Neutral Current π^0 Production by Neutrinos at SciBooNE

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Wine and Cheese Seminar

Contents

- Motivation of the measurement
- SciBooNE Experiment
- Analysis
- Result and Summary

Motivation

- Neutral Current π^0 Production (NCπ^0)
- Why NCπ^0？
- π^0 production mechanism
- Goals of the analysis

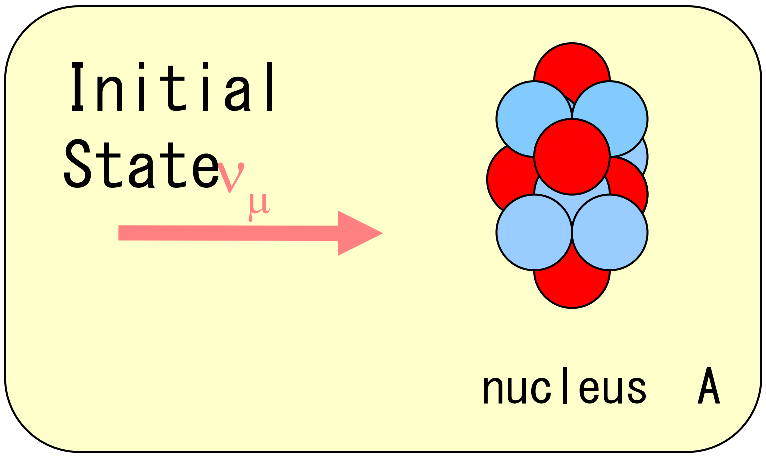
Neutral Current π^0 Production (NCπ^0)

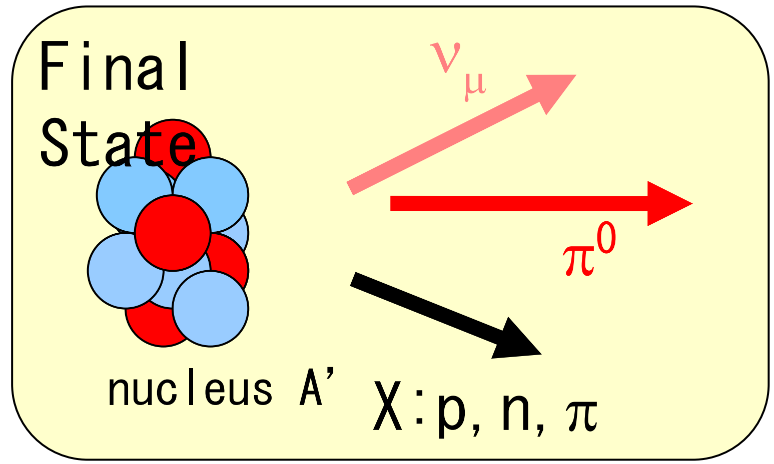
$\nu_\mu + A \rightarrow \nu_\mu + \pi^0 + X + A'$

A, A' : nucleus

X:mesons or baryons

Neutrino-nucleus scattering via neutral current with π^0 at final state





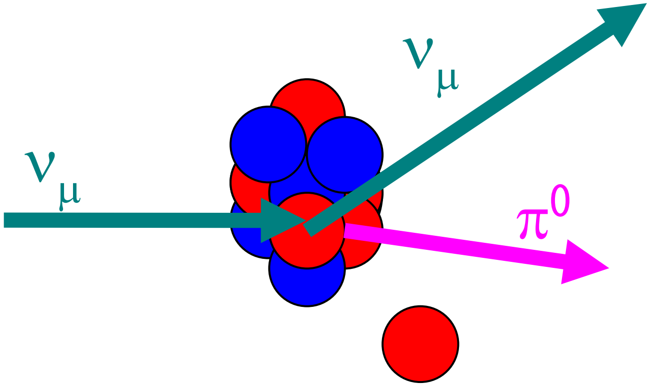
Topic of this talk

Measuring the cross section NCπ^0 at neutrino energy (E_ν) around 1 GeV

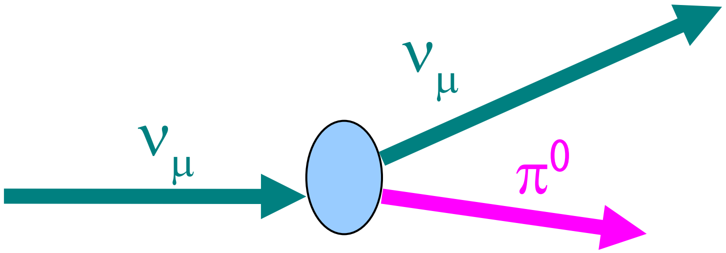
π^0 Production Mechanism

Two dominant mechanism at E_ν=1GeV

Resonant π: ν excites nucleon to a resonance decaying to π	Coherent π: ν interacts with whole a nucleus emitting π^0



recoil nucleon



No recoil nucleon

ν and π in a forward directio

resonant π: coherent π = 4:1 at SciBooNE (E_ν=0.7 GeV)

NCπ^0 generally means inclusive π^0 production for the resonant π and coherent π

Why NCπ^0 (1)

Neutrino Oscillation

Neutrino Oscillation : Neutrino produced as a specific flavor can be later measured as a different flavor. This occurs when $|\nu_{mass}\rangle \neq |\nu_{flavor}\rangle$ ($m_\nu != 0$)

Neutrino Mixing Matrix

Atmospheric ν ? solar ν

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

cij, sij : $\cos\theta_{ij}$, $\sin\theta_{ij}$ δ:CP phase($\delta != 0 \Leftrightarrow$ CP violation)

- θ_{12} and θ_{23} are measured to be 30° and 45°
- θ_{13} is not yet observed($\sin^2 2\theta_{13} < 0.15$)
- CP phase δ is always coupled with $\sin\theta_{13}$

→ θ_{13} measurement

Why NCπ^0 ? (2)

θ_{13} measurement by long baseline neutrino experiments

Searching $\nu_\mu \rightarrow \nu_e$ oscillation using long baseline ($O(100\text{km})$) ν_μ beam ($O(1\text{GeV})$) $\Leftrightarrow$ θ_{13} measurement ($P(\nu_\mu \rightarrow \nu_e) \propto \sin^2 2\theta_{13}$)

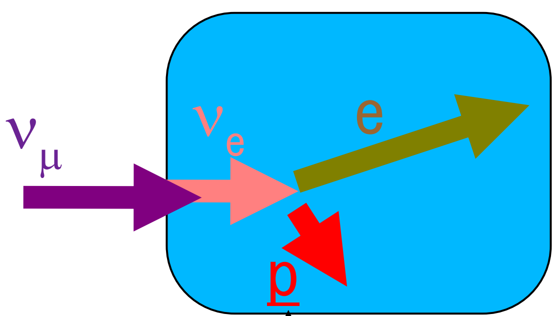
T2K (2009～)　NOvA (2012～)

ν_μ NCπ^0: One of the largest background for $\nu_\mu \rightarrow \nu_e$ search in the T2K experiment

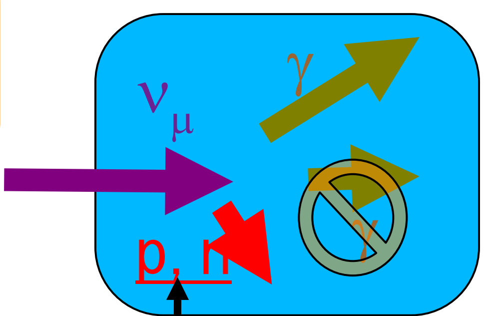
T2K: L_ν=295km, $\langle E_\nu \rangle$=0.8GeV, Super-K (water Cherenkov)

ν_e signal: $\nu_e + n \rightarrow e + p$

Background: ν_μ NCπ^0



Can not distinguish if 1γ is missed

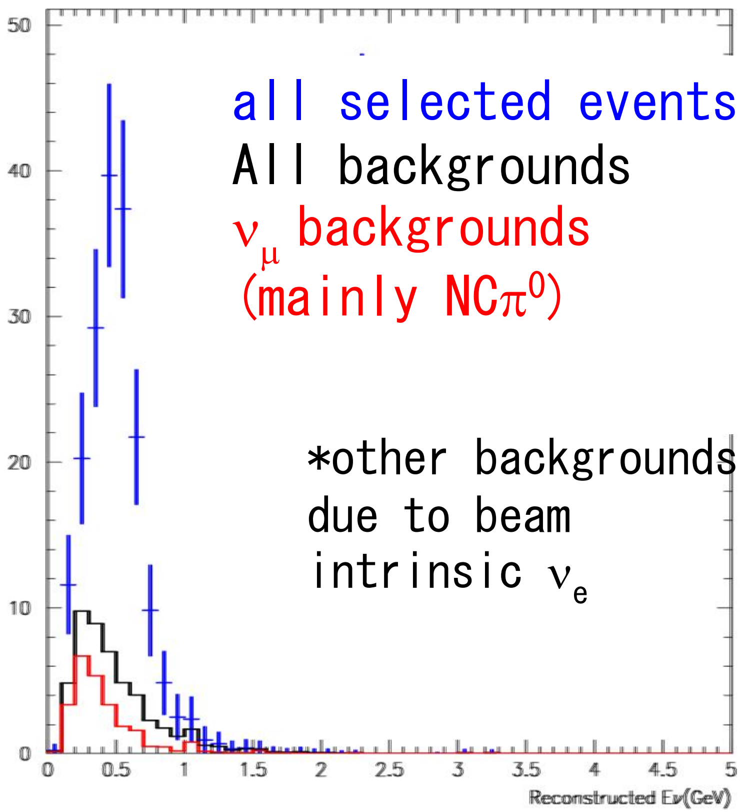


Nucleon is below Cherenkov threshold

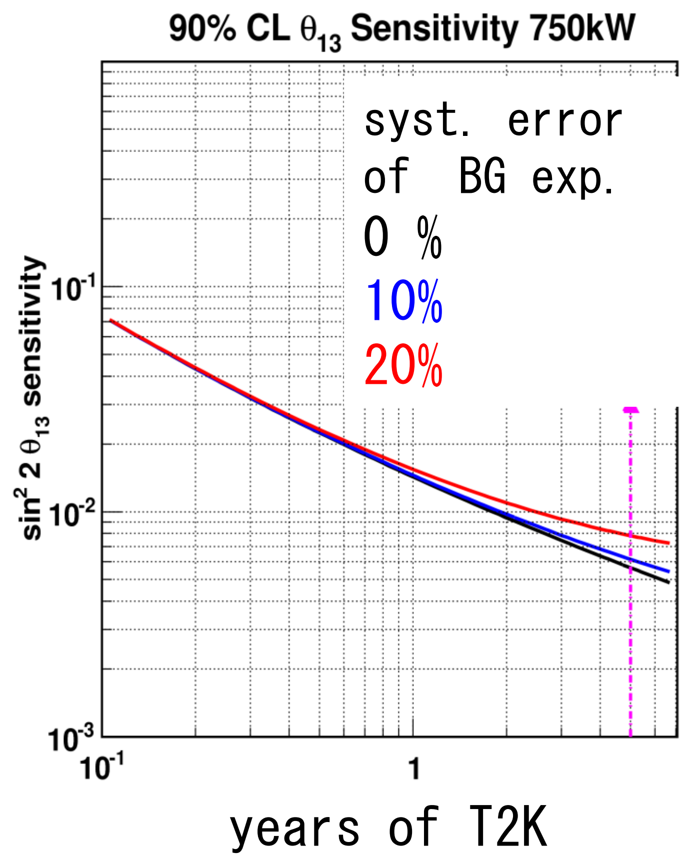
Goal1 : Total $NC\pi^0$ cross section

θ_{13} measurement in T2K

ν_e energy spectrum : assuming 5 years measurement and $\sin^2 2\theta_{13}$=0.1



$Sin^2 2\theta_{13}$ sensitivity: assuming 750kW beam and Super-K



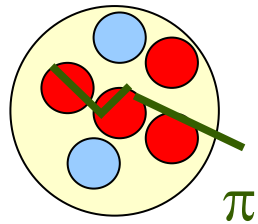
Need measure $\sigma(NC\pi^0)/\sigma(CC)$* within 10 % uncertainty

* The ratio to σ(CC) is enough because the T2K measure ν_μ flux using CC interactions

Goal2 : π Kinematics distribution

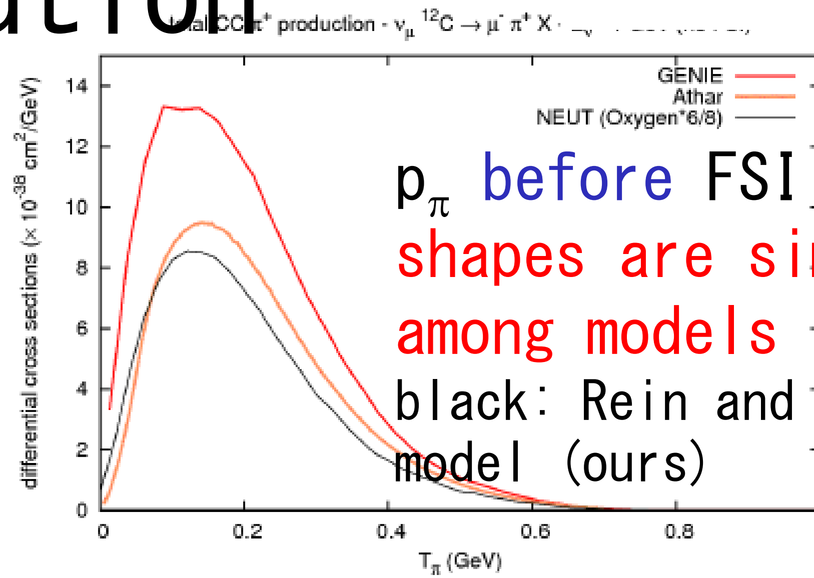
Intra-nuclear interaction (FSI)

- π^0 can be absorbed, scattered and newly produced in nucleus

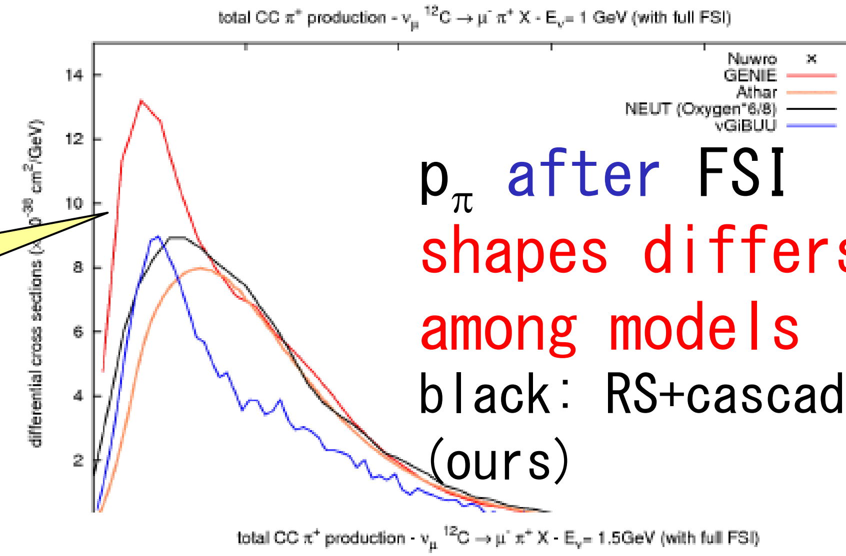


Need predict π^0 emitted from nucleus for different nuclear targets

Ex. SciBooNE CH
Super-K H_2O



p_π before FSI
shapes are similar among models
black: Rein and Sehgal model (ours)



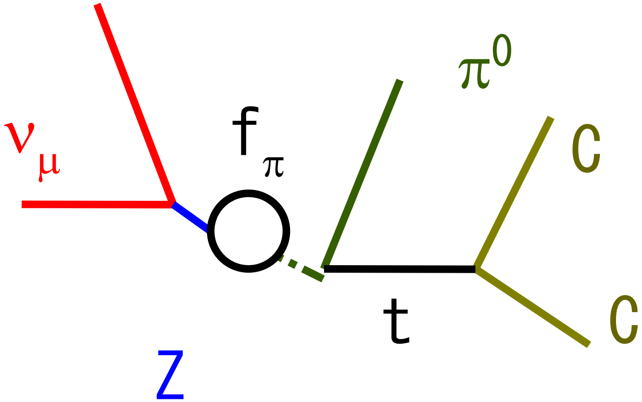
p_π after FSI
shapes differs among models
black: RS+cascade model (ours)

Large difference among models

→ Need measure the π kinematics as well as σ

by Jan Sobczyk's slides in Nuint. 2009

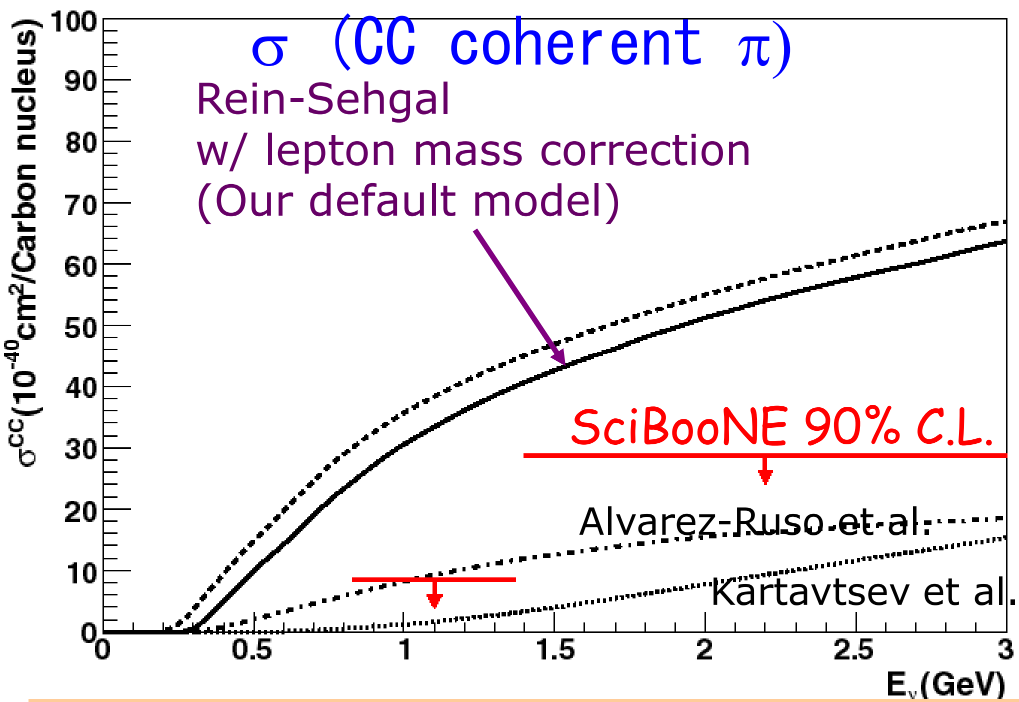
Goal3: NC coherent π measurements



1/t=R=2.3fm
t=100 MeV

interesting topic in a view of ν interaction physics

No observation of CC events in SciBooNE, K2K around 1GeV



MiniBooNE observed NC events

Our model (Rein and Sehgal)

- σ is expressed by $\sigma(\pi C \rightarrow \pi C)$ and f_π at $Q^2=0$ (PCAC)
- extrapolated to $Q^2 != 0$ multiplying $\{m_A^2/(Q^2+m_A^2)\}^2$ (m_A=1GeV)

→ $\sigma(CC) = 2\sigma(NC)$
$\sigma(\nu) = \sigma(\nu\text{-bar})$

→ Want check the MiniBooNE result by SciBooNE

Three Goals

We measure

1. σ(NCπ^0 resonant+coherent) at E_ν<1GeV with less than 10 % uncertainty
2. π^0 kinematics
3. σ(NC coherent π^0)

Result 1 & 2 were published in Phys. Rev. D81, 033004 (2010)

Result 3 is by updated analysis after this publication

SciBooNE
FNAL E954

SciBooNE Collaboration

Mar 18, 2008

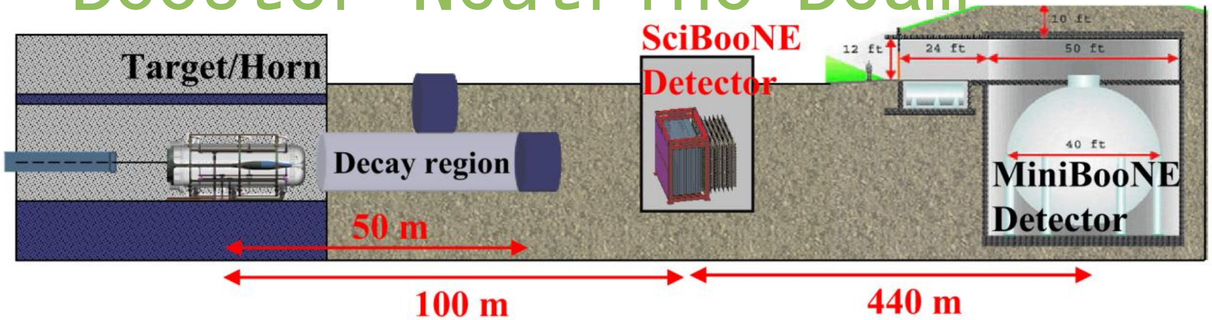
- Universitat Autonoma de Barcelona
- University of Cincinnati
- University of Colorado, Boulder
- Columbia University
- Fermi National Accelerator Laboratory
- High Energy Accelerator Research Organization (KEK)
- Imperial College London
- Indiana University
- Institute for Cosmic Ray Research (ICRR)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

~70 physicists
5 countries 17 institutions

Spokespeople:
M.O. Wascko (Imperial), T. Nakaya (Kyoto)

Motivations

Booster Neutrino Beam

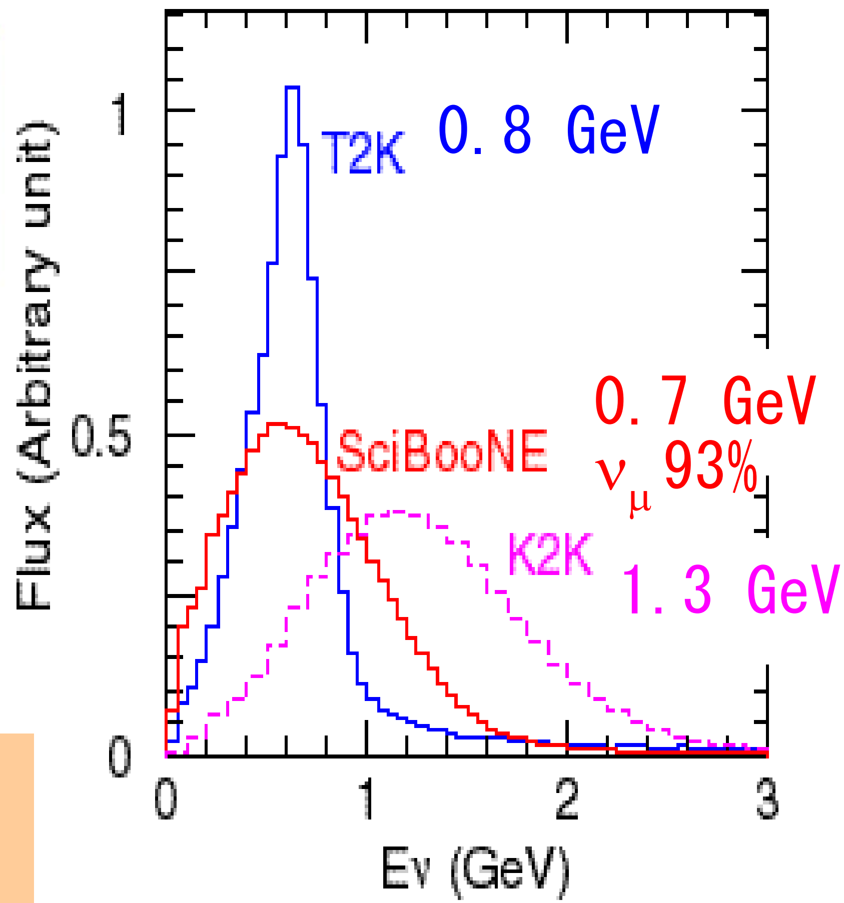


measurement of σ(ν-nucleus) at 1 GeV

- needed for the future neutrino oscillation experiments

→ $NC\pi^0$ measurement is one of the main modes of SciBooNE

Eν spectra



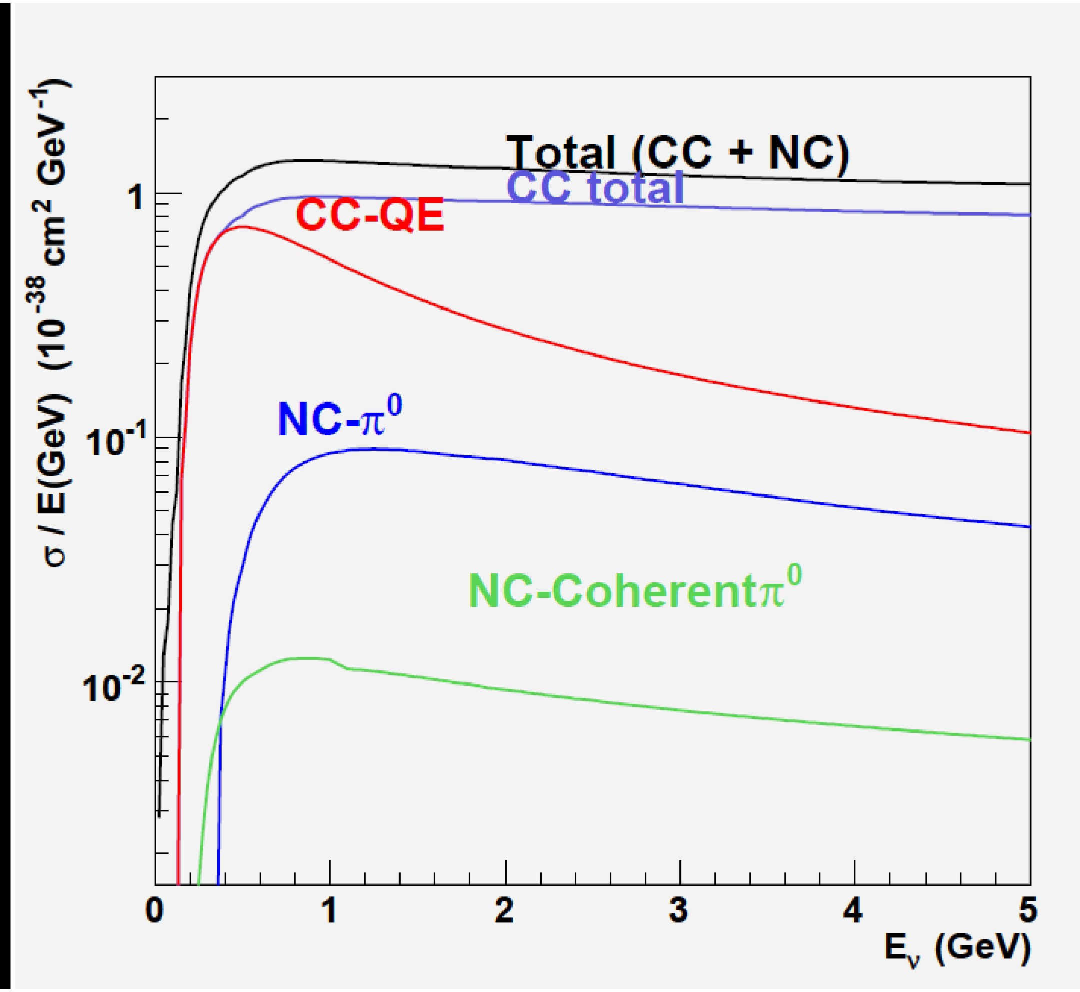
As a near detector of MiniBooNE

Short baseline neutrino oscillation search

→ SciBooNE results can be used in T2K

NEUT

Neutrino Event Generator



Used for Super-K、K2K、SciBooNE、T2K

Quasi Elastic (QE) $\nu_\mu n \rightarrow \mu p$

Llewellyn-Smith formalism

resonant π production

Rein-Sehgal (2007)

Coherent π production

Rein-Sehgal (2006)

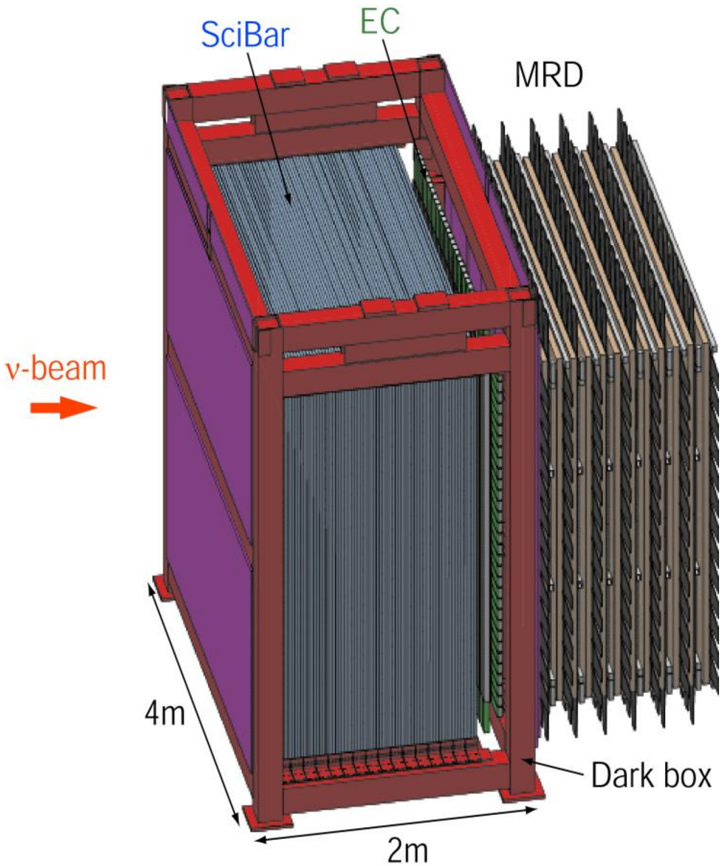
DIS

GRV98 PDF

Bodek-Yang correction

For recoil nucleon in nucleus, the relativistic Fermi gas model of Smith and Moniz is used

SciBooNE Detector



SciBar

Next page

EC (Electron Cather)

Spaghetti type EM calorimeter

- SciFi embedded in lead sheet
- detecting e and γ, 11 X_0
- 2 planes (horizontal vertical)

Muon Range Detector

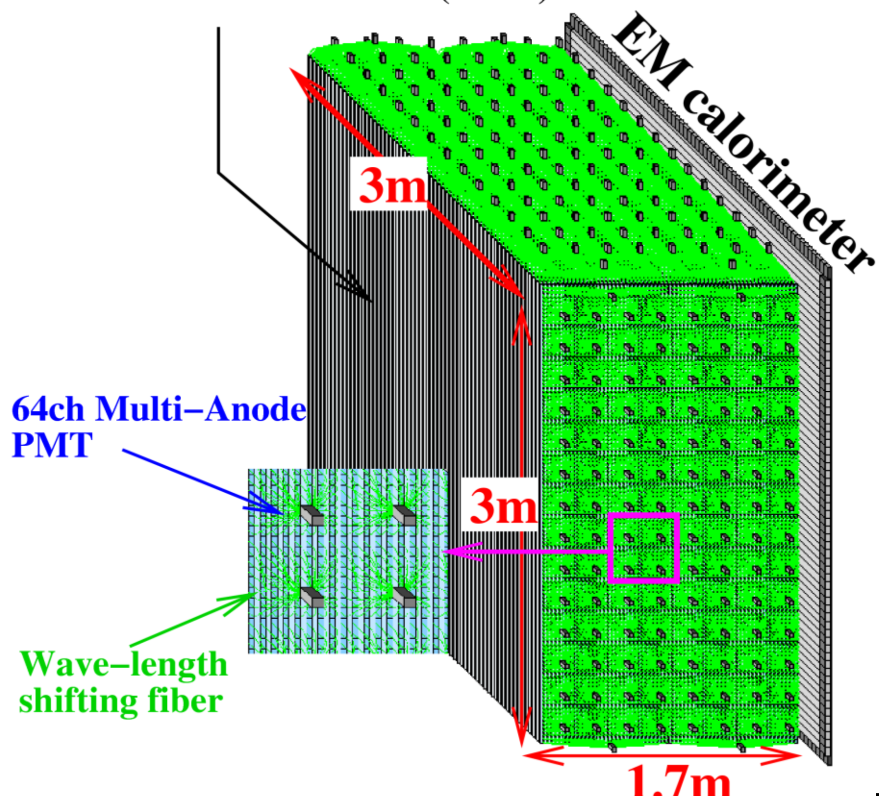
Iron-Scintillator sandwich detector

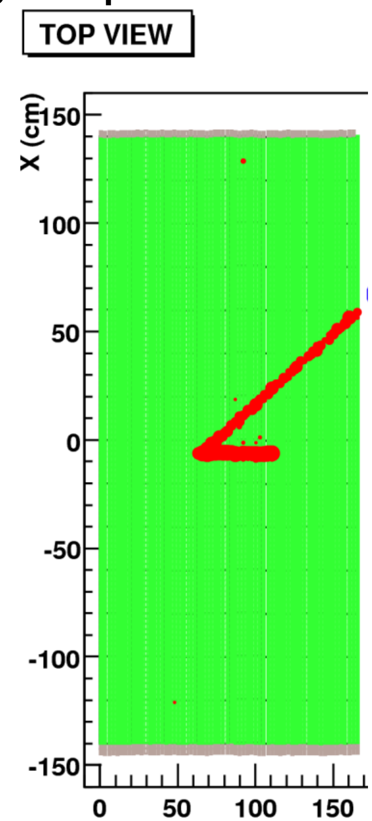
- μ momentum measurement

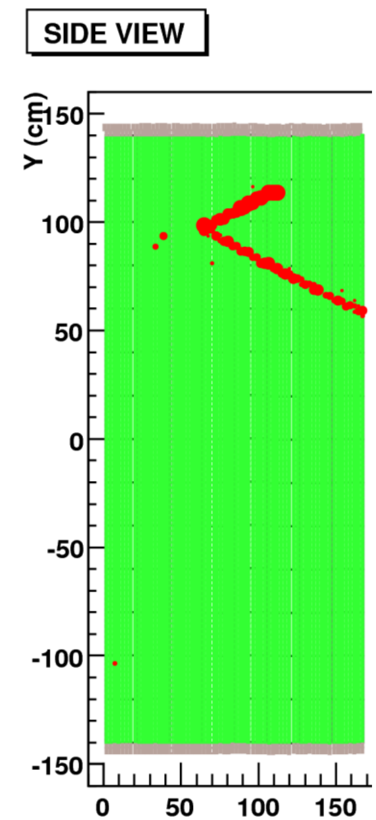
SciBar and EC are mainly used in this anlaysis

SciBar

Neutrino target and charged particle tracker







- Fully active and fine grained detctor (14336 scintillator bars)
- 3m x 3m x 1.7m , 15tons
- identification of p $\pi(\mu)$ by dE/dx

4 X_0 (X_0 = 40 cm)

3D event reconstruction is done using two 2D images (top view and side view)

NCπ^0 Event Selection

Signal Definition

$\nu_\mu + A \rightarrow \nu_\mu + \pi^0 + X + A'$ in SciBar

A, A' : nucleus

X: mesons or baryons

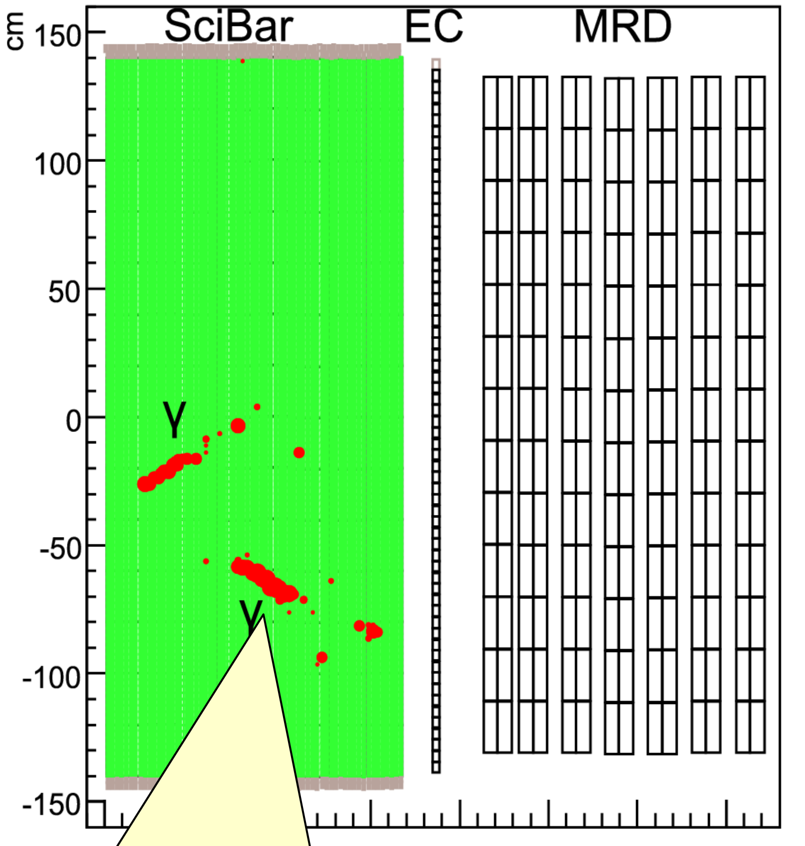
π^0 should be emitted by ν target nucleus

- including π^0 secondary produced by FSI

Note:

Must find 2γ converted to EM showers in SciBar. However, Only 30 % of $NC\pi^0$ as 2γ converted to EM showers

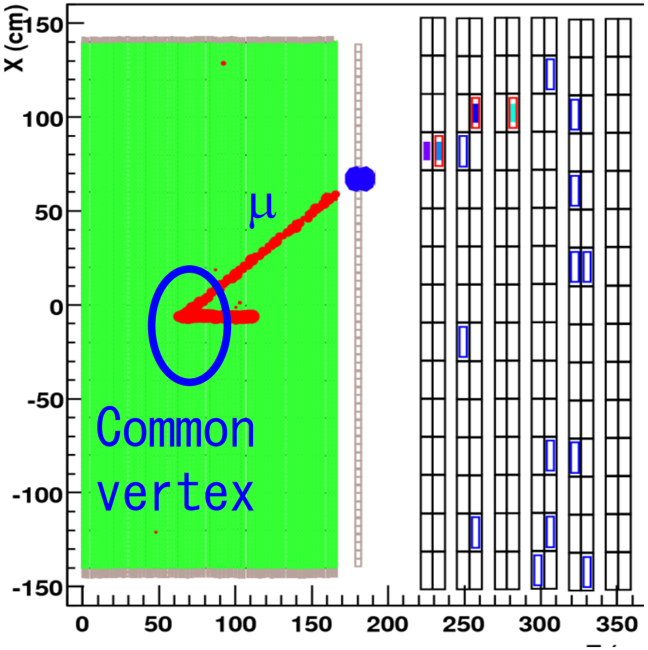
$NC\pi^0$ candidate



An EM shower is observed as "1 track + hits around the track"

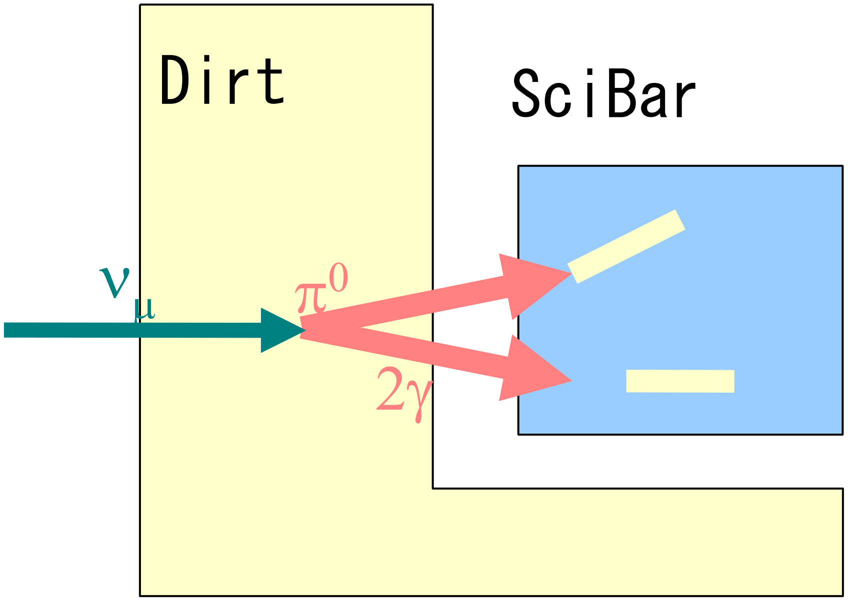
Main background events

Charged current



- #(CC) > 10x#($NC\pi^0$) before selections
- rejected by detecting μ or common vertex

Dirt background events



- charged particle can be rejected using the 1st layer
- γ, n survive after the 1st layer veto

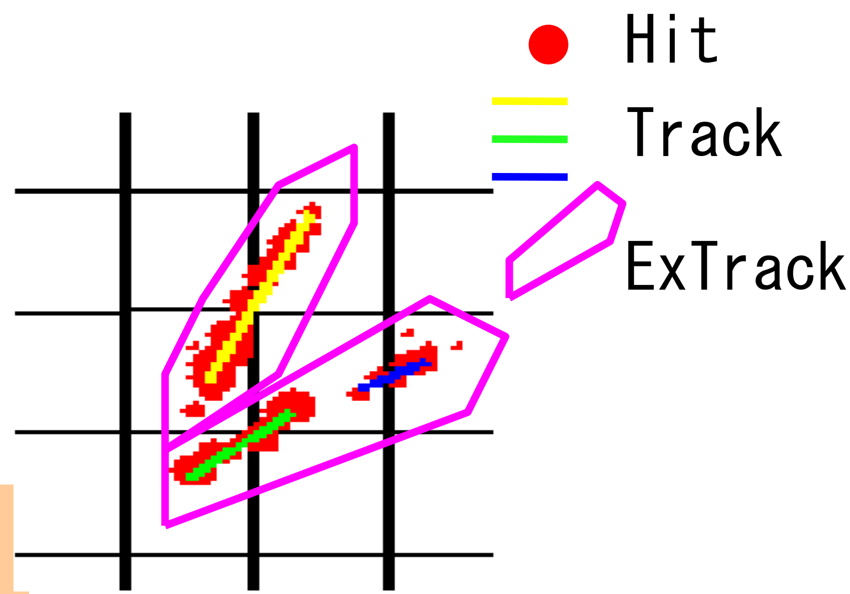
→ Need reject CC events and dirt background events

Particle Reconstruction

What is needed

- γ reconstruction (1 track + hits around the track)
- p、μ identification (CC rejection)
- finding common vtx (CC rejection)

→ Track Reconstruction



Normal Track (Track)

- fitting continuous hits with straight line
- Hit threshold is 2.5p.e.
- p and μ identification
- for all SciBooNE analysis

Extended Track (ExTrack)

- for γ reconstruction
- merging co-linear tracks
- collecting hits within less than 20 cm from original track
- not using proton track (dE/dx)

Overview of Event selections

Pre-selection

$>=$ 2 Tracks in FV
No 1st Layer hits

CC rejection by μ identification

No side escaping track (1)
No decay electron (2)
No track reaching MRD (3)

CC rejection using event topology

No common vertex (4)

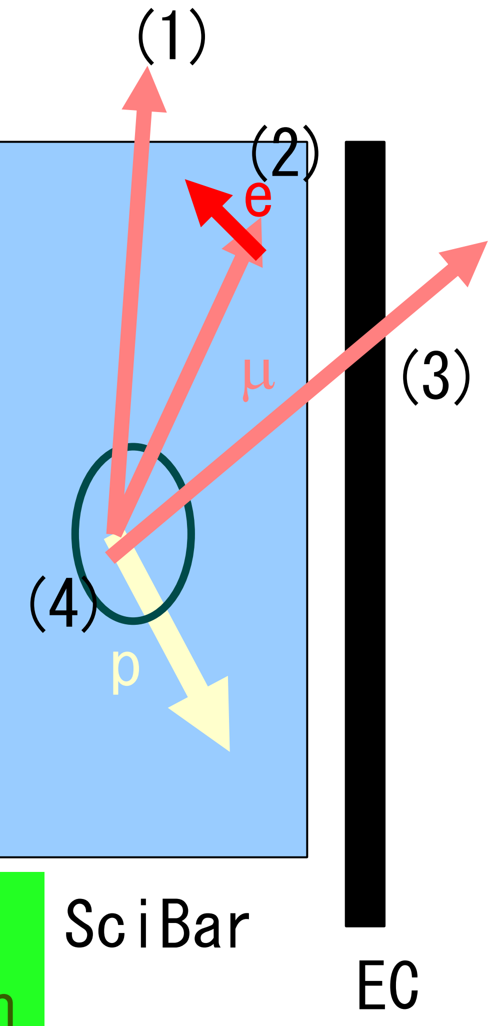
CC rejection → Using Track

π^0 selection by $\gamma(\pi^0)$ reconstruction

$>=$ 2 Extracks
π^0 vertex in SciBar
$M_{2\gamma} = \pi^0$ mass

γ, π^0 reconstruction → Using ExTrack

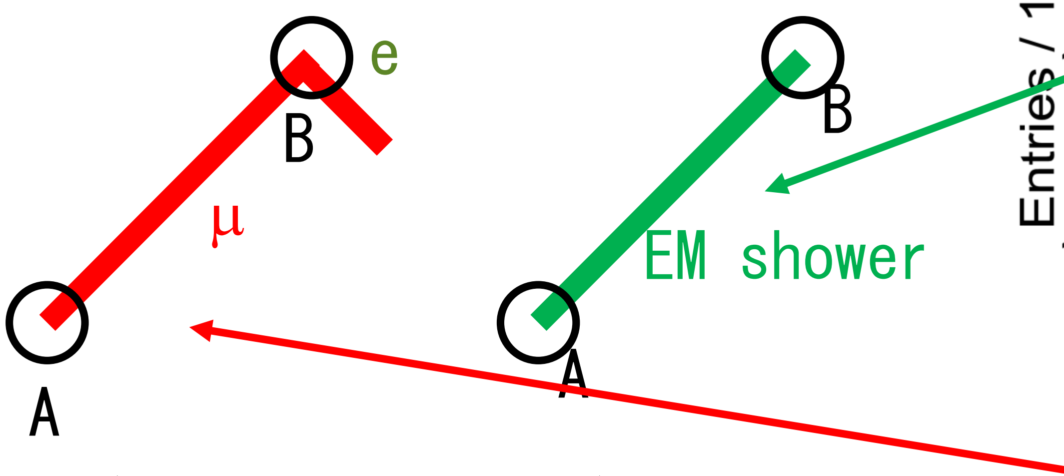
Typical CC events



μ identification using decay-e

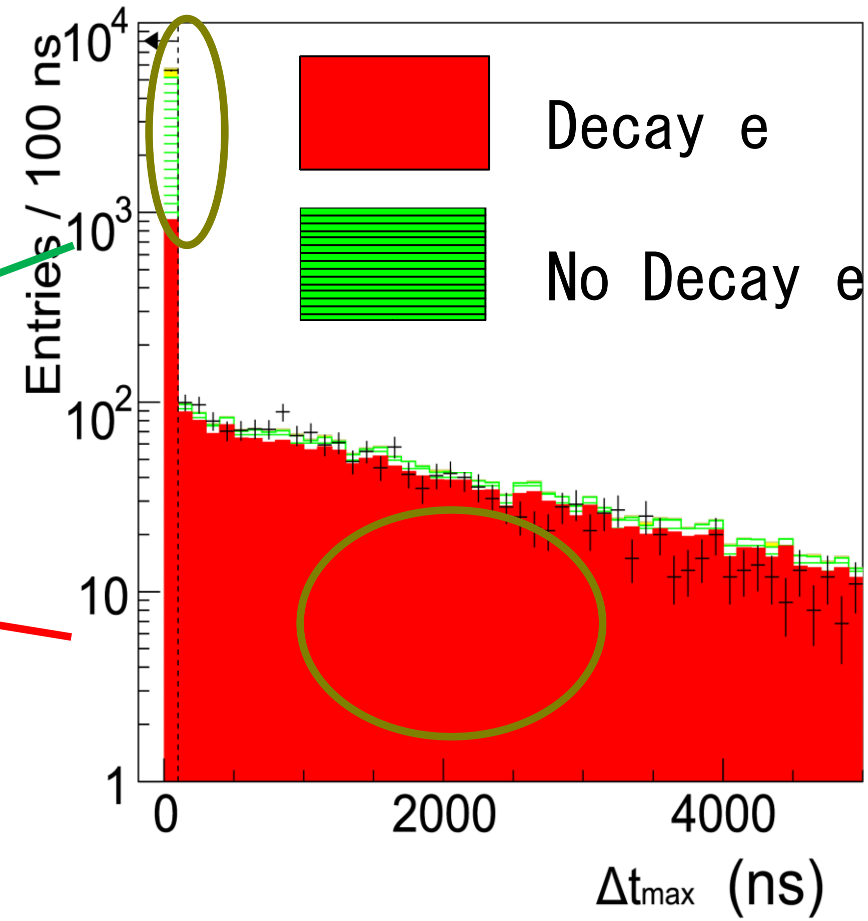
For tracks stopping in SciBar

Timing difference between track edges (No charged information is recorded for delayed particles)



Max(TimeB-TimeA)

Max(TimeB-TimeA)



= μ lifetime (2.2us)
Flight time (10 ns)

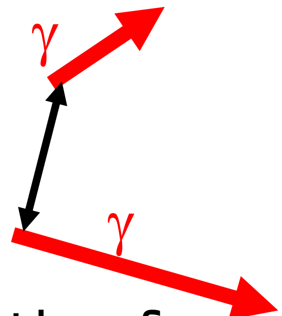
Select <100 ns

Efficiency 94%
Reject 31% of BG

CC rejection using track distance

2γ from π^0

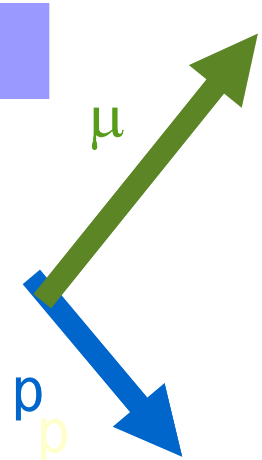
Isolated tracks



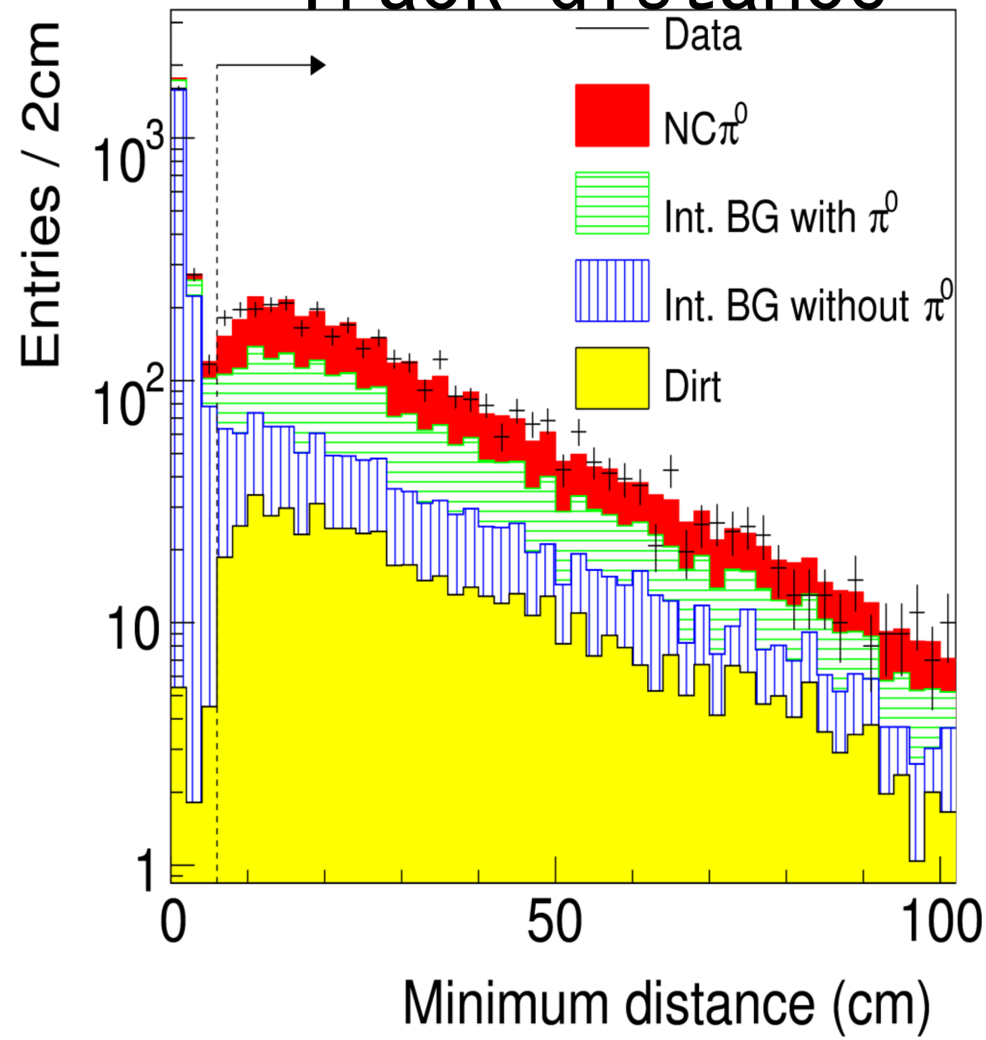
The radiation length of SciBar(C_8H_8) is 40 cm

Charged current

Common vertex



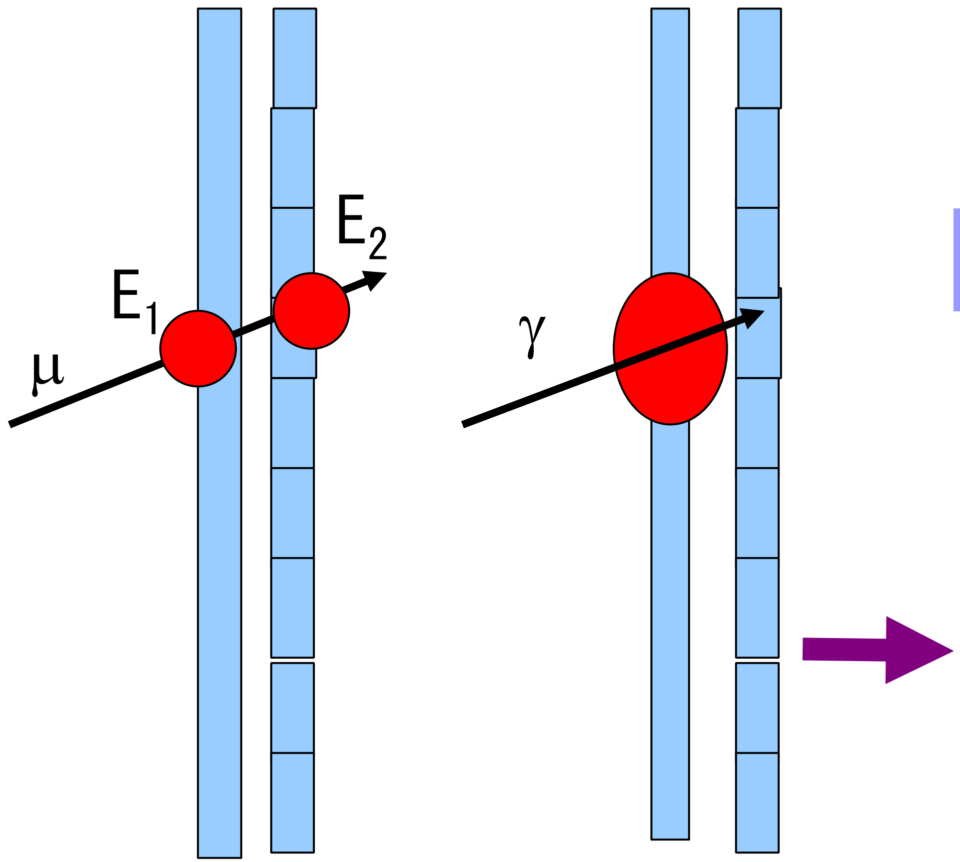
Track distance



Select >6cm

CC rejection using EC (1)

EC: spaghetti calorimeter, 2 planes



$R_{EC}=E_2/E_1$

μ

- small dE/dx
- same energy deposit for both plane

γ

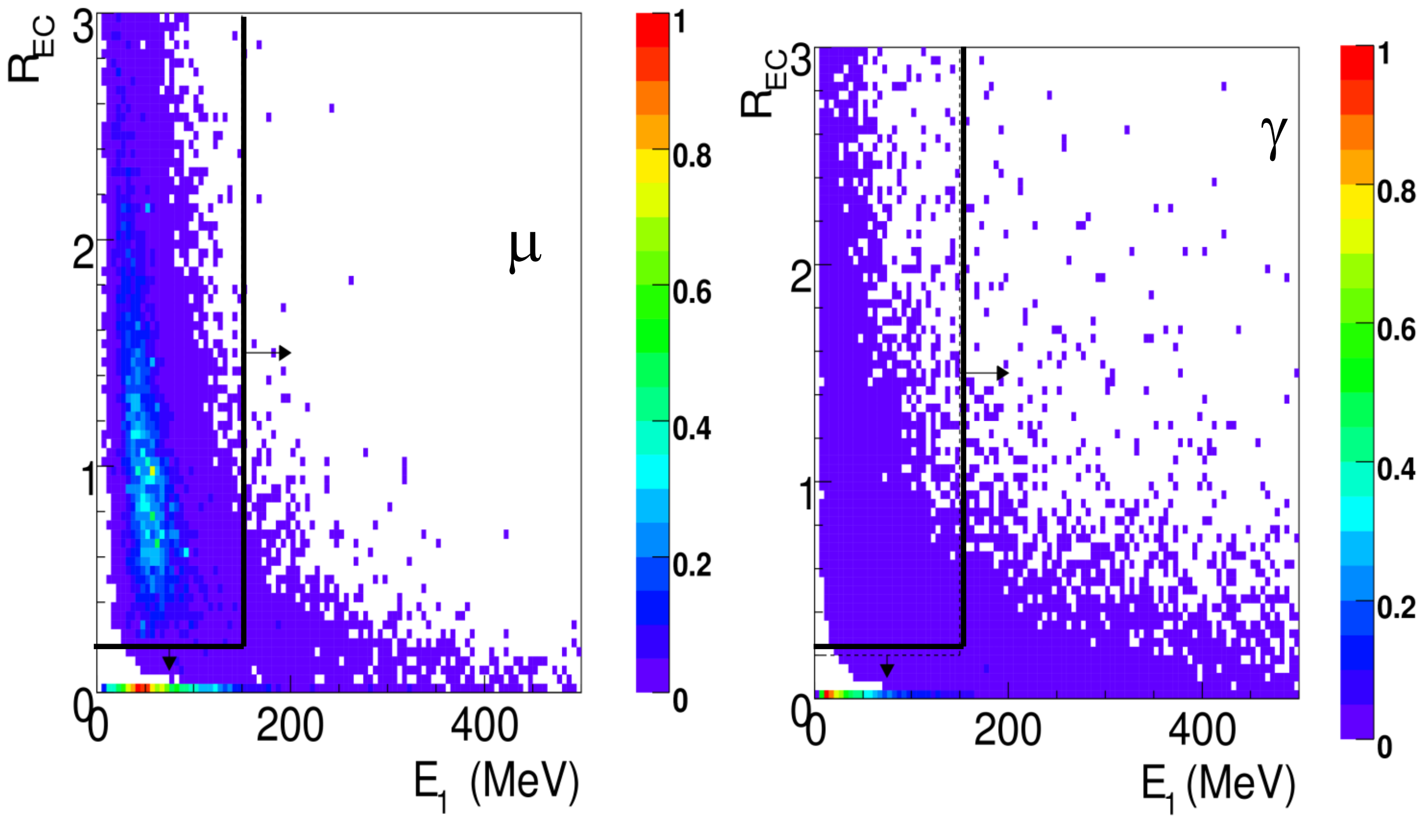
- Larger energy deposit in the upstream plane

E_1 : energy deposit in the upstream plane
R_{EC} : energy ratio of the donwstream plane to E_1

μ:E_1<100MeV, $R_{EC}\simeq 1$

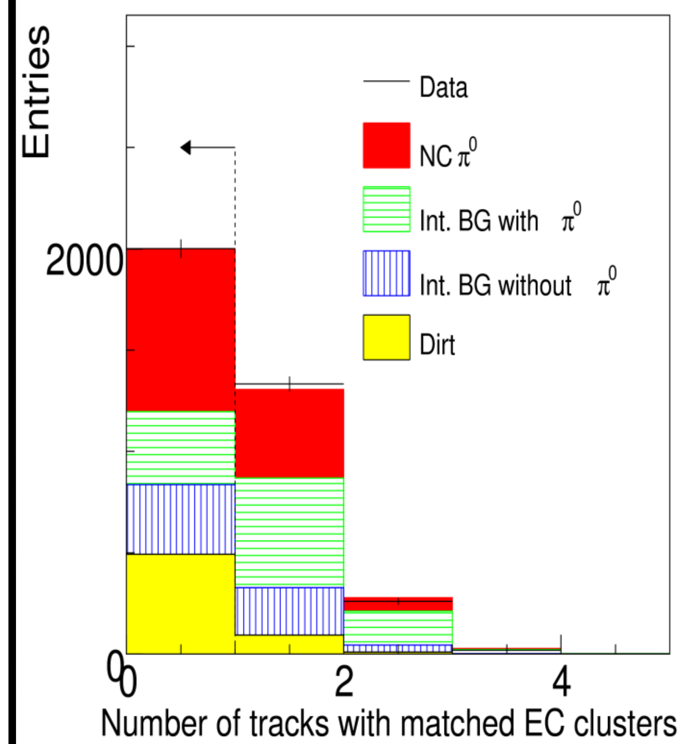
CC rejection using EC (2)

E_1 : energy deposit in the upstream plane
R_{EC} : energy ratio of the downstream plane to E_1



E1>150 or R_{EC}<0.2 for events w tracks reaching EC

Number of tracks with matched EC clusters



Select events w/o tracks reaching EC

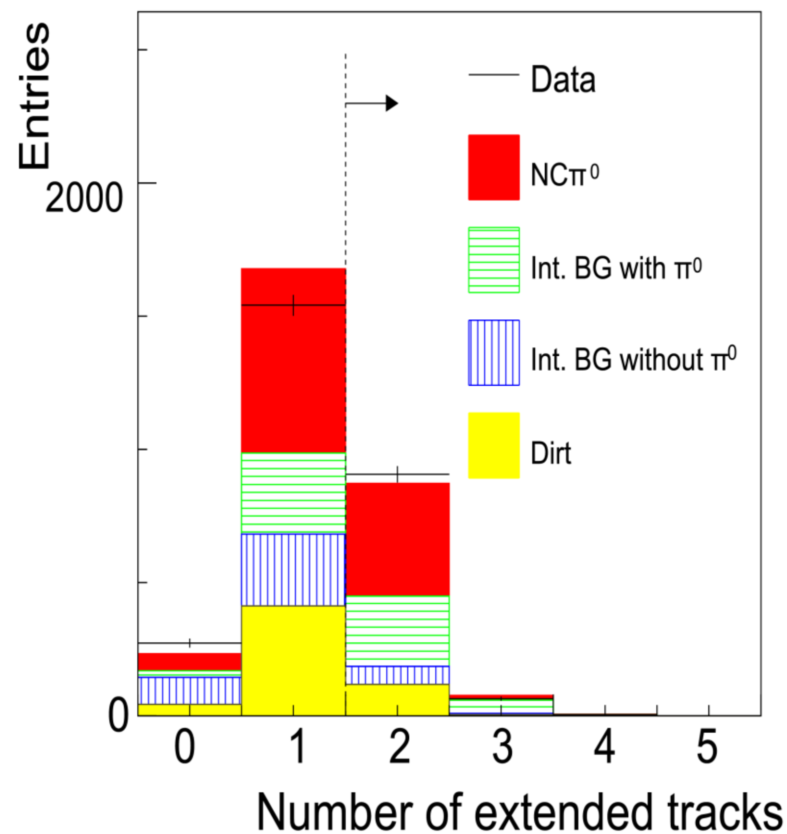
Efficiency 91%、reject 28% of BG

2γ selection using Extended track

Extended Track, again

- merging co-linear tracks
- collecting hits within less than 20 cm from original track
- Not using proton tracks (dE/dx)

#ExTracks

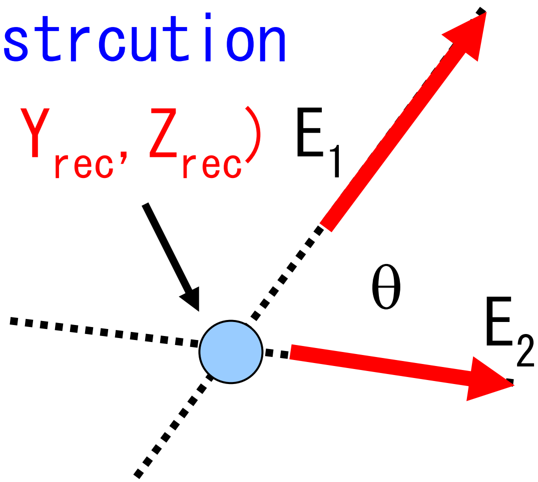


Select #ExTracks >= 2 for π^0 reconstuction

π^0 Selections

π^0 vertex and mass reconstrcution

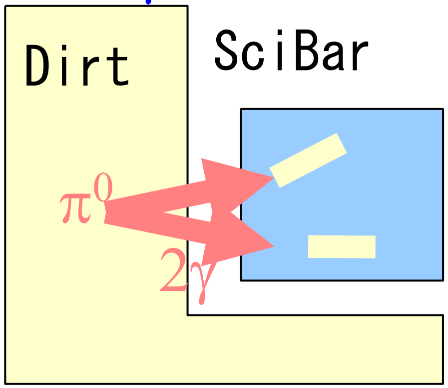
(X_{rec}, Y_{rec}, Z_{rec})

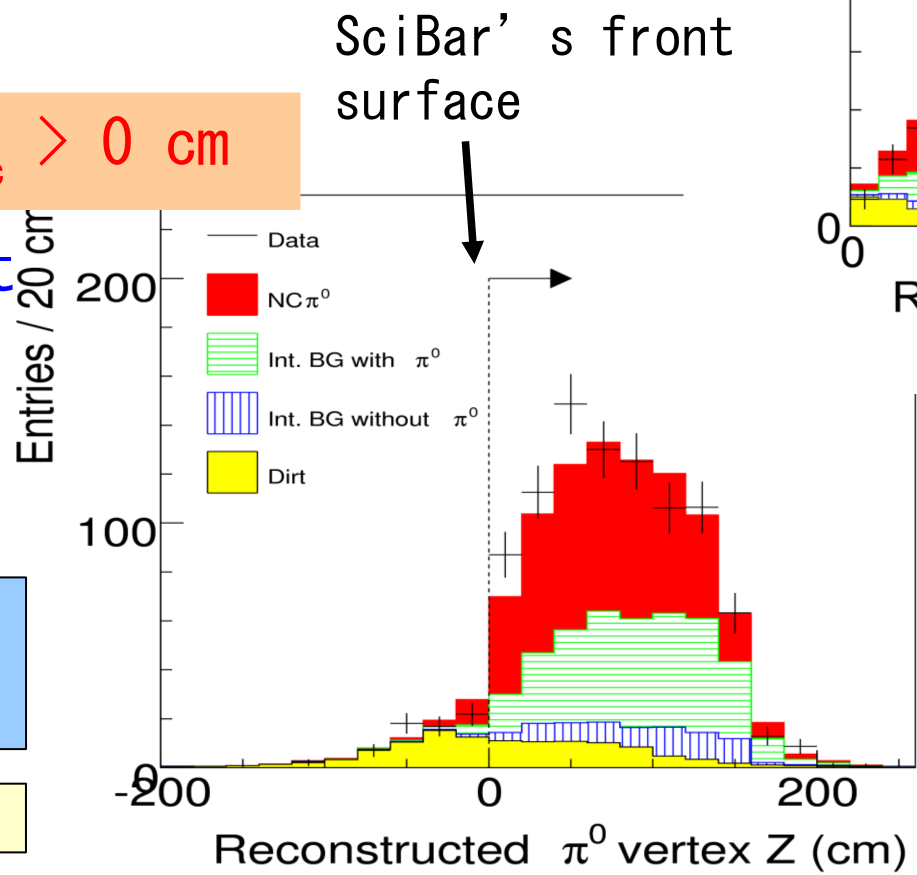


Z_{rec}

Z_{rec} > 0 cm

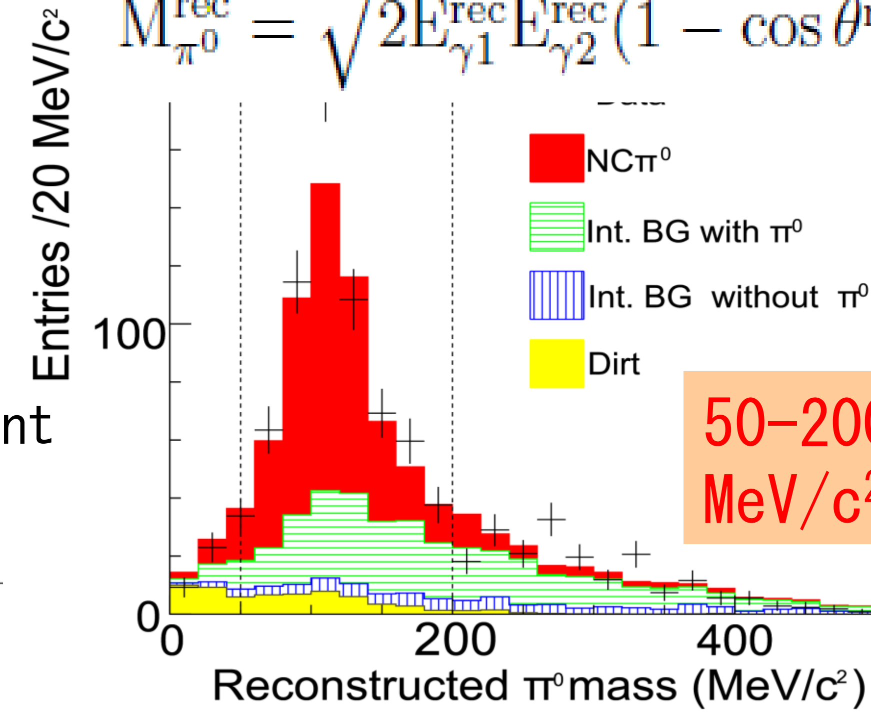
Rejecting dirt events due to $\pi^0 \rightarrow 2\gamma$





2γ invariant mass

$$M_{\pi^0}^{rec} = \sqrt{2E_{\gamma 1}^{rec} E_{\gamma 2}^{rec} (1 - \cos\theta^{rec})}$$



50-200 MeV/c^2

657 events selected
Efficiency: 5.3%
Expected BG: 240

Summary of Event Selections

	DATA	MC			$NC\pi^0$
		$NC\pi^0$ signal	Internal BG (CC)	Dirt BG	Efficiency
Pre selection	11,926	1,893	9,808 (9050)	895	27.3%
μ rejection (SciBar)	5,609	1,377	3,785 (3326)	606	19.8%
Isolated tracks	3,614	1,314	1,706 (1306)	595	18.9%
μ rejection (EC)	2791	1202	1088 (714)	579	17.3%
2γ selections	973	443	389 (294)	121	6.5%
π^0 vertex	905	428	382 (288)	65	6.2%
π^0 mass	657	368	202 (140)	38	5.3%

CC rejections

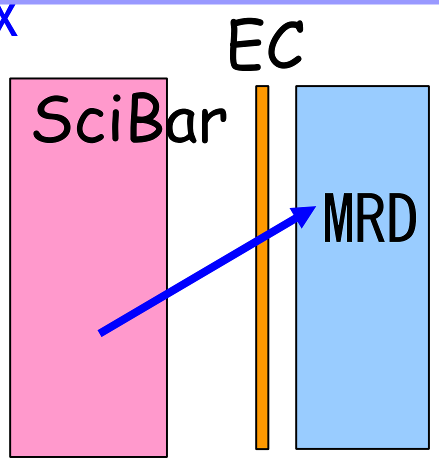
Dirt background rejections

Goal 1: NCπ^0 Cross section Measurement

CC event sample

Cross section ratio to CC events to reduce the flux

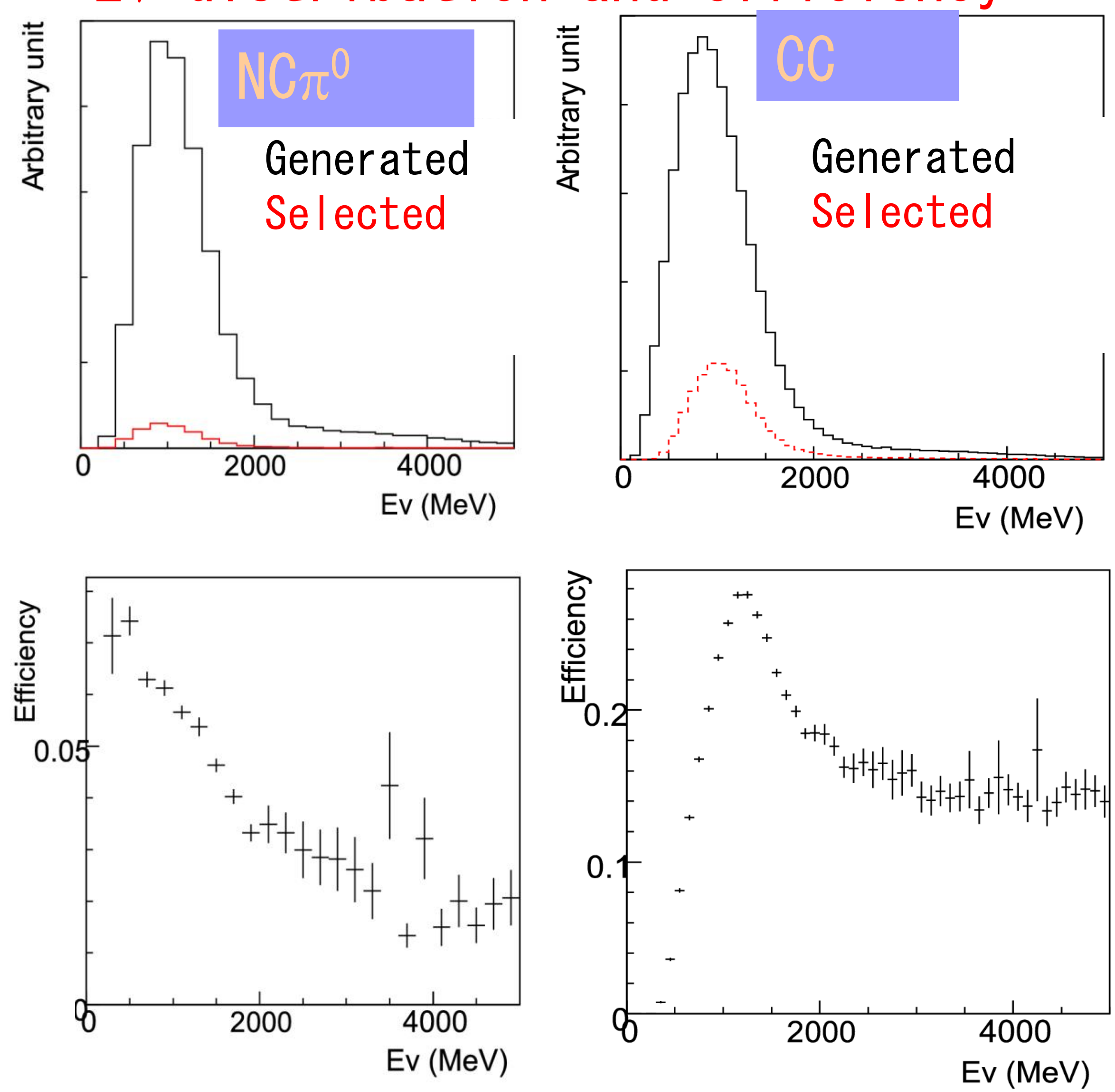
MRD-stopped sample



Track starting in SciBar and stopping in MRD

21702 events selected
Efficiency: 19 %
Expected BG: 2348

Eν distribution and efficiency



$\langle E_\nu \rangle$ = 1.1 GeV ($NC\pi^0$)
= 1.2 GeV (CC)

σ(NCπ⁰)/σ(CC)

$$\frac{\sigma(\mathrm{NC}\pi^0)}{\sigma(\mathrm{CC})} = \frac{N(\mathrm{NC}\pi^0)}{N(\mathrm{CC})} = \frac{(N_{\mathrm{obs}} - N_{\mathrm{BG}})\epsilon_{\mathrm{CC}}}{(N^{\mathrm{CC}}_{\mathrm{obs}} - N^{\mathrm{CC}}_{\mathrm{BG}})\epsilon_{\mathrm{NC}\pi^0}}$$

N_{obs}	657
N_{BG}	240
$\varepsilon_{NC\pi 0}$	0.05
$N^{CC}{}_{obs}$	21702
$N^{CC}{}_{BG}$	2348
ε_{CC}	0.19

$$(7.7 \pm 0.5(\mathrm{stat.}) \pm 0.5(\mathrm{sys.})) \times 10^{-2}$$

Total error : $\pm 0.7 \times 10^{-2}$

NEUT expectation 6.8×10^{-2}

- Achieve less than 10 % error
- Discrepancy from the expectation is 1.3 σ
- Largest systematic uncertainty is detector response

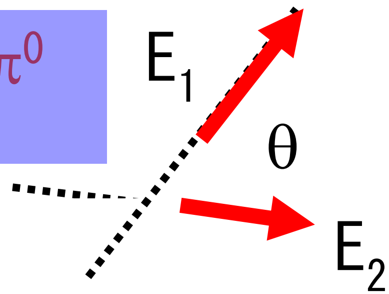
Systematic source

Source	Error ($\times 10^{-2}$)	
Detector response	−0.39	+0.38
ν interaction, nuclear model	−0.25	+0.30
Dirt background	−0.10	+0.10
ν beam	−0.11	+0.22
Total	−0.48	+0.54

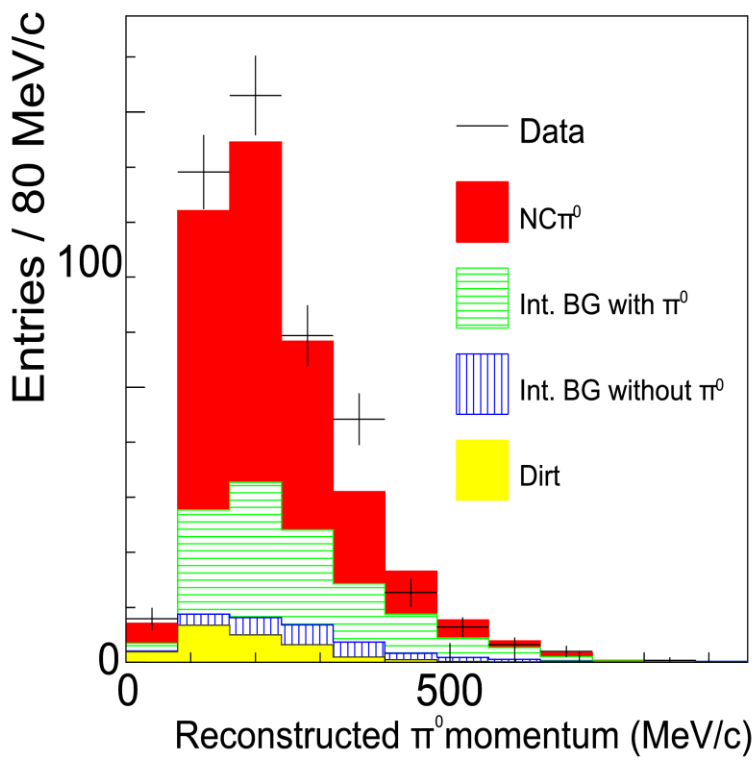
Goal 2 π^0 Kinematics

Reconstructed π^0 kinematics

Reconstructed π^0 momentum

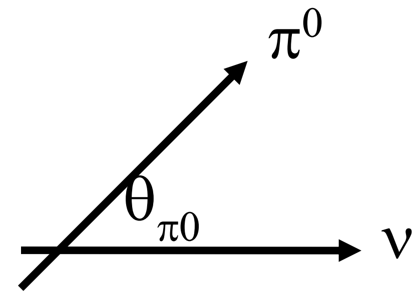


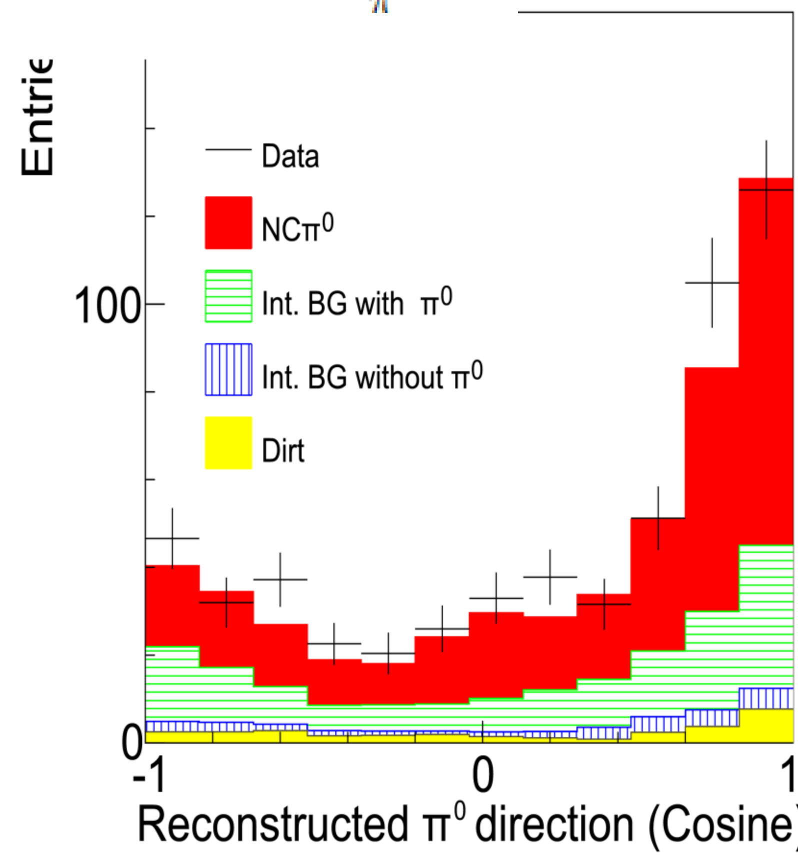
$$P^{rec}_{\pi^0} = \sqrt{E^{rec\,2}_{\gamma 1} + E^{rec\,2}_{\gamma 2} + 2E^{rec}_{\gamma 1}E^{rec}_{\gamma 2}\cos\theta^{rec}}$$



Reconstructed π^0 direction

$$\cos\theta^{rec}_{\pi^0} = \frac{P^{rec}_{z\pi^0}}{P^{rec}_{\pi^0}}$$





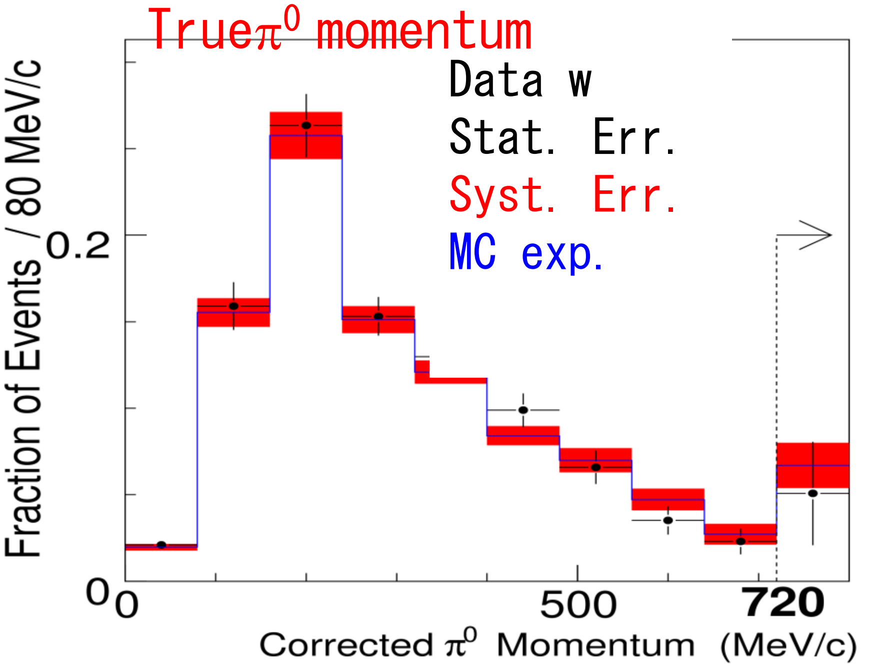
Good agreement between data and MC

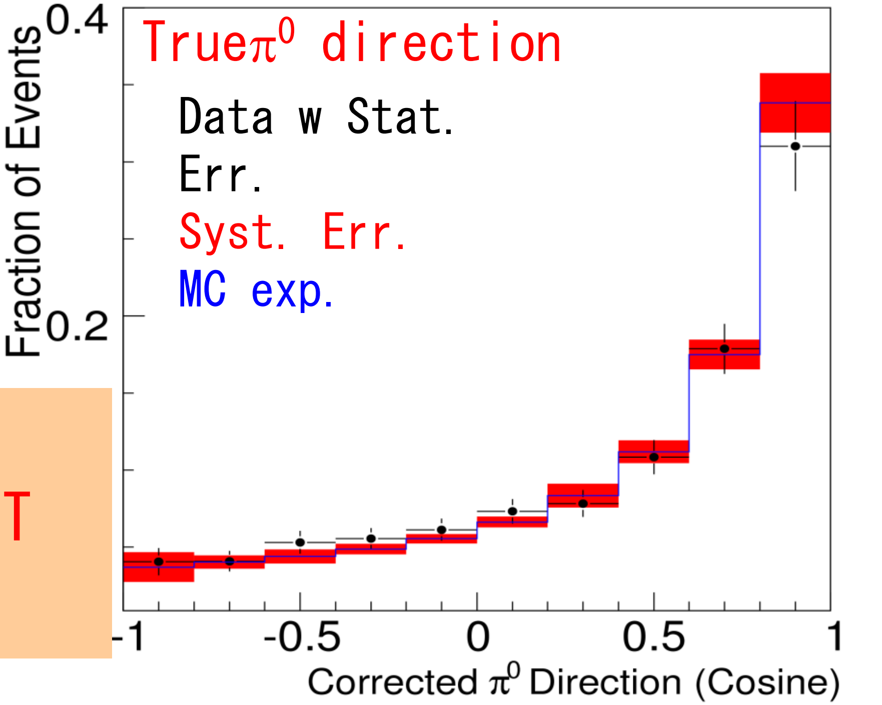
True π^0 Kinematics

True π^0 momentum and direction obtained as follows

1. BG subtraction using MC
2. Reconstructed → True using unfolding matrix obtained by MC
3. Efficiency correction
4. Normalized to be unity for both MC and Data (shape comparison)

Good agreement between data and MC
Can trust on the nuclear model in NEUT at this level of uncertainty (10 %)

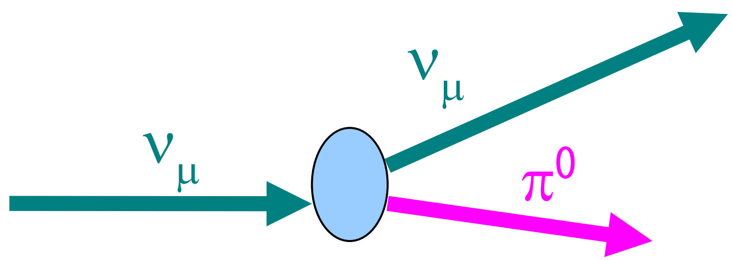




Goal 3: NC coherent π^0 production

Coherent π^0 Production

ν interact with whole nucleus



No nucleon recoil

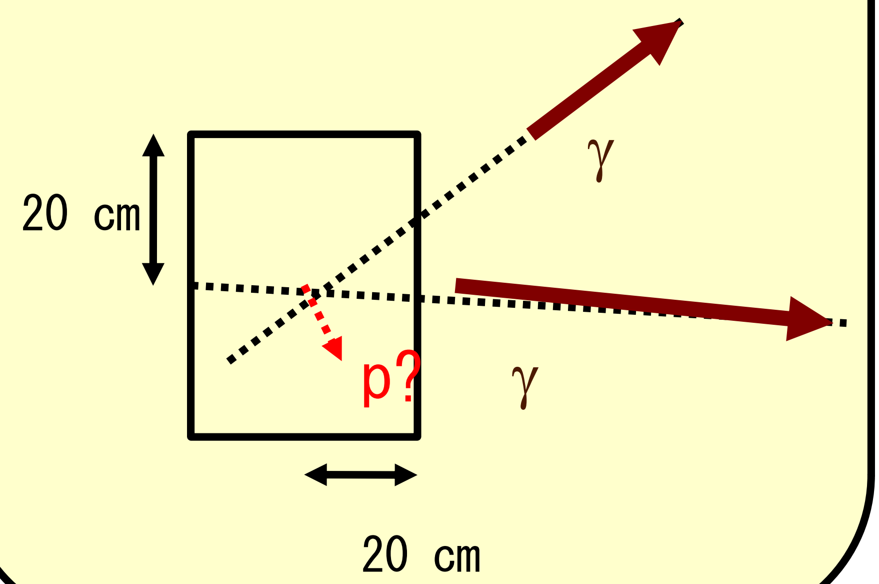
ν and π in the forward direction

SciBar can detect recoil protons due to its full activity

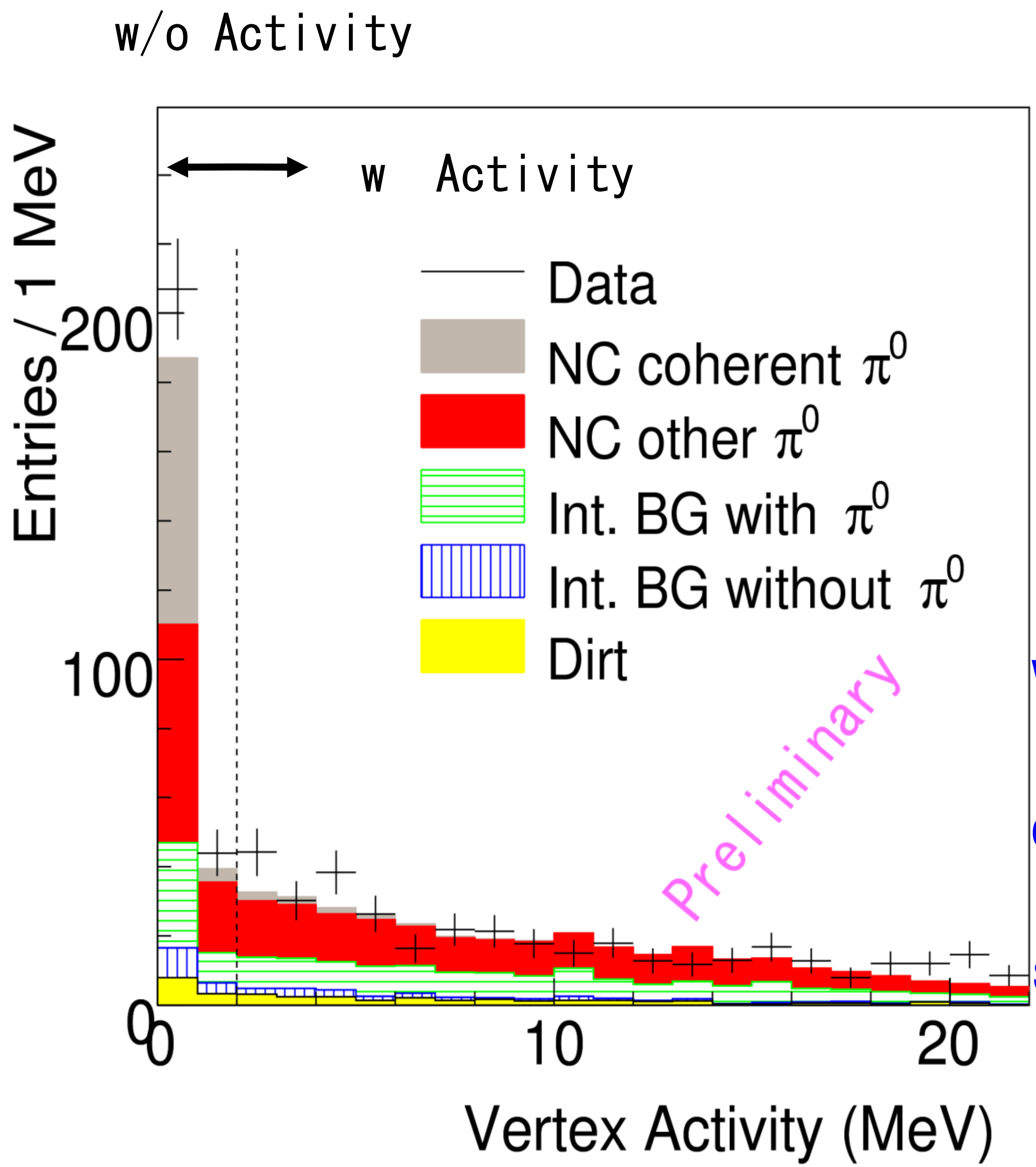
MiniBooNE measurement use only π^0 kinematics

Vertex Activity

Maximum energy deposit among hits within 20 cm square from the π^0 reconstructed vertex



Vertex Activity Distribution



Due to no recoil proton, coherent π^0 events concentrate on Vertex Activity = 0

Vertex Activity > 2 MeV
"with Activity sample"
otherwise,
"without Activity sample"

$E_{\pi 0}(1-\cos\theta_{\pi 0})$

interact with whole nucleus and emitting π^0

→ $$\frac{1}{|t|} > R$$

t:momentum transfer to nucleus
R:nuclear radius : 2.3fm for Carbon

→ $$E_{\pi^0}(1-\cos\theta_{\pi^0}) < \frac{1}{R}$$ ~100MeV

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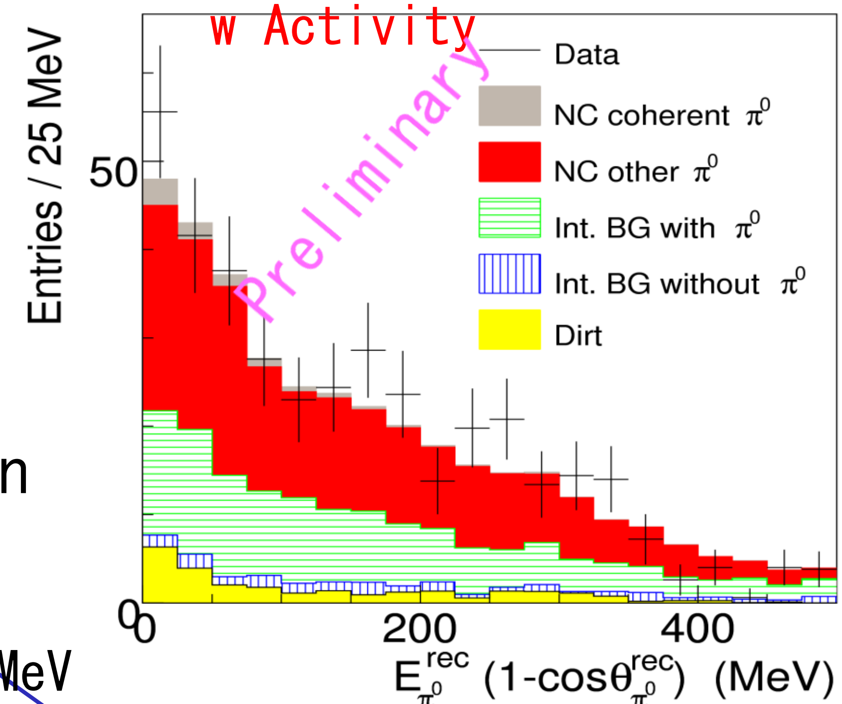
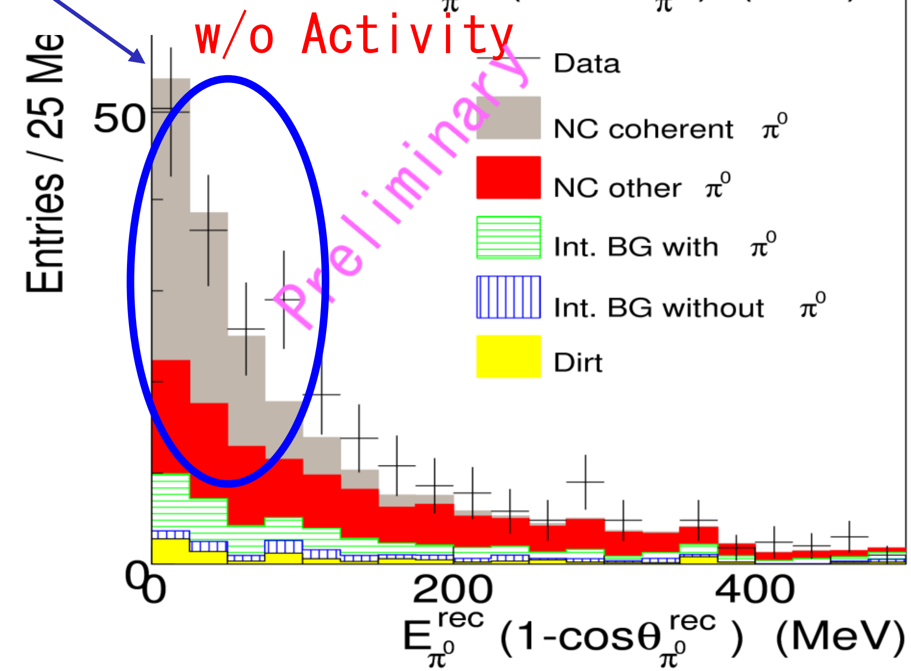
$E_{\pi 0}$: π^0 energy
$\theta_{\pi 0}$: π^0 direction to the ν beam axis





extracting coherent π^0 fraction by fitting $E^{rec}_{\pi 0}(1-\cos\theta^{rec}_{\pi 0})$ distributions with and without Activity

Fitting method

dividing selected NCπ^0 candidate events (MC) to 3 templates

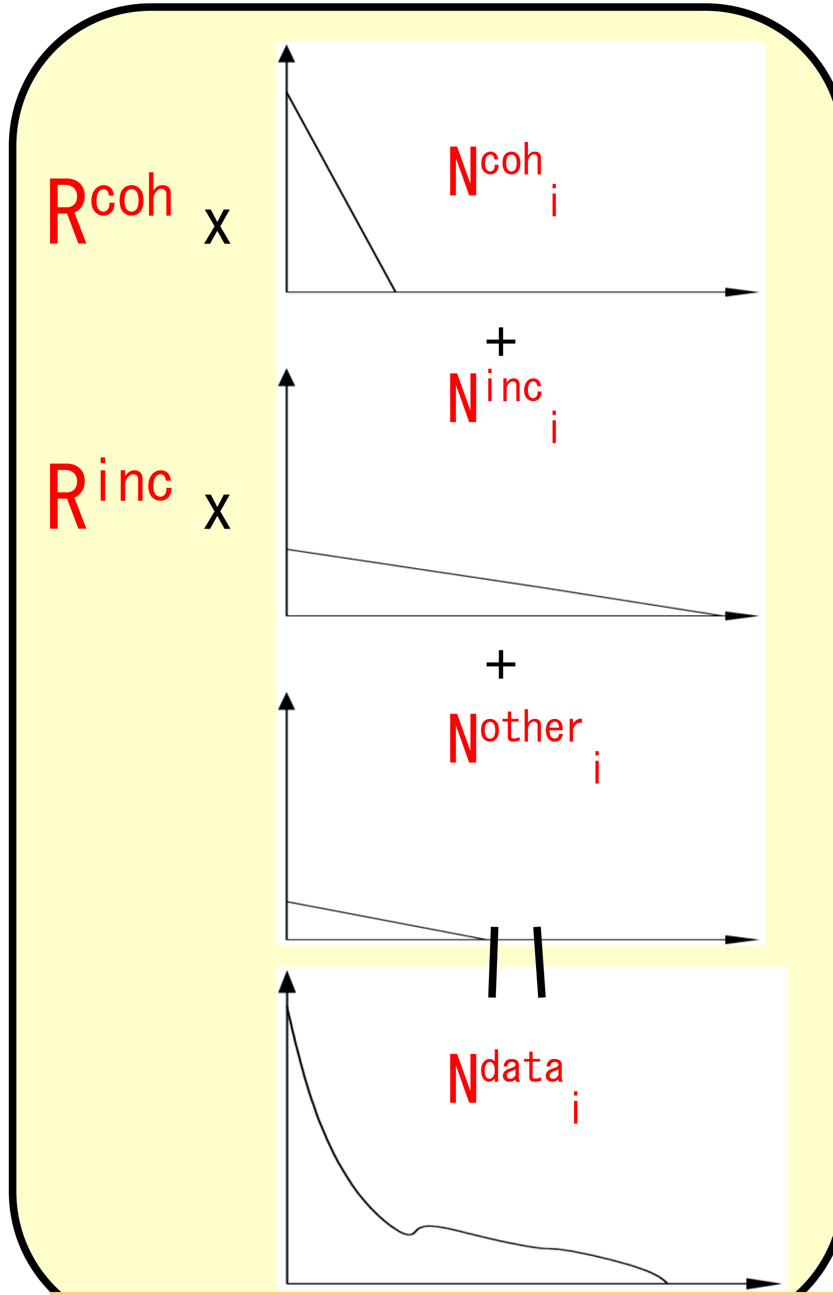
N^{coh}_i : NC coherent π^0
N^{inc}_i : NC incoherent π^0
N^{other}_i : other
i: index of bin

Two fitting parameters

R^{coh}: scaling N^{coh}_i default: 1
R^{inc}: scaling N^{inc}_i default: 1

Then, #expectation of the i-th bin is

$$N^{exp}_i = R^{coh}{}_i N^{coh}_i + R^{inc}{}_i N^{inc}_i + N^{other}_i$$



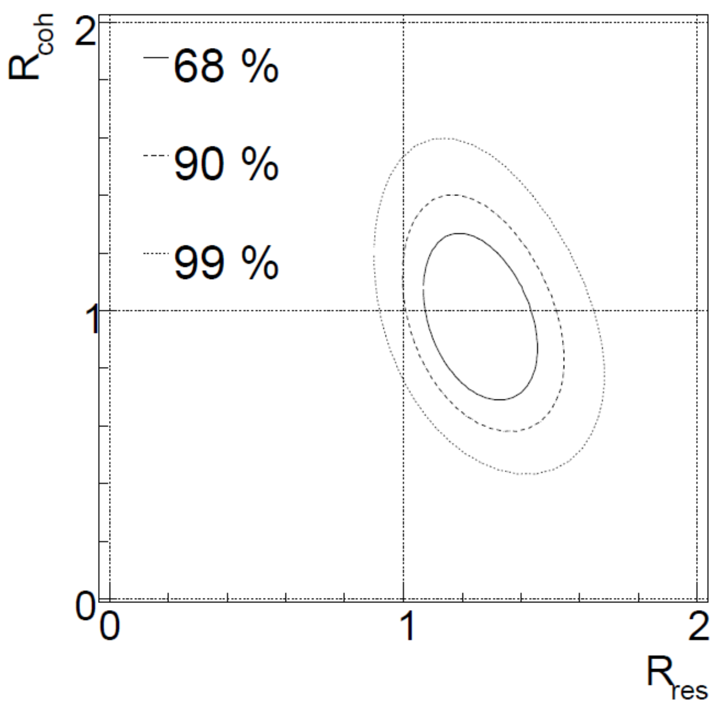
most probable R^{coh}, R^{inc}

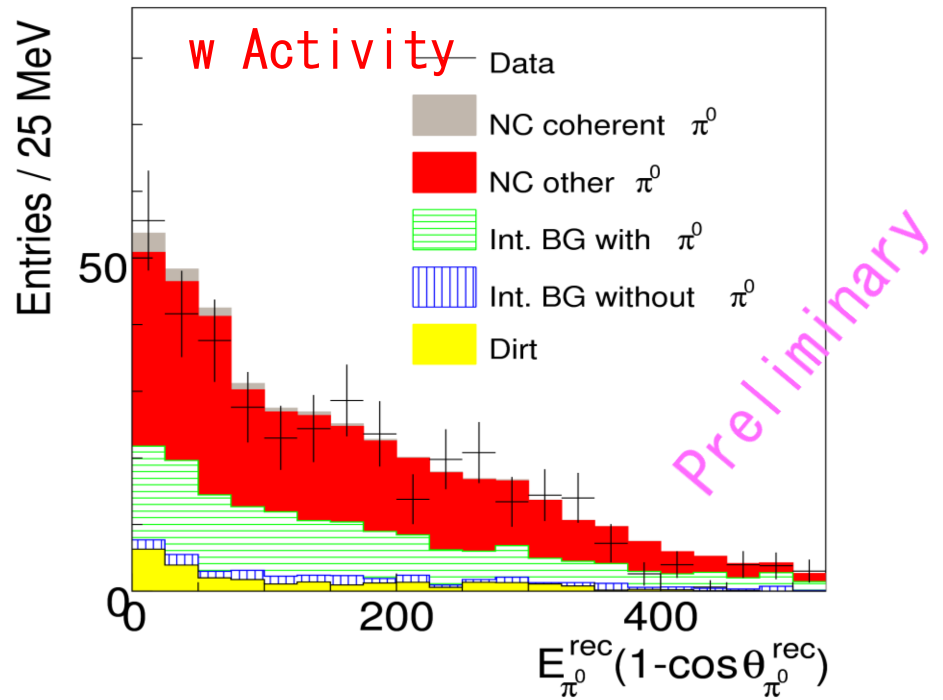
Fitting Result

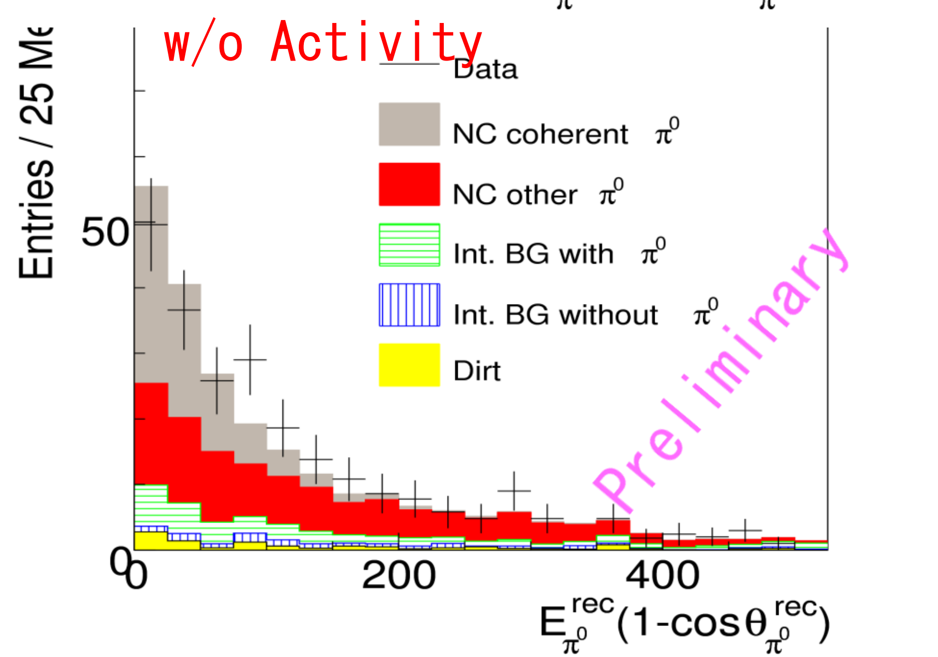
Result

R^{coh} = 0.97 +- 0.19
R^{inc} = 1.25 +- 0.13

χ^2/dof=31.5/39=0.81 before fit
χ^2/dof=26.5/37=0.71 after fit
#bins = 39







We observe NC coherent π^0

NC coherent π^0 cross section

Cross section ratio : $\sigma(\mathrm{NCcoherent}\pi)/\sigma(\mathrm{CC})$

$$\frac{\sigma(\mathrm{NCcoh}\pi^0)}{\sigma(\mathrm{CC})} = \mathrm{R_{coh}} \times \frac{\sigma(\mathrm{NCcoh}\pi^0)_{MC}}{\sigma(\mathrm{CC})_{MC}}$$

$$= \mathrm{R_{coh}} \times 1.21 \times 10^{-2}$$

$$= (1.17 \pm 0.23) \times 10^{-2},$$

Preliminary

$R_{coh} = 0.97 \pm 0.19$

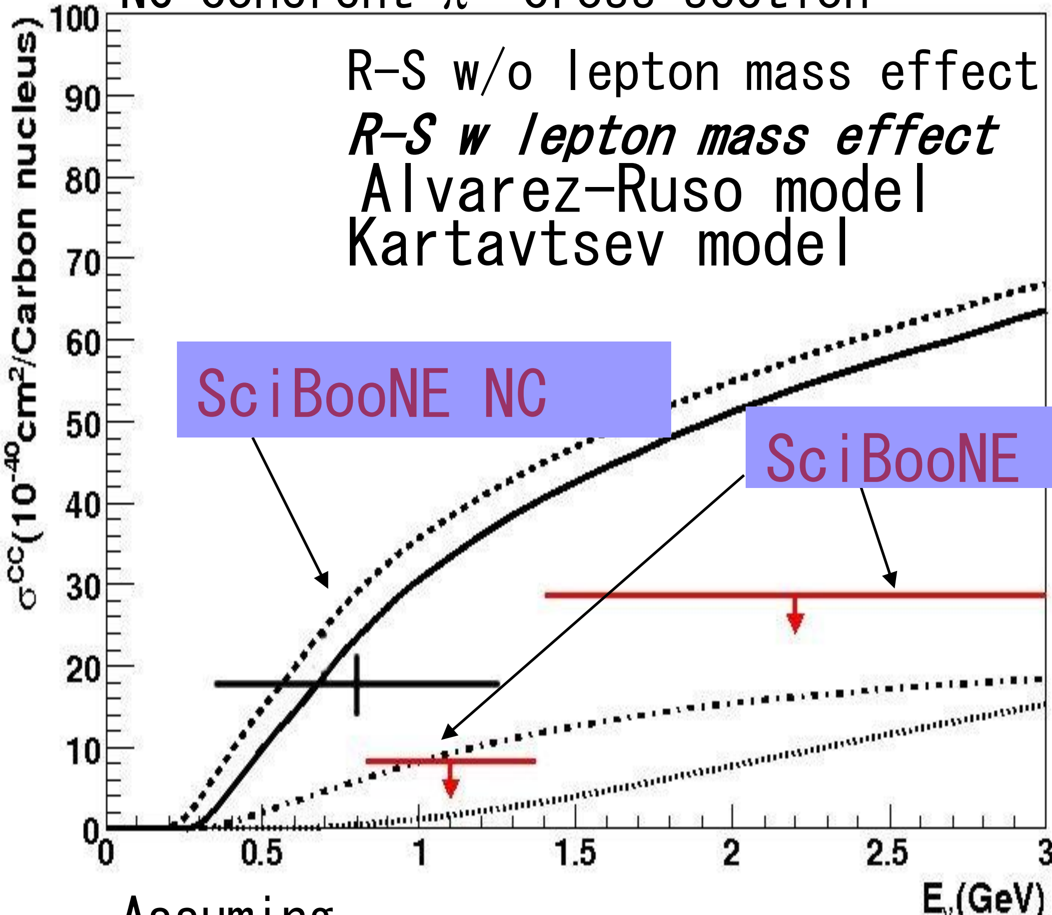
$[\sigma(\mathrm{NCcoh}\pi^0)/\sigma(\mathrm{CC})]\mathrm{MC} = 1.21 \times 10^{-2}$

- NC coherent π^0 measurement agrees with the RS prediction
- However, CC measurements (K2K, SciBooNE) disagree with the RS model

Discussion

Comparison with CC measurement

NC coherent π cross section



Assuming
σ(CC) = 7.6 x 10^{-39} cm^2 at 0.8 GeV
by NEUT
σ(CCcoh)=2σ(NCcoh)

Comparison with MiniBooNE NC result ($\sigma(NCcoh\pi)/(\sigma(NC1\pi^0))$

MiniBooNE NC

$19.5\pm1.1_{stat}\pm2.5_{sys}$ %

SciBooNE NC

17.9 ± 3.9 %

Preliminary

Good Agreement

- No contradiction among recent Measurements (SciBooNE, K2K, MiniBooNE)
- However, the RS model can not explain all of measurements

→ Further study is ongoing

Summary

1.

$$\frac{\sigma(\mathrm{NC}\pi^0)}{\sigma(\mathrm{CC})} = (7.7 \pm 0.5(\mathrm{stat.}) \pm 0.5(\mathrm{sys.})) \times 10^{-2}$$

→ achieve less than 10% error (total error: $0.7\mathrm{x}10^{-2}$) as required ν_e appearance search

2. π^0 kinematics (momentum and direction)

Our Measurements agree with the prediction

→ Can trust on the nuclear model in NEUT at this level of uncertainty (10 %)

3. NC coherent π^0 Production

$$\frac{\sigma(\mathrm{NCcoh}\pi^0)}{\sigma(\mathrm{CC})} = (1.17 \pm 0.23) \times 10^{-2},$$

Preliminary

→
- Agrees with Rein-Sehgal model in NC
- further study of CC on going

Expected SciBooNE Results in an year

Cross section measurement

- CC quasi elastic scattering
- ν_μ-bar CC coherent π production
- CC π^0 production
- NC elastic scattering

Neutrino oscillation measurement

- Neutrino flux measurement : ν_μ, ν_e and ν_μ-bar
- ν_μ disappearance search (joint analysis with MiniBooNE)

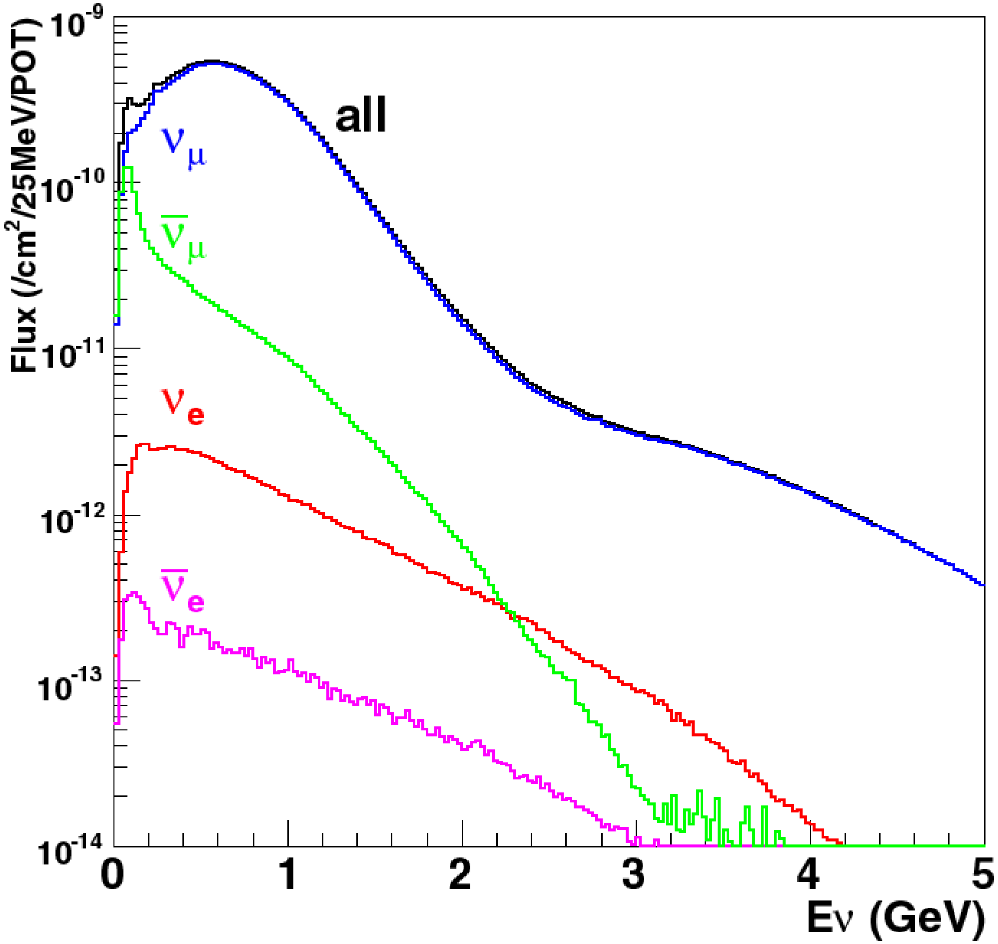
Many interesting results are coming soon !

Thank you

Backup

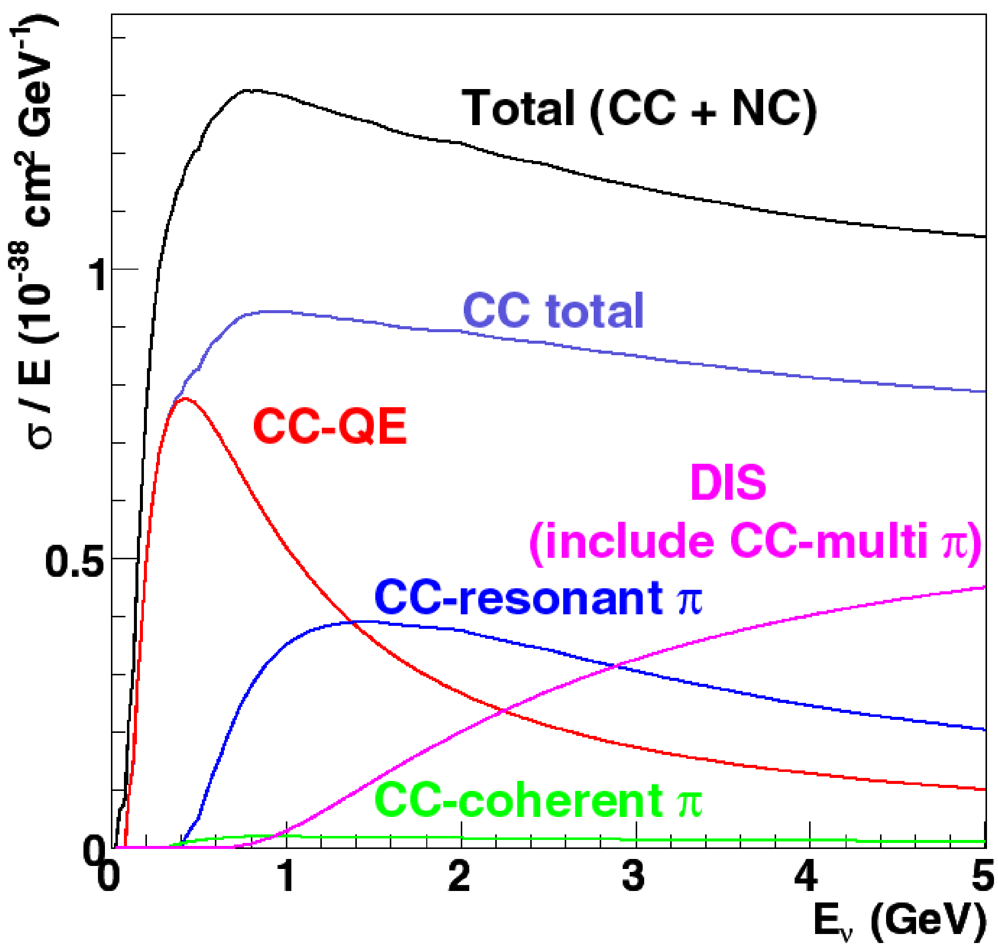
Booster Neutrino Beam (BNB)

Expected neutrino flux at SciBooNE
(neutrino mode)



- mean neutrino energy ~0.7 GeV
- 93% pure ν_μ beam
  - anti-ν_μ (6.4%)
  - ν_e + anti-ν_e (0.6%)
- antineutrino beam is obtained by reversing horn polarity

Neutrino event generator (NEUT)



- QE
  - Llewellyn Smith, Smith-Moniz
  - M_A=1.2GeV/c^2
  - P_F=217MeV/c, E_B=27MeV (for Carbon)
- Resonant π
  - Rein-Sehgal (2007)
  - M_A=1.2 GeV/c^2
- Coherent π
  - Rein-Sehgal (2006)
  - M_A=1.0 GeV/c^2

CC/NC -1π

- Deep Inelastic Scattering
  - GRV98 PDF
  - Bodek-Yang correction
- Intra-nucleus interactions

2γ selection using Extended track (1)

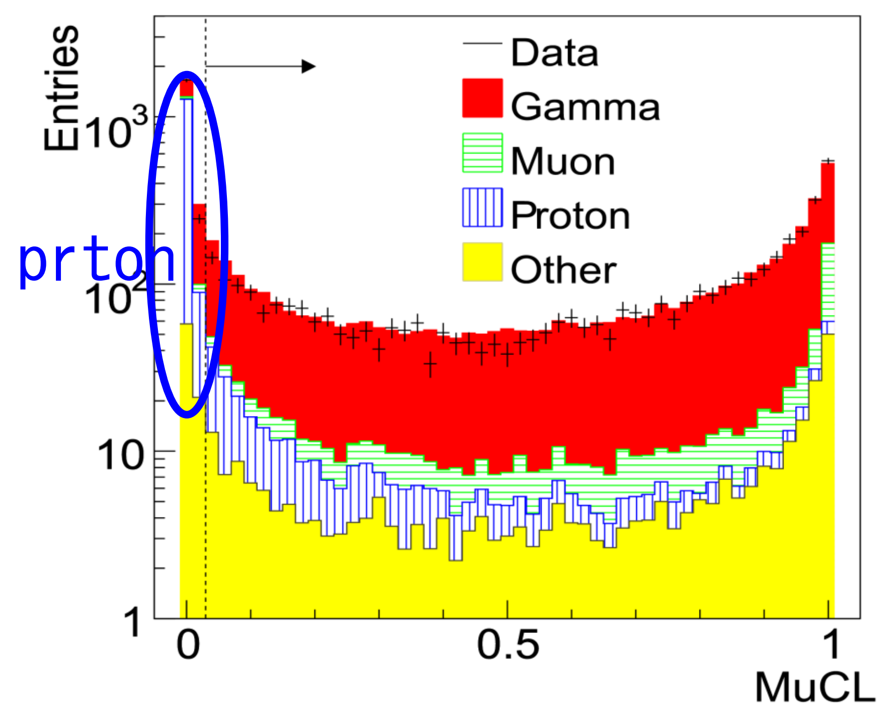
Extended Track

- merge co-linear tracks
- include hits within less than 20 cm from original track

Proton track is not included in Extrack

Proton Identification

Muon Confidence Level (Likelihood Using dE/dx in a track)

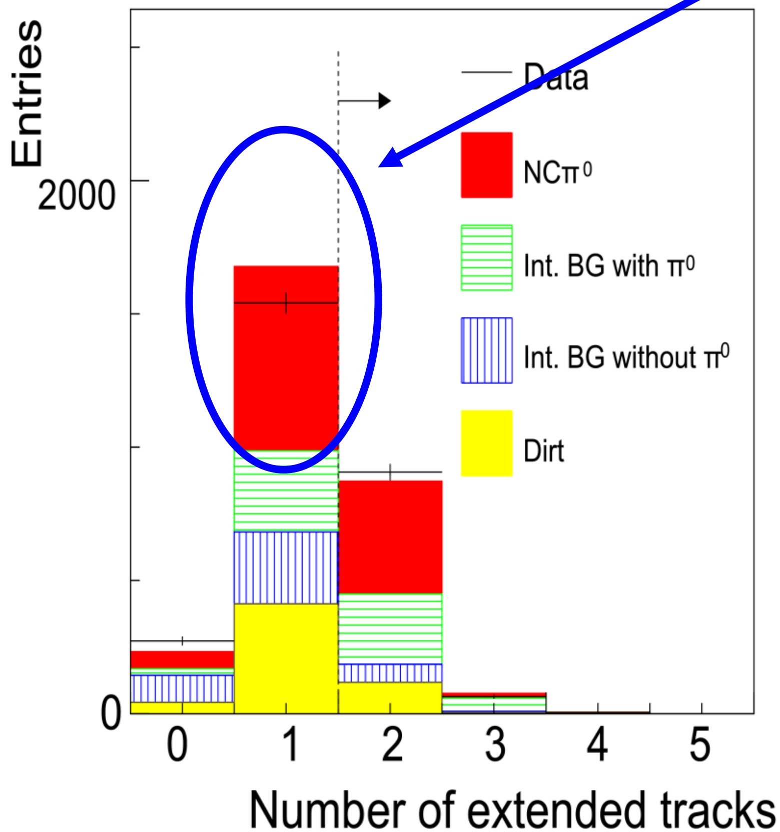


Extracks are reconstructed using tracks with MuCL > 0.03

2γ selection using Extended track (2)

#ExTracks >= 2 for
π^0 reconstruction

#ExTracks



58% of signals are rejected due to only 1 Extrack
1 ExTrack

Breakdown of such rejected events

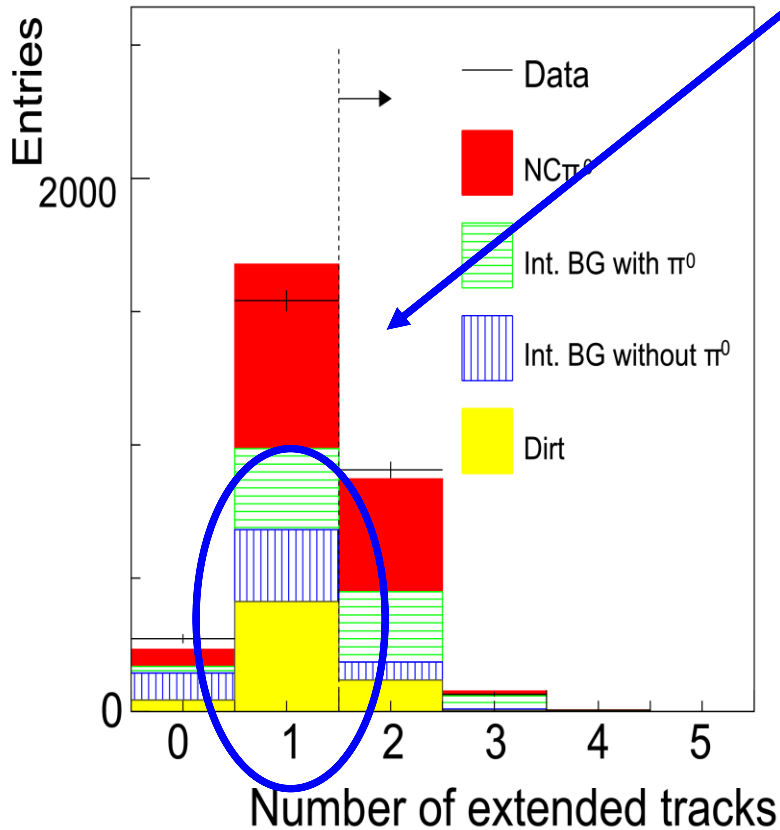
- only one γ reconstructed in a event mainly due to γ not converted in SciBar (67 %)
  → Unavoidable inefficiency
- 2γ are reconstructed. However, one of them is misidentified as proton (21%) or Back to back 2γ as 1 ExTrack (12 %)
  → Possibly improved

2γ selection using Extended track (3)

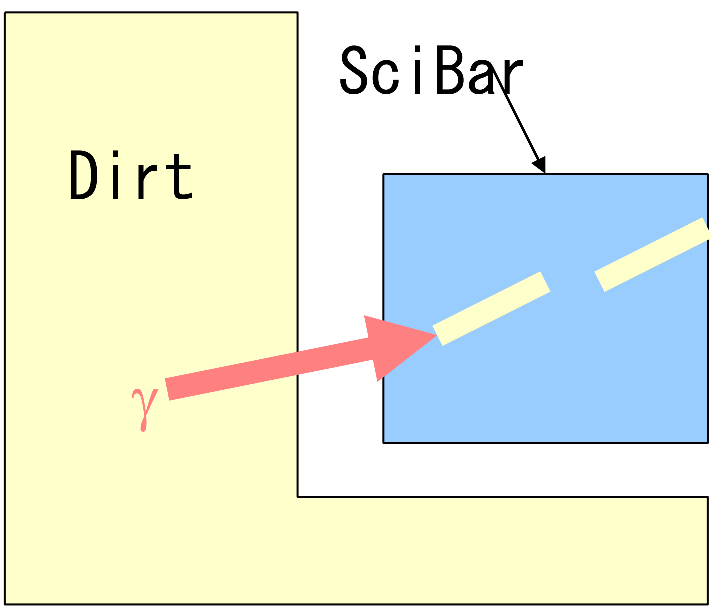
#ExTracks >= 2 for π^0 reconstruction

Dirt backgrounds are effectively rejected (1 ExTrack)

#ExTracks



70 % of the dirt backgrounds events is that 1γ from dirt comes to SciBar and makes 2 Tracks which are merged as 1 Extracks



Systematic uncertainties

Source	Error (x 10^{-2})	
Detector response	−0.39	+0.38
ν interaction, nuclear model	−0.25	+0.30
Dirt background	−0.10	+0.10
ν beam	−0.11	+0.22
Total	**−0.48**	**+0.54**

Detector Response

Crosstalk MAPMT: The fraction of light yield leaking to next pixel (3%). There is 10 % uncertainty

Hit threshold: 2.5 p.e. There is 20 % uncertainty on the conversion factor from ADC to #photo electrons

ν interaction and nuclear model

CCπ: 20 % uncertainty

πabsorption: 30 % uncertainty

dirt background events

Using events where the reconstructed π^0 vertex located at the outside of SciBar

ν beam

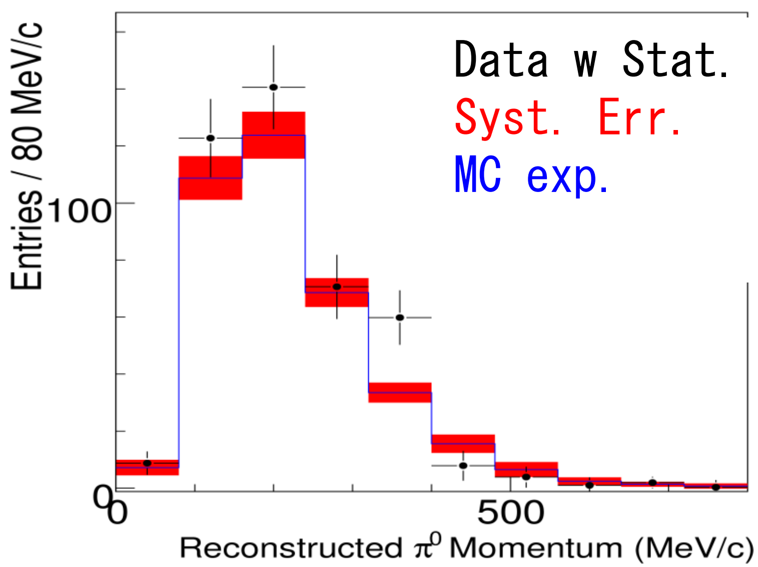
uncertainty of the cross section of interaction of primary proton with Be target

True π^0 momentum and direction (1)

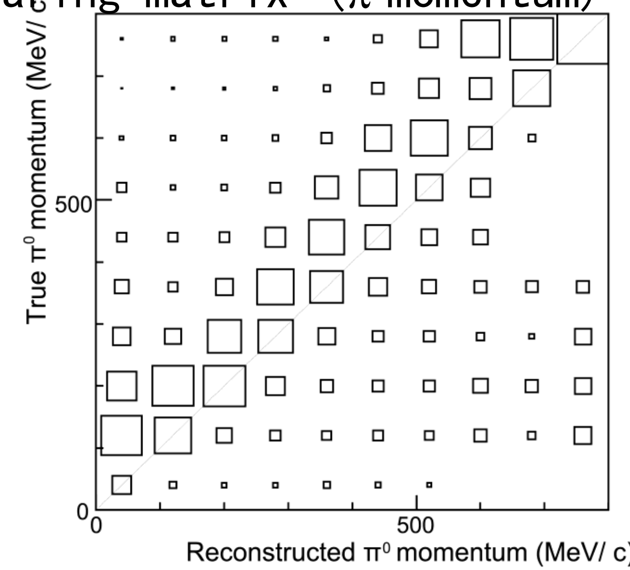
True π^0 kinematics distributions are made as follows

1. background subtraction

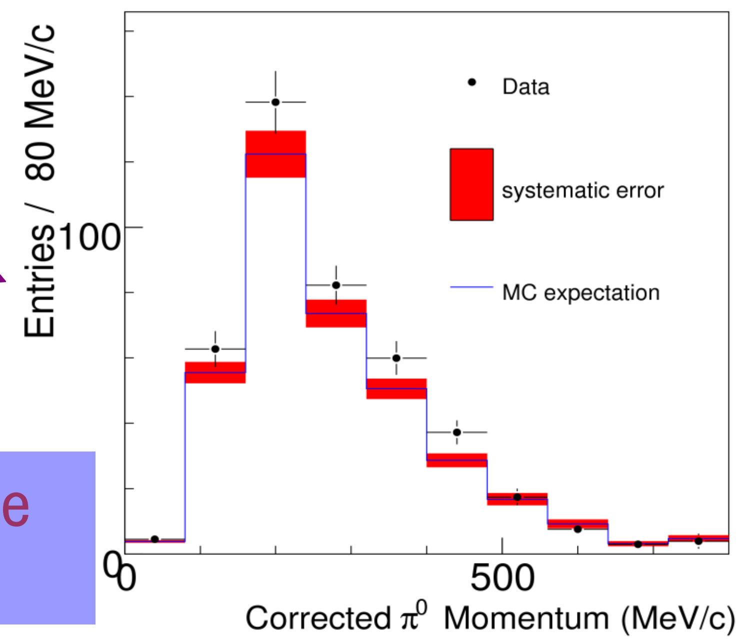
reconstructed π^0 momentum after background subtraction



Smearing matrix (π^0momentum)



True π^0 momentum



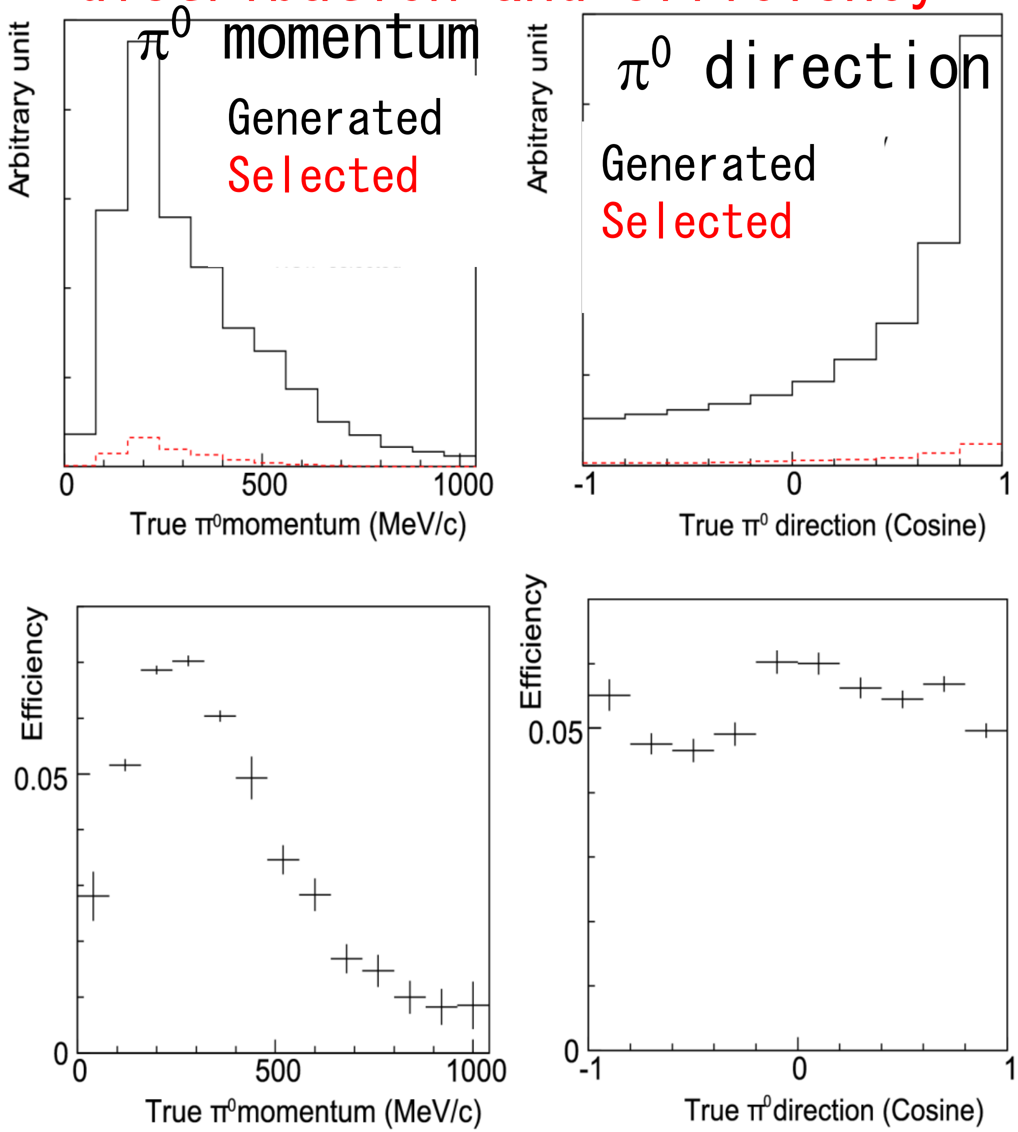
Err.

2. Conversion from reconstructed value to true value using smearing matrix

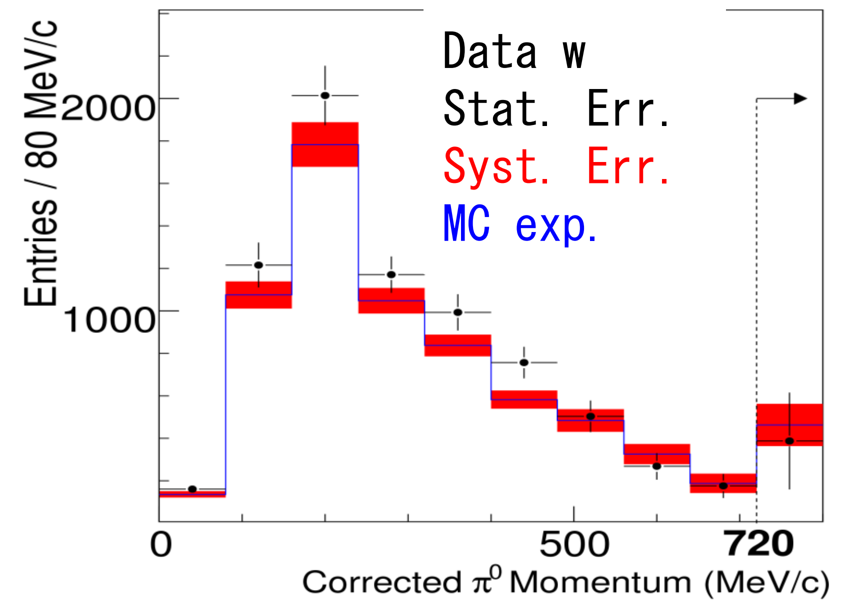
True π^0 momentum and direction (2)

3. efficiency correction

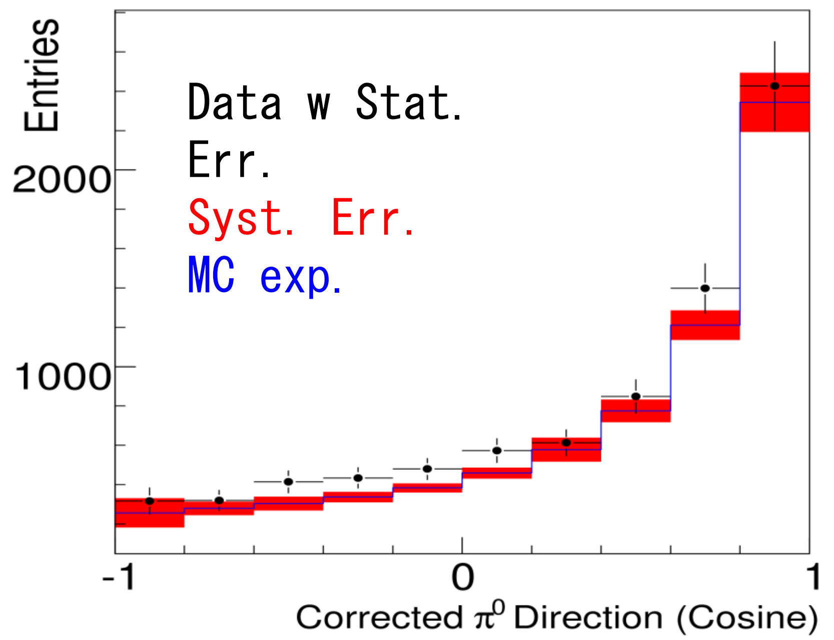
true π^0 kinematics distribution and efficiency



True π^0 momentum after correction



True π^0 direction after correction



χ^2 definition

$$\chi^2 = -2 \ln \frac{f(N^{\rm obs}; N^{\rm exp})}{f(N^{\rm obs}; N^{\rm obs})}$$

Poisson likelihood
smeared by Gaussian
function

$$f(N^{\rm obs}; N^{\rm exp}; V) = A \int \Big[\big[\prod_{i=1}^{N} dx_i \frac{{x_i}^{N_i^{\rm obs}} e^{-x_i}}{N_i^{\rm obs}!} \big]$$

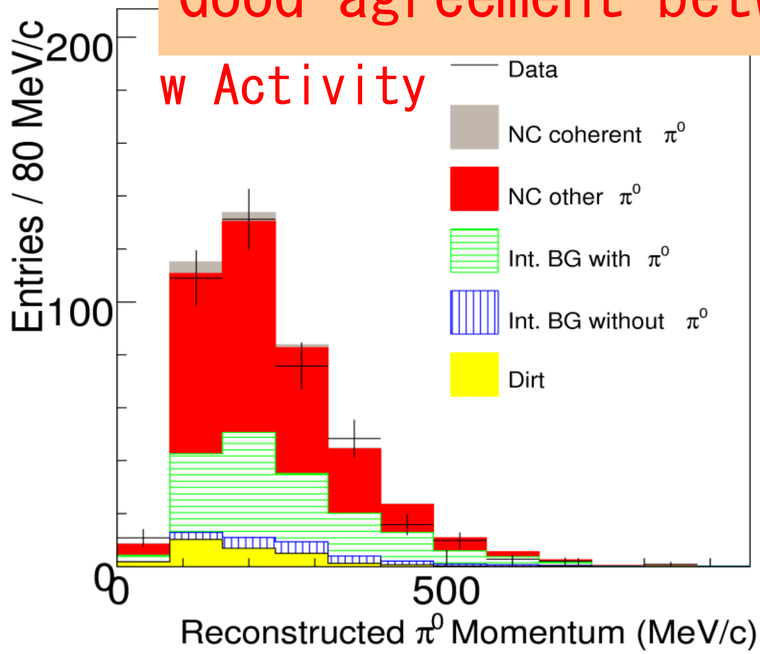
$$\times \exp\Big[-\frac{1}{2} \sum_{j=1}^{N} \sum_{k=1}^{N} (x_j - N_j^{\rm exp}) V_{jk}^{-1} (x_k - N_k^{\rm exp}) \Big] \Big]$$

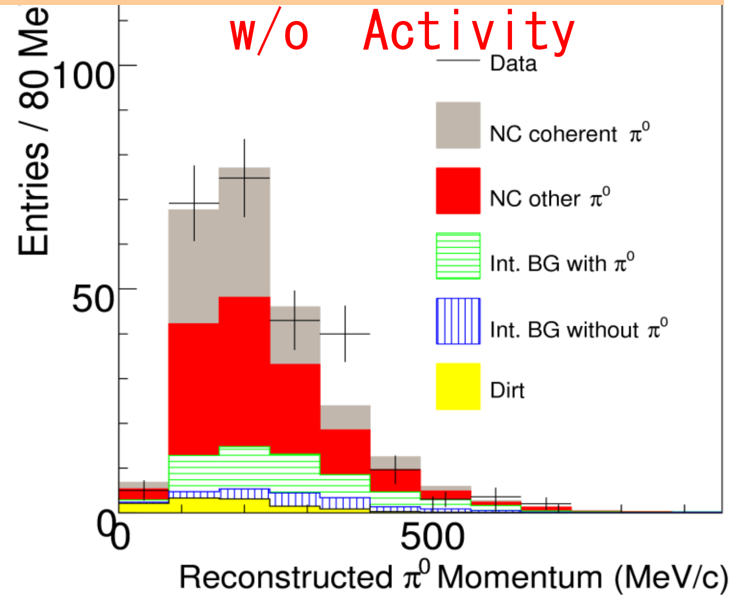
V: covariant matrix

π^0 momentum and direction

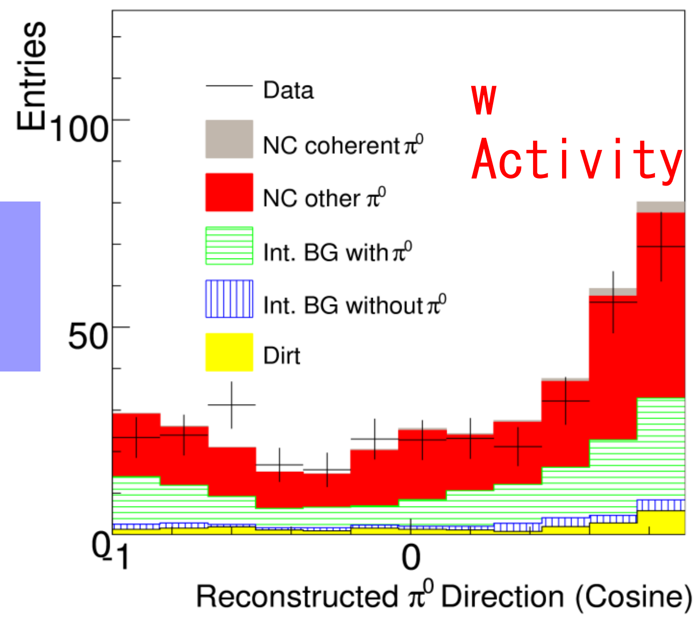
Good agreement between Data/MC

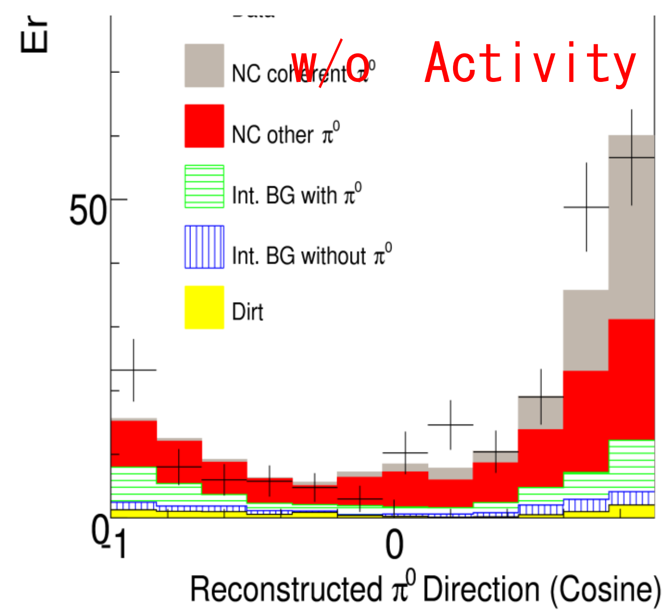
Reconstructed momentum



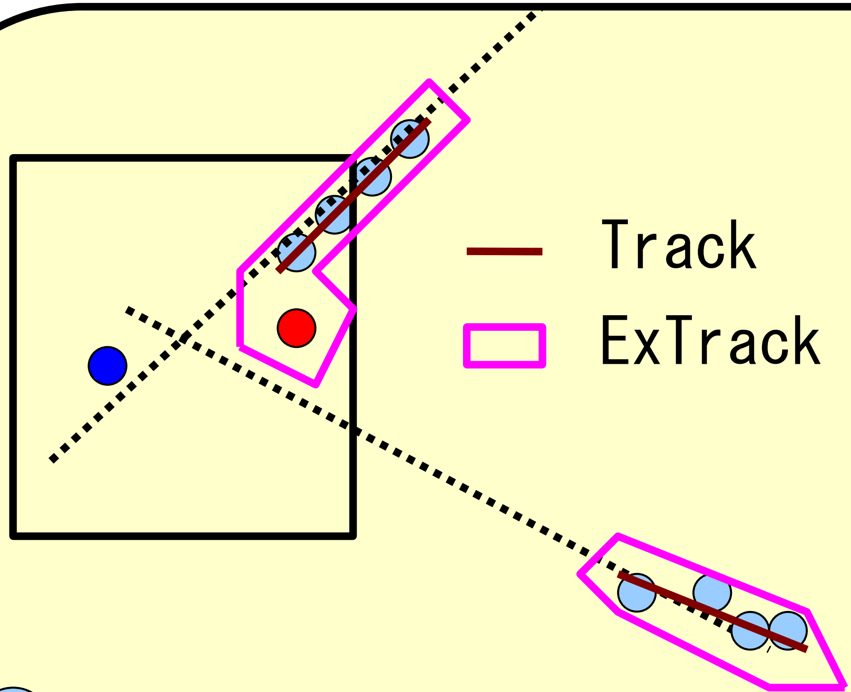


Reconstructed direction





Vertex Activity Search



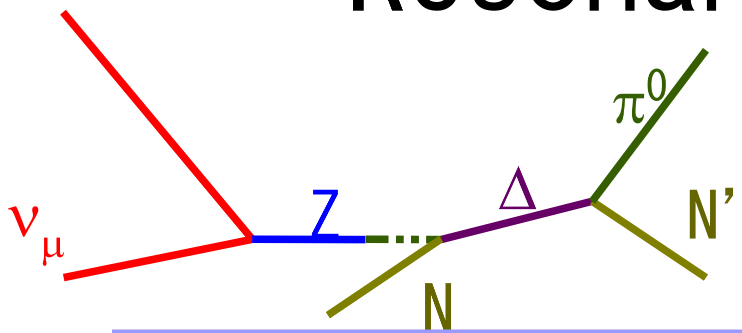
possibly hits due to γ

may include protons hits since these hits are up to 20 cm far from main track

possibly hits not due to γ

Skip [light blue circle] when we search the maximum energy deposit since we want to find proton hits

Resonant π



mainly by Δ(1232)

Rein-Sehgal (RS) model

- All resonance < 2 GeV (including in interference)
- Hadron Matrix Element :Feynman-Kislinger-Ravndal model (harmonic oscillator Hamiltonian)
- Hadron states: SU(6) wave function(spin, flavor)x excitation of harmonic oscillator (spatial)

→ widely used for neutrino oscillation experiments

No useful measurement* at E_ν < 1 GeV before this analysis

*Now, MiniBooNE and our result are published

NC inclusive π^0

MiniBooNE published NC1π^0 (coherent+incoherent) measurement

MiniBooNE NC1π^0 measurement

$\sigma(\mathrm{NC}1\pi^0)$ = $(4.76 \pm 0.05_{stat} \pm 0.40_{sys})\mathrm{x}10^{-40}\ \mathrm{cm}^{-2}$

at $\langle E_\nu \rangle$ = 0.8 GeV (absolute cross section)

Good agreement

SciBooNE (R_{inc}=1.25, R_{coh}=0.97)

$$\left(R_{\mathrm{inc}} \left(\frac{\sigma\left(\mathrm{NCincoh}1\pi^0\right)}{\sigma\left(\mathrm{CC}\right)} \right)_{\mathrm{MC}} + R_{\mathrm{coh}} \left(\frac{\sigma\left(\mathrm{NCcoh}\pi^0\right)}{\sigma\left(\mathrm{CC}\right)} \right)_{\mathrm{MC}} \right) \times < \sigma\left(\mathrm{CC}\right) >$$

= $(5.5 \pm 0.5)\mathrm{x}10^{-40}\ \mathrm{cm}^{-2}$* at $\langle E_\nu \rangle$ = 0.7 GeV

Preliminary

*Assuming

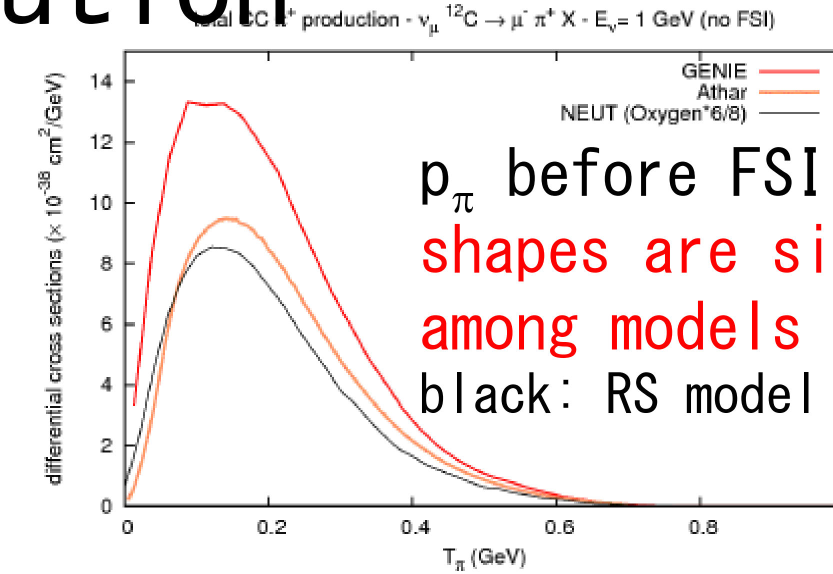
- R_{inc} scales NC incoherent 1 π^0
- CC cross section () by NEUT

The error is not final value

Goal2 : π kinematics distribution

Intra-nuclear Interaction (FSI)

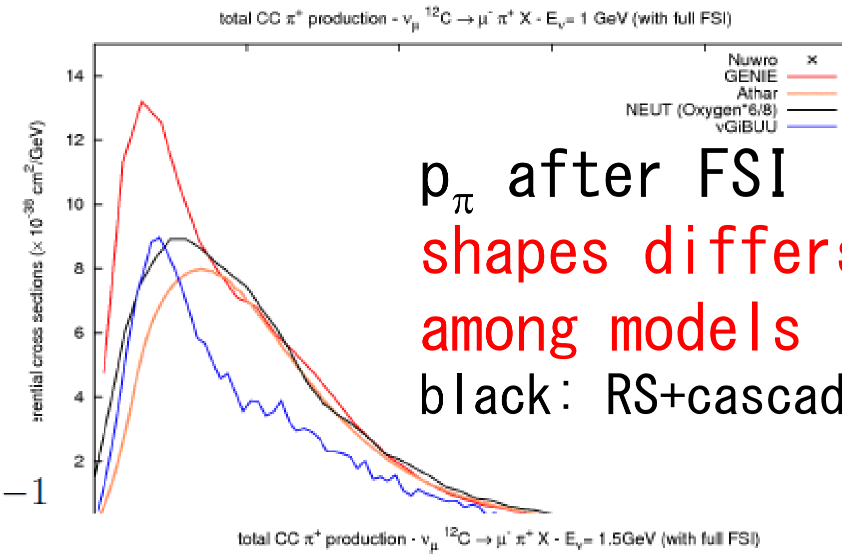
- π^0 by initial ν-nucleon interaction can be absorbed or scattered in nucleus
- π^0 can be newly produced in nucleus



p_π before FSI
shapes are similar among models
black: RS model

Our model (Cascade model)

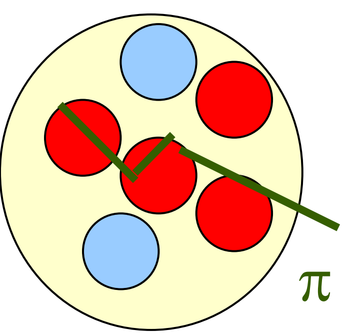
- simulate particles until emitting from the nucleus
- assume some model to describe σ(π-nucleus) and nuclear density



p_π after FSI
shapes differs among models
black: RS+cascade model

nuclear density

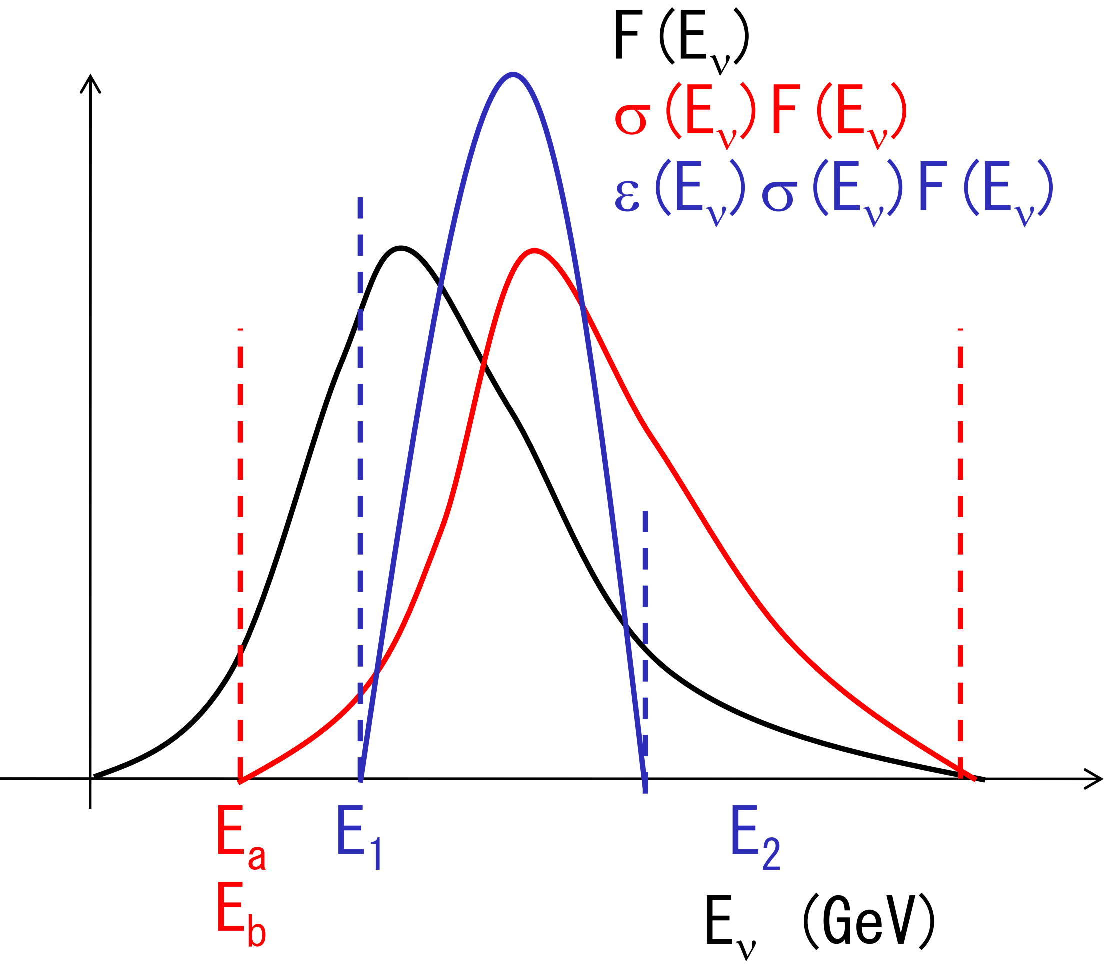
$$\rho(r) = \frac{Z}{A}\rho_0\left[1+\exp\left(\frac{r-c}{a}\right)\right]^{-1}$$



by Jan Sobczyk's slides in Nuint. 2009

Need measure the π kinematics as well as σ

How to define Neutrino Energy



Definition 1

$$\int_0^\infty E_\nu F(E_\nu)\,dE_\nu \Big/ \int_0^\infty F(E_\nu)\,dE_\nu$$

Definition 2

$$\int_{E_a}^{E_b} E_\nu F(E_\nu)\,dE_\nu \Big/ \int_{E_a}^{E_b} F(E_\nu)\,dE_\nu$$

Definition 3

$$\int_{E_1}^{E_2} E_\nu F(E_\nu)\,dE_\nu \Big/ \int_{E_1}^{E_2} F(E_\nu)\,dE_\nu$$