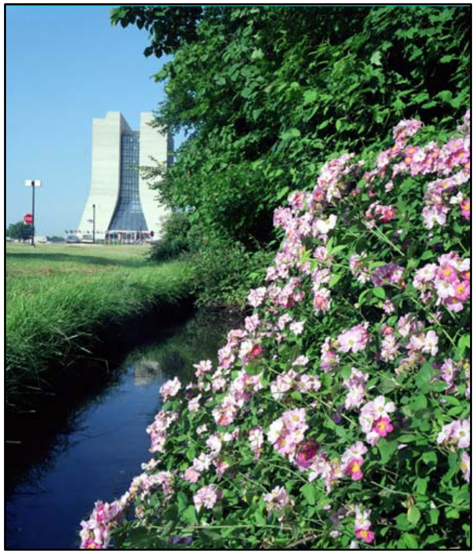
Neutral pion cross section measurement at K2K

C. Mariani (INFN Roma and University of Rome “La Sapienza”)
for the K2K collaboration



K2K collaboration

JAPAN: **High Energy Accelerator Research Organization (KEK) / Institute for Cosmic Ray Research (ICRR), Univ. of Tokyo / Kobe University / Kyoto University / Niigata University / Okayama University / Tokyo University of Science / Tohoku University**

KOREA: **Chonnam National University / Dongshin University / Korea University / Seoul National University**

U.S.A.: **Boston University / University of California, Irvine / University of Hawaii, Manoa / Massachusetts Institute of Technology / State University of New York at Stony Brook / University of Washington at Seattle**

POLAND: **Warsaw University / Solton Institute**

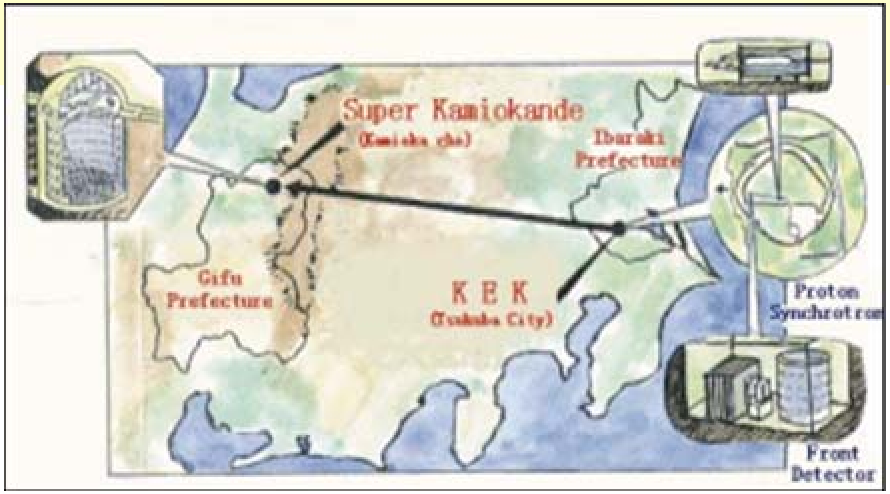
Since 2002

JAPAN: **Hiroshima University / Osaka University** **U.S.A.:** **Duke University**

CANADA: **TRIUMF / University of British Columbia**

ITALY: **Rome** **FRANCE:** **Saclay** **SPAIN:** **Barcelona / Valencia** **SWITZERLAND:** **Geneva**

RUSSIA: **INR-Moscow**



Outline

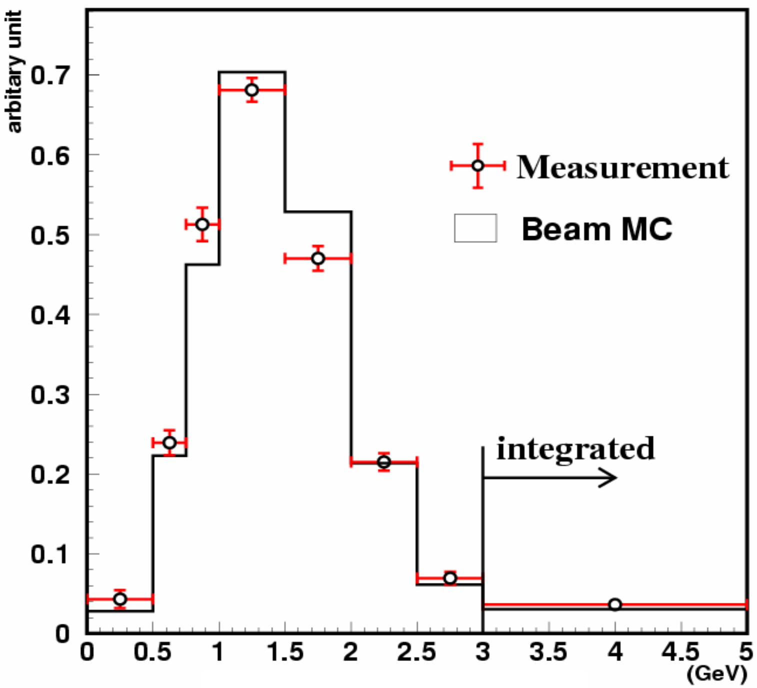
- K2K experiment:
  - neutrino beam;
  - near detectors;
  - MC of neutrino interaction;
- NC single π^o measurement (PRL B619, 255 (2005)):
  - Selection criteria of NC exclusive π^0 events and data/MC comparison;
  - Relative cross section measurement;
- CC inclusive π^0 measurement (PRD in preparation):
  - Inclusive signal definition;
  - Experimental signature;
  - Description of the normalization sample;
  - Description of the selection of photons in SB+EC;
  - π^o reconstruction;
  - Likelihood fit description and result;
  - Systematic error evaluation;
  - Cross-section measurement;
  - Comparison with others experiment.

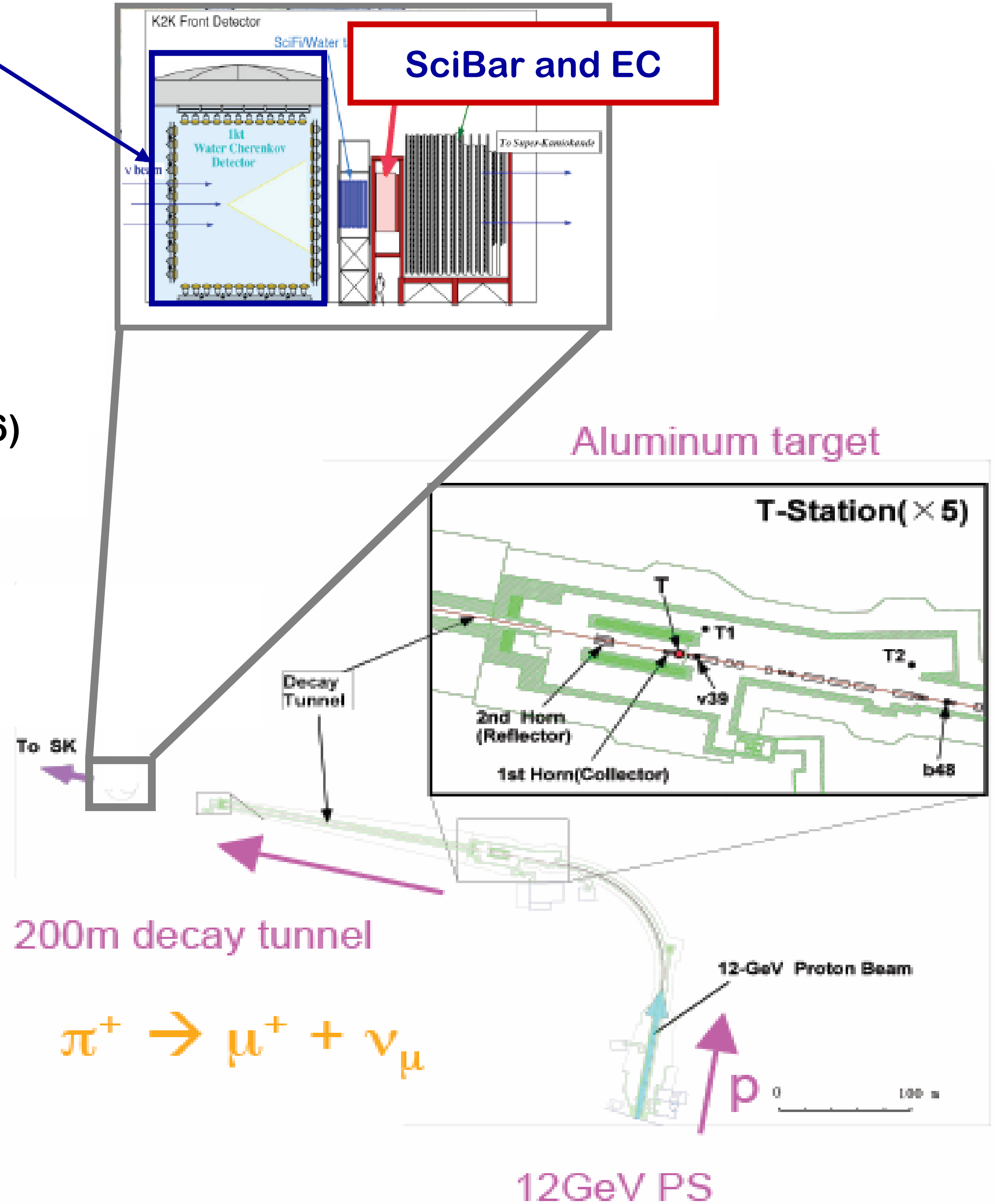
K2K neutrino beam

- almost pure ν_μ beam (~98%);
- ν_e contamination =(1.6±0.5)%

(PRL 96:181801, 2006)

- E_ν ~ 1.3 GeV;

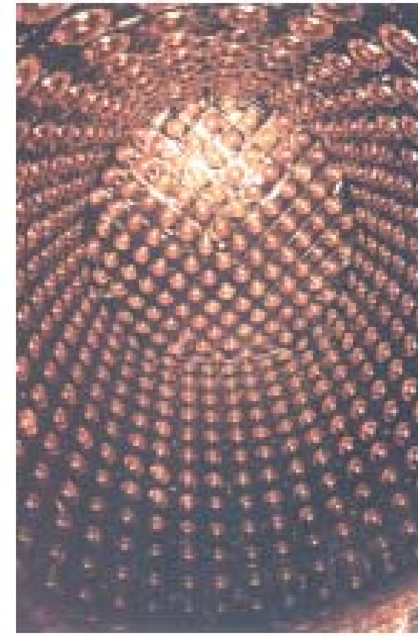


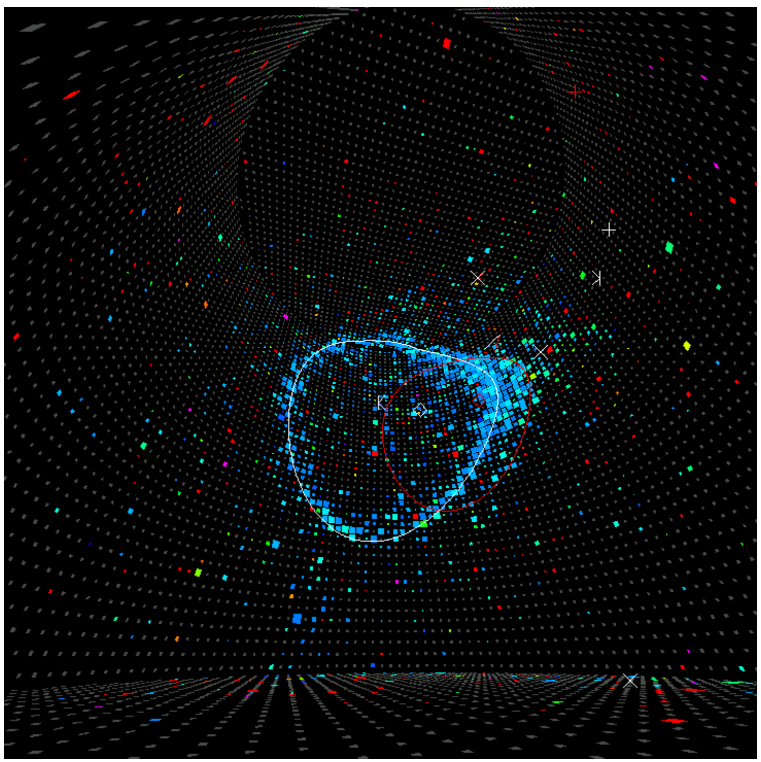


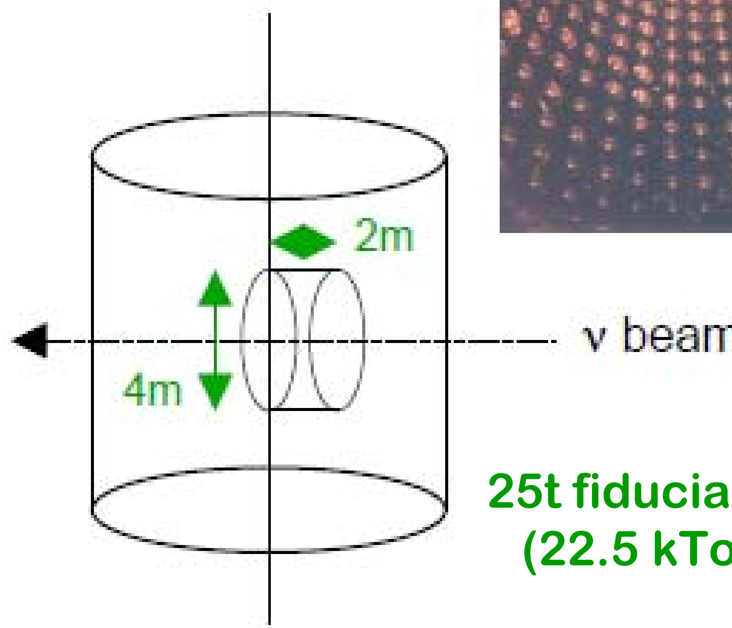
$\pi^+ \rightarrow \mu^+ + \nu_\mu$

1kTon detector

- 1000t cylindrical water tank
- a smaller version of Super-Kamiokande (~1/50 volume)
- 680 20inch PMTs with 70cm spacing (same as SK)
- the same detection mechanism, analysis algorithms and interaction MC as SK



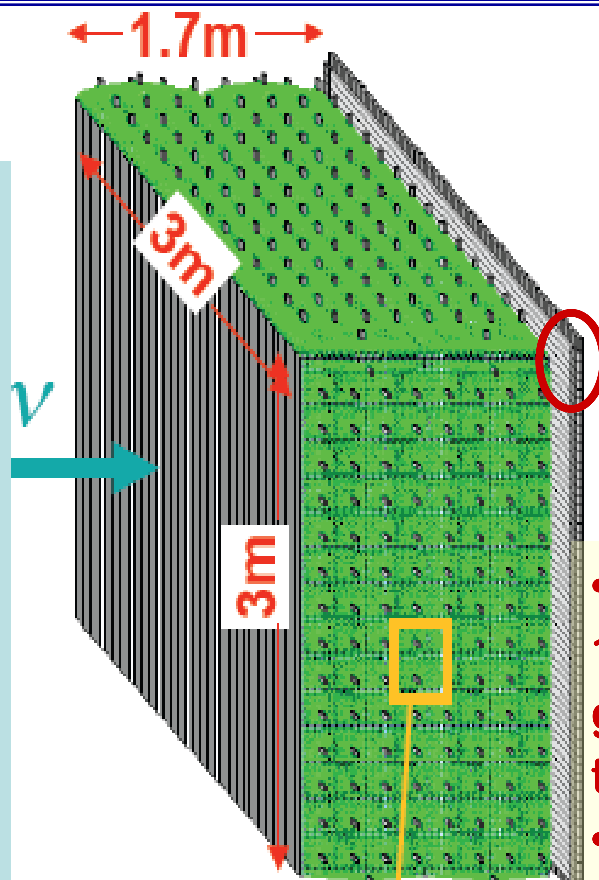


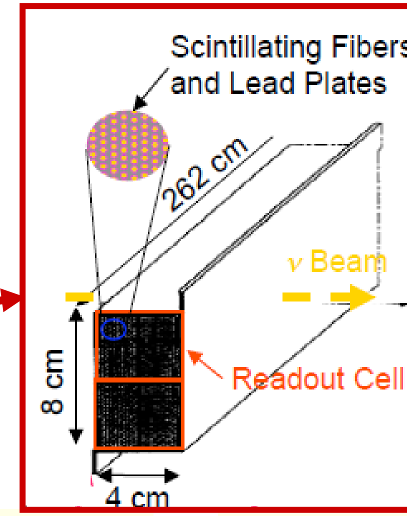


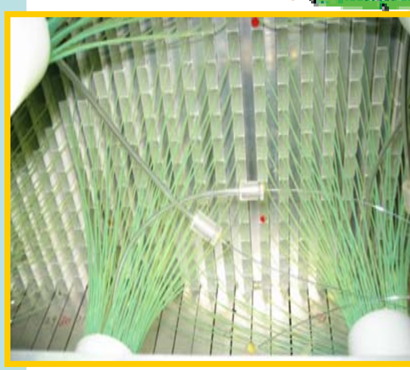
25t fiducial volume (22.5 kTons SK)

SciBar and EC

- Extruded scintillator bars with WLS fiber readout;
- Neutrino target is the scintillator itself;
- Volume: 3 x 3 x 1.7 m^3 (~16 tons);
- 2.5 x 1.3 x 300 cm^3 cell;
- ~15.000 channels;
- Light yield ~ 10p.e./MeV;
- Detect tracks down to 8cm;
- Distinguish protons from pions by using dE/dx;
- Wrong ID < 5% (<1GeV/c proton);
- High efficiency for CCQE 2-track;





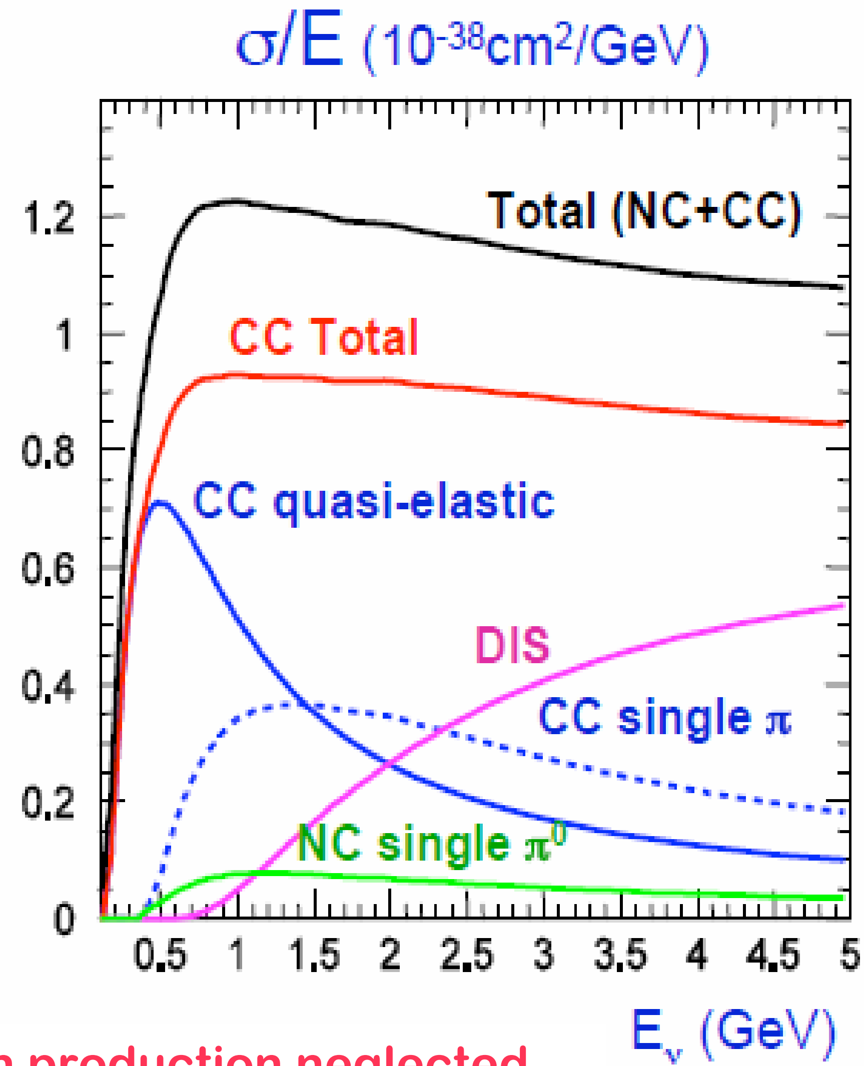


- Spaghetti calorimeter: 1mm scintillating fibers in grooves of lead foils 1mm thick;
- 4x4 cm^2 cell readout from both ends;
- 2 planes ($11X_0$):
  - Hor: 30 modules;
  - Ver: 32 modules;
- Energy resolution=13%/√E

K2K neutrino interaction MC

- CC quasi elastic (CCQE: ~40% of all CC)
  - Smith and Moniz with M_A=1.1GeV
- CC single π (resonance production) (~38% of all CC)
  - Rein & Sehgal's with M_A=1.1GeV
- DIS (~18% of all CC)
  - GRV94 + JETSET with Bodek and Yang correction at low q^2.
- CC coherent π (2~3% in all CC)
  - Rein & Sehgal model based on PCAC.
- NC

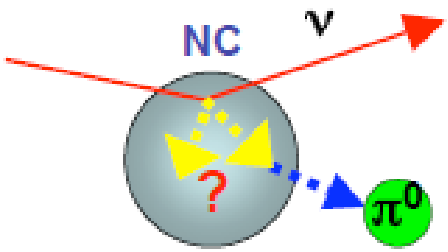
+ Nuclear Effects



CC Coherent pion production neglected according to the SciBar measurement (Hasegawa et al. PRL 95:252301, 2005)

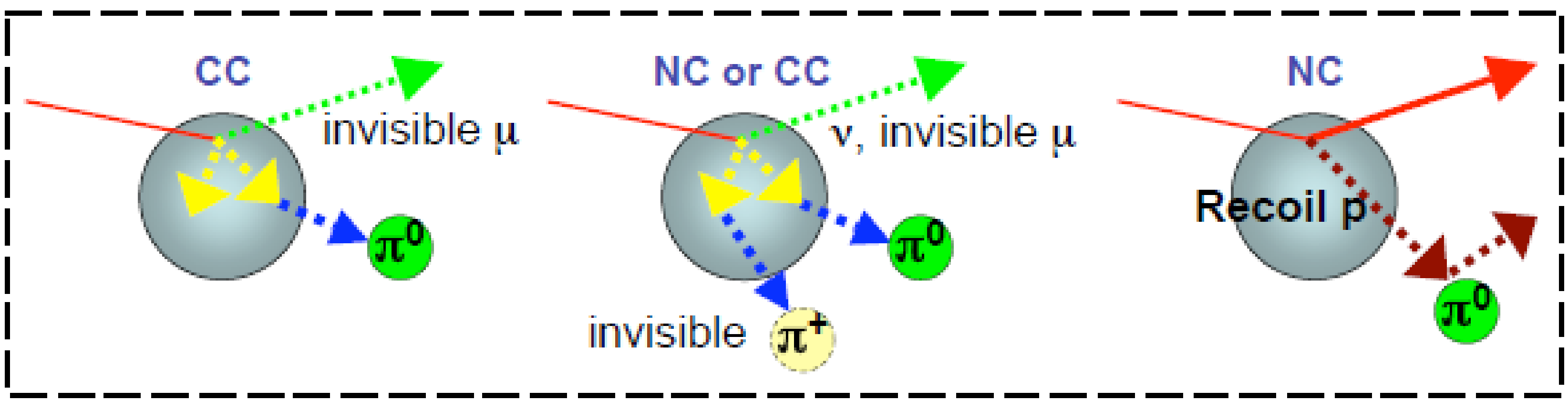
NC 1 π^0 measurement

NC 1π^0 definition



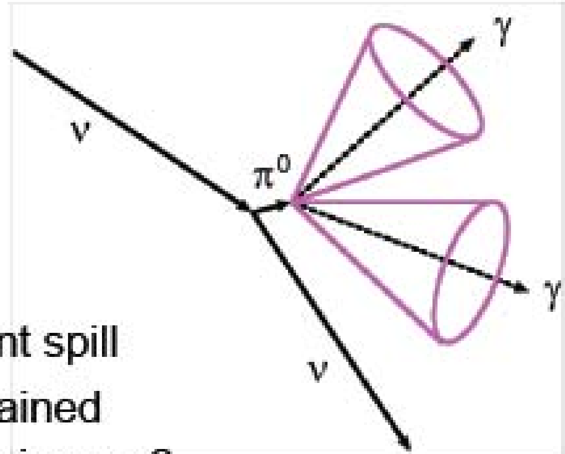
only one π^0 and no other mesons get out of a ^{16}O nucleus via NC interactions.
(after nuclear re-scatterings)

BG interactions



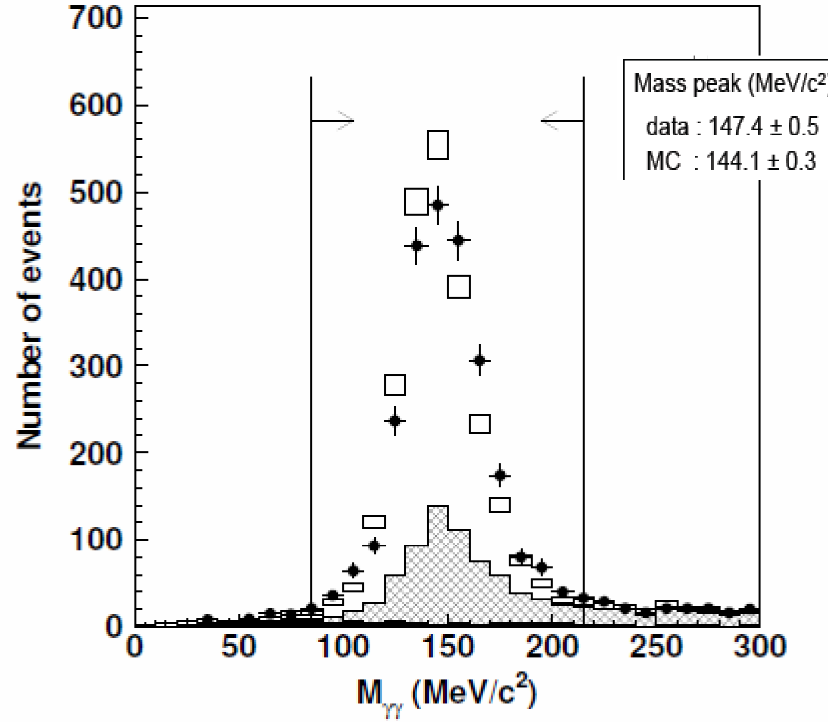
π^0 w/ invisible μ | π^0 w/ invisible π,μ | π^0 produced outside nuclei

Selection criteria and data/MC comparison



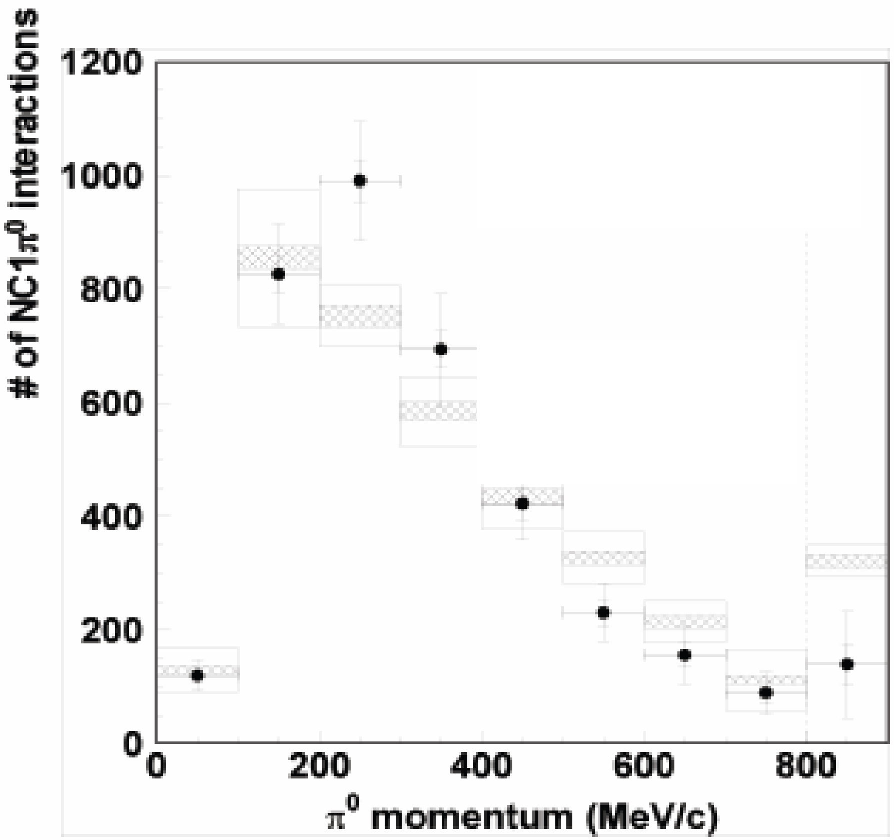
π^0 events

- single-event spill
- Fully-Contained
- number of rings = 2
- both e-like PID
- $M_{\gamma\gamma}$: 85 ~ 215 MeV/c^2



Invariant mass of two e-like ring events for the experimental data (black dots) and the neutrino MC simulation (box histogram). Error bars are statistical only. Main background are π^o's from non-NC1π^o events (hatched), with small contamination from interaction w/o π^o (black).

NC 1π^0 cross section measurement



data (inner: stat, outer: stat+sys)

MC true (inner: MC stat, outer: MC stat + sys error on shape from our MC model uncertainties)

normalized by the number of all events in 25t fiducial

$\sigma(NC1\pi^0) / \sigma(\nu_\mu CC) = 0.064$ from NEUT

$\sigma(\nu_\mu CC) \sim 1 \times 10^{-38}$ cm^2 / nucleon from NEUT

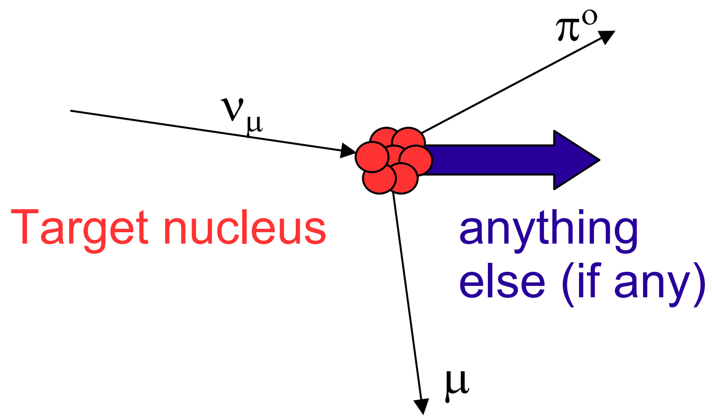
(K2K beam spectrum averaged) $\langle E\nu \rangle \sim 1.3$ GeV

$$\sigma(NC1\pi^0) / \sigma(\nu_\mu CC) = 0.063 \pm 0.001 (stat.) \pm 0.006 (sys.)$$

at the K2K beam energy, $\langle E\nu \rangle \sim 1.3$ GeV

CC inclusive π^0 measurement

Inclusive signal definition



We define signal an event with:

- **1 or more π^o's from the neutrino interaction vertex;**
- **1 or more π^o's from a re-interaction inside the target nucleus;**
- **1 or more η (decaying either in π^o's or photon pairs).**

5.4% single pion production:

4% single π°'s produced via resonances decay (mainly Δ);

1.4% π°'s produced by nuclear reinteractions in the target nucleus following a resonance production;

6.2% multi pion production (DIS with 1.3GeV < W < 2.0 GeV, $n\pi$ > 2):

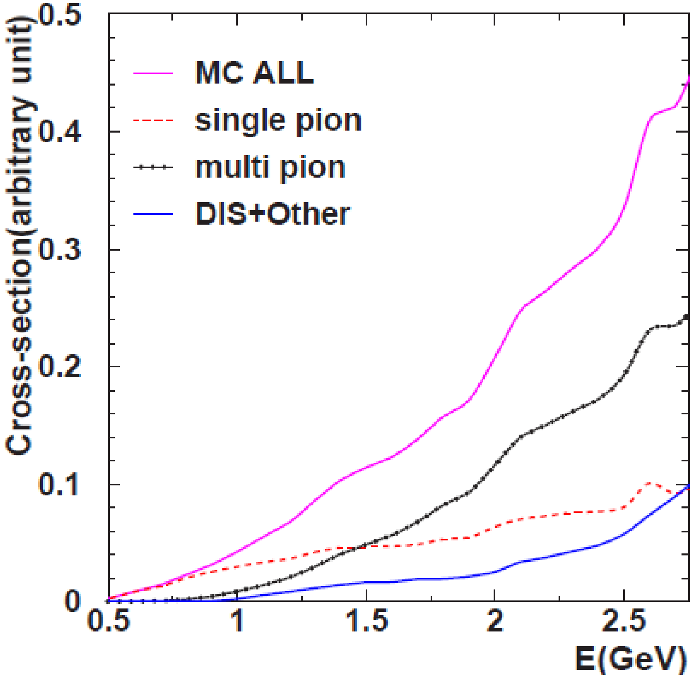
5.6% π°'s produced in multi pion interactions;

0.6% π°'s produced by nuclear reinteractions in the target nucleus following a multi-pion neutrino interaction;

1.5% from η decay:

- $\pi^{+} + \pi^{-} + \pi^{\circ}$ (22.6% of total η b.r.);
- $3\pi^{\circ}$ (32.5% of total η b.r.);
- 2 gamma (39.4% of total η b.r.);

0.4% from DIS;

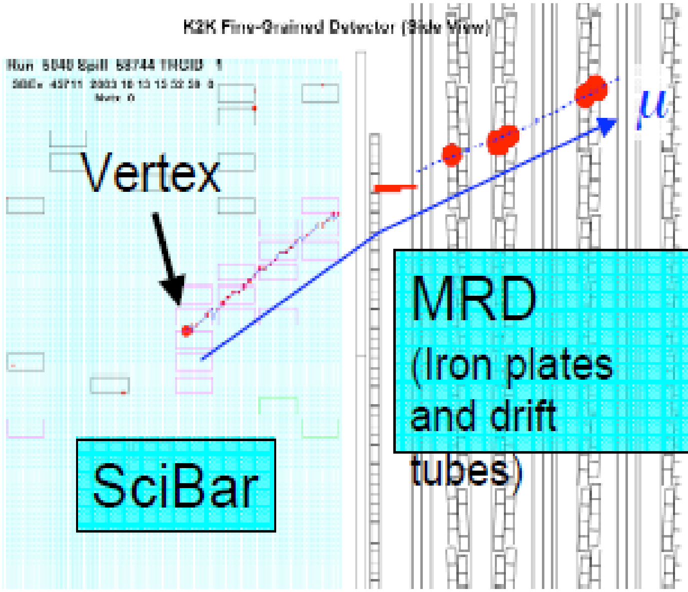


Normalization sample

The total number of selected CC interaction are 11606 (20.2×10^{18} POT), the simulated neutrino interactions are 1500000.

CC selection cut (eff.49.5%, pur.97.5%)

At least one track reconstructed in SciBar;
Track should be in FV: 10.9 m^3;
Track should be matched with MRD ;

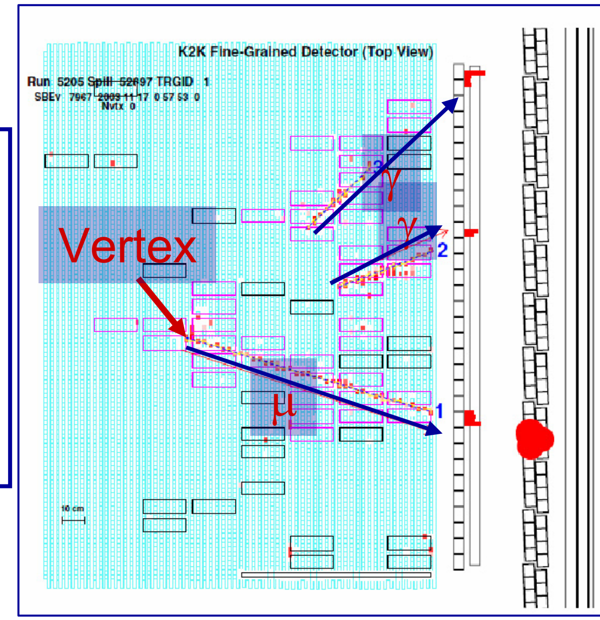


CCQE samples

1T-QE: a single reconstructed track;
2T-QE: 2 reconstructed tracks with $\Delta\theta_p < 20°$;
2T-nQE-π: 2 reconstructed tracks with $\Delta\theta_p \geq 20°$, pion like;
2T-nqe-p: 2 reconstructed tracks with $\Delta\theta_p \geq 20°$, proton like.

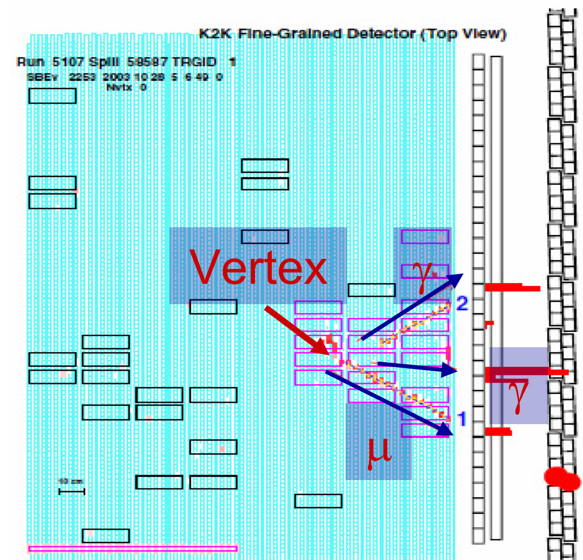
Experimental signature and gamma selection

Muon ID: one track matched to a MRD track corresponding to the muon produced in the CC interaction;



CC π^o features:

A muon track to define the neutrino interaction vertex, plus two photon conversions (tracks disconnected from the neutrino interaction vertex and pointing to it in SB, or/and a narrow cluster in the EC;
Possibly other tracks and/or EC clusters.



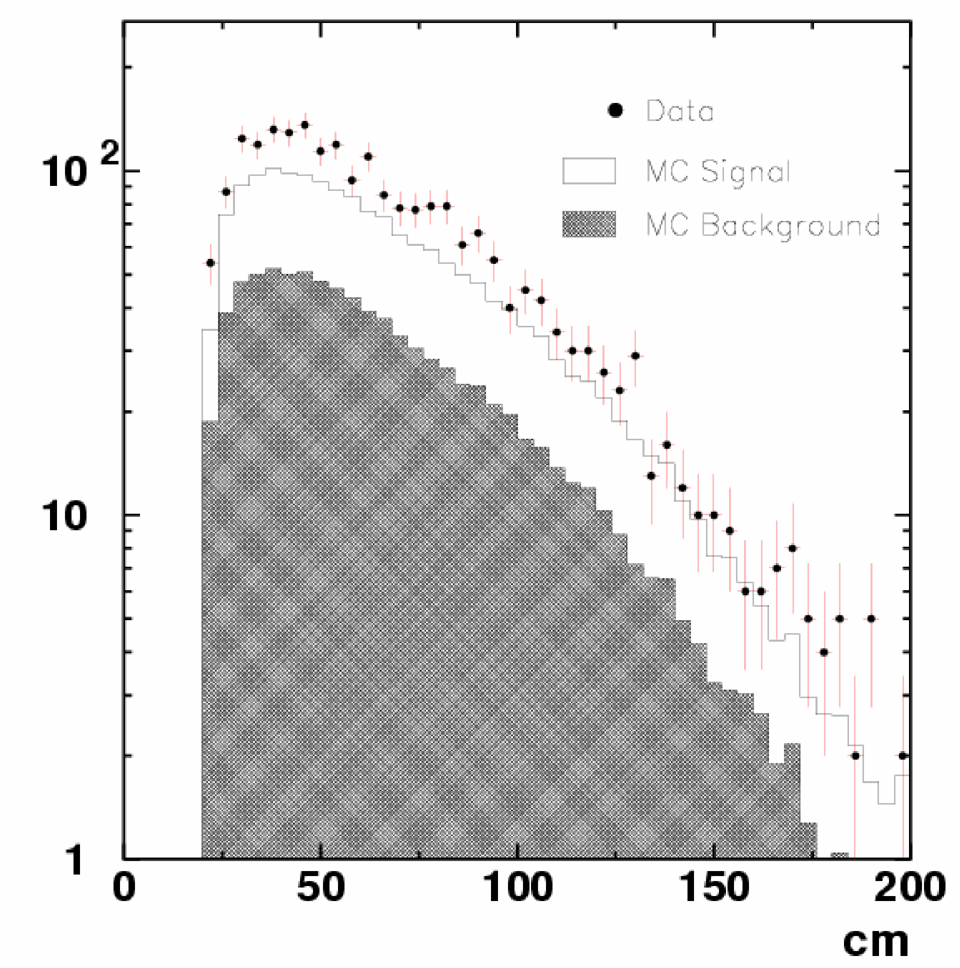
CC π^o selection:

Photon tracks should be reconstructed in FV: 13.3 m^3;
Not matched with a MRD 3D reconstructed track;
In time within 10 ns with the muon track;

Pointing within 25 cm and disconnected >20 cm (in both views) to the interaction vertex;

EC $E_{vert. Cluster} > 50$ MeV
EC $E_{hor. Cluster} > 25$ MeV

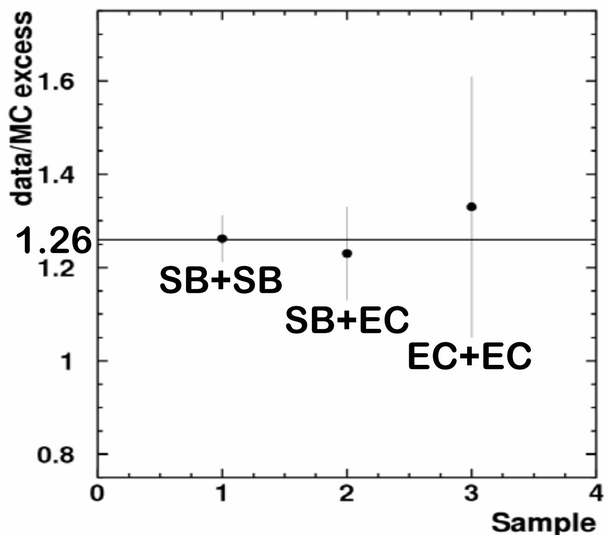
Disconnection from neutrino interaction vertex of candidate photon tracks



Events with at least 2 photon candidates

Sample	Sample number	Data	MC norm
2 γ in SB	1	353	279.6
1 γ in SB +1 γ in EC	2	96	77.8
2 γ in EC	3	30	22.6

The events with at least two photons reconstructed in data(MC) are 479(380). The excess is of 26 ± 4% between data and MC considering all the reconstructed sample.



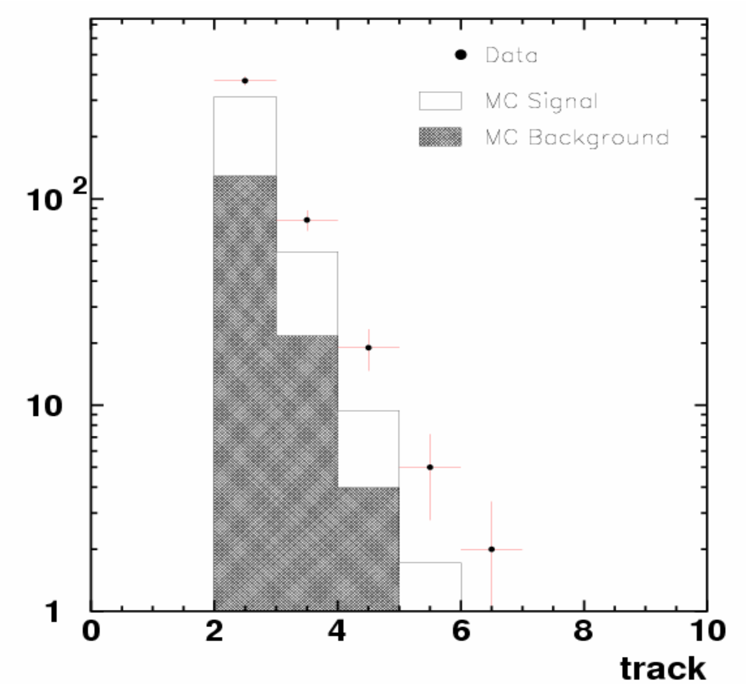
So the excess is consistently seen in both SciBar and EC which have different efficiencies and systematics.

π^0 combinatorial

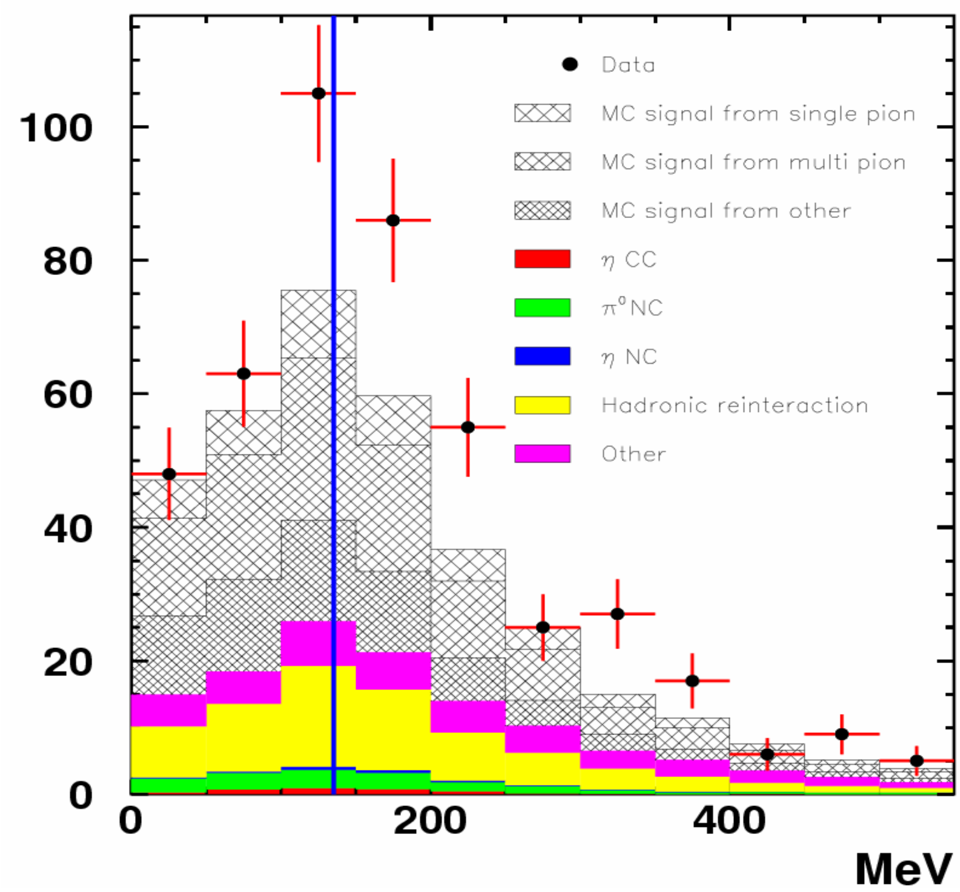
Photon candidates per event should be ≥ 2;

In 21% of the events selected we have >2 candidates, in this case we reconstruct the π^o mass as follows:

- **If all photons reconstructed in SB: π^o vertex closest to μ vertex (15%);**
- **If 1 or more photons are reconstructed in the EC: best mass (6%).**



π^0 invariant mass



479 π^o's are reconstructed in data and 380 in MC.
The overall efficiency is 7.6 % and the purity is 59%.

True π^o signal (59%)	
Composition:	**Source:**
• Prompt π^o: 82%; • π^o from reinteractions: 11%; • η decay: 7%;	• Single pion from resonances: 45%; • Multi pion from resonances: 49%; • DIS: 6%;

The Background (41%) is made of:

- **Reinteractions outside target nucleaus: 54%;**
- **NC interactions: 13%;**
- **Others: 33%;**

Neutrino energy reconstruction

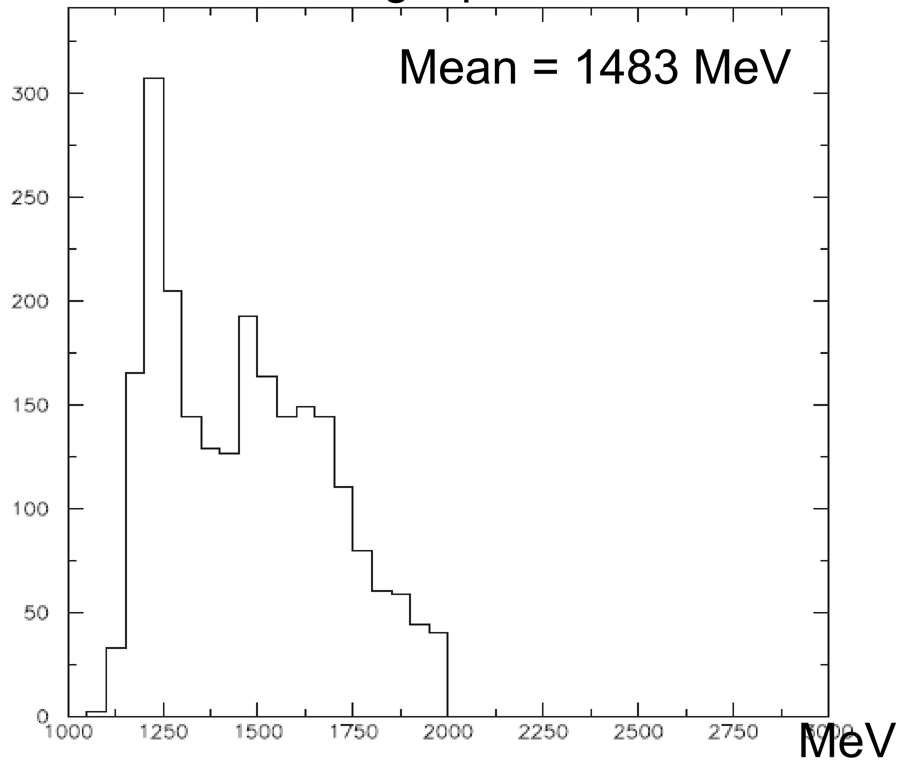
The neutrino energy in CC can be reconstructed from the muon energy and angle using the formula:

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

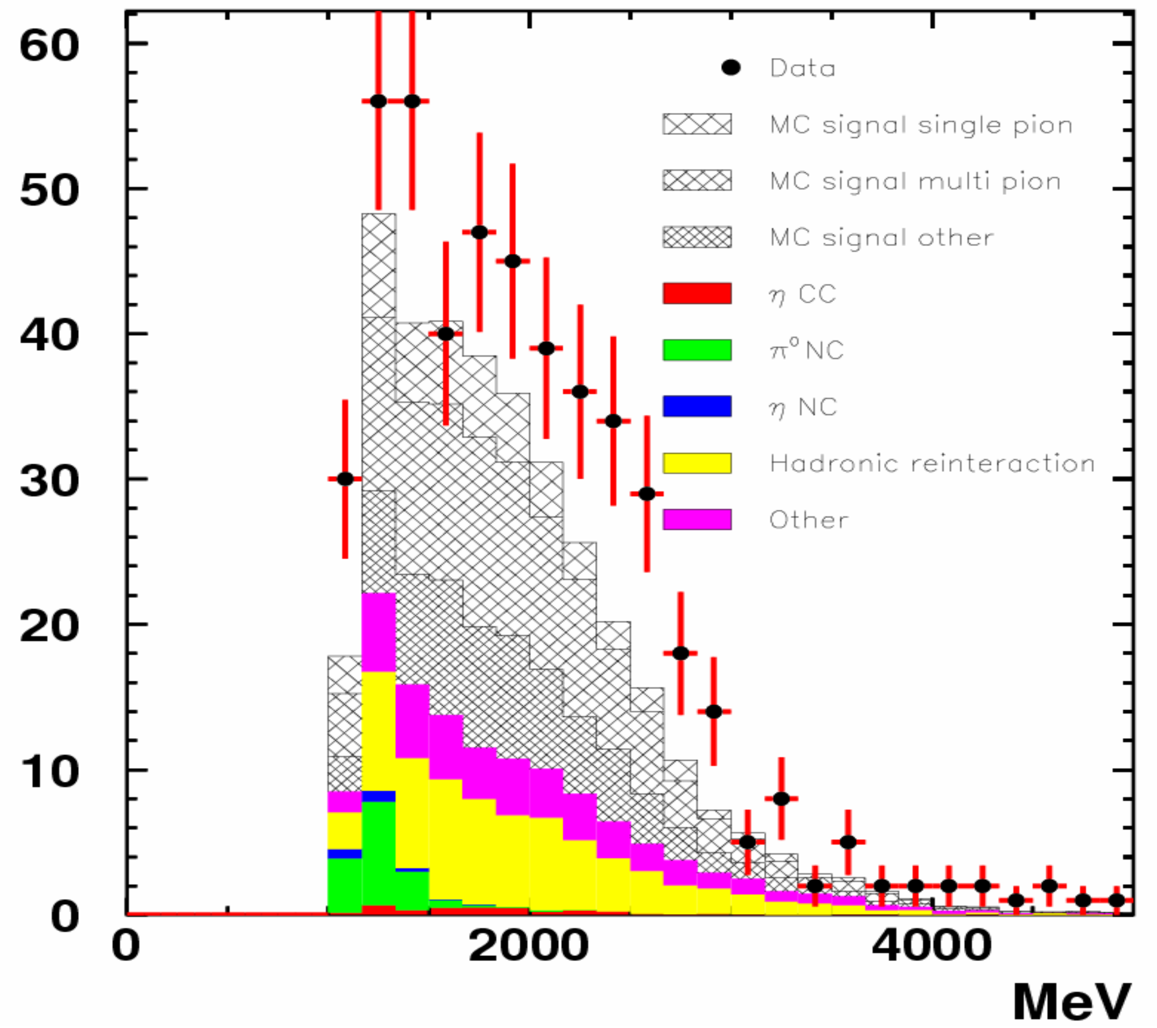
Where V= nuclear potential = 27 MeV and p_μ and θ_μ are the muon momentum and angle.

Our selected sample is mostly non-QE (98%), for the sub-sample of the single pion final state there is a broad spectrum of W^2 corresponding to the 18 different resonances taken into account in our reference MC simulation.
We use the average value of W=1.483GeV to reconstruct the neutrino energy, the resolution in the neutrino energy reconstruction is 600MeV.

W² true for single pion final state



Reconstructed neutrino energy before fit



Likelihood Fit description

We perform a maximum likelihood fit of

$$L = L_{CC\pi^o}(f_{norm}, R_{nQE/QE}, S_{\pi^o})\ x\ L_{norm}(f_{norm}, R_{nQE/QE})\ x\ L_{syst}$$

where Poiss(n, μ) is the poissonian for n events with expectation value μ;

$$L_{CC\pi^o} = \prod_k Poiss(data_k, pred_k)$$

We fit the 1-dimensional reconstructed neutrino energy distribution H_k:

- **H_k is the number of events in the bin k of 1-dimensional histogram;**
- **k=1,30 labels 30 bins between 0-5 GeV in the reconstructed neutrino energy;**
- **$data_k$ = number of events observed in bin k;**
- **$pred_k$ = number of events expected in bin k** $= f_{norm} \times \left[S_{\pi^o} \times \sum_i H_i^{Sign} + \sum_i H_i^{Bkg} \right]$

$$S_{\pi^o} = \frac{\sigma_{CC\pi^o}}{\sigma^{MC}_{CC\pi^o}}$$

$$L_{norm} = \prod_s Poiss(n_s, pred_s), \qquad s = \{1TQE, 2TQE, 2TnQE.p, 2TnQE.\pi\}$$

n_s and $pred_s$ are respectively the number of events observed in data and expected by MC for the different normalization sub-samples.

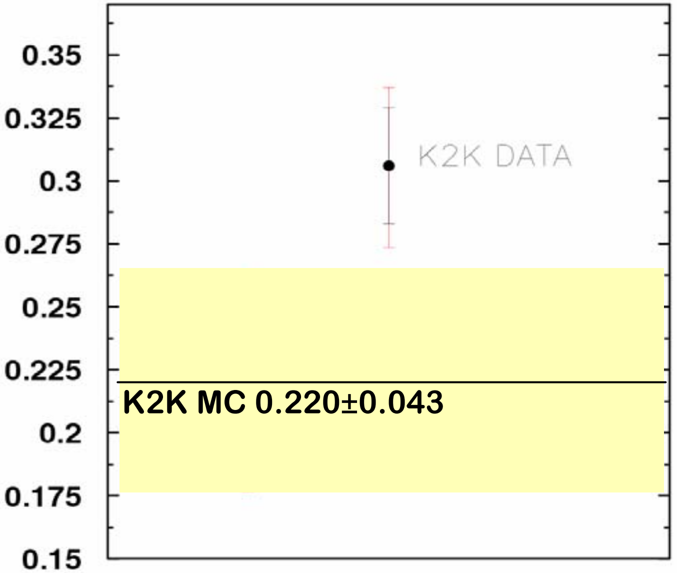
L_{syst} **is a term used in the systematic errors evaluation.**

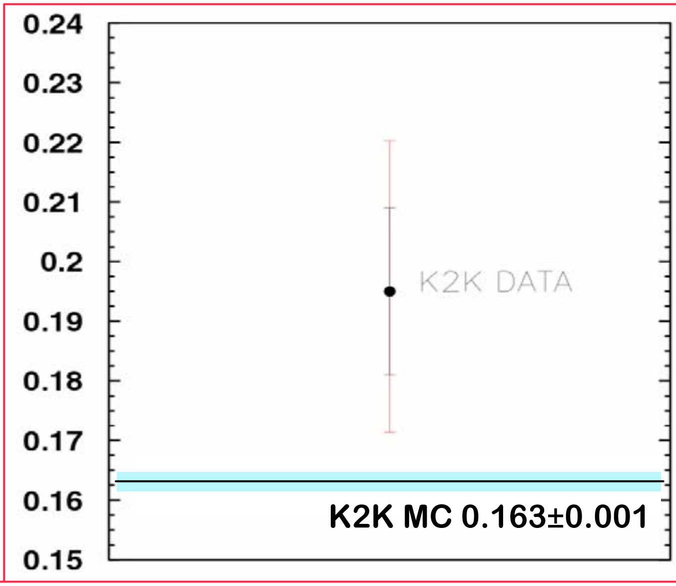
$\sigma_{CC}\ \pi^o$ cross-section

$$\frac{\sigma_{CC\pi^o}}{\sigma_{CCQE}} = 0.306 \pm 0.023(stat.)^{+0.023}_{-0.021}(syst.)$$

$$\frac{\sigma^{MC}_{CC\pi^o}}{\sigma^{MC}_{CCQE}} = 0.220 \pm 0.001(stat.) \pm 0.043(R_{nQE/QE} \pm 20\%)$$

The inclusive π^o production shows an excess of (39±15)% (statistical and systematic error added in quadrature). MC prediction is strongly dependent from the ratio R_{nQE}.





A result with the MC prediction almost independent from the ratio R_{nQE} is the inclusive π^o production normalized to the non quasi elastic charged current cross section

$$\frac{\sigma_{CC\pi^o}}{\sigma_{CCnQE}} = 0.195 \pm 0.014(stat.)^{+0.021}_{-0.019}(syst.)$$

$$\frac{\sigma^{MC}_{CC\pi^o}}{\sigma^{MC}_{CCnQE}} = 0.163 \pm 0.001(stat.) \pm 0.001(R_{nQE/QE} \pm 20\%)$$

The resulting double ratio nQE/QE is:

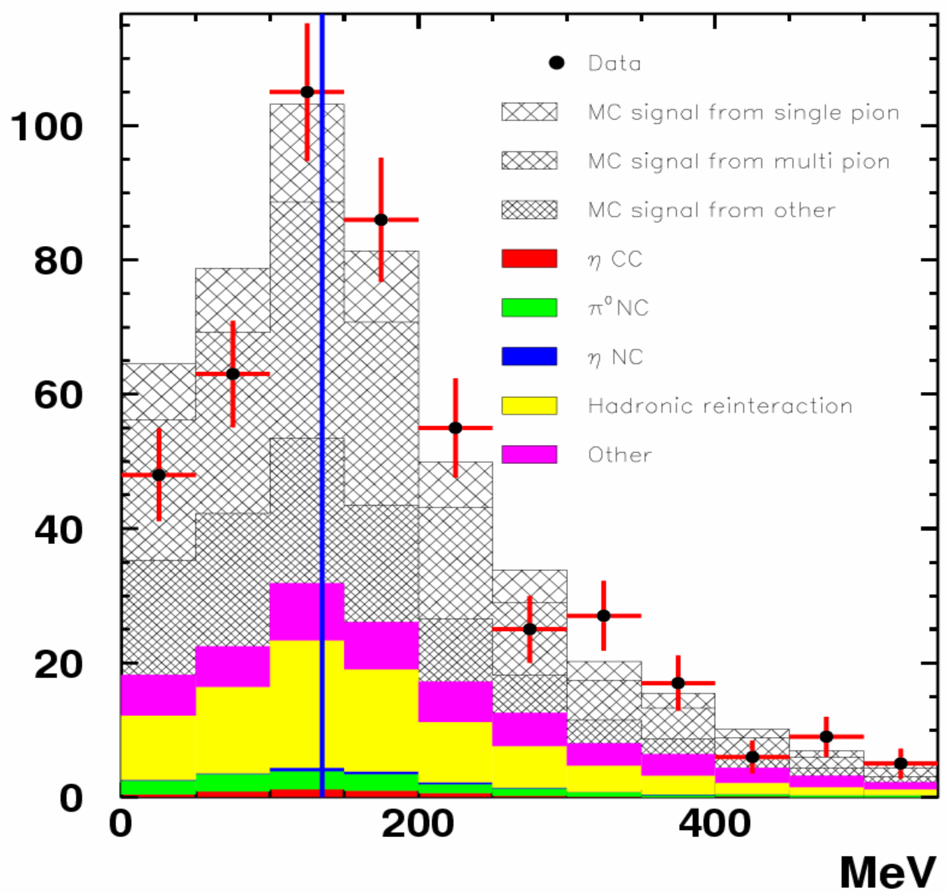
$$R_{nQE} = \frac{R_{nQE\ /QE}^{DATA}}{R_{nQE\ /QE}^{MC}} = 1.21 \pm 0.13$$

Fixing the CC single pion contribution to the value measured by K2K-SciBar (see L.Whitehead's presentation) we can read our π^o cross-section measurement in terms of the CC multi pion cross section:

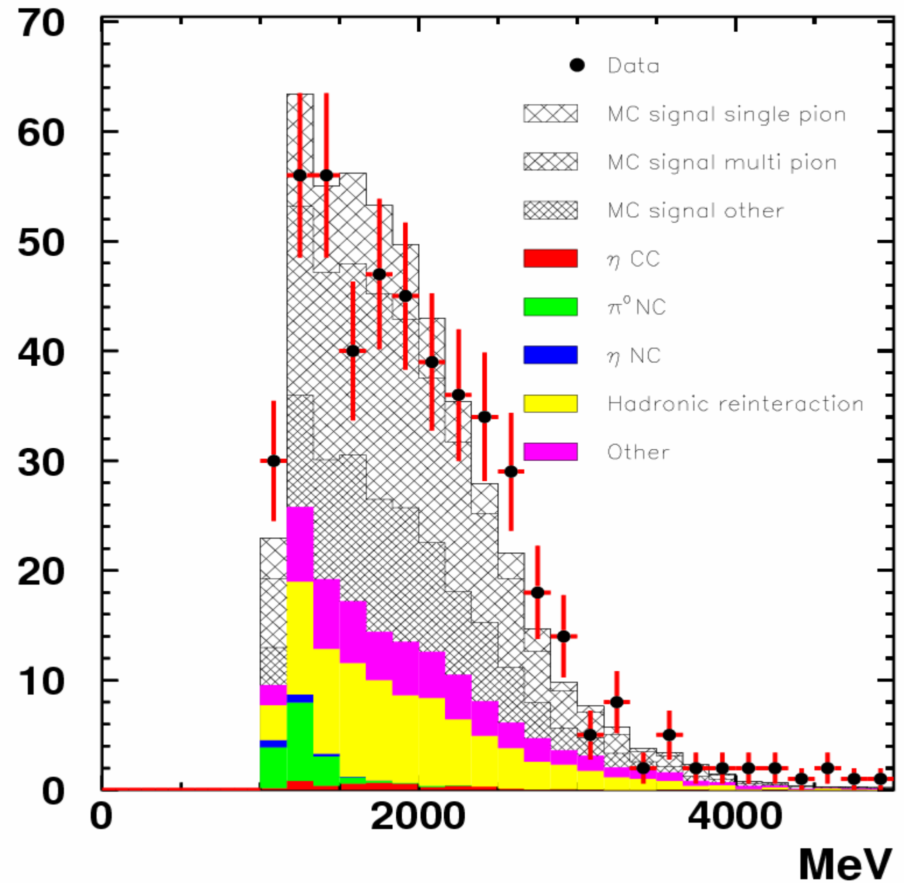
$$\frac{\sigma_{CCmulti-\pi}}{\sigma_{CCQE}} = 0.465 \pm 0.029(stat.) \pm 0.056(syst.)$$

$$\frac{\sigma_{CCmulti-\pi}^{MC}}{\sigma_{CCQE}^{MC}} = 0.358 \pm 0.001(stat.)$$

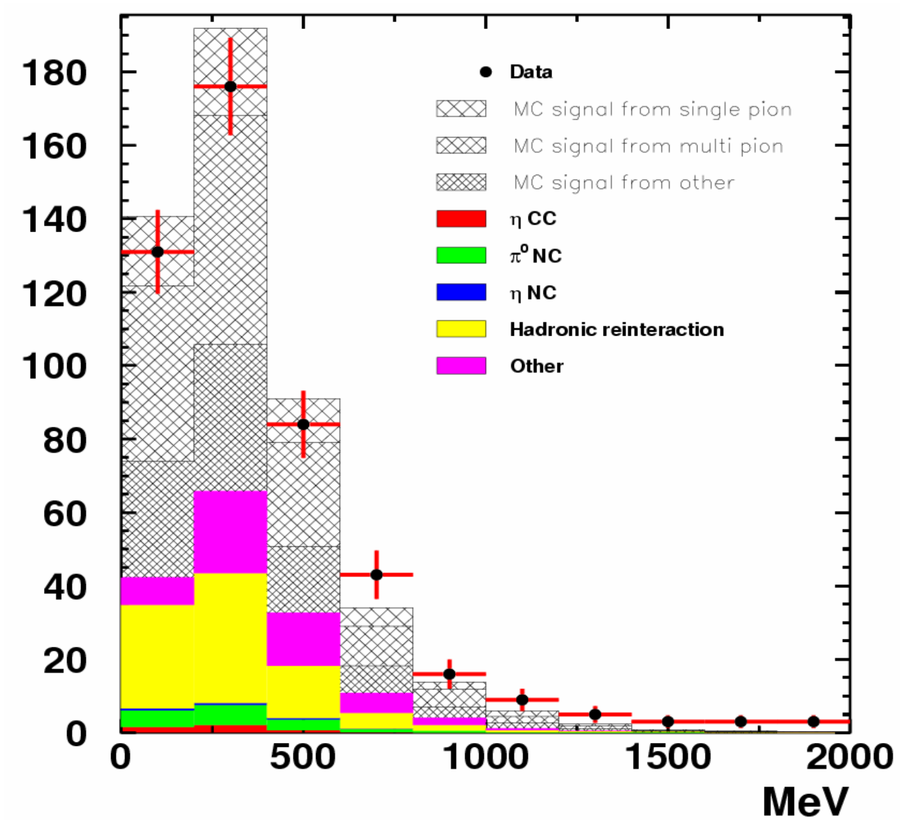
Reconstructed π^o mass after fit



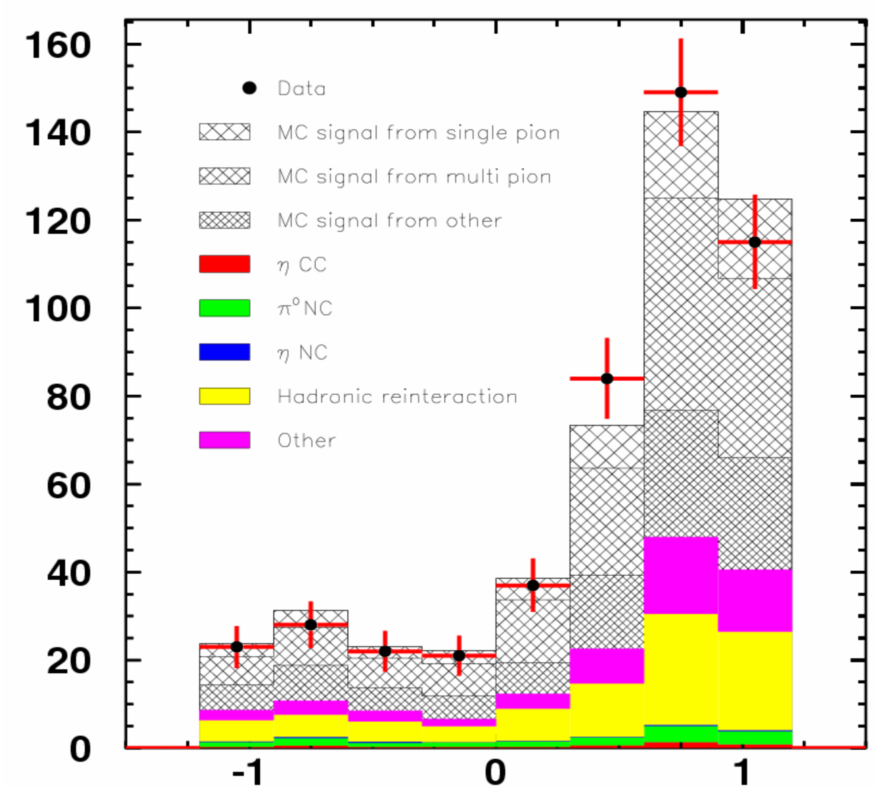
Reconstructed neutrino energy after fit



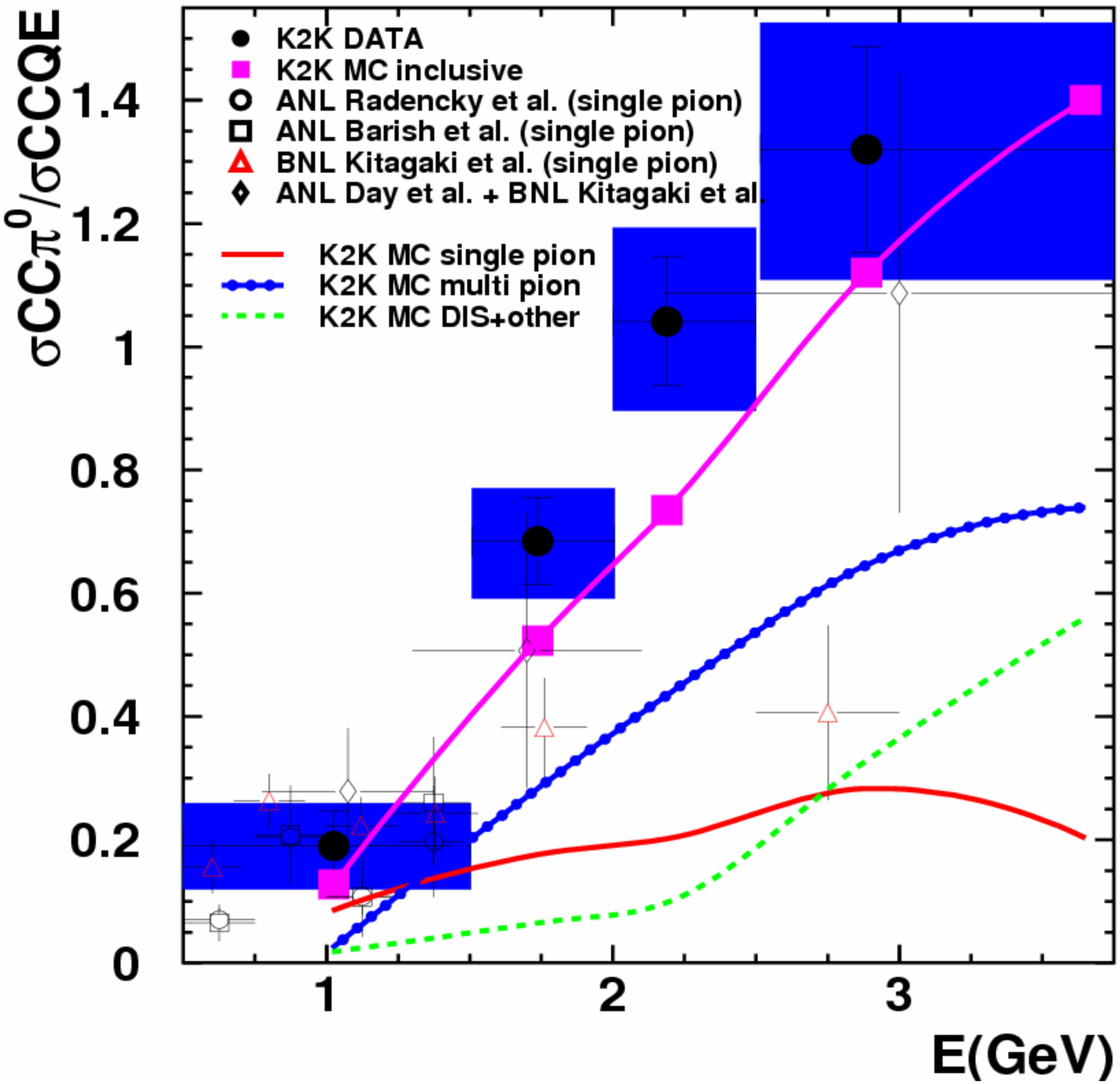
π^o momentum after fit



π^o cosθ



Comparison with other experiment



Summary

K2K-1kT measured NC single π^o production in water (O^{16}) with high statistic in good agreement with NEUT (including nuclear effects):

$$\frac{\sigma_{NC1\pi^o}}{\sigma_{CC}} = 0.064 \pm 0.001(stat.) \pm 0.006(syst.)$$

K2K-SciBar/EC measures CC inclusive π^o production in C_8H_8 (C^{12}) to be larger than NEUT expectations:

$$\frac{\sigma_{CC\pi^o}}{\sigma_{CCQE}} = 0.306 \pm 0.023(stat.)^{+0.023}_{-0.021}(syst.)$$

The larger π^o yield in CC, together with the agreement of the single-pion in the CC1π analysis, translates in an excess of (30±18)% of the NEUT multi-pion cross-section:

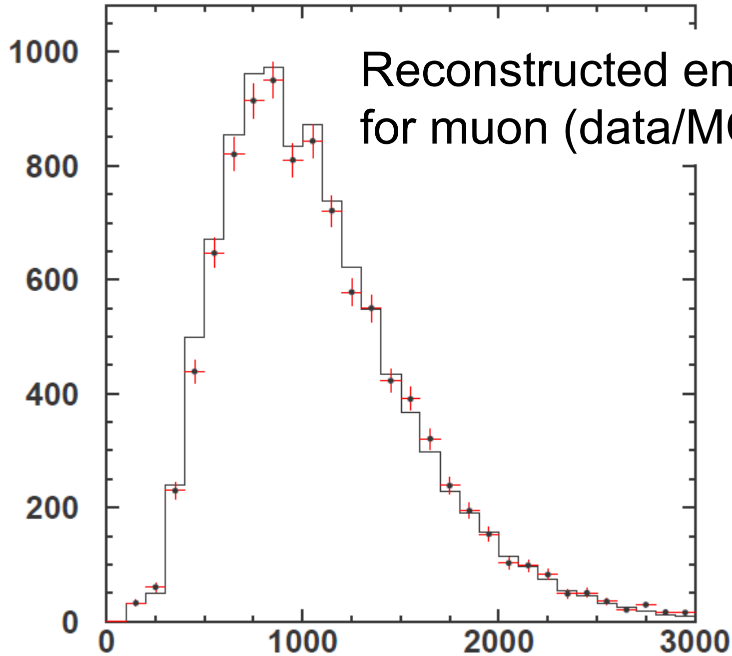
$$\frac{\sigma_{CCmulti-\pi}}{\sigma_{CCQE}} = 0.465 \pm 0.029(stat.) \pm 0.056(syst.)$$ **(NEUT: 0.358)**

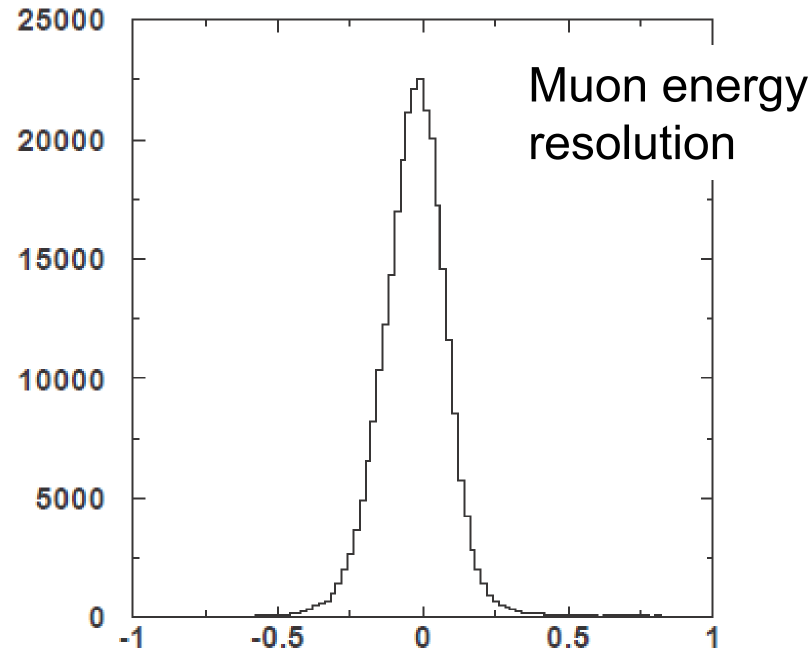
The π^o production in CC is larger but consistent with previous results (exclusive 1π^o and $\pi^+\pi^o$ on Deuterium) with improved precision.

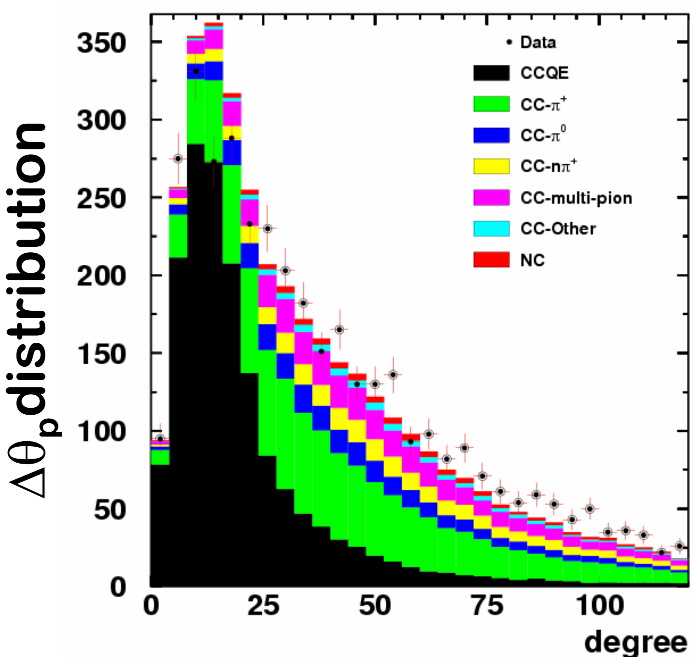
Backup

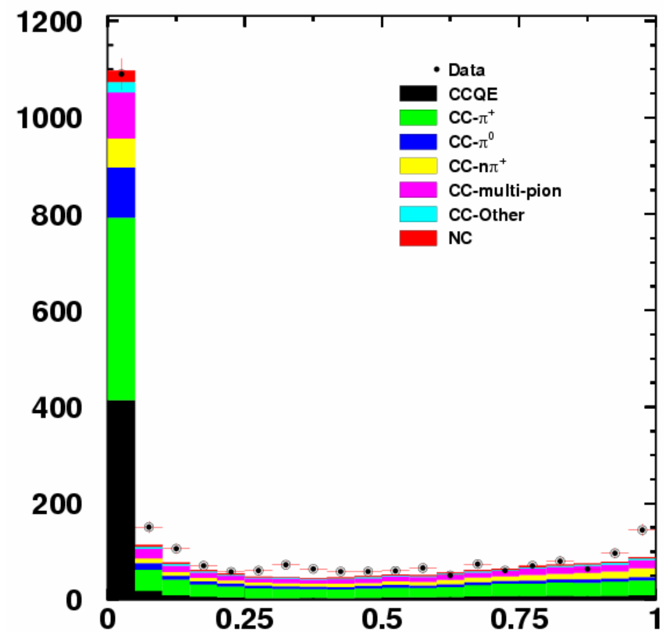
Sample	QE	nQE	NC	TOT MC	QE Efficiency %	QE Purity %	Data
1T-QE	158390	79018	6268	243676	71.8	65	6125
2T-QE	39075	12579	275	51415	19.7	76	1262
2T-nQE-π	4347	33497	1677	39521	2.3	11	1048

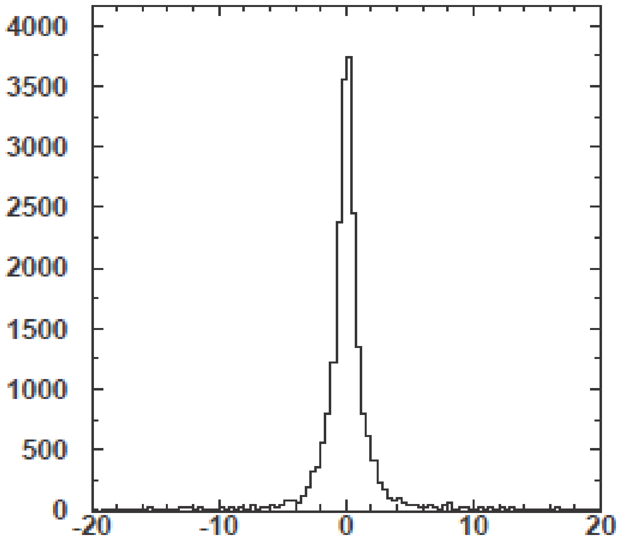
Table 2: CCQE samples, number of events selected in data, efficiency and purity for each sub-samples


Reconstructed energy
for muon (data/MC)
0
200
400
600
800
1000
0
1000
2000
3000

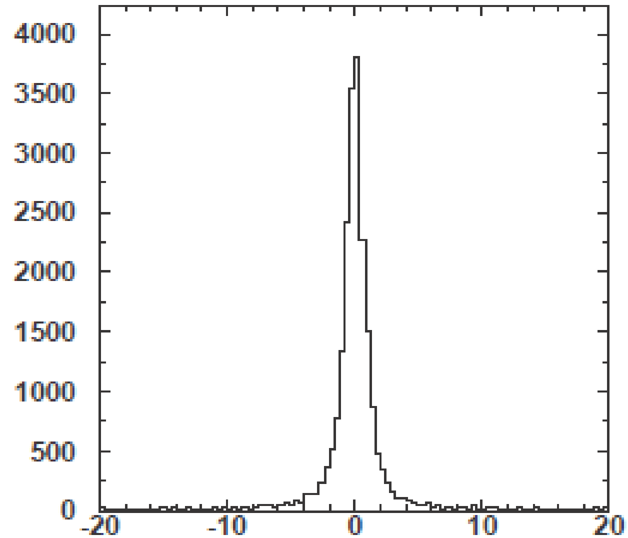

Muon energy
resolution
0
5000
10000
15000
20000
25000
-1
-0.5
0
0.5
1


$\Delta\theta_p$ distribution
Data
CCQE
CC-π^+
CC-π^0
CC-nπ^+
CC-multi-pion
CC-Other
NC
0
50
100
150
200
250
300
350
0
25
50
75
100
degree


Data
CCQE
CC-π^+
CC-π^0
CC-nπ^+
CC-multi-pion
CC-Other
NC
0
200
400
600
800
1000
1200
0
0.25
0.5
0.75
1

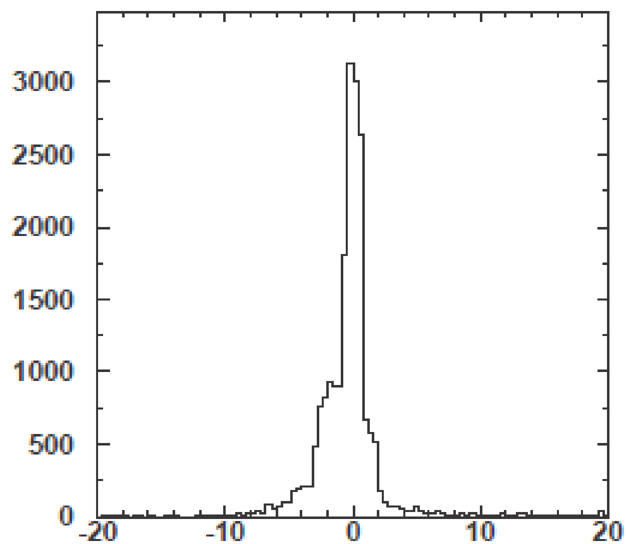


(a) Vertex(Rec.-True)(X), RMS=0.9cm



(b) Vertex(Rec.-True)(Y), RMS=0.9cm

Resolution on reconstructing neutrino interaction vertex

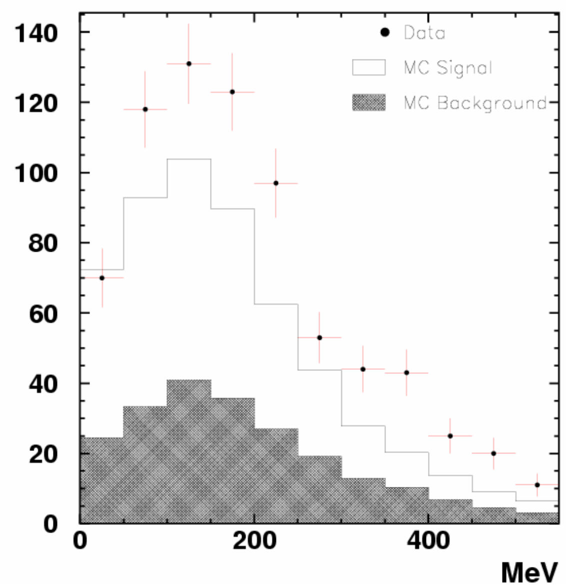


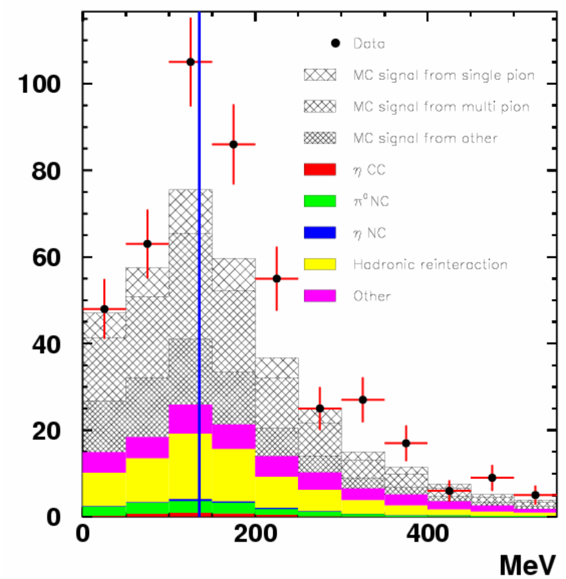
(c) Vertex(Rec.-True)(Z), RMS=1.6cm

Photon candidates per event should be ≥ 2;

In 21% of the events selected we have >2 candidates, in this case we reconstruct the π^o mass as follows:

- If all photons reconstructed in SB: π^o vertex closest to μ vertex (15%);
- If 1 or more photons are reconstructed in the EC: best mass (6%).





The energy resolution for photons is:

- **50 MeV for the higher energy photon;**
- **60 MeV for the lower energy photon.**

The 3D angle reconstruction resolution is:

- **0.15 rad for the higher energy photon;**
- **0.18 rad for the lower energy photon.**

We allow individual reweighting factors W_i for the individual contribution in our MC. $W_i = 1 \rightarrow$ standard reference MC.

$$pred_k = f_{norm} \times \left[S(W) \times \sum_i W_i H_{i,k}^{Sign} + \sum_i W_i H_{i,k}^{Bkg} \right]$$

← Signal → ← Bkg →

$$pred_s = f_{norm} \times \left[\sum_i W_i H_s \right]$$

$$S(W) = S_{\pi^o} \times \frac{\sum_k \sum_i H_{i,k}^{Sign}}{\sum_k \sum_i W_i H_{i,k}^{Sign}}$$

$$S_{\pi^o} = \frac{\sigma_{CC\pi^O}}{\sigma_{CC\pi^O}^{MC}}$$

i = interaction type;

f_{norm} **is the absolute normalization factor between data and MC and is a free likelihood parameter.**

The double ratio nQE/QE is defined as:

$$R_{nQE} = \frac{R_{nQE/QE}^{DATA}}{R_{nQE/QE}^{MC}}$$

The L_{syst} term is: $F_{syst} = \frac{\sum_i (W_i - 1)^2}{\sigma_{W^2}} = -2\log(L_{syst.})$

Cross-section measurement

For the inclusive π^o production normalized to the quasi elastic charged current cross section, our measurement shows an excess of the inclusive π^o production of (40±13)% (statistical and systematic error added in quadrature). The MC prediction is strongly dependent from the ratio R_{nQE}.

$$\frac{\sigma^{MC}_{CC\pi^o}}{\sigma^{MC}_{CCQE}} = 0.220 \pm 0.001(stat.) \pm 0.043(R_{nQE/QE} \pm 20\%)$$

$$\frac{\sigma_{CC\pi^o}}{\sigma_{CCQE}} = 0.306 \pm 0.023(stat.) \pm 0.025(syst.)$$

For the inclusive π^o production normalized to the non quasi elastic charged current cross section, our measurement shows an excess of (20±11)%. The MC prediction is almost independent from R_{nQE} which is the main source of the systematic error.

$$\frac{\sigma^{MC}_{CC\pi^o}}{\sigma^{MC}_{CCnQE}} = 0.163 \pm 0.001(stat.) \pm 0.001(R_{nQE/QE} \pm 20\%)$$

$$\frac{\sigma_{CC\pi^o}}{\sigma_{CCnQE}} = 0.195 \pm 0.014(stat.)^{+0.022}_{-0.019}(syst.)$$

The excess taking into account the measurement of CC pi+ cross section presented by Lisa could be interpreted as an excess of the CC multi pion cross section:

$$\frac{\sigma_{CCmulti-\pi}}{\sigma_{CCQE}} = 0.465 \pm 0.029(stat.) \pm 0.056(syst.)$$

Systematic error evaluation

CCnQE normalized sample

Source of systematic	Error[%]
π absorbtion cross-section	-1.1 +1.3
π inelastic cross-section	-1.8 +2.8
Proton rescattering	-0.6 +0.6
Pion interaction length	-1.2 +1.2
MC nuclear model	**-2.2 +3.1**
PMT resolution	-0.7 +0.1
Scintillator quenching	-0.3 +0.3
Cross-talk	-1.7 +1.6
PMT threshold	-0.8 +2.1
Detector effects	**-2.0 +2.7**
Normalization + $R_{nQE/QE}$	-7.5 +7.8
MC cross-section variation	-4.6 +4.7
Bodek and Yang correction	-1.8 +2.8
CCQE M_A	-0.7 +1.4
NC/CC ratio	-1.1 +1.3
Interaction model uncertainties	**-9.1 +9.7**
Fiducial Volume	-2.6 +2.5
Disconnection from muon vertex	-1.9 +2.4
Vertex pointing	-1.0 +1.8
EC cluster energy cut	-0.4 +1.2
Cuts variation	-3.4 +4.1
Total systematic uncertainties	**-10.1 +11.3**

CCQE normalized sample

Source of systematic	Error[%]
π absorbtion cross-section	-2.0 +2.1
π inelastic cross-section	-3.0 +1.8
Proton rescattering	-1.9 +0.3
Pion interaction length	-1.5 +1.5
MC nuclear model	**-4.1 +2.8**
PMT resolution	-0.5 +0.1
Scintillator quenching	-0.1 +0.5
Cross-talk	+1.2 +2.6
PMT threshold	-1.7 +2.0
Detector effects	**-1.8 +3.3**
Normalization + $R_{nQE/QE}$	-1.8 +1.8
MC cross-section variation	-3.4 +3.3
Bodek and Yang correction	-4.3 +3.5
CCQE M_A	-1.3 +2.4
NC/CC ratio	-0.5 +0.5
Interaction model uncertainties	**-5.9 +5.7**
Fiducial Volume	-2.6 +2.5
Disconnection from muon vertex $\pm 20\%$	-1.9 +2.4
Vertex pointing	-1.0 +1.8
EC cluster energy cut	-0.4 +1.2
Cuts variation	-3.4 +4.1
Total	**-8.1 +8.2**

To get the measurement as a function of the neutrino energy we take 4 energy bins:

- **E_ν < 1.5 GeV;**
- **1.5 GeV < E_ν < 2.0 GeV;**
- **2.0 GeV < E_ν < 2.5 GeV;**
- **$E_\nu \geq$ 2.5 GeV;**

The bin is chosen to have approximately the same statistics. Due to resolution effect an event with a reconstructed energy in the bin I can have a real energy in different bin j. We use a migration matrix to take into account for this effect:

$$N_i^{MC_{rec}} = M_{ij} N_j^{MC_{true}}$$

The migration matrix M_{ij} result:

$$\begin{pmatrix} 0.448 & 0.286 & 0.187 & 0.192 \\ 0.304 & 0.391 & 0.203 & 0.198 \\ 0.157 & 0.165 & 0.429 & 0.247 \\ 0.091 & 0.158 & 0.181 & 0.363 \end{pmatrix}$$

From the events observed in data in bin i, $N_i^{DATArec}$, subtracting the background events expected from MC N_i^{bkgMC} and using the inverse of the migration matrix above we compute the number of events background subtracted:

$$\widehat{N}_i = \frac{\sum_{j=1}^{4} (M^{-1})_{ij}(N_j^{DATA_{rec}} - N_j^{bkg^{MC}})}{\varepsilon_i}$$

Where ε_i=efficiency. Same procedure is applied also to the CCQE samples.

Comparison with other experiments

The ratio between π^o cross section and CCQE cross section is computed dividing the experimental result from old experiment (Barish, Kitagaki, Radencky and Day) by the CCQE cross section measured by Barish. To compare we have to rescale these results taking into account the different neutrino target:

$$\sigma(\nu(C_8H_8) \rightarrow \mu^- p\pi^0) = 48\sigma(\nu n \rightarrow \mu^- p\pi^0)$$

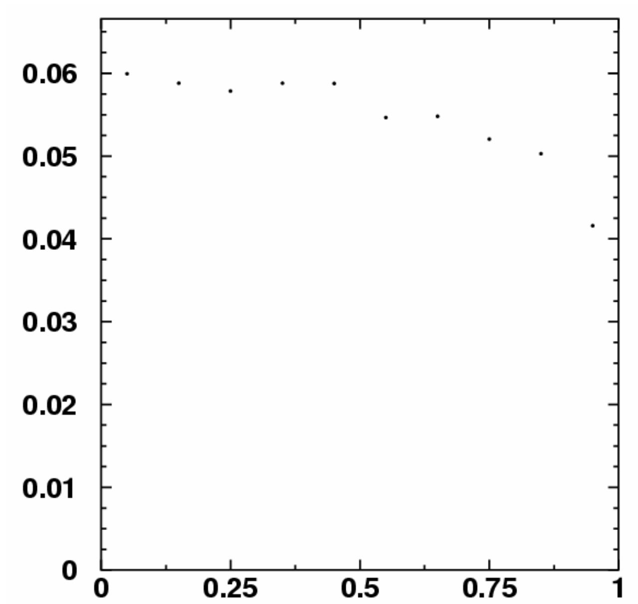
$$\sigma(\nu(C_8H_8) \rightarrow \mu^- p\pi^+\pi^0) = 56\sigma(\nu p \rightarrow \mu^- p\pi^+\pi^0)$$

$$\sigma(\nu^{QE}(C_8H_8)) = 48\sigma(\nu n)$$

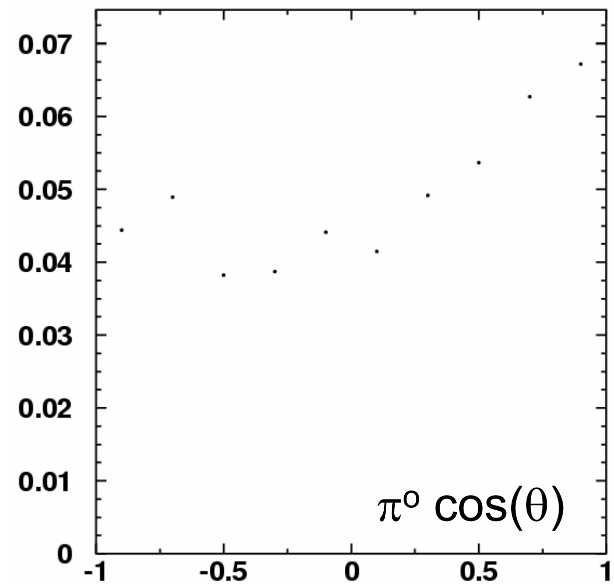
$$\frac{\sigma(\nu(C_8H_8) \rightarrow \mu^- p\pi^0)}{\sigma(\nu(C_8H_8))} = 1 \times \frac{\sigma(\nu D \rightarrow \mu^- p\pi^0)}{\sigma^{QE}(\nu D)}$$

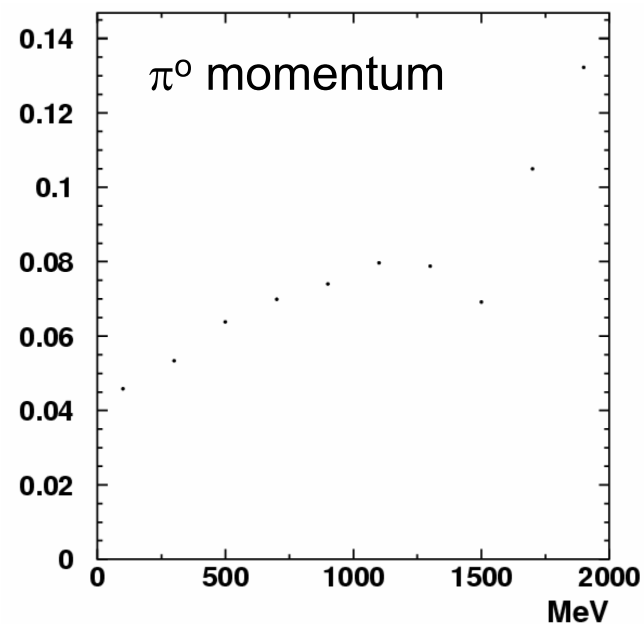
$$\frac{\sigma(\nu(C_8H_8) \rightarrow \mu^- p\pi^+\pi^0)}{\sigma(\nu(C_8H_8))} = 7/6 \times \frac{\sigma(\nu D \rightarrow \mu^- p\pi^+\pi^0)}{\sigma^{QE}(\nu D)}$$

Efficiency as a function of ...

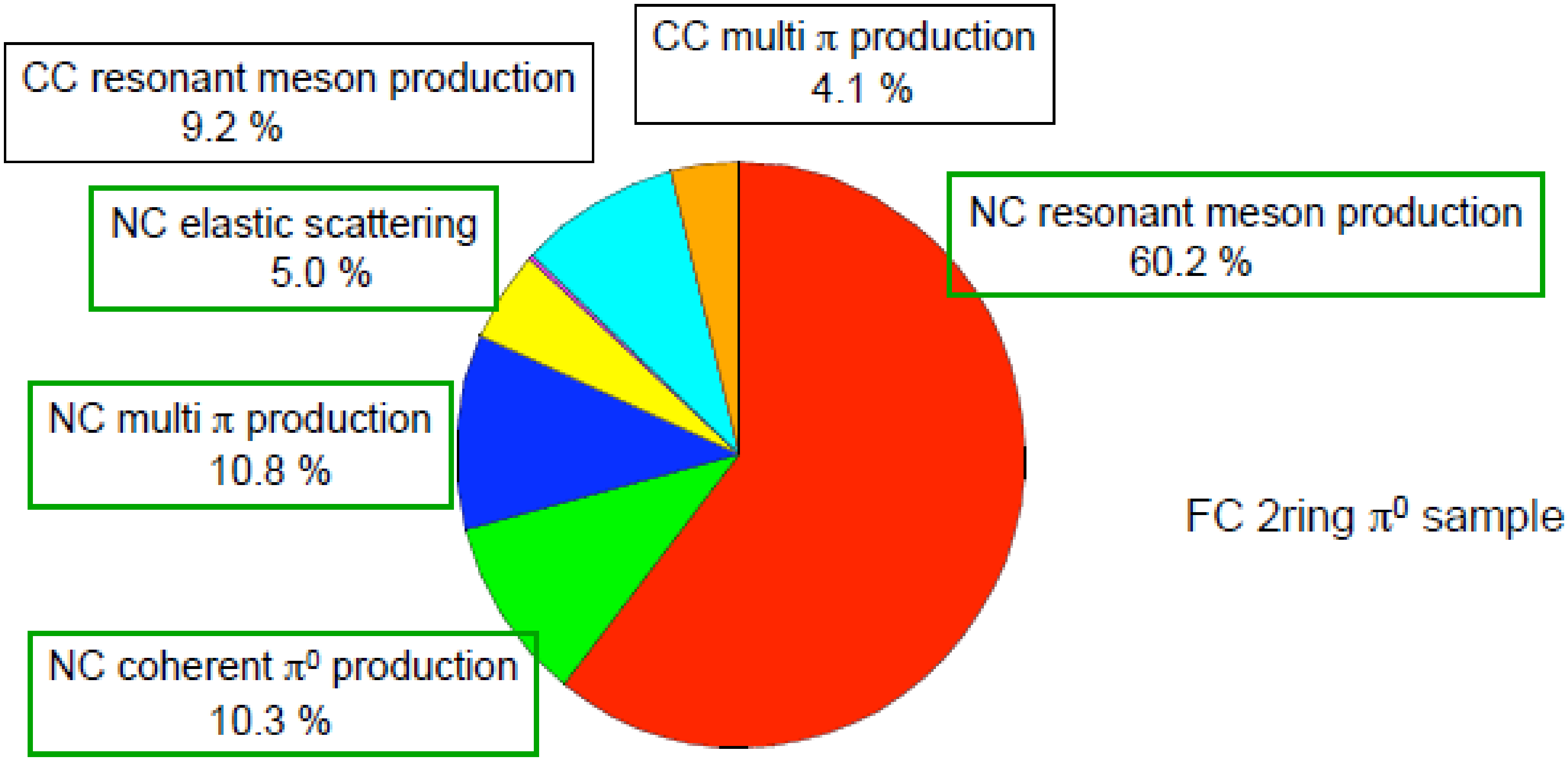


π° cos(θ*)





The fraction of each interaction channel



large NC fraction ~ 86 %

non-NC1π^0 subtraction

rec → true fiducial correction

sys.

true/rec = 1.03 ± 0.02

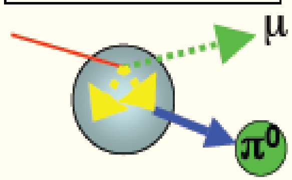
$$N_{NC1\pi 0} = \frac{N_{FC2R\pi 0}^{obs} \times r_{pure} \times corr_{fid}}{eff}$$

detection and reconstruction efficiency

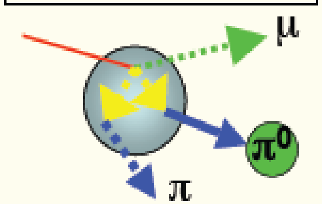
Background definition

	fraction
NC 1π^0	73 %

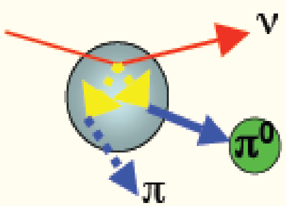
CC w/ invisible μ 7 %



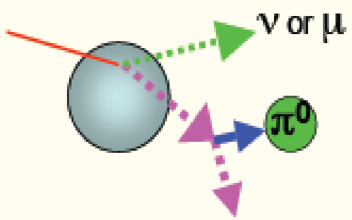
CC w/ invisible π, μ 3 %



NC w/ invisible π 7 %

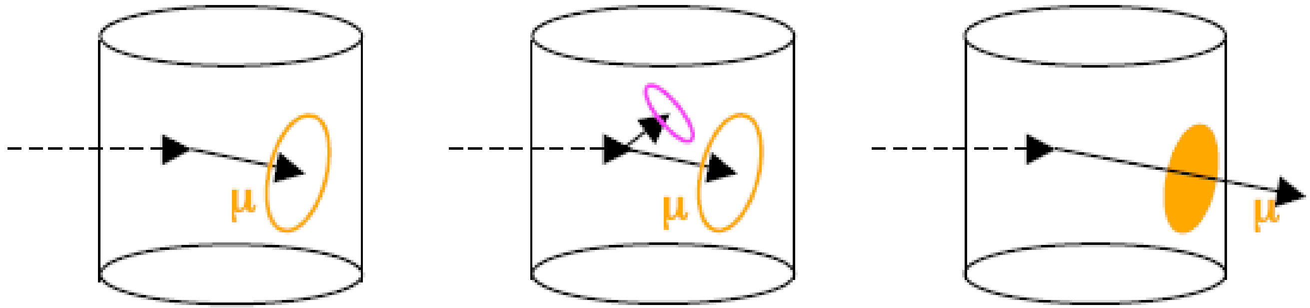


π^0 produced outside the nuclei 10 %



CC normalization

$\nu\mu$CC enriched sample :
FC single-ring μ-like + FC multi-ring μ-like + PC



	FC single-ring μ-like	FC multi-ring μ-like	PC
$\nu\mu$CC fraction	96.5 %	91.2 %	98.5 %

$$N(\nu_\mu CC) = N(FC\mu + PC)_{25t}^{obs} \times \text{purity} \times \text{corrfid} / \text{eff}$$

$$= 50226 \times 0.960 \times 1.02 / 0.846$$

0.960: BG: NC

0.846: inefficiency: multi-ring PID, FADC cut

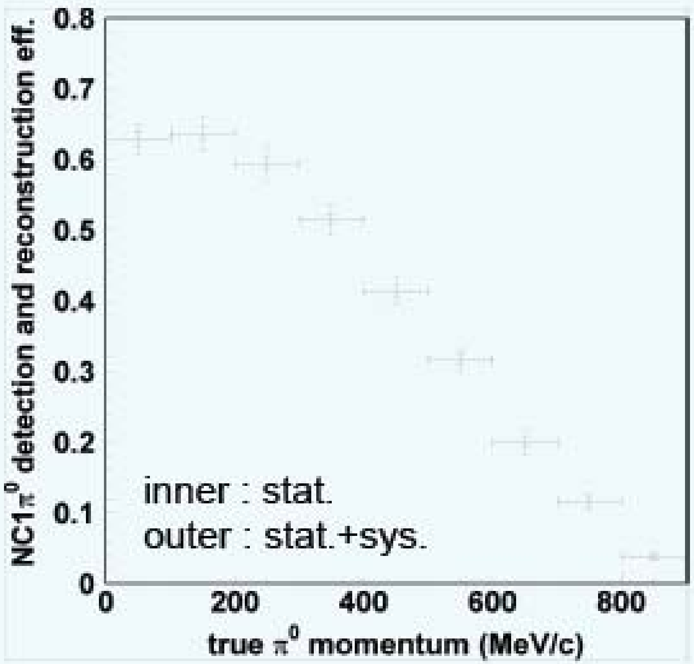
	N^{obs}
FC1Rμ	22612
FCmRμ	12386
PC	15228

$$= 5.78 \pm 0.03 \text{ (stat.)} \pm 0.26 \text{ (sys.)} \times 10^4$$

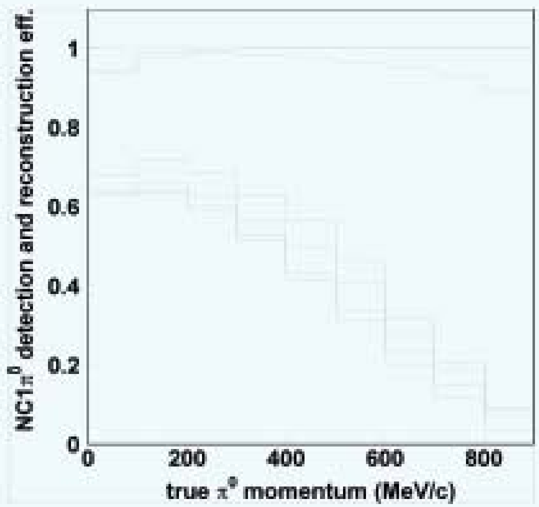
in 25 ton

efficiency correction

π^0 detection efficiency curve
estimated by MC



overall efficiency : ~47%



FADC peak cut
(effectively
1000p.e. cut)

FC cut

Nring = 2
1st ring is e-like
2nd ring is e-like
invariant mass cut

systematic errors for overall efficiency

ring counting	3.6 %
PID	2.1 %
escale(+-3%)	0.5 %
total	4.3 %

systematic error on purity

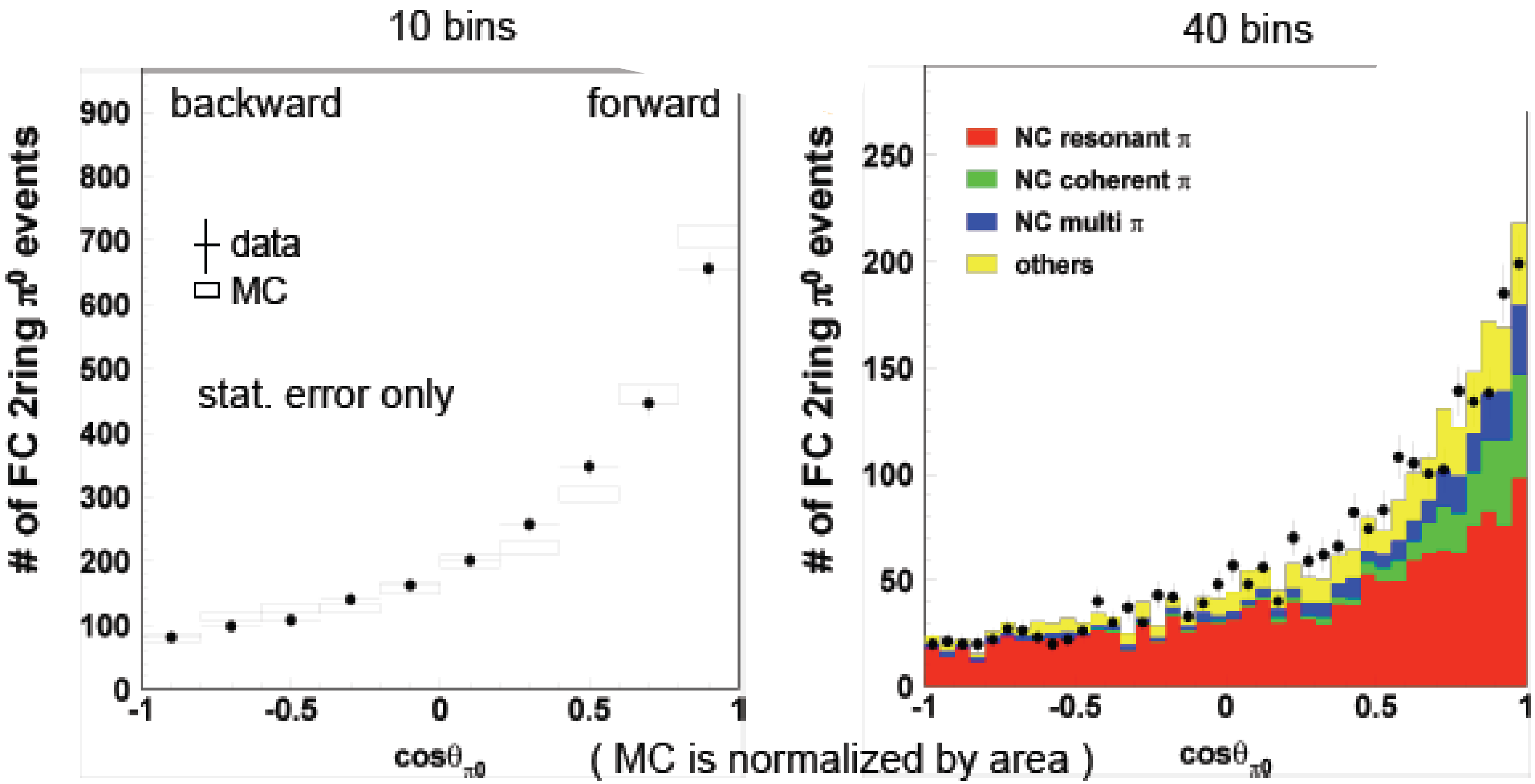
total: 6.9 %

ν cross section	6.2 %	
MA(QE) 1.1→1.0 && MA(1π) 1.1→1.0		0.2 %
QE cross section +-10%		<<1 %
1π cross section +-10%		0.9 %
DIS cross section +-5%		0.5 %
w/o Bodek reweighting(DIS)		5.1 %
w/o Marteau reweighting(coherent π)		1.5 %
CC/NC +-20%		2.8 %
nuclear rescattering	1.9 %	
absorption +-30%		1.6 %
inelastic scattering +-30%		1.0 %
π^0 from nucleon(or π) interaction in water (2nd interaction)	2.3 %	
total cross section +-20%		2.3 %

estimated by reweighting

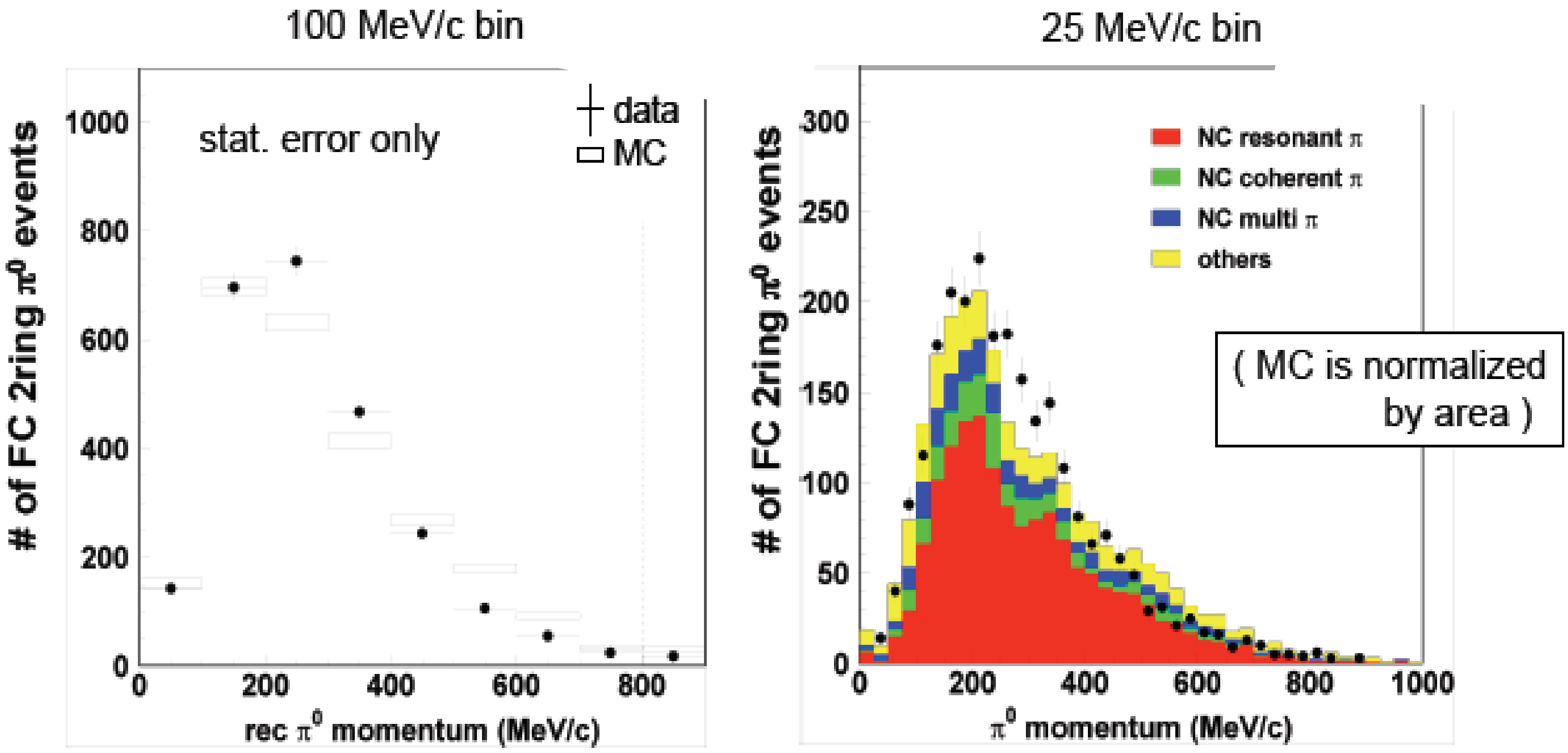
estimated from different MC sets generated with varied cross section

π^0 production angle distribution



Agreement between data and neutrino MC is good.

π^0 momentum distribution



The observed data is reproduced fairly well by our neutrino MC.