FNAL Director Review
Oct. 11, 2005 @ FNAL

Bring the SciBar detector to the Booster Neutrino Beam

T. Nakaya (Kyoto)

Outline

1. Low Energy ν cross sections -Wascko
2. FNAL Booster Neutrino Beam -Wascko
3. SciBar Detector -Nakaya
4. SciBar Physics Results from K2K -Nakaya
5. Current status of K2K cross section analysis (with a mystery) -Nakaya
6. MiniBooNE cross sections -Wascko
7. SciBar at BNB detector configuration -Wascko
8. Physics of SciBar at BNB. -Nakaya
9. SciBar at BNB for MiniBooNE -Wascko
10. Schedule -Wascko/Nakaya
11. Cost -Wascko

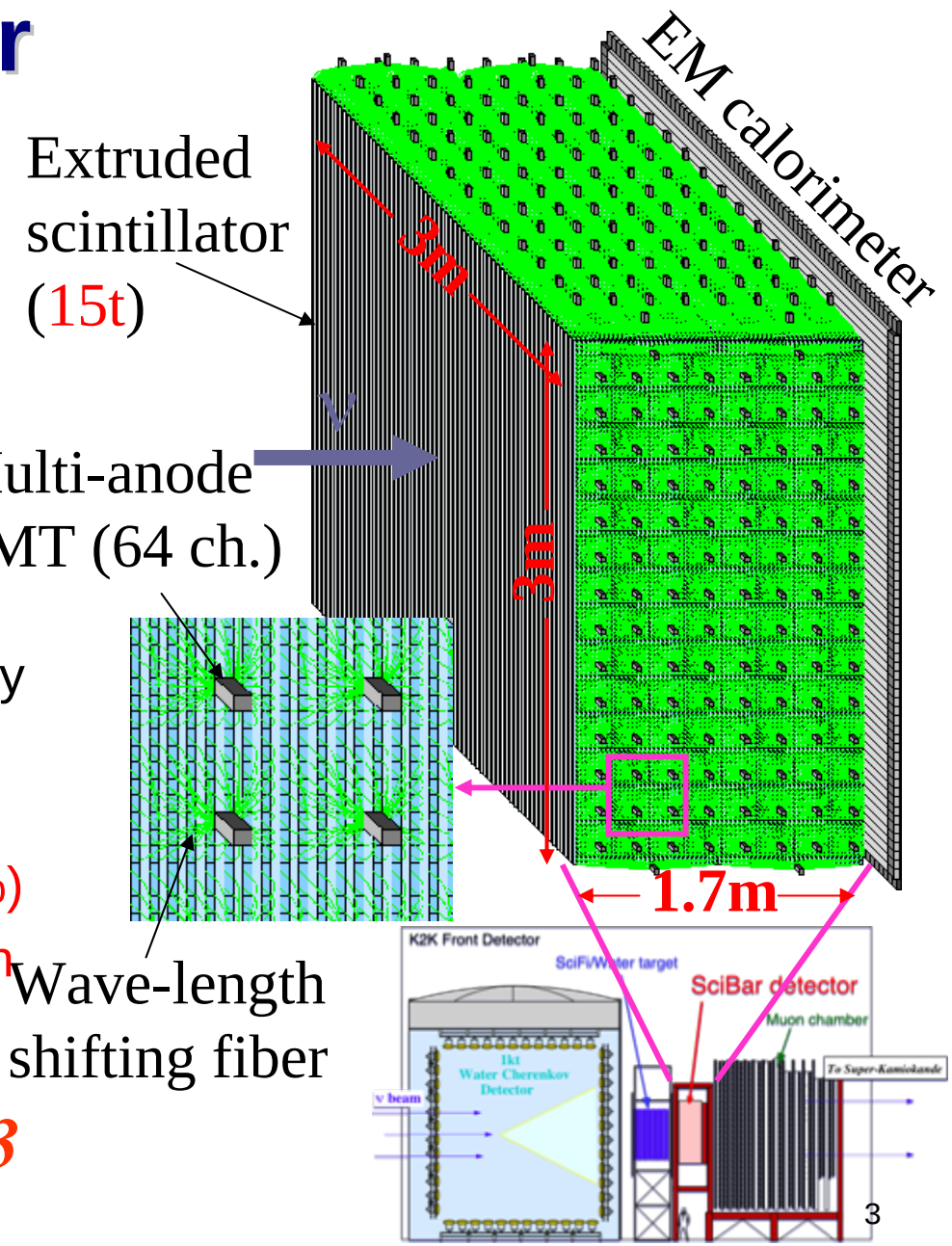
3. SciBar Detector

- Extruded scintillators with WLS fiber readout
- The scintillators are the neutrino target
- 2.5 x 1.3 x 300 cm^3 cell
- ~15000 channels
- Detect short tracks (>8cm)
- Distinguish a proton from a pion by dE/dx
- Total 15 tons

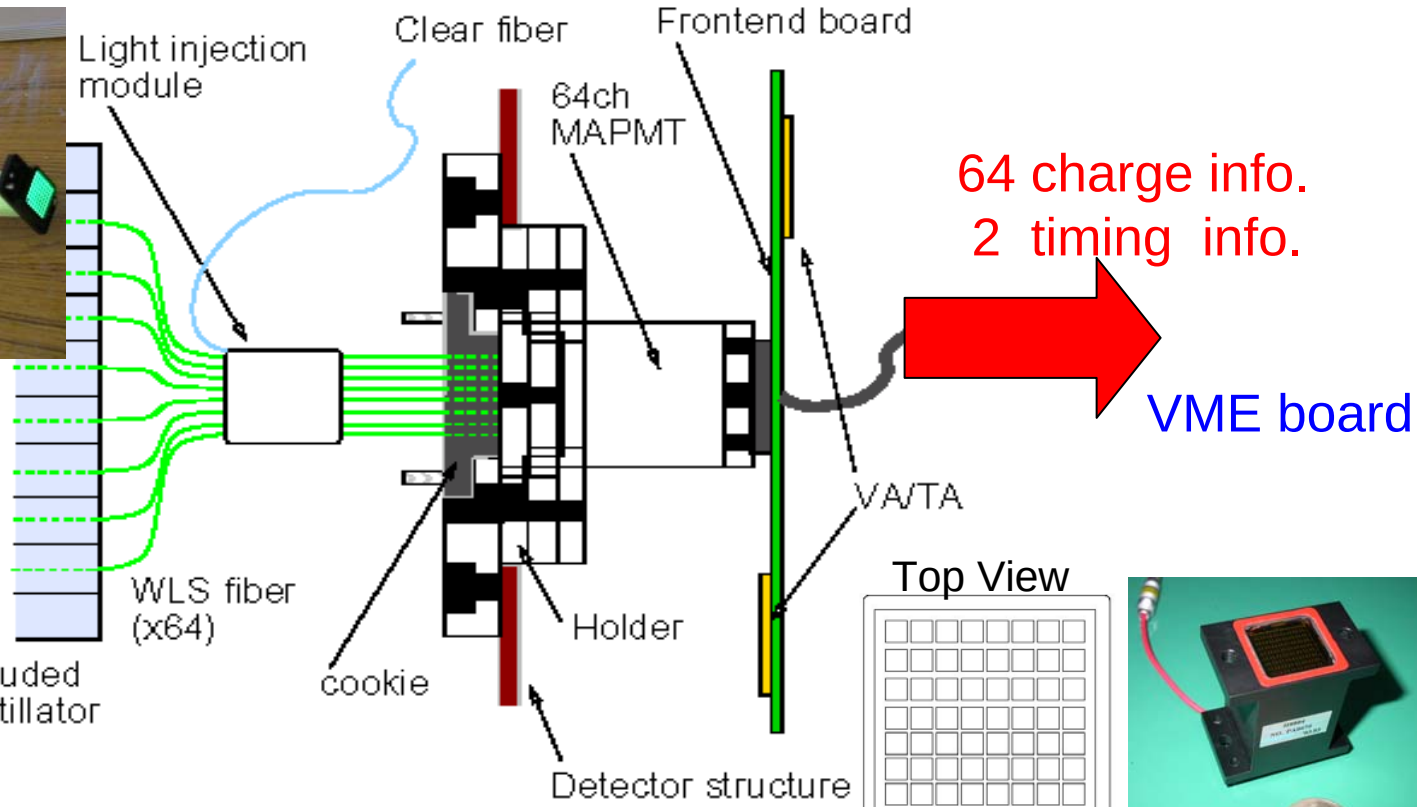
➔High track finding efficiency (>99%)

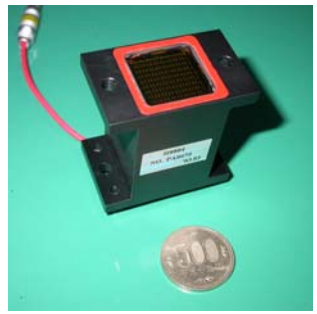
➔Clear identification of ν interaction process

Constructed in summer 2003



SciBar Components





Extruded Scintillator (1.3×2.5×300cm^3)
- made by FNAL (same as MINOS)

Wave length shifting fiber (1.5mmΦ)
- Long attenuation length (~350cm)

→ Light Yield : 18.9p.e./cm/MIP

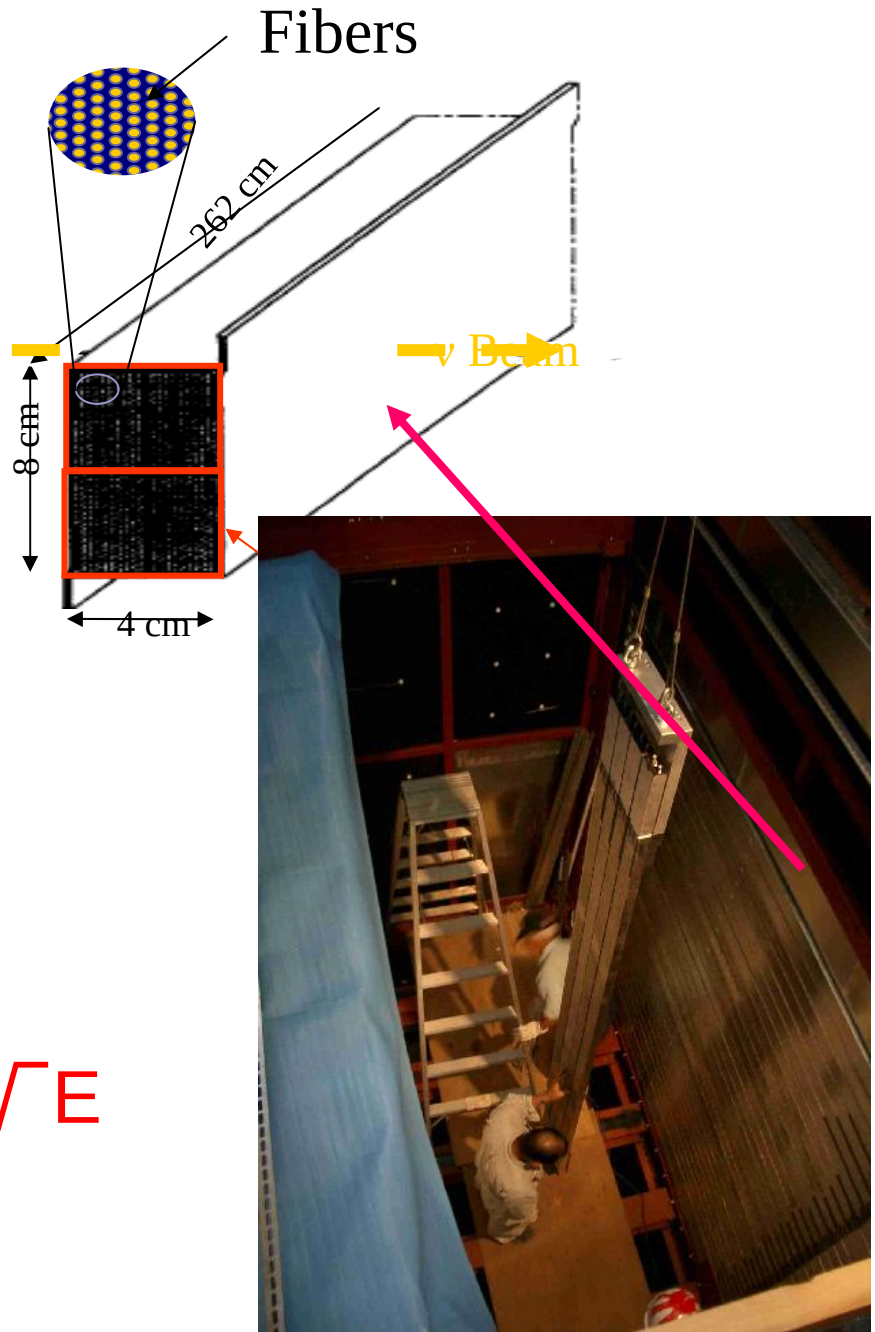
Multi-Anode PMT
- 2×2mm^2 pixel (3% cross talk @1.5mmΦ)
- Gain Uniformity (20% RMS)
- Good linearity (~200p.e. @6×10^5)

Readout electronics with VA/TA
- ADC for all 14,400 channels
- TDC for 450 sets (32 channels-OR)

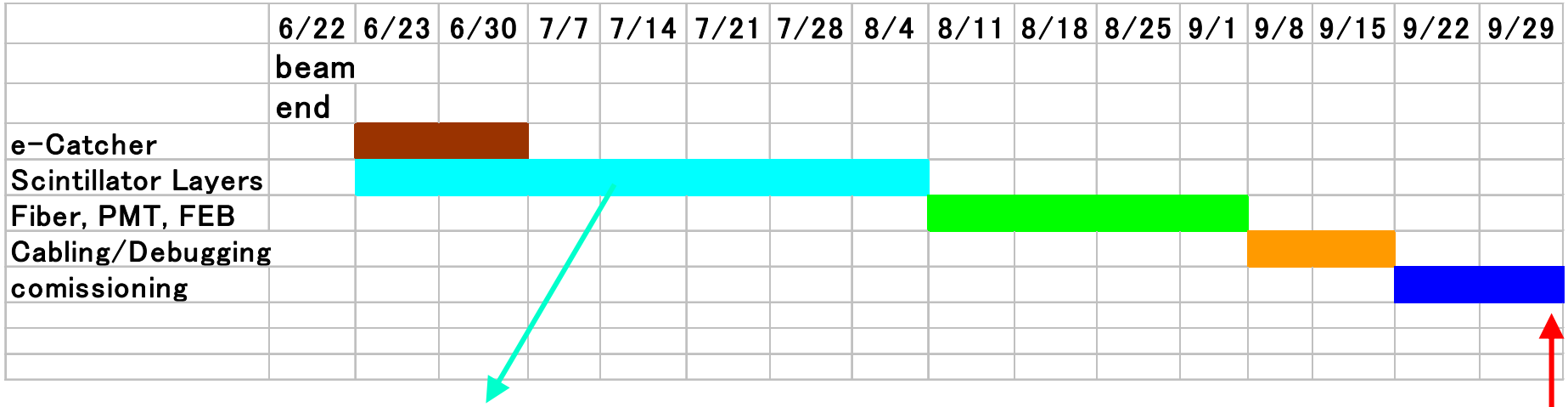
Electron Catcher

- "spaghetti" calorimeter re-used from CHORUS
- 1mm diameter fibers in the grooves of lead foils
- $4x4cm^2$ cell read out from both ends
- 2 planes ($11X_0$)

  Horizontal: 30 modules
  Vertical : 32 modules
- Expected resolution $14\%\sqrt{E}$
- Linearity: better than 10%



SciBar Installation in 2003

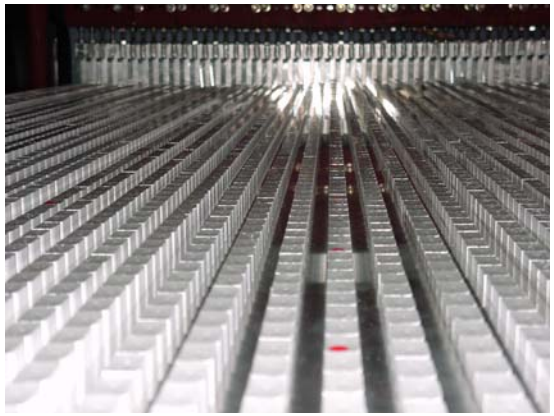


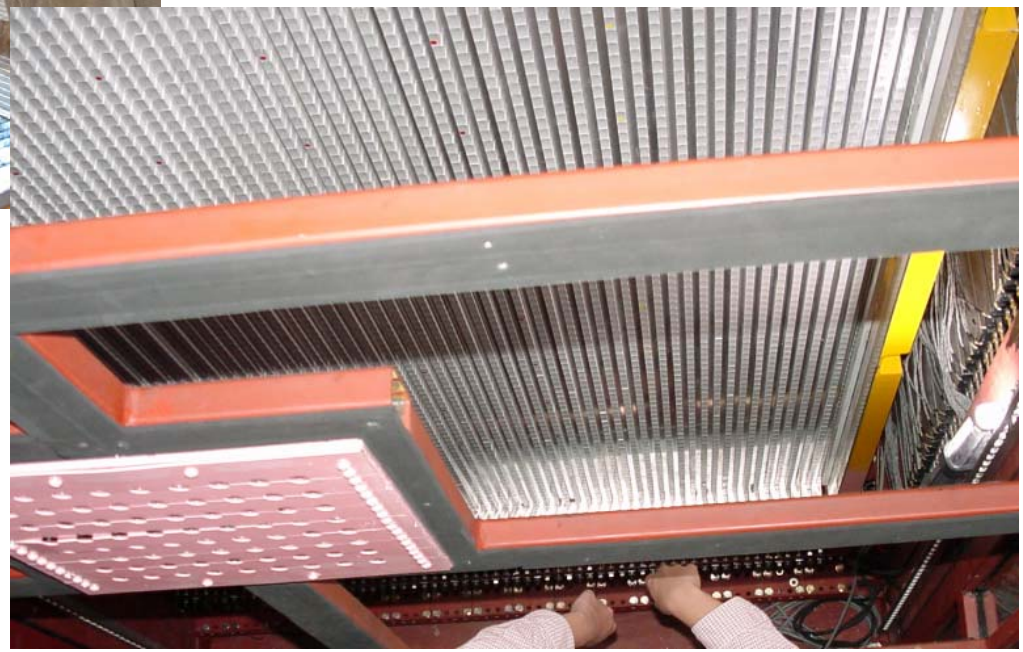
- Limited by the production of scintillator modules.
  - Two scintillator modules/day limited by gluing/drying.
  - It would take less than 10 days to install all the modules without construction.

K2K Beam ON

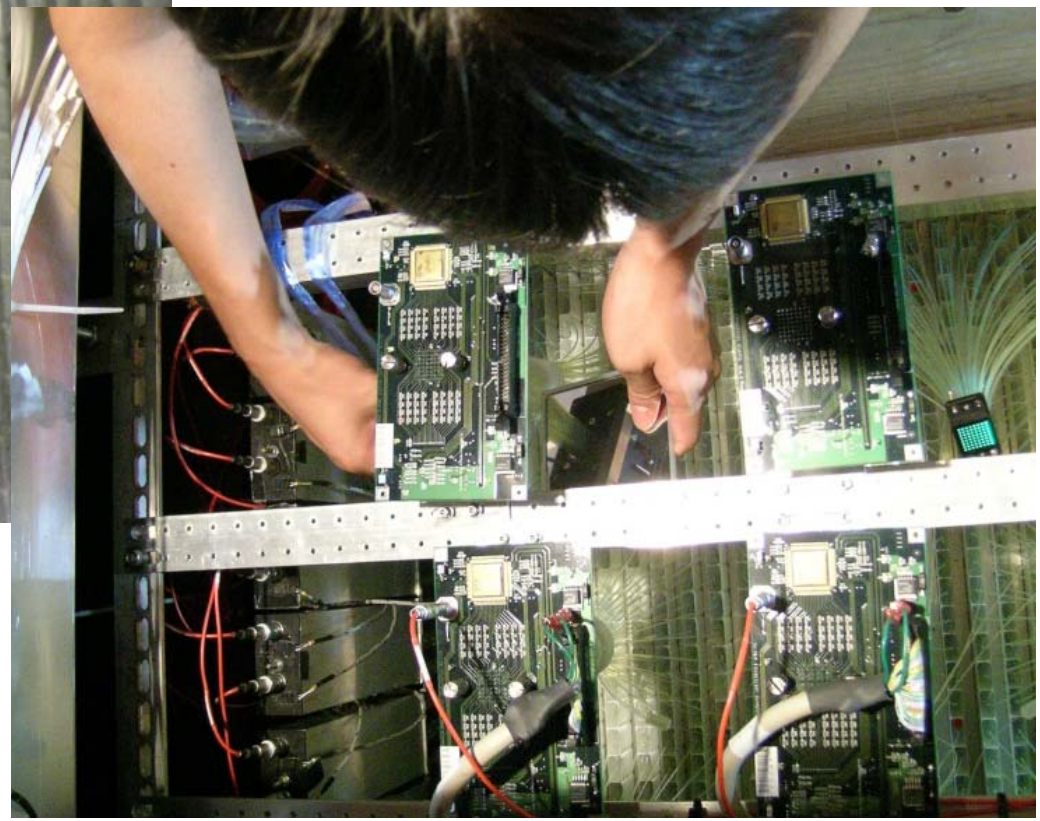
We constructed and installed the detector within three months in 2003.

SciBar Installation (1)

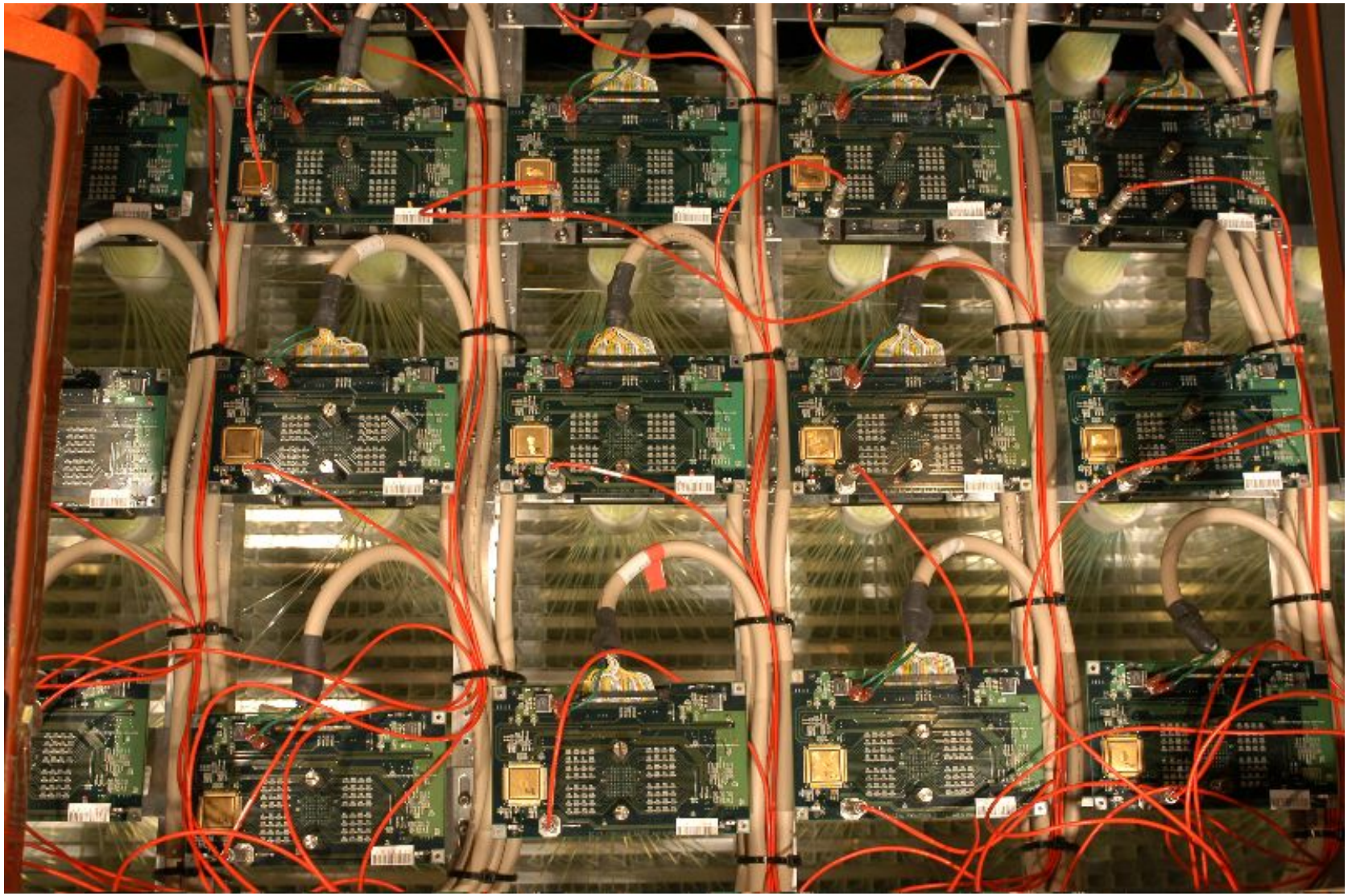




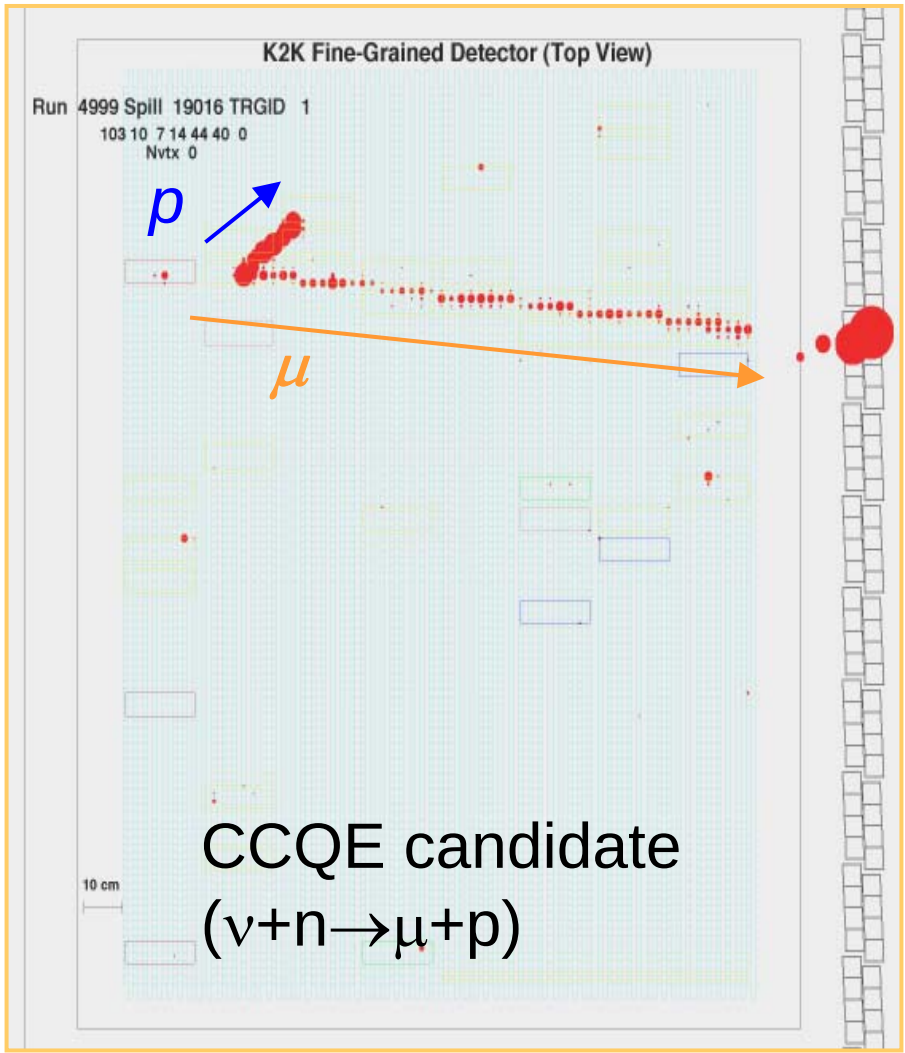
SciBar Installation (2)



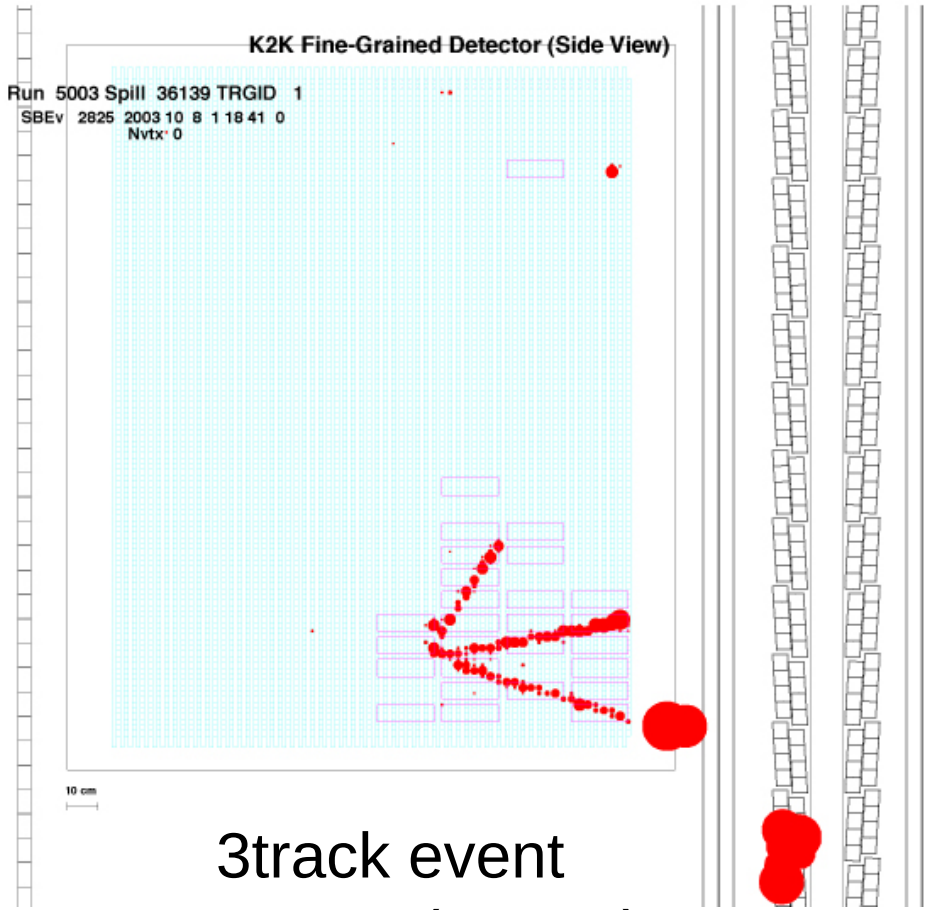
SciBar Installation – complete !



Event Display -1

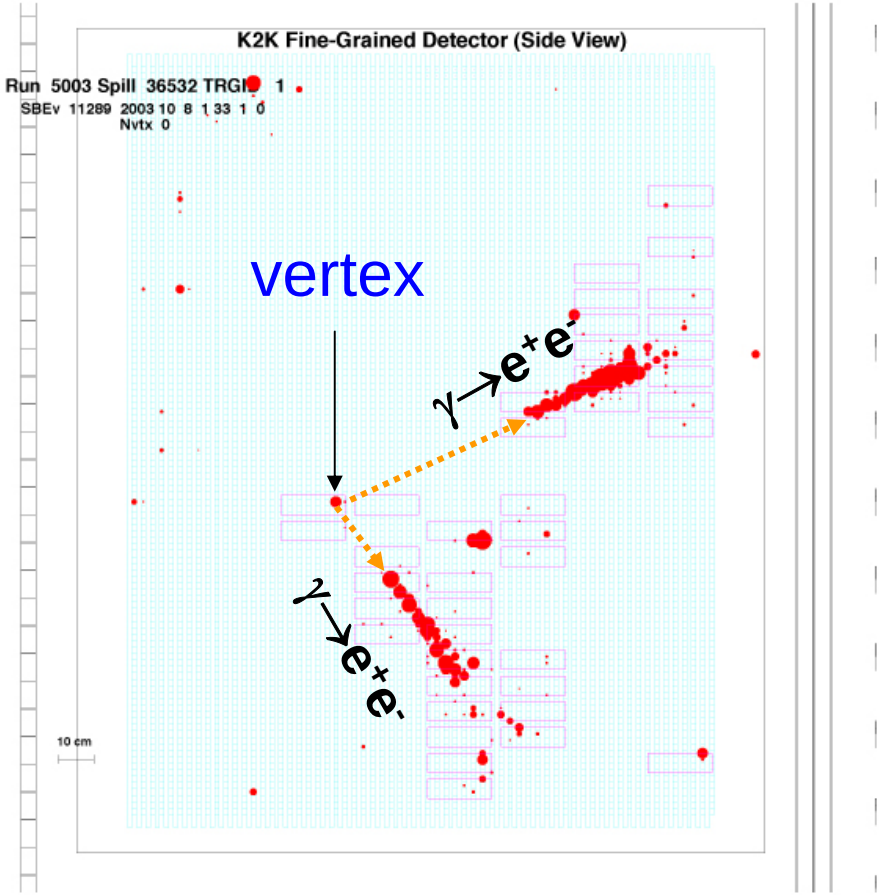


CCQE candidate
(ν+n$\rightarrow\mu$+p)



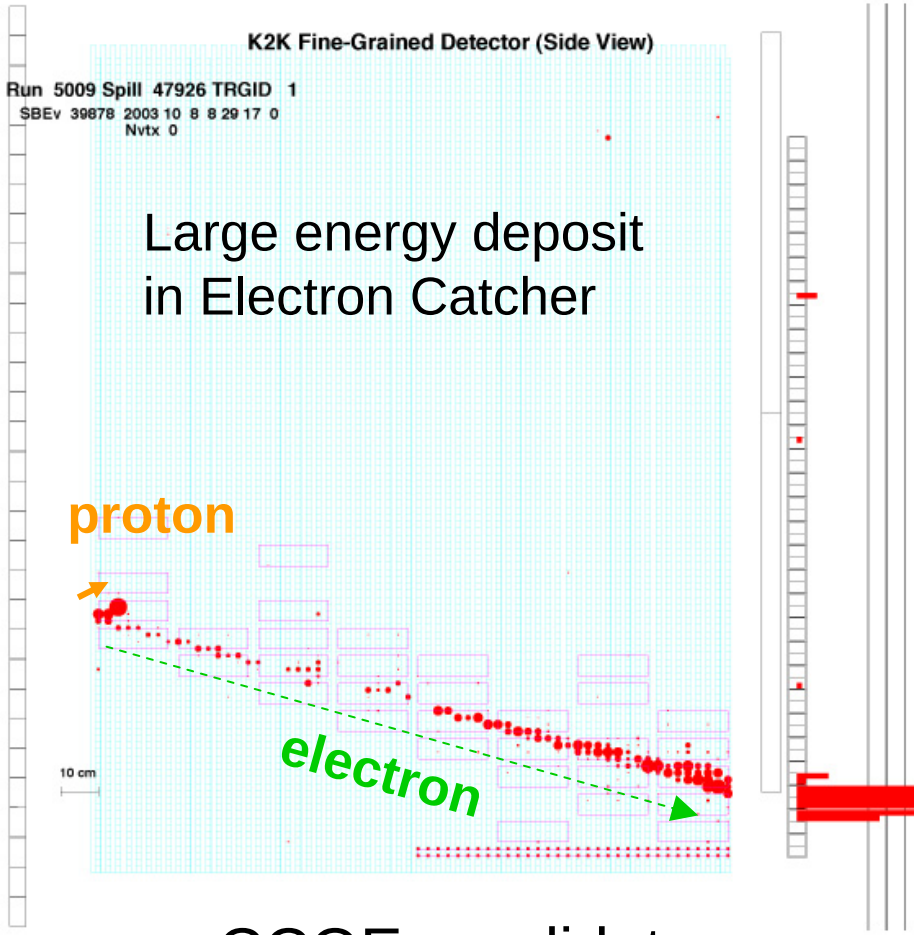
3track event
CC-1π (μ+p+π)
candidate

Event Display-2



NC π^0 candidate

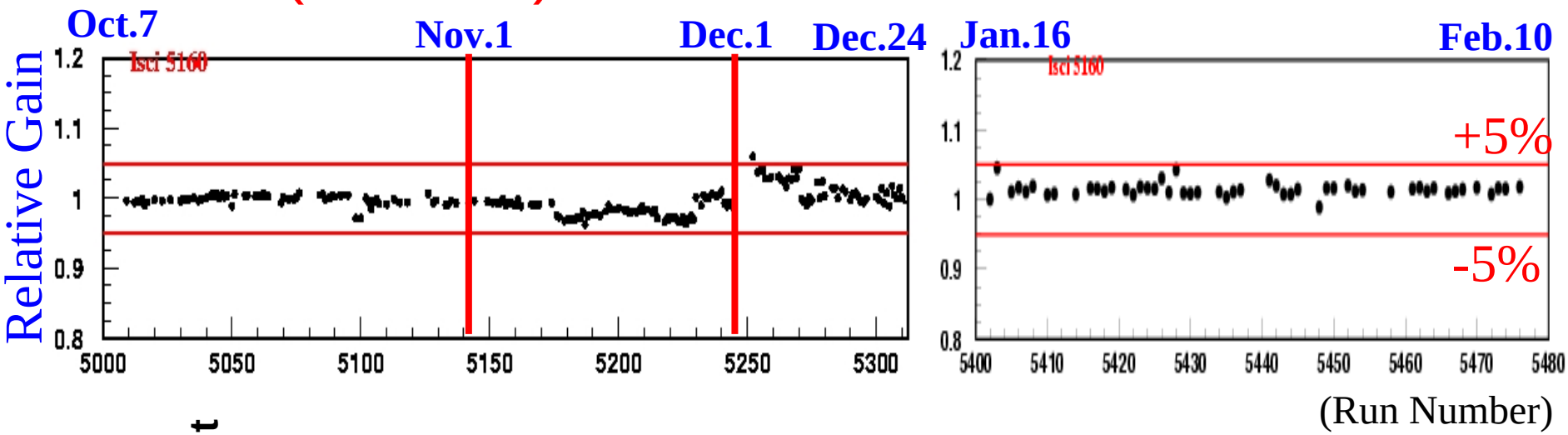
$\nu+N\rightarrow\nu+N+\pi^0$

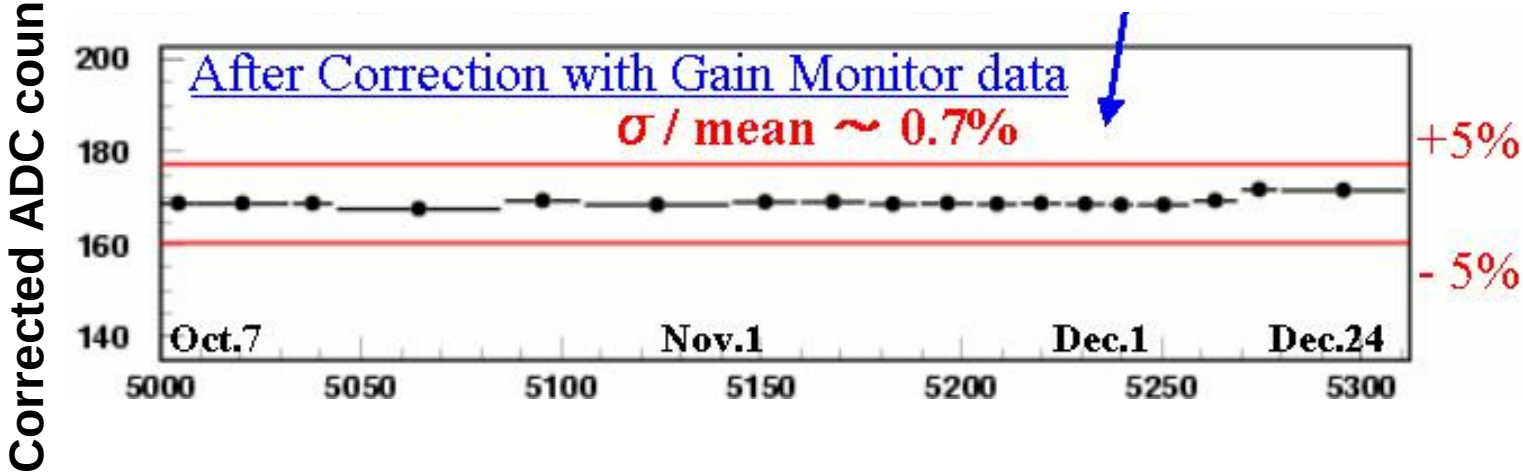


ν_e CCQE candidate

Gain calibration

14306 (99.85 %) channels are stable for 4 months.





Gain drift can be corrected within 1% level precision !

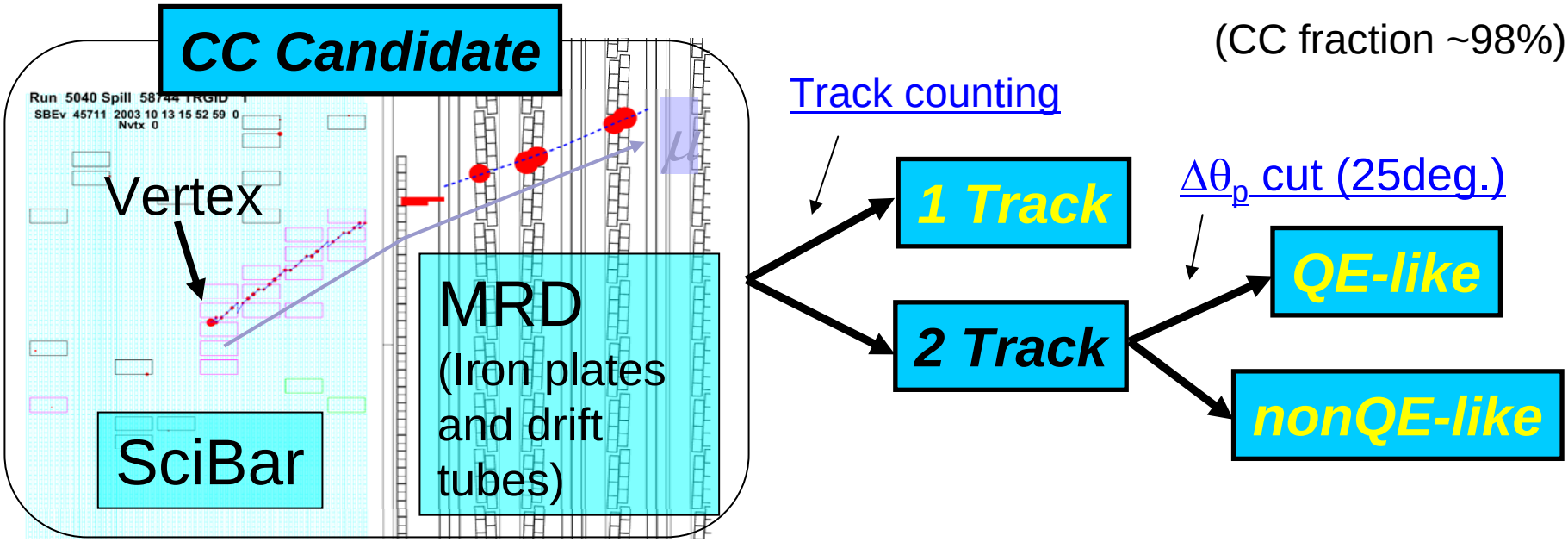
4. SciBar Physics Results from K2K

- **Physics Results based on 0.2×10^{20} POT (~25,000 ν events.)**
  - ν_μ flux measurement for oscillation analysis.
  - Upper limit on the CC-coherent π cross section.
  -
- On-going Analysis (not presented here)
  - CC-1π cross section and M_A
  - CCQE M_A
  - CC-multi π cross section
  - ν_e flux
  - π^0 process (NC and CC)
  - NC elastic scattering ($\nu+p\rightarrow\nu+p$)

2.1 ν_μ flux measurement for oscillation analysis

To select CC events, we use SciBar-MRD matching sample.

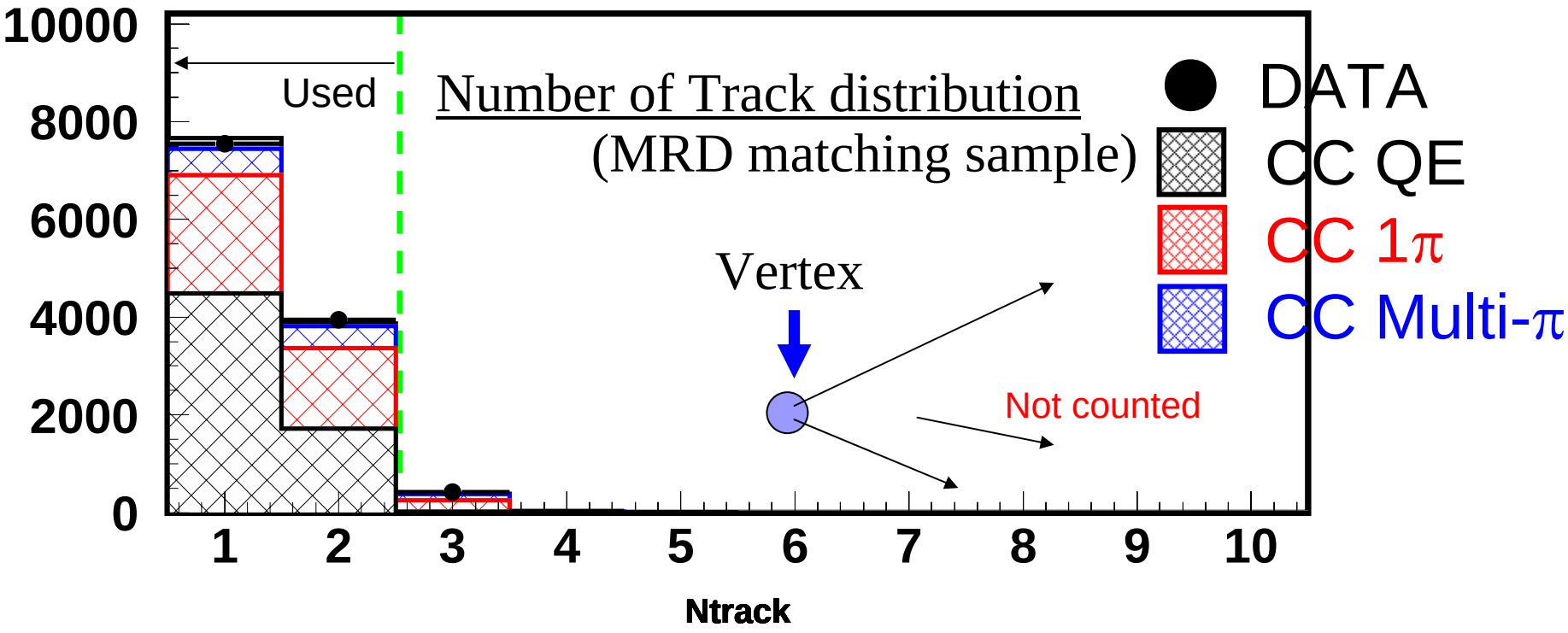
(CC fraction ~98%)



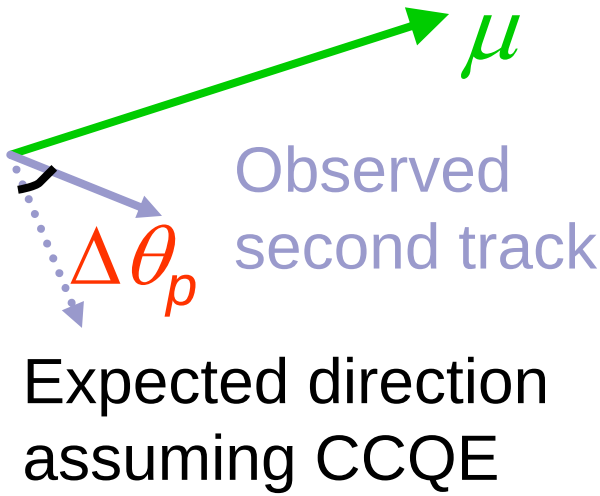
Event category		QE fraction (MC)
- 1track	7180 event	58.5%
- 2track QE-like	1716 event	71.5%
- 2track nQE-like	1934 event	17.0%

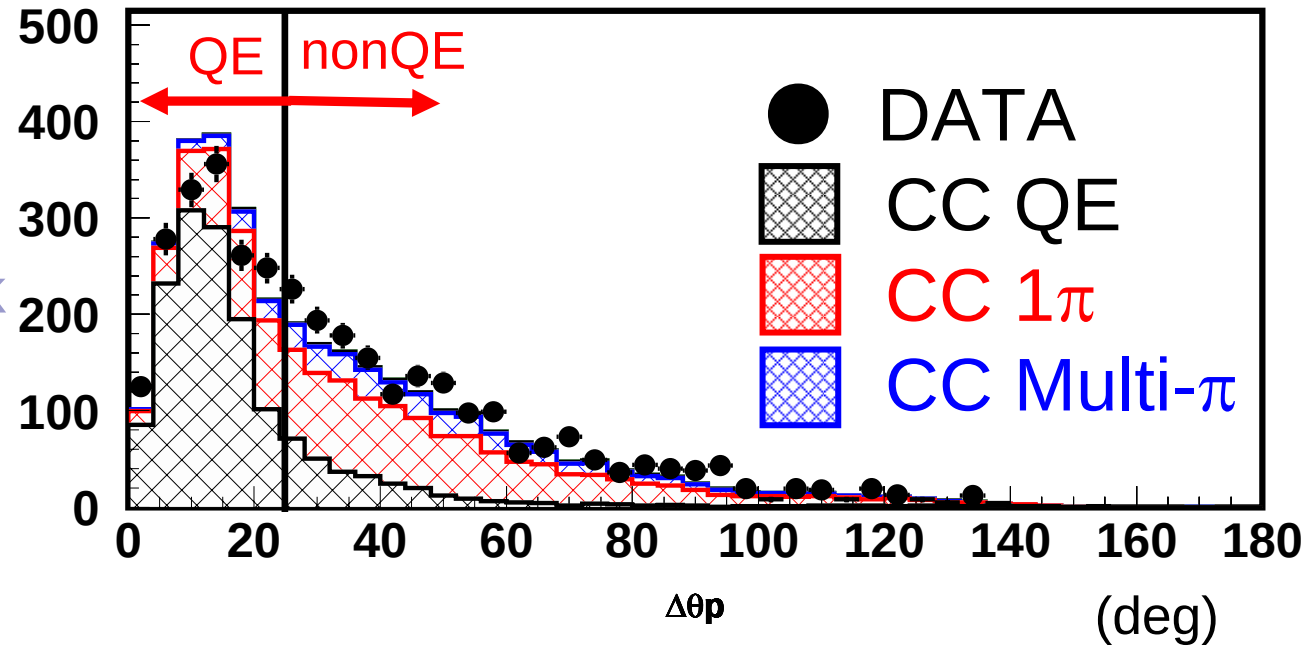
Number of tracks

Track:
More than two successive hits connected in each view (2D-track), and the 2D-tracks are matched as a 3D track.



$\Delta\theta_p$ cut





$\Delta\theta_p \leq 25°$: QE sample, $\Delta\theta_p > 25°$: nonQE sample

- Systematic error on nonQE/QE ratio : +5.1/-5.8%
  - Detector oriented +2.4/-1.3%
  - **Nuclear effect** +4.5/-4.9%
  - Possible angle bias for 2nd track /-2.9%

Energy Spectrum Measurement

- Neutrino energy can be reconstructed from p_μ and θ_μ for CC-QE event:

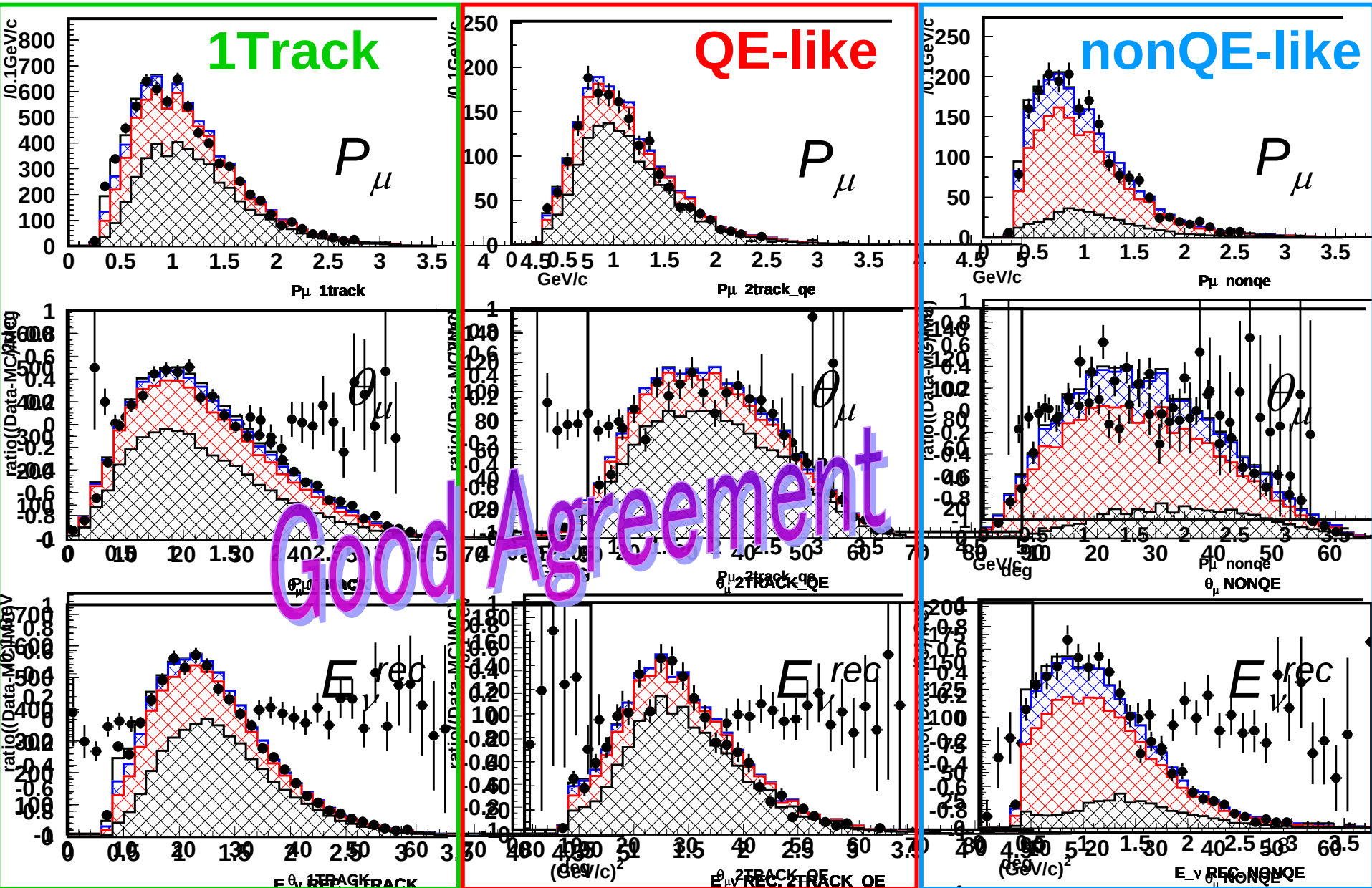
$$E_\nu^{\mathrm{rec}} = \frac{(m_N - V)E_\mu - m_\mu^2/2 + m_N V - V^2/2}{(m_N - V) - E_\mu + p_\mu \cos\theta_\mu}$$

V: nuclear potential energy

Fitting procedure

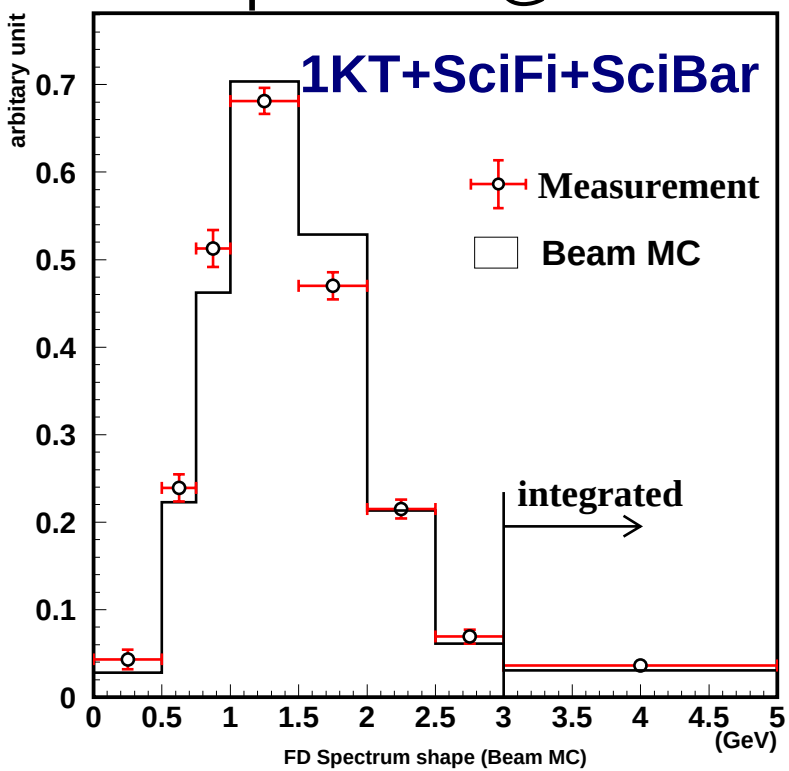
1. Select charged current events for a CCQE event
2. Fit (p_μ,θ_μ) 2-dimensional histograms with MC templates, and obtain neutrino energy spectrum and non-QE/QE ratio

Basic Distributions (SciBar)



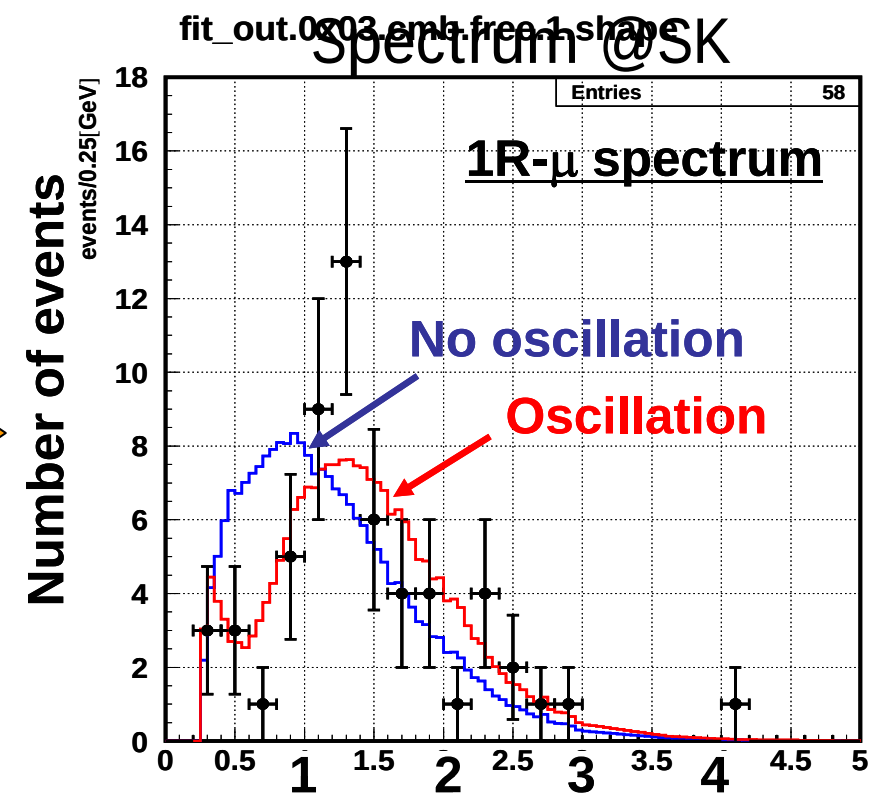
Neutrino energy spectrum

ν Spectrum @KEK



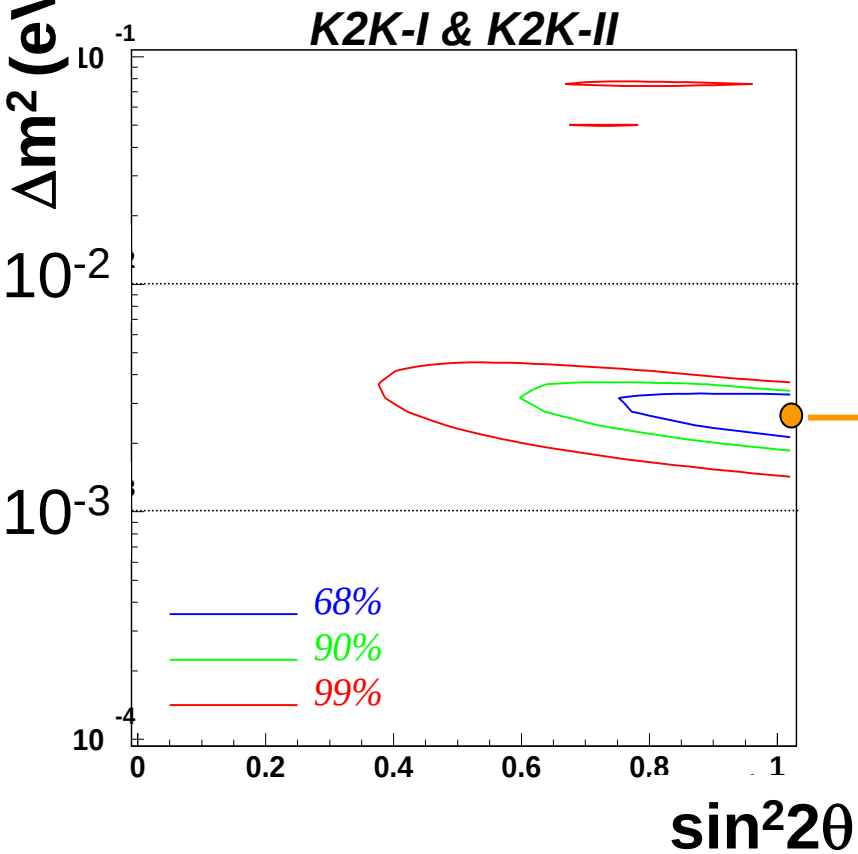
ν energy (GeV)

Reconstructed Energy Spectrum @SK



Reconstructed E_ν (GeV)

K2K Result



Best fit value

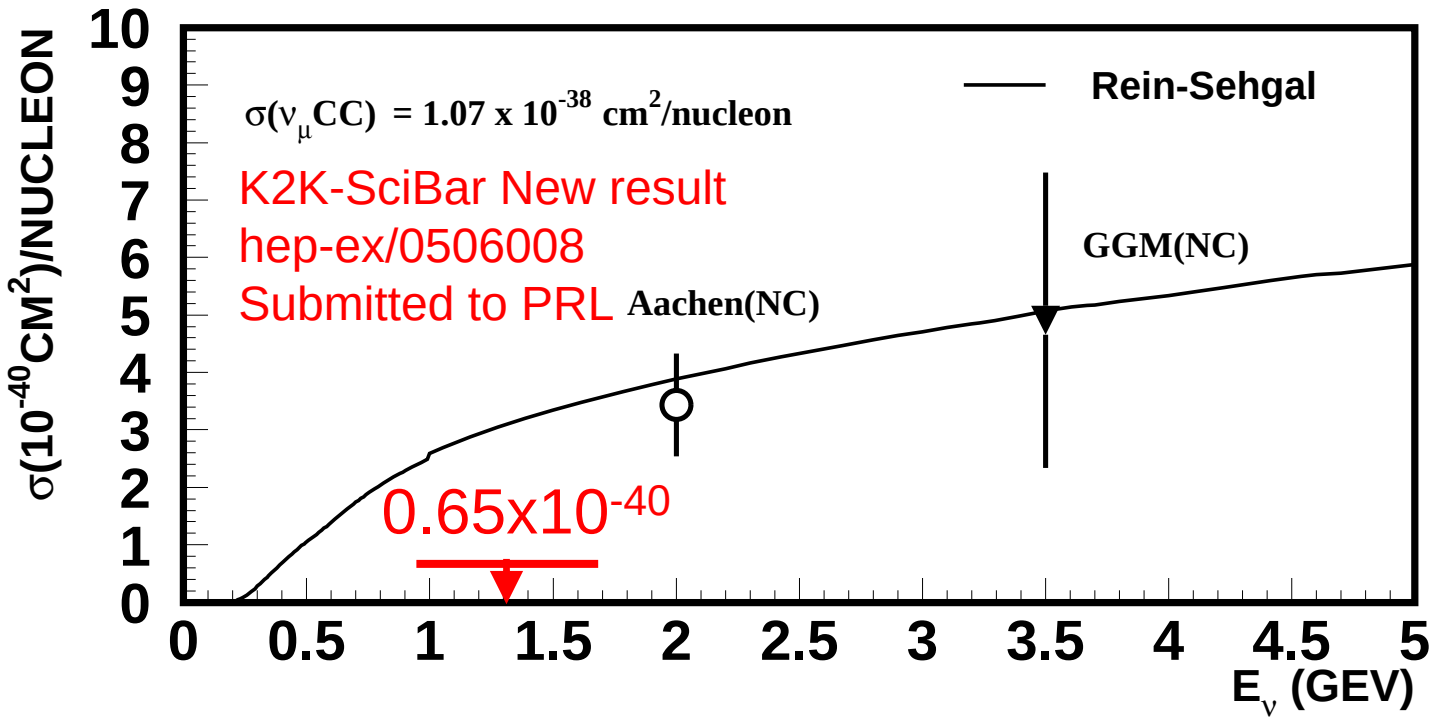
- **all region**
  - $\sin^2 2\theta = 1.19 \pm 0.23$
  - $\Delta m^2 = (2.55 \pm 0.40) \times 10^{-3} \text{eV}^2$
- **physical region**
  - $\sin^2 2\theta = 1.0$
  - $\Delta m^2 = (2.76 \pm 0.36) \times 10^{-3} \text{eV}^2$

$1.88 \times 10^{-3} \leq \Delta m^2 \leq 3.48 \times 10^{-3}$ eV^2
(90%CL) @ $\sin^2 2\theta = 1$

The K2K result is inconsistent with null oscillation at 4.2σ level.
K2K confirms ***neutrino oscillation*** *discovered in Super-K.*

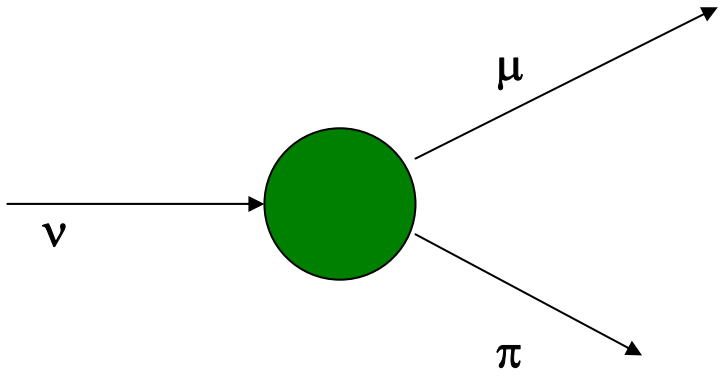
2.2 Upper limit on the CC-coherent π cross section

- For low energy neutrinos, we (K2K and MiniBooNE) observe a deficit of forward going muon events
  - What is the source? ⇛ No CC−coherent π process

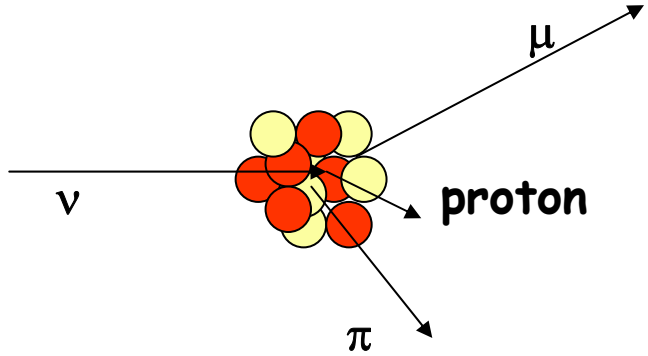


CC-coherent π signature

CC-coherent π (ν+A→μ+A+π)



CC-1π (ν+p→μ+p+π)



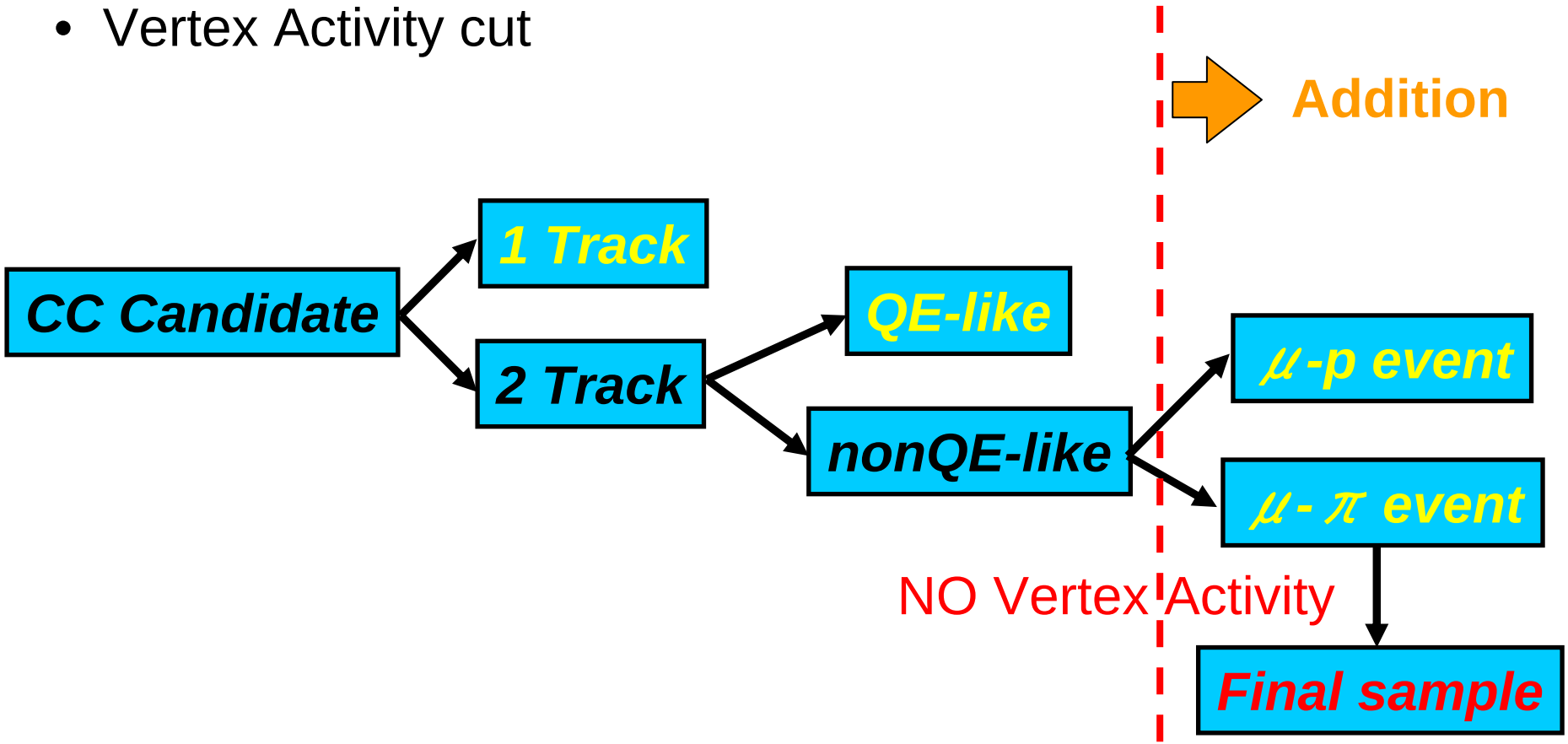
Coherent π signature

- One muon and one pion in the final state
- Low momentum transfer
- No vertex activity due to no proton

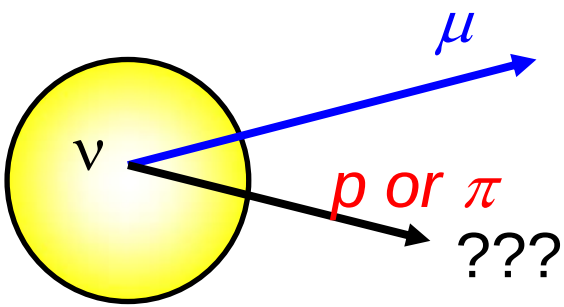
Analysis

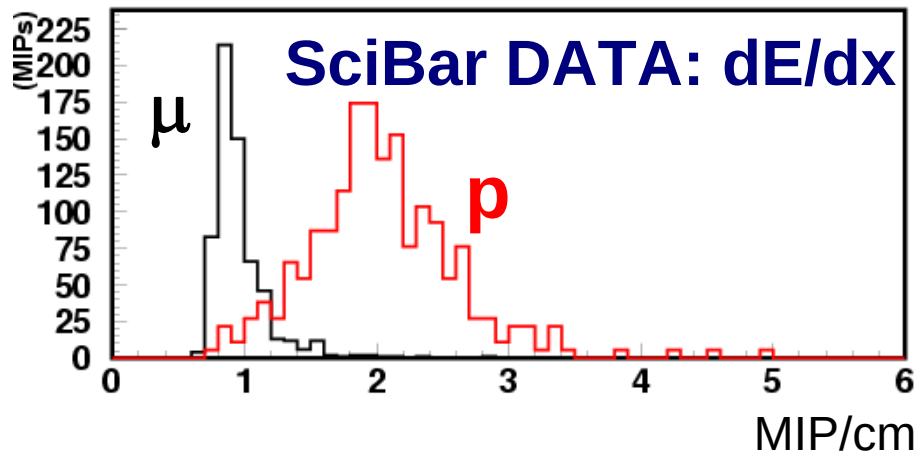
Additional cuts to the spectrum measurement.

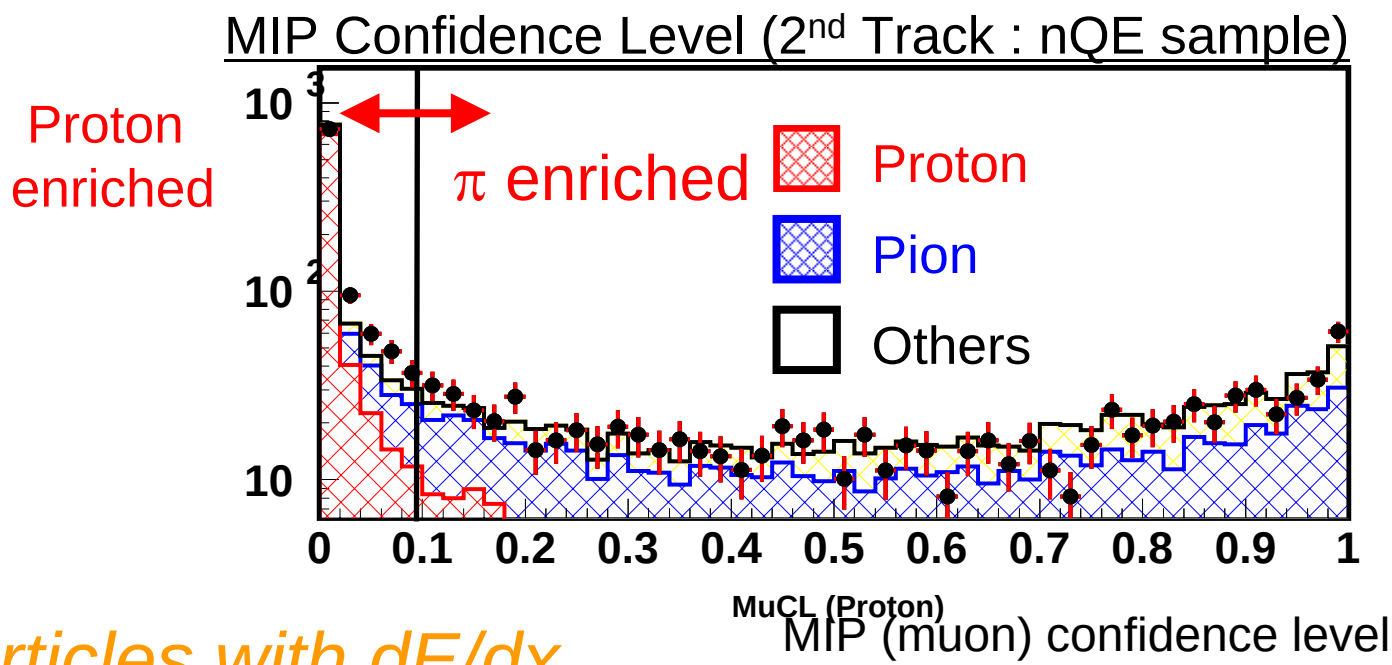
- Particle ID (proton or MIP(π))
- Vertex Activity cut



PID: μ -p / μ - π

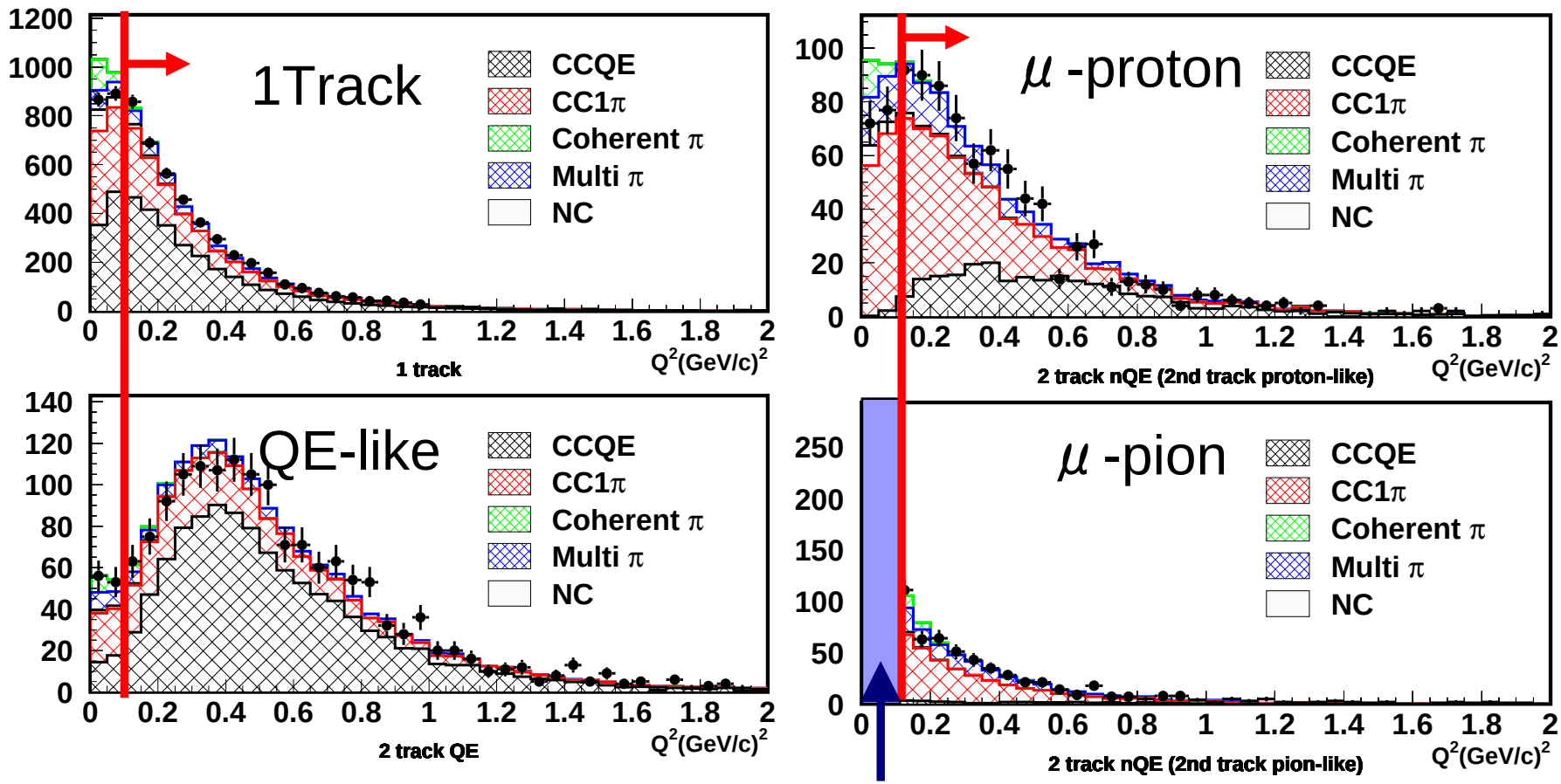






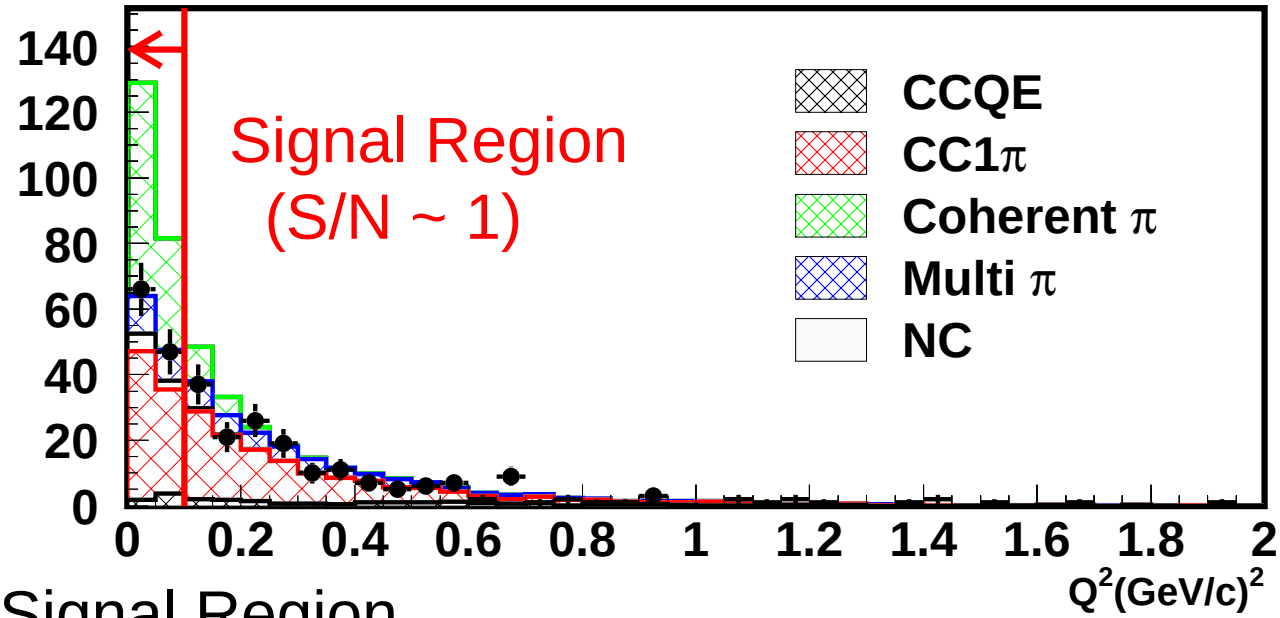
Separate particles with dE/dx

q^2_{rec} Distribution (w/o vertex activity cut)



Signal region

q^2_{rec} distribution w/ vertex activity cut



In the Signal Region,

- Observation: **113**
- BG estimate: 111.4±10.6(stat.)
- Signal prediction by the Rein&Sehgal model: 99

No Evidence of CC-coherent π process

at low energy

Upper limit on σ(CC-coherent π)/σ(ν_μCC)

$$\sigma(CC-coherent\ \pi)/\sigma(\nu_\mu CC)$$
$$=\{0.044\pm 0.291(stat.)^{+0.331}_{-0.363}(syst.)\}\times 10^{-2}$$
$$<0.608\times 10^{-2}\ (90\%CL)$$

⇔ Rein & Sehgal : 2.667×10^{-2}

Main Systematic uncertainties

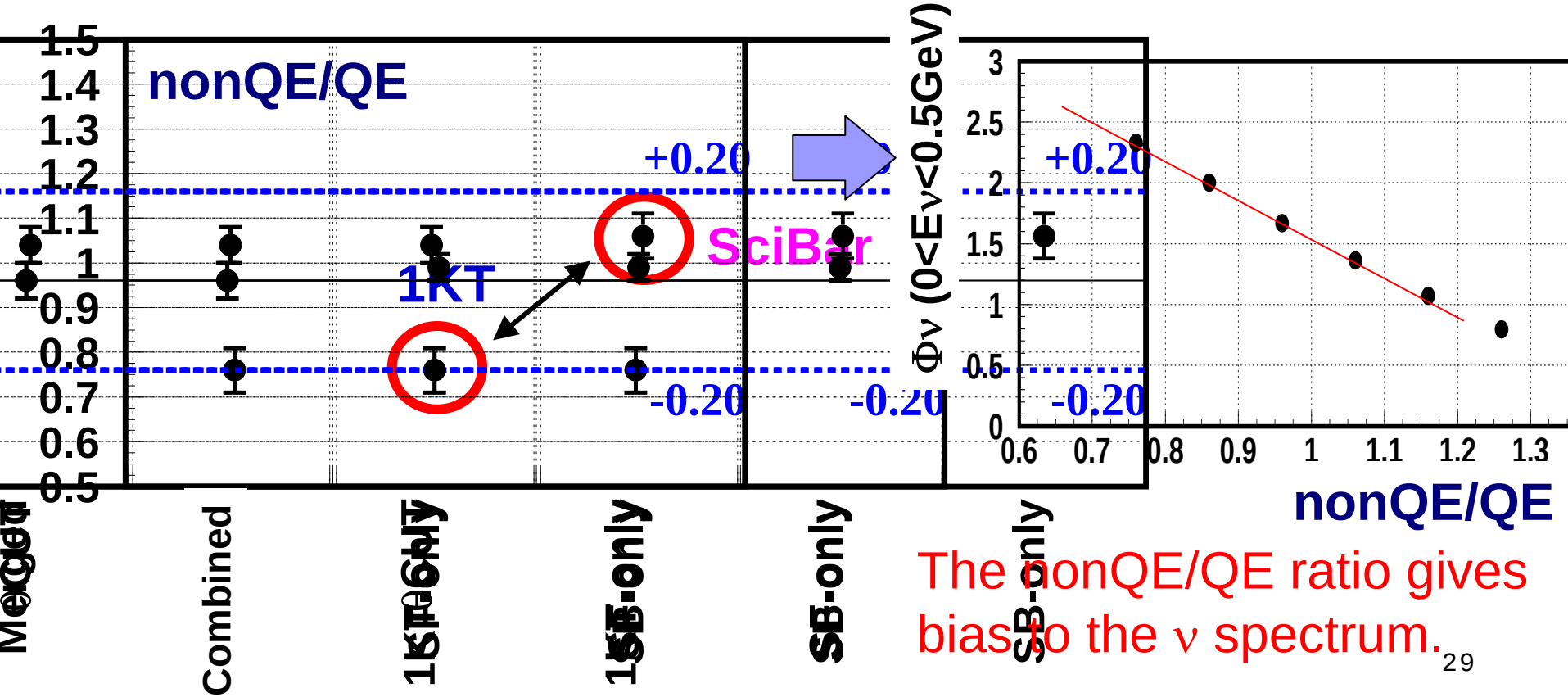
Nuclear effect and neutrino interaction (+0.273, -0.253)	
π absorption in the nucleus	+0.171, -0.08
BG estimation from CC-1π	+0.144, *

5. Current status of K2K neutrino cross section analysis (with a mystery)

1. nonQE/QE Ratio
   1. Larger M_A for q^2 shape?
   2. Absolute cross section with the K2K-HARP result
2. π^0
   1. Momentum distribution.
   2. NC coherent π^0 process?
3. ν_e flux

5.1 nonQE/QE ratio

- **1KT**: Extract the nonQE/QE ratio from the muon distributions: (p_μ, θ_μ).
- **SciBar**: Measure the nonQE/QE ratio from the muon distributions, 1track/2track ratio and nonQE/QE kinematics.



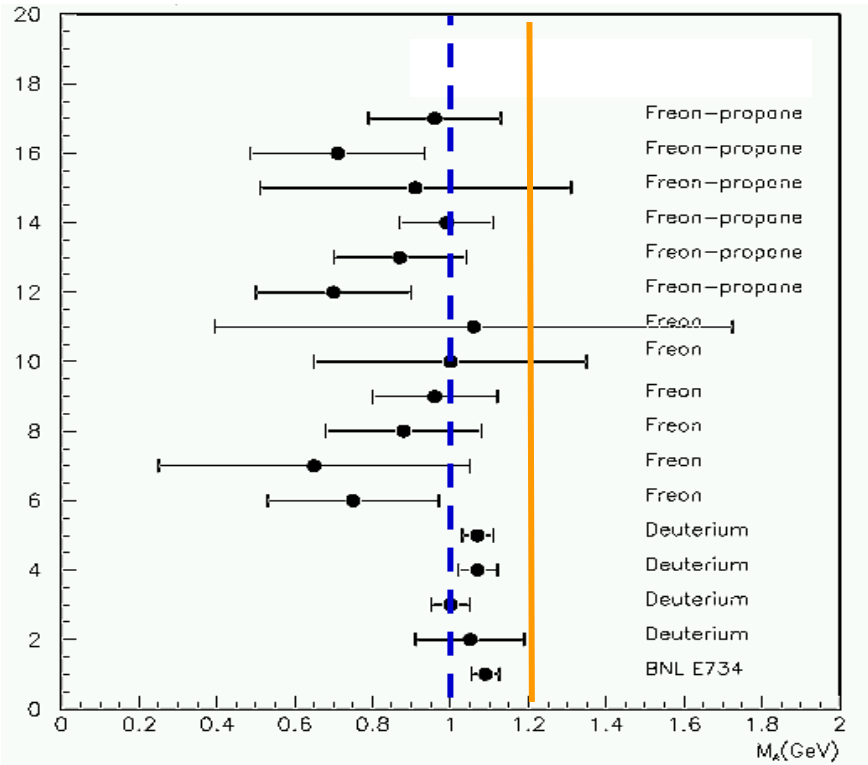
The nonQE/QE ratio gives bias to the ν spectrum.

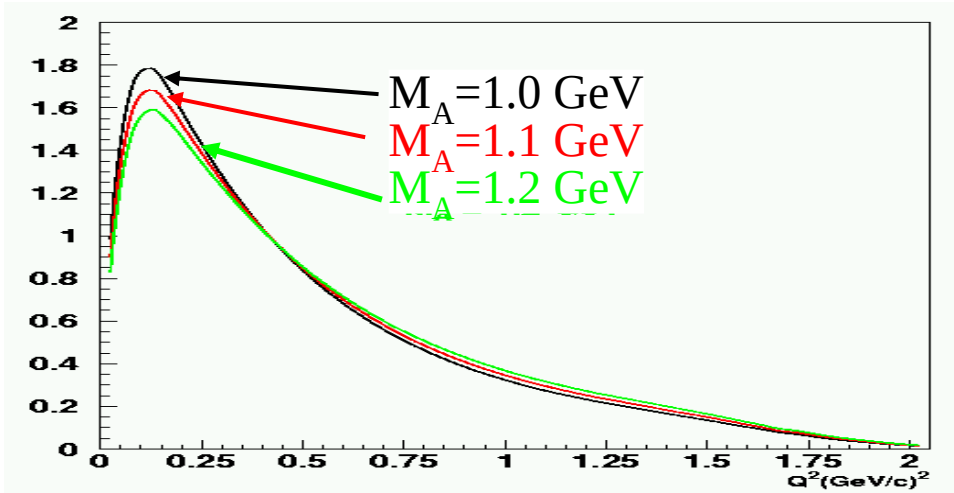
Shape versus Cross section

- 1KT: indicating smaller nonQE/QE

  ⇛ The μ distribution would be harder than the model. ⇛ larger M_A?

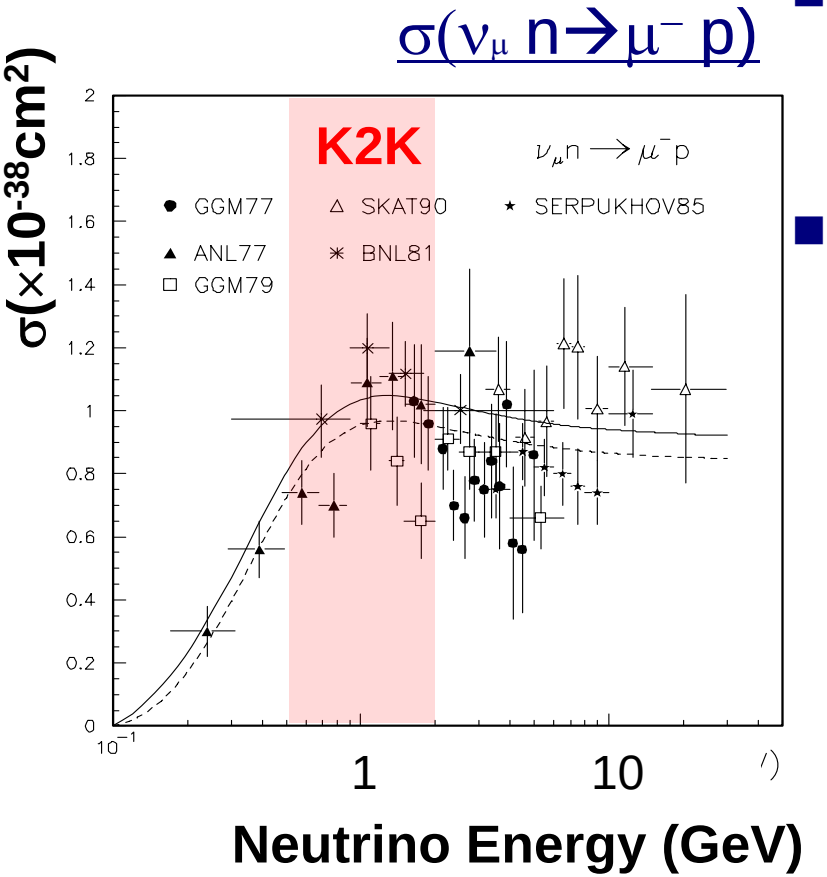
$\sigma_{CCQE} \propto M_A$





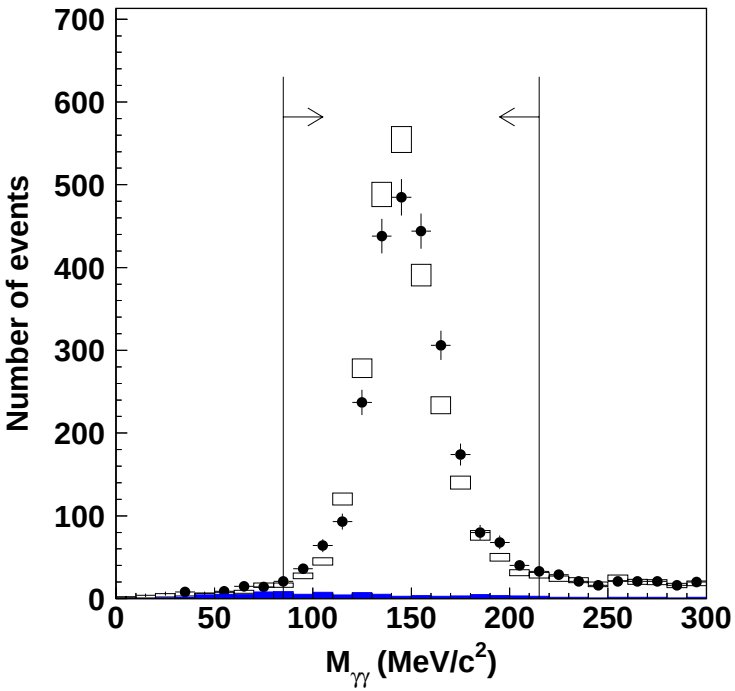
K2K-SciFi: M_A= 1.18 +/- 0.03 +/- 0.12

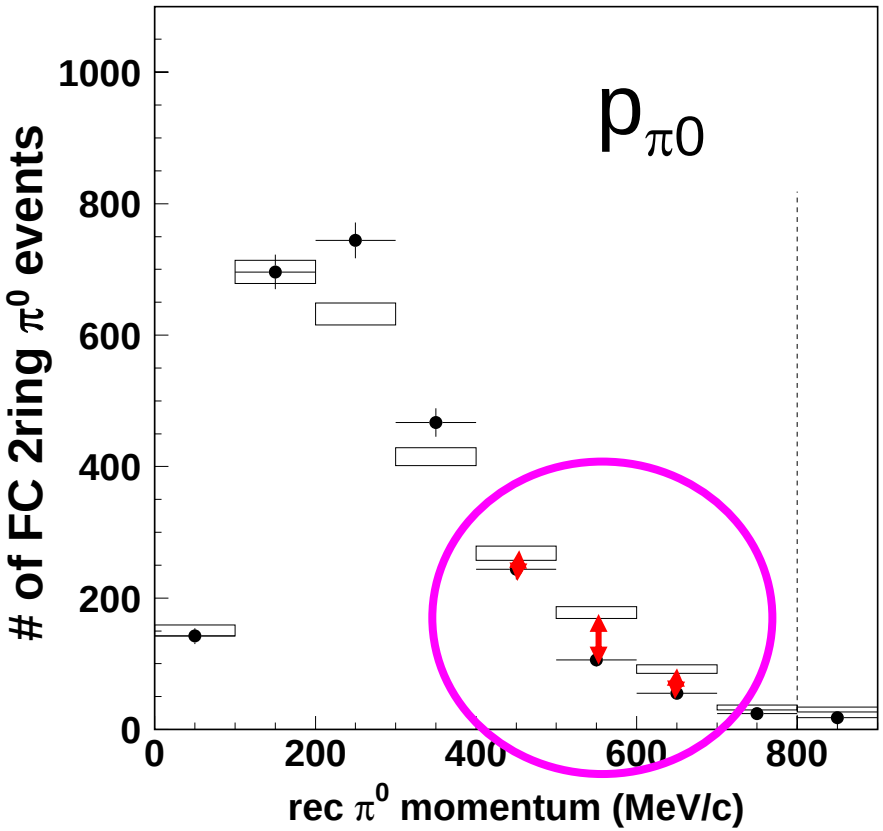
Larger M_A ⇛ Higher CCQE Cross Section?



- Using the K2K beam MC with the Sanford-Wang 2 parameterization
  - $N_\nu \propto \Phi \times \sigma \times \varepsilon$: Data/MC=0.923~1
- However, the K2K-HARP thin target data predicts a smaller neutrino flux.
  - Smaller Φ ⇛ Larger σ (M_A)?

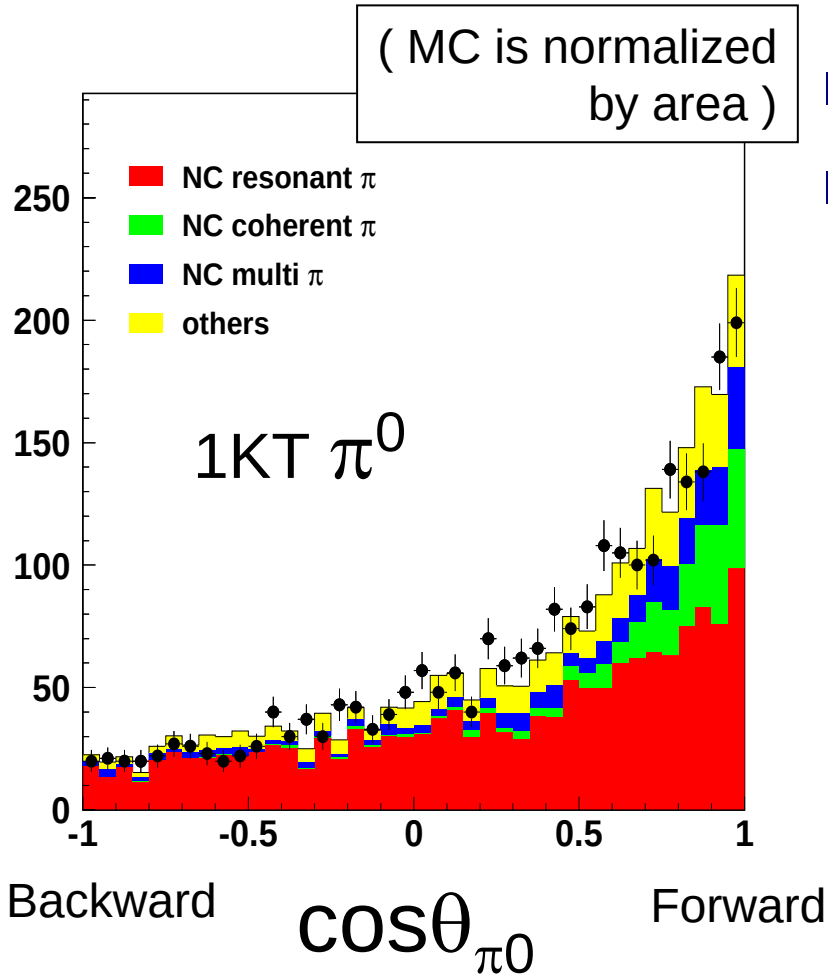
5.2 1KT-π^0





- $\sigma_{NC1\pi0}/\sigma_{CC\text{-}all}$=0.064±0.001 ±0.007 (MC: 0.065)
  - If there are less π^0 at higher momentum, then we will have less π^0 background in T2K

Does NC coherent π^0 exist?



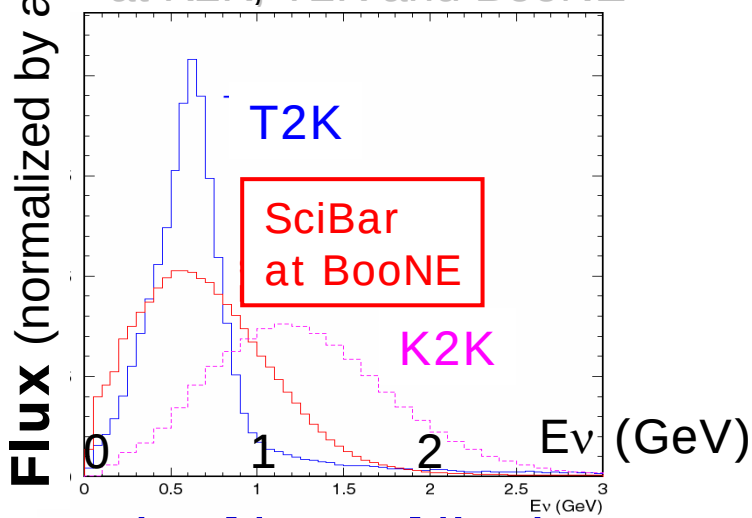
- No CC-coherent π
- The π^0 angle is not a good distinguished variable to select NC-coherent π^0 over the other π^0 process.
  - No clear answer from K2K yet
  - We need
    - Vertex Activity (SciBar)

    or
    - Anti-neutrino beam (less BG, ~1/3 resonance π^0)

7. Physics of SciBar at BNB

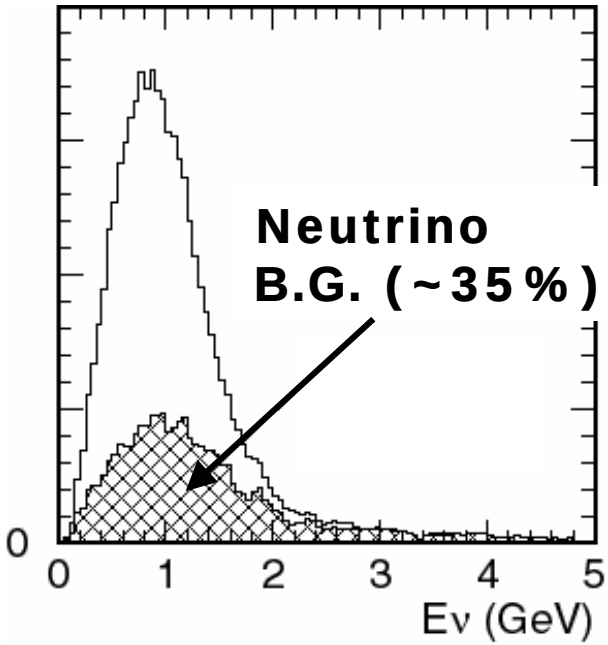
- ν run (Cross Section)
  - CC-1π cross section with M_A.
  - CCQE M_A measurement
  - NC π^0 measurement
  - Search for CC coherent π
  - Search for NC coherent π^0
  - Search for the radiative Delta decay (ν+N$\rightarrow\mu$+N'+γ)
  - Beam ν_e flux for MiniBooNE $\nu_\mu\rightarrow\nu_e$ appearance search
  - $\Phi_\mu\times\sigma$ for MiniBooNE $\nu_\mu\rightarrow\nu_\mu$ disappearance search

Comparison of ν_μ flux spectra at K2K, T2K and BooNE



Study ν interaction to improve MC modeling of those interactions

- Anti-ν run
  - CCQE measurement.
    - Negligible BG from ν.
    - Energy Dependence σ and M_A can be measured
  - CC-1π cross section with M_A.
  - NC π^0 measurement
    - Also $\nu+p\rightarrow\nu+p+\pi^0$ exclusive final-state search
  - Search for CC coherent π
  - Search for NC coherent π^0
  - Hyperon production in anti-ν mode
  - ν contamination for MiniBooNE anti-ν measurements.

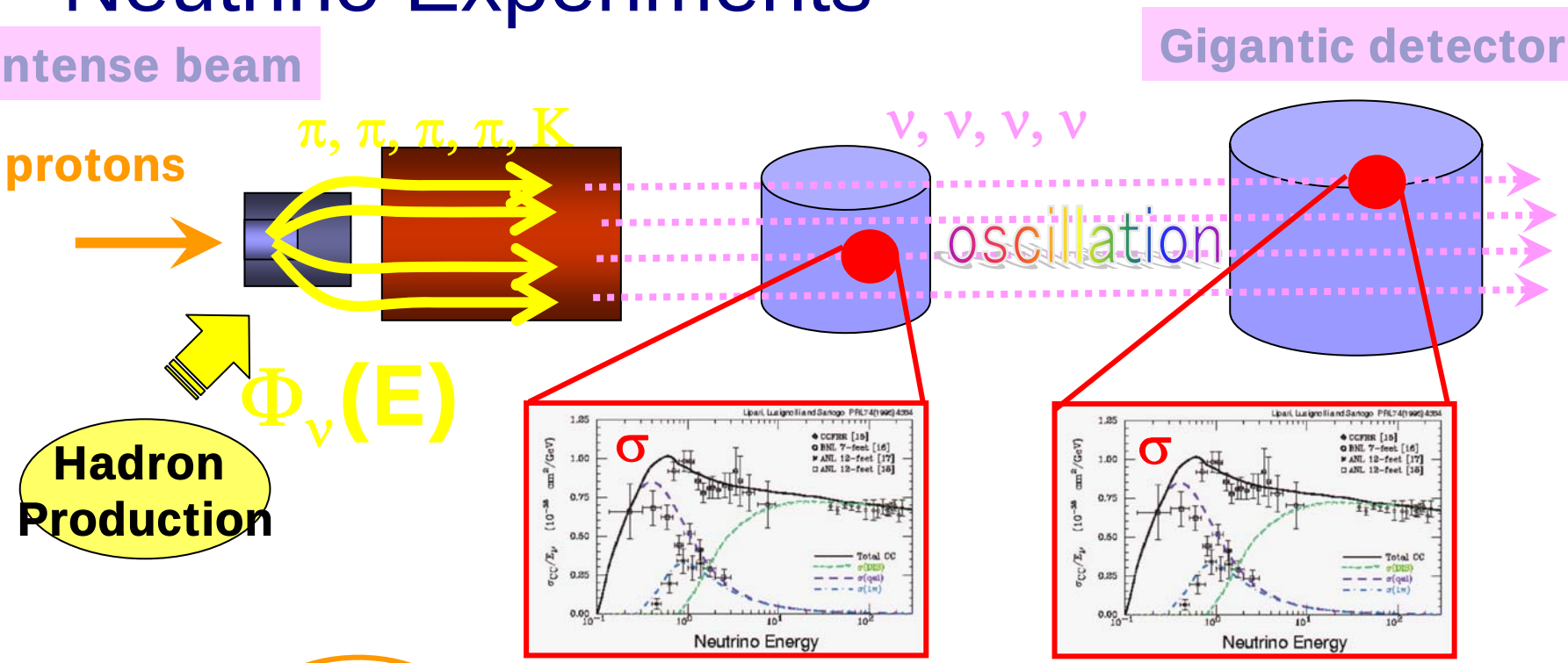


Why do the neutrino cross section help future experiments, like T2K?

- Observables $\propto$ Flux(Φ) $\times$ $\sigma(E_\nu)$ $\times$ efficiency (ε)

	Φ	$\sigma(E_\nu)$	ε	E_ν(GeV)
K2K-ND	☺(HARP)	Some results	Well-understood	1.3
MiniBooNE	☺(HARP)	Under Progress	Under calibration & tuning	0.7
SciBar@BNB	☺(HARP)	Will be good	Well-understood	0.7
T2K-ND280			need some time	0.7
MINERνA	☺(MIPP)	-----	??	2~5?

Neutrino Experiments



Near: $\int \Phi_{ND}(E_\nu) \times \sigma_i(E_\nu) \times \varepsilon^i_{ND}(E_\nu) dE_\nu$

Far: $\int \Phi_{ND}(E_\nu) \times R(E_\nu) \times P(E_\nu) \times \sigma_j(E_\nu) \times \varepsilon^j_{SK}(E_\nu) dE_\nu$

$R(E_\nu)$: Far/Near Flux ratio ⇐ beam MC, hadron production

$P(E_\nu)$: Neutrino Oscillation Probability

Neutrino run (0.5×10^{20} POT)

of interactions
in 10 ton Fiducial Volume

ν_μ ~**78,000**

ν_e~ **700**

cf. K2K-SciBar (0.2×10^{20} POT) : ~25,000 ν_μ

The well-developed analysis and MC simulation software in K2K are used for these studies.

Further Improvements are also expected and promising.

Event Selection with MRD matching (Pμ, θμ)

1 track

~13,500 events

QE~67%

2 track QE

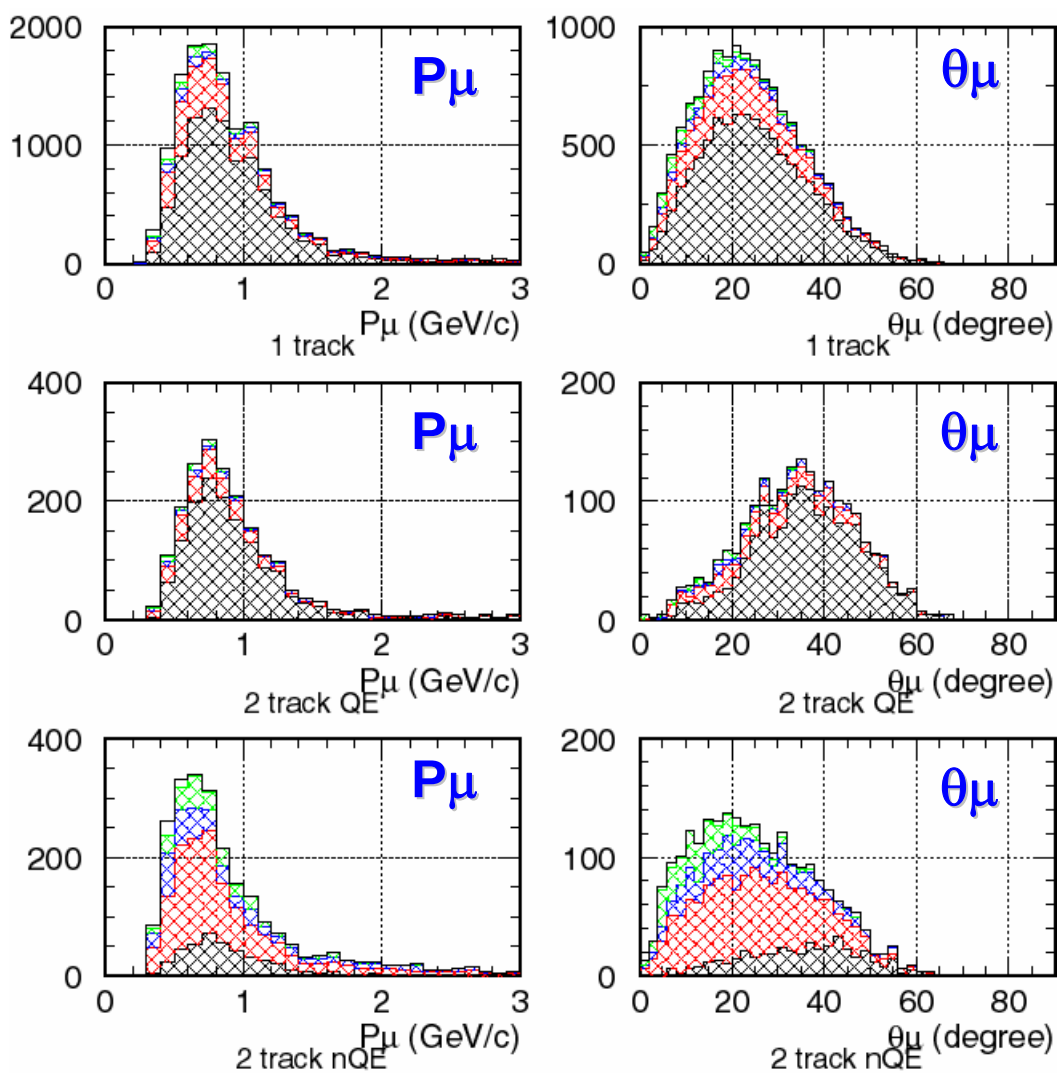
~1,970 events

QE~76%

2 track non-QE

~2,360 events

CC-1π~49%



CC-QE

CC-1π

CC-coh. π

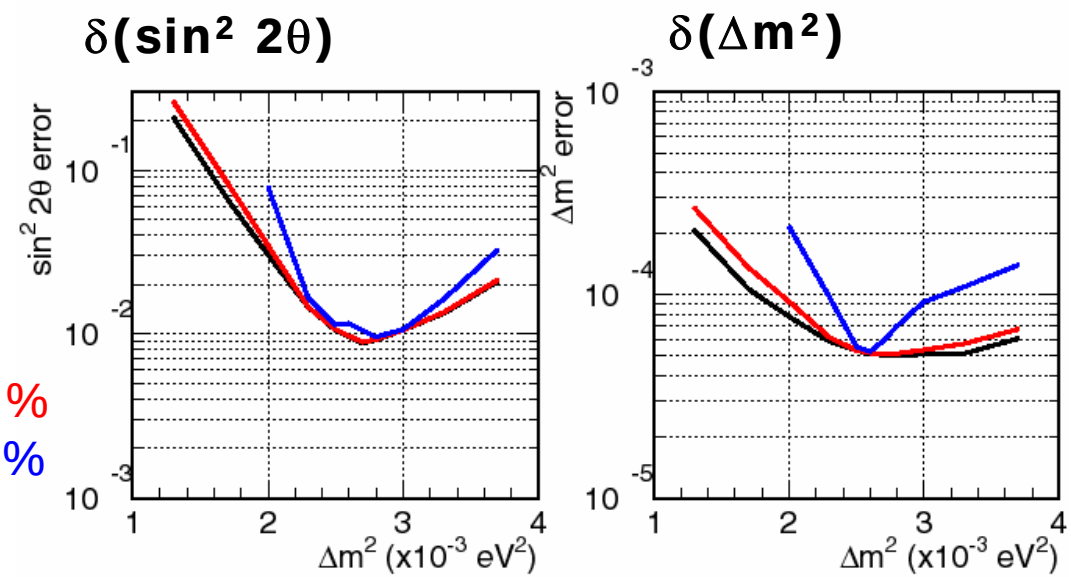
CC-multi π

CC-1π^+ measurement

- Physics motivation for T2K
  - Dominant background to ν_μ disappearance in T2K
  - The uncertainty of nonQE/QE needs to be known to ~5%

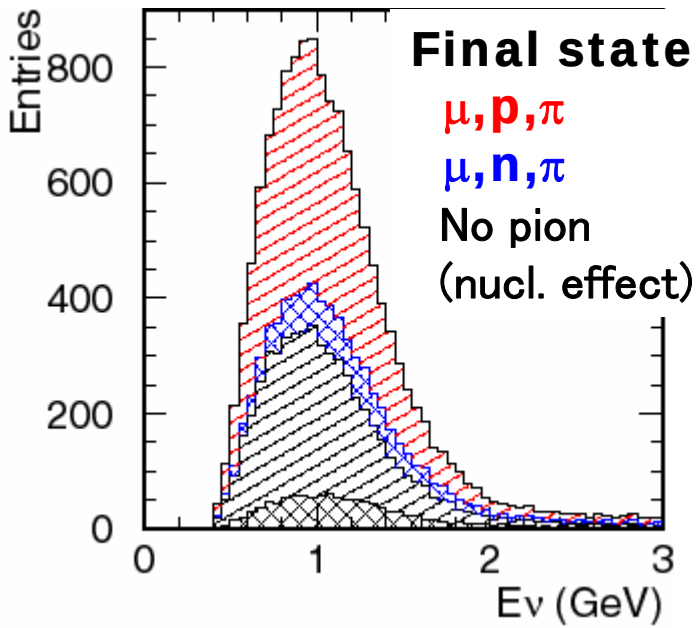
The ν_μ disappearance measurement error (90%CL)

— stat. only
— δ(nQE/QE) = 5%
— δ(nQE/QE) = 20%

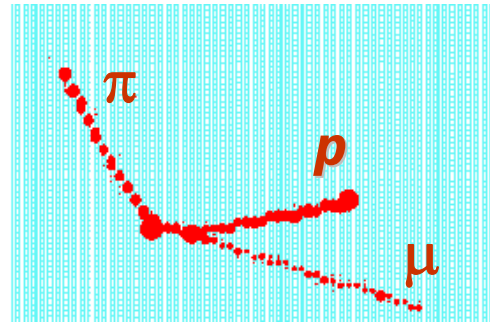


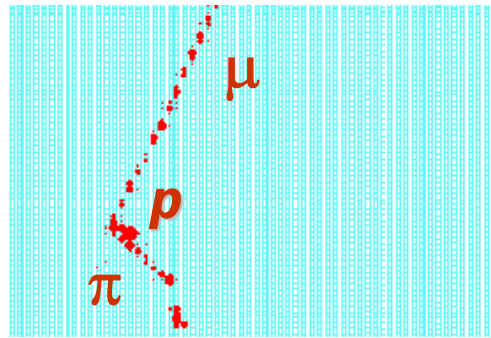
CC-1π^+ measurement (cont'd)

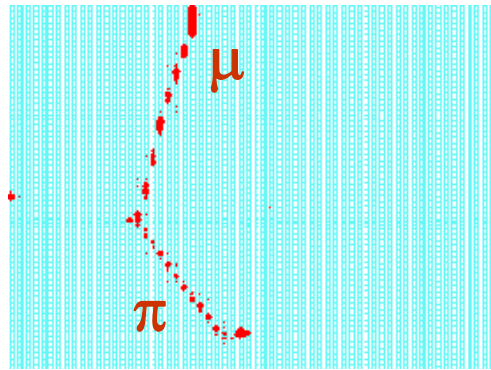
Eν distribution for CC-1π^+

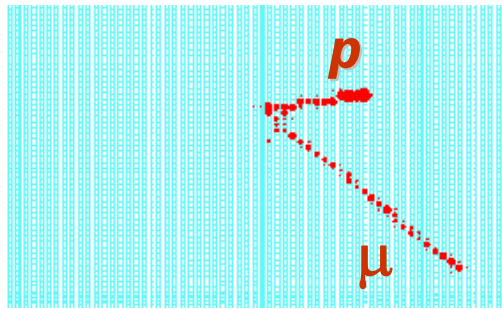


Clear event-by-event final-state tagging!







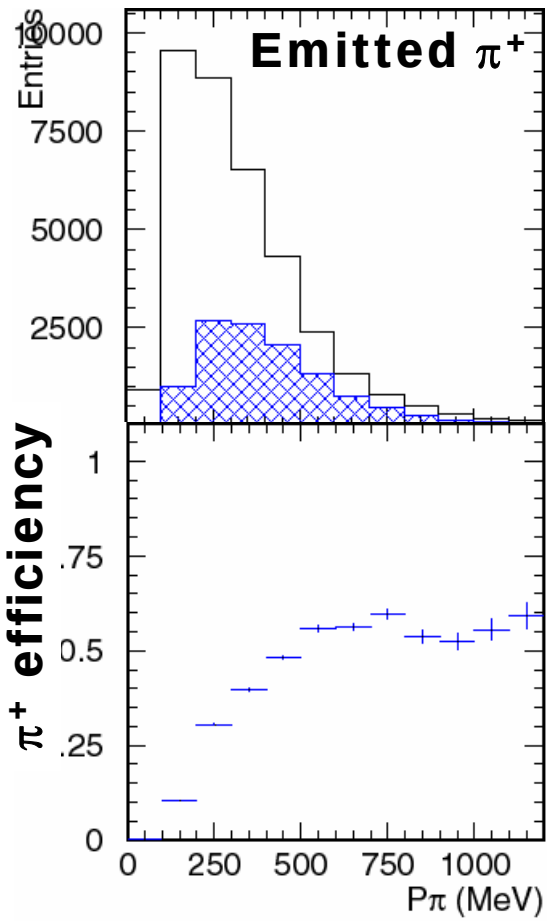


SciBar has an ability to separate the final state

Sensitive to the nuclear effect

CC-1π^+ measurement (cont'd)

π^+ detection efficiency as a function of Pπ^+



CC-1π^+ signature:
2-track, both are MIP-like

Selection criteria	#(CC-1π^+) [events]	Purity	Efficiency
Generated in FV	13,892	-------	100%
CC inclusive sample (SciBar+EC+MRD)	8,977	24.1%	64.6%
# of tracks =2	2,705	32.6%	19.5%
2nd track = MIP-like	1,355	46.8%	9.8%

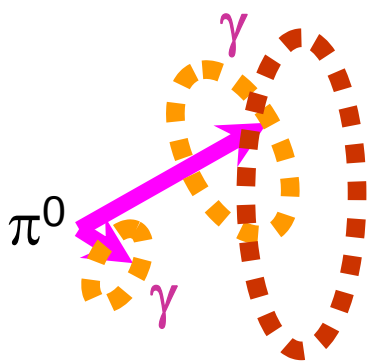
Additional vertex activity can separate $\nu+p\rightarrow\mu+p+\pi^+$ from $\nu+n\rightarrow\mu+n+\pi^+$

Statistics will allow a 5% measurement

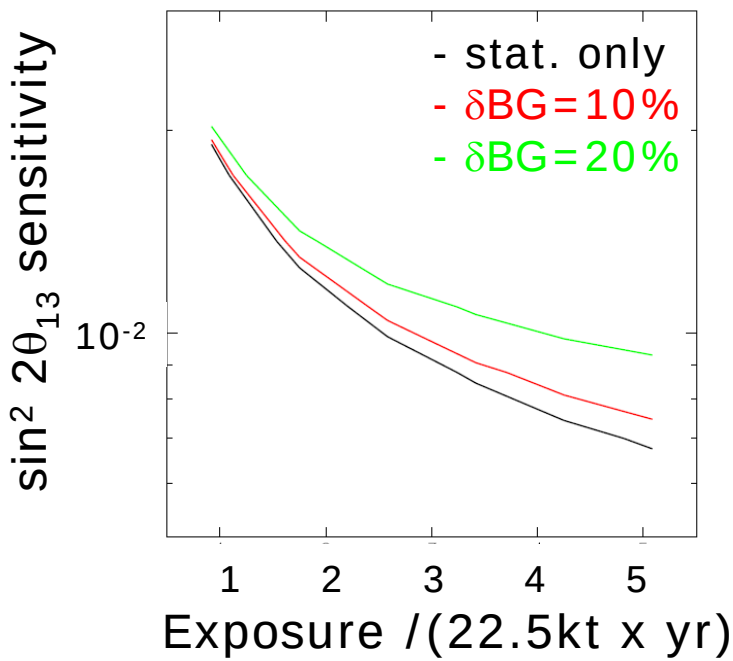
NC-1π^0 measurement

- Physics motivation for T2K
  - Dominant background to ν_e appearance in T2K
  - Need to be known to 10% level

2-ring merged to 1-ring in Cherenkov detector

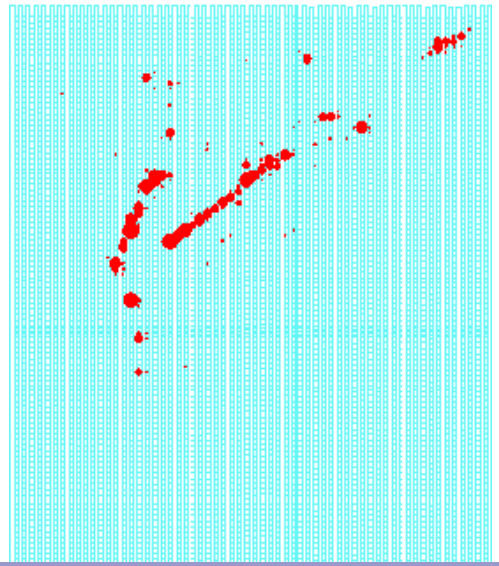


200~700MeV/c π^0s



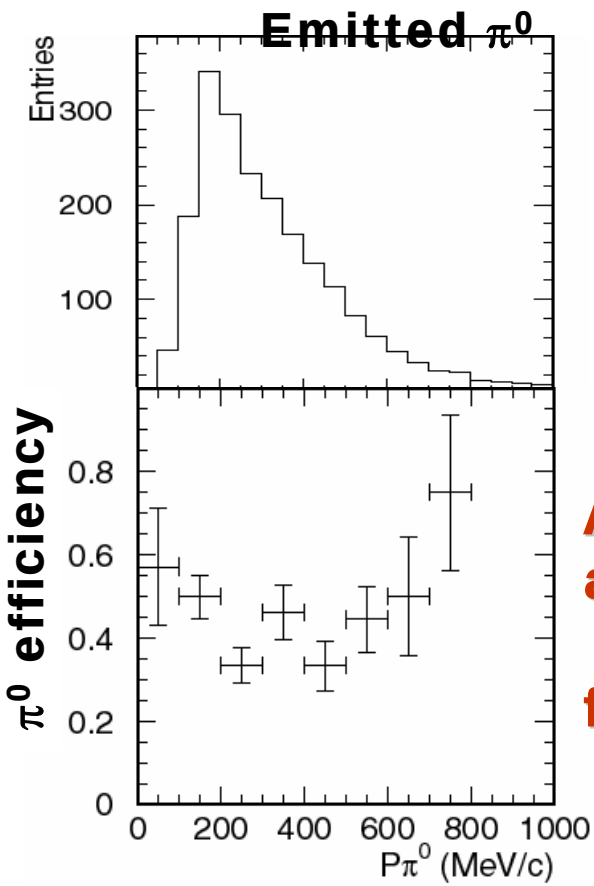
NC-1π^0 measurement (cont'd)

NC-1π^0 event display



π^0s are detected as two shower-like tracks in SciBar

π^0 detection efficiency as a function of Pπ^0

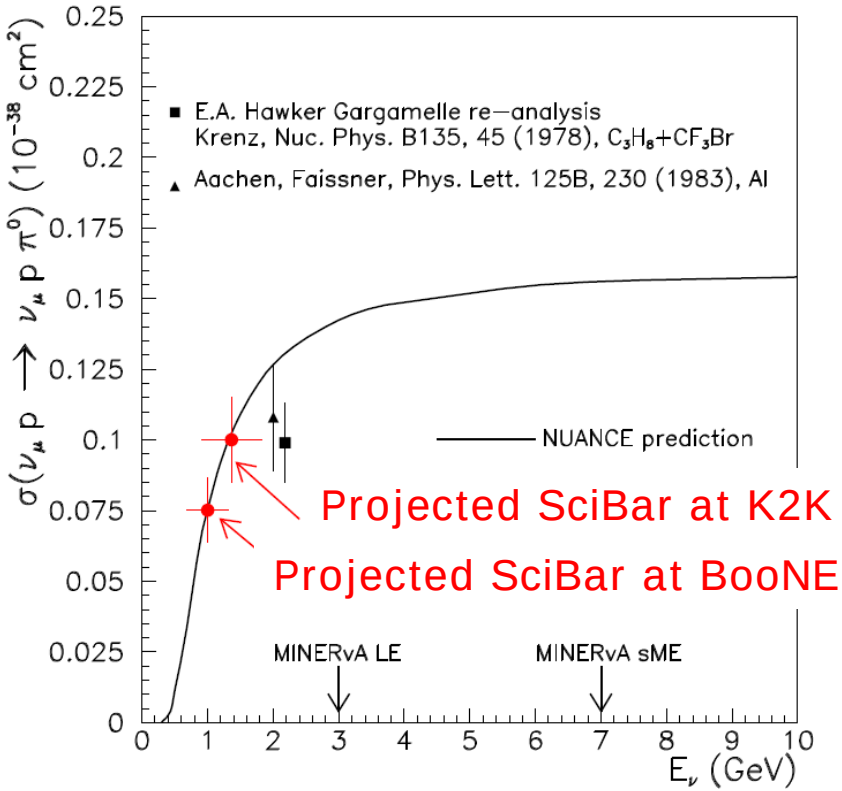


- Good efficiency for high-momentum π^0
- Reconstructed π^0 ~800events

Additional vertex activity can separate
$\nu + p \rightarrow \nu + p + \pi^0$
from
$\nu + n \rightarrow \nu + n + \pi^0$

NC-1π^0 measurement (cont'd)

$\sigma(\nu + p \rightarrow \nu + p + \pi^0)$



10% measurement can be obtained

Map out energy dependence at point where cross section turns over

Anti-neutrino run (1.5×10^{20} POT)

of interactions in FV

$\bar{\nu}_\mu$ ~40,000

ν_μ ~22,000

MRD matching sample (Pμ, θμ)

w/ vertex activity cut

1 track

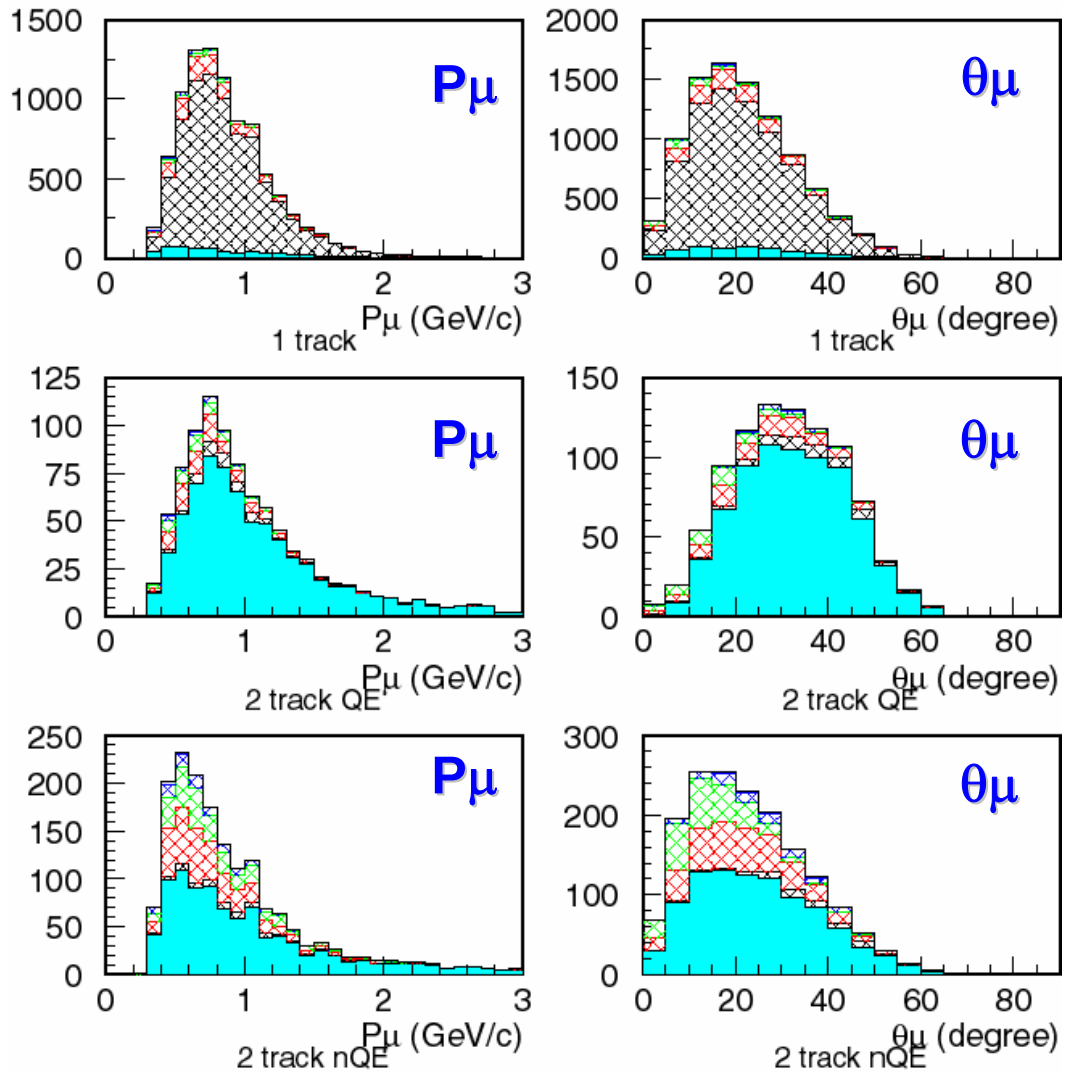
~9,300 events
QE~80%
ν_μ BG=7%

2 track QE

~910 events
ν_μ BG~80%

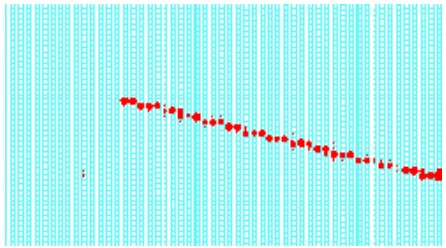
2 track non-QE

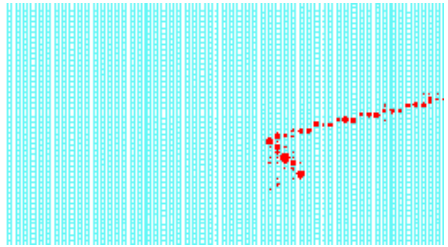
~1,700 events
ν_μ BG~56%
CC-1π~21%
CC-coh. π~15%



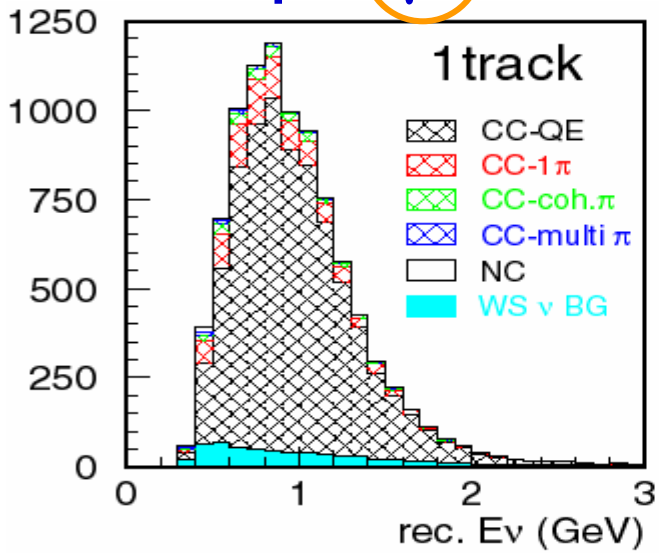
CC-QE
CC-1π
CC-coh. π
CC-multi π
ν_μ BG

Reconstructed Eν





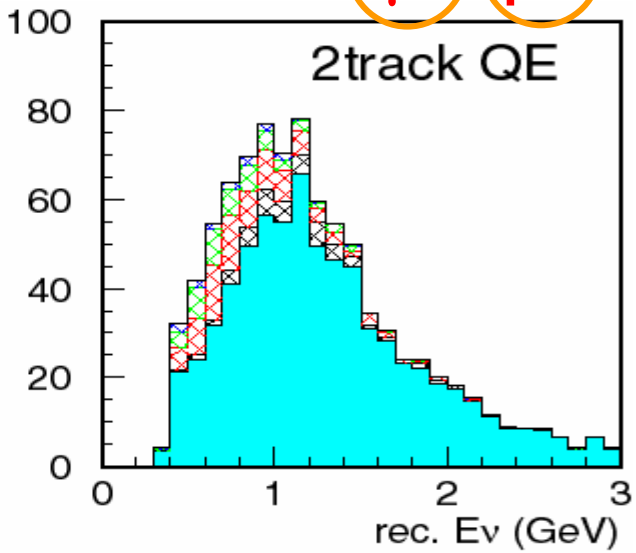
$\bar{\nu}+p \rightarrow \mu^{+}+n$



Anti-ν QE: ~80%

WS ν BG: ~7%

$\nu+n \rightarrow \mu^{-}+p$



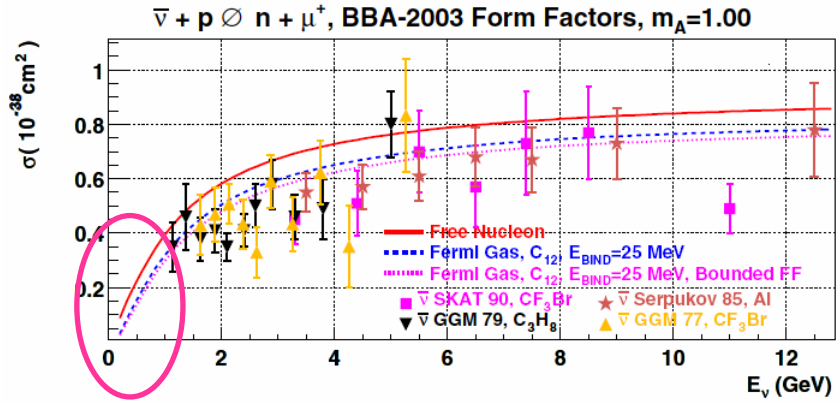
WS ν CCQE: ~80%

Can see the proton ⇒ see neutrino background in anti-ν beam

Anti-neutrino CCQE measurement

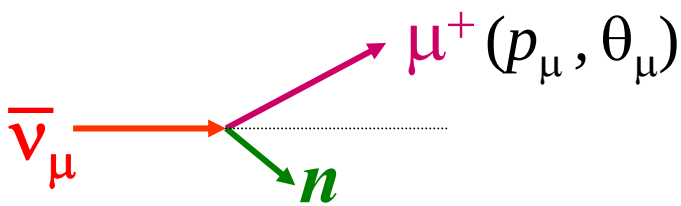
Physics motivation

- The first anti-neutrino CCQE σ measurement below 1GeV
- It is important for T2K phase-II



No data

CC-QE: $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$

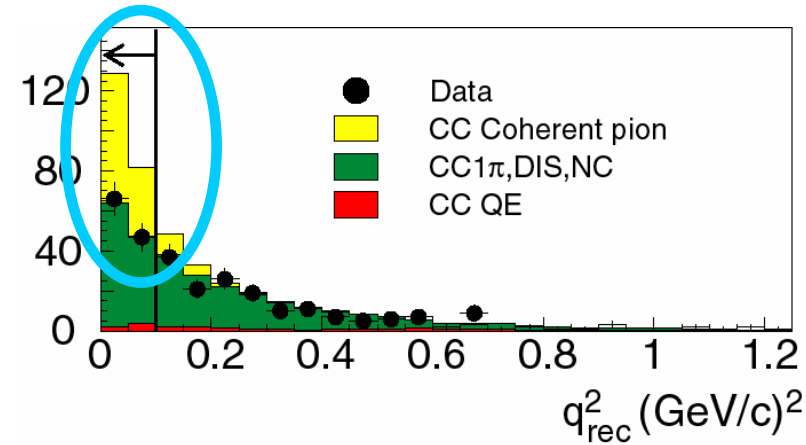


$$E_\nu^{rec} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

- **Detected as a 1-track event in SciBar**
- **Can reconstruct neutrino energy**

CC-coherent π measurement

- CC-coherent π: **ν+A→μ+A+π**



- Physics motivation
  - SciBar observed no CC-coherent π production in the K2K beam (hep-ex/0506008)

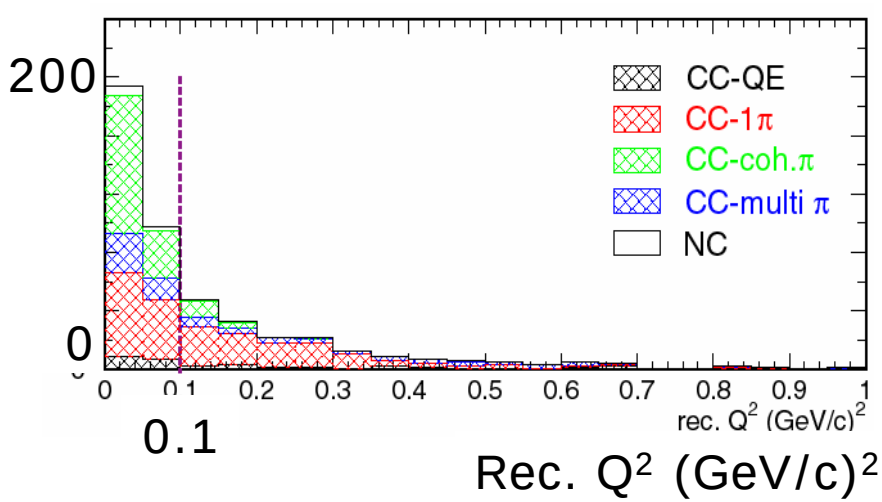
$$\frac{\sigma(CC-Coh\ \pi)}{\sigma(\nu_\mu CC)} < 0.60\times10^{-2}\ @\ 90\%CL$$

  - It will be a good check by using both neutrino and anti-neutrino beam

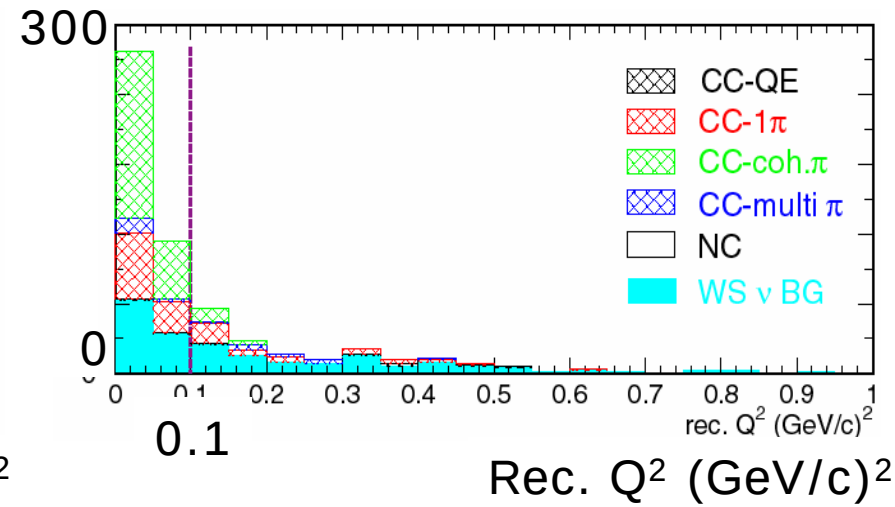
CC-coherent π measurement (cont'd)

Rec. Q^2 distribution of final sample

Neutrino Run(0.5×10^{20}POT)



Anti-neutrino Run(1.5×10^{20}POT)



#(coherent π)~160events
Efficiency = 0.11
Purity = 0.44

#(coherent π)~240events
Efficiency = 0.11
Purity = 0.49

We can measure in both neutrino and anti-neutrino beam

9. Schedule

- Independent of this proposal, we will disassemble the SciBar detector soon.
  - November 2005:
    - Dismount the PMT, FEB, and WLS fibers.
  - Some time between December 2005 and February 2006:
    - Uninstall the scintillator modules.
- For shipping SciBar to FNAL, it may take ~2 months.
  - Once the detector arrives here, we can install it within two months including commissioning time (see page 5).

So, the schedule depends on when the experimental hall is excavated.

Supplement

SciBar Cost

- The total cost of SciBar detector:

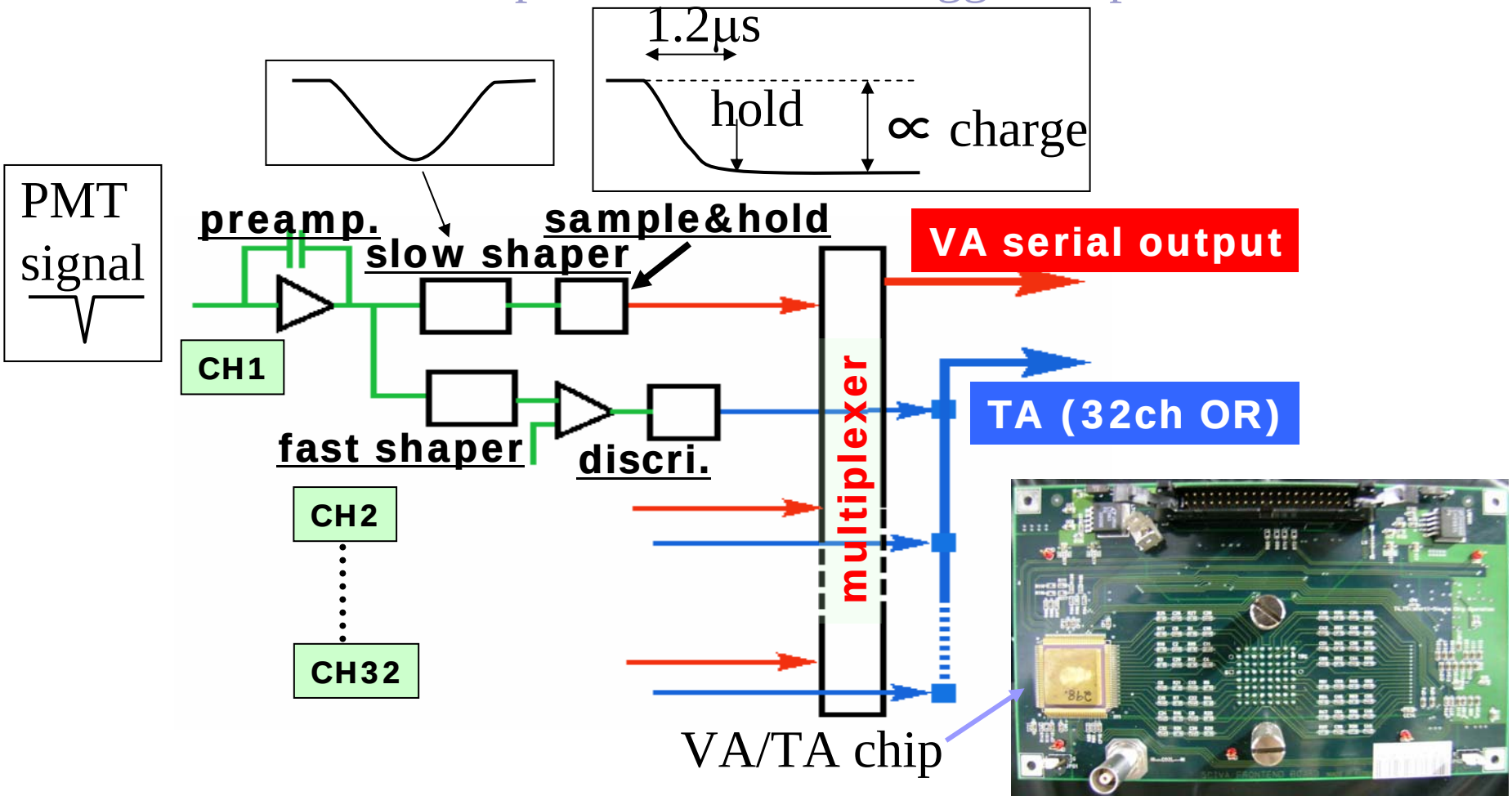
~$2M just for materials and equipments without including labor cost and contingency.

(In US $ counting, it will be ~$3M).

- Scintillator: $300k
- WLS fiber: $250k
- MA-PMT: $450k
- Front-End electroncis: $350k
- Back-End electronics: $250k
- Detector structure, Air-conditioner and Dark Room.: $200k

Readout Electronics

- VA/TA chip (Analog ASIC)
  - 32 inputs → shaping → sample & hold → serial analog output → comparator → OR → trigger output



Data Taking modes

	beam		pedestal		LED		Cosmic ray
0.6s	35μs		100ns, 1take		1μs,1take		Suppression mode

Read out : ~100ms/event

Data

ADC for all channels

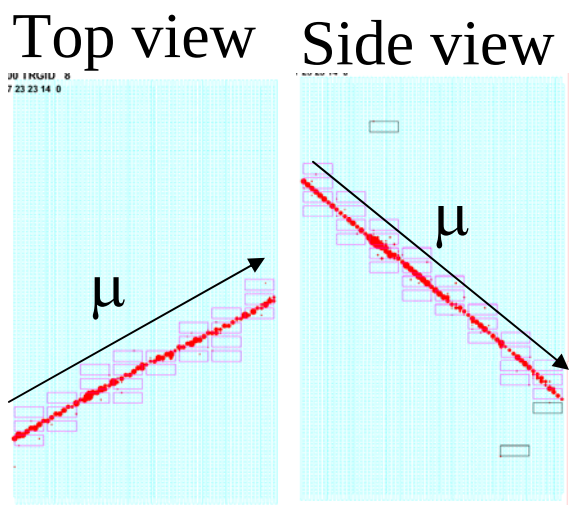
TDC for all TA's -> each 32channel -> 2 TDC for each PMT

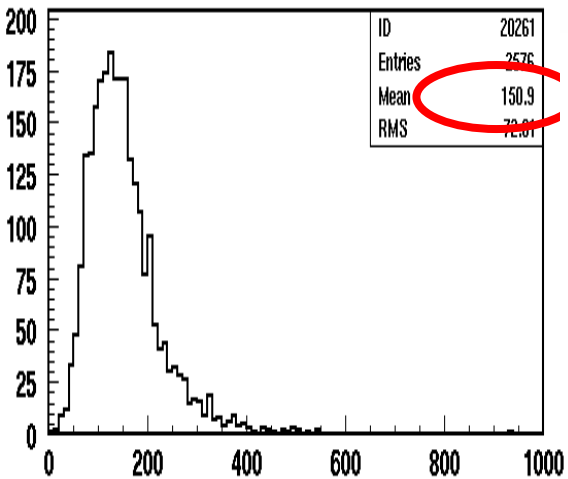
Suppression mode : ADC only for TA hit channel

For EC, ADC for all channels, no TDC

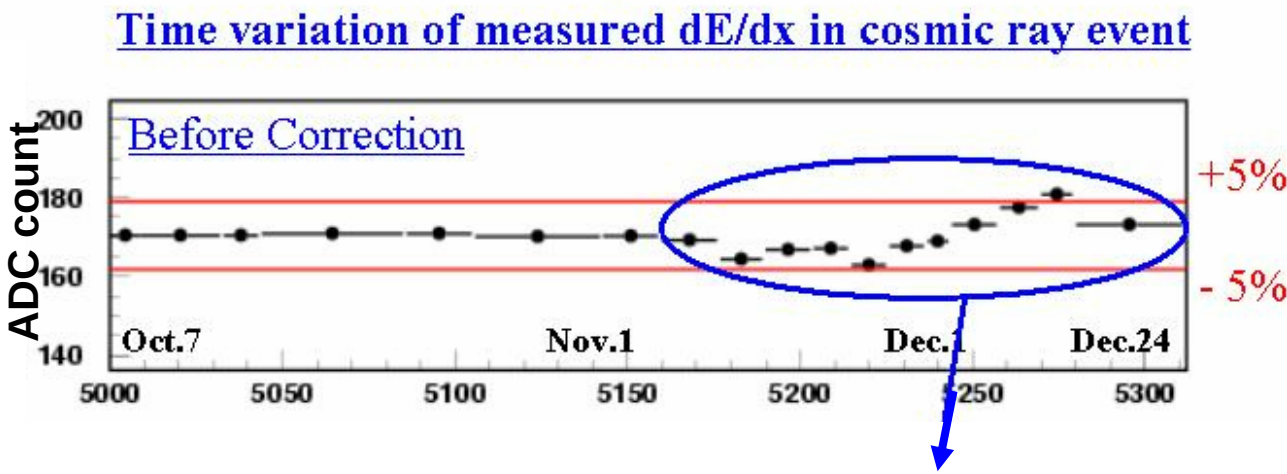
Cosmic Ray Data

- We use penetrating cosmic-ray muon as a (strip to strip) relative energy calibration source.
- Mean ~ 140 count (design value)
- response is very stable





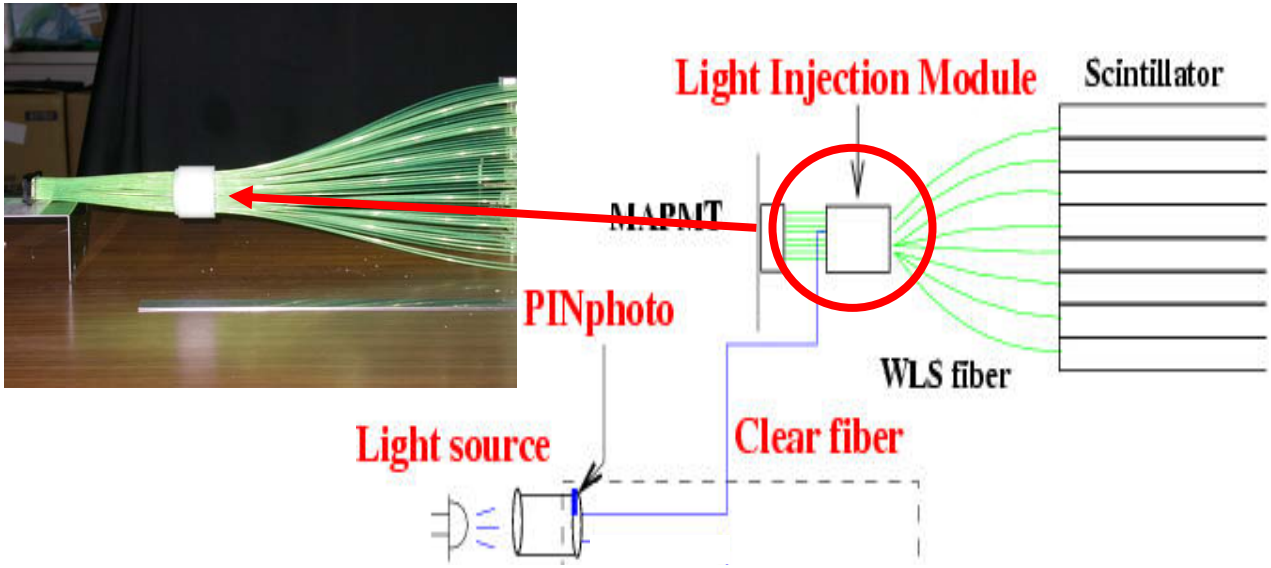
Typical ADC distribution



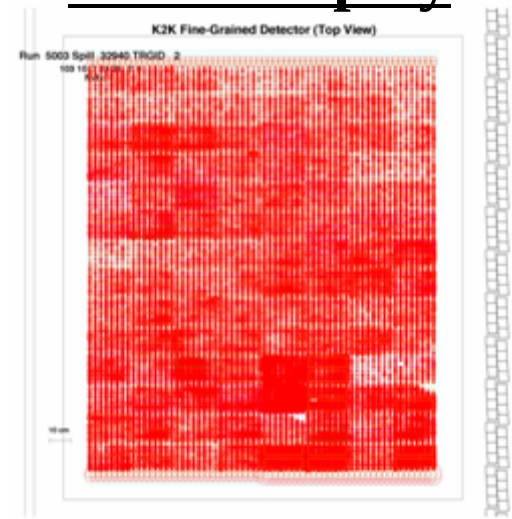
This fluctuation come from PMT Gain variation

Gain Monitor (1)

High Accuracy gain monitoring SystEm (HASE moni)

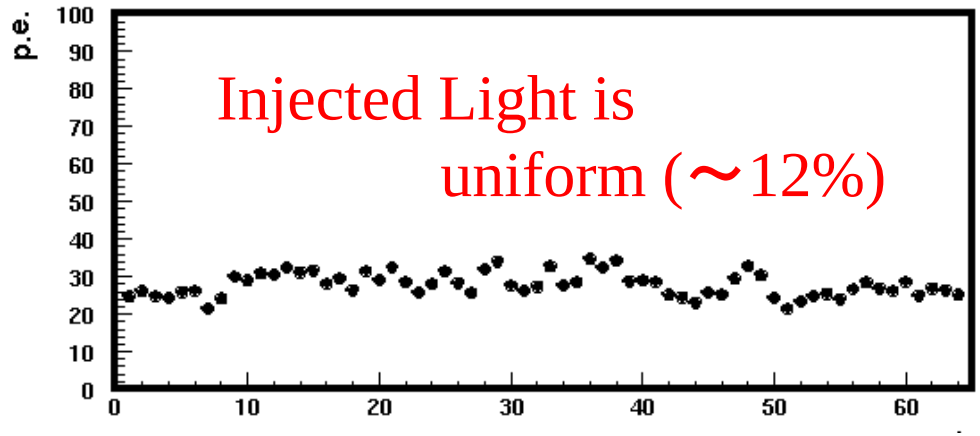


Event Display



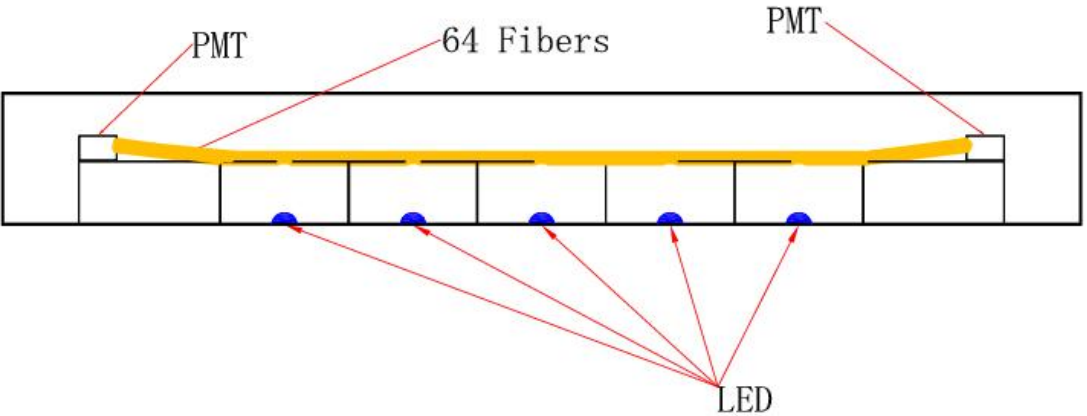
Feature

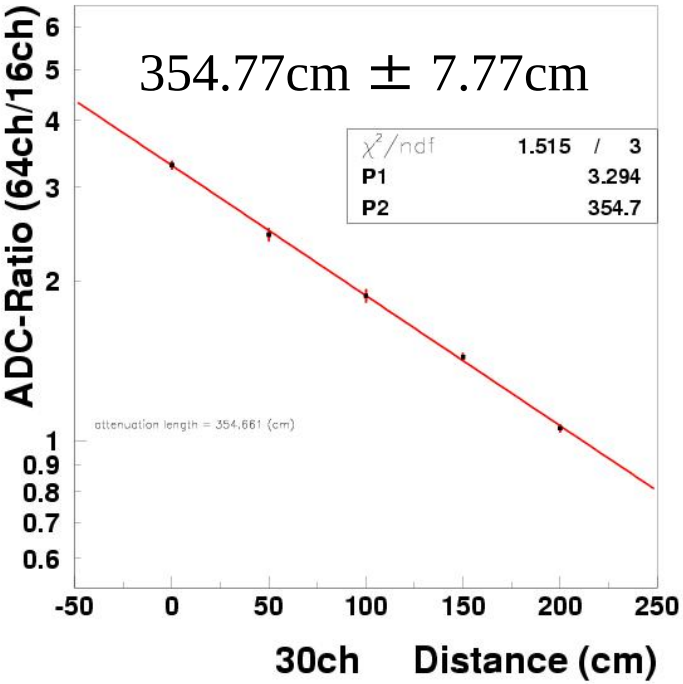
- Monitoring all channels at once with only 4 LEDs.
- Very uniform light (No PMT saturation)

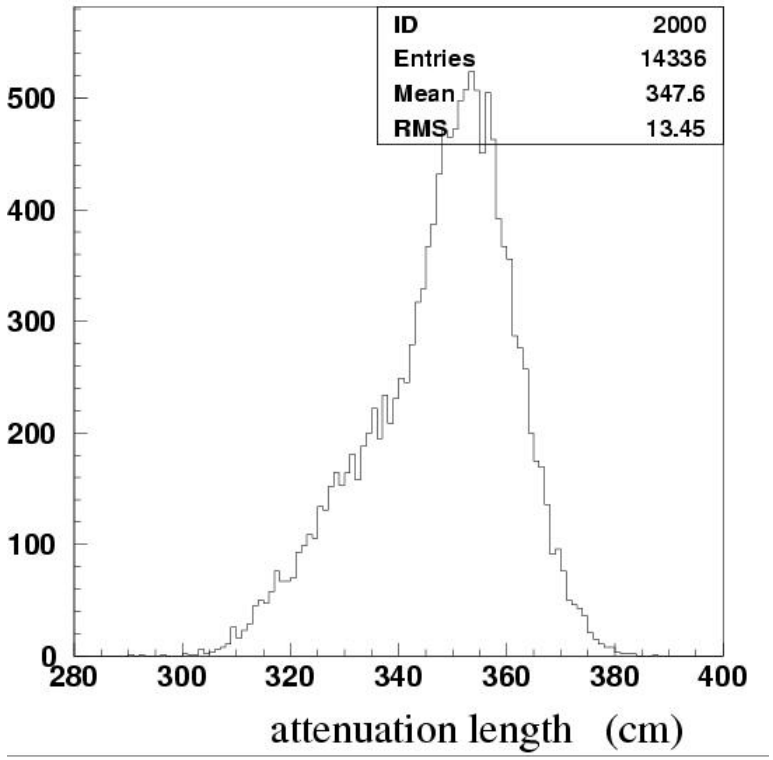


Fiber Attenuation

Semi-Auto Attenuation Measurement System





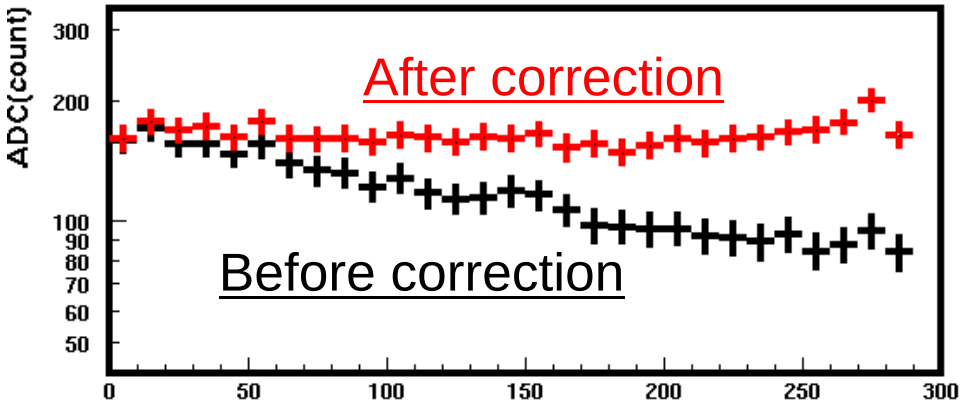


- We measured all(~15,000) Fiber's attenuation length before installation within 2% precision. → We can correct the attenuation effect ~1.4% precision.

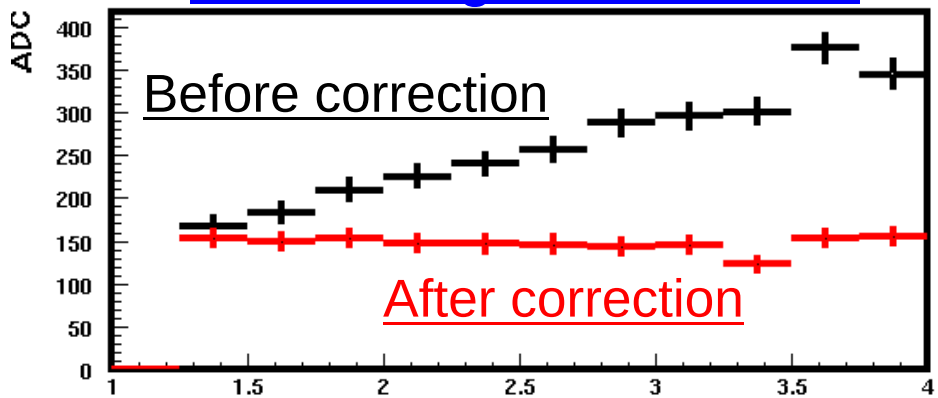
Energy Calibration

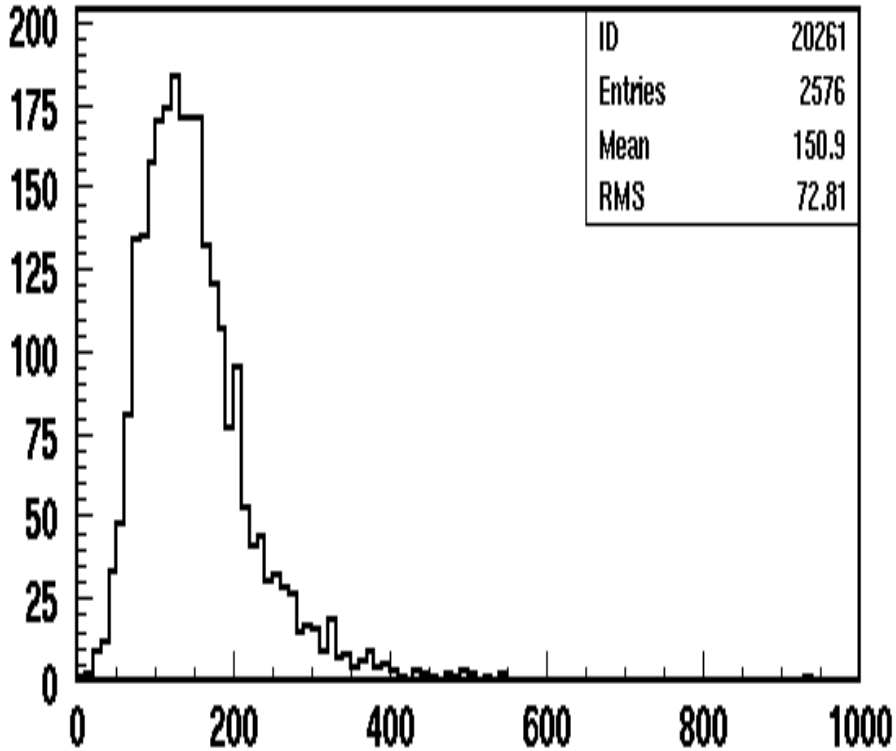
- Use Cosmic Ray Muon for strip to strip relative energy scale calibration
- All samples can be used by correction of Attenuation and Pass length in strip (100 Hits/strip/hour → Less than 1% precision can be possible for 5days)

Attenuation Correction

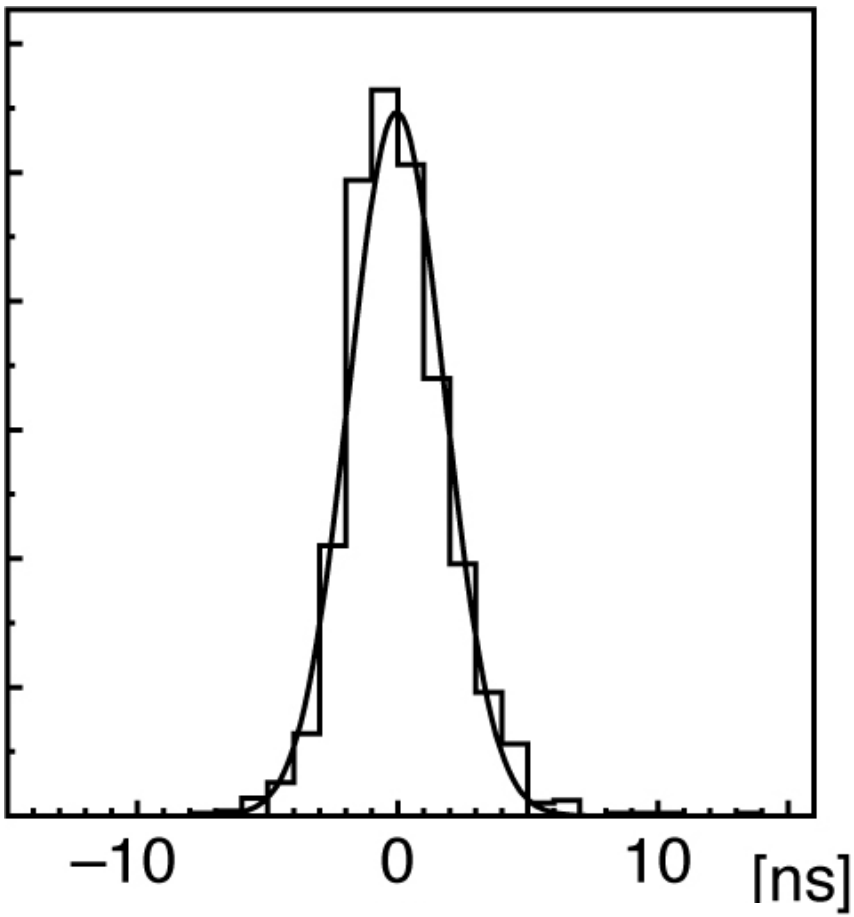


Pass Length Correction



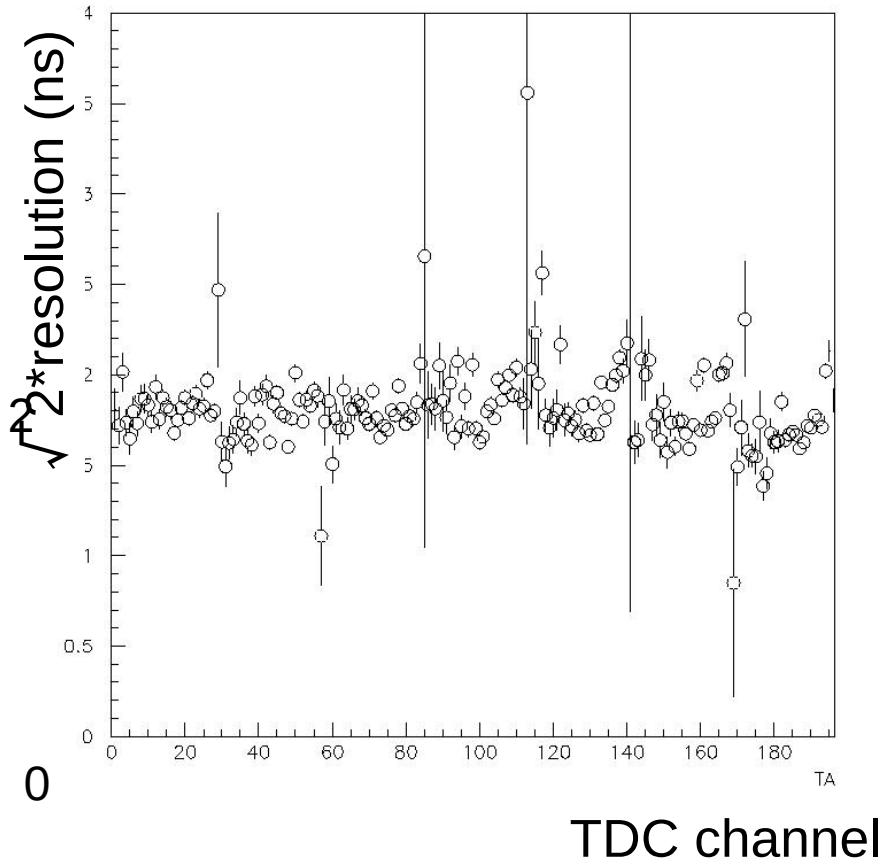


Timing Resolution



Difference of timing between
two TDC channels
In cosmic ray event

Timing resolution: 1.34ns



Expected Performance

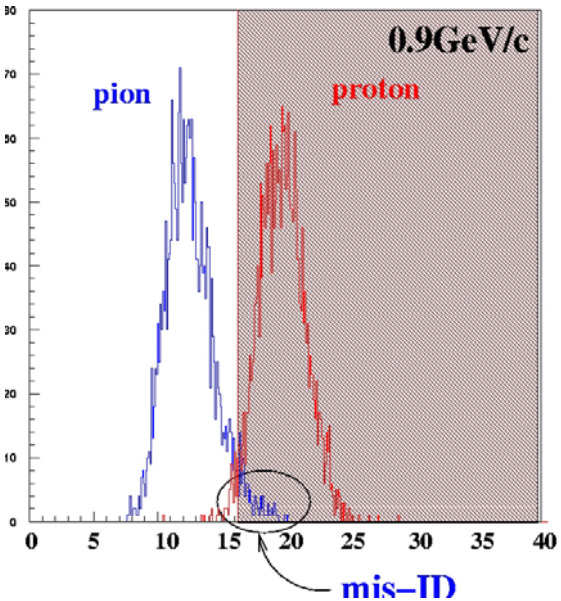
- PID (p/π)
- Momentum reconstruction

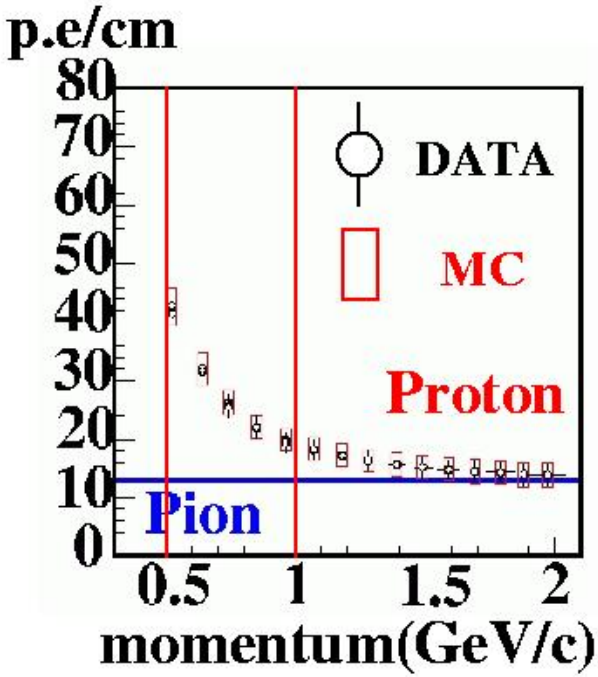
Using dE/dx Info.

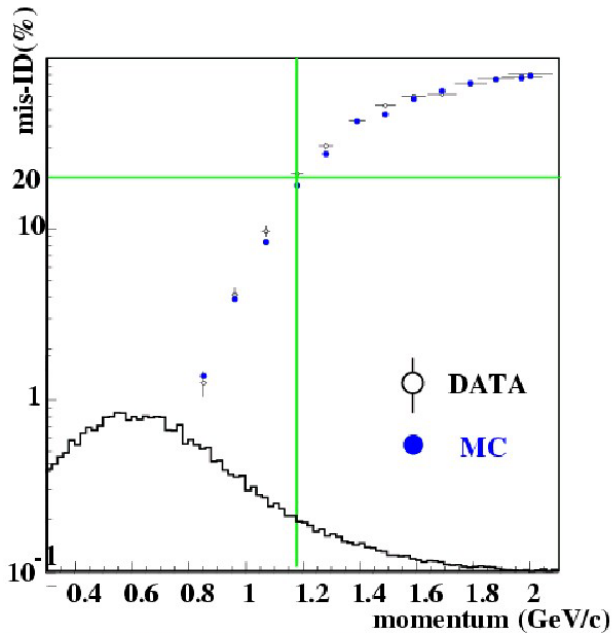
Result from Beamtest 2001 (only using 10cm dE/dx info)

p/π missID probability : ~ 1% (@ 0.8GeV/c) @ P_eff=95%

Momentum (for proton) : less than 10% (below 1.0GeV/c)

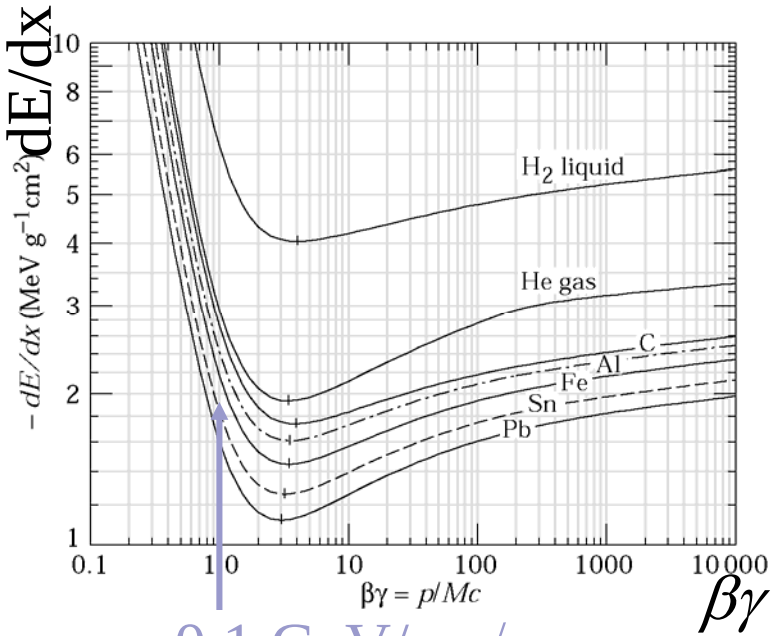






High Efficiency in finding/identifying low energy CCQE events

Particle ID (Results From Beam Test)



~ 0.1 GeV/c π/μ

~ 1.0 GeV/c proton

Miss ID probability :

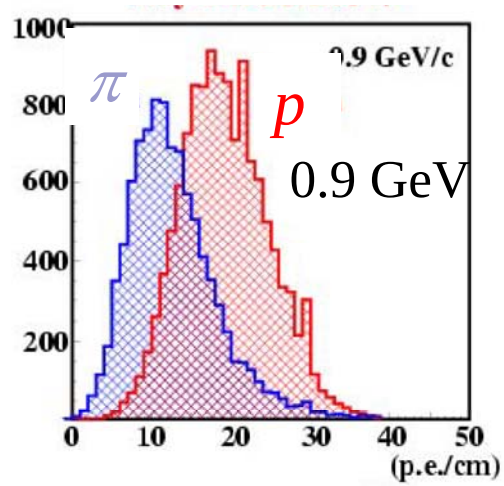
< 20 % (1.2 GeV/c proton)

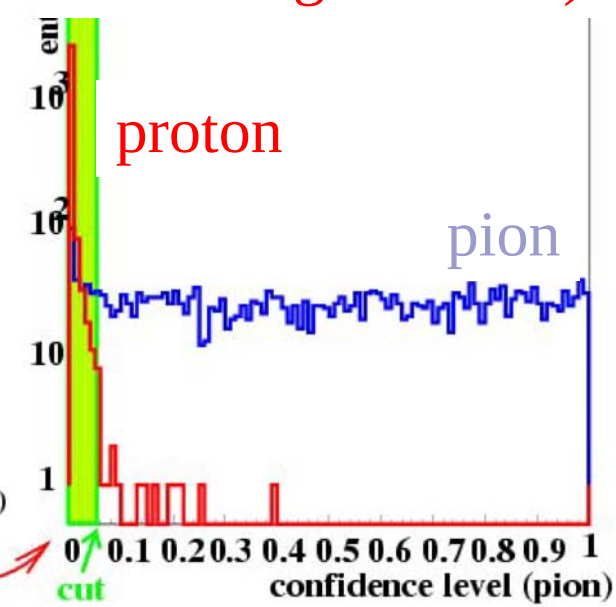
< 5 % (< 1.0 GeV/c proton)

With 95 % proton efficiency

Pion confidence level (using only 10 hits along the track)

1 cell ADC





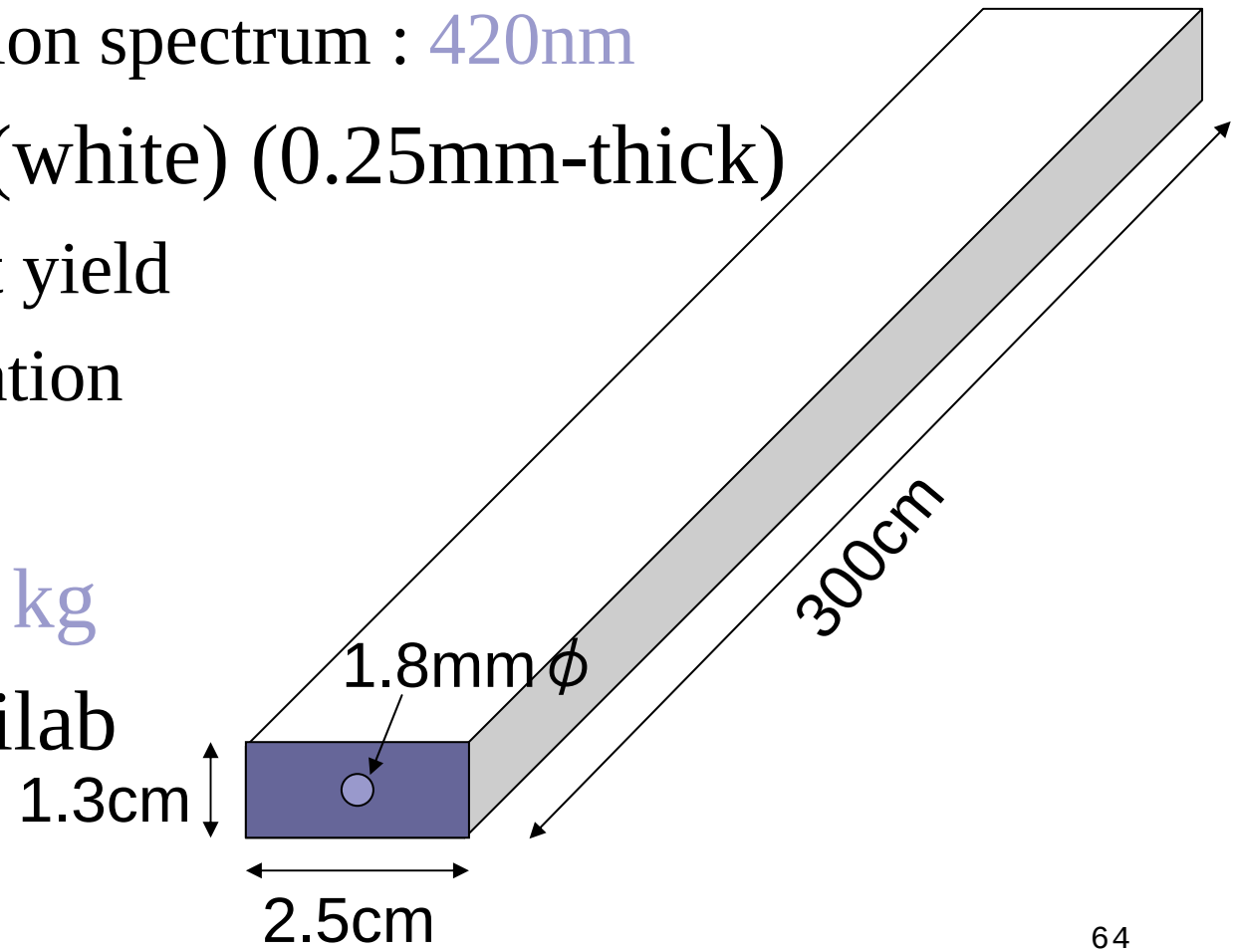
- dE/dx

proton > π/μ

(~1GeV/c)

Extruded Scintillator

- Polystylene with PPO 1% and POPOP 0.3%
  - Usual plastic scintillator component
  - Peak of emission spectrum : 420nm
- TiO_2 reflector (white) (0.25mm-thick)
  - Increases light yield
  - Optically isolation
  - Extruded
- Cheap : ~$20 / kg
- Made by Fermilab

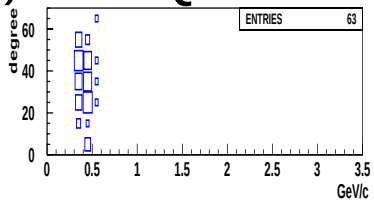


$$\chi^2 = \chi^2_{1kt} + \chi^2_{SciFi} + \chi^2_{SciBar} + \chi^2_{PIMON}$$

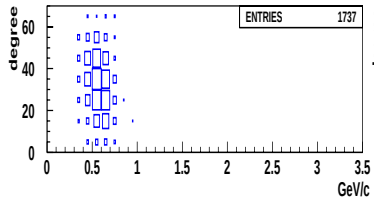
MC templates (SciBar 1-track)

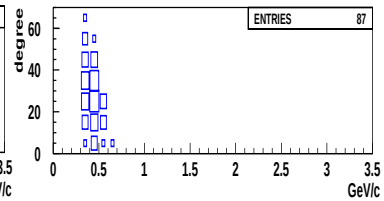
E_ν (GeV) QE nonQE

0.0–0.5

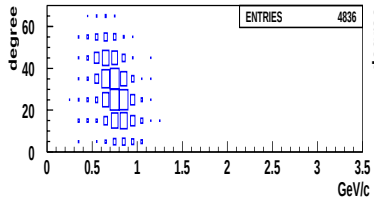


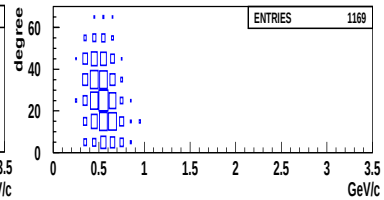
0.5–0.75



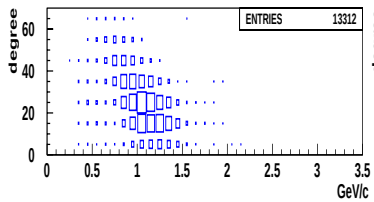


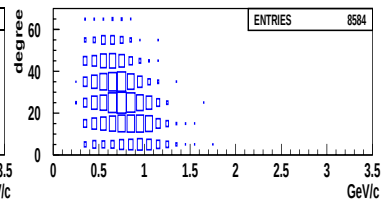
0.75–1.0





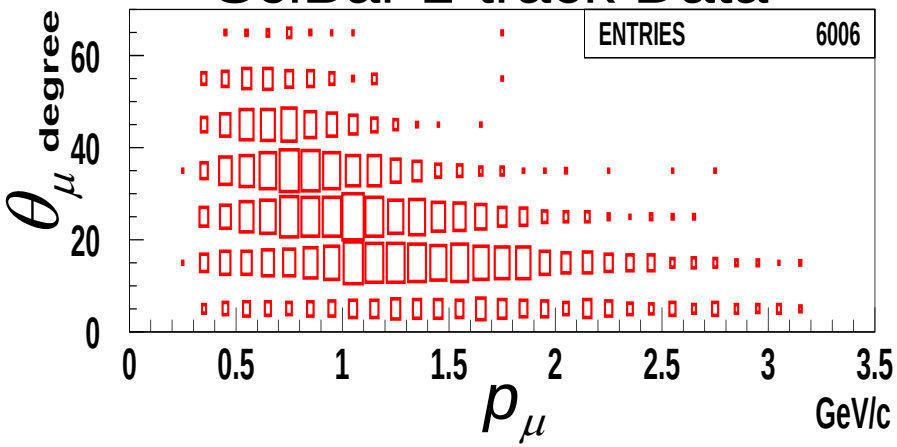
1.0–1.5



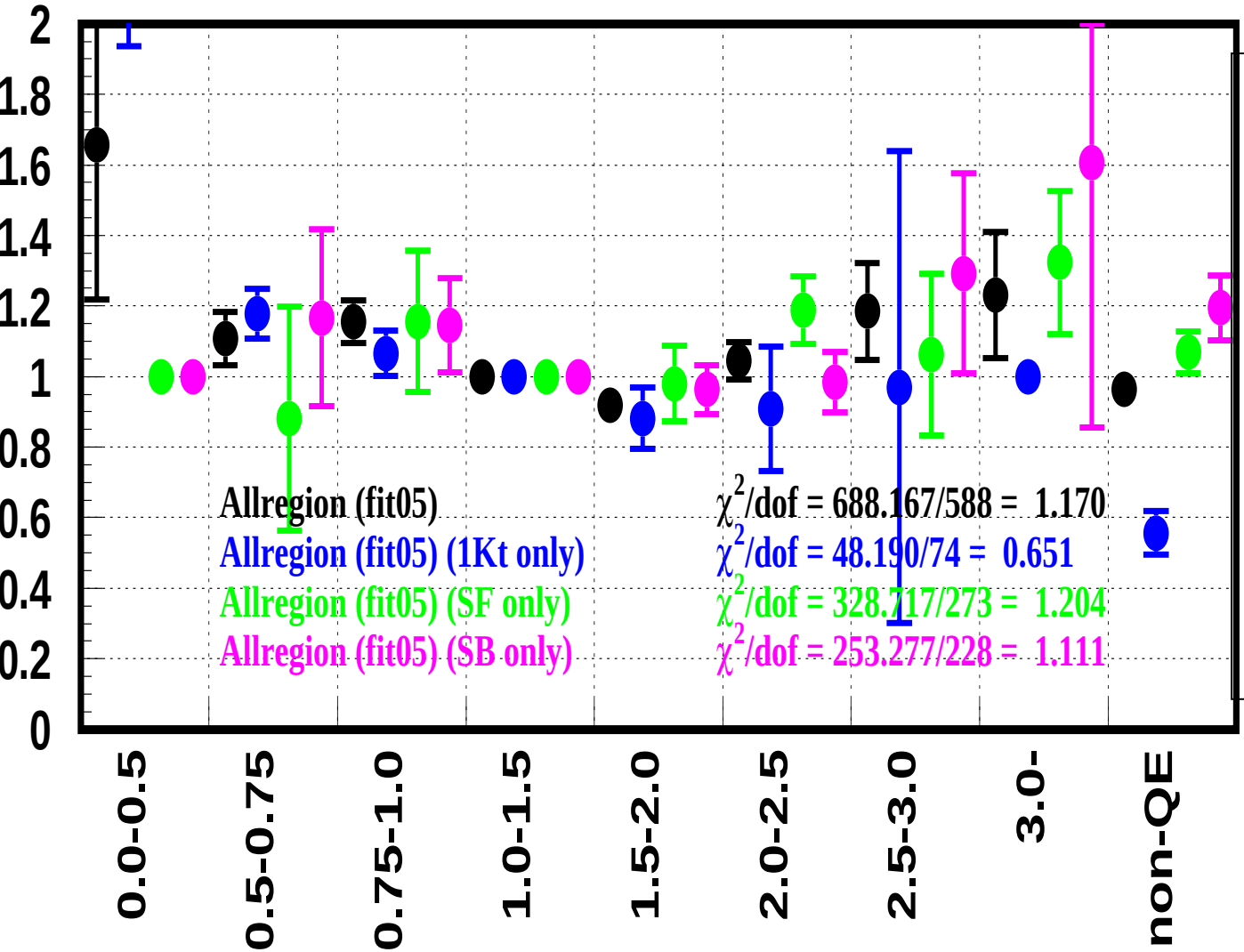


⋮ ⋮ ⋮

SciBar 1-track Data



Merged Fit result



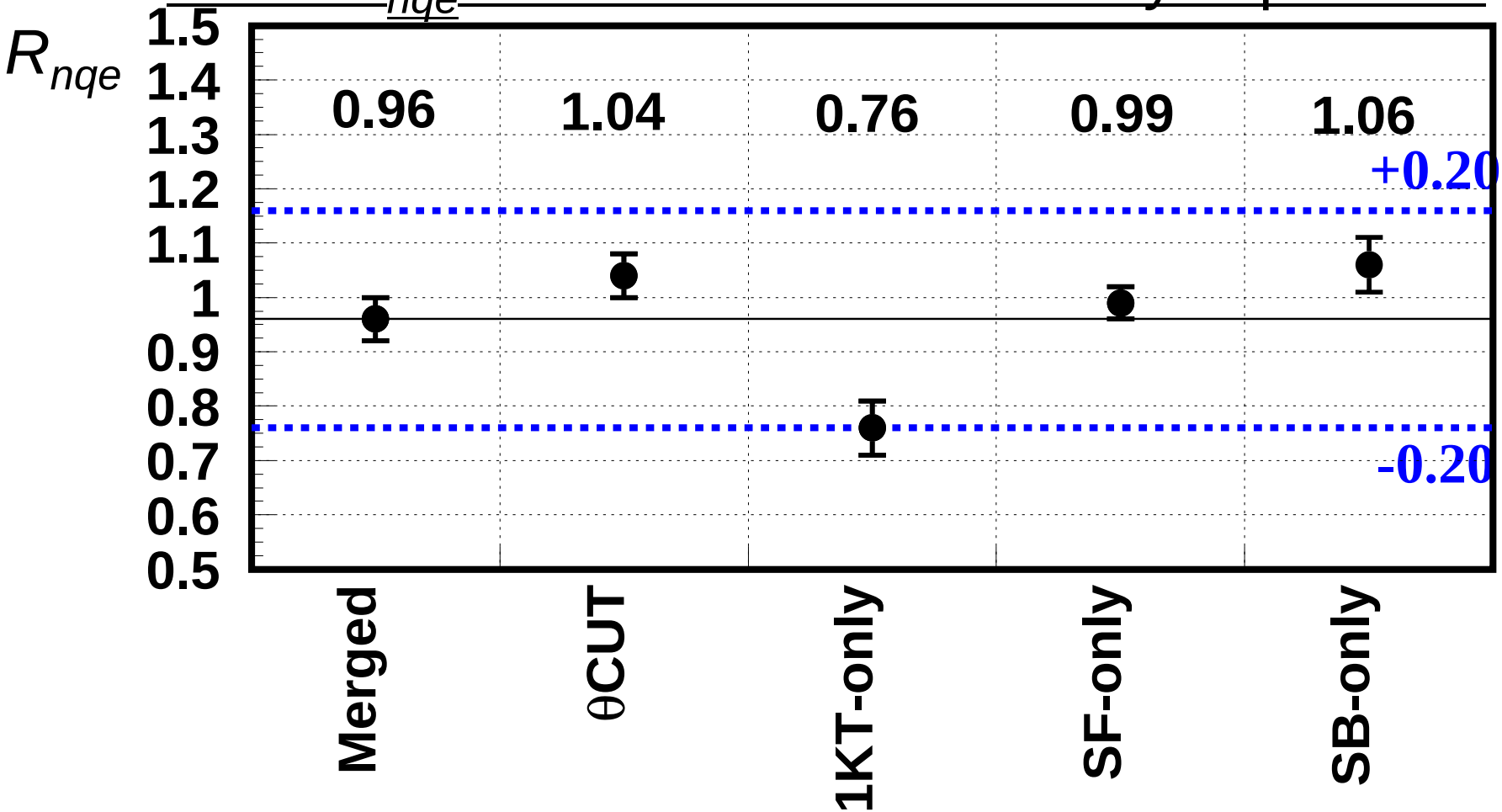
Merged
χ^2/dof = 688.2/588
= 1.170
1kt part
χ^2/nbins = 85.6/80
SciFi part
χ^2/nbins = 336.3/286
SciBar part
χ^2/nbins = 265.5/239
PIMON part
χ^2/nbins = 0.8/3

Fitted flux is consistent both Merged and each FD result.

Fit05(Allregion) Fit05(1Kt_only) Fit05(SF_only) Fit05(SB_only)

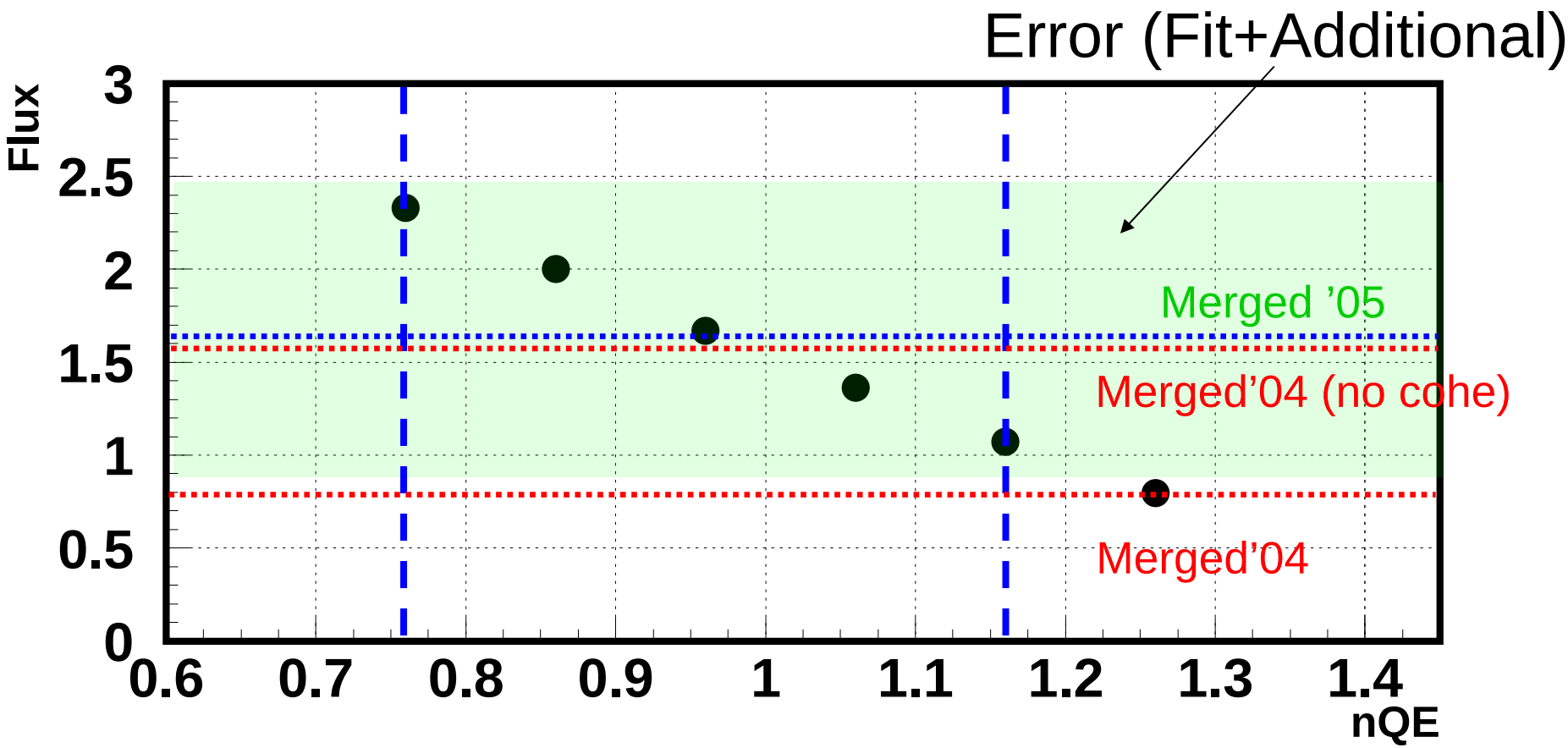
R_{nqe} error

Fitted R_{nqe} value w/ fixed flux and syst. params.



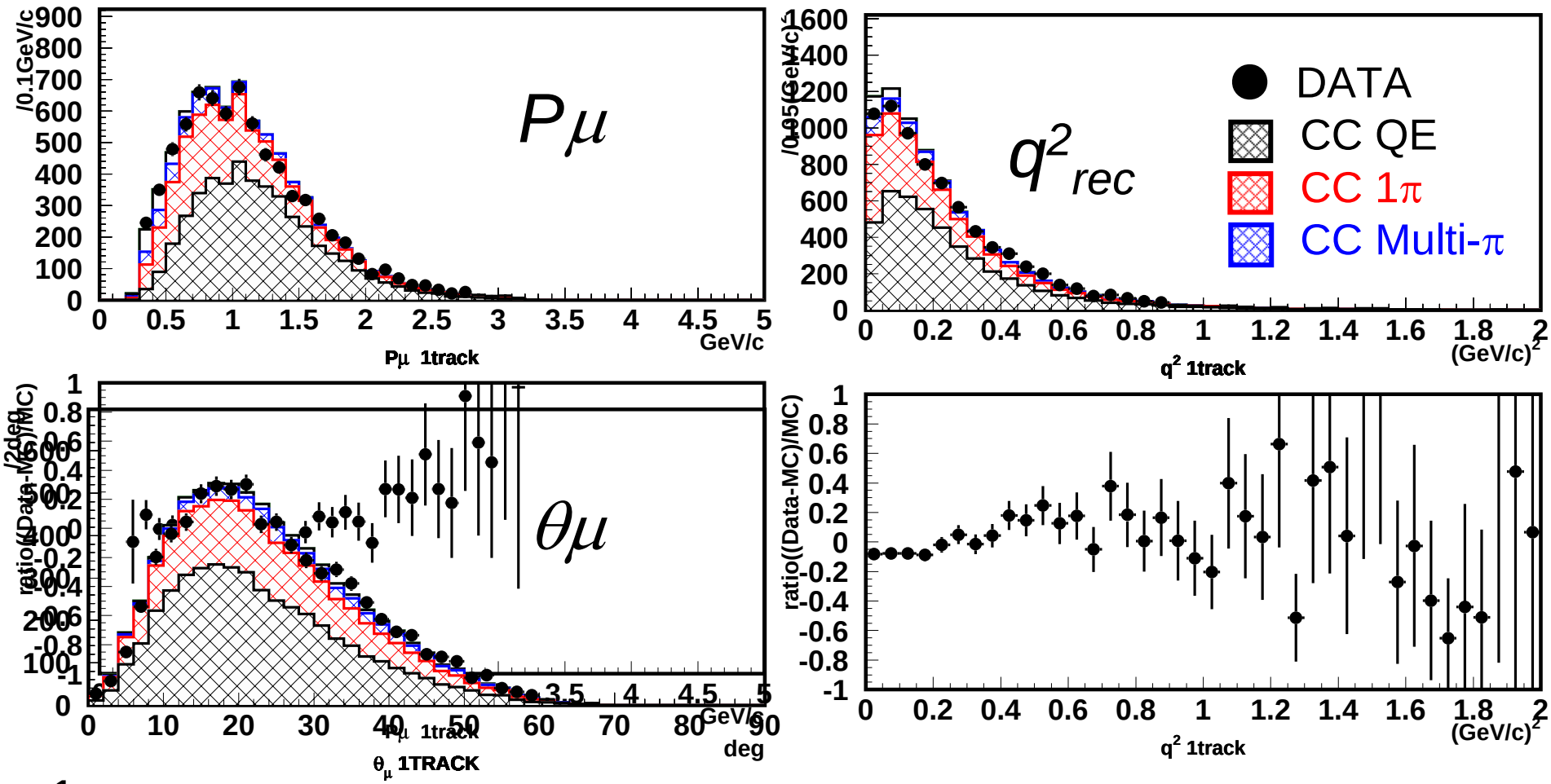
- 1KT/SF/SB show different R_{nqe} values systematically.
- To cover this difference, we quote '±0.20' on the fitting error additionally.

0.0-0.5GeV bin



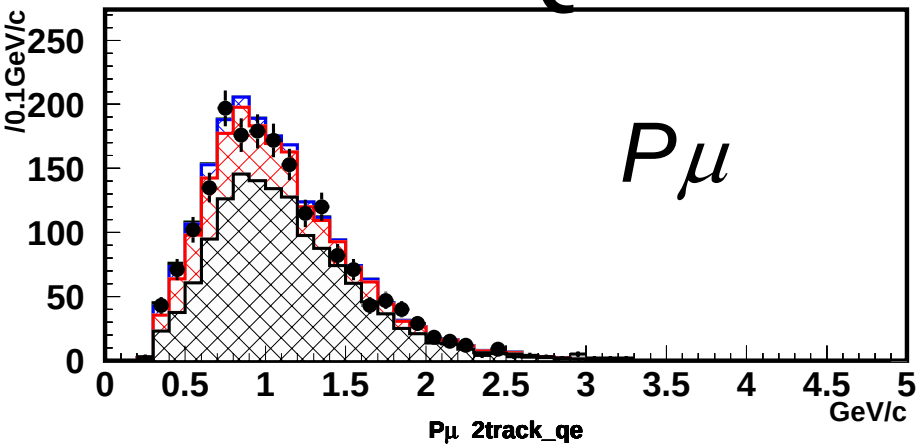
- The previous data returns consistent value when CC coherent pion is removed.
- Additional nonQE error almost covers the discrepancy between '04 result and '05 result.

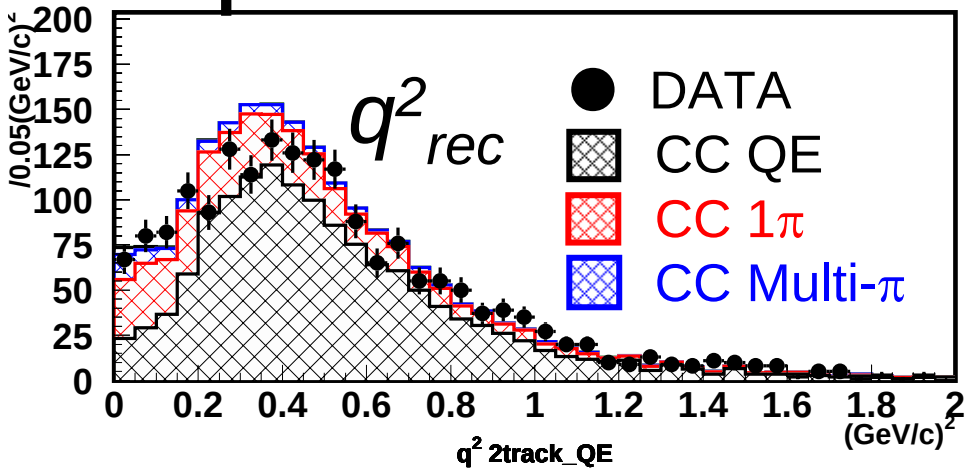
1 Track sample (before fitting)

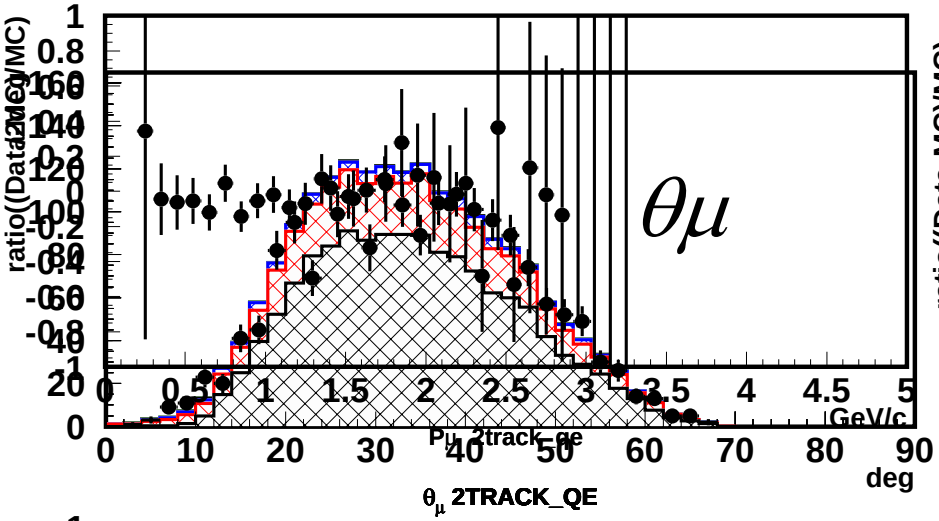


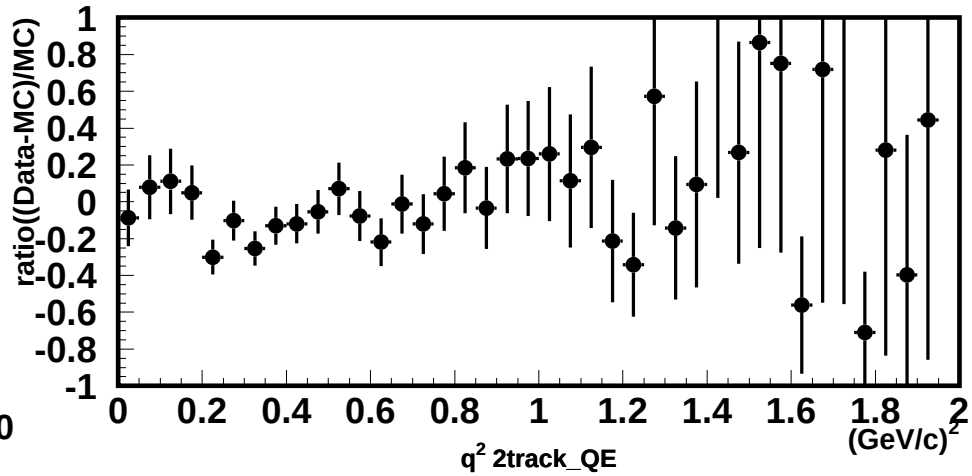
Clear low-q2 deficit is not seen.

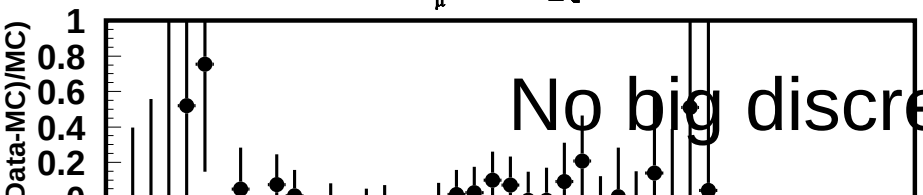
2 track QE-like sample





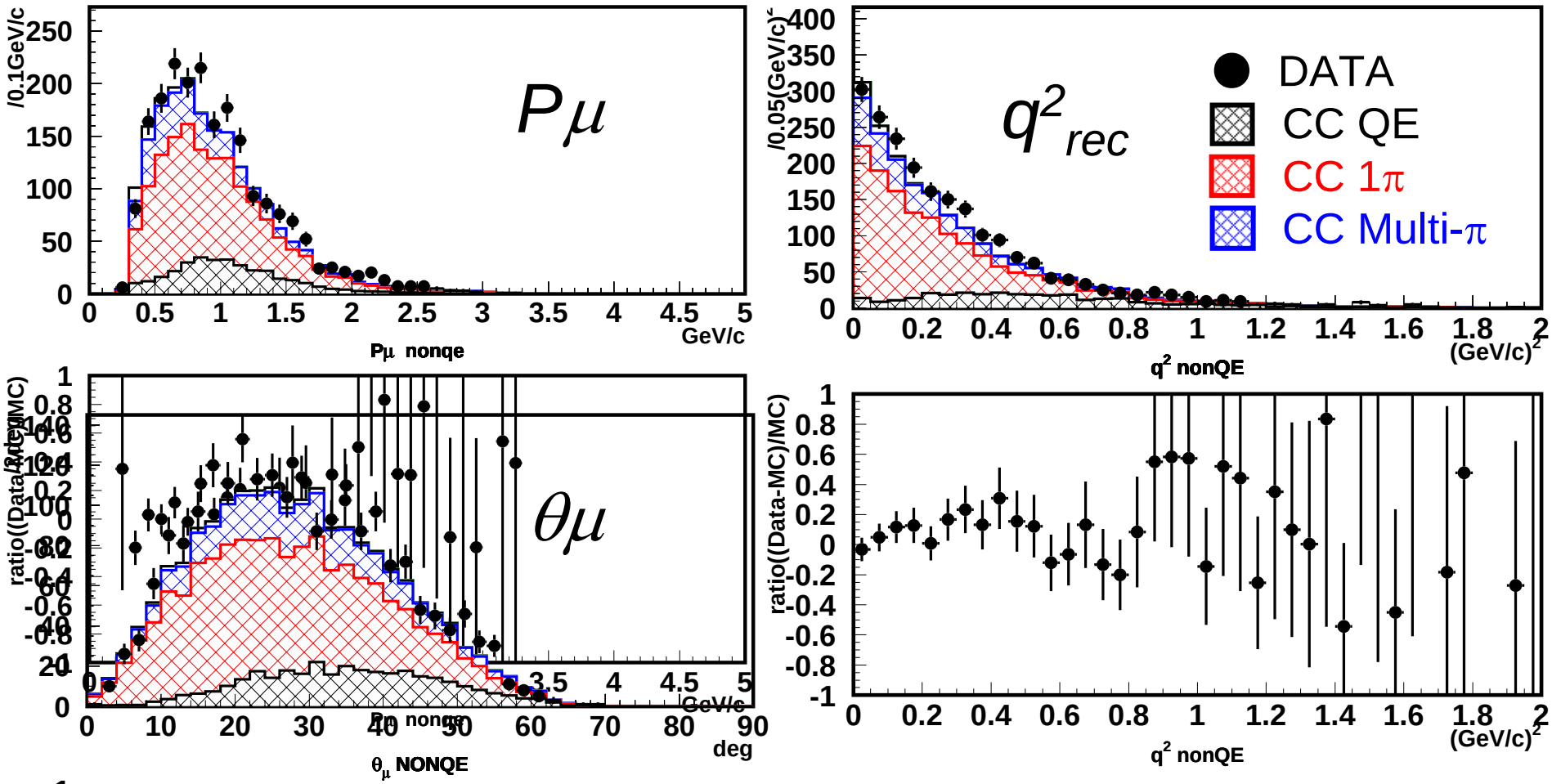






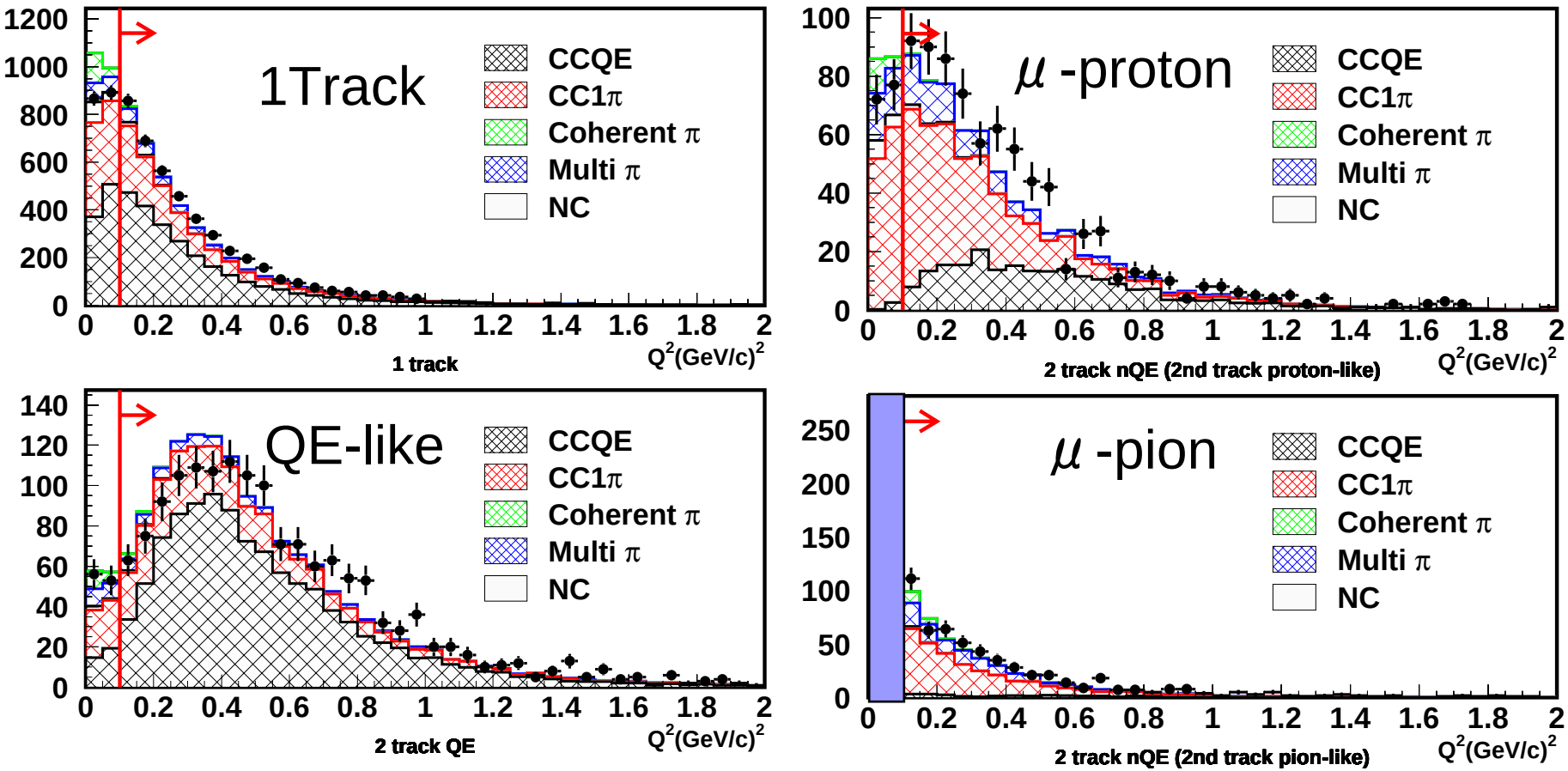
No big discrepancy is found.

2 Track nonQE-like sample



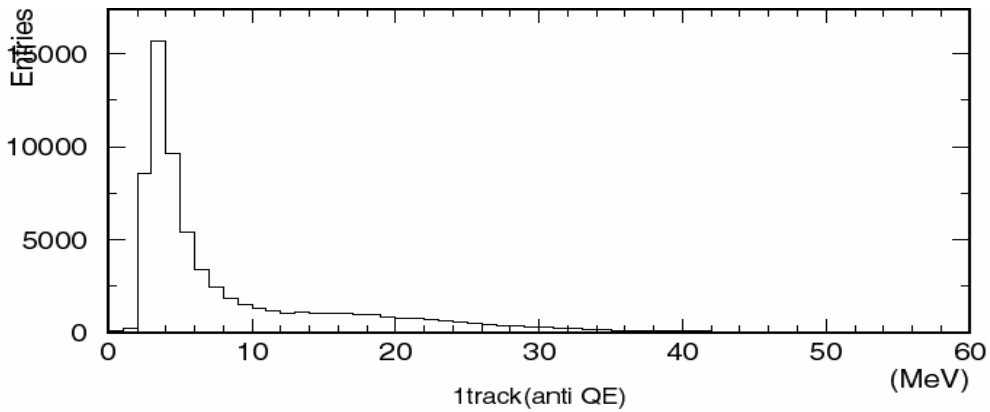
No big discrepancy is found.

q^2 distribution (Before FIT)



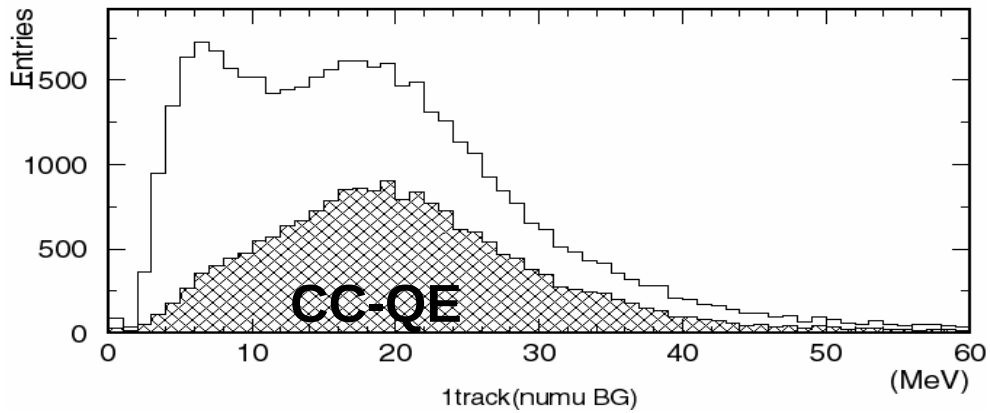
Vertex activity (1track sample)

1track sample
(anti-ν CCQE)



Rec. vertexから
半径10cm以内の
Hitのうち、最大の
Energy deposit

1track sample
(WS ν BG)



10MeV以上をカットする