Upgrade of the near detectors towards CP violation search in T2K/T2K-II

Benjamin Quilain (Kavli IPMU, The University of Tokyo)
on behalf of the ND280-upgrade taskforce and WAGASCI collaboration

Outline :

1. Introduction to T2K.

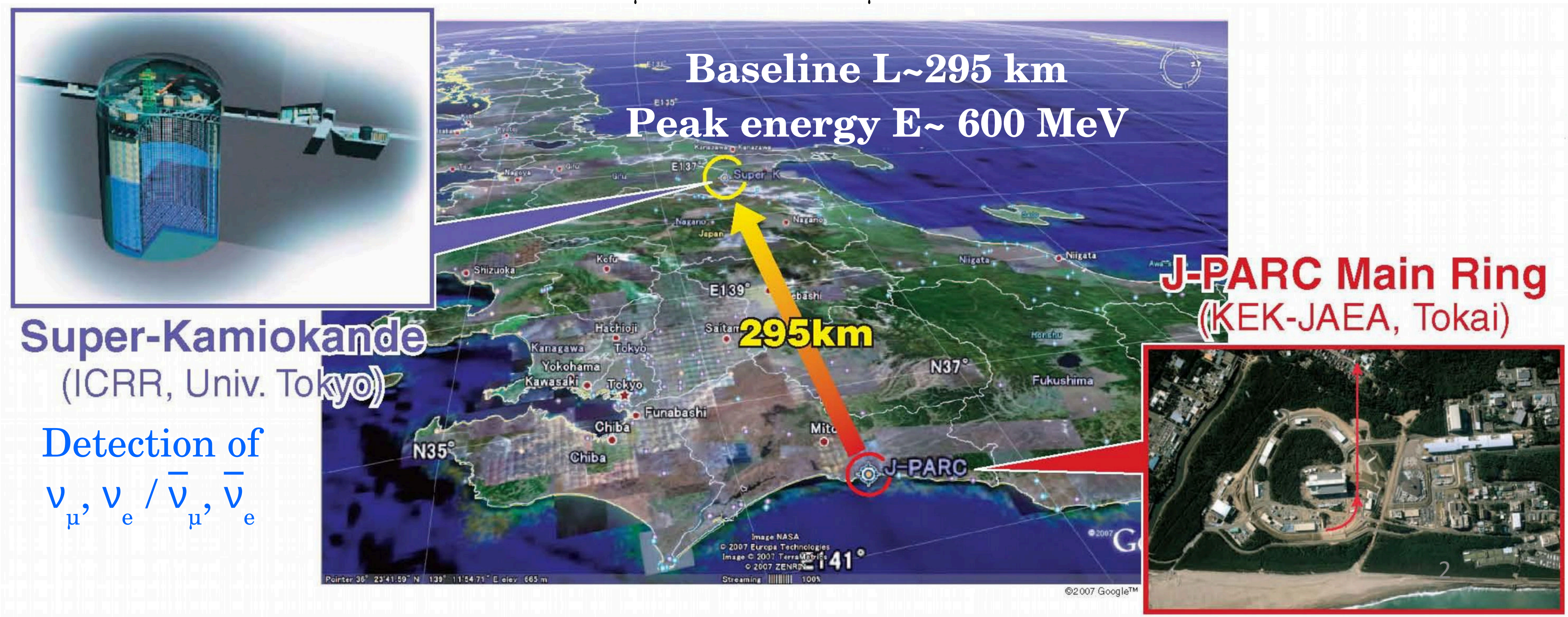
2. Upgrade of the off-axis near detector, ND280.

3. A new water-based detector : WAGASCI

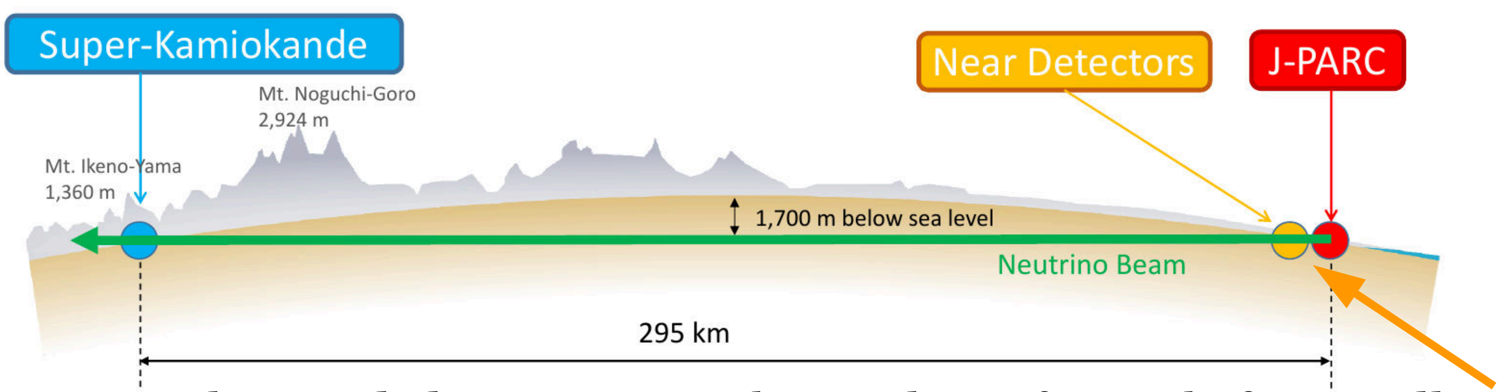
NNN17 conference, 2017/10/26

I-Introduction to T2K

- Observation of ν_e appearance in a ν_μ beam and ν_μ disappearance & $\bar{\nu}$ equivalents.



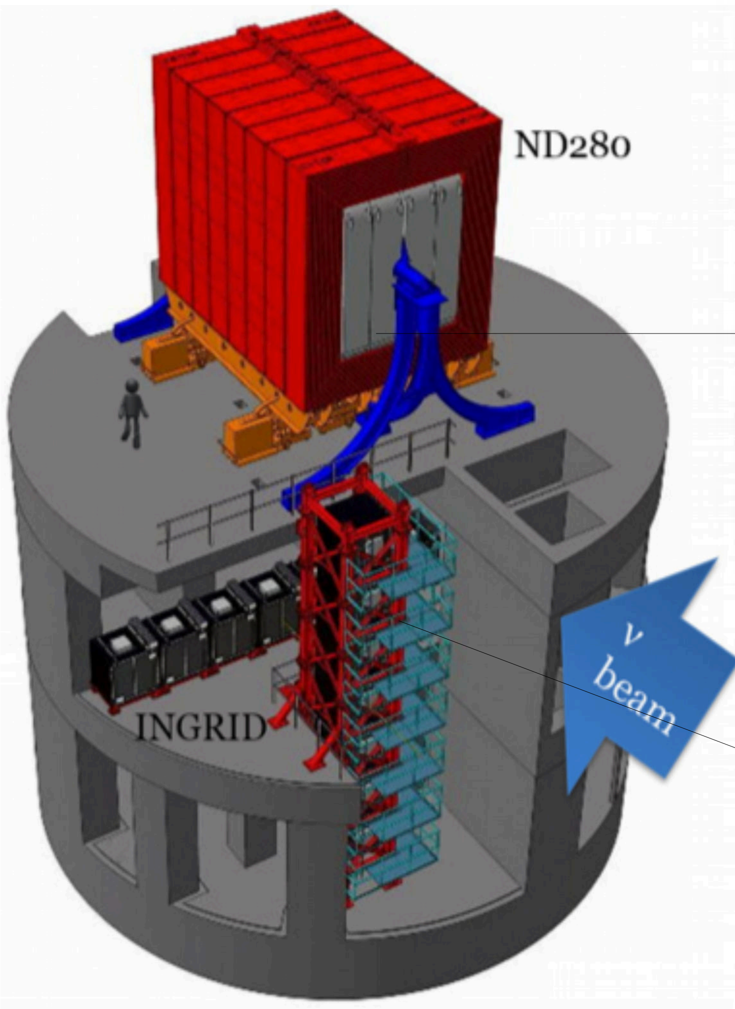
- **Off-axis experiment :** neutrino beam aimed at 2.5° from Super-K to maximize the oscillation at 295 km → Tune energy spectrum (600 MeV)

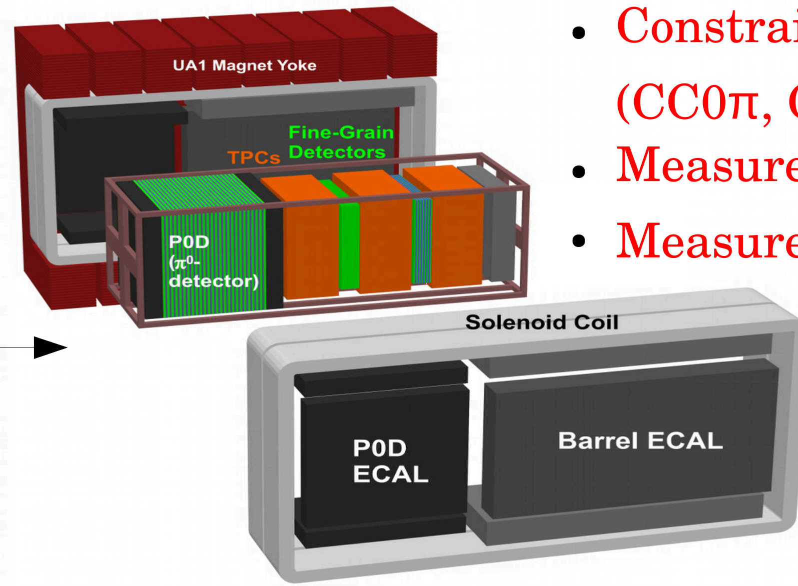


- Near detector complex needed to constraint beam shape & rate before oscillation

ND280 detectors constraints on flux

Complementary near detectors

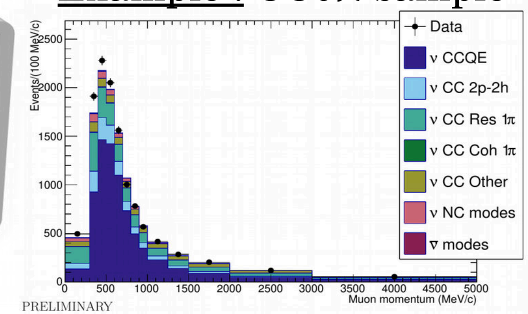




Off-axis near detector: ND280

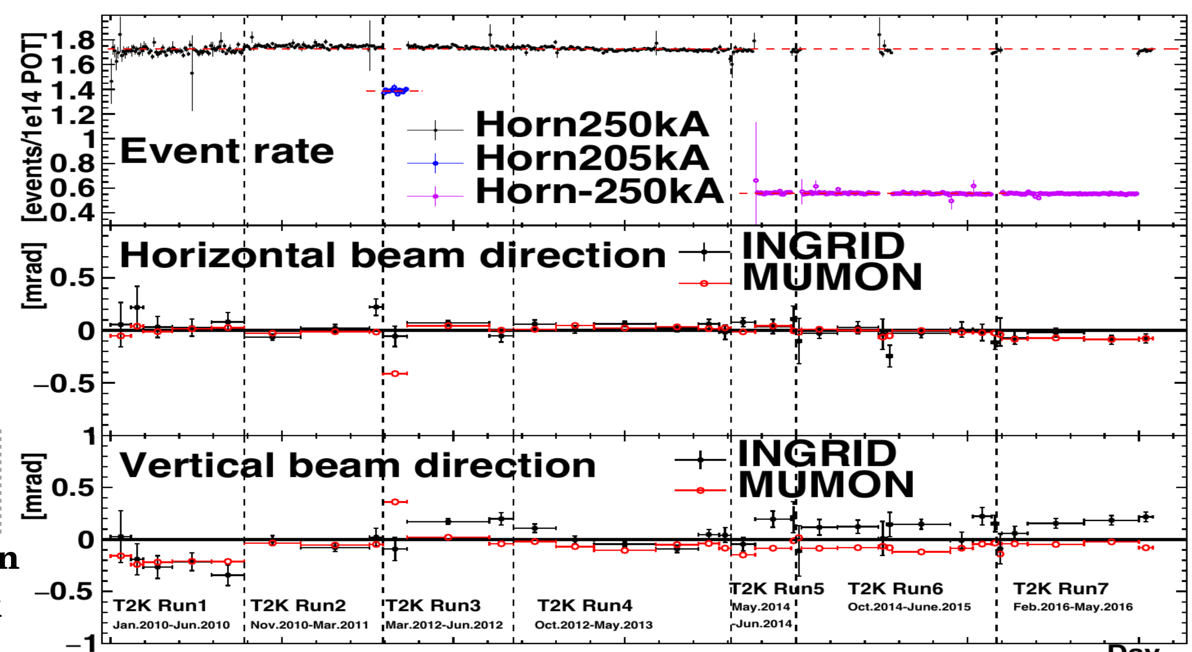
- Constraints on ν_μ spectrum (CC0π, CC1π, CCOthers)
- Measure ν_e beam contamination
- Measure cross sections

Example : CC0π sample



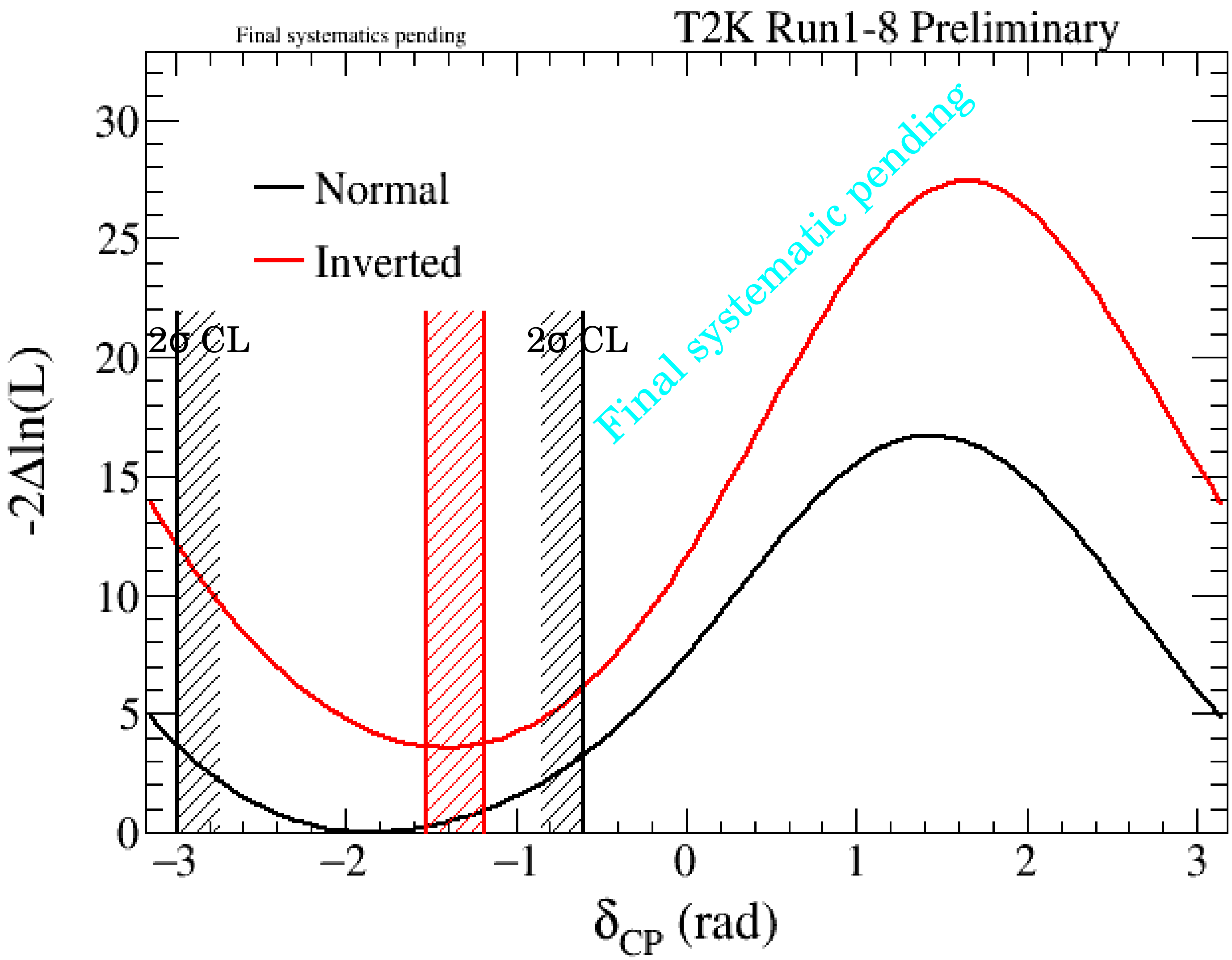
On-axis near detector: INGRID

- Beam stability
- Off-axis angle : constrains neutrino spectra



2 % on peak

Last T2K results



<u>One of summer 2017 results :</u> CP conservation is excluded with 2σ CL.

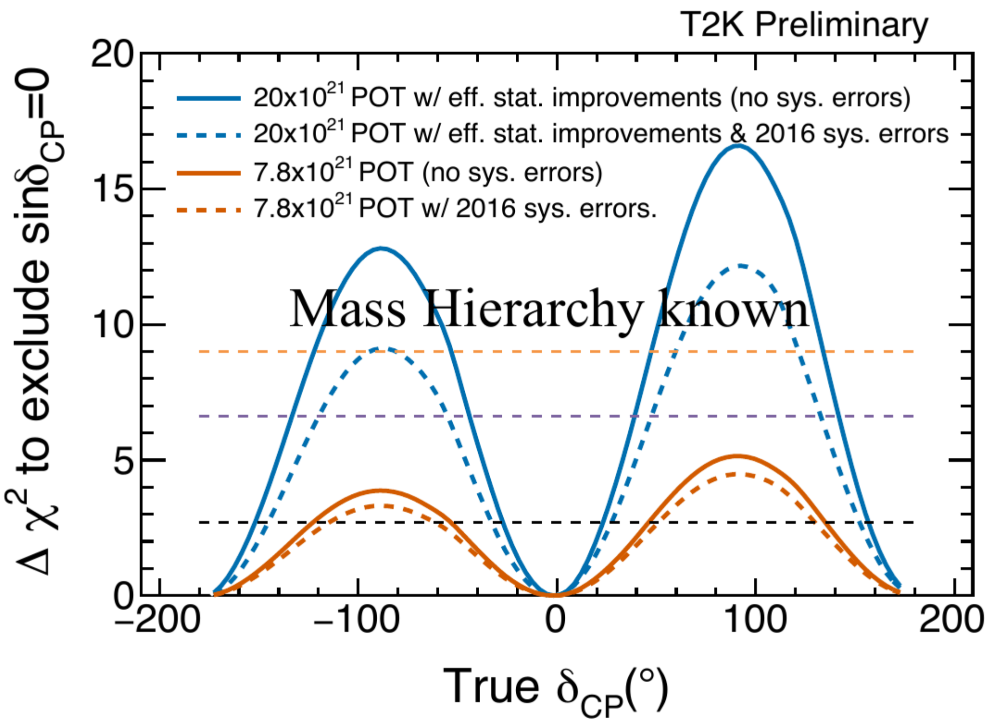
→ See H. O'Keefe talk's.

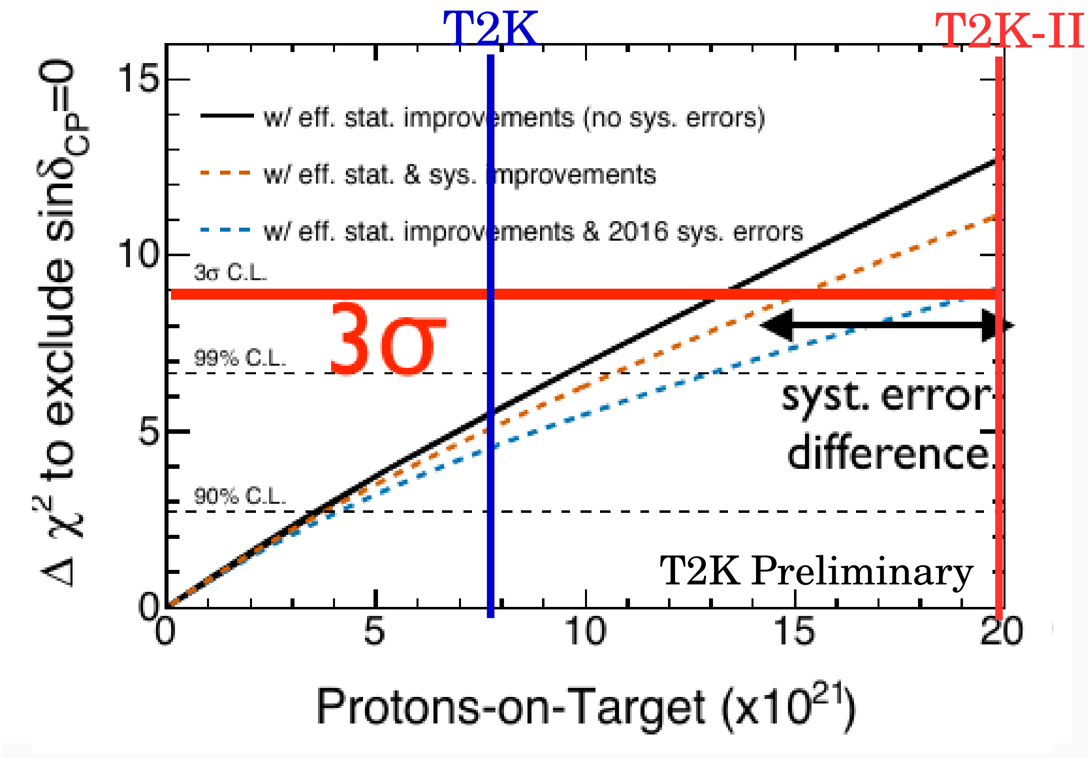
<u>This talk :</u> How can we walk towards new achievements ?

General requirements to decrease the systematics

- Motivations for T2K phase II: First experiment to exclude CP conservation > 3σ !

- Limited by our current systematics in far detector (Super-K) sample : from 5.1 % to 6.8 %





- W/o decreasing current systematics: phase space very limited even for 20 x 10^{21} POT.
  → A 3σ exclusion possible almost only if $\delta_{CP}=-\pi/2$ and normal hierarchy.

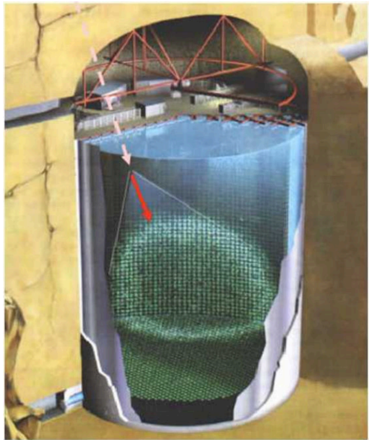
- Decreasing systematics to 4 % <=> 5 x 10^{21} POT (>2 times current T2K statistics).

List of current systematic uncertainties

2016 analysis error table

	$\delta_{N_{SK}}/N_{SK}$ (%)				
	1-Ring μ		1-Ring e		
Error Type	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode	$\nu/\bar{\nu}$
SK Detector	3.9	3.3	2.5	3.1	1.6
SK Final State & Secondary Interactions	1.5	2.1	2.5	2.5	3.5
ND280 Constrained Flux & Cross-section	2.8	3.3	3.0	3.3	2.2
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.0	0.0	2.6	1.5	3.1
NC 1γ Cross-section	0.0	0.0	1.5	3.0	1.5
NC Other Cross-section	0.8	0.8	0.2	0.3	0.2
Total Systematic Error	5.1	5.2	5.5	6.8	5.9
External Constraint on θ_{12}, θ_{13}, Δm^2_{21}	0.0	0.0	4.1	4.0	0.8

- Uncertainty on extrapolation of ND280 constraints to SK
  Same flux, target, acceptance between near and far.

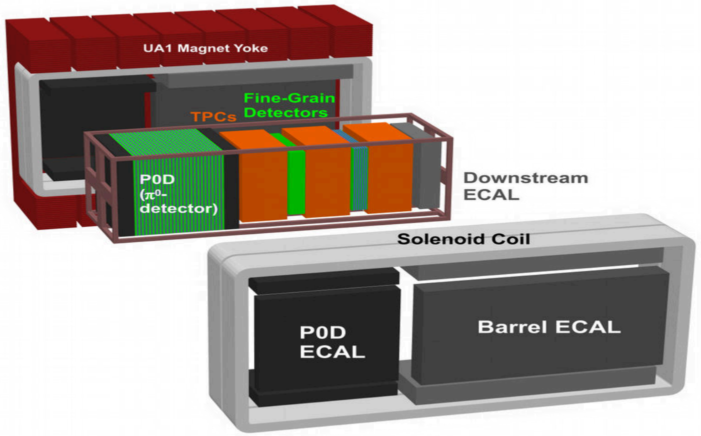


Far detector

Near detector

Target : 100 % H_2O vs 80 % CH + 20% H_2O

Acceptance : 4π vs Foward



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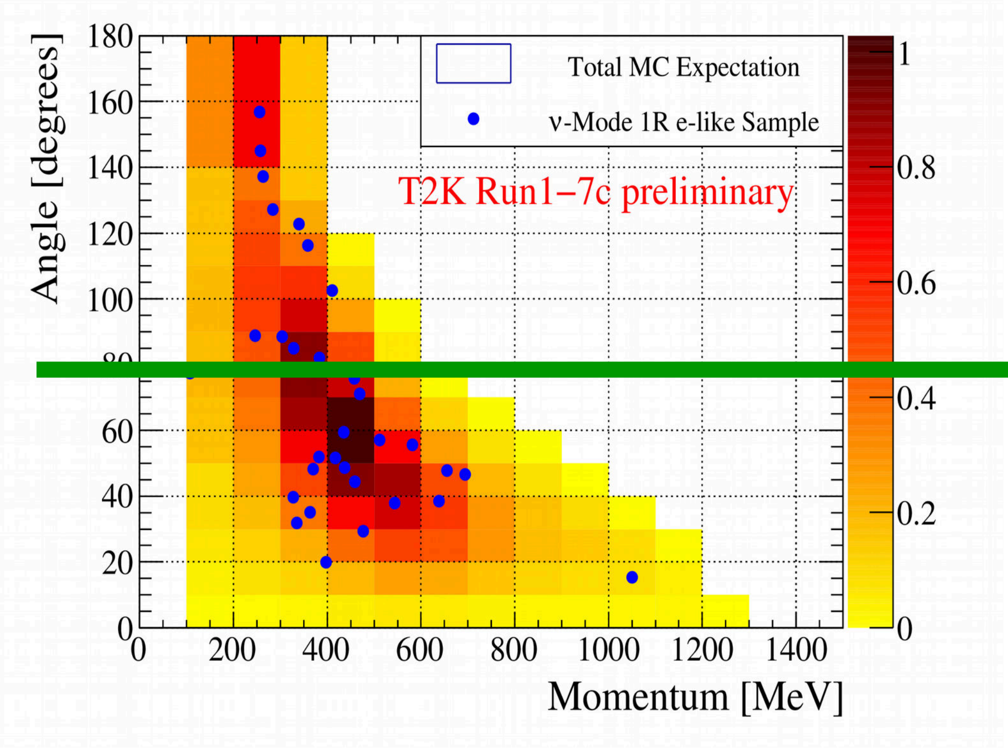
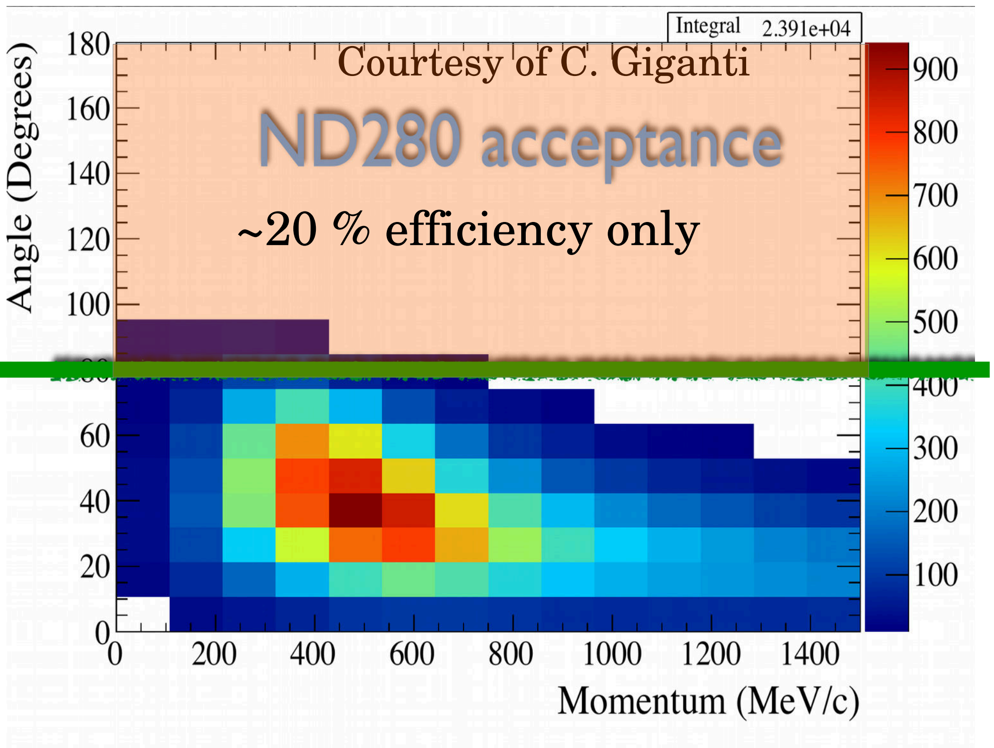
- Uncertainty on extrapolation of ND280 constraints to SK
  Same flux, target, acceptance between near and far.

- Important cross-section model dependency that might be not represented in this table.

Q^2 dependency of the cross-section, 2p2h interactions, Final State Interactions etc.

SK predictions constrained model independently → Measurement from ND.





<u>Need a ND that has:</u>

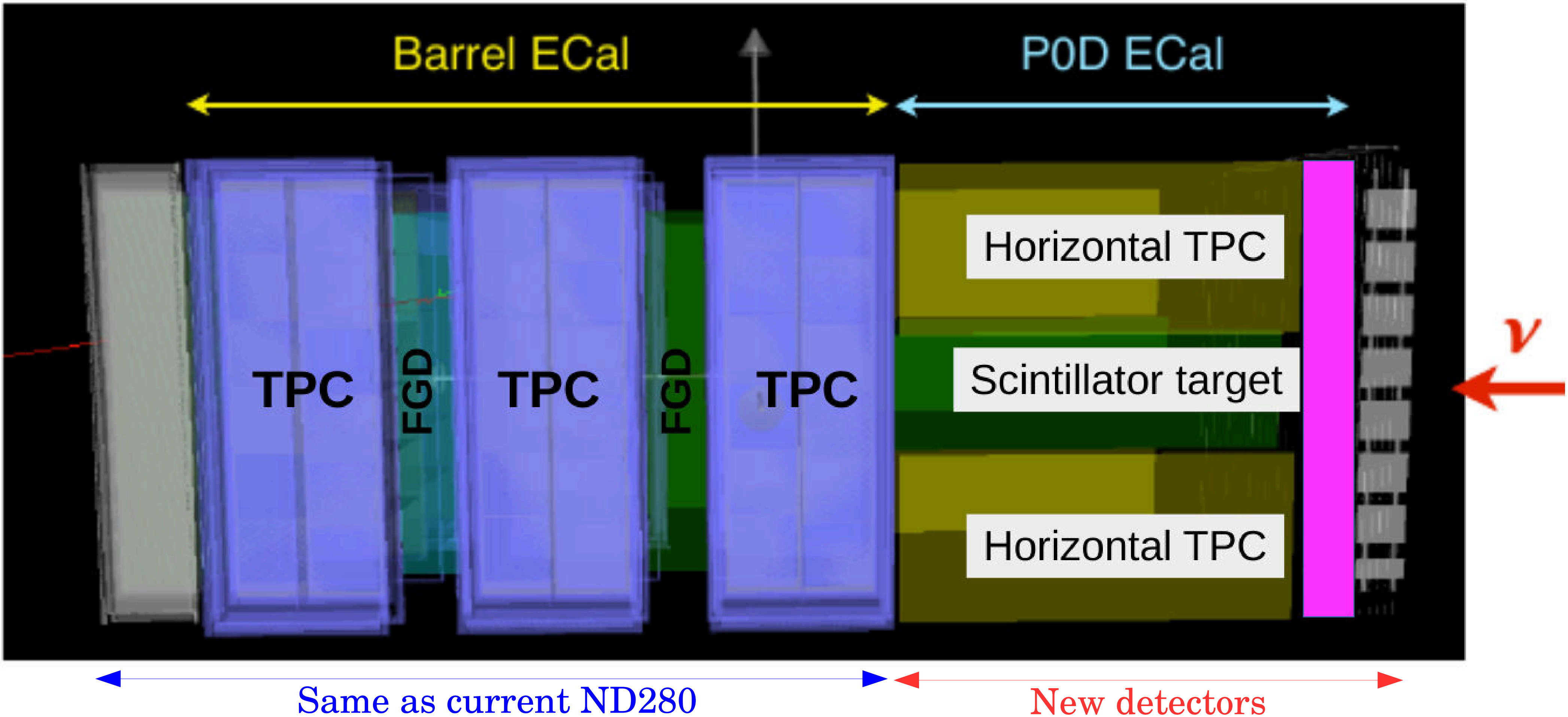
1. Similar nucleus target as Super-K <u>(O if possible, C otherwise)</u>: ~~cross-section models~~

2. 4π angle acceptance as SK (4π) for lepton kinematics : ~~Efficiency corrections~~

3. High granularity to identify interaction final states (track low momenta hadrons) → Improve the energy reconstruction.

II-Upgrade of the ND280 detector

Proposal for the ND280 upgrade



1. Existing two FGD targets : H_2O + CH ~ 1.8 T each

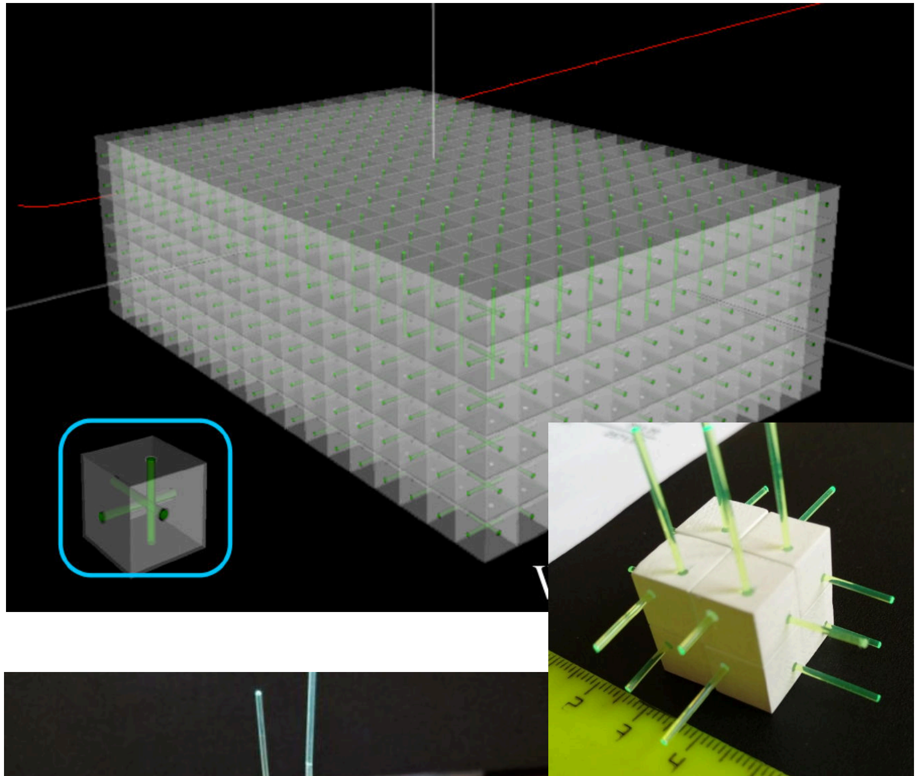
2. One new fully active plastic target embedded in 4π tracker ~ 1.5 T

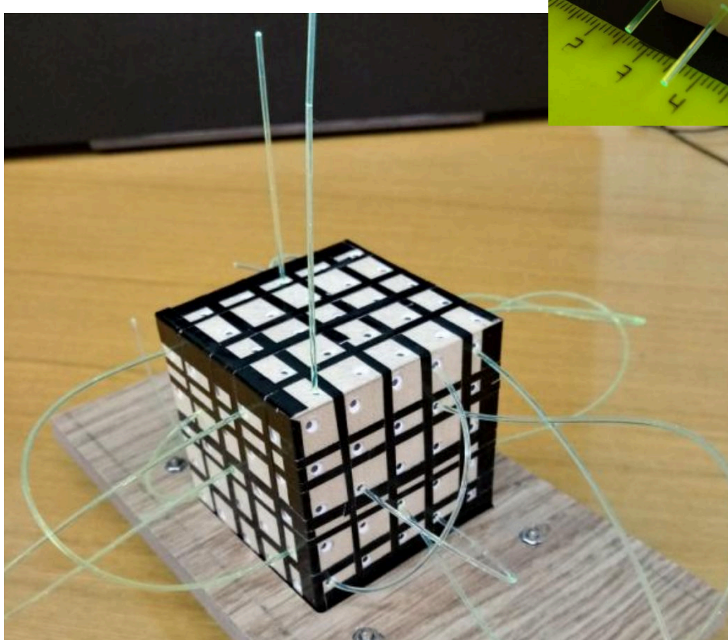
Maximal acceptance coverage

3. Use 3 ND280 TPC + build 2 new TPCs & support structure
→ particle momenta can be measured in all direction (SK 4π angular acceptance)

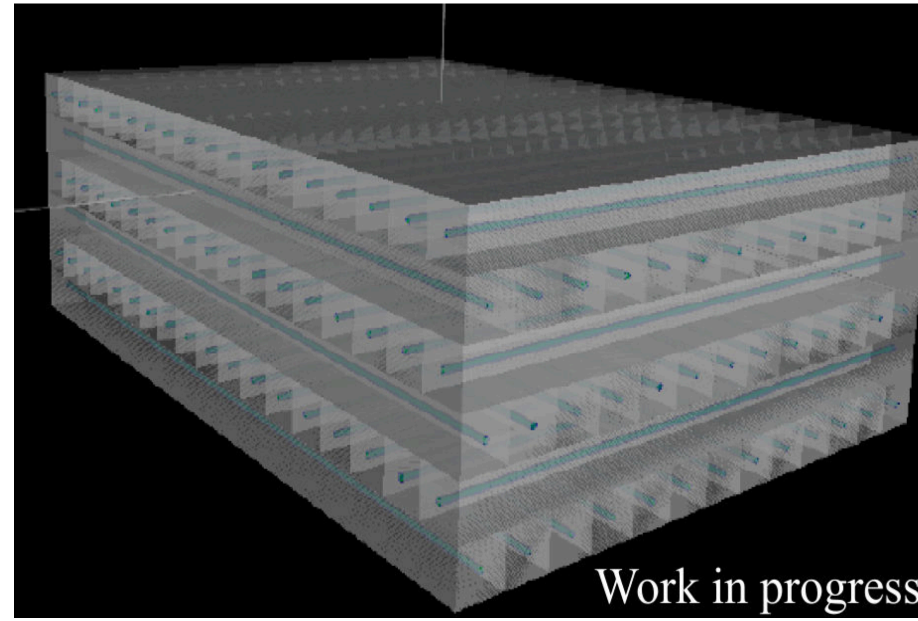
Candidates for the new target

Super-FGD





Horizontal FGD



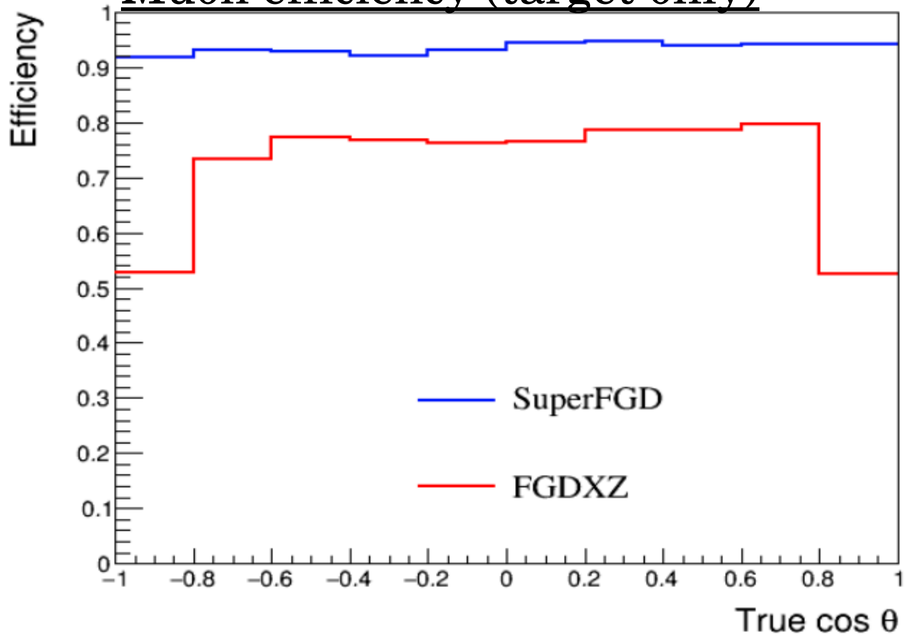
	Super-FGD	Horizontal FGD
Pros	4π High resolution for low momenta hadrons	Well known, easy assembly Low cost
Cons	Challenging assembly Large costs	Not 4π

Main candidate : R&D already started at INR

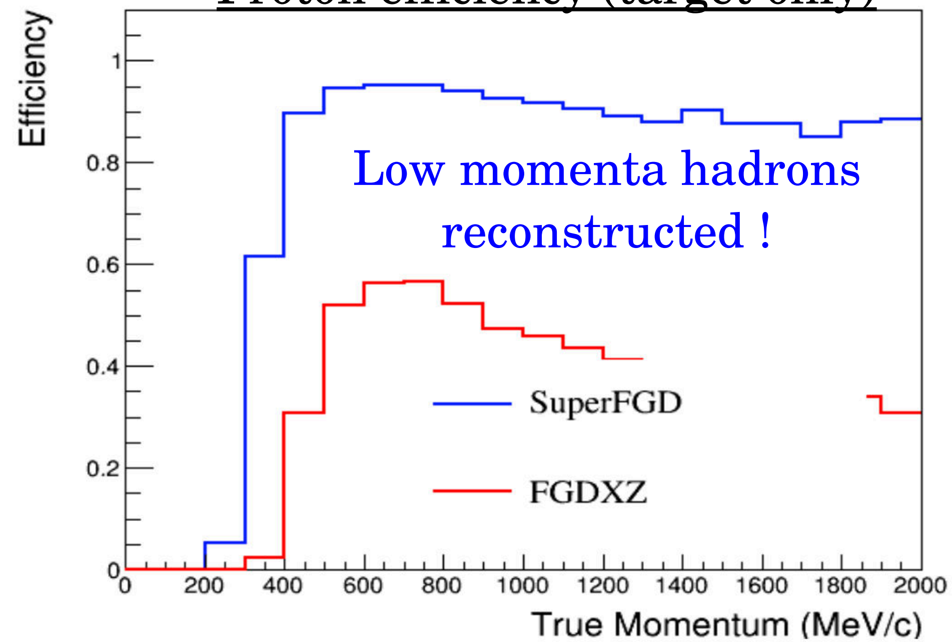
→ Now prototype @CERN for test beam

Impact on the reconstruction efficiency

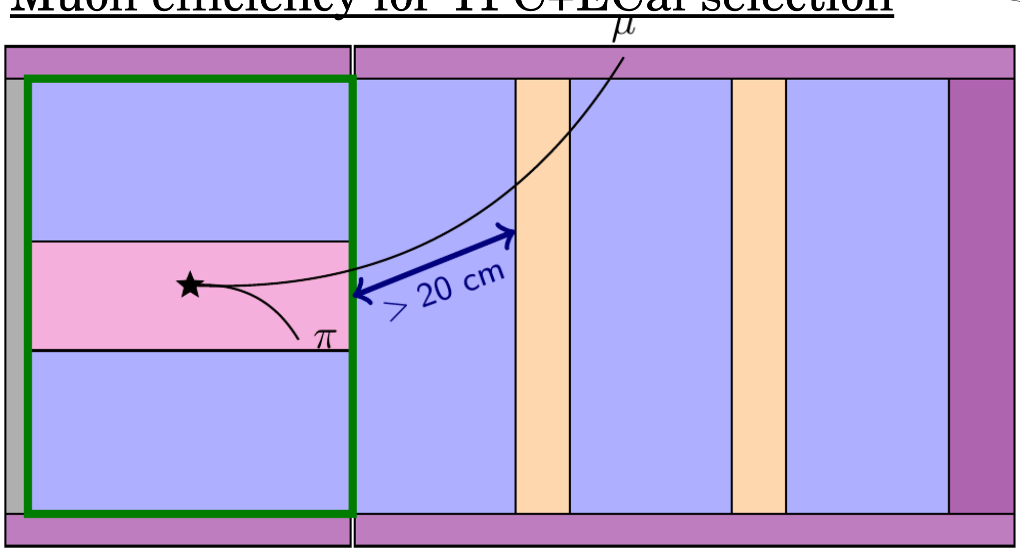
Muon efficiency (target only)

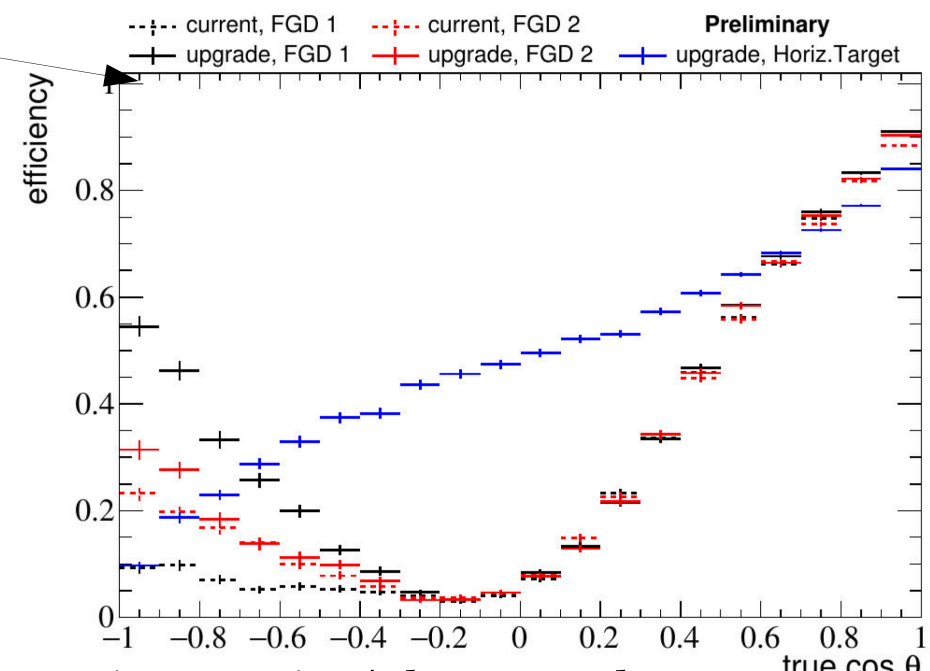


Proton efficiency (target only)



Muon efficiency for TPC+ECal selection

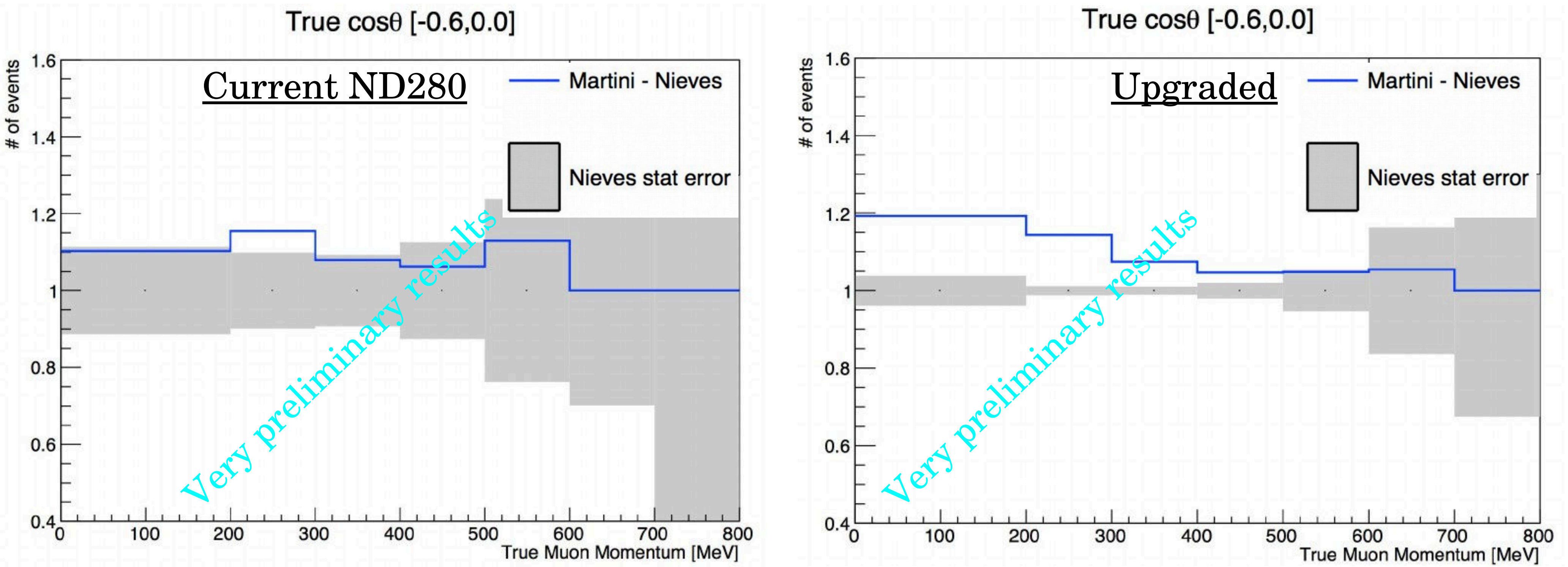




Muon reconstruction @large angle : Increase from 10 % → 50 % w/ the upgrade

Fake data studies

- Extrapolation at FD should be driven by data, not models !
- Test upgrade capability to reduce model dependency : one example on 2p2h models.
- 2 fake data set: Nieves 2p2h (current BANFF) and w/ Martini-model w/ 8 x 10^{21}POT



- Potential degeneracy of data sets at small angle can be solved at high angle with the upgrade → Reduce the model dependency when extrapolating at SK.
- It is only 1 example. Cross-section models have high Q^2 dependency : crucial to probe different effects at high angle

III-A new water-based detector : WAGASCI

Reminder of our wishlist :

1. 4π angle acceptance as SK (4π) for lepton kinematics : ~~Efficiency corrections~~

2. High granularity to identify interaction final states (track low momenta hadrons).

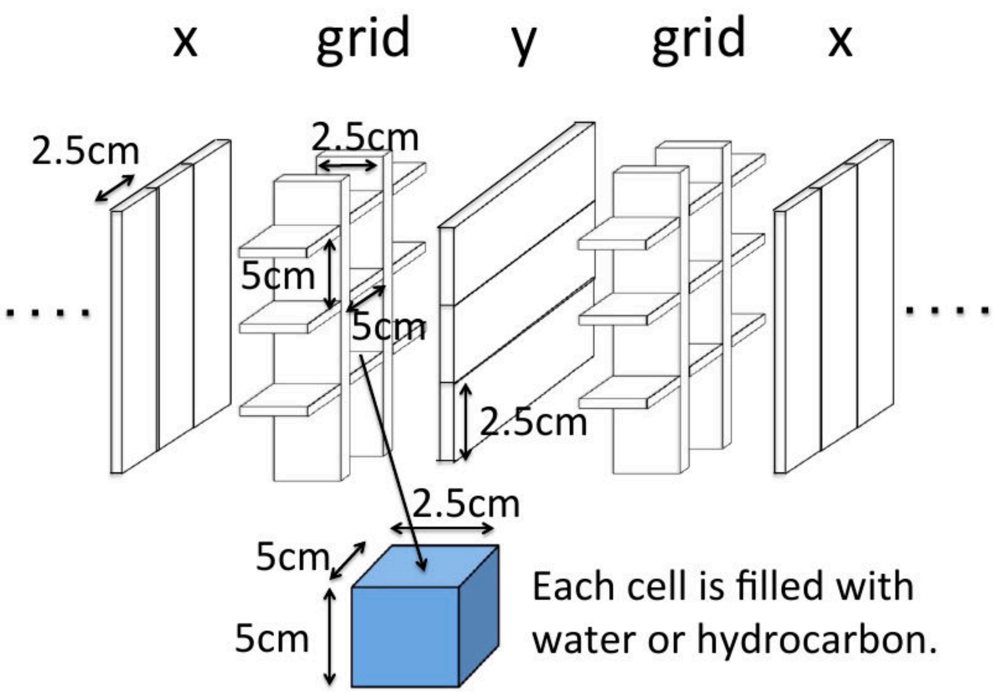
3. Similar nucleus target as Super-K (O if possible, C otherwise): ~~cross-section models~~

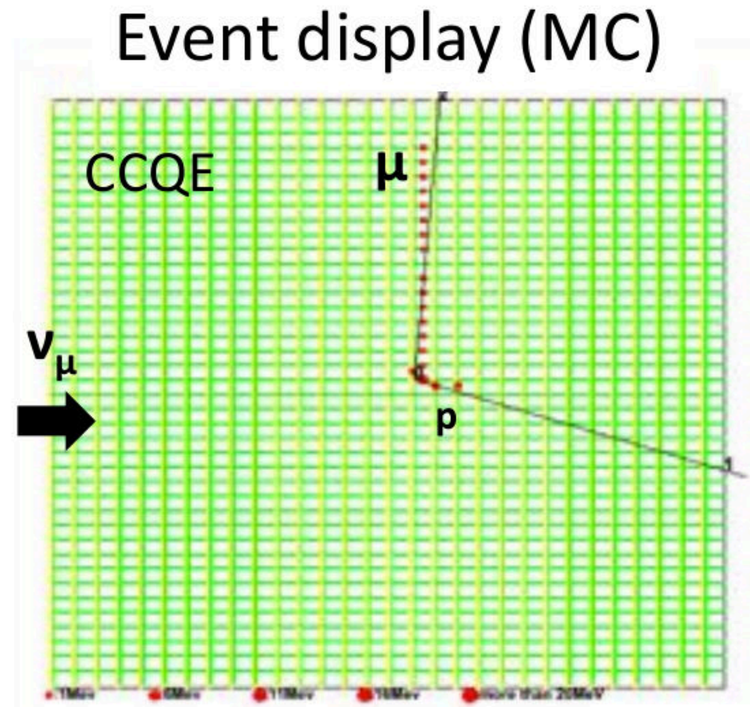
→ How about constraints on water target at large angles? → WAGASCI

WAGASCI tracker: Alternance of XY planes & 3D grid scintillators.

4π angular acceptance

Good vertex resolution (even for large angle tracks)





Goal : Cross-section measurement on water (& H_2O/CH ratio) with high angle acceptance.

Module ID card :

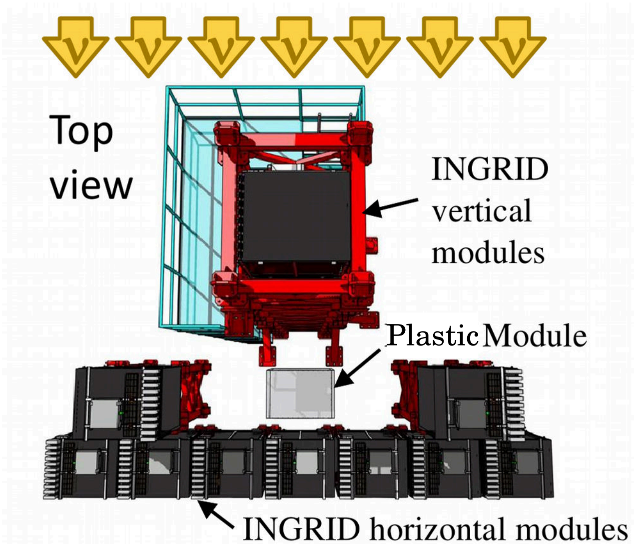
Module size : 100 x 100 x 40 cm^3 **~ 0.4 tons**.

Cell size (resolution) : 5.0 x 5.0 x 2.5 cm^3 cells

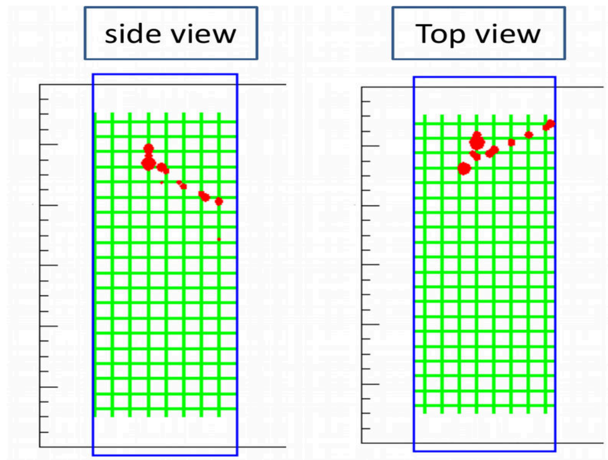
Plastic background substraction : **H_2O:CH(Plastic)=8:2** in H_2O module.

Stage 0 : the prototype module

First : Construct one H_2O module and installed @beam-axis (0 deg off-axis) in autumn 2016.

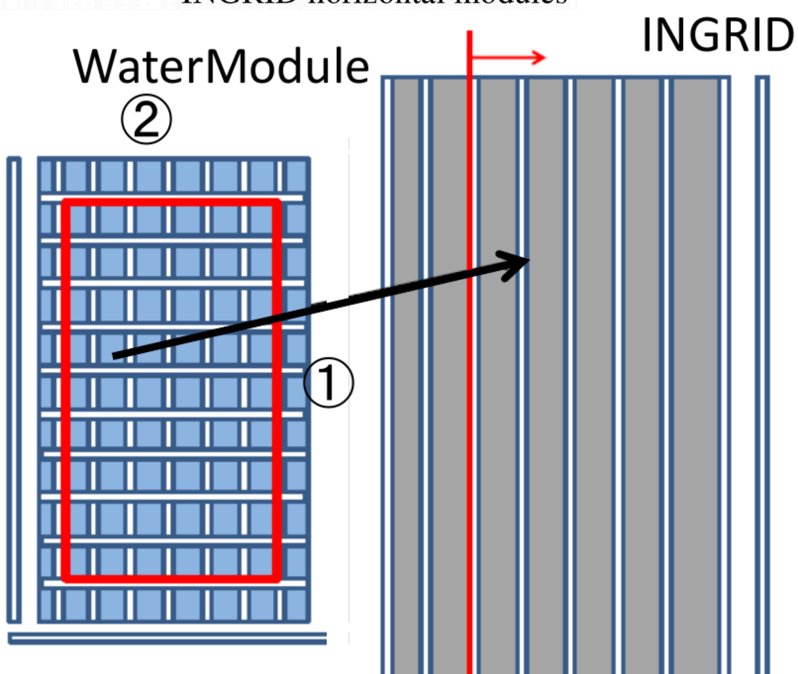


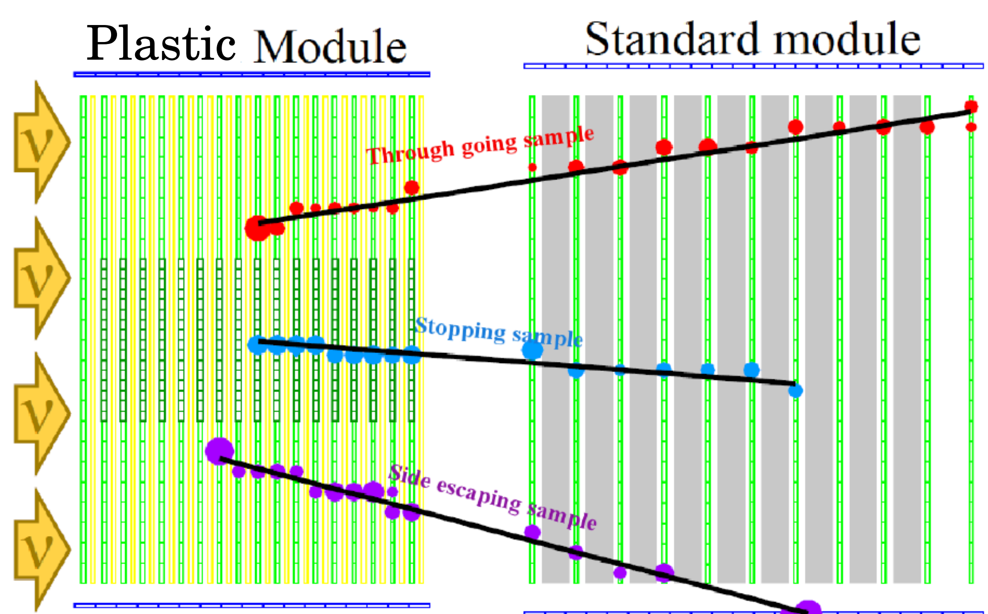
Our first neutrino event !



Goals :

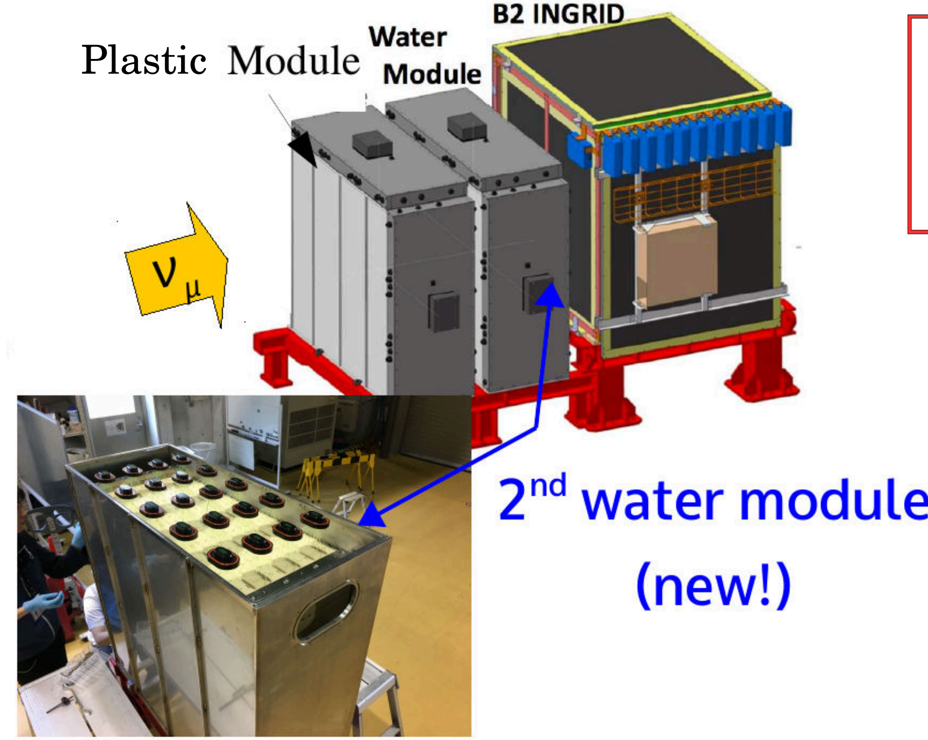
1. Demonstrate module performances
2. Measure absolute XSection of ν / $\bar{\nu}$ on H_2O and H_2O/CH ratio on-axis (E~1.5 GeV)





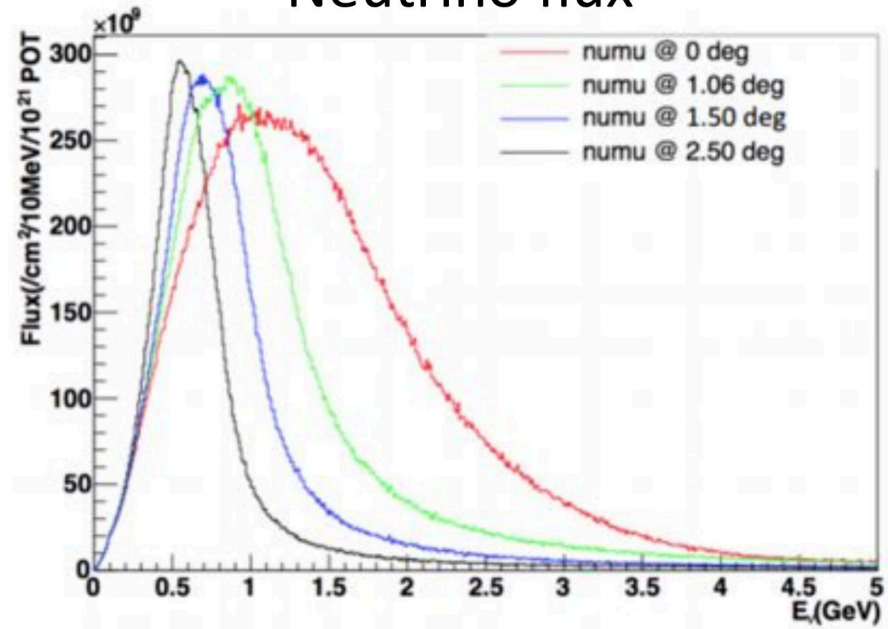
Stage 1 : foward measurement off-axis

Second : Construct another H_2O module and installed @1.6° off-axis few weeks ago.

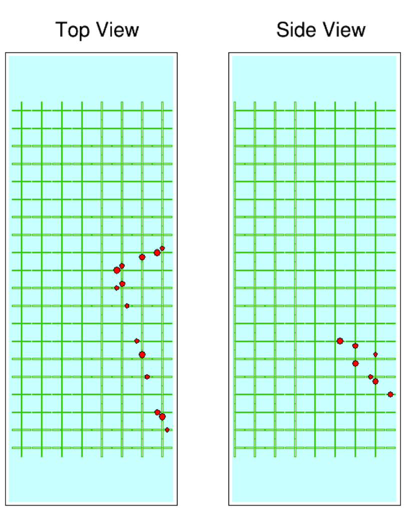


Goals :
Reproduce on-axis measurement at lower energy (~SK neutrino).

Neutrino flux



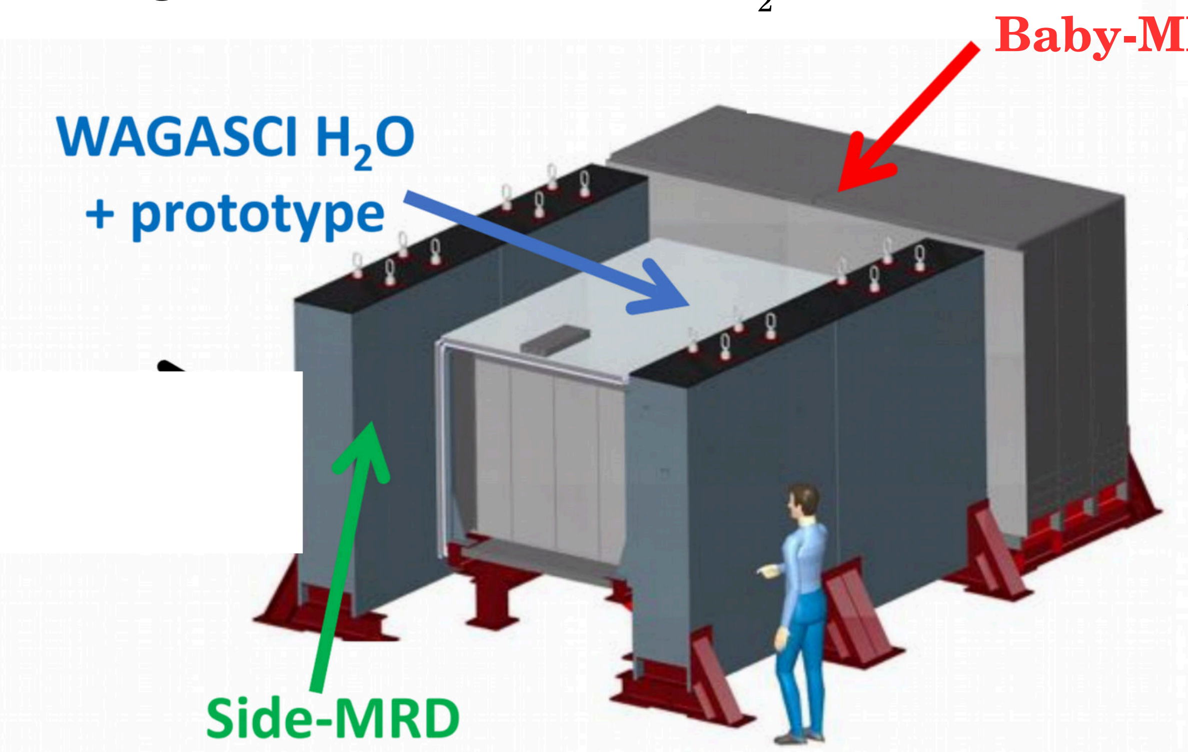
Our first neutrino event !

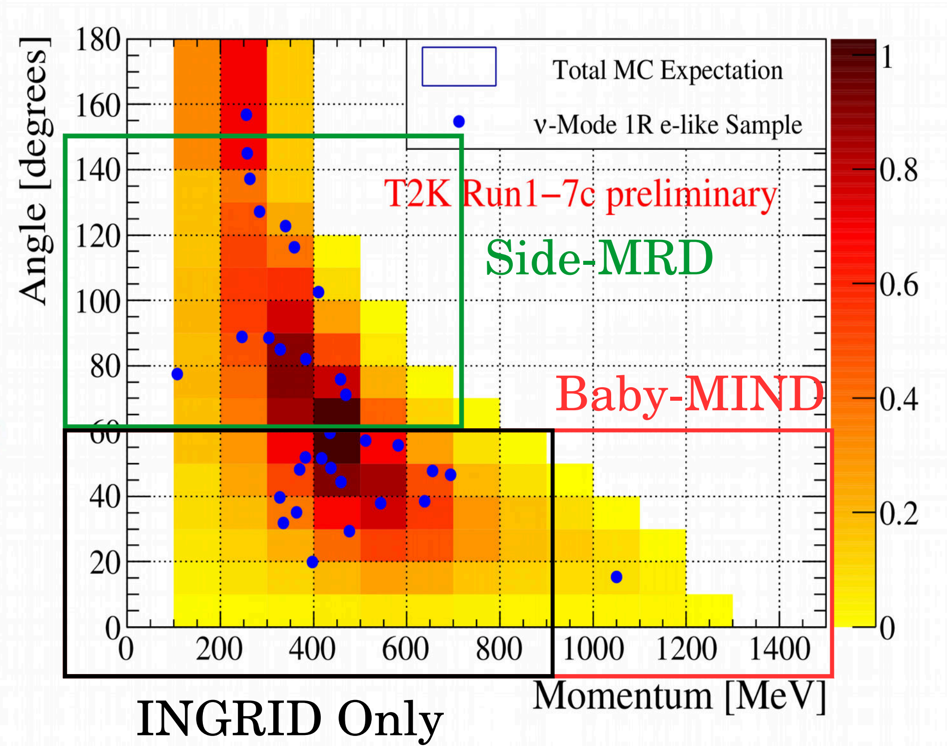


Limited to foward direction (<45 degrees) : muon should penetrate INGRID module for ID.

Final Stage : off-axis 4π measurement

Final goal : 4π cross-section on H_2O @1.6° off-axis → Covers SK phase space.





Requires :

1. Measure momentum 2 GeV/c with 50 MeV/c resolution

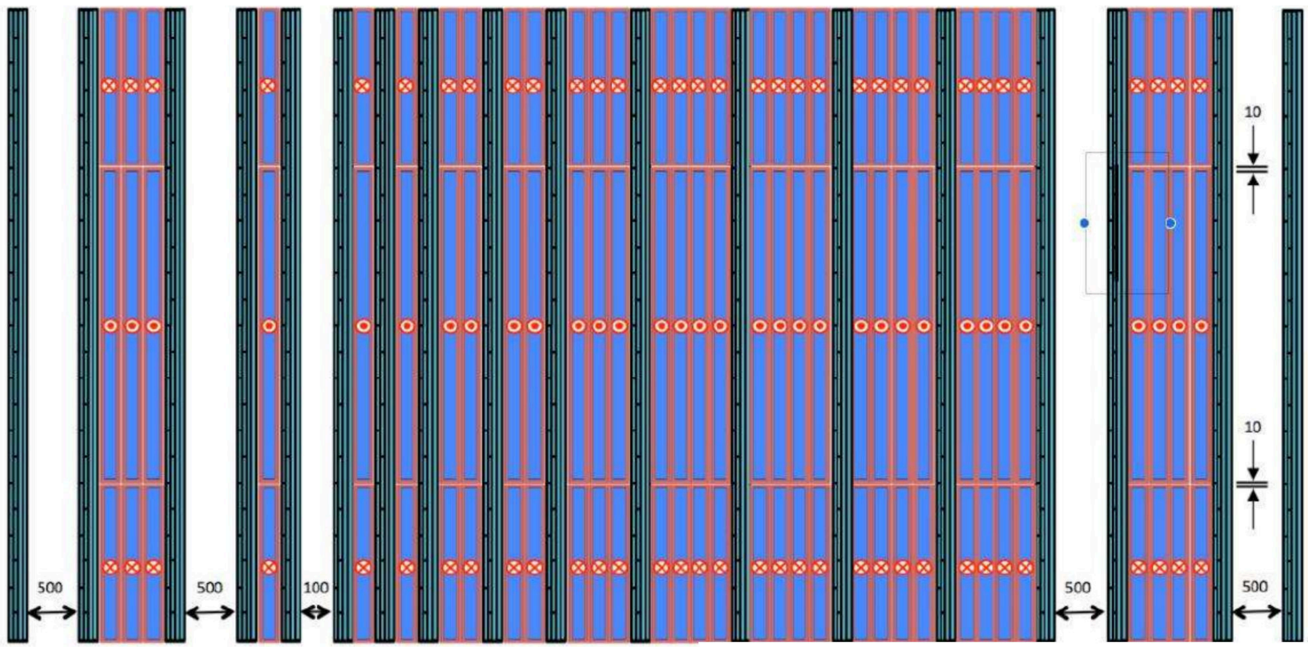
2. Separate 25 % ν contamination in $\bar{\nu}$-mode (Baby-MIND)

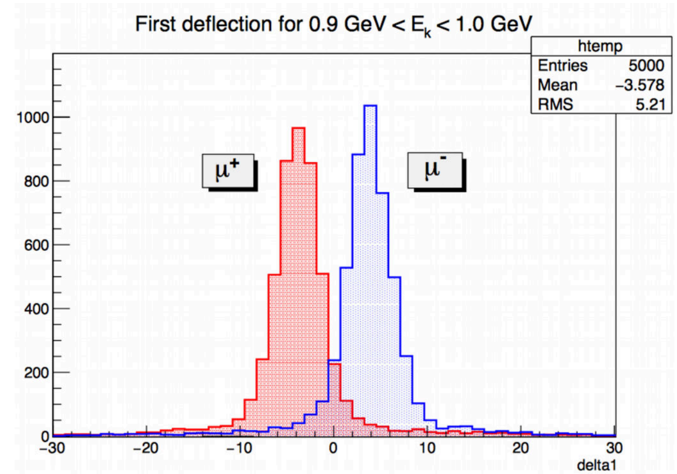
3. High angle muon range detectors (Side-MRD).
2 modules of vertical scintillators of 180 x 20 x 0.7 cm^3.

INGRID cannot separate + 150 MeV/c resolution up to 900 MeV/c
→ Baby-MIND

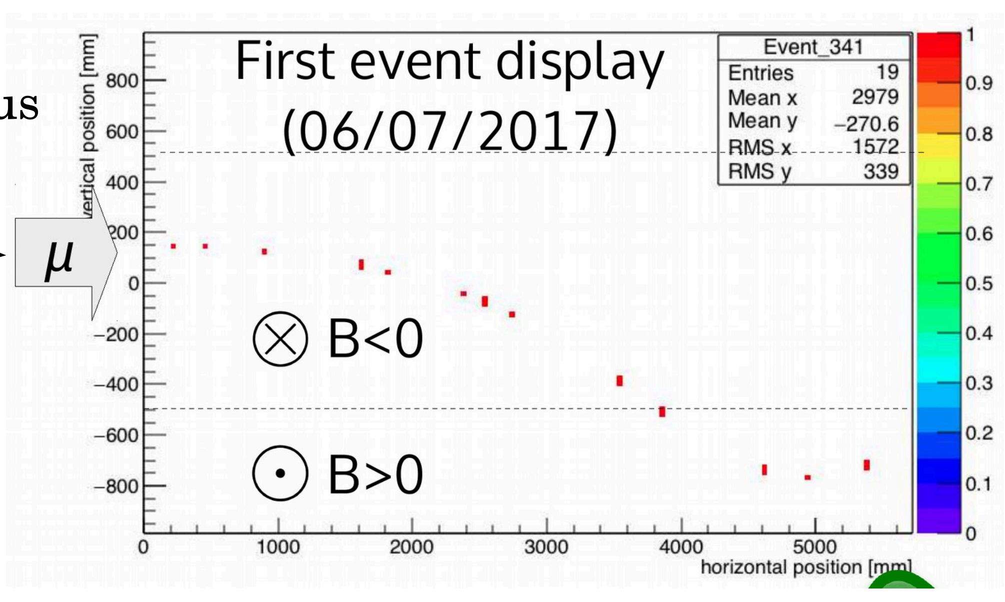
→ Assembly is starting at Yokohama National University : ready before Apr. 2018

(Iron-) Magnetized downstream detector : 33 iron layers sandwiched w/scintillators





- Beam tests @CERN in June & July with various beam of different energy & polarization.
  Example of muons

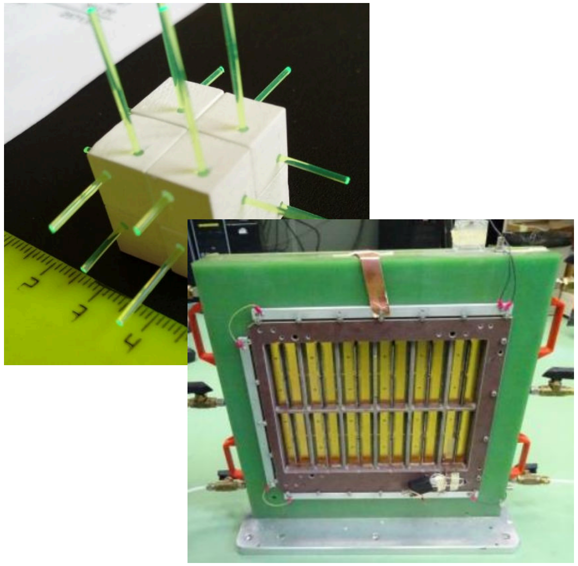


- Arrive @JPARC in Dec 2017.

- Start 4π measurement in April 2018.

Conclusions

T2K-II aims for the first evidence of CP violation → Requires ND upgrade for a better coverage of the SK phase space.



1. Upgrade the existing ND280 detector :

Upgrade has actively started
→ Relies on horizontal TPC and 4π fully active target.

R&D has already started both for Super-FGD target and new TPC

→ Goal to be installed by 2020.

2. Use measurements of a new water-based 4π detector : WAGASCI

1. Promising cross-section results for CCinclusive, and exclusive channels are coming
→ On-axis foward measurements

2. A 2nd WAGASCI module successfuly started taking data from Oct. → New results @1.6°.

3. Start 4π measurement from April 2018.

→ Walk towards the first hint of 3σ CP violation in neutrino !

Additional slides

Choice of a fully active target

ND280 upgrade will have a fully active target :

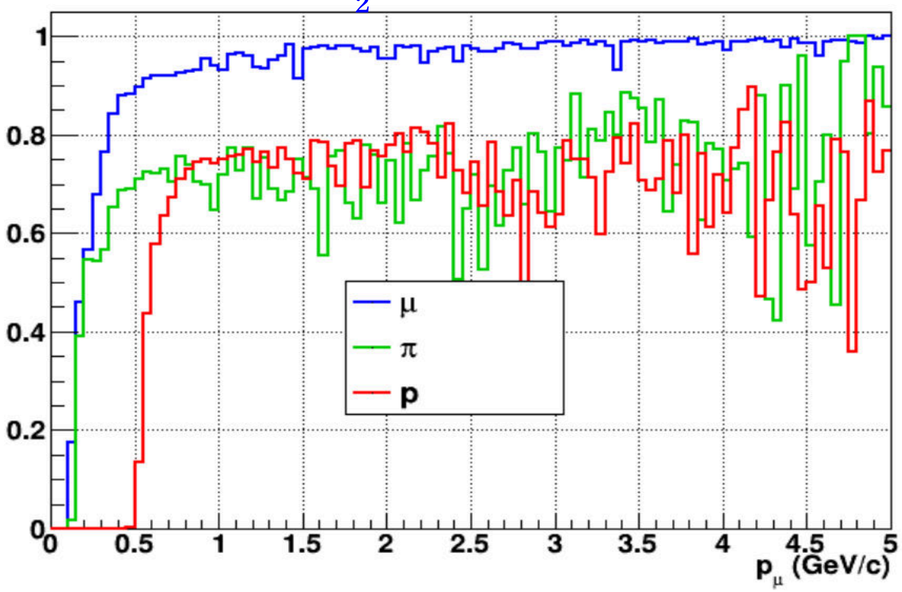
C target : (Not H_2O)
Difficult to use active water

→

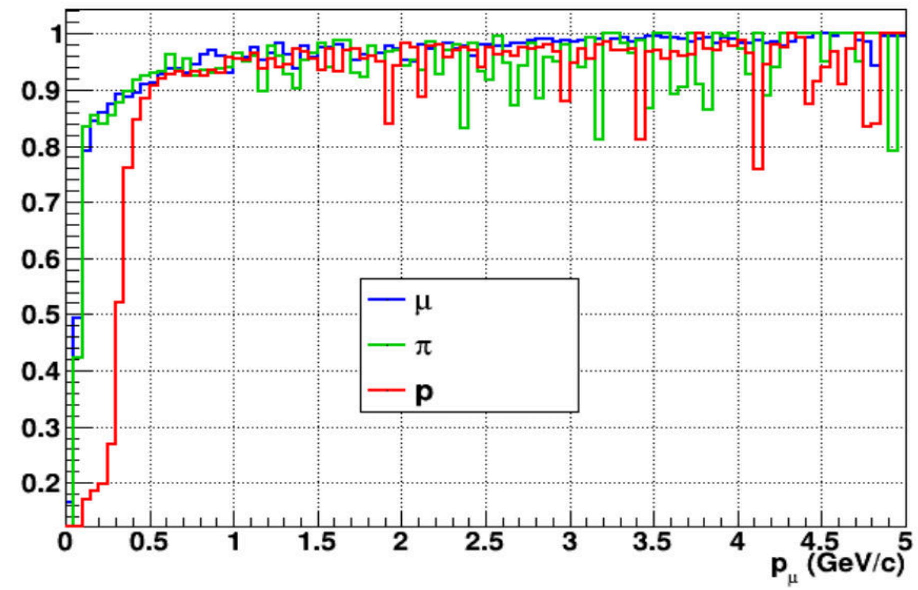
1. FGD2 40 % water → O/C difference extrapolated at SK for foward region.
2. Likely that statistics at large angle ≪ model differences between O and C.
3. There is WAGASCI (see end of this talk)

High granularity :
low momenta hadron tracks, calorimetric information

H_2O module



Empty module



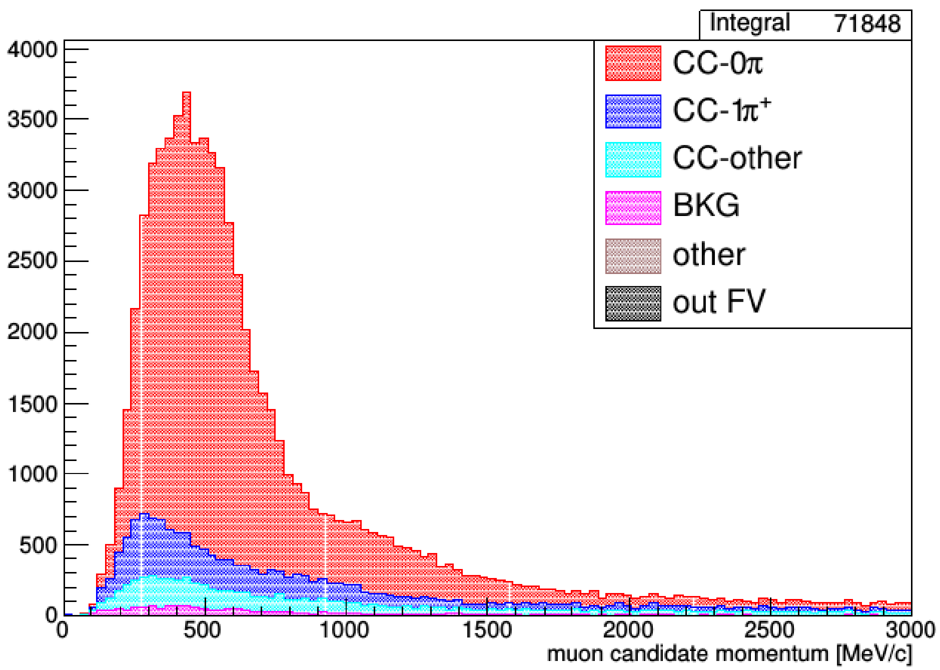
Impact on the selected interaction

M. Lamoureux

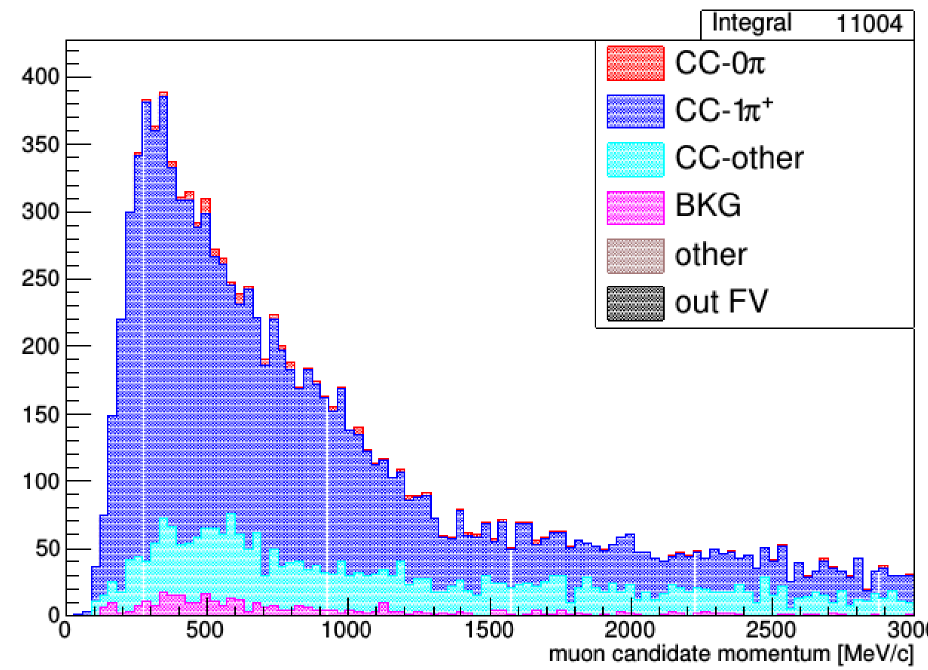
		# evts (/10^{21} POT)	purity (in %) CC0π	CC1π	CCother
current	FGD 1	47337	75.9	64.4	61.8
	FGD 2	45939	75.7	65.1	64.4
upgrade	FGD 1	48374	74.7	64.5	70.2
	FGD 2	45719	73.4	63.8	70.1
	H.Targ.	100295	74.1	72.9	70.6

Muons not contained in the target only

CC-0π selection

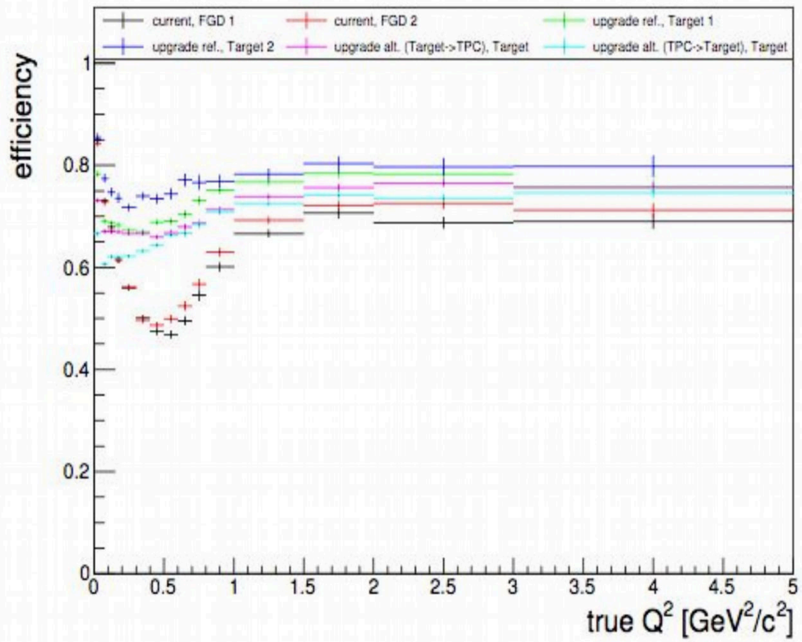


CC-1π selection



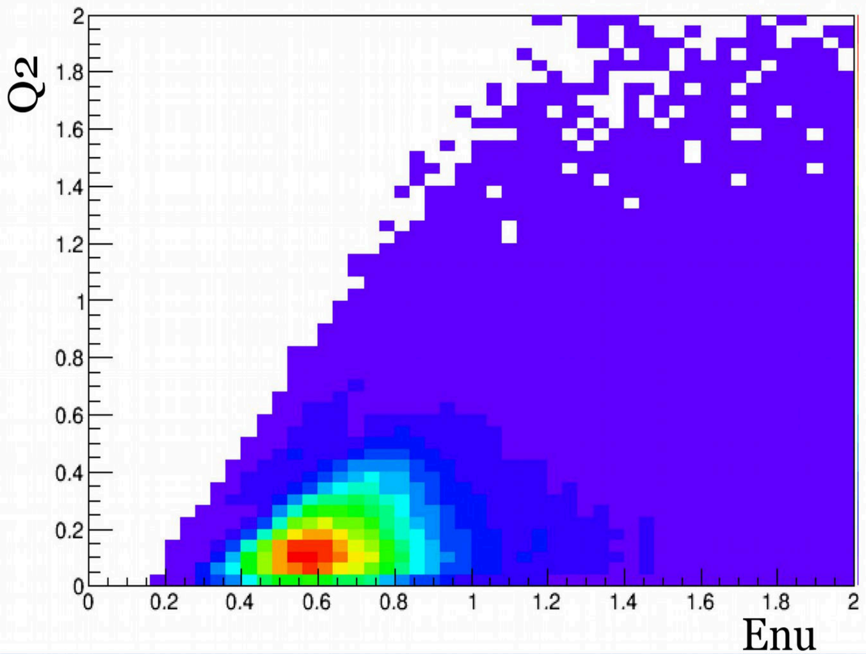
Fake data studies

Important to improve the Q2 coverage to better constrain the non-CCQE xsec components

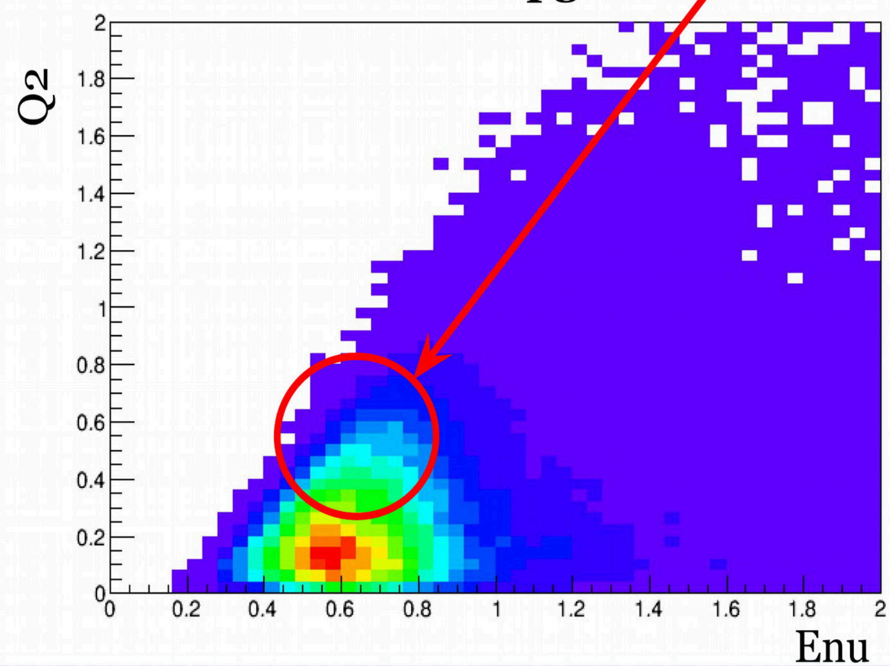


Region of interest of T2K

Current



Reference upgrade

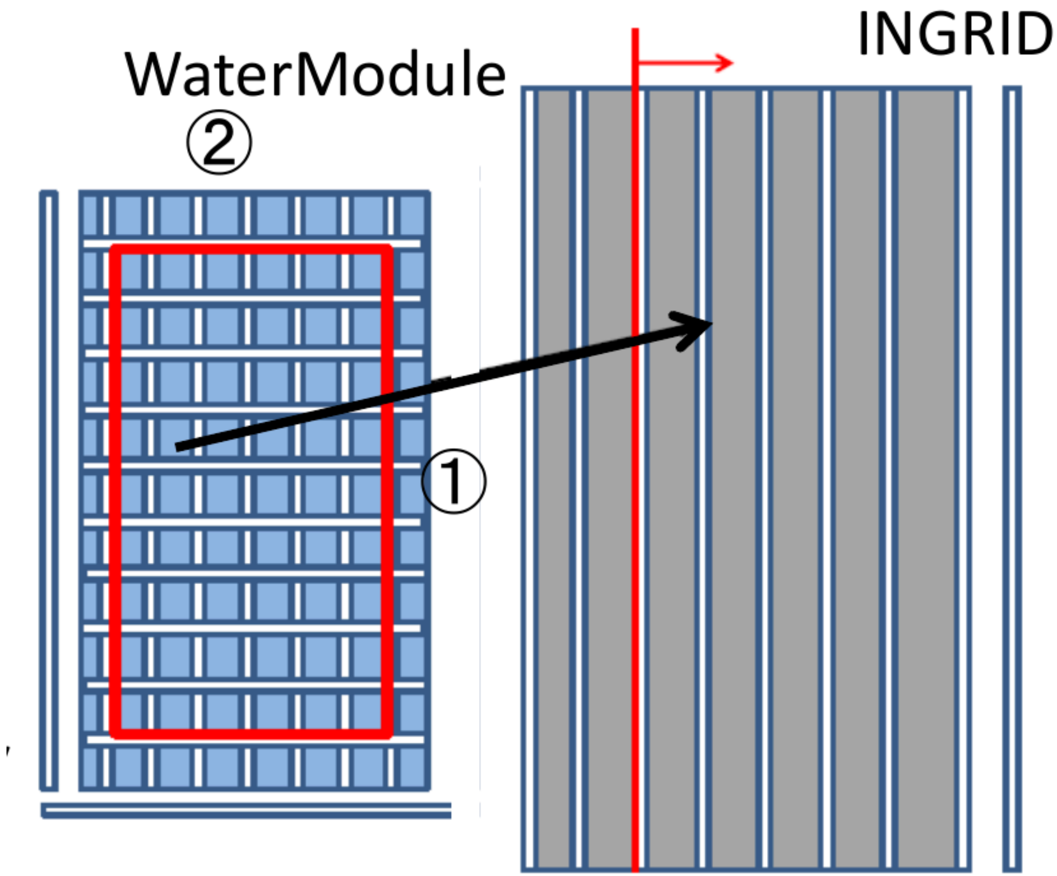


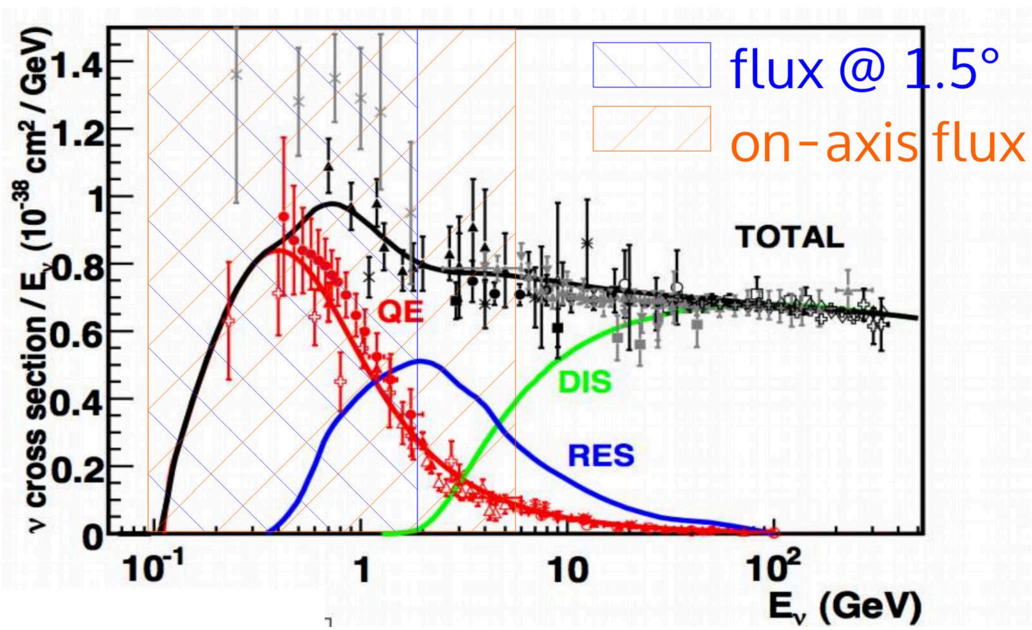
Benjamin Quilain

Goals :

Measure absolute XSection of ν / $\bar{\nu}$ on H_2O and H_2O/CH ratio for CC-inc., CC0π, CC1π.

→ Use the prototype module and the proton module.





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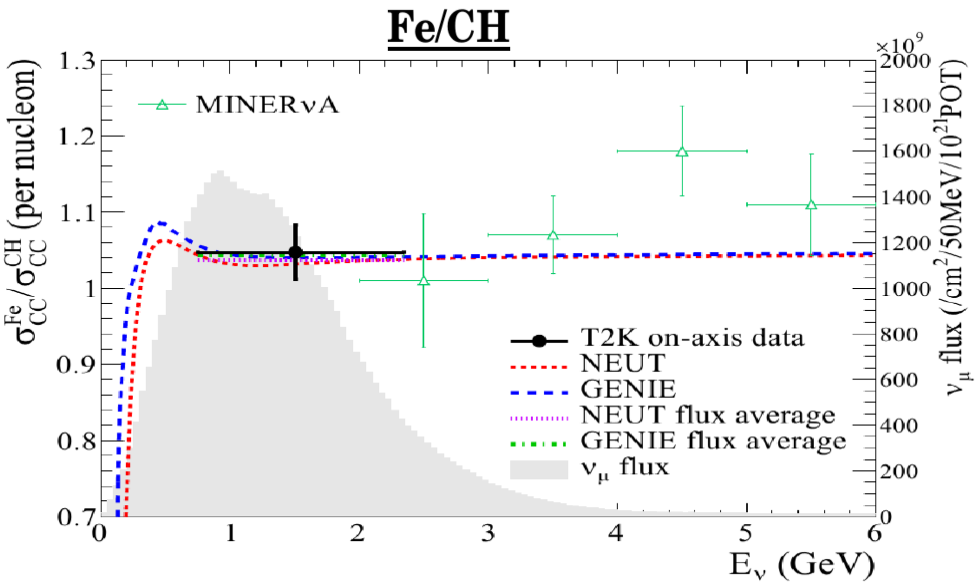
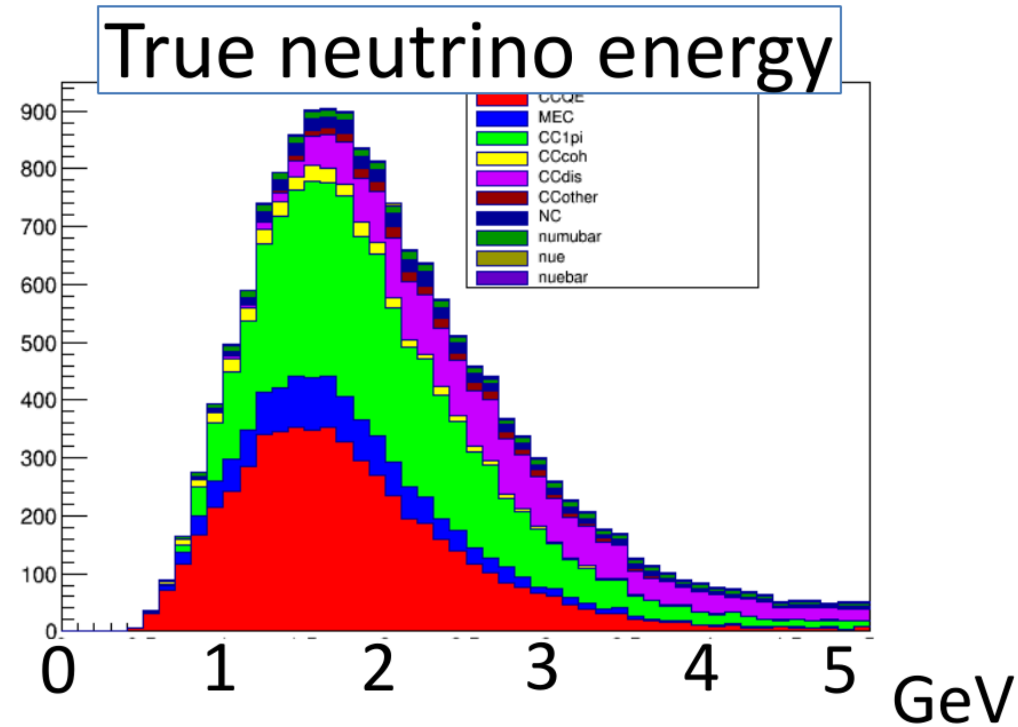




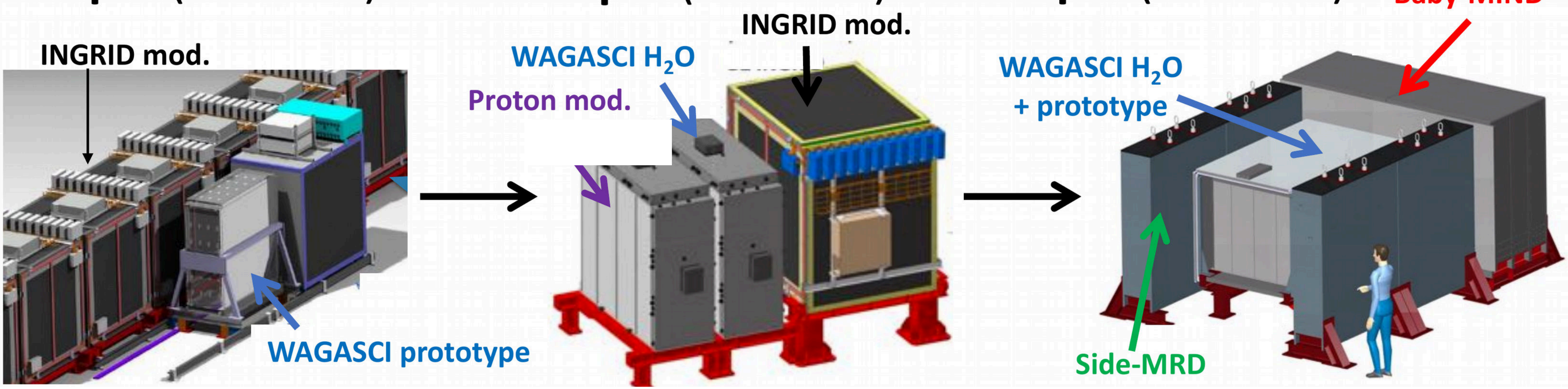
The selection is not detailed here, but very similar to INGRID and PM.

<u>After selection, for 7x10^{20} POT</u>

Selection	Data	MC							
		CC	NC	$\overline{\nu_\mu}$	ν_e, $\overline{\nu_e}$	CH B.G.	Wall B.G.	ING B.G.	All
Vertexing		4.16×10^4	1.66×10^2	1.12×10^3	3.78×10^2	1.03×10^4	9.10×10^5	2.64×10^5	1.23×10^6
Front veto		2.62×10^4	1.04×10^3	7.05×10^2	2.33×10^2	6.31×10^3	8.09×10^4	1.34×10^4	1.29×10^5
Fiducial		1.17×10^4	4.68×10^2	3.36×10^2	1.06×10^2	3.32×10^3	3.49×10^2	5.34×10^2	1.69×10^4
Track angle		1.13×10^4	4.53×10^2	3.34×10^2	1.05×10^2	3.21×10^3	3.47×10^2	5.26×10^2	1.63×10^4

→ Statistical uncertainty is 1.3% for H_2O measurement and 1.6% for H_2O/CH.

Step 0 (JFY2016) **Step 1** (JFY2017) **Step 2** (JFY2018)



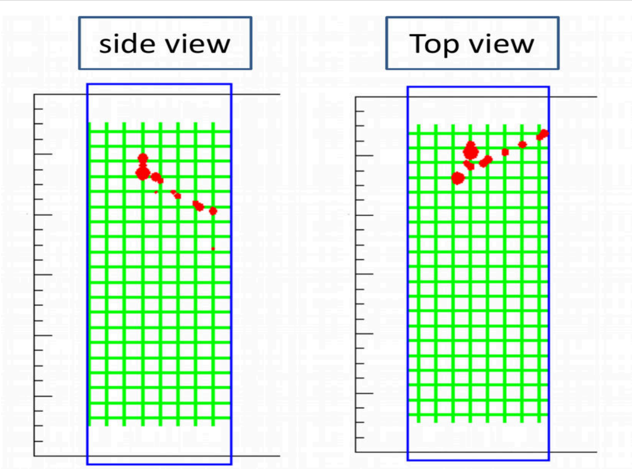
Oct. 2016 Oct. 2017 Apr. 2018

<u>On-axis :</u>
Prototype module
ν measurement

<u>On-axis :</u>
Prototype module
$\bar{\nu}$ measurement

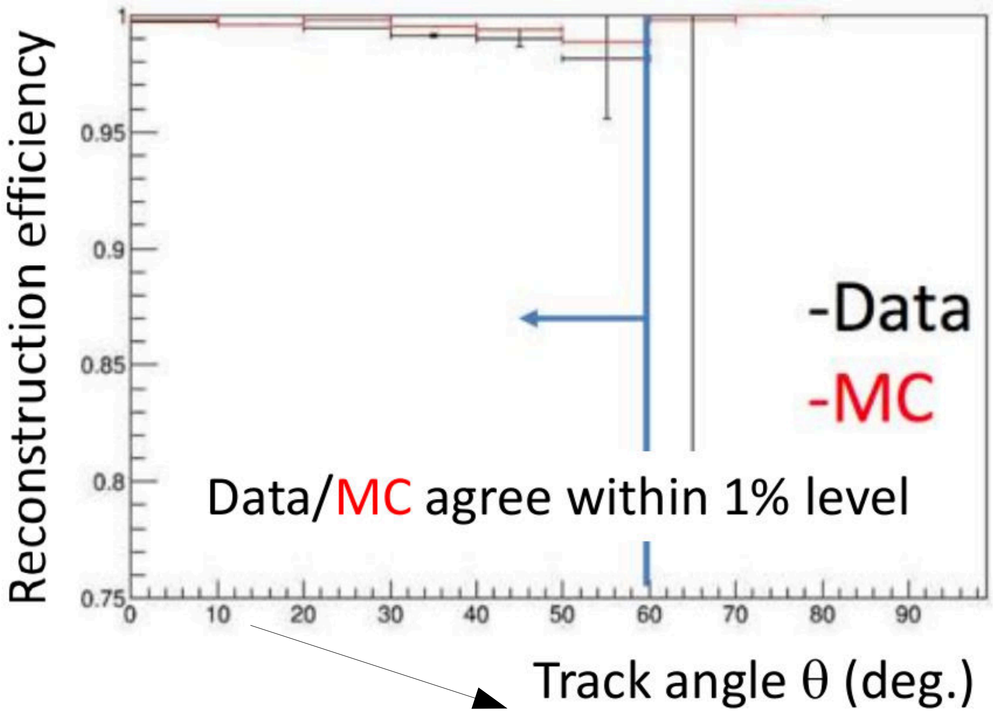
<u>1.5° off-axis :</u>
H_2O module
$\bar{\nu}$ measurement

<u>1.5° off-axis :</u>
H_2O + prototype modules +
Side-MRD + Baby-MIND

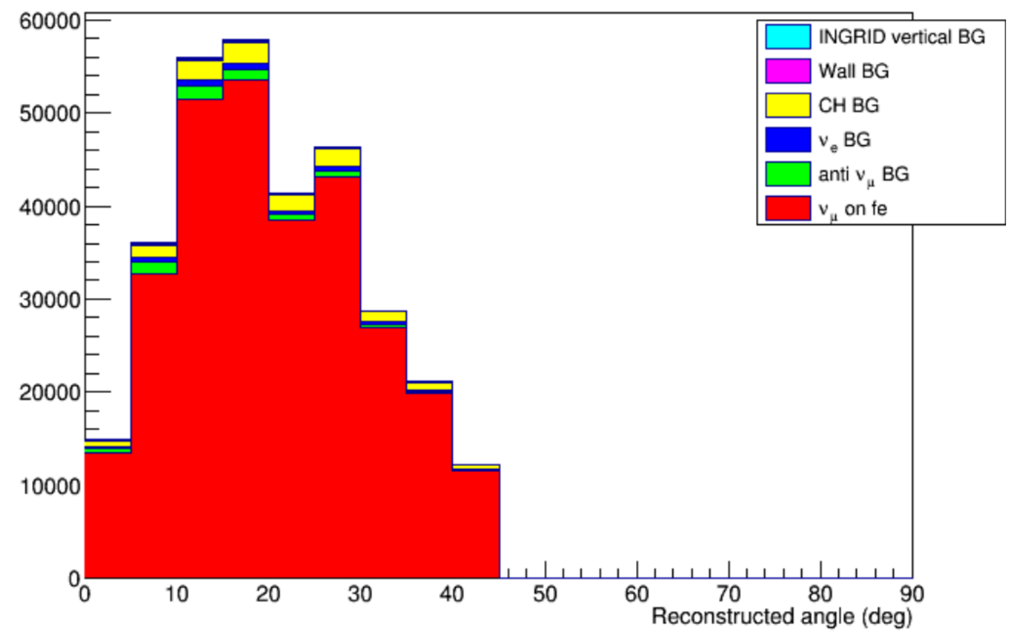


Results of stage 0 : the prototype module

Track reconstruction efficiency :



CC-inclusive results:



Confirmed light-yield & 2π abilities.

CC-inclusive measurement passed the T2K cross-section group review (T. Koga).

Other results will be released soon : differential measurements (M. Licciardi & B. Quilain)

Systematic errors (so far):

Absolute H_2O systematic error ~10 %

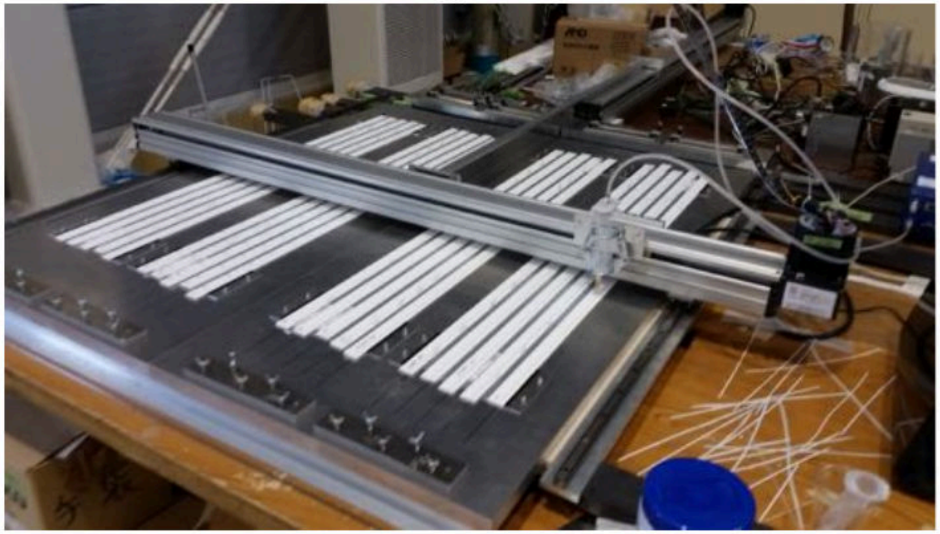
H_2O/CH ratio systematic error ~ 3-5 %

Detector error dominated by external background contamination → No veto planes.

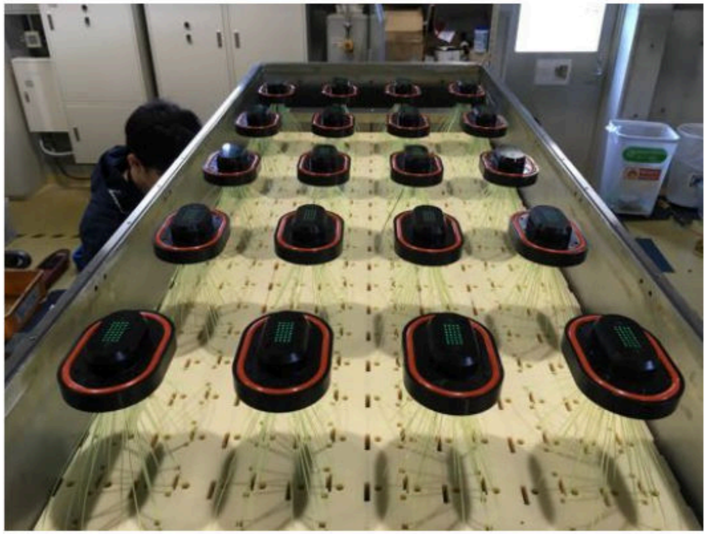
Assembly status of stage 1

July 2017 : Assembly of WAGASCI H2O module completed. Leakage tests. Channel testing with Easiroc module.

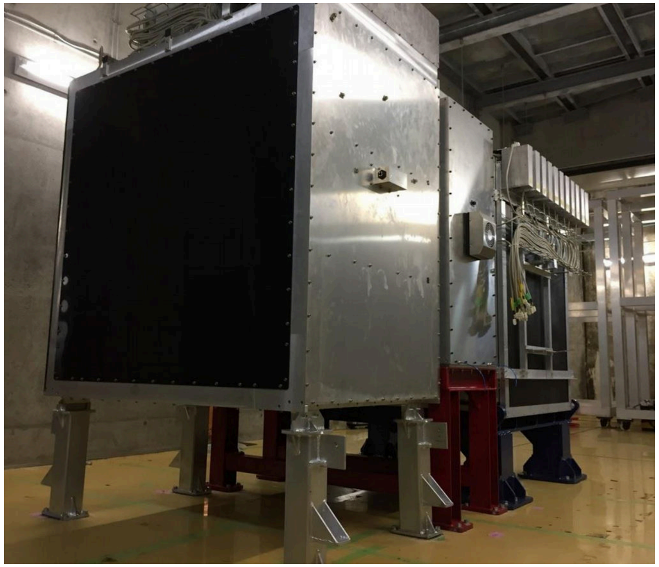
Glue WLS fibers to grooves of scintillators



Assembly of H_2O module

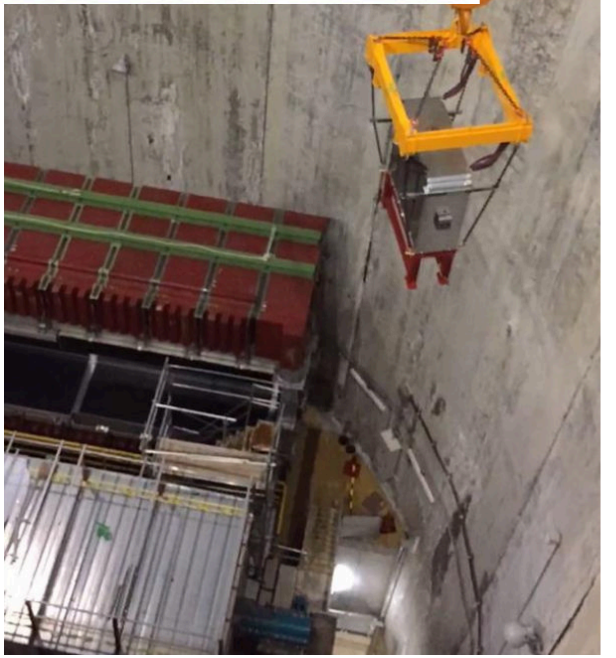


5th of August 2017 : installation of WAGASCI H2O module at B2.

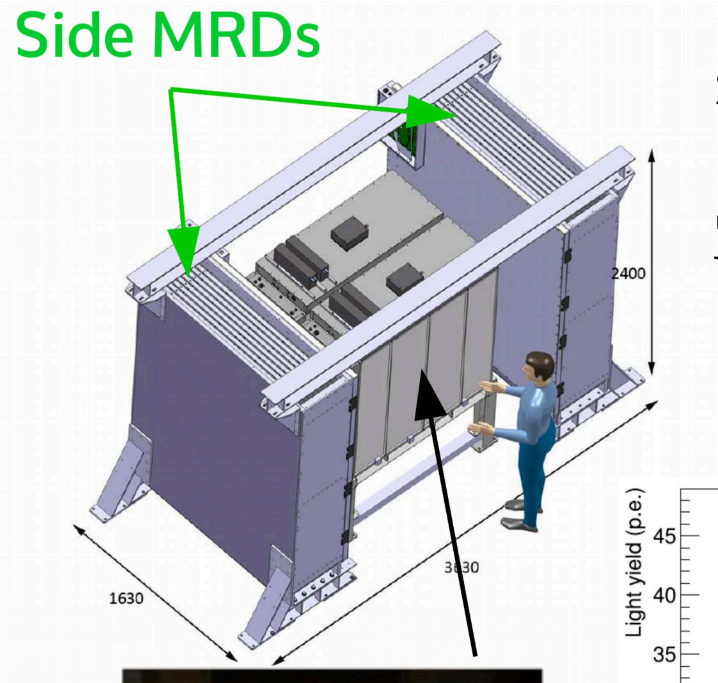


Successfully done !

Proton module, water module and one INGRID module areat B2 !



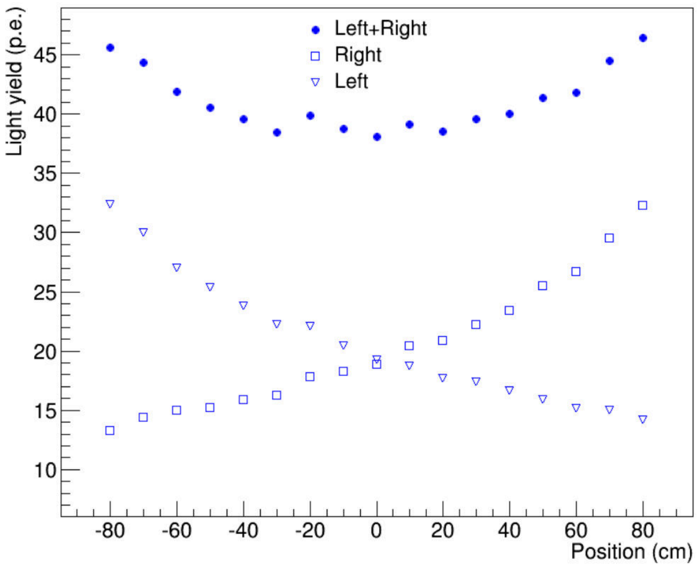
<u>Goals :</u> Extend the foward measurements to the high angle region.



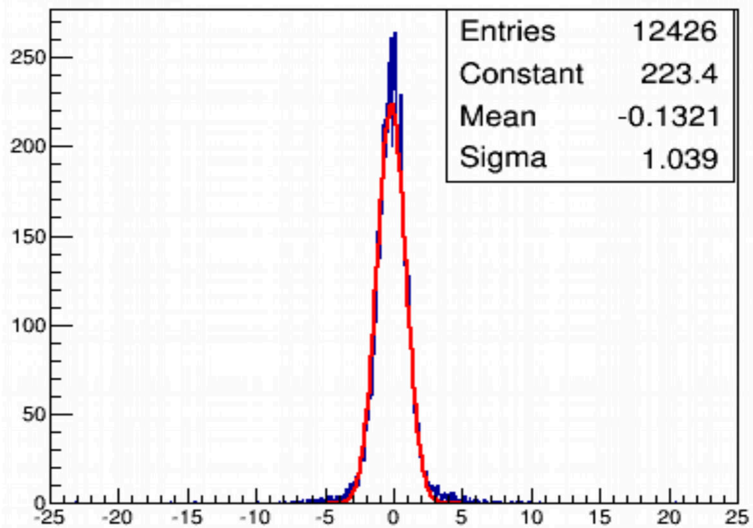
2 modules of vertical scintillators of 180 x 20 x 0.7 cm^3.

S-shape scintillator w/ 2 read-out : allows to determine the Y position with time-difference

<u>Light yield :</u>



<u>Timing resolution :</u>

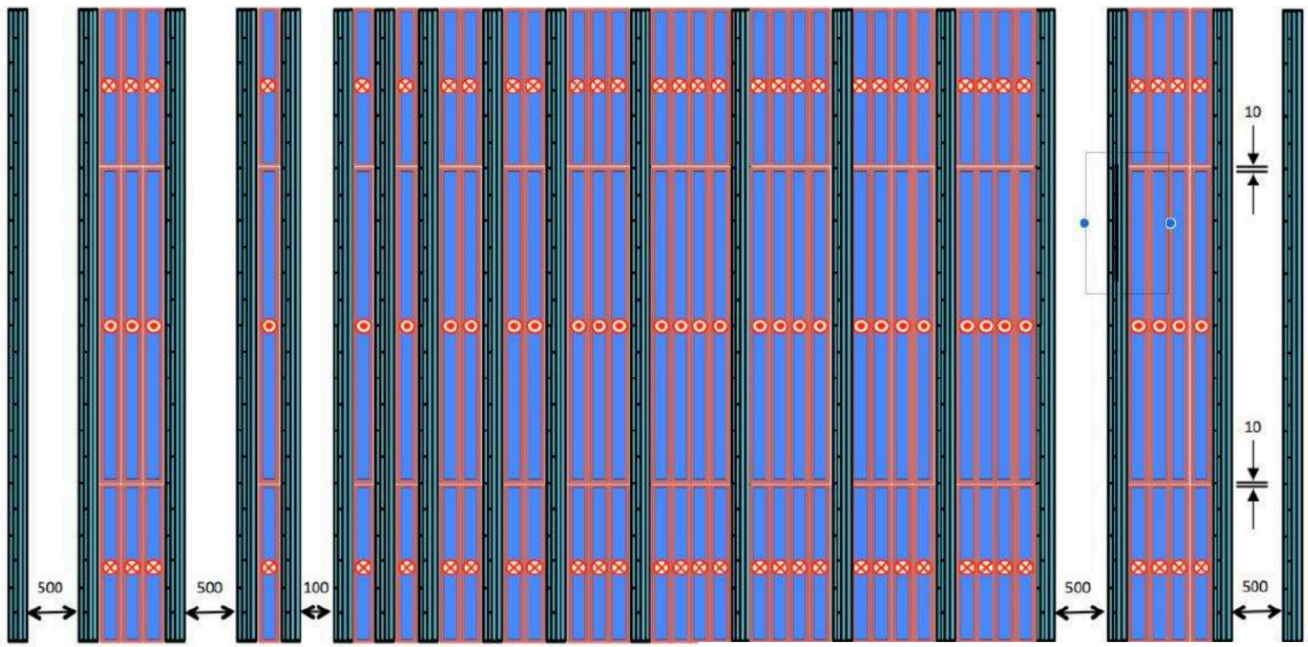


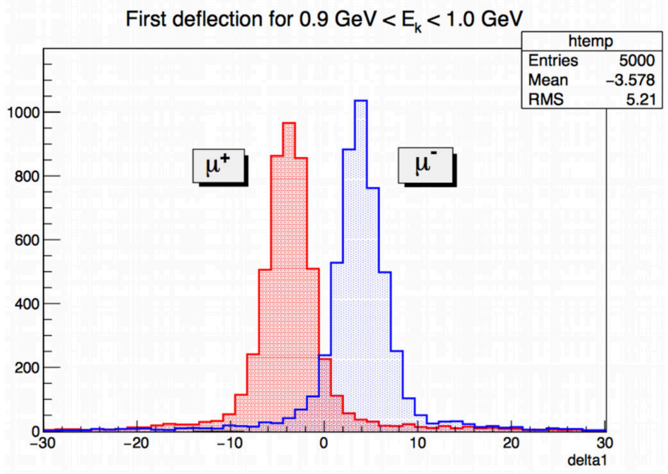
<u>Spatial resolution in Y direction :</u>

$$\sigma_x = 6.01\ (cm/ns) \times 1.04\ ns = 6.25\ cm$$

→ Assembly is starting at YNU. Will be ready before Apr. 2018

(Iron-) Magnetized downstream detector : 33 iron layers sandwiched w/scintillators





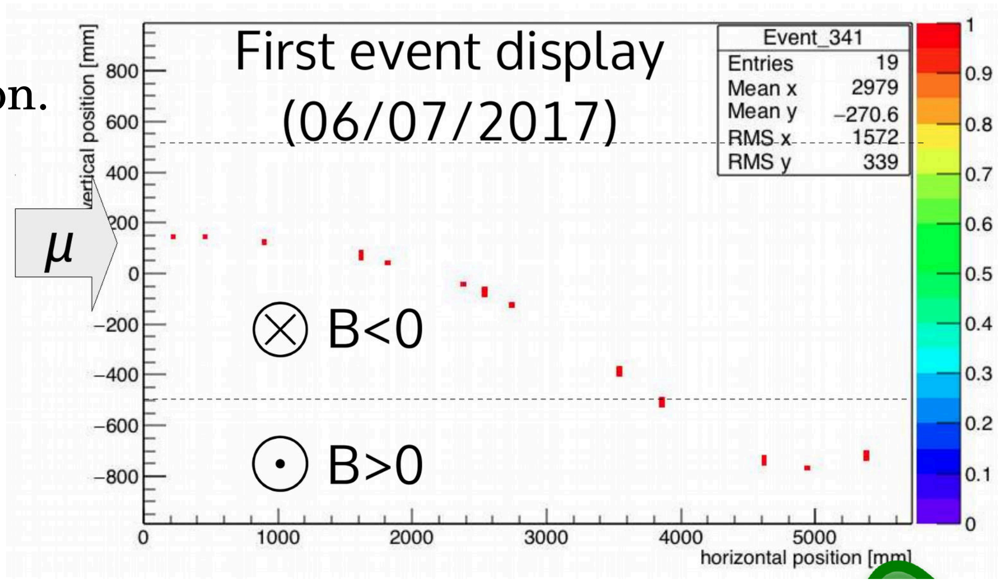
<u>Goals :</u>

1. separate $\nu/\bar{\nu}$ by observing the muon charge.
2. Determine p_μ < 2 GeV/c w/ <100 MeV resolution.

Beam tests @CERN in June & July with various beam of different energy & polarization.

Shipped to JPARC in October 2017.

→ Ready for Apr. 2018.

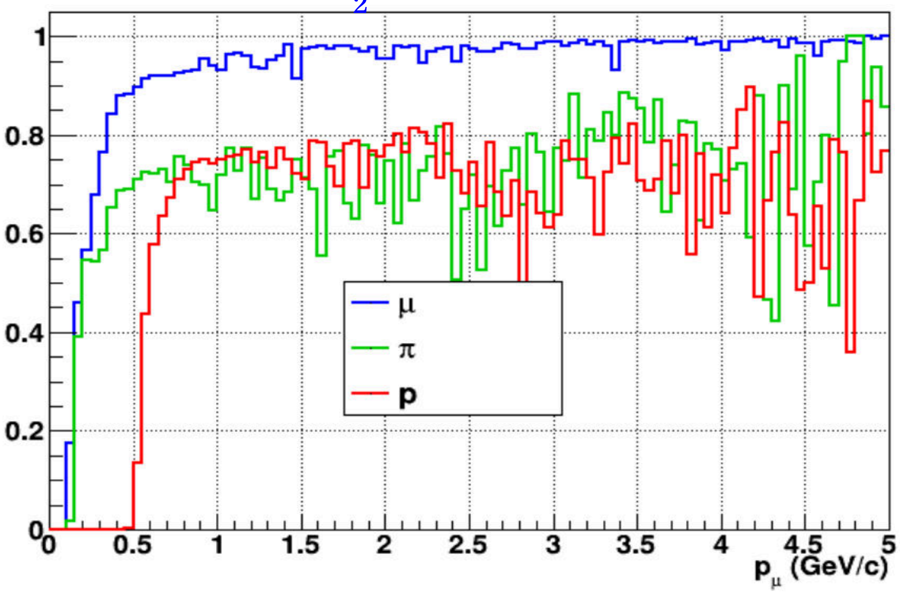


Measurents with an empty module

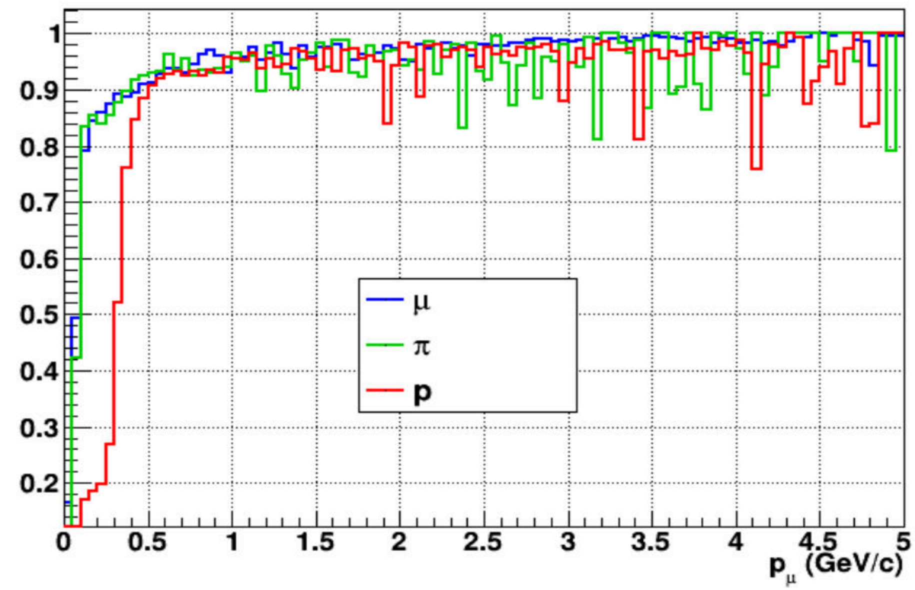
Benjamin Quilain

Reconstruction efficiencies :

H_2O module



Empty module



Proton threshold : 550 → 300 MeV/c :

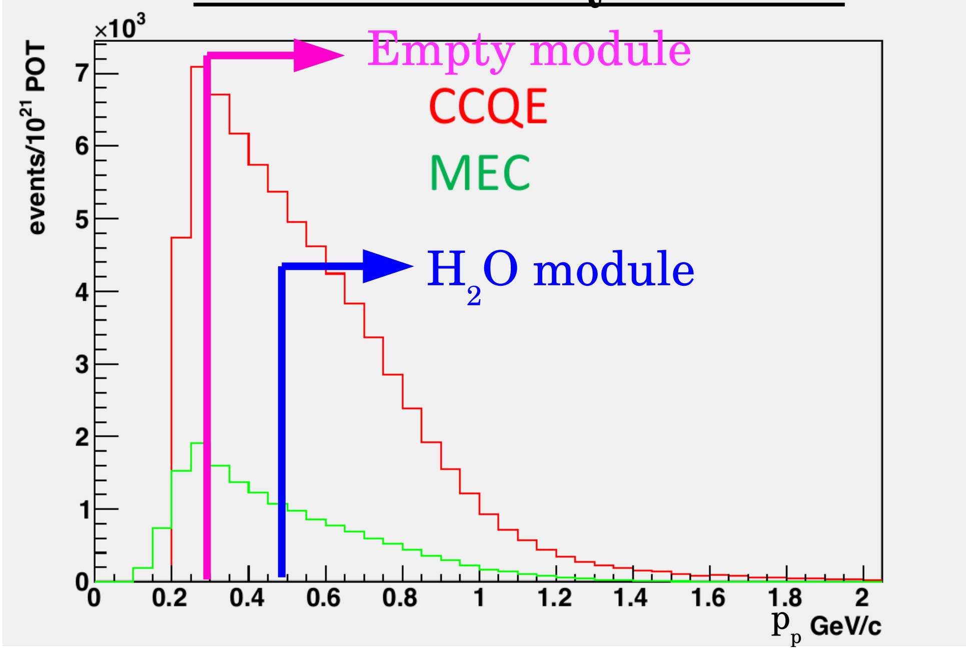
26 % → 70 % of protons are reconstructed

MEC & FSI studies possible !

52 % → 87 % of pions reconstructed

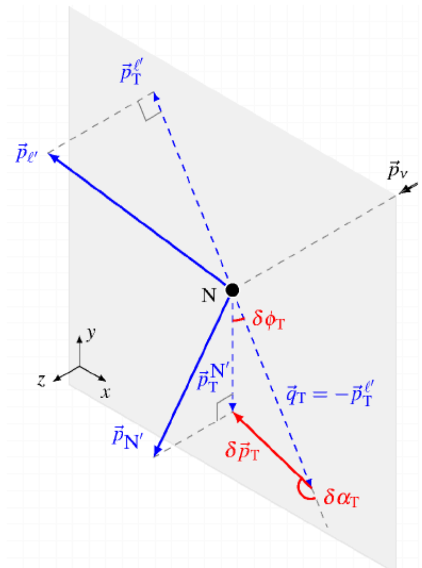
Statistical limitations (1/4 of the water module mass) → Measurement request ~ 4.5×10^{21} POT

Protons from CCQE & MEC :

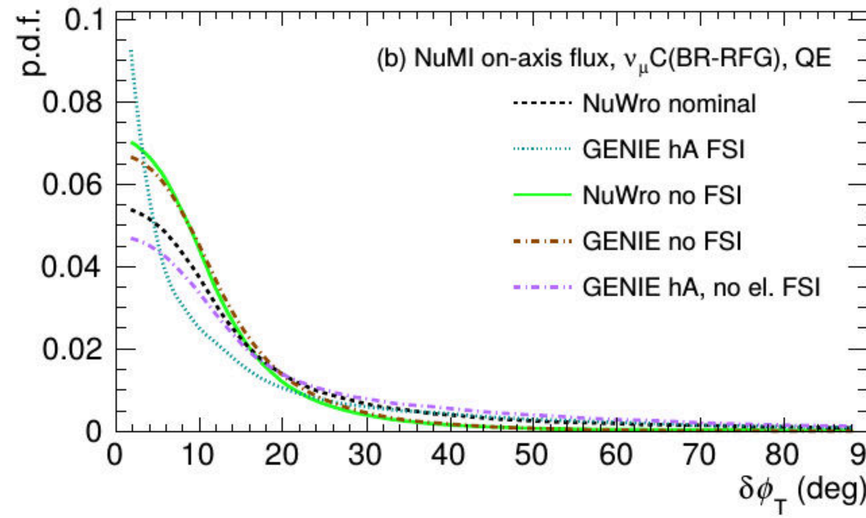


Using transverse variables

Separation on CCQE & 2p2h & FSI effects use proton counting & transverse variables

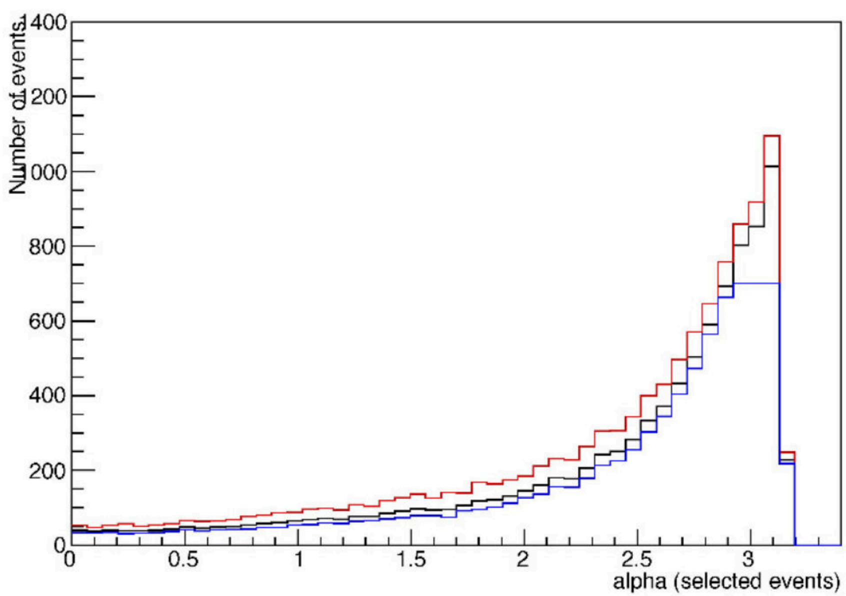


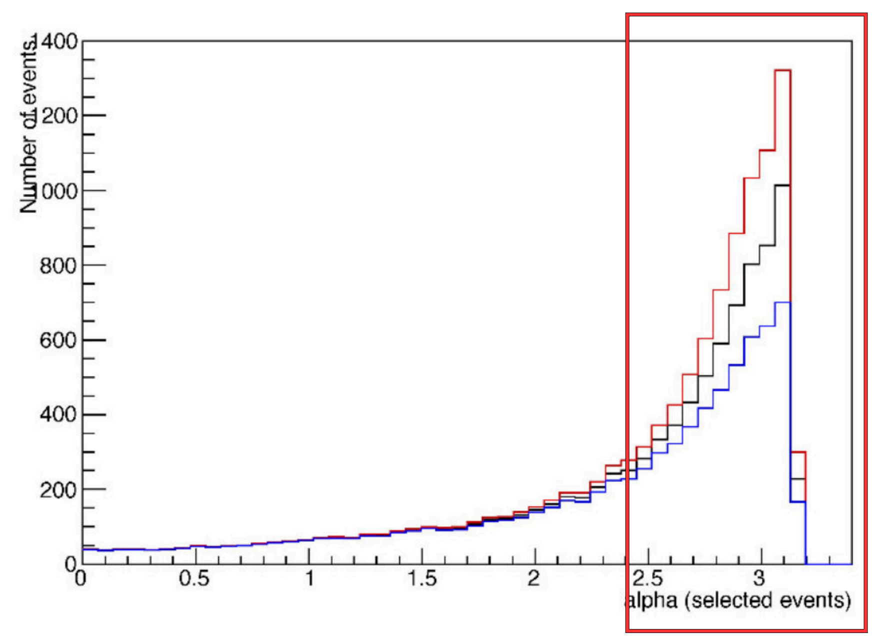
p_p



[7] X-G. Lu, Measurement of nuclear effects in neutrino interactions with minimal dependence on neutrino energy, *Preprint* hep-ex/1512.05748.
[8] X-G. Lu *et al* , , Phys. Rev. D **92(5)**, 051302 (2015).

First results using the PM : no 2π capabilities + most of the track exits → no p measurement





→ Promising separation already seen between 2p2h and Ma effect → will try to pursue