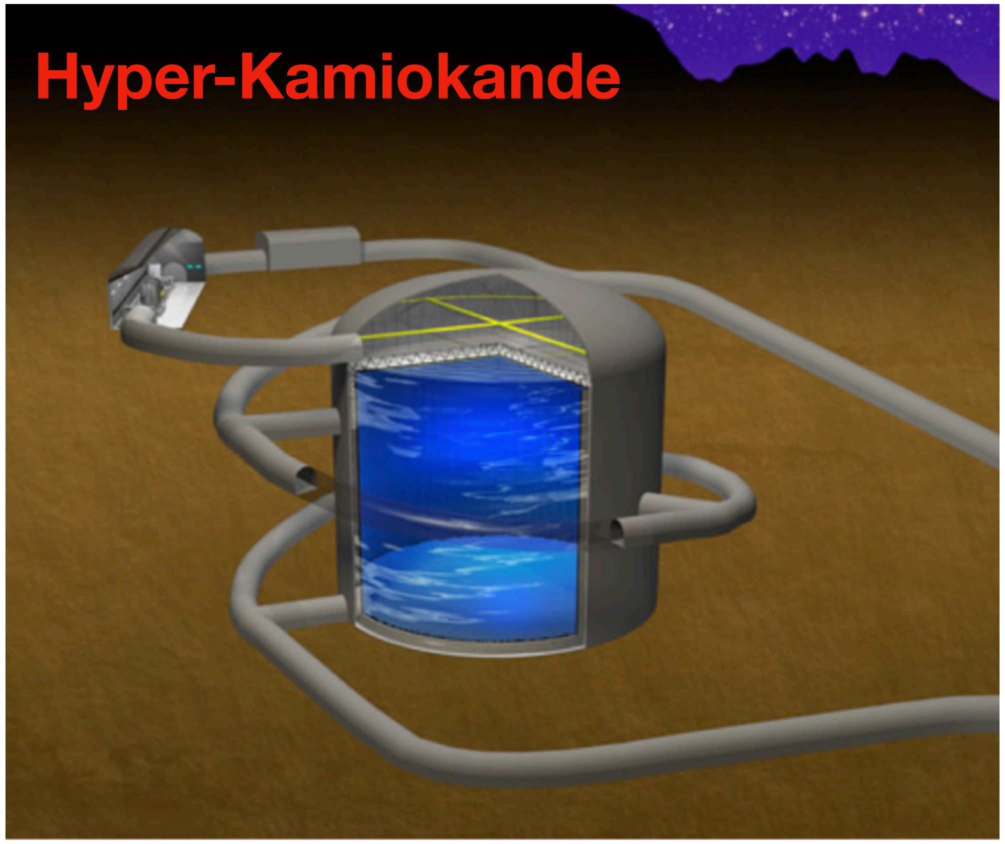
Recent measurements & prospects of WAGASCI-BabyMIND

Son Cao (KEK/J-PARC)
on behalf of the WAGASCI-BabyMIND collaboration

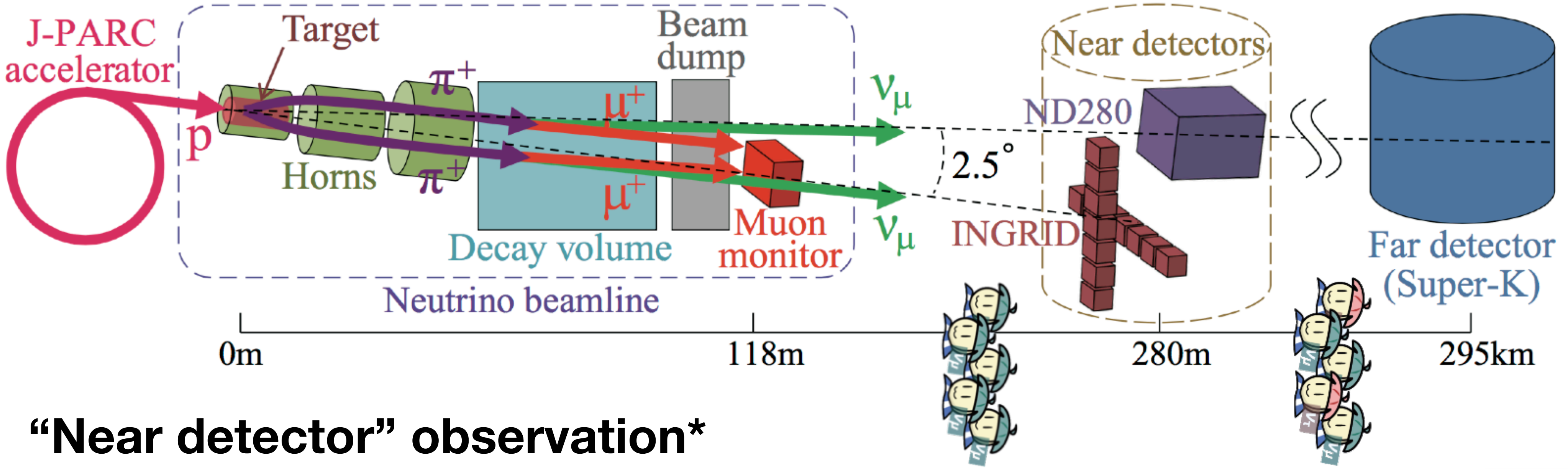
3 neutrinos and beyond,
ICISE, Quy Nhon, VN, August 4-10, 2019

Why do we care about neutrino-water interaction?

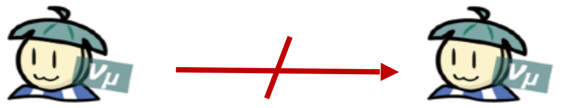


- **On-going T2K (2010-)**
  - Super-Kamiokande (50kton of water) as Far Detector
- **Incoming T2HK (2027 (?)~)**
  - Hyper-Kamiokande (260kton of water, effectively 8 times of Super-Kamiokande) as Far Detector
- **And other neutrino experiments using water as targets and at sub-GeV to few-GeV range**

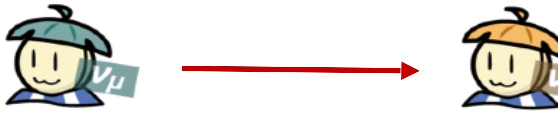
Neutrino oscillation measurements and the role of neutrino-nucleus interaction



Disappearance channel



Appearance channel



“Near detector” observation*

$$\boxed{N^{\nu_\alpha}(E_\nu^{reco.}, \vec{s}\,) = \Phi^{\nu_\alpha}_{flux}(E_\nu^{true}) \times \sigma^{\nu_\alpha}_{int.}(E_\nu^{true}, \vec{s}\,) \times M_{det.} \times \epsilon^{\nu_\alpha}_{det.}(E_\nu^{true}, \vec{s}\,) \times M(E_\nu^{true.}, E_\nu^{reco.})}$$

$\vec{s}$ limited phase space of final state particles detected by detector

“Far detector” observation

$$\boxed{N^{\nu_\beta}(E_\nu^{reco.}, \vec{s}\,) = \Phi^{\nu_\alpha}_{flux}(E_\nu^{true}) \times \sigma^{\nu_\beta}_{int.}(E_\nu^{true}, \vec{s}\,) \times M_{det.} \times \epsilon^{\nu_\beta}_{det.}(E_\nu^{true}, \vec{s}\,) \times M(E_\nu^{true.}, E_\nu^{reco.})} \times \boxed{P(\nu_\alpha \rightarrow \nu_\beta)}$$

ν_α flux wo/ oscillation

Neutrino-nucleus cross sections

Number of target nuclei

Detection efficiency

Detection response

Oscillation prob.

The two measurements are essentially the same except a factor of oscillation probability.

* *assume no oscillation at Near Detector*

Why it's not trivial?

"Near detector" observation

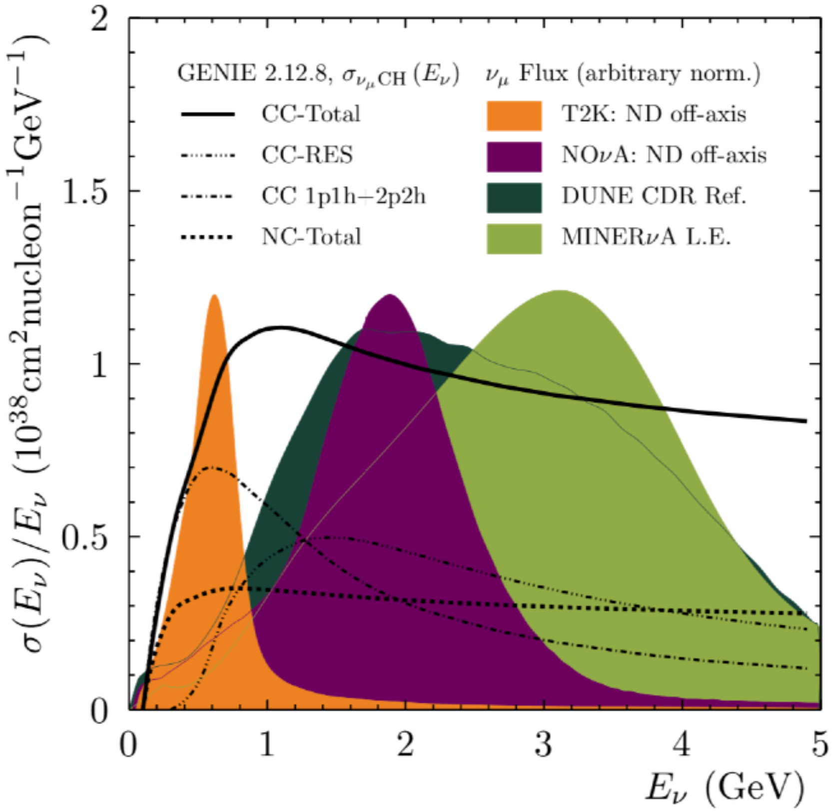
$$\boxed{N^{\nu_\alpha}(E_\nu^{reco.},\vec{s}) = \Phi^{\nu_\alpha}_{flux}(E_\nu^{true}) \times \sigma^{\nu_\alpha}_{int.}(E_\nu^{true},\vec{s}) \times M_{det.} \times \epsilon^{\nu_\alpha}_{det.}(E_\nu^{true},\vec{s}) \times M(E_\nu^{true.},E_\nu^{reco.})}$$

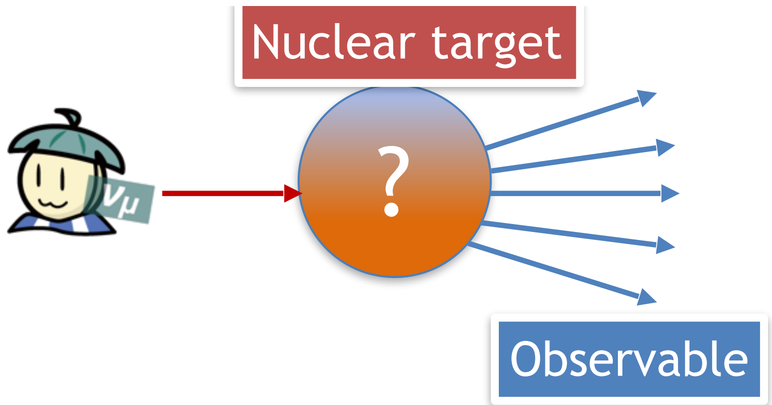
Two detector concept: Make a ratio to extract oscillation prob. can reduce systematics <u>but not completely</u>

"Far detector" observation

$$\boxed{N^{\nu_\beta}(E_\nu^{reco.},\vec{s}) = \Phi^{\nu_\alpha}_{flux}(E_\nu^{true}) \times \sigma^{\nu_\beta}_{int.}(E_\nu^{true},\vec{s}) \times M_{det.} \times \epsilon^{\nu_\beta}_{det.}(E_\nu^{true},\vec{s}) \times M(E_\nu^{true.},E_\nu^{reco.})} \times \boxed{P(\nu_\alpha \to \nu_\beta)}$$

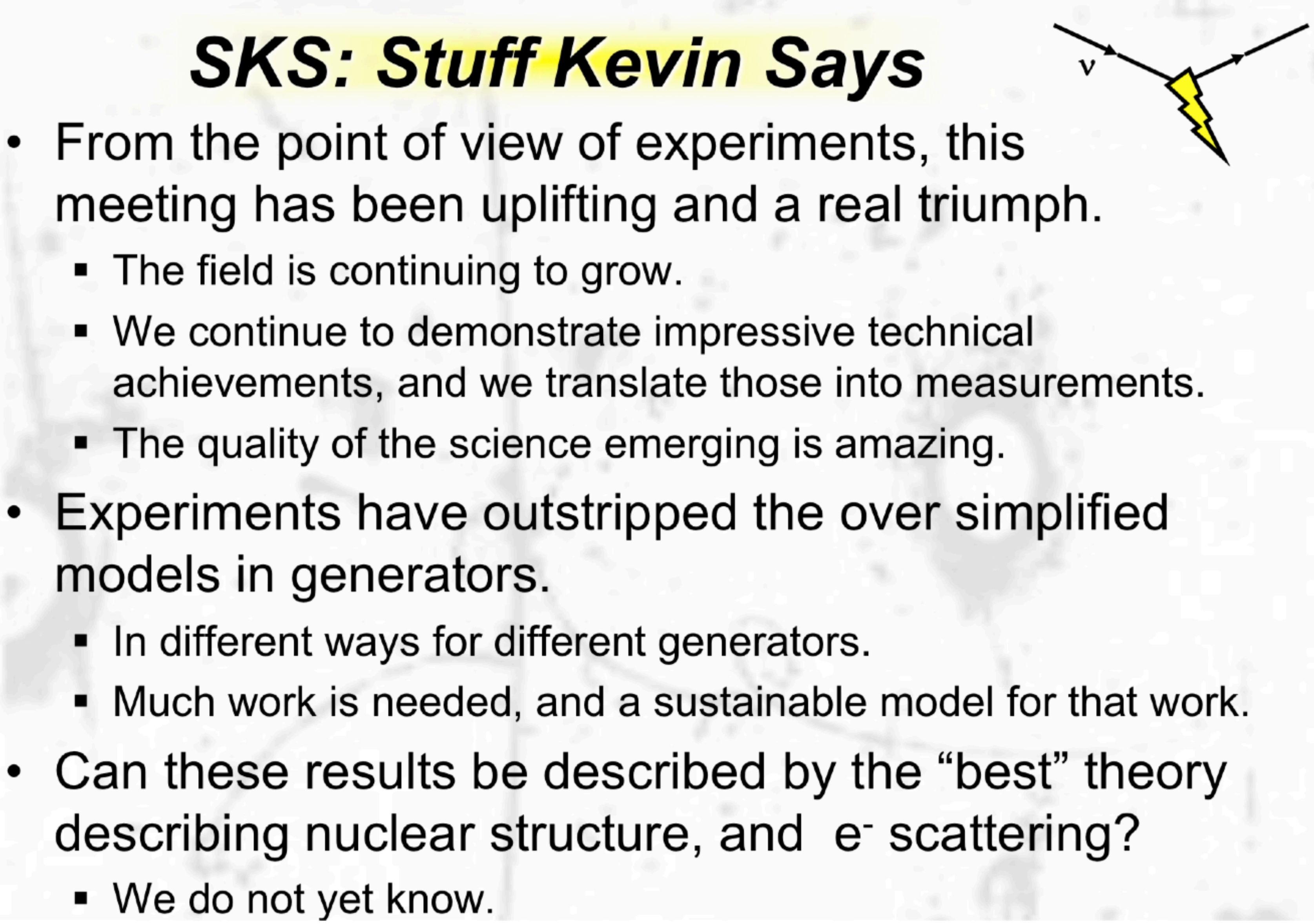
- Two detectors have different angular acceptance to the beam which is not mono-energetic ➔ **what observed are different convolutions of flux and cross section (and also the different acceptance to final state particles) w/ contribution from multiple interaction types (energy at transition region)**
- Neutrino exp. use nuclear target (C/O/Ag…) which modify the cross section, the final state (topology & kinematics) ➔ **What observed can't be translated directly to the neutrino-nucleon interaction modes (CCQE (or 1p1h), CC-RES, DIS)**
- **Measurements based on the final state topologies**. Ex. "*CC0pi*": where is one lepton, no pion (or sometime no meson) and number of nucleon can be arbitrary
  - 1p1h + 2p2h + CC resonance pion prod. w/ pion absorbed
  - (Cherenkov detector couldn't detect proton < 1.4GeV), for them, 1p1h & 2p2h are the same





Where are we in understanding neutrino-nucleus interactions?

Kevin McFaland @ NuINT18



SKS: Stuff Kevin Says

- From the point of view of experiments, this meeting has been uplifting and a real triumph.
  - The field is continuing to grow.
  - We continue to demonstrate impressive technical achievements, and we translate those into measurements.
  - The quality of the science emerging is amazing.
- Experiments have outstripped the over simplified models in generators.
  - In different ways for different generators.
  - Much work is needed, and a sustainable model for that work.
- Can these results be described by the "best" theory describing nuclear structure, and e^- scattering?
  - We do not yet know.

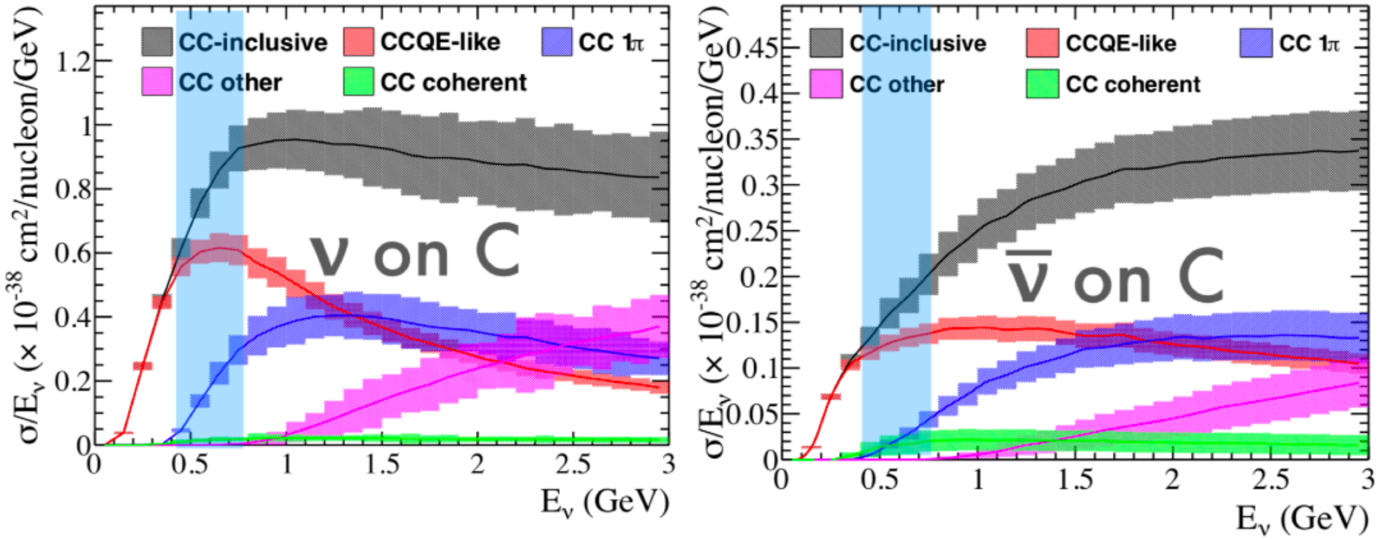
~~Beginning~~ Re-branding of a new field?

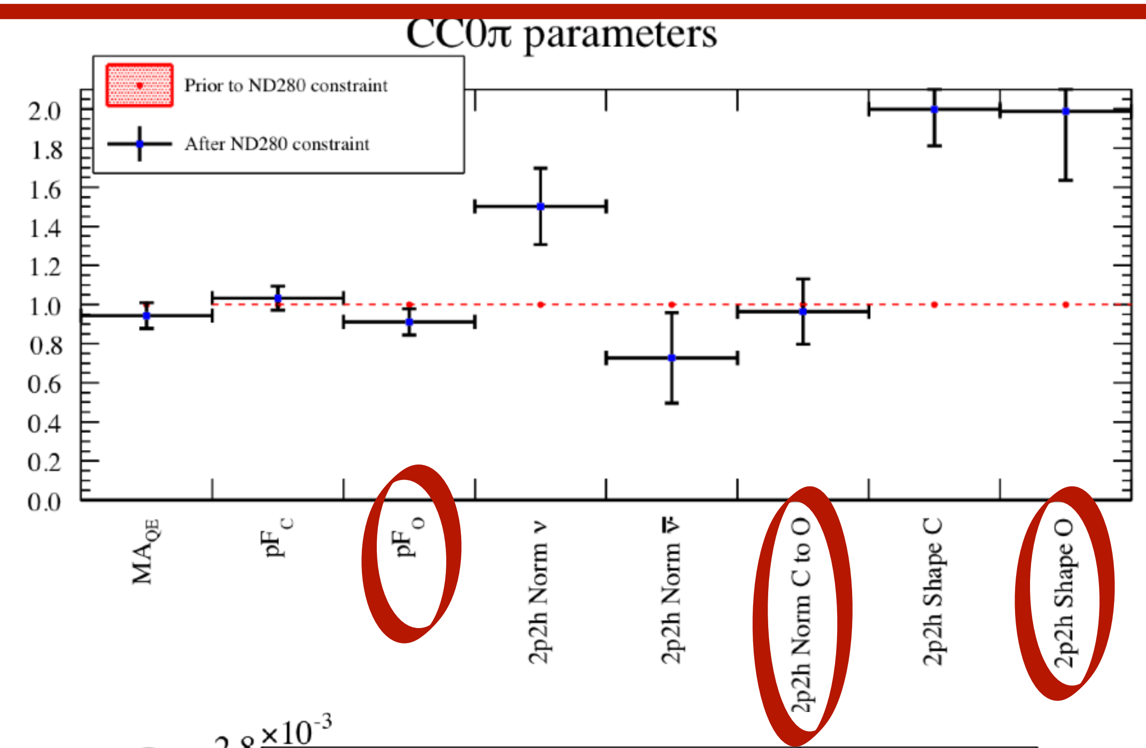
Electroweak Nuclear Physics

We need to collaborate w/ nuclear physicists

More clean data, more model-indepent analysis approaches, more theoretical calculation & prediction implemented in neutrino event generator are vital to pave the way toward "the best" nuclear model

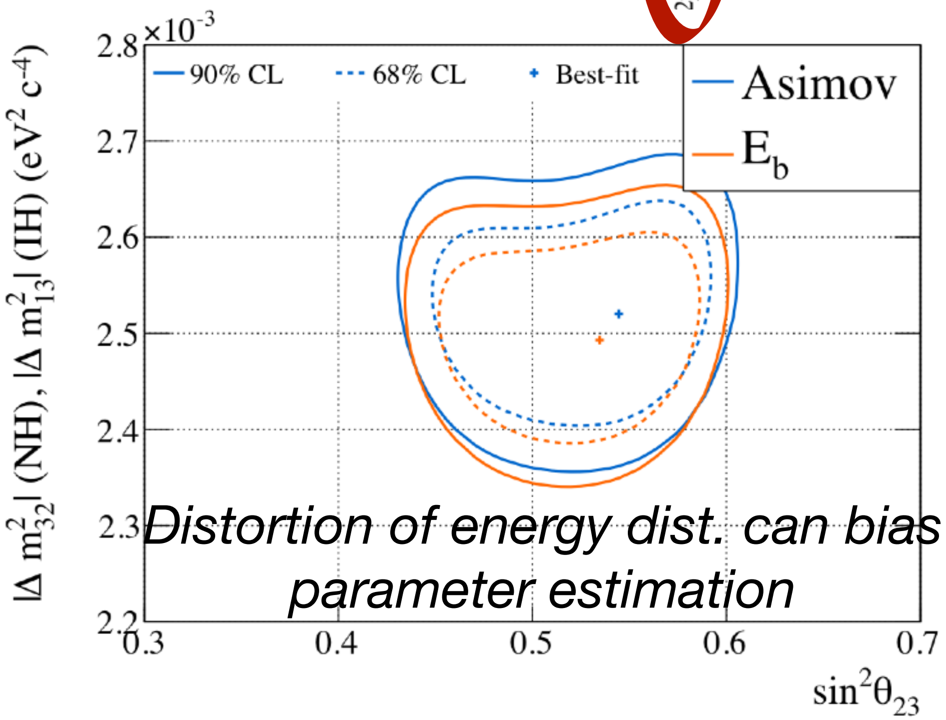
Where are we in understanding neutrino-nucleus interactions?





without constraint from T2K near detector

	1-Ring μ		1-Ring e		
Error source	FHC	RHC	FHC	RHC	FHC CC1π
Beam	8.0%	7.3%	8.0%	8.1%	8.9%
Cross-section (all)	12.3%	10.3%	12.3%	10.1%	8.7%
Beam + Cross-section (all)	14.5%	12.6%	14.5%	13.0%	12.6%
Total	15.0%	13.0%	15.0%	13.7%	20.1%



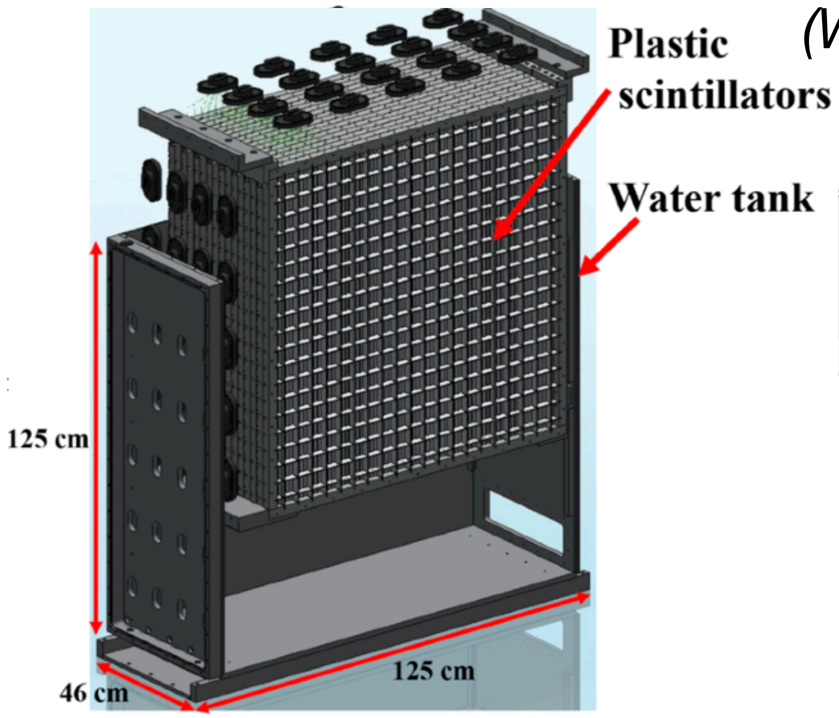
Distortion of energy dist. can bias parameter estimation

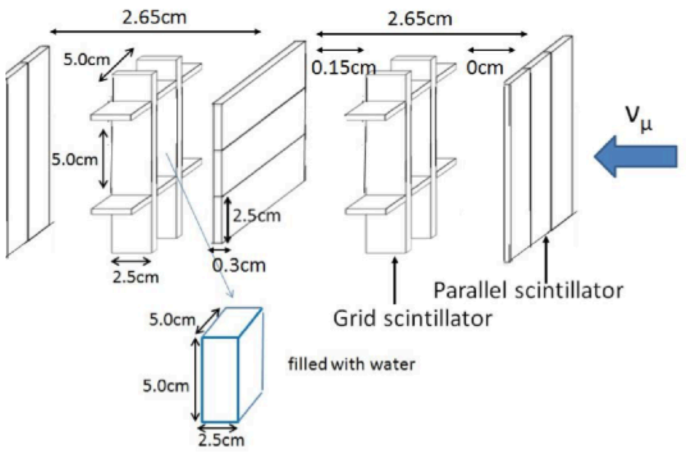
More clean data, more model-indepent analysis approaches, more theoretical calculation & prediction implemented in neutrino event generator are vital to pave the way toward "the best" nuclear model

WAGASCI-BabyMIND

WAGASCI

(WAter-Grid-And-SCintillator)



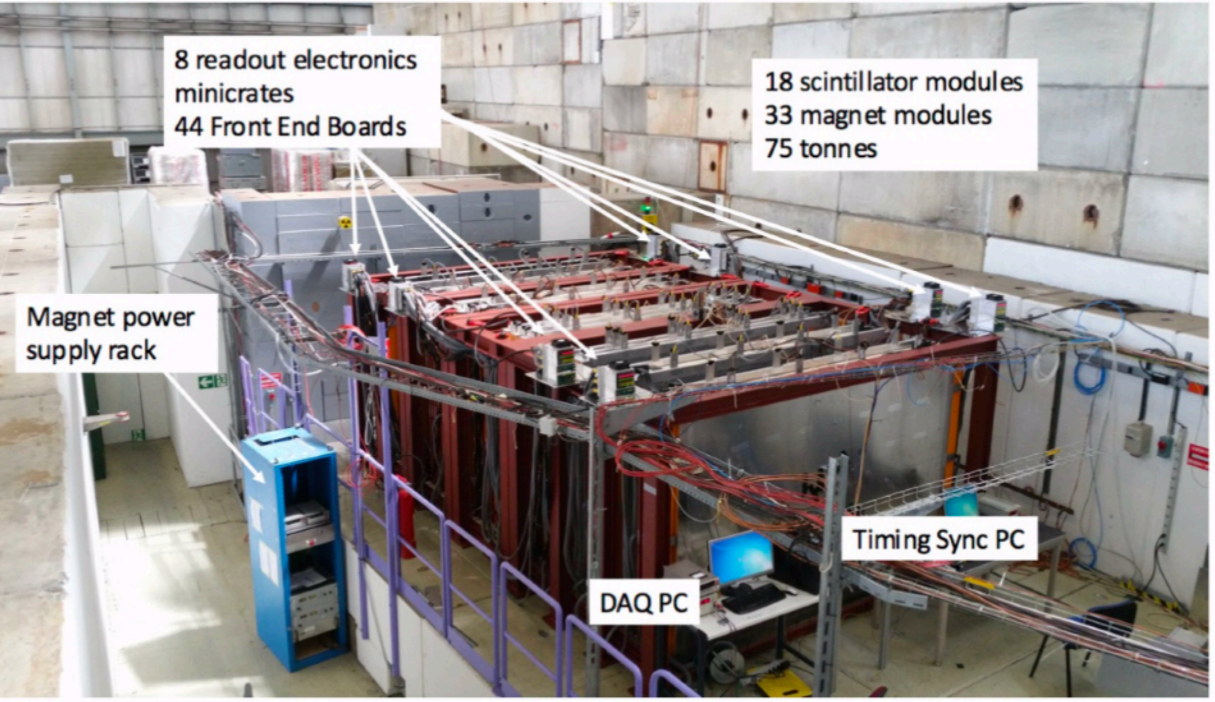


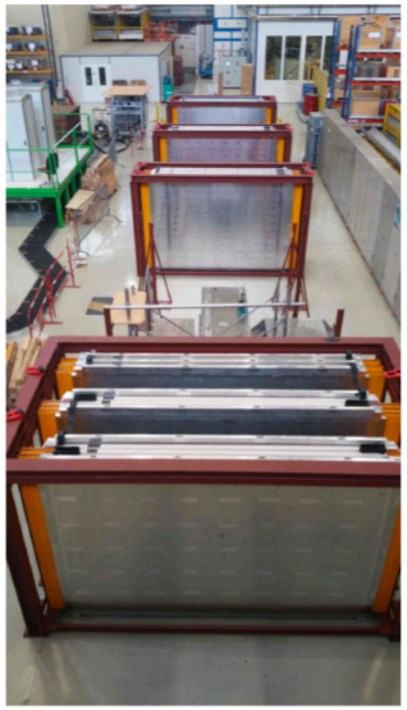
WAGASHI

Japan traditional sweet

BabyMIND

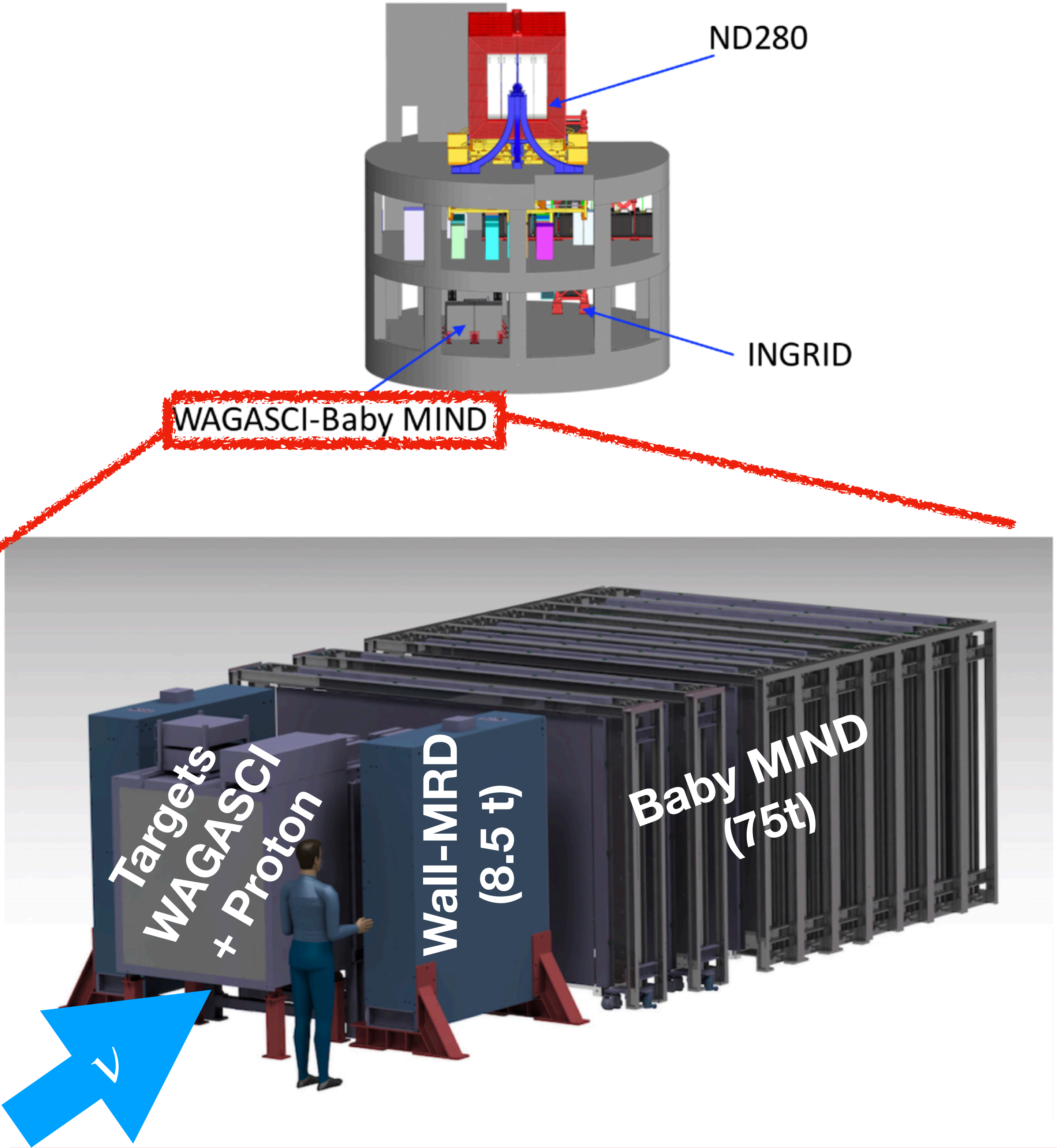
(Prototype Magnetized Iron Neutrino Detector)

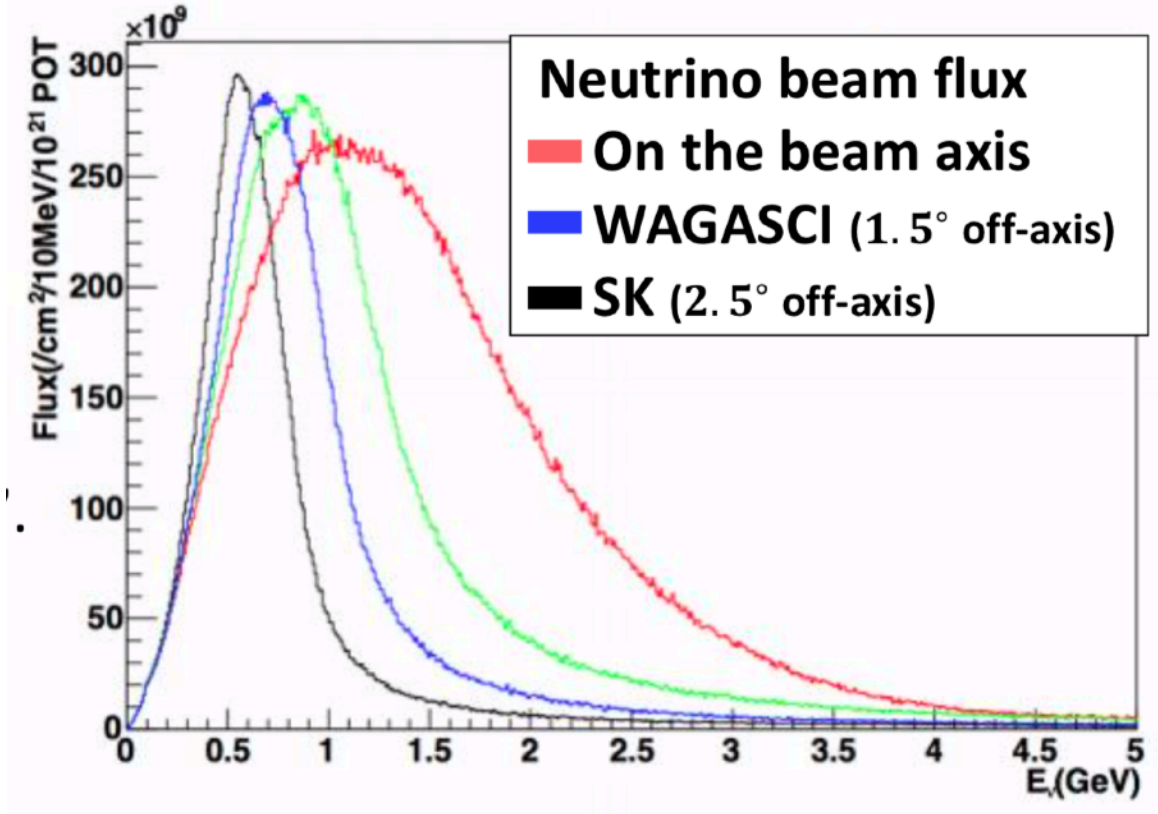




(?)

WAGASCI-BabyMIND (cont’d)





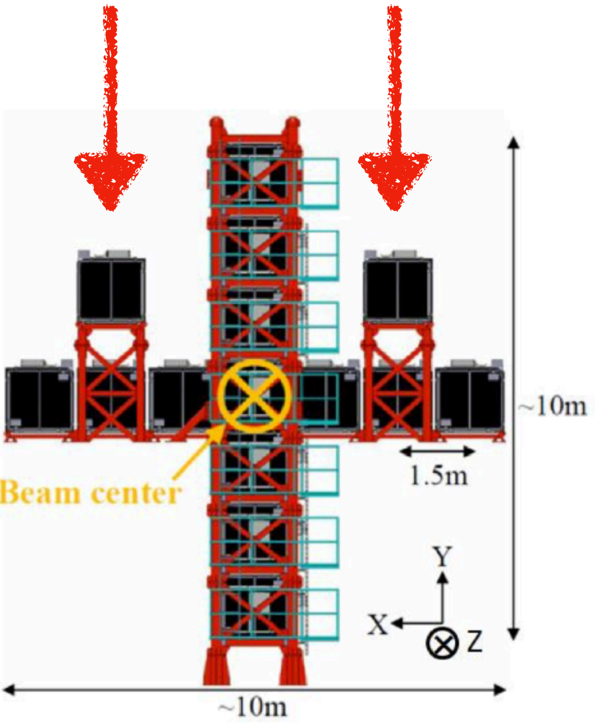
Target materials

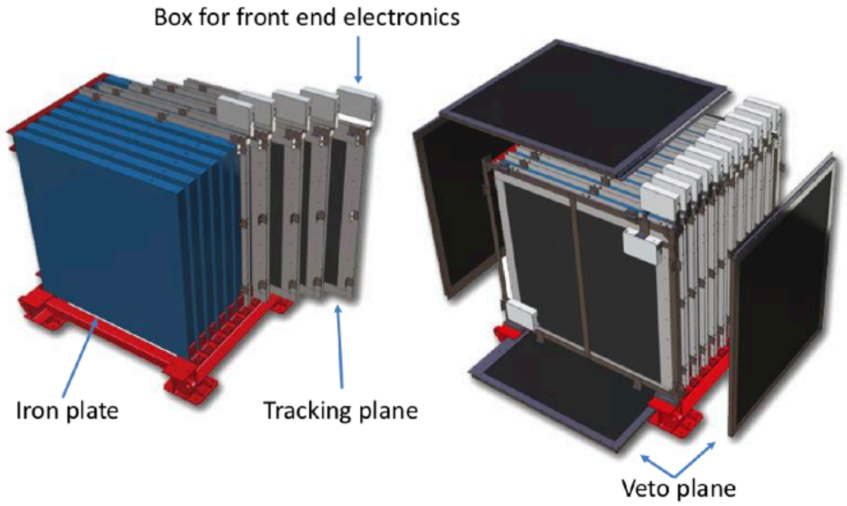
- Two WAGASCI modules: 0.60t of H_20 (H_20: CH = 4:1) per each
- Proton Module (refurbished): 0.56t of fully active scintillator plastics

WAGASCI-BabyMIND: Hybrid and Refurbished detector module

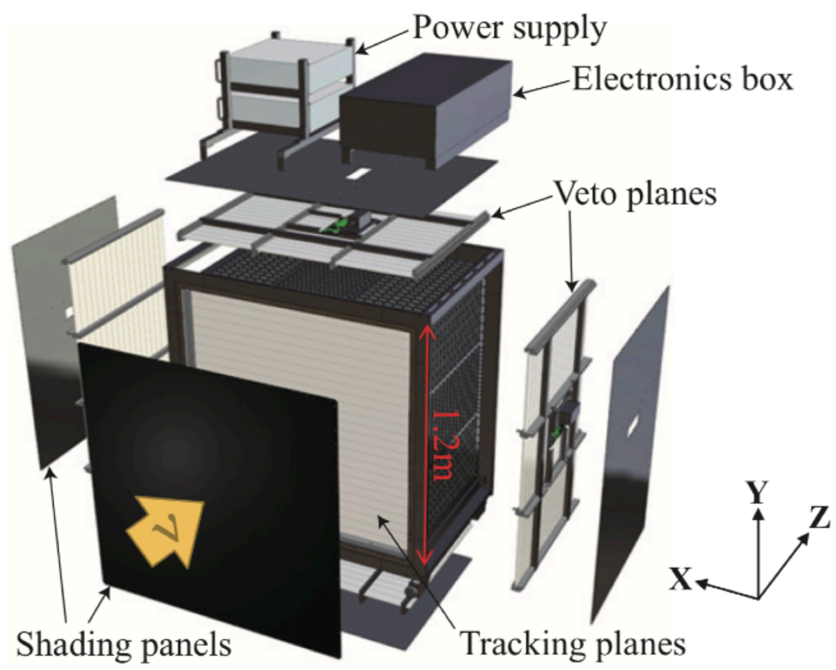
INGRID

(Interactive Neutrino GRID)





Proton Module

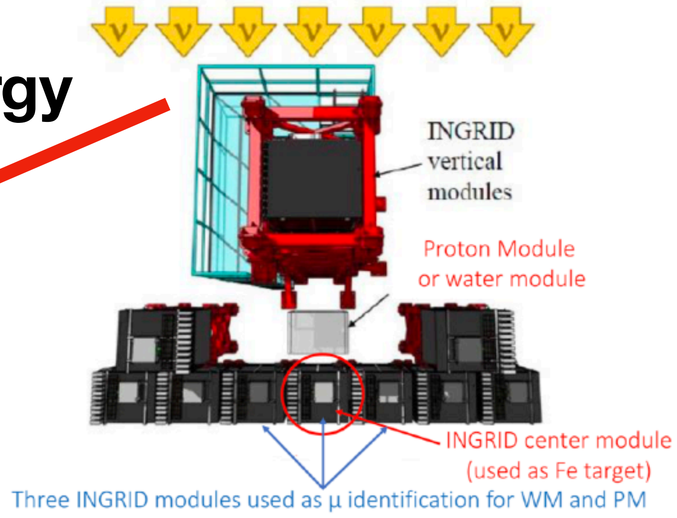


- INGRID, placed at on-axis to neutrino beam, is to measure the neutrino beam intensity & profile
- 16 scintillator-steel interleaved modules (7.1t per each) are produced; 2 modules can be moved to different places and reused for other purpose, here as muon tracker before babyMIND and wallMRD are completed

- Fully active scintillator detector built for tagging proton and pion , dedicated for cross section study
- Proton Module can be moved to different places and in these analyses, it used as CH-targeted detectors

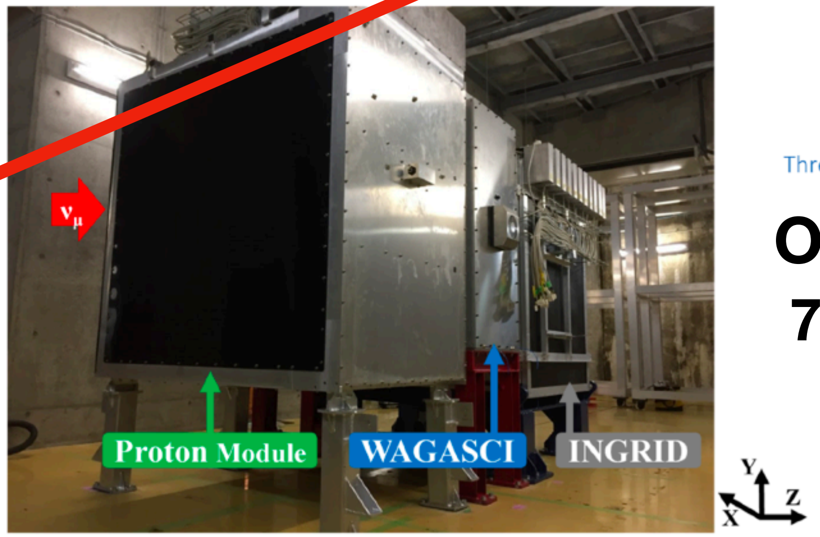
WAGASCI-BabyMIND: Time evolution

On-axis
1.5 GeV mean energy



Oct. 2016 - April 2017
7.25x10^{20} POT ν-mode

1.5^{o} off-axis
0.86 GeV mean energy



Oct. 2017 - May 2018
8.5x10^{20} POT anti-ν-mode
(commissioning w/ ν-mode)

To take data with neutrino flux at lower energy; *better* O/C ratio measurement

1.5^{o} off-axis
0.86 GeV mean energy

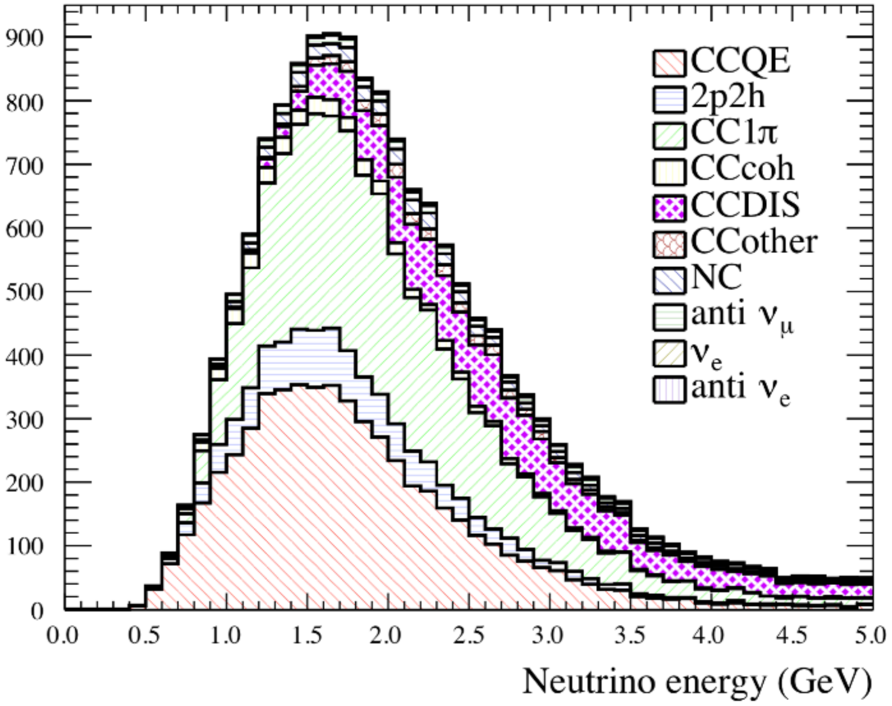
Nov. 2019 ~

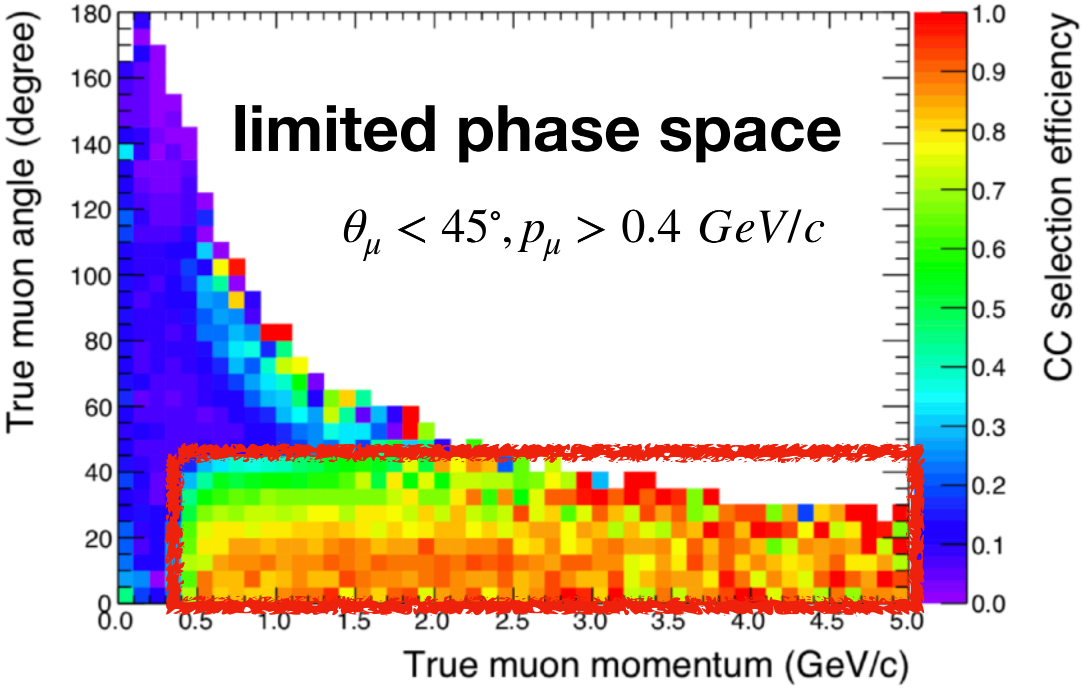
To enlarge coverage of lepton scattering/ momentum determination and charge identification

Inclusive charged-current cross section on H20, CH, Fe and their ratios

arXiv:1904.09611
(to be published on PTEP)

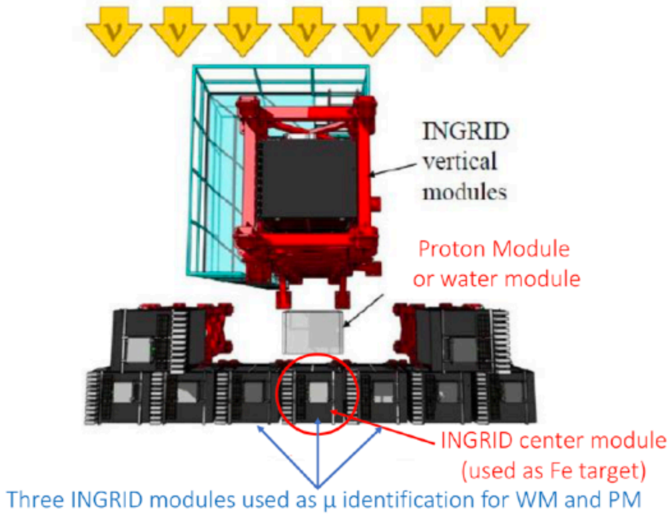
MC information





limited phase space

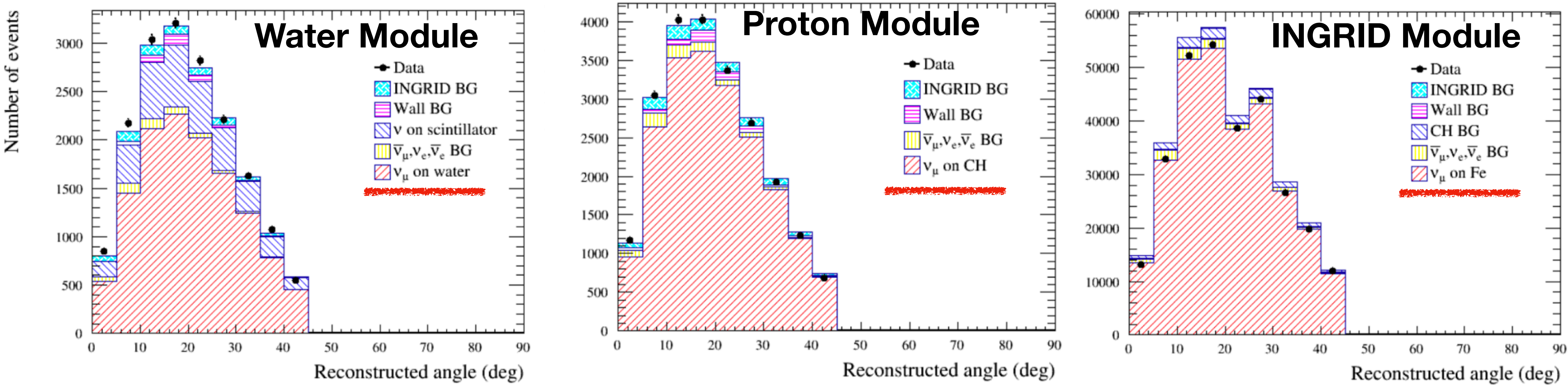
$\theta_\mu < 45^\circ, p_\mu > 0.4\ GeV/c$



Oct. 2016 - April 2017

7.25x10^{20} POT ν-mode

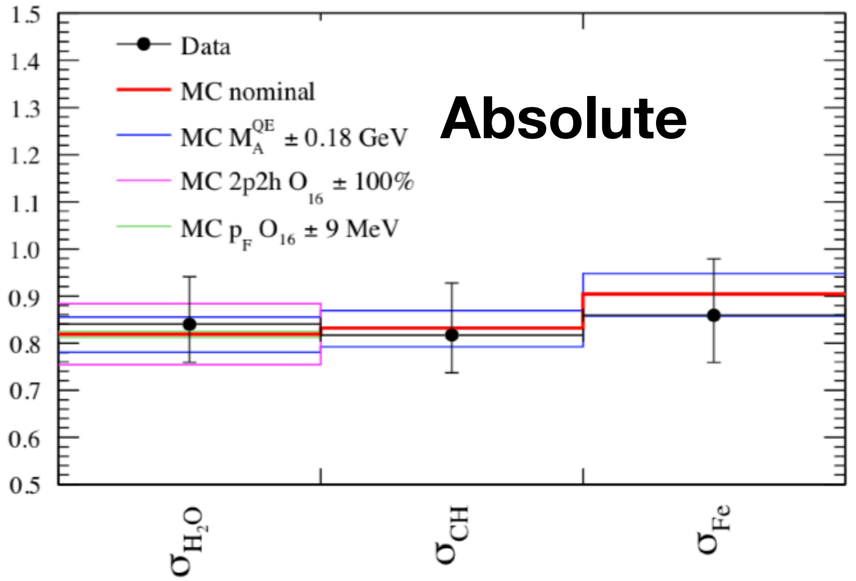
Data vs. MC* after selection

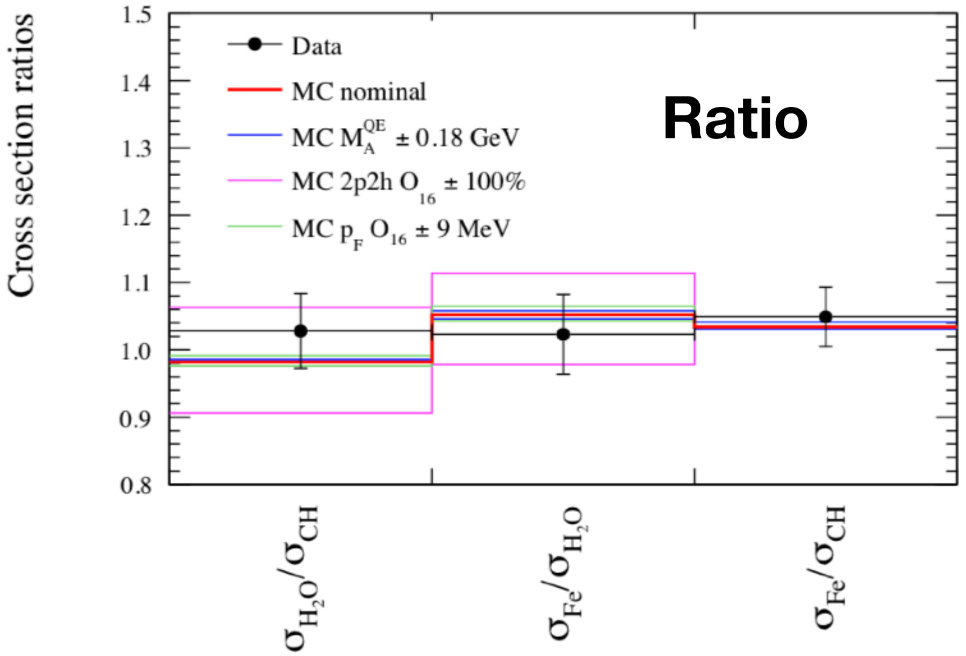


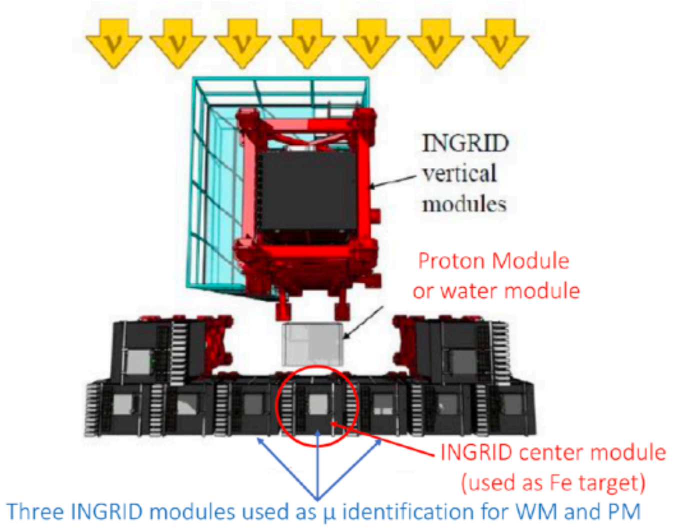
**NEUT 5.3.3: relativistic FG with RPA; 2p2h model included*

Inclusive charged-current cross section on H20, CH, Fe and their ratios

arXiv:1904.09611
(to be published on PTEP)







Oct. 2016 - April 2017

7.25x10^{20} POT ν-mode

$$\sigma_{\rm CC}^{\rm H_2O} = (0.840 \pm 0.010({\rm stat.})^{+0.10}_{-0.08}({\rm syst.})) \times 10^{-38}\ {\rm cm^2/nucleon},$$

$$\sigma_{\rm CC}^{\rm CH} = (0.817 \pm 0.007({\rm stat.})^{+0.11}_{-0.08}({\rm syst.})) \times 10^{-38}\ {\rm cm^2/nucleon},$$

$$\sigma_{\rm CC}^{\rm Fe} = (0.859 \pm 0.003({\rm stat.})^{+0.12}_{-0.10}({\rm syst.})) \times 10^{-38}\ {\rm cm^2/nucleon}.$$

$$\frac{\sigma_{\rm CC}^{\rm H_2O}}{\sigma_{\rm CC}^{\rm CH}} = 1.028 \pm 0.016({\rm stat.}) \pm 0.053({\rm syst.}),$$

$$\frac{\sigma_{\rm CC}^{\rm Fe}}{\sigma_{\rm CC}^{\rm H_2O}} = 1.023 \pm 0.012({\rm stat.}) \pm 0.058({\rm syst.}),$$

$$\frac{\sigma_{\rm CC}^{\rm Fe}}{\sigma_{\rm CC}^{\rm CH}} = 1.049 \pm 0.010({\rm stat.}) \pm 0.043({\rm syst.}).$$

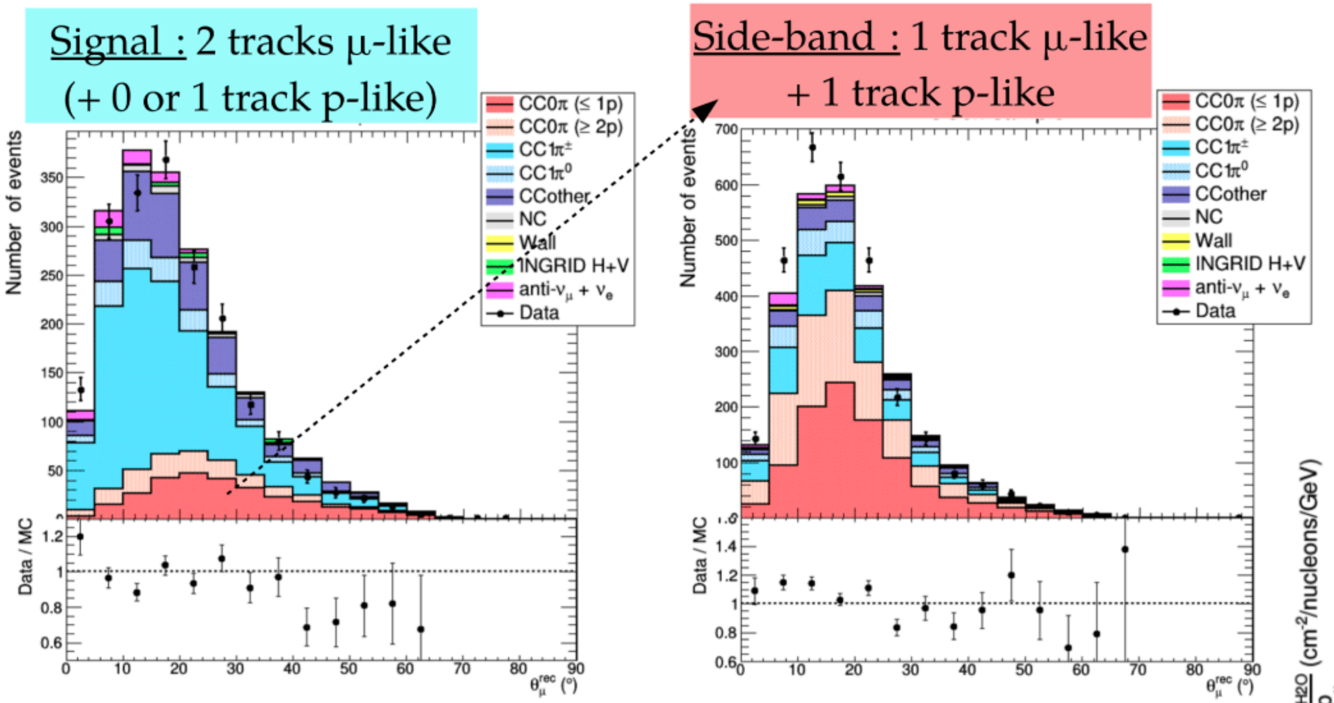
- 10%-14% errors for absolute measurement; 5% for ratio measurements
- Unprecedented precision for the measurements of neutrino-water interactions
- Good agreements with interaction models used in T2K exp.

Exclusive charged-current single pion production on H_20, CH and their ratios

(to be published)

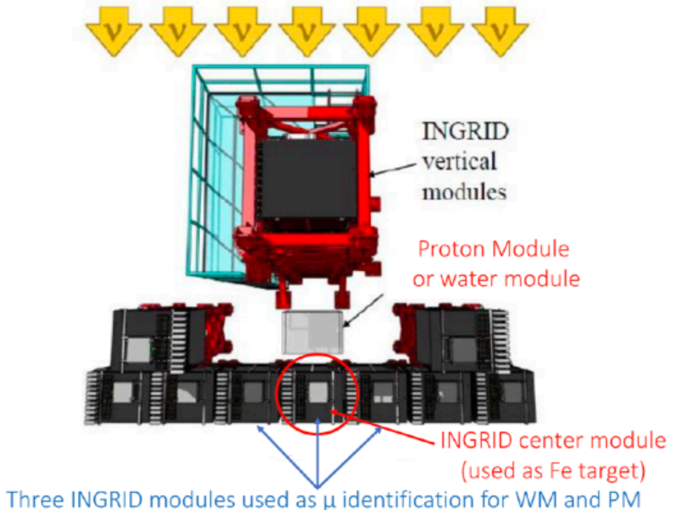
$\boxed{\text{CC}}\,\boxed{1\pi}: \nu_\mu + \mathcal{N} \rightarrow \boxed{\mu^-} + \boxed{\pi^\pm} + \mathcal{N}'$

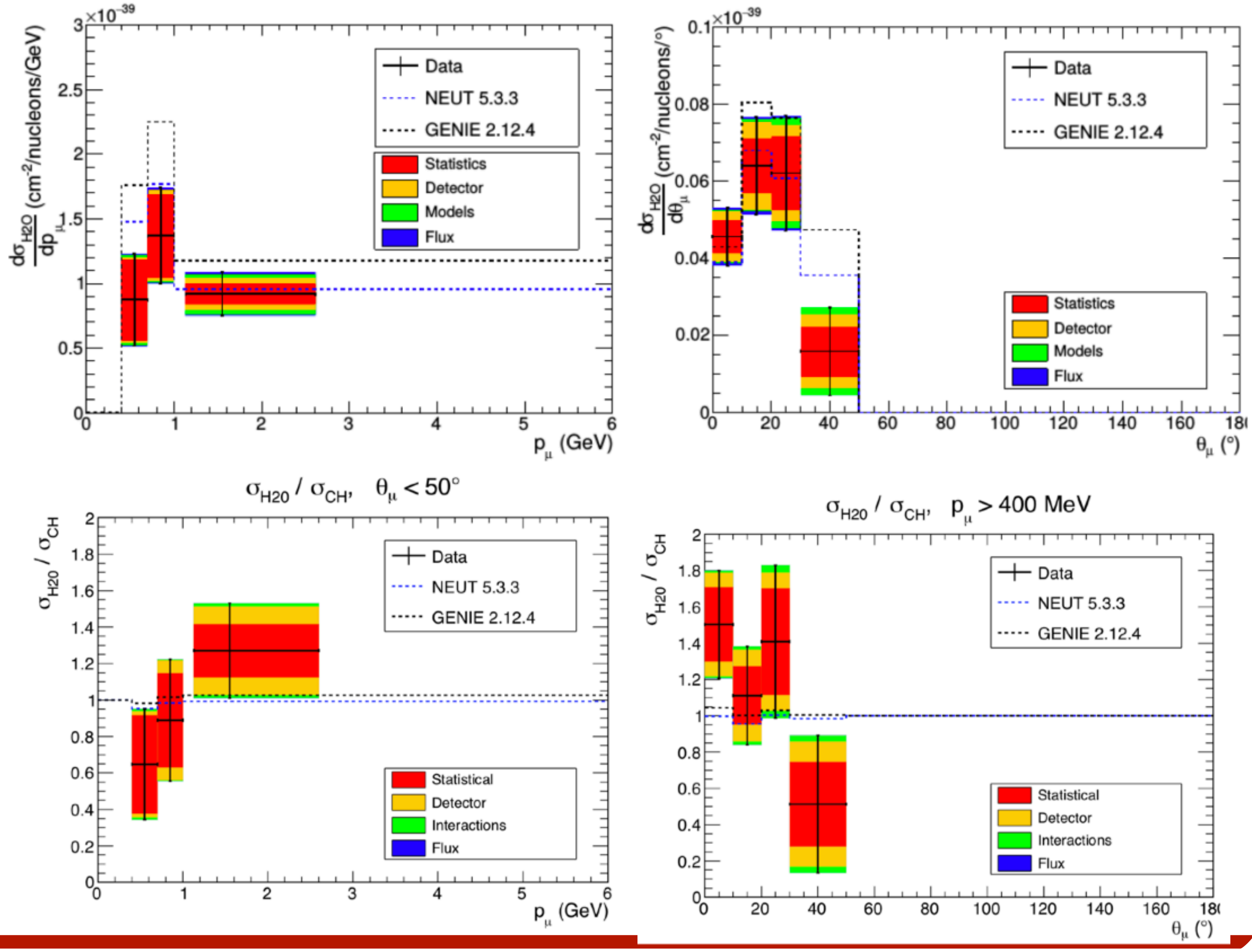
$\boxed{\text{CC}}\,0\pi : \nu_\mu + \mathcal{N} \rightarrow \boxed{\mu^-} + \mathcal{N}'$



Signal : 2 tracks μ-like (+ 0 or 1 track p-like)

Side-band : 1 track μ-like + 1 track p-like

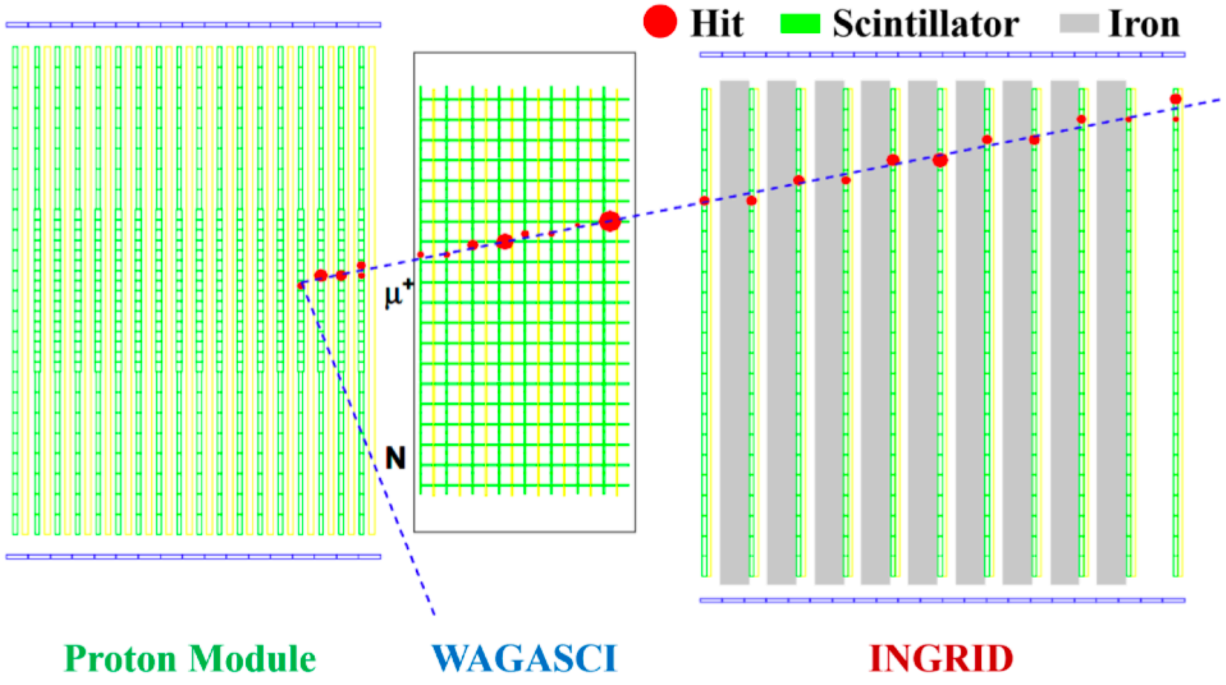




- Neither event generator describes the data well
- Both seems overestimate at low momentum of leptons

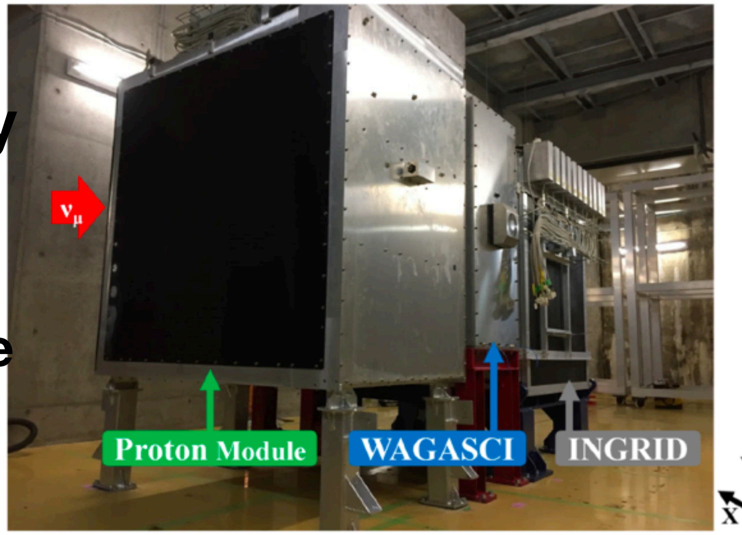
Exclusive charged-current 0-pion, 0-proton on H_20, CH at 1.5° off-axis

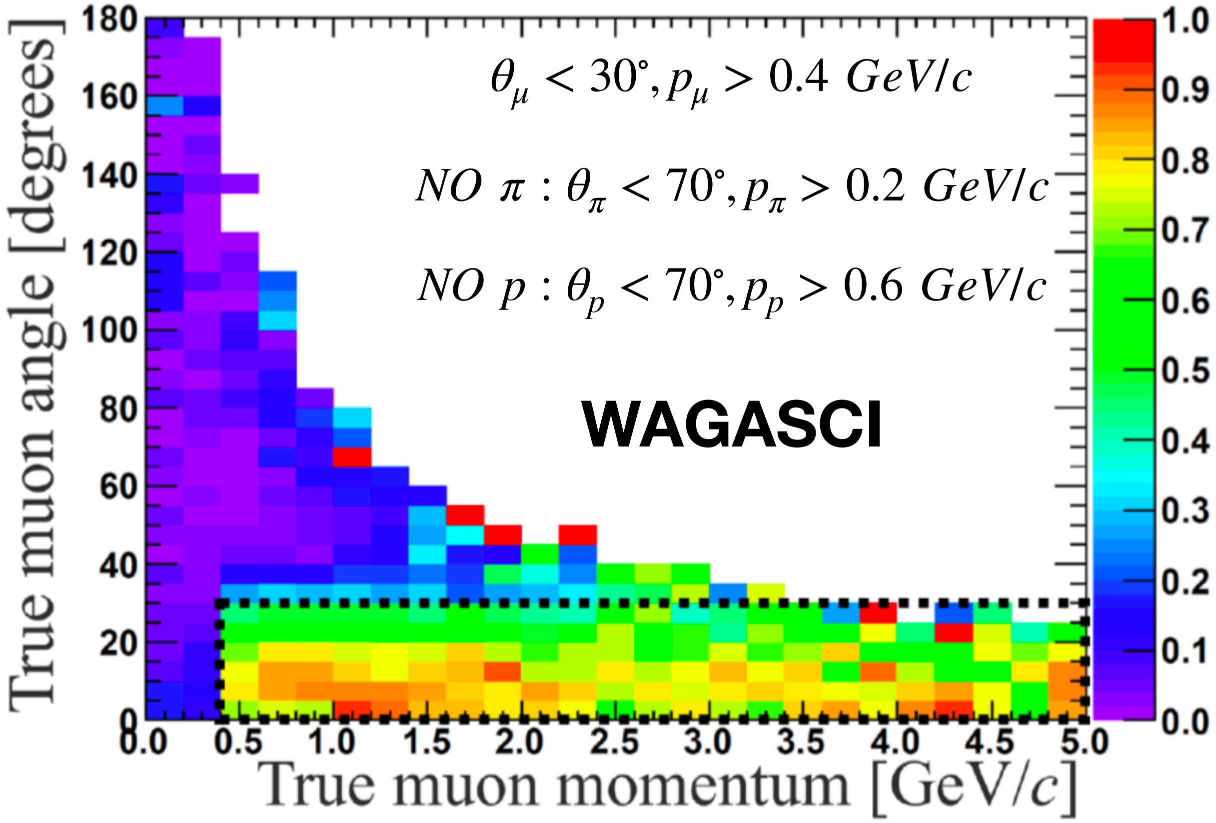
(to be published)

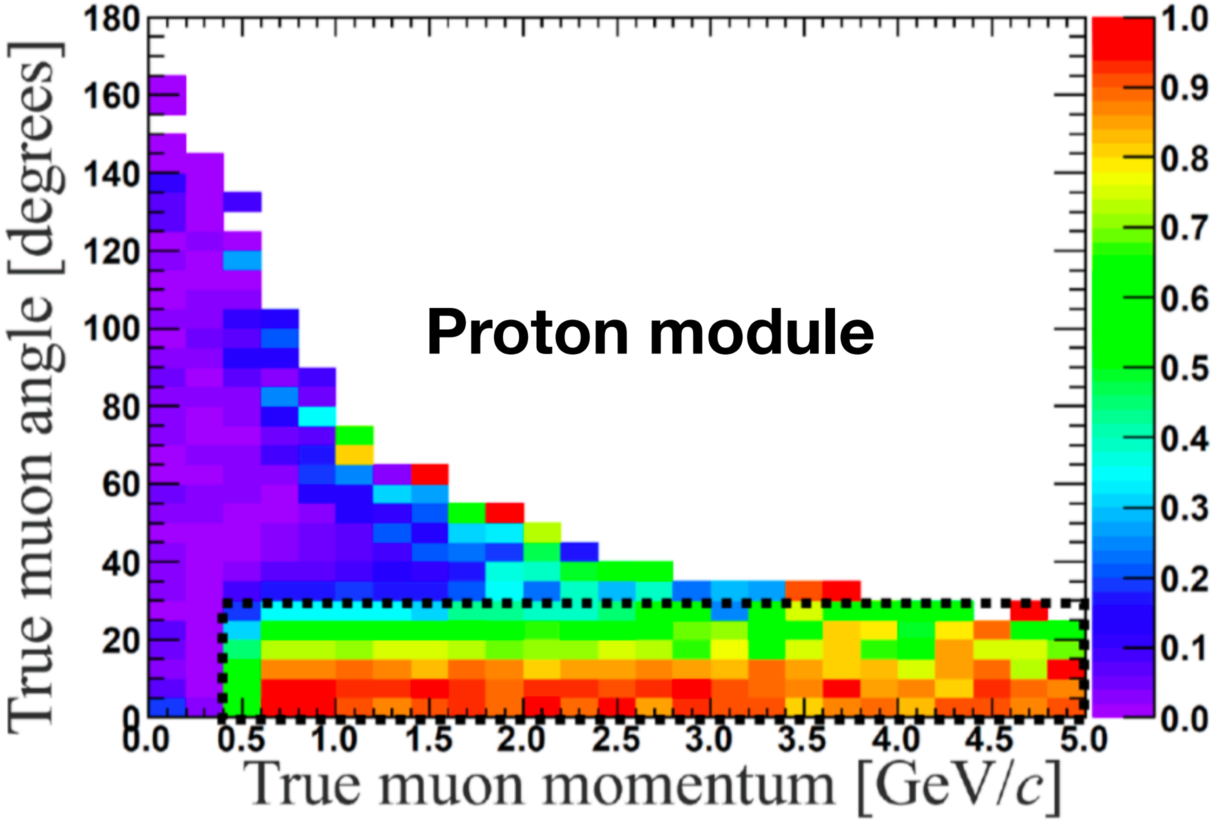


1.5° off-axis
0.86 GeV mean energy

Oct. 2017 - May 2018
7.91×10^{20} POT anti-ν-mode

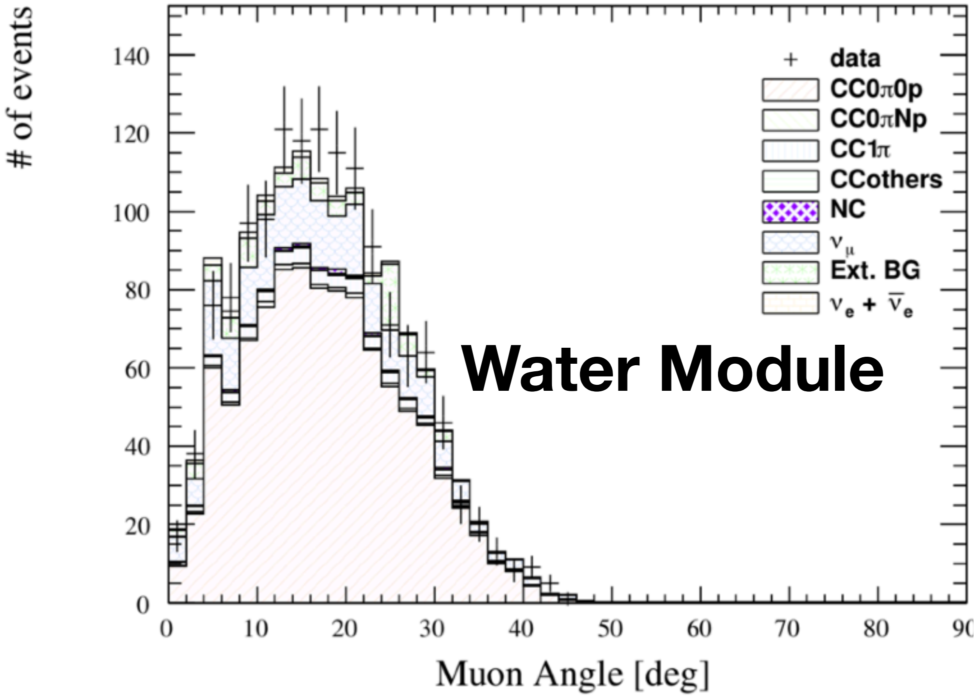




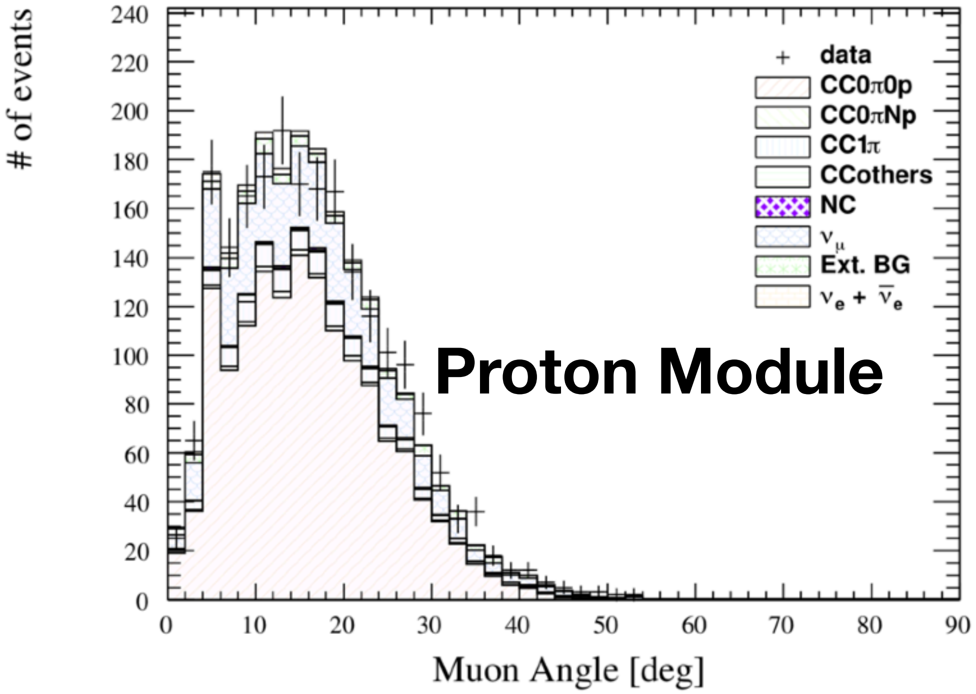


Exclusive charged-current 0-pion, 0-proton on H$_2$0, CH at 1.5^o off-axis

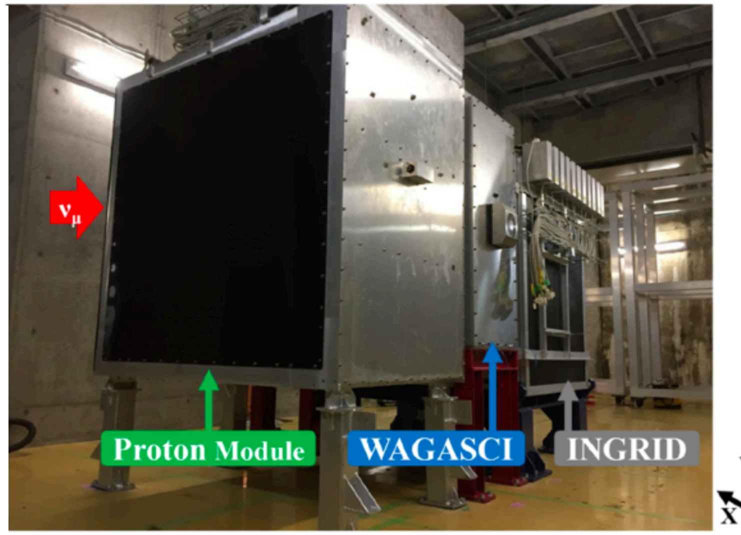
(paper in preparation)



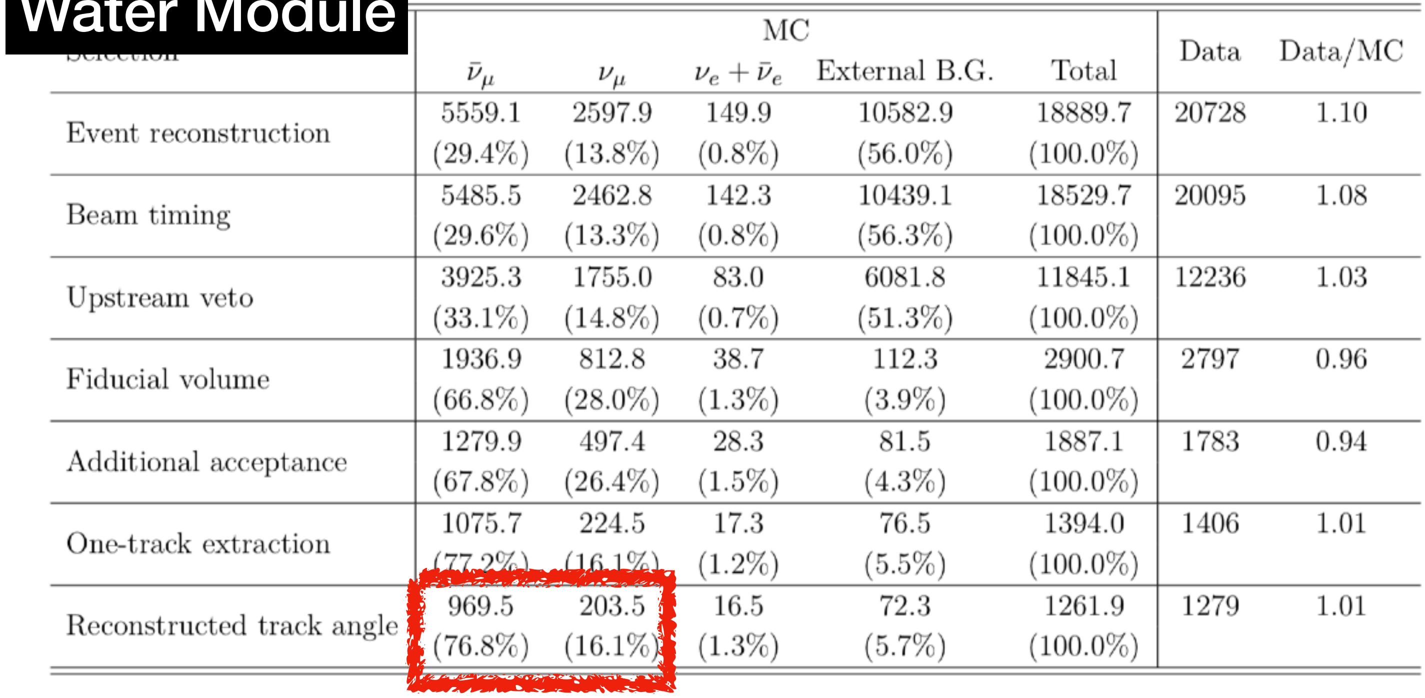
Water Module



Proton Module

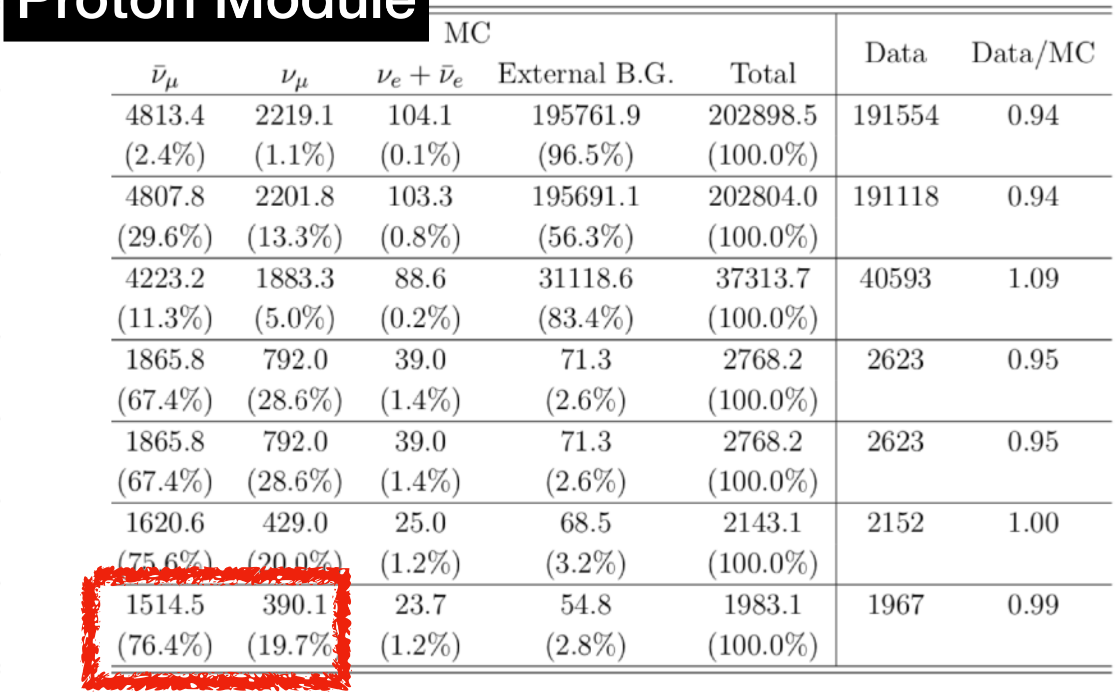


Water Module



Selection	MC					Data	Data/MC
	$\bar{\nu}_\mu$	ν_μ	$\nu_e + \bar{\nu}_e$	External B.G.	Total		
Event reconstruction	5559.1 (29.4%)	2597.9 (13.8%)	149.9 (0.8%)	10582.9 (56.0%)	18889.7 (100.0%)	20728	1.10
Beam timing	5485.5 (29.6%)	2462.8 (13.3%)	142.3 (0.8%)	10439.1 (56.3%)	18529.7 (100.0%)	20095	1.08
Upstream veto	3925.3 (33.1%)	1755.0 (14.8%)	83.0 (0.7%)	6081.8 (51.3%)	11845.1 (100.0%)	12236	1.03
Fiducial volume	1936.9 (66.8%)	812.8 (28.0%)	38.7 (1.3%)	112.3 (3.9%)	2900.7 (100.0%)	2797	0.96
Additional acceptance	1279.9 (67.8%)	497.4 (26.4%)	28.3 (1.5%)	81.5 (4.3%)	1887.1 (100.0%)	1783	0.94
One-track extraction	1075.7 (77.2%)	224.5 (16.1%)	17.3 (1.2%)	76.5 (5.5%)	1394.0 (100.0%)	1406	1.01
Reconstructed track angle	969.5 (76.8%)	203.5 (16.1%)	16.5 (1.3%)	72.3 (5.7%)	1261.9 (100.0%)	1279	1.01

Proton Module

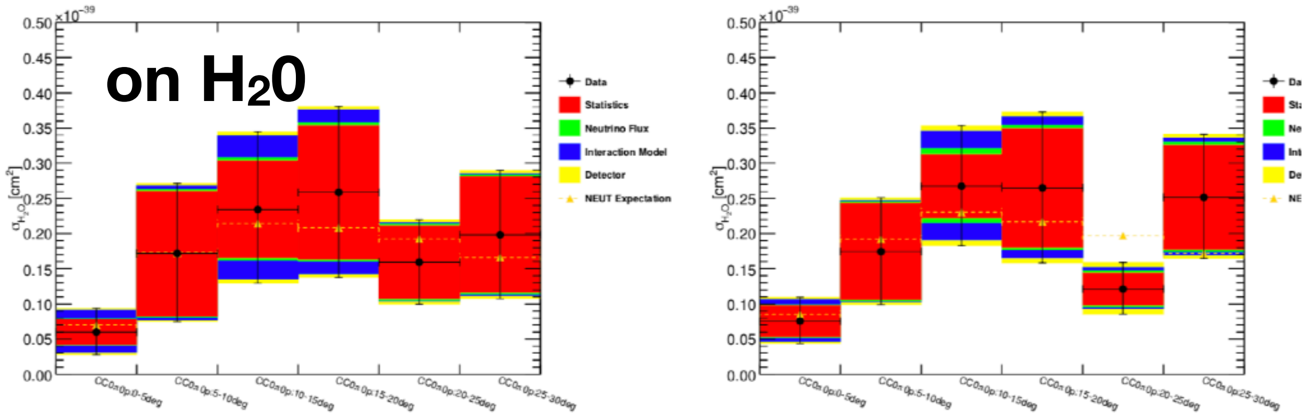


MC					Data	Data/MC
$\bar{\nu}_\mu$	ν_μ	$\nu_e + \bar{\nu}_e$	External B.G.	Total		
4813.4 (2.4%)	2219.1 (1.1%)	104.1 (0.1%)	195761.9 (96.5%)	202898.5 (100.0%)	191554	0.94
4807.8 (29.6%)	2201.8 (13.3%)	103.3 (0.8%)	195691.1 (56.3%)	202804.0 (100.0%)	191118	0.94
4223.2 (11.3%)	1883.3 (5.0%)	88.6 (0.2%)	31118.6 (83.4%)	37313.7 (100.0%)	40593	1.09
1865.8 (67.4%)	792.0 (28.6%)	39.0 (1.4%)	71.3 (2.6%)	2768.2 (100.0%)	2623	0.95
1865.8 (67.4%)	792.0 (28.6%)	39.0 (1.4%)	71.3 (2.6%)	2768.2 (100.0%)	2623	0.95
1620.6 (75.6%)	429.0 (20.0%)	25.0 (1.2%)	68.5 (3.2%)	2143.1 (100.0%)	2152	1.00
1514.5 (76.4%)	390.1 (19.7%)	23.7 (1.2%)	54.8 (2.8%)	1983.1 (100.0%)	1967	0.99

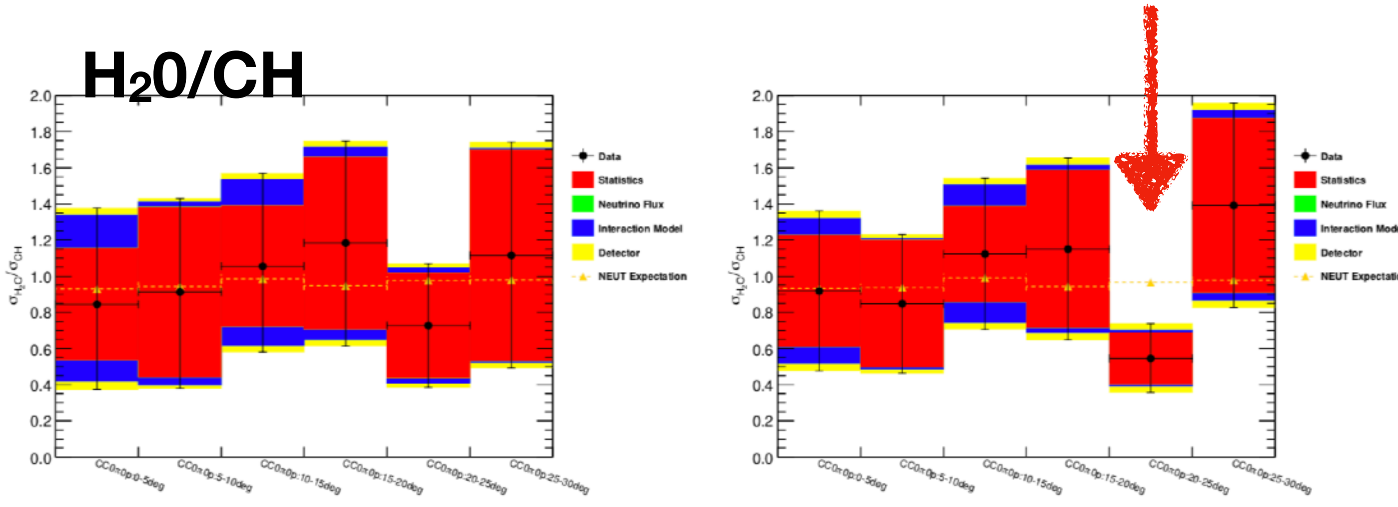
After selection, 76%-77% coming from muon anti-neutrinos; 16%-20% from muon neutrinos (wrong-side). Good data-MC comparison is shown in every step of selection

Exclusive charged-current 0-pion, 0-proton on H_20, CH at 1.5° off-axis

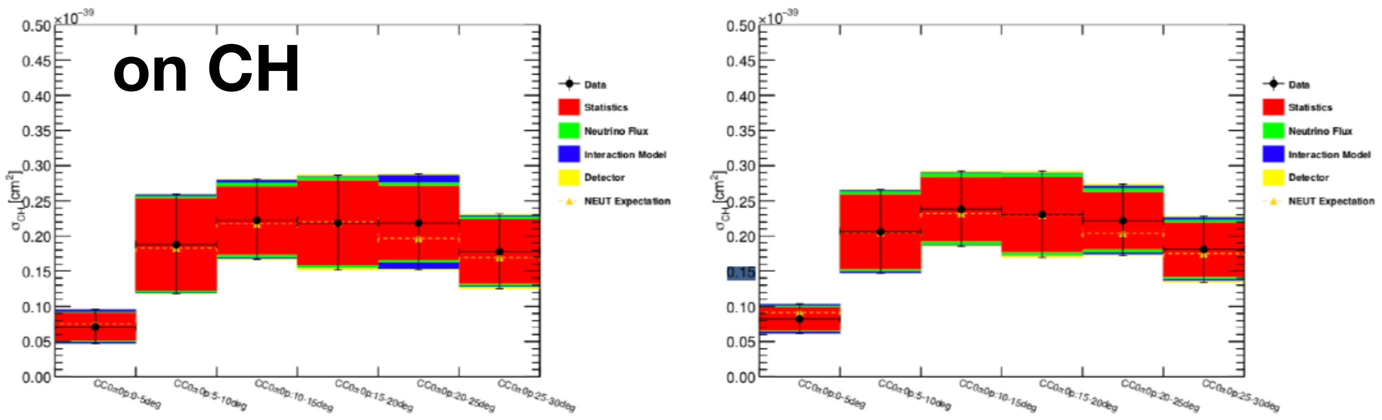
(paper in preparation)



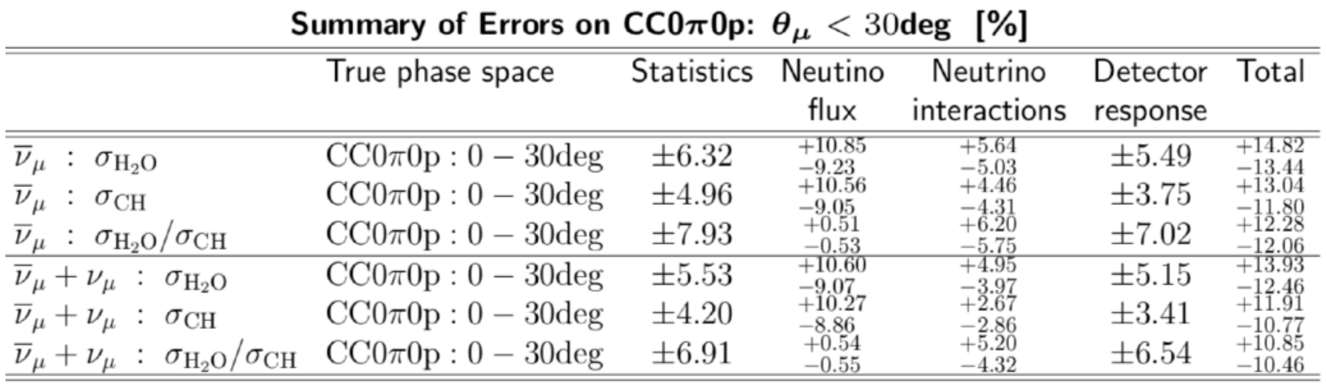
on H_20



H_20/CH



on CH



Summary of Errors on CC0π0p: $\theta_\mu < 30$deg [%]

	True phase space	Statistics	Neutino flux	Neutrino interactions	Detector response	Total
$\overline{\nu}_\mu : \sigma_{\mathrm{H_2O}}$	$\mathrm{CC0\pi0p : 0 - 30deg}$	± 6.32	$^{+10.85}_{-9.23}$	$^{+5.64}_{-5.03}$	± 5.49	$^{+14.82}_{-13.44}$
$\overline{\nu}_\mu : \sigma_{\mathrm{CH}}$	$\mathrm{CC0\pi0p : 0 - 30deg}$	± 4.96	$^{+10.56}_{-9.05}$	$^{+4.46}_{-4.31}$	± 3.75	$^{+13.04}_{-11.80}$
$\overline{\nu}_\mu : \sigma_{\mathrm{H_2O}}/\sigma_{\mathrm{CH}}$	$\mathrm{CC0\pi0p : 0 - 30deg}$	± 7.93	$^{+0.51}_{-0.53}$	$^{+6.20}_{-5.75}$	± 7.02	$^{+12.28}_{-12.06}$
$\overline{\nu}_\mu + \nu_\mu : \sigma_{\mathrm{H_2O}}$	$\mathrm{CC0\pi0p : 0 - 30deg}$	± 5.53	$^{+10.60}_{-9.07}$	$^{+4.95}_{-3.97}$	± 5.15	$^{+13.93}_{-12.46}$
$\overline{\nu}_\mu + \nu_\mu : \sigma_{\mathrm{CH}}$	$\mathrm{CC0\pi0p : 0 - 30deg}$	± 4.20	$^{+10.27}_{-8.86}$	$^{+2.67}_{-2.86}$	± 3.41	$^{+11.91}_{-10.77}$
$\overline{\nu}_\mu + \nu_\mu : \sigma_{\mathrm{H_2O}}/\sigma_{\mathrm{CH}}$	$\mathrm{CC0\pi0p : 0 - 30deg}$	± 6.91	$^{+0.54}_{-0.55}$	$^{+5.20}_{-4.32}$	± 6.54	$^{+10.85}_{-10.46}$

- 10%-15% uncertainty for differential cross section measurement on water
- Overall agrees within 1-sigma uncertainty with neutrino interaction models used in T2K experiment
- Except, MC seems overestimate at phase space of muon scatting angles 20°-25°

WAGASCI-BabyMIND prospects

Limitation of previous measurements

Problem solver: Baby-MIND and Wall-MRD

- Angular acceptance for lepton is limited 30°-45°
- Momentum measurement of lepton limits to 1GeV
- Can't measure the charge, particularly important when taking data in anti-neutrino mode

1.5° off-axis
0.86 GeV mean energy

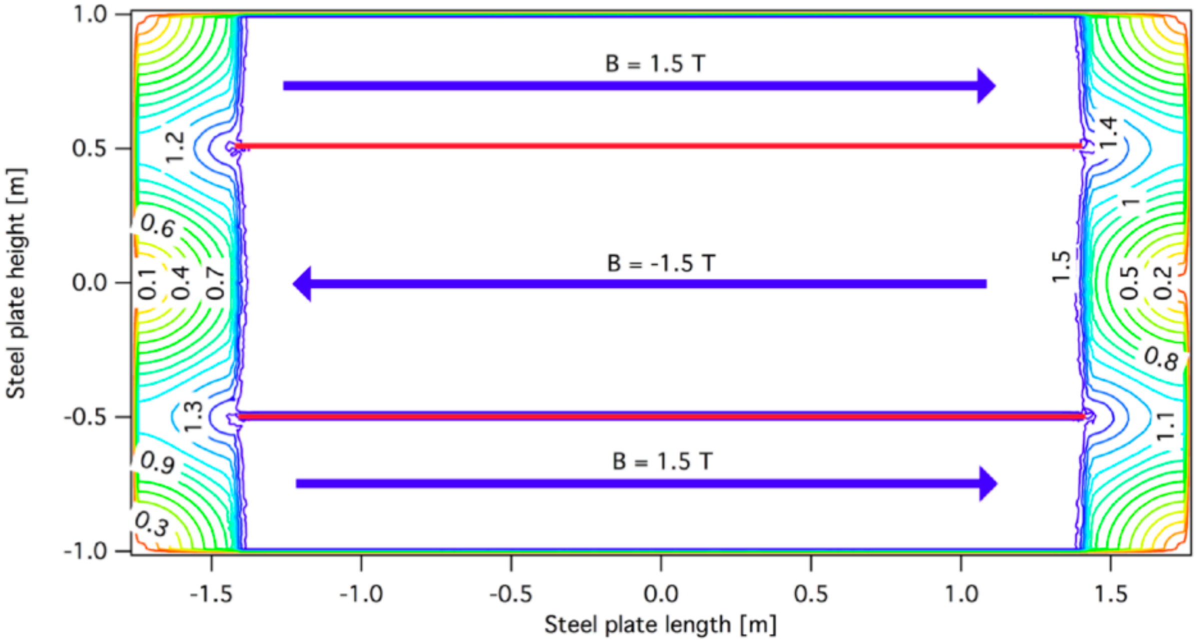
Nov. 2019 ~

To take advance of beam usage, human power, and analysis framework sharing, WAGASCI-BabyMIND is integrated into T2K as a near detector project

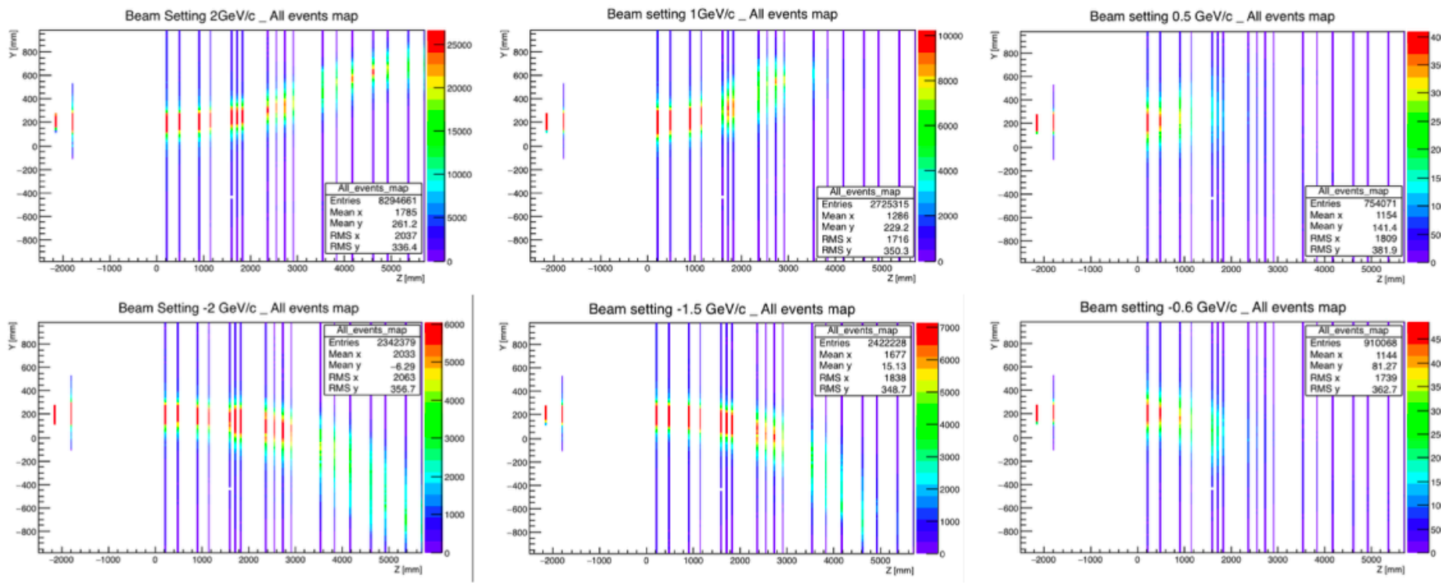
Plan to take 1yr. data, for both neutrino and anti-neutrino mode, >5x10^{20} POT per each mode

BabyMIND
Muon range & charge identification

Magnetic field map



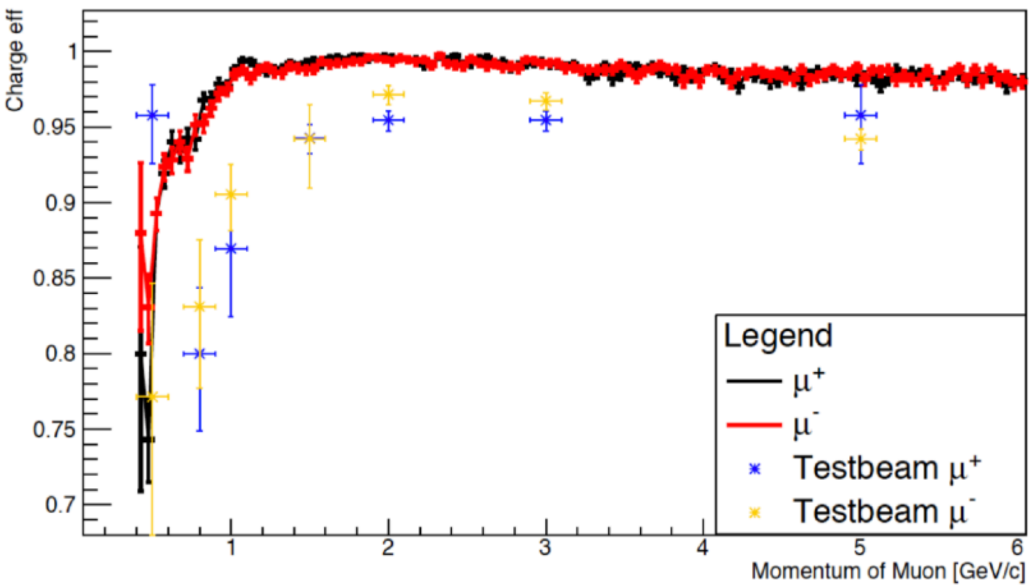
2GeV muon **1GeV muon** **0.5GeV muon**



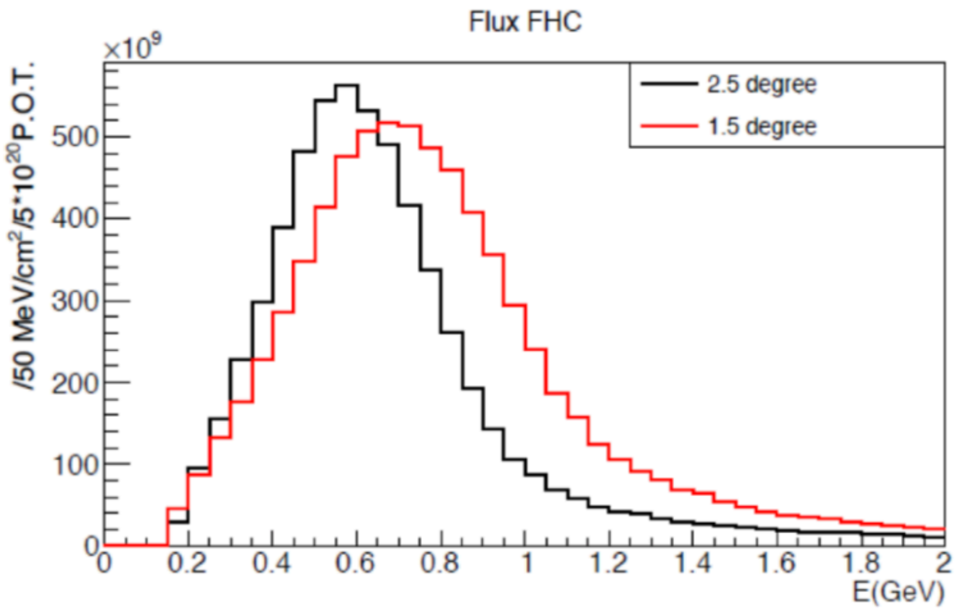
Beam test at CERN 2017

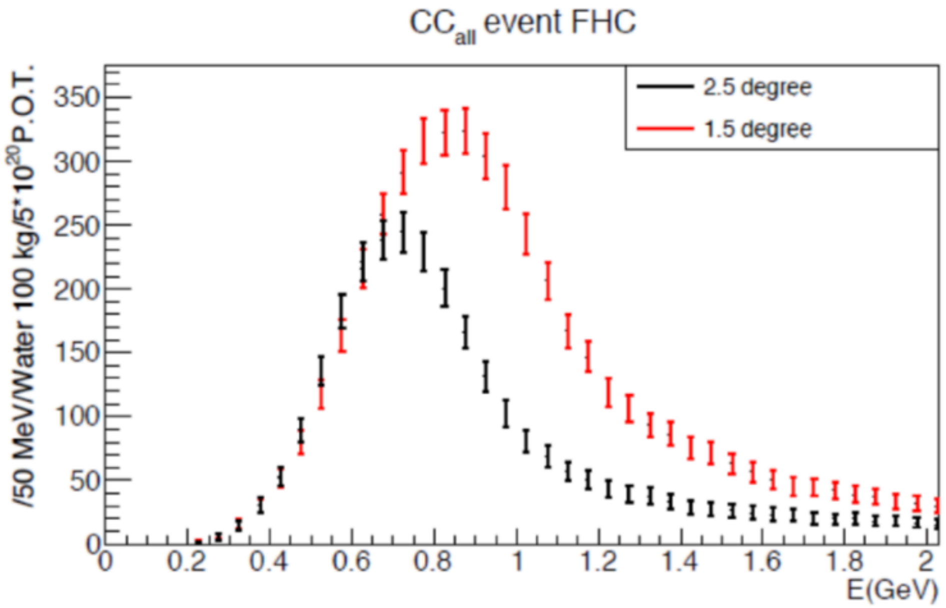
- Sheets of iron interleaved with scintillator detector modules
- Individually magnetized; flexibility in detector module arrangement
- 1.5T for a current of 140A current
- High capability in charge identification and muon ranging

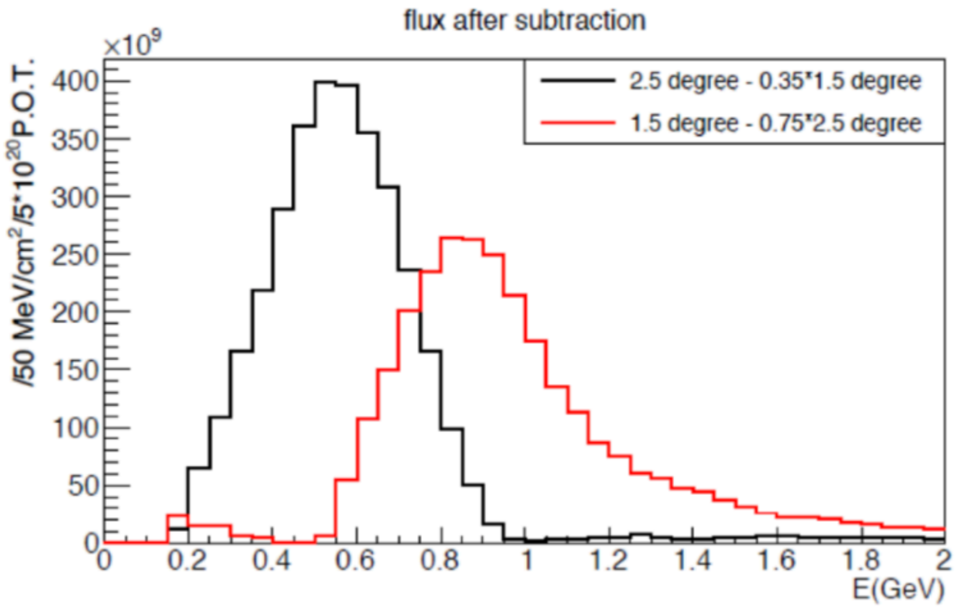
Baby MIND charge ID efficiency

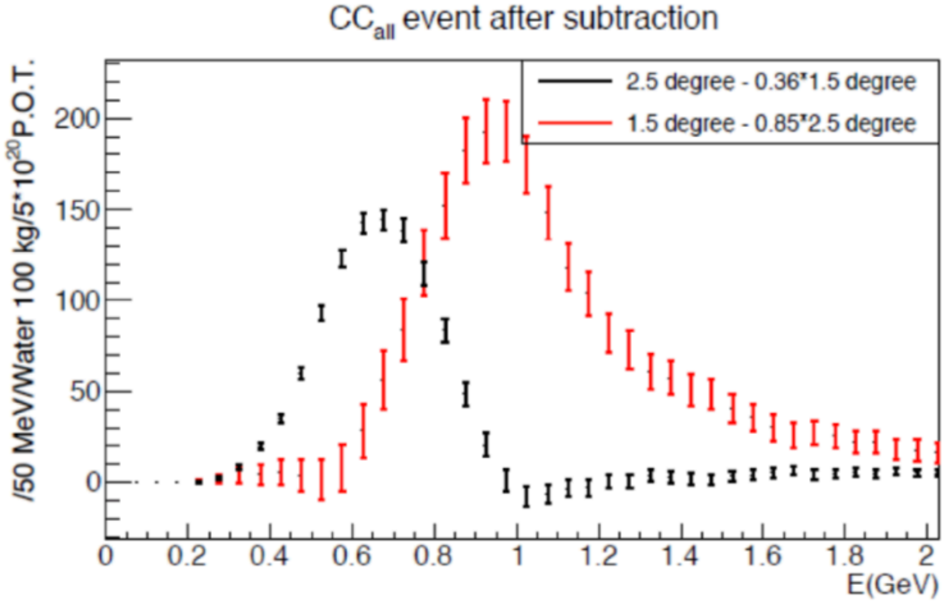


Explore multi off-axis detectors: flux subtraction as a promising gem









Subtracting flux at different off-axis detectors results in narrower-band flux, make (double) differential cross section more interesting/power to test the interaction models

Summary

- Neutrino-water interaction is important for on-going T2K and future Hyper-K and other relevant neutrino experiments
- WAGASCI-BabyMIND aims for precision measurements of neutrino-water interactions
    - With WAGASCI provisional setups, we have provided measurements with unprecedented precision
    - We're ready to take data with full setup from fall 2019