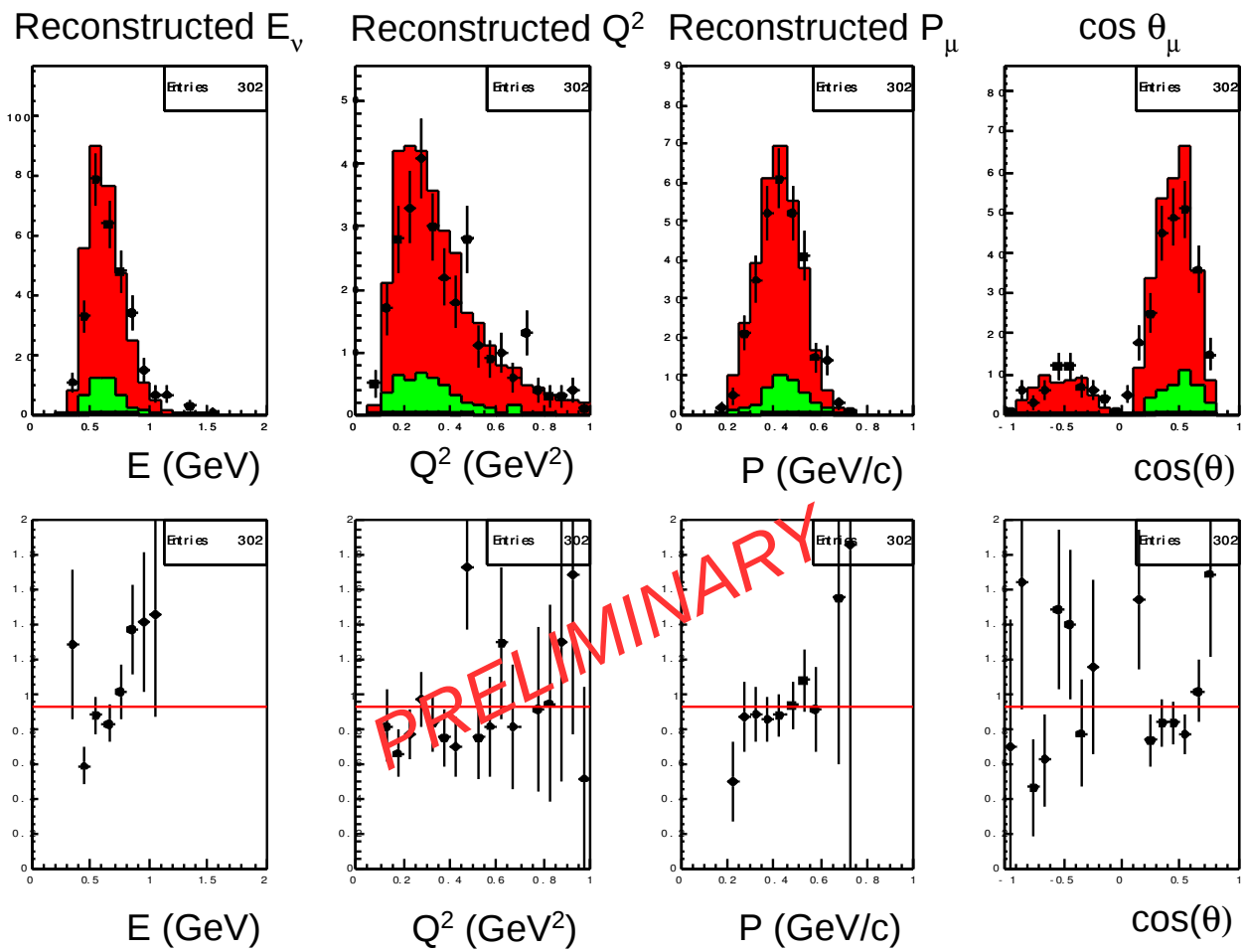


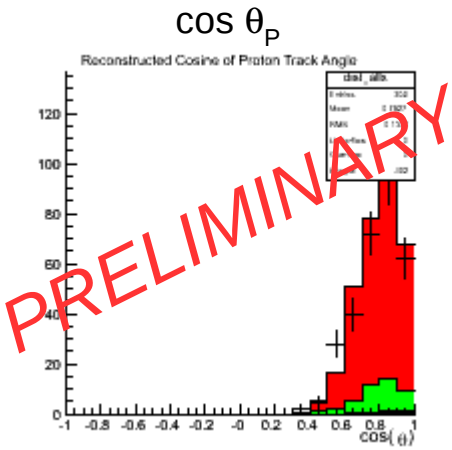
$$E_\nu^{reco} = \frac{m_n E_\mu - m_n^2/2}{m_n - E_\mu + P_\mu \cos\theta_\mu}$$

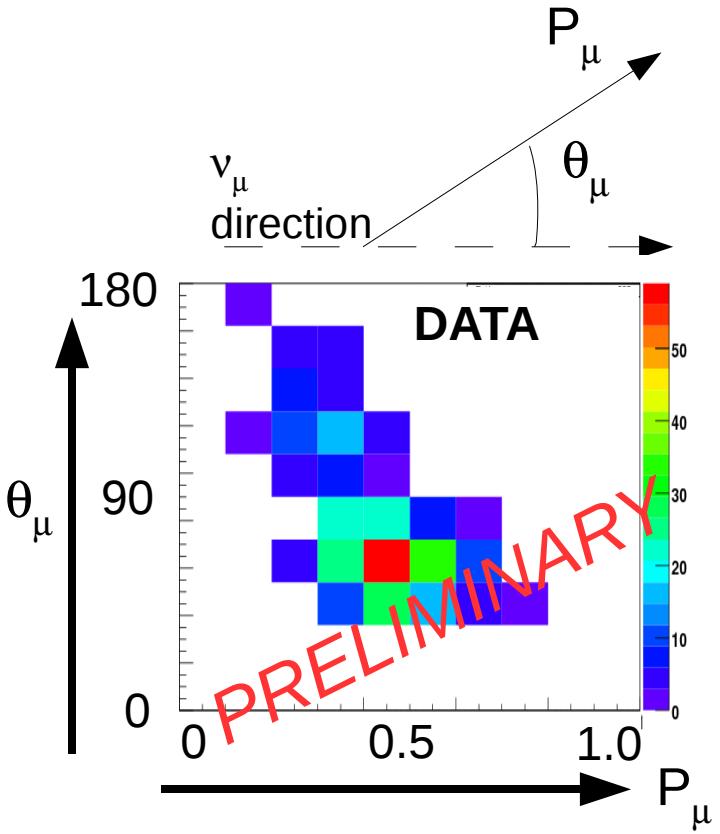
- Data tends to higher E_ν^{reco} and Q^2
- Data excess in backwards tracks



Signal: 2 Track μ + p

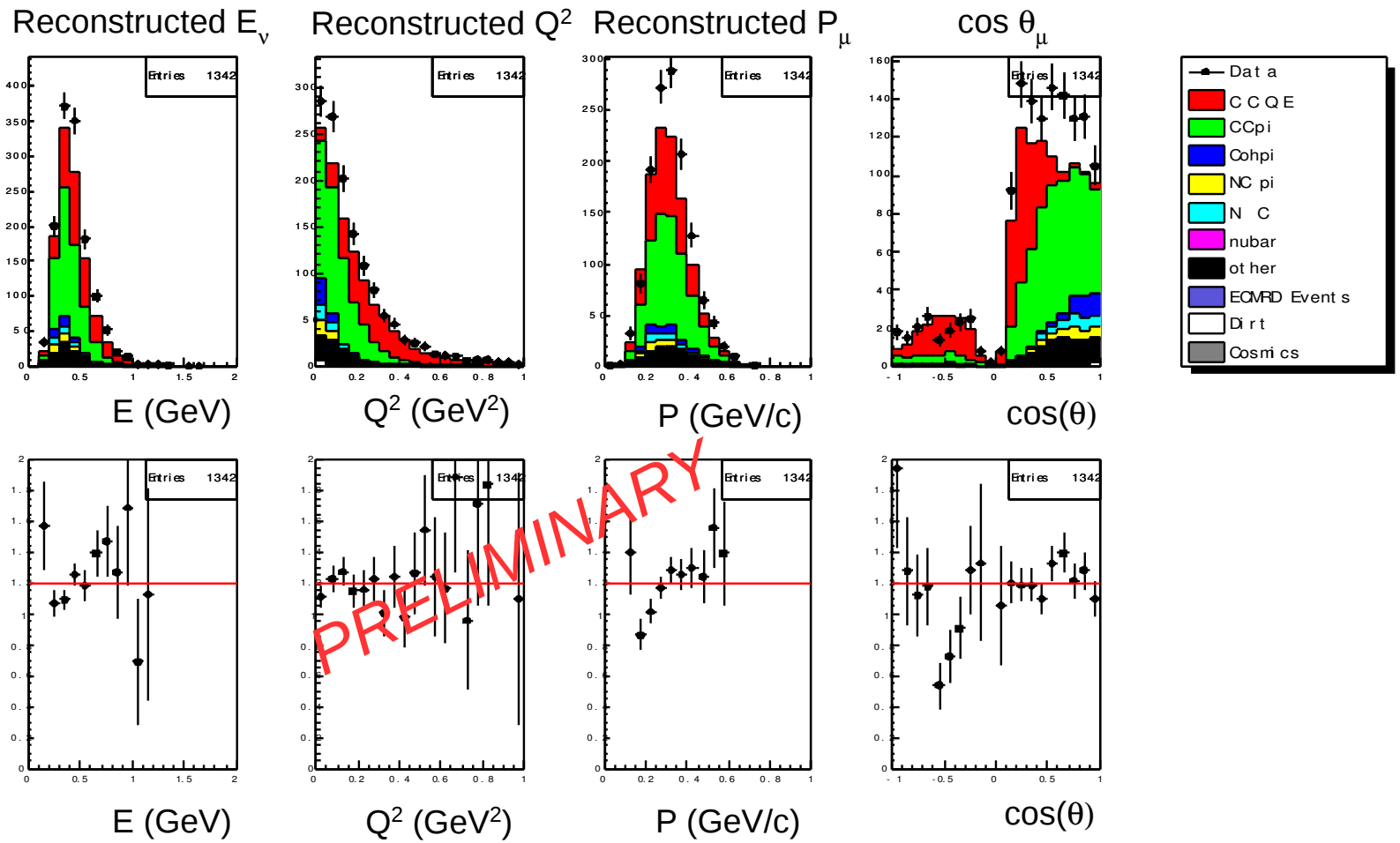






- Reconstruct backwards muons, all protons forward
- Soft backwards muons

Bkg: 2 Track μ + π



- Used to constrain background in cross-section fit

Data Set

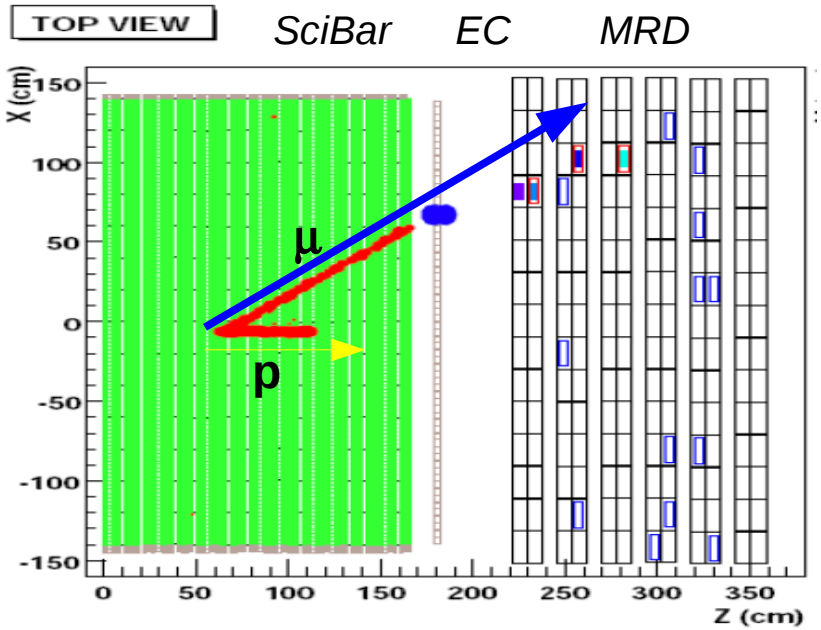
Sample	Data	CCQE	CCπ	Other
mu	3494	55.5%	33.2%	11.3%
mu + p	302	86.3%	12.6%	1.1%
mu + pi	1117	34.0%	47.9%	18.1%

CCQE Analyses:
MRD Matched Events

SciBar-MRD match analysis

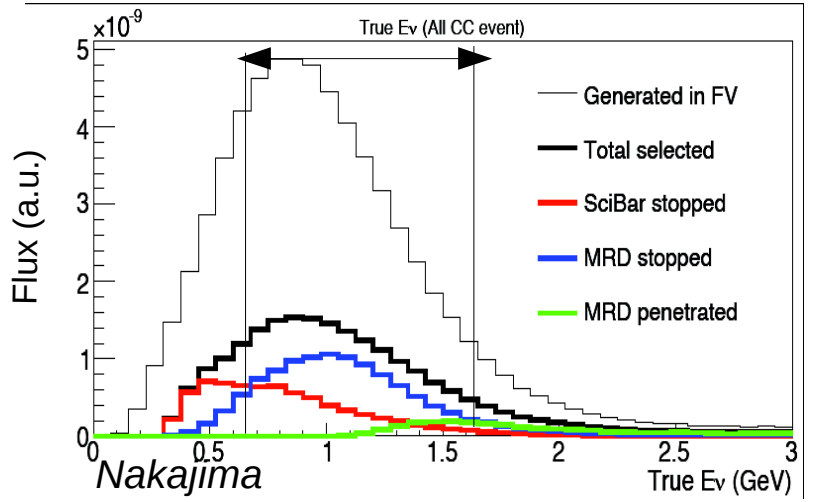
- Event selection:
  - Interactions inside SciBar
  - Require 1 and only 1 track reaching and stopping within the MRD (defined as μ-like track).

SciBooNE display of a typical muon neutrino CCQE event candidate.



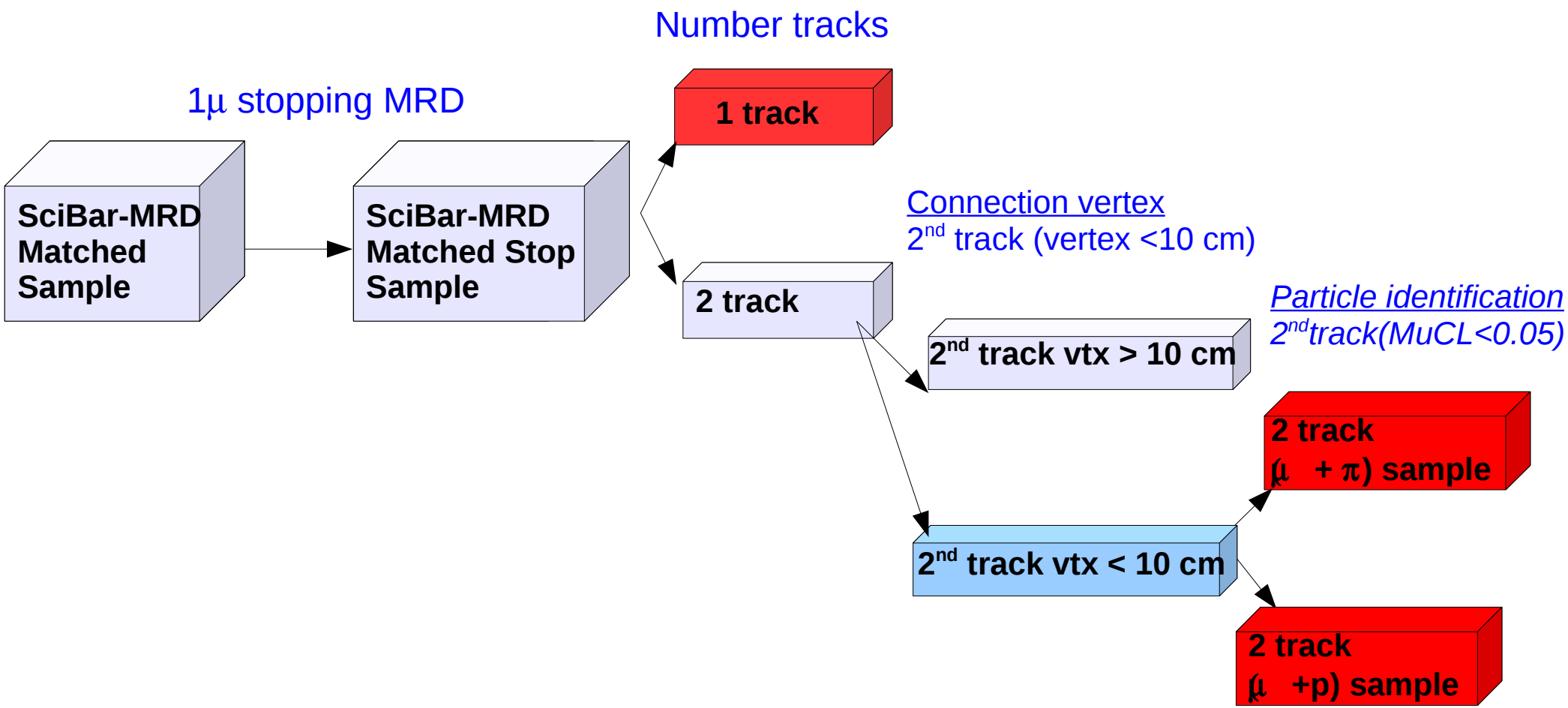
- Comparing the neutrino energy acceptance for the two CCQE analysis (SciBar stopped and MRD stopped samples), this analysis cover larger neutrino energy regions.

Eν acceptance for different sample selections



Nakajima

CCQE data selection tree



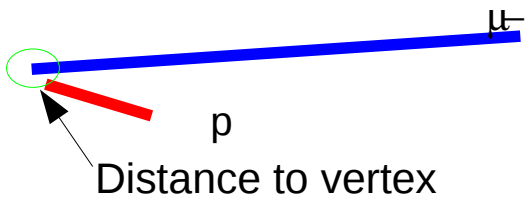
CCQE cut selection

Number Tracks

- 2 track event.
- 1 track events (low energy protons not detected).

Connection vertex

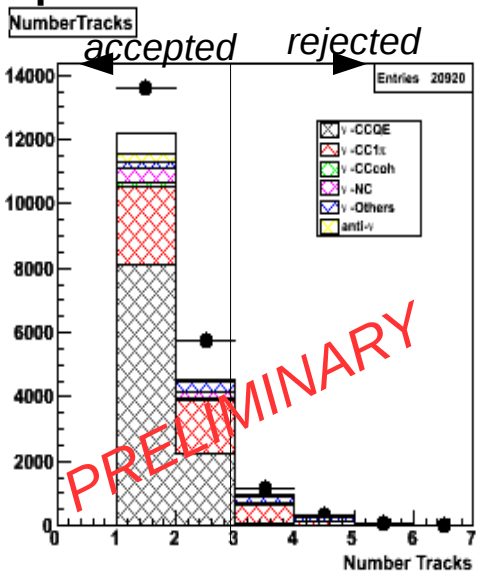
- On CCQE interactions, the proton is produced closed to the interaction vertex.



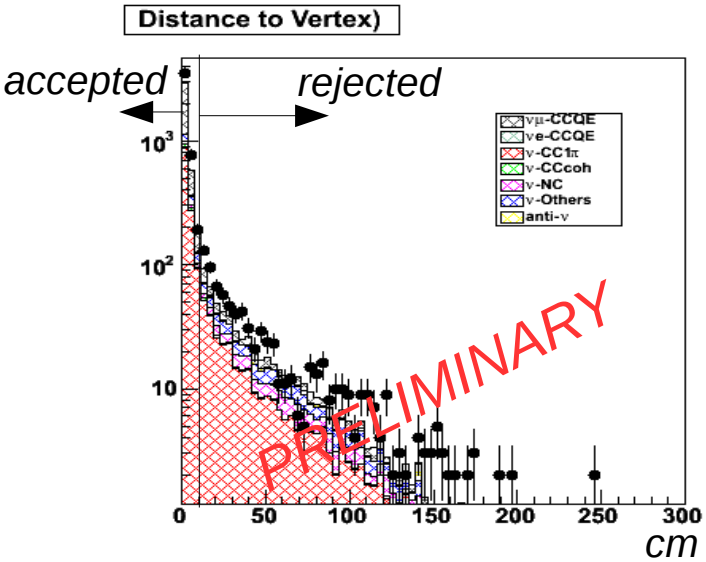
Particle identification

- p/π identification using the dEdx information (Muon Confidence Level).

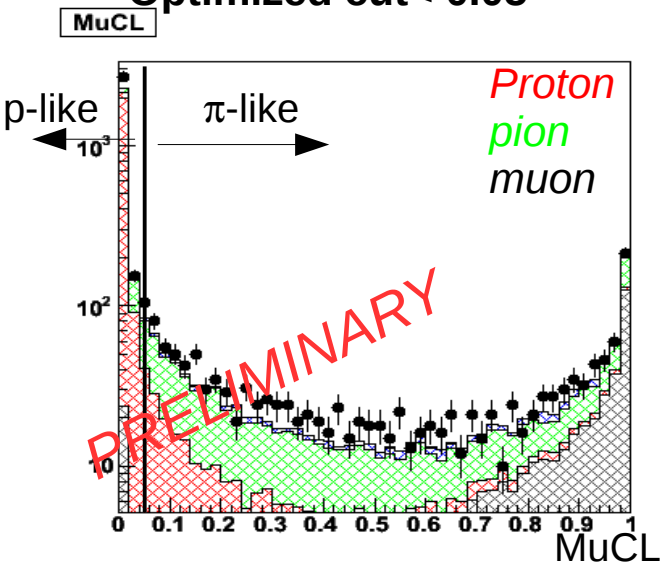
Optimized cut<= 2 tracks



Optimized cut< 10 cm



Optimized cut< 0.05



Summary table

CCQE enriched sample

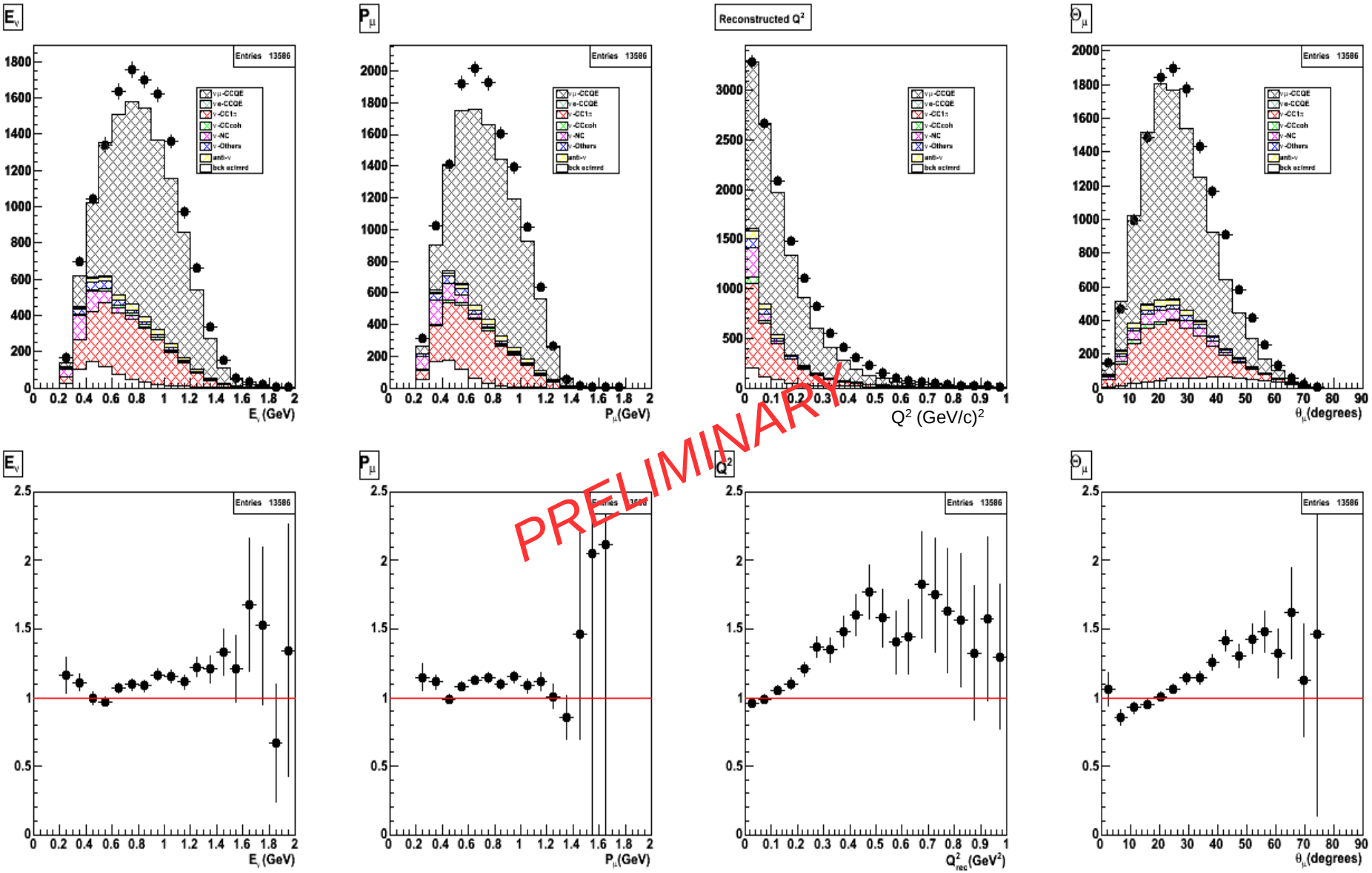
Contains the statistics

SAMPLE	DATA	CCQE efficiency(%)	CCQE Purity(%)	data/mc(POT-norm)
1 track	13586	11	66.2	1.11
2 track (μ + p)	2680	2.3	68.6	1.17
2 track (μ + π)	1508	0.5	30.7	1.26

NonQE enriched sample (controls the background)

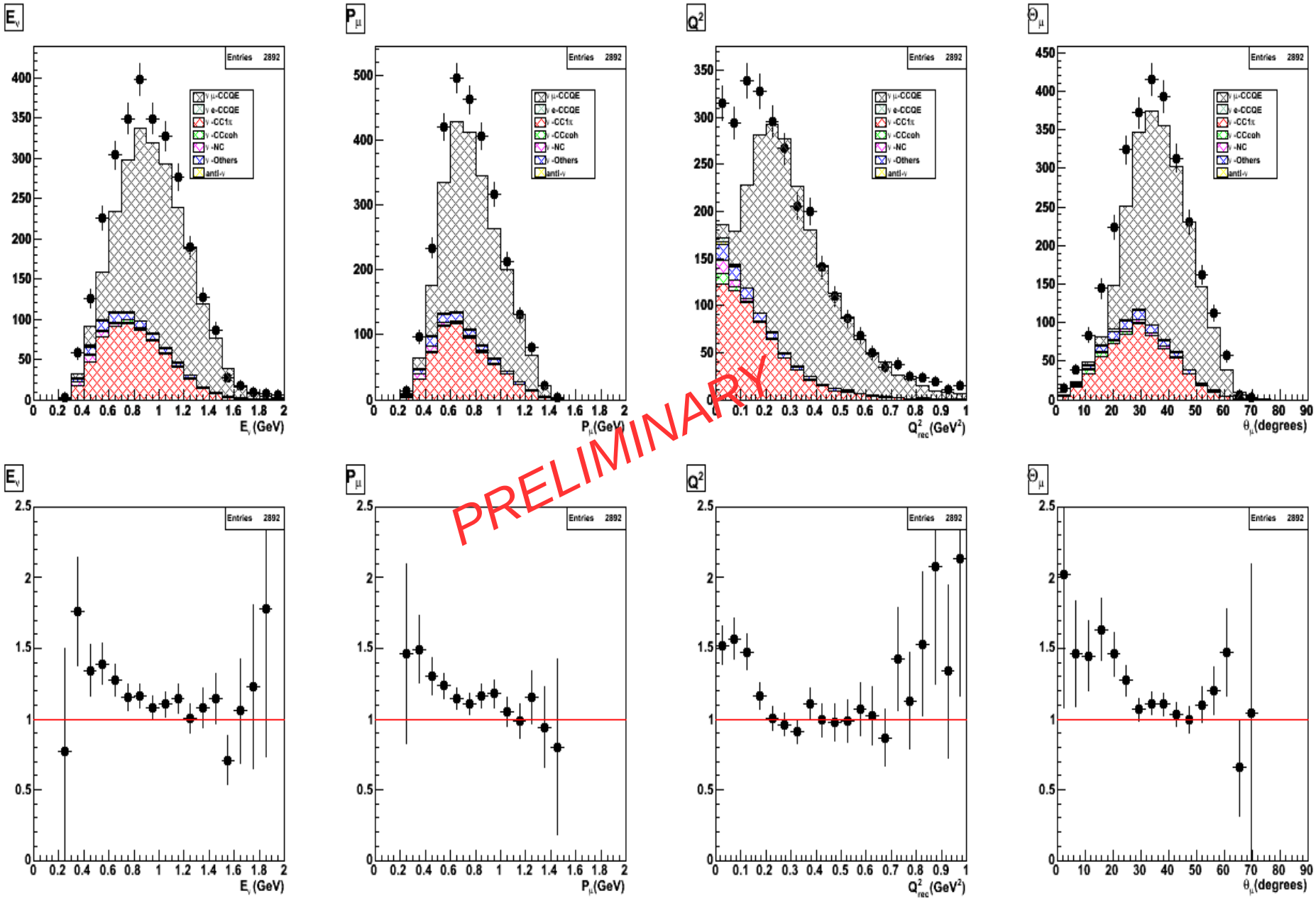
Note: Efficiency calculated with respect to the total CCQE interactions in the SciBar Fiducial Volume

1 Track: Reco. Kinematics

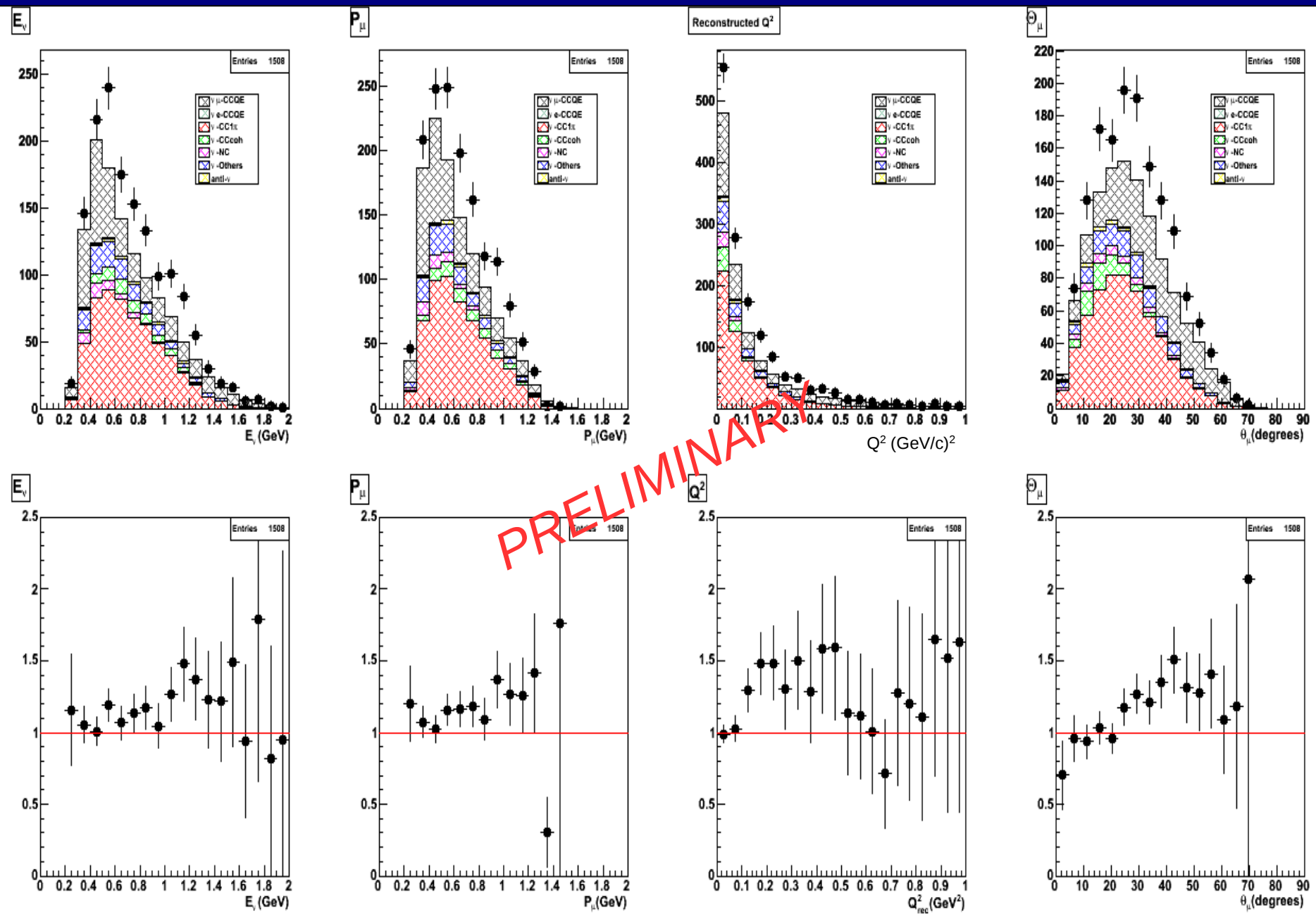


Reconstructed E_ν, Q^2 assuming CCQE kinematics.

2 Track (μ + p): Reco. Kinematics



2 Track (μ + π): Reco. Kinematics



Fit method: description (I)

Minimize the $\chi 2$ function using the binned likelihood method with the assumption that observed events follows the Poisson distribution.

$$2 * \sum_{i,j} \left[N_{ij}^{\exp} - N_{ij}^{obs} + N_{ij}^{obs} \times \left(\ln \frac{N_{ij}^{obs}}{N_{ij}^{\exp}} \right) \right] \qquad \textbf{(1.1)}$$

•Using the information of two observables

($P\mu$,$\theta\mu$):

- For DATA: $\mathbf{N_{ij}^{obs} = N^{DATA}(P\mu_i, \theta\mu_j)}$
- For MC:

$$N^{MC}(P\mu_i, \theta\mu_j) = \left[\overbrace{\underbrace{\sum_k}_{\text{True E}\nu\text{ bins}} N_k^{QE}(P\mu_i, \theta\mu_j)}^{QE} + \overbrace{N^{NonQE}(P\mu_i, \theta\mu_j)}^{nonQE} \right];$$

Fit method: description (II)

Then, we add the fit parameters:

$$N^{MC}(P\mu_i, \theta\mu_j) = F_N \left[\sum_k a_k N_k^{QE}(P\mu_i, \theta\mu_j) + a_{bck} N^{NonQE}(P\mu_i, \theta\mu_j) \right];$$

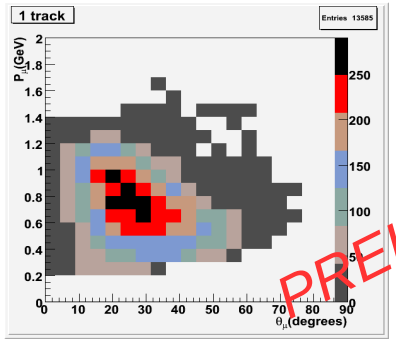
- $\mathbf{a_k}$: information about the shape in each true neutrino bin (fixing 1 ak parameter).
- $\mathbf{a_{bck}}$. information about background.
- **Fn** : information about the DATA/MC normalization.

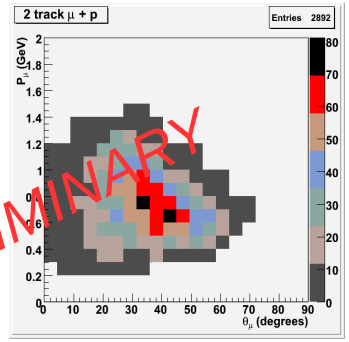
- For this analysis:
  - 20 **Pμ** bins and 20 **θμ** bins.
  - 10 true energy bins → 10 ak parameters, fixing a(En=0.8 GeV).
  - Finally, we fit $\chi^2(a_k, a_{bck}, F_N)$ containing 9(ak)+2(abck,Fn) parameters. Once fitted, we use the fitted values to determine the cross section:

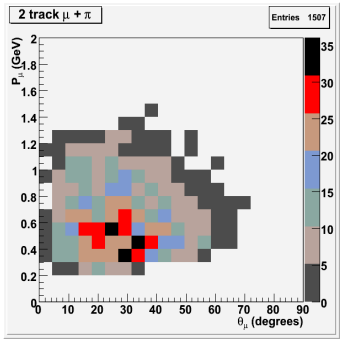
$$\sigma_k^{DATA} = F_N * a_k * \sigma_k^{MC\,true}$$

(Pμ , θμ) distributions

DATA: Pμ .vs. θμ for 1 track sample 2 track (μ +p) 2 track (μ π)

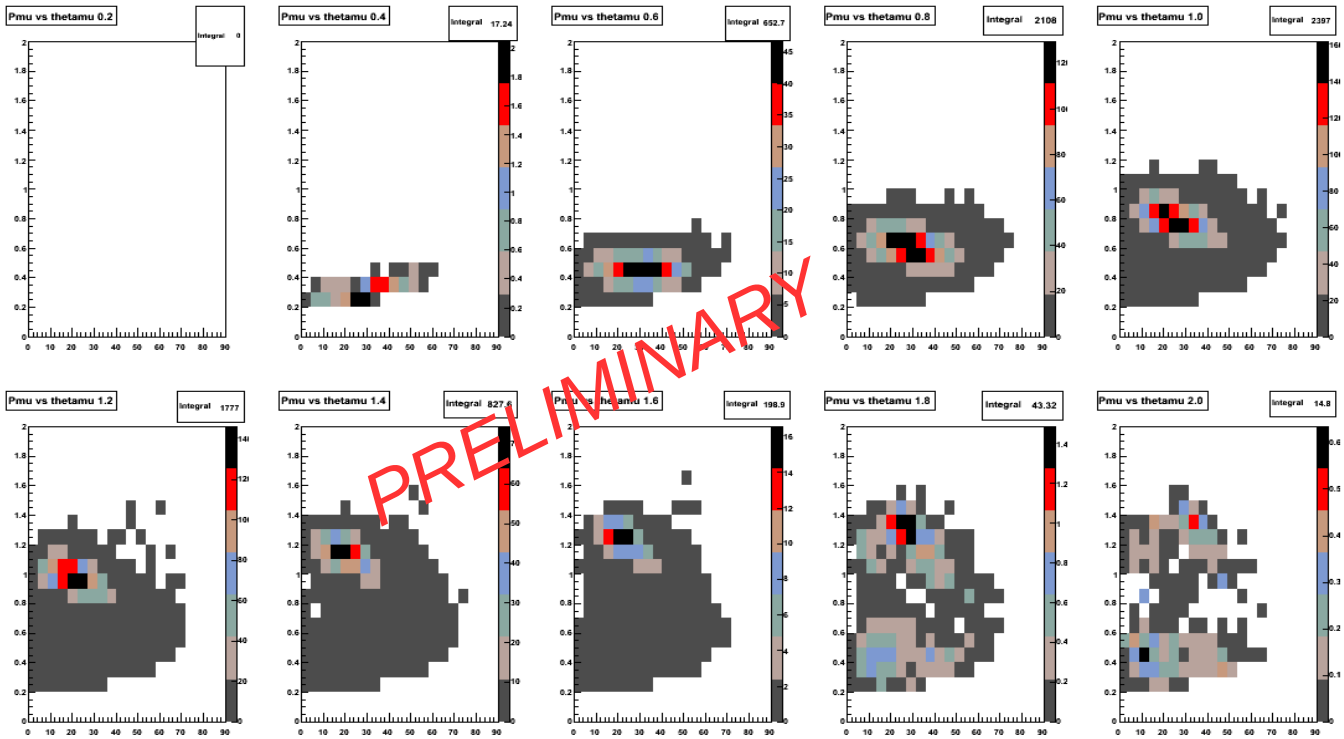






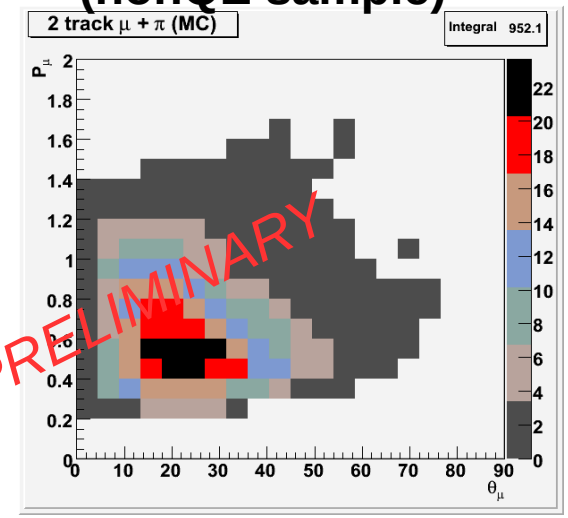
PRELIMINARY

MC: Pμ .vs. θμ for 1 track sample **QE**



PRELIMINARY

Pμ .vs. θμ for 2 track (μ π) **(nonQE sample)**



PRELIMINARY

Fit parameters after the fit

Before fit;
χ^2/dof = 1395.38/567= 2.46

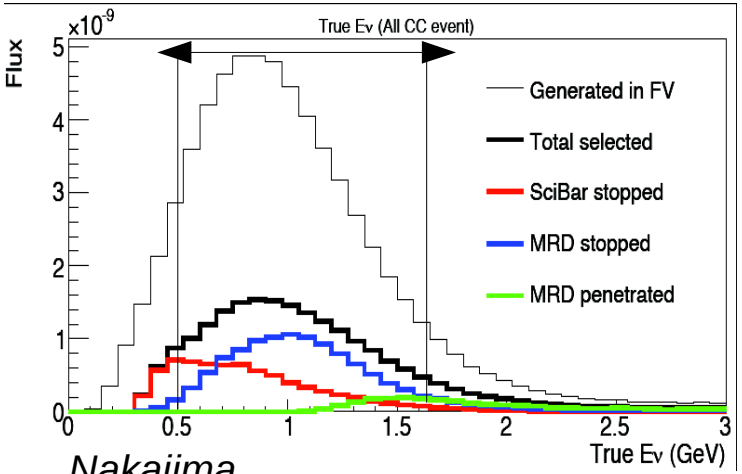
After fit:
χ^2/dof = 983.05/556 = 1.76

Although the fit uses energy region 0-2 GeV, our sample selection is only sensitive to the energy region 0.6 < Eν < 1.6 GeV. (high statistics).

PARAMETER	VALUE	STAT. ERROR
a(0.6-0.8)	1.00	0.07
a(0.8-1.0)	1.00	fixed
a(1.0-1.2)	1.10	0.07
a(1.2-1.4)	1.01	0.07
a(1.4-1.6)	1.10	0.17

a_bck	1.45	0.07
Fn	1.00	0.04

Eν acceptance for different sample selections

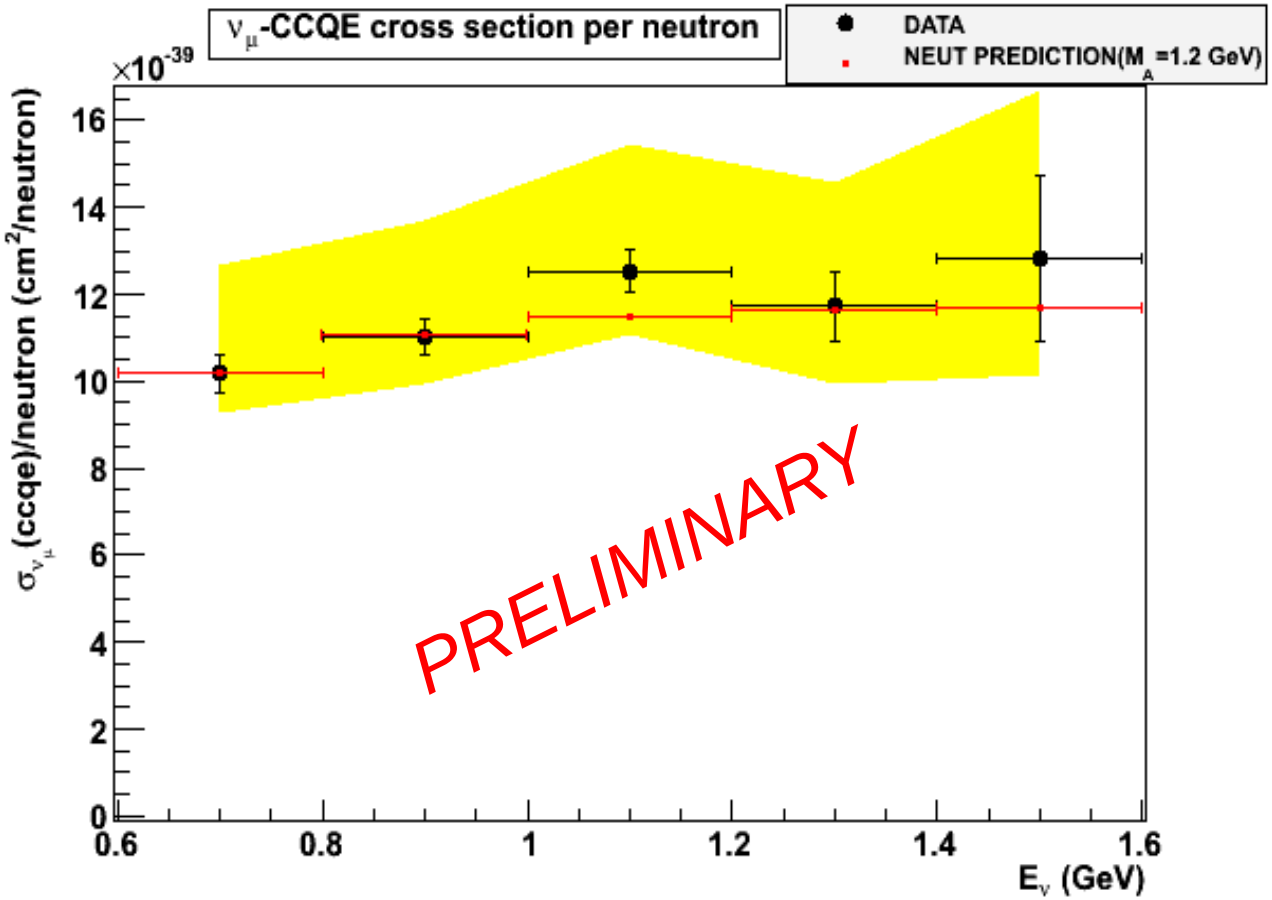


Nakajima

$\nu\mu$ -CCQE cross section

Statistics errors: black arrow

flux systematic errors: yellow band

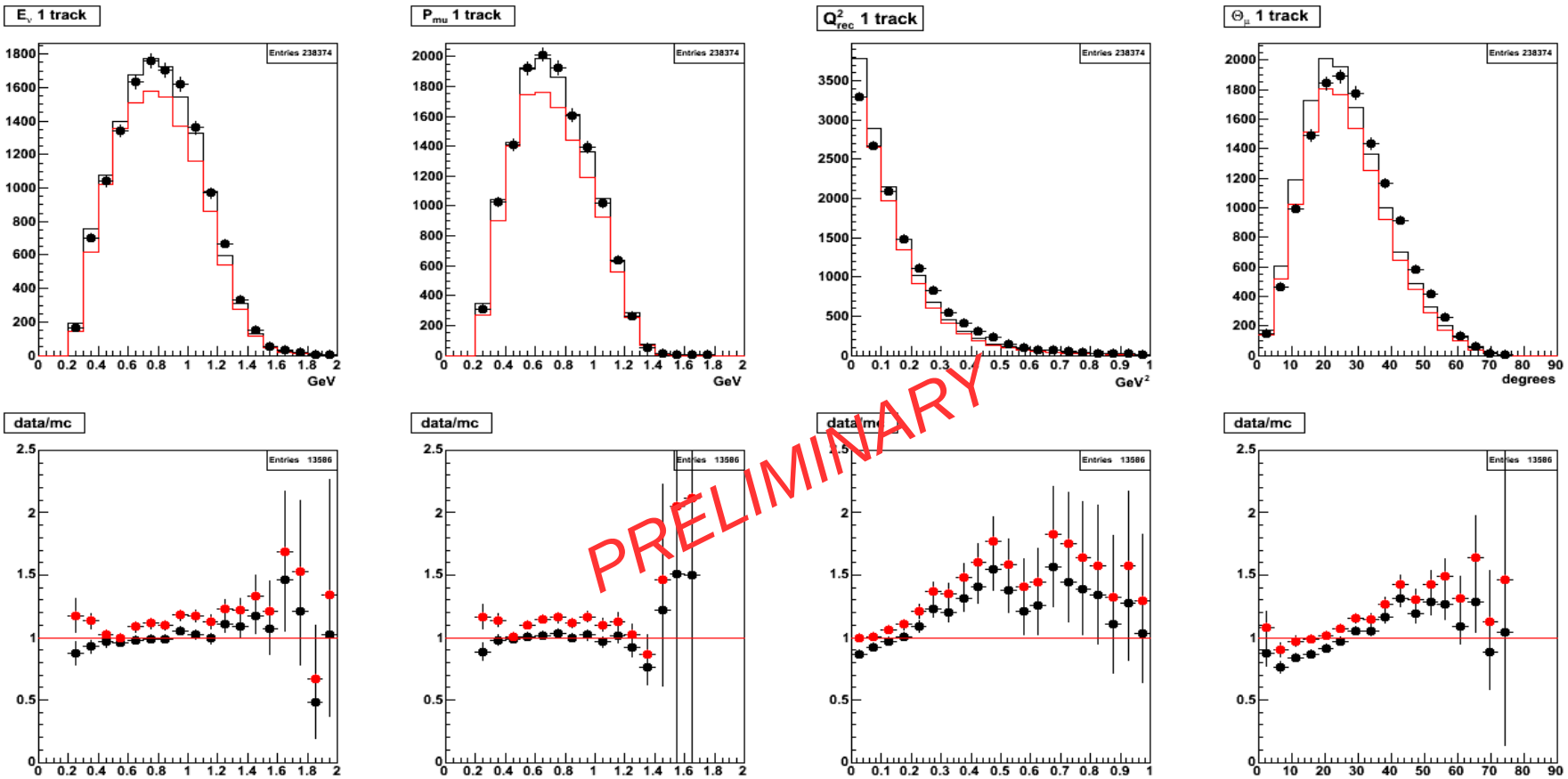


Good agreement between data and NEUT prediction.

1 Track: before/after fit

Just give an example of how much improve our data/mc agreement

MC before fit
MC after fit



The $E\nu_{reco}$ and $P\mu$ distributions are now in much better agreement.

Also Q^2_{rec} and $\theta\mu$ has improved.

The others two samples shows good improvement too (backup)!!

Conclusions

- The $\nu_\mu - \sigma(ccqe)(E_\nu)$ in the energy region $0.6<E\nu<1.6$ GeV has been presented
- The SciBar contained analysis will report soon results on $\nu_\mu - \sigma(ccqe)(E_\nu)$, covering the low neutrino energy region.
- CCQE differential cross section ($d\sigma(E_\nu)/dQ^2$)will also be studied in near future.

Thank you!