FJPPL : NU_05

Precision neutrino cross-section measurements and modeling for long-baseline oscillation experiments

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Joint Workshop of the **France Korea** (FKPPL) and **France Japan** (TYL/FJPPL)
International Associated Particle Physics Laboratories

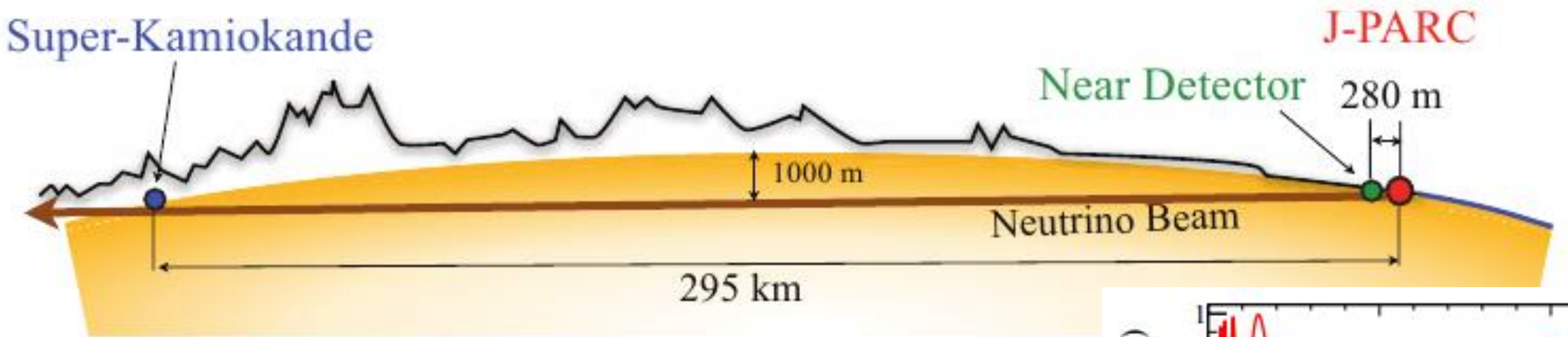
2016/05/18 @KIAS

Contents

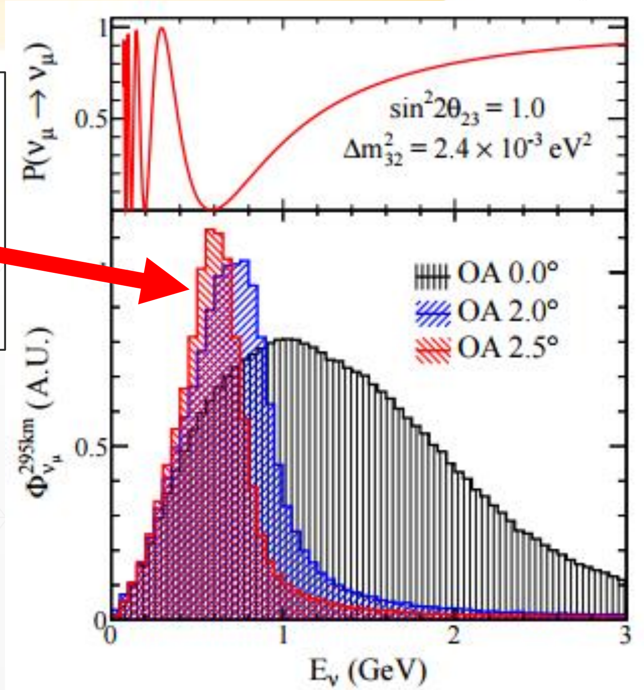
Cross section measurements in the T2K experiment

Overview of the T2K experiment

Long-baseline neutrino oscillation measurement



- High intensity, almost pure (anti-)neutrino beam
- Use off-axis method (2.5 degrees)
- Measure neutrino oscillation parameters
- Aim to discover CP violation of the lepton sector

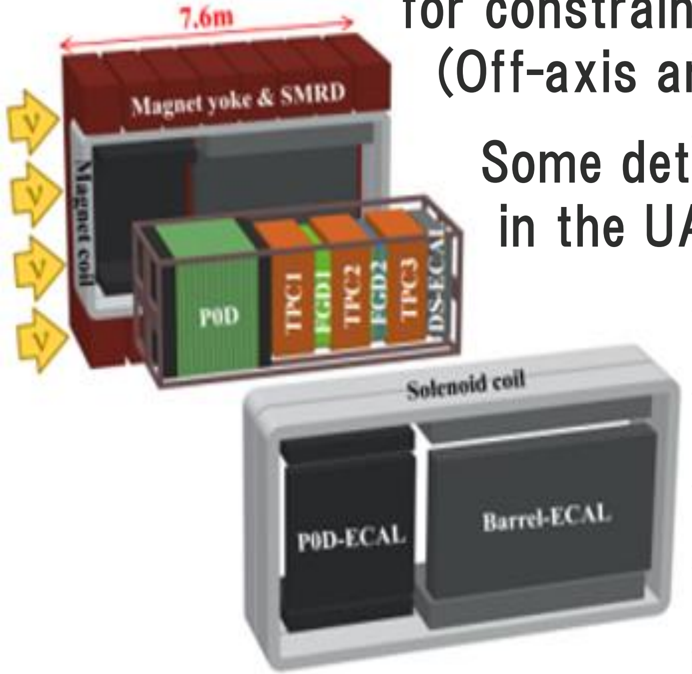


$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{atmospheric\ \ mixing} \times \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}}_{reactor\ \ mixing} \times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{solar\ \ mixing}$$

T2K Near-detectors

ND280

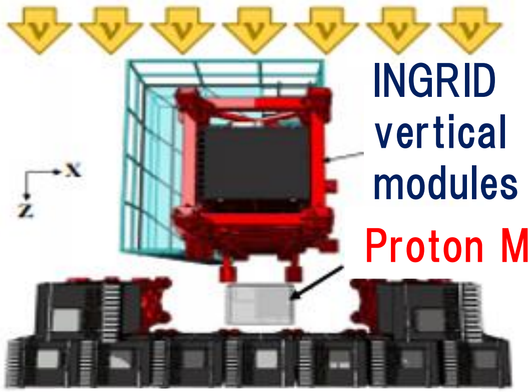
Measure the unoscillated neutrino flux for constraining the flux & cross section (Off-axis angle : 2.5 degrees)



Some detectors are installed in the UA1 magnet (0.2 T)

- P0D
- TPC
- FGD
- ECal
- SMRD

INGRID



Tracker

- FGD : Scintillators (FGD1)
  Scintillators + H_2O (FGD2)
- TPC : Mainly Ar (95%) filled
  Tracking & Particle ID

Measure the beam direction, beam profile, and beam stability (located at on-axis)

INGRID (16 modules)

- Fe + Scintillators (sandwich structure)

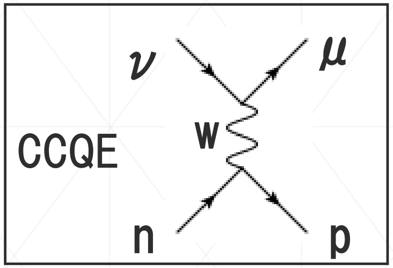
Proton Module (1 module)

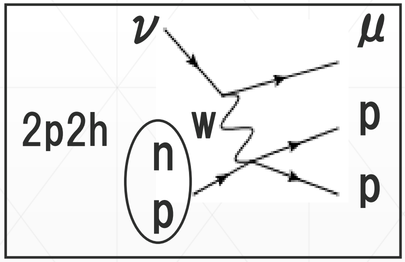
- Fully active scintillator tracker

T2K systematic errors

Large nuclear-model uncertainties…

- Target difference between Near-detector (CH) and Far-detector (H_2O)
  - Some measurements on carbon & on water are described later
- 2p2h interaction can look like CCQE signal event in the final state at SK
  - Due to nuclear effects, 2p2h contributes to the signal





Systematic error source	Error (ν_μ -> ν_μ)	Error (ν_μ -> ν_e)	Error ($\bar{\nu}_\mu$ -> $\bar{\nu}_\mu$)	Error ($\bar{\nu}_\mu$ -> $\bar{\nu}_e$)
ν flux & cross section	3.1%	2.7%	3.4%	3.0%
ν cross section (Non-cancelled)	4.7%	5.0%	10.0%	9.8%
SK FSI & SI	3.0%	2.4%	2.1%	2.2%
Total	6.8%	7.7%	11.6%	11.0%

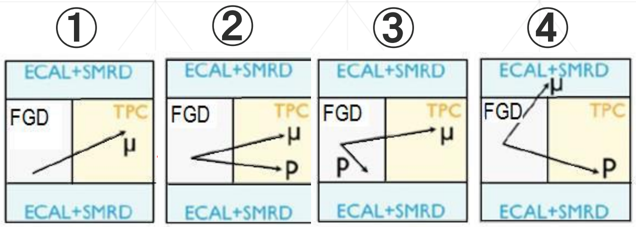
Need model-independent measurements !

- As a function of measured variables (muon kinematics)
  - No dependence on model to translate to neutrino energy
- Charged current process w/o pions in the final state (CC0pi)
  - Less dependence on FSI model

CC0pi on carbon @ND280

arxiv:1602.03652,
under publication on PRD

In order to confirm the robustness of the measurement,
two analyses have been performed



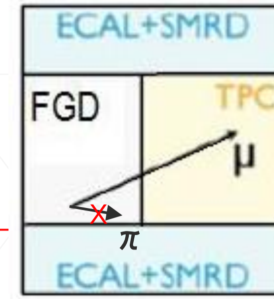
Analysis I

Selection

① Only muon in TPC
② 1 muon + 1 proton in TPC
③ 1 muon in TPC + 1 proton in FGD
④ 1 proton in TPC + 1 muon in FGD

Method to extract the cross section

- Likelihood fit



Analysis II

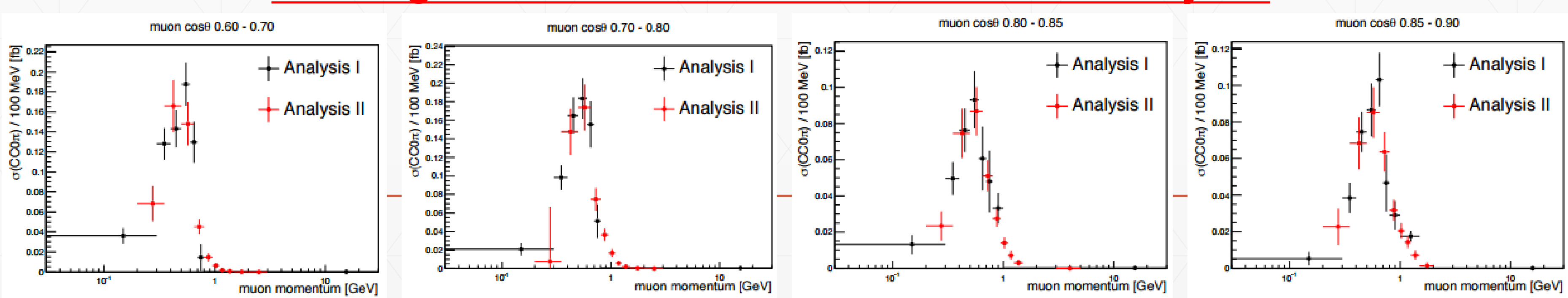
Selection

- Only muon in TPC + no pion in final state
  (e.g. no pion-like tracks in FGD)
  - No proton information used

Method to extract the cross section

- Bayesian unfolding

Good agreement can be seen between two analyses



CC0pi on carbon @ND280

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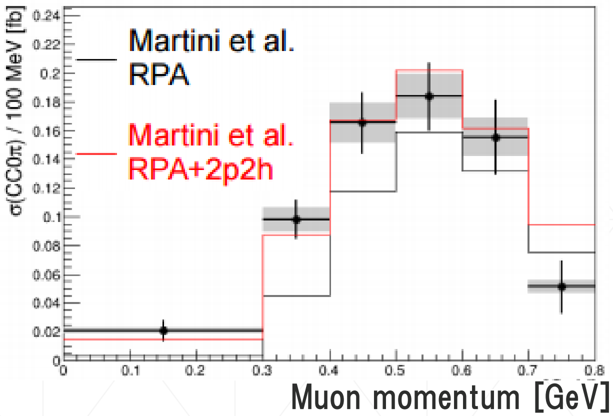
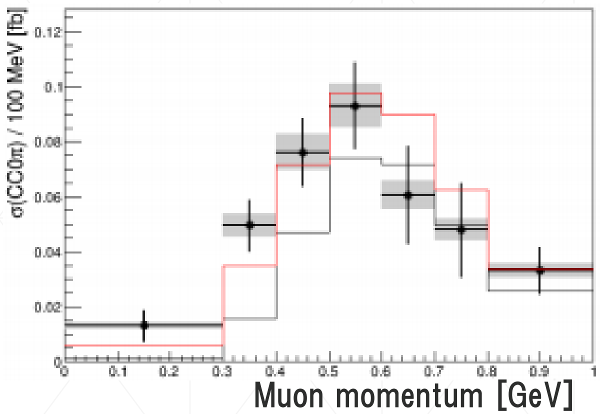
Analysis I

Results indicate the presence of 2p2h interactions,
but it is difficult to make a conclusion …more data desired !

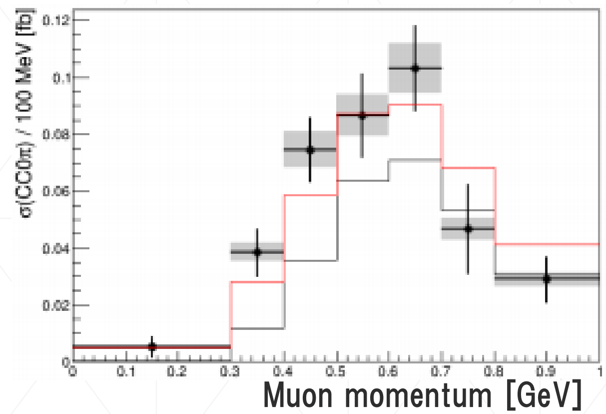
Muon $\cos\theta$ 0.70 - 0.80

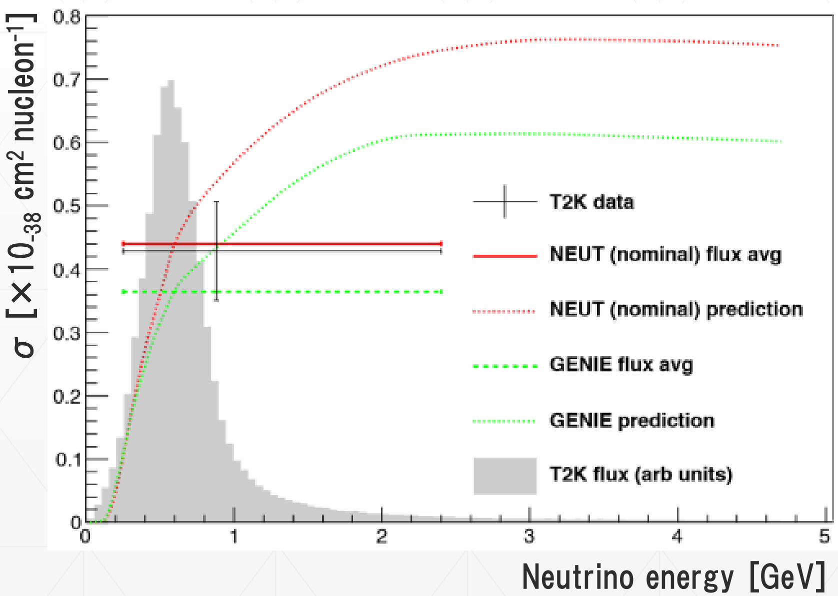


Muon $\cos\theta$ 0.80 - 0.85



Muon $\cos\theta$ 0.85 - 0.90





Results are in agreement
with both NEUT and GENIE predictions

Integrated cross sections [$\times 10^{-38}$ cm^2 nucleon^{-1}]

Ⅰ : 0.417 ± 0.047 (syst.) ± 0.005 (stat.)
(NEUT prediction : 0.444)

Ⅱ : 0.202 ± 0.0359 (syst.) ± 0.0026 (stat.)
(NEUT prediction : 0.232)

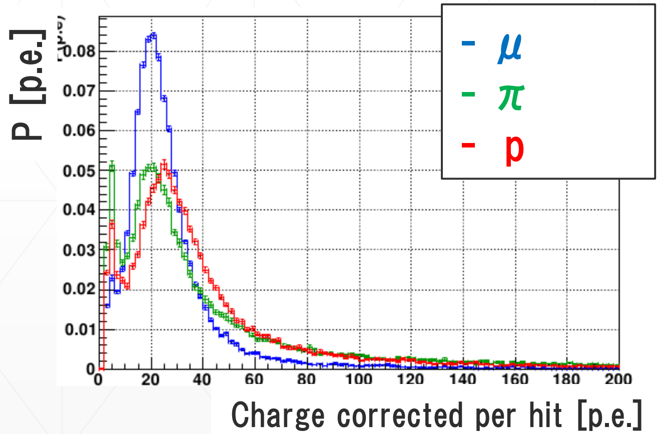
CC0pi on carbon @Proton Module

Combination of measurements at on/off-axis would give a model-independent estimation of the energy dependence of the cross section

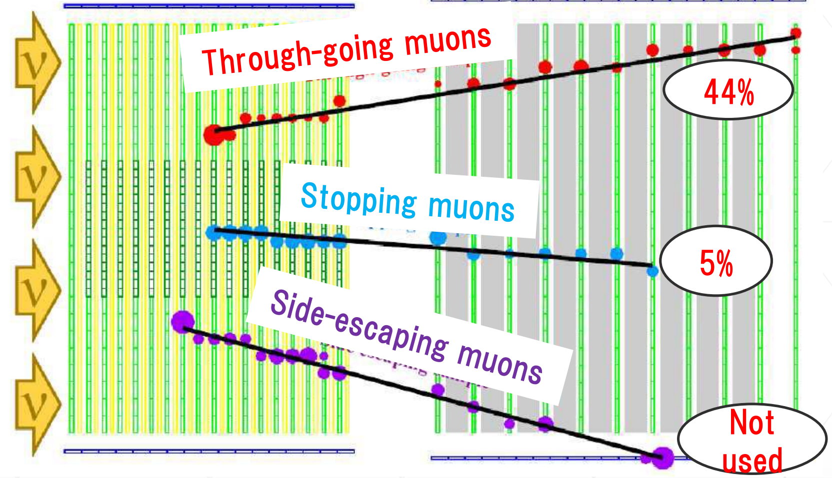
MC study is now on-going !

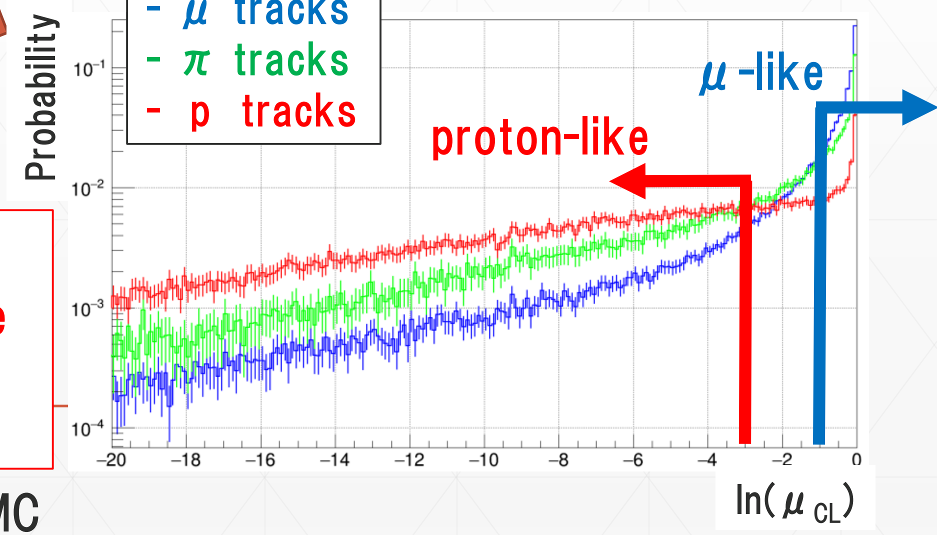
No B-field at Proton Module...
-> Use INGRID penetration distance for p_μ determination (~100 MeV/c resolution)

PID is based on dE/dx



Deduce confidence level





Selection cut for PID

- C.L. > -2.5 : μ-like, C.L. < -3.5 : proton-like
- π track looks μ-like
  -> Only 1 μ-like track is required

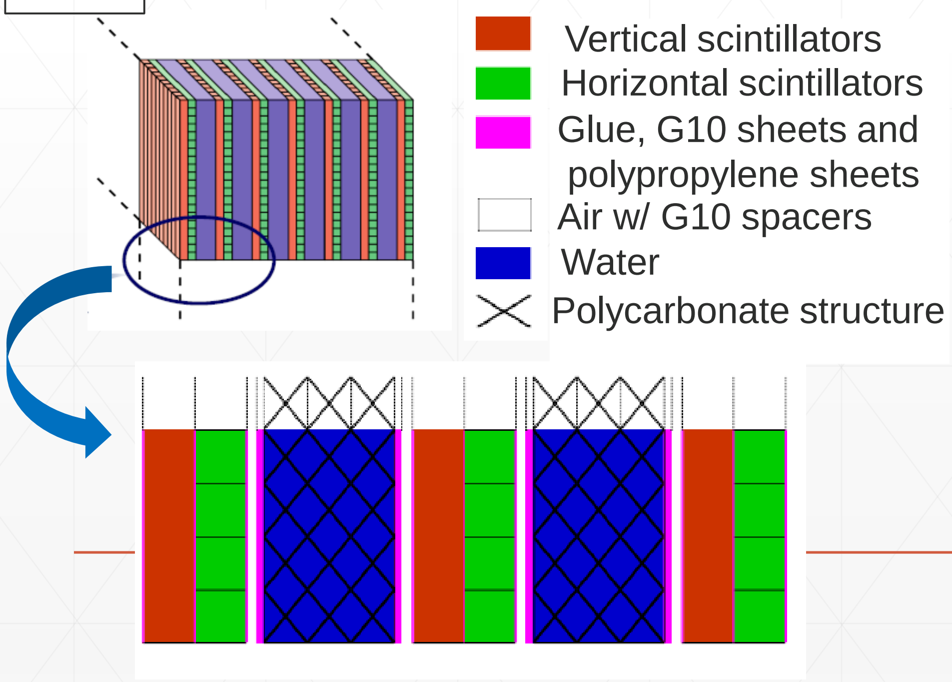
Selection efficiency is about 80% in MC

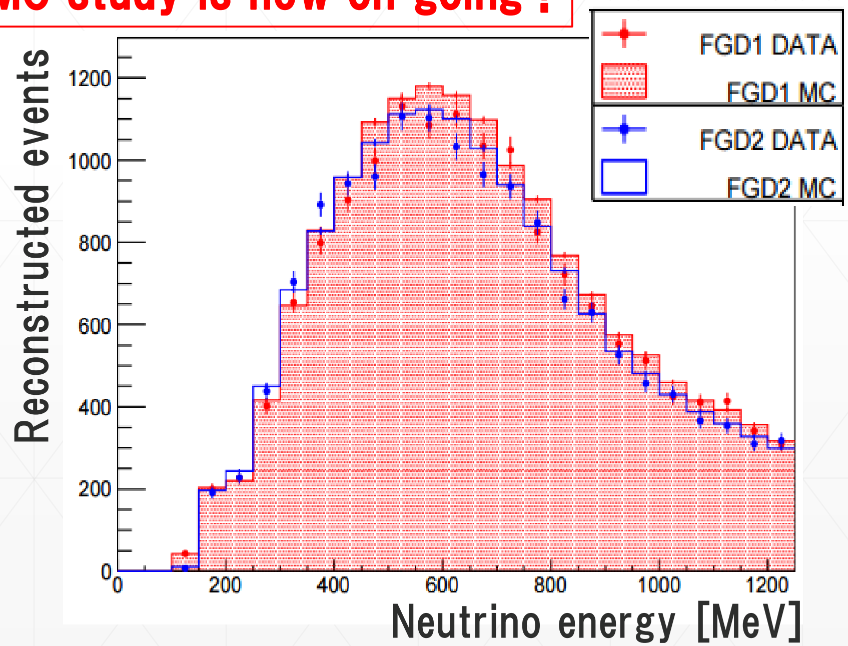
CC0pi on water @ND280 (FGD)

- Extract the dependence of nuclear effects on the target nucleus
  - Useful since the T2K far detector is composed of water
- Scintillators : Water = 50 : 50 (volume) in FGD2
  - FGD1 contains only scintillators
- Subtraction method used to extract the cross section (σ^{water}) and ratio ($\frac{\sigma^{water}}{\sigma^{scinti}}$)
  - Water = FGD2 - Scintillators

MC study is now on-going !

FGD2



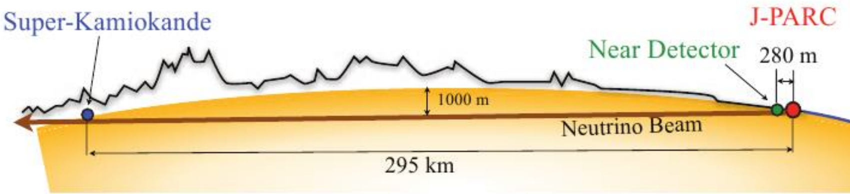


Neutrino energy is well reproduced by MC for both FGDs

New experiment for measuring H_2O / CH cross sections
- WAGASCI experiment -

Motivation of the WAGASCI experiment

SK
Target : H_2O
Acceptance : 4π



ND280
Target : CH
Acceptance : Forward

Systematic error source	Error (ν_μ -> ν_μ)	Error (ν_μ -> ν_e)	Error ($\bar{\nu}_\mu$ -> $\bar{\nu}_\mu$)	Error ($\bar{\nu}_\mu$ -> $\bar{\nu}_e$)
ν cross section due to target difference btw. ND280 and SK	4.7%	5.0%	10.0%	9.8%
Total	6.8%	7.7%	11.6%	11.0%

In order to reduce this large uncertainty, we are constructing **a new detector** for measuring... (for charged current interactions)

- <u>Cross section on H_2O and CH with 10% accuracy, respectively</u>
  Flux uncertainty is a main error
- <u>Cross section ratio between H_2O and CH within 3% accuracy</u>
  Taking the ratio, flux uncertainty is expected to be canceled

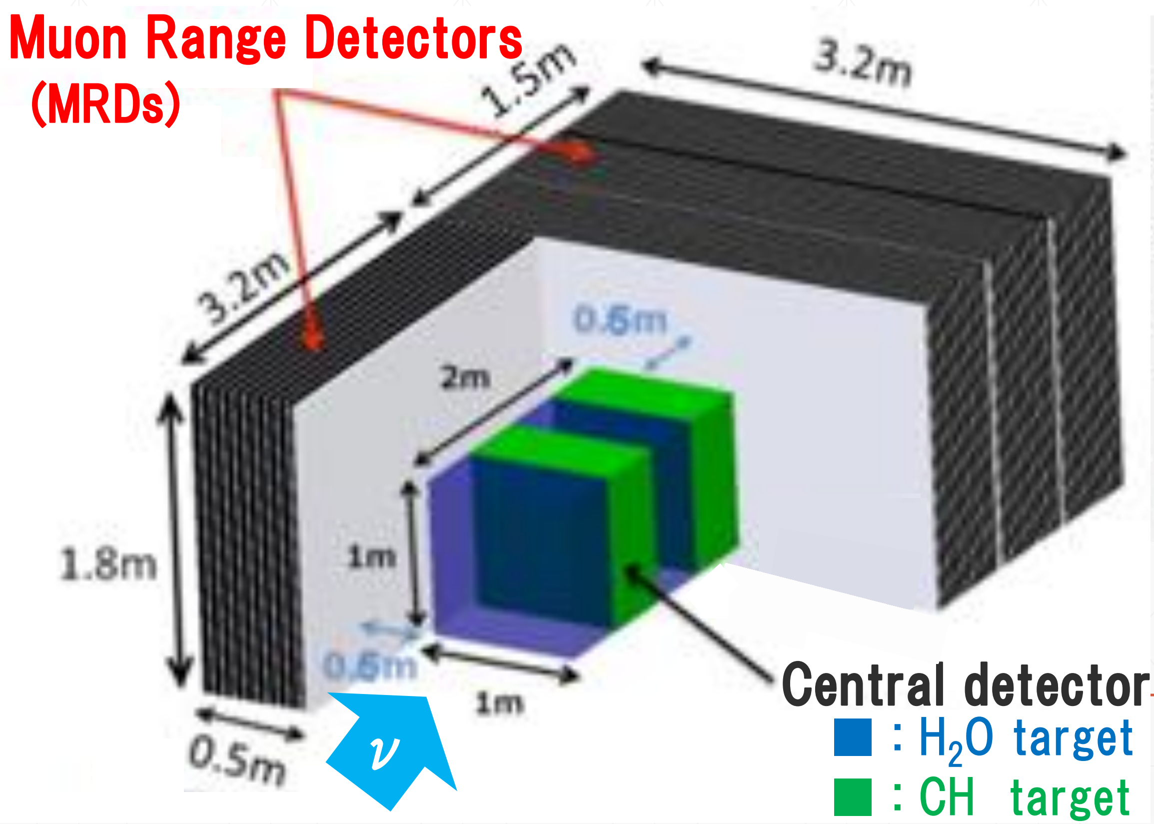
Detector geometry

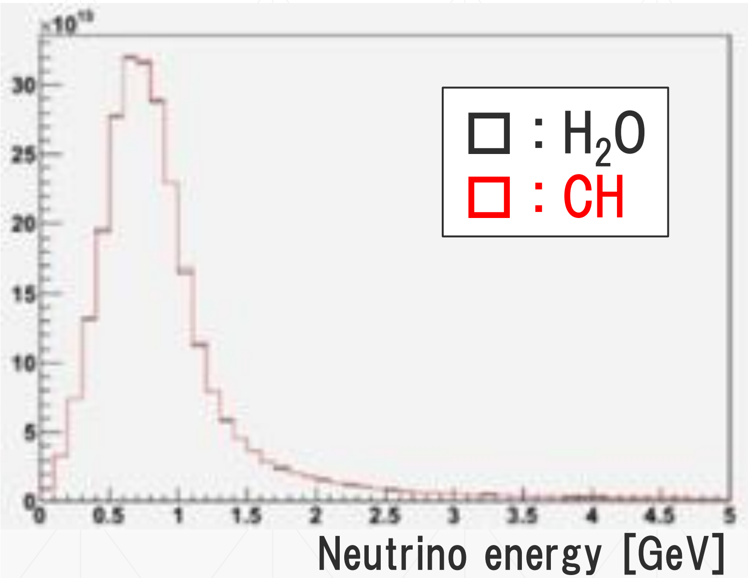
Central detector

- H_2O module ×2 + CH module ×2
- Target (H_2O/CH) + plastic scintillators
- Each target has 1×1×1 m^3 volume and 1 ton mass

Muon range detectors (MRDs)

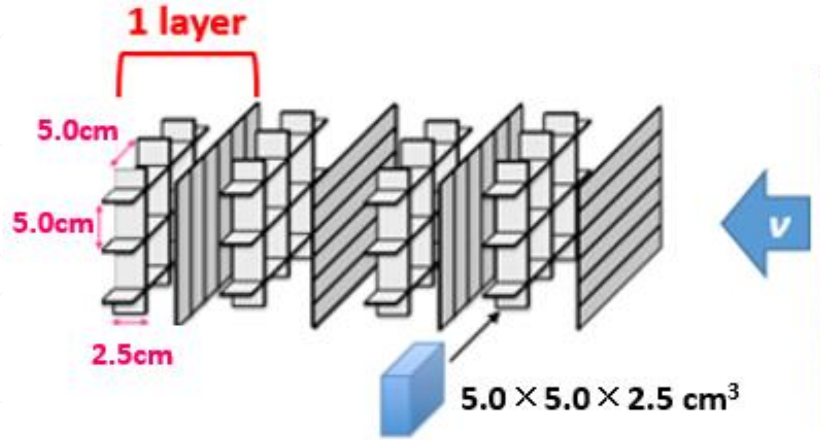
- Iron plates + plastic scintillators
- Identify muons and measure their momentum





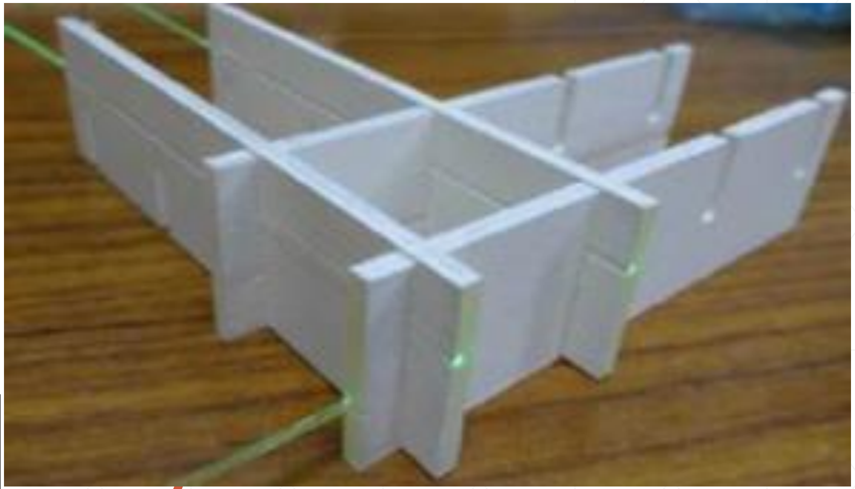
Similar energy spectrum between targets

Detector components



3D grid-like scintillators
- Each space is filled with target materials
- Target : scintillator = 79 : 21 (volume)

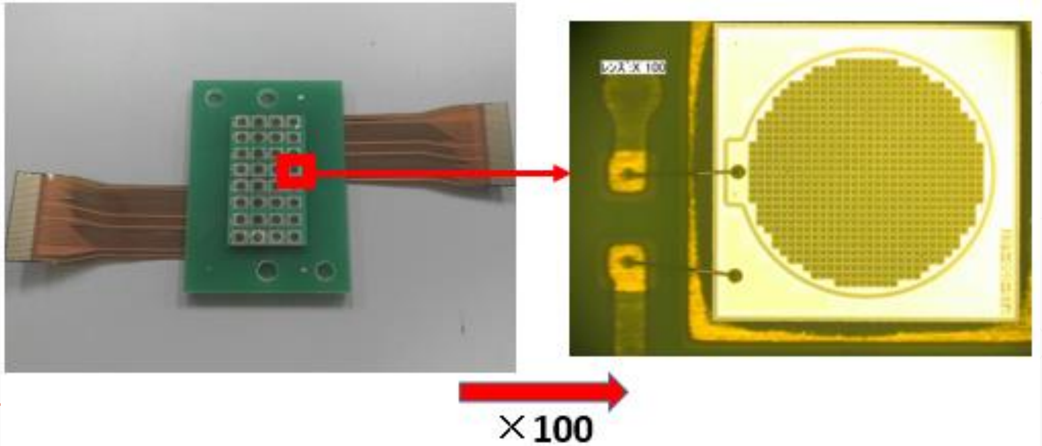
Scintillator
- 3 mm thickness
- WLS fiber is put on each groove



Connected to MPPCs

Box for Japanese cake, "wagashi"

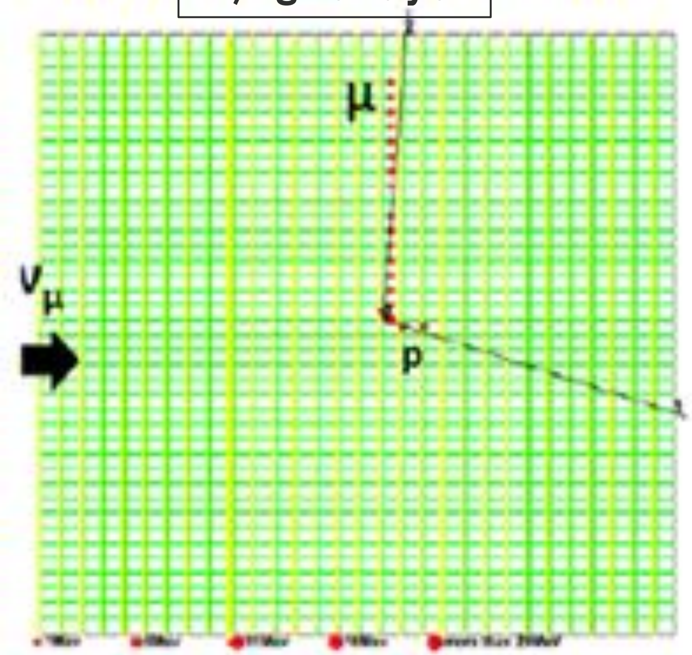
WAter **G**rid **A**nd **SCI**ntillator
→ WAGASCI



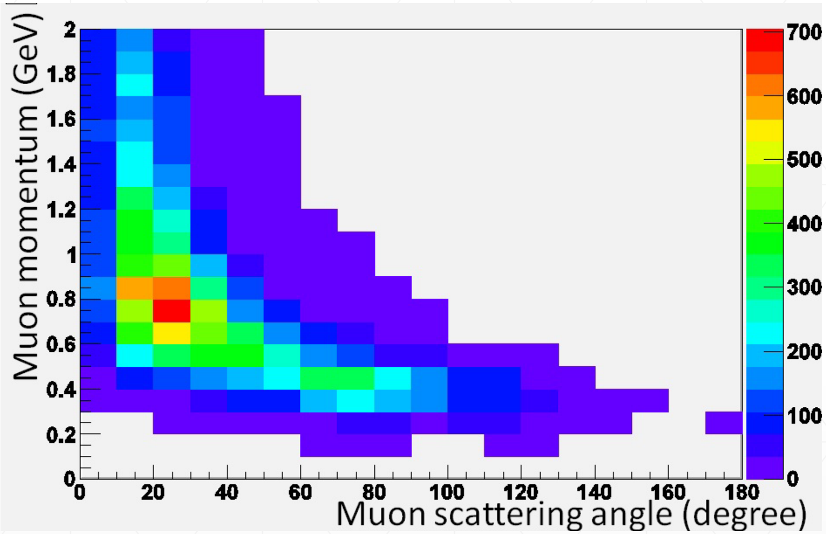
32 ch array-type MPPC

Expected performance in MC

w/ grid layer



- Large angular acceptance
- Wide momentum coverage



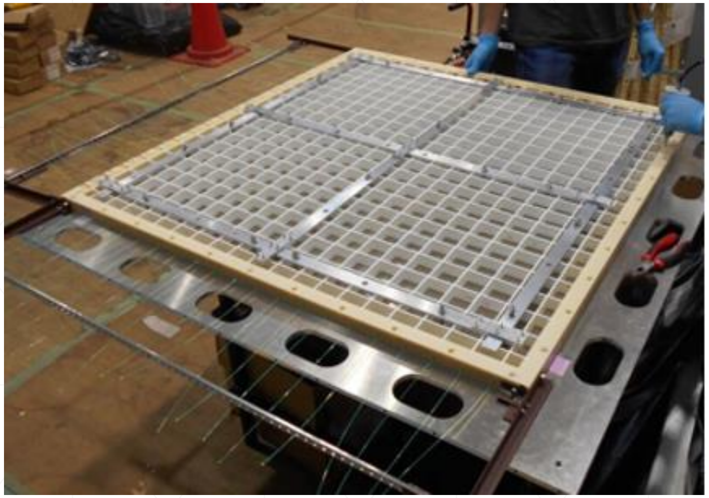
[MC events after the selection]

	CC (Signal)	NC	Background from outside	All
Event rate / 10^{21} POT	**29450**	1060	1640	32150
Fraction	**91.6%**	3.3%	5.1%	100%

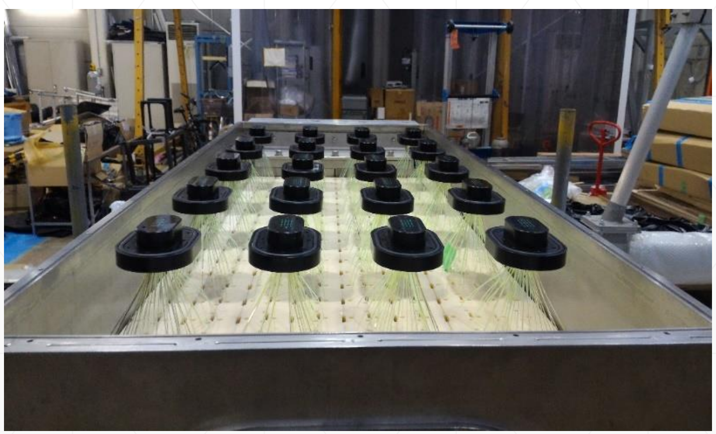
High statistics & Low backgrounds are expected

Detector construction

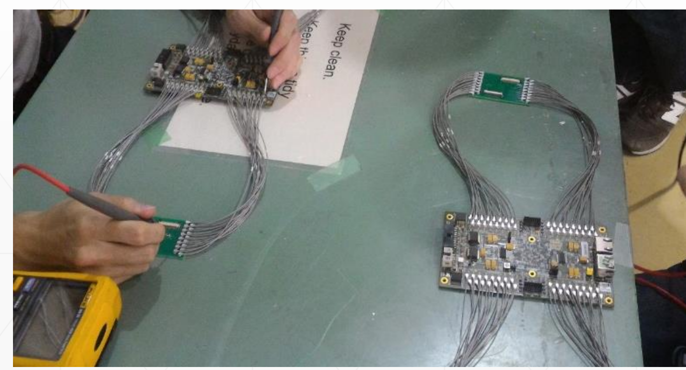
Designed by LLR group



1 water module has been constructed as a prototype detector (Oct. - Dec. 2015)



Complete module is installed into the water tank



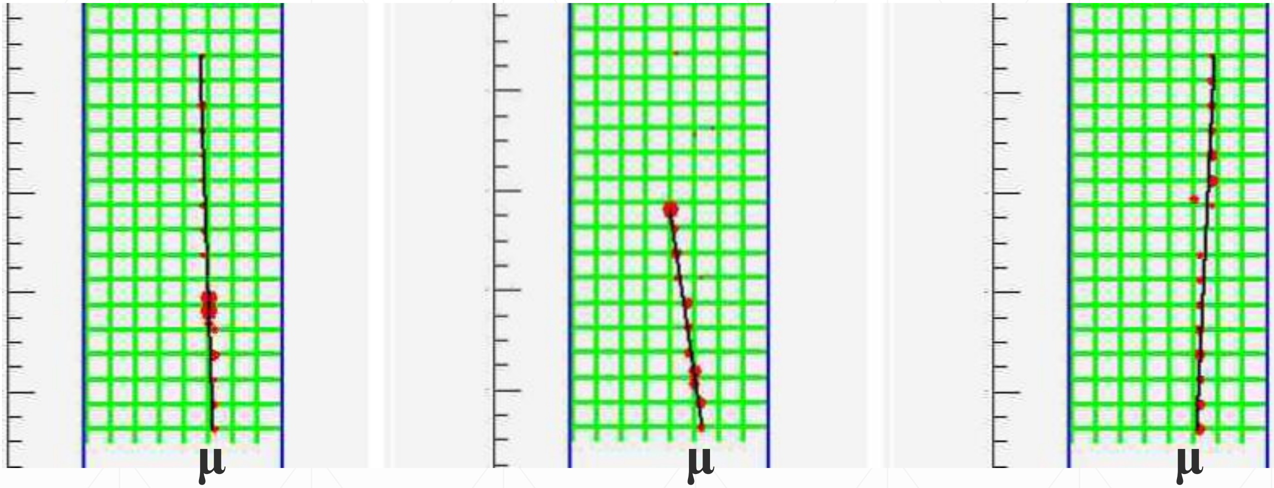
Electronics boards have been also prepared

Schedule

Prototype detector

● ～ May 2016 : Performance test by cosmic-rays

- Event displays (3 samples) show a muon is well reconstructed



● Jun 2016 ～ Summer 2016 : Commissioning / Cosmic data taking

● Autumn 2016 ～ : Start neutrino beam measurement

WAGASCI detector

● ～ Summer 2017 : Detector construction

● Autumn 2017 ～ : Start neutrino beam measurement

Summary

- **Model-independent measurements in the T2K experiment**
  - Measure CC0pi cross section on C at off-axis
    - Hint of 2p2h interaction
  - Measure CC0pi cross section on C at on-axis
    - Combine with measurements at off-axis
  -- Measure CC0pi cross section on H_2O at off-axis
    - Extract the dependence of nuclear effects on target nucleus

- **New experiment is on-going to measure H_2O/CH cross section ratio**
  - Detector has 3D grid-like scintillators -> large angular acceptance
  - Prototype H_2O module has been complete, and the data taking will be started from the beginning of Jun 2016

Projects are all very fine !

Stay tuned for more results of cross section measurements…

Backups

Members

French group

Sara Bolognesi
Sandrine Emery
Marco Zito
Margherita Buizza Avanzini
Olivier Drapier
Michel Gonin
James Imber
Thomas Mueller
Jacques Dumarchez
Claudio Giganti
Bris Popov

Japanese group

Toshihumi Tsukamoto
Takashi Kobayashi
Tsuyoshi Nakaya
Yoshihiro Seiya
Kazuhiro Yamamoto
Akihiro Minamino
Taichiro Koga
Naruhiro Chikuma
Fuminao Hosomi
Tatsuya Hayashino
Kenichi Kin

\+ Matthieu Licciardi (From FY2016) + Jun Harada

Neutrino Oscillation Probability

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2(\frac{1.27\Delta m^2_{31}[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}),$$

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\cos^4 \theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23}) \sin^2(\frac{1.27\Delta m^2_{32}[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}),$$

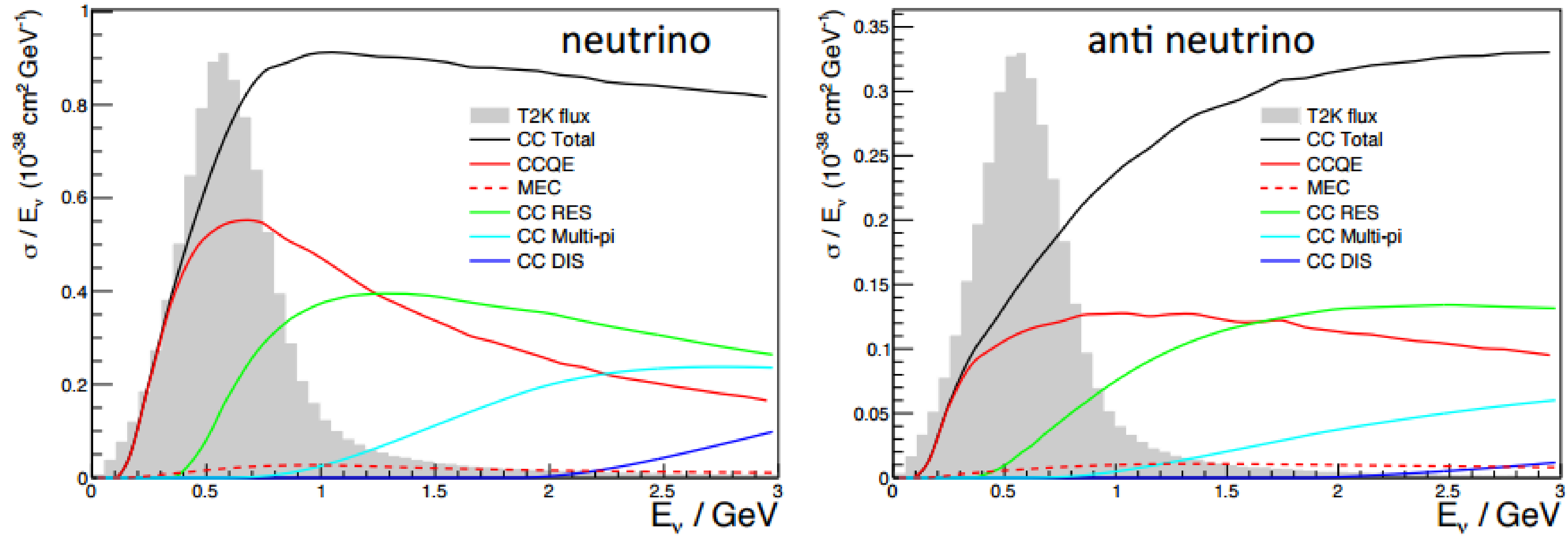
Oscillation phase

to be minimum...

$$\frac{1.27\Delta m^2_{32}L}{E} = \frac{\pi}{2}$$

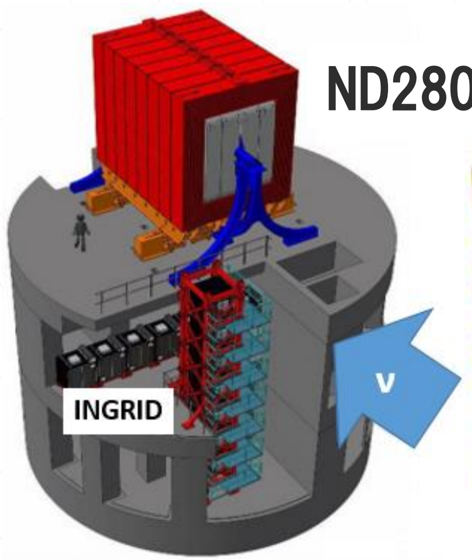
$$\mathbf{E \simeq 0.6\ GeV}$$

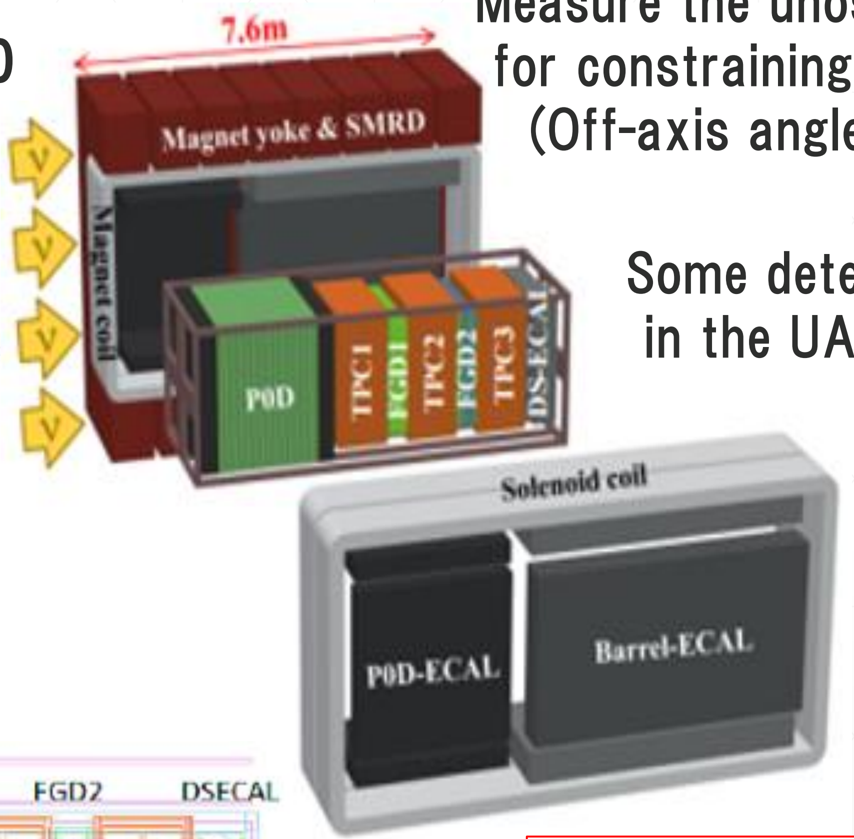
Neutrino interaction ratio (CC)



The fraction of CC events at the T2K energy is about 80%

T2K Near-detector (Off-axis)

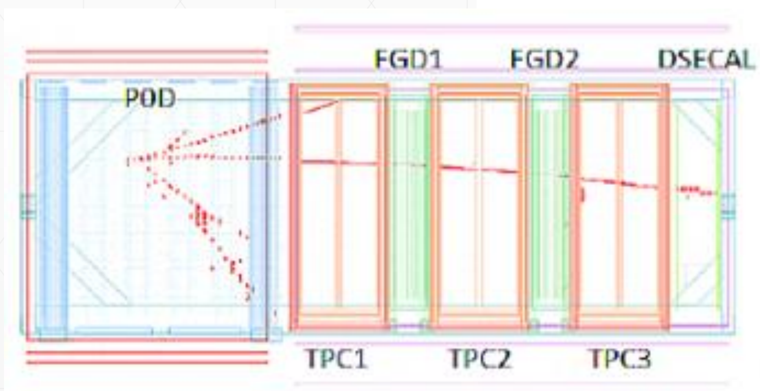




Measure the unoscillated neutrino flux
for constraining the flux & cross section
(Off-axis angle : 2.5 degrees)

Some detectors are installed
in the UA1 magnet (0.2 T)

- P0D
- TPC
- FGD
- ECal
- SMRD



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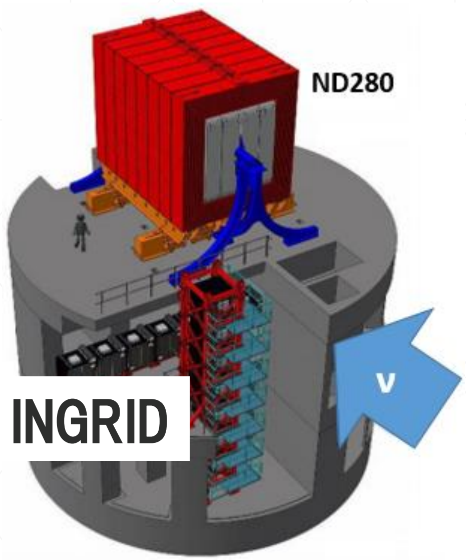

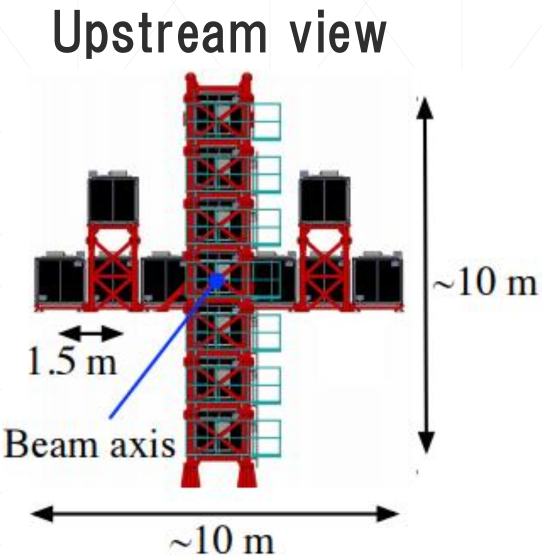

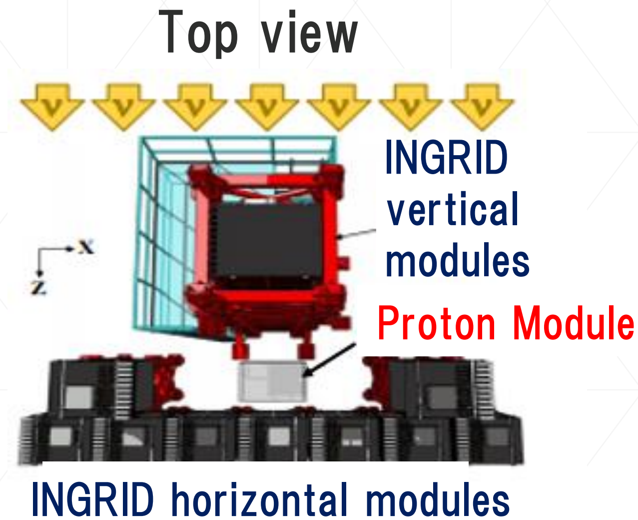

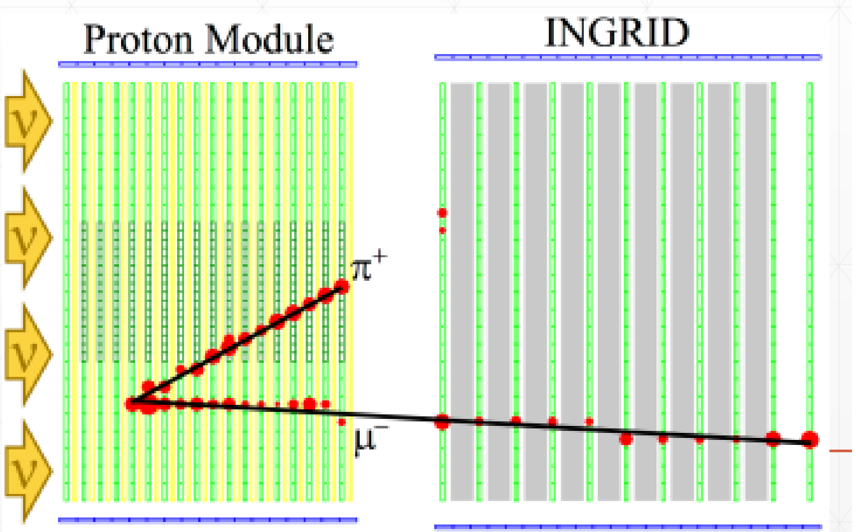

Measure the beam direction, beam profile, and beam stability.

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Selection

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③ 1 muon in TPC + 1 proton in FGD
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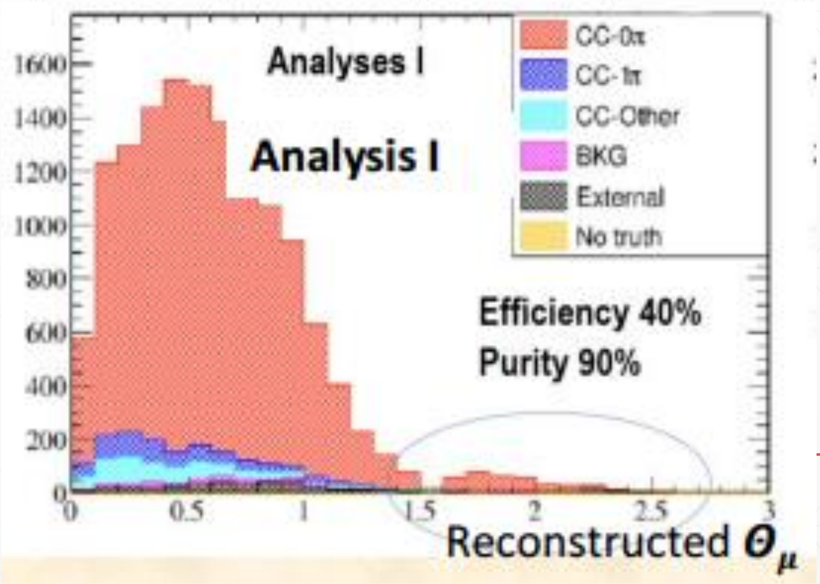
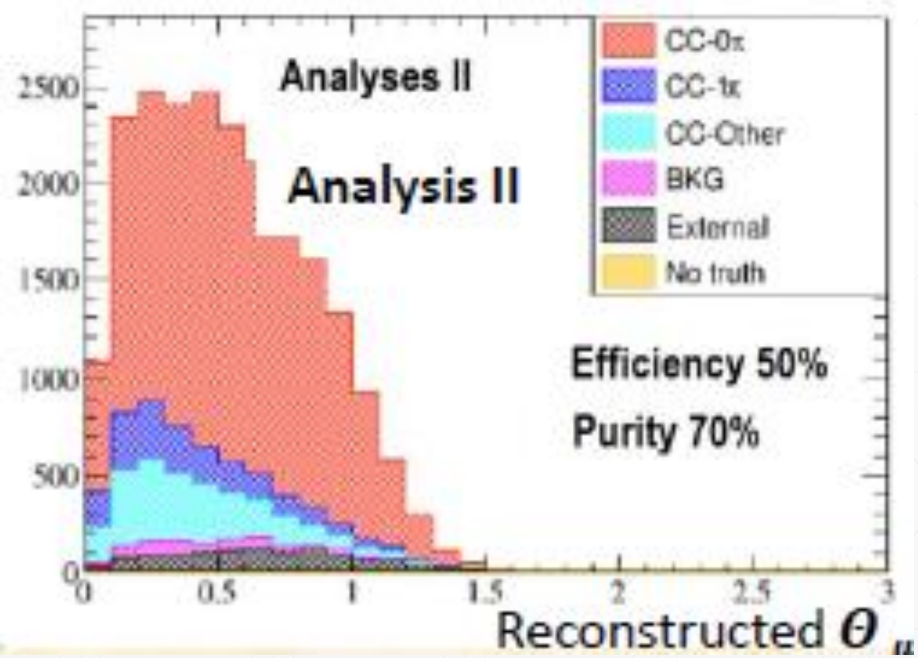


Analysis II

Good efficiency

Selection

● Only muon in TPC + no π in final state
- No proton information used



CC0pi on carbon @ND280

arxiv:1602.03652,
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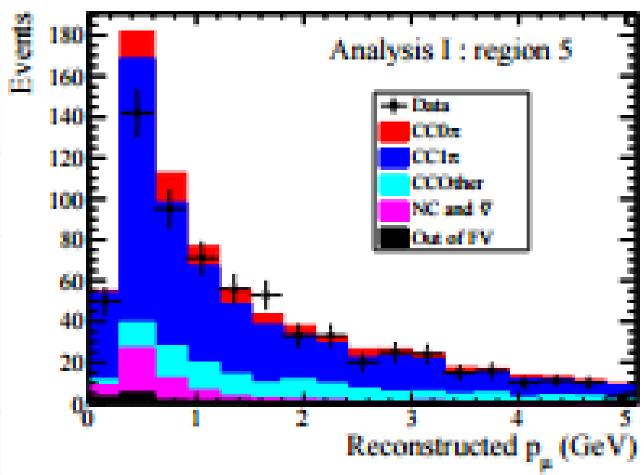
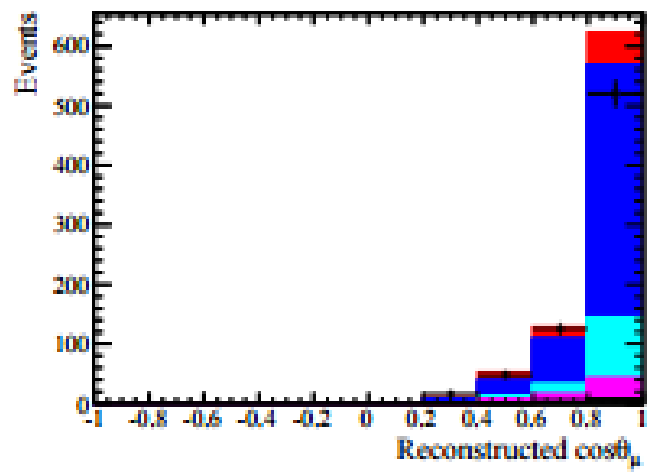
Analysis I

There are two additional control regions are selected in order to constrain charged current event rate with single-pion and multiple-pion production.

After pre-selection (e.g. ①), a reconstructed negative track in TPC with muon-like PID and a positive track in TPC with pion-like PID are required.

- Events with exactly two tracks are included in region 5 : CC1π control region
- Events with more than two tracks are included in region 6 : CC_{other} control region





The fraction of CC0π signal in the control regions is very low and the CC1π (CC_{other}) purity is quite good !

CC0pi on carbon @ND280

arxiv:1602.03652, under publication on PRD

Likelihood fit (Analysis I)

- To predict true spectrum from reconstructed spectrum

# of events in true bin = [Signal events in reco bin + bkgd events in reco bin] x MC based reco -> true

$$N_i = \sum_j^{bins\ by\ topo} \left[c_i \left(N_j^{MC\ CC0\pi} \prod_a^{model} w(a)_{ij}^{CC0\pi} \right) + \sum_k^{bkg\ reactions} N_j^{MC\ bkg\ k} \prod_a^{model} w(a)_{ij}^{k} \right] t_{ij}^{det} r_j^{det}$$

DATA/MC: parameter fitted

Free nuisance parameter (theory + detector)

- Simultaneously fit four topologies and two control samples.

Minimizer:

$$\chi^2 = \chi^2_{stat} + \chi^2_{syst} = \sum_j^{reco\ bins} 2\left(N_j - N_j^{obs} + N_j^{obs} \ln \frac{N_j^{obs}}{N_j}\right) + \chi^2_{syst}$$

- Extract flux integrated cross section

$$\begin{aligned} \chi^2_{syst} &= (\vec{r}^{\,det} - \vec{r}^{\,det}_{prior})(V^{det}_{cov})^{-1}(\vec{r}^{\,det} - \vec{r}^{\,det}_{prior}) \\ &+ (\vec{a}^{\,theory} - \vec{a}^{\,theory}_{prior})(V^{theory}_{cov})^{-1}(\vec{a}^{\,theory} - \vec{a}^{\,theory}_{prior}) \end{aligned}$$

CC0pi on carbon @ND280

arxiv:1602.03652,
under publication on PRD

Bayesian unfolding (Analysis II)

- To predict true spectrum from reconstructed spectrum

Prediction in true bin:

$$N_{t_j}^{unfolded} = \frac{1}{\epsilon_j} \sum_i P(t_j|r_i)(N_{r_i} - B_{r_i})$$

Signal - Background

Reconstructed bins

Unsmearing matrix:

Smearing matrix

$$P(t_j|r_i) = \frac{P(r_i|t_j)P(t_j)}{P(r_i)}$$

Probability of event being in reco and true bin

Extracted from MC

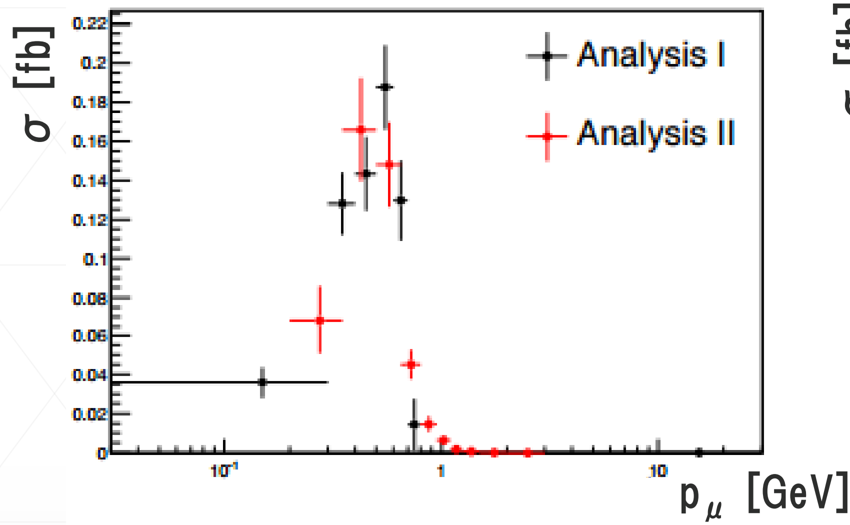
- Extract flux-integrated cross section from the true prediction

CC0pi on carbon @ND280

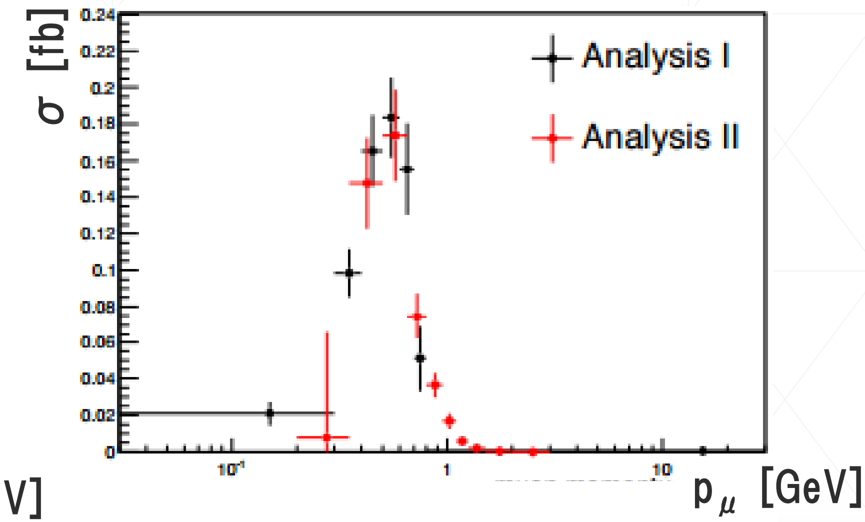
arxiv:1602.03652,
under publication on PRD

Good agreement between two analyses

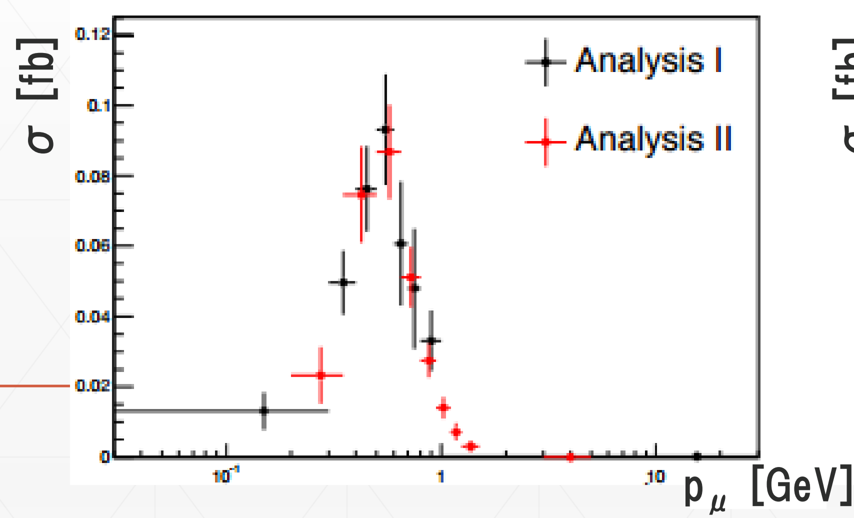
muon $\cos\theta$ 0.60 - 0.70



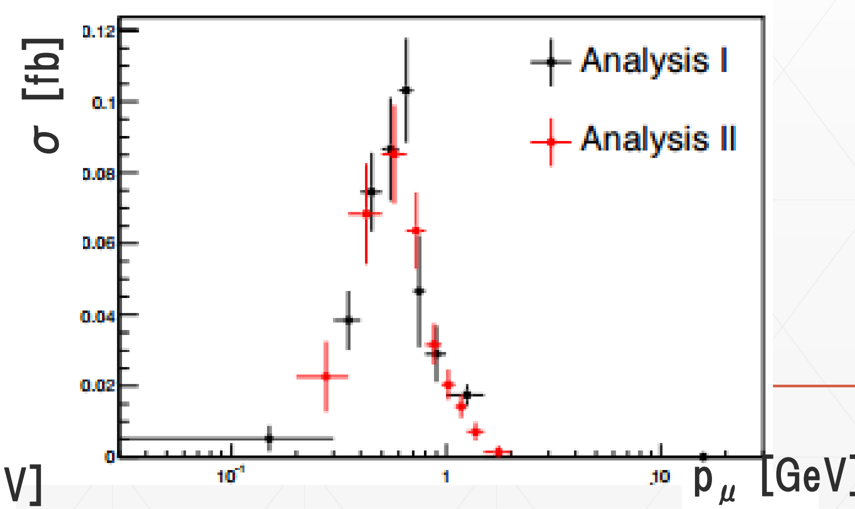
muon $\cos\theta$ 0.70 - 0.80



muon $\cos\theta$ 0.80 - 0.85



muon $\cos\theta$ 0.85 - 0.90

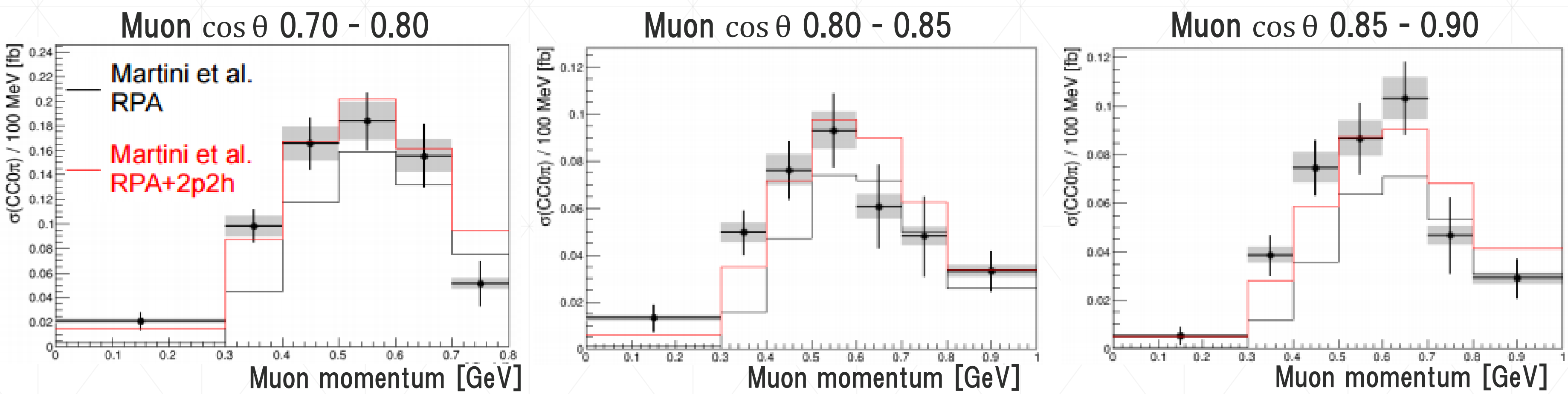


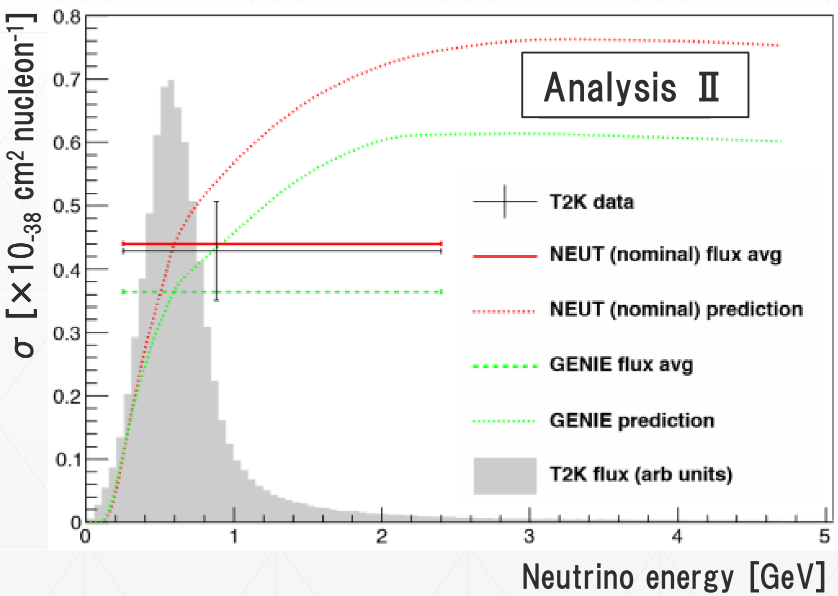
CC0pi on carbon @ND280

arxiv:1602.03652,
under publication on PRD

Analysis I

Results indicate the presence of 2p2h interactions,
but it is difficult to make a conclusion …more data desired !





Results are in agreement
with both NEUT and GENIE predictions

Integrated cross sections [$\times 10^{-38}$ cm^2 nucleon^{-1}]

Ⅰ : 0.417 ± 0.047 (syst.) ± 0.005 (stat.)
(NEUT prediction : 0.444)

Ⅱ : 0.202 ± 0.0359 (syst.) ± 0.0026 (stat.)
(NEUT prediction : 0.232)

CC0pi on carbon @Proton Module

PID selection

- Estimate a confidence level that a particle is a muon on a plane-by-plane basis
- The expected dE/dx distribution of muons is obtained from the beam-induced muon backgrounds which are mainly created by the neutrino interactions in the walls of the detector hall

$$\mathrm{C.L.} = P \times \sum_{i=0}^{n-1} \frac{(-\ln P)^i}{i!}, \quad P = \prod_{i=1}^{n} CL_i$$

n : Number of penetrated scintillator plane

CL_i : Calculated confidence level at the i-th plane as a function of dE/dx

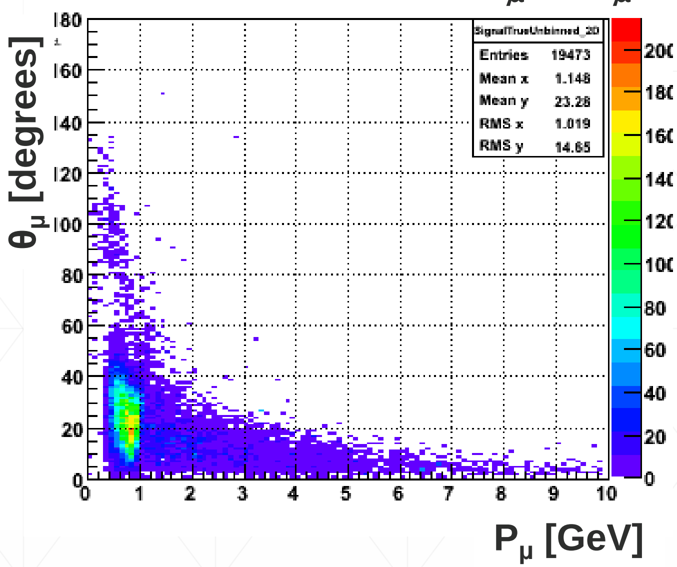
In the case where the track penetrates only two planes,

$$\mathrm{C.L.} = 1 - \int_P^1 dx \int_{P/x}^1 dy$$

$$= P\,(1 - \ln P)$$

CC0pi on carbon @Proton Module

[True] : Event in bin p_μ, θ_μ



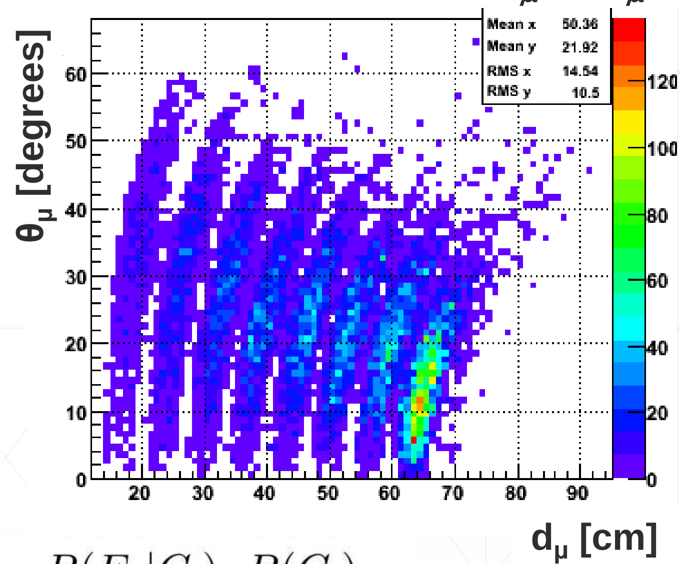
P(Recon.|True)

(MC simulation)

P(True|Recon.)

(Baye theorem)

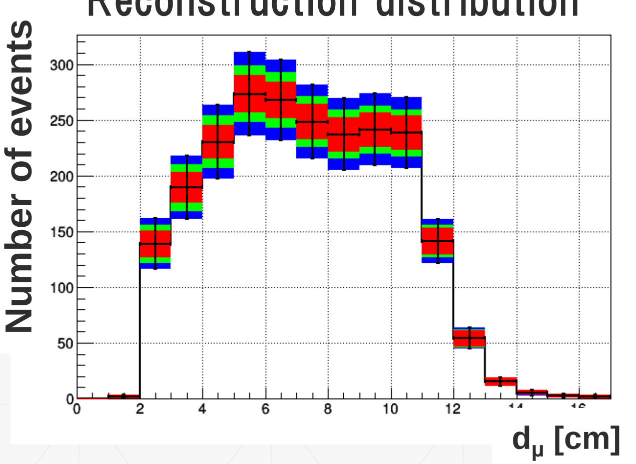
[Recon.] : Event in bin d_μ, θ_μ



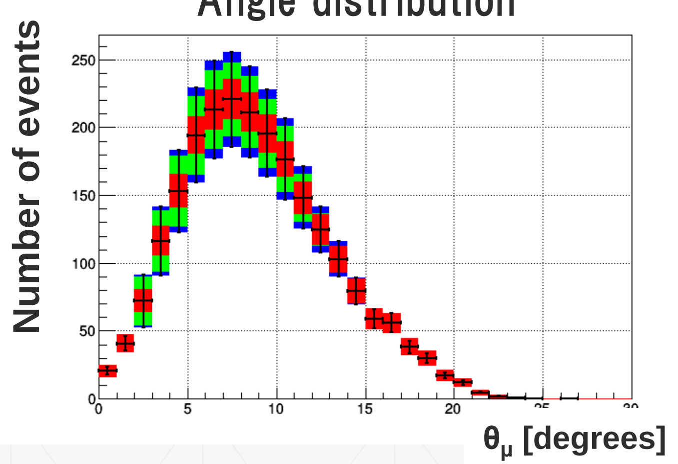
Bayesian unfolding method is used.

$$P(C_i|E_j) = \frac{P(E_j|C_i)\cdot P(C_i)}{\sum_k P(E_j|C_k)\cdot P(C_k)}$$

Reconstruction distribution



Angle distribution

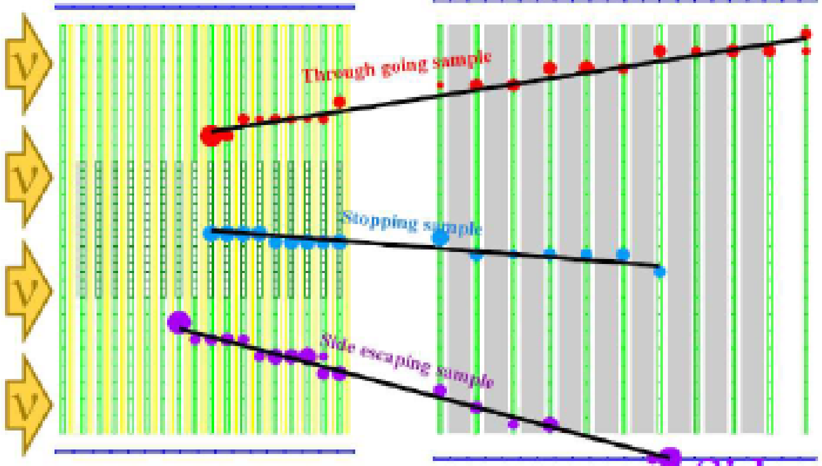


Uncertainty : 10～20%
- Not enhanced by the unfolding method

Data box will be opened very soon !

CC0pi on carbon @Proton Module

- 3 samples for muon propagating through downstream INGRID detector :



Through-going μ:

→ High momentum sample (p_μ > 1GeV).

→ Differential θ_μ

→ High statistics (~40 % of the total sample) since on-axis flux highly energetic.

Stopping μ:

→ Differential p_μ : 0.1 → 1GeV .

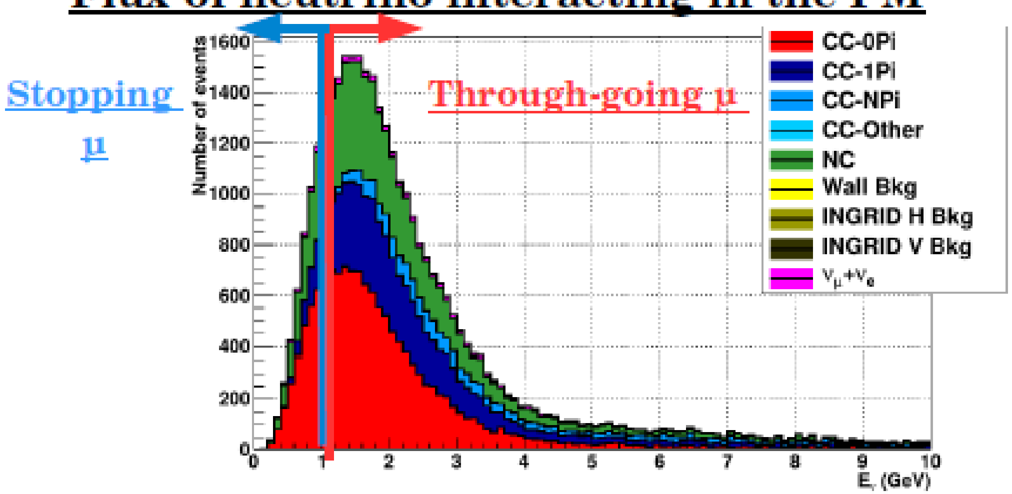
→ Differential θ_μ

→ Low statistics (~5 % of the total sample).

Side escaping μ:

→ No p_μ : prediction → not used

- Flux of neutrino interacting in the PM



- Most of the μ are through-going (44 % of all interactions, 5 % for stopping)

- PM flux spread from 0.5 → 3 GeV : covers both MiniBooNE & Minerνa → ideal to check incompatibilities.

CC0pi on carbon @ND280 (FGD)

$$\hat{N}_k = \frac{U_{kj}}{\epsilon_k} \cdot N_j^{sel}$$

$$\sigma_k^{water} \sim \hat{N}_k^{fgd2} - \hat{N}_k^{scint}$$

$$\frac{\sigma_k^{water}}{\sigma_k^{scint}} \sim \frac{\hat{N}_k^{fgd2} - \hat{N}_k^{scint}}{\hat{N}_k^{scint}}$$

$$\hat{N}_k^{water} = \hat{N}_k^{fgd2} - \sigma_k^{scint} \cdot T^{fgd2\_XYlike} \cdot \phi^{fgd2}$$

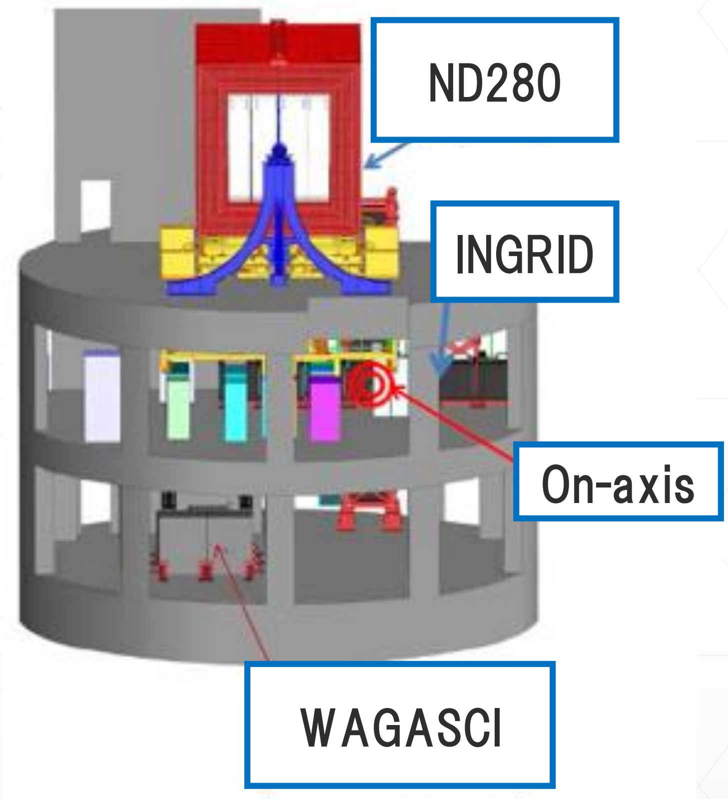
where $T^{fgd2\_XYlike} = T^{fgd2\_XY} + T^{fgd2\_virtualXY}$

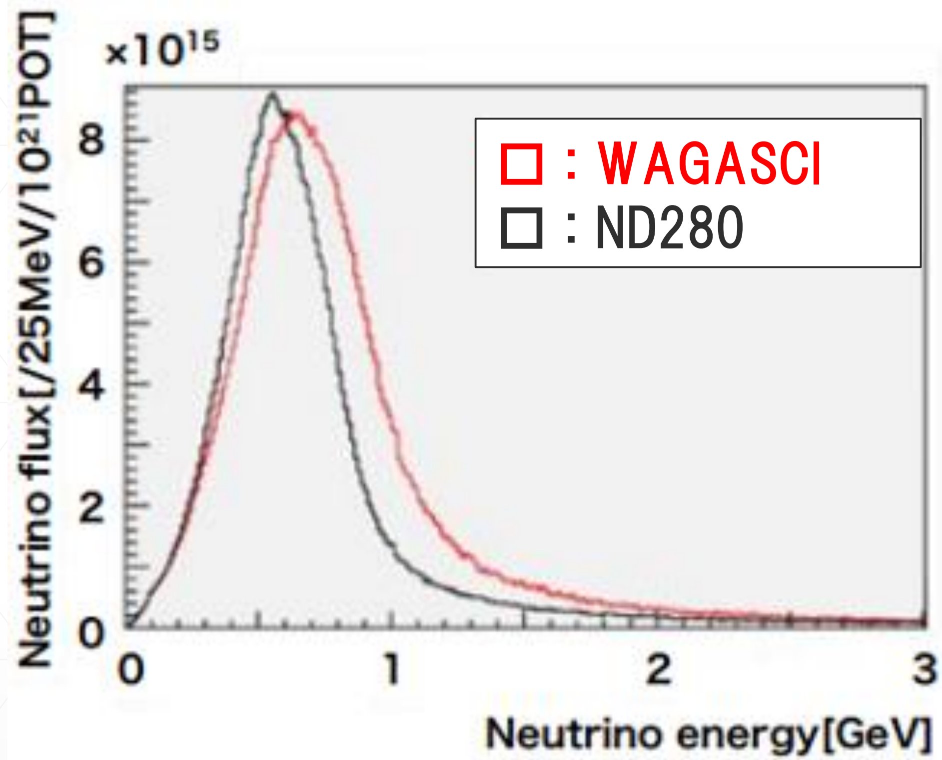
$$\sigma_k^{scint} = \frac{\hat{N}_k^{fgd1}}{T^{fgd1} \cdot \phi^{fgd1}}$$

$$\boxed{\sigma_k^{water} = \frac{\hat{N}_k^{fgd2}}{T^{fgd2\_waterlike} \cdot \phi^{fgd2}} - \frac{\hat{N}_k^{fgd1}}{T^{fgd1} \cdot \phi^{fgd1}} \cdot \frac{T^{fgd2\_XYlike}}{T^{fgd2\_waterlike}}}$$

$$\boxed{\frac{\sigma_k^{water}}{\sigma_k^{scint}} = \frac{\hat{N}_k^{fgd2}}{\hat{N}_k^{fgd1}} \cdot \frac{T^{fgd1}}{T^{fgd2\_waterlike}} \cdot \frac{\phi^{fgd1}}{\phi^{fgd2}} - \frac{T^{fgd2\_XYlike}}{T^{fgd2\_waterlike}}}$$

Detector candidate location

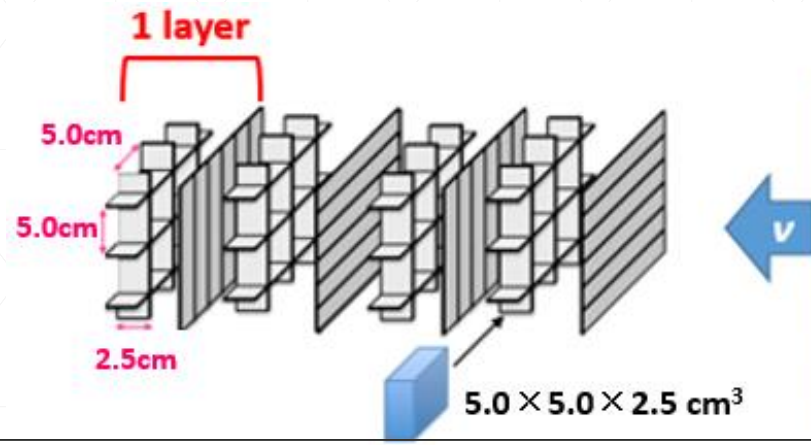




In the T2K near-detector hall at an off-axis angle 1.6 degrees
- ND280 is located at an off-axis angle 2.5 degrees

Neutrino energy spectrum is similar between WAGASCI and ND280

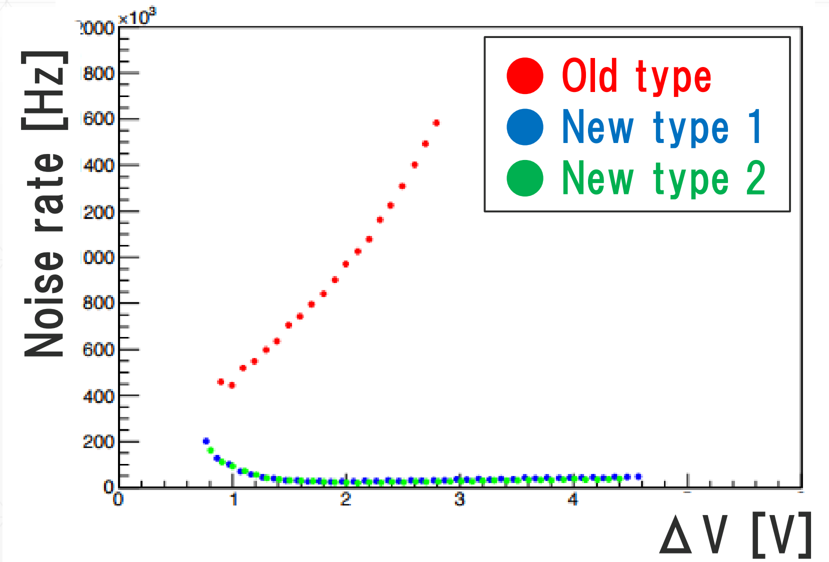
Detector components

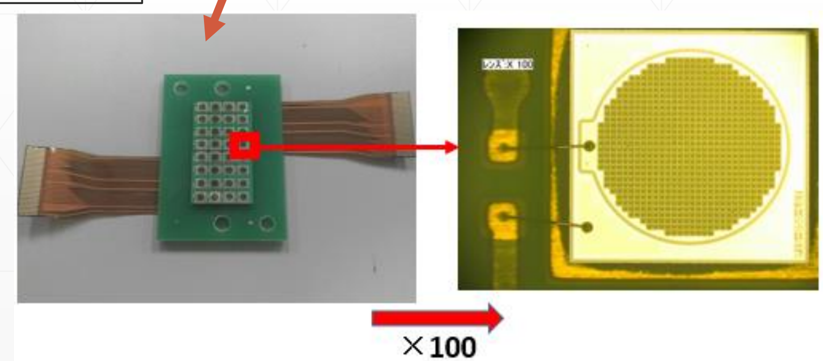


Scintillator
- 3 mm thickness
- WLS fiber is put on each groove

3D grid-like scintillators
- Each space is filled with target materials
- Target : scintillator = 79 : 21 (volume)

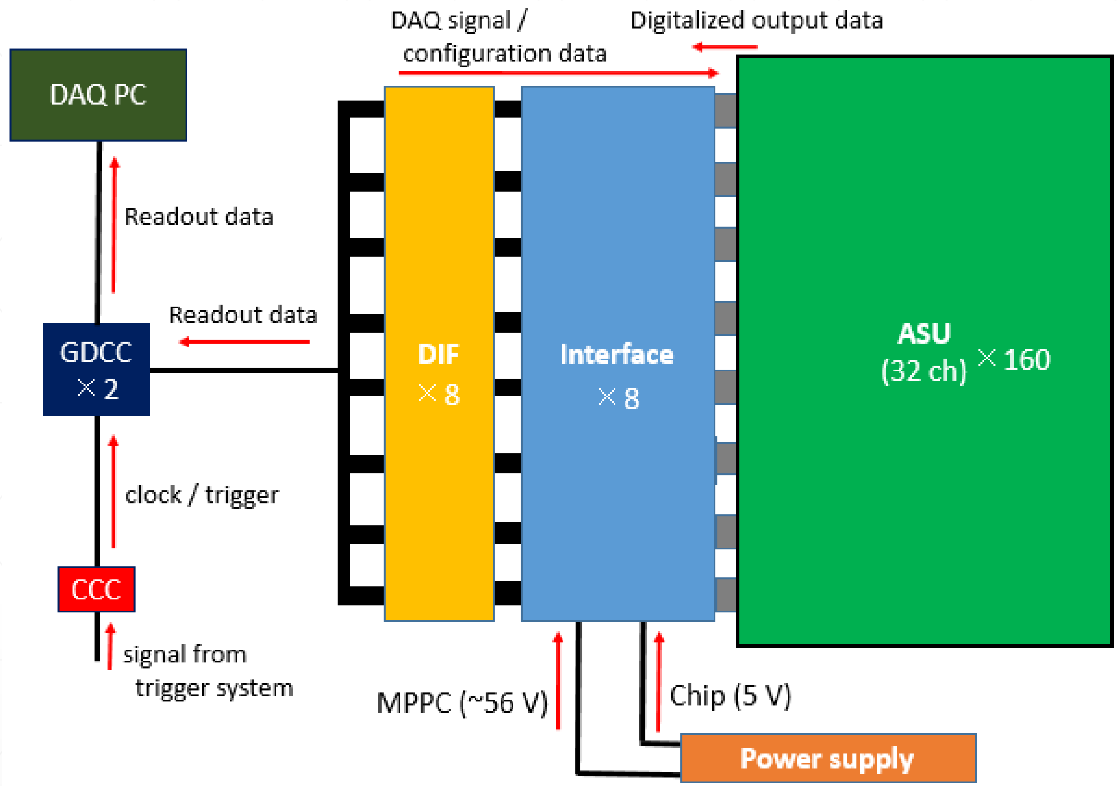
Connected to array-type MPPCs



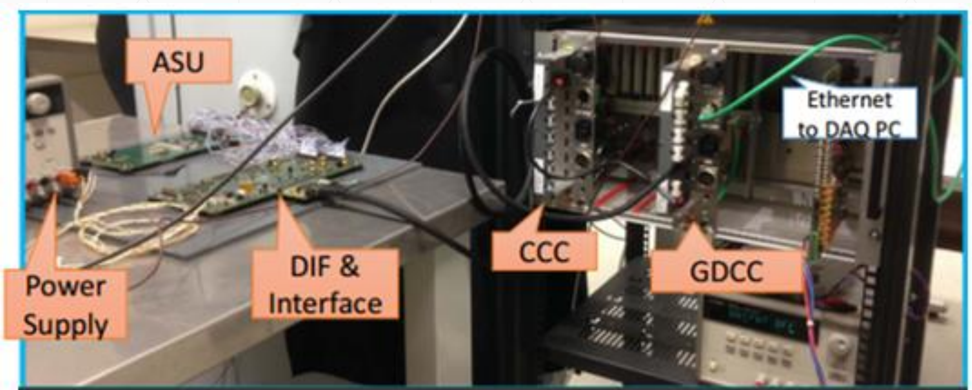


Multi-pixel photon counter (MPPC)
- 32 ch new MPPC
- Low noise

WAGASCI electronics

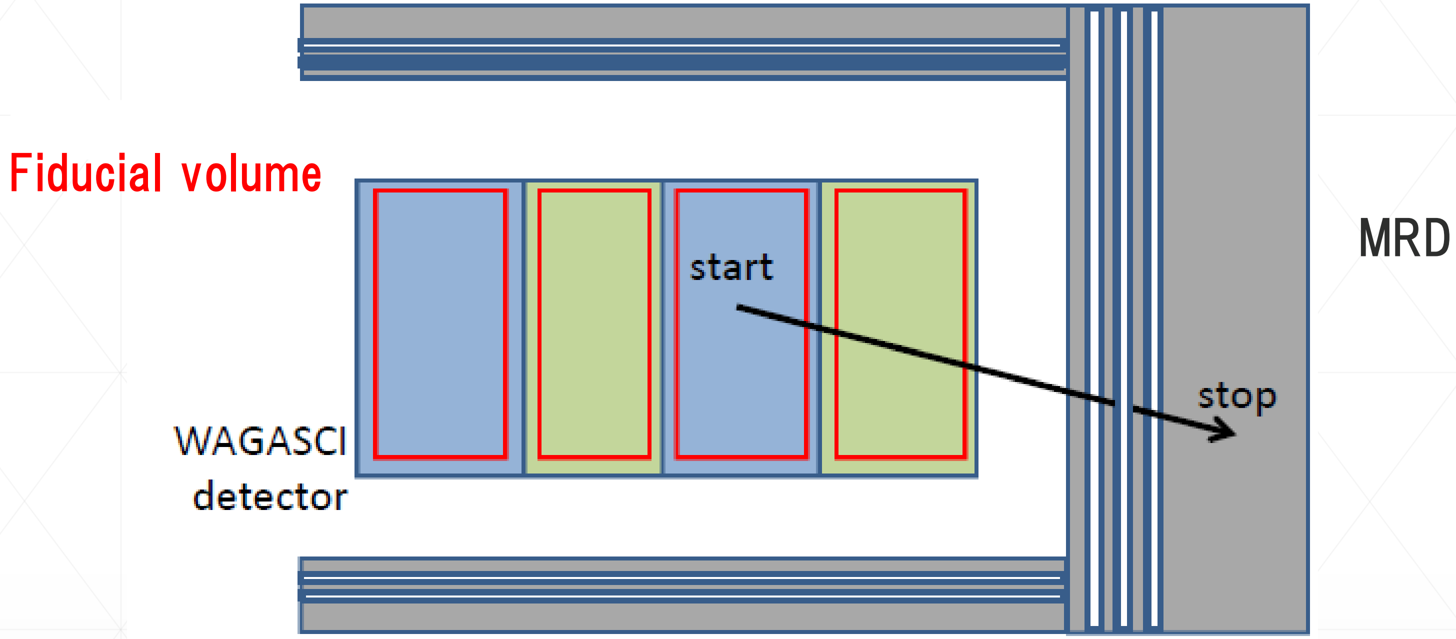


Read-out electronics is tested by LLR group, in France
OMEGA SPIROC2D chip will be used in ASU boards.



Setup for the test operation

WAGASCI event selection



① **Identify muon**

- At least one track should penetrate more then one iron layer in MRD

② **Measure muon momentum**

- Track should stop in MRD or penetrate all layers

③ **Reject background from outside**

- Vertex should be in Fiducial volume
- Track should go outside from target module