Measurement of ν_μ CC coherent pion production cross section in the T2K on-axis neutrino beam

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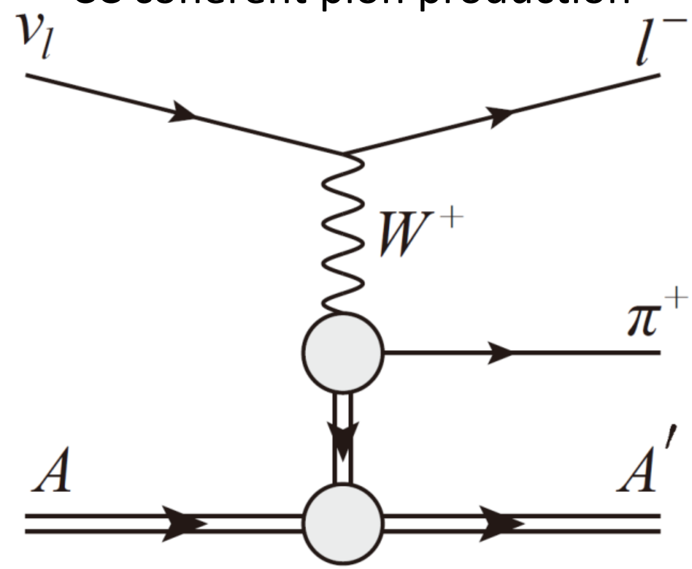
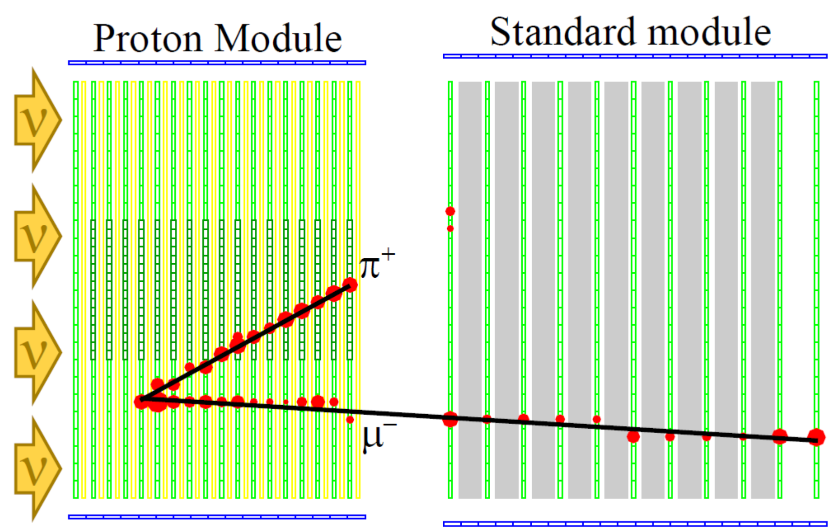
Overview

- The T2K experiment
- Introduction to CC coherent pion
- Event selection
- Analysis strategy
- Systematic errors
- Results

Feynman diagram of
CC coherent pion production



Event display of CC coherent pion production

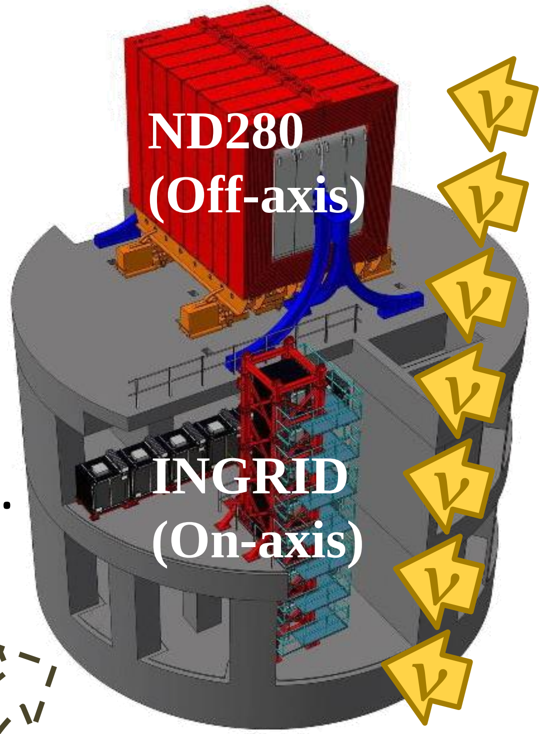


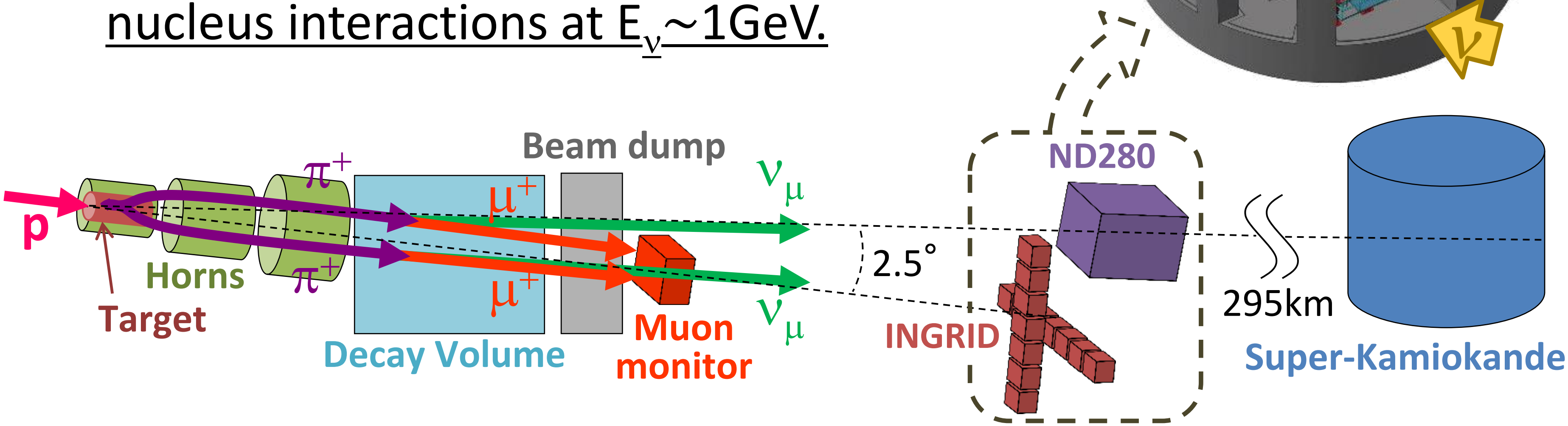
The T2K experiment

- High intensity neutrino beam from J-PARC.
- Super-Kamiokande, located 295km from neutrino generation point.
- ND280 (off-axis) and INGRID (on-axis) located 280m from neutrino generation point.

- Precise measurement of neutrino oscillations.
- <u>Precise measurement of neutrino nucleus interactions at E_ν~1GeV.</u>

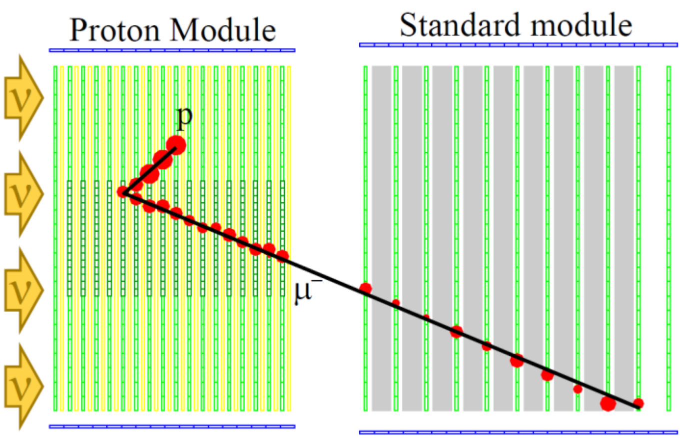
T2K Near detectors



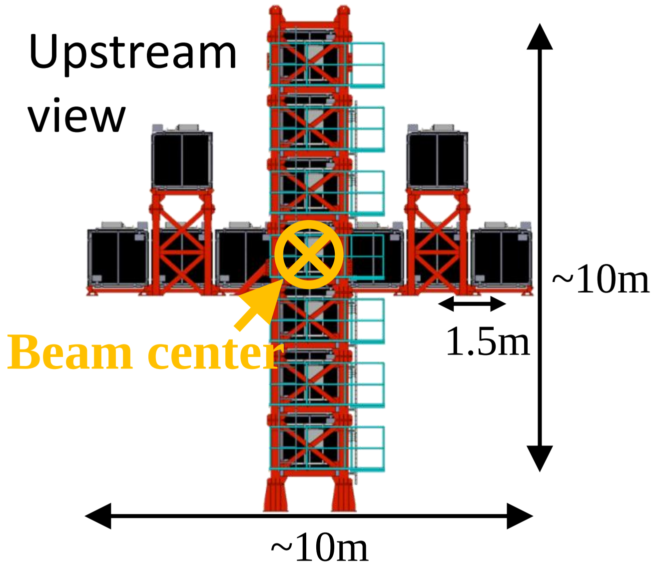


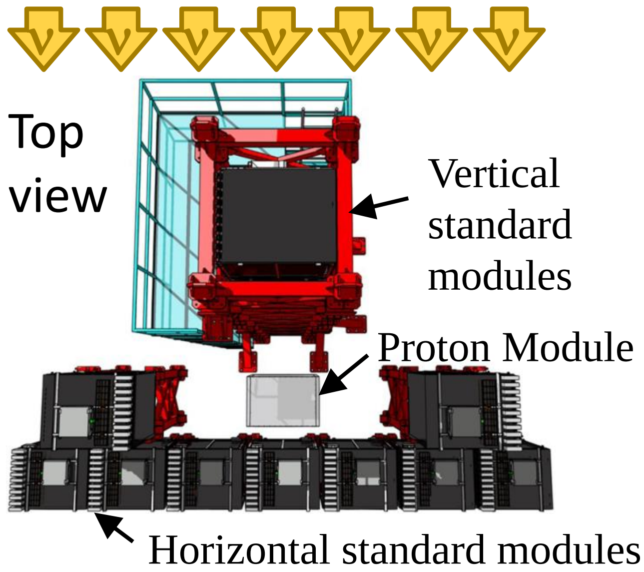
INGRID (on-axis near detector)

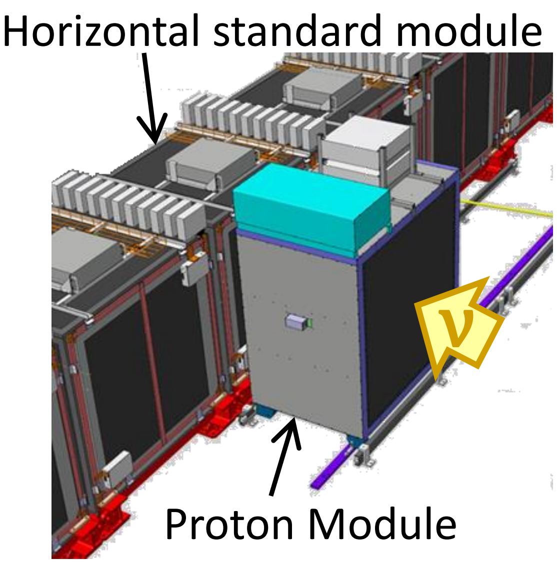
- 16 standard modules.
  - Sandwich structure of iron and scintillators.
  - Main purpose is beam monitoring.
- 1 extra module, (Proton Module).
  - Full scintillator module.
  - Developed for the cross section study.



- In this study, Proton Module is used as target, and standard module is used to identify muons from neutrino interactions.



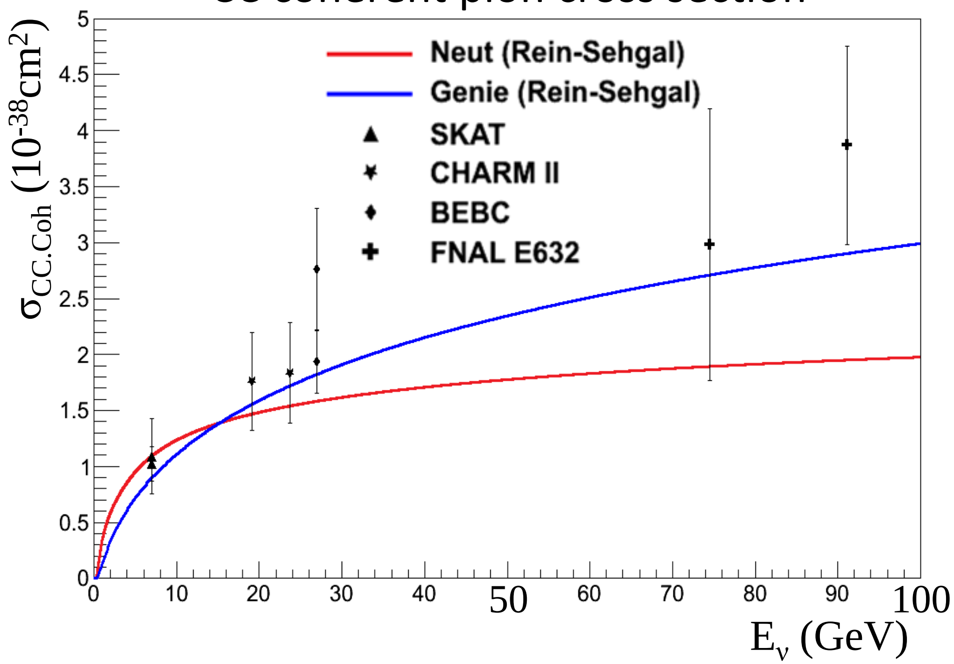




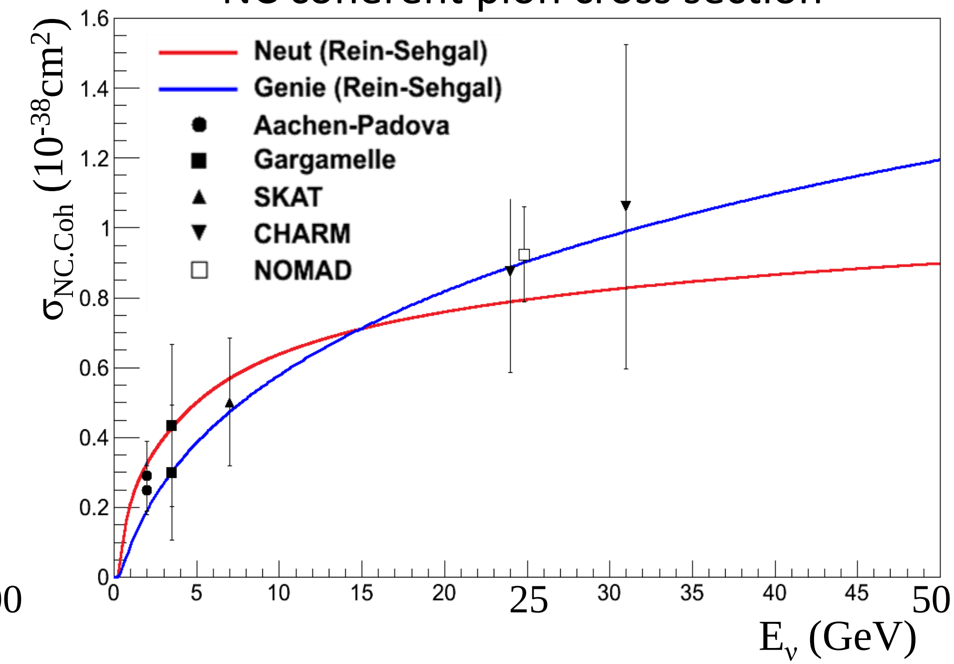
Coherent pion production in high energy region

- NEUT and GENIE are used to generate neutrino interactions.
- Both use Rein-Sehgal model for coherent pion production.
  - GENIE takes into account the lepton mass terms, while NEUT doesn't.
  - Different πN cross section is used.
- Coherent pion production signal was observed at high energy region (3~300GeV) via both CC and NC as expected by the Rein-Sehgal model.

CC coherent pion cross section



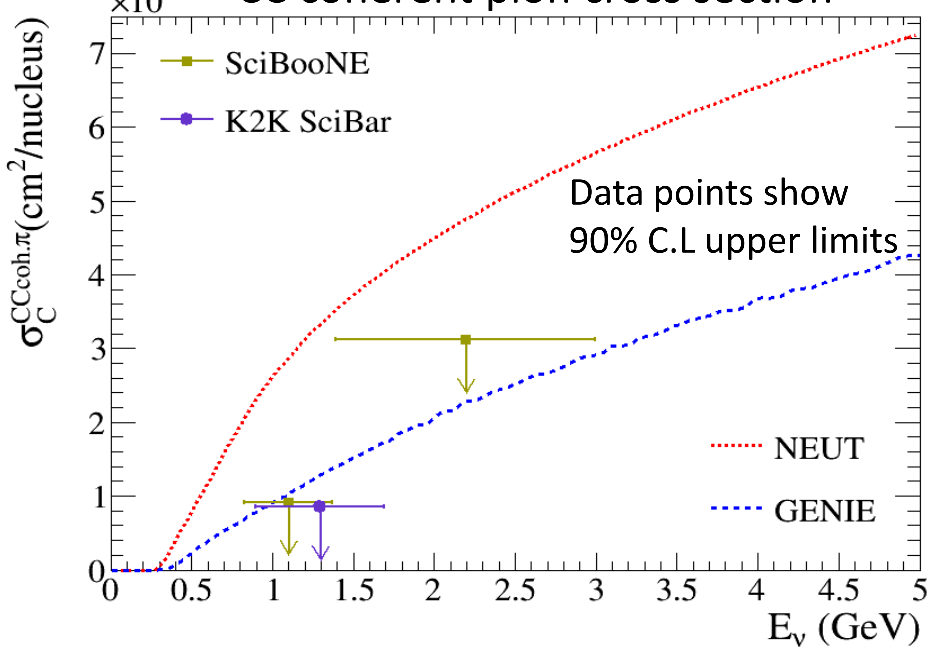
NC coherent pion cross section



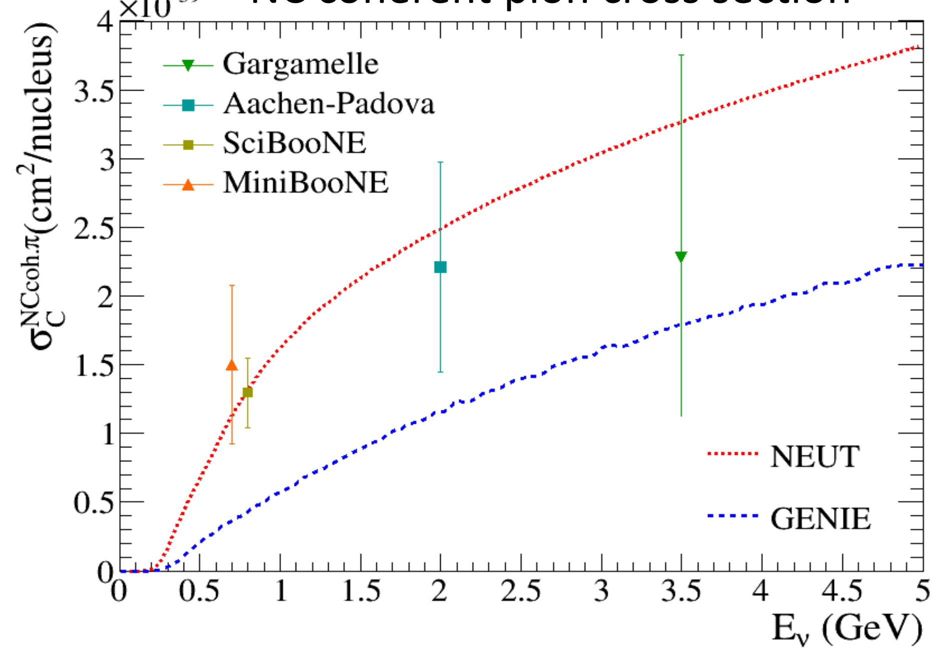
Coherent pion production in a few GeV region

- NEUT and GENIE predictions in a few GeV region differ by a factor of two.
- K2K and SciBooNE reported null observations of charged current coherent pion production in a few GeV region.
- MiniBooNE and SciBooNE observed the neutral current coherent pion production at similar neutrino energy.

CC coherent pion cross section

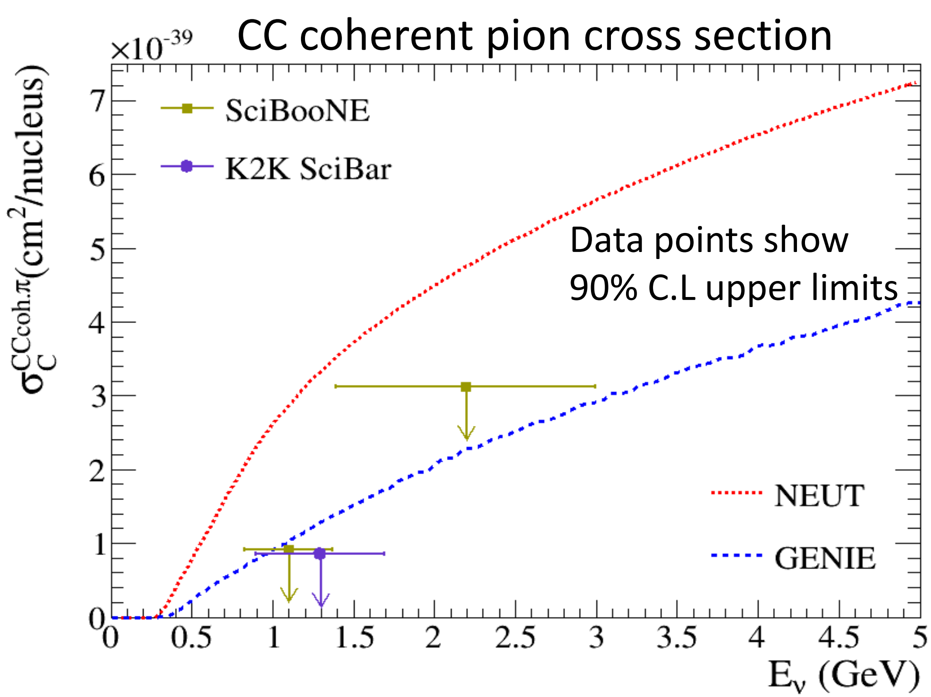


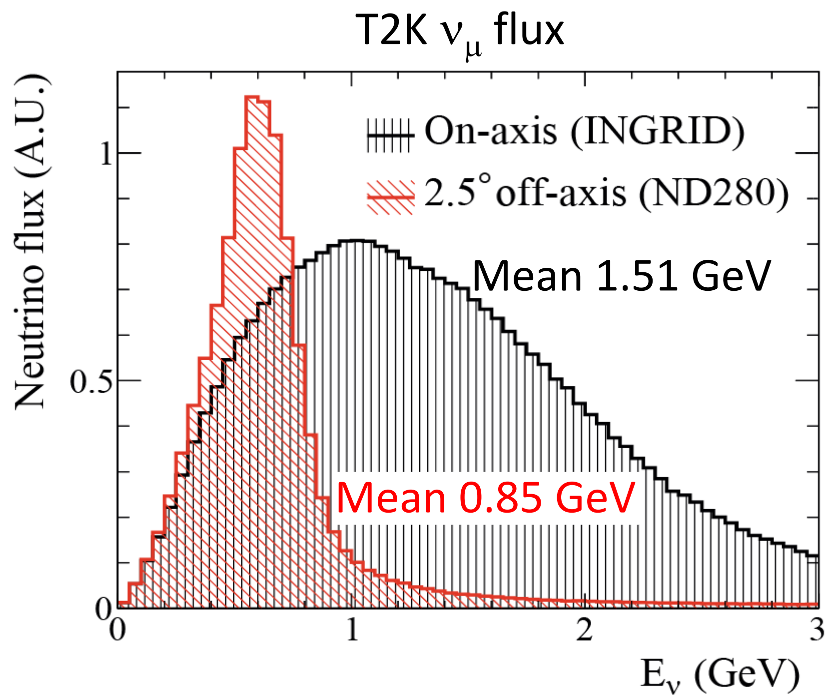
NC coherent pion cross section



Motivation of this study

- We investigate the CC coherent pion at a few GeV region using T2K on-axis neutrino beam and INGRID.
- In this study, NEUT was used to estimate background and efficiency.
- GENIE was used for the comparison of cross section results in addition to NEUT.

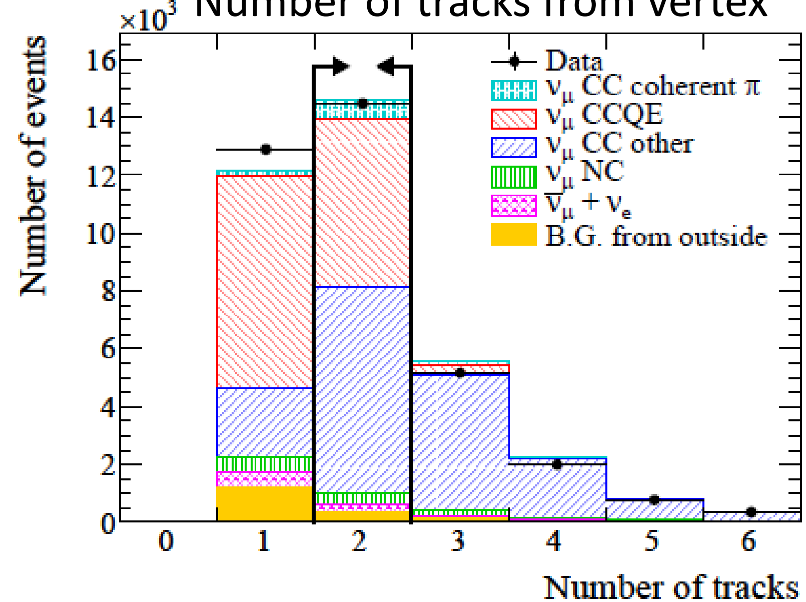




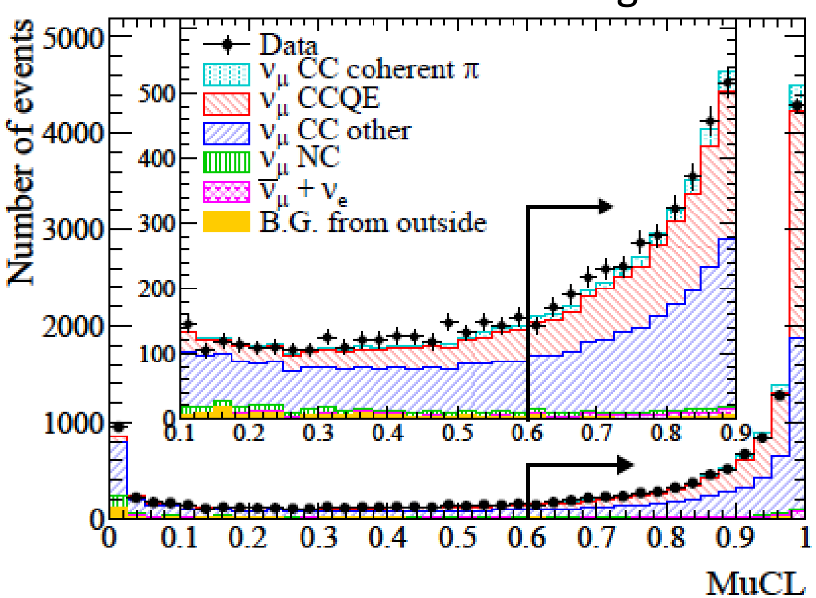
Number of tracks & particle identification

- Select two-track sample. (A muon and a pion.)
- Muon confidence level (MuCL) is defined with control muon sample for PID.
- Longer track : muon-like
- Shorter track : pion-like

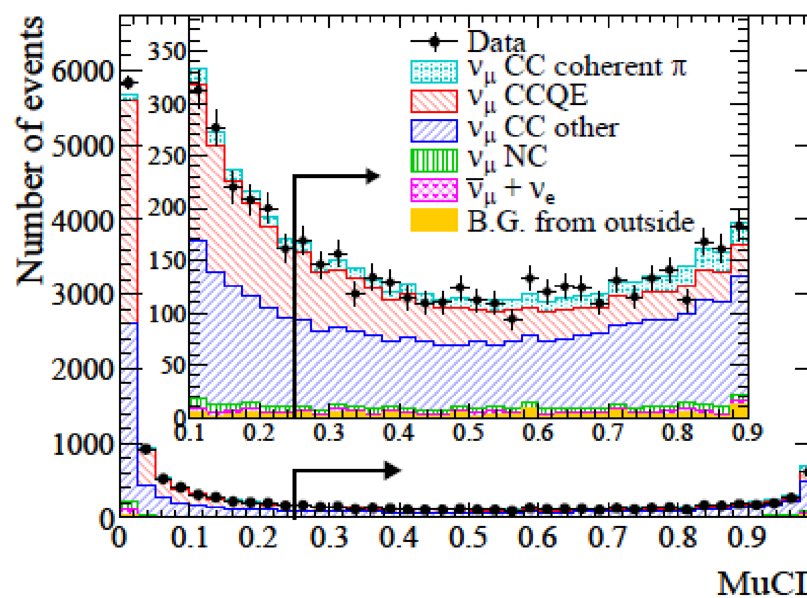
Number of tracks from vertex



Particle identification for longer track

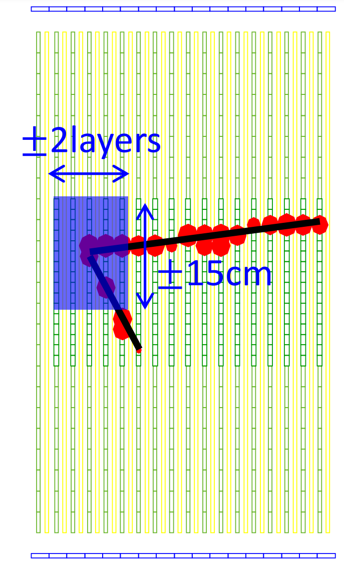


Particle identification for shorter track

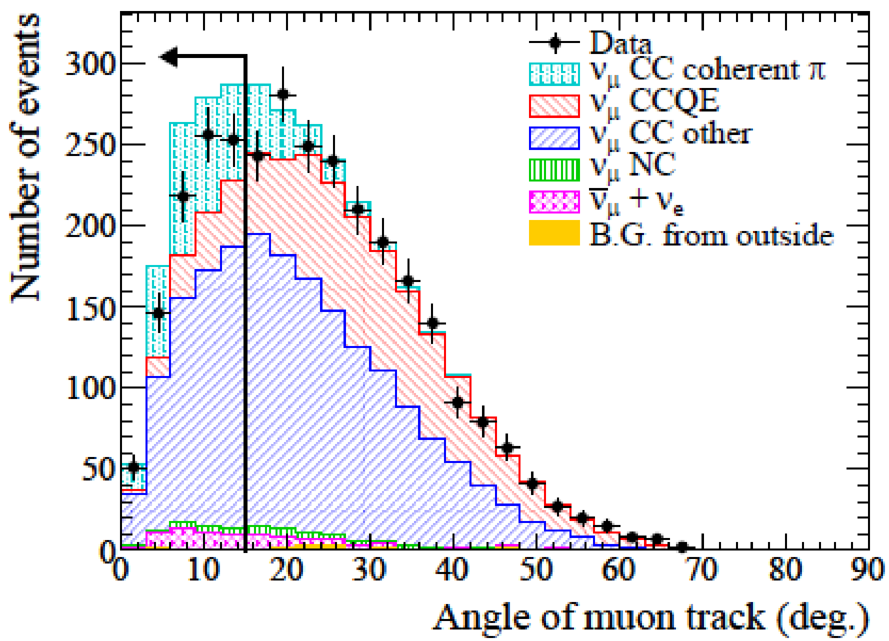


Muon angle & vertex activity

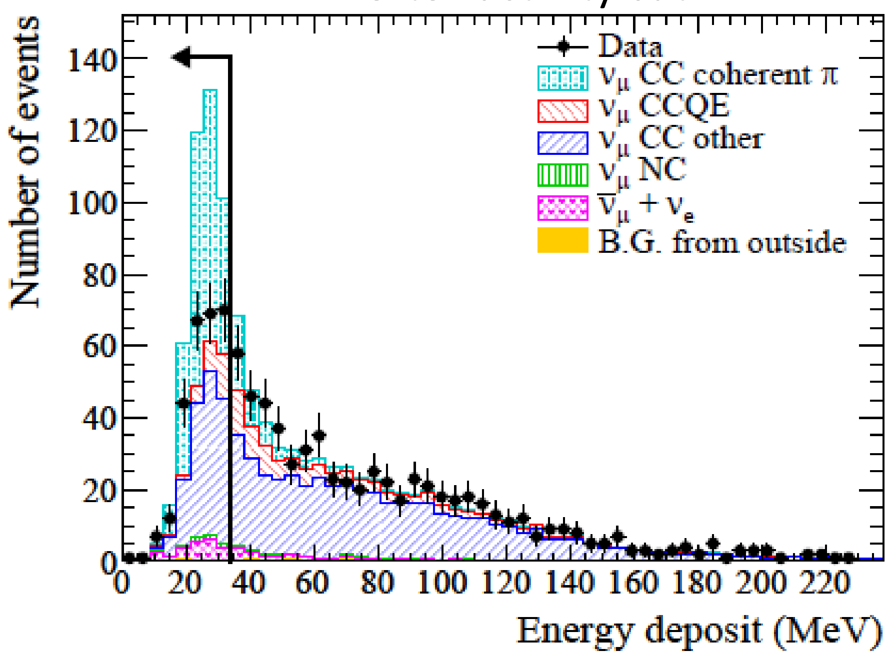
- Select events with muons scattered very forward.
  - Momentum transfer of coherent pion production is small.
- Select events without large activity around vertex.
  - Reject events with low energy protons ($\nu_\mu p \to \mu^- \pi^+ p$).



Muon angle cut



Vertex activity cut



Analysis strategy

- Flux averaged CC coherent pion cross section is calculated with background subtraction and efficiency correction.

N_{sel}	: Number of selected events (data)
N_{BG}	: Number of selected BG events (MC)
Φ	: Integrated ν_μ flux (MC)
T	: Number of target nuclei
ε_{CCcoh}	: Detection efficiency of CC coherent pion events (MC)

$$\sigma_{CCcoh} = \frac{N_{sel} - N_{BG}}{\Phi T \varepsilon_{CCcoh}}$$

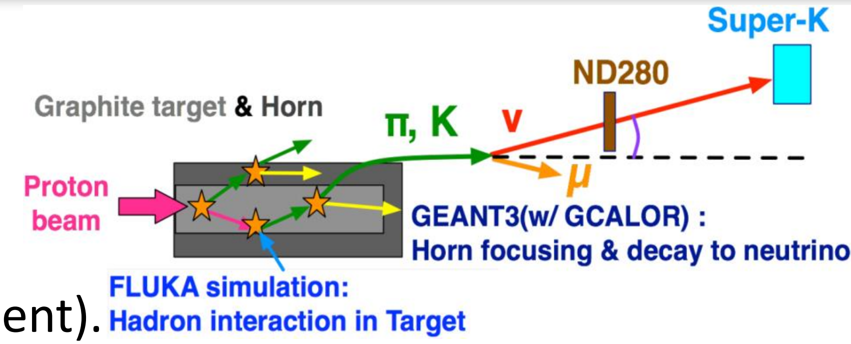
- Purity of CC coherent pion events is 53.3%.
- Efficiency of CC coherent pion events is 16.0%.
- CC resonant pion events are dominant background events.

MC expected background ratio to all selected events

	Fraction
CCQE	6.50%
CC resonant pion	24.36%
CC other	9.00%
NC events	1.16%
$\bar{\nu}_\mu$ events	5.22%
ν_e events	0.06%
External	0.39%

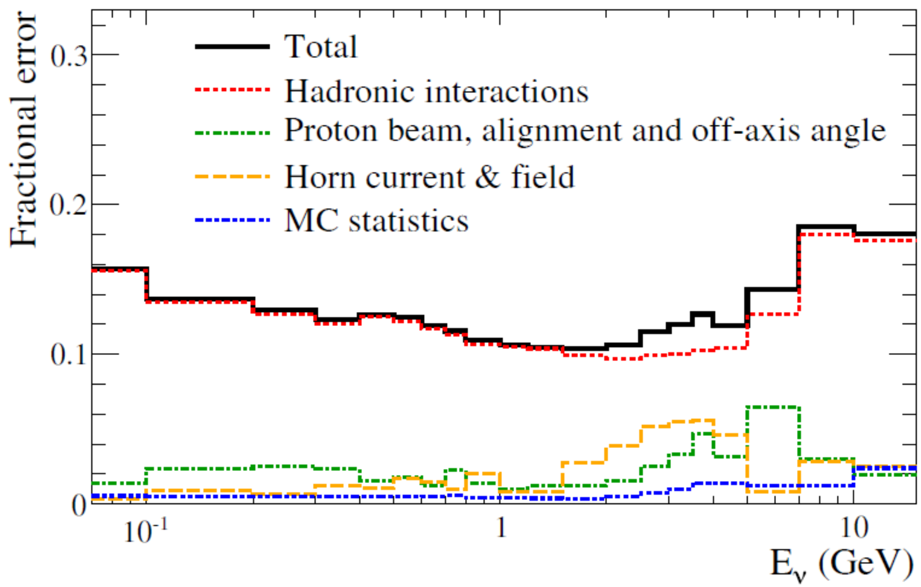
Systematic error from neutrino flux

- Source of the flux uncertainty:
  - Hadron interaction uncertainties.
  - T2K beamline uncertainties (proton beam position and intensity, beam direction, horn current, alignment).

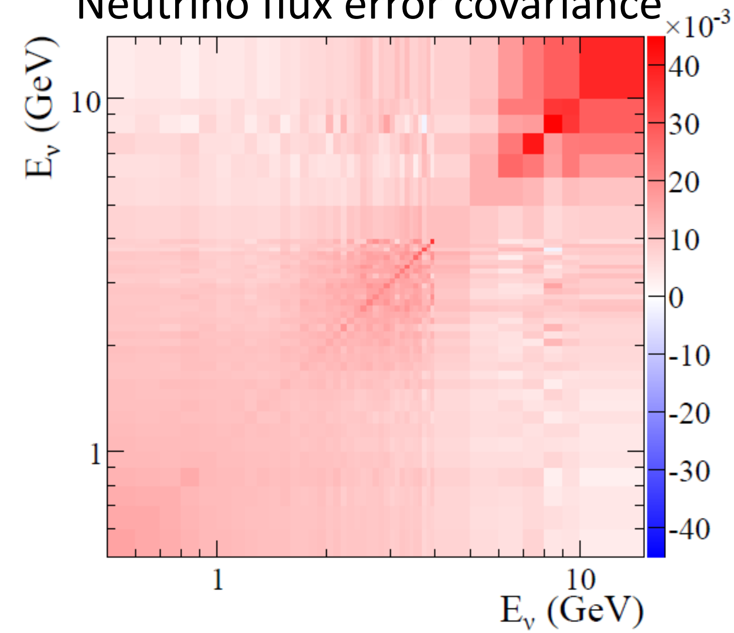


- Total neutrino flux uncertainty is ~10%.
- Hadron interaction uncertainty is dominant error source.
- Systematic error is evaluated by toy MC generated from the covariance matrix.

Fractional neutrino flux error



Neutrino flux error covariance



Systematic error from neutrino interaction

- Fit the external data with free model parameters in NEUT.
- Introduce ad hoc parameters to take into account remaining differences between data and NEUT.
- Estimate values and errors of the model and ad hoc parameters.
- Introduce, additional FSI uncertainties.

Neutrino interaction parameters

	Parameter	Value	Error
Model parameters	M_A^{QE}	1.21GeV	16.53%
	M_A^{RES}	1.21GeV	16.53%
	π-less Δ decay	0.2	20%
	Spectral function	0	100%
	Fermi momentum (CH)	217MeV/c	13.83%
	Binding energy (CH)	25MeV	36%
Ad hoc parameters	CCQE norm. ($E_\nu < 1.5$GeV)	1	11%
	CCQE norm. ($1.5 < E_\nu < 3.5$GeV)	1	30%
	CCQE norm. ($E_\nu > 3.5$GeV)	1	30%
	CC1π norm. ($E_\nu < 2.5$GeV)	1	21%
	CC1π norm. ($E_\nu > 2.5$GeV)	1	21%
	CC other shape	0	40%
	NC1π^0 norm.	1	31%
	NC coherent π norm.	1	30%
	NC1$\pi^\pm$ norm.	1	30%
	NC other norm	1	30%
	W shape	8.77MeV	52%
	CC1π^+ shape	0	50%

Systematic errors

- Detector error:
  - Error sources: target mass, dark count, hit detection efficiency, light yield, event pileup.
  - Additional data-MC discrepancy in each event selection step is included as the detector error.
- Systematic errors from neutrino flux and CC resonant pion production uncertainties are large.

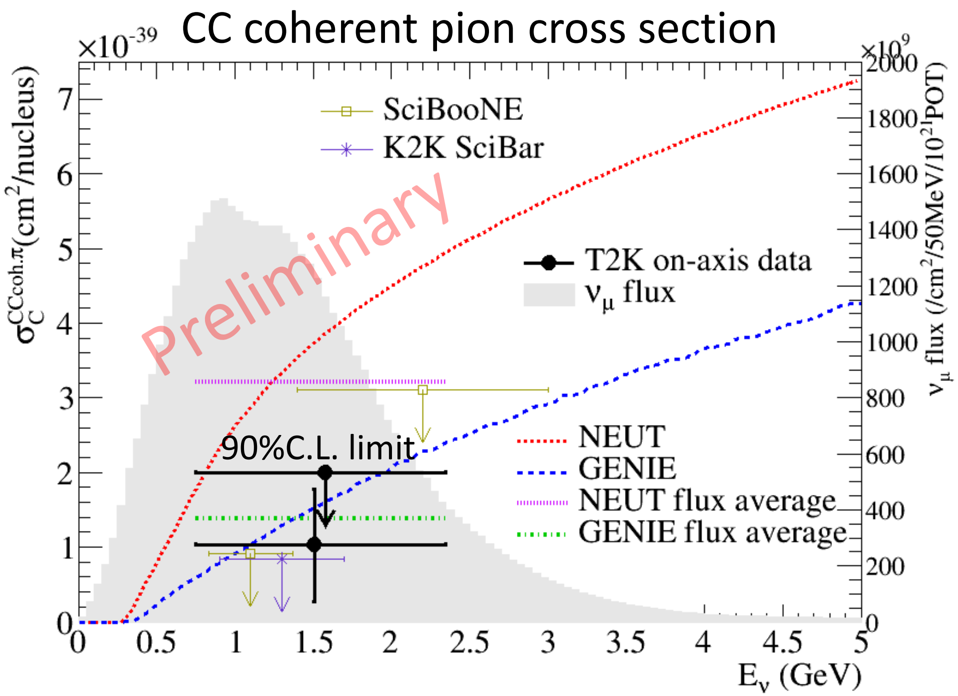
Summary of systematic errors

Source	Error
Neutrino flux	$-35.68\% + 43.20\%$
Neutrino interaction + FSI	$-46.03\% + 43.17\%$
Detector	$\pm 30.91\%$
Total	$-65.93\% + 68.45\%$

→ Error from CC resonant pion uncertainties is $-32.76\% + 31.47\%$

CC coherent pion cross section result

- CC coherent pion cross section at mean energy of 1.5GeV is $\sigma_{CCcoh} = (1.03 \pm 0.25(stat.)^{+0.70}_{-0.68}(syst.)) \times 10^{-39}$ cm²/nucleus
- 90% C.L upper limit is $\sigma_{CCcoh} < 1.98 \times 10^{-39}$ cm²/nucleus
- It agrees well with the prediction by GENIE, but is significantly smaller than prediction by NEUT.
- It is compatible with CC coherent pion results from K2K and SciBooNE.
- Significance of the signal excess corresponds to 1.5σ. (SciBooNE and K2K results are consistent with null CC coherent pion.)

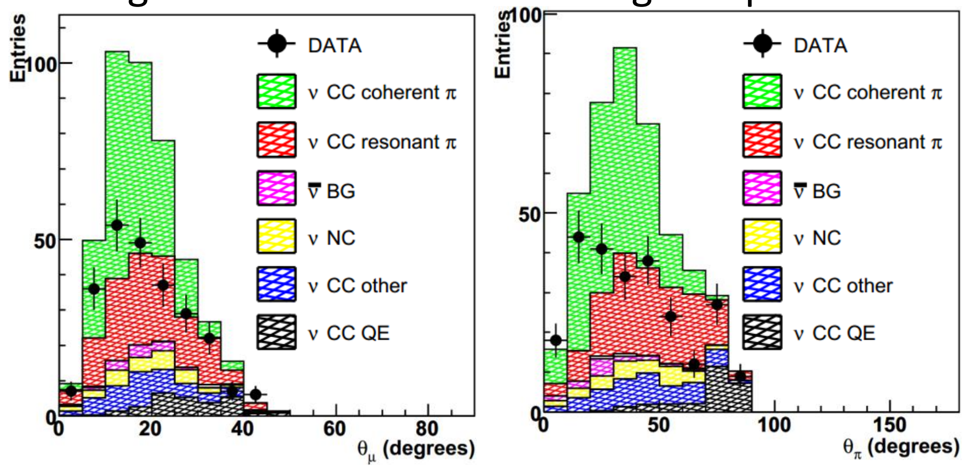


Track angle of CC coherent pion candidates

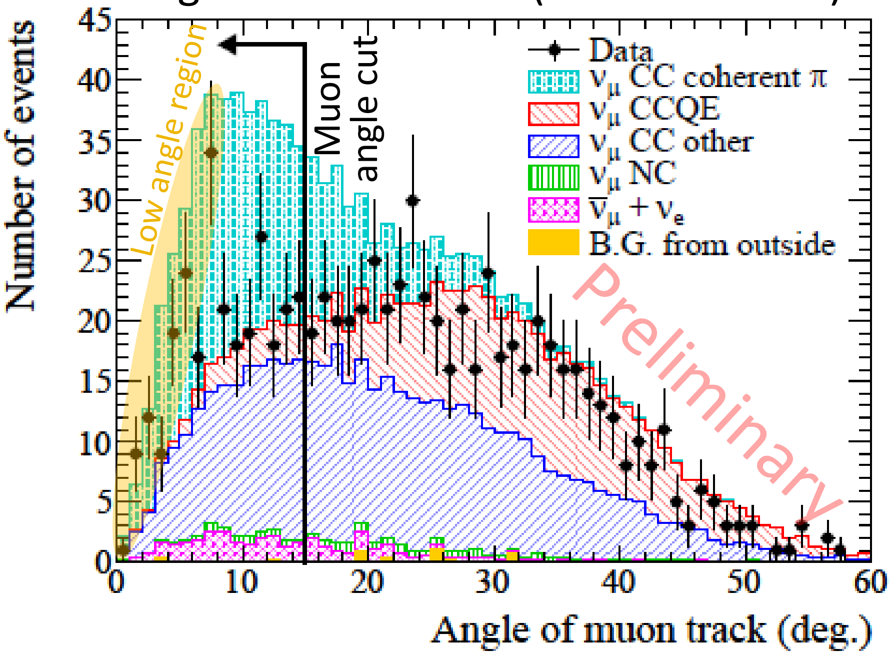
- In the angular distributions of the selected sample, data agree with MC in small angle regions, but disagree with MC in large angle regions.
- Similar tendency is seen in the SciBooNE result.

SciBooNE result (MC uses NEUT)

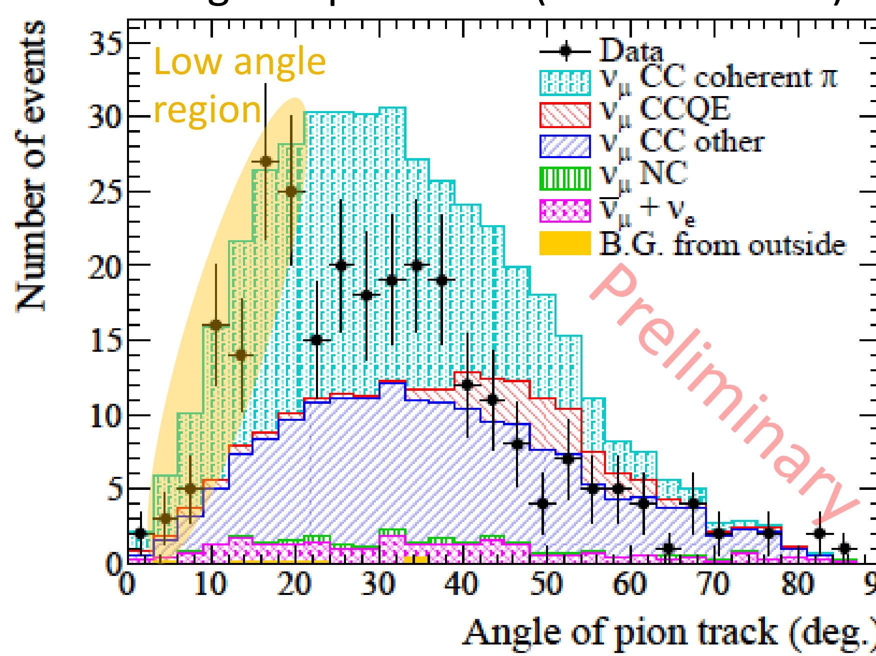
Angle of muon track
Angle of pion track



Angle of muon track (MC uses NEUT)



Angle of pion track (MC uses NEUT)



Summary

- Flux averaged CC coherent pion cross section on C at mean energy of 1.51GeV was measured using T2K on-axis neutrino detector, INGRID.
- Cross section result agrees well with the prediction by GENIE, but is significantly smaller than prediction by NEUT.
- Significance of the signal excess is 1.5σ.
- In the angular distributions of the selected sample, data agree with MC in small angle regions, but disagree with MC in large angle regions.
- CC coherent pion cross section measurement using T2K off-axis neutrino detector, ND280 is ongoing.

Backup

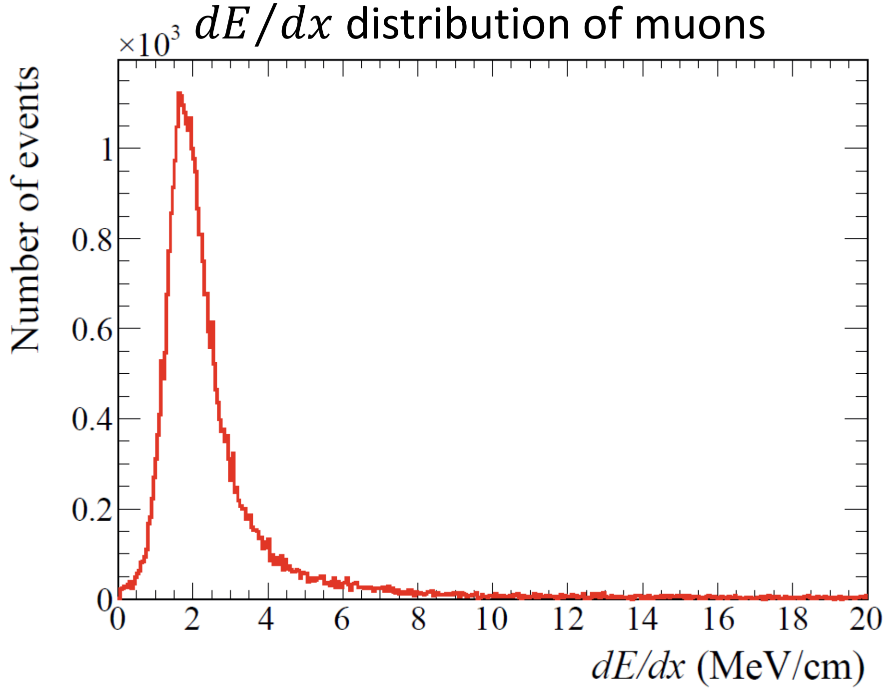
Particle identification

- Muon confidence level (MuCL) is defined with muons from surrounding material.
  - The dE/dx distribution of muons obtained by muons from the walls.
  - The cumulative distribution function of the muon dE/dx distribution corresponds to the confidence level.
  - Combine the confidence levels obtained from all the planes.

$$\mathrm{MuCL} = P \times \sum_{i=0}^{n-1} \frac{(-\ln P)^i}{i!}, \;\; P = \prod_{i=1}^{n} CL_i$$

Confidence level of i^{th} plane

dE/dx distribution of muons



cumulative distribution function of the muon dE/dx distribution